Detection Prospects of Ultra-heavy dark matter candidates at CTAO

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with

Snowmass Dark Sector Working group and

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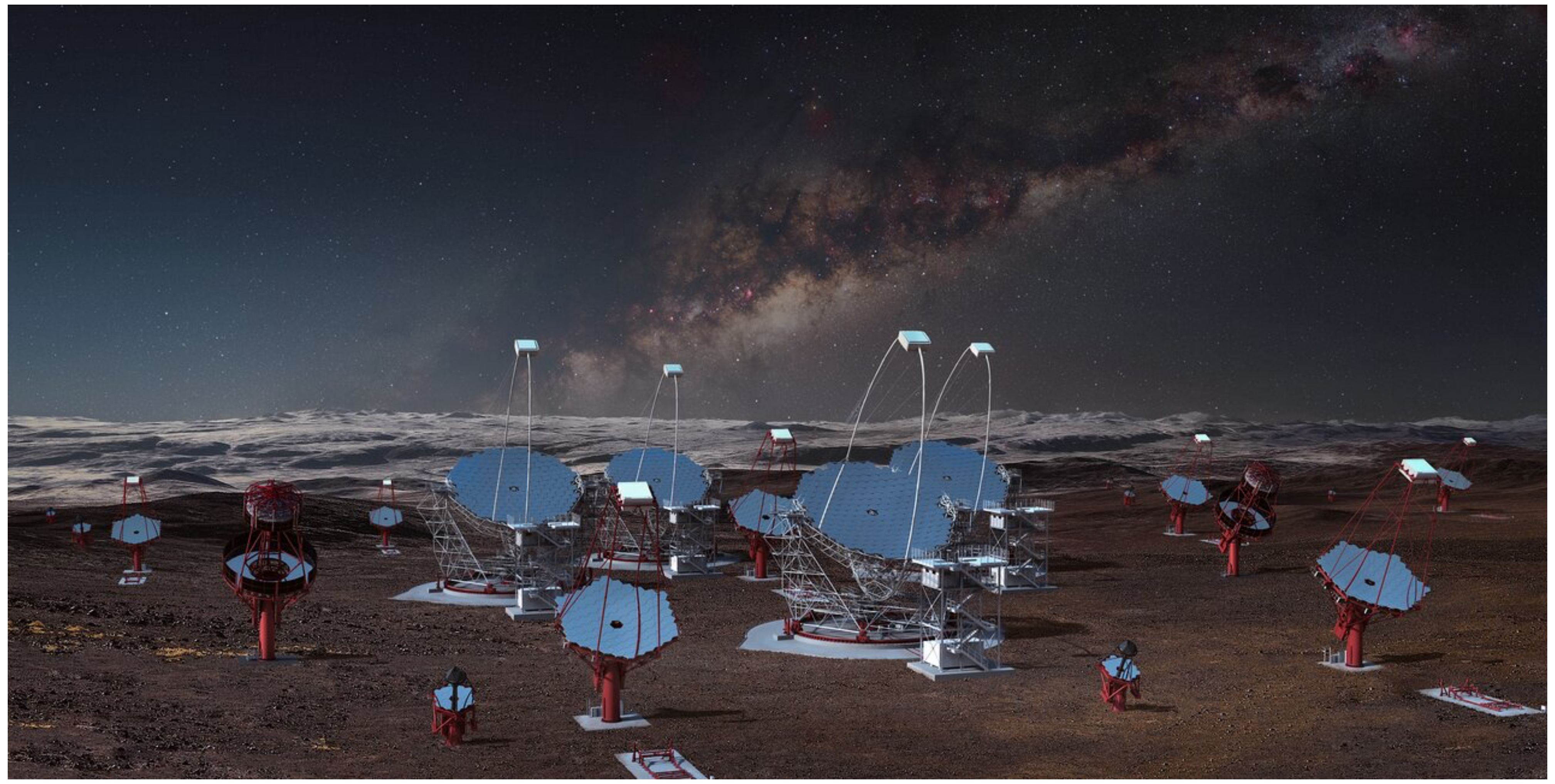
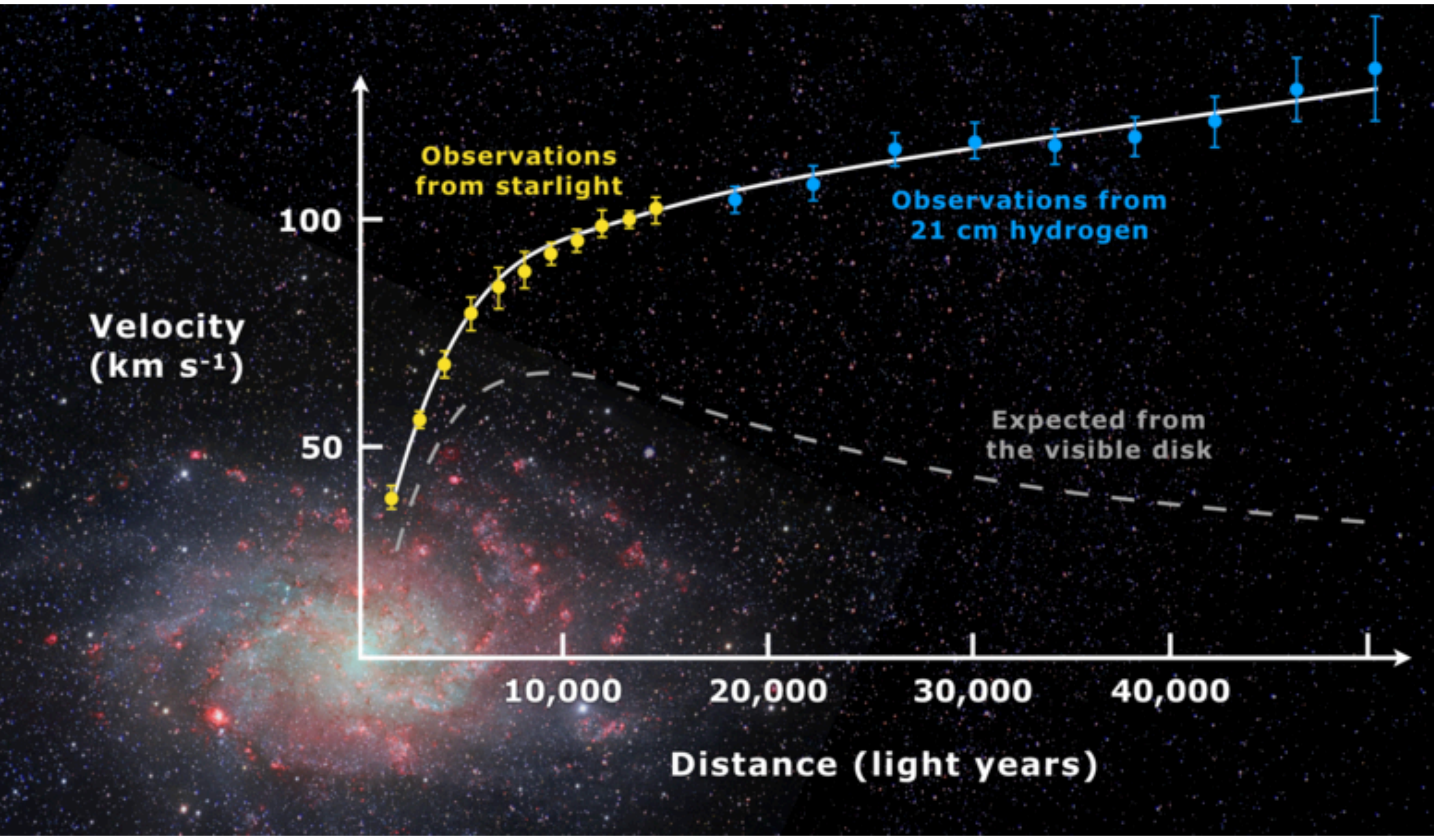
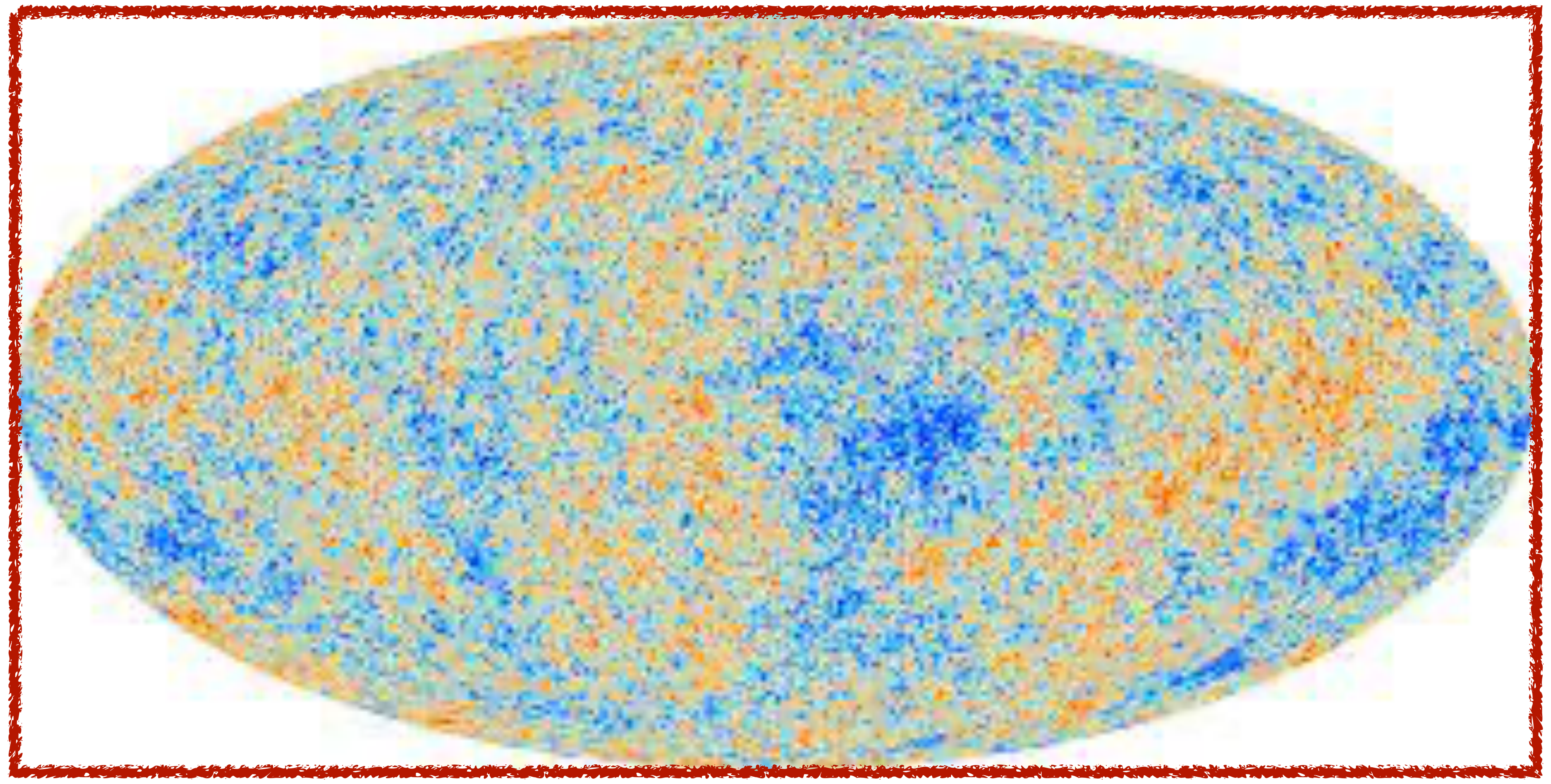
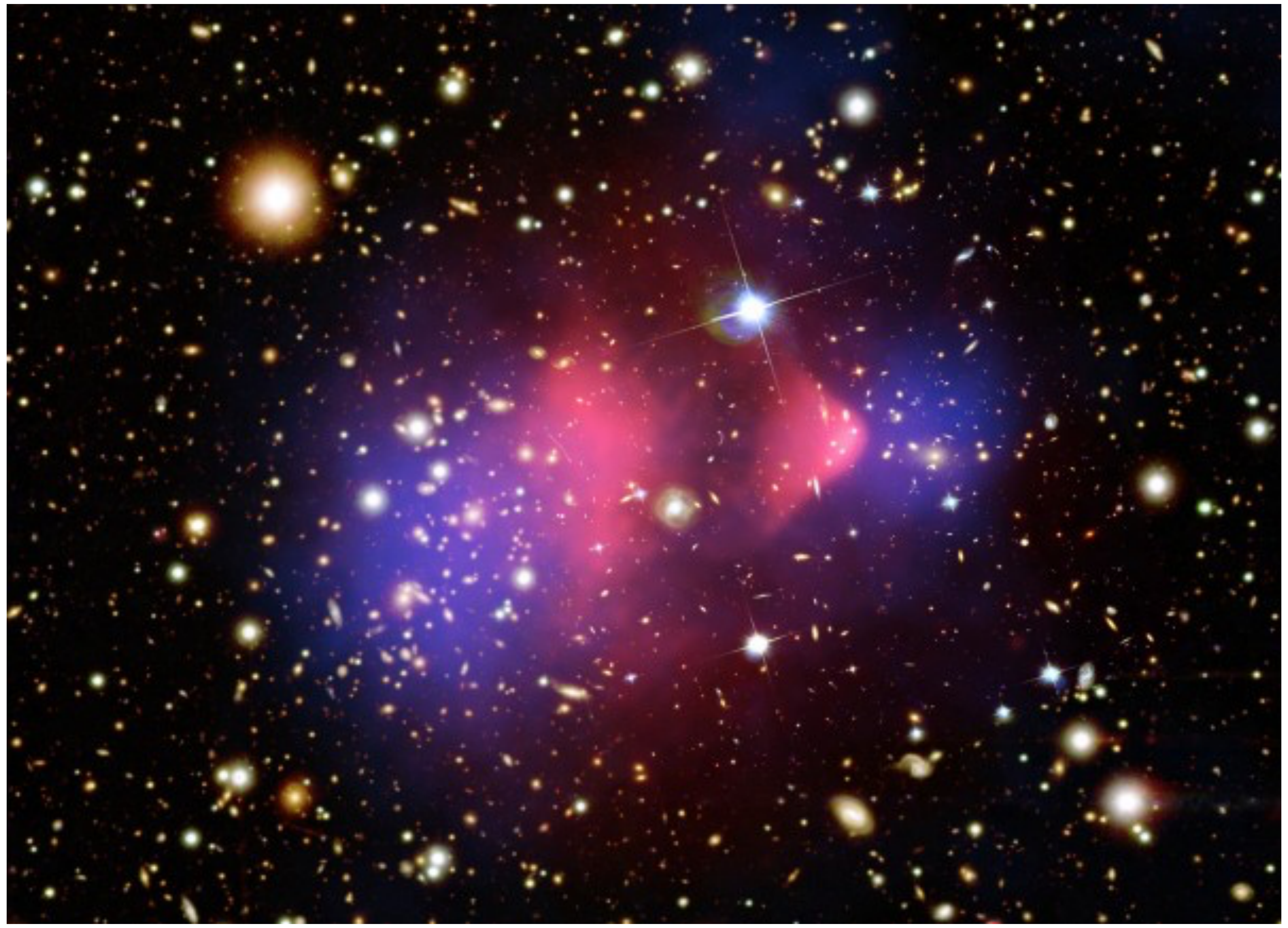
Joshua Gill (UNSW) and George Sanamyan (University of Adelaide)

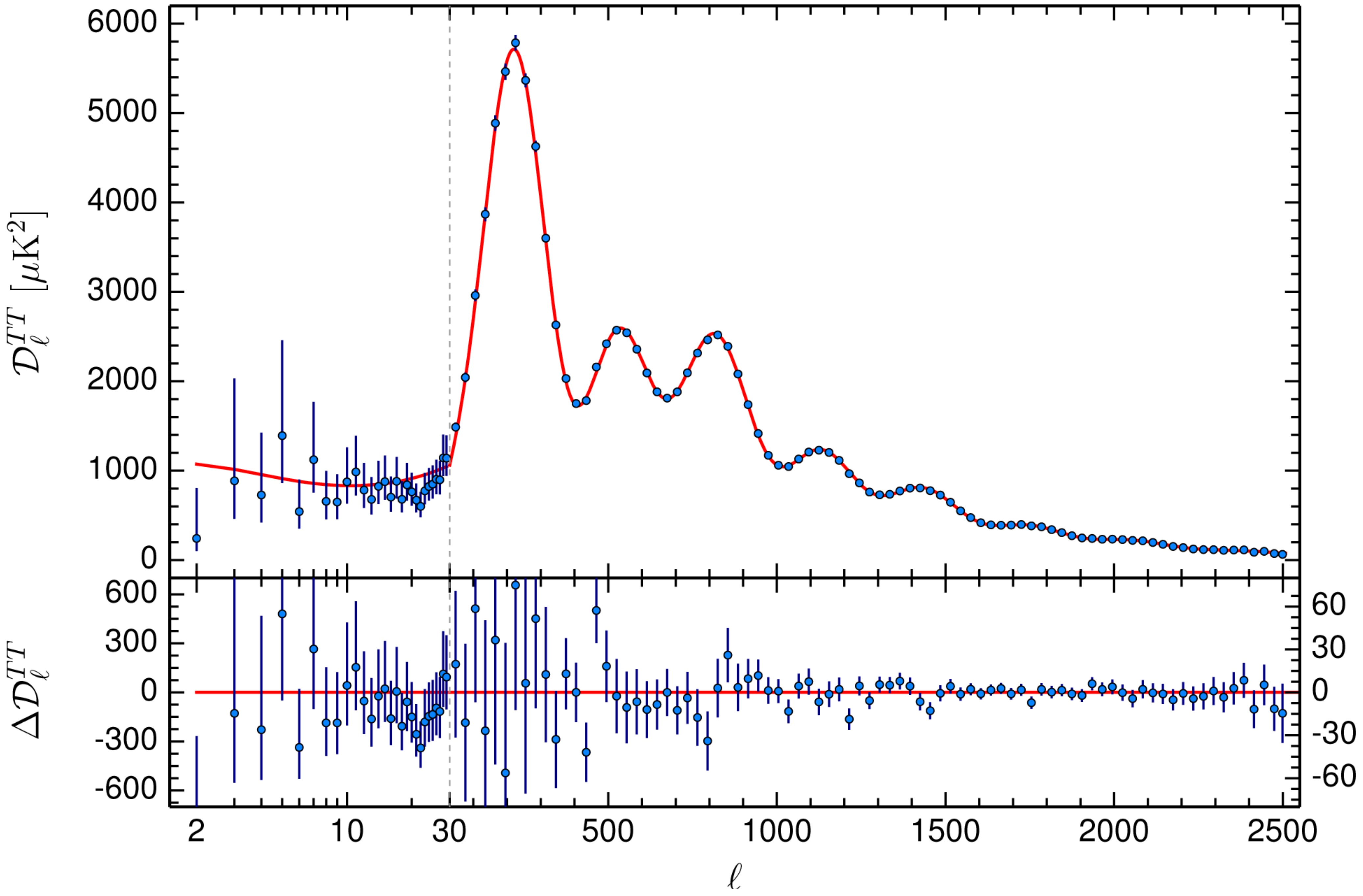


Dark Matter through the ages









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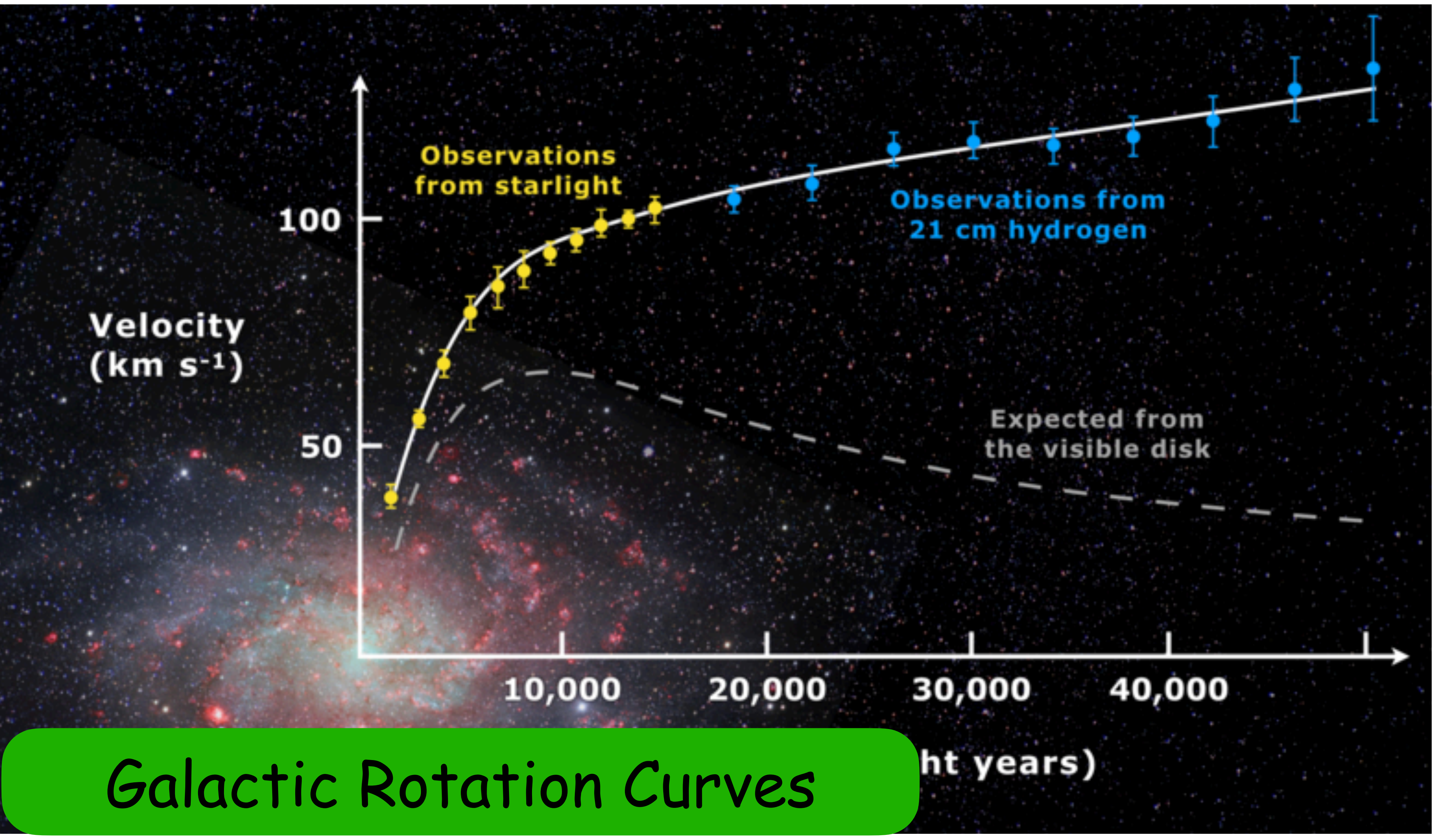
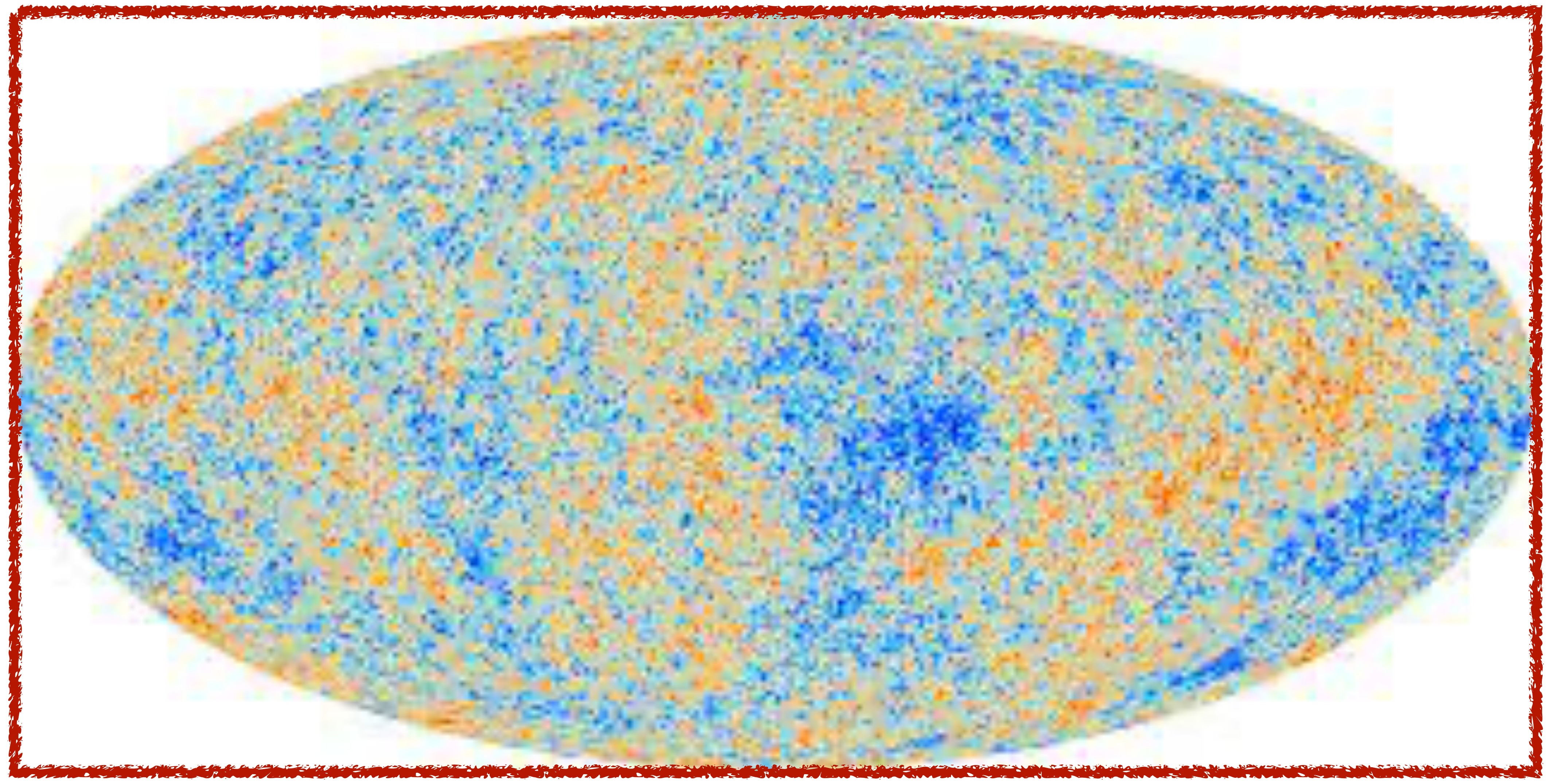
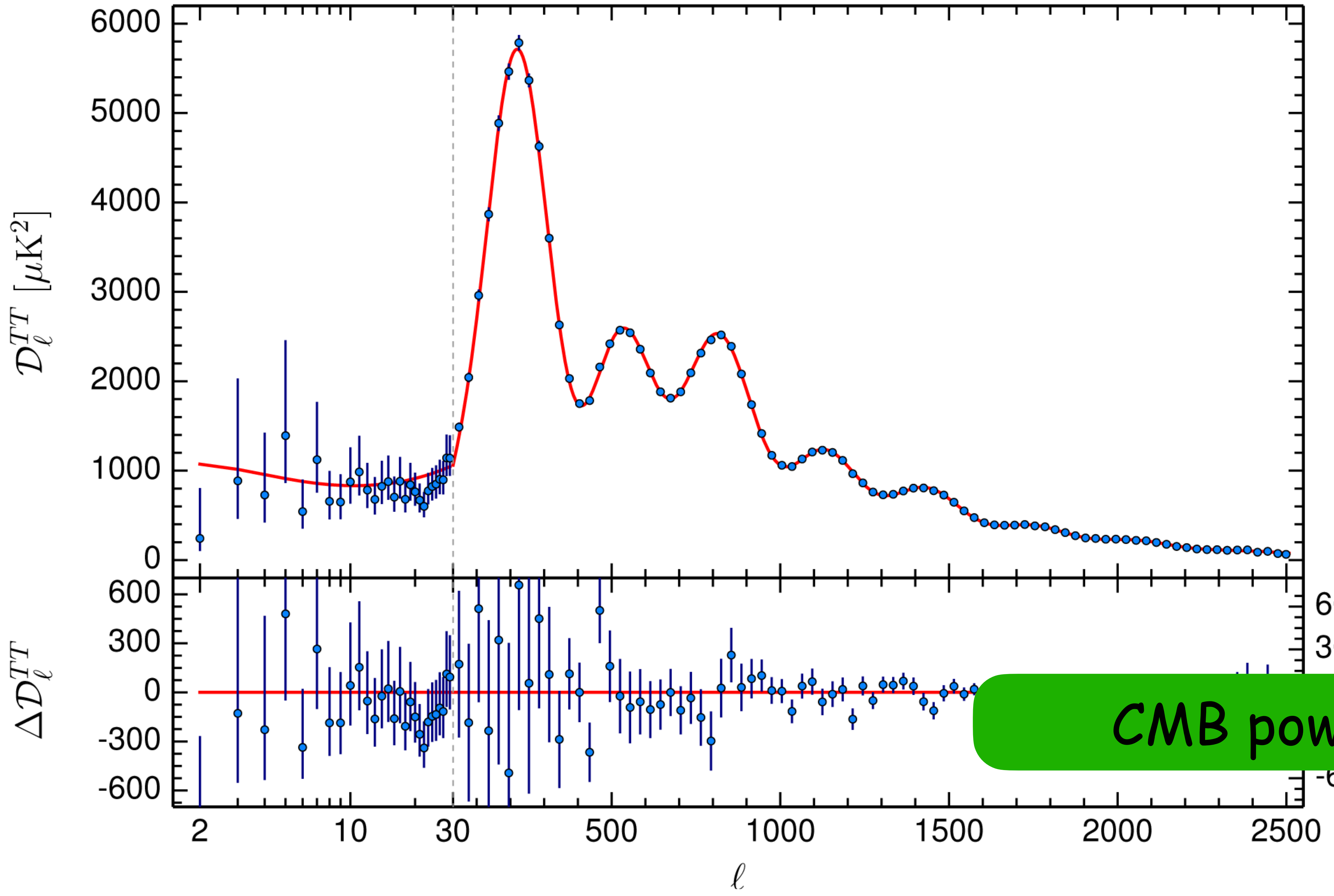


Galactic Rotation Curves

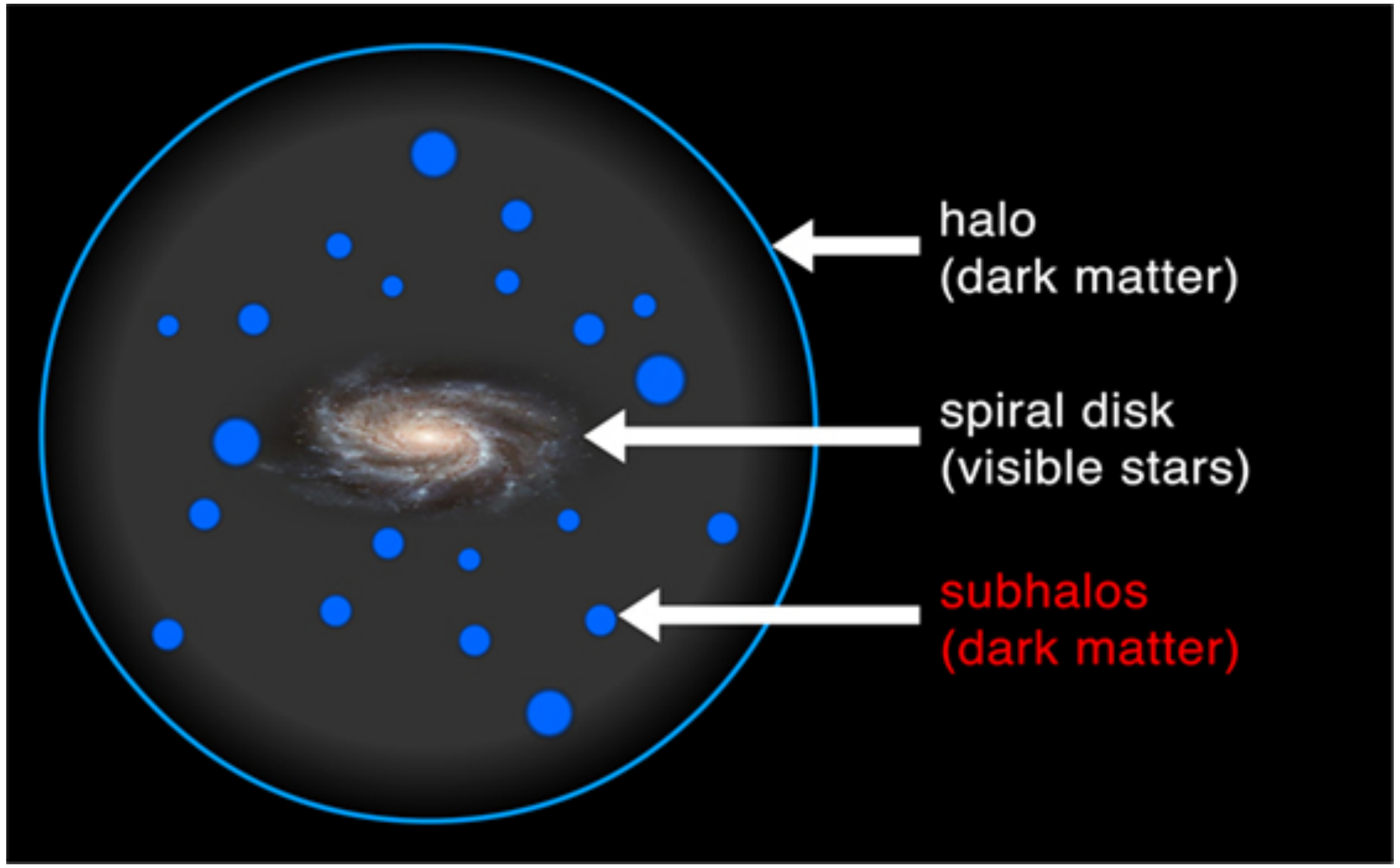


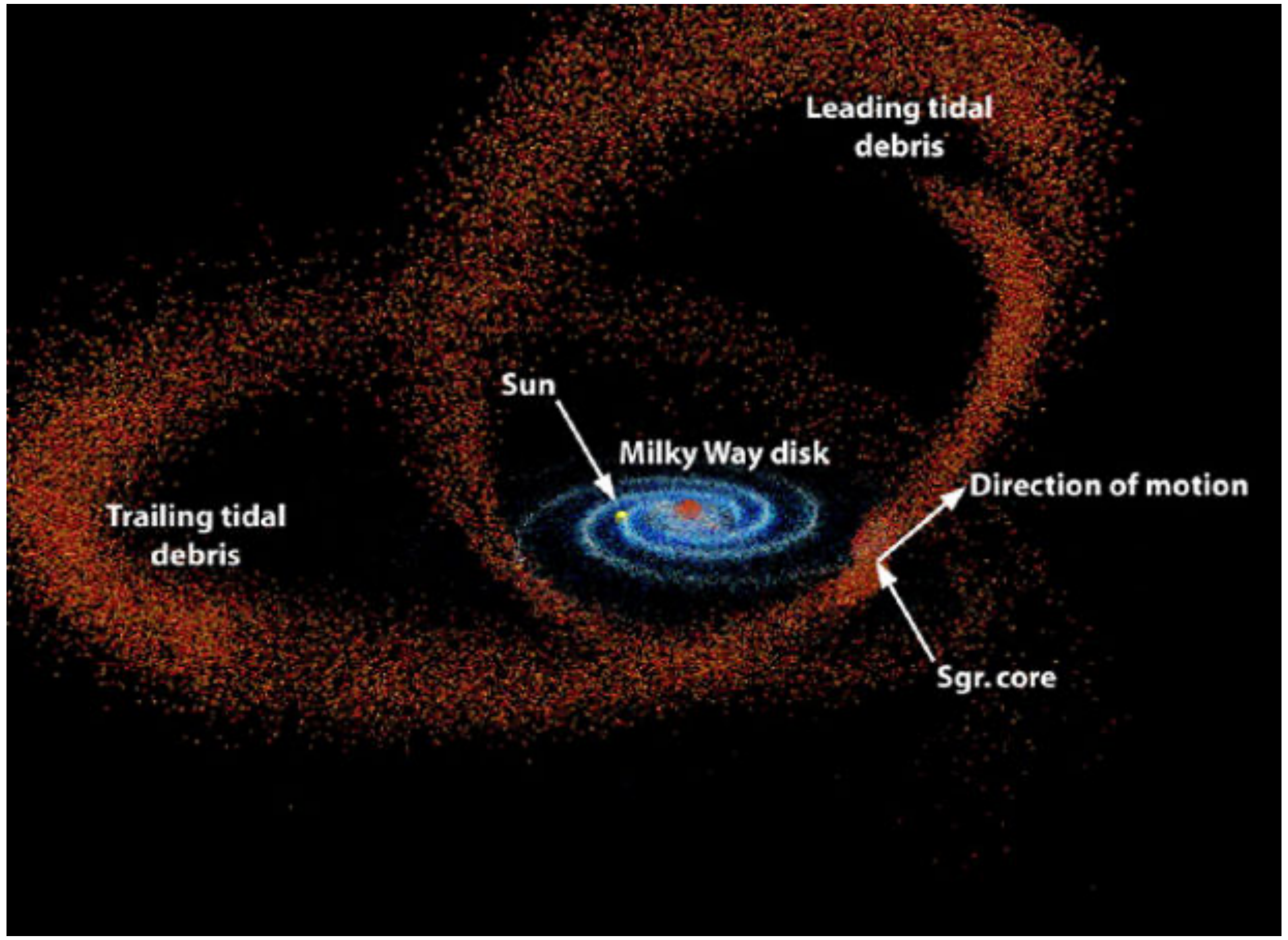
Gravitational Lensing in Bullet Cluster .
Pink- X-Ray image
Blue : Gravitational lensing image



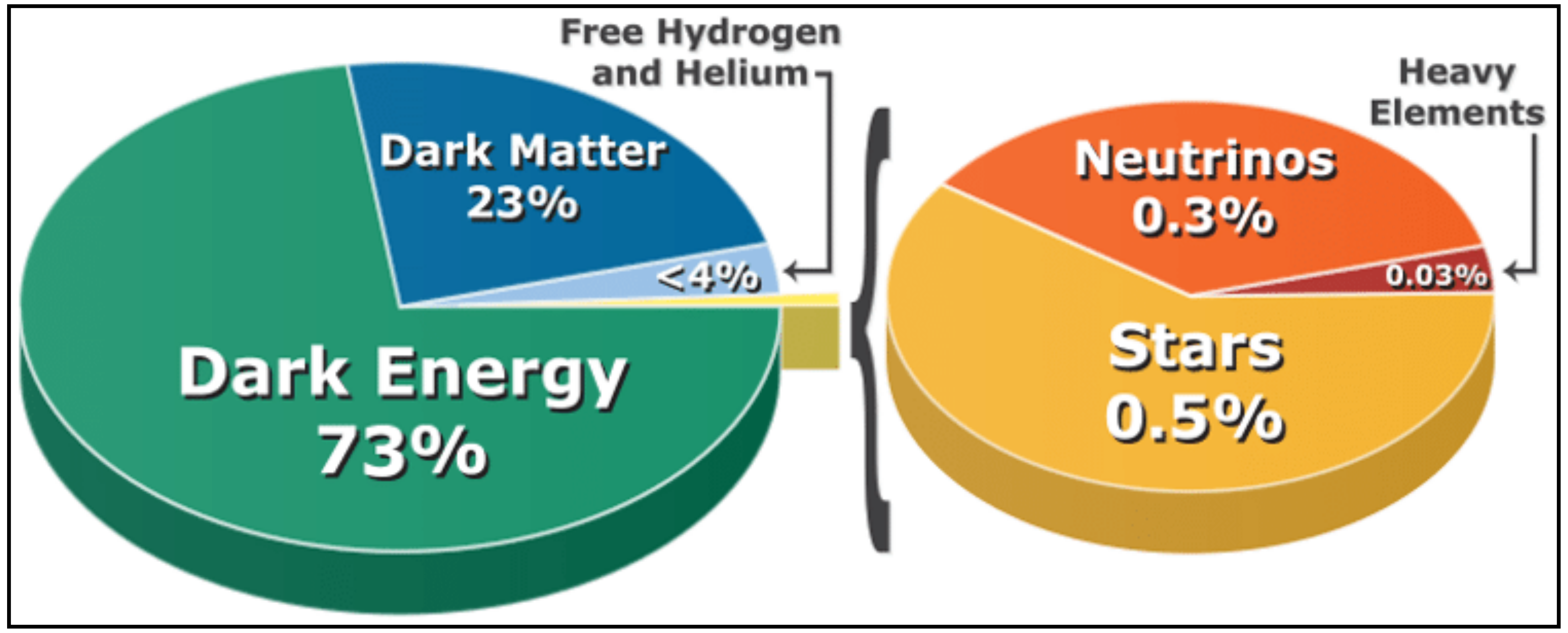
CMB power spectrum

Properties and the Particle Physics of Dark Matter



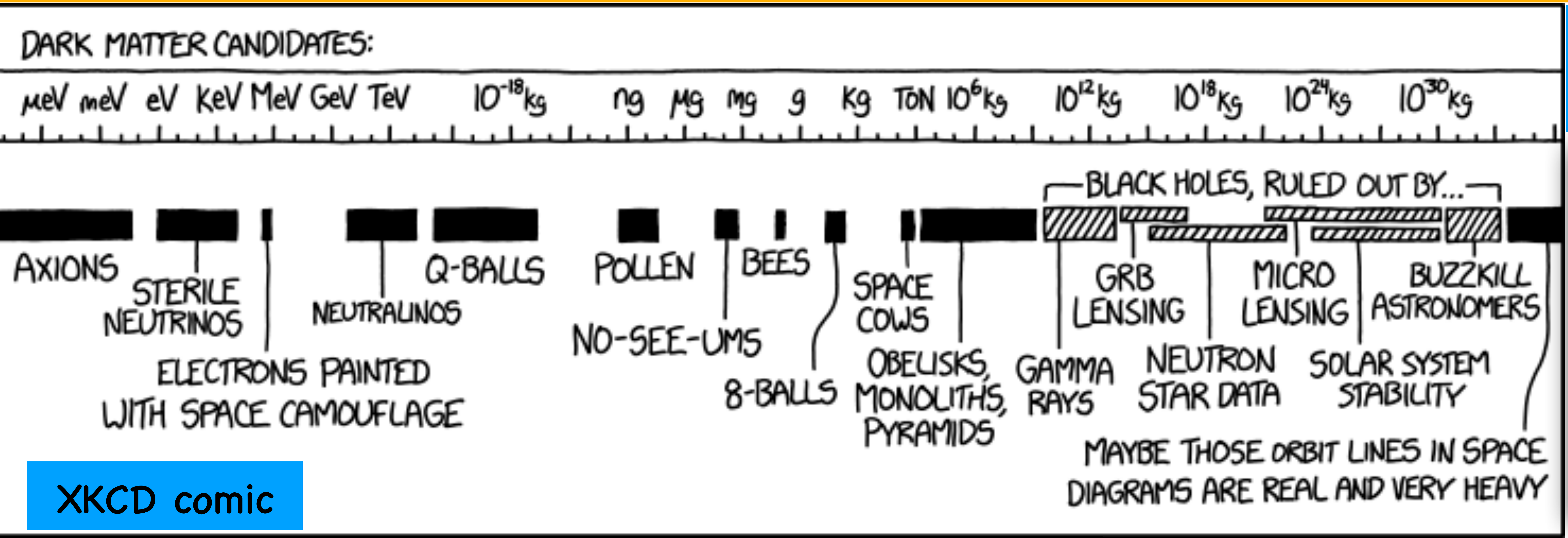


- Cold and Neutral: Non relativistic today.
- Preserves the success of Big Bang Nucleosynthesis (Formation of Atoms and Nuclei in the early Universe)
- "Almost" **Dark** with respect to other forces of nature.
- Collisionless within the DM sector at large scales.
- Stable, on Cosmological time scales.
- Forms halos in the galaxy



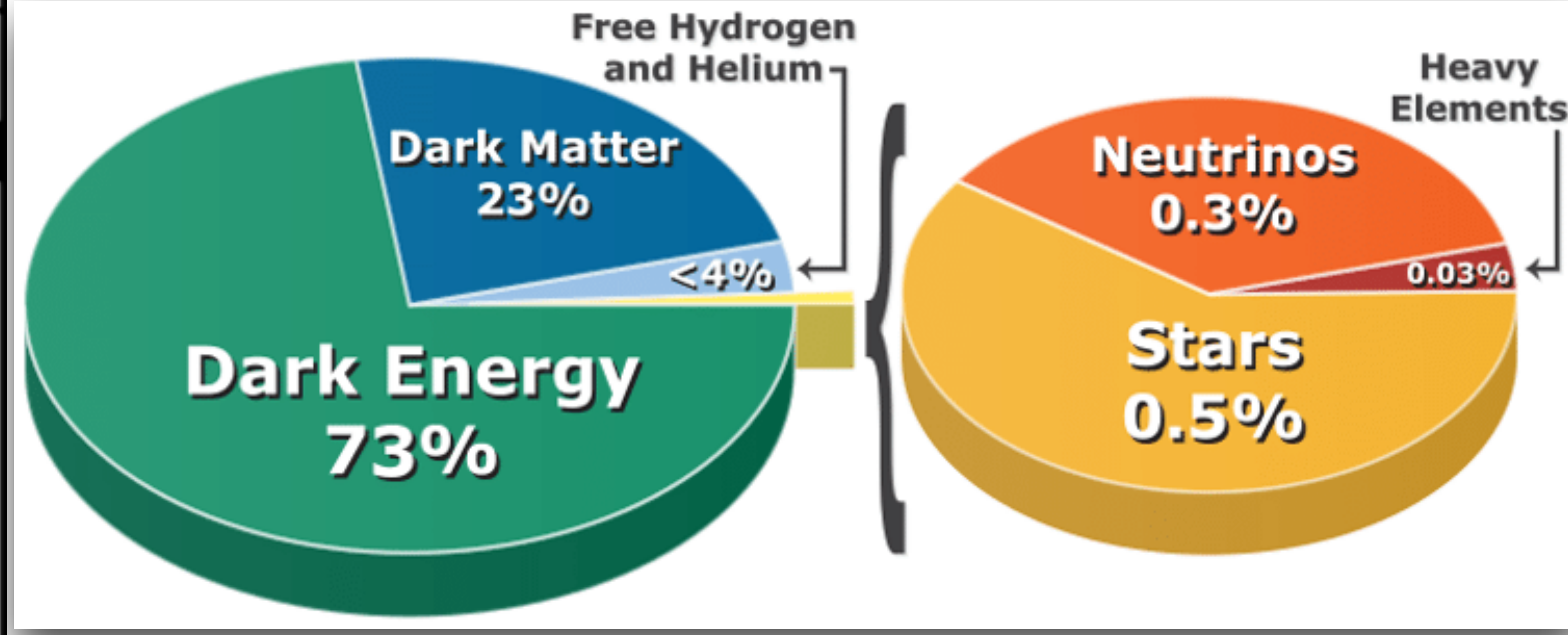
Dark Matter belongs in Astronomy/Cosmology .
Why should we care about colliders ?

Dark Matter wiithin Beyond Standard Model



XKCD comic

Dark Matter can be multi-component, more than one species in this list



Tim Tait for Snowmass

Fermions or Bosons ?

Fermions

1. Tremaine-Gunn bound from fermion phase space saturation : ~1 eV
2. Thermal Warm Dark Matter bound :

Lyman-alpha forest constraints - matter power spectrum bounds > 5 KeV

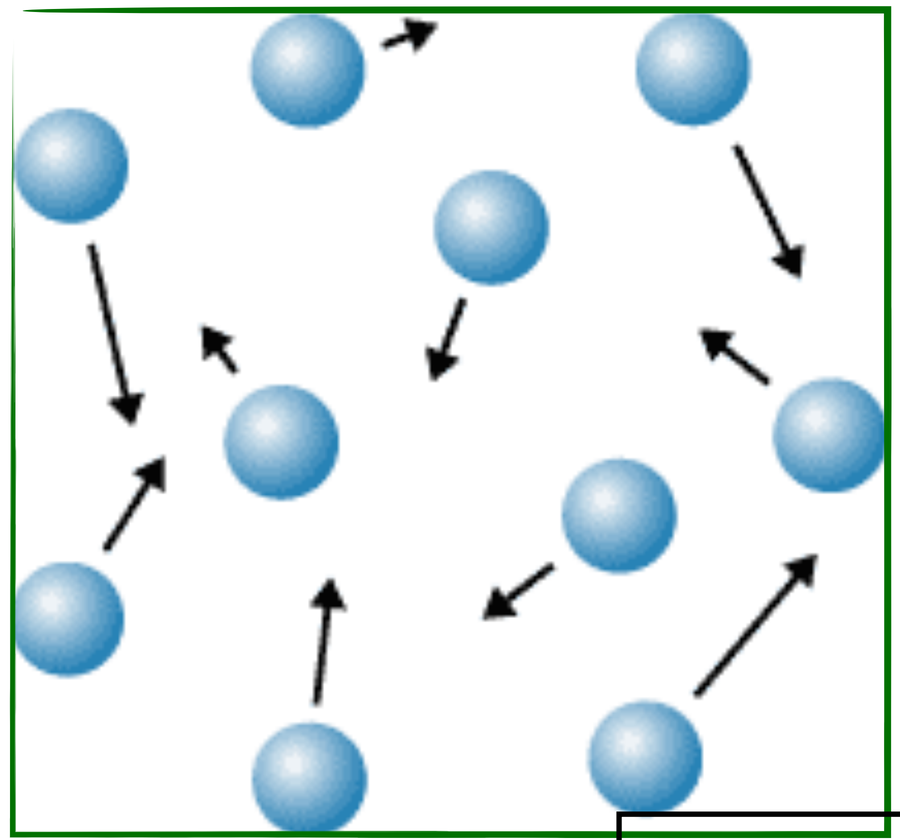
Bosons

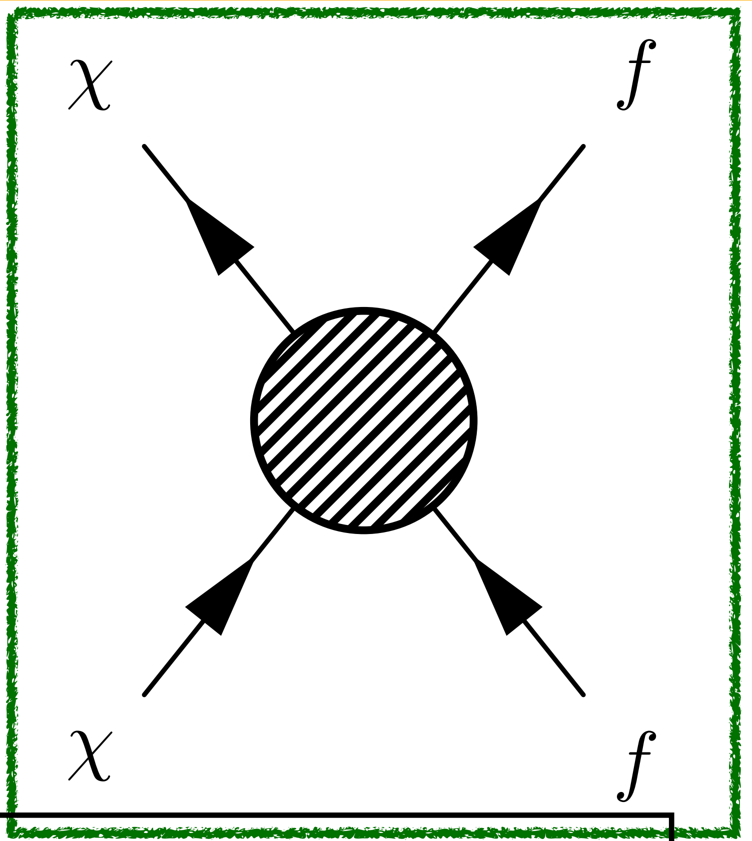
Ultralight bosonic DM behaves as a coherent field, let's take $m_{\rm DM} \approx 10^{-22}$ eV

De-Broglie wavelength $\lambda_{\rm dB} = \dfrac{2\pi}{m_{\rm DM} v} \approx 0.4\ \mathrm{kpc} \left(\dfrac{10^{-22}\mathrm{eV}}{m_{\rm DM}}\right)$

We only know the density, therefore the mass of the DM candidates can have a large range

Standard Model in the Early Universe





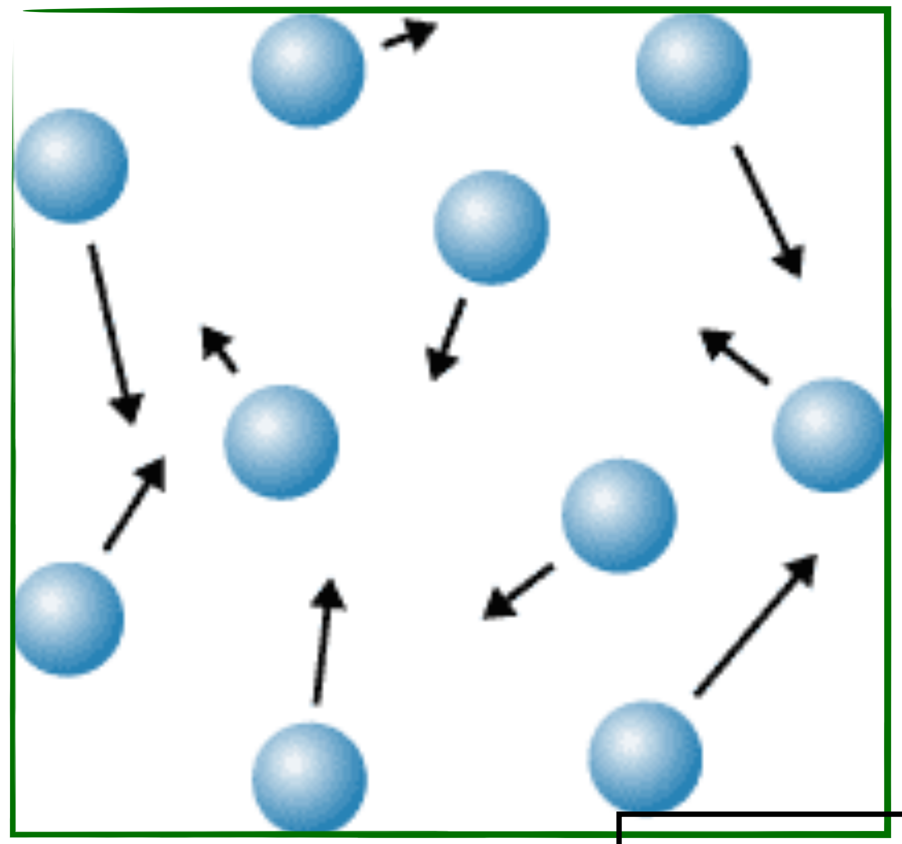
$$e^- \; \gamma \to e^* \to e^- \; \gamma \,.$$

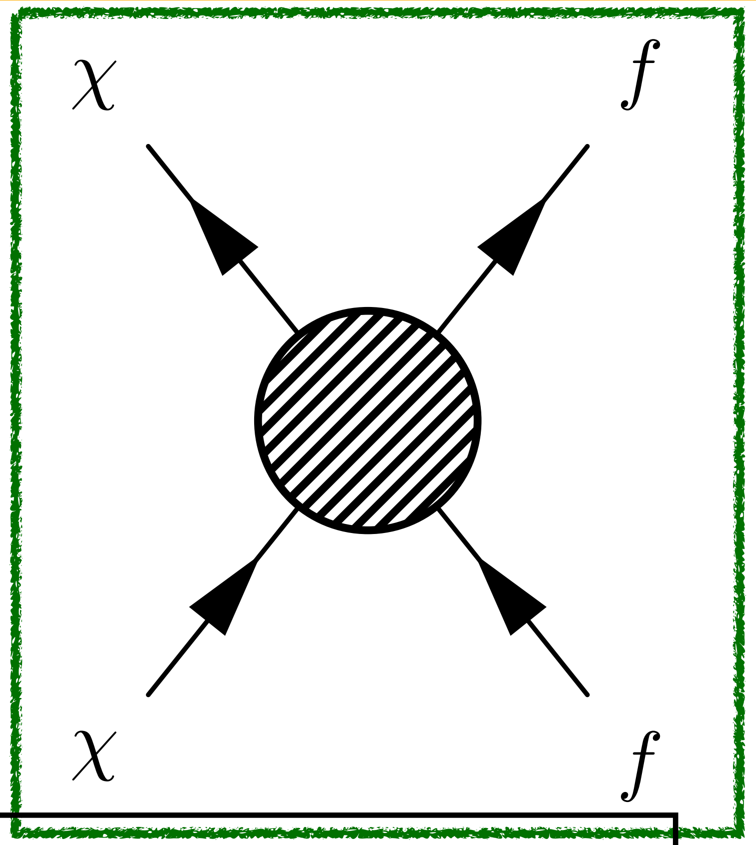
DM in **kinetic and chemical Equilibrium** with Standard Model particle bath

$$\left. f\bar{f} \to \chi\bar{\chi}, \chi\bar{\chi} \to f\bar{f} \right\} \longrightarrow \text{At high temperatures the reaction rates are equal}$$

As the Universe expands and cools, the interaction rate falls below Hubble expansion, particles fall out of equilibrium

Standard Model in the Early Universe





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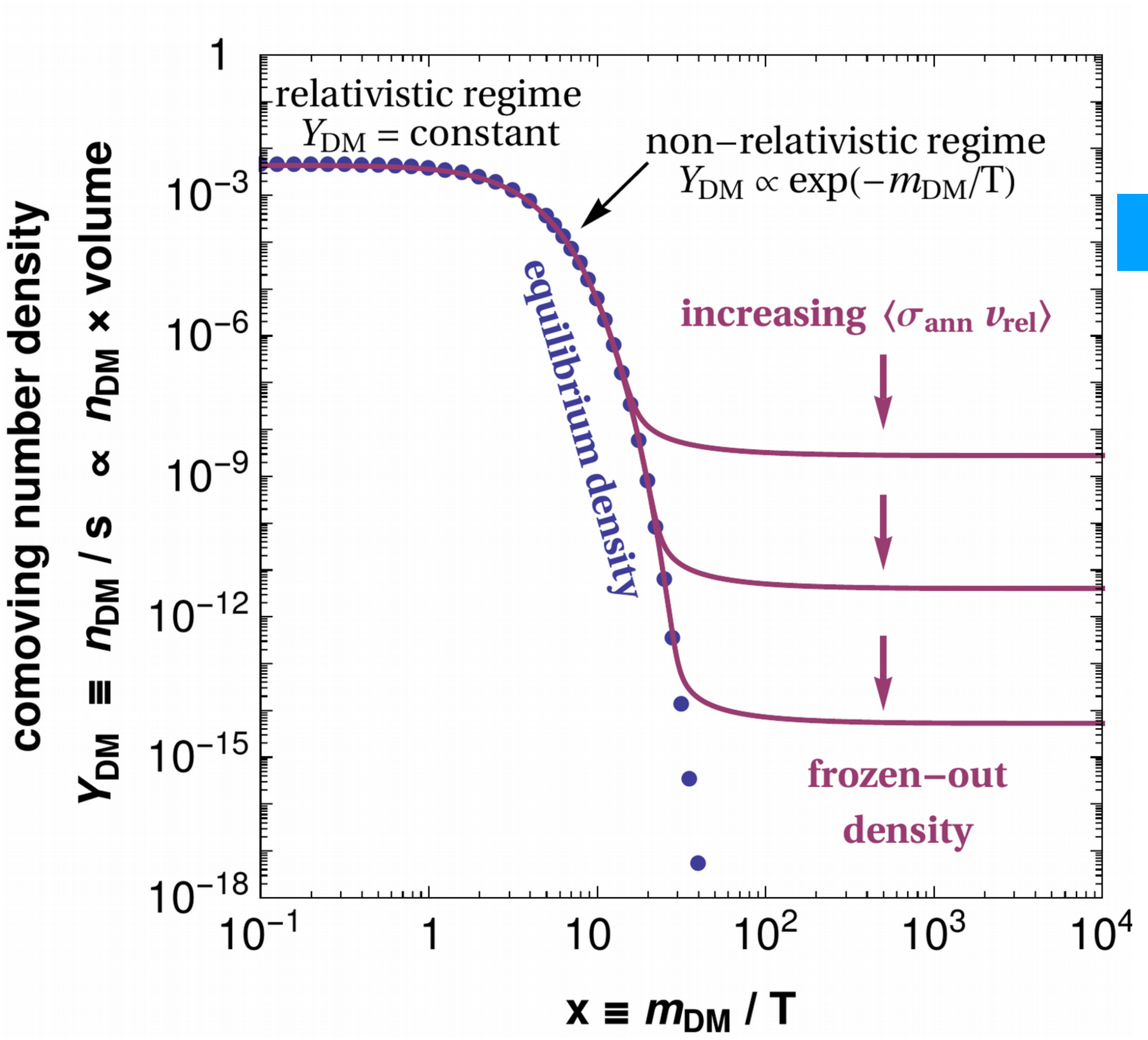

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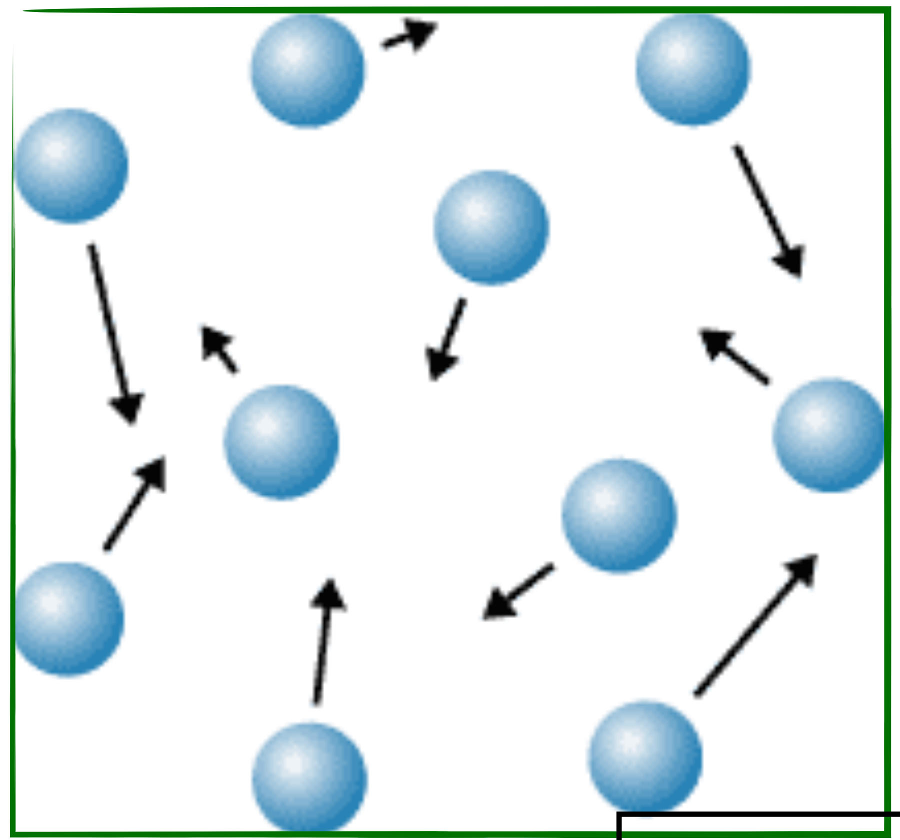
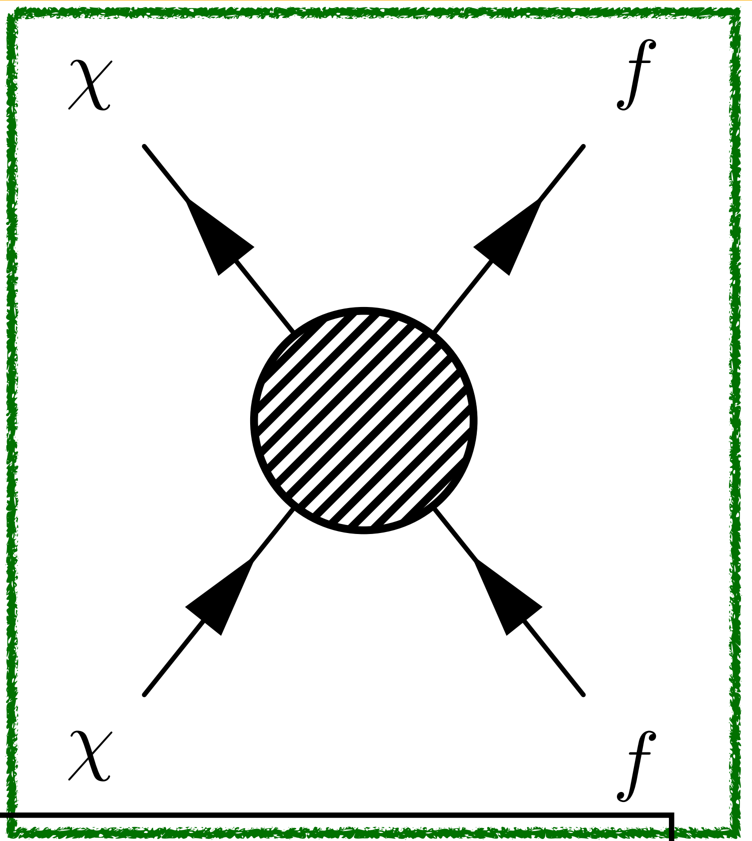
$$\underbrace{\frac{dn}{dt}}_{\text{Time Evolution}} + \underbrace{3Hn}_{\text{Hubble Friction}} = -\underbrace{\langle\sigma v\rangle}_{\text{Velocity Averaged Cross Section}} \left(n^2 - \underbrace{n_{eq}^2}_{\text{Equilibrium number density}}\right)$$

$$\boxed{\Omega_\chi h^2 \approx 0.12 \, \frac{x_{dec}}{23} \, \frac{\sqrt{g_{eff}}}{10} \, \frac{1.7 \cdot 10^{-9}\, \text{GeV}^{-2}}{\langle\sigma_{\chi\chi}\, v\rangle}}$$

Relic Density of dark matter.
The larger the annihilation cross section, the smaller the relic.

Standard Model in the Early Universe





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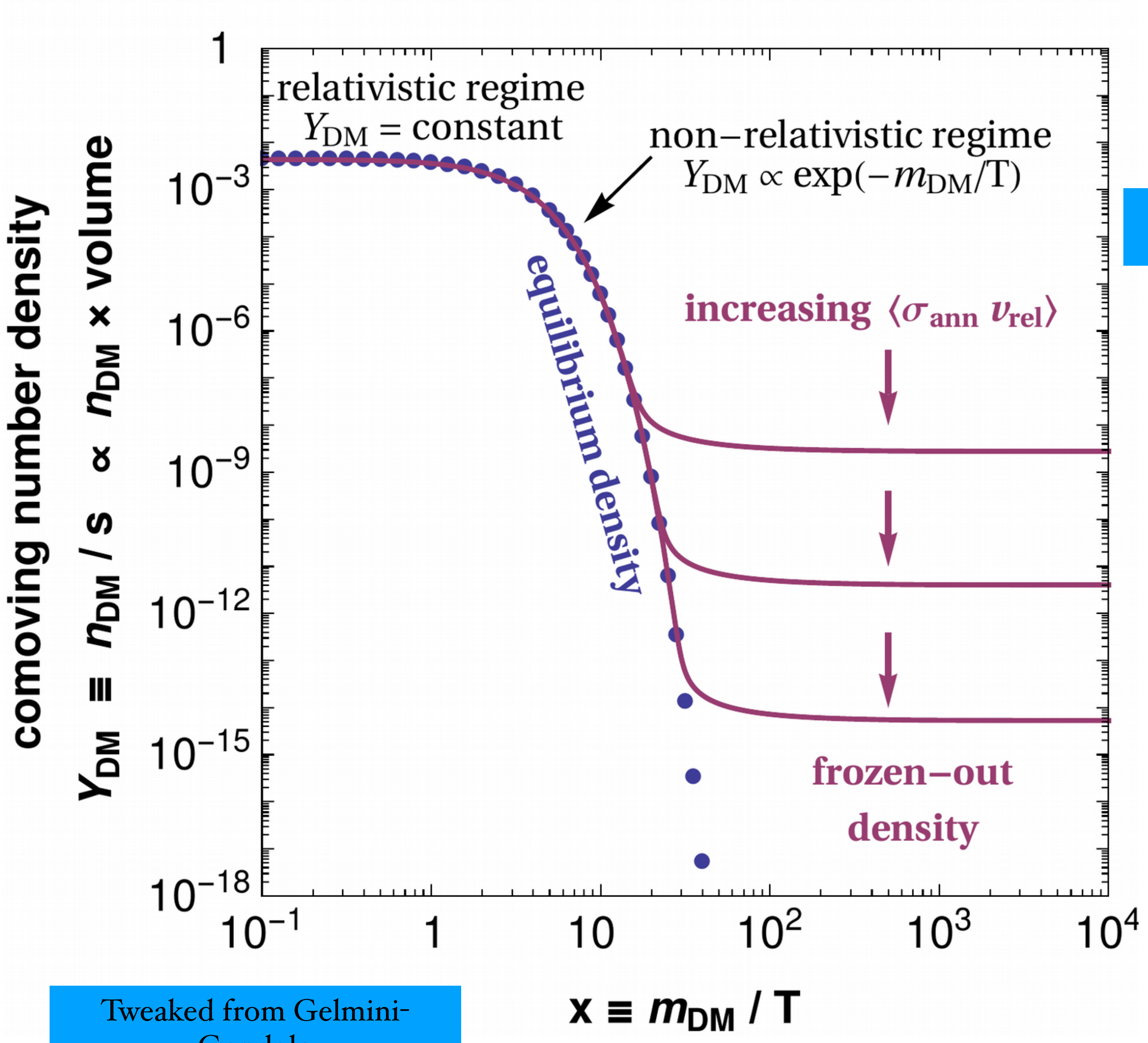
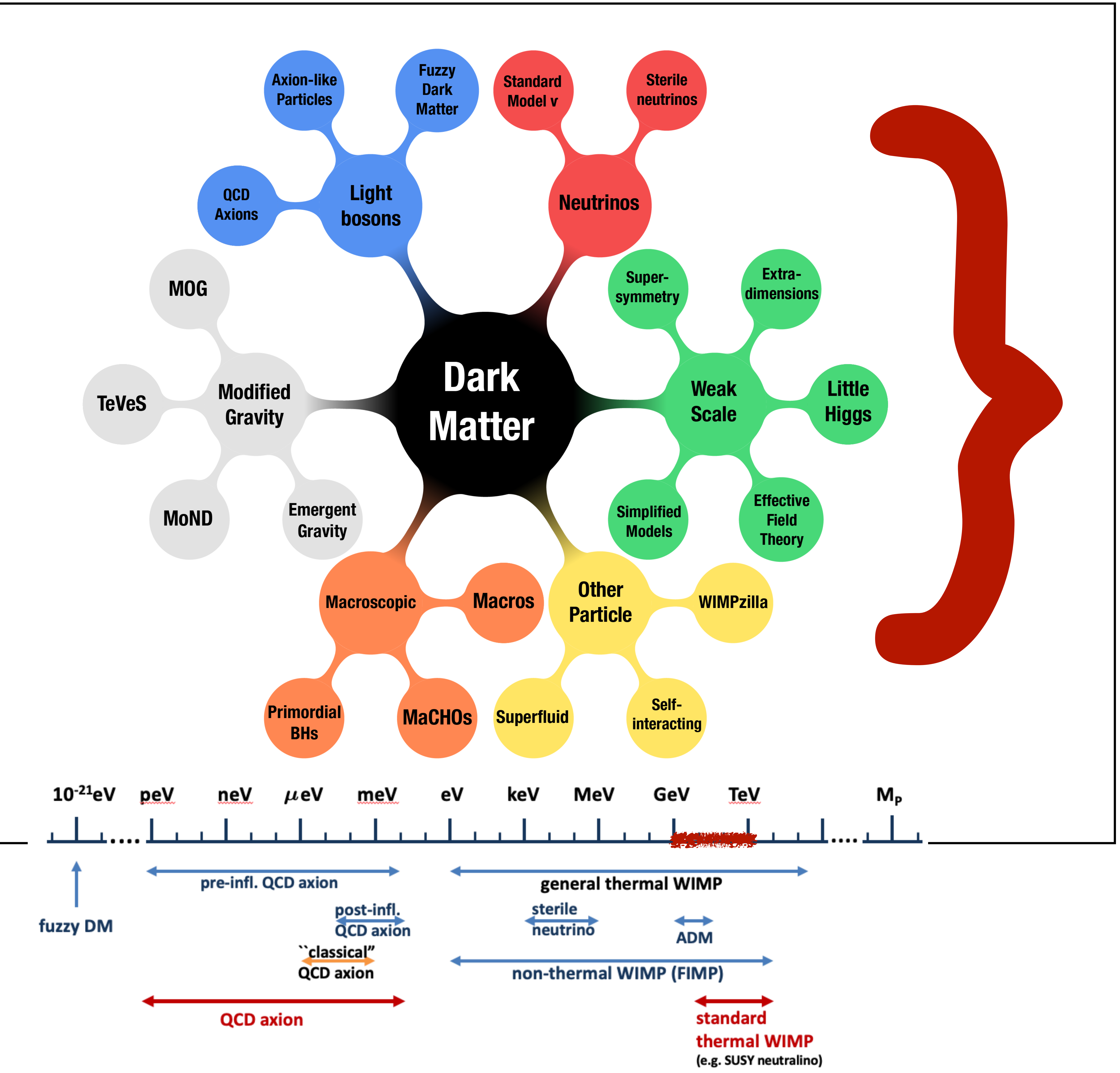
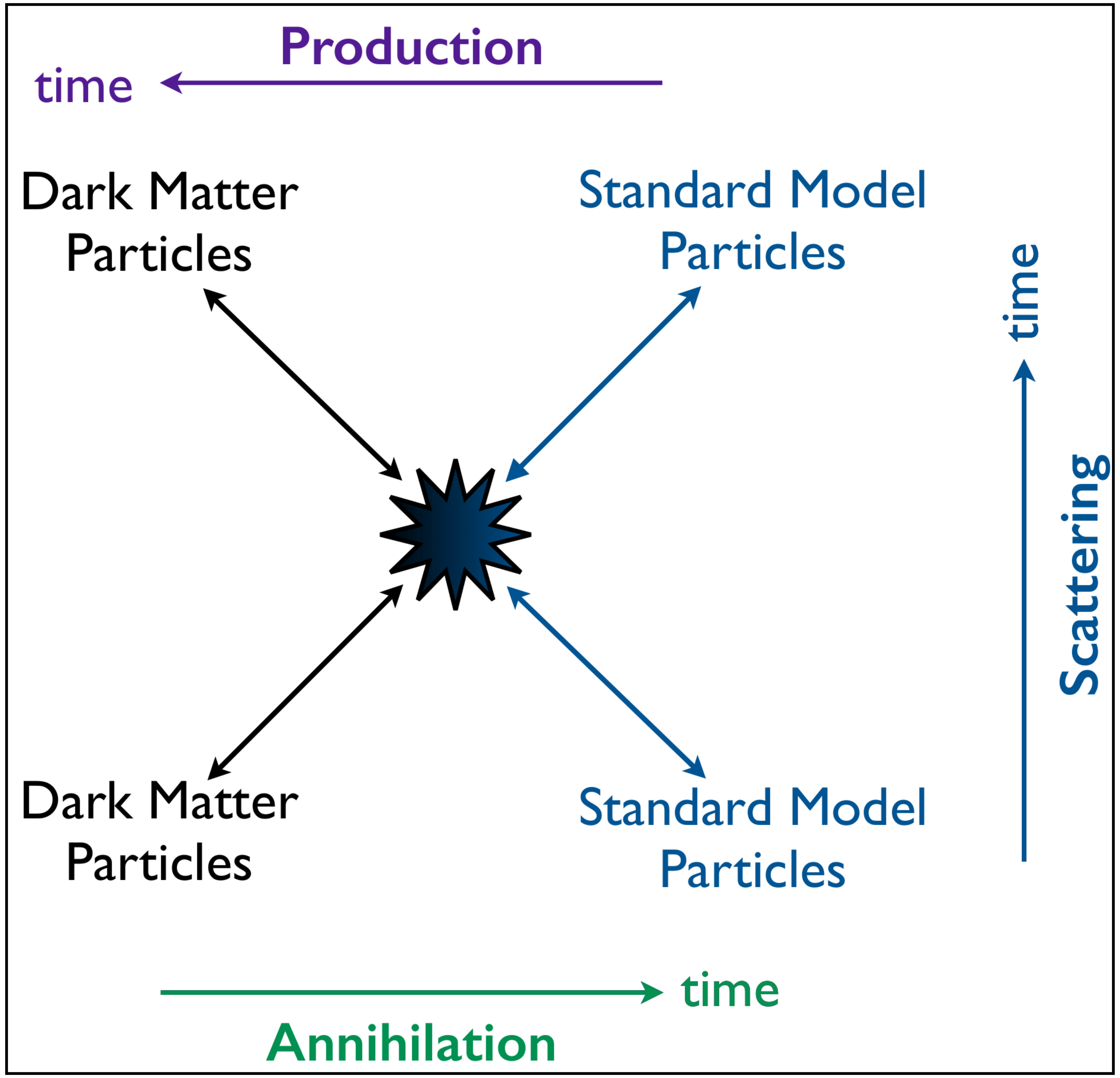


Tweaked from Gelmini-Gondolo

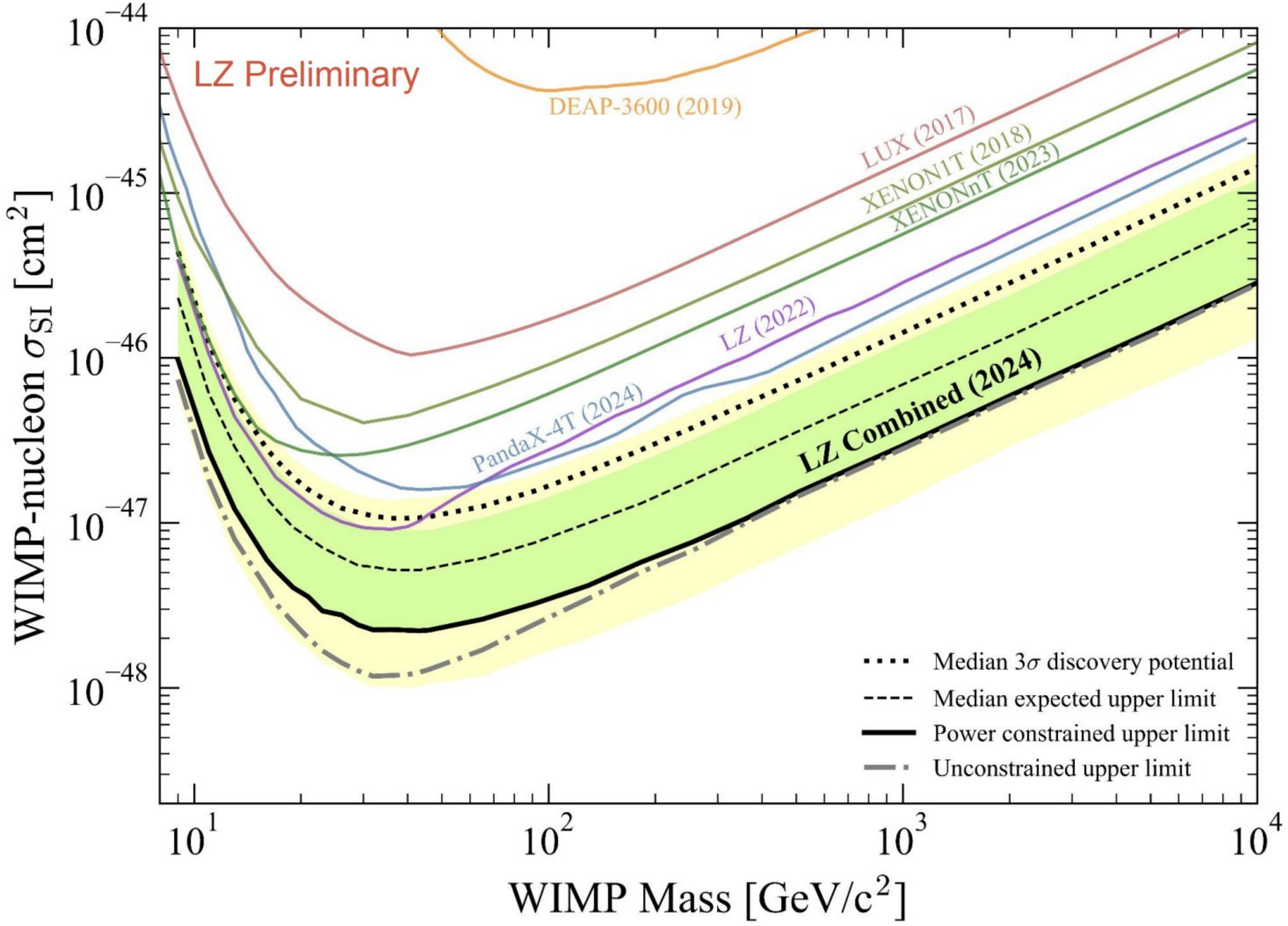
Particle of GeV-few TeV mass with weak scale couplings !!!
New Physics !!!!!!
Weakly Interacting Massive Particle (WIMP) Miracle !!!!!!!!!!

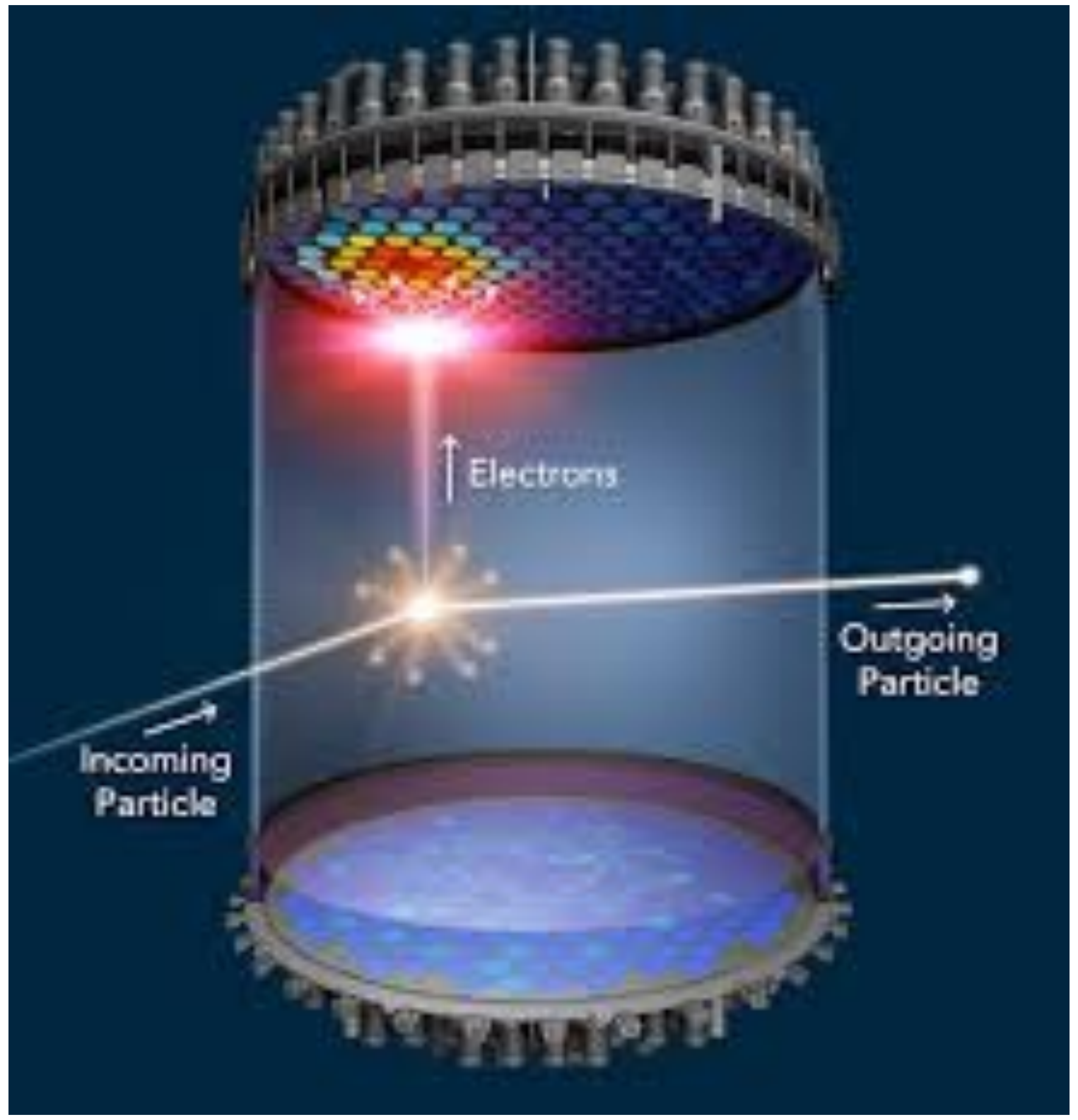
Dark Matter Detection





Dark Matter Direct Detection





Source: KIPAC

[Submitted on 15 Jul 2019 (v1), last revised 18 Feb 2020 (this version, v5)]

Death and Serious Injury by Dark Matter

Jagjit Singh Sidhu, Robert J Scherrer, Glenn Starkman

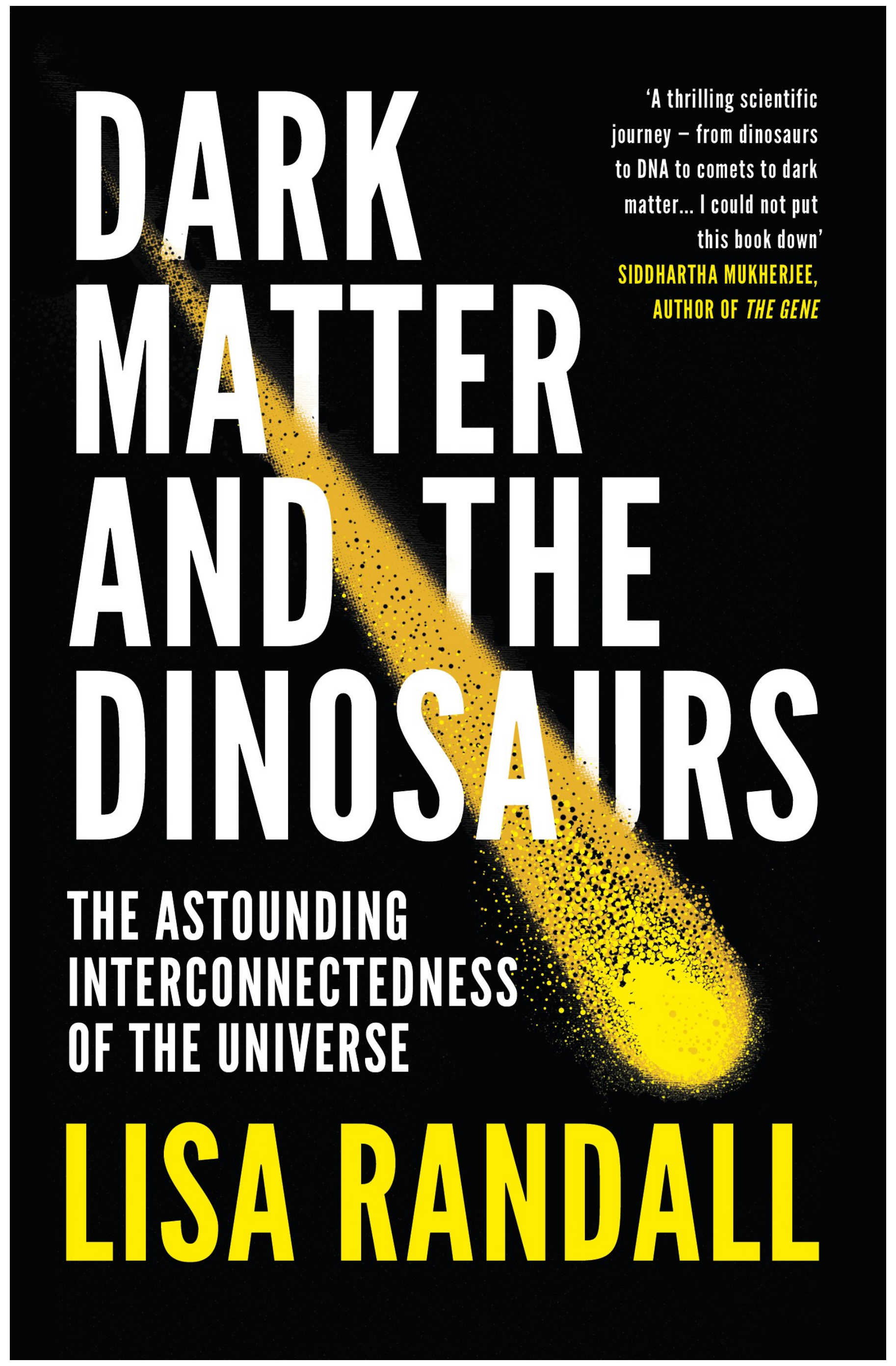
Macroscopic dark matter refers to a variety of dark matter candidates that would be expected to (elastically) scatter off of ordinary matter with a large geometric cross-section. A wide range of macro masses M_X and cross-sections σ_X remain unprobed. We show that over a wide region within the unexplored parameter space, collisions of a macro with a human body would result in serious injury or death. We use the absence of such unexplained impacts with a well-monitored subset of the human population to exclude a region bounded by $\sigma_X \geq 10^{-8} - 10^{-7}$ cm^2 and $M_X < 50$ kg. Our results open a new window on dark matter: the human body as a dark matter detector.

Dark Matter as a Trigger for Periodic Comet Impacts

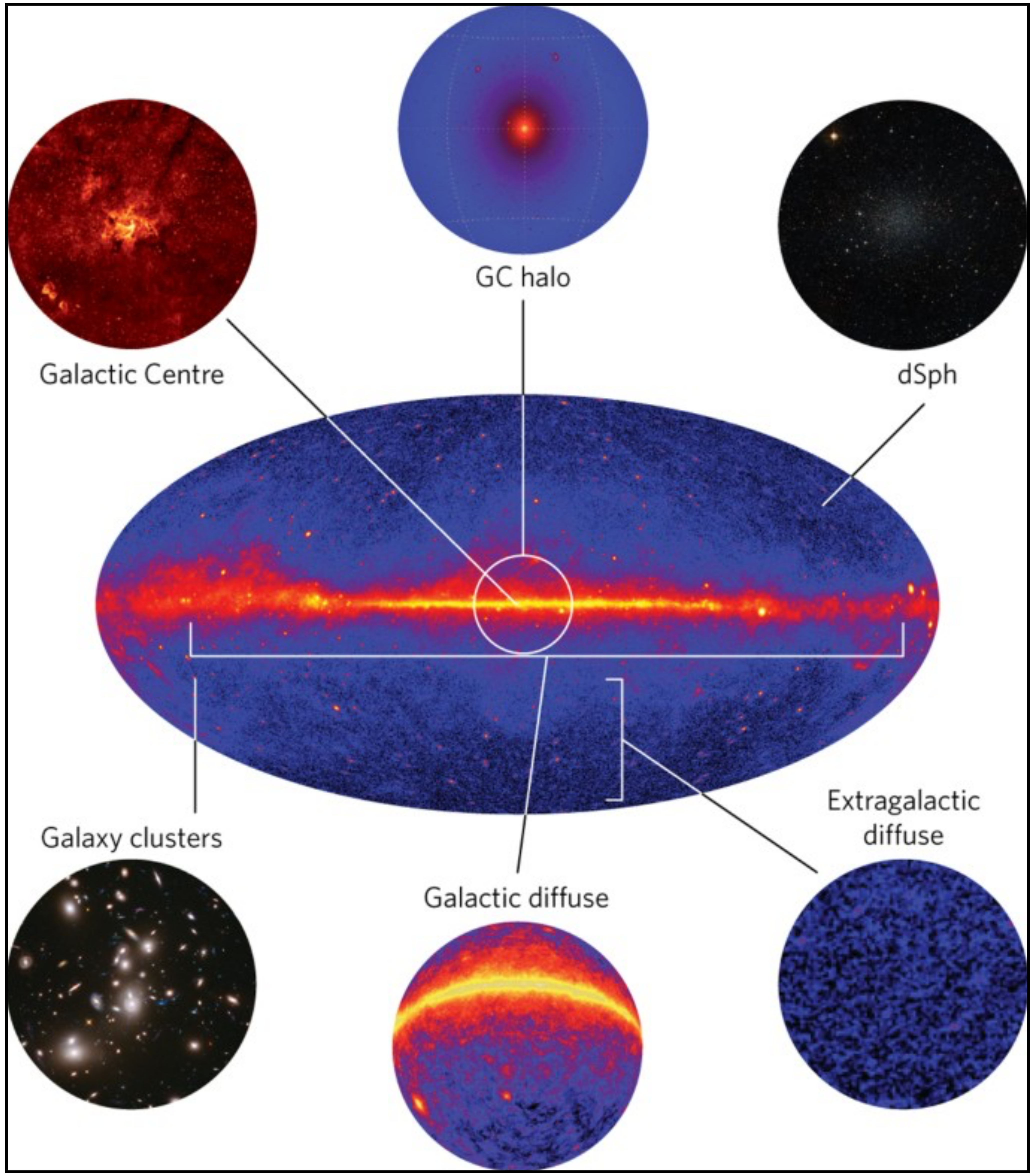
Lisa Randall, Matthew Reece

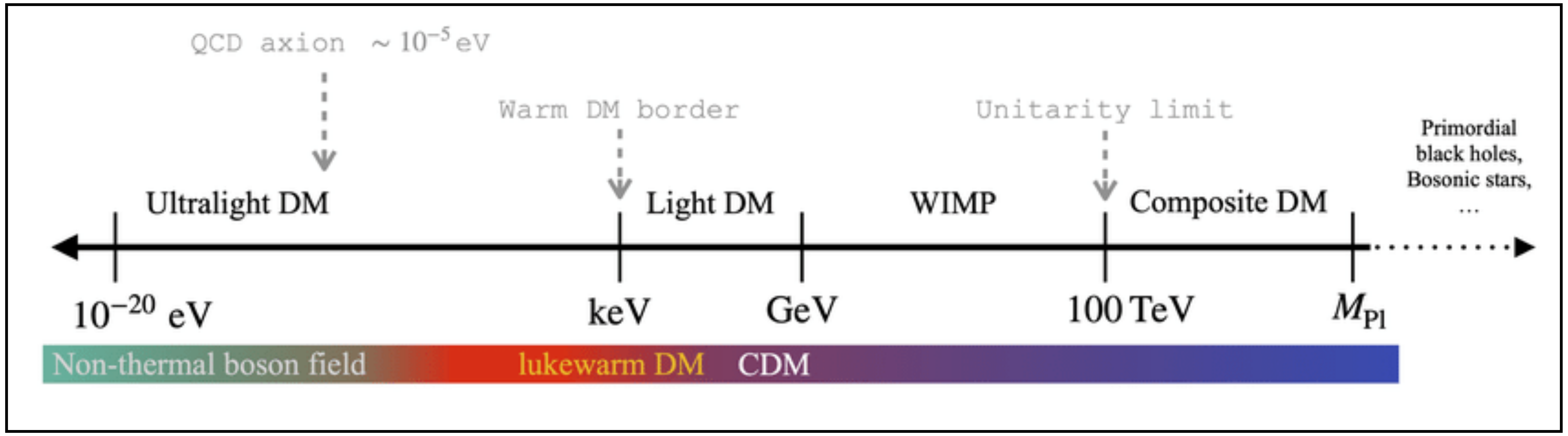
ew PDF

Although statistical evidence is not overwhelming, possible support for an approximately 35 million year periodicity in the crater record on Earth could indicate a nonrandom underlying enhancement of meteorite impacts at regular intervals. A proposed explanation in terms of tidal effects on Oort cloud comet perturbations as the Solar System passes through the galactic midplane is hampered by lack of an underlying cause for sufficiently enhanced gravitational effects over a sufficiently short time interval and by the time frame between such possible enhancements. We show that a smooth dark disk in the galactic midplane would address both these issues and create a periodic enhancement of the sort that has potentially been observed. Such a disk is motivated by a novel dark matter component with dissipative cooling that we considered in earlier work. We show how to evaluate the statistical evidence for periodicity by input of appropriate measured priors from the galactic model, justifying or ruling out periodic cratering with more confidence than by evaluating the data without an underlying model. We find that, marginalizing over astrophysical

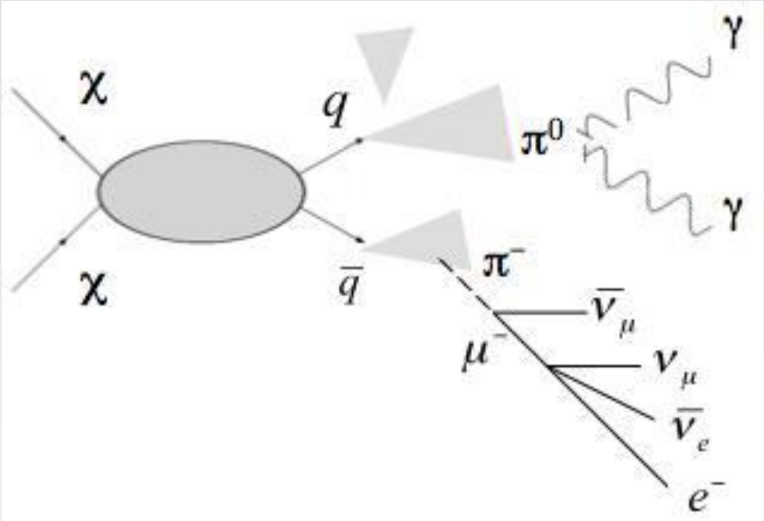


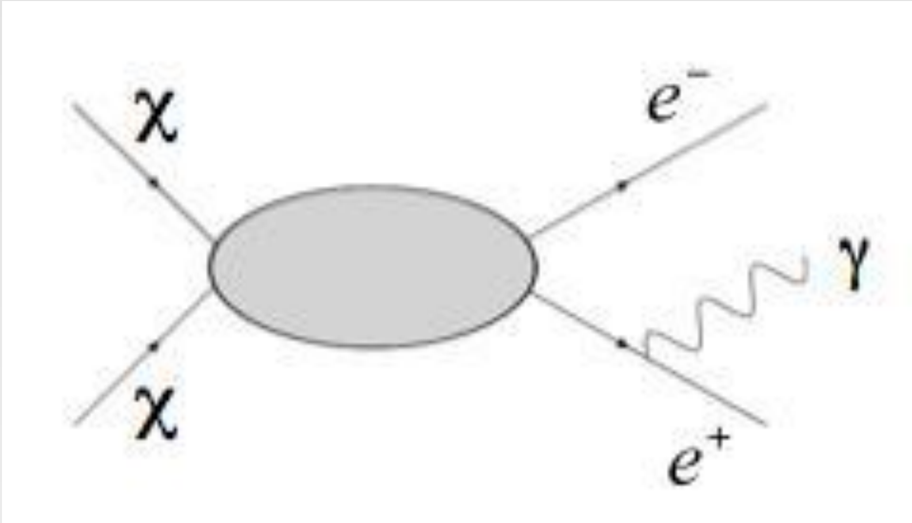
Dark Matter Indirect Detection





- WIMPs are stable particles that can annihilate each other

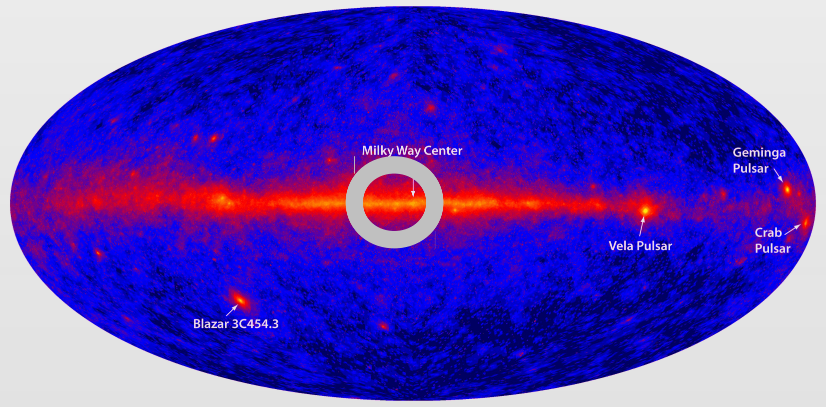




- As results of their annihilation, particles of the standard model will be produced : protons, electrons, neutrinos, **gamma-rays.**

Dark Matter Indirect Detection

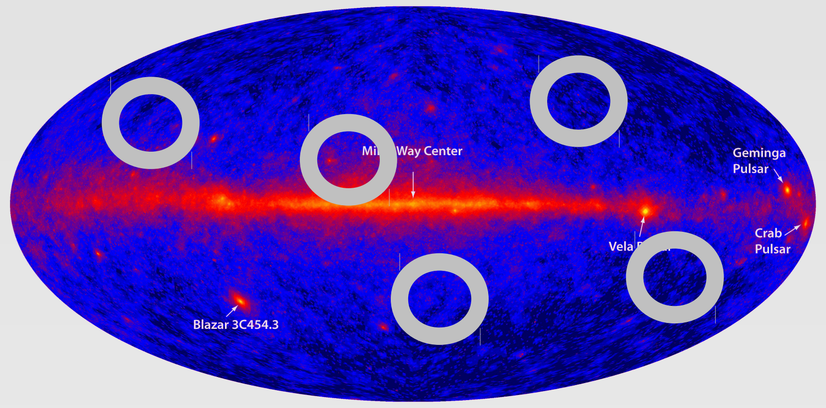
Galactic Centre



Pros: High DM density, highest expected signal rates

Cons: Large Uncertainties, many astrophysical backgrounds

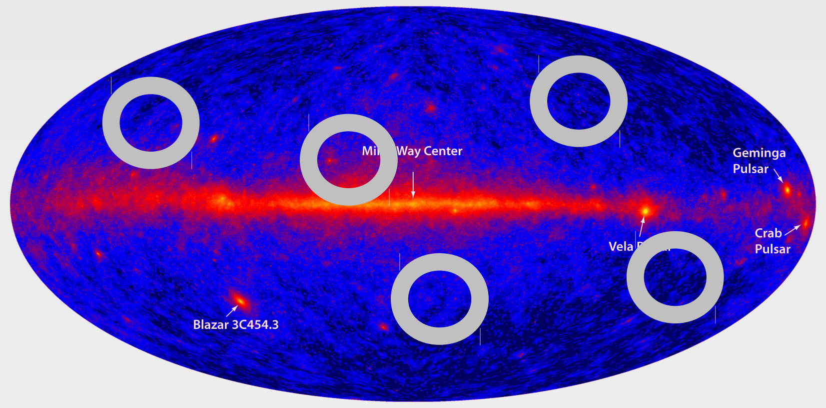
Dwarf galaxies



Pros: Large no. of independent objects, background free

Cons: Limited DM density

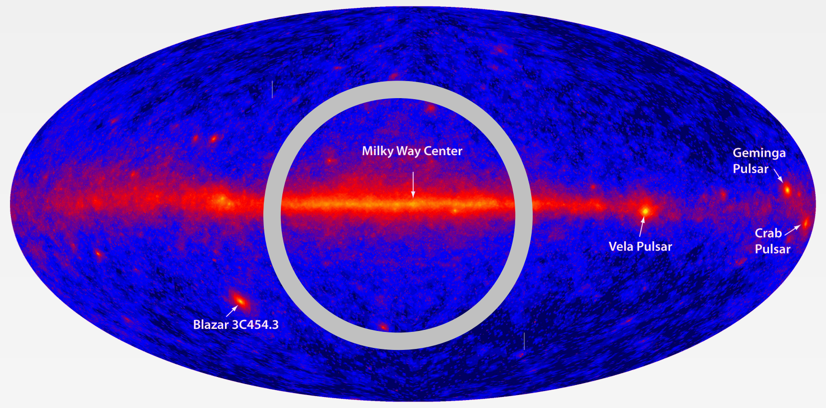
Galaxy Clusters



Pros: Large no. of independent sources, large amount of DM

Cons: Distance, Background

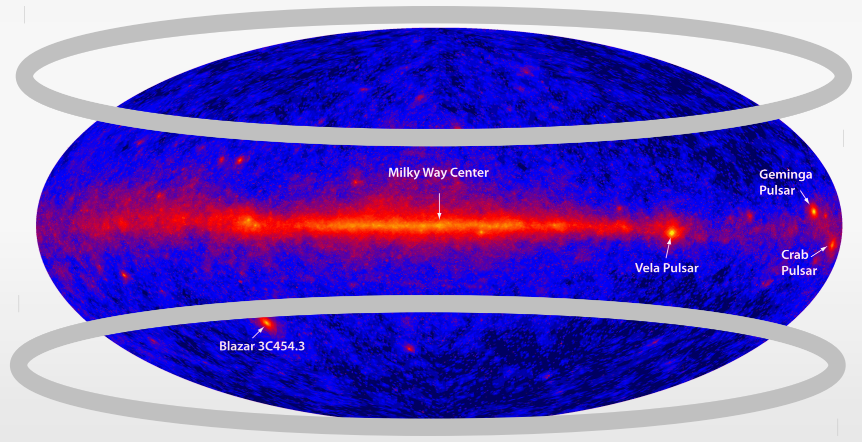
Galactic Halo



Pros: Large integration region, DM profile well understood

Cons: Background

Extragalactic



Pros: Large integration region

Cons: Background

Dark Matter Indirect Detection

Differential Intensity from a direction (particles per area, time, solid angle and energy)

$$\frac{dN_{\text{ann}}}{dA\,dt\,d\Omega\,dE} = \underbrace{\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_x}{dE}}_{\text{Particle Physics Input}}\frac{1}{4\pi}\underbrace{J_{\text{ann}}(\psi)}_{\text{Astrophysical "J" factor}}$$

Annihilation

Particle Physics Input

Astrophysical "J" factor

$$\frac{dN_{\text{dec}}}{dA\,dt\,d\Omega\,dE} = \frac{1}{m_\chi\,\tau}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\text{dec}}(\psi)$$

decay

Dark Matter Indirect Detection

Relic Considerations

$$\Omega_\chi h^2 \sim \frac{3\times10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_A v\rangle} \longrightarrow 3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1} \longrightarrow$$ Satisfies the observed relic

Dark Matter distribution from numerical structure formation simulations

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

$r_s \sim 20$ kpc

$\rho_\odot = 0.3\,\mathrm{GeV/cm^3}$

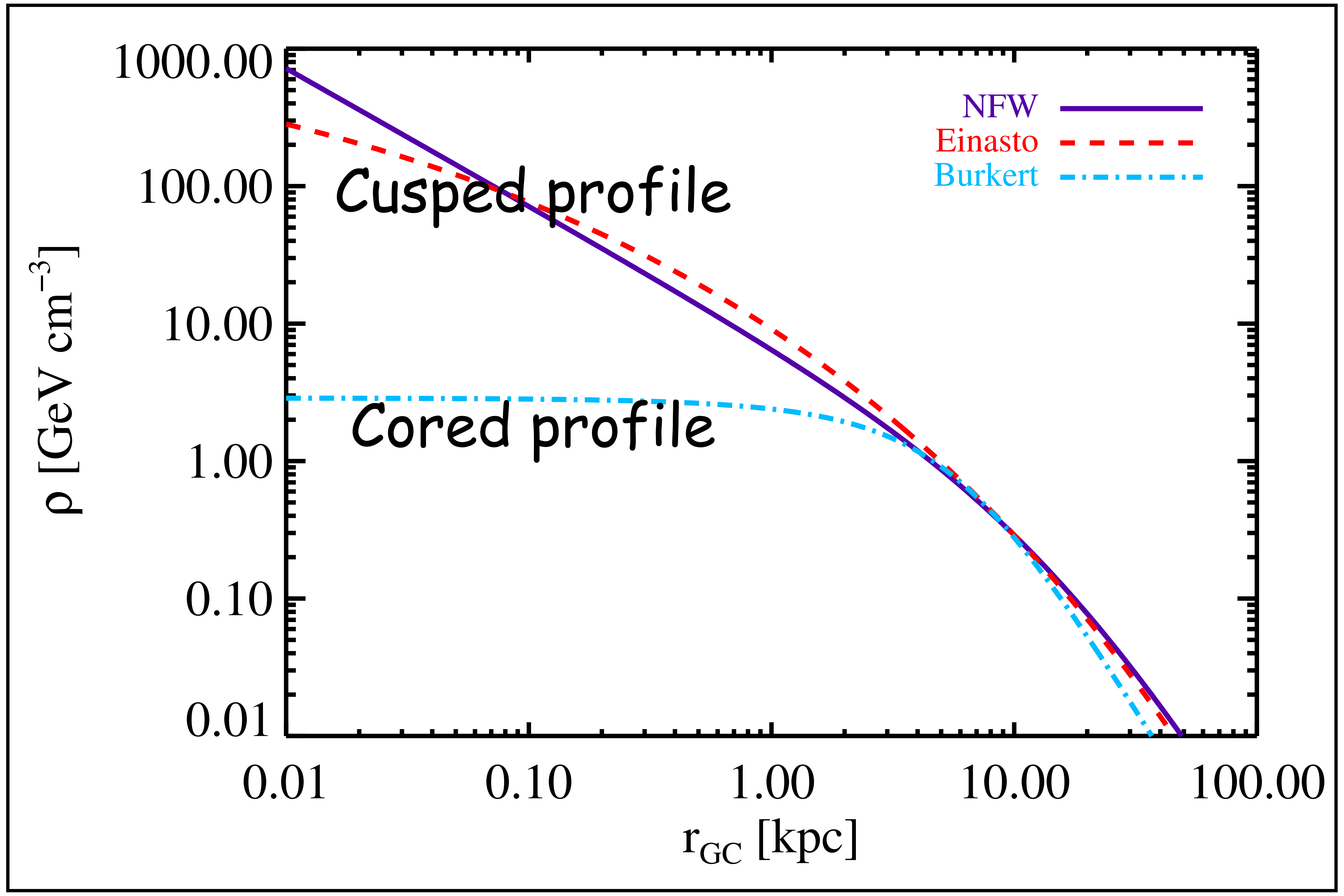
$$\rho_{\mathrm{GNFW}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma\left[1+\left(\frac{r}{r_s}\right)\right]^{3-\gamma}}$$

An updated simulation, Salucci

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

$$\rho_{\mathrm{Ein}}(r) = \rho_0 \exp\left\{-\left(\frac{2}{a}\right)\left[\left(\frac{r}{r_s}\right)^a - 1\right]\right\}$$

$$\rho_{\mathrm{Burk}}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\frac{r^2}{r_s^2}\right)}$$



Dark Matter Indirect Detection

Astrophysical J-factor

$$r(l,\psi) = \sqrt{r_\odot^2 + l^2 - 2r_\odot l\cos(\psi)}$$

$$J_{\rm ann}(\psi) = \int_{\rm los} \rho^2(\psi,l)dl$$

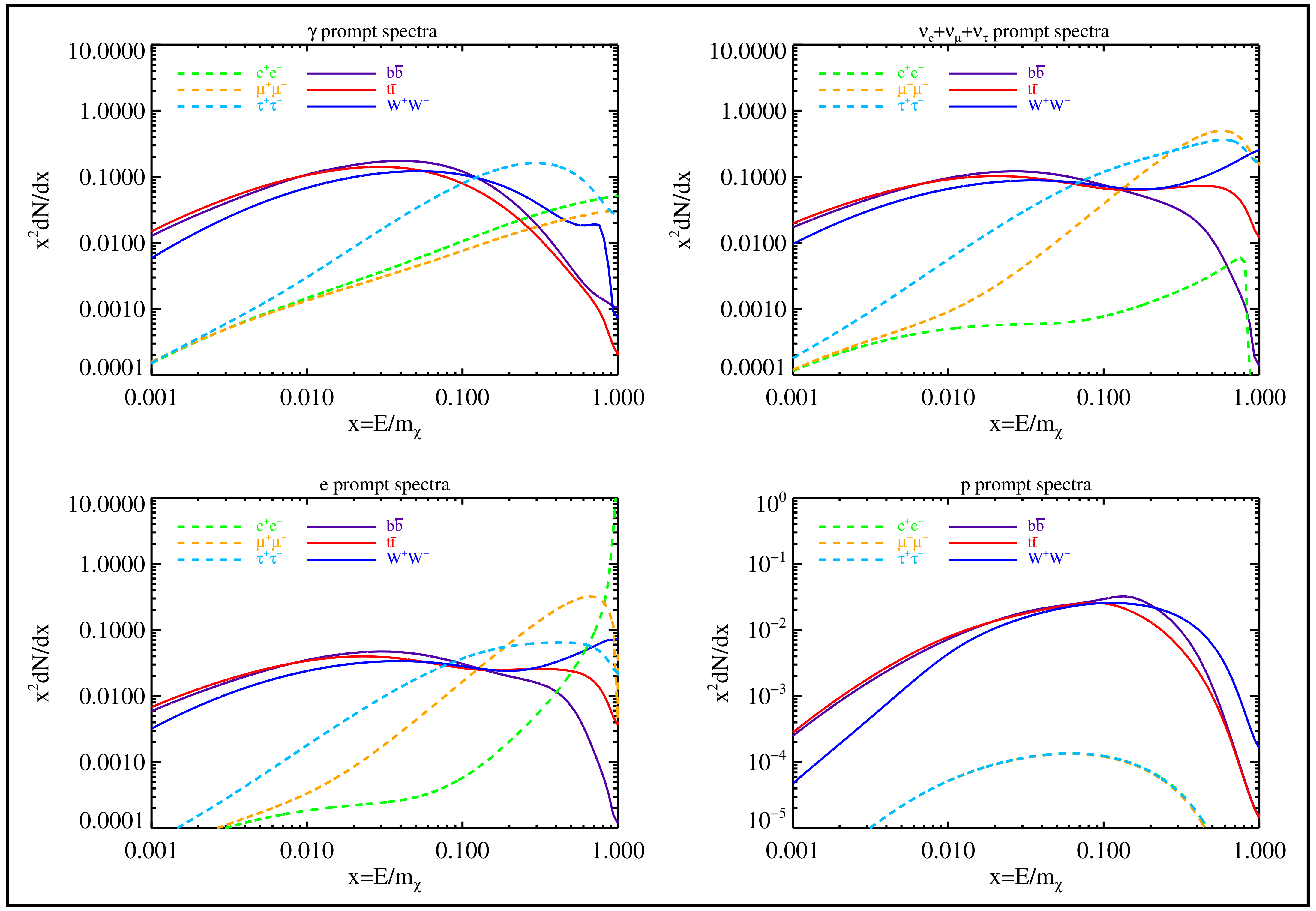
$$J_{\rm dec}(\psi) = \int_{\rm los} \rho(\psi,l)dl$$

Line of sight integral of DM column density

Target	$\log_{10}(J_{\rm ann})$
Galactic Center	21.5
Dwarf galaxies (best)	19
Galaxy clusters (best)	18

Particle Spectra

$$\frac{dN_x}{dE} = \sum_f B_f \frac{dN_{x,f}}{dE}$$



$m_\chi = 500$ GeV

PPPC4DMID

Dark Matter Indirect Detection at CTAO

Signal and Background

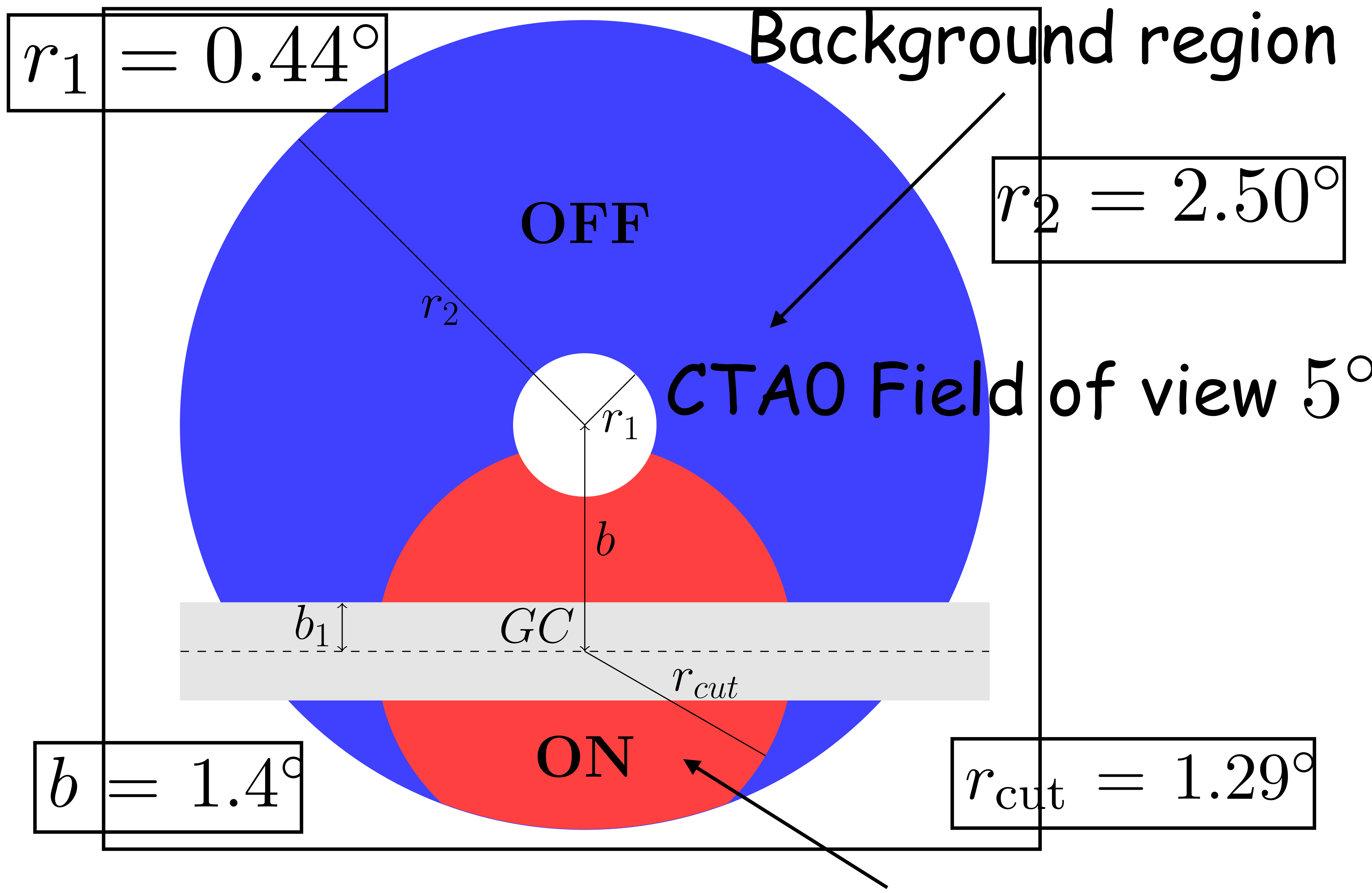
Background primarily cosmic ray electrons (CREs)

$$N_{\rm ann} = t_{\rm obs}\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}N_{\gamma,{\rm obs}}\int_{\Delta\Omega} J_{\rm ann}(\psi)d\Omega$$

$$\Delta\Omega_{\rm ON} = 9.9\times\ 10^{-4}\ {\rm sr}$$
$$\Delta\Omega_{\rm OFF} = 4.0\times 10^{-3}\ {\rm sr}$$

$$N_{\gamma,{\rm obs}} = \int_{\Delta E}\int_{-\infty}^{+\infty}\frac{dN_\gamma(\bar E)}{dE}A_{\rm eff}(\bar E)\frac{e^{-\frac{(E-\bar E)^2}{2\sigma^2}}}{\sqrt{2\pi\sigma^2}}d\bar E dE$$

$$N_{\rm bg} = t_{\rm obs}\Delta\Omega\int_{\Delta E}\int_{-\infty}^{+\infty}\frac{dN_{\rm CRE}(\bar E)}{dE\,dA\,dt\,d\Omega}A_{\rm eff}(\bar E)\frac{e^{-\frac{(E-\bar E)^2}{2\sigma^2}}}{\sqrt{2\pi\sigma^2}}d\bar E\,dE$$



Optimized parameters for Array B

For 200h of observation, assuming a DM mass 1 TeV, no. of signal events in the 30 GeV-1 TeV range

$N_{\rm ann,ON}\ \sim\ 2000$ $\quad$ $\alpha N_{\rm ann,OFF}\ \sim\ 620$ $\quad$ $N_{\rm bg,ON} = \alpha N_{\rm bg,OFF} \sim 1.5\times 10^6$

GC plane excluded within b1 < 0.3°, Negligible non-DM gamma rays

Pierre, Siegal-Gaskins, Scott, 2014

Rodd, Slatyer et al 2020

Also see Balazs et al, 2021, 2024,...

Snowmass , 2021

Dark Matter Indirect Detection at CTAO

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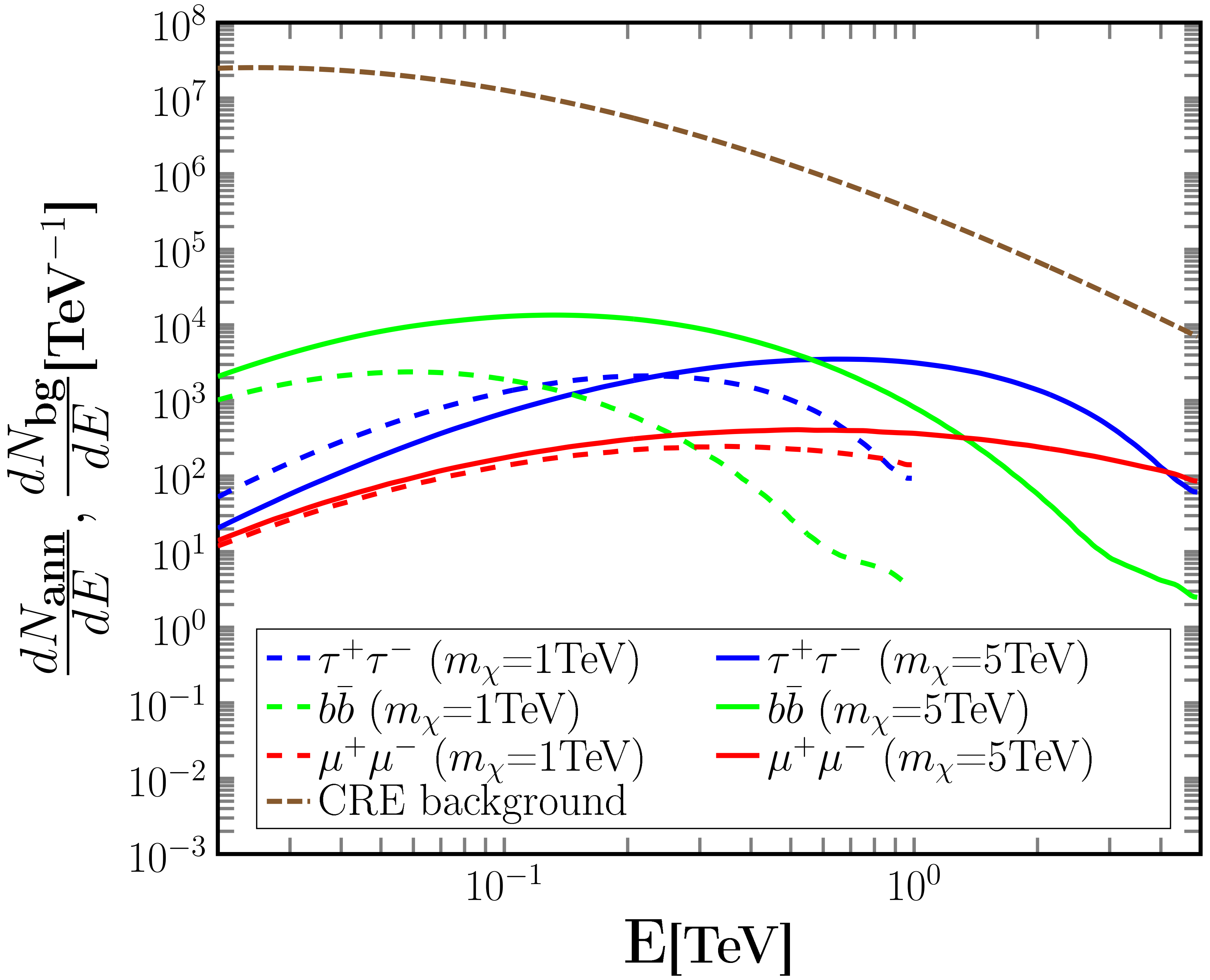
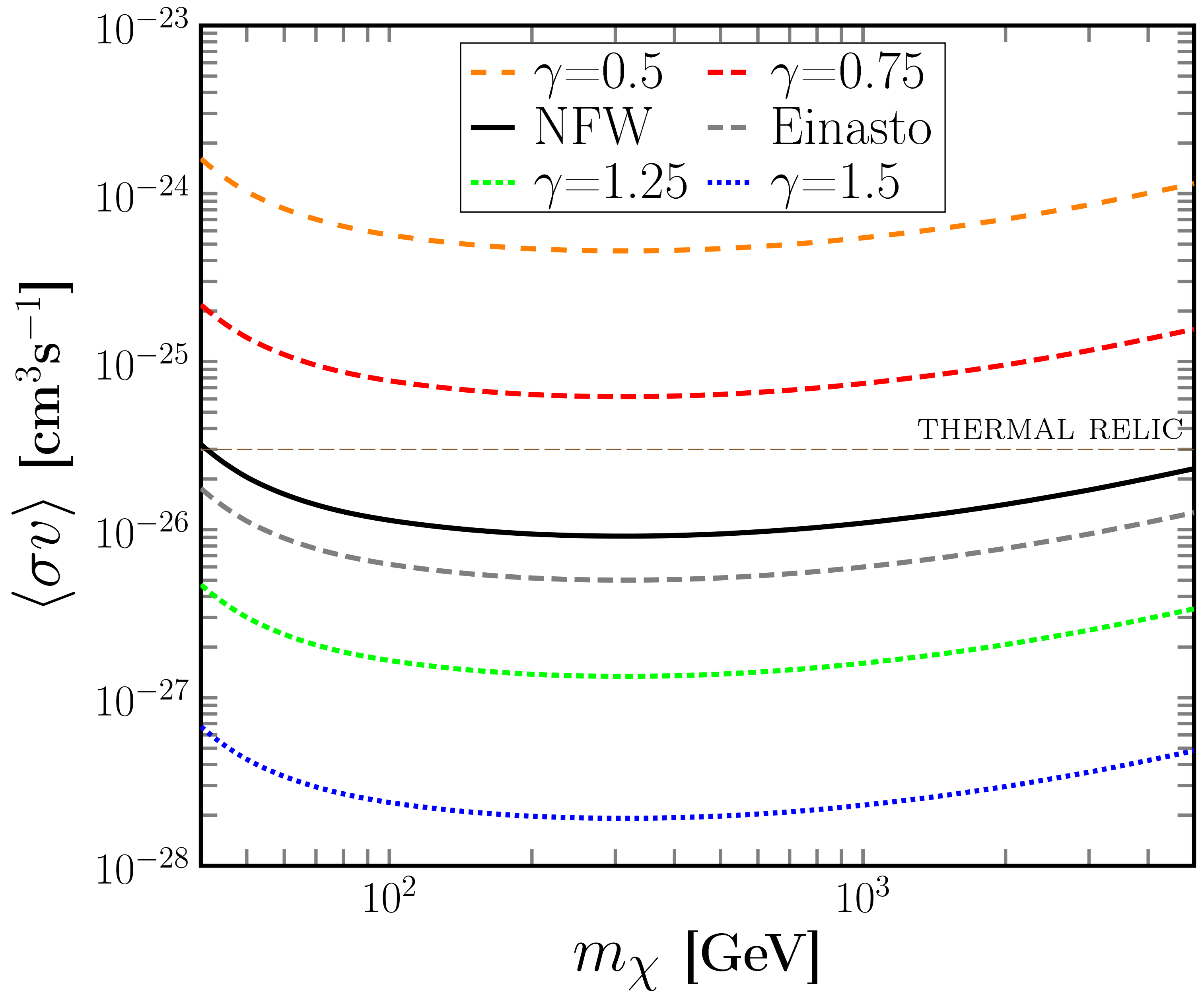
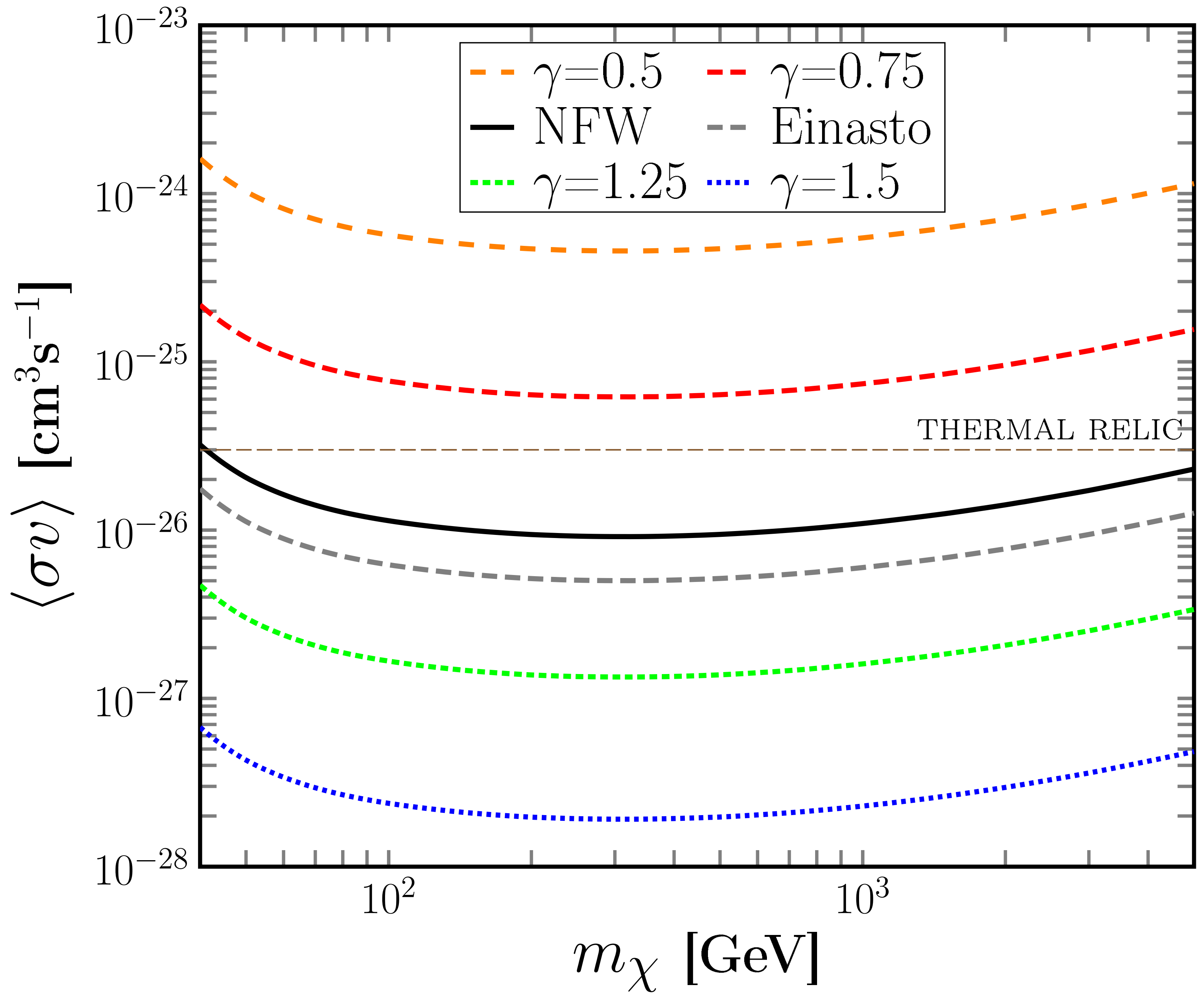


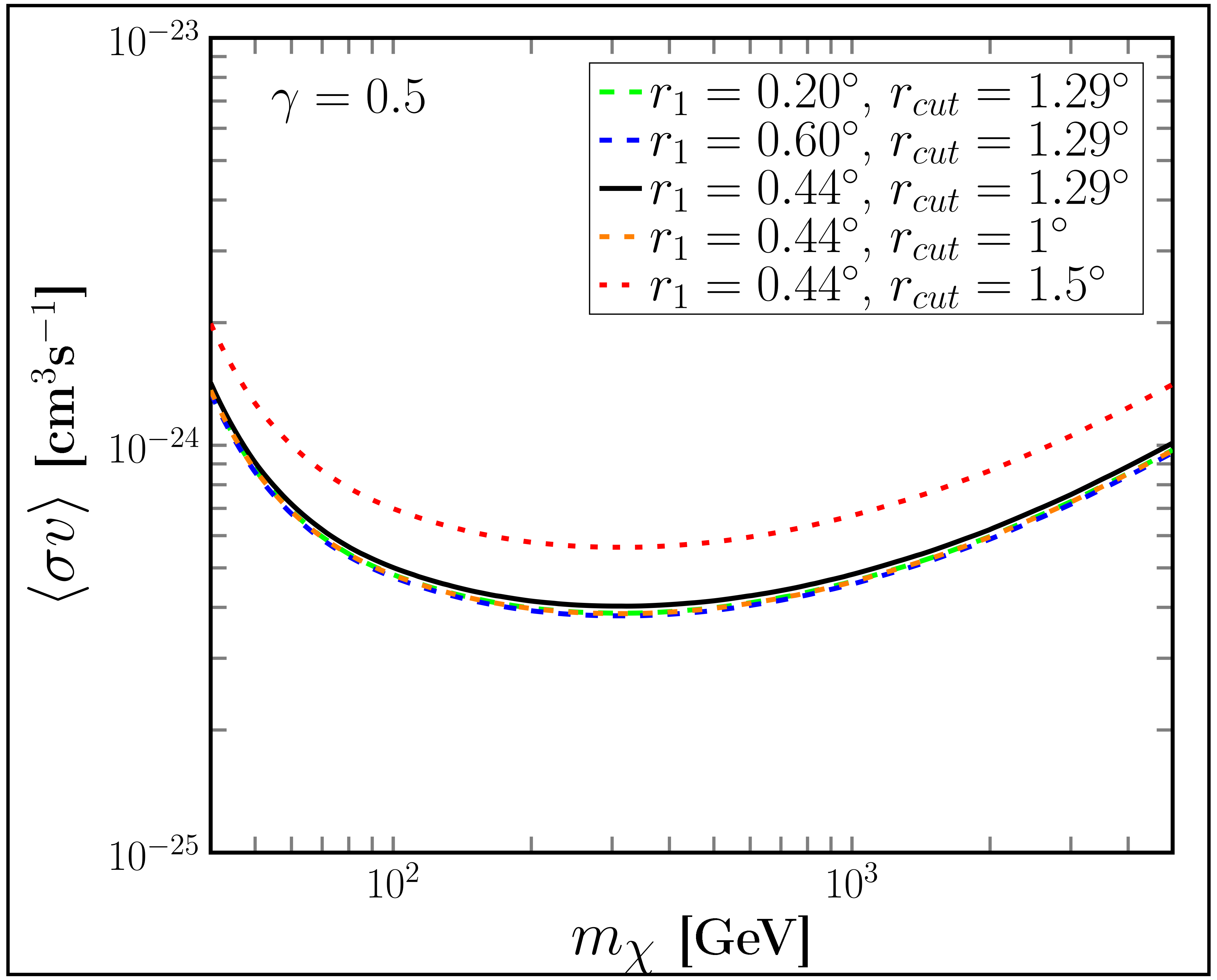


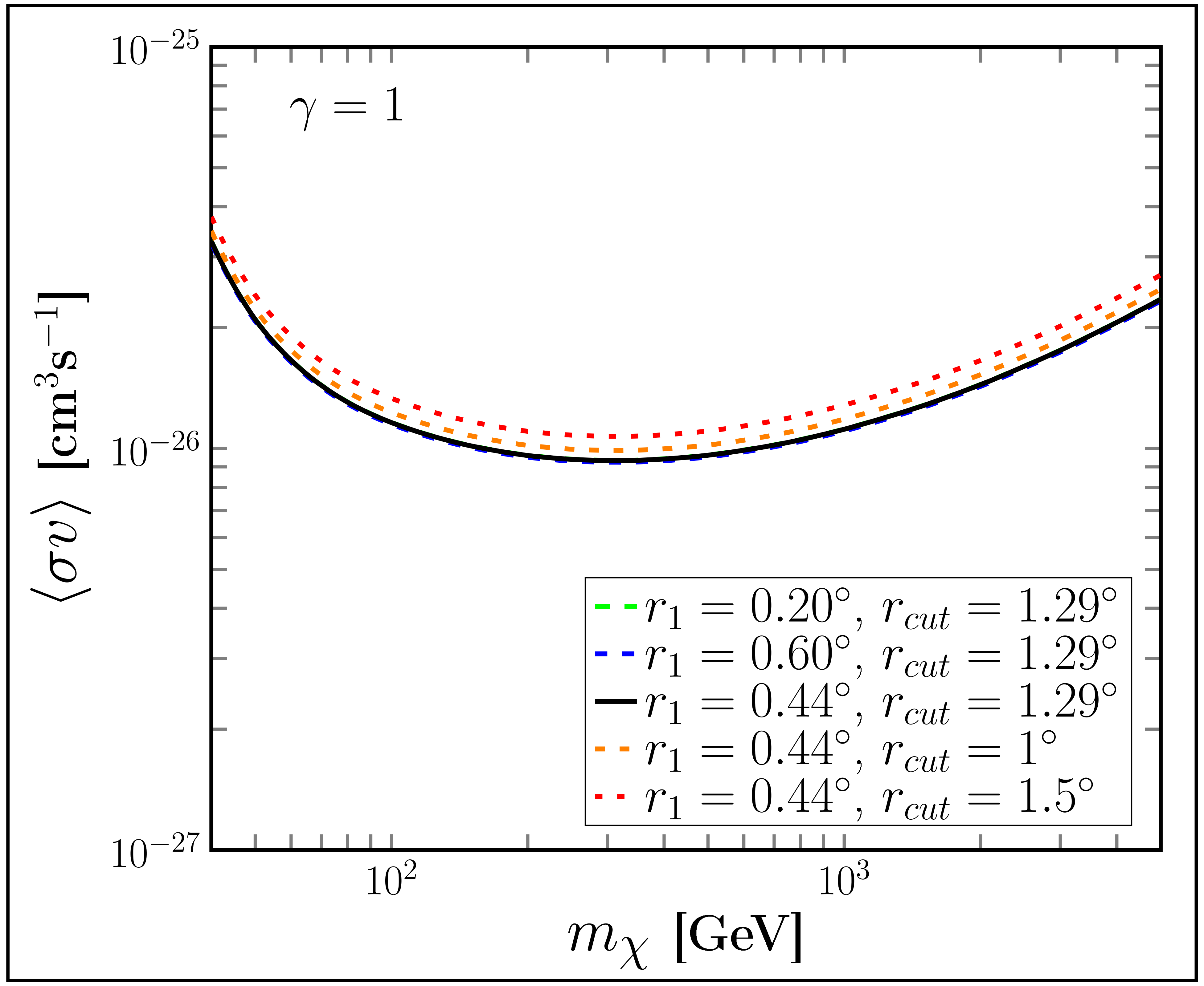


$$\rho_{\rm NFW}(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

$$\rho_\gamma(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)^\gamma\left[1+\left(\frac{r}{r_s}\right)\right]^{3-\gamma}}$$

Dark Matter at CTAO





Dark Matter Indirect Detection of Ultra-Heavy dark matter

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

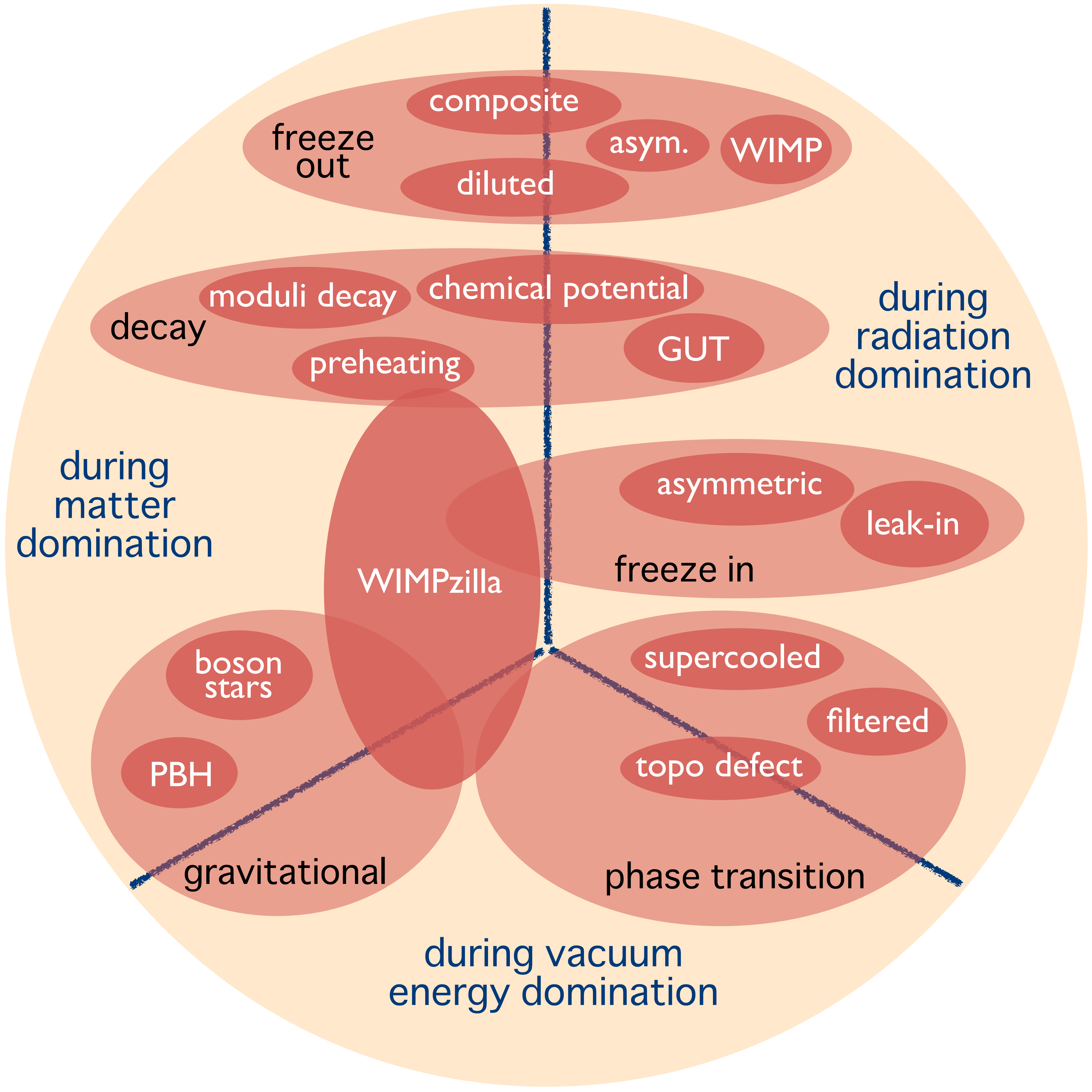
Snowmass2021 Cosmic Frontier White Paper:
Ultraheavy particle dark matter

$\boxed{m_\chi \gtrsim 10 \text{ TeV}}$ $\boxed{m_\chi \lesssim m_{\rm pl} \approx 10^{19} \text{ GeV}}$

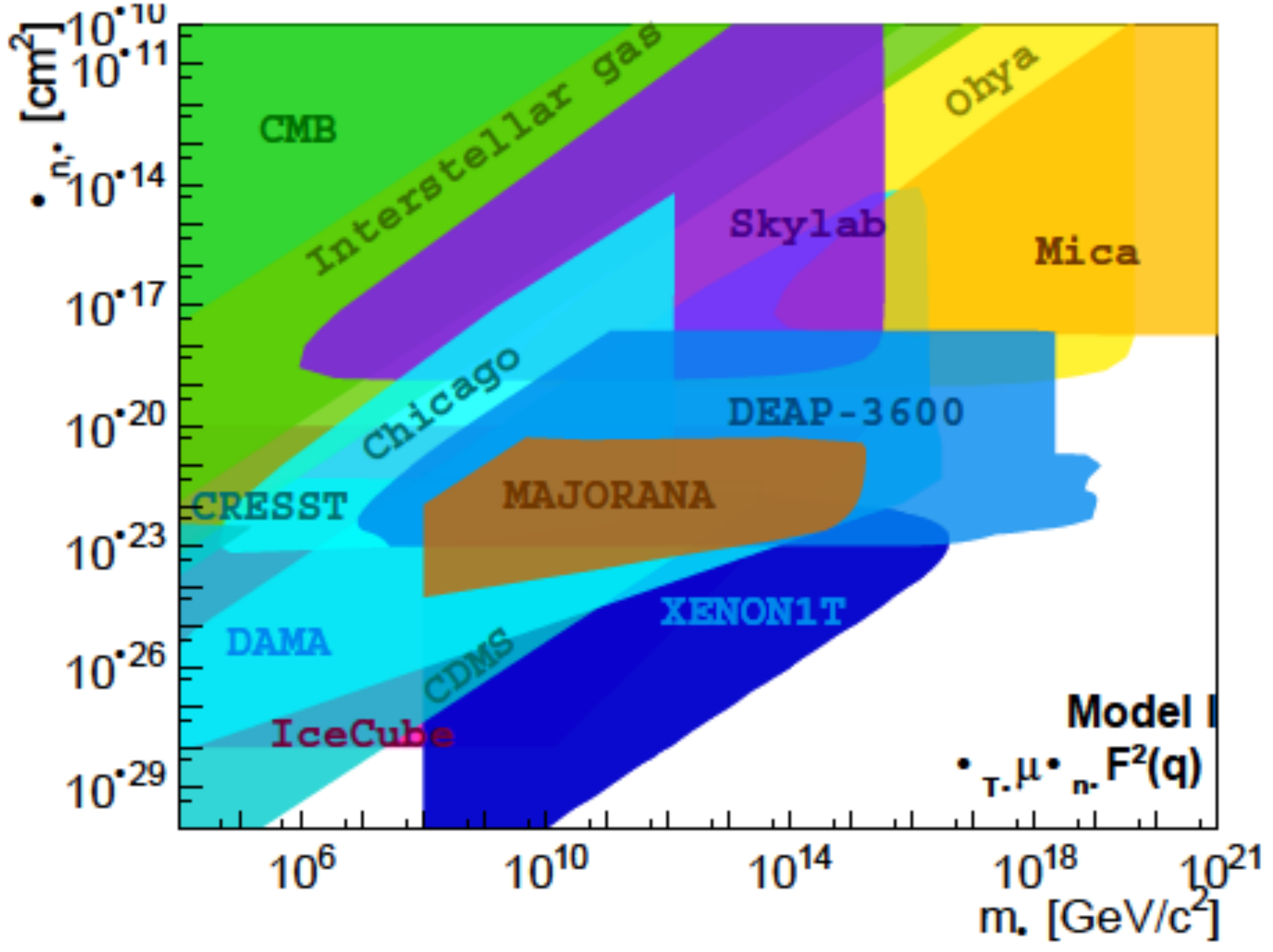
DM Flux on Earth $\boxed{\Phi = n\bar{v} \approx \frac{0.85}{\text{m}^2 \text{ yr}} \times \left(\frac{m_{\rm pl}}{m_\chi}\right)}$ $1 \text{ event/m}^2\text{/yr}$

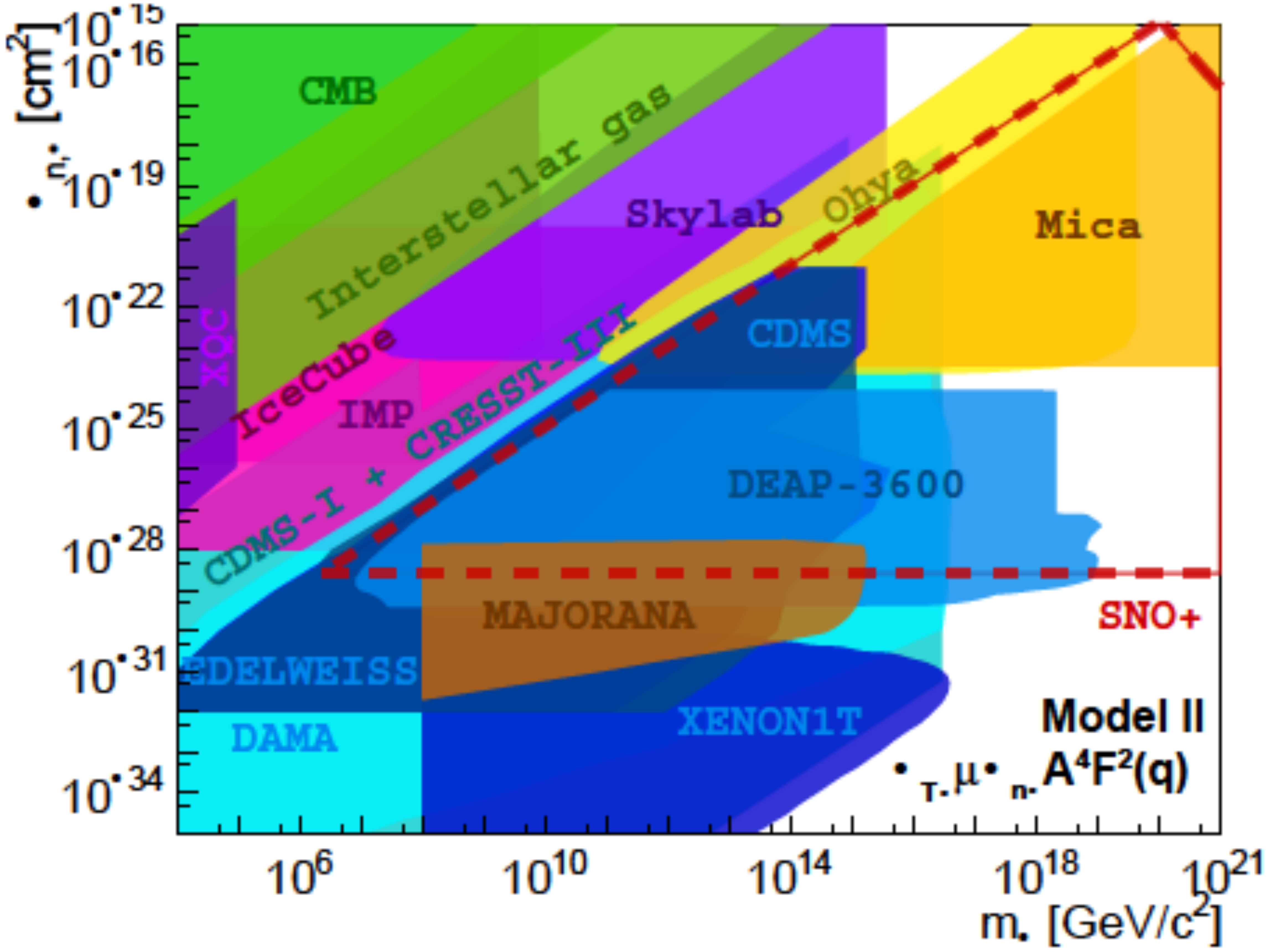
1. Traditional upper-bound on heavy fundamental dark matter candidate via freeze-out = 100 TeV
2. Can be avoided by Early Matter domination, Sommerfeld Enhancements.
3. Other mechanisms, Freeze-in, PBHs, Monopoles, dark stars, …

production of ultra-heavy dark matter



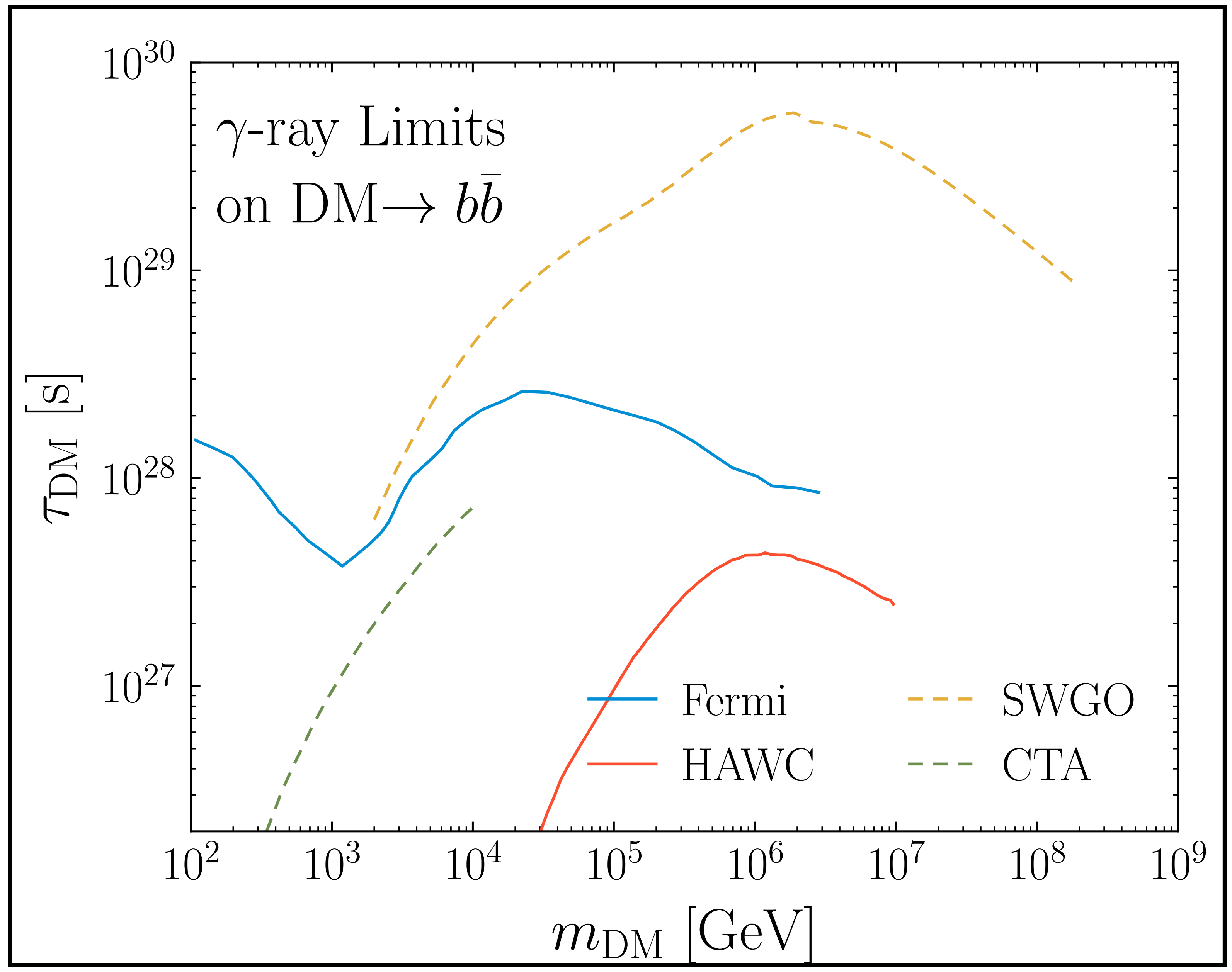
Dark Matter Indirect Detection





Dark Matter Indirect Detection at CTAO

Experiment	Final state	Threshold/sensitivity	Field of view	Location
Current experiments				
Fermi	Photons	10 MeV – 10^3 GeV	Wide	Space
HESS	Photons	30 GeV - 100 TeV	Targeted	Namibia
VERITAS	Photons	85 GeV - > 30 TeV	Targeted	USA
MAGIC	Photons	30 GeV - 100 TeV	Targeted	Spain
HAWC	Photons	300 GeV - >100 TeV	Wide	Mexico
LHAASO (partial)	Photons	10 TeV - 10 PeV	Wide	China
KASCADE	Photons	100 TeV - 10 PeV	Wide	Germany
KASCADE-Grande	Photons	10 - 100 PeV	Wide	Italy
Pierre Auger Observatory	Photons	1 - 10 EeV	Wide	Argentina
Telescope Array	Photons	1 - 100 EeV	Wide	USA
IceCube	Neutrinos	100 TeV - 100 EeV	Wide	Antarctica
ANITA	Neutrinos	EeV - ZeV	Wide	Antarctica
Pierre Auger Observatory	Neutrinos	0.1 - 100 EeV	Wide	Argentina
Future experiments				
CTA	Photons	20 GeV - 300 TeV	Targeted	Chile & Spain
SWGO	Photons	100 GeV - 1 PeV	Wide	South America
IceCube-Gen2	Neutrinos	10 TeV - 100 EeV	Wide	Antarctica
LHAASO (full)	Photons	100 GeV - 10 PeV	Wide	China
KM3NeT	Neutrinos	100 GeV - 10 PeV	Wide	Mediterranean Sea
POEMMA	Neutrinos	20 PeV - 100 EeV	Wide	Space



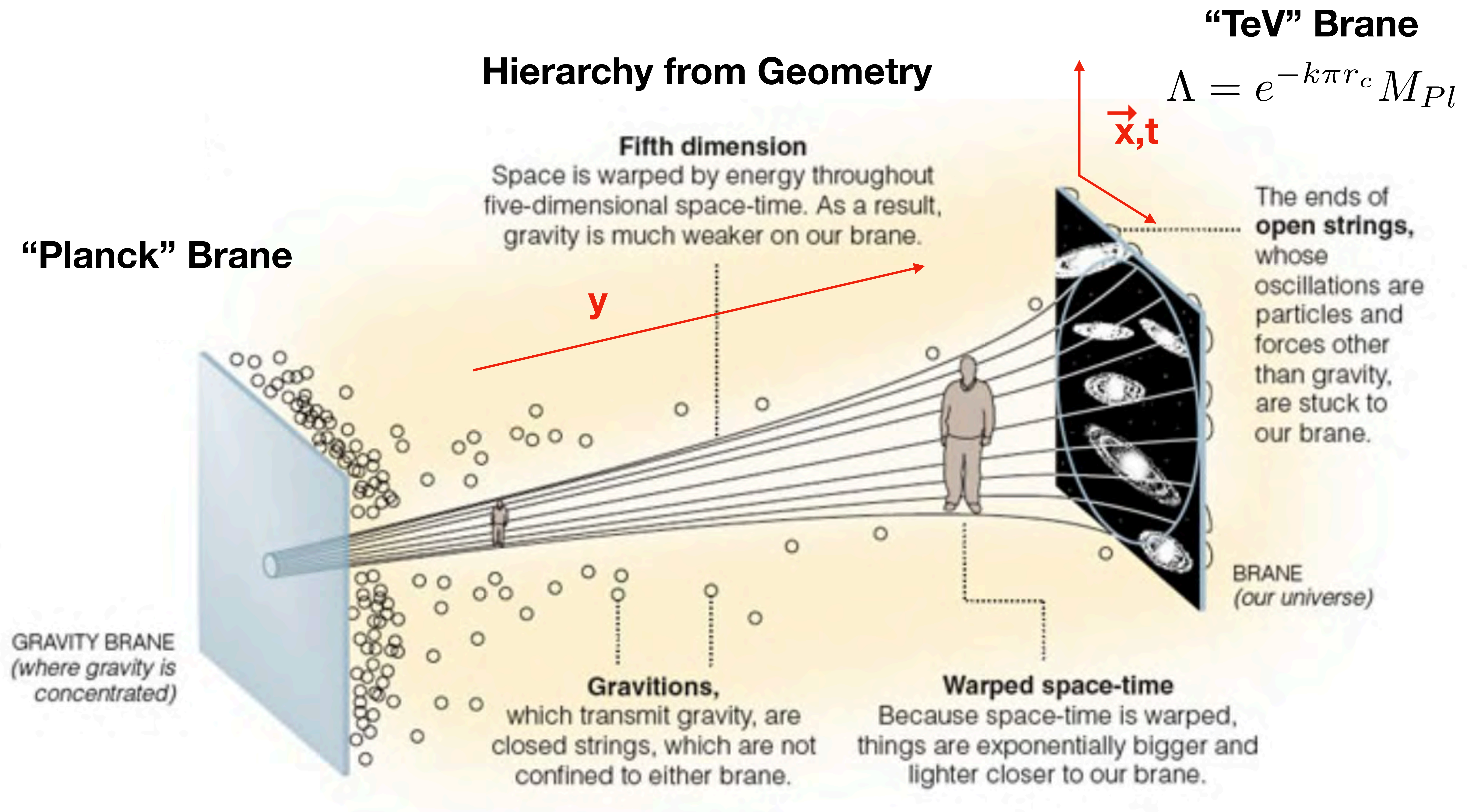
CTAO with sensitivity

Upto 300 TeV will probe

DM with a factor 10 bette

Snowmass 2021

Compact Extra Dimensions : Randall-Sundrum Models

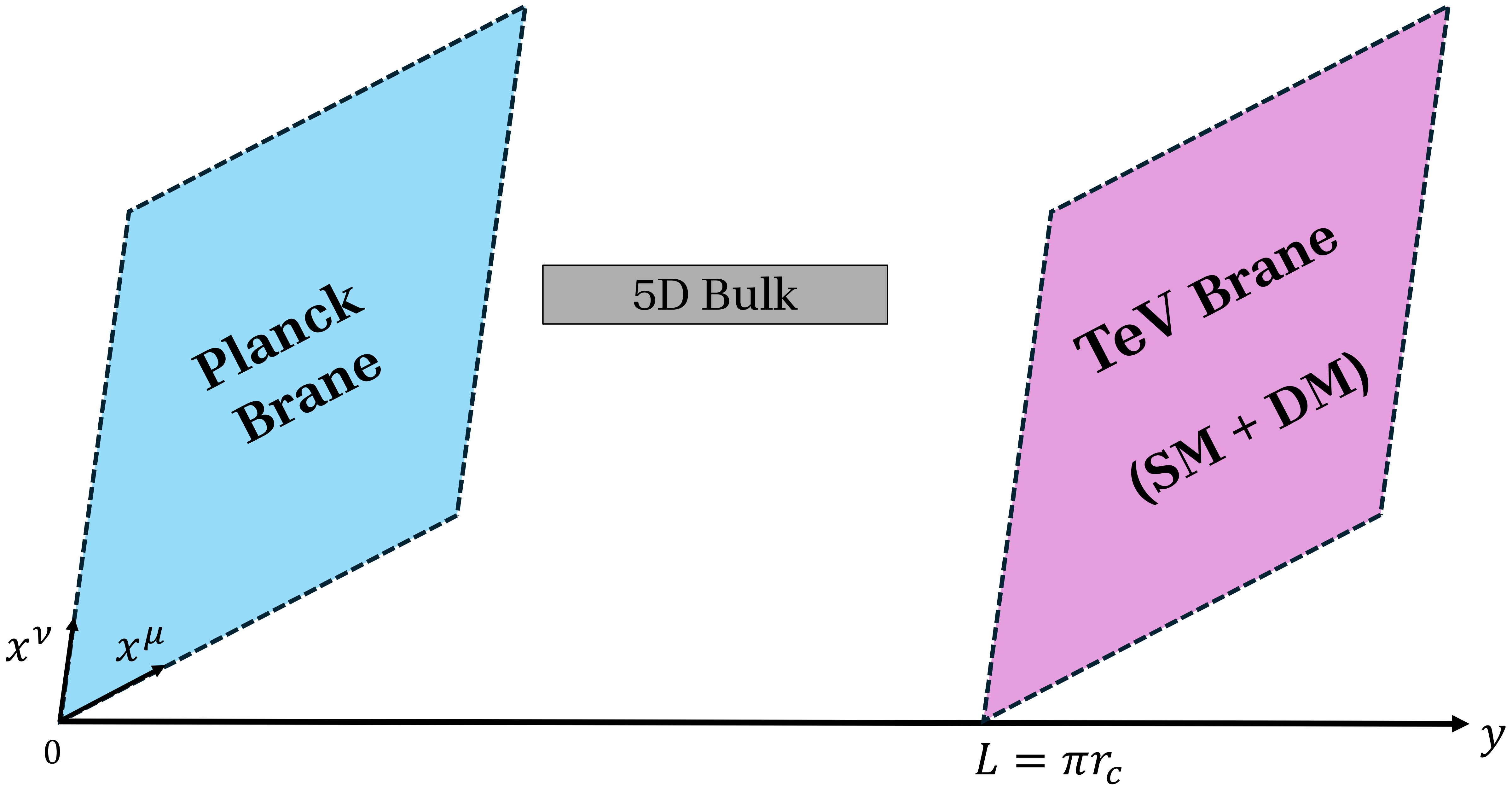


$$ds^2 = e^{-2k|y|}(dt^2 - d\vec{x}^2) - dy^2$$

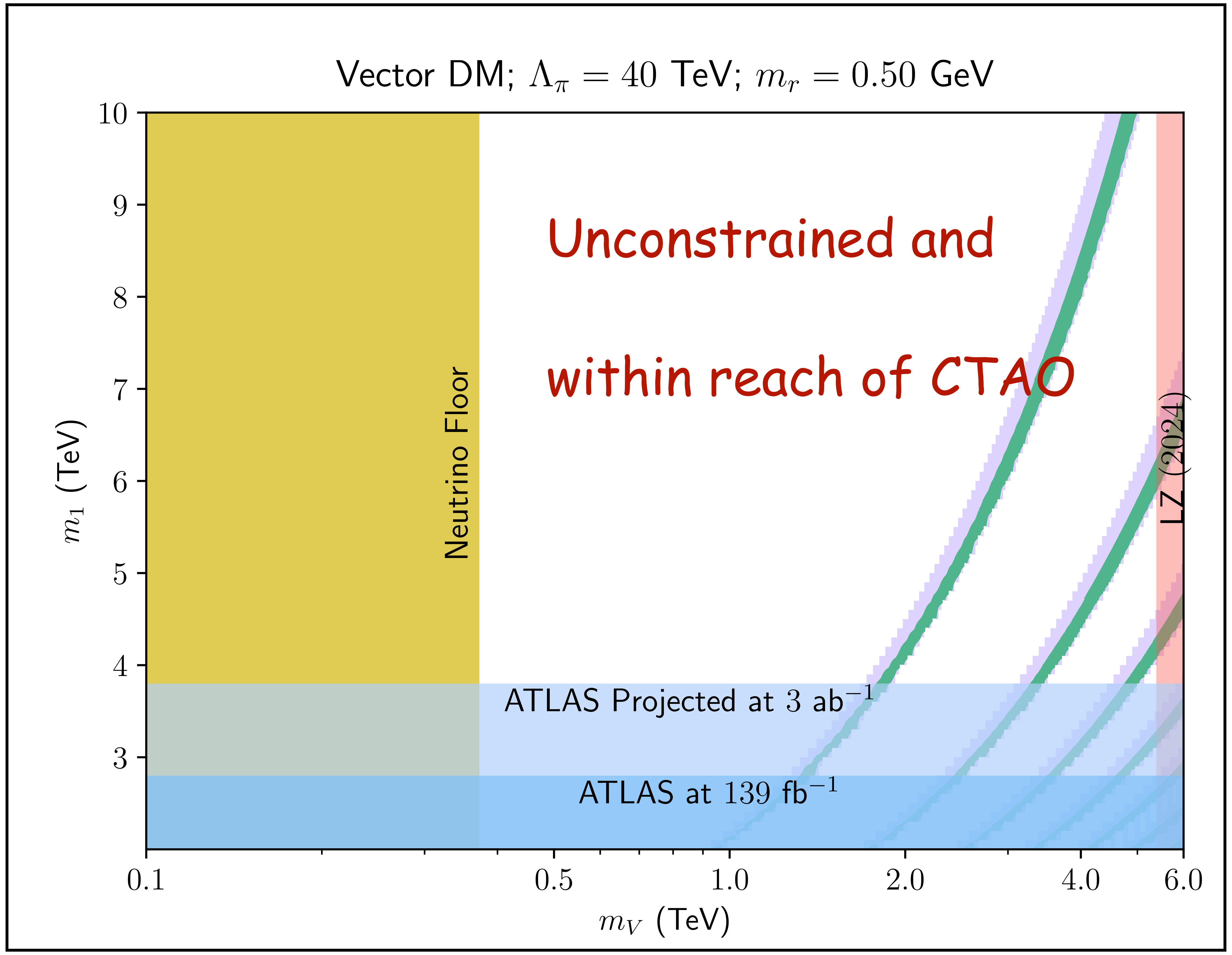
An examply where CTAO will provide the only way of probing DM

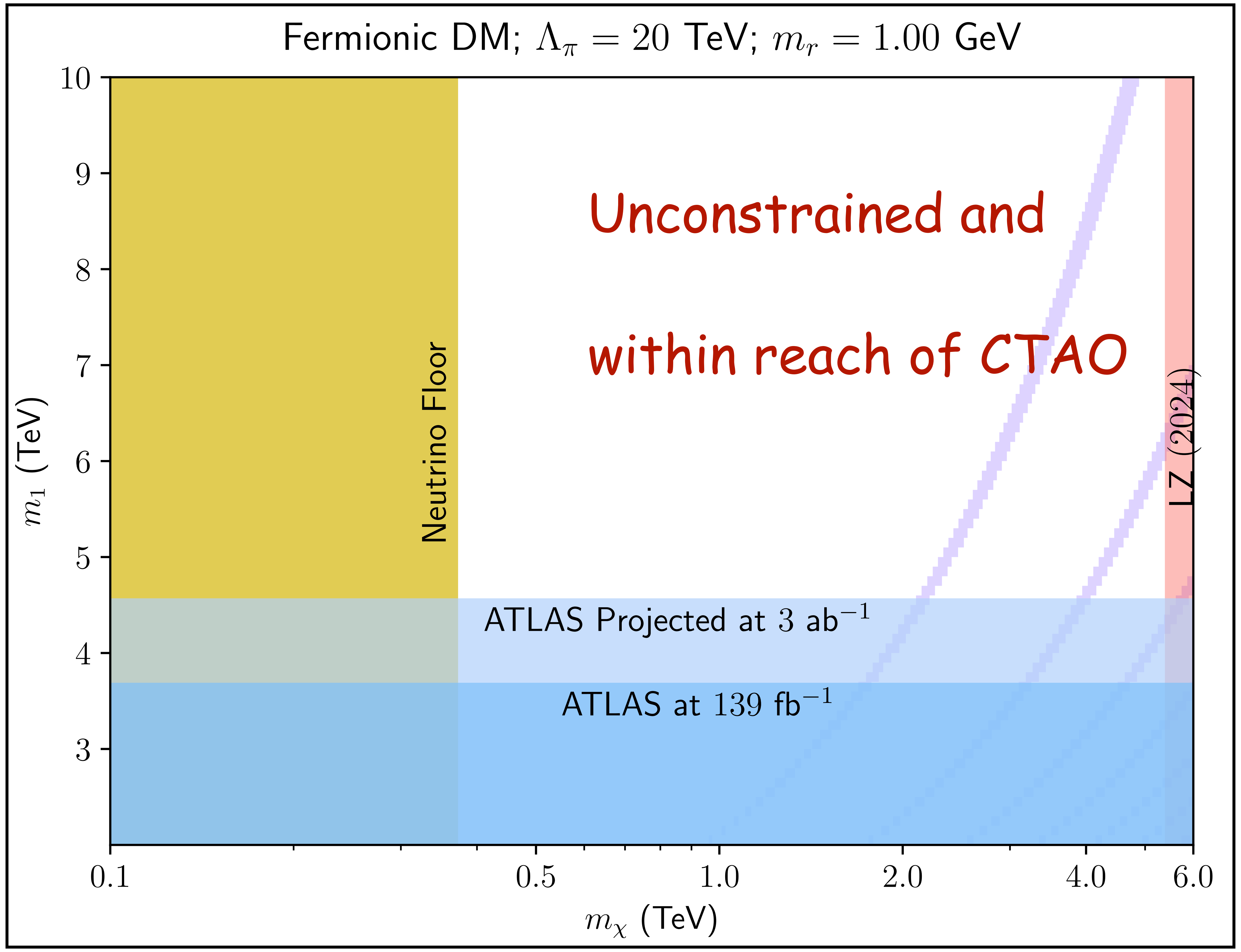
Dark Matter candidates : Fermions, Vectors or scalar particles

Mediators : Kaluza-Klein particles from the gravity sector



Dark matter models within CTAO reach





Chivukula, Gill, Sanmayan, Sengupta et al, PRD 2025

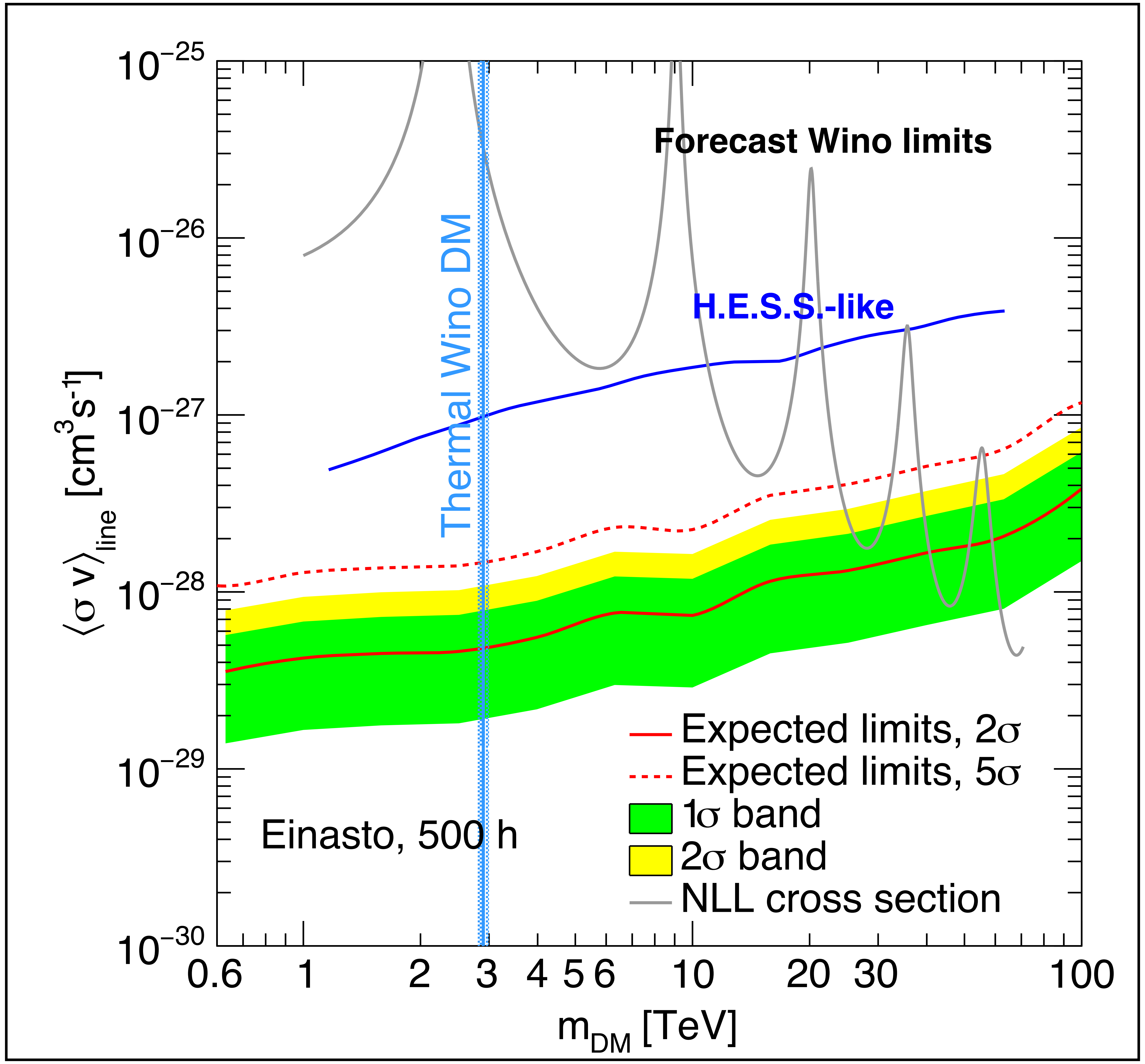
Relic is achieved only at EFT scales upto 80 TeV,

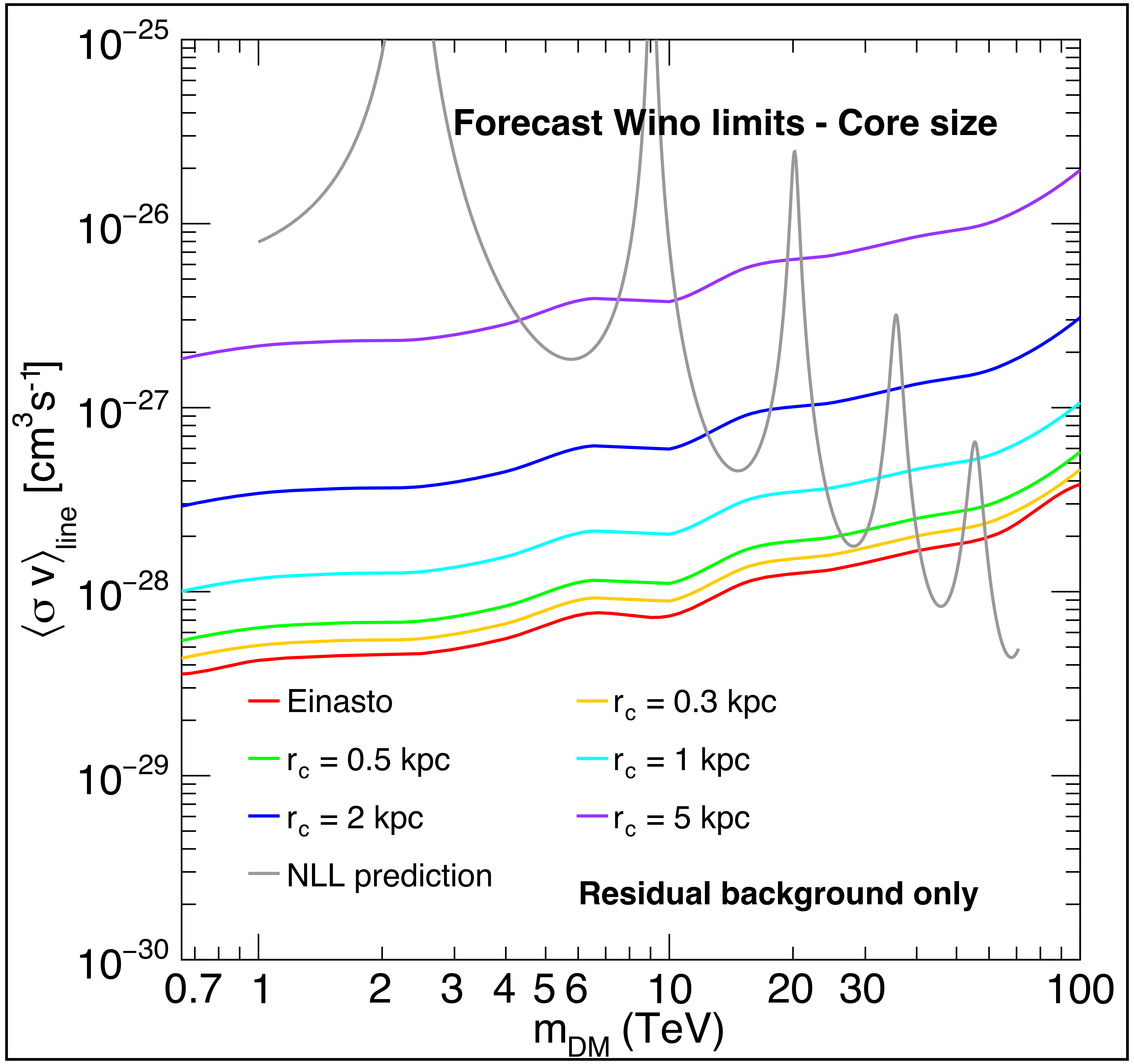
and for dark matter masses of around 1-6 TeV

Direct Detection Constraints rules models out with a light radion

Collider constraints rule out a large part of the parameter space

Ultraheavy Dark matter models within CTAO reach





Rodd, Slatyer 2021

Conclusions

- Dark Matter searches are ramping up from all directions
- Direct detection and collider searches will cover most of the 100 GeV - few TeV space
- For high mass dark matter models, the only robust way of discovery is through indirec detection
- Need improvements in theoretical predictions, electroweak corrections, Sommerfeld, SCET, ..
- Once operational, CTAO will provide the best coverage for dark matter masses upto 3 TeV

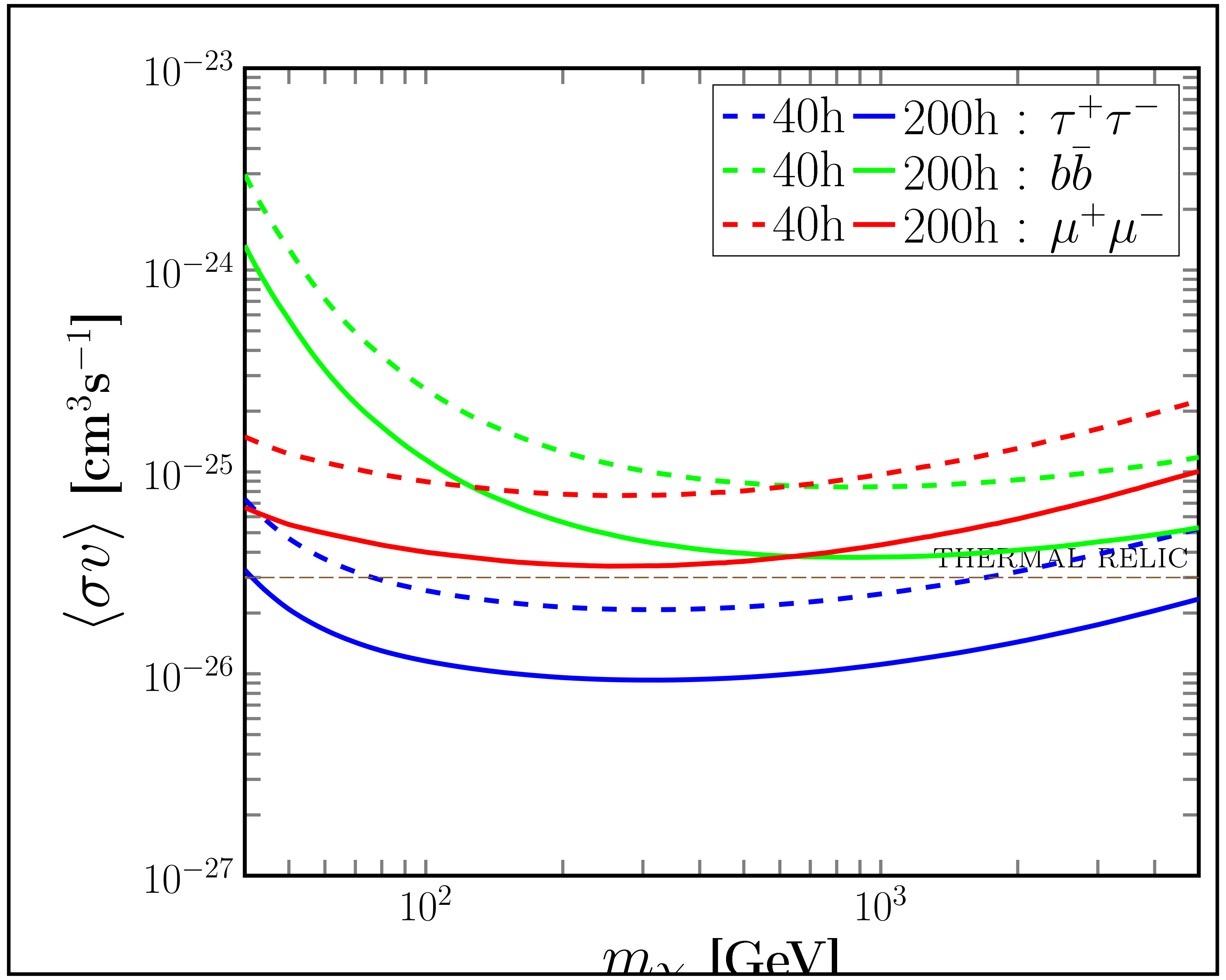
Likelihoods

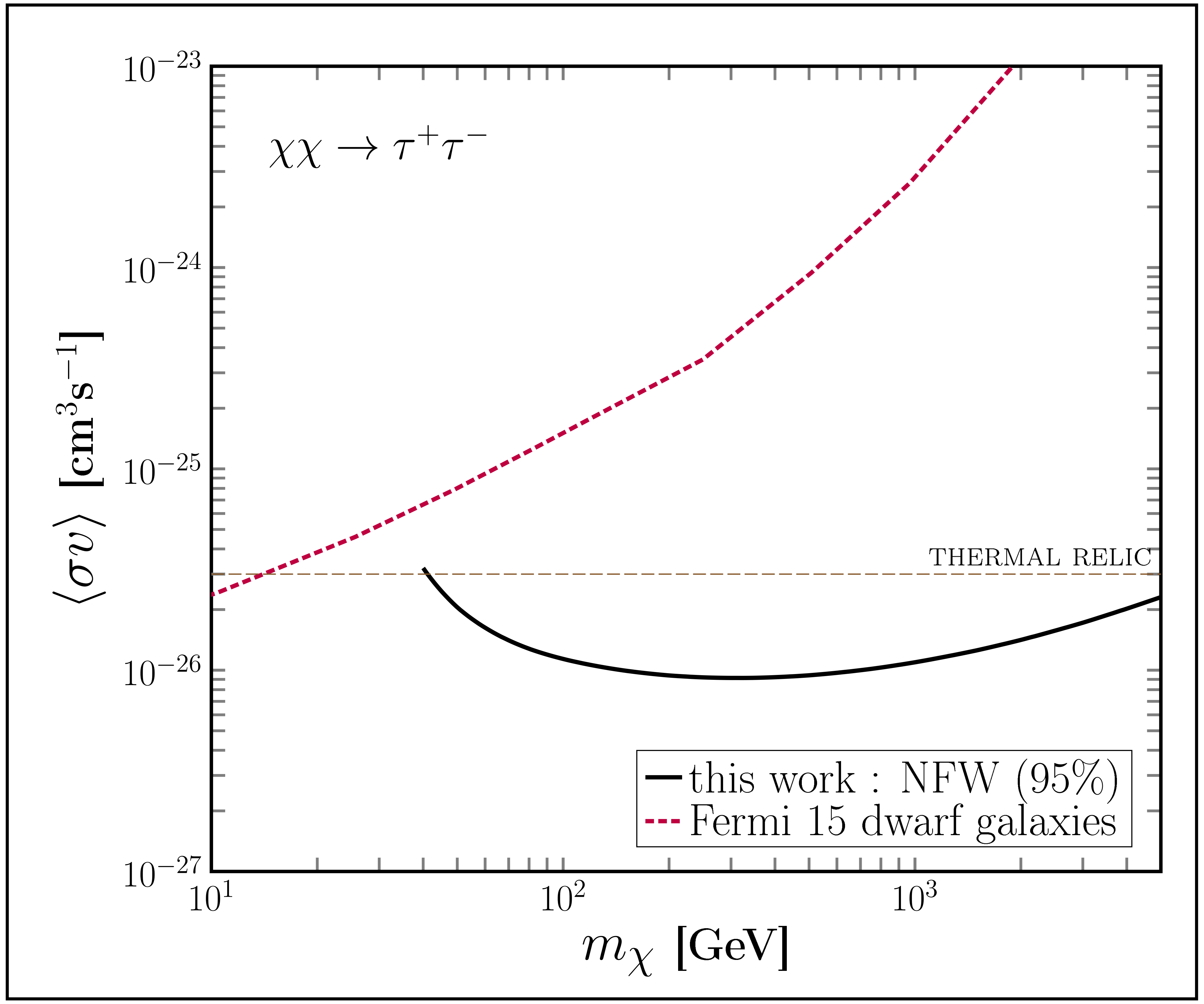
$$\theta_{\text{diff}} = \theta_{\text{ON}} - \alpha\theta_{\text{OFF}}$$

$$\boxed{\mathcal{L}(\theta_{\text{diff}}) = e^{-(N_{\text{ON}}+\alpha N_{\text{OFF}})}\left(\frac{N_{\text{ON}}}{\alpha N_{\text{OFF}}}\right)^{\frac{\theta_{\text{diff}}}{2}} I_{|\theta_{\text{diff}}|}(2\sqrt{\alpha N_{\text{ON}} N_{\text{OFF}}})}$$

Background only $\theta_{\text{diff}} = 0$

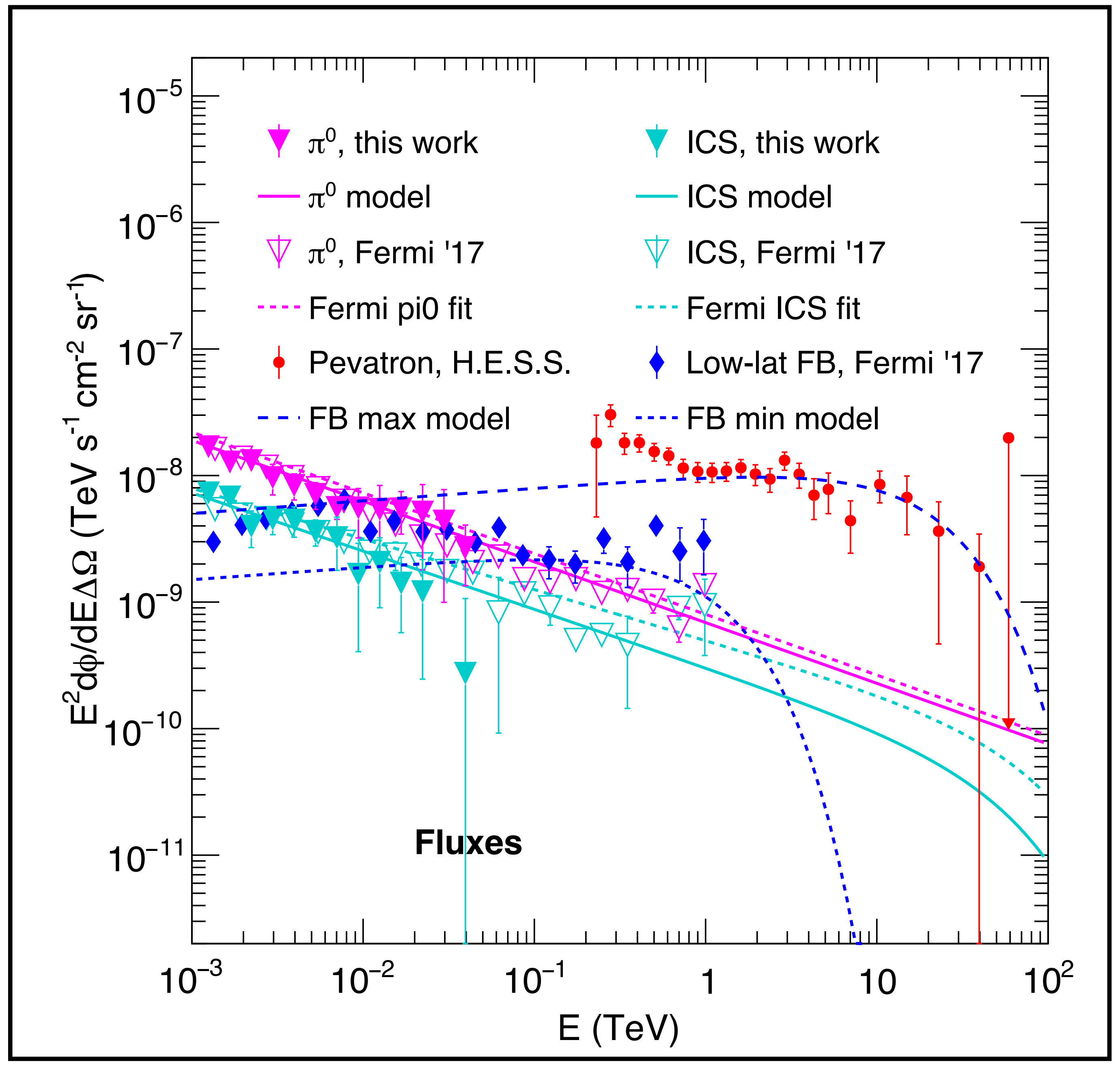
Comparisons

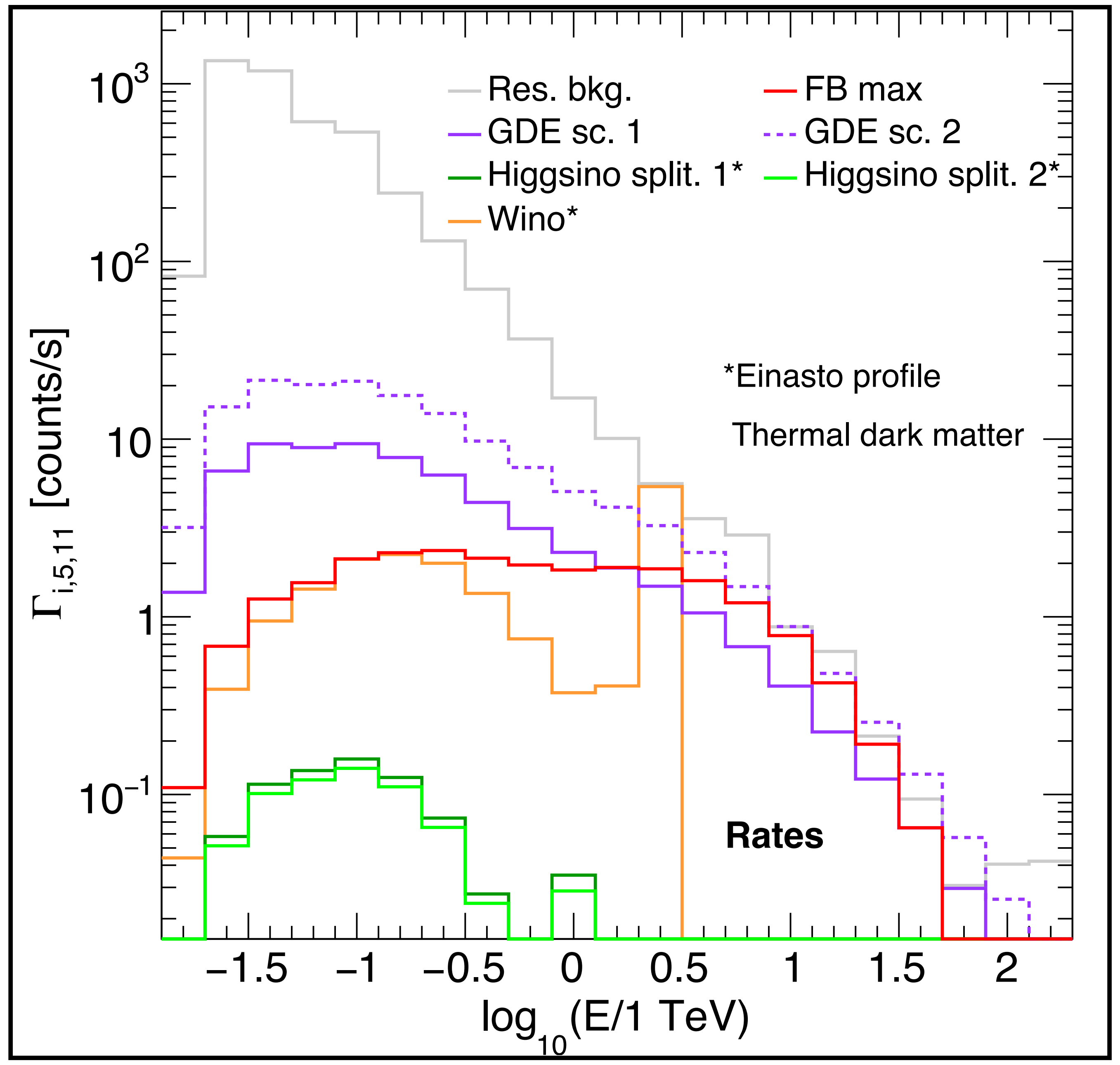




Backgrounds

1. Cosmic Ray Electrons.
2. Definition of region of interest.
3. TeV diffuse emission in Galactic Centre
4. Fermi-LAT High-Energy Sources
5. Fermi-Bubbles at low Galactic Latitudes





$$\frac{d\Gamma^{\rm S}_{\gamma,jk}}{dE_\gamma}(E_\gamma) = \int_{-\infty}^{+\infty} dE'_\gamma \, \frac{d\Phi^{\rm S}_{\gamma,jk}}{dE_\gamma}(E'_\gamma)\, A^\gamma_{\rm eff}(E'_\gamma)\, G(E_\gamma, E'_\gamma)$$

$$\boxed{s_{\gamma,ijk} = T_{\rm obs} \int_{\Delta E_i} dE_\gamma \, \frac{d\Gamma^{\rm S}_{\gamma,jk}}{dE_\gamma}}$$

$$\frac{d\Gamma^{\rm B}_{\gamma,jk}}{dE_\gamma}(E_\gamma) = \int_{-\infty}^{+\infty} dE'_\gamma \int_{\Delta\Omega_{jk}} d\Omega \left[\frac{d\Phi^{\rm CR}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma)\, A^{\rm CR}_{\rm eff}(E'_\gamma) + \frac{d\Phi^{\rm Std}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma, \Delta\Omega) A^\gamma_{\rm eff}(E'_\gamma) \right] G(E_\gamma, E'_\gamma). \qquad (14)$$

Rodd, Slatyer 2020

Snowmass 2021

$$\boxed{\begin{aligned}\frac{d\Phi^{\rm Std}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma, \Delta\Omega) =& \frac{d\Phi^{\rm PL}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma, \Delta\Omega) + \frac{d\Phi^{\rm GDE}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma, \Delta\Omega) \\ &+ \frac{d\Phi^{\rm FB}_{\gamma,jk}}{dE_\gamma d\Omega}(E'_\gamma, \Delta\Omega). \qquad (15)\end{aligned}}$$