Gamma-ray cosmology

an introduction

2024.06.20, CTAO School, Bertinoro

Jonathan Biteau

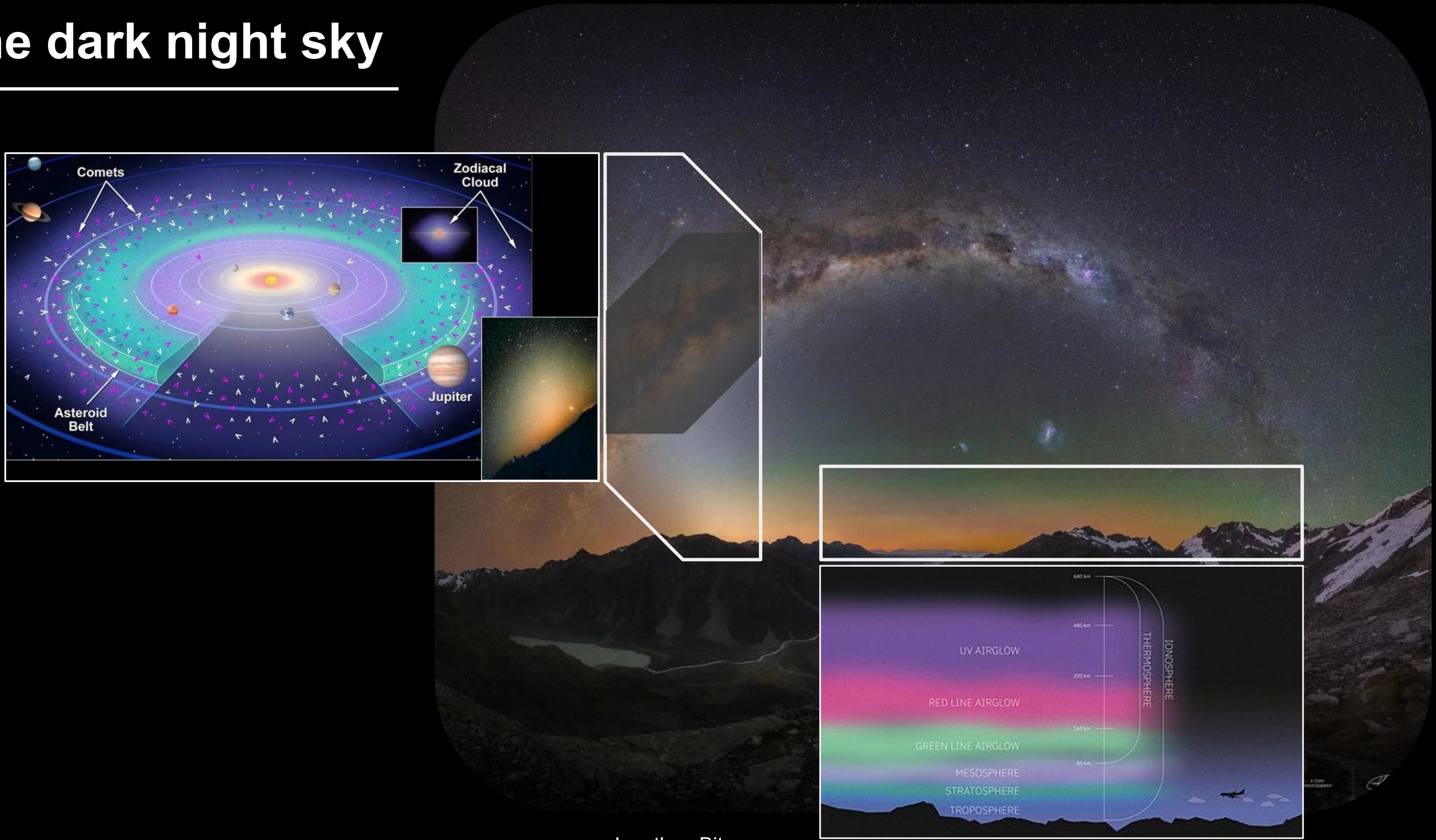
The dark night sky

Aoraki National Park, New Zealand.
Credit: chaka160, reddit/itookapicture

The dark night sky

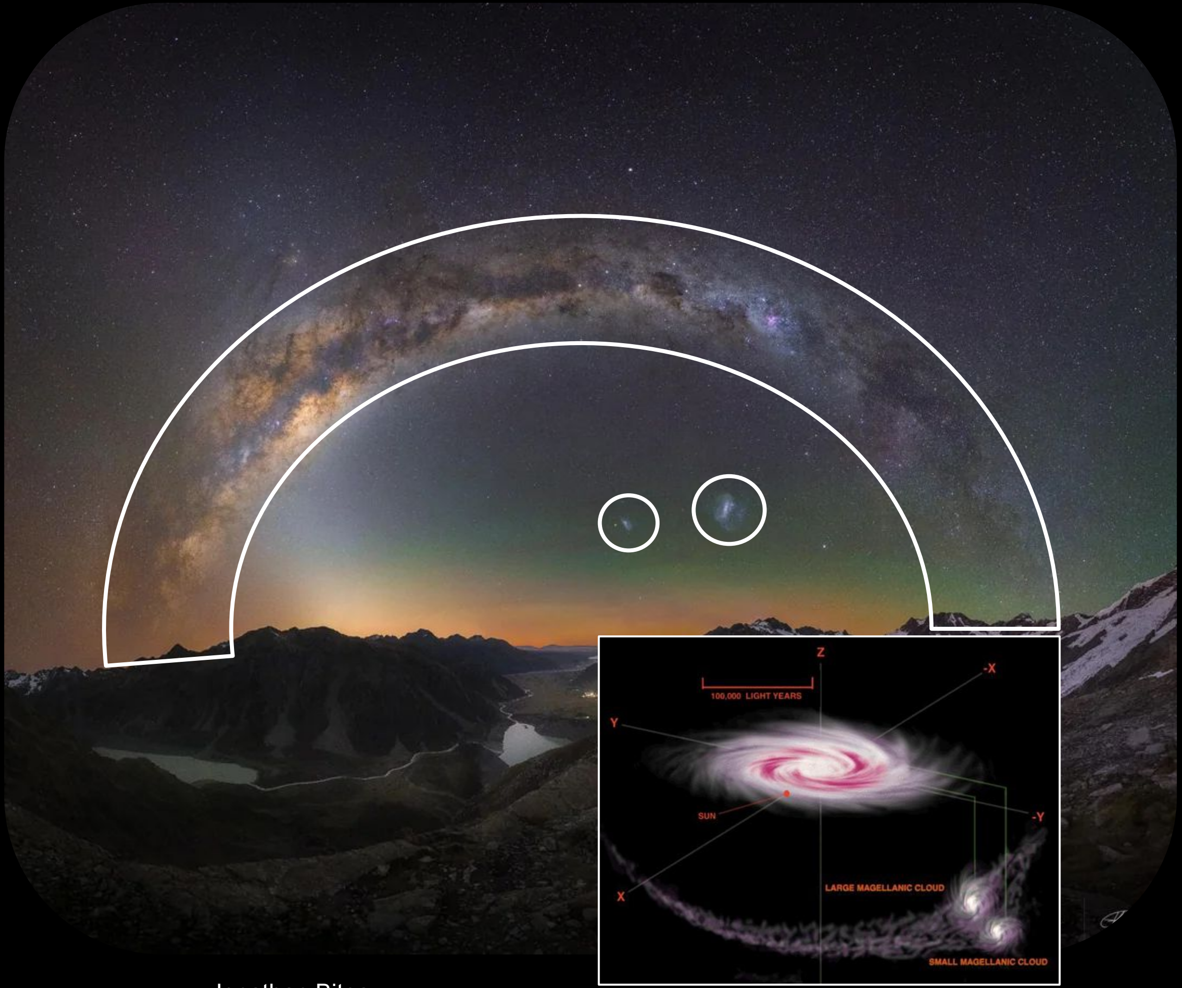
You said dark?

The dark night sky

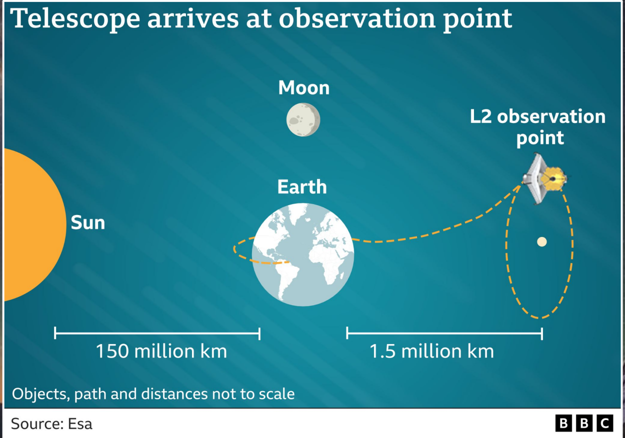


The dark night sky

You said dark?



The dark night sky



Crédit : ESA/Webb, NASA & CSA, A. Martel.

The de Chéseaux - Olbers paradox

see The Conversation article at [this link]

Why is the sky not covered by stars / galaxies ?

“Infinity of the sphere of stars” (Halley, 1721) at [this link]

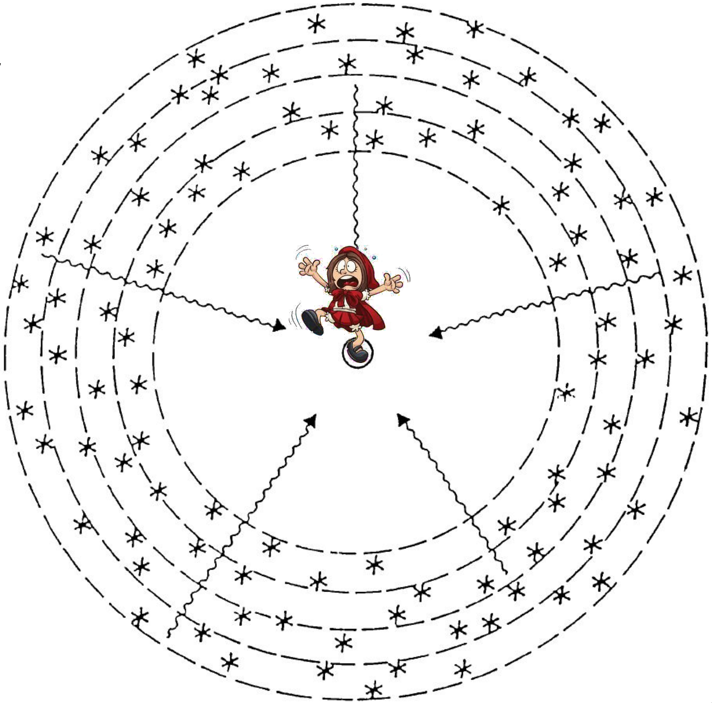
Riddle from Digges (1576) in his translation of Copernicus’ *De revolutionibus*

Formulation by de Chéseaux (1744), **Olbers** (1823):

$\mathbf{\Phi}_{\mathbf{total}} = \int \mathrm{d}r\ \mathbf{\Phi}_{\mathbf{star}} \times \mathbf{N}_{\mathbf{star}}(r; r+dr)$, with $\mathbf{\Phi}_{\mathbf{star}} \propto \mathbf{1 / 4\pi r^2}$ and $\mathbf{N}_{\mathbf{star}}(r; r+dr) \propto \mathbf{4\pi r^2\ dr}$

$\mathbf{\Phi}_{\mathbf{total}} \rightarrow \infty$ in a static unbounded universe (Descartes, Newton)

Credit: Harrison ‘90



Olbers' paradox: a founding pillar of cosmology

Quoting Malcolm Longair:

When I began research in radio astronomy as a research student in 1963, my supervisor Dr Peter Scheuer gave me a copy of Sir Hermann Bondi's classic text *Cosmology* to absorb and warned me that

There are only $2\frac{1}{2}$ facts in cosmology.

Fact 1. The sky is dark at night

This is the well-known observation which leads to what is known as *Olbers' paradox* although the paradox was well known to earlier cosmologists. Sir Hermann in his text *Cosmology* gives a thought-provoking discussion of the meaning of the paradox (Bondi 1952). The fact that the sky is not as bright as the surface of the Sun provides us with some very general information about the Universe. Probably the most general way of expressing the significance of this observation is that the Universe must, in some sense, be far from equilibrium although in what way it is in disequilibrium cannot be deduced from this very simple observation.

Fact 2. The galaxies are receding from each other as expected in a uniform expansion

This was Hubble's great discovery of 1929 and I will say much more about it in a moment. The $2\frac{1}{2}$th fact was as follows:

Fact $2\frac{1}{2}$. The contents of the Universe have probably changed as the Universe grows older

The reason for the ambiguous status of this fact was that the evidence for the evolution of extragalactic radio sources as the Universe grows older was then a matter of considerable controversy, particularly with the proponents of Steady-State cosmology. I was plunged straight into this debate as soon as I began my research programme with Martin Ryle and Peter Scheuer. As we will see, this is no longer a controversial issue – there is no question at all

Modern Cosmology - a Critical Assessment,
M. S. Longair 1993

A modern version of the riddle

What remains once the foregrounds (nearby trees) have been removed?

Part I - Baryons and light: where to find them

from the cosmic web to the cosmic energy inventory

Part II - A cosmic history of light emission

from the first stars to the current spectrum of the universe

Part III - The gamma-ray probe

gamma-ray propagation on cosmological scales

Some useful references: Fukugita & Peebles '04, Madau & Dickinson '14, Pueschel & Biteau '21

Part I - Baryons and light: where to find them

from the cosmic web to the cosmic energy inventory

Part II - A cosmic history of light emission

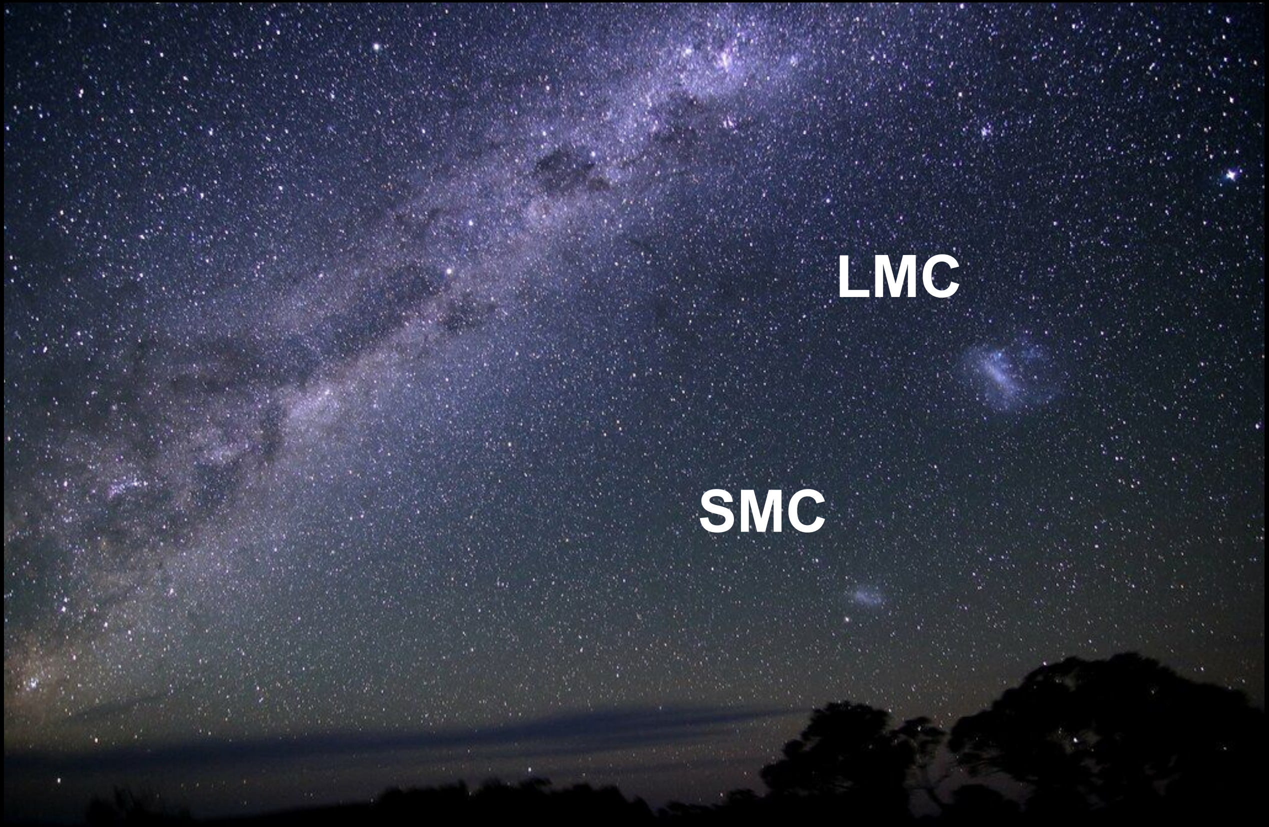
from the first stars to the current spectrum of the universe

Part III - The gamma-ray probe

gamma-ray propagation on cosmological scales

Some useful references: Fukugita & Peebles ‘04, Madau & Dickinson ‘14, Pueschel & Biteau ‘21

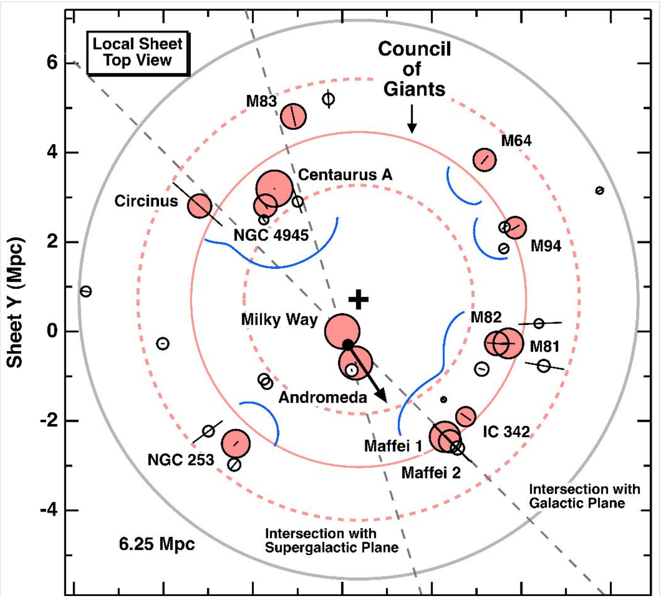
Distance to the Milky Way largest satellites?

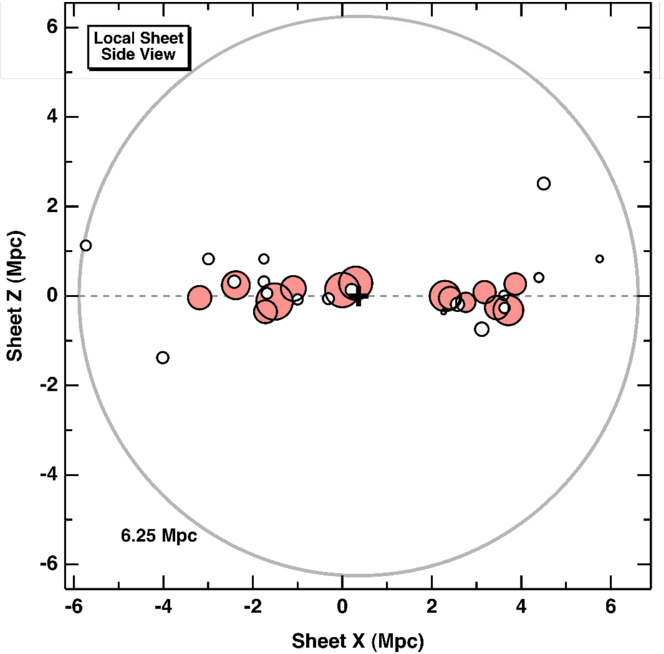


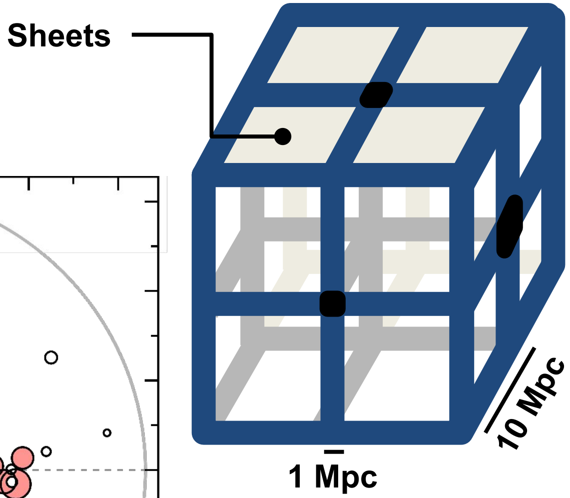
Distance to the closest giant spiral galaxy?

Our location in the cosmic web

The Local Sheet



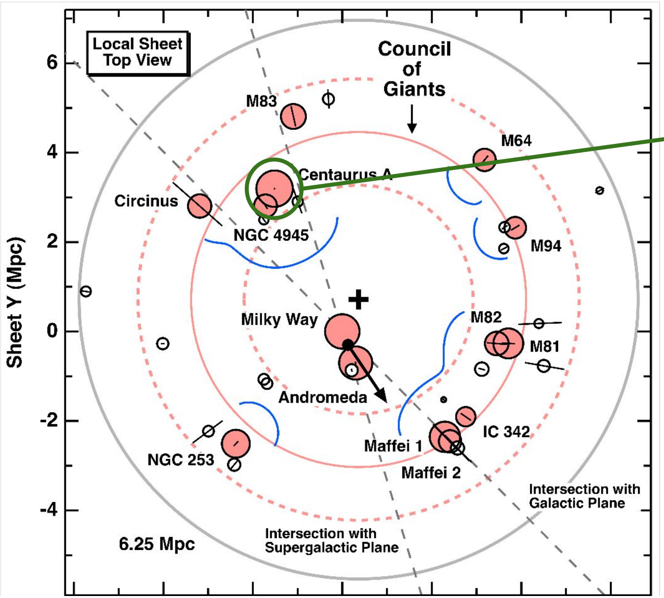




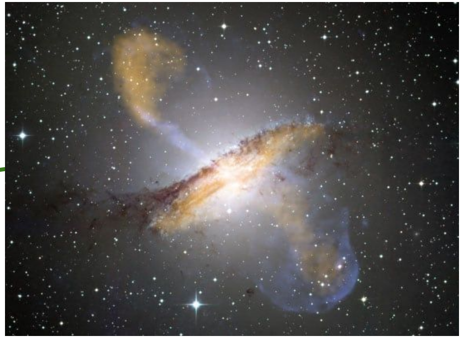
McCall '14 (The Council of Giants)

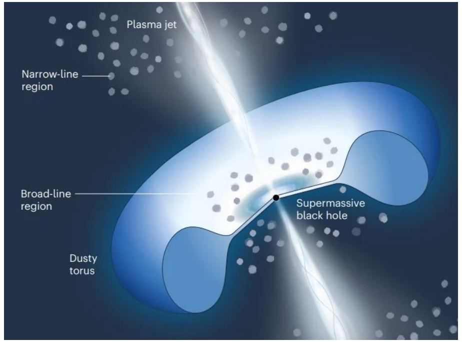
Zoom on the Local Sheet

Active galaxies in the Local Sheet



The jetted AGN Centaurus A

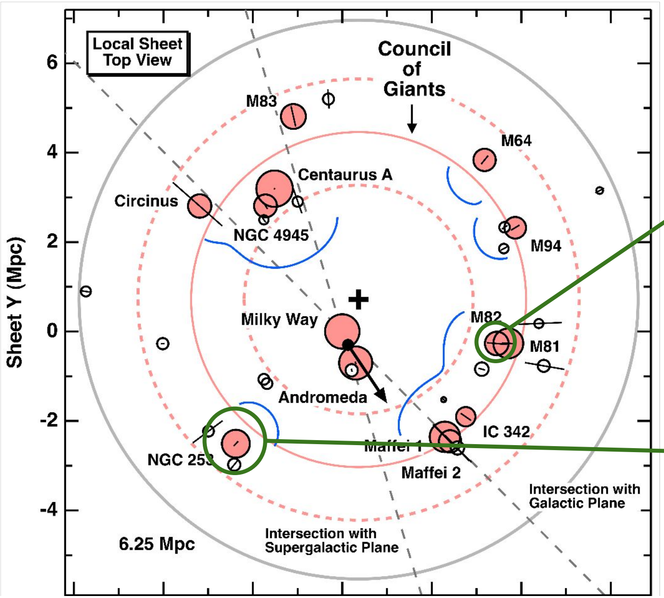




Credit: McCall '14

Zoom on the Local Sheet

Starburst galaxies in the Local Sheet



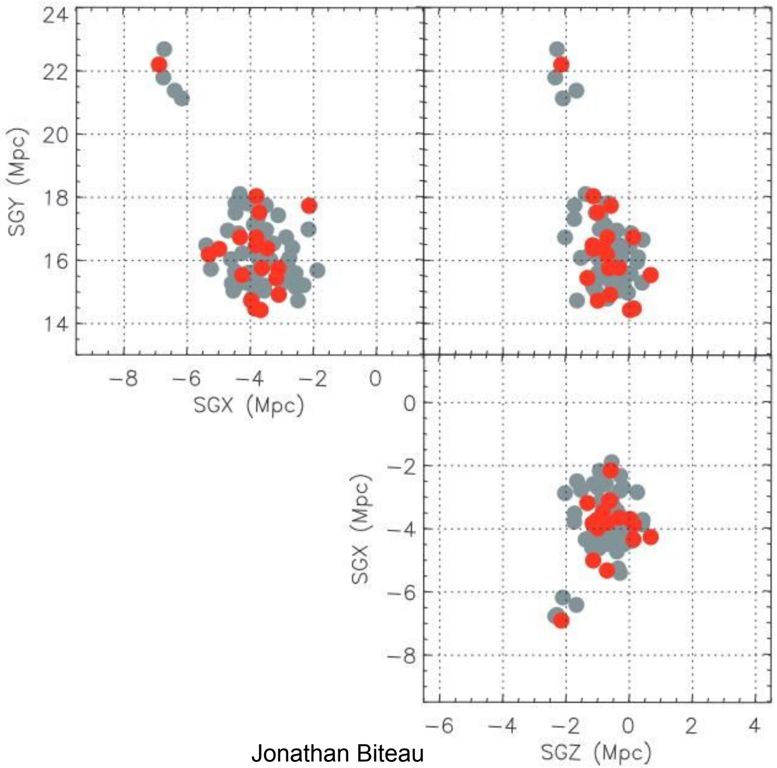
Credit: McCall '14

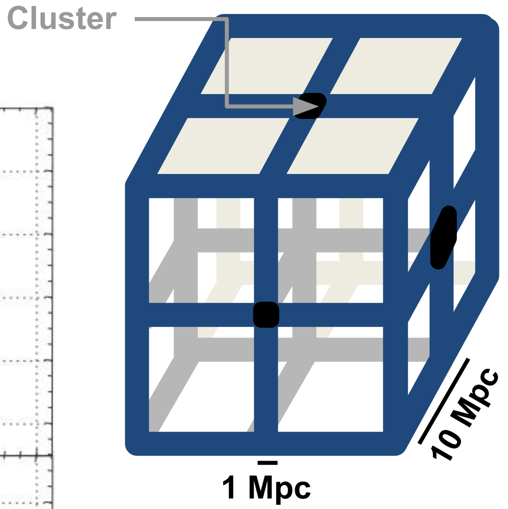
The starburst galaxy M 82 (Credit: Hubble space telescope + Hα from FOCAS)

The starburst galaxy NGC 253 (Credit: Chandra X-ray Center)

Our location in the cosmic web

The closest galaxy cluster: the Virgo cluster

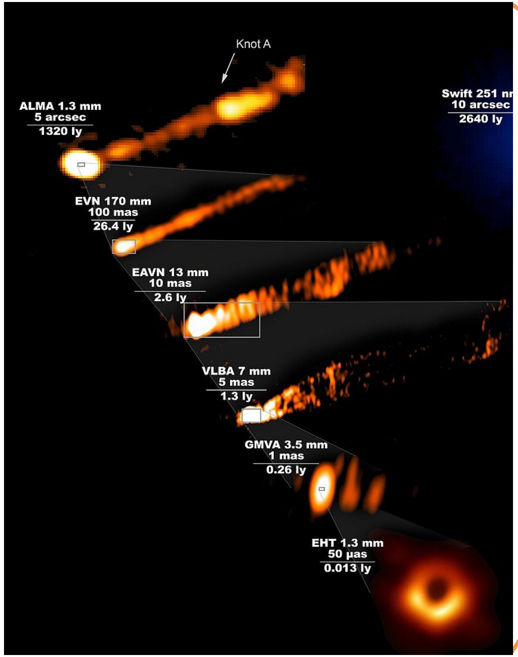


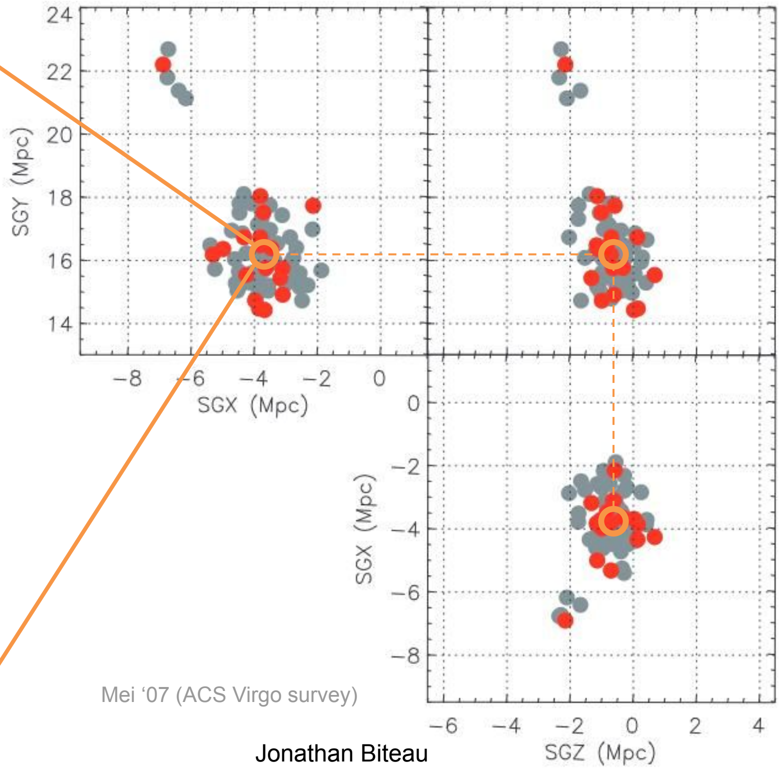


Our location in the cosmic web

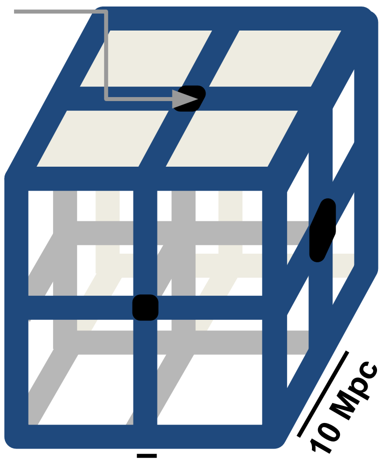
At the center of the Virgo cluster

The jetted AGN M 87



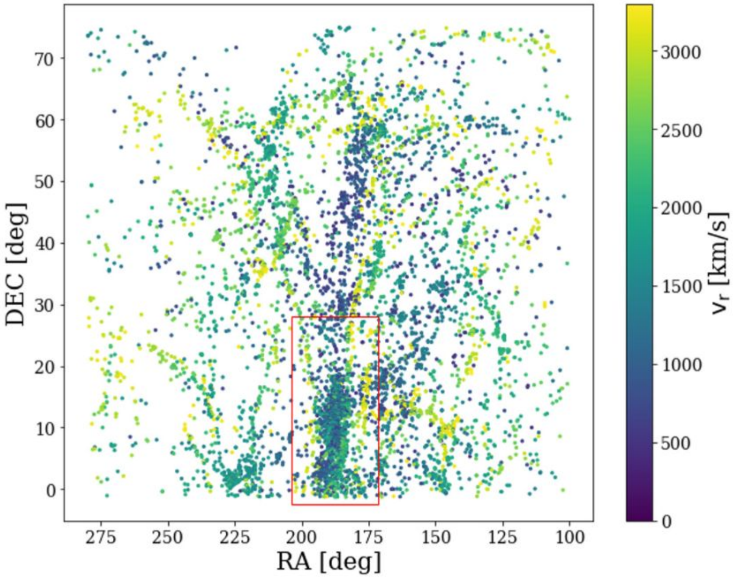


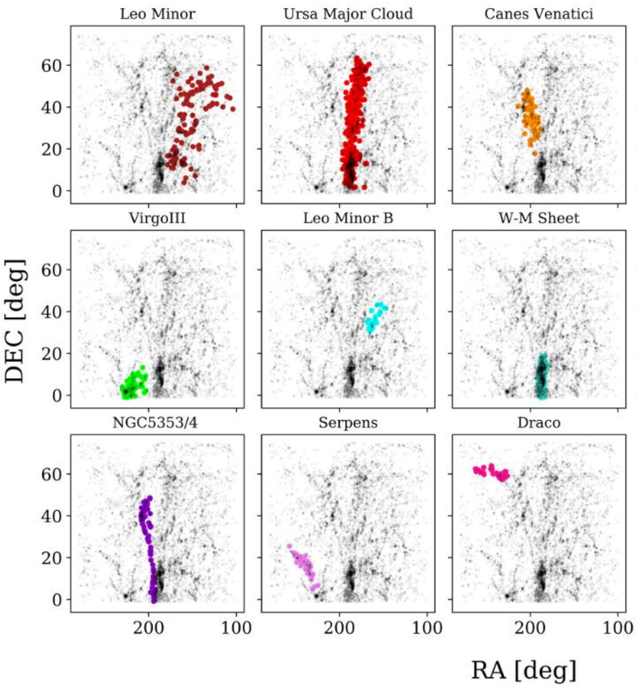
Mei ‘07 (ACS Virgo survey)

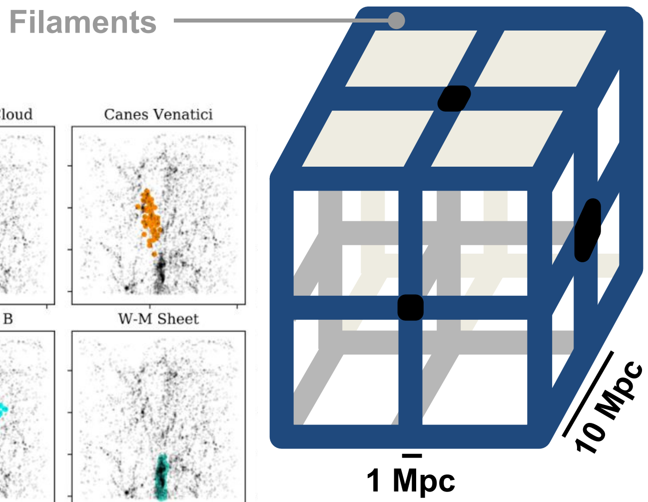


Our location in the cosmic web

The closest galaxy cluster: the Virgo cluster and its filaments

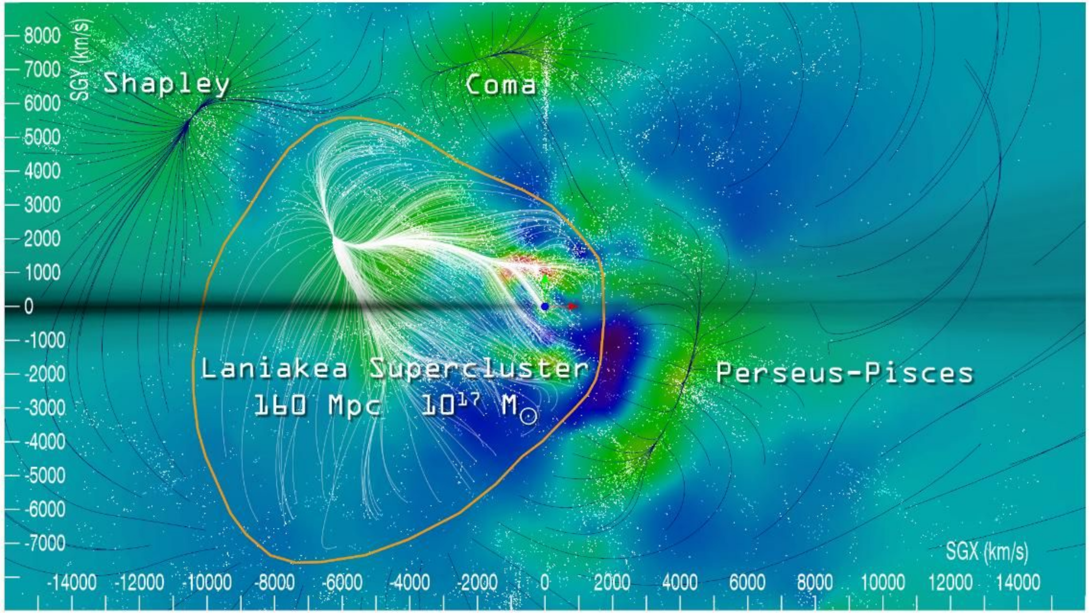




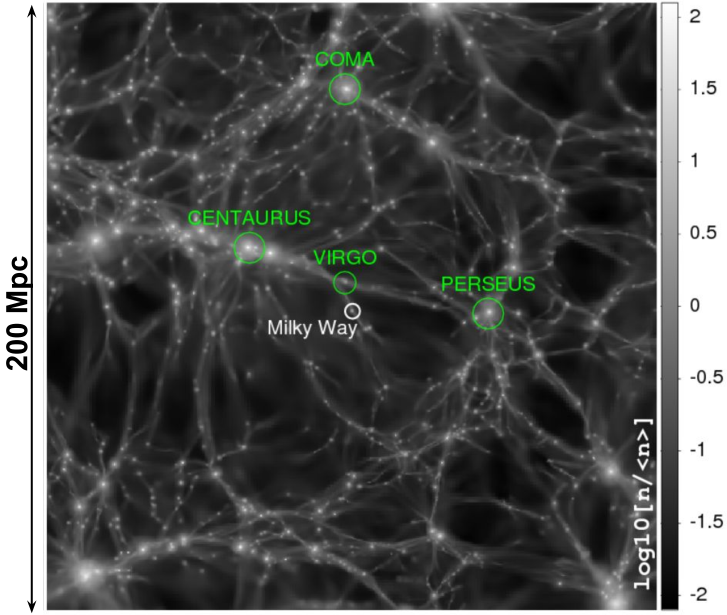


Our location in the cosmic web

Our supercluster: Laniakea



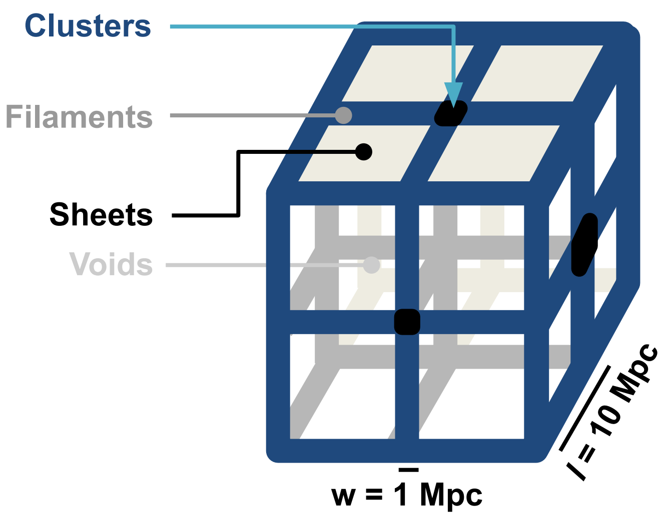
Tully+ '14 (Cosmic V-web)



Hackstein+ '18 (Cosmic V-web constrained simulation / CLUES)

Relevant scales

Exercise 1. Volume filling factor of large-scale structures
Assess the relative volume occupancy of clusters, filaments and sheets using w = 1 Mpc and l = 10 Mpc.



Relevant scales

Exercise 1. Volume filling factor of large-scale structures
Assess the relative volume occupancy of clusters, filaments and sheets using w = 1 Mpc and l = 10 Mpc.

$$\mathrm{VFF_c} = \left(\frac{w}{l}\right)^3$$

$$\mathrm{VFF_f} = 3\left(\frac{w}{l}\right)^2\left(1-\frac{w}{l}\right)$$

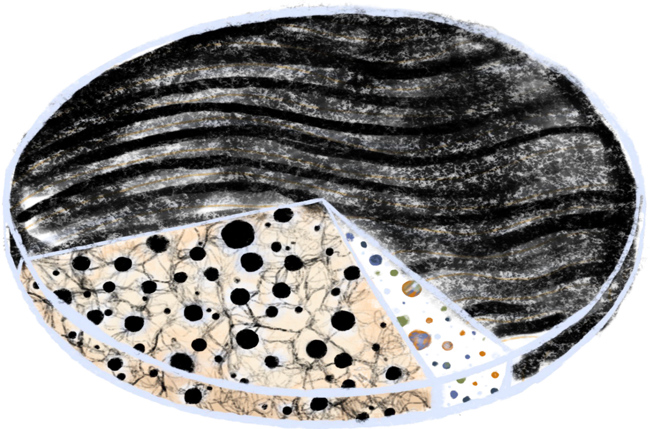
$$\mathrm{VFF_s} = 3\frac{w}{l}\left(1-\frac{w}{l}\right)^2$$

$$\mathrm{VFF_v} = \left(1-\frac{w}{l}\right)^3$$

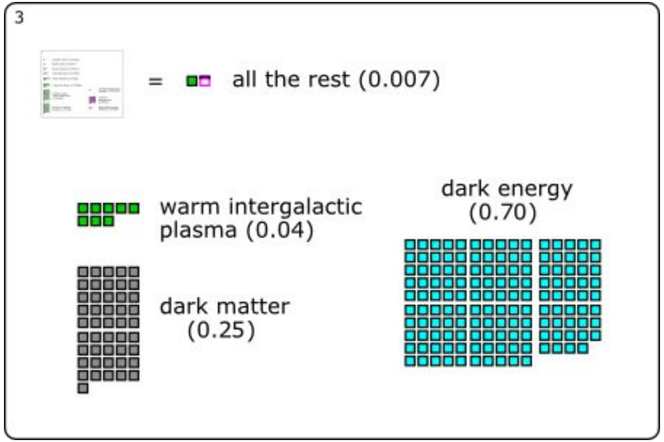
Structure type	Cubic cell $w/l = 0.1$	Cosmic simulation results
Voids	72.9%	76%
Sheets	24.3%	18%
Filaments	2.7%	5%
Clusters	0.1%	0.5%

Credit: Oei+ ‘22

Cosmic energy inventory



Credit: Fukujita et Peebles ‘04

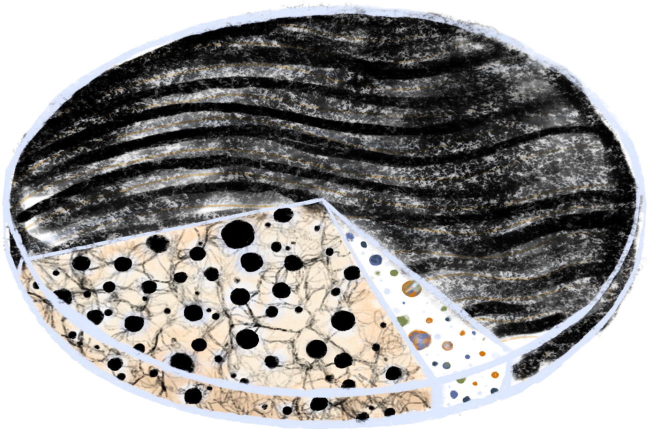


Nobel in physics 2019
J. Peebles (cosmology)

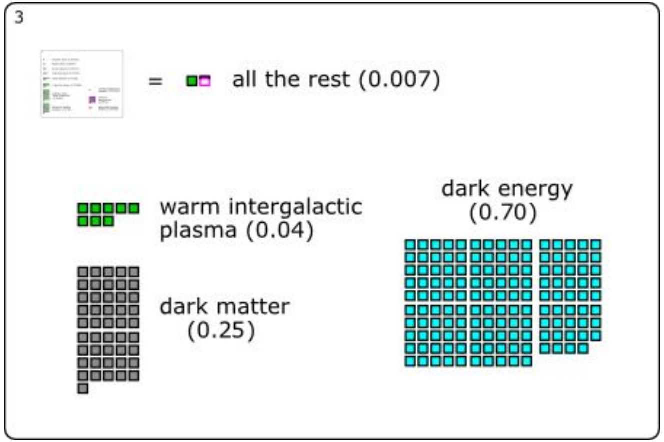
Cosmic energy inventory

$$u_c = \rho_c c^2 = \frac{3H^2}{8\pi G} c^2$$

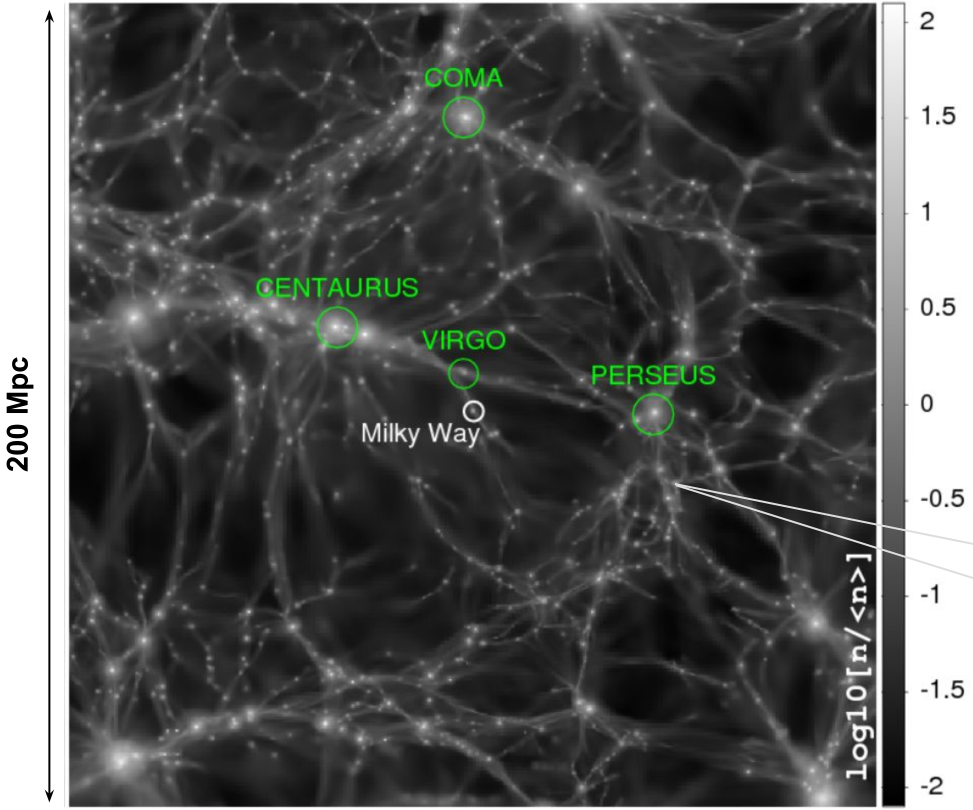
$$u_c \approx 4.8\,\mathrm{GeV\,m^{-3}}$$

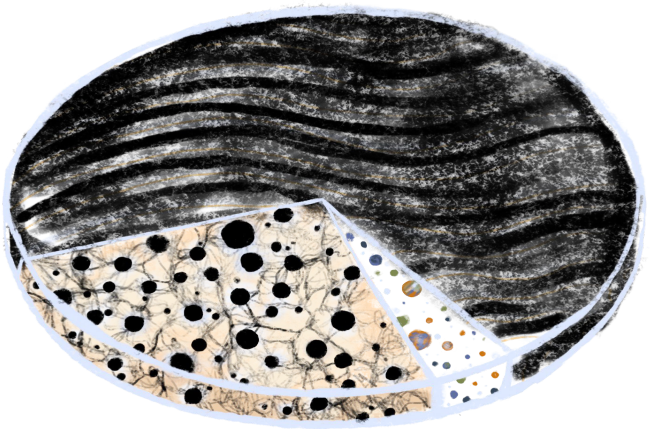


Credit: Fukujita et Peebles ‘04

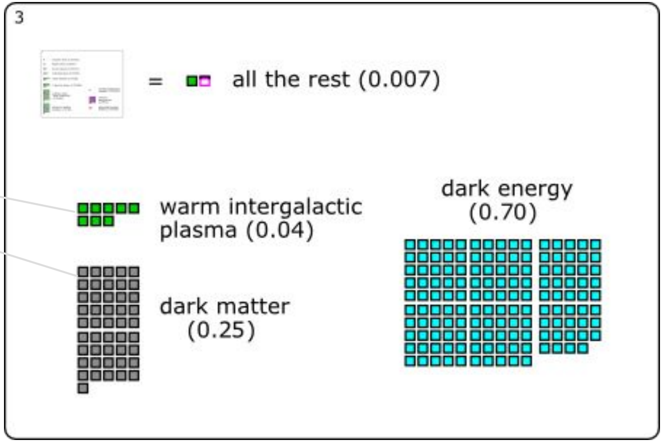


Cosmic energy inventory



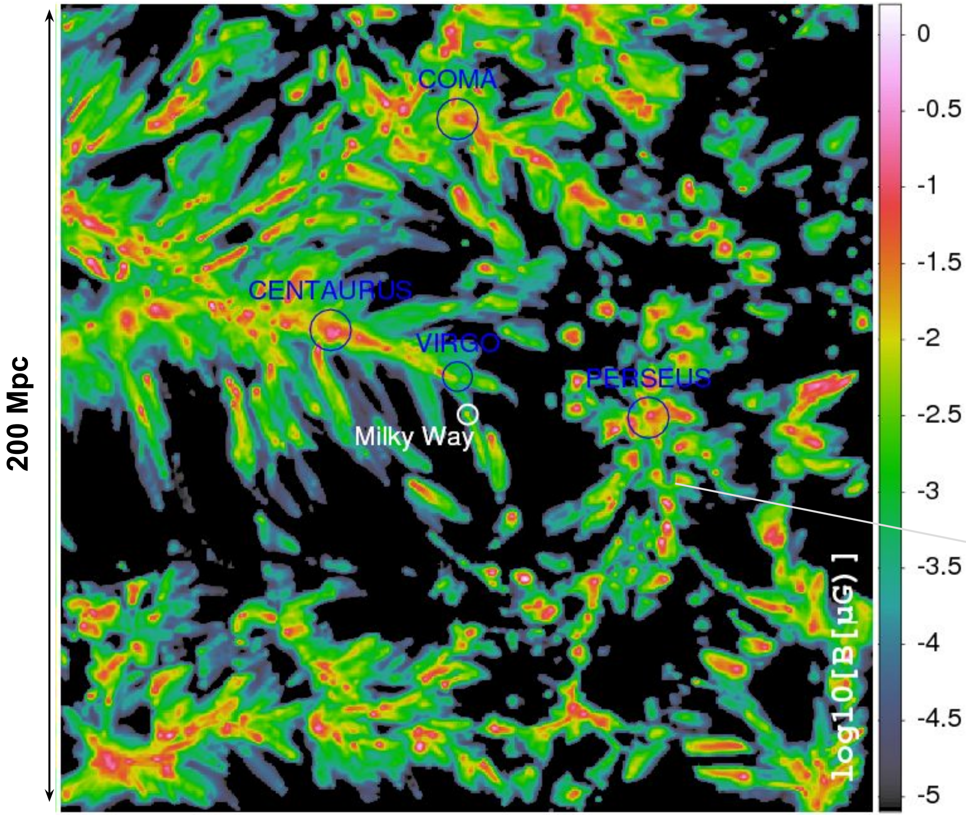


Credit: Fukujita et Peebles '04

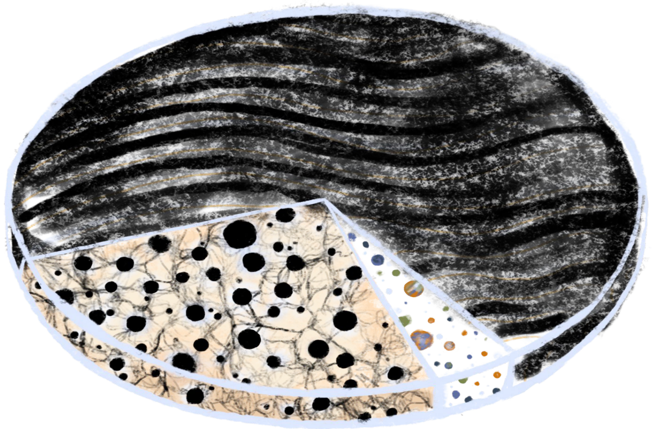


Credit: Hackstein+ 2018 (Cosmic V-web constrained sim. / CLUES)

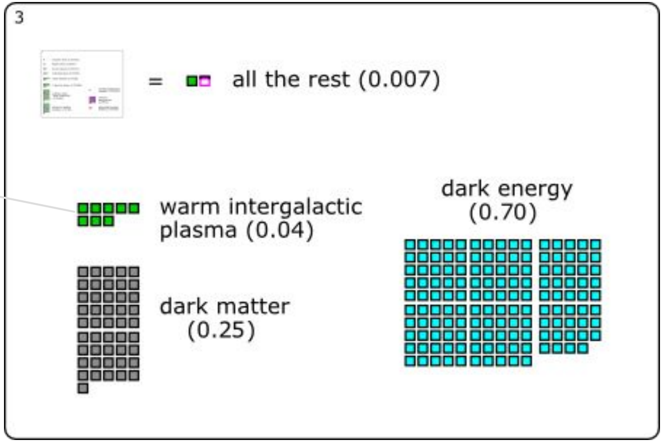
Cosmic energy inventory



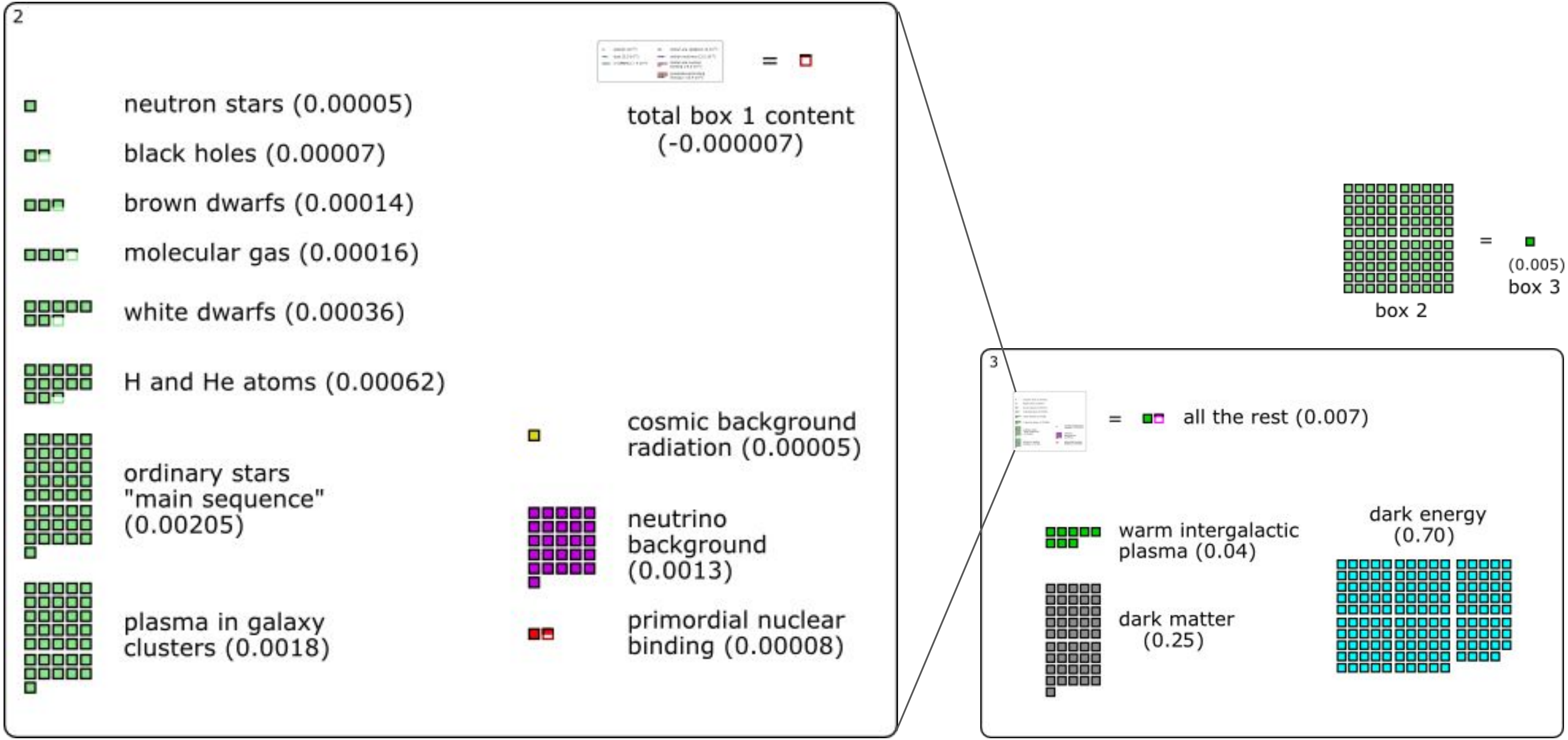
Credit: Hackstein+ 2018 (Cosmic V-web constrained sim. / CLUES)



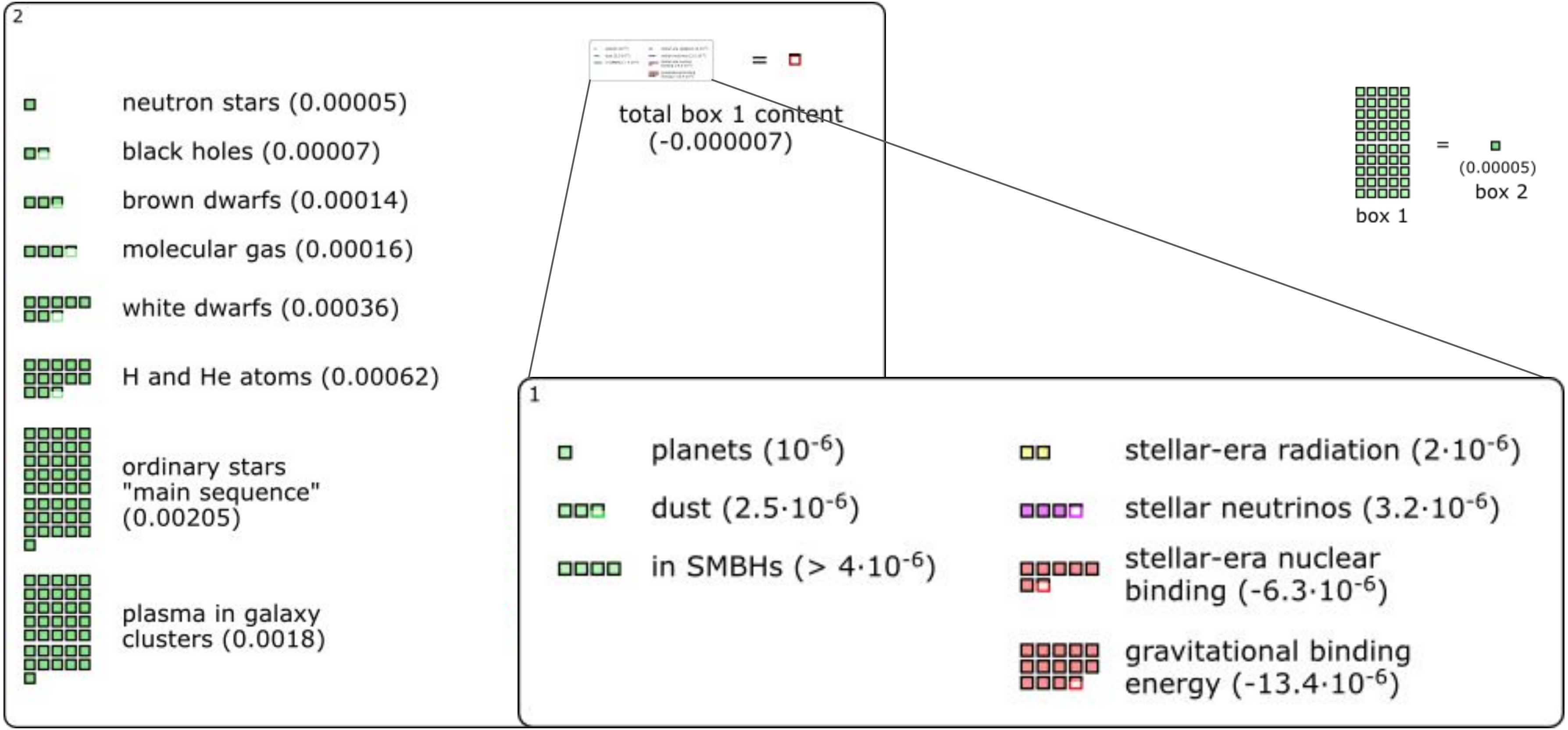
Credit: Fukujita et Peebles ‘04



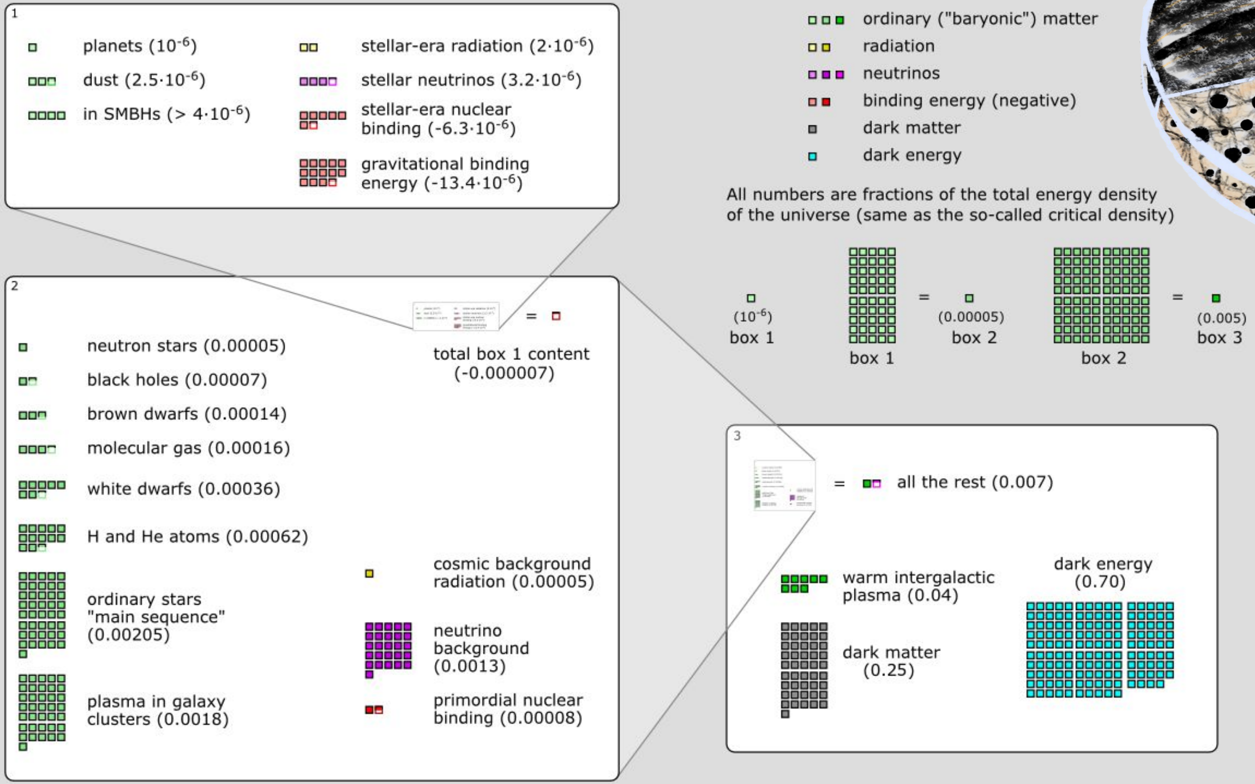
Cosmic energy inventory



Cosmic energy inventory



Cosmic energy inventory



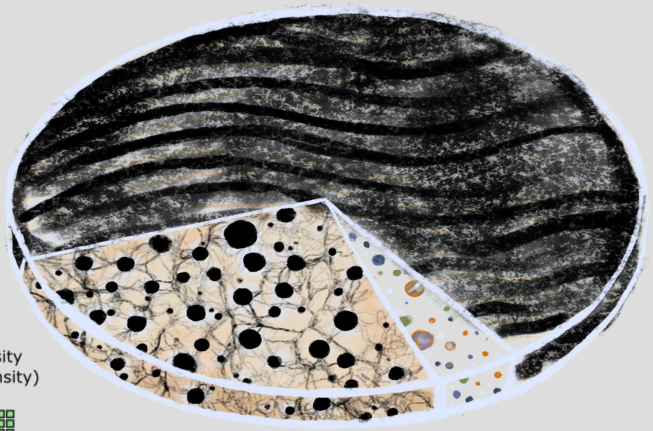
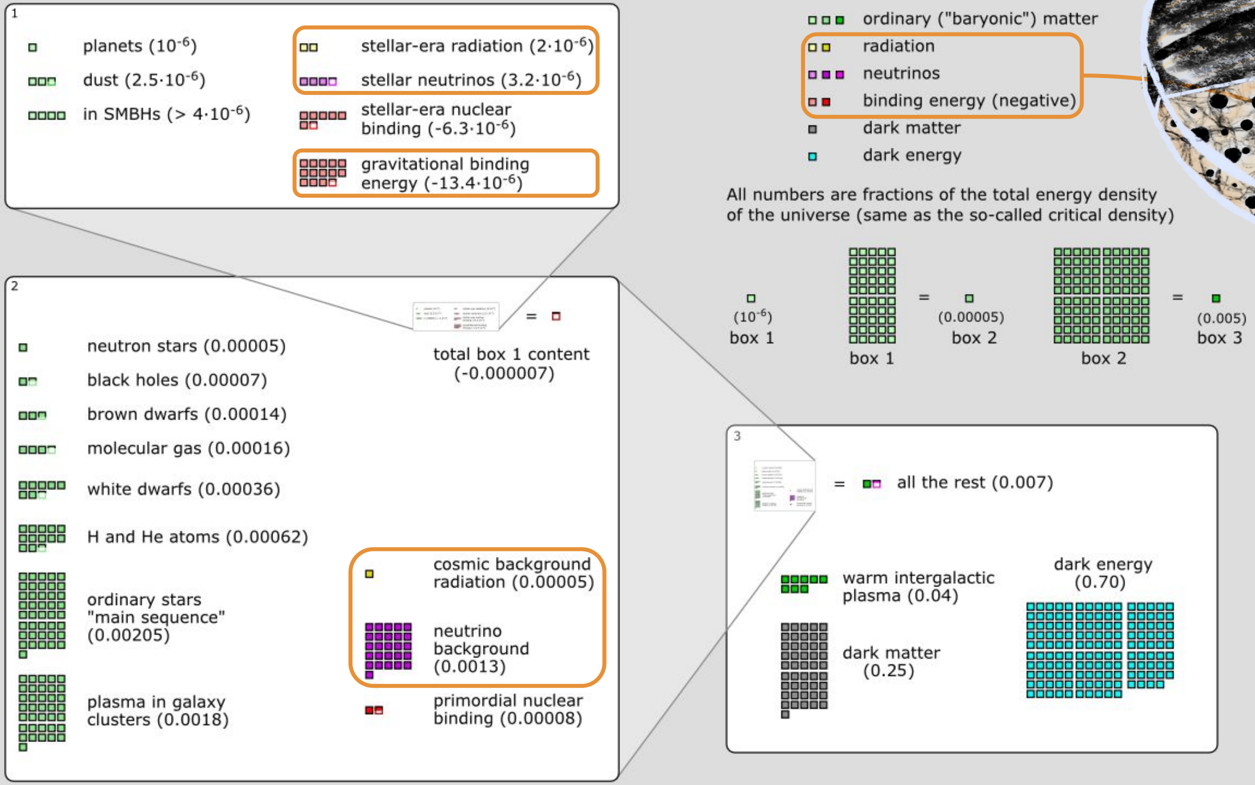
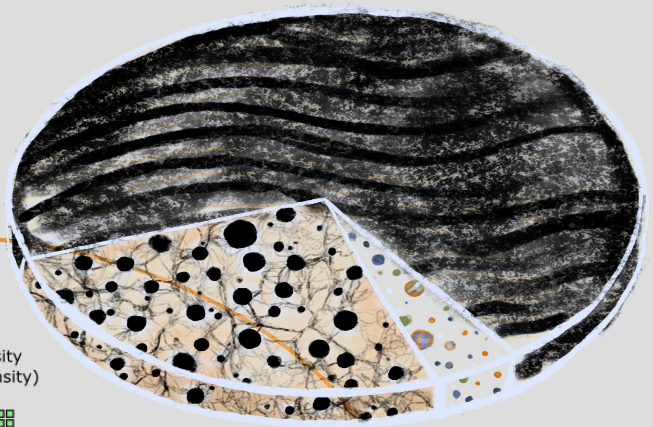


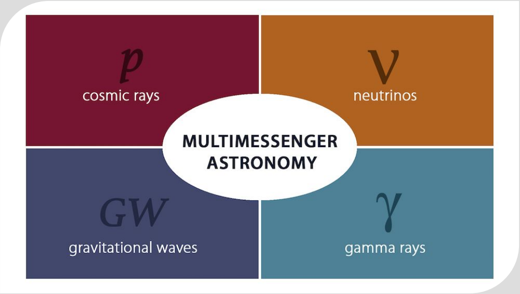
Chart by Markus Pössel [www.haus-der-astronomie.de] - Published under CC BY-NC-SA 3.0
Data from M. Fukugita & P.J.E. Peebles, "The Cosmic Energy Inventory" (2004) [adsabs.harvard.edu/abs/2004ApJ...616..643F]
Chart style following Randall Munroe's xkcd.com/radiation

Cosmic energy inventory





Nearly all our information on the universe: 4 messengers



Data from M. Fukugita & P.J.E. Peebles, "The Cosmic Energy Inventory" (2004) [adsabs.harvard.edu/abs/2004ApJ...616..643F]
Chart style following Randall Munroe's xkcd.com/radiation

Part I - Baryons and light: where to find them

from the cosmic web to the cosmic energy inventory

Part II - A cosmic history of light emission

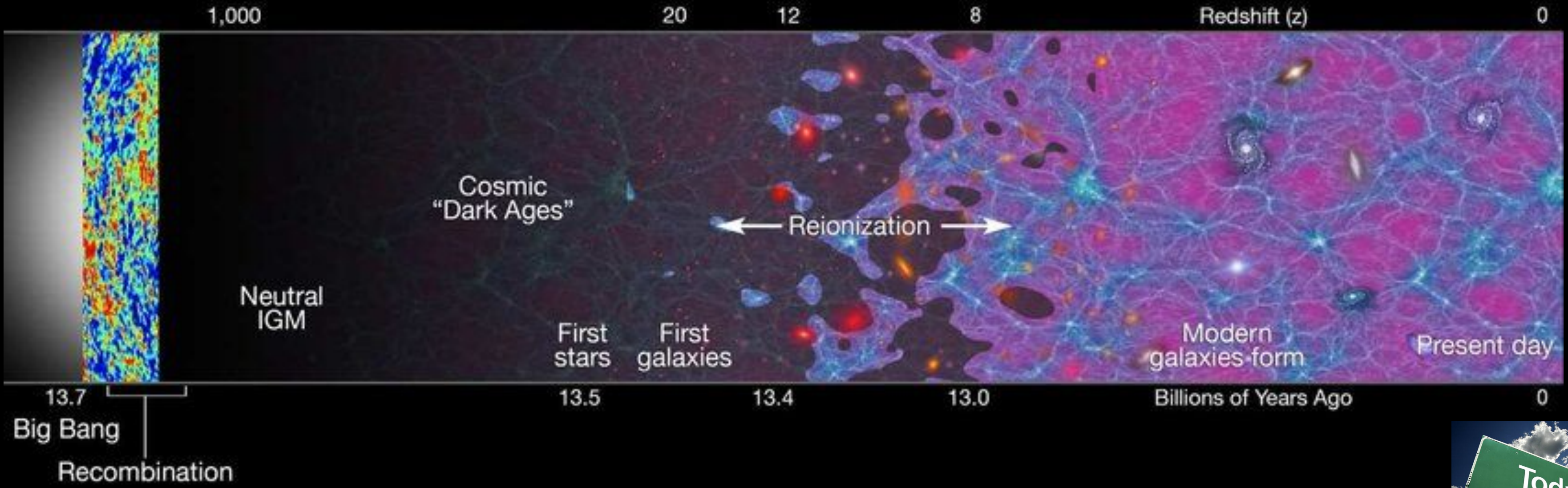
from the first stars to the current spectrum of the universe

Part III - The gamma-ray probe

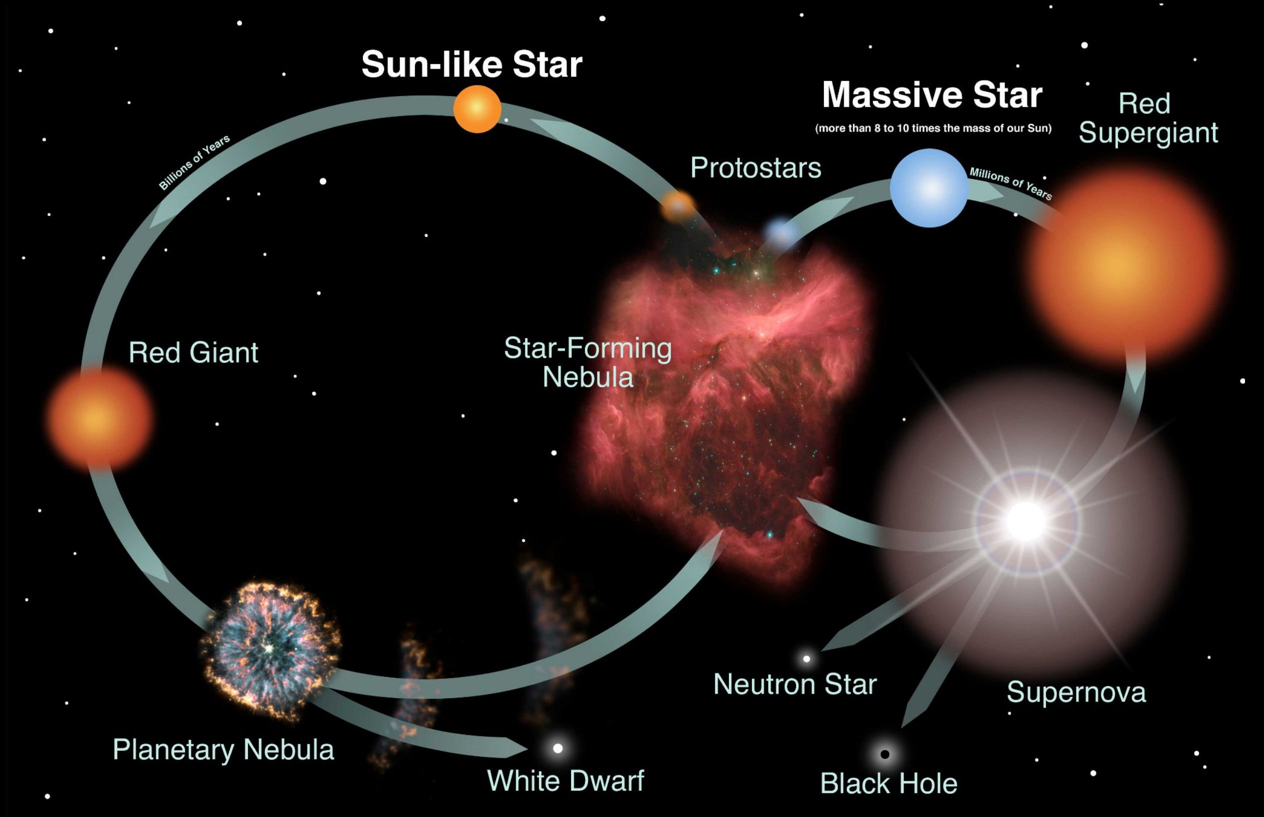
gamma-ray propagation on cosmological scales

Some useful references: Fukugita & Peebles ‘04, Madau & Dickinson ‘14, Pueschel & Biteau ‘21

Cosmic timeline

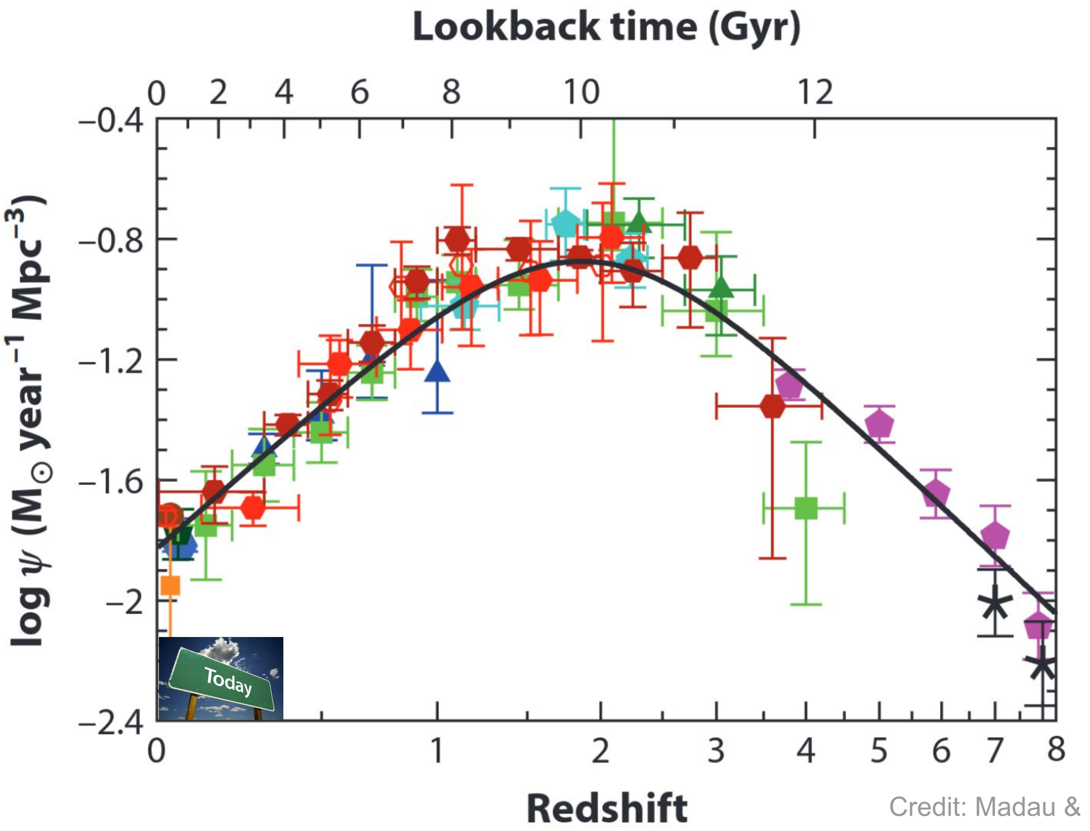


Power source of cosmic emissions: star formation



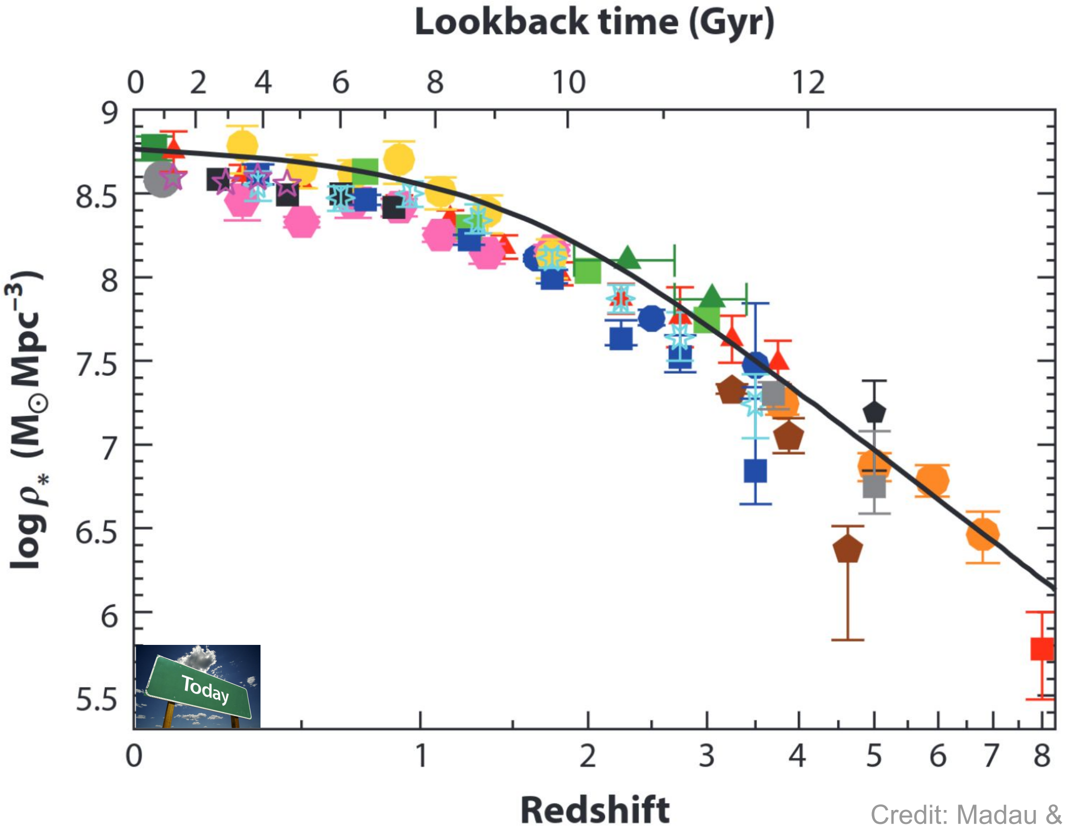
Credit: NASA and the Night Sky Network

Power source of cosmic emissions: star formation



Credit: Madau & Dickinson ‘14

Power source of cosmic emissions: star formation



Credit: Madau & Dickinson '14

Power source of cosmic emissions: star formation

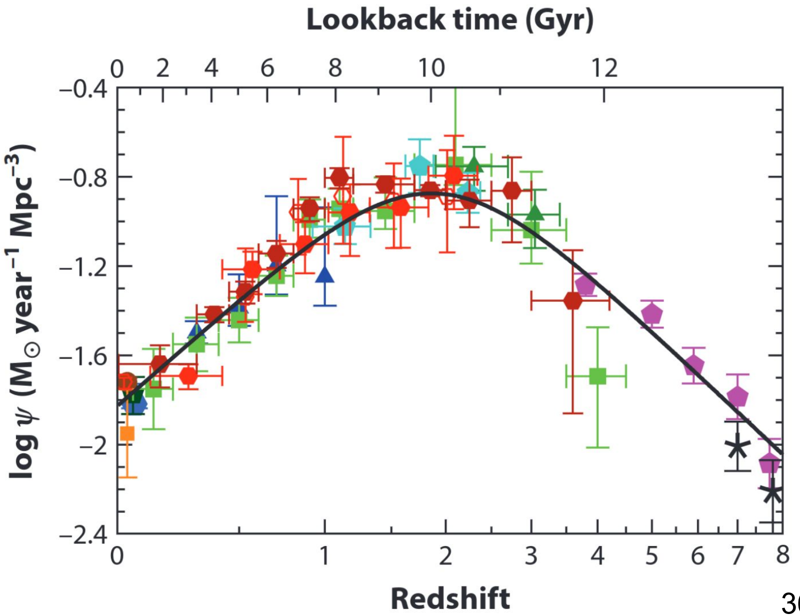
Exercise 2. Cosmic energy density of photons produced by nucleosynthesis

1. Estimate the efficiency of conversion of matter into light, $\epsilon_\odot$, within stars similar to the Sun. Its bolometric luminosity is $L_\odot = 3.8 \times 10^{26}$ W.

2. Discuss the efficiency of this light production compared with that of the pp chain:
   $4p + 2e^- \rightarrow {}^4He^{2+} + 2\,\nu_e$,

   which releases 26.1 MeV of energy in the form of photons (and 0.6 MeV in the form of neutrino kinetic energy).

3. From the light-to-matter conversion efficiency in the sun and the star formation rate density, calculate the energy density in the field of photons emitted by all the stars in the universe.



Power source of cosmic emissions: star formation

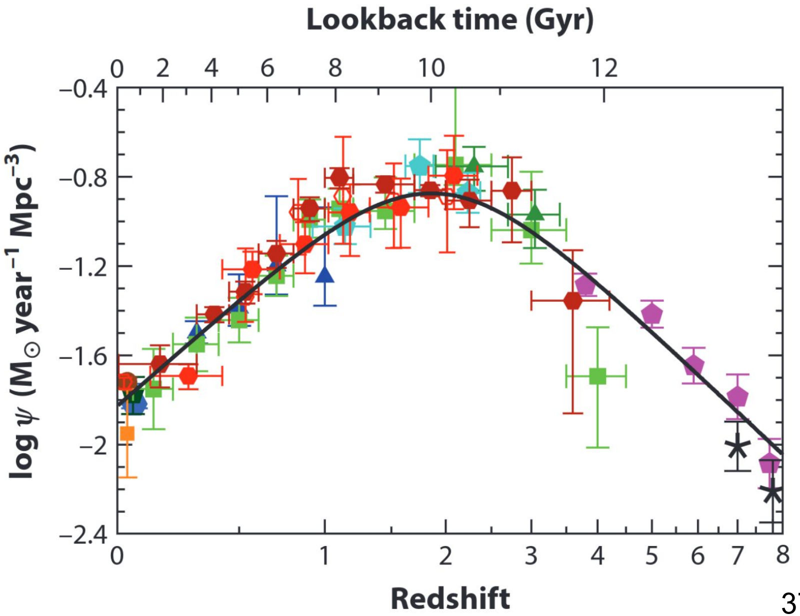
Exercise 2. Cosmic energy density of photons produced by nucleosynthesis

1. Estimate the efficiency of conversion of matter into light, $\epsilon_\odot$, within stars similar to the Sun. Its bolometric luminosity is $L_\odot = 3.8 \times 10^{26}$ W.

2. Discuss the efficiency of this light production compared with that of the pp chain: $4p + 2e^- \rightarrow {}^4He^{2+} + 2\,\nu_e$,

   which releases 26.1 MeV of energy in the form of photons (and 0.6 MeV in the form of neutrino kinetic energy).

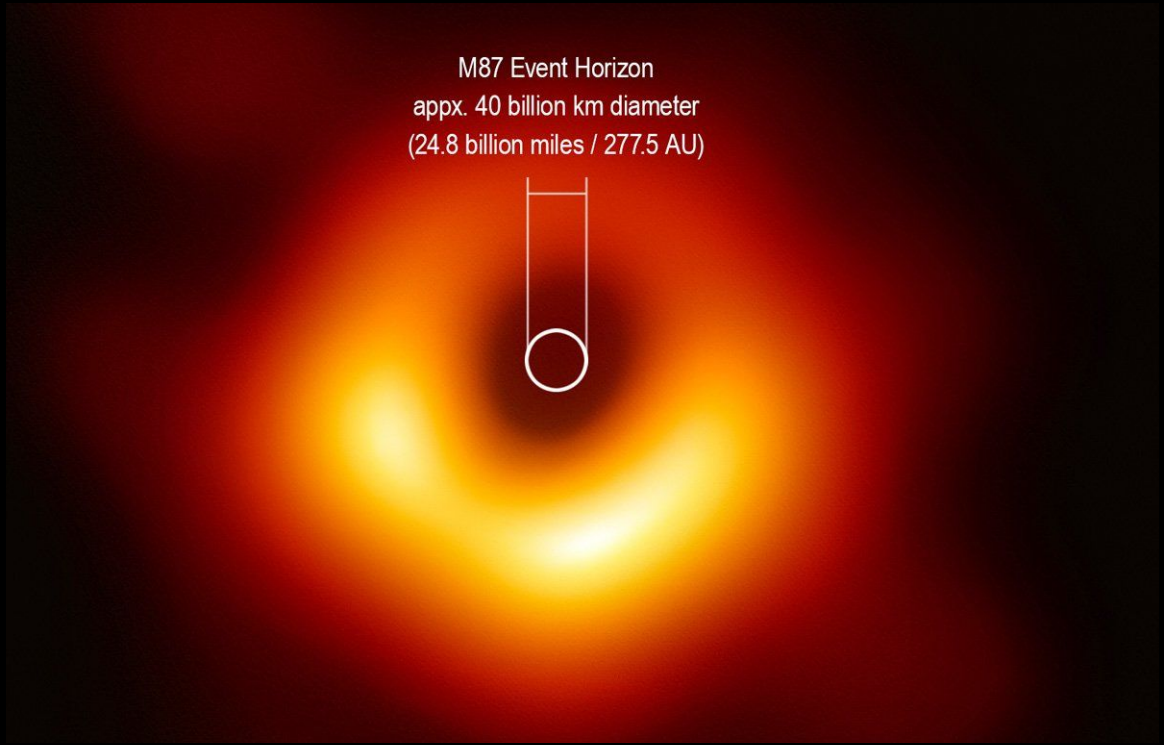
3. From the light-to-matter conversion efficiency in the sun and the star formation rate density, calculate the energy density in the field of photons emitted by all the stars in the universe.



star light -> 13×10^3 eV / m^3

Jonathan Biteau

Power source of cosmic emissions: black hole accretion



ratio of radiated power to rate of mass-energy deposition in the disc, measured by an observer at infinity:

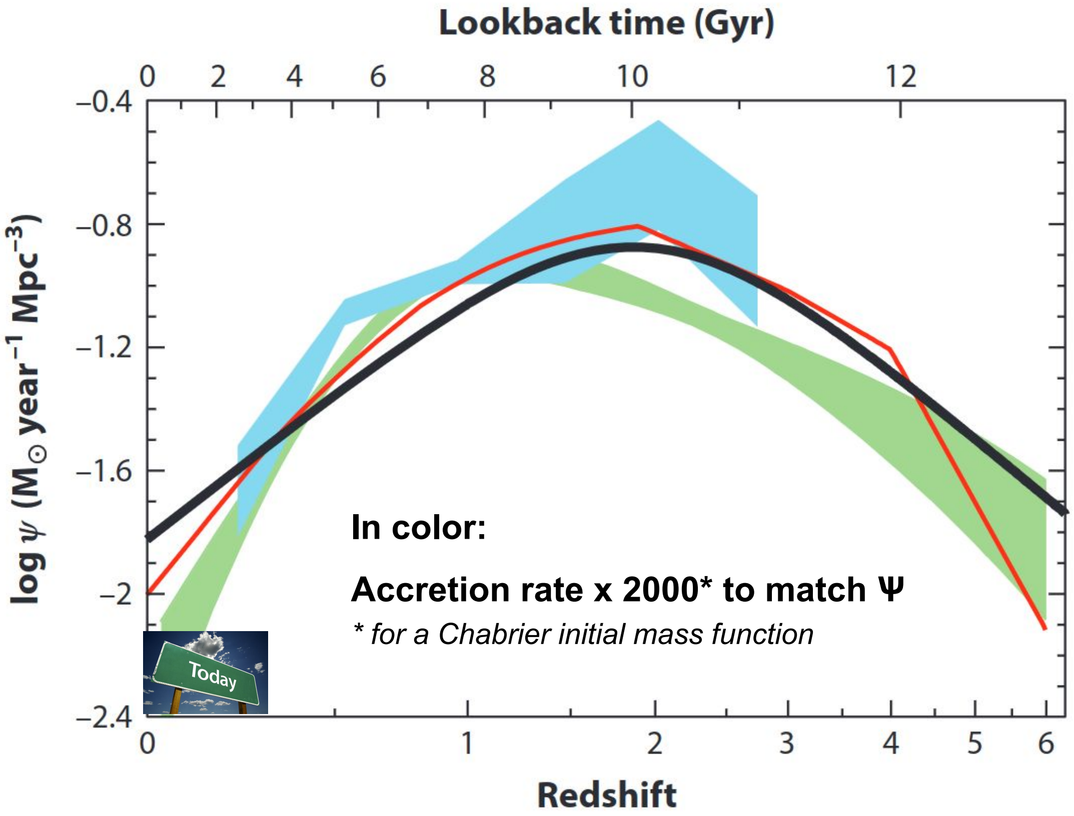
ϵ_{accr} = 5.7-30.8%

see Thorne, ‘74

Nobel in physics 2019
K. Thorne (GW)

$M_\bullet = (6.5 \pm 0.2_{stat} \pm 0.7_{sys}) \times 10^9\, M_\odot$ (EHT Collab. ‘19)

Power source of cosmic emissions: black hole accretion



In color:

Accretion rate x 2000* to match Ψ

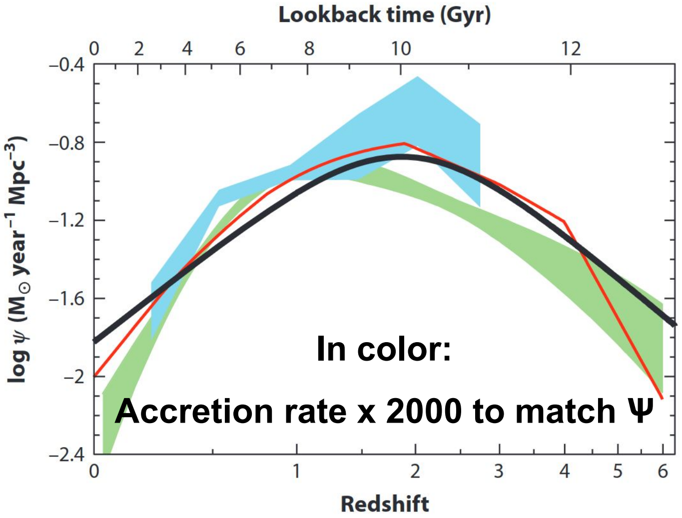
** for a Chabrier initial mass function*

Power source of cosmic emissions: black hole accretion

Exercise 3. Cosmic energy density of photons from accretion

1. What is the fraction of mass energy that can be converted to radiation for a black hole accreting at the rate M for a radiative efficiency 5.7% < ϵ_{accr} < 30.8% ?

2. Estimate the energy density of photons from matter accreted by massive black holes.



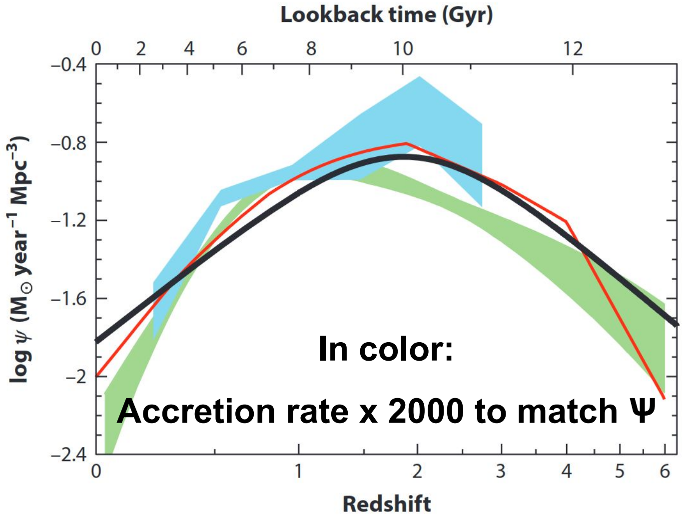
Power source of cosmic emissions: black hole accretion

Exercise 3. Cosmic energy density of photons from accretion

1. What is the fraction of mass energy that can be converted to radiation for a black hole accreting at the rate M for a radiative efficiency $5.7\% < \epsilon_{accr} < 30.8\%$?

2. Estimate the energy density of photons from matter accreted by massive black holes.

accretion light -> 1.5×10^3 eV / m^3



Brightness of the sky

The **energy density** u of an isotropic field of relativistic particles is linked to its **bolometric intensity** I, i.e. integrated over all frequencies, also known as the **surface brightness,** in W m^{-2} sr^{-1} or eV s^{-1} m^{-2} sr^{-1}:

$$I = \frac{c}{4\pi} u$$

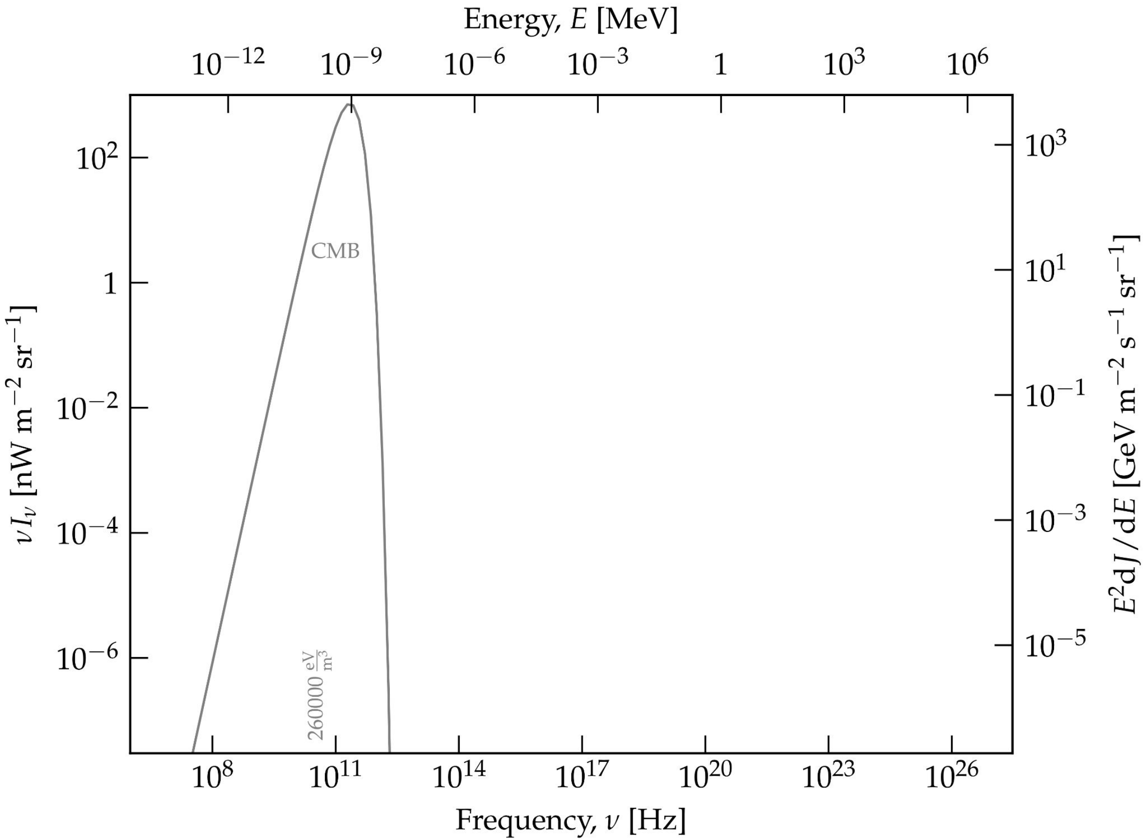
We can also define the **specific intensity** I_ν of an isotropic relativistic particle field, i.e. its intensity per unit frequency:

$$I_\nu = \frac{\mathrm{d}I}{\mathrm{d}\nu}$$

We often plot $\boldsymbol{\nu I_\nu}$ **as a function of ln($\boldsymbol{\nu}$)** or $\log_{10}(\nu)$, the integral of which gives the bolometric intensity:

$$\begin{aligned}\int \nu I_\nu \,\mathrm{d}\ln\nu &= \int \nu I_\nu \frac{\mathrm{d}\nu}{\nu} \\ &= \int I_\nu \,\mathrm{d}\nu \\ &= I \\ &= \frac{c}{4\pi} u\end{aligned}$$

The spectrum of the universe



The spectrum of the universe

CMB: cosmic microwave background

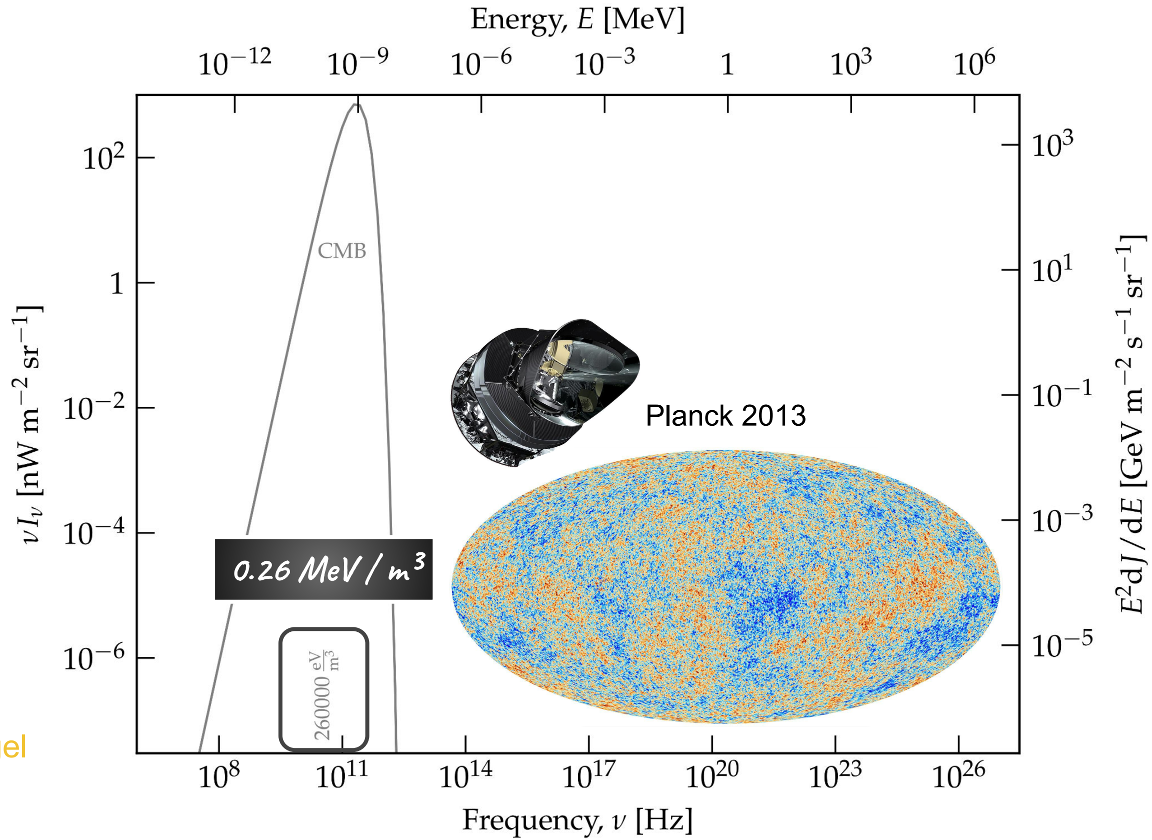
THE black body at T_0 = 2.7 K, discovered in 1964.

emitted at T = 3000 K during decoupling
between photons and matter (t = 370,000 ans).

Nobel in physics 1978
A. Penzias & R. Wilson (CMB)
P. L. Kapista (low-T physics)

Nobel in physics 2006
J. C. Mather & G. F. Smoot

Shaw in astronomy 2010
C. L. Bennet, L. A. Page, D. N. Spergel

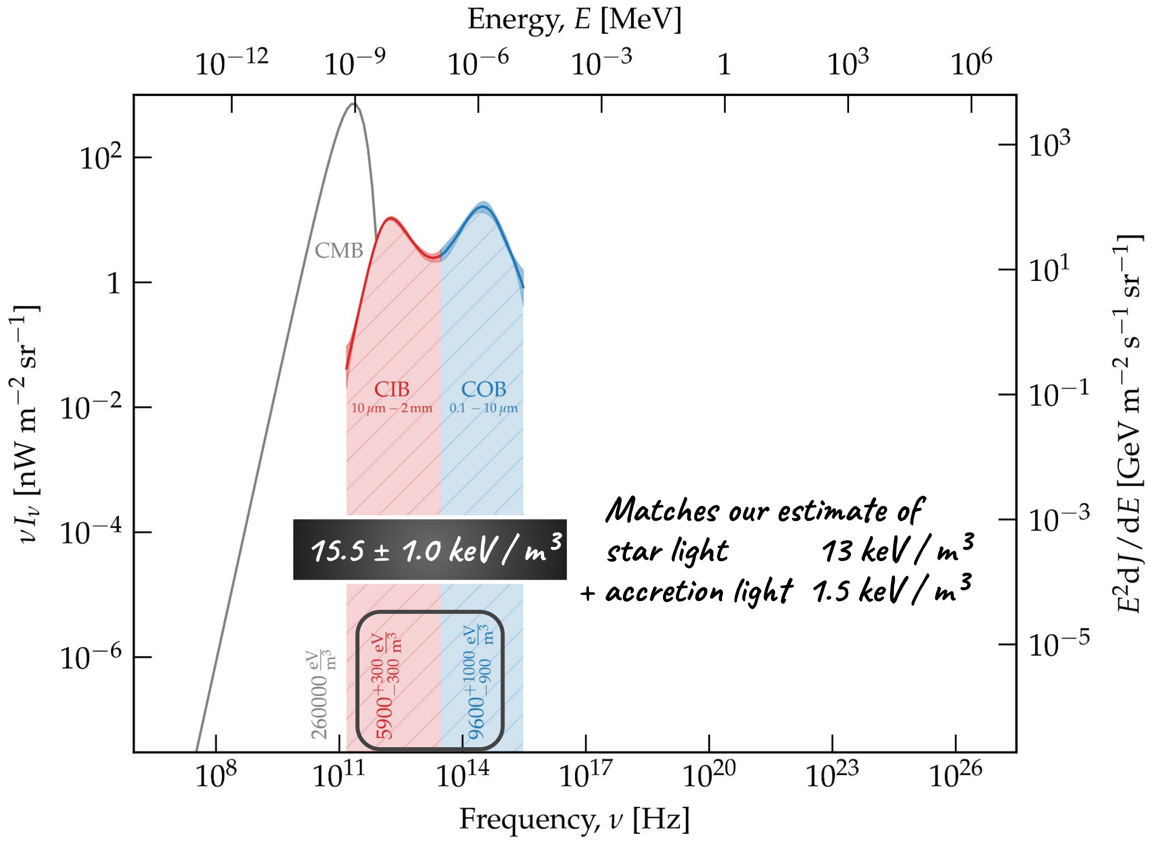


The spectrum of the universe

CIB, COB: cosmic infrared and optical backgrounds

CIB discovered in 1996.

Emitted since reionization ($t \gtrsim 0.5$ Gyr) by all stars and galaxies



Shaw in astronomy 2018
J. L. Puget (CIB)

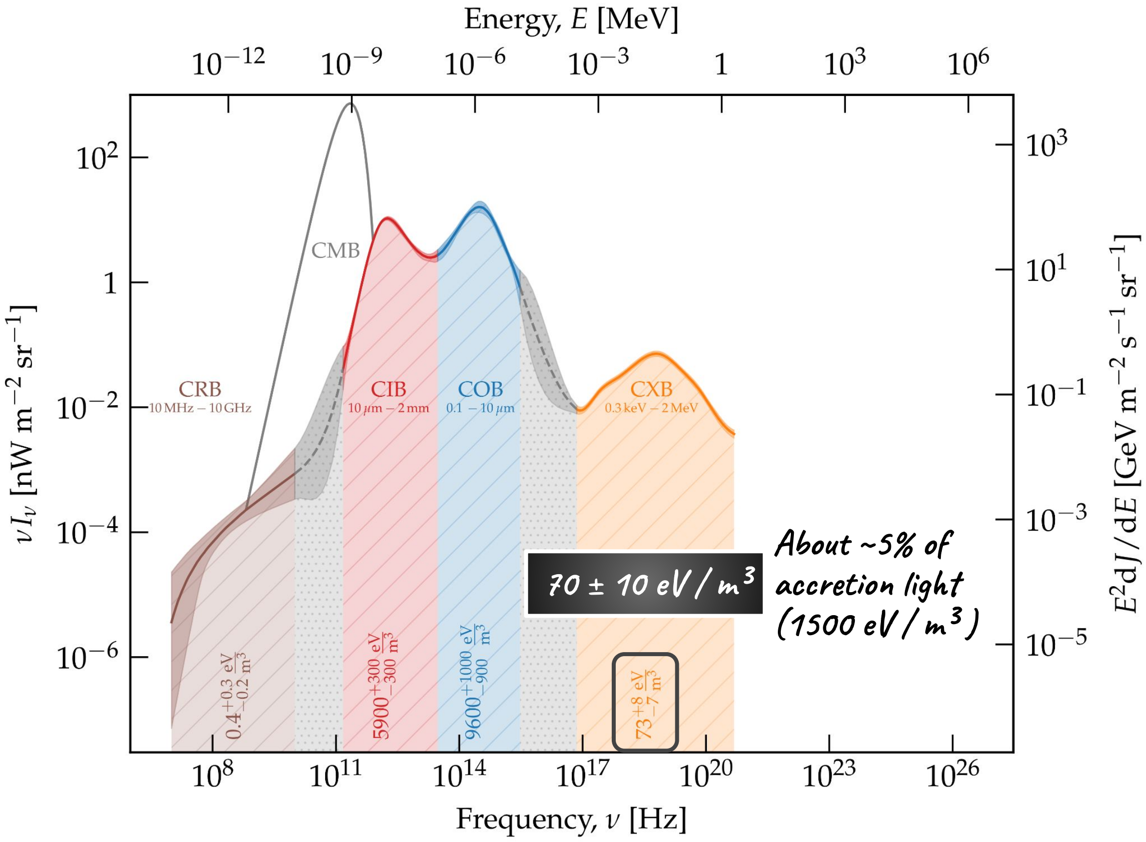
The spectrum of the universe

CRB, CXB: cosmic radio and X-ray backgrounds

CXB discovered in 1962.

Radiation of the electrons accelerated in the winds of starforming and active galaxies

Nobel in physics 2002
R. Giacconi (CXB)



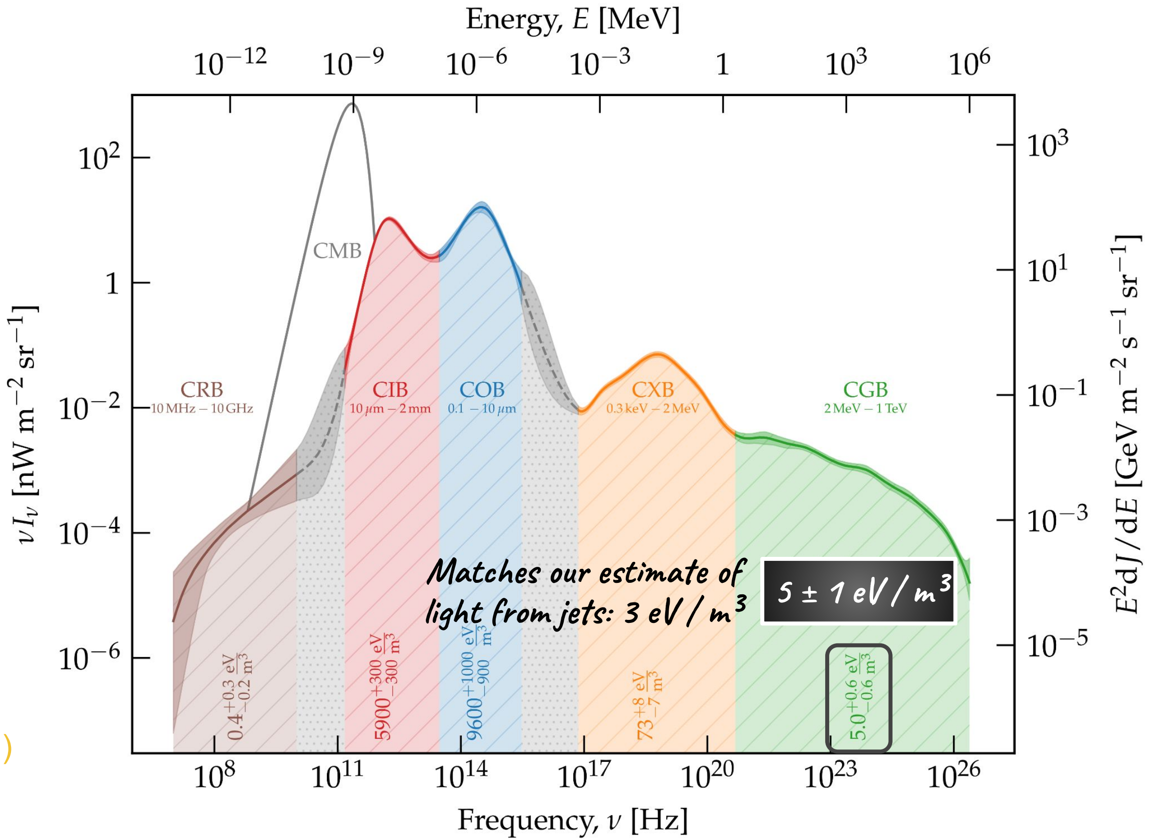
The spectrum of the universe

CGB: cosmic gamma-ray background

CGB discovered en 1977.

Radiation of the electrons accelerated in
jetted active galactic nuclei
around supermassive black holes

Shaw in astronomy 2020
R. D. Blandford (active galactic nuclei)



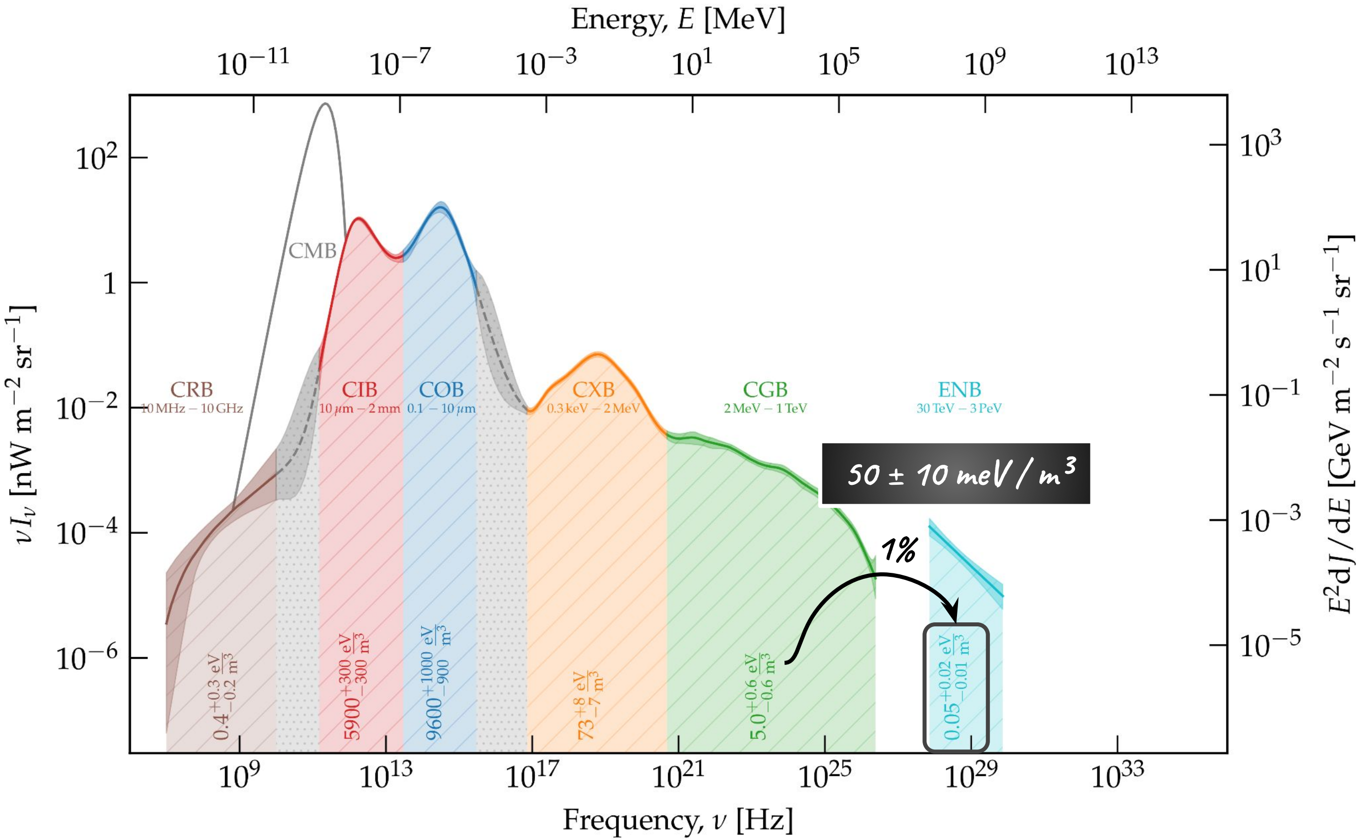
The spectrum of the universe

ENB: extragalactic neutrino background

ENB discovered in 2013.

To date, no source detected at the 5σ level…

But exciting pieces of evidence!

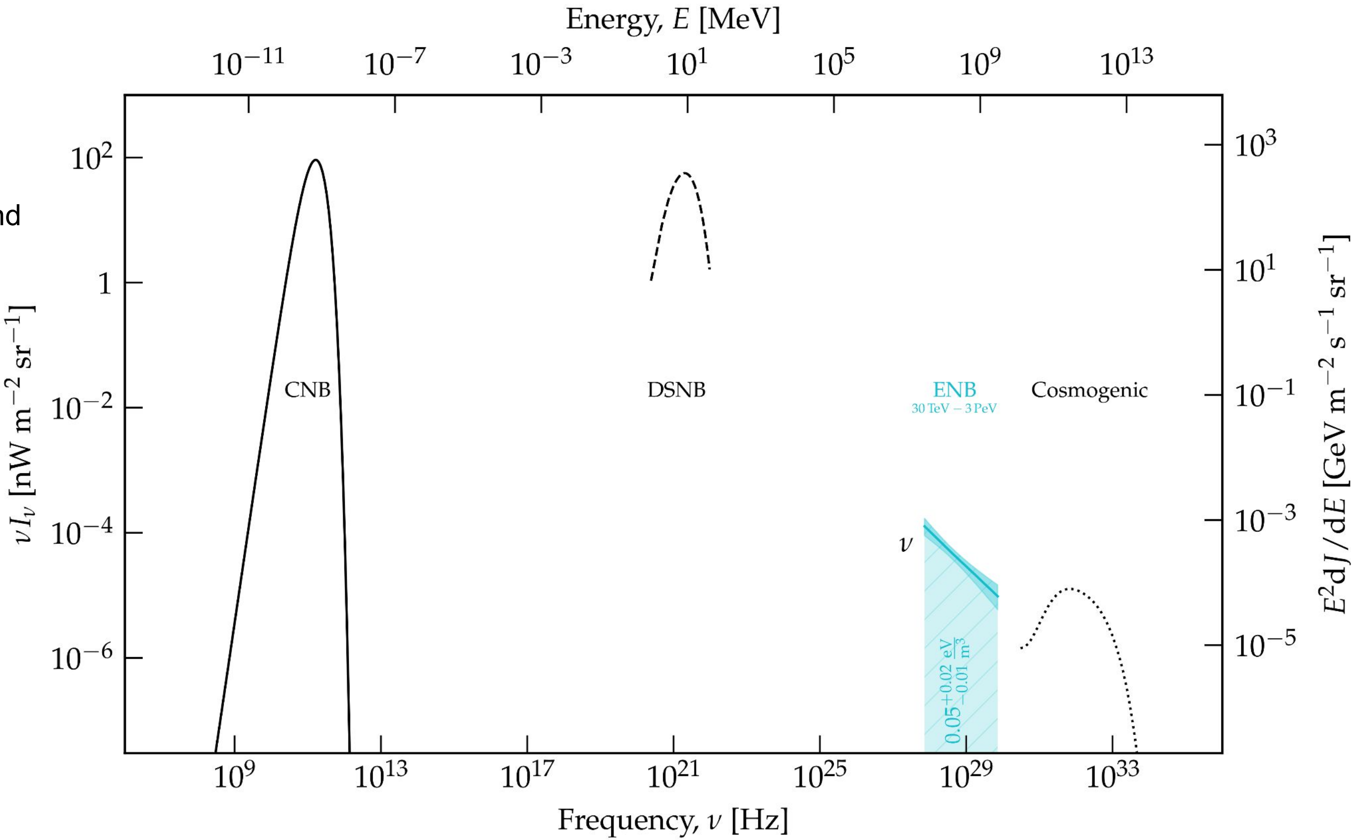


The spectrum of the universe

Other neutrino backgrounds

Not detected

- **CNB**: cosmic neutrino background emitted at t ~ 1 s
- **DSNB**: diffuse supernova background
- **Cosmogenic neutrinos**, from the propagation of ultra-high energy cosmic rays



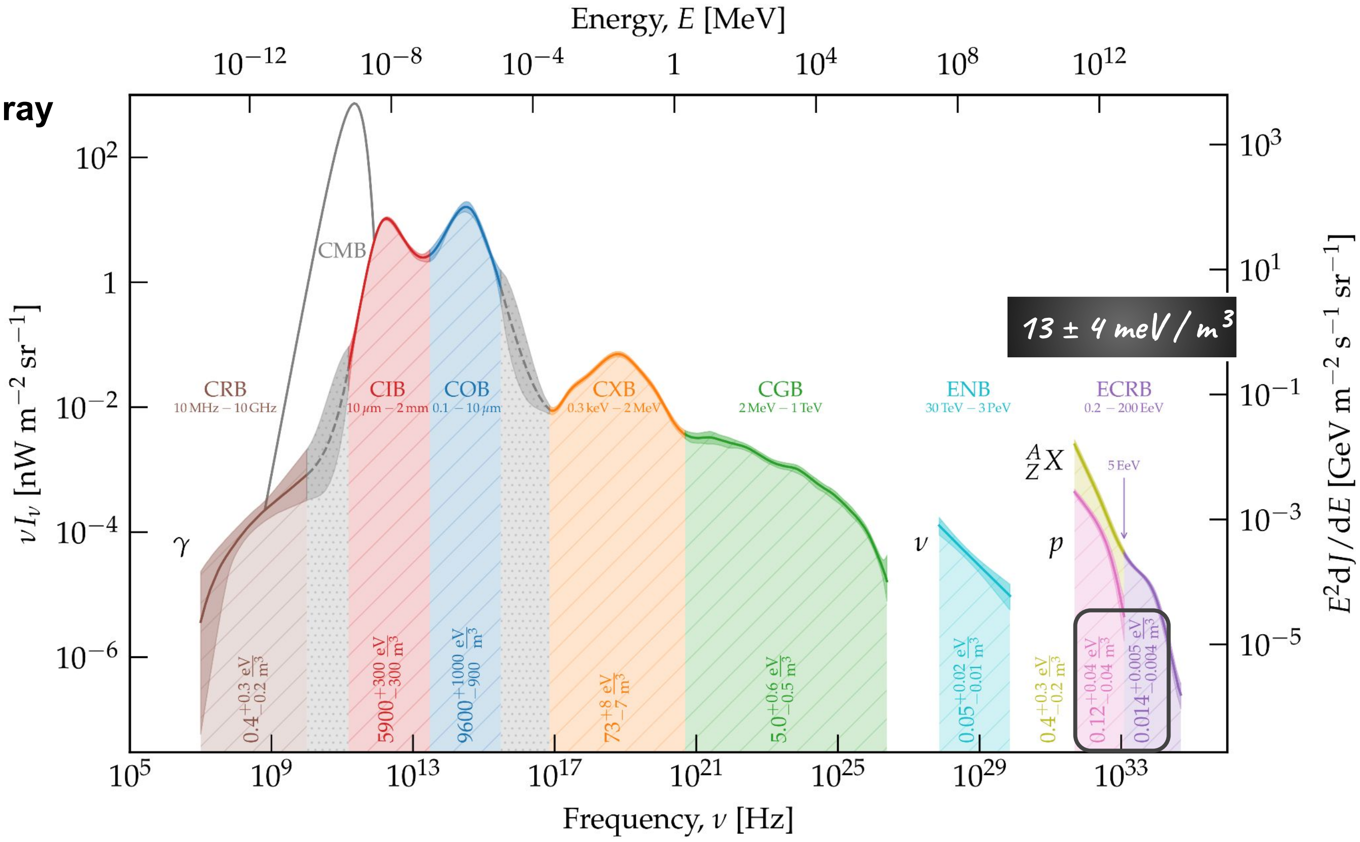
The spectrum of the universe

ECRB: extragalactic cosmic ray background

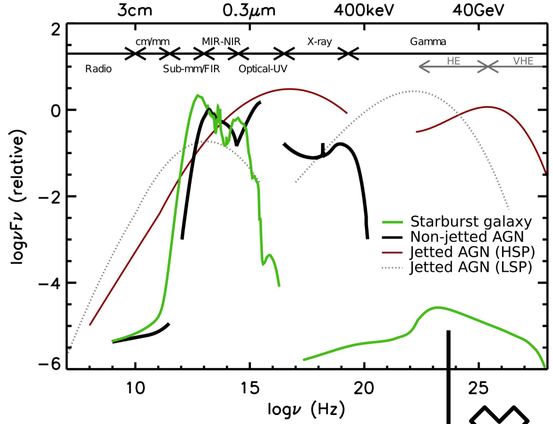
Discovered in 1962.

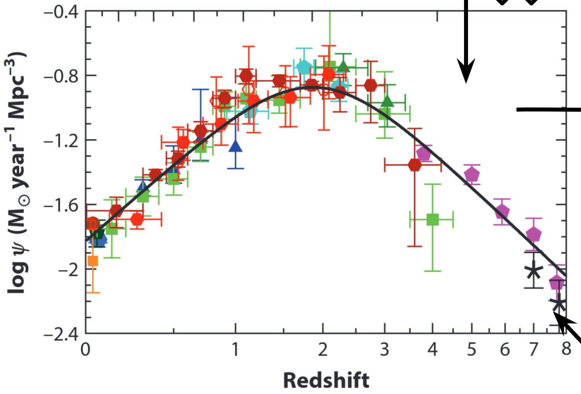
Extremely low flux:
1 per year per km^2 over 4π above the ankle at 5 EeV.

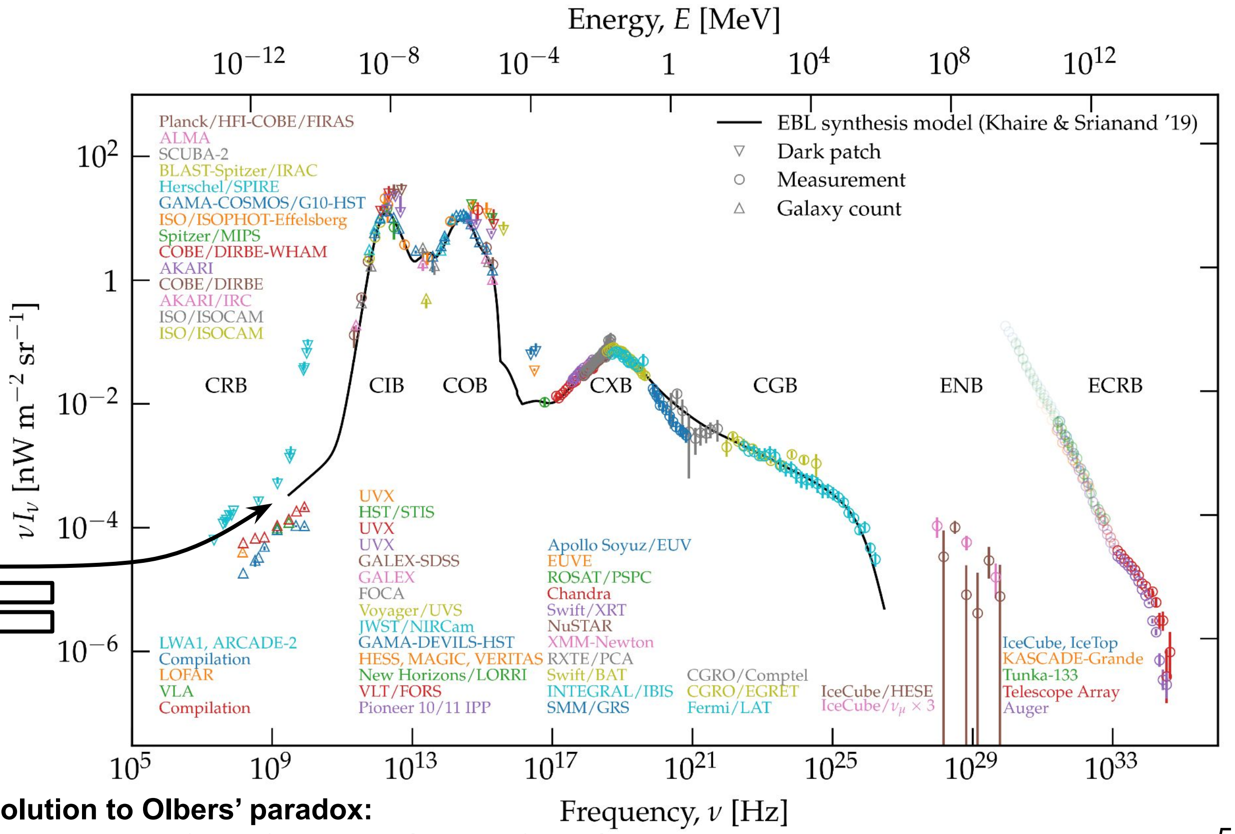
Dipole in the sky firmly detected but no source identified (yet!)



Synthesis models of all galaxies







Solution to Olbers' paradox:
finite history of star formation (limited forest)

Part I - Baryons and light: where to find them

from the cosmic web to the cosmic energy inventory

Part II - A cosmic history of light emission

from the first stars to the current spectrum of the universe

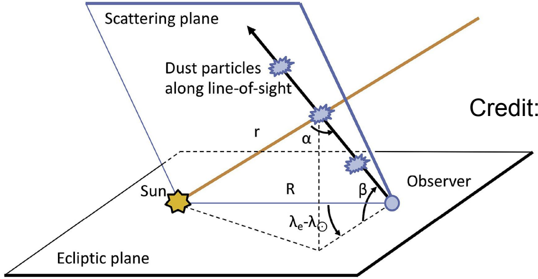
Part III - The gamma-ray probe

gamma-ray propagation on cosmological scales

Some useful references: Fukugita & Peebles ‘04, Madau & Dickinson ‘14, Pueschel & Biteau ‘21

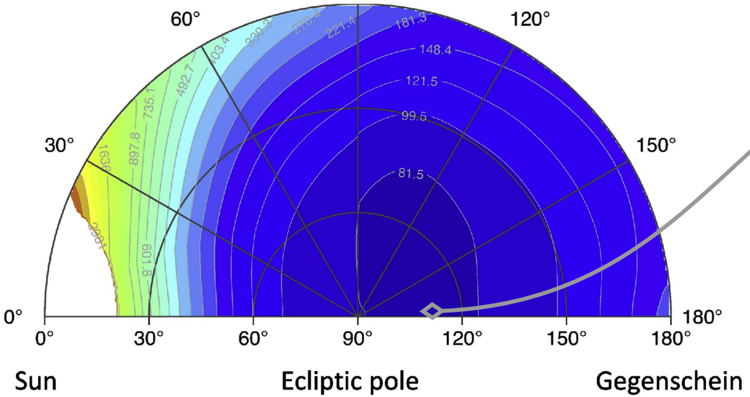
Contaminants in the O/IR

Zodiacal light, integrated star light, diffuse galactic light (cirrus)[1]

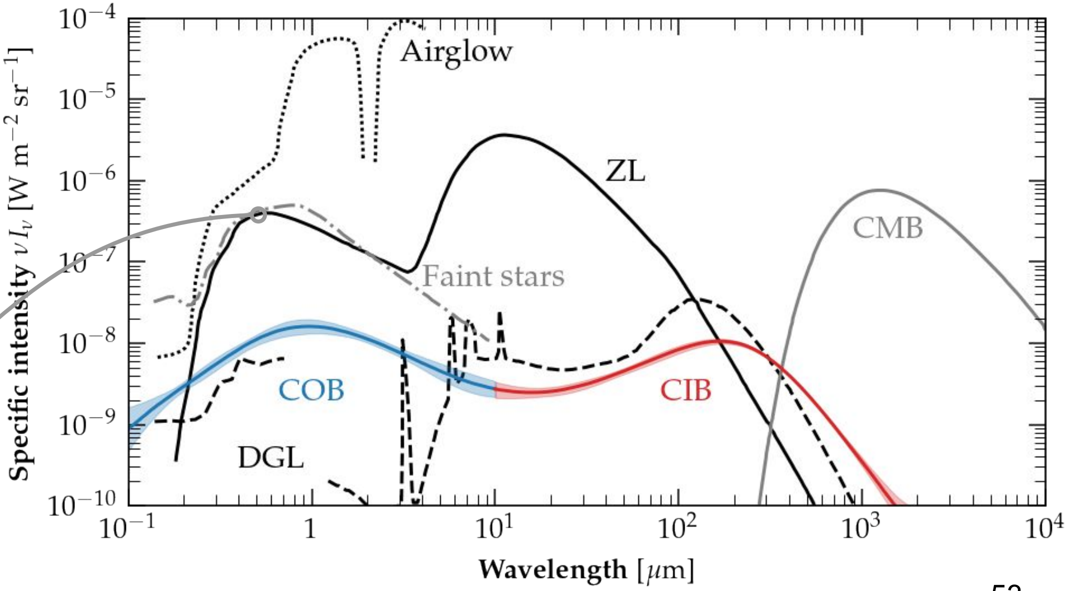


Credit: Lasue 2020

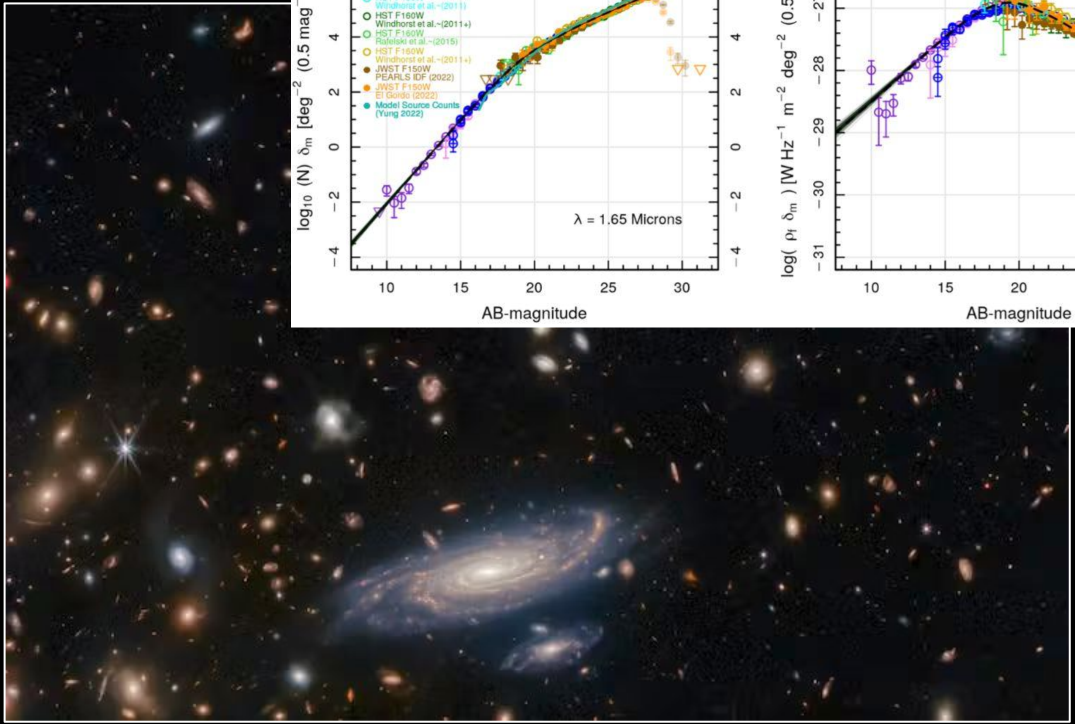
@ 0.55 µm

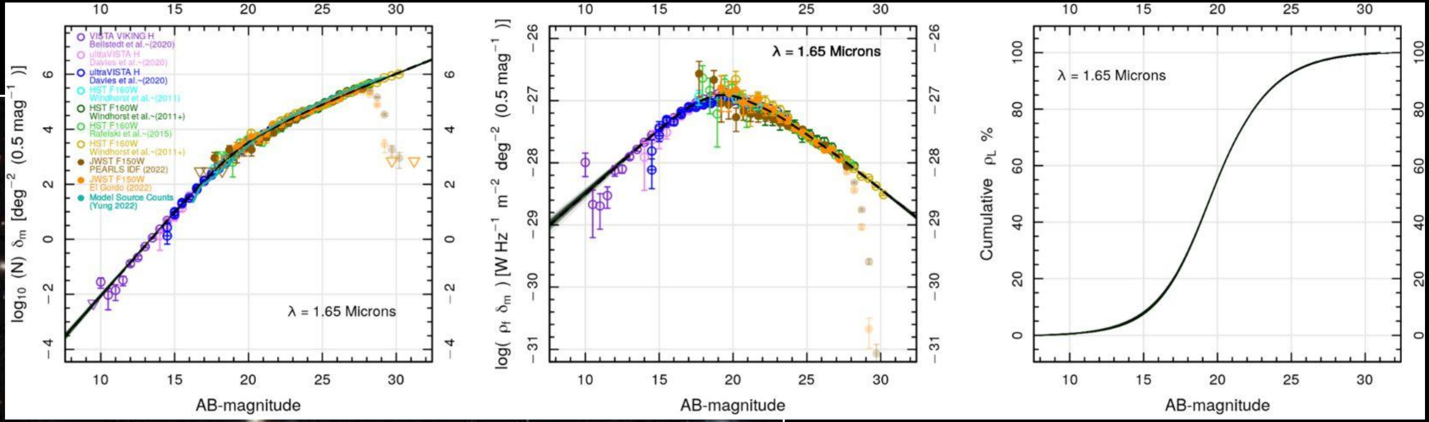


Credit: L. Gréaux
Adapted from Leinert '97 & JB '23



Integrated galaxy light (galaxy counts)

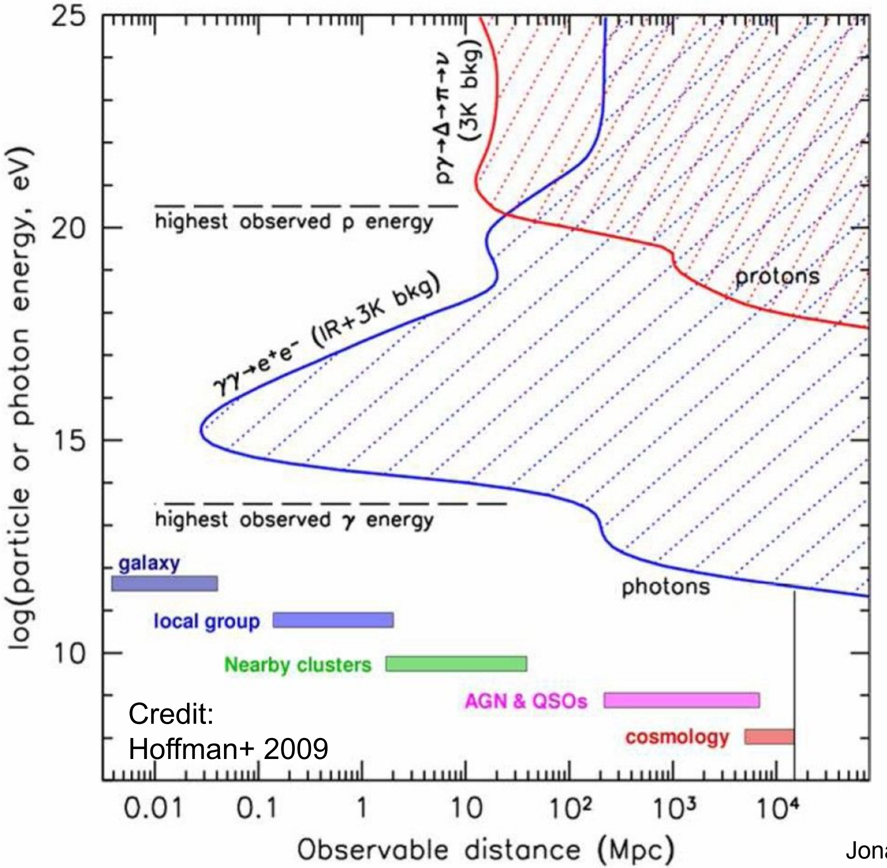




Windhorst+ ‘23

Crédit : ESA/Webb, NASA & CSA, A. Martel.

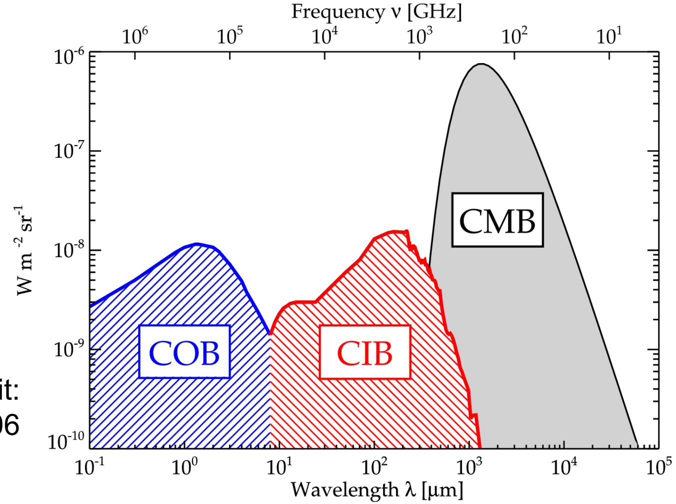
Cosmic propagation of TeV gamma rays and EeV cosmic rays



Credit:
Hoffman+ 2009

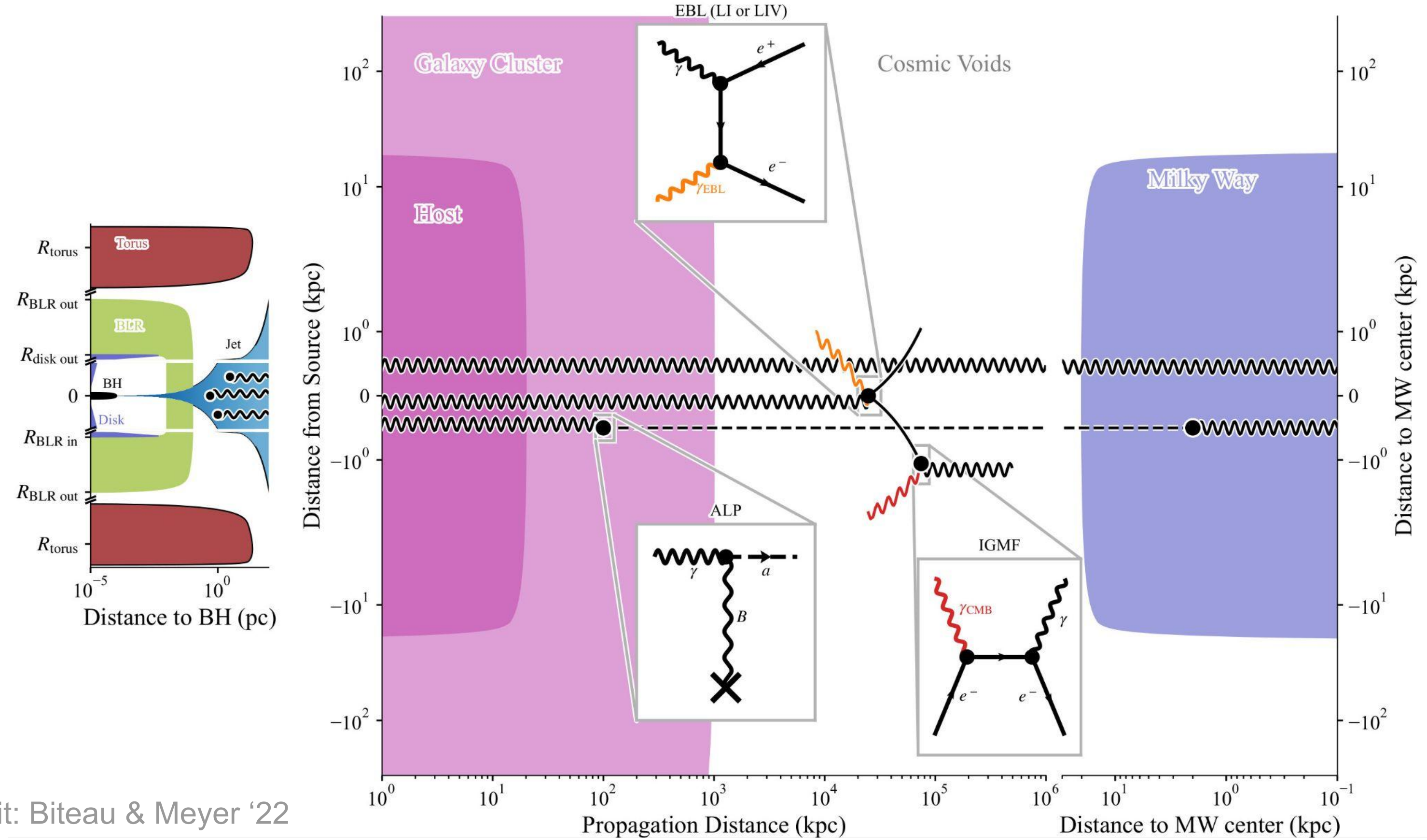
p + γ(CIB/CMB)→ p/n + π (or p + $e^{+/-}$)
→ $2m_p\, m_\pi\, /\, 4E_{EBL/CMB}$ ~ **50 EeV** x ($\lambda_{CMB\,/\,CIB}$ / **1000 μm**)

γ + γ(COB/CIB) → $e^+ e^-$
→ $(2m_e)^2\, /\, 4E_{EBL/CMB}$ ~ **1 TeV** x ($\lambda_{CIB\,/\,COB}$ / **1 μm**)



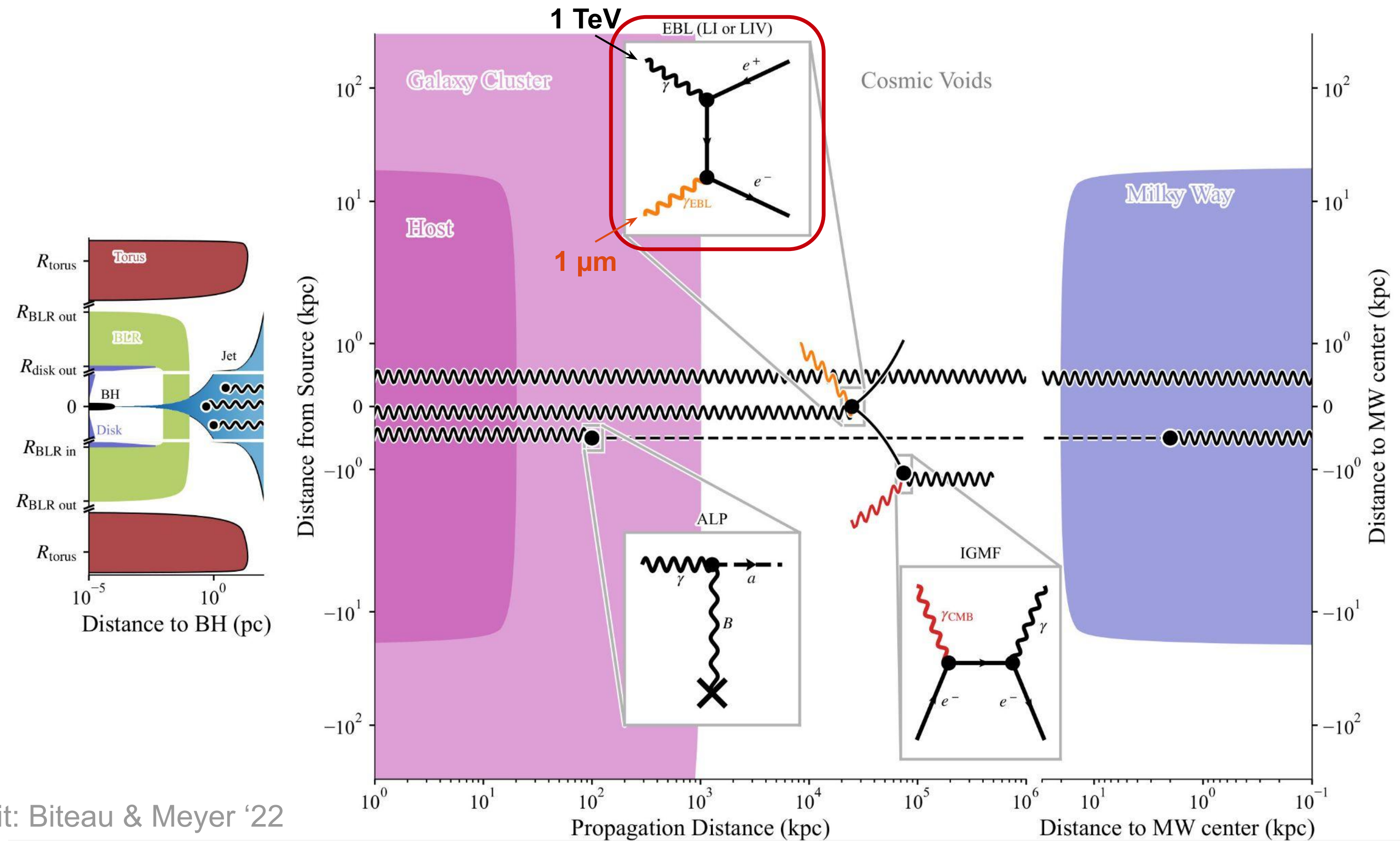
Credit:
Dole+ 2006

ɣ-ray propagation from sources down to Earth



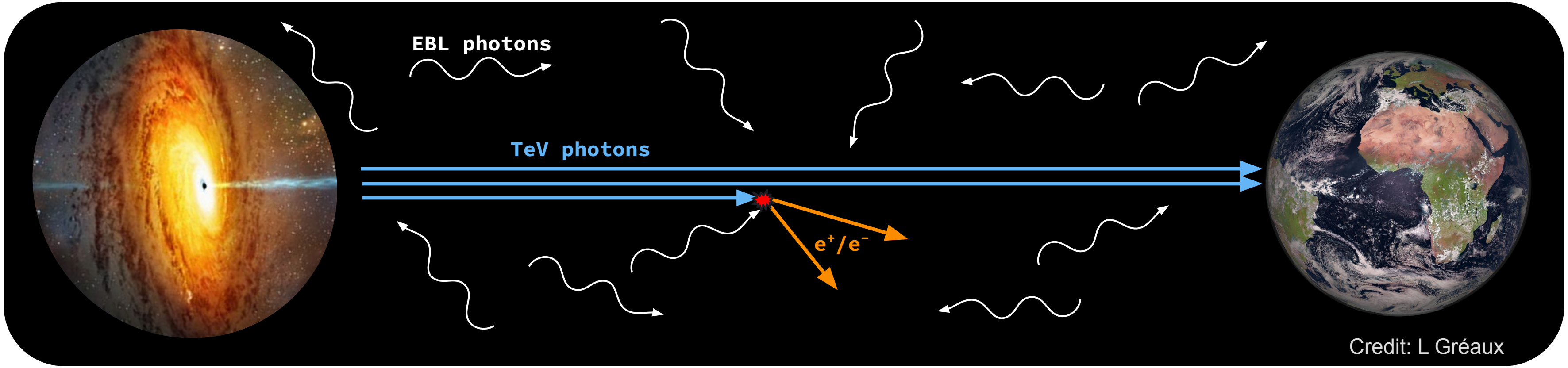
Credit: Biteau & Meyer ‘22

ɣ-ray propagation from sources down to Earth



Credit: Biteau & Meyer ‘22

TeV ɣ-ray flux suppression



TeV gamma-ray suppression $$\Phi_{\mathrm{obs}}(E,z) = \Phi_{\mathrm{int}}(E) \times e^{-\tau(E,z)}$$

where the **optical depth τ** is the integral of the interaction rate **(inverse mean free path Γ)** over light travel time **(light travel distance *L*)**:

$$\tau(E,z) = \int_0^z \mathrm{d}z' \, \frac{\partial L}{\partial z'} \Gamma_{\gamma\gamma}^{-1}(E(1+z'),z')$$

TeV ɣ-ray flux suppression

TeV gamma-ray suppression $\Phi_{\rm obs}(E,z) = \Phi_{\rm int}(E) \times e^{-\tau(E,z)}$

where the **optical depth τ** is the integral of the interaction rate **(inverse mean free path Γ)** over light travel time **(light travel distance *L*)**:

$$\tau(E,z) = \int_0^z {\rm d}z' \, \frac{\partial L}{\partial z'} \Gamma^{-1}_{\gamma\gamma}(E(1+z'), z')$$

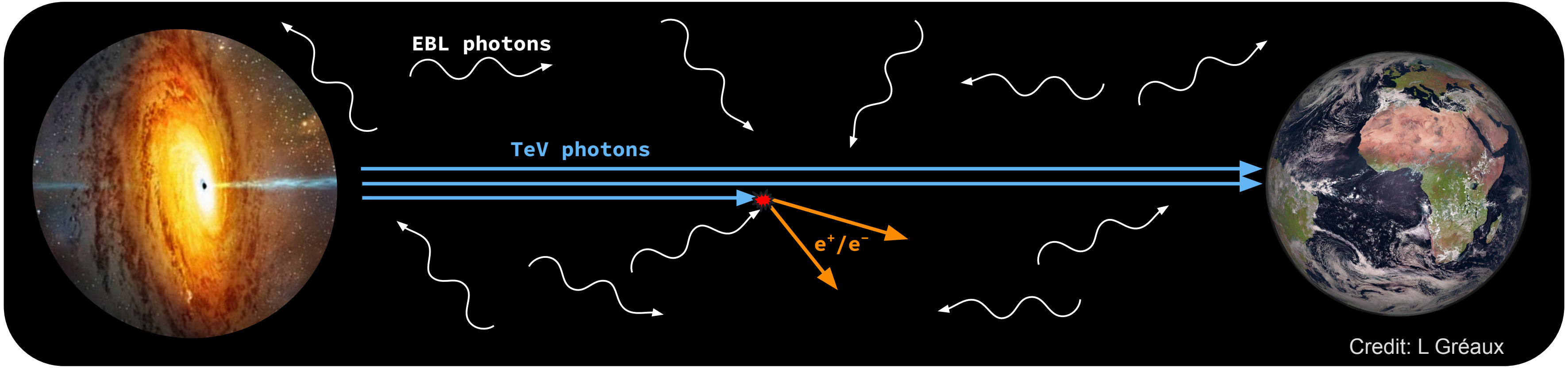
Light travel distance given by ΛCDM model $\frac{\partial L}{\partial z} = \frac{c}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$

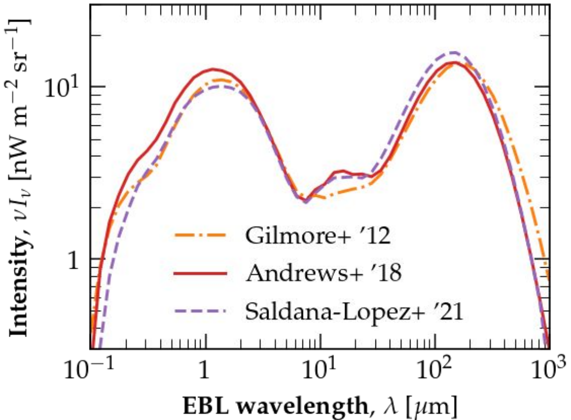
Mean free path given by EBL photon density and Breit-Wheeler cross section ($\gamma\gamma \rightarrow e^+ e^-$)

$$\Gamma^{-1}_{\gamma\gamma}(E', z) = \int_0^{+\infty} {\rm d}\epsilon \, \frac{\partial n}{\partial \epsilon} \int_{-1}^{1} {\rm d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}\Big[E', \epsilon, \mu\Big]$$

integrated over comoving EBL photon energy ϵ and photon-gamma angle θ, with $\mu = 1 - \cos\theta'$

TeV ɣ-ray flux suppression



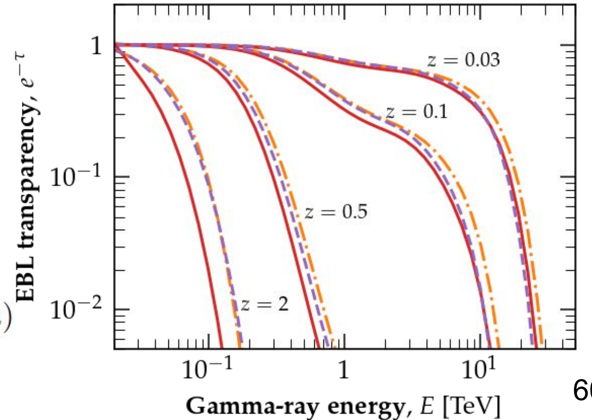


TeV gamma-ray suppression

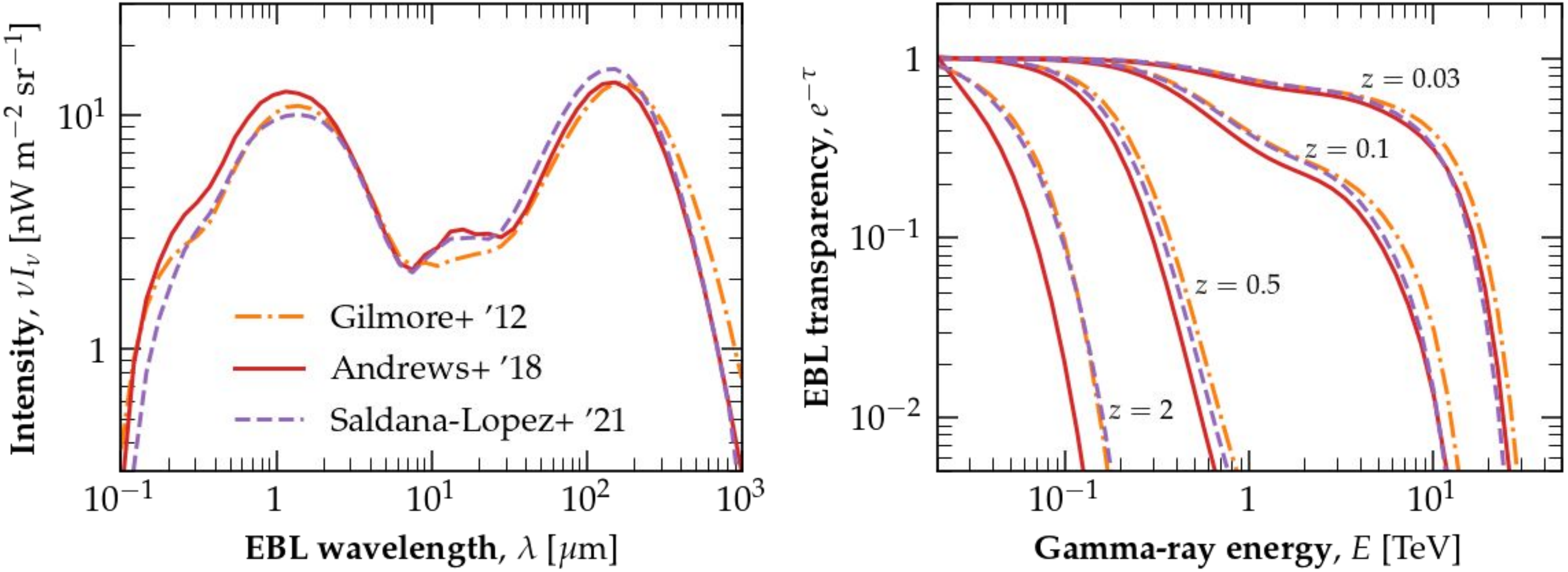
$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$

with

$$\tau(E_\gamma, z_0) = \int_0^{z_0} \mathrm{d}z \, \frac{\partial L}{\partial z}(z) \int_0^{\infty} \mathrm{d}\epsilon \, \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} \mathrm{d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$



TeV ɣ-ray flux suppression



How do I account for it?

Getting started | User guide | Tutorials | API reference | Developer guide | Release notes | 1.2

Search the docs ...

Gammapy analysis workflow and package structure
How To
Model gallery
- Constant spatial model
- Disk spatial model
- Gaussian spatial model
- Generalized gaussian spatial model
- Piecewise norm spatial model
- Point spatial model
- Shell spatial model
- Shell2 spatial model
- Template spatial model
- **EBL absorption spectral model**
- Broken power law spectral model
- Compound spectral model
- Constant spectral model
- Exponential cutoff power law spectral model
- Exponential cutoff power law spectral model used for 3FGL
- Exponential cutoff power law norm spectral model
- Gaussian spectral model
- Log parabola spectral model

Note

Go to the end to download the full example code or to run this example in your browser via Binder

EBL absorption spectral model

This model evaluates absorbed spectral model.

The EBL absorption factor given by

$$\exp\left(-\alpha \times \tau(E, z)\right)$$

where $\tau(E, z)$ is the optical depth predicted by the model (`EBLAbsorptionNormSpectralModel`), which depends on the energy of the gamma-rays and the redshift z of the source, and α is a scale factor (default: 1) for the optical depth.

The available EBL models are defined in `EBL_DATA_BUILTIN`.

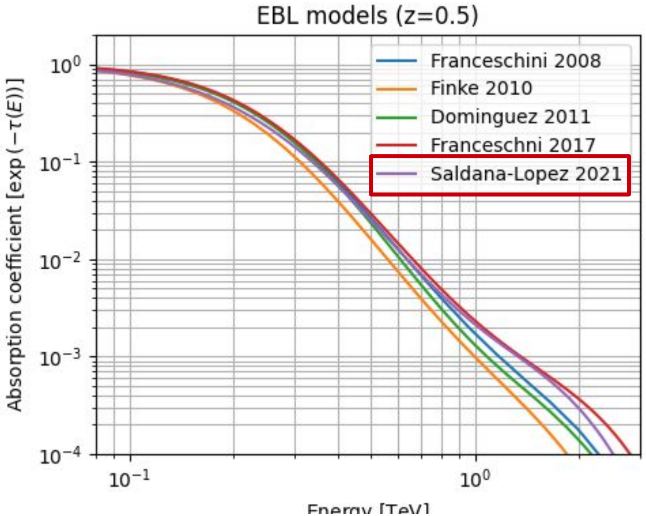
Example plot

Here is an example plot of the model:

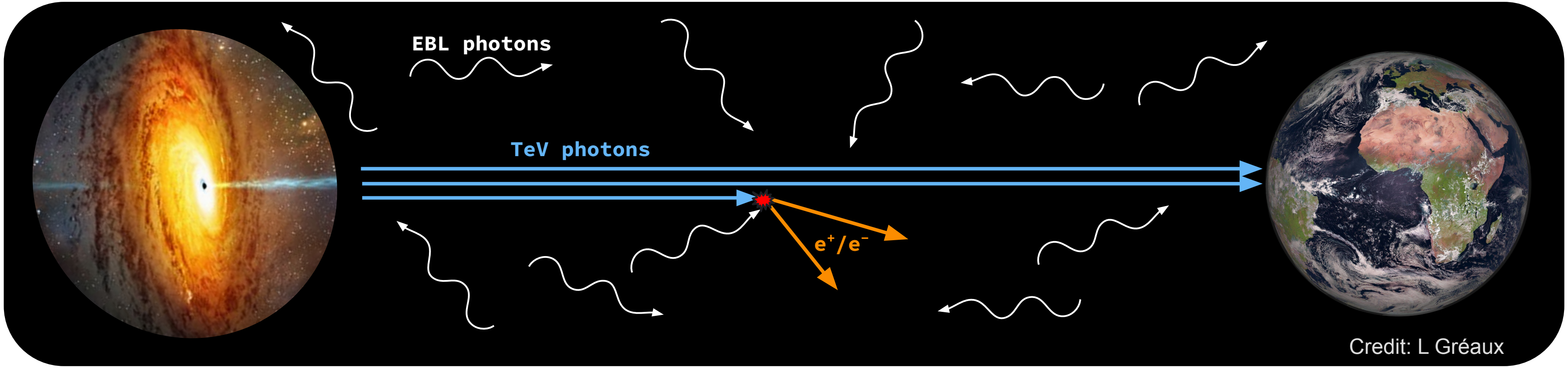
```
from astropy import units as u
import matplotlib.pyplot as plt
from gammapy.modeling.models import (
    EBL_DATA_BUILTIN,
    EBLAbsorptionNormSpectralModel,
    Models,
    PowerLawSpectralModel,
    SkyModel,
)
```

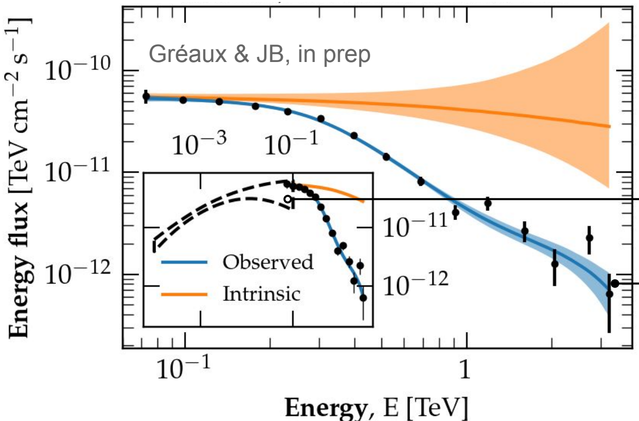
On this page
Example plot
YAML representation

GammaPy tutorial at [this link]



TeV ɣ-ray flux suppression

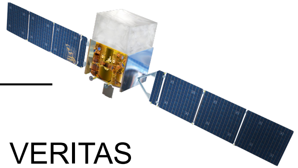




TeV gamma-ray suppression

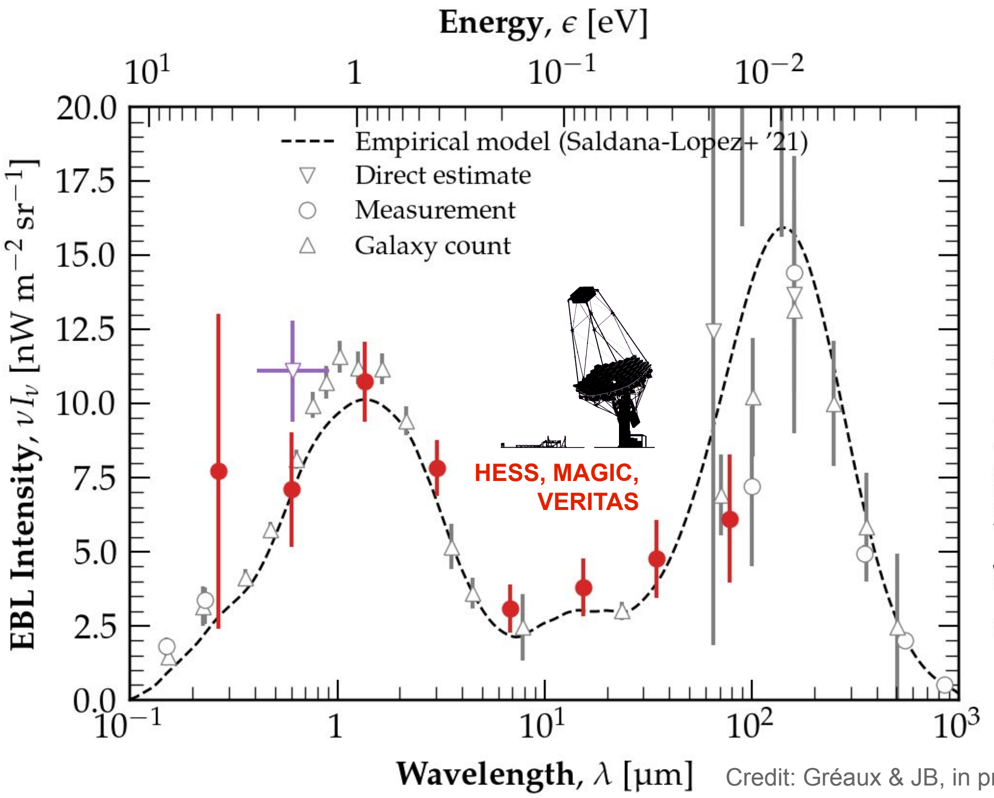
$\Phi_{obs} = \Phi_{int} \times e^{-\tau}$

with *Fermi*-LAT (GeV range)



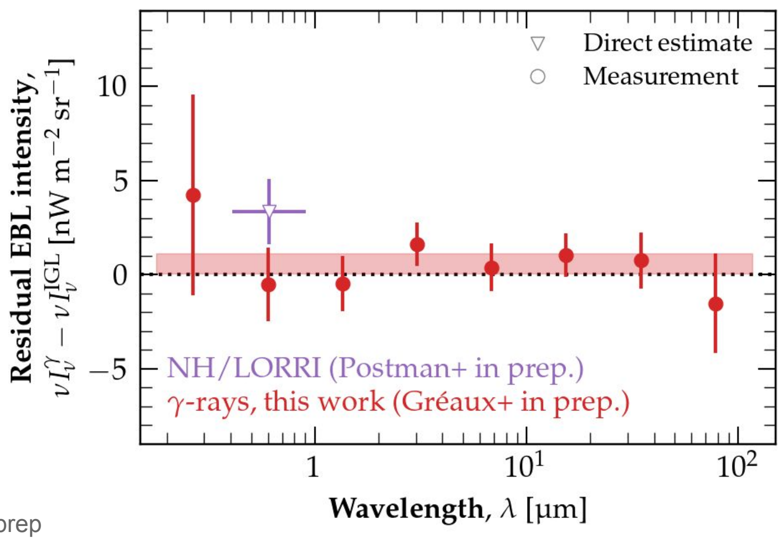
HESS, MAGIC, VERITAS (TeV range)

New ɣ-ray reconstruction of the COB and CIB

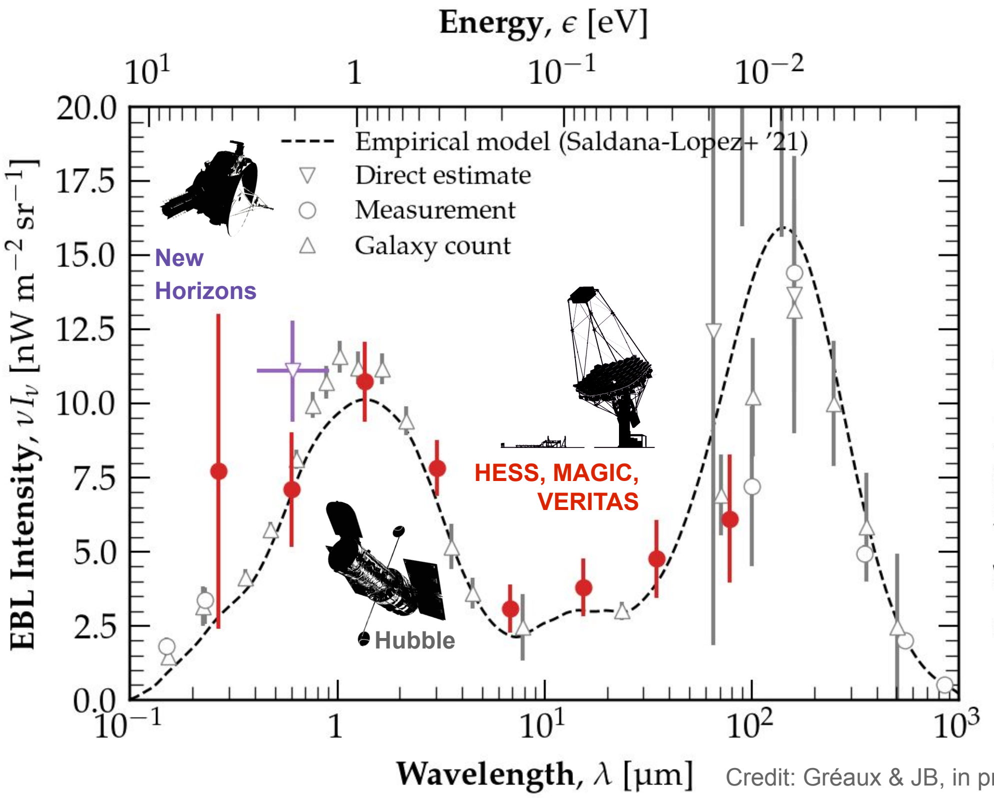


Credit: Gréaux & JB, in prep

Combining the info from hundreds of TeV spectra from HESS/MAGIC/VERITAS



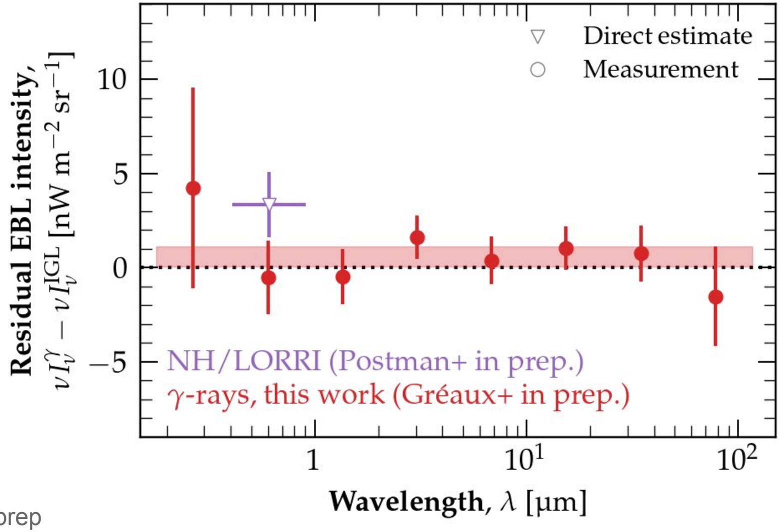
New ɣ-ray reconstruction of the COB and CIB



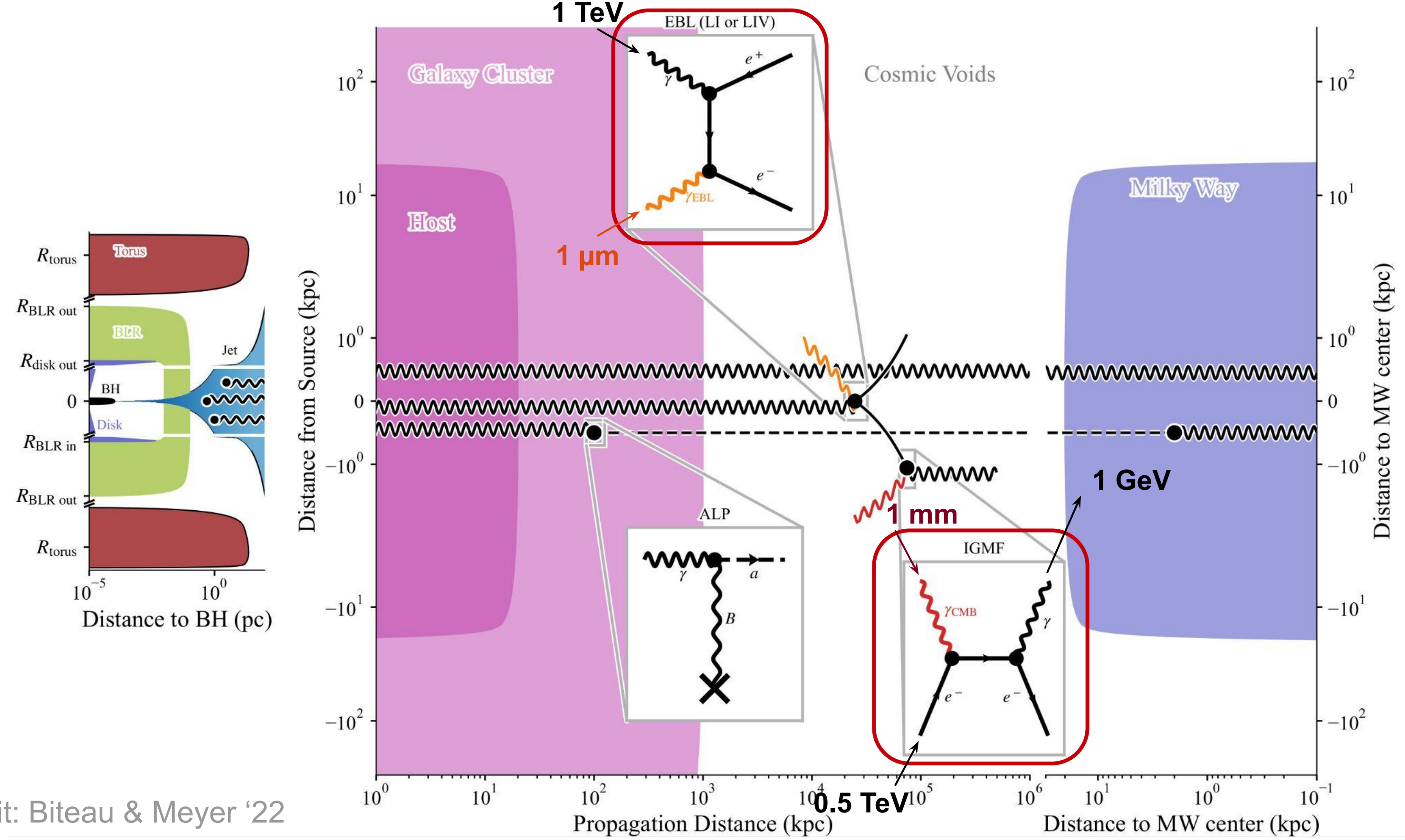
Credit: Gréaux & JB, in prep

Good match: probe of H_0

as $\tau_{\gamma\gamma} \propto I_{EBL} \times c / H_0 = (1+f_{diff}) \times I_{IGL} \times c / H_0$



ɣ-ray propagation from sources down to Earth



Credit: Biteau & Meyer '22

Absence of secondary signal

Discovery of extreme TeV blazars in 2006

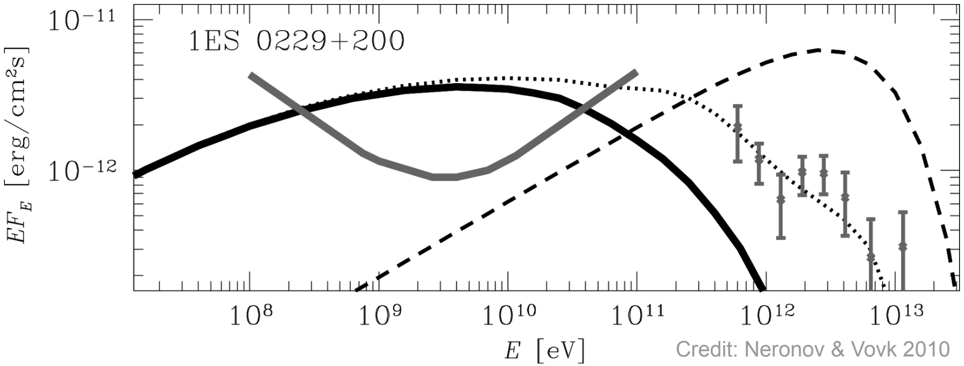
Hard TeV photon spectrum when corrected for absorption

Intrinsic emission expected to be faint in the GeV band

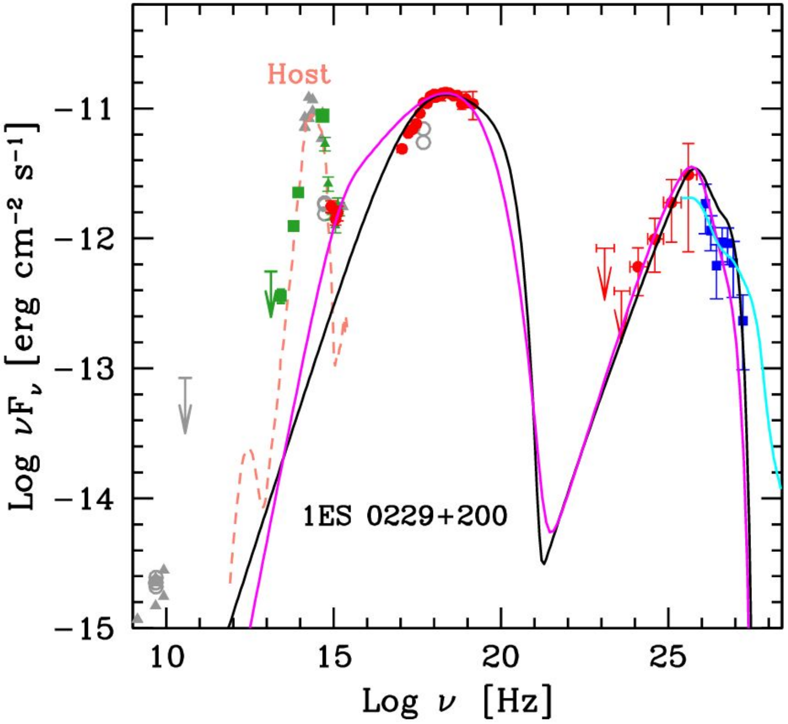
Reproprocessed emission?

None in 2010 within point spread function

⇒ minimum *B*-field needed to spread out the signal



Credit: Neronov & Vovk 2010



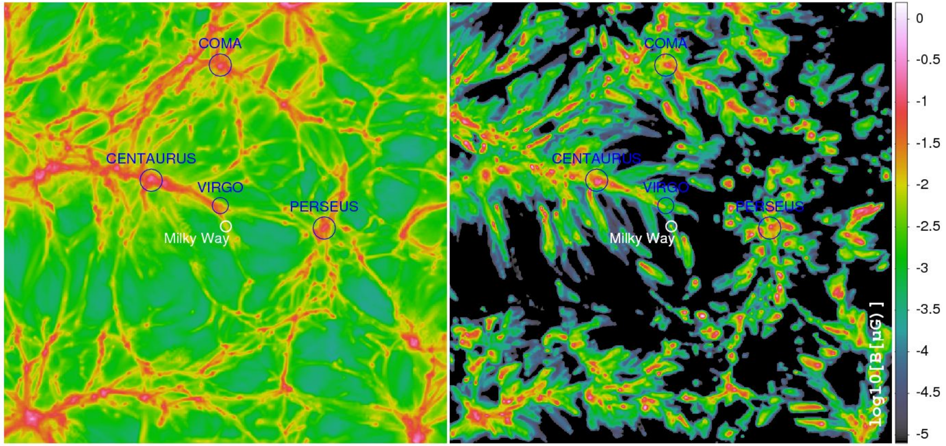
Credit: Biteau+ 2020

Magnetic fields in voids

Status and expectations

Current-generation (GeV+TeV - TeV extension): *B* > 10-100 fG

5σ CTA-discovery potential up to 300 fG



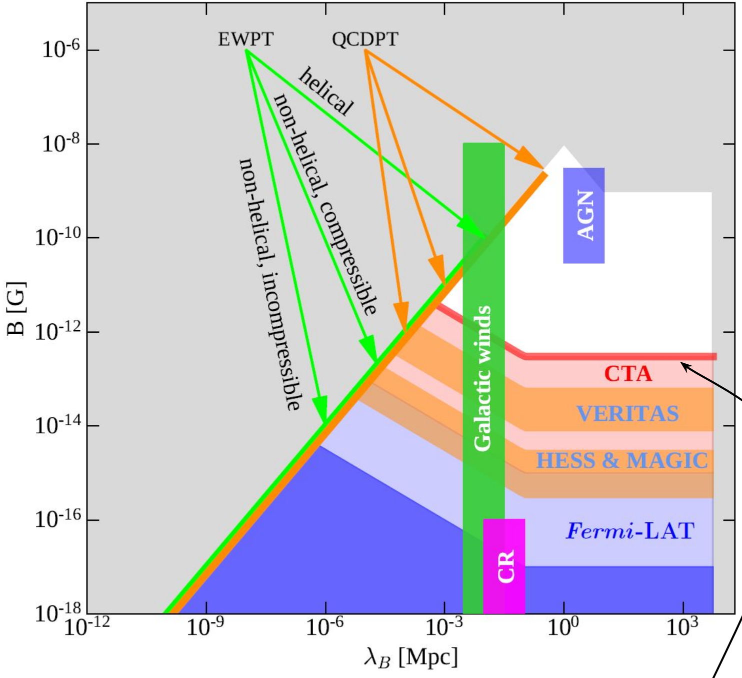
Credit: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG

Astrophysical origin simulation
B(void) < 1 pG

In practice… largely unknown!

Credit: CTA Consortium 2021

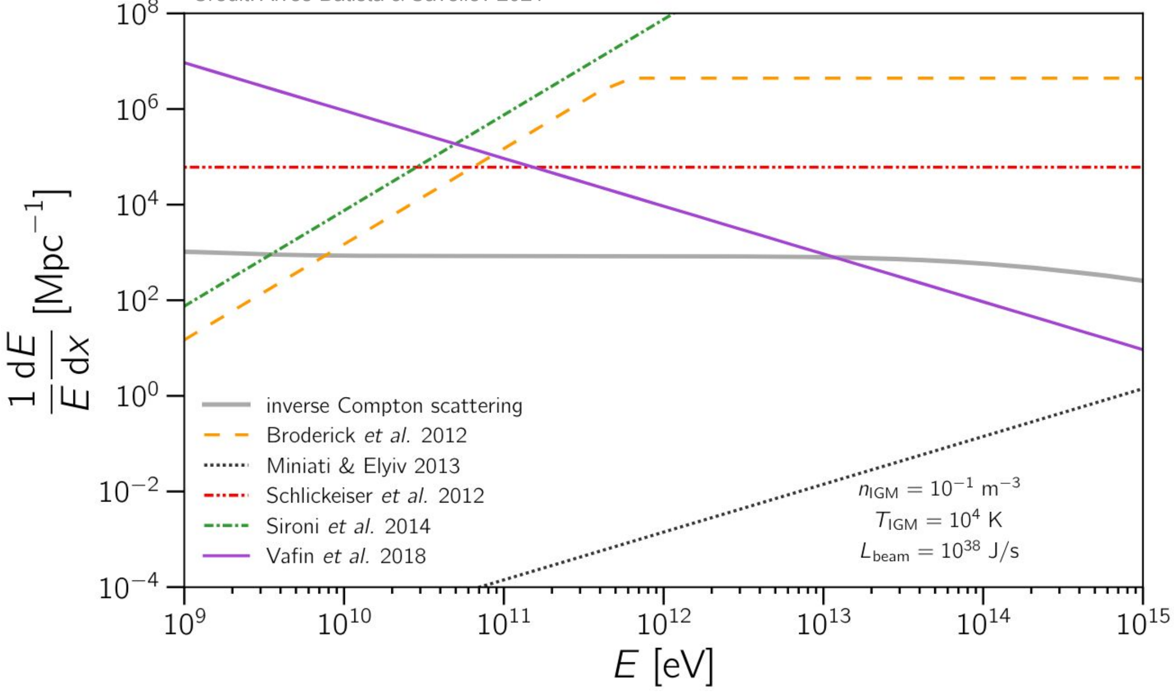


1ES 0229+200 (z=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

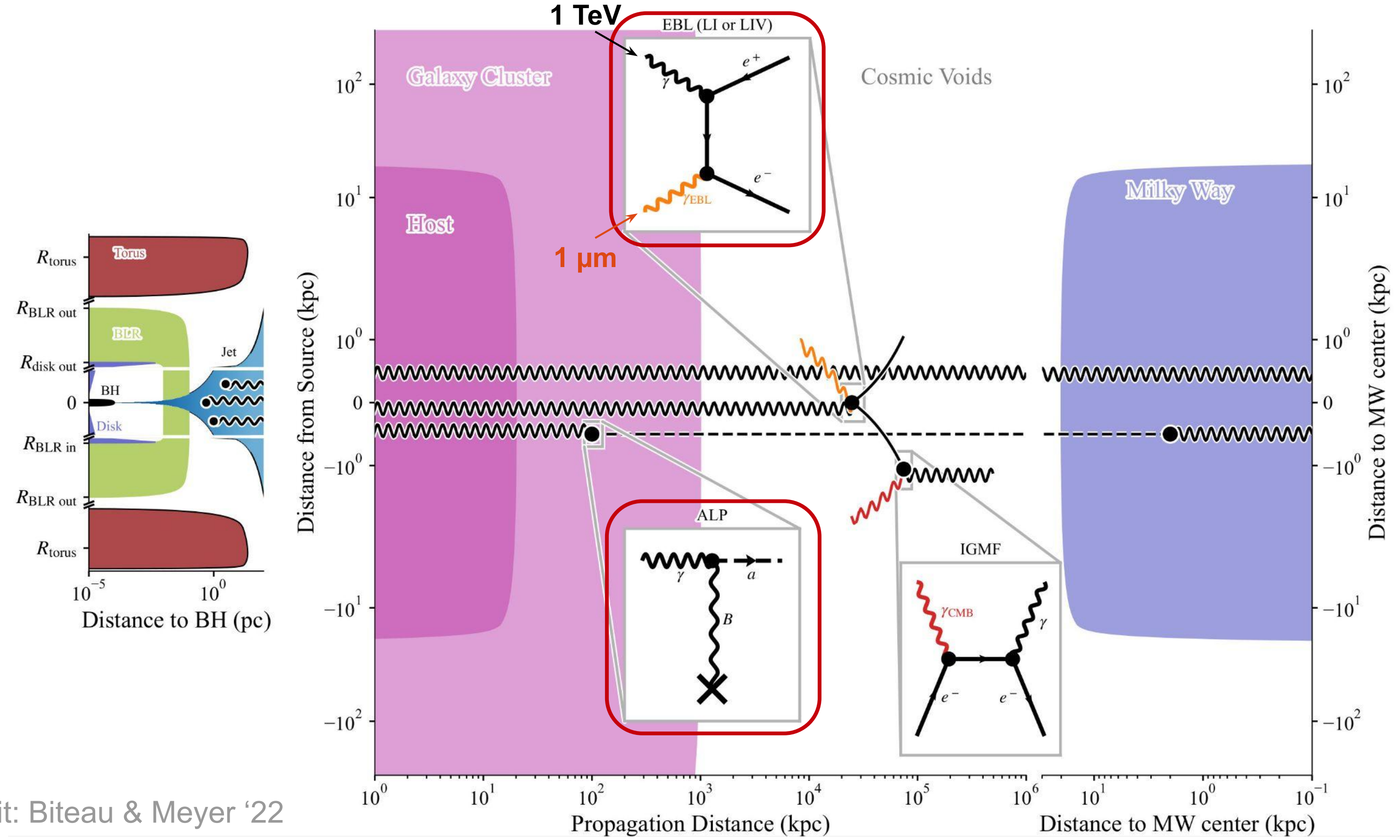
Alternative cooling

Plasma instabilities faster than inverse Compton? Energy-loss? Diffusion?

Credit: Alves-Batista & Saveliev 2021



ɣ-ray propagation from sources down to Earth

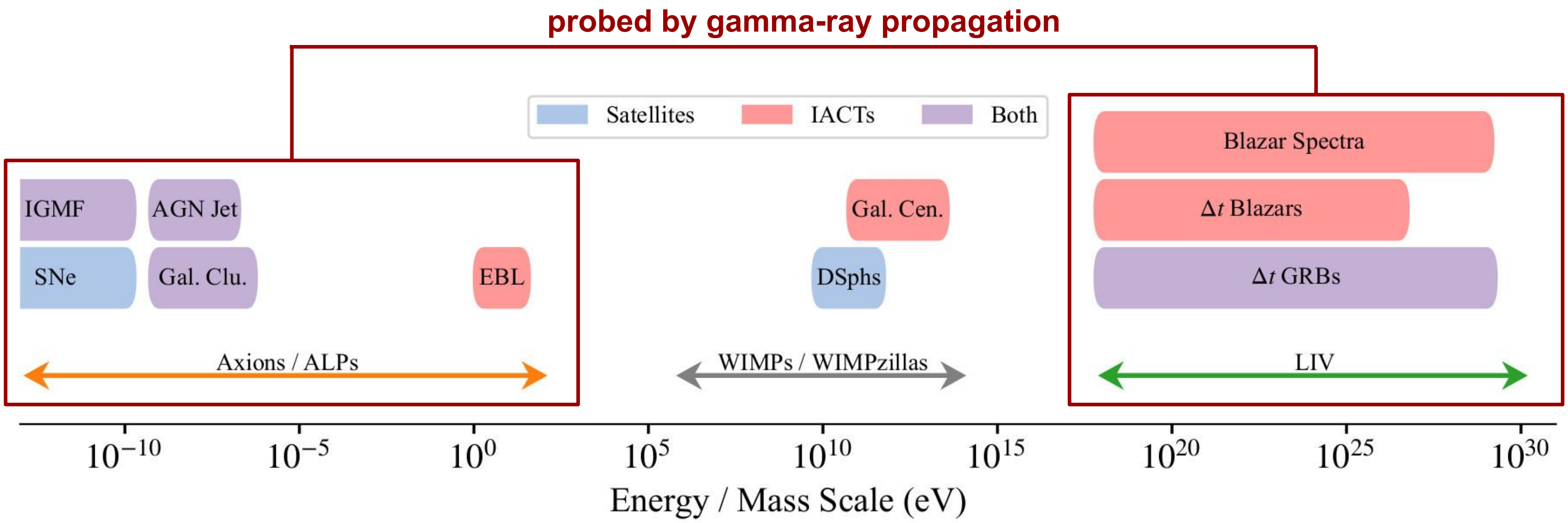


Credit: Biteau & Meyer '22

Open questions: fundamental physics

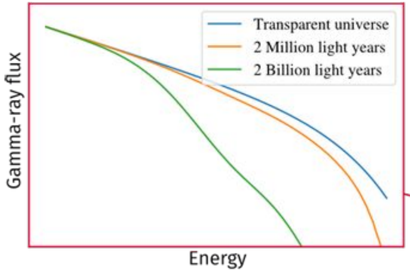
Dark matter: what is that? Theories beyond QFT and GR: is there anything to observe?

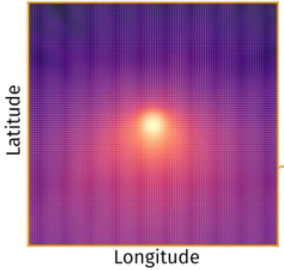
- Top-down processes (*heavy axion-like particles* /*or WIMPs*/): decay /*or self annihilation*/ into photons
- Mixing with light axion-like particles (ALP): CTAO starts probing ALP dark-matter parameter space (*CTA* 2021)
- LIV linearly modified dispersion relation (CPT-odd): Planck scale ~excluded by spectra & Δt!



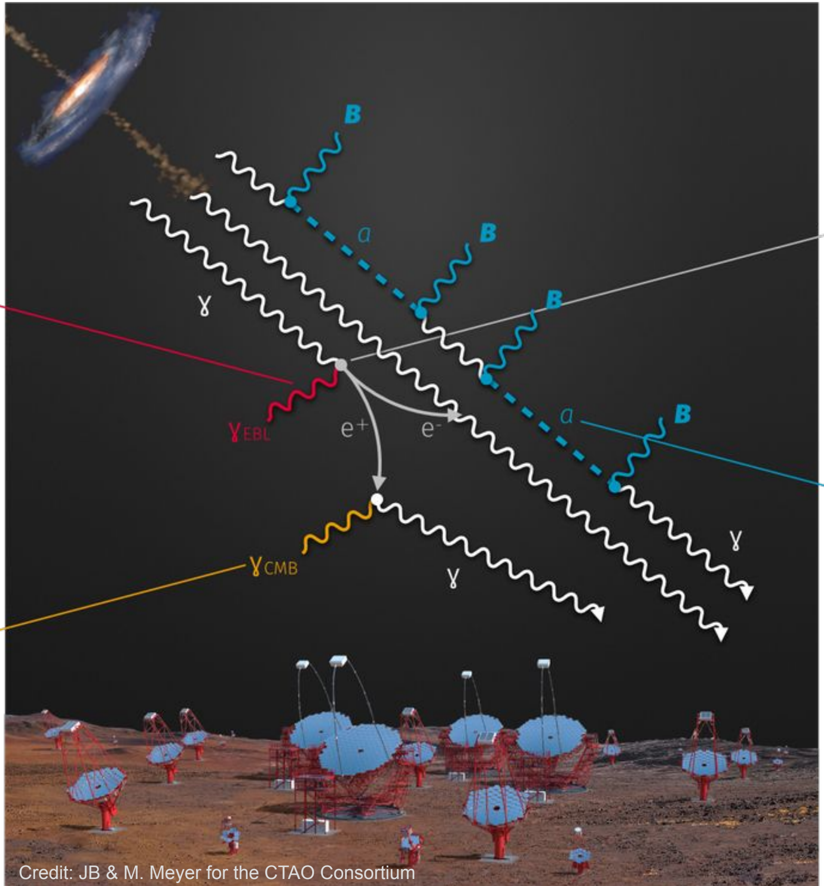
Conclusion: ɣ-ray cosmology with CTAO

All optical light in the universe!

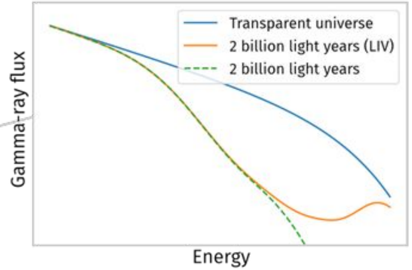


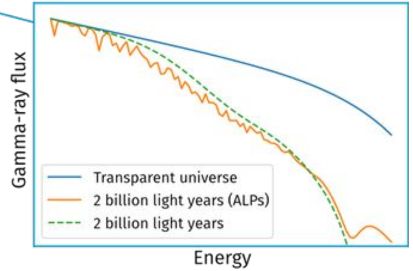


Plasma and B-fields in cosmic voids?



Quantum gravity at test?



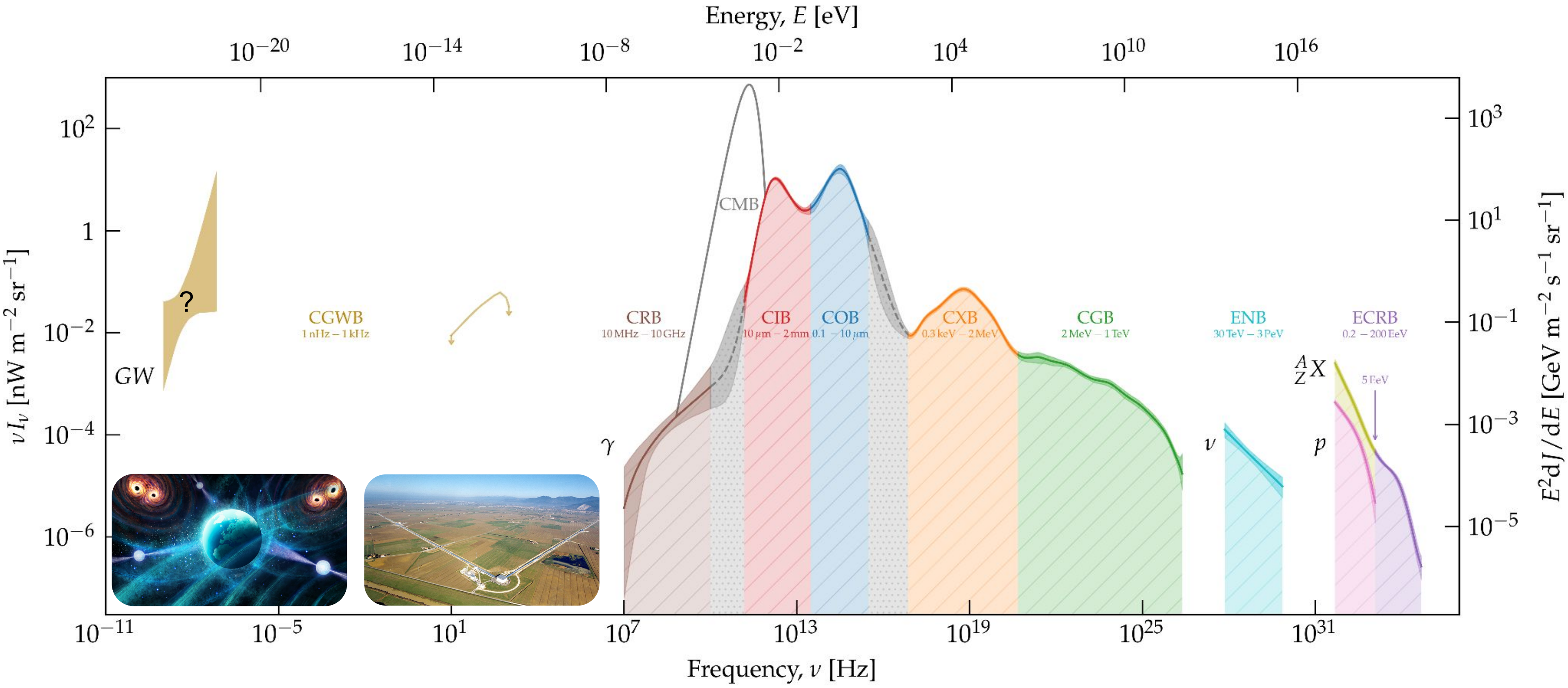


Super-light dark-matter candidates?

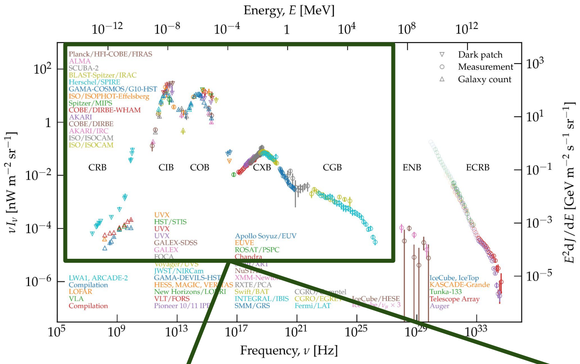
Backup

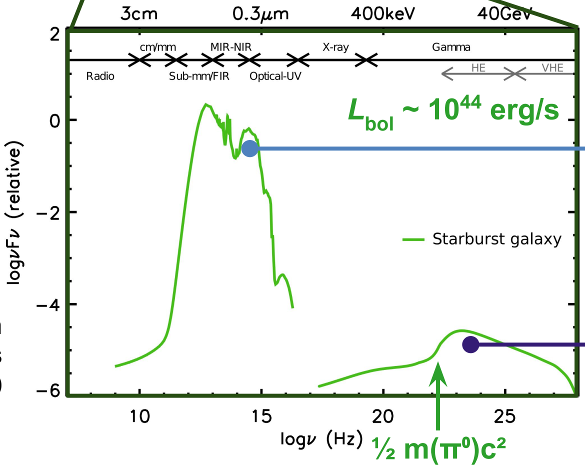
III. Multi-messenger emissions on cosmic scales

2. The spectrum of the universe



Power source #1: Star formation

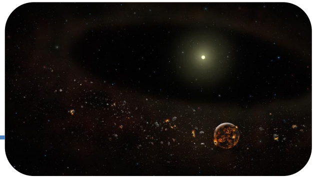




Adapted from C. Harrison's thesis (2014)

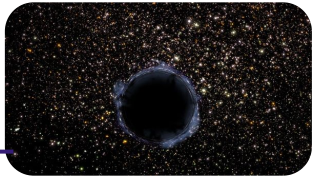
Light-weight long-lived stars

Credit: Gemini Obs./AURA/Cook

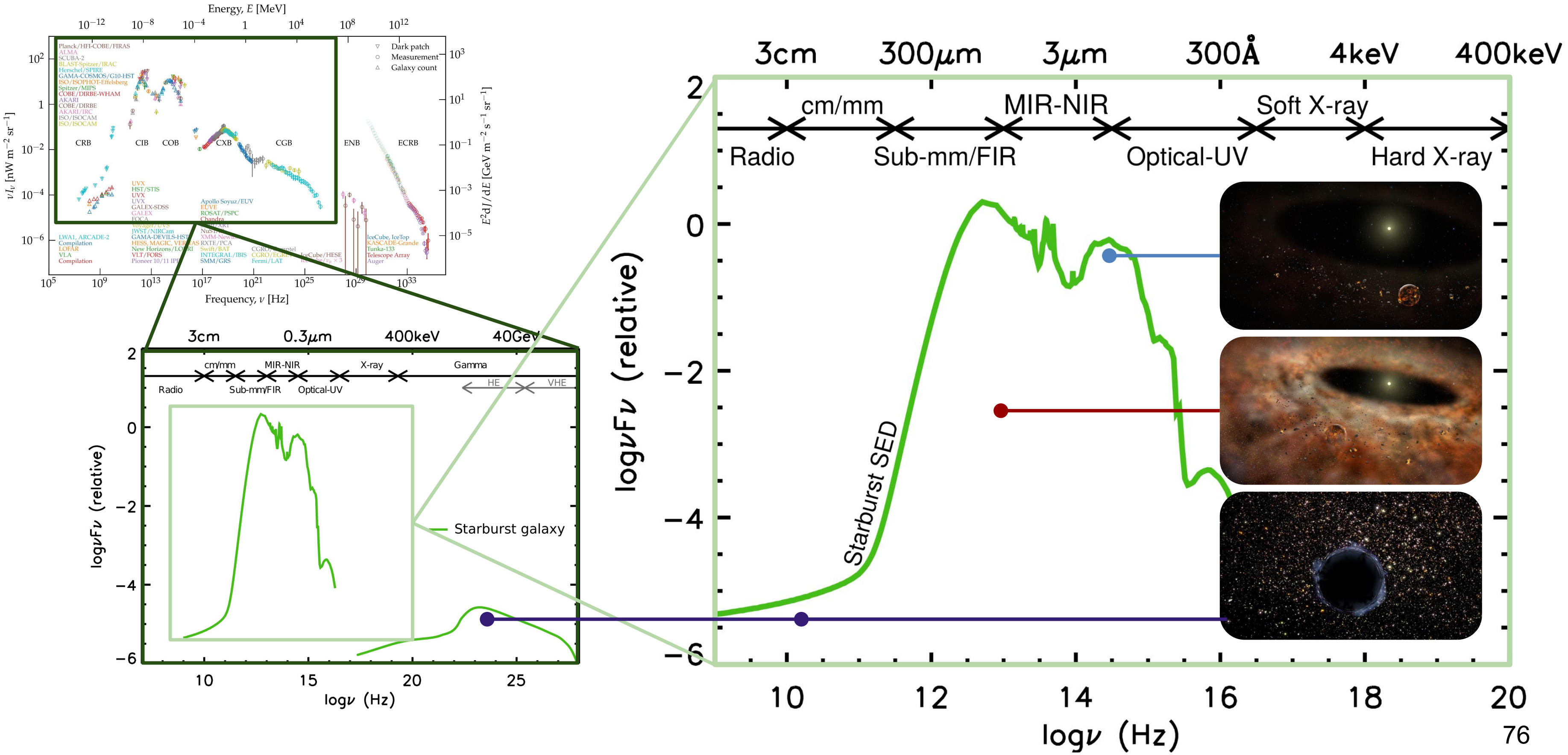


Massive short-lived stars

Credit: NASA/ESA/Bacon (STScI)



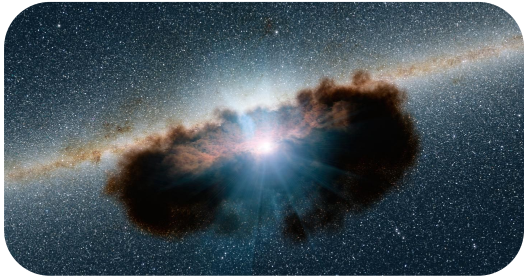
Power source #1: Star formation

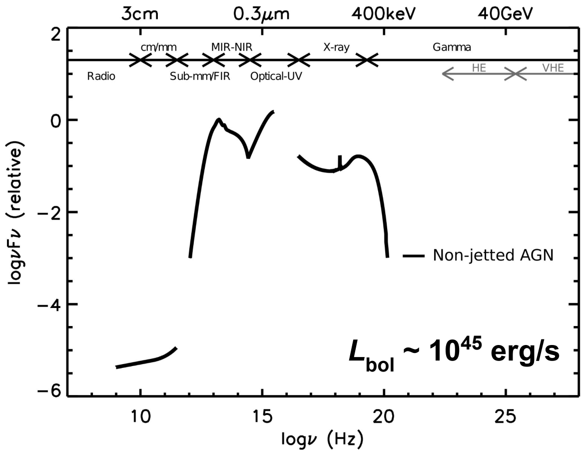


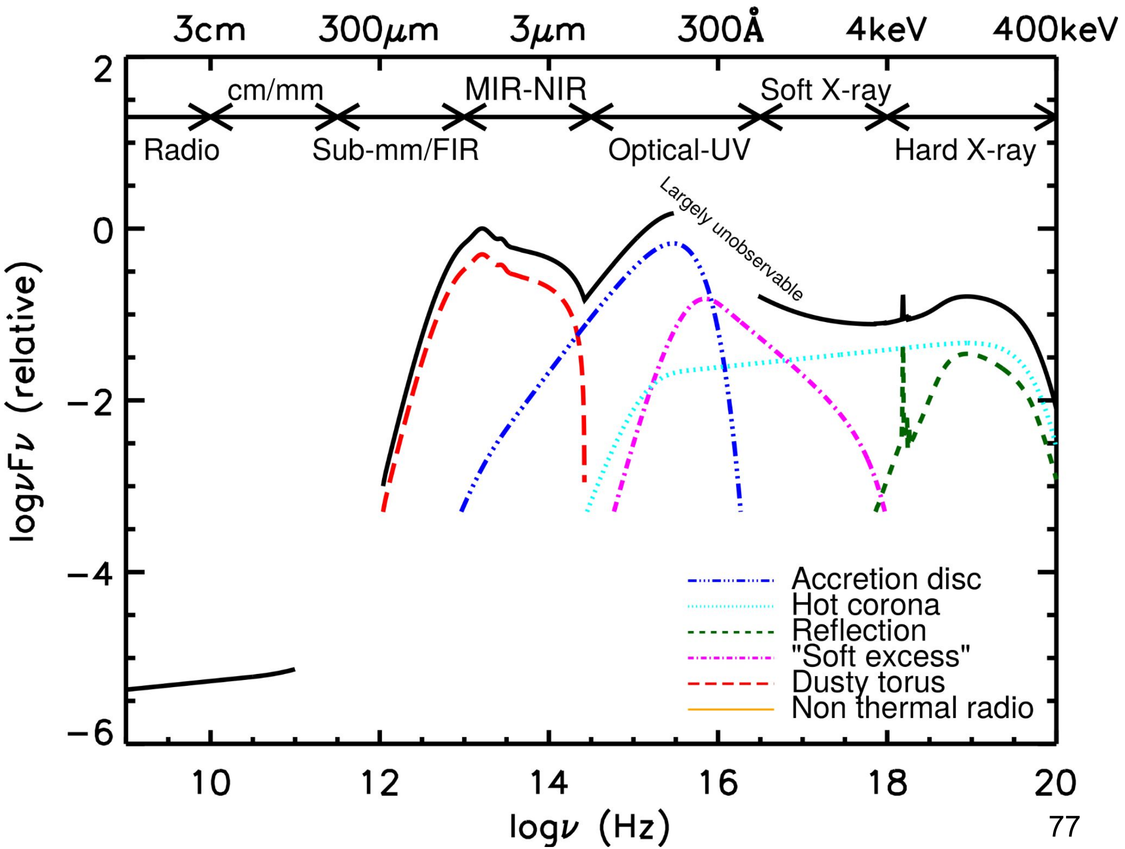
Power source #2: Supermassive black-hole accretion

Non-jetted AGN

Credit: NASA/JPL-Caltech



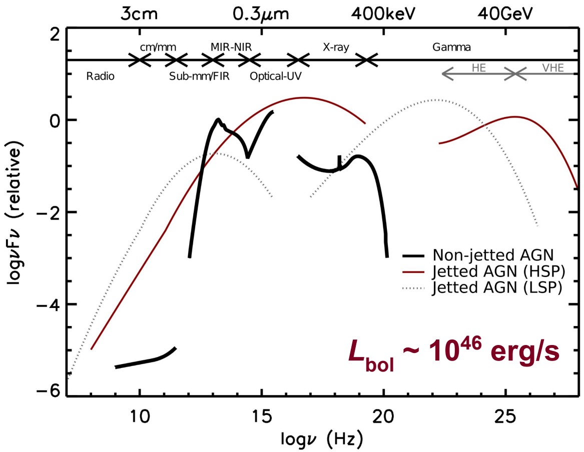


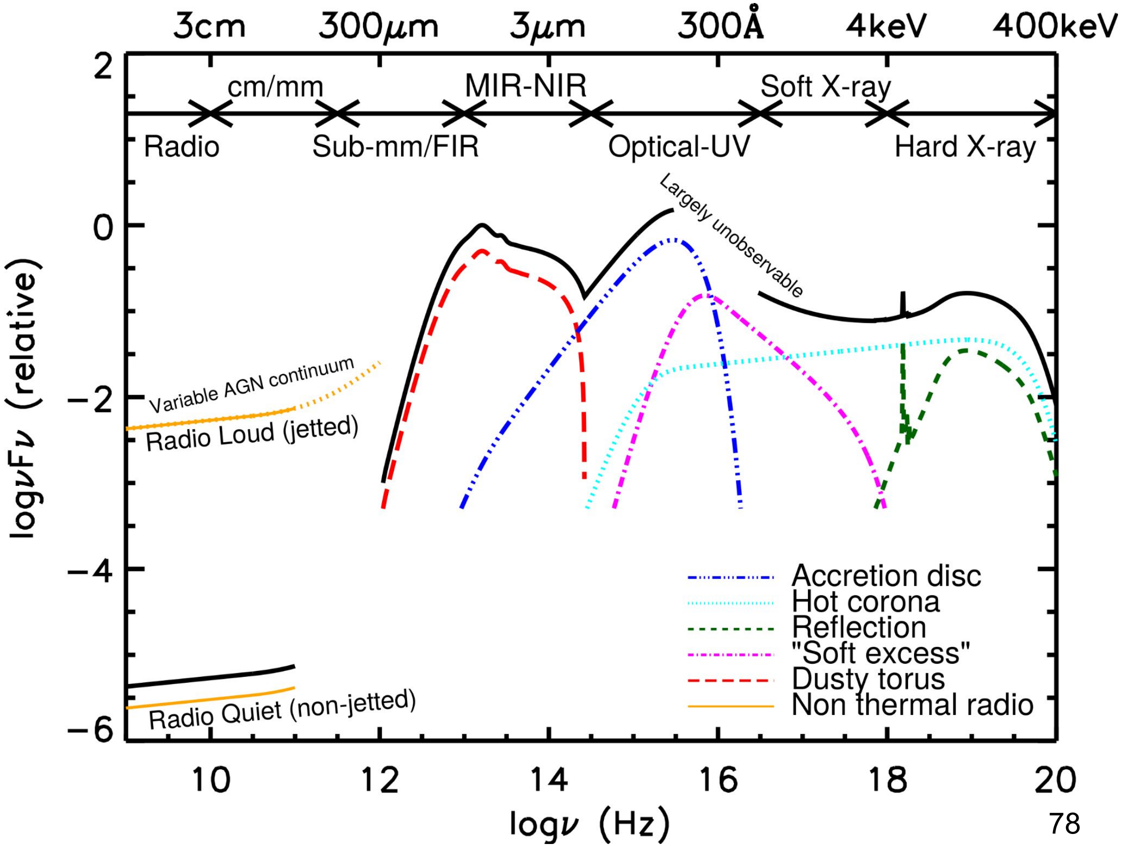


Power source #3: Supermassive black-hole ejection

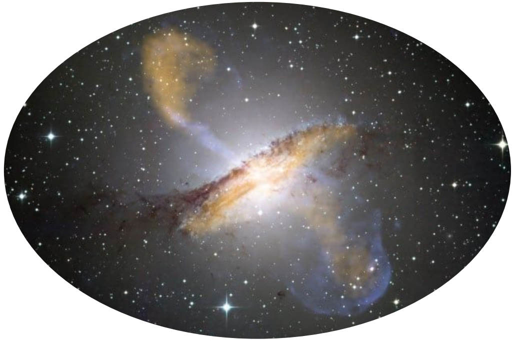
Jetted AGN

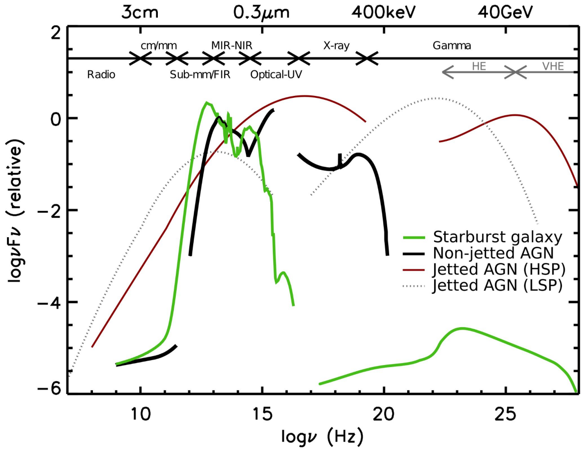
Credit: ESA/NASA/AVO/Padovani

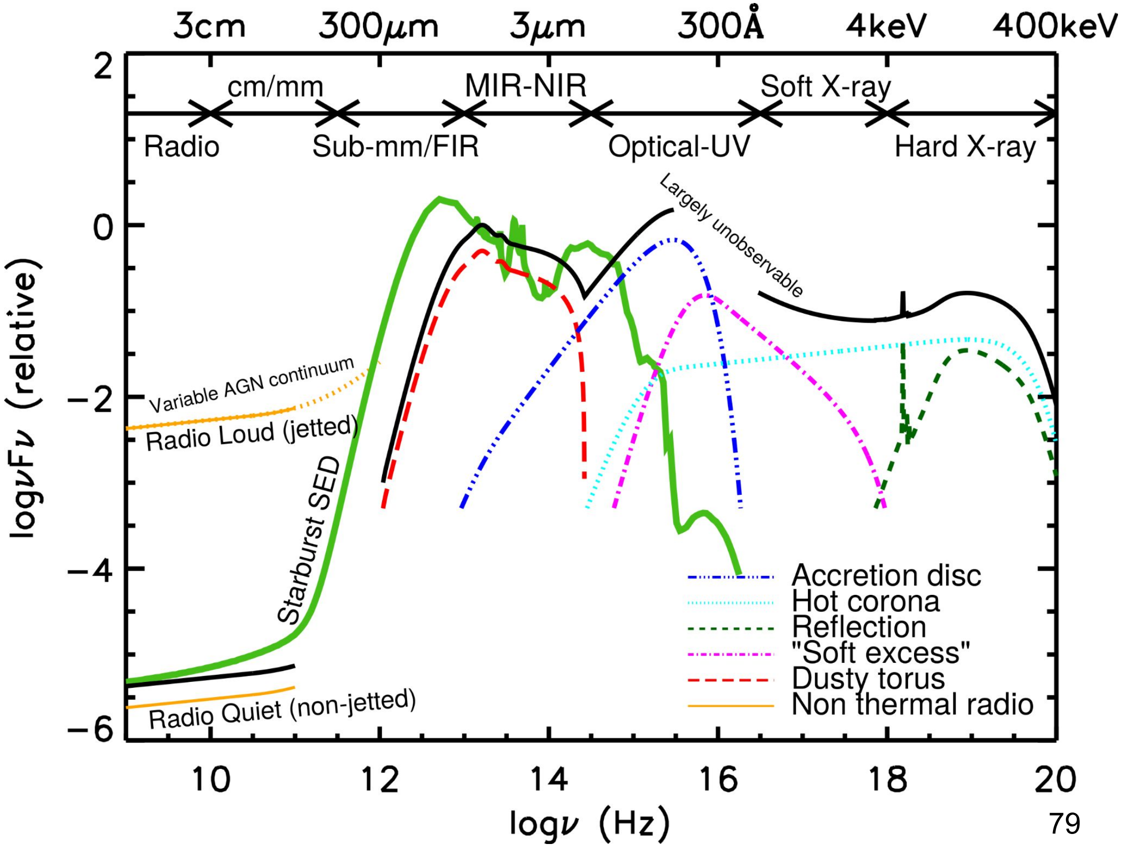




In some galaxies: star-formation + black-hole activity!







II. Cosmic-scale engines behind astrophysical emissions

3. Ejection

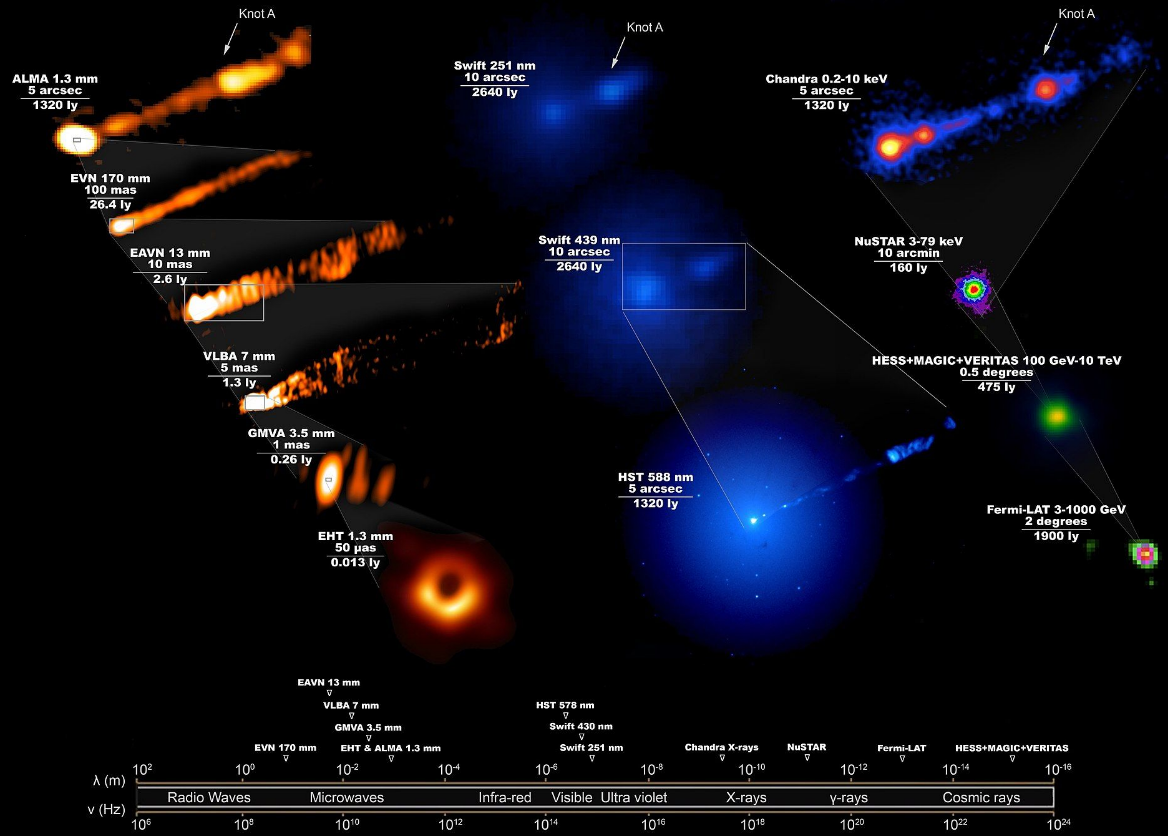
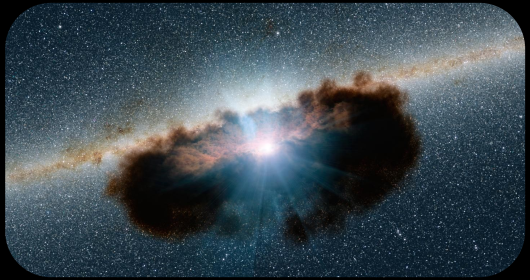


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Non-jetted AGN → 90%

Credit: NASA/JPL-Caltech

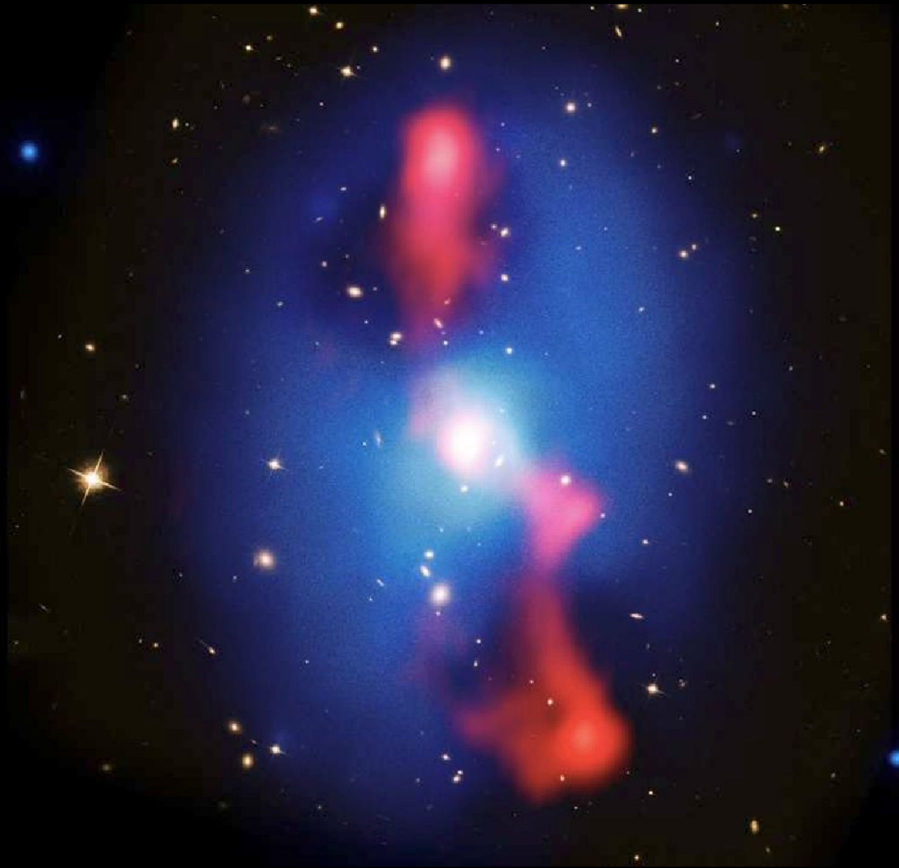


Jetted AGN → 10%

Credit: ESA/NASA/AVO/Padovani

II. Cosmic-scale engines behind astrophysical emissions

3. Ejection



Radio

X-rays

Optical

Galaxy cluster
MS 0735.6+7421

Mass-energy from accretion injected into jet kinetic energy ~ 0.5%

See Merloni & Heinz, ‘08

Jet kinetic energy to radiation ~ 10%

for active galactic nuclei,
gamma-ray bursts,
microquasars
(see next course)

II. Cosmic-scale engines behind astrophysical emissions

2. Ejection

Exercise 4. Cosmic energy density of photons from jets

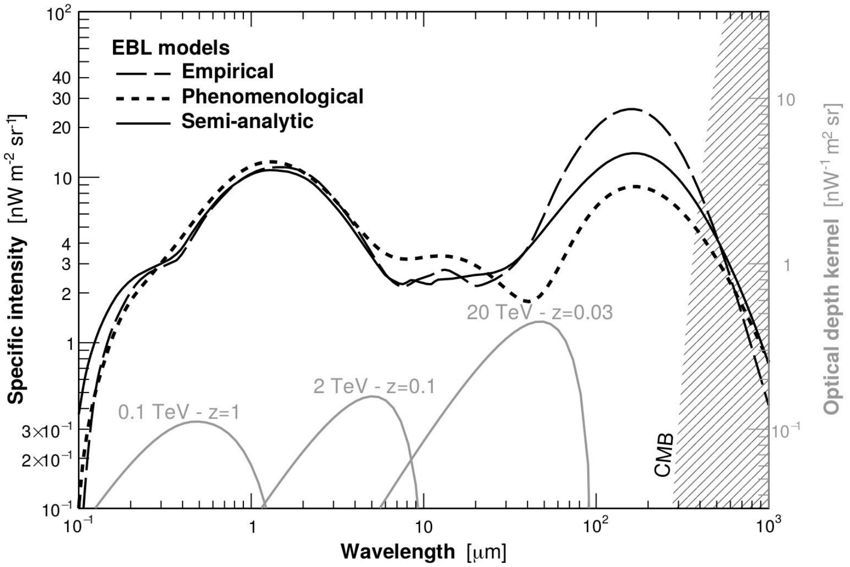
1. Estimate the energy density of photons from jets emitted in the vicinity of massive black holes.

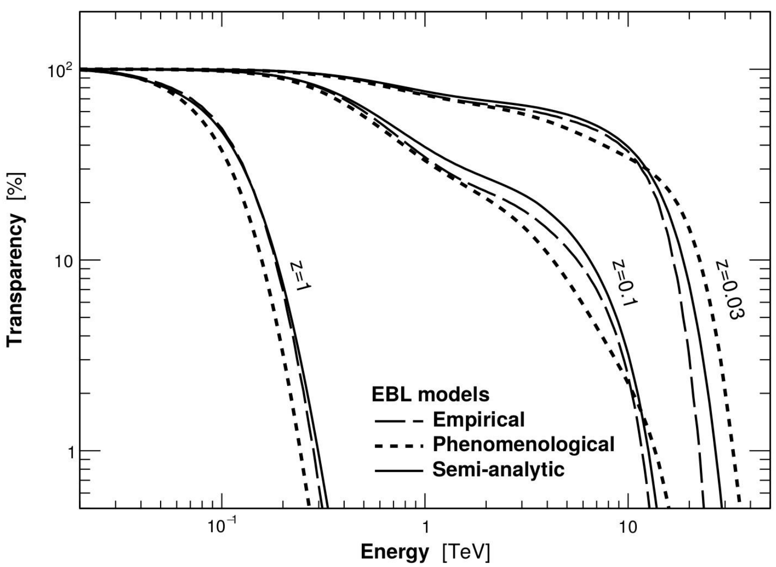
The models and the gamma-ray technique

Models of the COB + CIB (= extragalactic background light, EBL)

- Empirical models: extrapolate on local data — here Dominguez +11
- Phenomenological models: SFR + population synthesis — here Finke+ 10
- Semi-analytic models: N-body simulations — here Gilmore+ 12

Credit: Pueschel & JB 2021

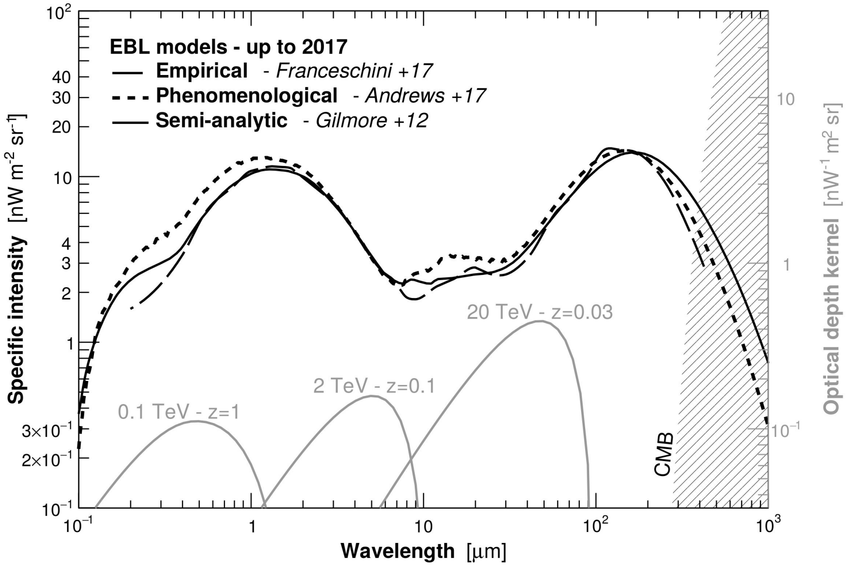


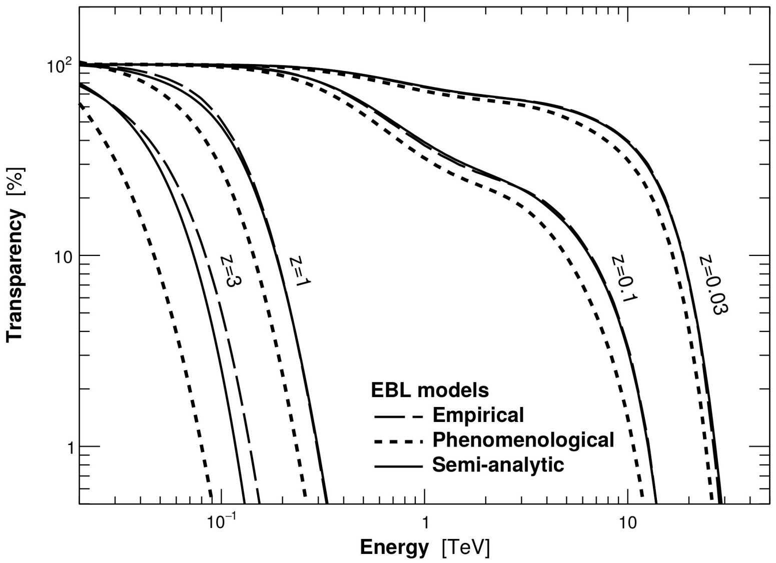


The models and the gamma-ray technique

Models of the COB + CIB (= extragalactic background light, EBL)

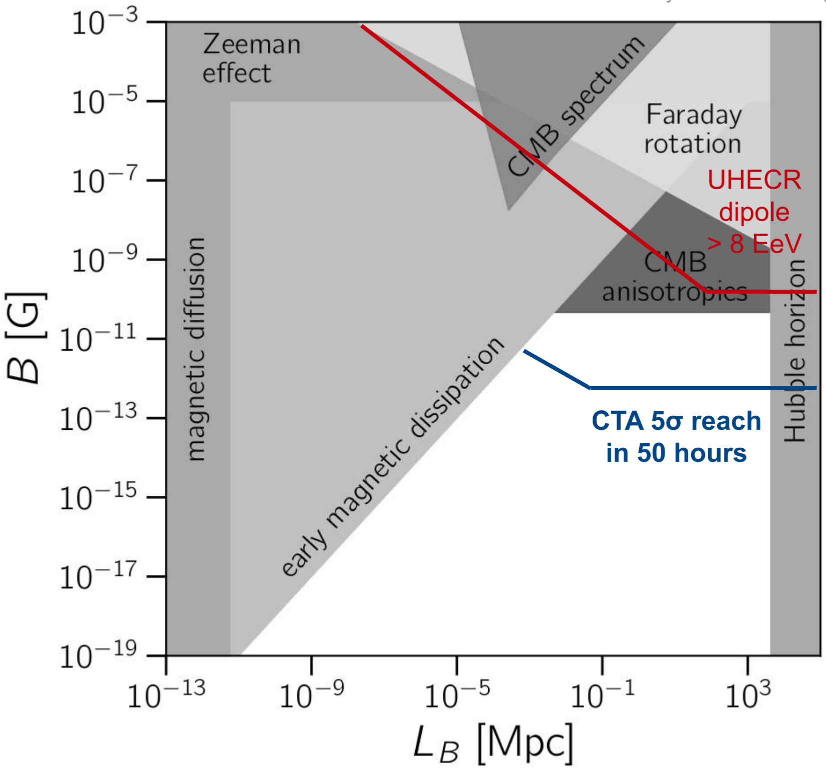
- Empirical models: extrapolate on local data — here Franceschini +17
- Phenomenological models: SFR + population synthesis — here Andrews+ 17
- Semi-analytic models: N-body simulations — here Gilmore+ 12



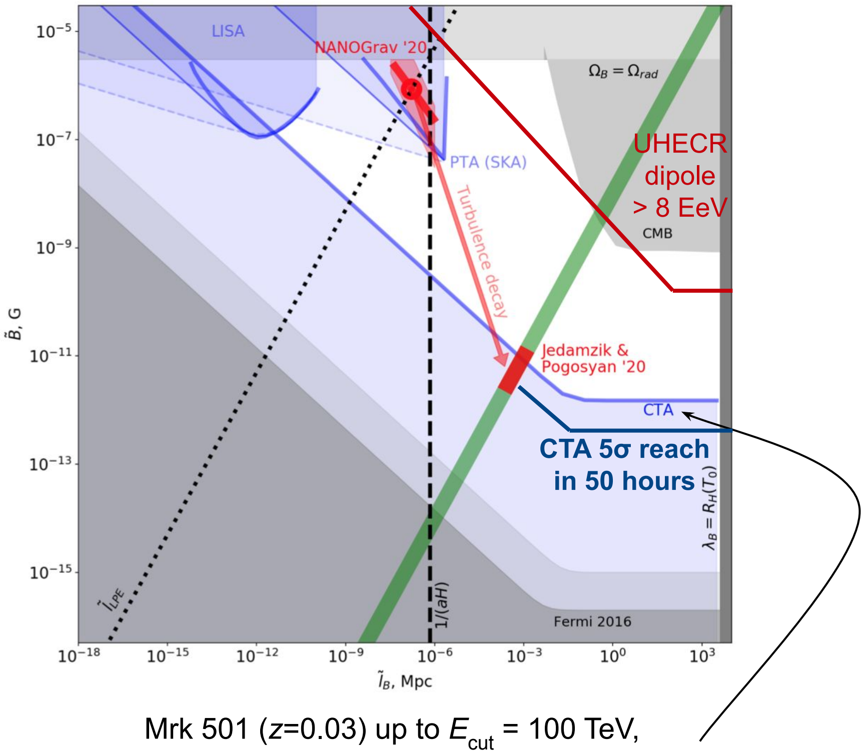


Multi-wavelength and multi-messenger constraints

Credit: R. Alves-Batista in Pueschel & JB 2021 + Bray & Scaife 2018 (UHECR)

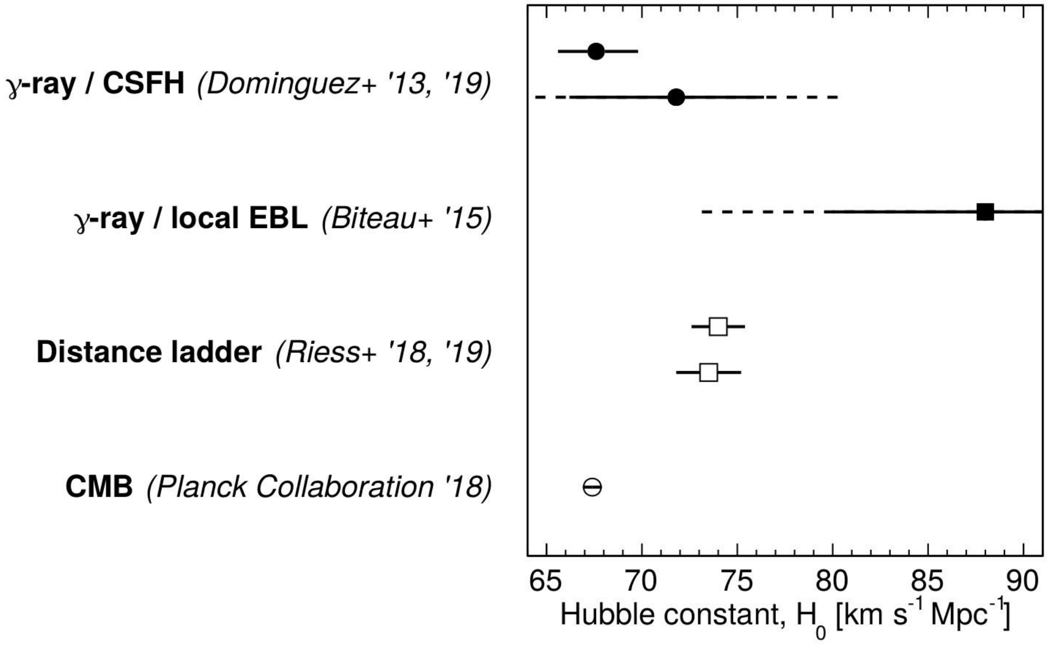


Credit: Neronov+ 2021+ Bray & Scaife 2018 (UHECR)



Mrk 501 (z=0.03) up to E_{cut} = 100 TeV, 350h of CTAO-North to reach 5σ

Hubble constant



Credit: Pueschel & JB 2021

How to:

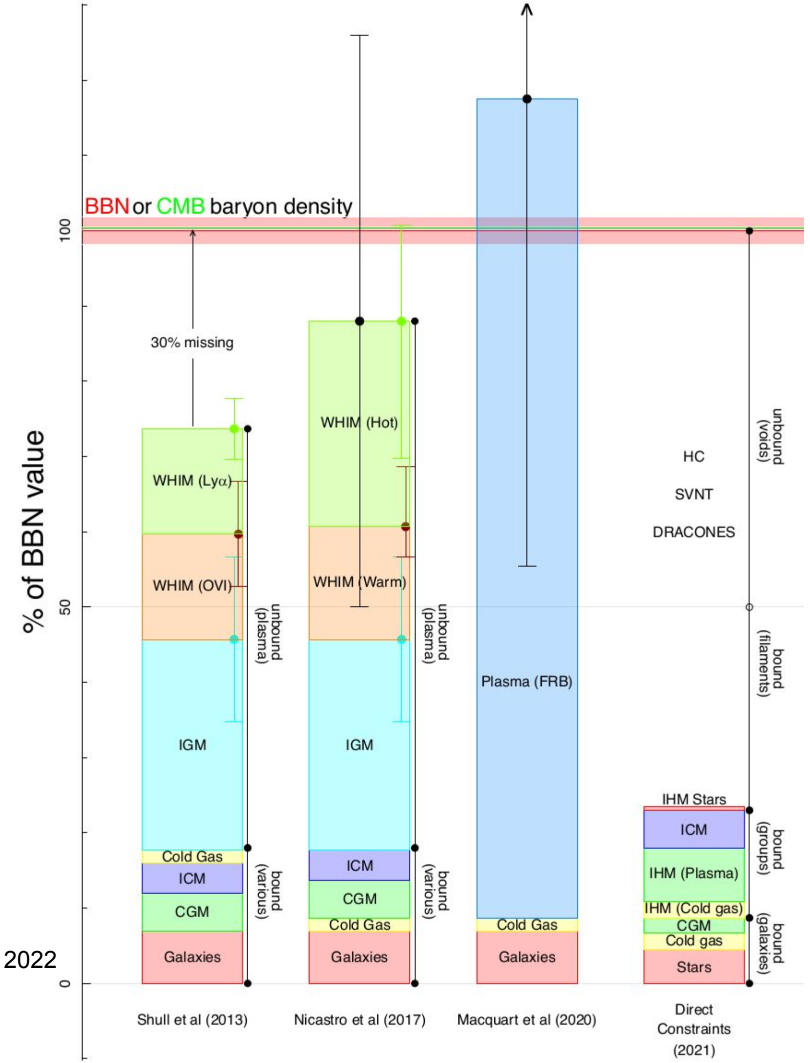
$$F_{\rm obs}(E) = F_{\rm emitted}(E(1+z_0)) \times \exp[-\tau_{\gamma\gamma}(E,z_0)]$$

$$\tau_{\gamma\gamma}(E,z_0) = \int_0^{z_0} \Gamma^{-1}_{\gamma\gamma}(E(1+z),z)\frac{{\rm d}\ell(z)}{{\rm d}z}{\rm d}z$$

$$\Gamma^{-1}_{\gamma\gamma}(E',z) = \int_0^{\infty} {\rm d}\epsilon' \frac{{\rm d}n(\epsilon',z)}{{\rm d}\epsilon'} \int_{-1}^{1} {\rm d}\cos\theta' \frac{1-\cos\theta'}{2}\sigma_{\gamma\gamma}(\beta')\Theta(\epsilon'-\epsilon'_{\rm th})$$

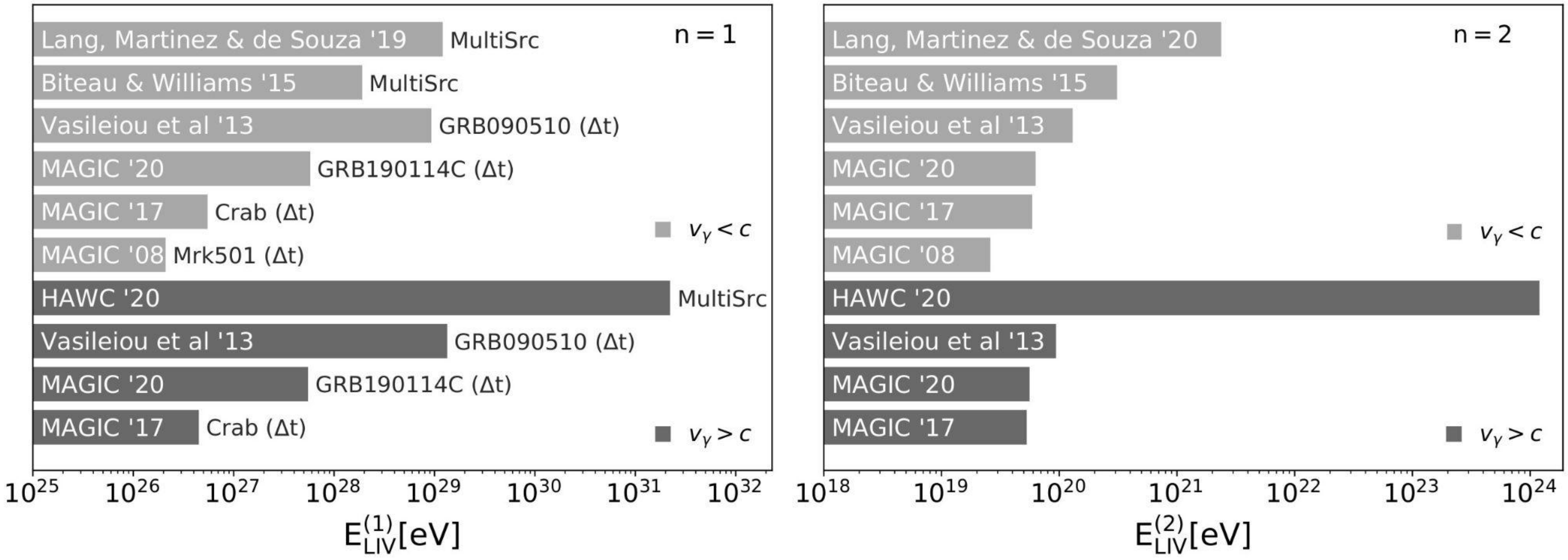
$$\partial n/\partial\epsilon = (1+z)^3/c \times \int_z^{\infty} {\rm d}z'\, {\rm d}\ell/{\rm d}z' \times j(\epsilon',z')/\epsilon'$$

Missing baryons



Credit: Driver 2022

Lorentz invariance violation: status



Credit: H. Martinez-Huerta
in Pueschel & JB 2021