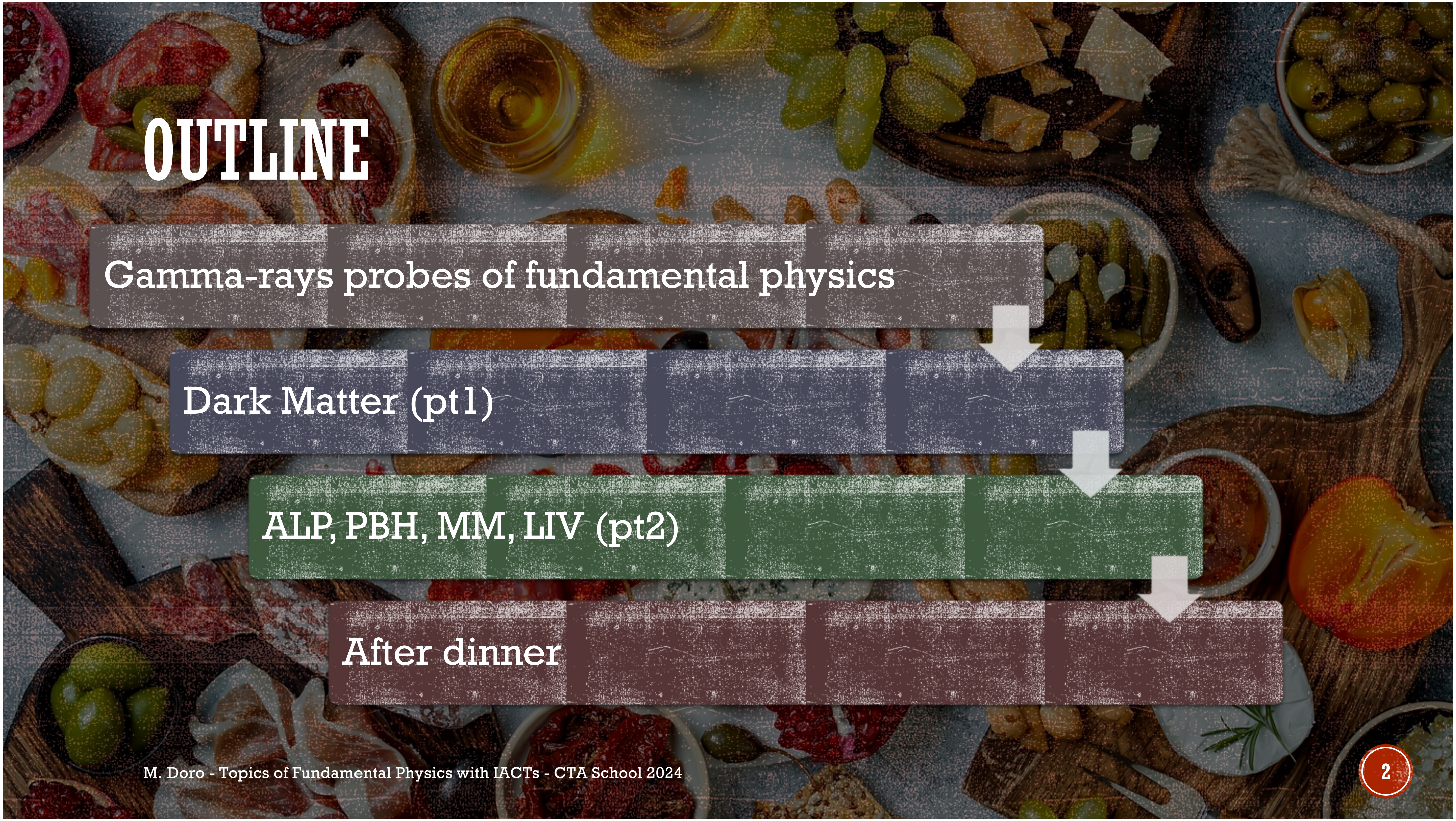
LUNCH WITH ZWICKY'S – PT1

Michele Doro, University of Padova

michele.doro@unipd.it

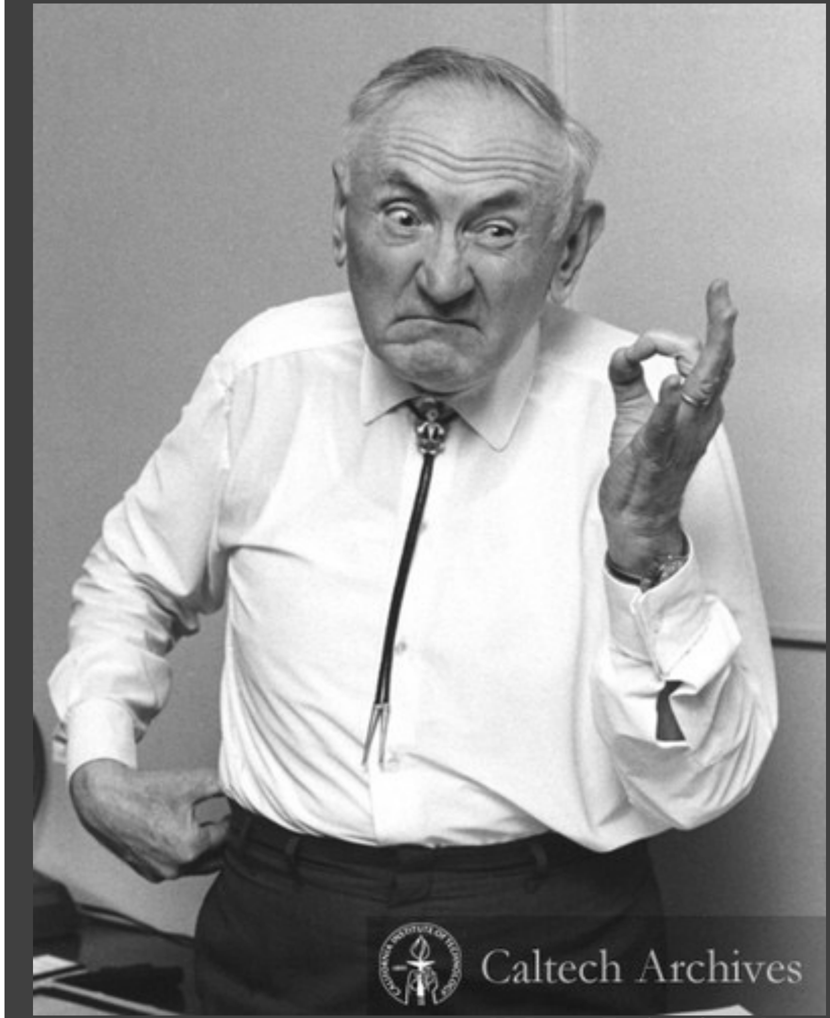
OUTLINE



- Gamma-rays probes of fundamental physics
- Dark Matter (pt1)
- ALP, PBH, MM, LIV (pt2)
- After dinner

LET'S LEAP

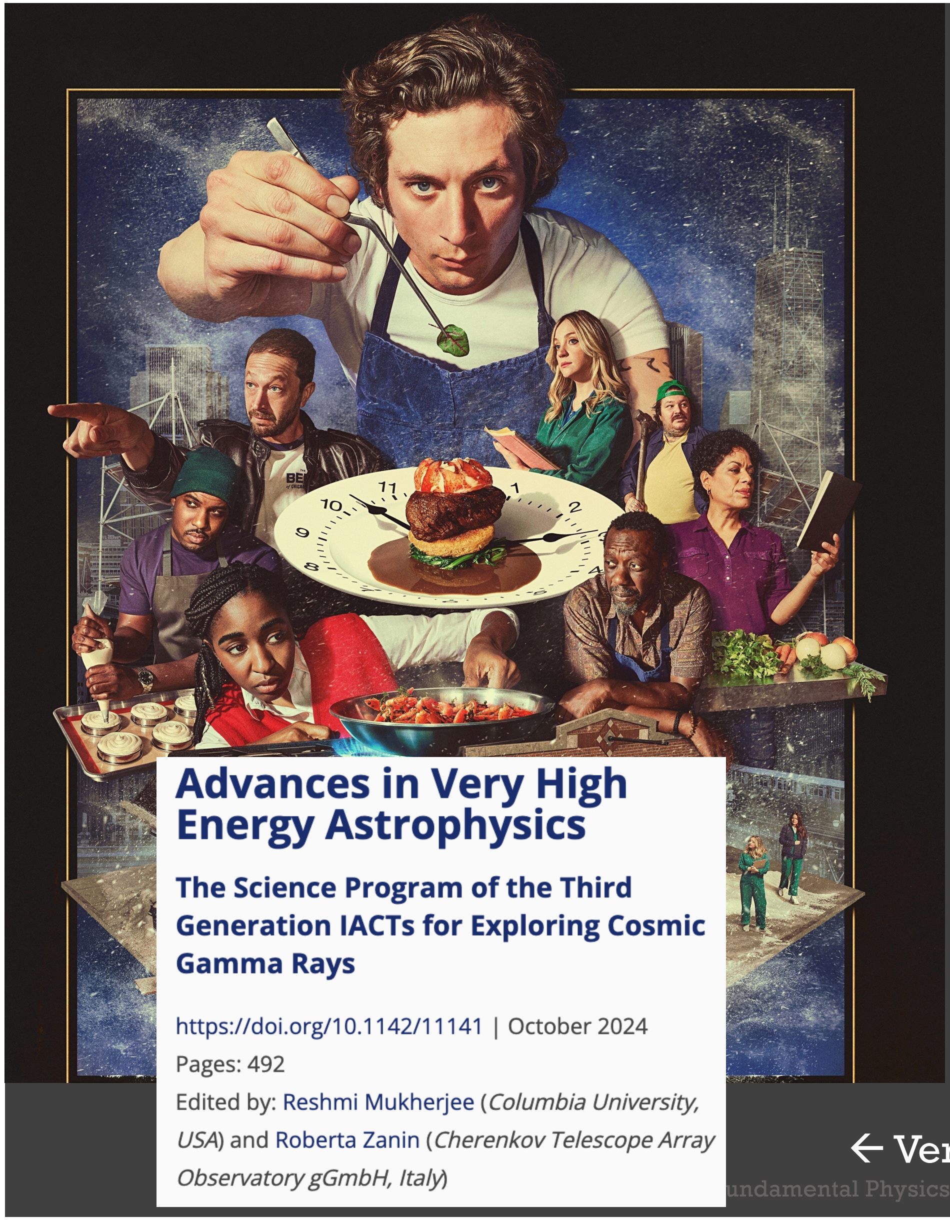
OUR GUEST: FRITZ ZWICKY



I have a good idea every two years. Give me a topic, I will give you the idea! [Reputed to have been a remark made to the head of his department at Caltech.]

- Fritz Zwicky (1898-1974) was a Swiss astronomer. He worked most of his life at the California Institute of Technology

Astronomers are spherical bastards. No matter how you look at them they are just bastards.



Advances in Very High Energy Astrophysics

The Science Program of the Third Generation IACTs for Exploring Cosmic Gamma Rays

https://doi.org/10.1142/11141 | October 2024

Pages: 492

Edited by: Reshmi Mukherjee (*Columbia University, USA*) and Roberta Zanin (*Cherenkov Telescope Array Observatory gGmbH, Italy*)

FROM OUR COOKBOOK

‘Dark matter and fundamental physics with IACTs’

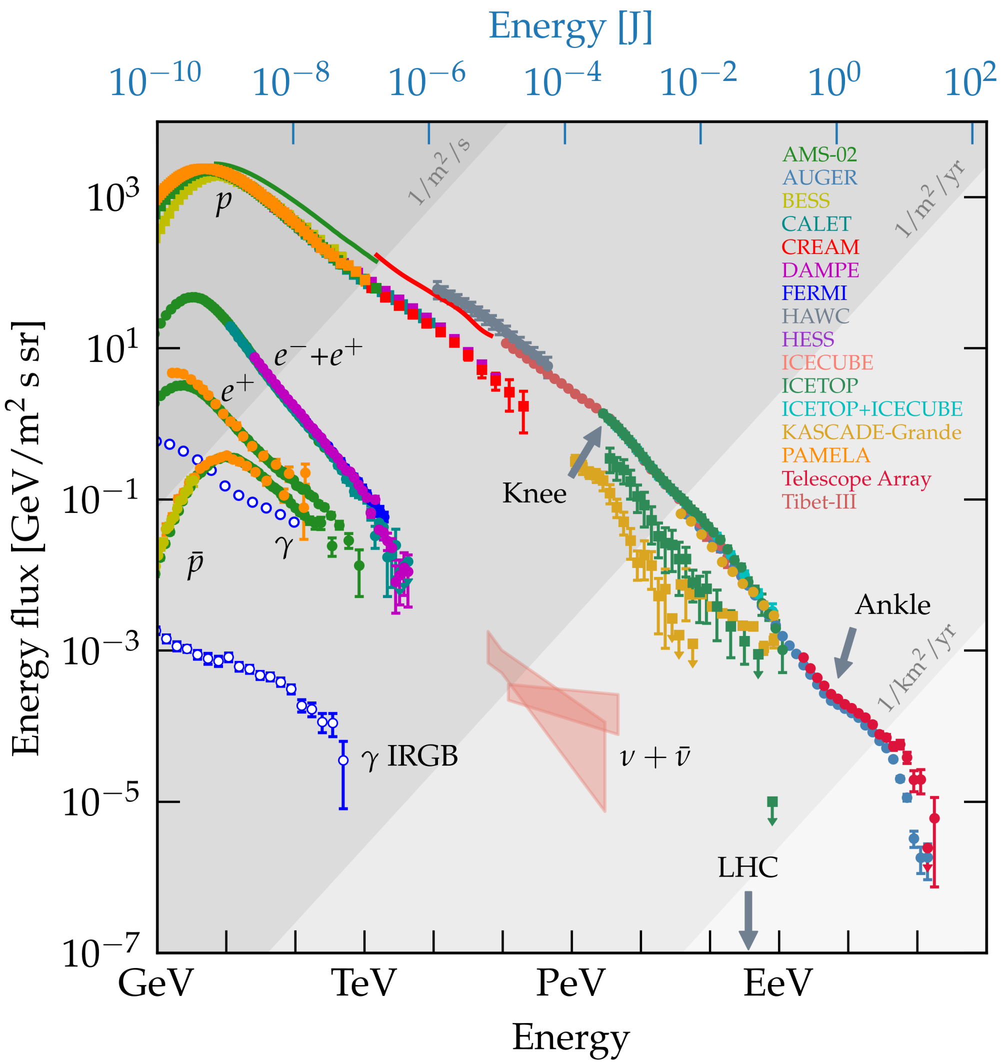
https://arxiv.org/abs/2111.01198

And many other chefs: FG Saturni, G Rodriguez, A Morselli, J Coronado, S. Abe, T Inada, I Batkovic, M. Shoaib, D. Perri, T Kobayashi, G D’Amico, …

← Very slow cuisine

#1 GAMMA-RAY PROBES FOR FUNDAMENTAL PHYSICS

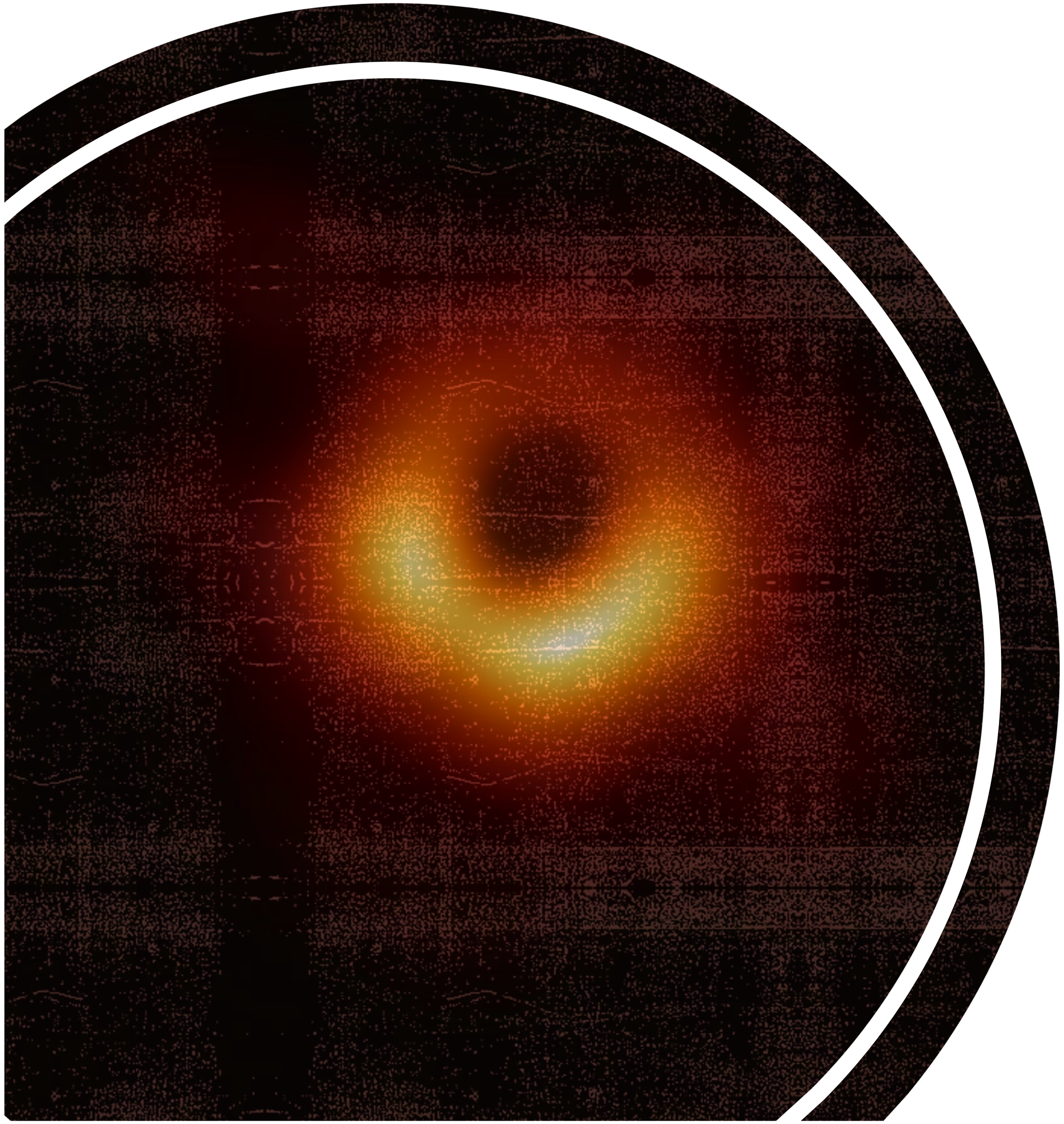
Why they are best suited for fundamental physics (and can't possibly do that at CERN)



Evoli, Carmelo. (2018). The Cosmic-Ray Energy Spectrum. Zenodo. https://doi.org/10.5281/zenodo.2360277

1/ A NEVERENDING POWERFUL ENGINE

- Cosmic rays power up gamma rays
- Immense energy budget, e.g. a GRB can give 10^{53} erg
- Acceleration (and emission) for kyears



2/ PARTICLE INJECTION THROUGH GRAVITY

We can use the inevitable gravity infall

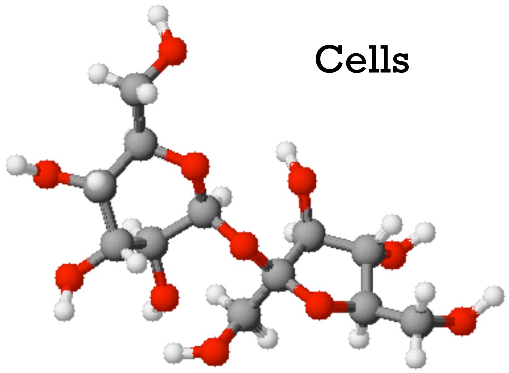
- Capture→ increase cross sections
- Energy budget → e.g. around BH, NS, GRB
- Efficient energy conversion

ENERGY CONVERSION EFFICIENCY

$$\eta = \frac{\Delta E}{\Delta m c^2}$$

Credit: Gabriele Ghisellini

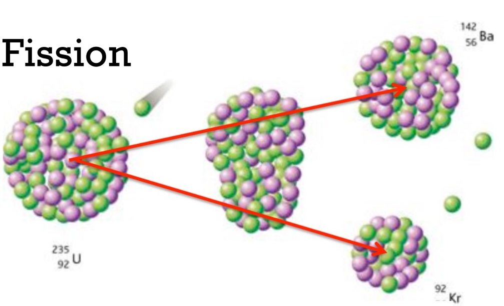
$$\eta = \frac{mgh}{mc^2} = \frac{980\times10^{4}\ (h/100\ \mathrm{m})}{9\times10^{20}\ \mathrm{erg}} \sim 10^{-14}$$



Cells

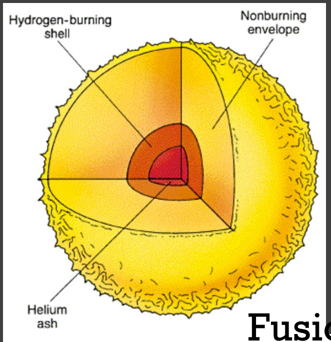
Sugar saccharose $C_{12}H_{22}O_{11}$

$$\eta = \frac{E}{mc^2} = \frac{1.6\times10^{11}\mathrm{erg}}{9\times10^{20}\ \mathrm{erg}} = 1.8\times10^{-10}$$



Fission

$$\eta = \frac{E}{mc^2} = \frac{0.2\times10^{9}\mathrm{eV}}{235\times9.4\times10^{8}\ \mathrm{eV}} \sim 9\times10^{-4}$$



Fusion

$$\eta = 0.008 \times 0.1 \sim 8\times10^{-4}$$

$$\eta = \frac{mv^2}{2\ mc^2} = \frac{(v/c)^2}{2} = 4\times10^{-15}$$

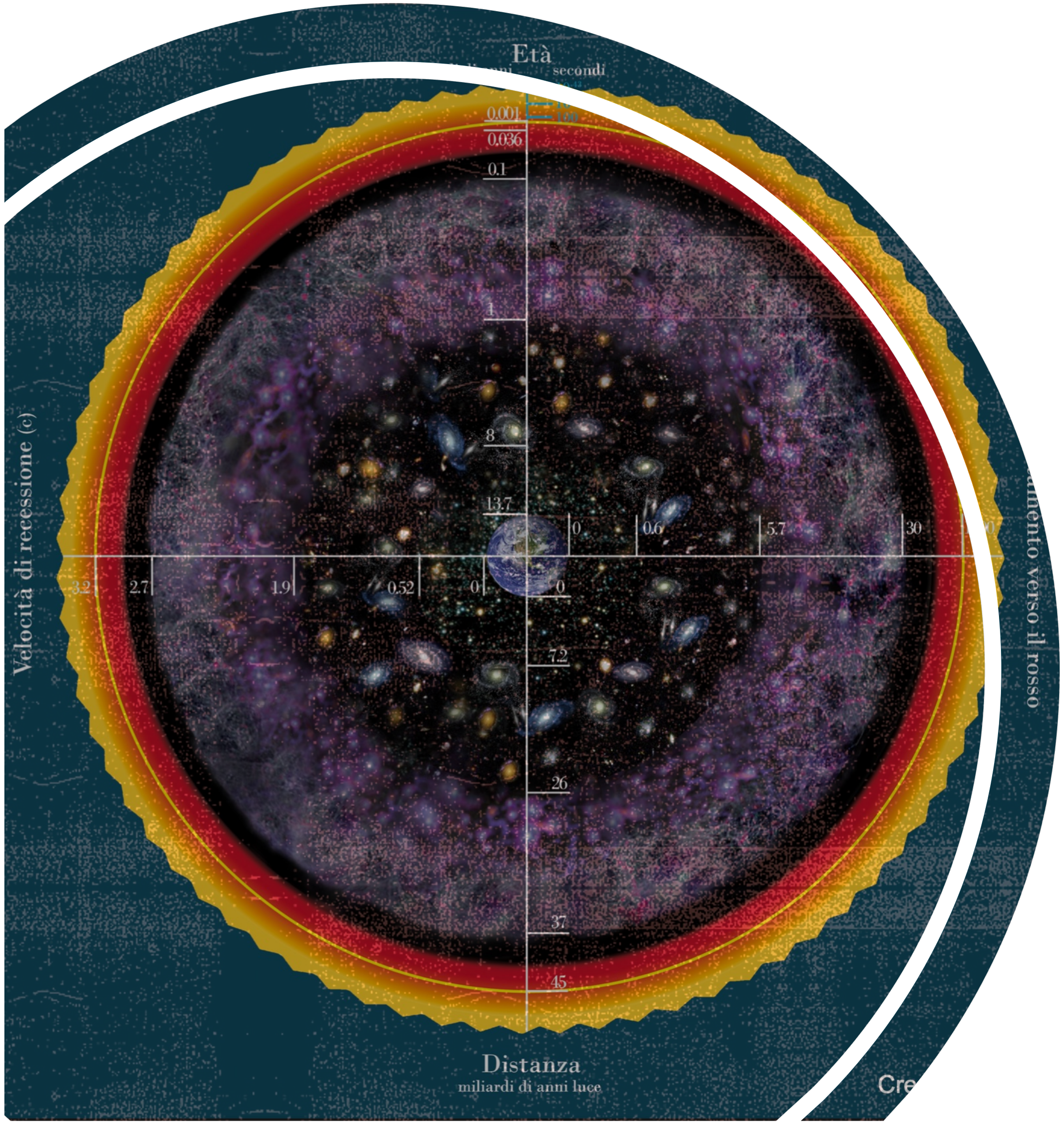
$$\eta = \frac{1}{2}\,\frac{GM\ m}{R\ mc^2} = \frac{R_g}{2R}$$

(Newton)

$R_{min}=R_g$ for max spin

η = 0.1 up to 0.3 for accreting Kerr

(Thorne 1974)



3/ A HUGE FIDUCIAL VOLUME

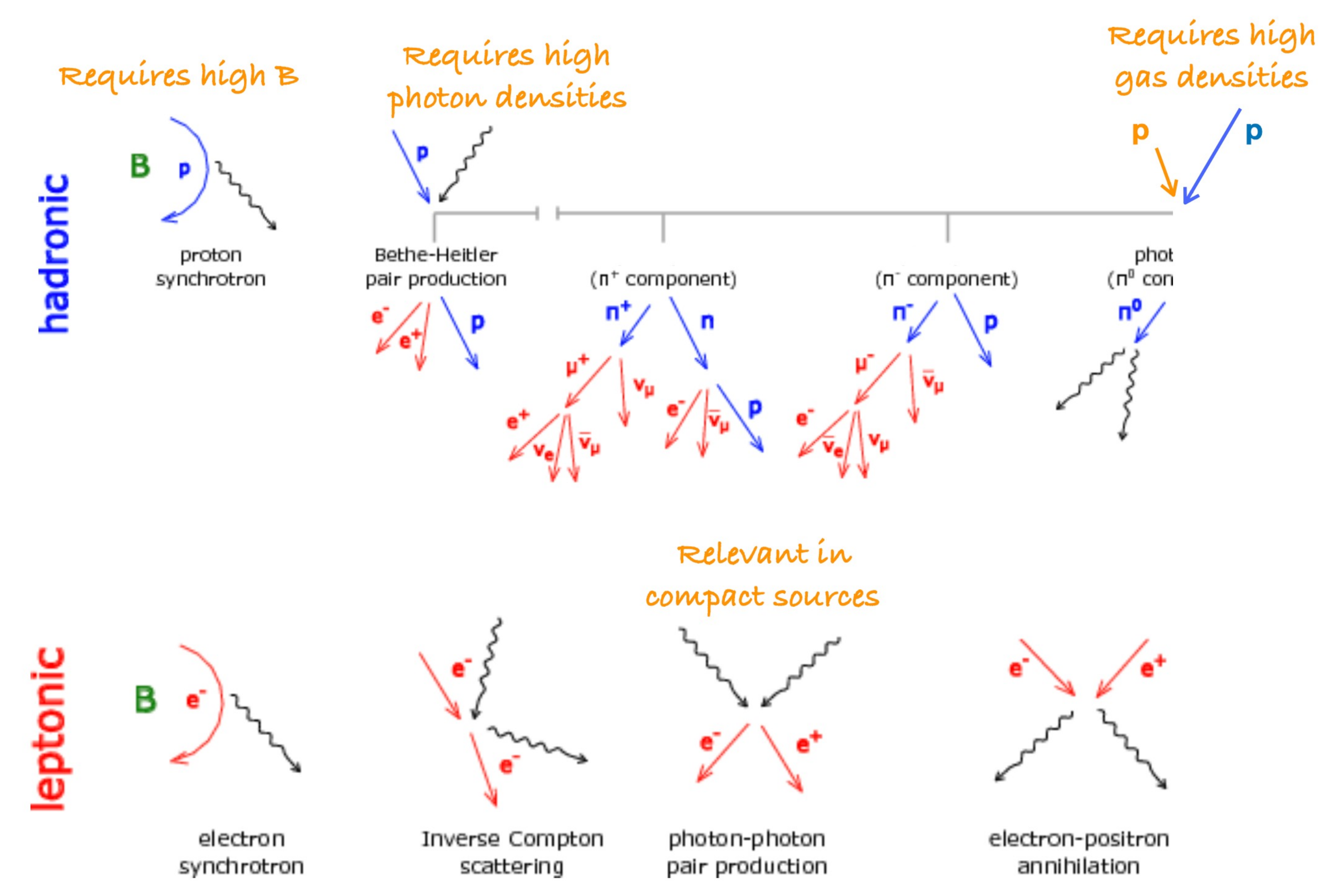
- Signals from CMB and further
- Direct signal and signal through-Universe
- There are several ‘beam dumps’

GENERATE A GAMMA-RAY

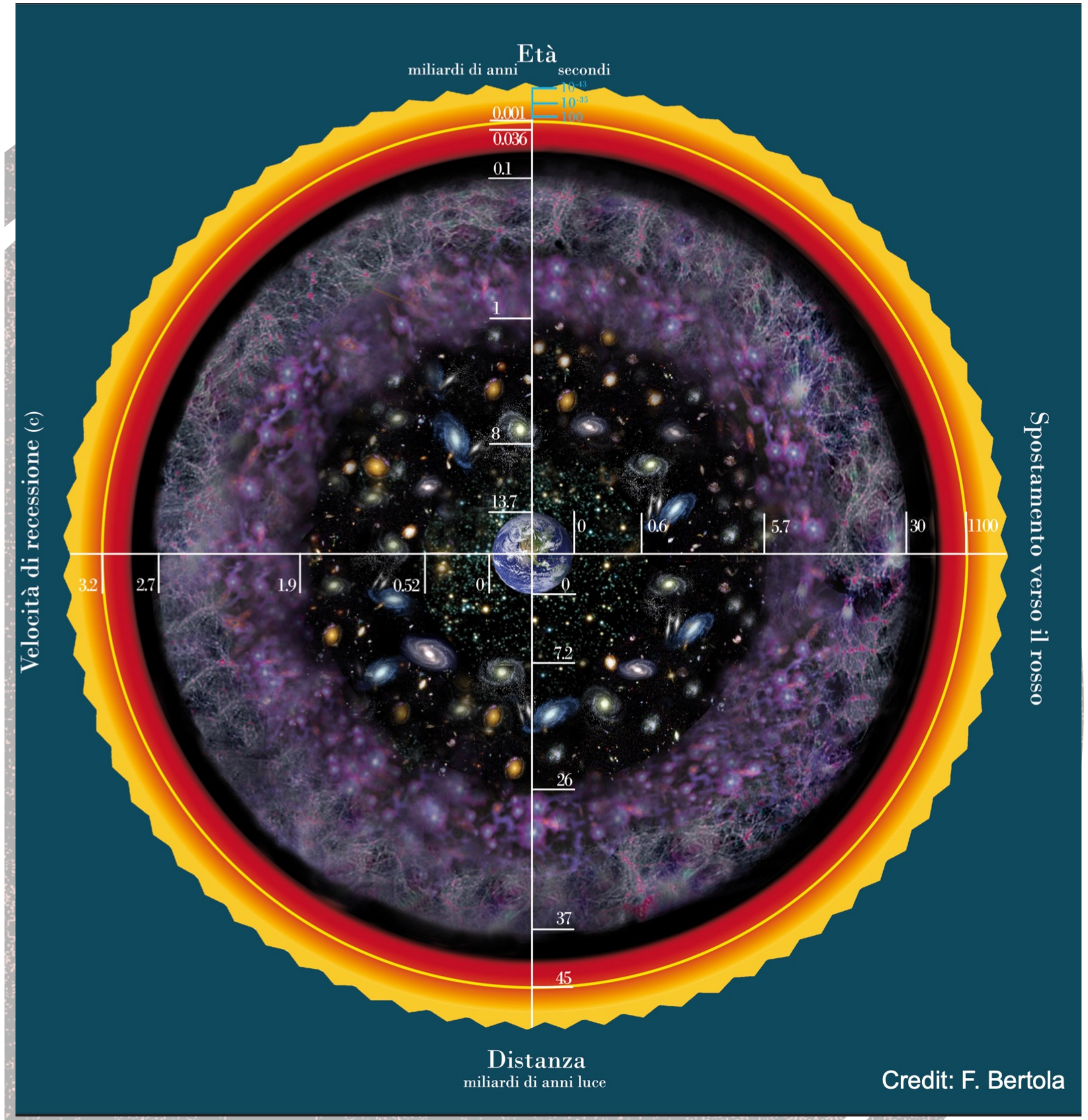
Interaction with **magnetic fields**

Interaction with **radiation fields**

Interaction with **particle fields**



Credit: Fabrizio Tavecchio



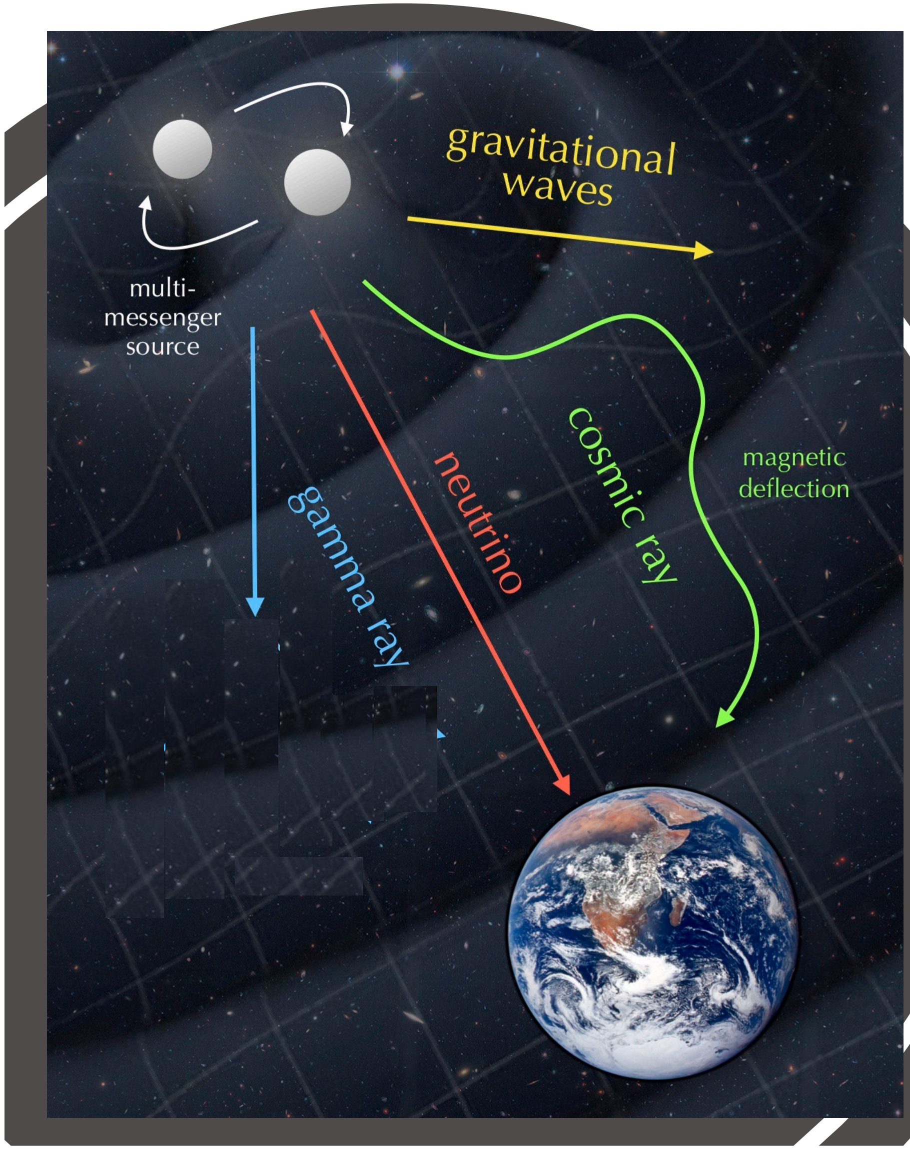
Credit: F. Bertola

3/ TIME OF FLIGHT AND TRACKING

- Astrophysics events have time variability
- We can trace particle interactions from similar targets at different times
- Check when the Universe was different from now

4/ VARIOUS SENSING SYSTEM

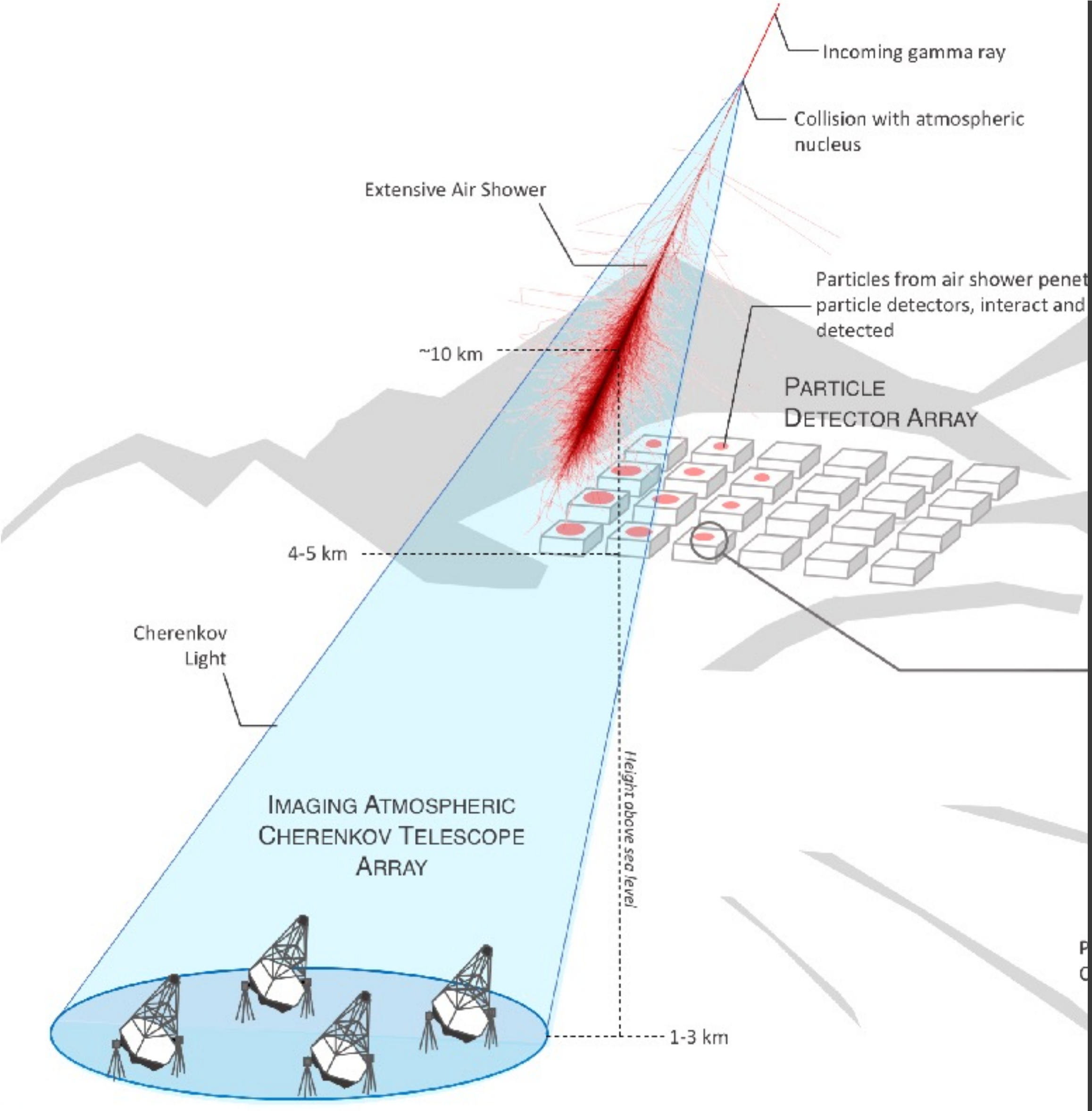
- Cosmic rays → but deflected
- Neutrinos → but rare
- GW → indeed!
- GAMMA-RAYS → yes!




The MAGIC telescopes – Credit: Chiara Righi

#2 IACTS

A great instrumental success



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

#2 IACTS AND SFDS

HAWC, LHAASO
And soon SWGO

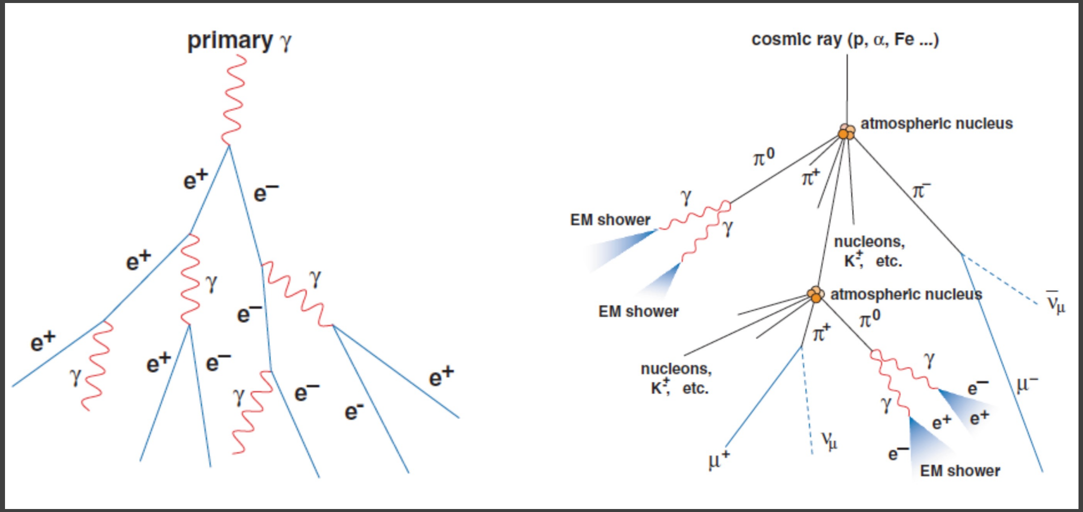
IACTS AND SFDS FOR FUND

- Pros
  - Sensitivity at energies not achievable with accelerators
  - Multiple targets alike, time varying, multiple phenomena at emission
  - Long distance amplify small signals
  - <ns time resolution
  - 10% energy resolution
  - (SFDs) wide FOVs, always listening

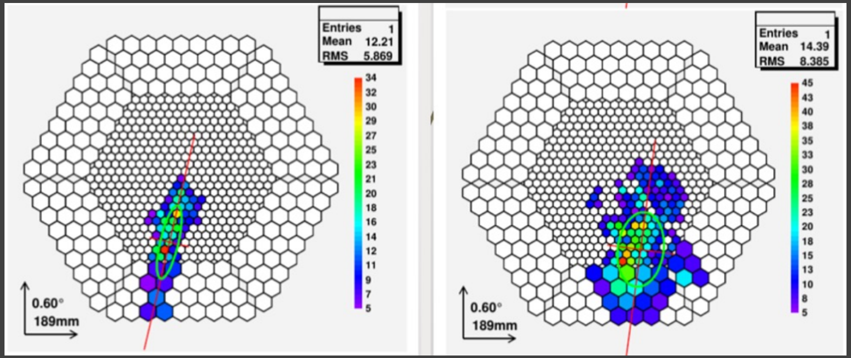
- Cons
  - Need data reduction, risk to miss fun(d)?
  - IACTs (know where to point)

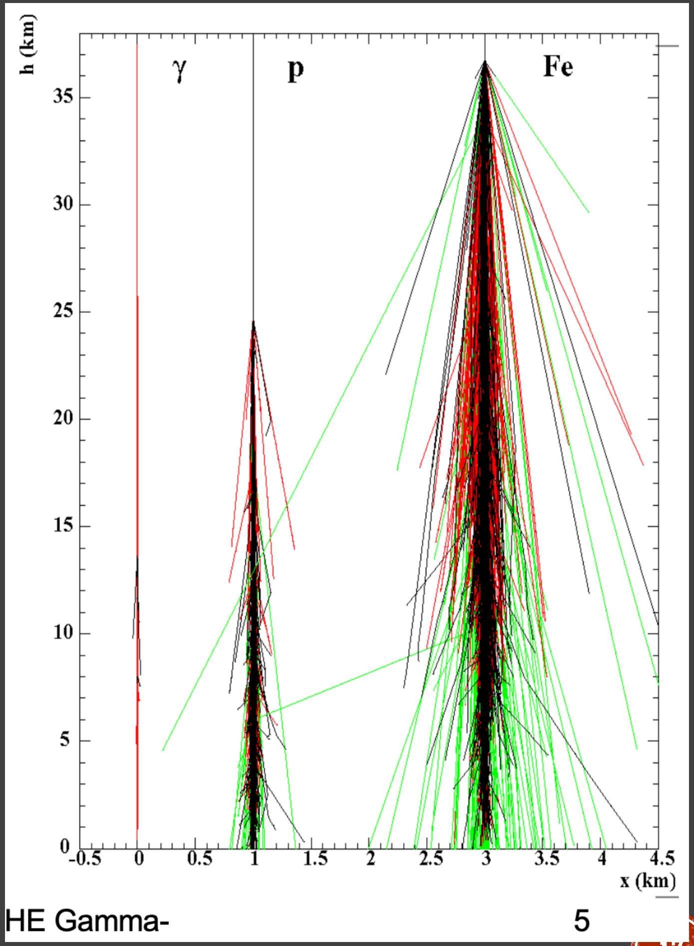
THERE'S MORE THAN JUST GAMMAS

- Ample bkg: 1 to 1000 gammas/protons

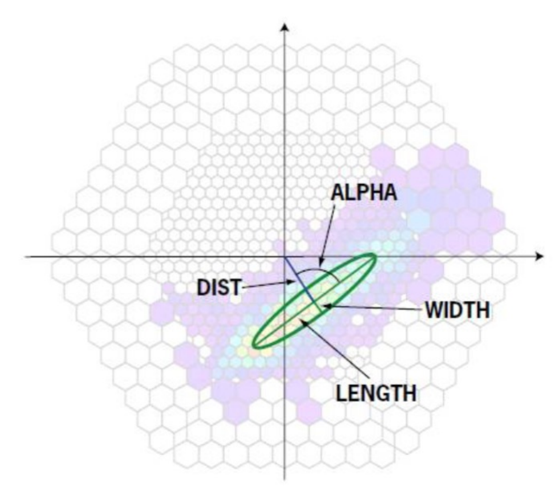


- Selection based on image momenta (Hillas criteria)





STD PIPELINES

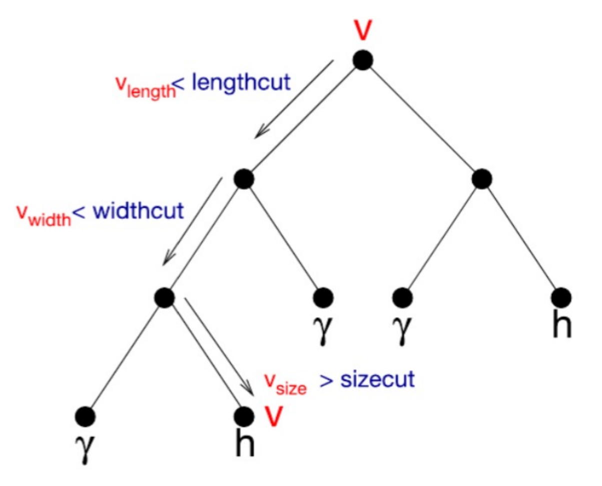


1

You prepare events

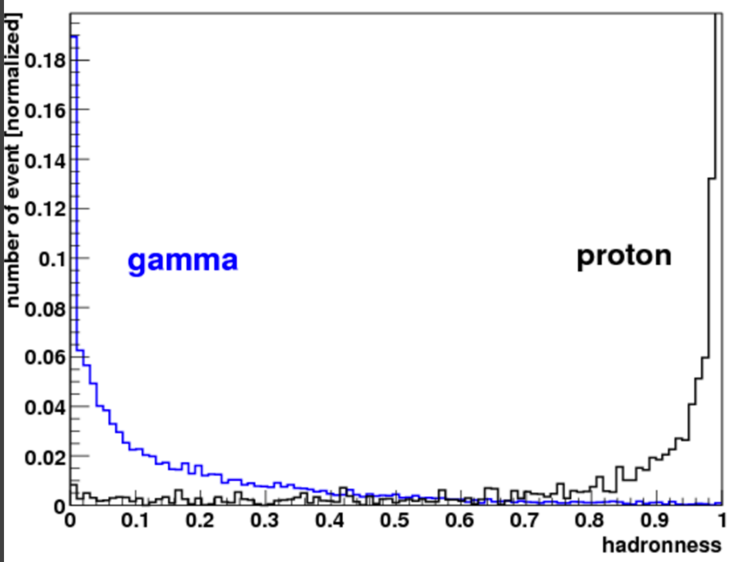
2

You classify events



3

You select events



A LOT OF 'LEFTOVERS'

- **Background events rate**
  - One large night: 8h*3600s*200 = 5.76 MEvents
  - **Lifetime: 12 Gevents**
- In the case of MAGIC **these millions of events are safely stored** in the database
- What for CTA?
- ← **Is this really trash**? Can there be something peculiar in these leftovers?

MAIN DISHES

- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$

BEVERAGES

- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$

DESSERTS

- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$
- LOREM IPSUM.........................13$

THE MENU

- Dark Matter particles
- Axion Like Particles
- Magnetic monopoles
- Primordial black holes
- LIV
    - Quark nuggets
    - Hubble constant ← J. Biteau
    - Other DM cases
    - Tau-neutrinos
    - Heavier nuclei searches
    - …

We may skip some plates!

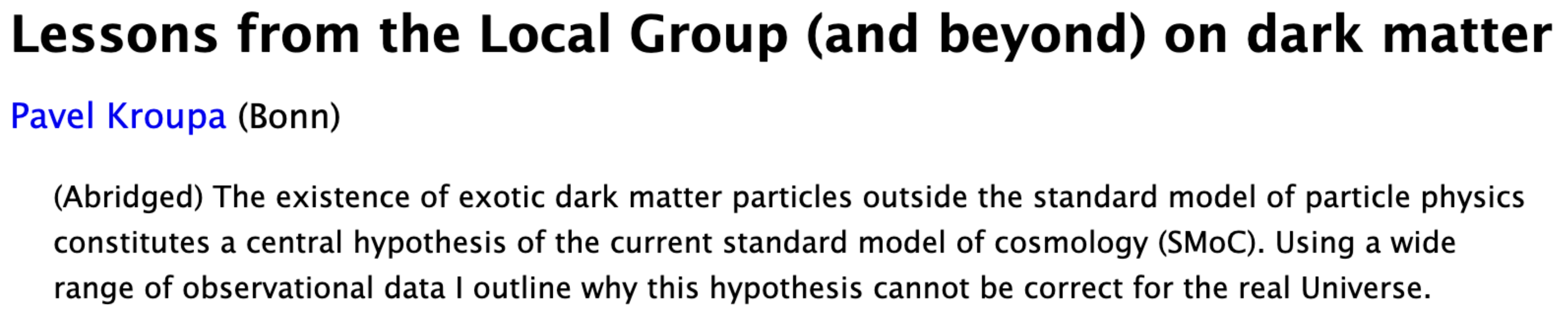
DARK MATTER

Better served cold

DISCLAIMER

In the following, PARTICLE DARK MATTER.

- There are theories of modified gravity (MOG) $r^{2+\alpha(E)}$ and Modified Newtonian Dynamics (MOND) motivated (only?) by the fact that particle DM cannot explain well galactic scale gravitation.
- However, cosmological evidences and the bullet cluster (see later) put seriousy MOND chefs into stress
- There are even online ~~debates/~~fights: https://youtu.be/dEsKnCx32L8?si=SvtPWxavhAHyM286

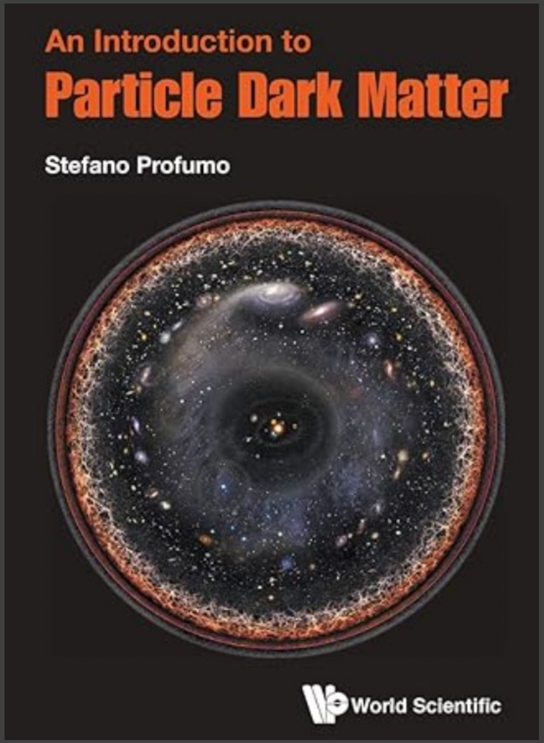


Lessons from the Local Group (and beyond) on dark matter

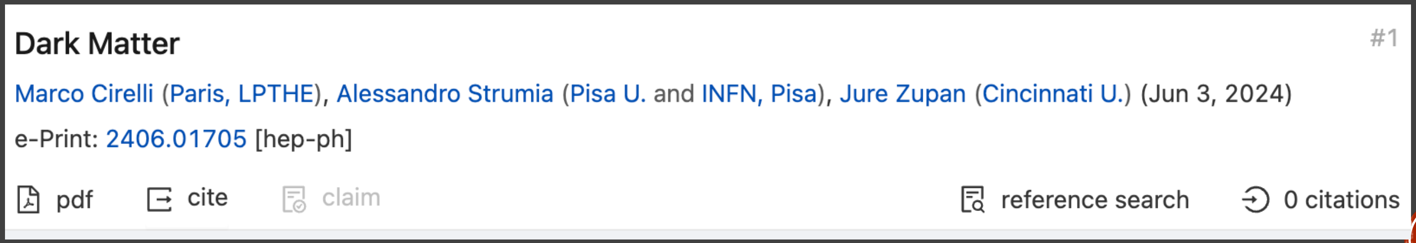
Pavel Kroupa (Bonn)

(Abridged) The existence of exotic dark matter particles outside the standard model of particle physics constitutes a central hypothesis of the current standard model of cosmology (SMoC). Using a wide range of observational data I outline why this hypothesis cannot be correct for the real Universe.

SHORT SELECTION OF REFERENCES



- Book Profumo
- Excellent review:
  - Feng “Dark Matter Candidates from Particle Physics and Methods of Detection” https://inspirehep.net/literature/847767
  - Bertone+ “Particle dark matter: Evidence, candidates and constraints” https://inspirehep.net/literature/648746
- History of DM
  - Bertone+ “History of Dark Matter” https://inspirehep.net/literature/1459227
- Lectures:
  - Slatyer “TASI Lecture” https://inspirehep.net/literature/1630762

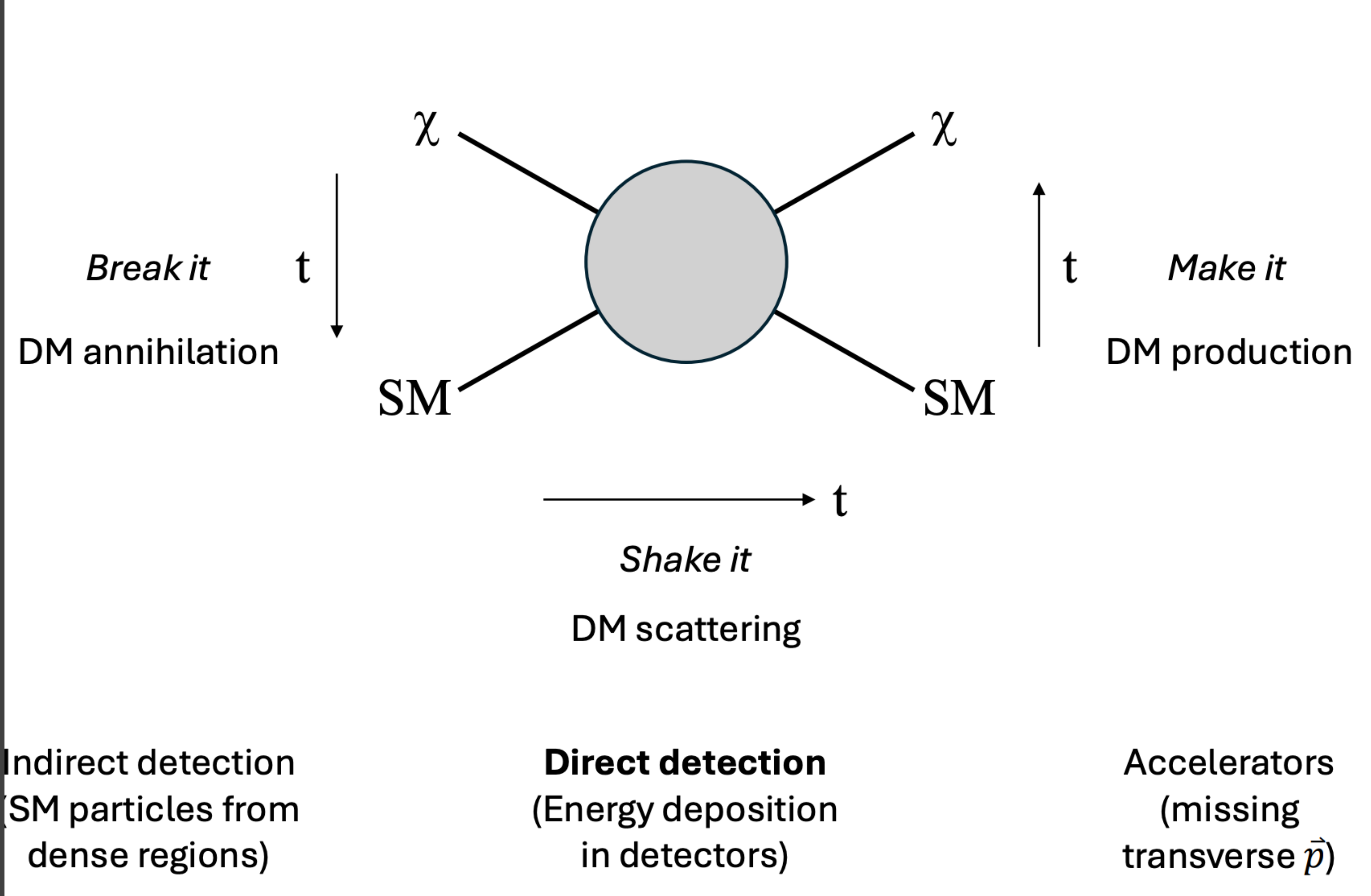


Dark Matter #1

Marco Cirelli (Paris, LPTHE), Alessandro Strumia (Pisa U. and INFN, Pisa), Jure Zupan (Cincinnati U.) (Jun 3, 2024)

e-Print: 2406.01705 [hep-ph]

BREAK IT, SHAKE IT, MAKE IT



Break it

DM annihilation

Make it

DM production

Shake it

DM scattering

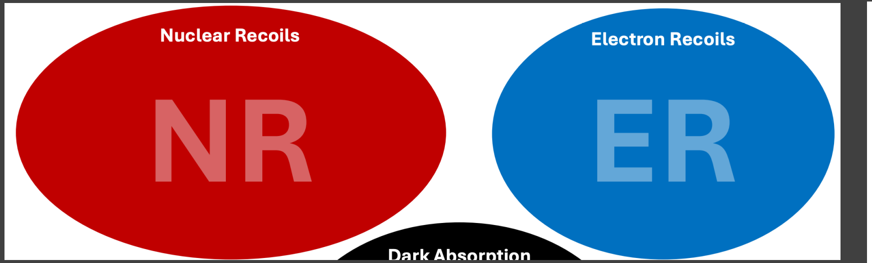
Indirect detection (SM particles from dense regions)

Direct detection (Energy deposition in detectors)

Accelerators (missing transverse $\vec{p}$)

Focus only on Indirect DM detection

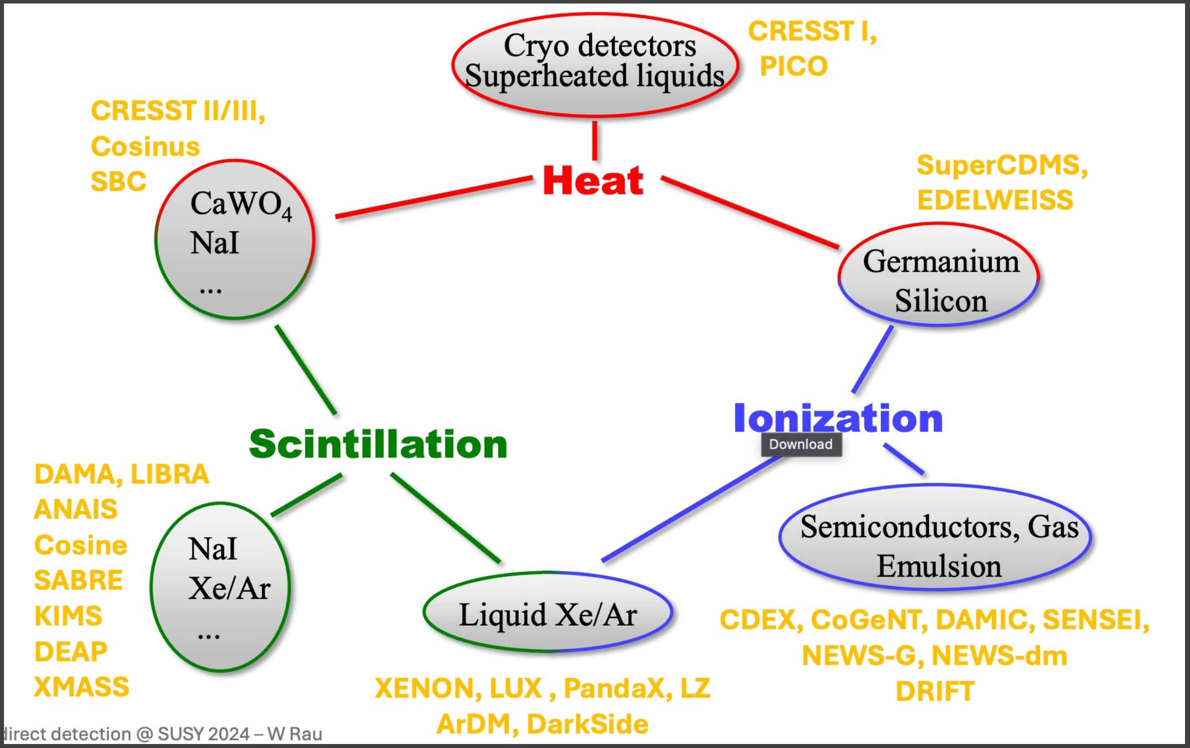
DIRECT DETECTION EXPERIMENTS



Nuclear recoils: heavy elements (e.g. Ge)
Electron recoils:noble gases

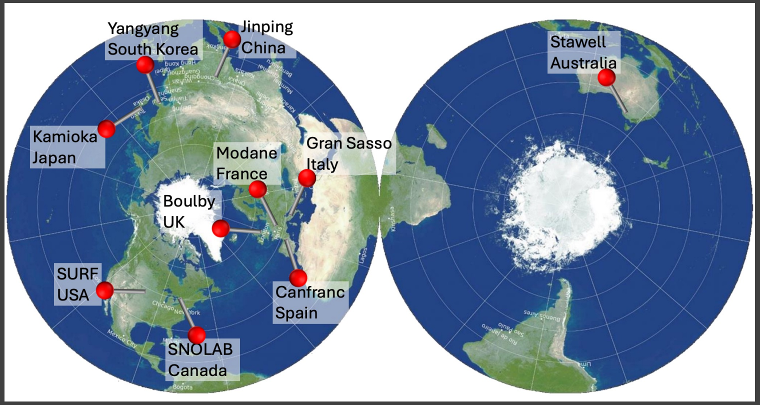
Interaction with matter can be

- Spin Independent
- Spin Dependent (different for n,p)

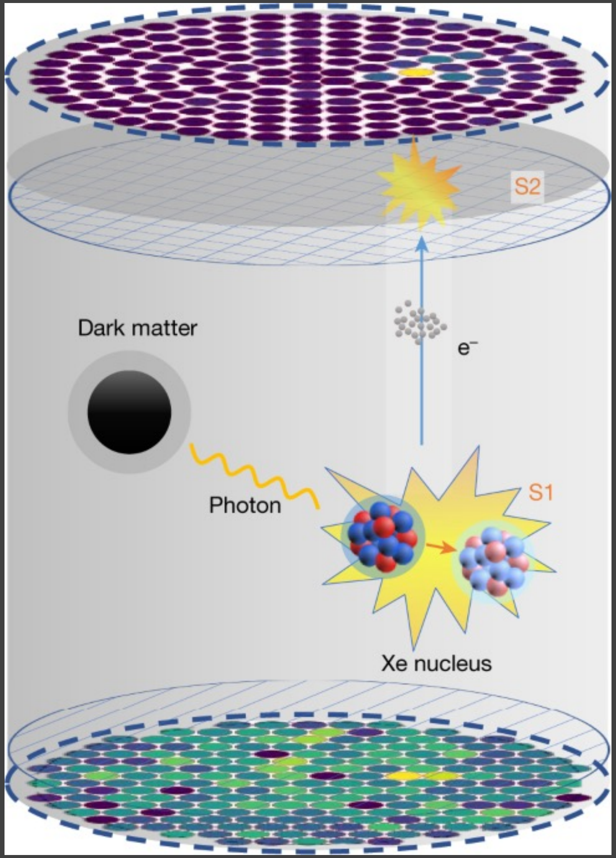


Several signals

DIRECT DETECTION EXPERIMENTS

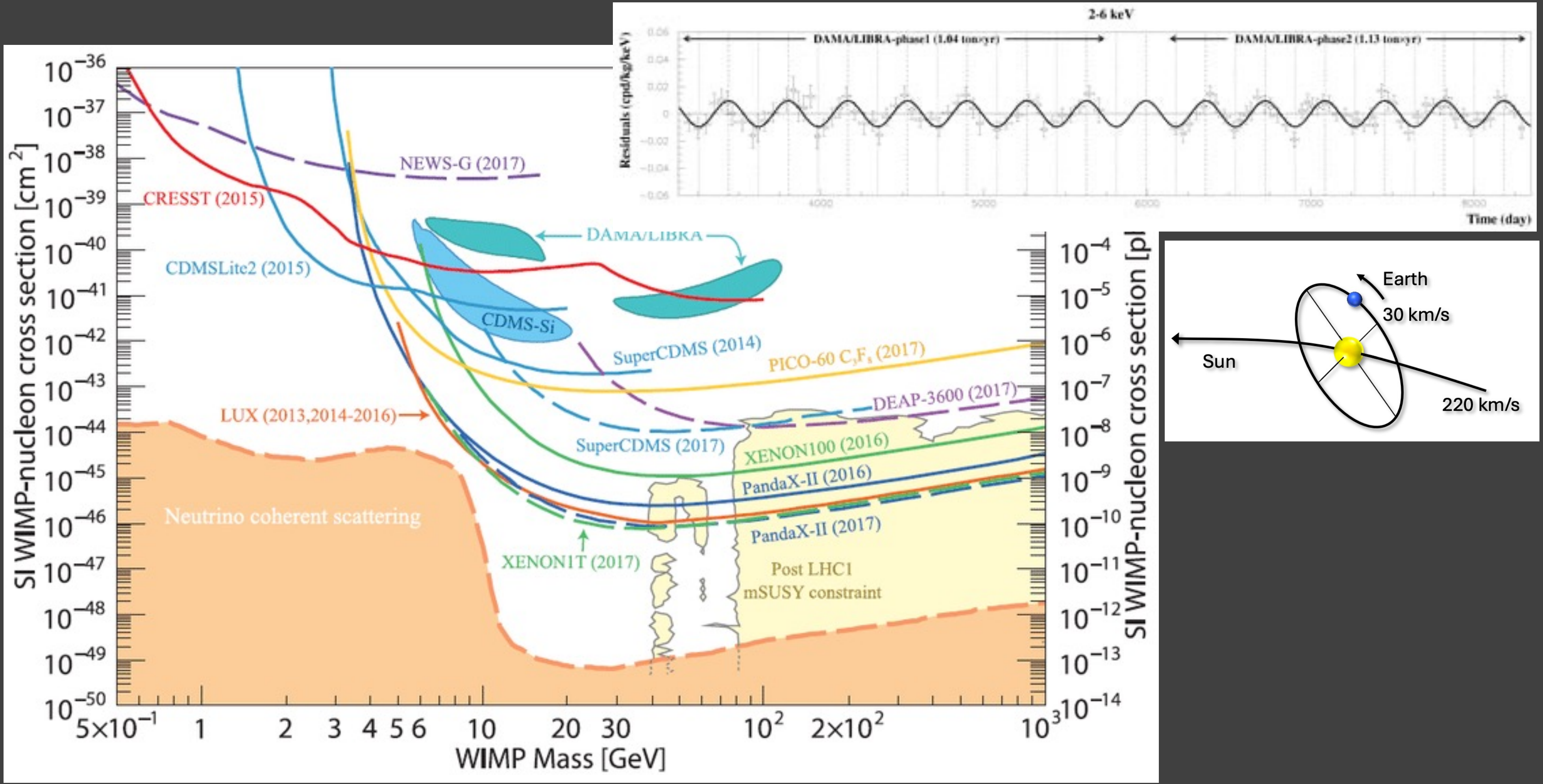


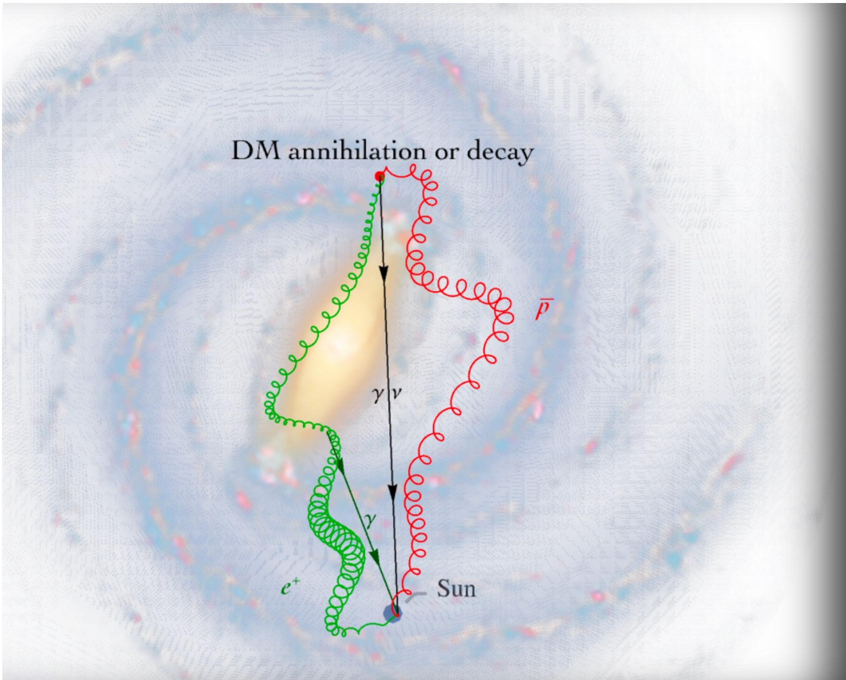
Cryogenic detectors in underground labs to keep noise down

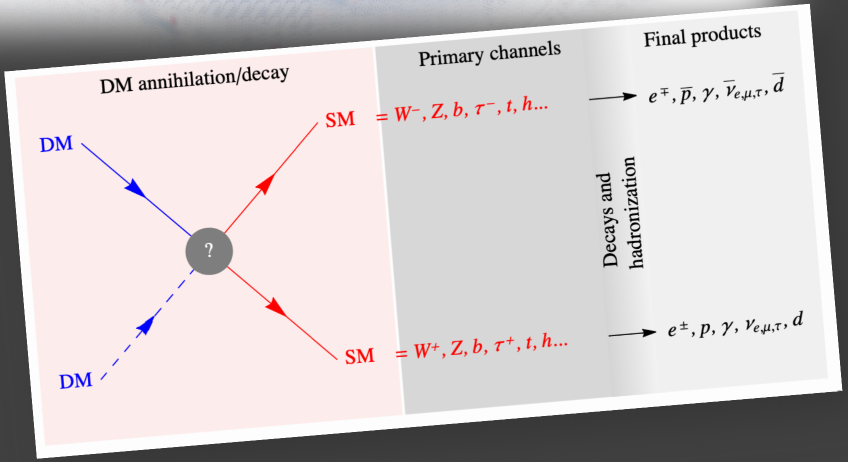


e.g. Xenon -1 ton at LNGS Italy

DIRECT DETECTION EXPERIMENTS



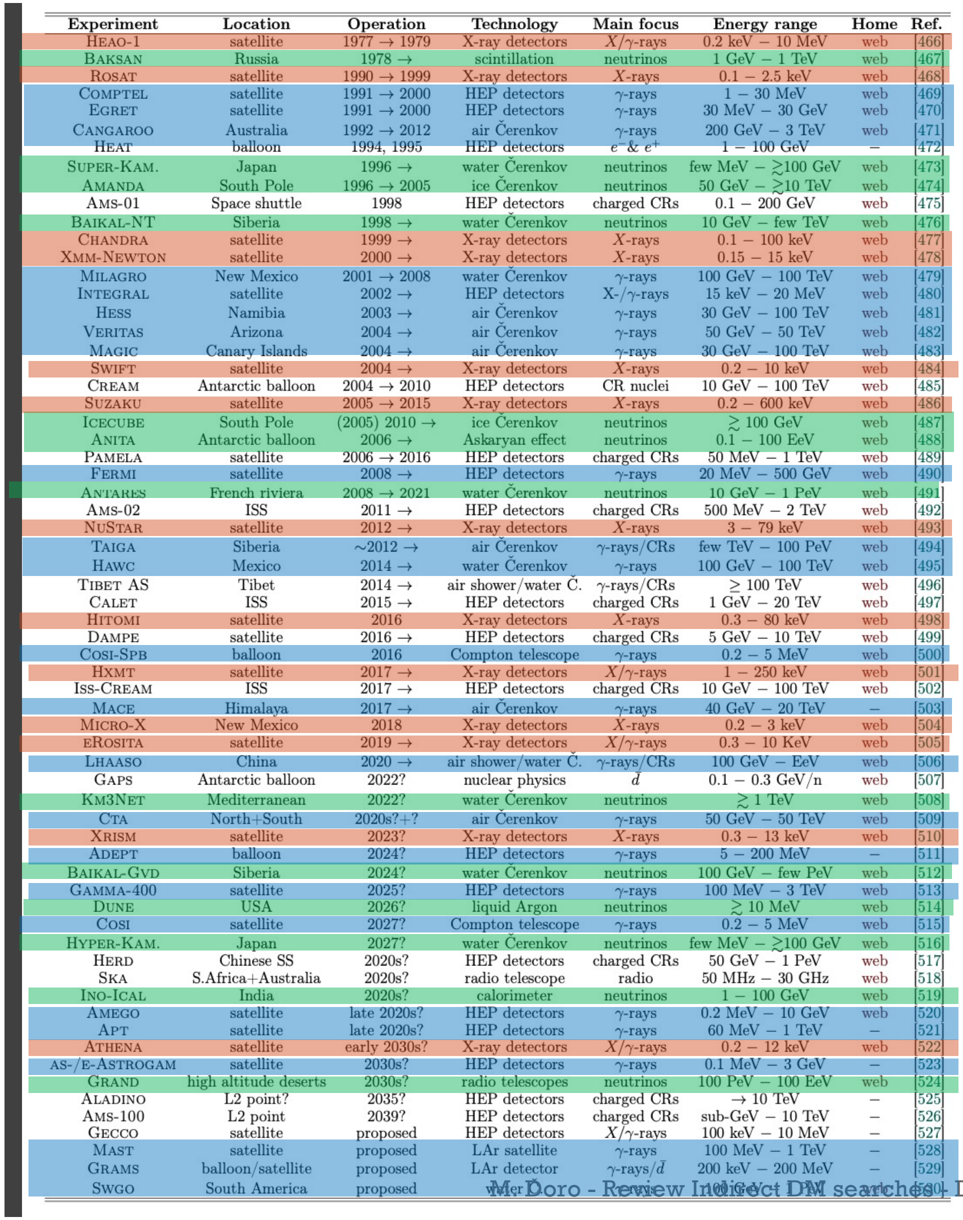




NOT ONLY GAMMA-RAYS

- Neutral particles ← trace-back origin
  - **Prompt Gamma-ray**
  - Reprocessed X-radio
  - Neutrinos

- Charged particles: all but most interesting are antiparticles (less background) ← overall abundances
  - Positron
  - Antiprotons
  - antideuterons



Experiment	Location	Operation	Technology	Main focus	Energy range	Home	Ref.
HEAO-1	satellite	1977 → 1979	X-ray detectors	X/γ-rays	0.2 keV – 10 MeV	web	[466]
BAKSAN	Russia	1978 →	scintillation	neutrinos	1 GeV – 1 TeV	web	[467]
ROSAT	satellite	1990 → 1999	X-ray detectors	X-rays	0.1 – 2.5 keV	web	[468]
COMPTEL	satellite	1991 → 2000	HEP detectors	γ-rays	1 – 30 MeV	web	[469]
EGRET	satellite	1991 → 2000	HEP detectors	γ-rays	30 MeV – 30 GeV	web	[470]
CANGAROO	Australia	1992 → 2012	air Čerenkov	γ-rays	200 GeV – 3 TeV	web	[471]
HEAT	balloon	1994, 1995	HEP detectors	e^-& e^+	1 – 100 GeV	–	[472]
SUPER-KAM.	Japan	1996 →	water Čerenkov	neutrinos	few MeV – $\gtrsim$100 GeV	web	[473]
AMANDA	South Pole	1996 → 2005	ice Čerenkov	neutrinos	50 GeV – $\gtrsim$10 TeV	web	[474]
AMS-01	Space shuttle	1998	HEP detectors	charged CRs	0.1 – 200 GeV	web	[475]
BAIKAL-NT	Siberia	1998 →	water Čerenkov	neutrinos	10 GeV – few TeV	web	[476]
CHANDRA	satellite	1999 →	X-ray detectors	X-rays	0.1 – 100 keV	web	[477]
XMM-NEWTON	satellite	2000 →	X-ray detectors	X-rays	0.15 – 15 keV	web	[478]
MILAGRO	New Mexico	2001 → 2008	water Čerenkov	γ-rays	100 GeV – 100 TeV	web	[479]
INTEGRAL	satellite	2002 →	HEP detectors	X-/γ-rays	15 keV – 20 MeV	web	[480]
HESS	Namibia	2003 →	air Čerenkov	γ-rays	30 GeV – 100 TeV	web	[481]
VERITAS	Arizona	2004 →	air Čerenkov	γ-rays	50 GeV – 50 TeV	web	[482]
MAGIC	Canary Islands	2004 →	air Čerenkov	γ-rays	30 GeV – 100 TeV	web	[483]
SWIFT	satellite	2004 →	X-ray detectors	X-rays	0.2 – 10 keV	web	[484]
CREAM	Antarctic balloon	2004 → 2010	HEP detectors	CR nuclei	10 GeV – 100 TeV	web	[485]
SUZAKU	satellite	2005 → 2015	X-ray detectors	X-rays	0.2 – 600 keV	web	[486]
ICECUBE	South Pole	(2005) 2010 →	ice Čerenkov	neutrinos	$\gtrsim$ 100 GeV	web	[487]
ANITA	Antarctic balloon	2006 →	Askaryan effect	neutrinos	0.1 – 100 EeV	web	[488]
PAMELA	satellite	2006 → 2016	HEP detectors	charged CRs	50 MeV – 1 TeV	web	[489]
FERMI	satellite	2008 →	HEP detectors	γ-rays	20 MeV – 500 GeV	web	[490]
ANTARES	French riviera	2008 → 2021	water Čerenkov	neutrinos	10 GeV – 1 PeV	web	[491]
AMS-02	ISS	2011 →	HEP detectors	charged CRs	500 MeV – 2 TeV	web	[492]
NUSTAR	satellite	2012 →	X-ray detectors	X-rays	3 – 79 keV	web	[493]
TAIGA	Siberia	~2012 →	air Čerenkov	γ-rays/CRs	few TeV – 100 PeV	web	[494]
HAWC	Mexico	2014 →	water Čerenkov	γ-rays	100 GeV – 100 TeV	web	[495]
TIBET AS	Tibet	2014 →	air shower/water Č.	γ-rays/CRs	$\geq$ 100 TeV	web	[496]
CALET	ISS	2015 →	HEP detectors	charged CRs	1 GeV – 20 TeV	web	[497]
HITOMI	satellite	2016	X-ray detectors	X-rays	0.3 – 80 keV	web	[498]
DAMPE	satellite	2016 →	HEP detectors	charged CRs	5 GeV – 10 TeV	web	[499]
COSI-SPB	balloon	2016	Compton telescope	γ-rays	0.2 – 5 MeV	web	[500]
HXMT	satellite	2017 →	X-ray detectors	X/γ-rays	1 – 250 keV	web	[501]
ISS-CREAM	ISS	2017 →	HEP detectors	charged CRs	10 GeV – 100 TeV	web	[502]
MACE	Himalaya	2017 →	air Čerenkov	γ-rays	40 GeV – 20 TeV	–	[503]
MICRO-X	New Mexico	2018	X-ray detectors	X-rays	0.2 – 3 keV	web	[504]
EROSITA	satellite	2019 →	X-ray detectors	X/γ-rays	0.3 – 10 KeV	web	[505]
LHAASO	China	2020 →	air shower/water Č.	γ-rays/CRs	100 GeV – EeV	web	[506]
GAPS	Antarctic balloon	2022?	nuclear physics	$\bar{d}$	0.1 – 0.3 GeV/n	web	[507]
KM3NET	Mediterranean	2022?	water Čerenkov	neutrinos	$\gtrsim$ 1 TeV	web	[508]
CTA	North+South	2020s?+?	air Čerenkov	γ-rays	50 GeV – 50 TeV	web	[509]
XRISM	satellite	2023?	X-ray detectors	X-rays	0.3 – 13 keV	web	[510]
ADEPT	balloon	2024?	HEP detectors	γ-rays	5 – 200 MeV	–	[511]
BAIKAL-GVD	Siberia	2024?	water Čerenkov	neutrinos	100 GeV – few PeV	web	[512]
GAMMA-400	satellite	2025?	HEP detectors	γ-rays	100 MeV – 3 TeV	web	[513]
DUNE	USA	2026?	liquid Argon	neutrinos	$\gtrsim$ 10 MeV	web	[514]
COSI	satellite	2027?	Compton telescope	γ-rays	0.2 – 5 MeV	web	[515]
HYPER-KAM.	Japan	2027?	water Čerenkov	neutrinos	few MeV – $\gtrsim$100 GeV	web	[516]
HERD	Chinese SS	2020s?	HEP detectors	charged CRs	50 GeV – 1 PeV	web	[517]
SKA	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz	web	[518]
INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV	web	[519]
AMEGO	satellite	late 2020s?	HEP detectors	γ-rays	0.2 MeV – 10 GeV	web	[520]
APT	satellite	late 2020s?	HEP detectors	γ-rays	60 MeV – 1 TeV	–	[521]
ATHENA	satellite	early 2030s?	X-ray detectors	X/γ-rays	0.2 – 12 keV	web	[522]
AS-/E-ASTROGAM	satellite	2030s?	HEP detectors	γ-rays	0.1 MeV – 3 GeV	–	[523]
GRAND	high altitude deserts	2030s?	radio telescopes	neutrinos	100 PeV – 100 EeV	web	[524]
ALADINO	L2 point?	2035?	HEP detectors	charged CRs	→ 10 TeV	–	[525]
AMS-100	L2 point	2039?	HEP detectors	charged CRs	sub-GeV – 10 TeV	–	[526]
GECCO	satellite	proposed	HEP detectors	X/γ-rays	100 keV – 10 MeV	–	[527]
MAST	satellite	proposed	LAr satellite	γ-rays	100 MeV – 1 TeV	–	[528]
GRAMS	balloon/satellite	proposed	LAr detector	γ-rays/$\bar{d}$	200 keV – 200 MeV	–	[529]
SWGO	South America	proposed	water Čerenkov	γ-rays	100 GeV – 1 PeV	web	[530]

Cirelli+ 2406.01705

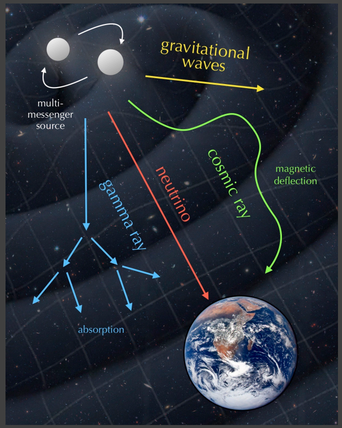
WE HAVE OUR TOOLBOX

Gamma-rays

X-rays

Neutrinos

Charged particles

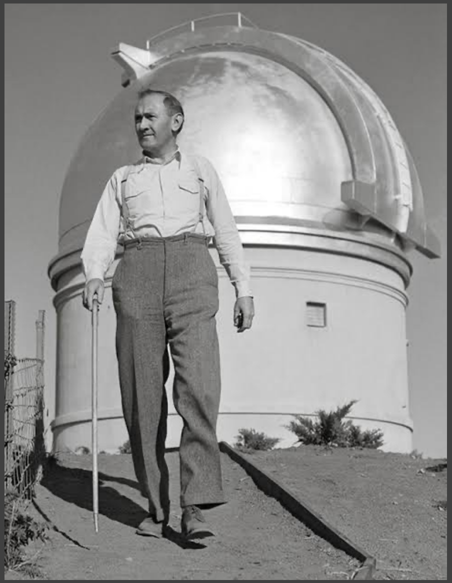


STEPS TO OUR KITCHEN

- DM evidences
- Some DM facts
- IACT observations
- For your next future

GRAVITATIONAL BALANCE IN GALAXY CLUSTERS

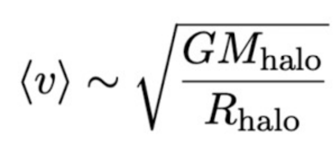
F. Zwicky ’30s



- The virial theorem states that for a stable system of discrete particles, bound by conservative forces:

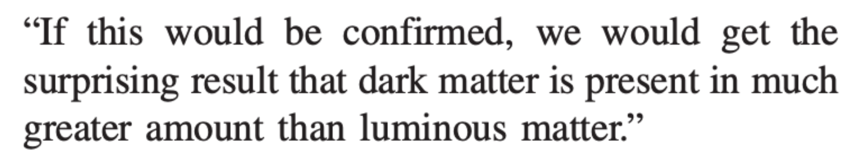
$$< K > = \frac{1}{2} < U >$$

- If you take U grav = GmM/R^2 and K=1/2 mv^2, you obtain

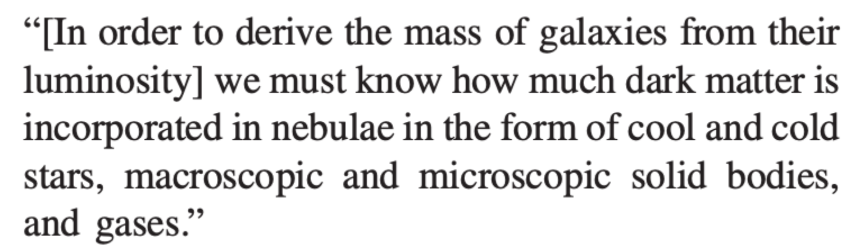


$$\langle v \rangle \sim \sqrt{\frac{GM_{\mathrm{halo}}}{R_{\mathrm{halo}}}}$$

- Zwicky applied this to Coma galaxy cluster assuming 800 galaxies of M=10^9 solar masses in a circle of 10^6 ly and obtaining $< v > \sim 80\ km/s$ much smaller than the observed $< v > \sim 1000\ km/s$



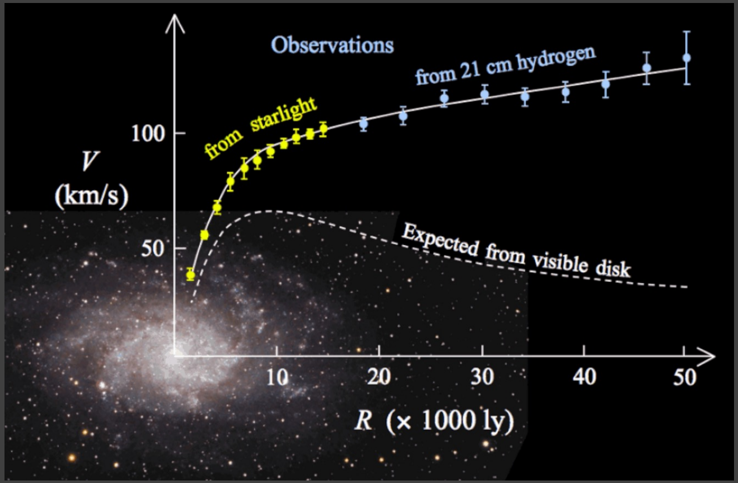
“If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.”



“[In order to derive the mass of galaxies from their luminosity] we must know how much dark matter is incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases.”

GRAVITATIONAL DYNAMICS IN GALAXIES

Vera Cooper Rubin ’60s



- A stable object at orbit r has centripetal acceleration $F = mv^2 r$ provided by gravity $F = GM(< r)m/r^2$.
- This translates into $v(r) = \sqrt{\frac{GM(<r)}{r}}$
- Vera Cooper (Rubin), Bosma (during PhD) made systematic in the 70s studies on motion of stars in galaxies

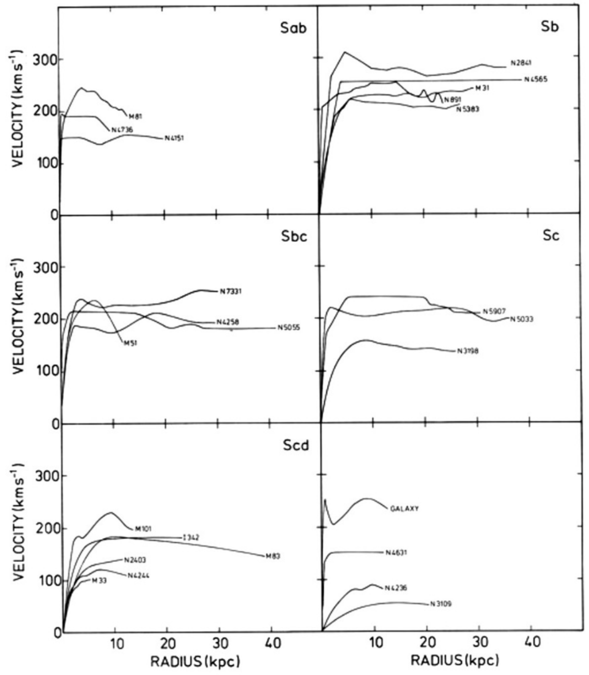
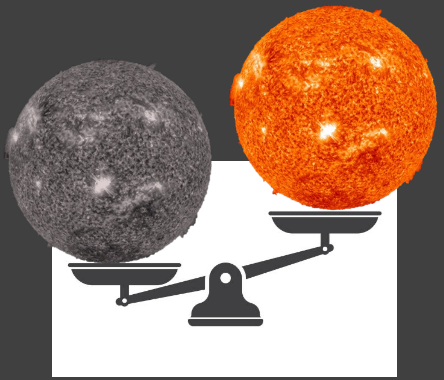


FIG. 5. The rotation curves of the 25 galaxies. From Bosma, 1978.

SOMEDARK NUMBERS



Mass TO LIGHT ratio

- A usual way to assess the amount of DM is through the mass-to-light ratio M/L, in units M_Sun/L_Sun
- For the Sun M/L=1, for stars in general M/L<5/10
- For systems of objects where DM is: M/L~100/1000

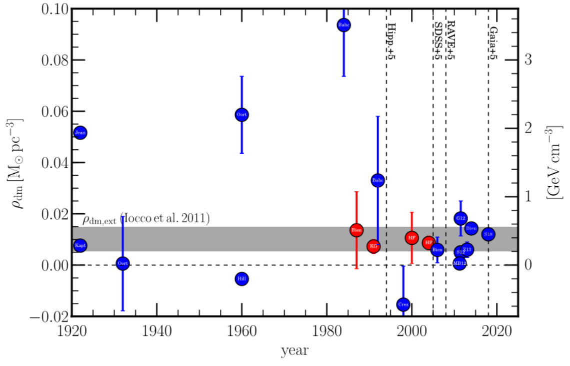


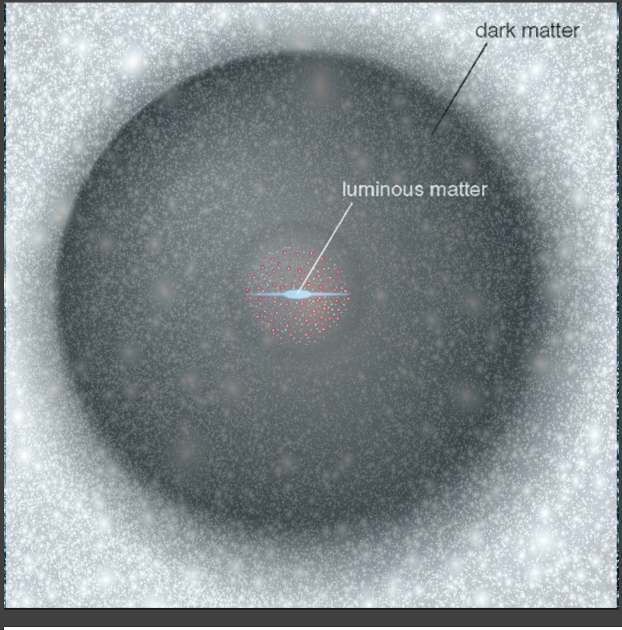
FIG. 6. Time line of local dark matter density measurements. From Read, 2014.

Local DM density

500 g inside Earth

- Again by using local stellar motions, local density of 'mass' inferred starting from '20s
- Latest results by considering large stellar samples and a model for the MW
- Current value 0.3/0.4 GeV cm-3

DM HALO / A NON COLLISIONAL DM SPHERE



- To explain rotation curve, one need a spherical DM halo
- By considering local density and total galactic mass, Rhalo=100kpc = 10x visible

$10^{12} M_\odot$ $\quad$ 0,3 GeV/cm^3

$$M_{\rm halo} \sim 4\pi \int_0^{R_{\rm halo}} dr\, r^2 \rho(r) \longrightarrow R_{\rm halo} \sim 100 \ \ {\rm kpc}\,,$$

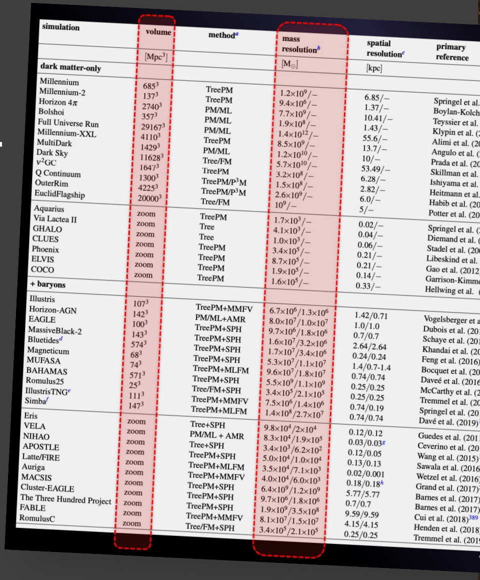
- A sphere of self-graviting, non-collision, DM 'gas' would have such a density profile and velocity function
- However, infinite mass at growing radii

$$\rho(r) \propto 1/r^2 \quad \text{and} \quad f(v) \propto e^{-v^2/\sigma^2}\,.$$

$$\nabla^2\Psi = -4\pi G\rho \longrightarrow \rho(r) = \frac{\sigma^2}{2\pi G r^2}\,.$$

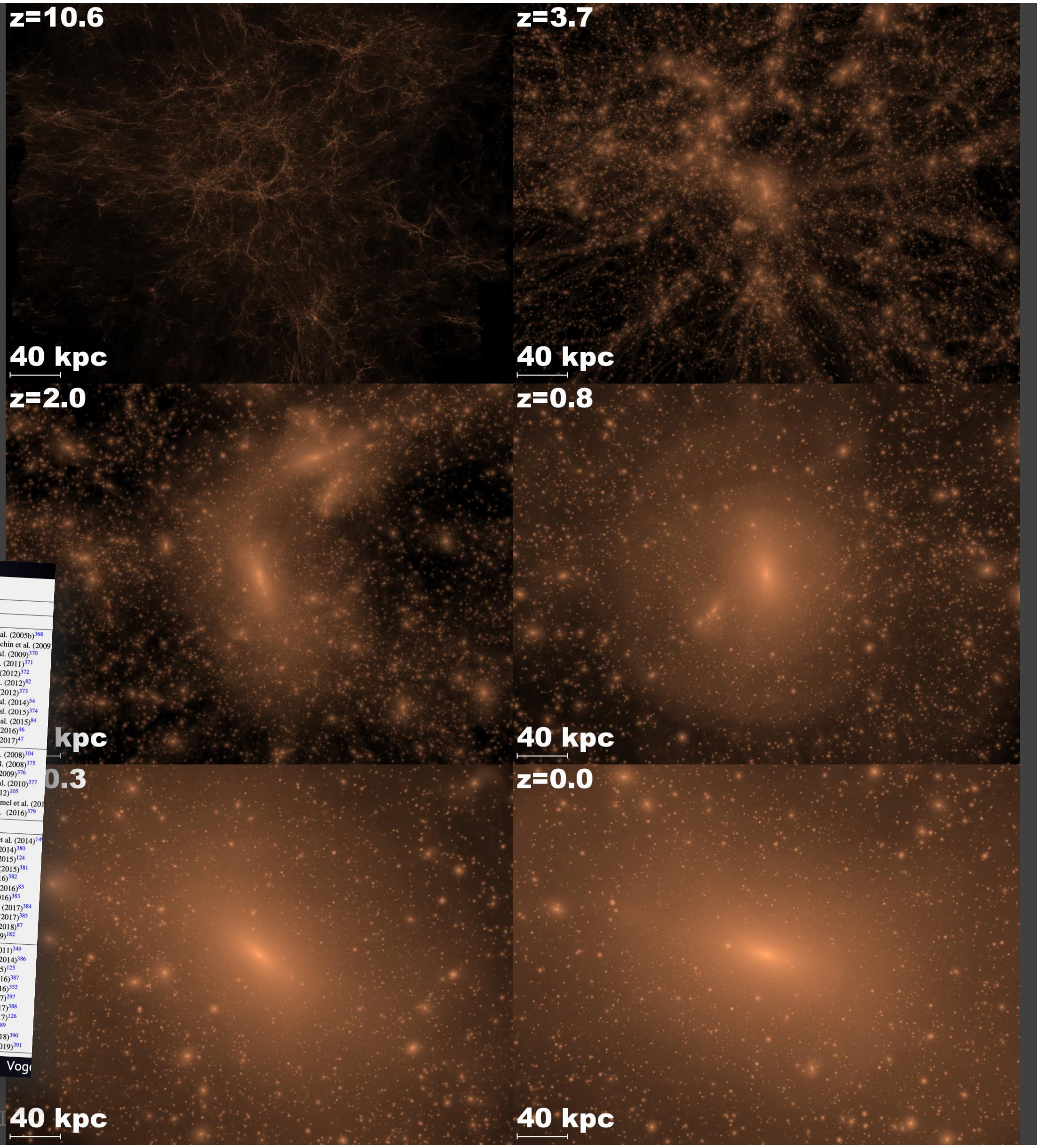
N-BODY SIMULATIONS

- DM particles in a starting grid
  - Gaussian fluctuations
  - No baryons / collisionless
  - Min mass = 10^4-10^6 solar masses
- Huge computing power
- One obtains
  - Main halo
  - Subhalos
  - filaments



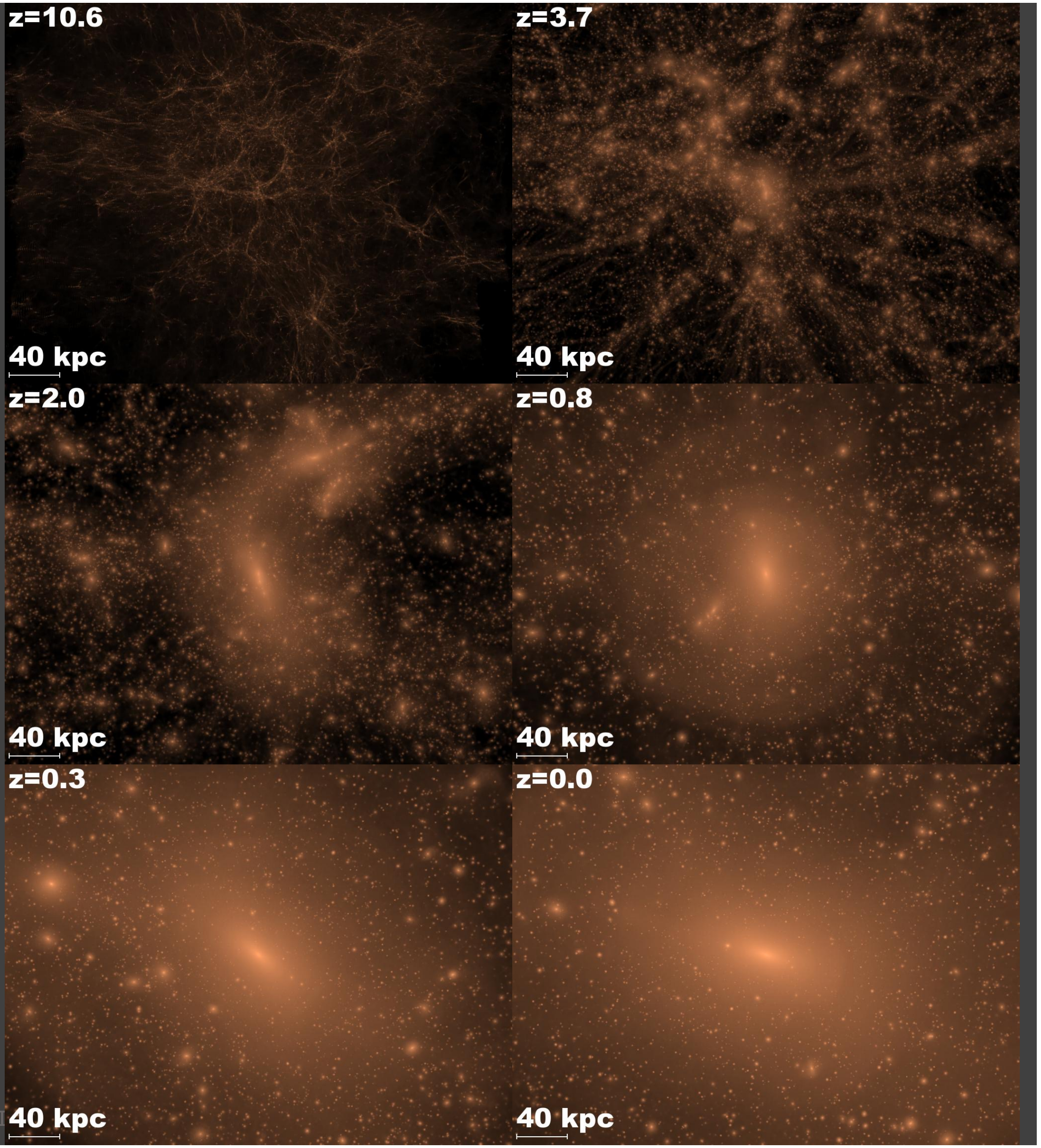
simulation	volume	method[a]	mass resolution[b]	spatial resolution[c]	primary reference
	[Mpc^3]		[M$_\odot$]	[kpc]	
dark matter-only					
Millennium	685^3	TreePM	$1.2\times10^9/-$	$6.85/-$	Springel et al. (2005b)[368]
Millennium-2	137^3	TreePM	$9.4\times10^6/-$	$1.37/-$	Boylan-Kolchin et al. (2009
Horizon 4π	2740^3	PM/ML	$7.7\times10^9/-$	$10.41/-$	Teyssier et al. (2009)[370]
Bolshoi	357^3	PM/ML	$1.9\times10^8/-$	$1.43/-$	Klypin et al. (2011)[371]
Full Universe Run	29167^3	PM/ML	$1.4\times10^{12}/-$	$55.6/-$	Alimi et al. (2012)[372]
Millennium-XXL	4110^3	TreePM	$8.5\times10^9/-$	$13.7/-$	Angulo et al. (2012)[82]
MultiDark	1429^3	PM/ML	$1.2\times10^{10}/-$	$10/-$	Prada et al. (2012)[373]
Dark Sky	11628^3	Tree/FM	$5.7\times10^{10}/-$	$53.49/-$	Skillman et al. (2014)[54]
ν^2GC	1647^3	TreePM	$3.2\times10^8/-$	$6.28/-$	Ishiyama et al. (2015)[374]
Q Continuum	1300^3	TreePM/P^{3}M	$1.5\times10^8/-$	$2.82/-$	Heitmann et al. (2015)[84]
OuterRim	4225^3	TreePM/P^{3}M	$2.6\times10^9/-$	$6.0/-$	Habib et al. (2016)[46]
EuclidFlagship	20000^3	Tree/FM	$10^9/-$	$5/-$	Potter et al. (2017)[47]
Aquarius	zoom	TreePM	$1.7\times10^3/-$	$0.02/-$	Springel et al. (2008)[104]
Via Lactea II	zoom	Tree	$4.1\times10^3/-$	$0.04/-$	Diemand et al. (2008)[375]
GHALO	zoom	Tree	$1.0\times10^3/-$	$0.06/-$	Stadel et al. (2009)[376]
CLUES	zoom	TreePM	$3.4\times10^5/-$	$0.21/-$	Libeskind et al. (2010)[377]
Phoenix	zoom	TreePM	$8.7\times10^5/-$	$0.21/-$	Gao et al. (2012)[105]
ELVIS	zoom	TreePM	$1.9\times10^5/-$	$0.14/-$	Garrison-Kimmel et al. (201
COCO	zoom	TreePM	$1.6\times10^5/-$	$0.33/-$	Hellwing et al. (2016)[379]
+ baryons					
Illustris	107^3	TreePM+MMFV	$6.7\times10^6/1.3\times10^6$	1.42/0.71	Vogelsberger et al. (2014)[14
Horizon-AGN	142^3	PM/ML+AMR	$8.0\times10^7/1.0\times10^7$	1.0/1.0	Dubois et al. (2014)[380]
EAGLE	100^3	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	Schaye et al. (2015)[124]
MassiveBlack-2	143^3	TreePM+SPH	$1.6\times10^7/3.2\times10^6$	2.64/2.64	Khandai et al. (2015)[381]
Bluetides[d]	574^3	TreePM+SPH	$1.7\times10^7/3.4\times10^6$	0.24/0.24	Feng et al. (2016)[382]
Magneticum	68^3	TreePM+SPH	$5.3\times10^7/1.1\times10^7$	1.4/0.7-1.4	Bocquet et al. (2016)[85]
MUFASA	74^3	TreePM+MLFM	$9.6\times10^7/1.8\times10^7$	0.74/0.74	Daveé et al. (2016)[383]
BAHAMAS	571^3	TreePM+SPH	$5.5\times10^9/1.1\times10^9$	0.25/0.25	McCarthy et al. (2017)[384]
Romulus25	25^3	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	Tremmel et al. (2017)[385]
IllustrisTNG[e]	111^3	TreePM+MMFV	$7.5\times10^6/1.4\times10^6$	0.74/0.19	Springel et al. (2018)[87]
Simba[f]	147^3	TreePM+MLFM	$1.4\times10^8/2.7\times10^7$	0.74/0.74	Davé et al. (2019)[182]
Eris	zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	0.12/0.12	Guedes et al. (2011)[349]
VELA	zoom	PM/ML + AMR	$8.3\times10^4/1.9\times10^5$	0.03/0.03[g]	Ceverino et al. (2014)[386]
NIHAO	zoom	Tree+SPH	$3.4\times10^3/6.2\times10^2$	0.12/0.05	Wang et al. (2015)[125]
APOSTLE	zoom	TreePM+SPH	$5.0\times10^4/1.0\times10^4$	0.13/0.13	Sawala et al. (2016)[387]
Latte/FIRE	zoom	TreePM+MLFM	$3.5\times10^4/7.1\times10^3$	0.02/0.001	Wetzel et al. (2016)[352]
Auriga	zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	0.18/0.18[h]	Grand et al. (2017)[297]
MACSIS	zoom	TreePM+SPH	$6.4\times10^9/1.2\times10^9$	5.77/5.77	Barnes et al. (2017)[388]
Cluster-EAGLE	zoom	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	Barnes et al. (2017)[126]
The Three Hundred Project	zoom	TreePM+SPH	$1.9\times10^9/3.5\times10^8$	9.59/9.59	Cui et al. (2018)[389]
FABLE	zoom	TreePM+MMFV	$8.1\times10^7/1.5\times10^7$	4.15/4.15	Henden et al. (2018)[390]
RomulusC	zoom	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	Tremmel et al. (2019)[391]

Voge



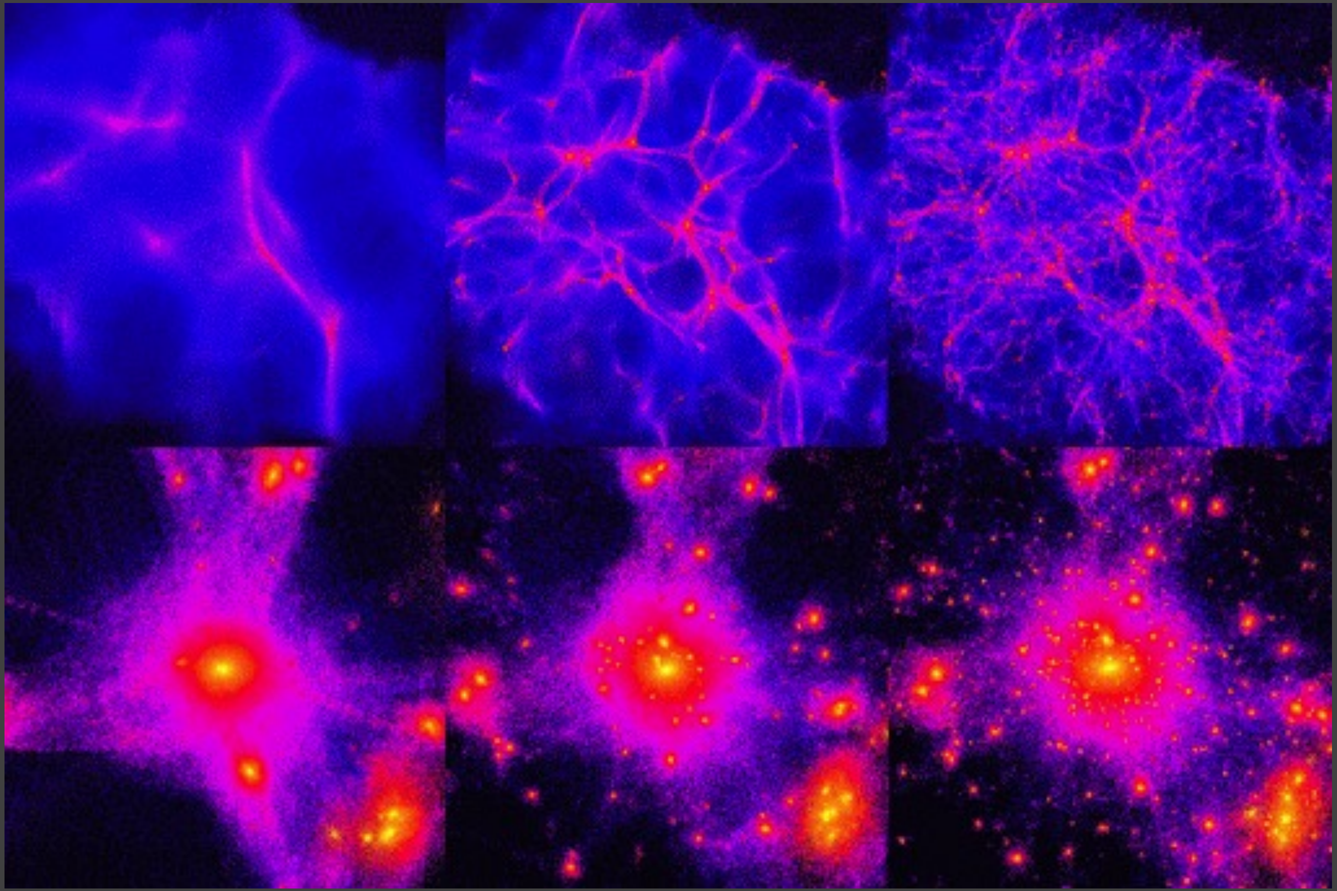
N-BODY SIMULATIONS

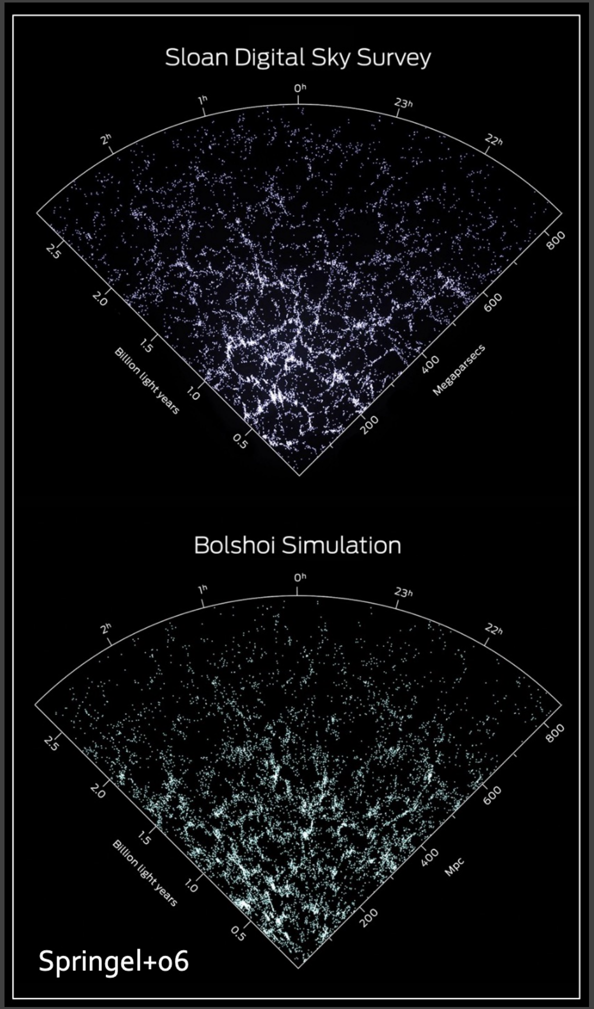
- Provide relations M(r), N(M), N(r) of DM subhaloes required to make the signal model



COLD DARK MATTER

Different free-streaming lengths

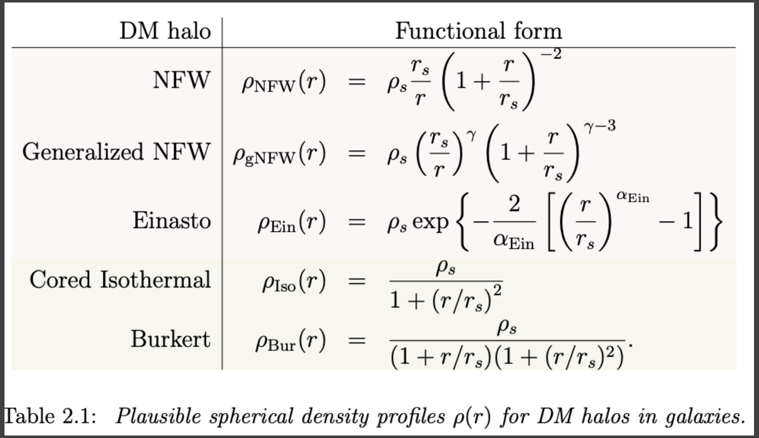




Springel+06

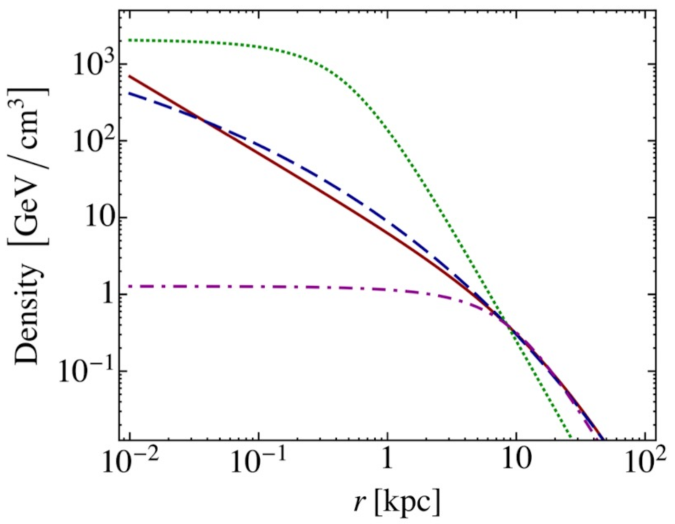
Confirm LCDM scenarios

N-BODY SIMULATIONS: DENSITY PROFILES



DM halo	Functional form
NFW	$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$
Generalized NFW	$\rho_{\rm gNFW}(r) = \rho_s \left(\frac{r_s}{r}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{\gamma-3}$
Einasto	$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha_{\rm Ein}}\left[\left(\frac{r}{r_s}\right)^{\alpha_{\rm Ein}}-1\right]\right\}$
Cored Isothermal	$\rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$
Burkert	$\rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}.$

Table 2.1: *Plausible spherical density profiles $\rho(r)$ for DM halos in galaxies.*

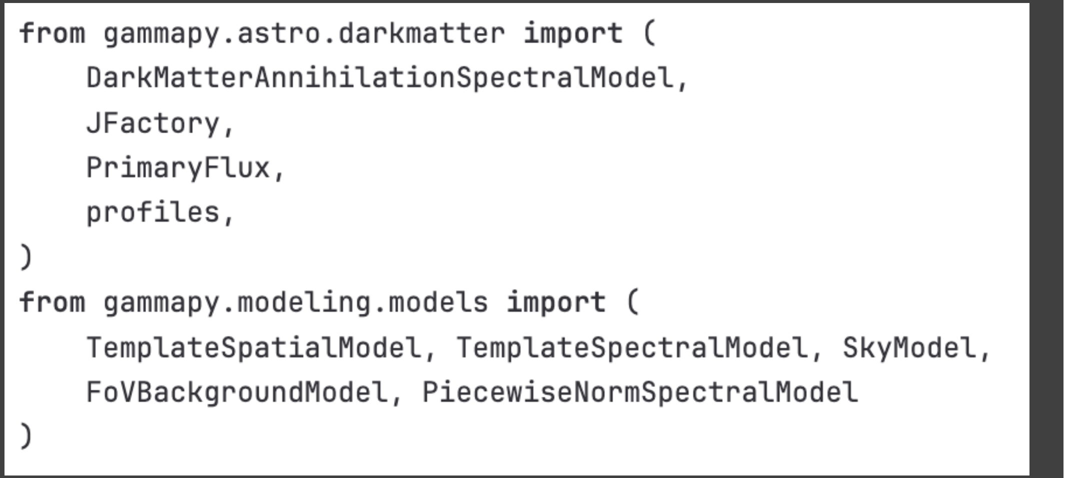


- Cuspy profile: NFW, gNFW, Einasto
  - Preferred by N-body simulations
- Cored profile: isothermal, Burkert
  - Preferred by observations

GAMMAPY

```
import darkpipe as dp
```

In development by S. Abe

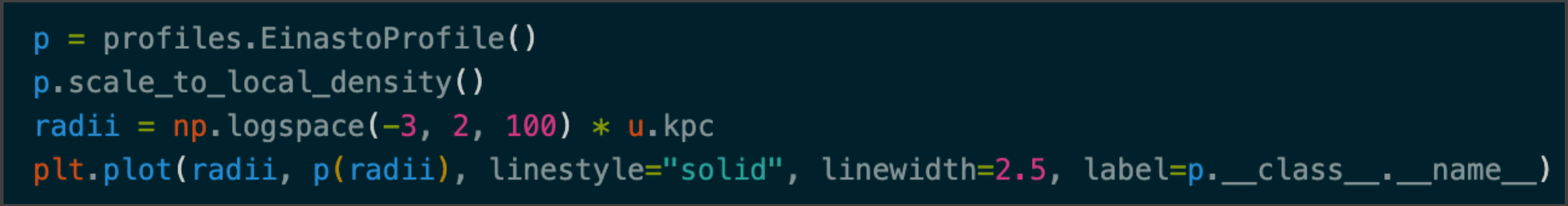


```
from gammapy.astro.darkmatter import (
    DarkMatterAnnihilationSpectralModel,
    JFactory,
    PrimaryFlux,
    profiles,
)
from gammapy.modeling.models import (
    TemplateSpatialModel, TemplateSpectralModel, SkyModel,
    FoVBackgroundModel, PiecewiseNormSpectralModel
)
```

Prepare WIMP Models

```
# config for a DM component
channel = 'W'
mass = 10*u.TeV
profile = profiles.NFWProfile()
```

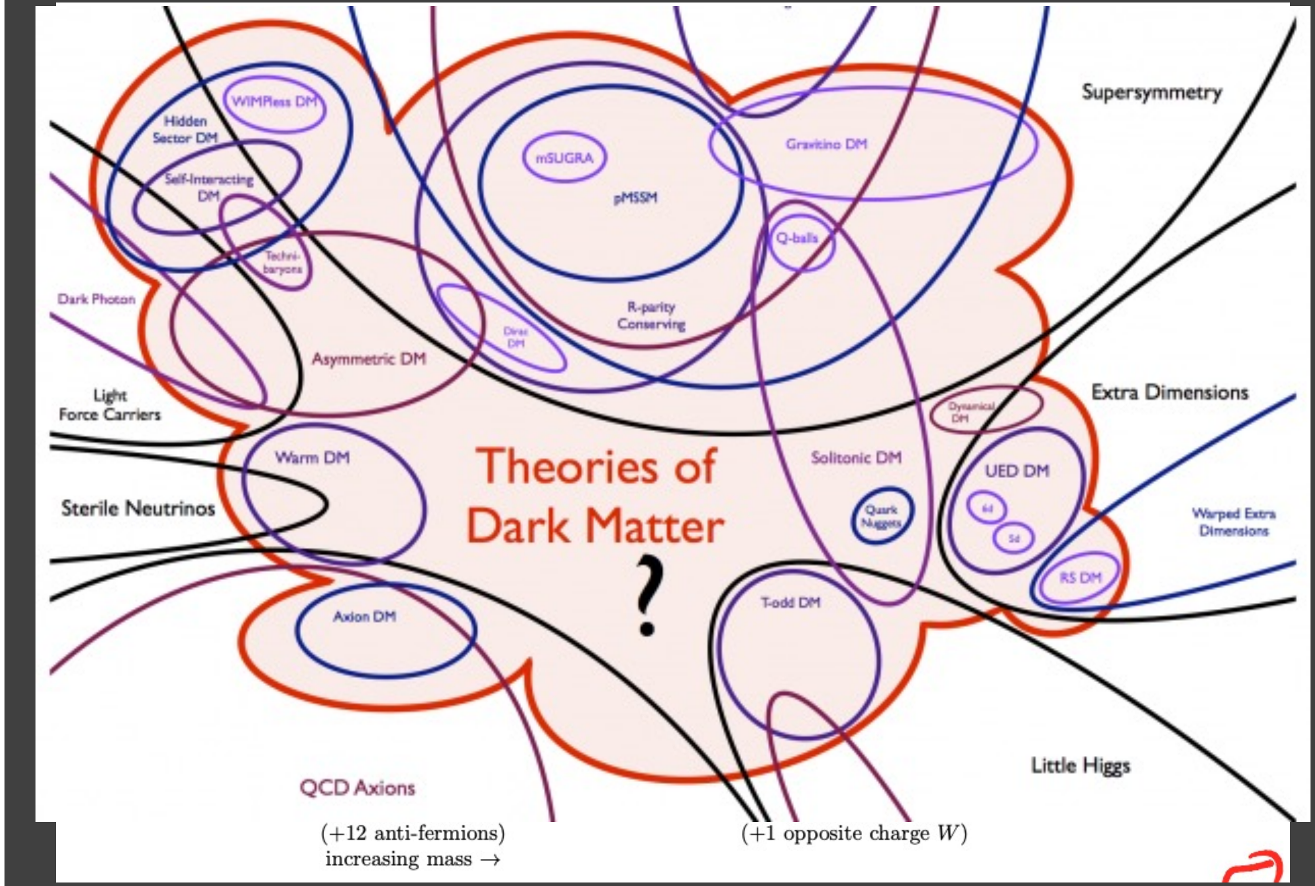
```
%%time
m = dp.DarkMatterModelGenerator(
    geom_image = geom.to_image(),
    profile = profile,
    mass = mass,
    channel = channel,
)
```



```
p = profiles.EinastoProfile()
p.scale_to_local_density()
radii = np.logspace(-3, 2, 100) * u.kpc
plt.plot(radii, p(radii), linestyle="solid", linewidth=2.5, label=p.__class__.__name__)
```

SM PARTICLES CANNOT BE DM, SO, A NEW PARTICLE?

Tim Tait



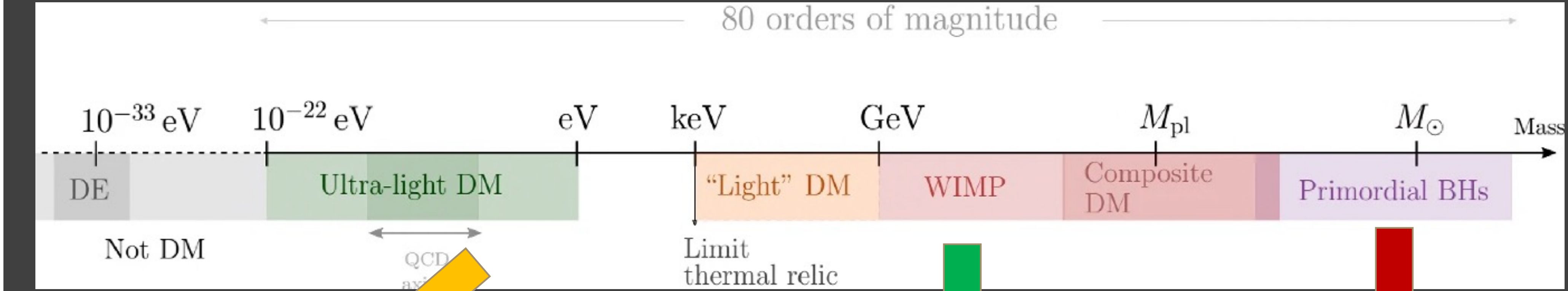
SM particles can account for a tiny fraction of DM

To convince Zwicky models must be natural, non ad-hoc

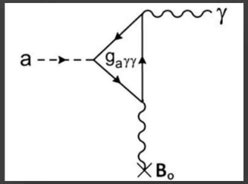
- you have to invent measurement and instruments!
- strong claims requires strong evidences!

CAN BE PROBED WITH GAMMA-RAYS

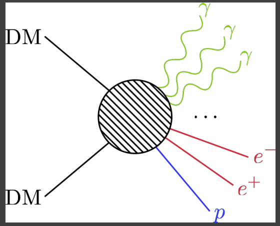
Elisa Ferreira 2021



While axions, signals can travel long distances in space and leave imprint in g-ray spectra



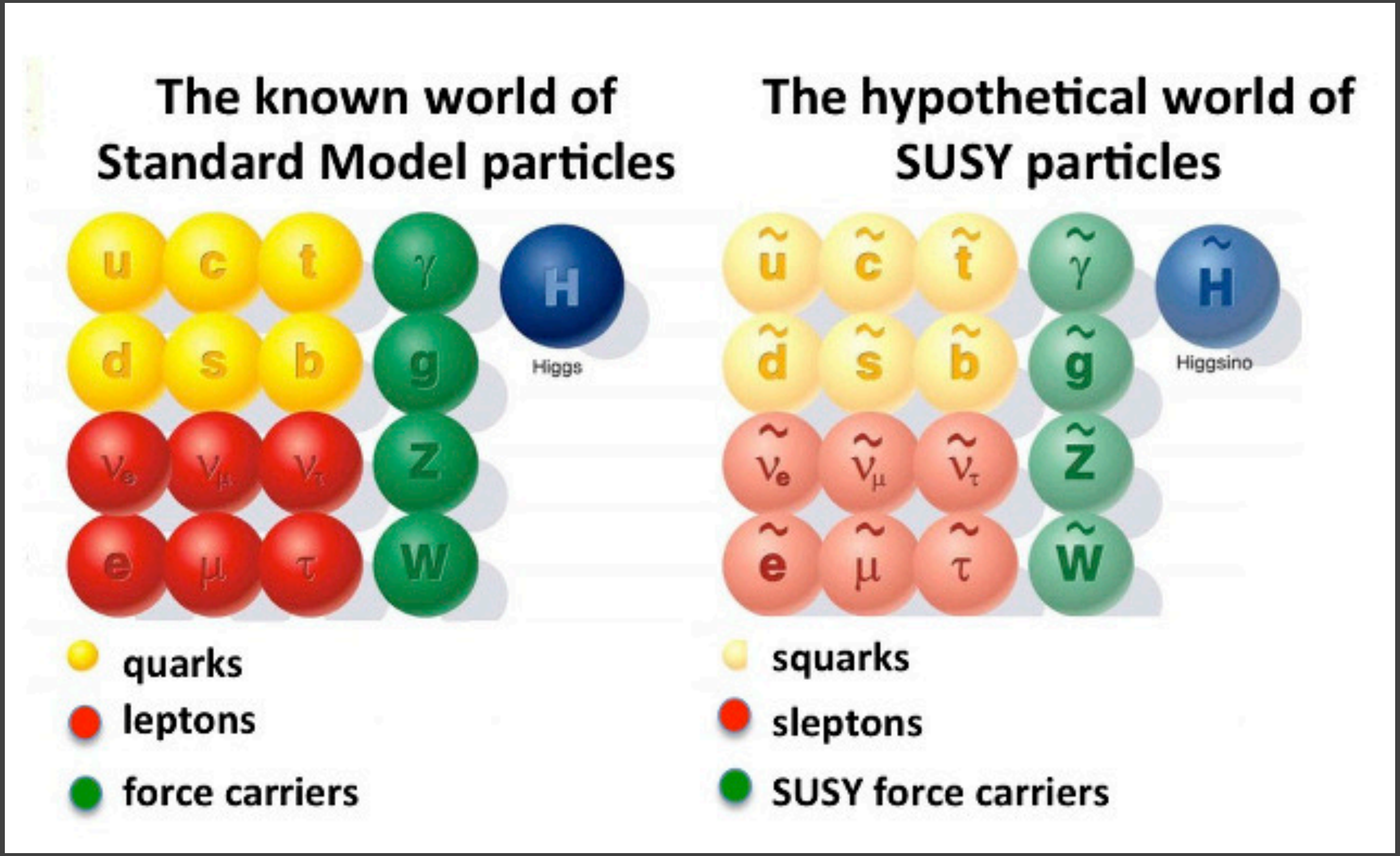
Annihilation/Decay of TeV DM in space



TeV emission during/after PBH evaporation

WIMP = Weakly-Interacting Massive Particle

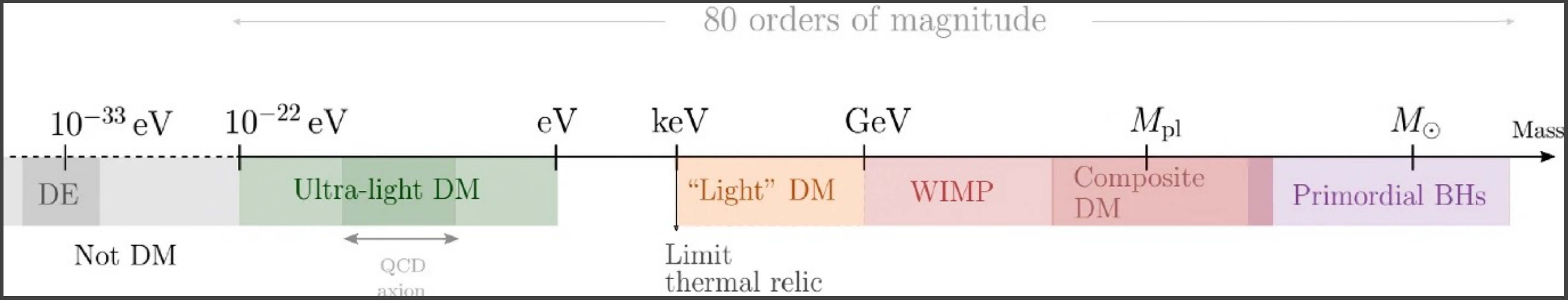
SUPER SYMMETRY / WIMP



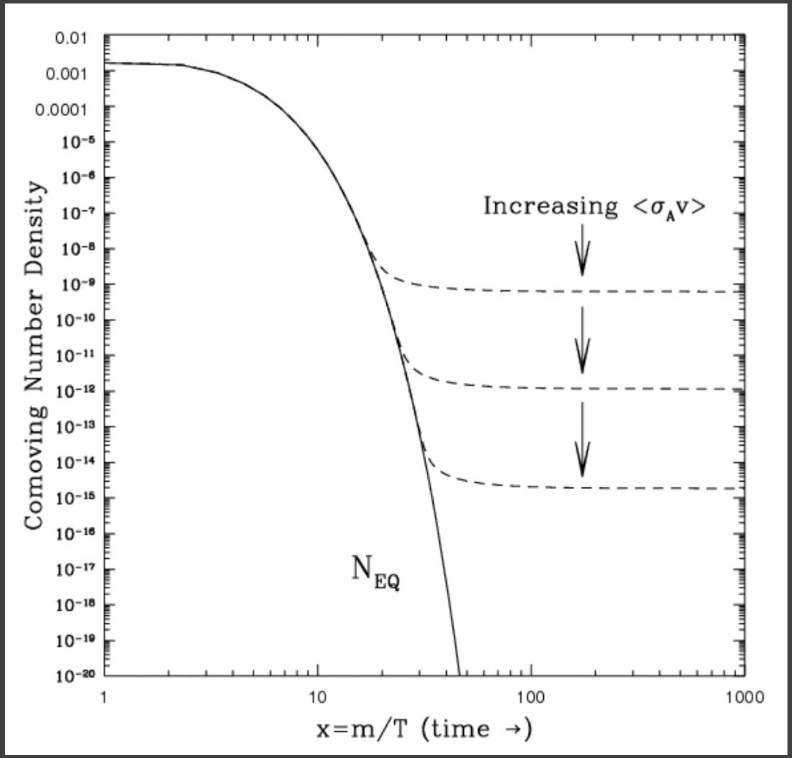
- Lightest Supersymmetric particle (LSP) is a ‘natural DM candidate
- Neutralino, wino, higgsinos are prototype LSP

TWO FLAVOURS

- The particle has been in thermal equilibrium sometimes in the early Universe → WIMP, etc
- The particle has NOT been in thermal equilibrium sometimes in the early Universe → ALP, PBH, etc



THERMAL RELICS: THE WIMP MIRACLE



- An early phase with total chemical equilibrium, DM←→ SM

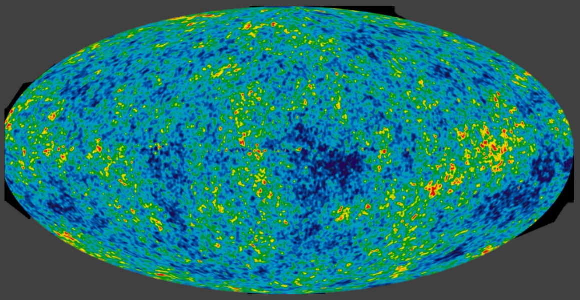
$$\frac{dn}{dt} + 3Hn = (n_{\mathrm{eq}}^2 - n^2)\langle \sigma v_{\mathrm{rel}} \rangle .$$

- Universe expands, annihilation stops (freeze-out)

$$dn/dt + 3(\dot{a}/a)n = 0$$

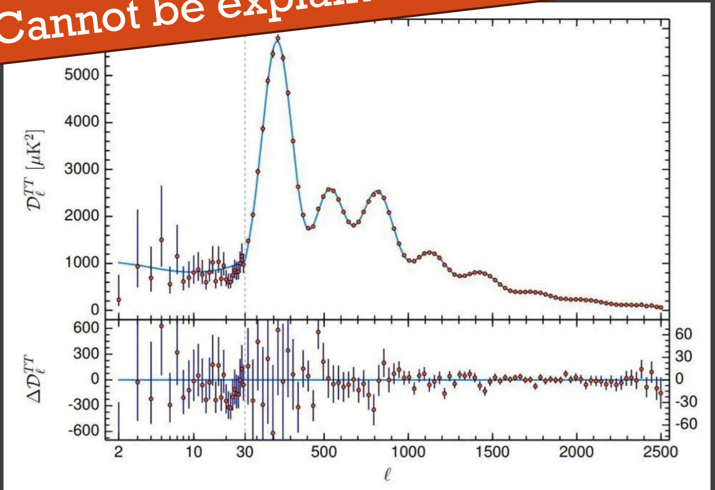
$$\Omega_X h^2 \approx 0.12 \left(\frac{2.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right) \left(\frac{80}{g_\star} \right)^{1/2} \left(\frac{m_X/T_{\mathrm{F}}}{23} \right),$$

THE CMB IMPRINT



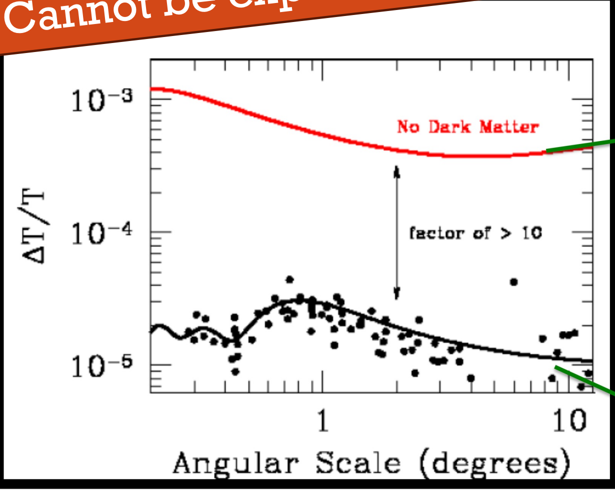
- During CMB time Universe is matter dominated
- Recombination: increase of neutral hydrogen
- 100 GeV DM annihilation can ionize roughly 10% of the hydrogen in the universe! So this effect would be very visibile on CMB

Cannot be explained with MOND



Power spectrum of anisotropies due to non-collisional matter

Cannot be explained with MOND

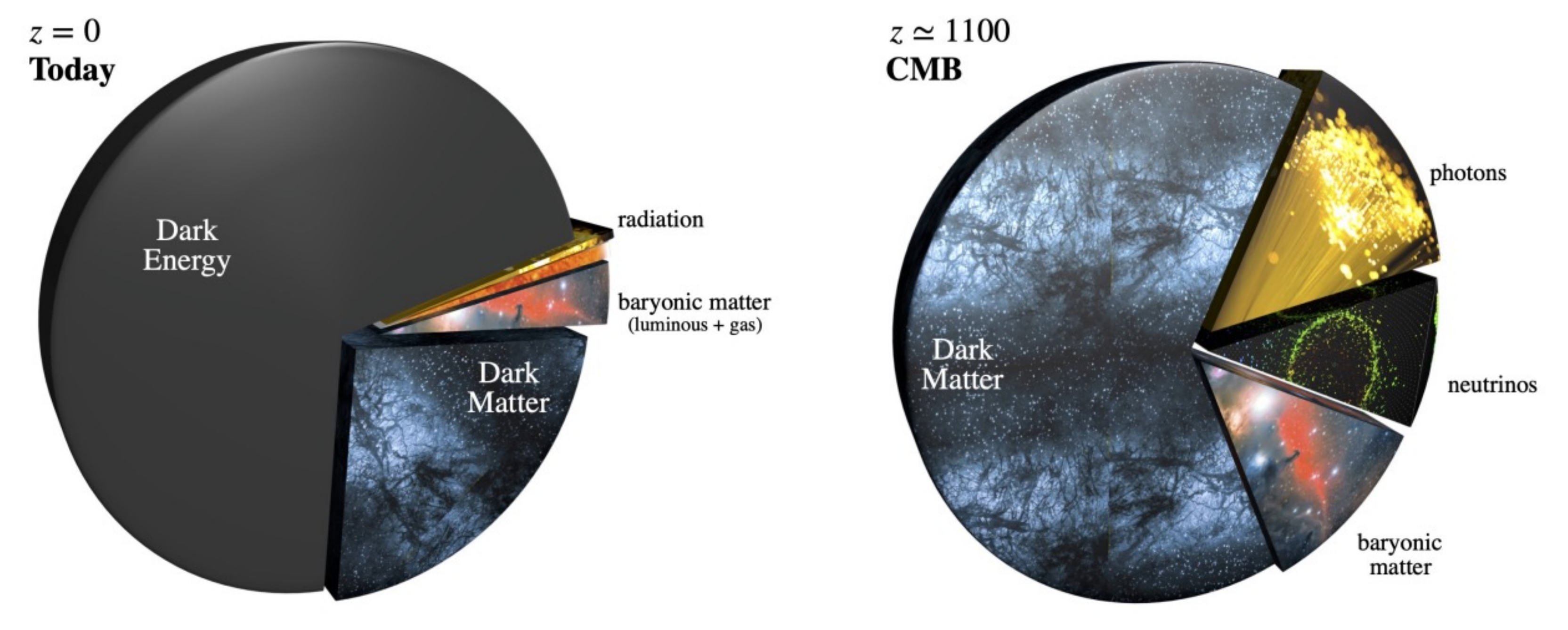


Amplitude of fluctuations **needed** to account for the structure we see today if there was no DM

Actual CMB data

CMB fluctuations ARE NOT large enough to produce the observed Large Scale Structure without the help of CDM

OUR UNIVERSE: THE DM PIE

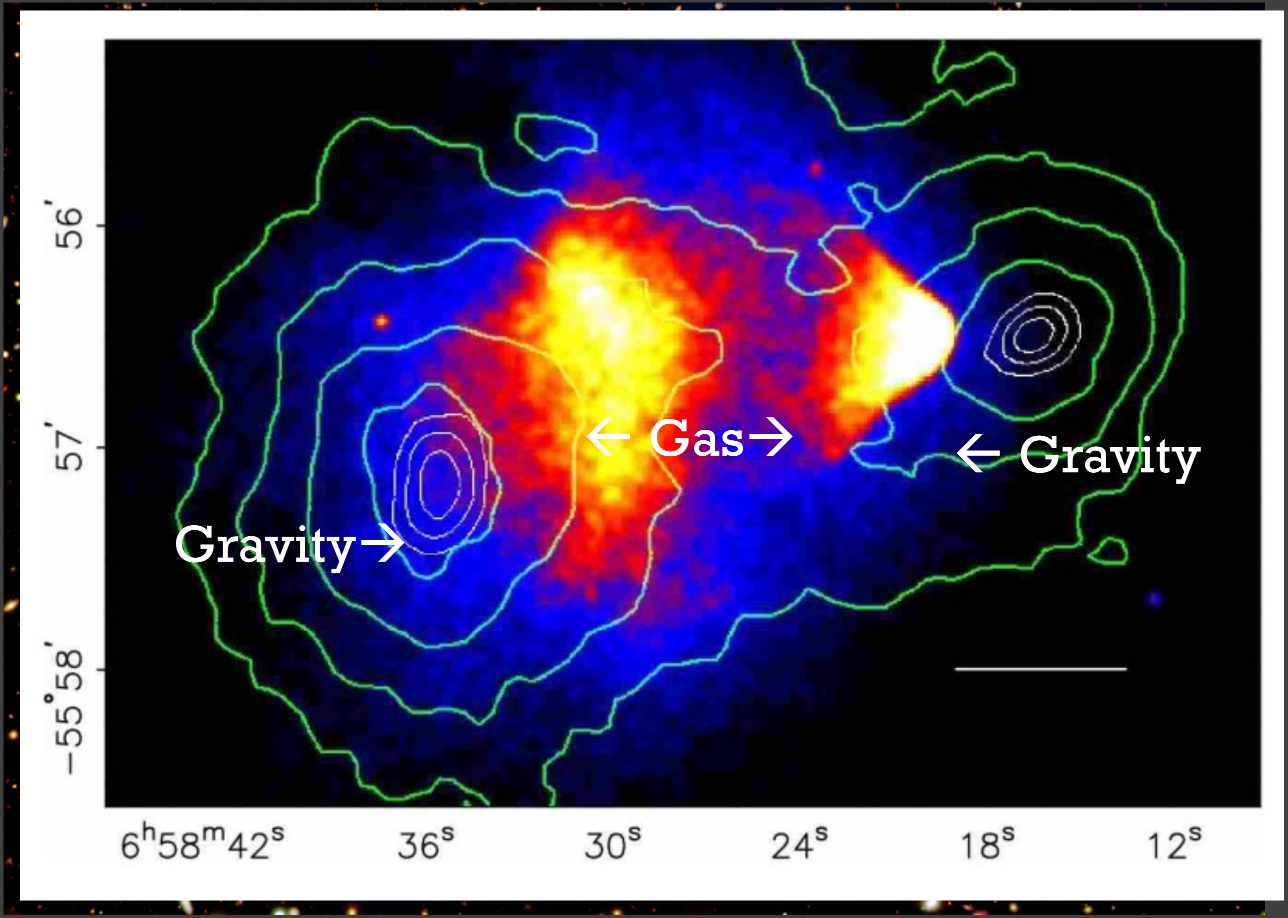


DM have led Structure formation

Cirelli+ 2024

~25% of the Universe energy budget in dark matter
~80% of matter has always been dark

BULLET CLUSTER



Non collisional matter is very weakly interacting!

Harvey et al. (2015) report the results on 72 similar merger events and conclude that the existence of particle DM can be established with a significance of more than 7σ.

Cannot be explained with MOND

https://youtu.be/rLx_TXhTXbs

SUMMARY

Observational evidence of dark matter (DM)

Evidence has been reported at all scales, but is only astrophysical as of today.

Galactic scales

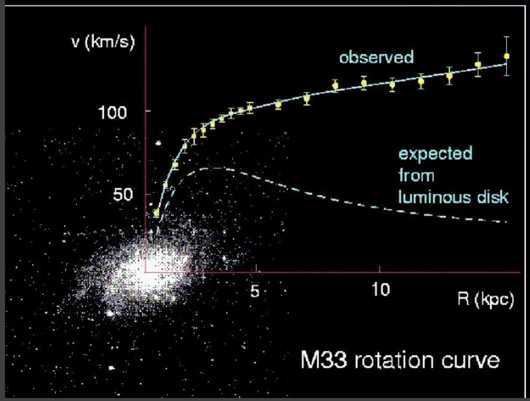
a) Rotation curves of spirals
b) Weak lensing
c) Velocity dispersions of satellite galaxies
d) Velocity dispersions in dSphs

Galaxy clusters scales

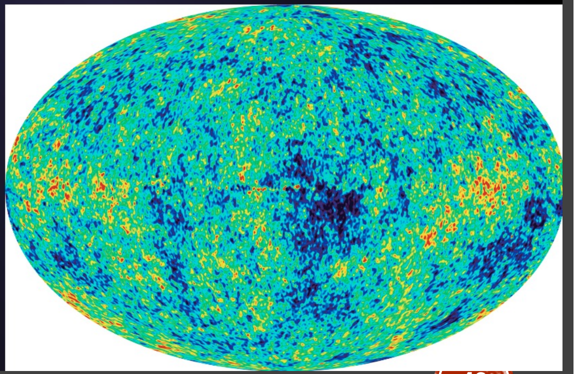
a) Velocity dispersions of individual galaxies
b) Strong and weak lensing
c) Peculiar velocity flows
d) X-ray emission

Cosmological scales

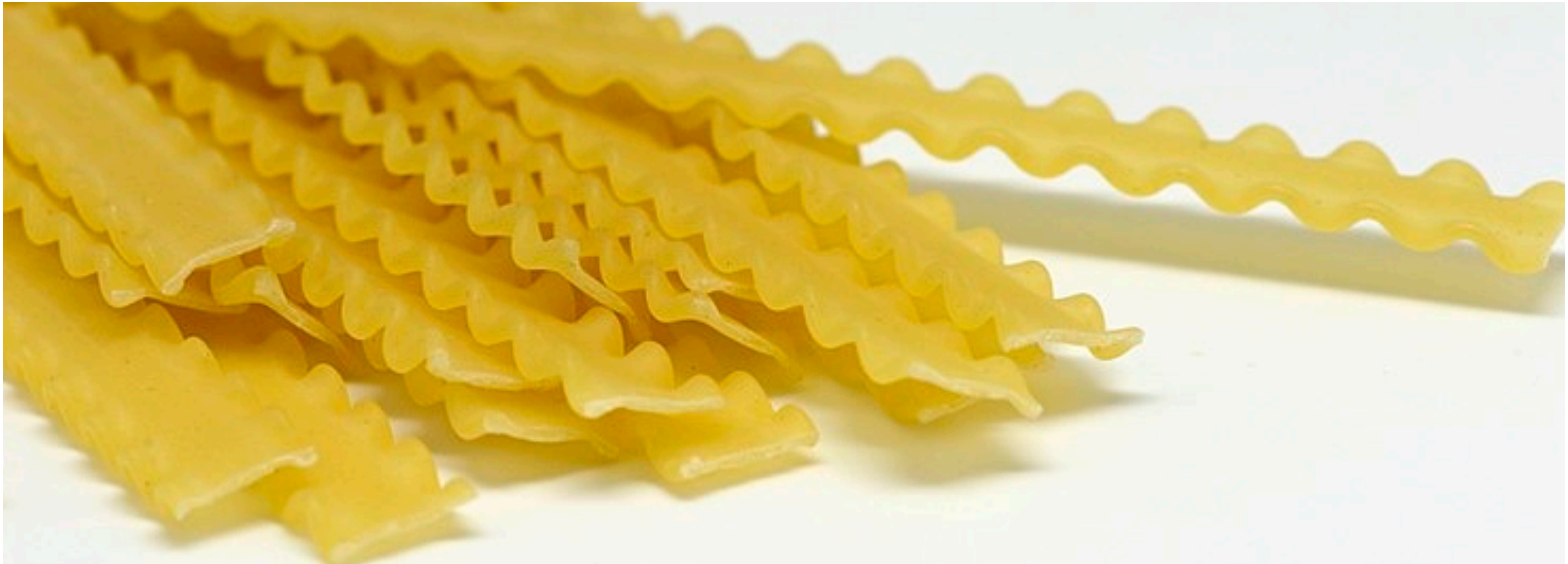
a) CMB anisotropies
b) Growth of structure
c) LSS distribution
d) BAOs
e) SZ effect



M33 rotation curve

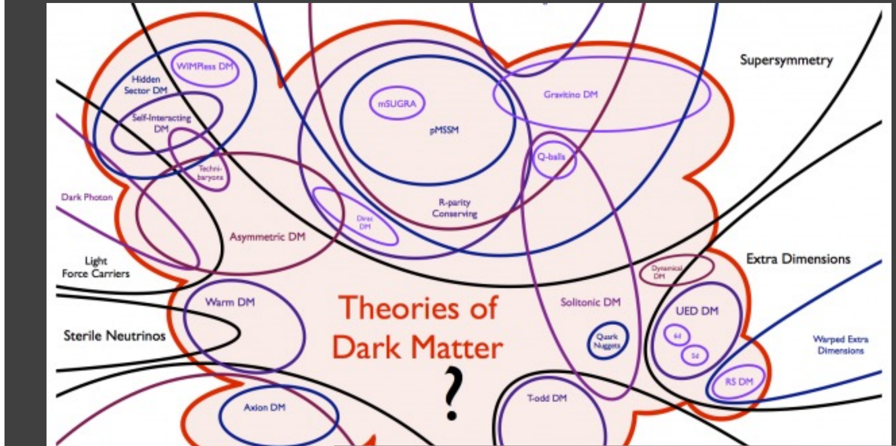


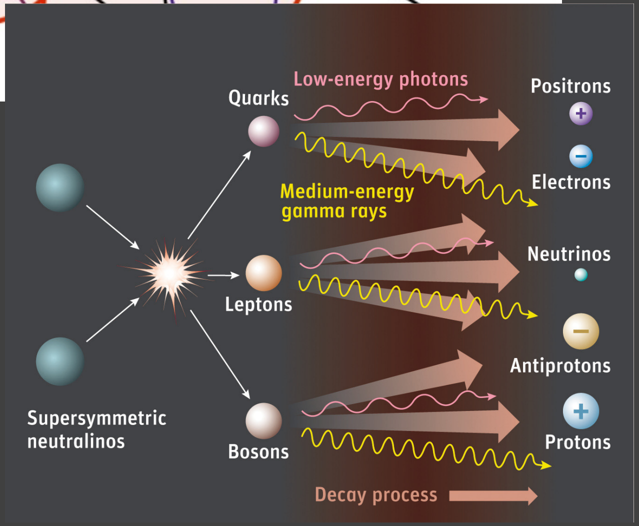
Sanchez Conde



GAMMA-RAY PROBES FOR DARK MATTER

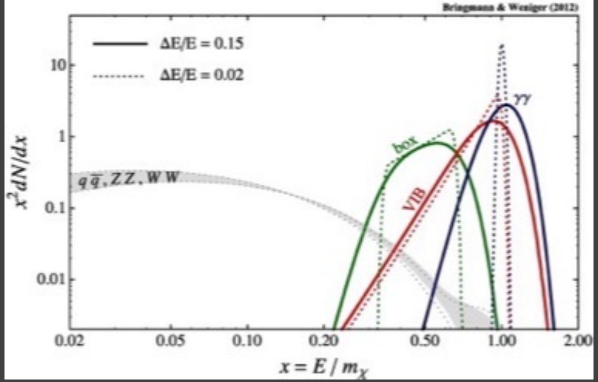
GAMMA-RAYS IN EVERY RECIPE



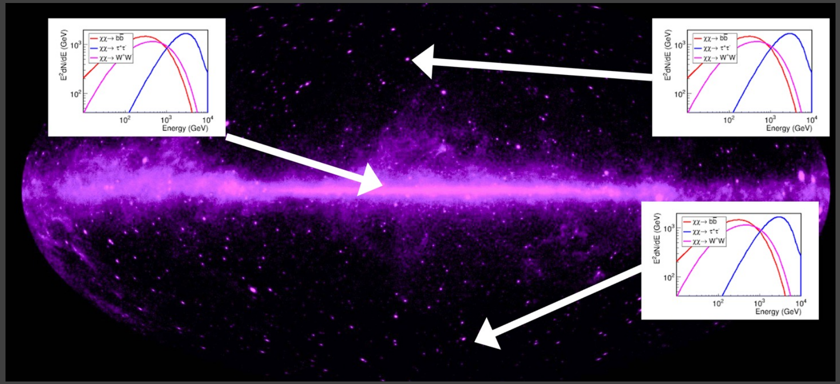


#0 Gamma-rays expected in HE interactions

#1 Peculiarity of gamma-ray spectra (no astro-like)



#2 Same signal at different targets



#3 Know where to point

G-RAY SIGNAL MODEL

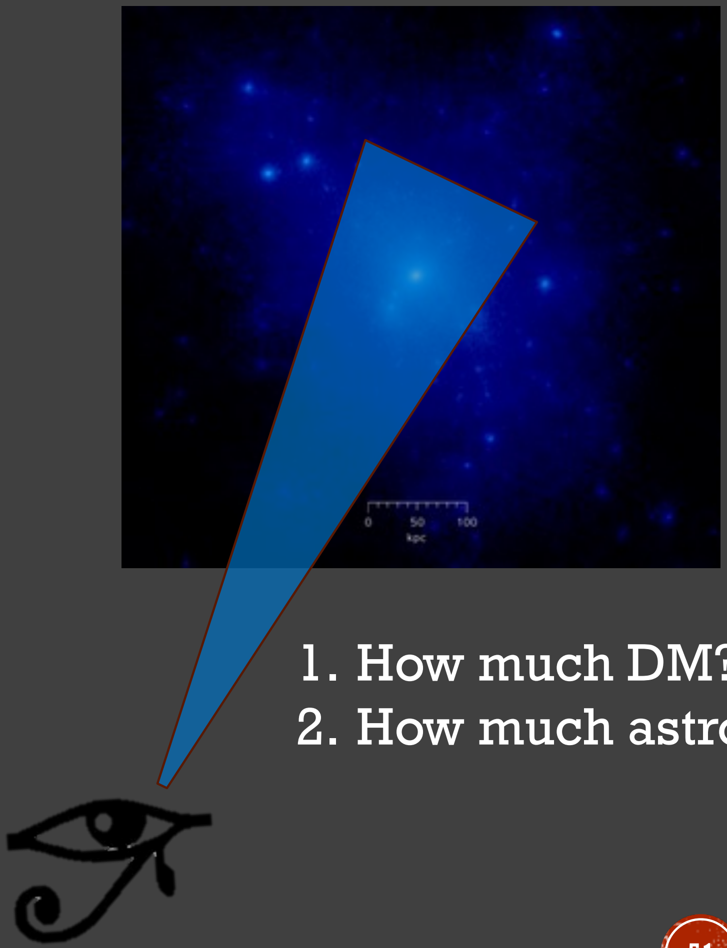
$$\frac{d\Phi_\gamma}{dE_\gamma} = \begin{cases} \dfrac{\langle \sigma v \rangle}{4k\pi\ m_\chi^2} \sum_i \mathrm{BR}_i \dfrac{dN_\gamma^i}{dE_\gamma} \cdot J_{\mathrm{ann}}(\Delta\Omega) & \text{Annihilating DM} \\[2ex] \dfrac{1}{4\pi\ m_\chi} \sum_i \Gamma_i \dfrac{dN_\gamma^i}{dE_\gamma} \cdot J_{\mathrm{dec}}(\Delta\Omega) & \text{Decaying DM} \end{cases}$$

Particle physics to understand the process from DM to SM

➕

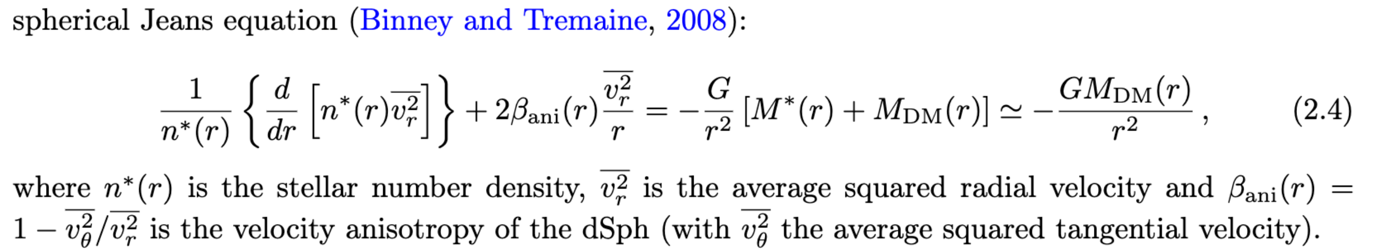
Astrophysics to guess the amount of DM in the sky or an object

$$\begin{cases} J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(\ell,\Omega)\, d\ell\, d\Omega & \text{Annihilating DM} \\[2ex] J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Decaying DM} \end{cases}$$



1. How much DM?
2. How much astro?

J-FACTOR

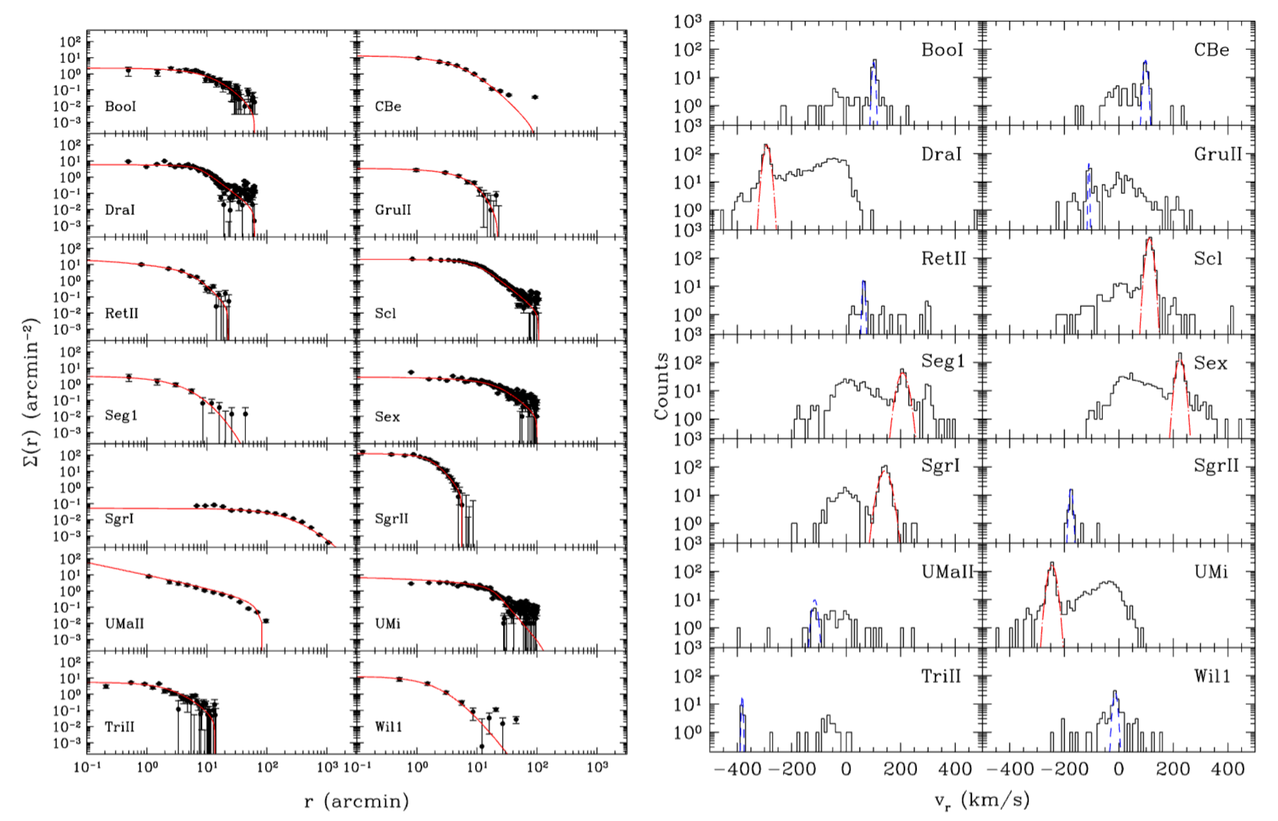


spherical Jeans equation (Binney and Tremaine, 2008):

$$\frac{1}{n^*(r)}\left\{\frac{d}{dr}\left[n^*(r)\overline{v_r^2}\right]\right\}+2\beta_{\rm ani}(r)\frac{\overline{v_r^2}}{r}=-\frac{G}{r^2}\left[M^*(r)+M_{\rm DM}(r)\right]\simeq-\frac{GM_{\rm DM}(r)}{r^2}\,, \tag{2.4}$$

where $n^*(r)$ is the stellar number density, $\overline{v_r^2}$ is the average squared radial velocity and $\beta_{\rm ani}(r) = 1-\overline{v_\theta^2}/\overline{v_r^2}$ is the velocity anisotropy of the dSph (with $\overline{v_\theta^2}$ the average squared tangential velocity).

From dSphs KSP paper in prep



- Inferred with **Jeans equilibrium equation**
- DM halo shape: **N-body/models**
- Stars trace gravity: need **velocity dispersion**

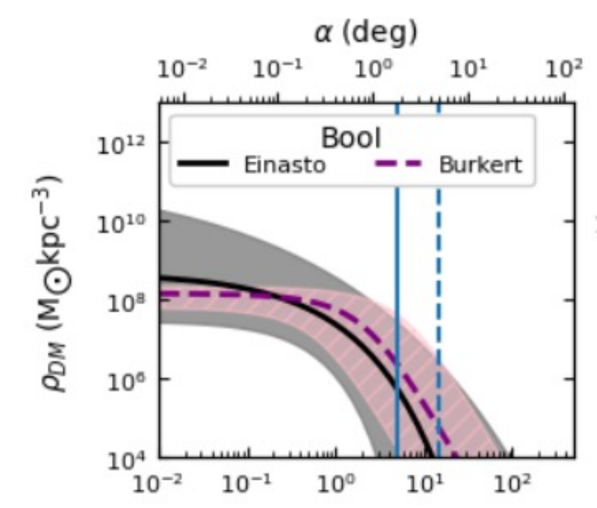
CLUMPY

- Main tool: MCMC Jeans analysis of stellar kinematics with CLUMPY
- (Charbonnier+ 2012, Bonnivard+ 2016, Hütten+ 2019).

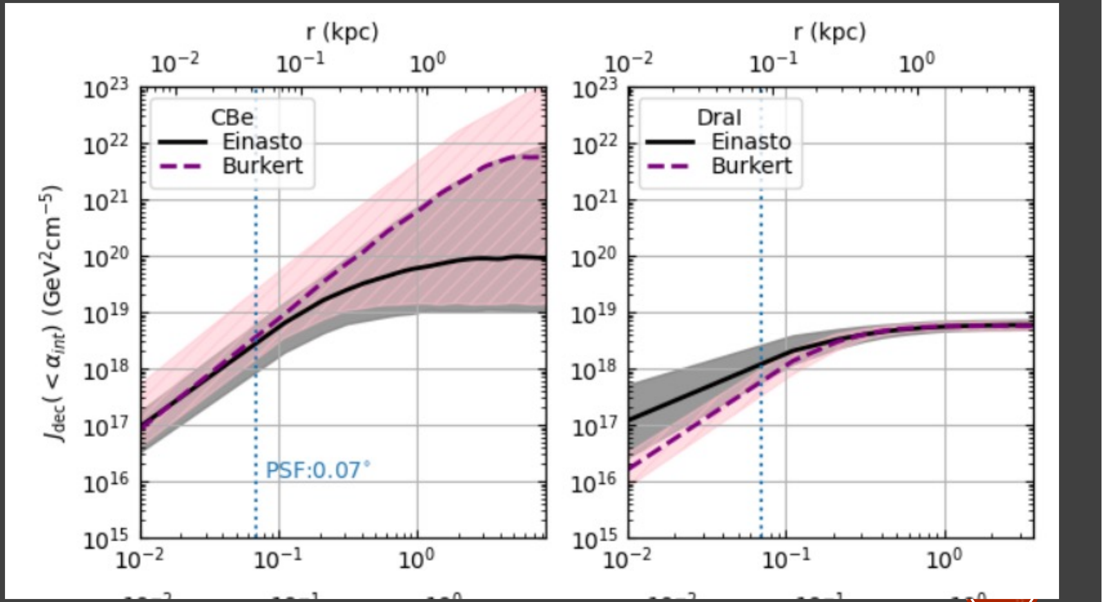
$$J_{\text{ann}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{los} \rho^2(l,\Omega) dl d\Omega.$$

From dSphs KSP paper in prep

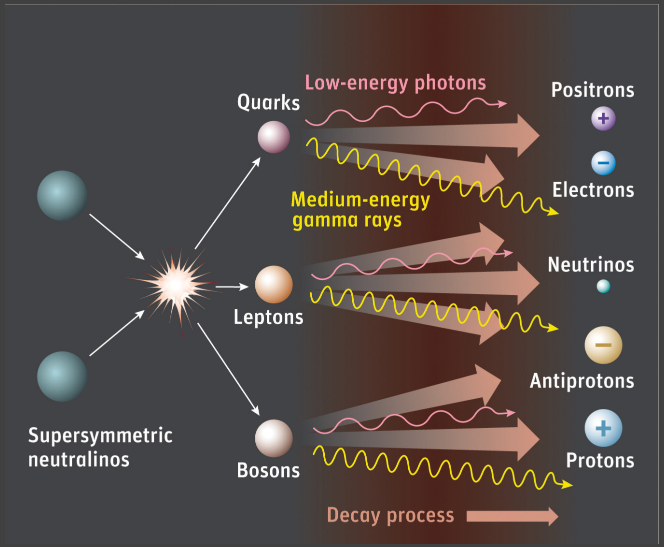
Density radial profiles



J-factors within angle



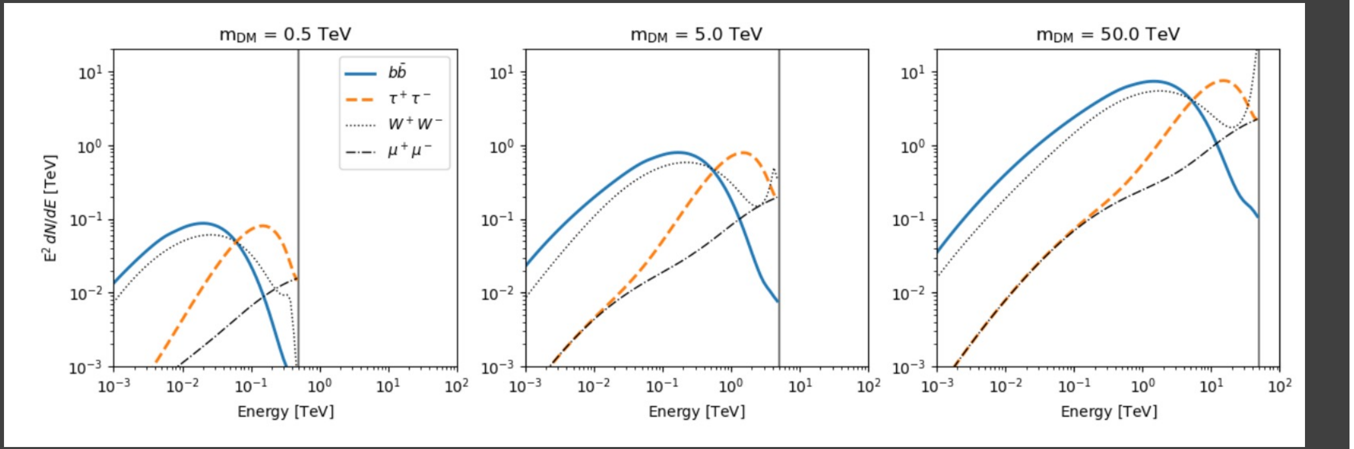
GAMMA-RAYS



- ○ Gamma-yield per annihilation/decay studies with microphysics model
- ○ However, generally speaking, quark hadronization very common: $\pi^0 \rightarrow \gamma\gamma$ and leptonic channels
- ○ We can be pretty model-independent

Peculiar spectrum:

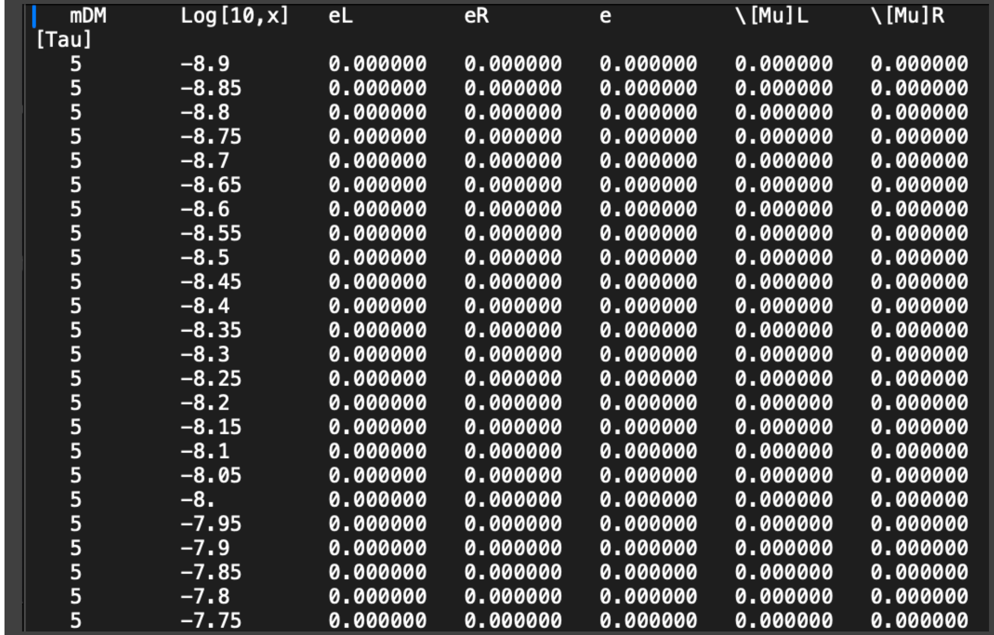
- Cutoff at DM mass (annihilation) and ½ DM mass (decay)
- Limited confusion with astrophysical sources



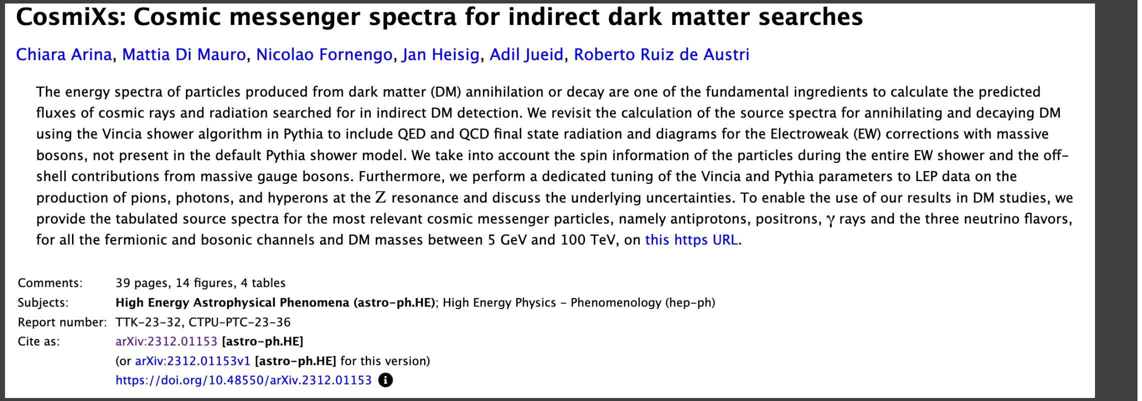
From dSphs KSP paper in prep

PPPC 4 DM ID - A POOR PARTICLE PHYSICIST COOKBOOK FOR DARK MATTER INDIRECT DETECTION

http://www.marcocirelli.net/pppc4dmid.html



```
  mDM       Log[10,x]   eL        eR        e         \[Mu]L    \[Mu]R
[Tau]
  5         -8.9        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.85       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.8        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.75       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.7        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.65       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.6        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.55       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.5        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.45       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.4        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.35       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.3        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.25       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.2        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.15       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.1        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.05       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -8.         0.000000  0.000000  0.000000  0.000000  0.000000
  5         -7.95       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -7.9        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -7.85       0.000000  0.000000  0.000000  0.000000  0.000000
  5         -7.8        0.000000  0.000000  0.000000  0.000000  0.000000
  5         -7.75       0.000000  0.000000  0.000000  0.000000  0.000000
```

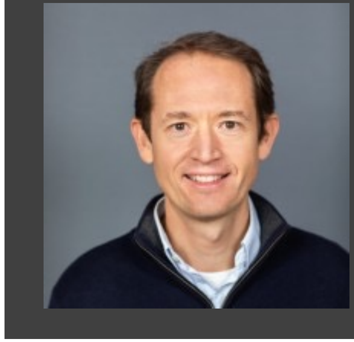


CosmiXs: Cosmic messenger spectra for indirect dark matter searches

Chiara Arina, Mattia Di Mauro, Nicolao Fornengo, Jan Heisig, Adil Jueid, Roberto Ruiz de Austri

The energy spectra of particles produced from dark matter (DM) annihilation or decay are one of the fundamental ingredients to calculate the predicted fluxes of cosmic rays and radiation searched for in indirect DM detection. We revisit the calculation of the source spectra for annihilating and decaying DM using the Vincia shower algorithm in Pythia to include QED and QCD final state radiation and diagrams for the Electroweak (EW) corrections with massive bosons, not present in the default Pythia shower model. We take into account the spin information of the particles during the entire EW shower and the off-shell contributions from massive gauge bosons. Furthermore, we perform a dedicated tuning of the Vincia and Pythia parameters to LEP data on the production of pions, photons, and hyperons at the Z resonance and discuss the underlying uncertainties. To enable the use of our results in DM studies, we provide the tabulated source spectra for the most relevant cosmic messenger particles, namely antiprotons, positrons, γ rays and the three neutrino flavors, for all the fermionic and bosonic channels and DM masses between 5 GeV and 100 TeV, on this https URL.

Comments:	39 pages, 14 figures, 4 tables
Subjects:	**High Energy Astrophysical Phenomena (astro-ph.HE)**; High Energy Physics - Phenomenology (hep-ph)
Report number:	TTK-23-32, CTPU-PTC-23-36
Cite as:	arXiv:2312.01153 **[astro-ph.HE]** (or arXiv:2312.01153v1 **[astro-ph.HE]** for this version) https://doi.org/10.48550/arXiv.2312.01153

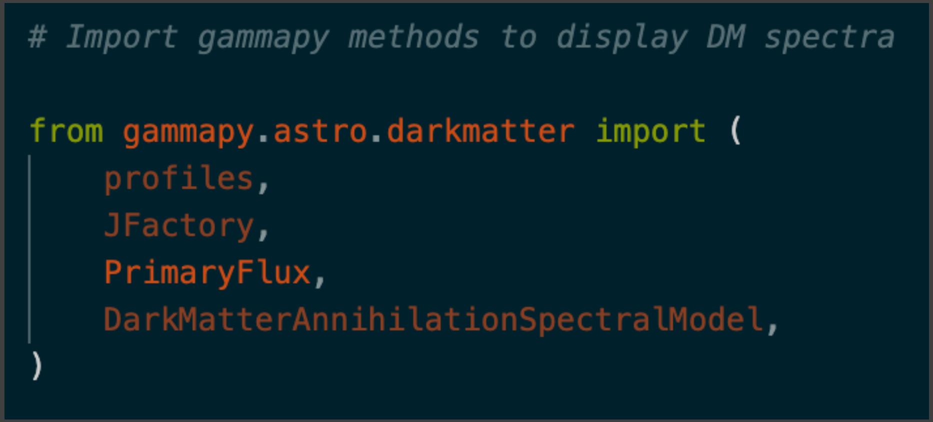


Available in gammapy with ‘gammapy download dataset’. Look for AtProduction_gammas.dat file

Marco Cirelli

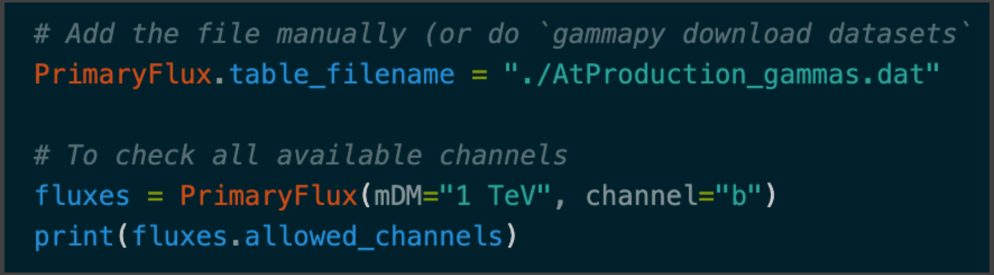
- Recently new improved model (especially at high energies) by Arina+ called CosmiXs
- Same format as AtProduction_gammas.dat
- Already implemented in gammapy

GAMMAPY AND PPPC



```
# Import gammapy methods to display DM spectra

from gammapy.astro.darkmatter import (
    profiles,
    JFactory,
    PrimaryFlux,
    DarkMatterAnnihilationSpectralModel,
)
```



```
# Add the file manually (or do `gammapy download datasets`
PrimaryFlux.table_filename = "./AtProduction_gammas.dat"

# To check all available channels
fluxes = PrimaryFlux(mDM="1 TeV", channel="b")
print(fluxes.allowed_channels)
```

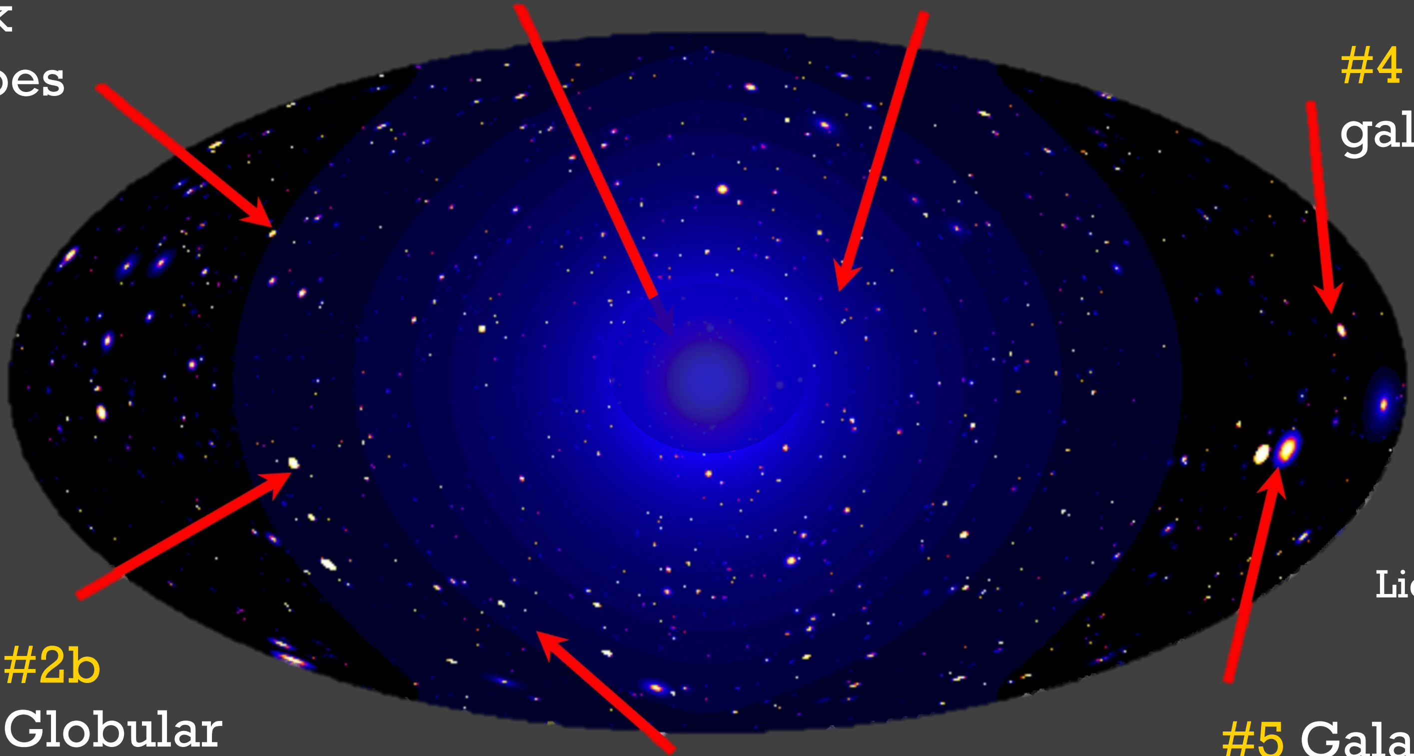
```
channels = ["b", "tau", "W", "mu"]
# and so on

# zip it for the loop
for mDM, ax in zip(mDMs, axes):
    fluxes.mDM = mDM
    ax.set_title(rf"m$_{{\mathrm{{DM}}}}$ = {mDM}")
    ax.set_yscale("log")

    for channel, label, linestyle, linewidth, color in
        fluxes.channel = channel
        fluxes.table_model.plot(
            energy_bounds=[mDM / 100, mDM],
            ax=ax,
            label=label,
            linestyle=linestyle,
            linewidth=linewidth,
            color=color,
            yunits=u.Unit("TeV"), # Must be set
            sed_type="e2dnde",
        )
```

WHERE TO FIND DM
IN THE COSMIC KITCHEN

A POSSIBLE G-RAY DM SKY FROM WIMPS



#1 Galactic Center and halo

#3 Dark subhaloes

#4 Other galaxies

#2 Dwarf galaxies (MW satellites) Spheroidal and Irregular

#2b Globular clusters

#6 Diffuse signal, lines, holes in stellar streams, …

#5 Galaxy clusters

Lidia Pieri+

FOCUS ON CTA

- KSP/CTAC:
  - Galactic Center JCAP 01 (2021) 057
  - LMC Mon.Not.Roy.Astron.Soc. 523 (2023)
  - Perseus Galaxy Cluster 2309.03712
  - dSphs in prep.

- Friends:
  - DM lines 2403.04857
  - Dark subhalos e.g. Phys.Dark Univ. 32 (2021)
  - Higgsino DM 2405.13104 , Wino DM Phys.Rev.D 103 (2021), Secluded DM Phys.Lett.B 797 (2019)
  - …

GALACTIC CENTRE - JCAP 01 (2021) 057

Will be observed with multiple pointings

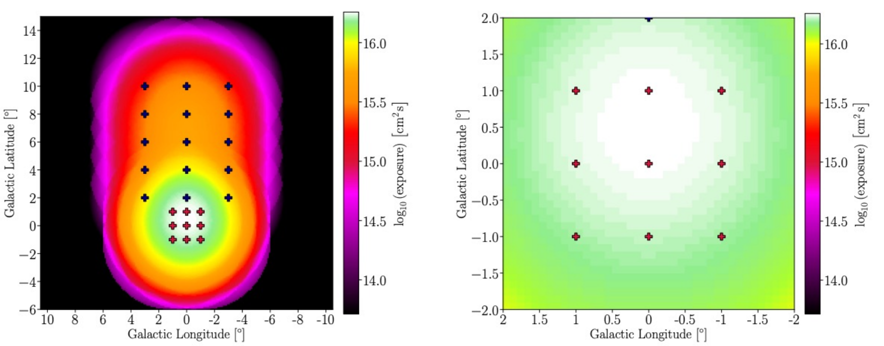


Figure 1: The left panel shows the exposure map for CTA's Galactic centre (GC) and extended GC surveys, at an energy of 1 TeV. The right panel shows a zoom into the GC survey region. The nine pointing positions of the GC survey mode are marked with red

Must be computed in gammapy

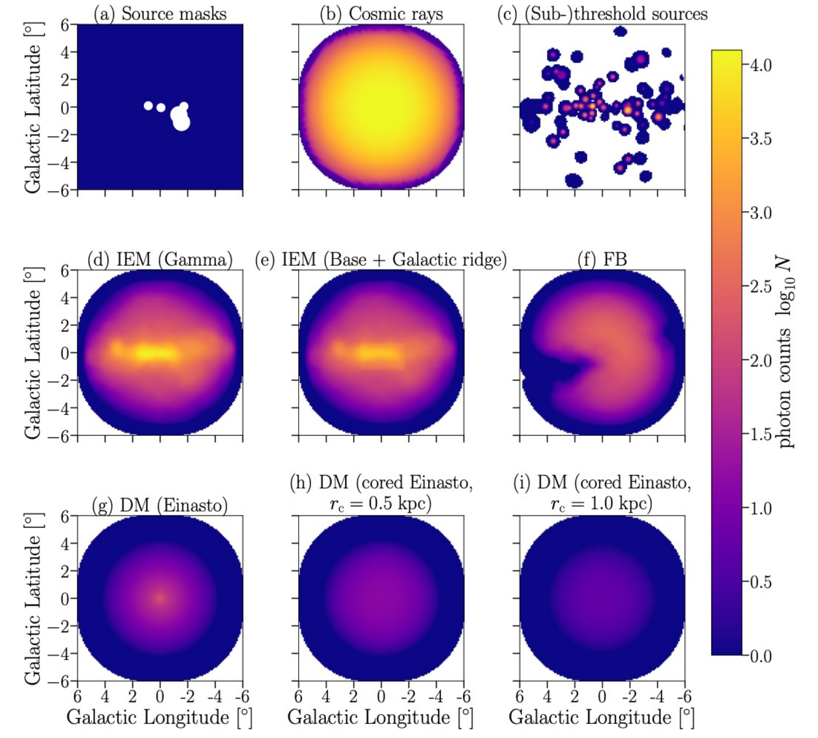
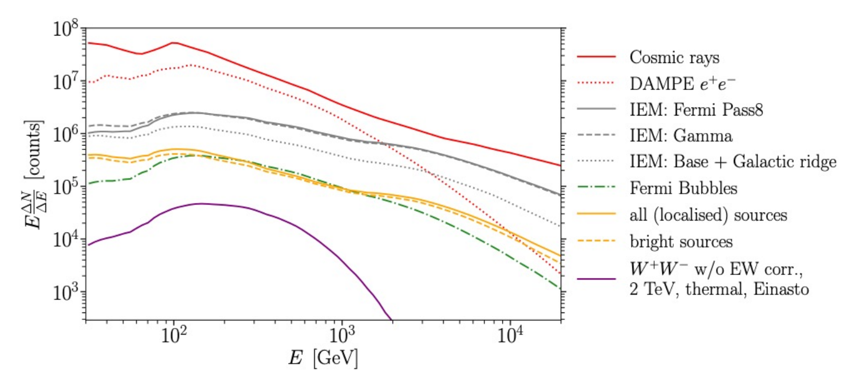


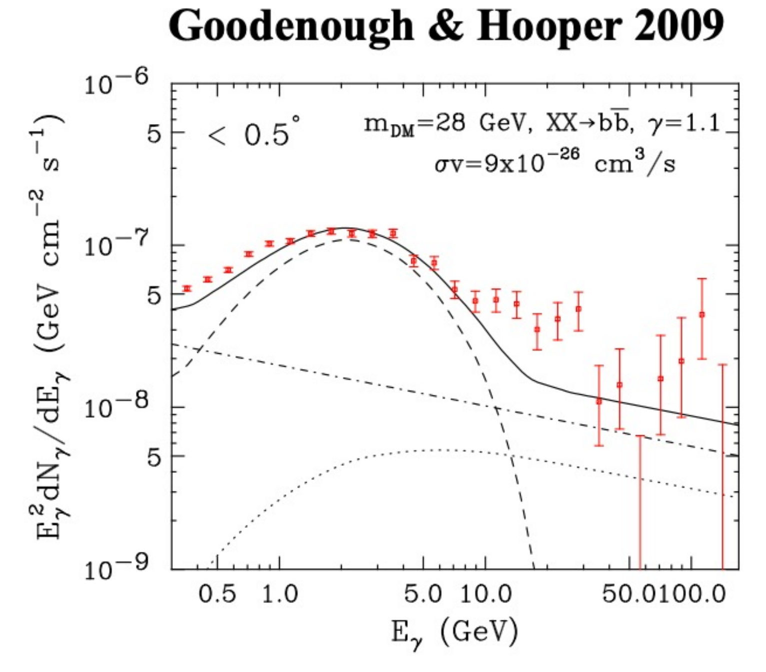
Figure 3: Background and signal templates computed by ctools for the GC survey observation, showing the expected photon counts in the energy range from 100 to 500 GeV. The (logarithmic) colour code indicates the number of expected counts N per 0.1° × 0.1° pixel. See text for a description of each of the individual templates shown here.

Backgrounds

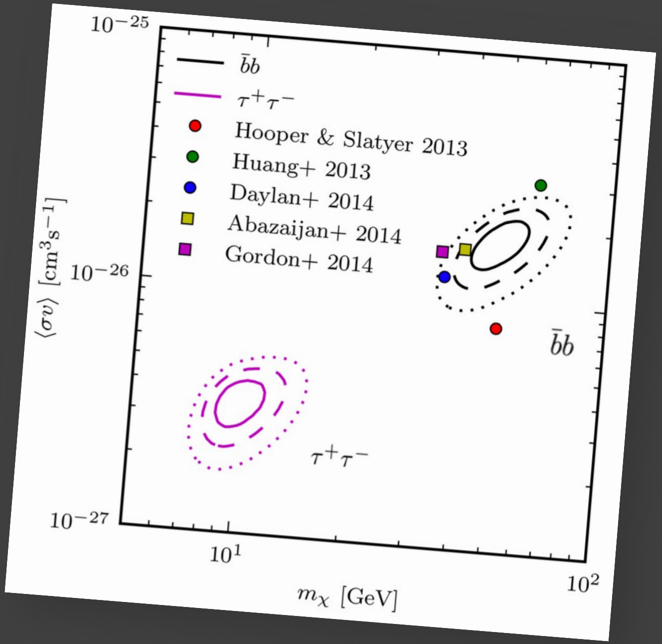


HINTS OF DM? LST SOUTH!

Found excess in the vicinities of the GC,


Goodenough & Hooper 2009

Compatible with
- DM signal at few GeV
- 1+ pulsars

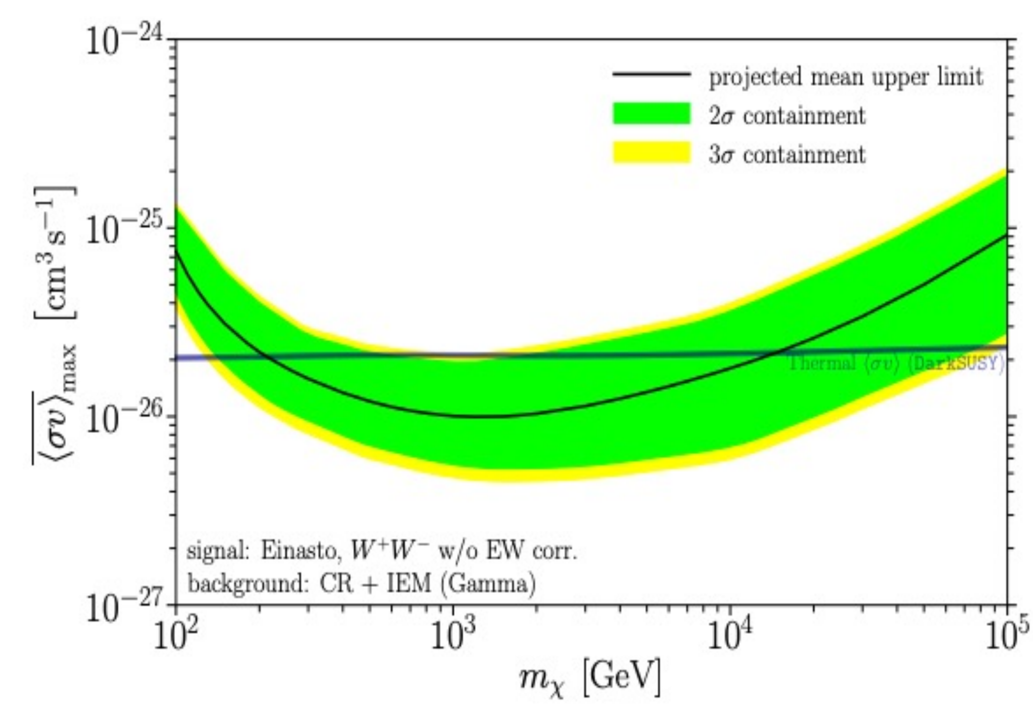


- The Galactic Center as a Dark Matter Gamma-Ray Source
- A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nuclear Physics B 113B (2002) 213-220 [astro-ph/0211327] A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio Astroparticle Physics 21, 267-285, 2004 [astro-ph/0305075]
- Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope Lisa Goodenough, Dan Hooper arXiv:0910.2998
- Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope Vincenzo Vitale, Aldo Morselli, the Fermi/LAT Collaboration
- Proceedings of the 2009 Fermi Symposium, 2-5 November 2009, eConf Proceedings C091122 arXiv:0912.3828 21 Dec 2009
- Search for Dark Matter with Fermi Large Area Telescope: the Galactic Center
- V.Vitale, A.Morselli, the Fermi-LAT Collaboration NIM A 630 (2011) 147–150 (Available online 23 June 2010)
- Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope Dan Hooper, Lisa Goodenough. (21 March 2011). 21 pp. Phys.Lett. B697 (2011) 412-428
- Background model systematics for the Fermi GeV excess F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 arXiv:1409.0042v1
- Fermi–LAT observations of high-energy γ-ray emission toward the galactic centre M. Ajello et al.[Fermi-LAT Coll.] Apj 819:44 2016 arXiv:1511.02938
- The Fermi galactic center GeV excess and implications for dark matter M. Ajello et al.[Fermi-LAT Coll.] Apj 819:44 2016 arXiv:1511.02938
- Revisiting the Gamma-Ray Galactic Center Excess with Multi-Messenger Observations IC, Zhong, McDermott, Surdutovich, PRD 105, 10[illegible]23 (2022)

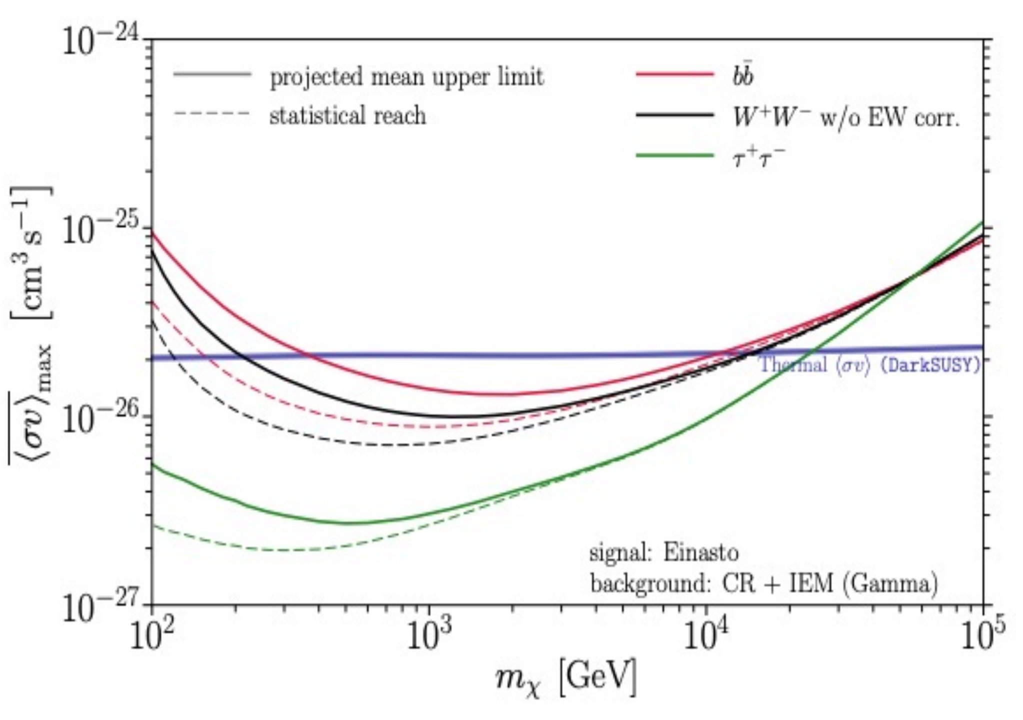
ANNIHILATION OF DM IN THE GC

$$\frac{d\Phi^{\mathrm{PP}}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{dN}{dE'}$$

Annihilation results for W+W-

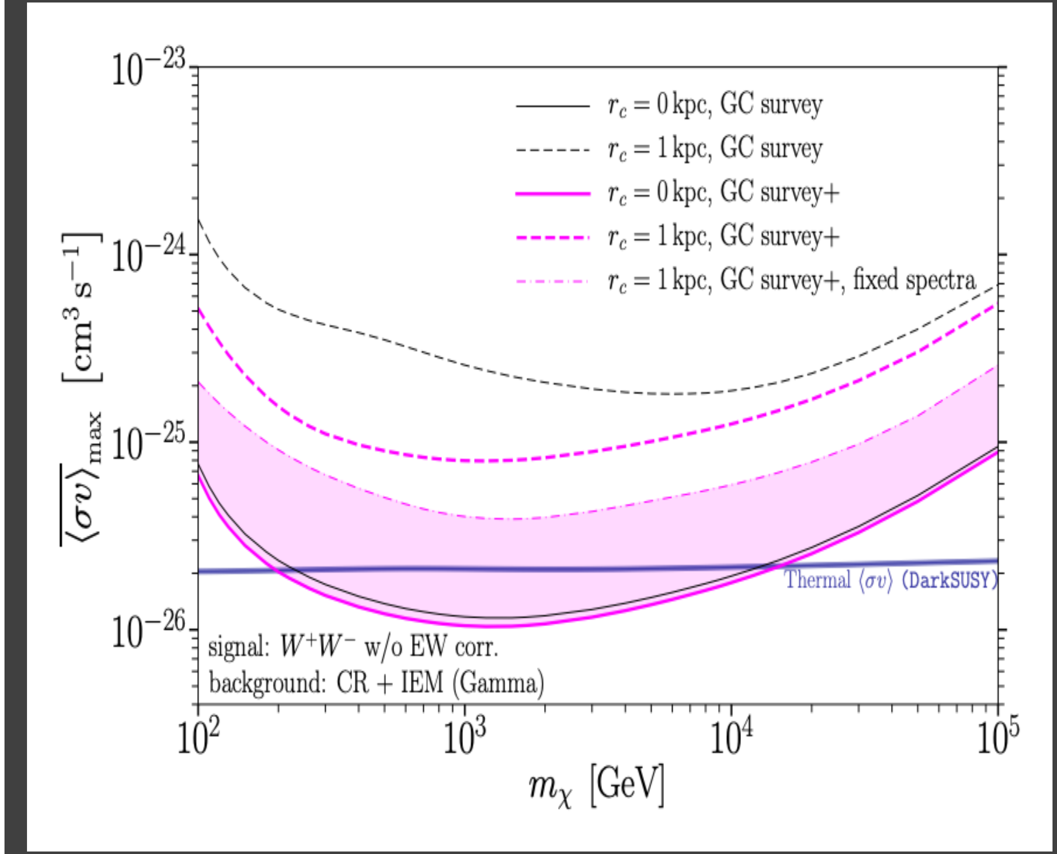


Different channels

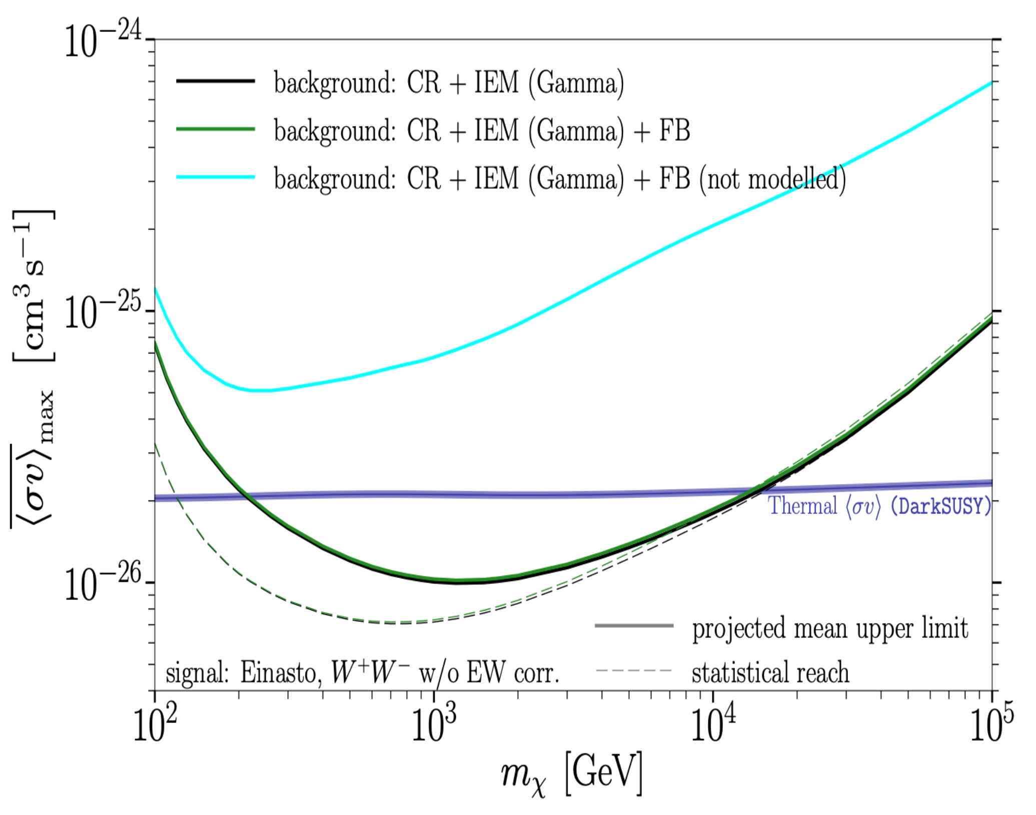


UNCERTAINTIES ON DM AND ASTRO

Limits strongly affected by signal model



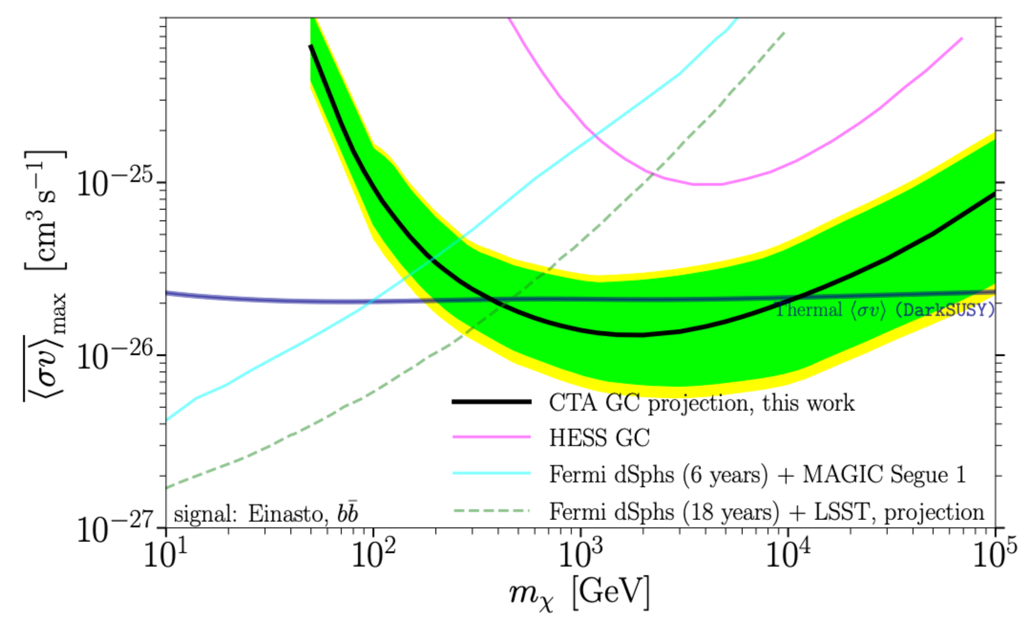
And backgrounds models

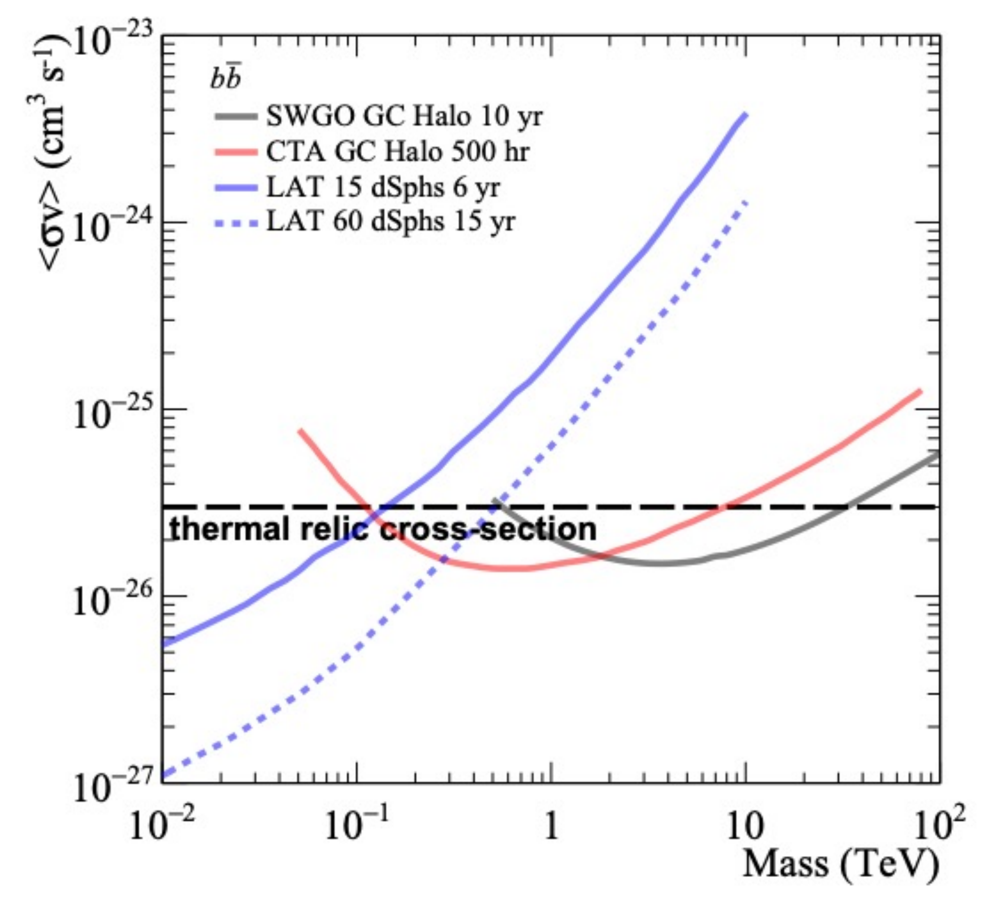


IN COMPARISON

- Stronger than HESS and entering deep into the thermal value
- Stronger than Fermi-LAT > 400 GeV

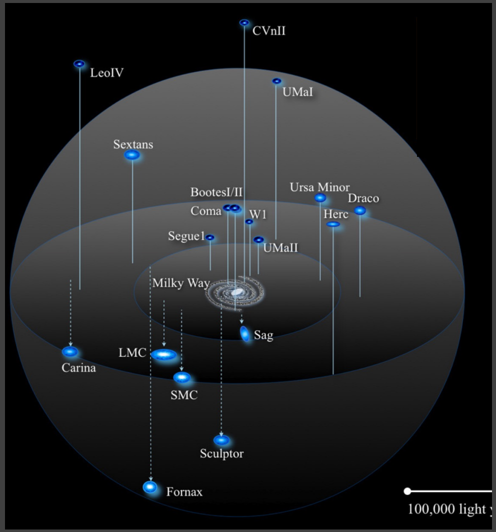
- From above SWGO may rule!



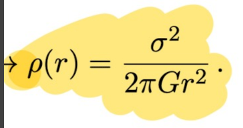


#3.2 DWARF SPHEROIDAL GALAXIES

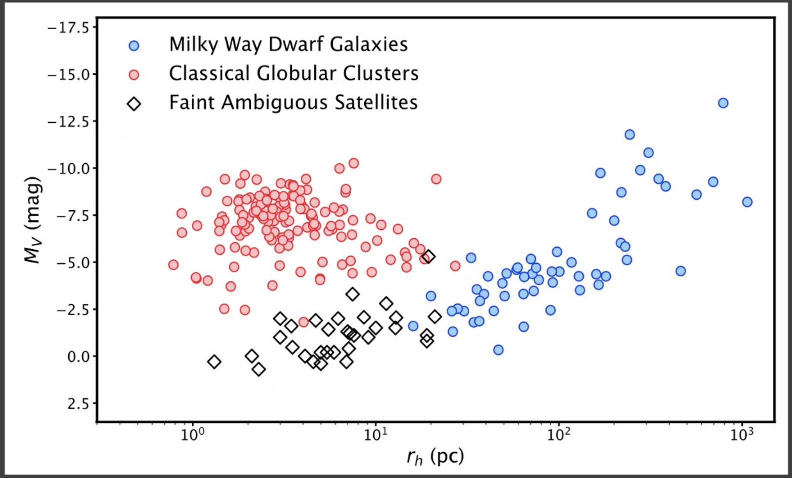
https://arxiv.org/abs/2311.10147



- Gravitationally bound to MW halo
- Pressure supported system
- DM density given by velocity dispersion (Jeans equation)

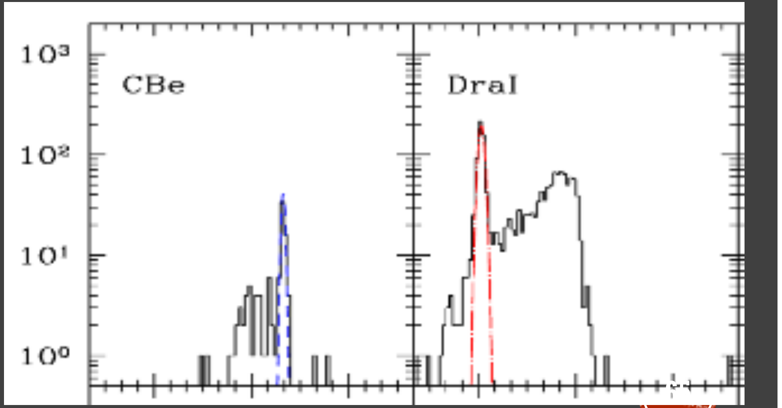


$$\rightarrow \rho(r) = \frac{\sigma^2}{2\pi G r^2}.$$

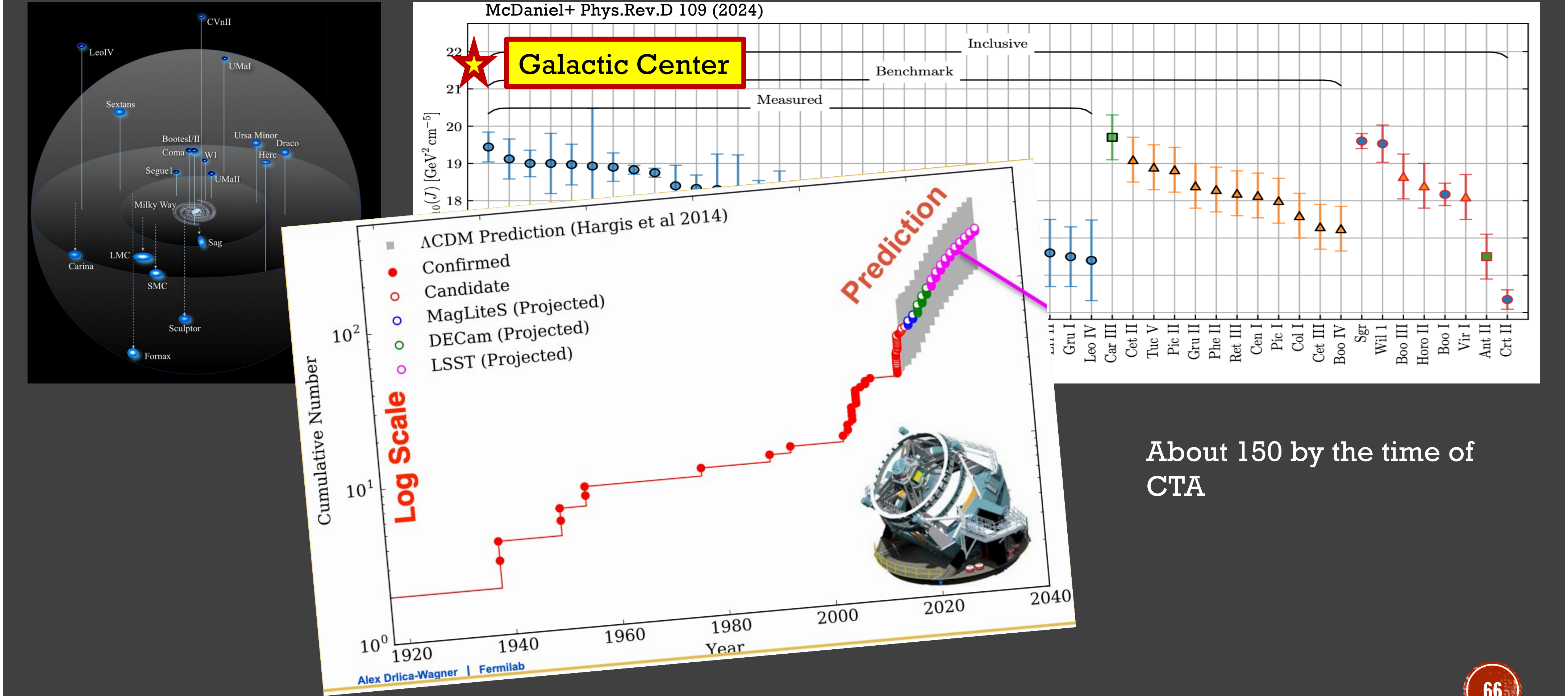


- Size, concentration and metallicity different than globular clusters
- Mass to light ratio ~100/1000 that of Sun
- Clean targets: no astrophysical background

velocity dispersion : Issue with stellar association…very few candidates

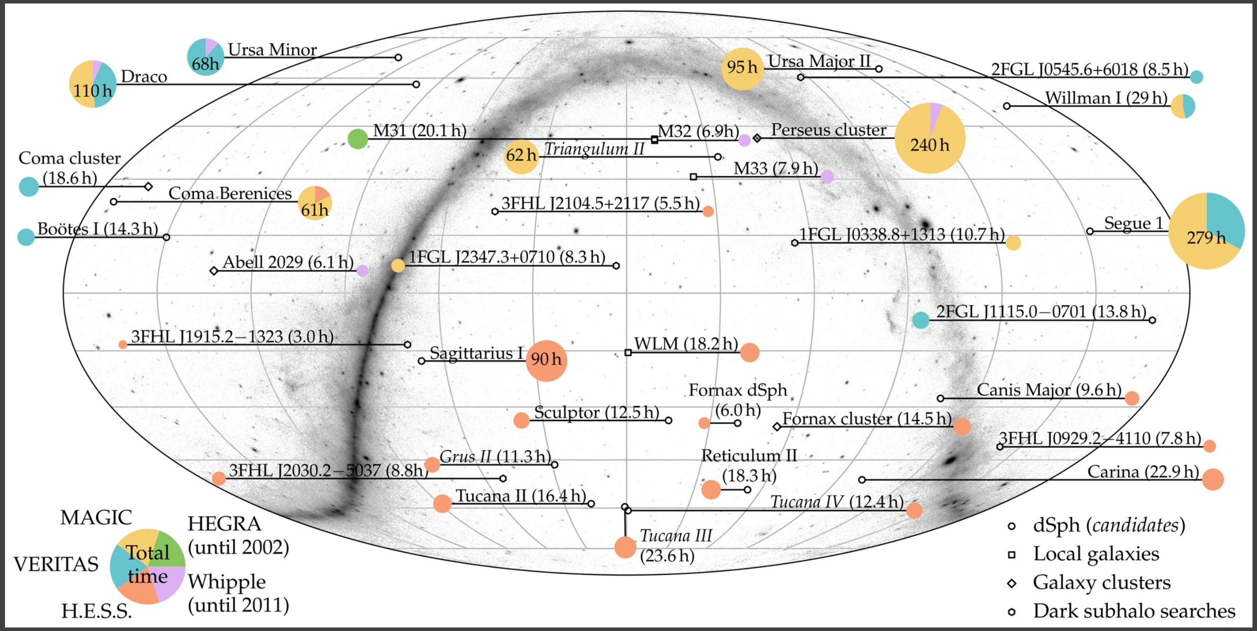


#3.2 THE DWARF MW GALAXIES

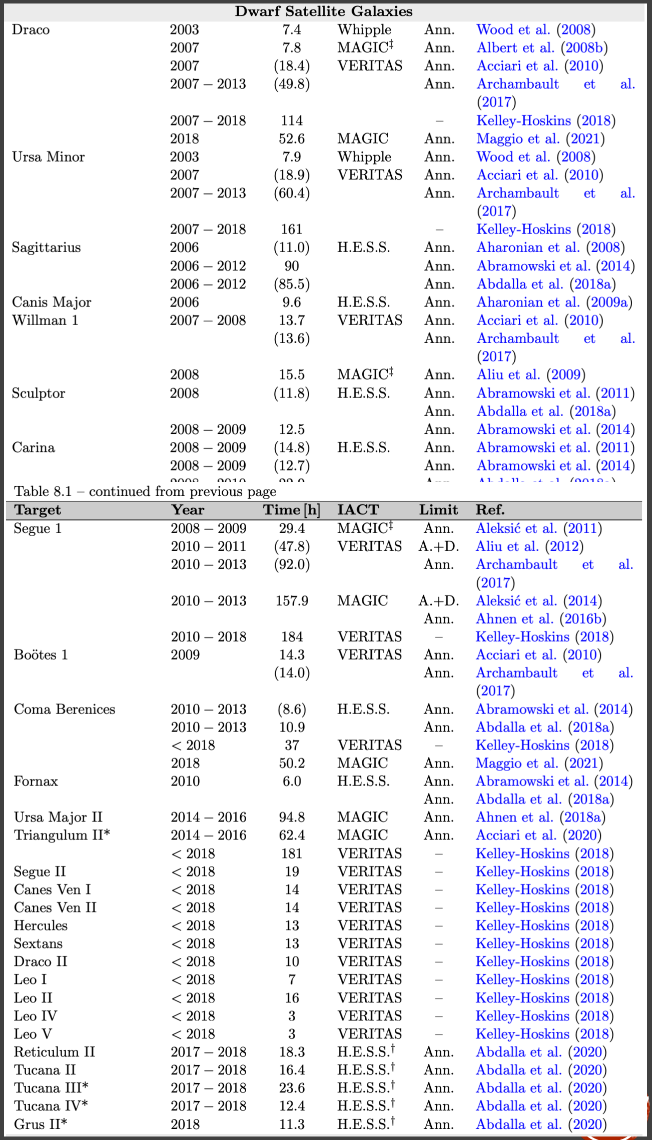

McDaniel+ Phys.Rev.D 109 (2024)

About 150 by the time of CTA

A BUNCH OF THEM HUNTED



Hutten+ Galaxies 10 (2022) 5



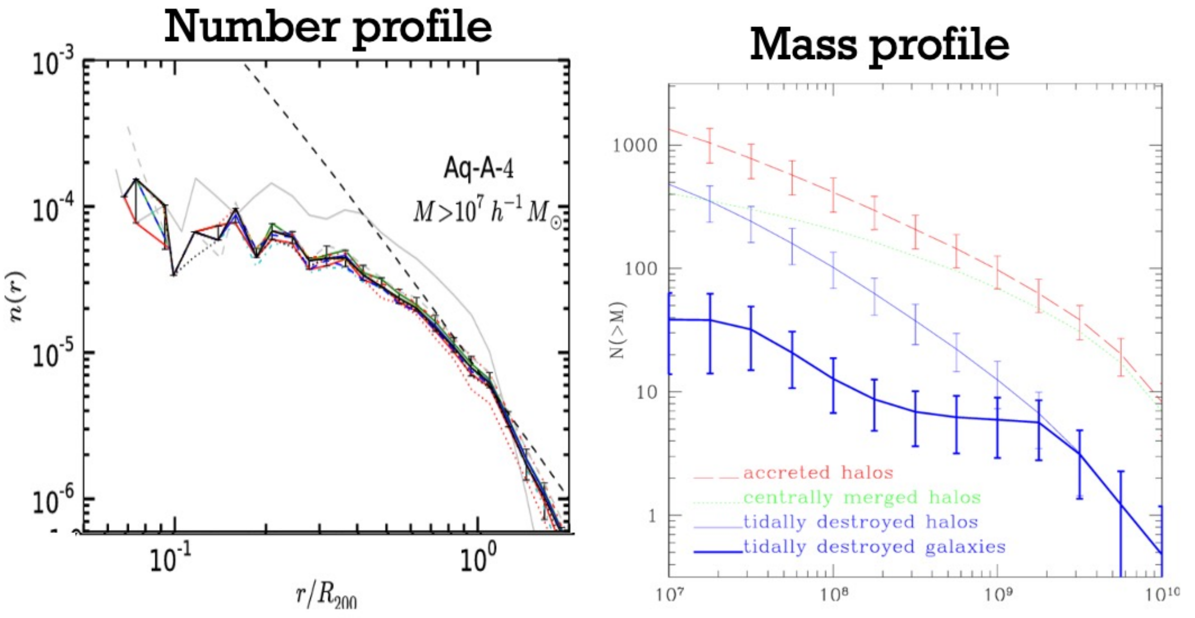
Dwarf Satellite Galaxies					
Draco	2003	7.4	Whipple	Ann.	Wood et al. (2008)
	2007	7.8	MAGIC‡	Ann.	Albert et al. (2008b)
	2007	(18.4)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(49.8)		Ann.	Archambault et al. (2017)
	2007 – 2018	114		–	Kelley-Hoskins (2018)
	2018	52.6	MAGIC	Ann.	Maggio et al. (2021)
Ursa Minor	2003	7.9	Whipple	Ann.	Wood et al. (2008)
	2007	(18.9)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(60.4)		Ann.	Archambault et al. (2017)
	2007 – 2018	161		–	Kelley-Hoskins (2018)
Sagittarius	2006	(11.0)	H.E.S.S.	Ann.	Aharonian et al. (2008)
	2006 – 2012	90		Ann.	Abramowski et al. (2014)
	2006 – 2012	(85.5)		Ann.	Abdalla et al. (2018a)
Canis Major	2006	9.6	H.E.S.S.	Ann.	Aharonian et al. (2009a)
Willman 1	2007 – 2008	13.7	VERITAS	Ann.	Acciari et al. (2010)
		(13.6)		Ann.	Archambault et al. (2017)
	2008	15.5	MAGIC‡	Ann.	Aliu et al. (2009)
Sculptor	2008	(11.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
				Ann.	Abdalla et al. (2018a)
	2008 – 2009	12.5		Ann.	Abramowski et al. (2014)
Carina	2008 – 2009	(14.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2008 – 2009	(12.7)		Ann.	Abramowski et al. (2014)

Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Segue 1	2008 – 2009	29.4	MAGIC‡	Ann.	Aleksić et al. (2011)
	2010 – 2011	(47.8)	VERITAS	A.+D.	Aliu et al. (2012)
	2010 – 2013	(92.0)		Ann.	Archambault et al. (2017)
	2010 – 2013	157.9	MAGIC	A.+D.	Aleksić et al. (2014)
				Ann.	Ahnen et al. (2016b)
	2010 – 2018	184	VERITAS	–	Kelley-Hoskins (2018)
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al. (2010)
		(14.0)		Ann.	Archambault et al. (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski et al. (2014)
	2010 – 2013	10.9		Ann.	Abdalla et al. (2018a)
	< 2018	37	VERITAS	–	Kelley-Hoskins (2018)
	2018	50.2	MAGIC	Ann.	Maggio et al. (2021)
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski et al. (2014)
				Ann.	Abdalla et al. (2018a)
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al. (2018a)
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al. (2020)
	< 2018	181	VERITAS	–	Kelley-Hoskins (2018)
Segue II	< 2018	19	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Hercules	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Sextans	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Draco II	< 2018	10	VERITAS	–	Kelley-Hoskins (2018)
Leo I	< 2018	7	VERITAS	–	Kelley-Hoskins (2018)
Leo II	< 2018	16	VERITAS	–	Kelley-Hoskins (2018)
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Leo V	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)

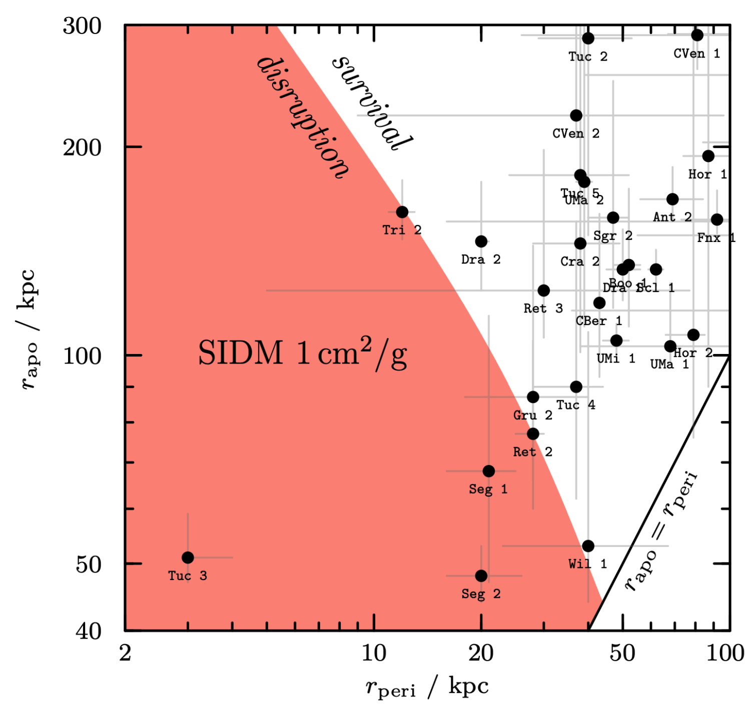
MD+ 2111.01198

WHAT WE EXPECT (N-BODY SIMULATIONS)



Many toward the center of the main halo

Few with very large mass



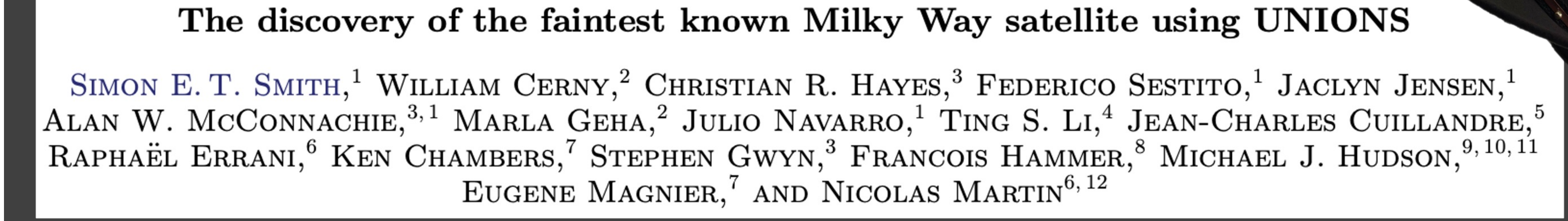
Errani, 2023

Home message: 1+ big guy expected from theory!

Tidal stripping seems to maintain DM cores (Errani's work)

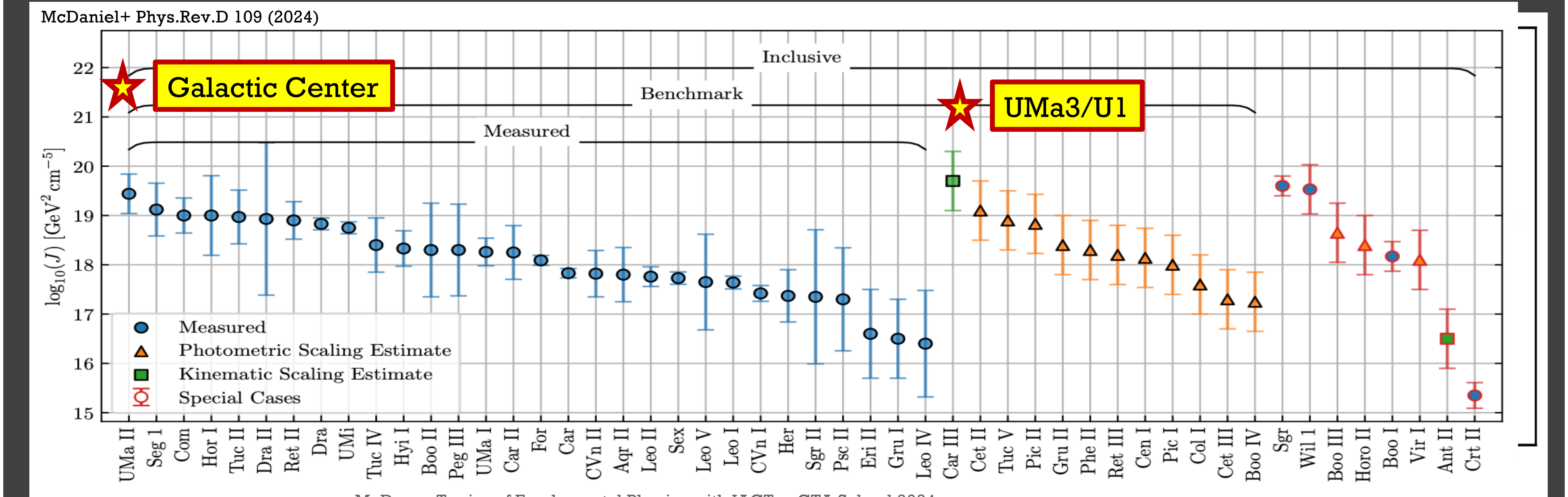
THE BIG GUY?

https://arxiv.org/abs/2311.10147



The discovery of the faintest known Milky Way satellite using UNIONS

Simon E. T. Smith,[1] William Cerny,[2] Christian R. Hayes,[3] Federico Sestito,[1] Jaclyn Jensen,[1]
Alan W. McConnachie,[3,1] Marla Geha,[2] Julio Navarro,[1] Ting S. Li,[4] Jean-Charles Cuillandre,[5]
Raphaël Errani,[6] Ken Chambers,[7] Stephen Gwyn,[3] Francois Hammer,[8] Michael J. Hudson,[9,10,11]
Eugene Magnier,[7] and Nicolas Martin[6,12]



McDaniel+ Phys.Rev.D 109 (2024)

Galactic Center

UMa3/U1

FEW STARS

https://arxiv.org/abs/2311.10147

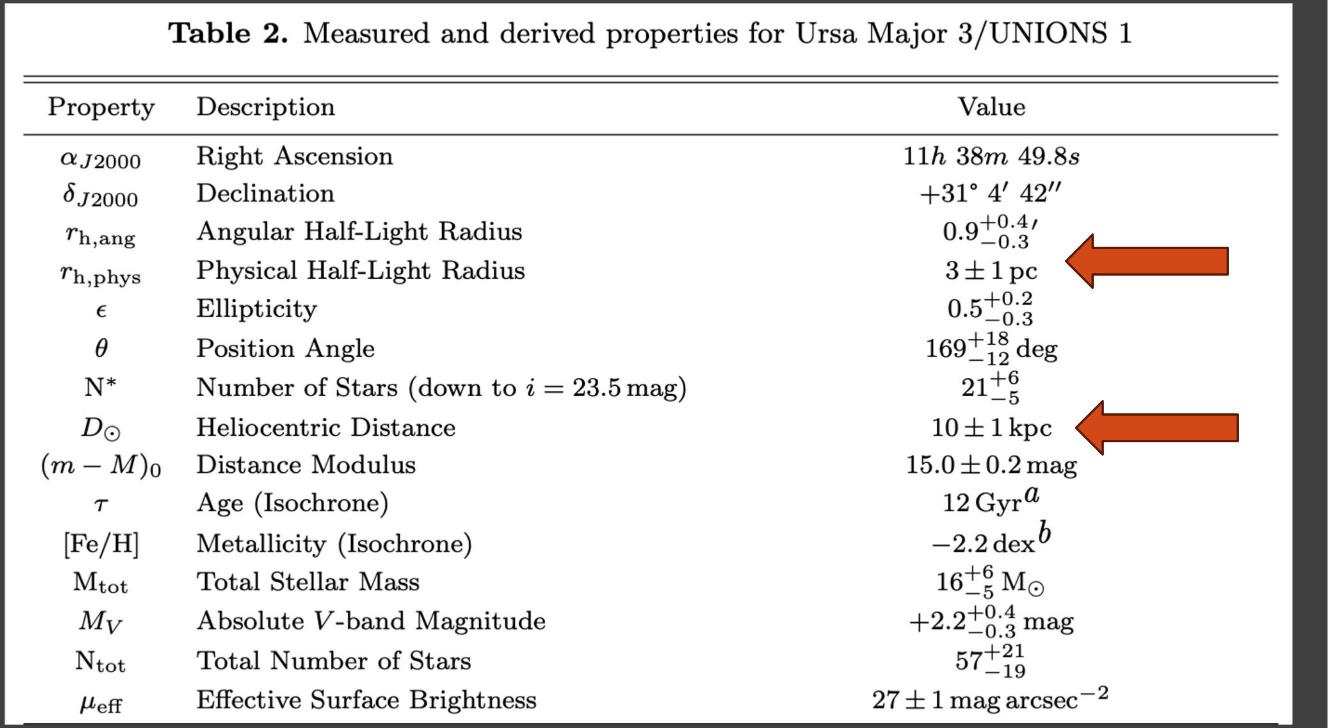
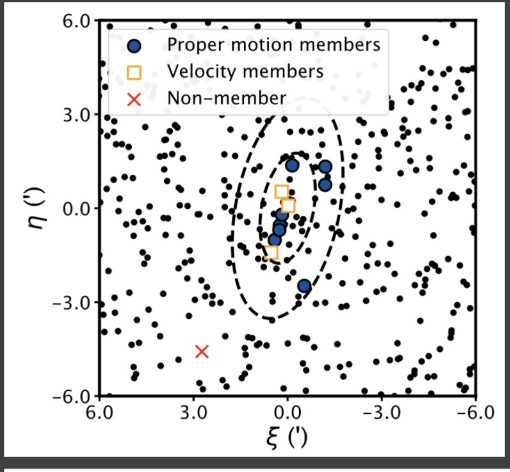
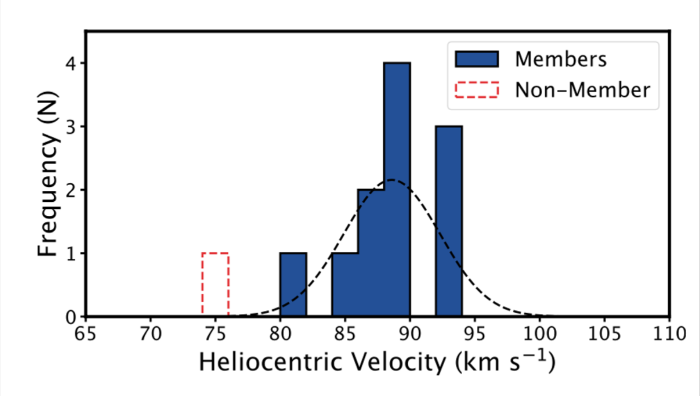
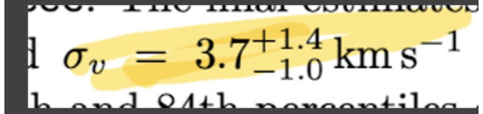


Table 2. Measured and derived properties for Ursa Major 3/UNIONS 1

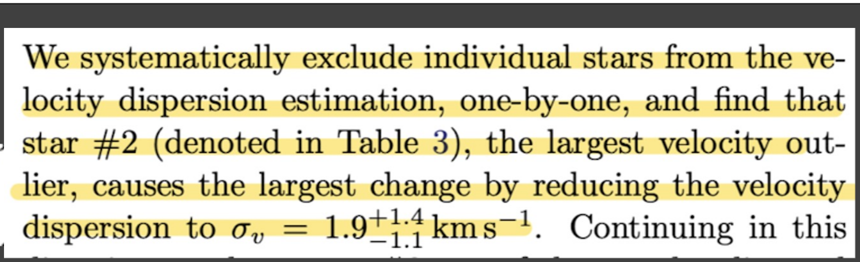
Property	Description	Value
α_{J2000}	Right Ascension	$11h\ 38m\ 49.8s$
δ_{J2000}	Declination	$+31°\ 4'\ 42''$
$r_{\mathrm{h,ang}}$	Angular Half-Light Radius	$0.9^{+0.4}_{-0.3}{}'$
$r_{\mathrm{h,phys}}$	Physical Half-Light Radius	3 ± 1 pc
ϵ	Ellipticity	$0.5^{+0.2}_{-0.3}$
θ	Position Angle	169^{+18}_{-12} deg
N*	Number of Stars (down to $i = 23.5$ mag)	21^{+6}_{-5}
$D_\odot$	Heliocentric Distance	10 ± 1 kpc
$(m-M)_0$	Distance Modulus	15.0 ± 0.2 mag
τ	Age (Isochrone)	$12\,\mathrm{Gyr}^a$
[Fe/H]	Metallicity (Isochrone)	$-2.2\,\mathrm{dex}^b$
$\mathrm{M_{tot}}$	Total Stellar Mass	$16^{+6}_{-5}\,\mathrm{M_\odot}$
M_V	Absolute V-band Magnitude	$+2.2^{+0.4}_{-0.3}$ mag
$\mathrm{N_{tot}}$	Total Number of Stars	57^{+21}_{-19}
μ_{eff}	Effective Surface Brightness	$27 \pm 1\,\mathrm{mag\,arcsec^{-2}}$





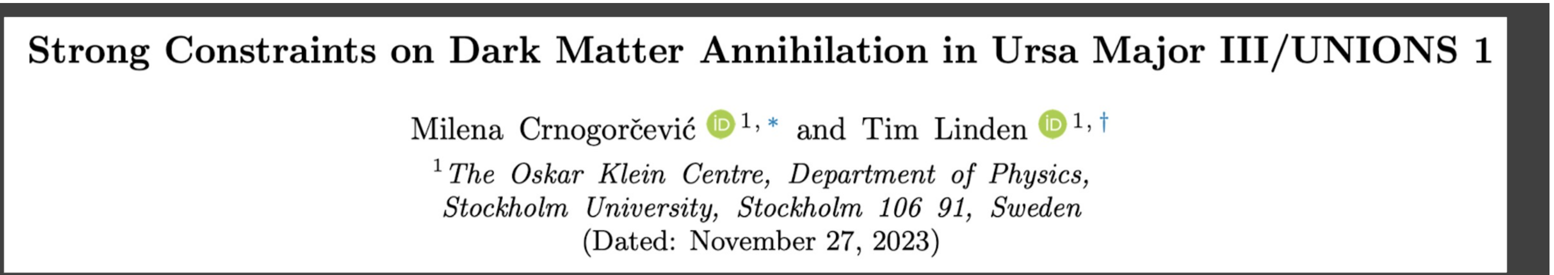


$\sigma_v = 3.7^{+1.4}_{-1.0}\,\mathrm{km\,s^{-1}}$



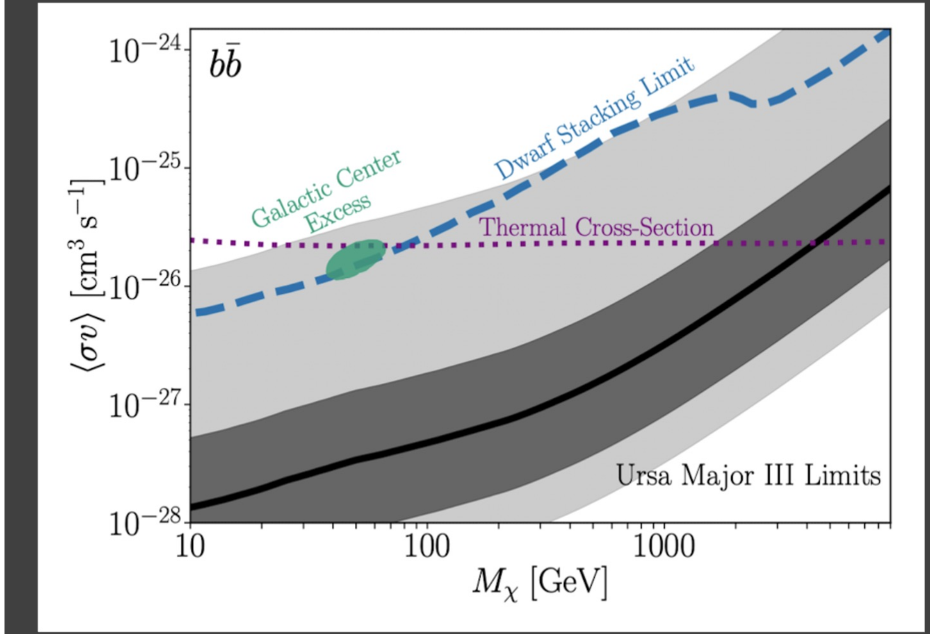
We systematically exclude individual stars from the velocity dispersion estimation, one-by-one, and find that star #2 (denoted in Table 3), the largest velocity outlier, causes the largest change by reducing the velocity dispersion to $\sigma_v = 1.9^{+1.4}_{-1.1}\,\mathrm{km\,s^{-1}}$. Continuing in this

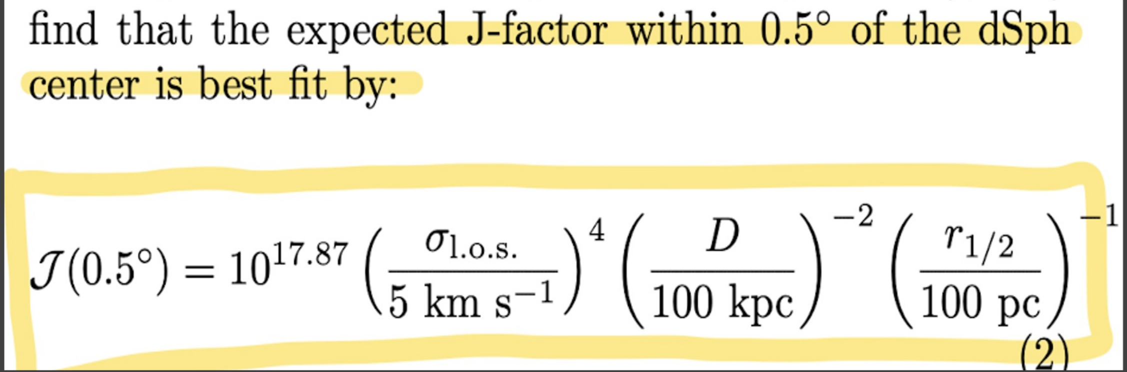
FERMI-LAT



Strong Constraints on Dark Matter Annihilation in Ursa Major III/UNIONS 1

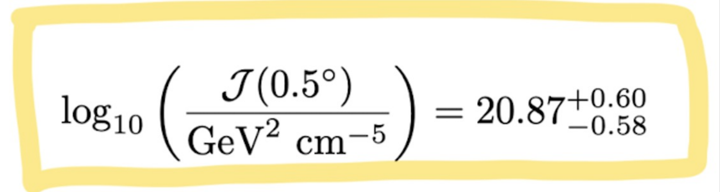
Milena Crnogorčević [1, *] and Tim Linden [1, †]
[1] *The Oskar Klein Centre, Department of Physics,*
Stockholm University, Stockholm 106 91, Sweden
(Dated: November 27, 2023)



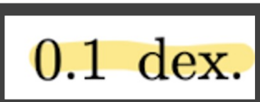


find that the expected J-factor within 0.5° of the dSph center is best fit by:

$$\mathcal{J}(0.5^\circ) = 10^{17.87} \left(\frac{\sigma_{\rm l.o.s.}}{5\ {\rm km\ s^{-1}}}\right)^4 \left(\frac{D}{100\ {\rm kpc}}\right)^{-2} \left(\frac{r_{1/2}}{100\ {\rm pc}}\right)^{-1} \tag{2}$$



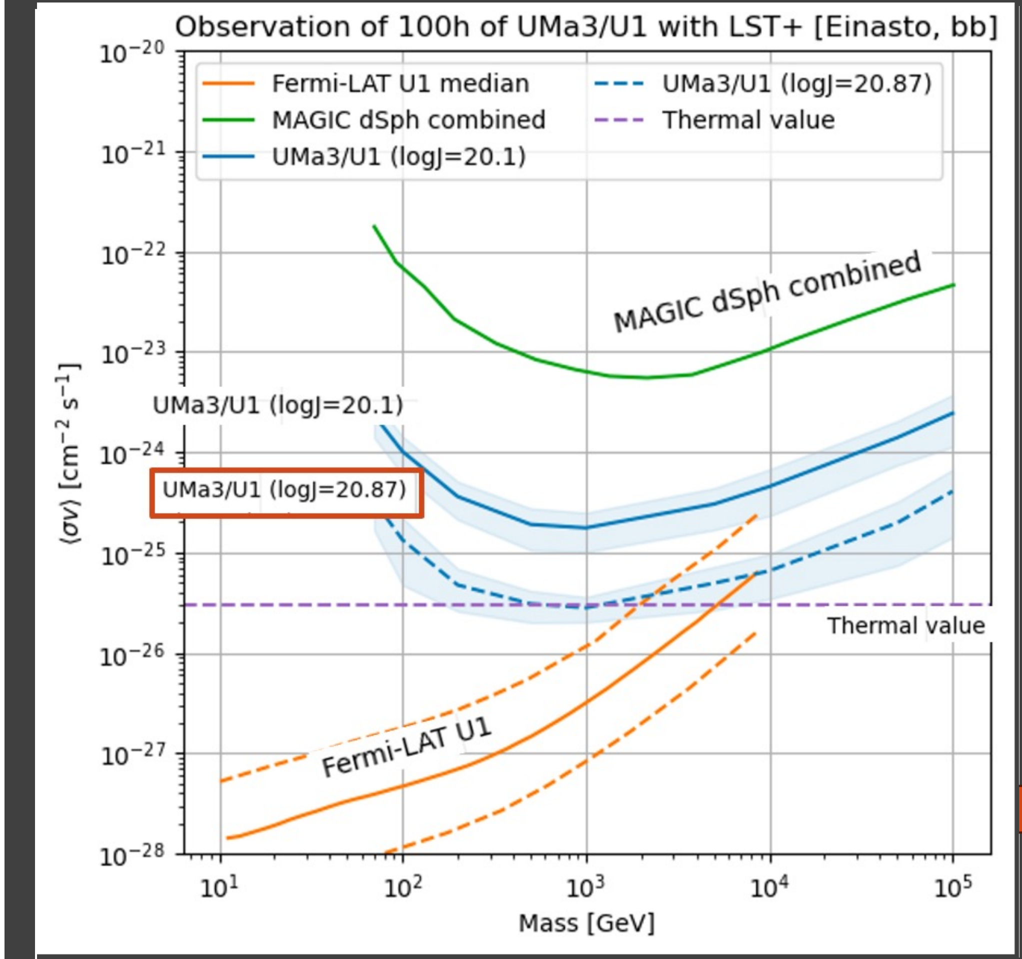
$$\log_{10}\left(\frac{\mathcal{J}(0.5^\circ)}{{\rm GeV^2\ cm^{-5}}}\right) = 20.87^{+0.60}_{-0.58}$$



0.1 dex.

300x that of Sculptor dSph!

DSPH LIMITS FROM IACTS AND FERMI

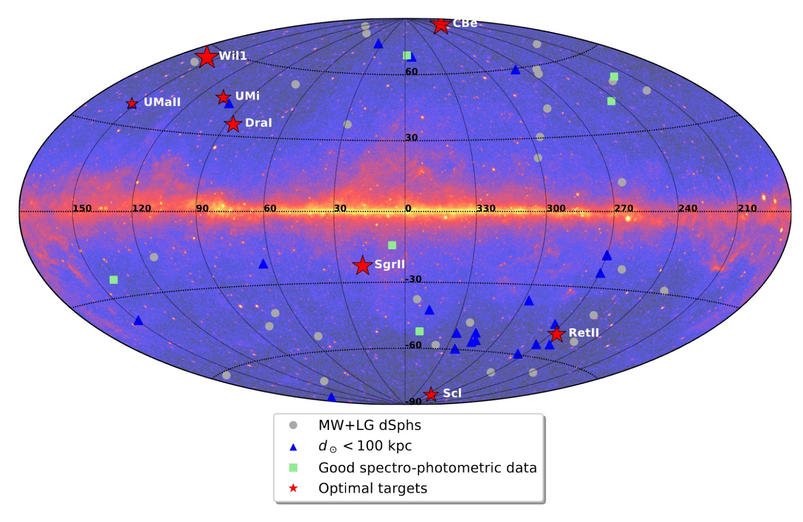


- ○ Upper limits on several targets (individual/combined)
- ○ Far less constraining than GC limits (but more robust)
- ○ Still far from ‘thermal value’

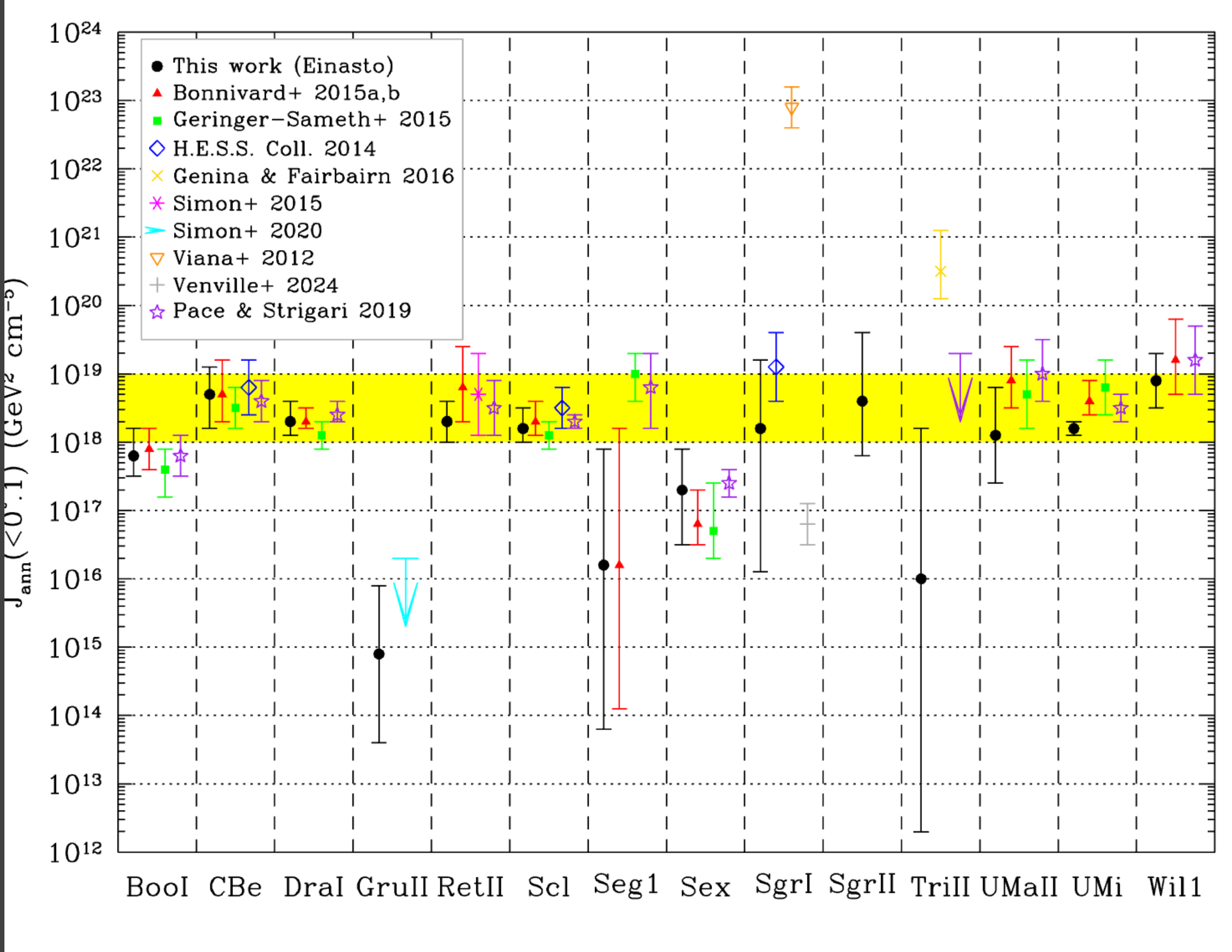
← LSTs north alone

- ○ If UMa3/U1 confirmed dSph (and observed) huge jump in constraints

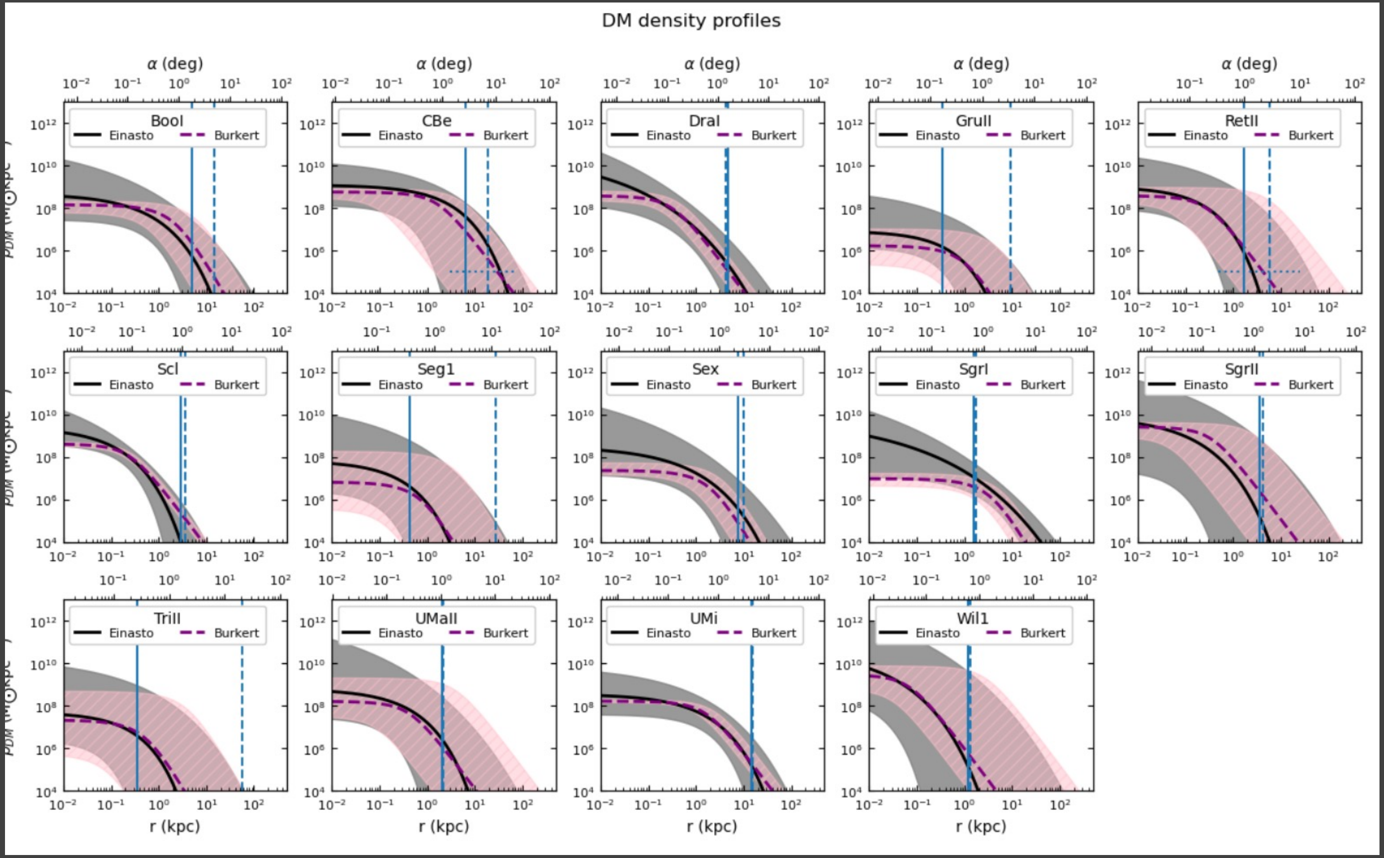
CTA KSP – IN PREP



CLUMPY

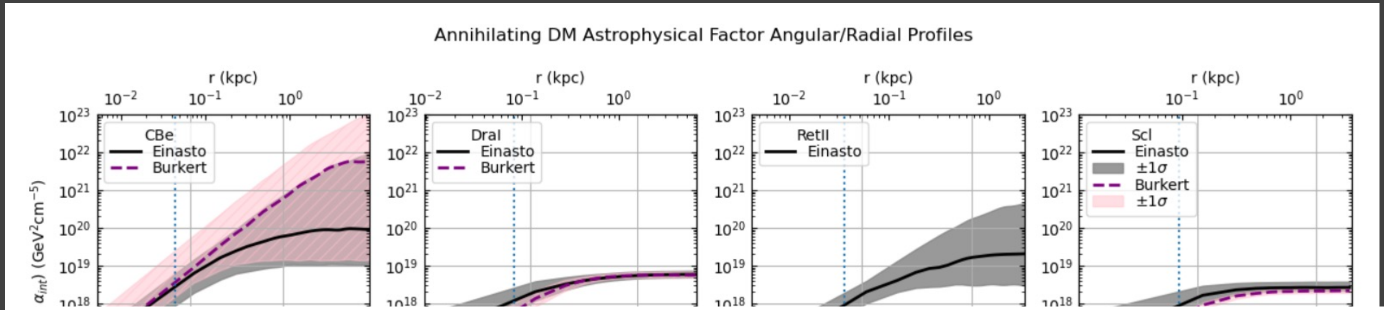


DWARF DENSITY PROFILES GENERATED

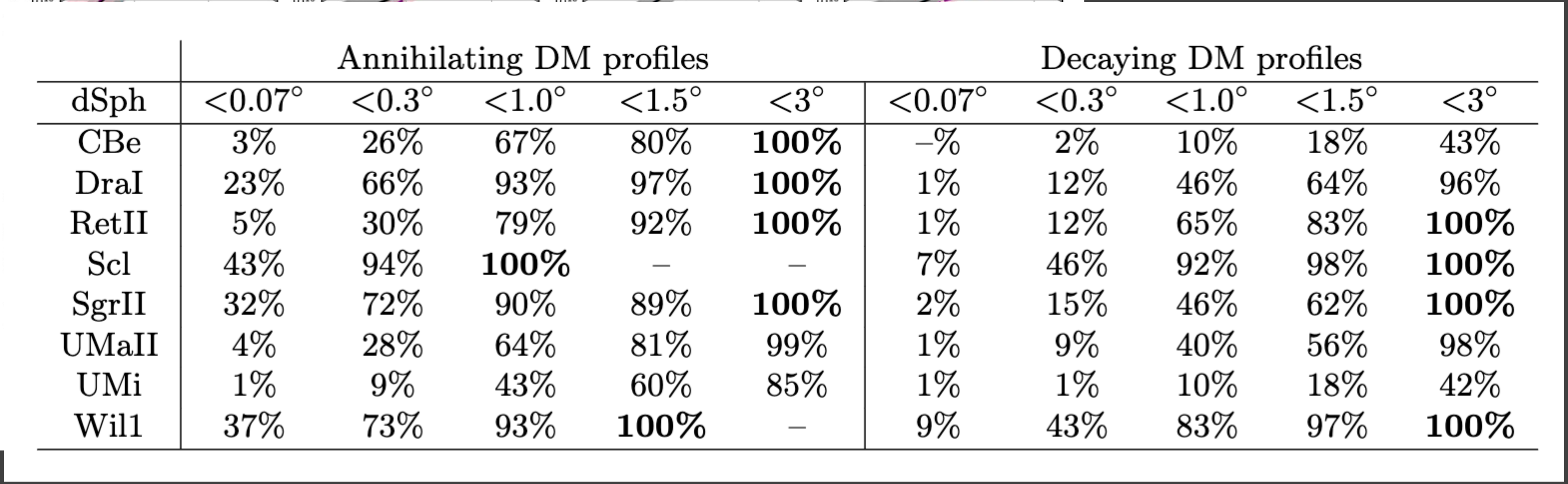


MD
Francesco Saturni
Gonzalo Saturni
Aldo Morselli

AND J-FACTOR PROFILES

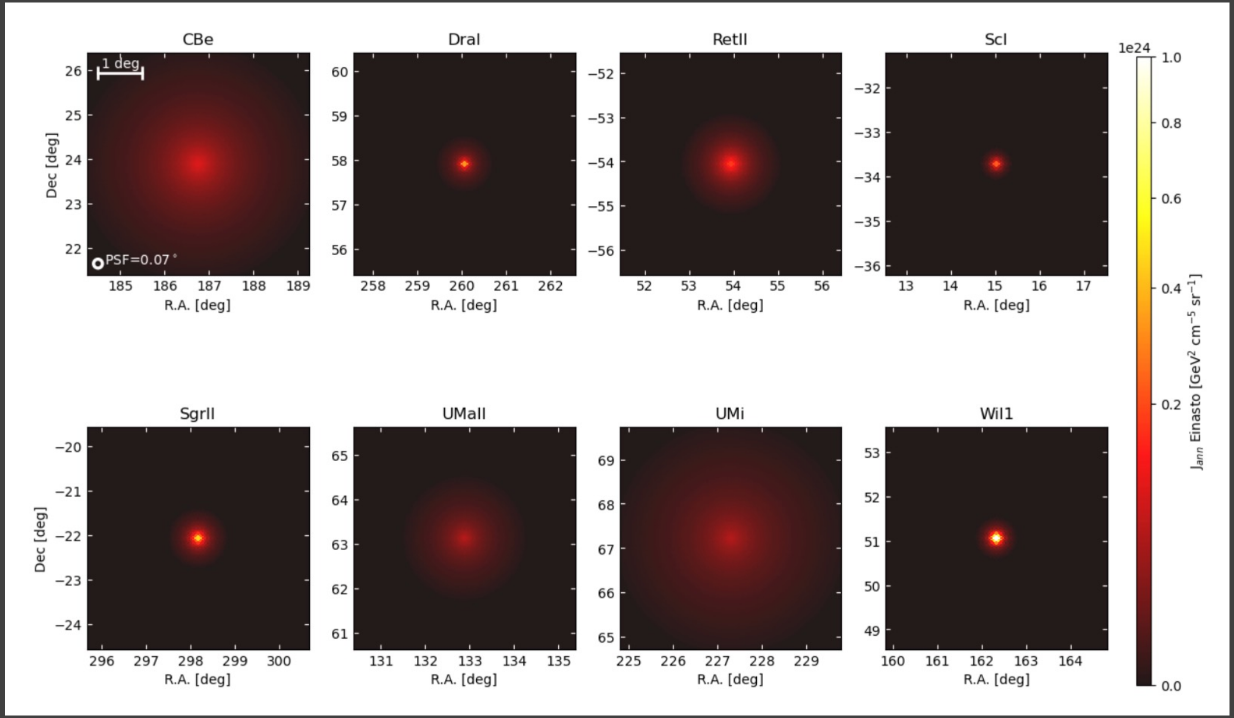


MD
Francesco Saturni
Gonzalo Saturni
Aldo Morselli



	Annihilating DM profiles					Decaying DM profiles				
dSph	<0.07°	<0.3°	<1.0°	<1.5°	<3°	<0.07°	<0.3°	<1.0°	<1.5°	<3°
CBe	3%	26%	67%	80%	**100%**	–%	2%	10%	18%	43%
DraI	23%	66%	93%	97%	**100%**	1%	12%	46%	64%	96%
RetII	5%	30%	79%	92%	**100%**	1%	12%	65%	83%	**100%**
Scl	43%	94%	**100%**	–	–	7%	46%	92%	98%	**100%**
SgrII	32%	72%	90%	89%	**100%**	2%	15%	46%	62%	**100%**
UMaII	4%	28%	64%	81%	99%	1%	9%	40%	56%	98%
UMi	1%	9%	43%	60%	85%	1%	1%	10%	18%	42%
Wil1	37%	73%	93%	**100%**	–	9%	43%	83%	97%	**100%**

GENERATION OF SIGNAL MODEL



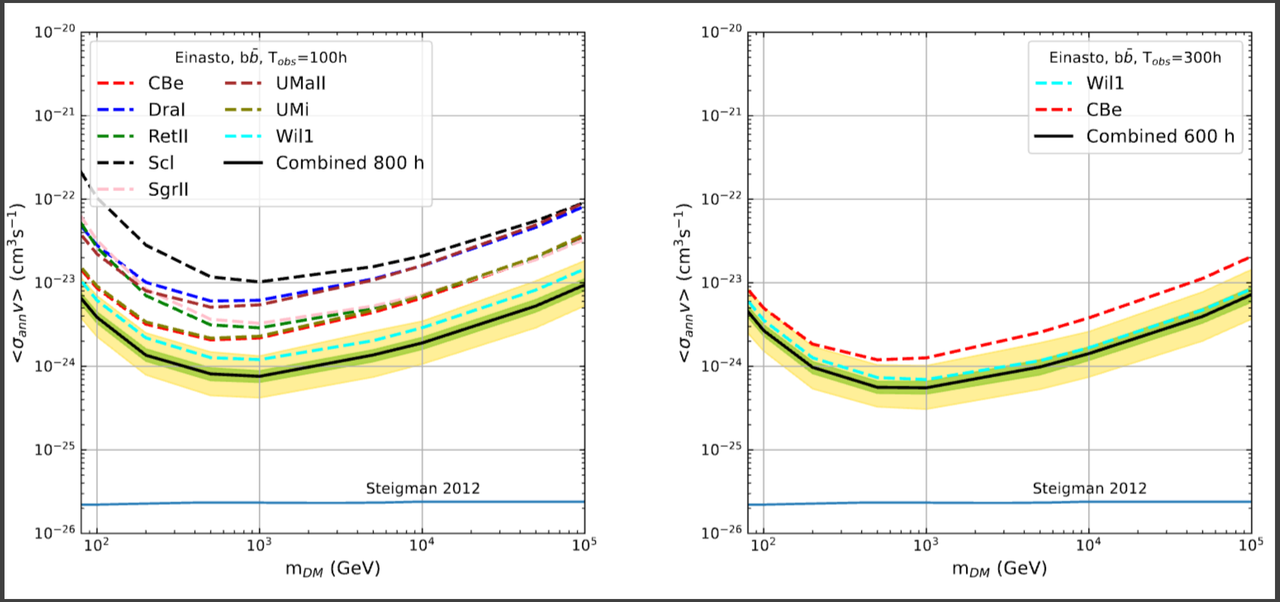
No std DM CTA gammapy pipeline

If interested (gammapy)
- Gonzalo Rodriguez +→ KSPs
- dmpipe → Shotaro Abe+

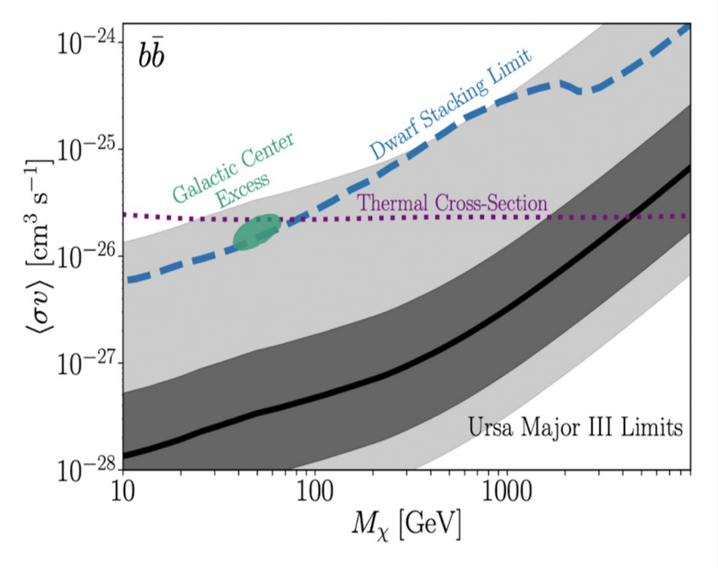
If interested (ctools)
- Eckner+ → GC

Dmtools? Judit Perez Romero

CHAMPIONS DSPHS DOMINATES



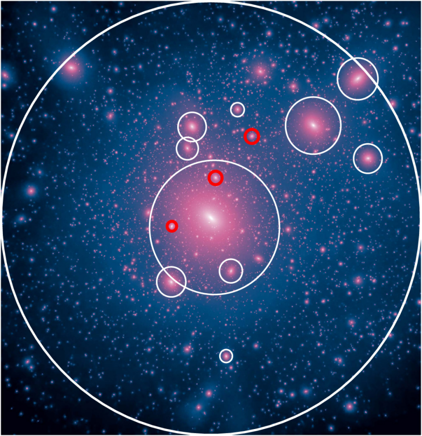
- And maybe new date before CTA advent



Limits dominated by best dSphs

Do we observe one/few/many?
Strategy unclear

3.3 THE DARK SUBHALOES



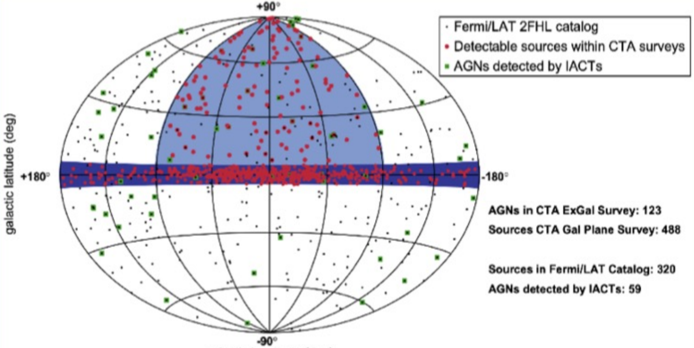
It is possible that a fraction of DM subhalos did not accrete baryons. This would result:

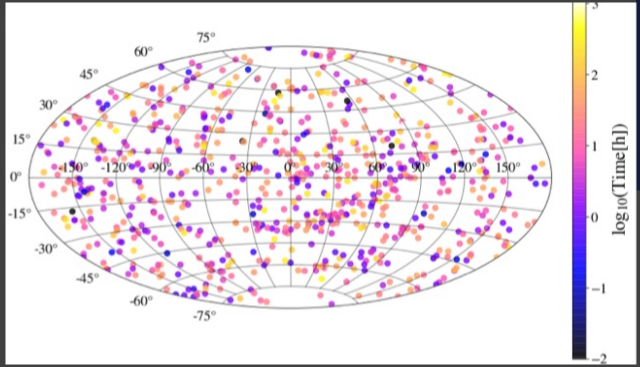
- more likely high density in the center (DM spikes)
- no visible from stars

Detectable through gravitational interaction: stellar streams gaps or micro-lensing?. For small FOV instrument it's hard to spot them other than serendipitously.

EGAL survey
CTA KSP, 25% of the sky, 3h per pointing

Pros: large area, uniform exposure
Cons: only 3h of exposure



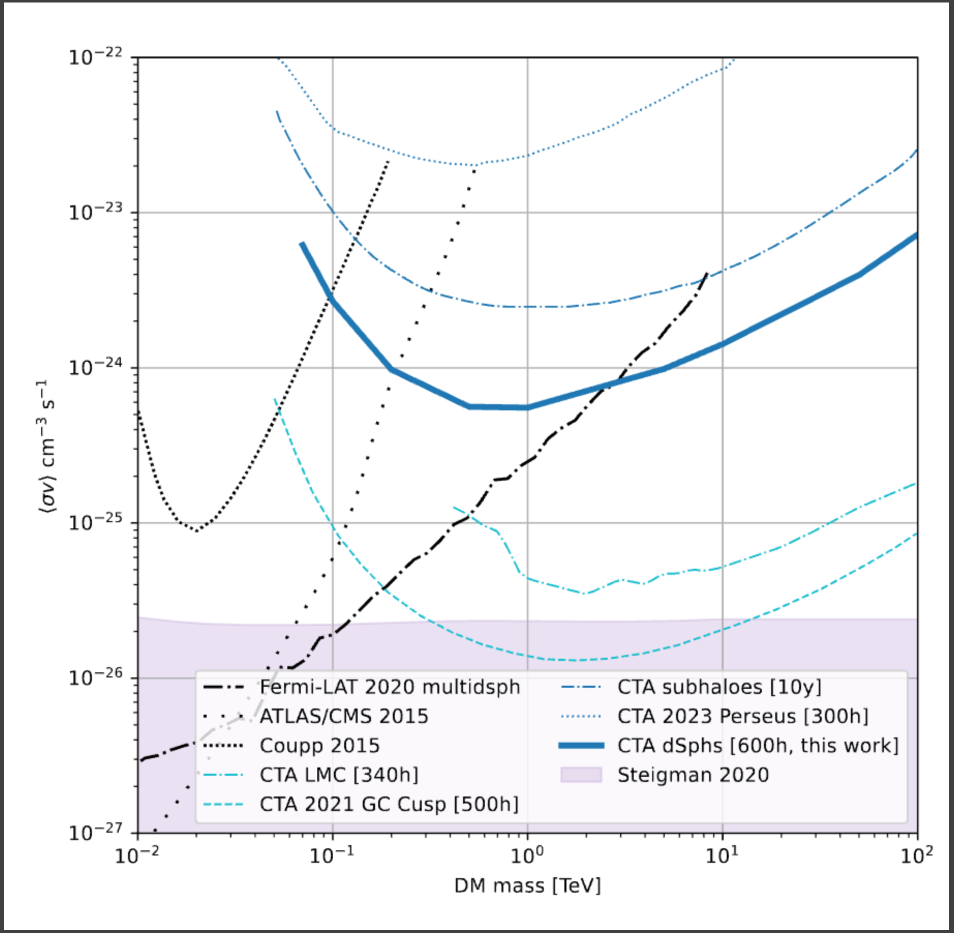


Overall exposure
Serendipitous discovery in the FoV of any CTA pointing

Pros: larger area, larger exposures
Cons: difficult to estimate time+area, off-axis sensitivity

J. Coronado-Blázquez, MD, M.A. Sanchez Conde. Phys.Dark Univ. 32 (2021)

ALL IN ONE PLOT

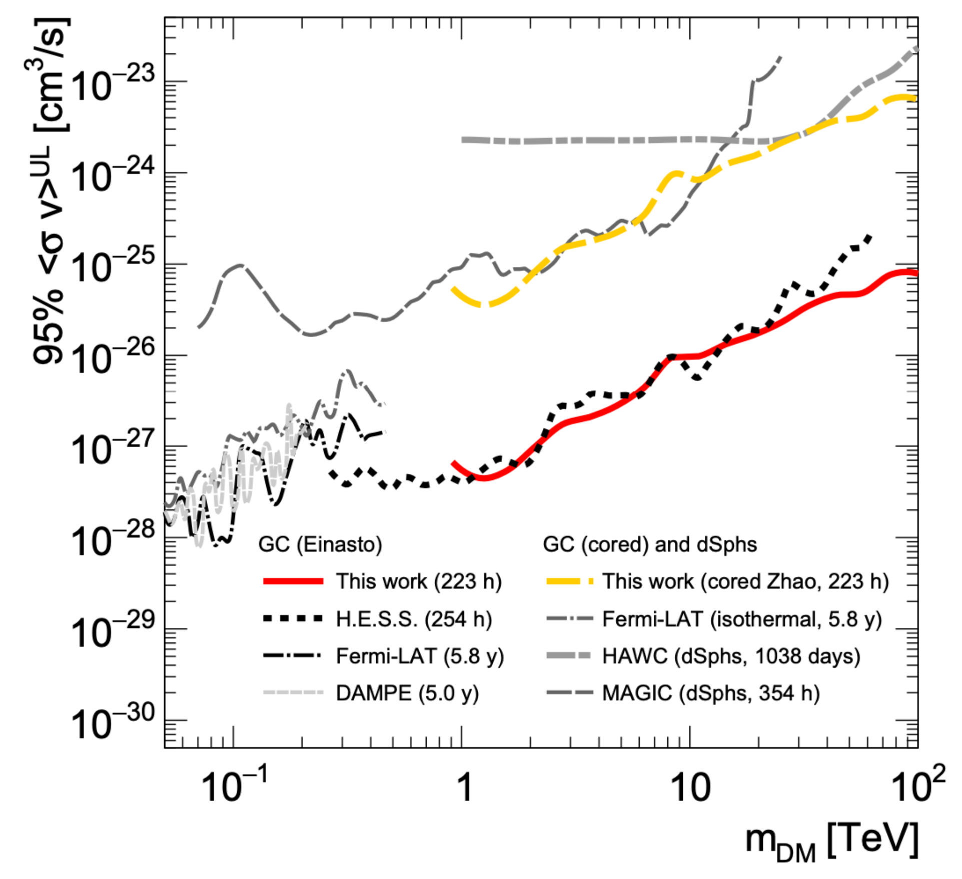


- **Galaxy clusters** …poor for annihilating DM
- **Known dSphs**…weak limits
- **LMC and GC** strong limits, but robust?

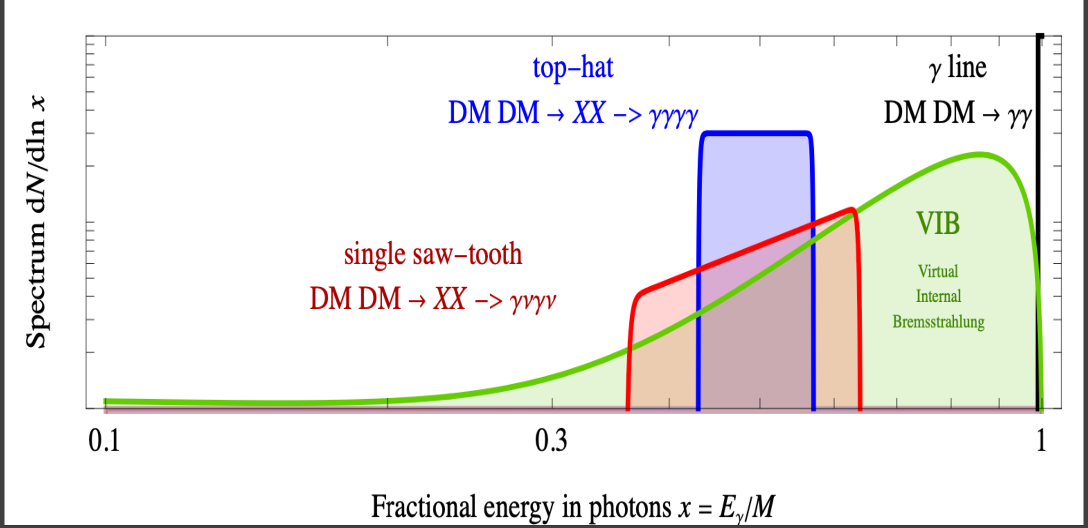
- Waiting for **champion dSph**!

3.5 SEARCH FOR DM LINES AND BOXES

MAGIC Phys.Rev.Lett. 130 (2023) 6

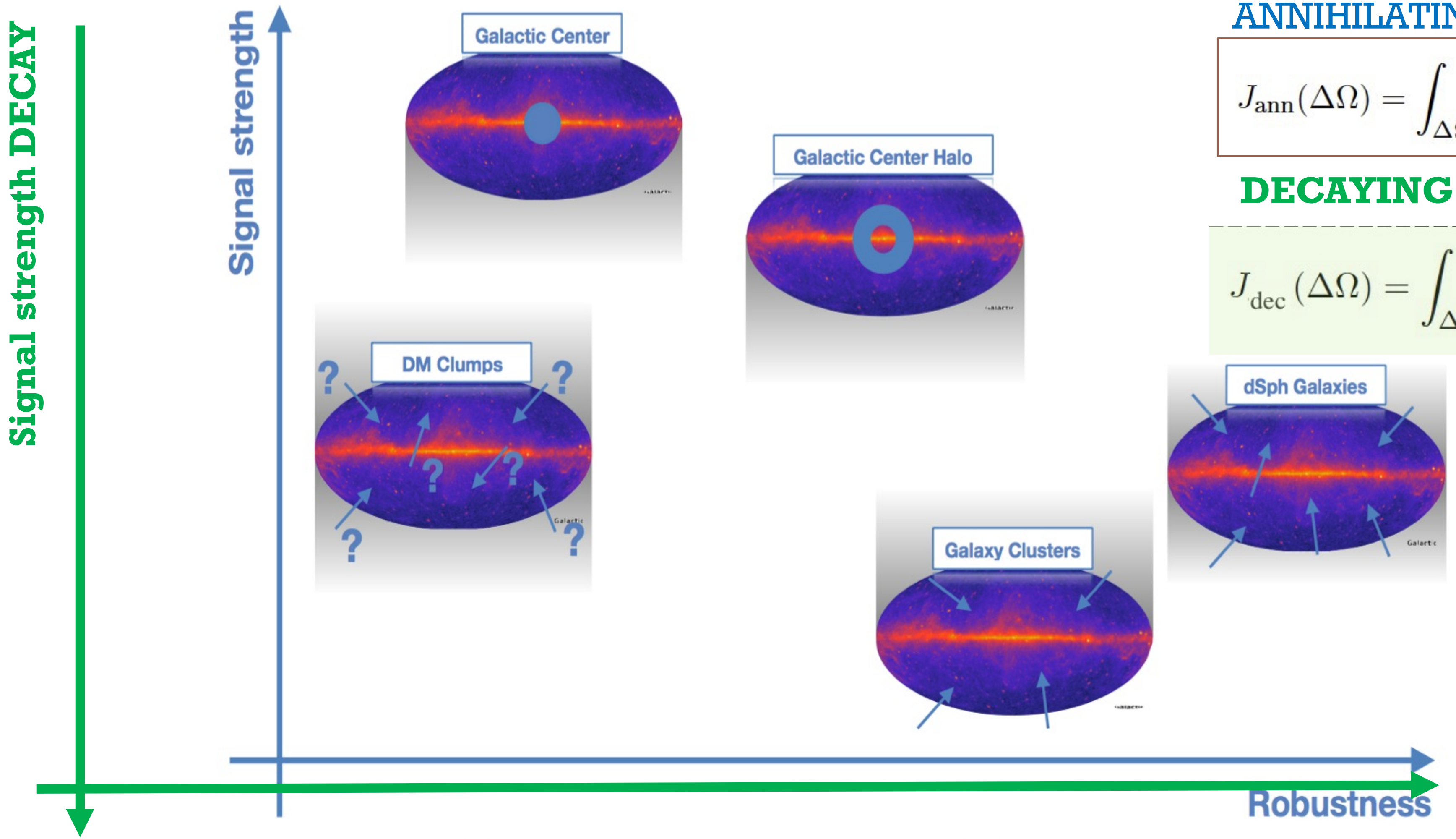


2403.04857



- Smoking gun signatures of dark matter
- Better have a nice energy resolution CTA!

RECAP FOR ANNIHILATION + DECAY



ANNIHILATING DARK MATTER

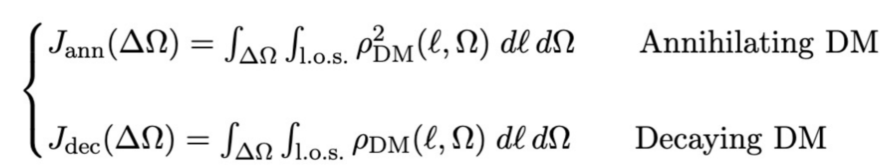
$$J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho^2(l,\Omega)\,dl\,d\Omega.$$

DECAYING DARK MATTER

$$J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho\,(l,\Omega)\,dl\,d\Omega.$$

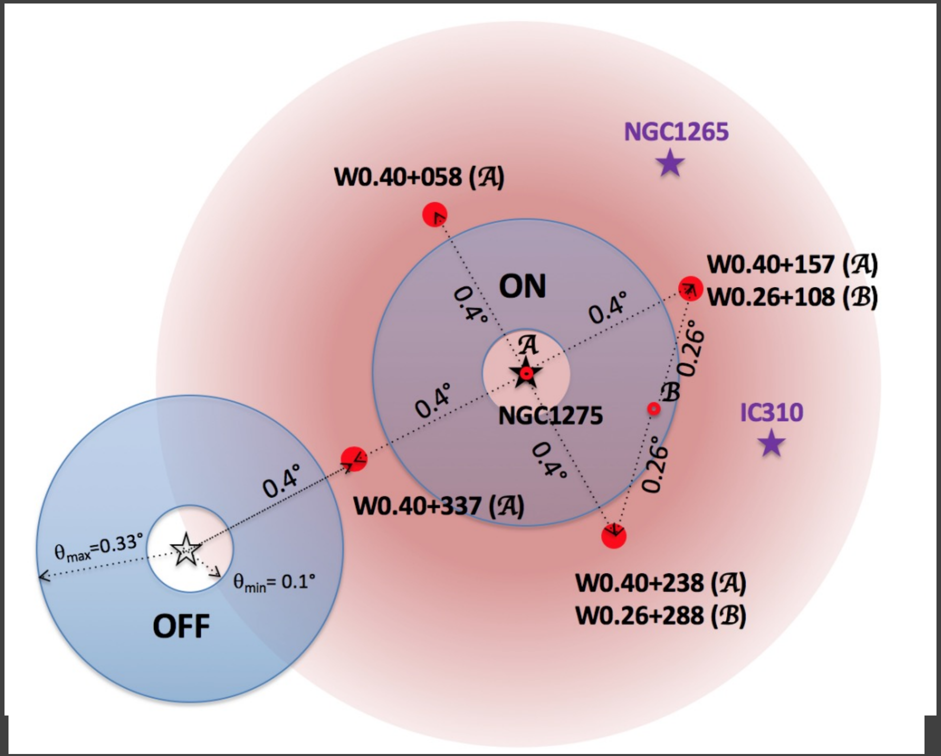
3.6 DECAY DM SEARCHES

- Best done on object with ‘a lot of DM’ as opposed to ’highly-dense’
- Better done in galaxy clusters
- Most DM dominated: Fornax, Perseus, Virgo --> See Biteau to know where we are

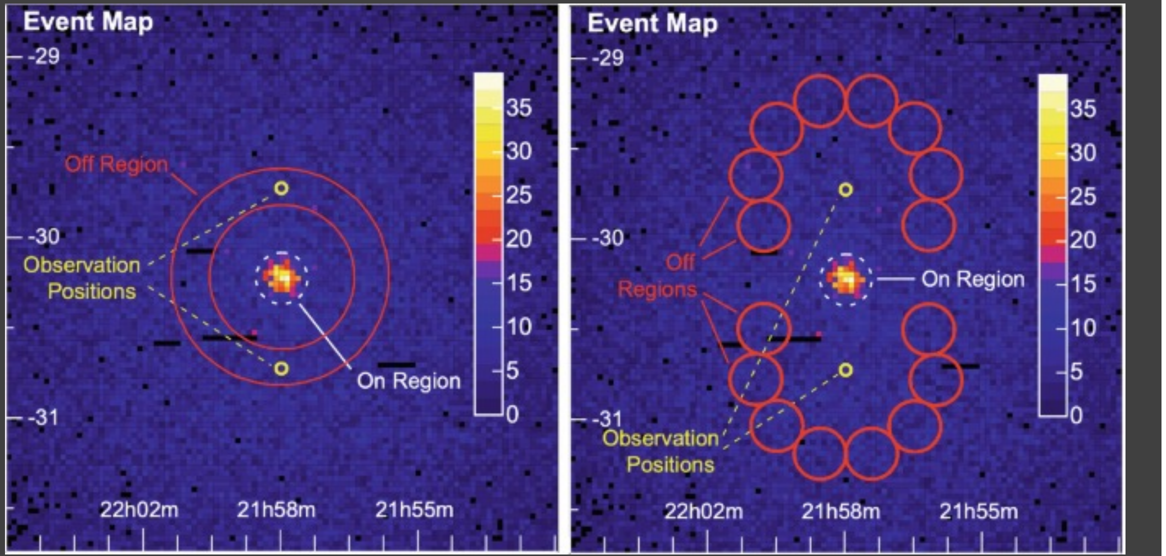


$$\begin{cases} J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho^2_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Annihilating DM} \\ J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Decaying DM} \end{cases}$$

ON/OFF TEMPLATE BACKGROUND



MAGIC s.Dark Univ. 22 (2018)



- Background control regions (OFF) where to estimate the signal
- What if src is extended? Template background method

LIMITS: DARK MATTER LIFETIME (CTA)

MAGIC s.Dark Univ. 22 (2018)

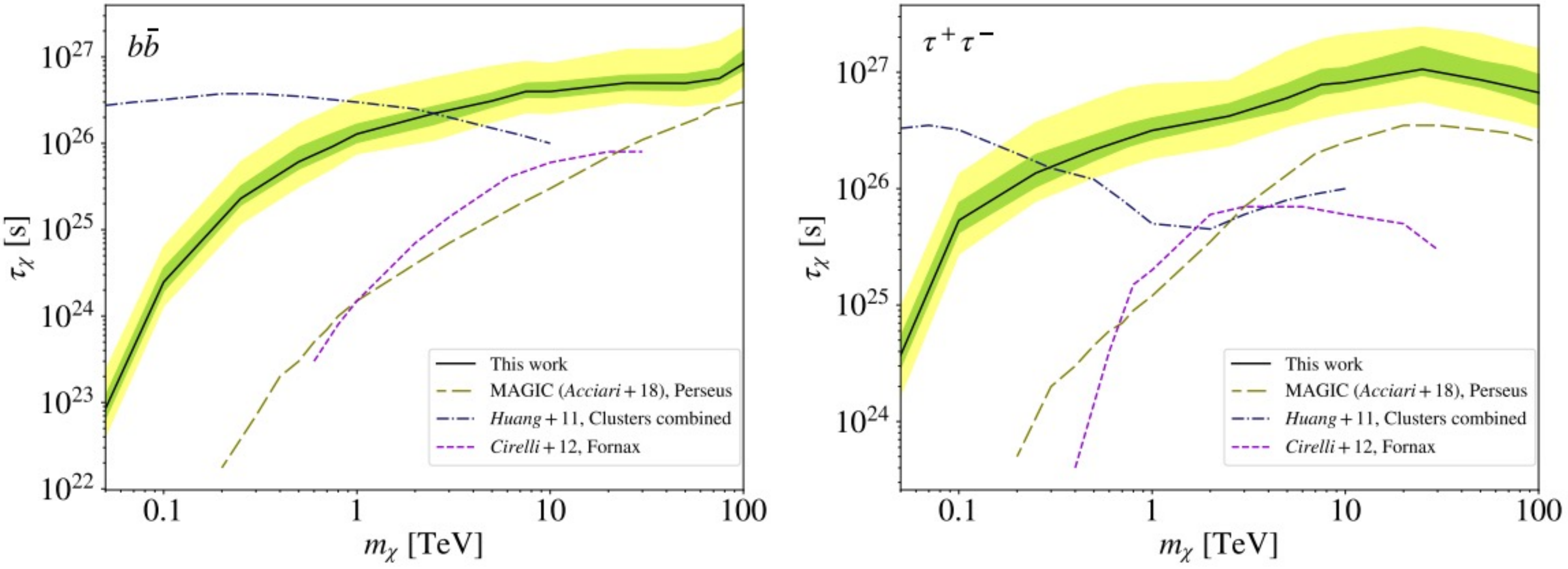
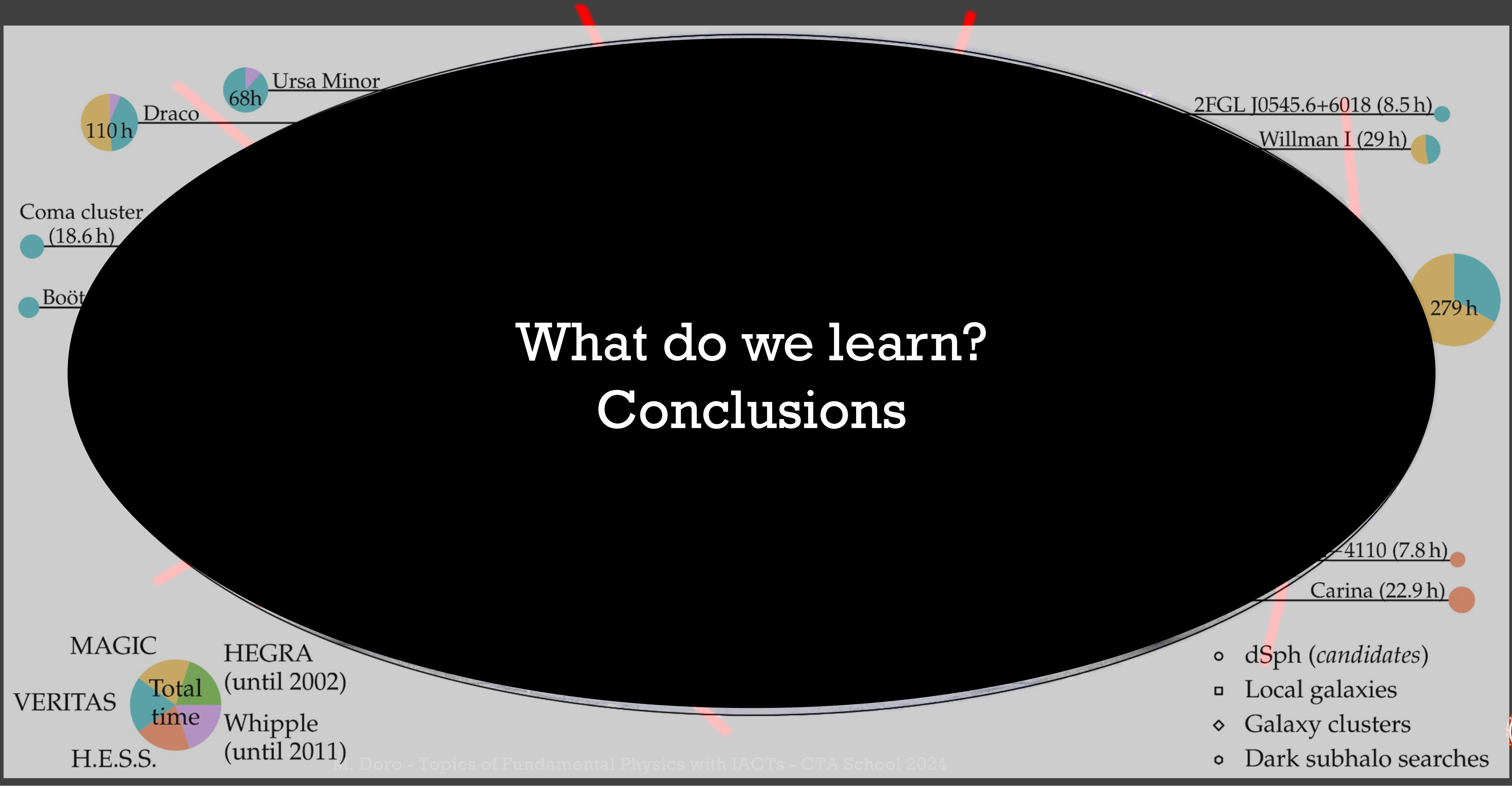


Figure 21. Sensitivity of CTA to a DM decay signal from the Perseus cluster, at 95% C.L., in terms

CLOSING REMARKS

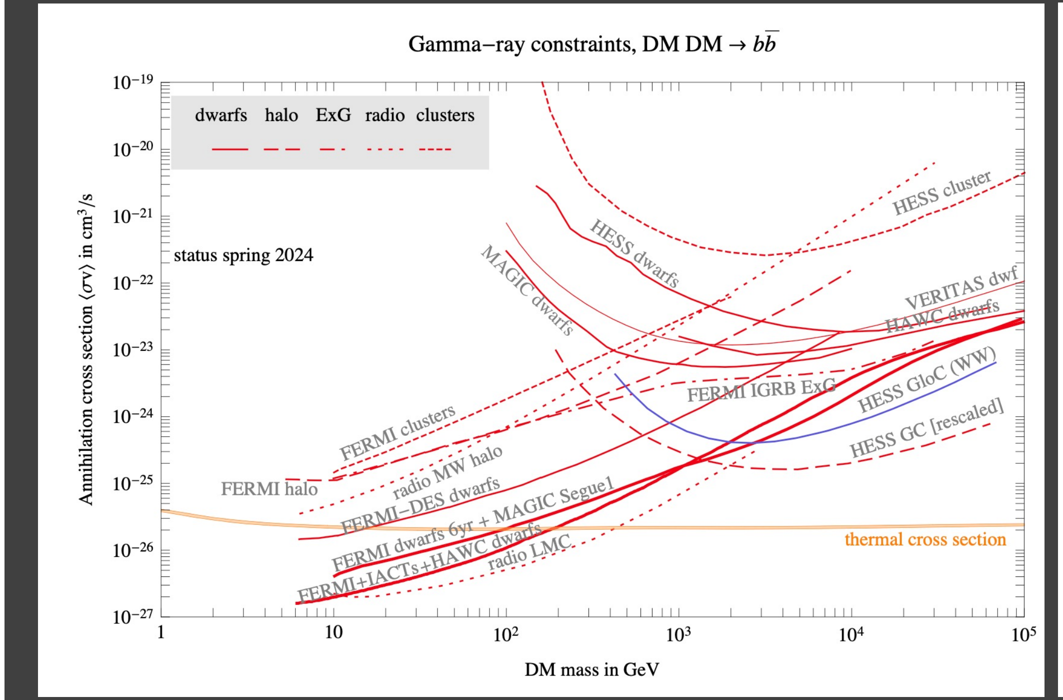
Galaxies **2022**, *10*(5), 92

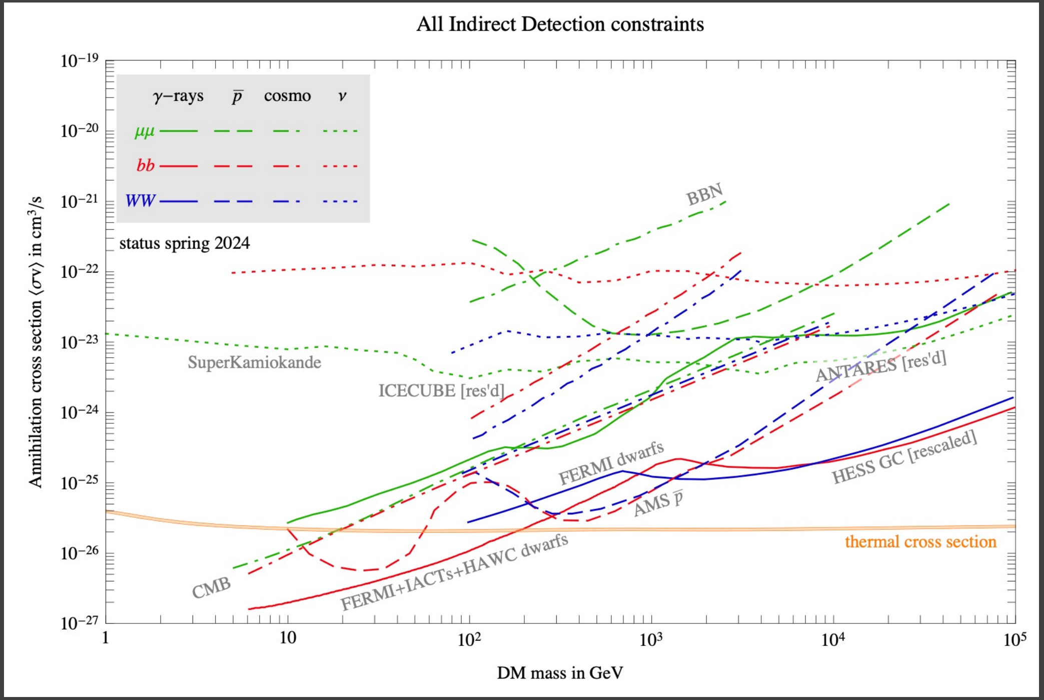


What do we learn?
Conclusions

DM GAMMA ANNIHILATION

Cirelli+ 2024



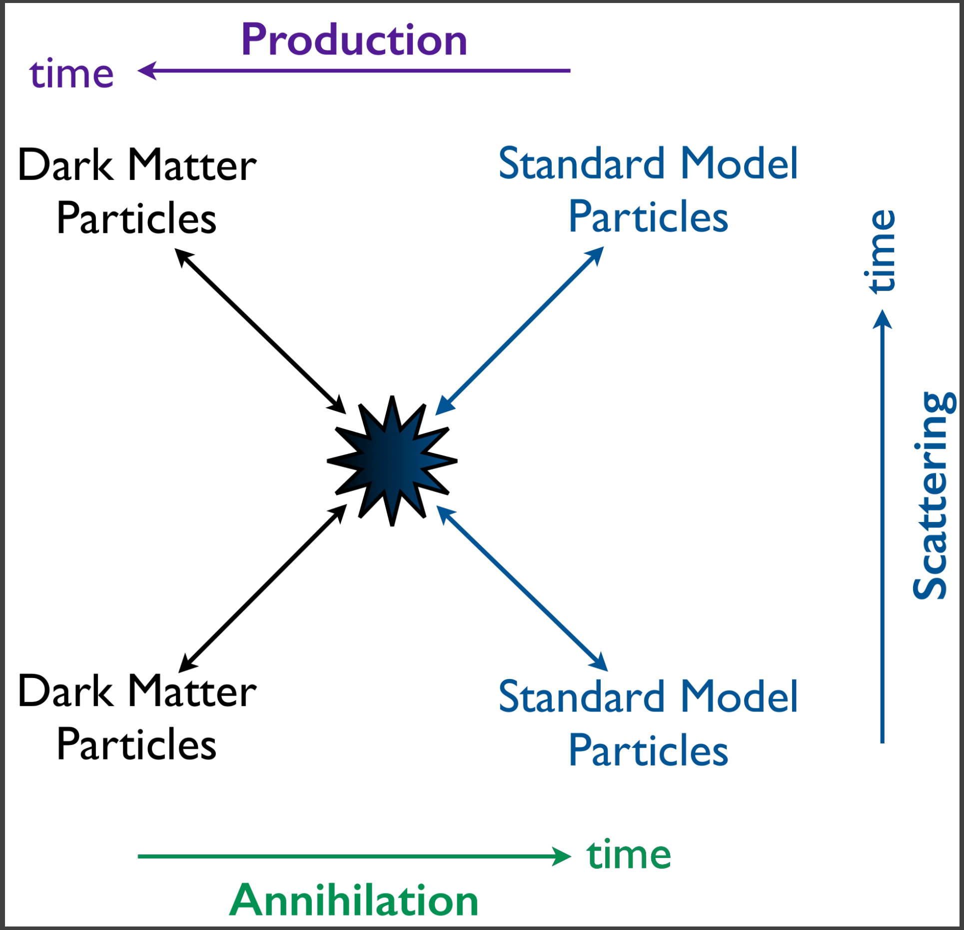


IACTs dominates the TeV, but..

Still better than any

COMPLEMENTARITY

M. Cahill-Rawley 1411.3353



Production

time

Dark Matter Particles

Standard Model Particles

time

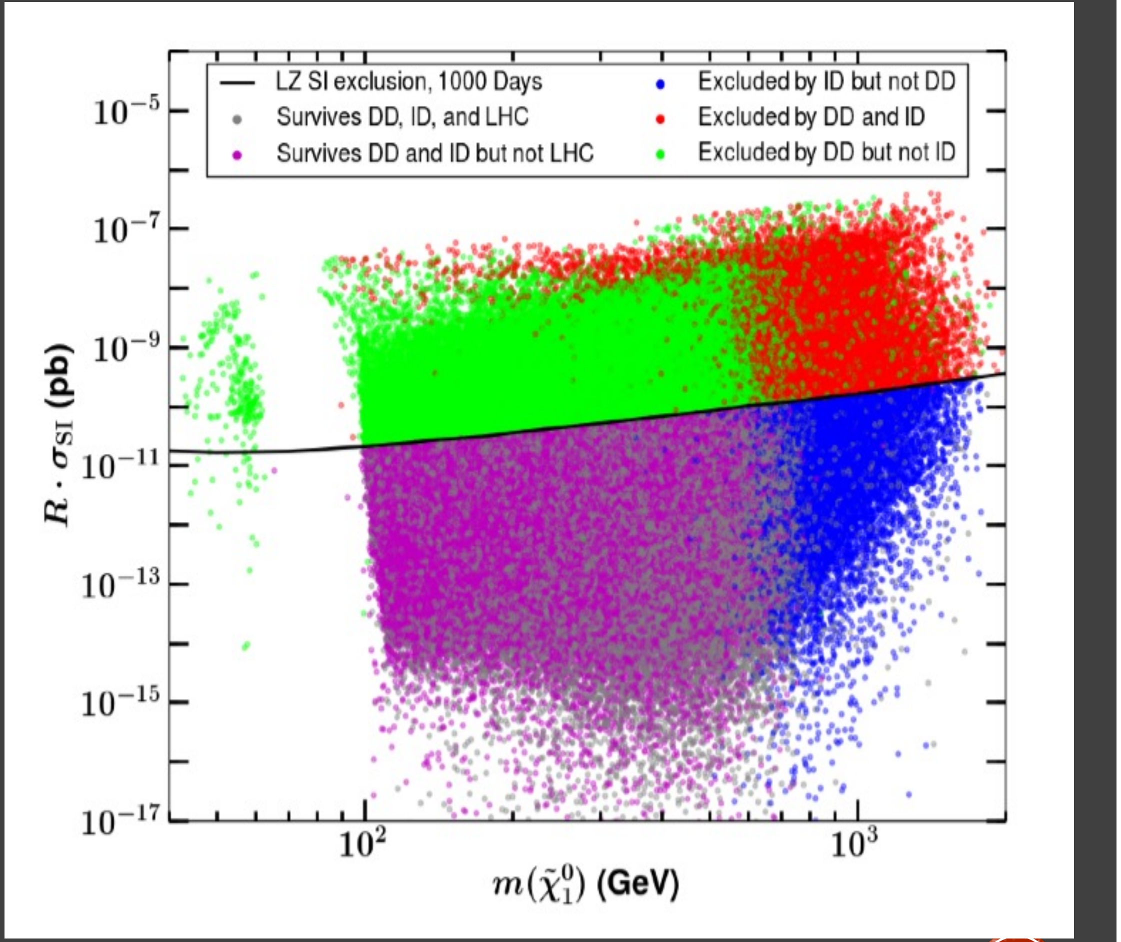
Scattering

Dark Matter Particles

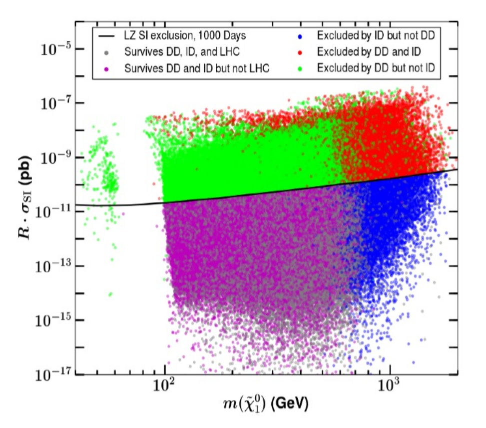
Standard Model Particles

time

Annihilation



CONCLUSIONS DM



- Incontrovertible evidences of particle DM, don't trust the colleagues that tell you it does not exist
- From the astrophysical point of view:
  A coherent picture of astrophysical DM give us the possibility to find a super-target, very DM dominated (dsph, dark subhalo, BHs)
- However, where to point?
- Important to create sinergies with spectrometers → campaigns!
- CTA DM pipeline being developed→ datachallenge!
- From the particle physics point of view, gamma-rays are rather 'model independent' therefore any null result is a relevant limit

HOWEVER, AFTER 15 YEARS…PATIENCE REQUIRED

MD, M.A. Sanchez-Conde, M. Huetten.
https://arxiv.org/abs/2111.01198

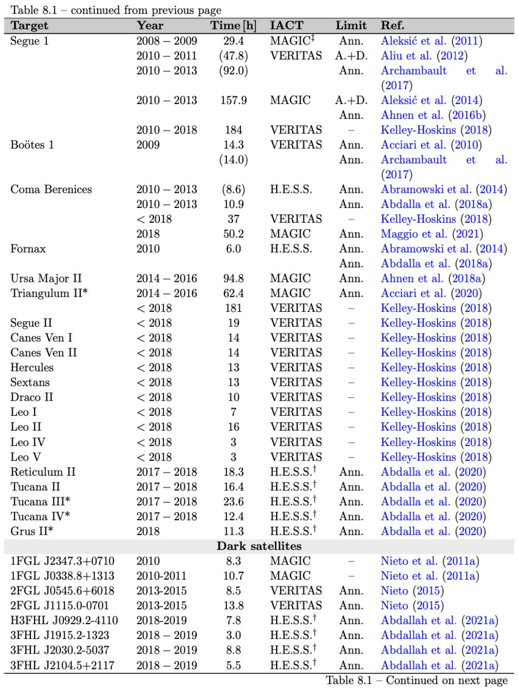
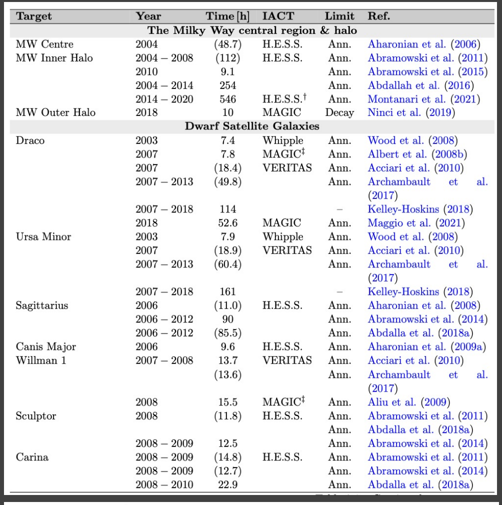


Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Segue 1	2008 – 2009	29.4	MAGIC‡	Ann.	Aleksić et al. (2011)
	2010 – 2011	(47.8)	VERITAS	A.+D.	Aliu et al. (2012)
	2010 – 2013	(92.0)		Ann.	Archambault et al. (2017)
	2010 – 2013	157.9	MAGIC	A.+D.	Aleksić et al. (2014)
				Ann.	Ahnen et al. (2016b)
	2010 – 2018	184	VERITAS	–	Kelley-Hoskins (2018)
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al. (2010)
		(14.0)		Ann.	Archambault et al. (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski et al. (2014)
	2010 – 2013	10.9		Ann.	Abdalla et al. (2018a)
	< 2018	37	VERITAS	–	Kelley-Hoskins (2018)
	2018	50.2	MAGIC	Ann.	Maggio et al. (2021)
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski et al. (2014)
				Ann.	Abdalla et al. (2018a)
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al. (2018a)
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al. (2020)
	< 2018	181	VERITAS	–	Kelley-Hoskins (2018)
Segue II	< 2018	19	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Hercules	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Sextans	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Draco II	< 2018	10	VERITAS	–	Kelley-Hoskins (2018)
Leo I	< 2018	7	VERITAS	–	Kelley-Hoskins (2018)
Leo II	< 2018	16	VERITAS	–	Kelley-Hoskins (2018)
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Leo V	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Dark satellites					
1FGL J2347.3+0710	2010	8.3	MAGIC	–	Nieto et al. (2011a)
1FGL J0338.8+1313	2010-2011	10.7	MAGIC	–	Nieto et al. (2011a)
2FGL J0545.6+6018	2013-2015	8.5	VERITAS	Ann.	Nieto (2015)
2FGL J1115.0-0701	2013-2015	13.8	VERITAS	Ann.	Nieto (2015)
H3FHL J0929.2-4110	2018-2019	7.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J1915.2-1323	2018 – 2019	3.0	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2030.2-5037	2018 – 2019	8.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2104.5+2117	2018 – 2019	5.5	H.E.S.S.†	Ann.	Abdallah et al. (2021a)

Table 8.1 – Continued on next page



Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)
MW Outer Halo	2018	10	MAGIC	Decay	Ninci et al. (2019)
Dwarf Satellite Galaxies					
Draco	2003	7.4	Whipple	Ann.	Wood et al. (2008)
	2007	7.8	MAGIC‡	Ann.	Albert et al. (2008b)
	2007	(18.4)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(49.8)		Ann.	Archambault et al. (2017)
	2007 – 2018	114		–	Kelley-Hoskins (2018)
	2018	52.6	MAGIC	Ann.	Maggio et al. (2021)
Ursa Minor	2003	7.9	Whipple	Ann.	Wood et al. (2008)
	2007	(18.9)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(60.4)		Ann.	Archambault et al. (2017)
	2007 – 2018	161		–	Kelley-Hoskins (2018)
Sagittarius	2006	(11.0)	H.E.S.S.	Ann.	Aharonian et al. (2008)
	2006 – 2012	90		Ann.	Abramowski et al. (2014)
	2006 – 2012	(85.5)		Ann.	Abdalla et al. (2018a)
Canis Major	2006	9.6	H.E.S.S.	Ann.	Aharonian et al. (2009a)
Willman 1	2007 – 2008	13.7	VERITAS	Ann.	Acciari et al. (2010)
		(13.6)		Ann.	Archambault et al. (2017)
	2008	15.5	MAGIC‡	Ann.	Aliu et al. (2009)
Sculptor	2008	(11.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
				Ann.	Abdalla et al. (2018a)
	2008 – 2009	12.5		Ann.	Abramowski et al. (2014)
Carina	2008 – 2009	(14.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2008 – 2009	(12.7)		Ann.	Abramowski et al. (2014)
	2008 – 2010	22.9		Ann.	Abdalla et al. (2018a)

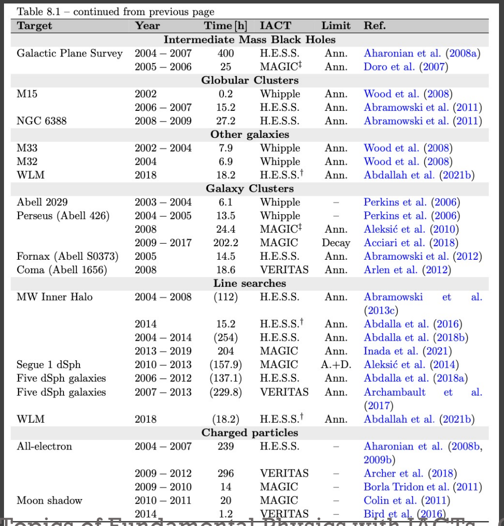


Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Intermediate Mass Black Holes					
Galactic Plane Survey	2004 – 2007	400	H.E.S.S.	Ann.	Aharonian et al. (2008a)
	2005 – 2006	25	MAGIC‡	Ann.	Doro et al. (2007)
Globular Clusters					
M15	2002	0.2	Whipple	Ann.	Wood et al. (2008)
	2006 – 2007	15.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
NGC 6388	2008 – 2009	27.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
Other galaxies					
M33	2002 – 2004	7.9	Whipple	Ann.	Wood et al. (2008)
M32	2004	6.9	Whipple	Ann.	Wood et al. (2008)
WLM	2018	18.2	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Galaxy Clusters					
Abell 2029	2003 – 2004	6.1	Whipple	–	Perkins et al. (2006)
Perseus (Abell 426)	2004 – 2005	13.5	Whipple	–	Perkins et al. (2006)
	2008	24.4	MAGIC‡	Ann.	Aleksić et al. (2010)
	2009 – 2017	202.2	MAGIC	Decay	Acciari et al. (2018)
Fornax (Abell S0373)	2005	14.5	H.E.S.S.	Ann.	Abramowski et al. (2012)
Coma (Abell 1656)	2008	18.6	VERITAS	Ann.	Arlen et al. (2012)
Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)
Segue 1 dSph	2010 – 2013	(157.9)	MAGIC	A.+D.	Aleksić et al. (2014)
Five dSph galaxies	2006 – 2012	(137.1)	H.E.S.S.	Ann.	Abdalla et al. (2018a)
Five dSph galaxies	2007 – 2013	(229.8)	VERITAS	Ann.	Archambault et al. (2017)
WLM	2018	(18.2)	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Charged particles					
All-electron	2004 – 2007	239	H.E.S.S.	–	Aharonian et al. (2008b, 2009b)
	2009 – 2012	296	VERITAS	–	Archer et al. (2018)
	2009 – 2010	14	MAGIC	–	Borla Tridon et al. (2011)
Moon shadow	2010 – 2011	20	MAGIC	–	Colin et al. (2011)
	2014	1.2	VERITAS	–	Bird et al. (2016)

Thanks!

BACKUPS