Gamma-ray signals from light dark matter

Maíra Dutra

NPP fellow

NASA Goddard Space Flight Center

In collaboration with
Tonia Venters

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Chicago 2024
TeV Particle Astrophysics 2024

Outline

1. Introduction: motivation for LDM
2. MeV γ rays from LDM
3. Results: the dark photon portal
4. Conclusions

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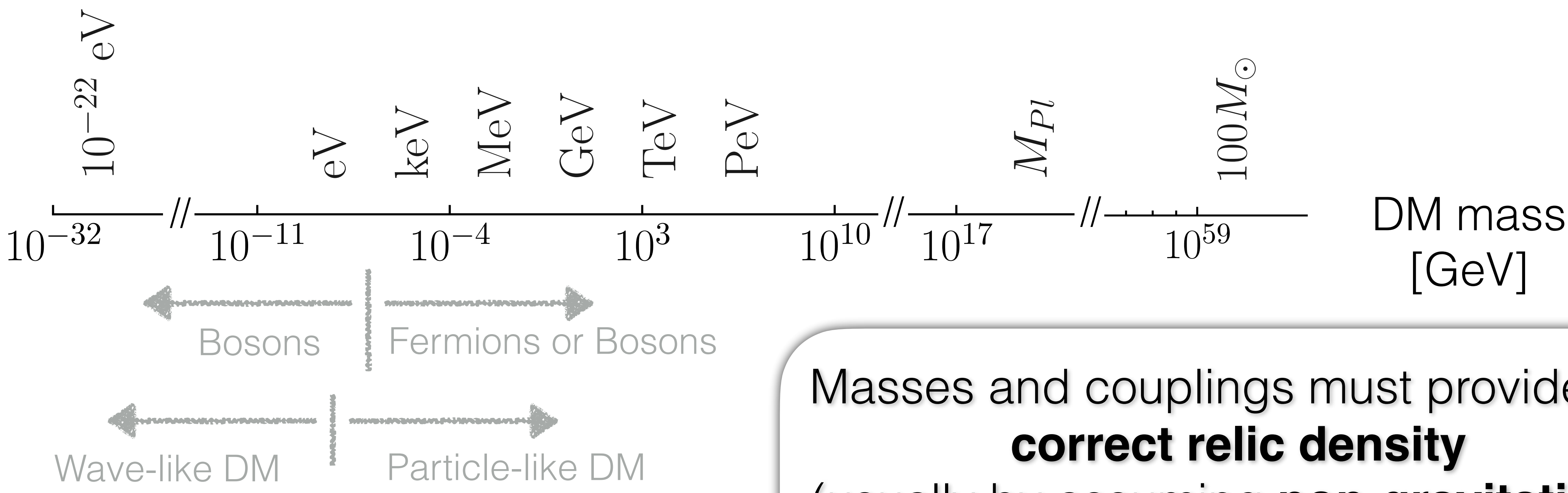

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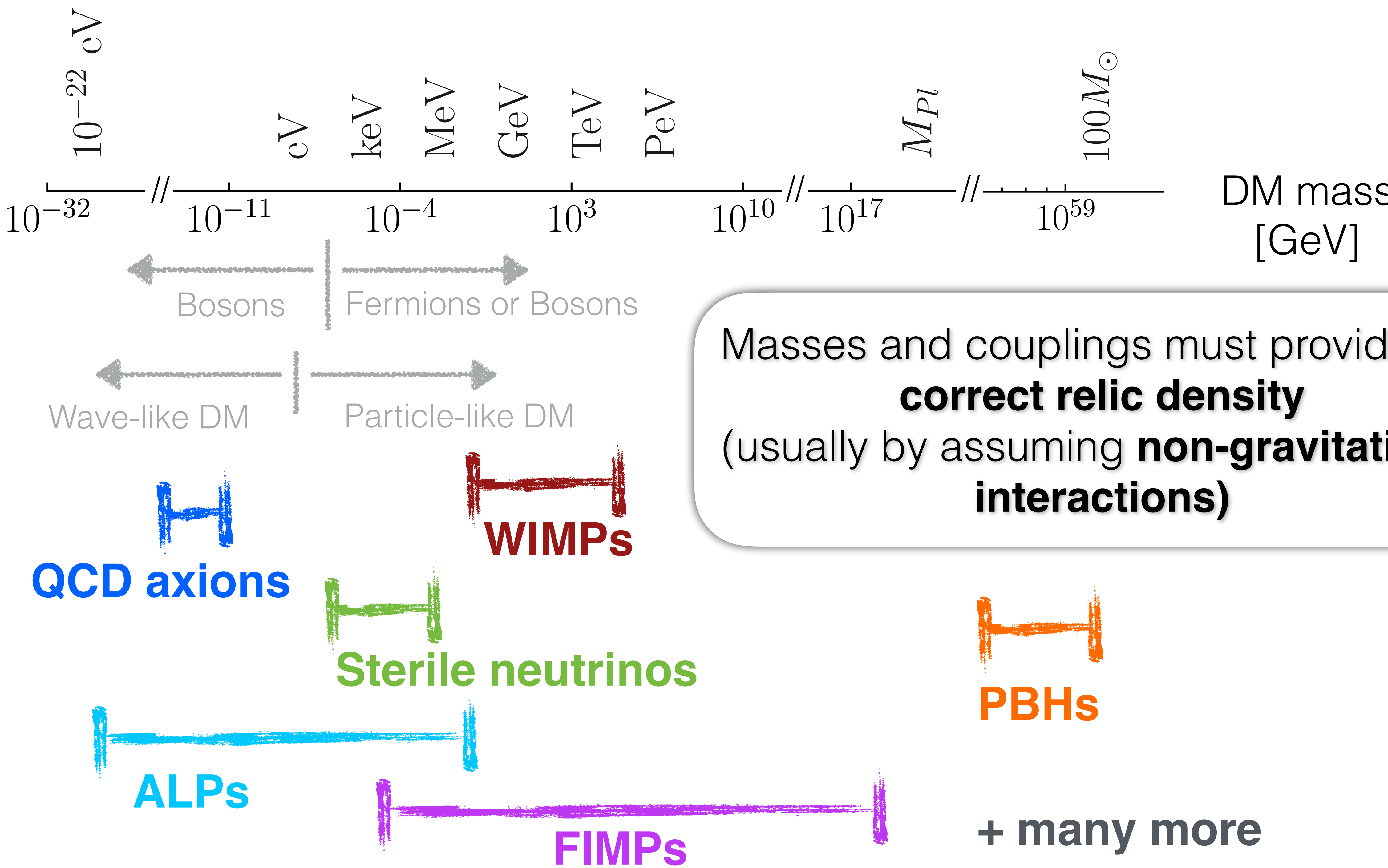

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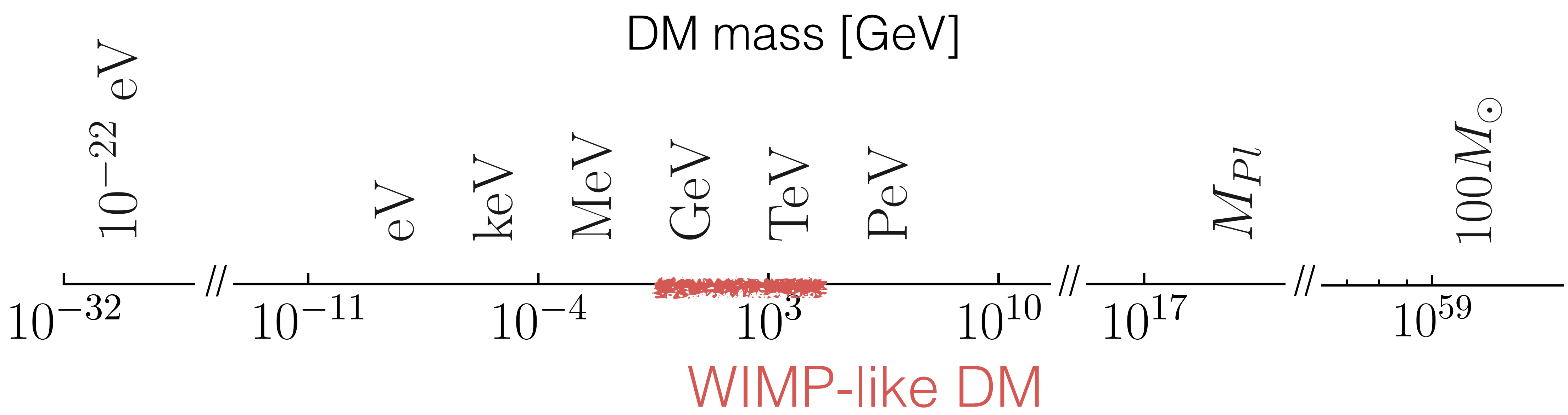
+ many more

Light dark matter: keV-GeV mass range



GeV-TeV DM: **detectable signals** in colliders, direct, and indirect detection experiments if we assume sizeable couplings;
Their correct relic density is easily achieved (freeze-out)

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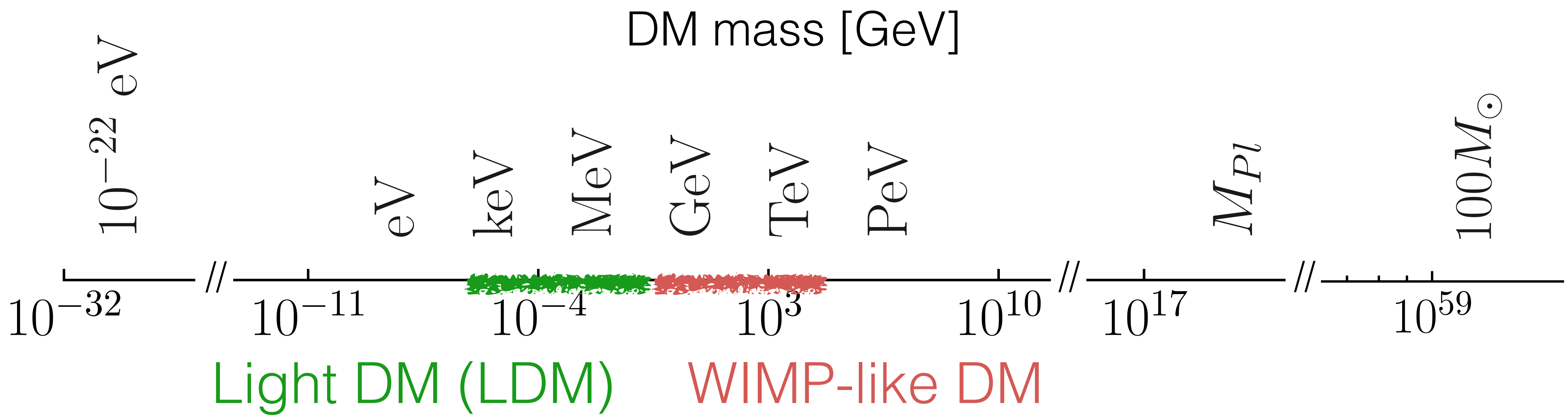

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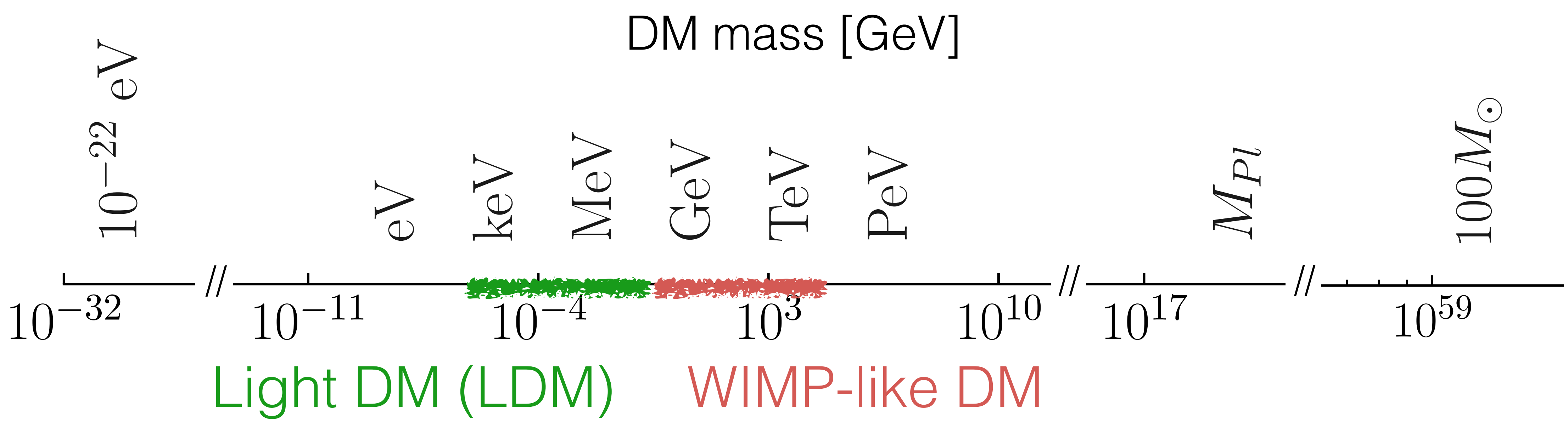

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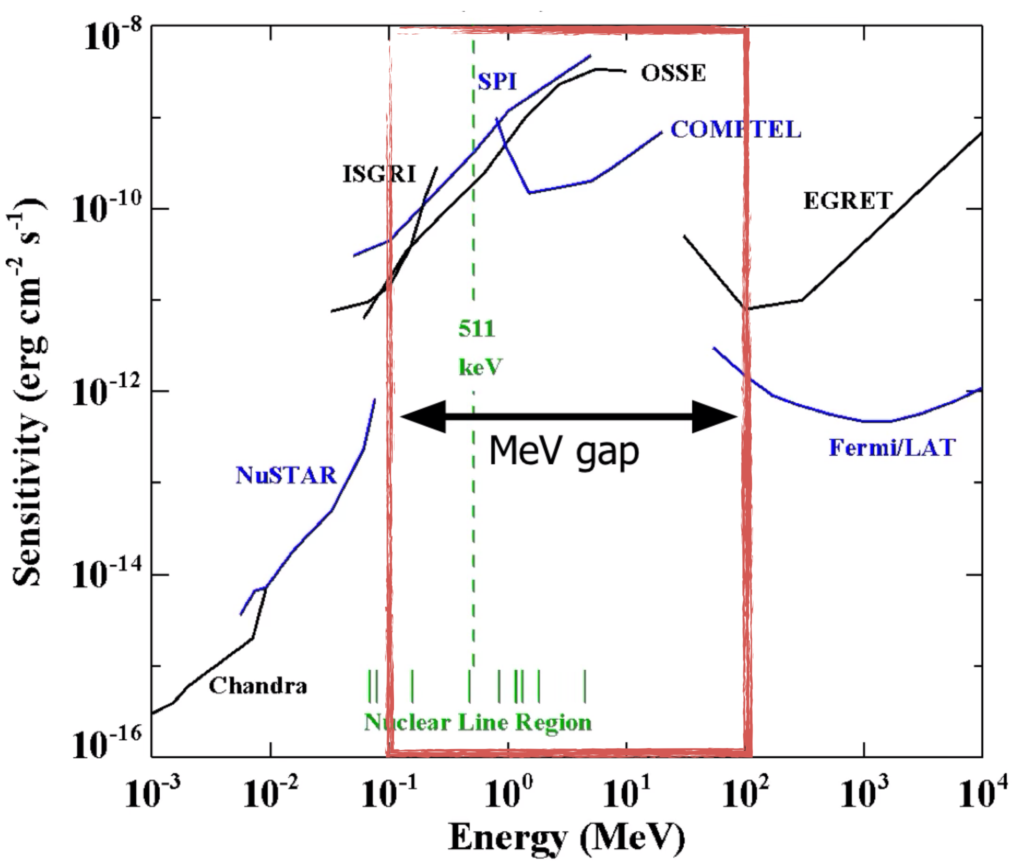
The **annihilation or decay** of light dark matter,
as well as the **evaporation** of primordial black holes,
can generate detectable **gamma rays in the MeV band**

Filling the 'MeV gap'



Technical difficulties reduce the sensitivity of γ-ray telescopes in the MeV band:

- Low photon-matter cross-section
- High background

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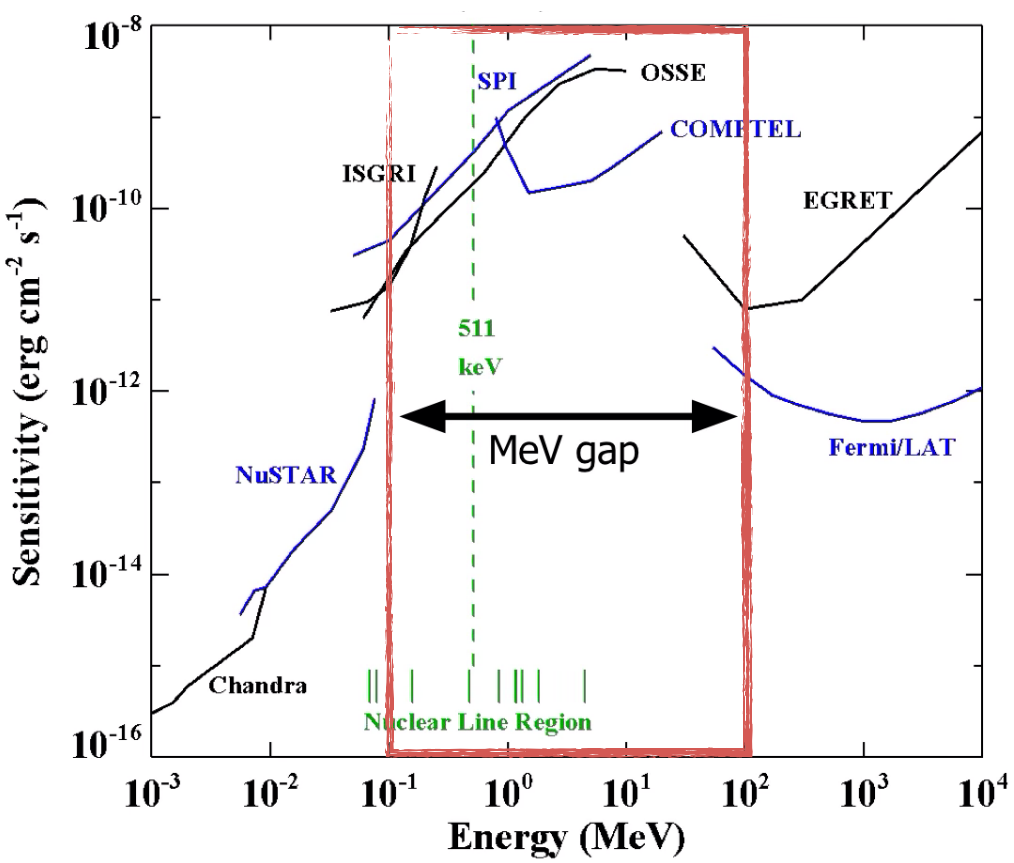

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COSI: upcoming MeV γ-ray telescope

- NASA Small Explorer satellite with a planned **launch in 2027**
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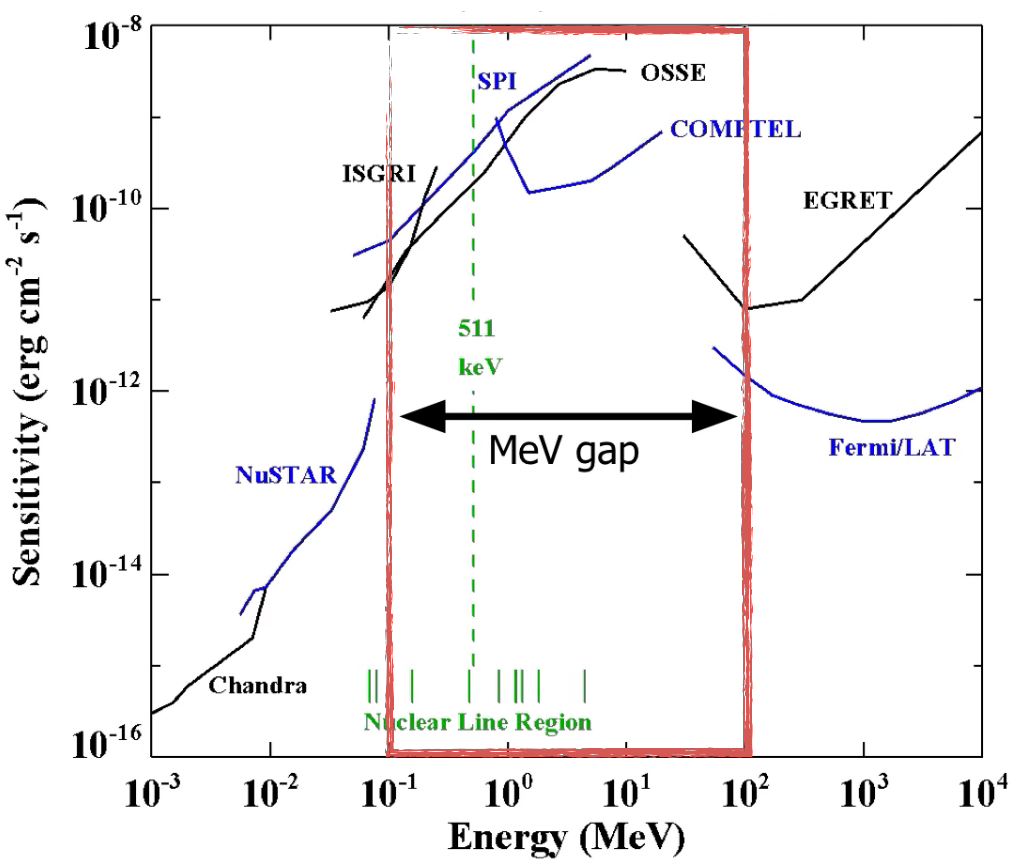

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Proposed MeV γ-ray telescopes

50 keV - 10 MeV

Compton + Coded mask

100 keV - 1 GeV

Compton + Pair

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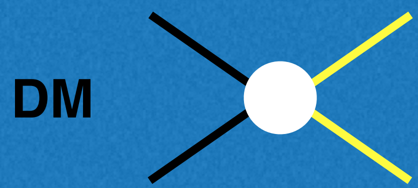
MeV γ-rays from light dark matter

Indirect detection of sub-GeV dark matter



- **light leptons** ($\nu_\alpha, e^\pm, \mu^\pm$)
- **photons** (γ)
- **light quarks** (u, d, s)
- **gluons** (g)

⊢ **light mesons** ($\pi^0, \pi^\pm, \eta, \ldots$)

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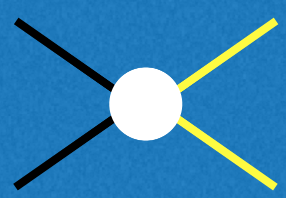
DM



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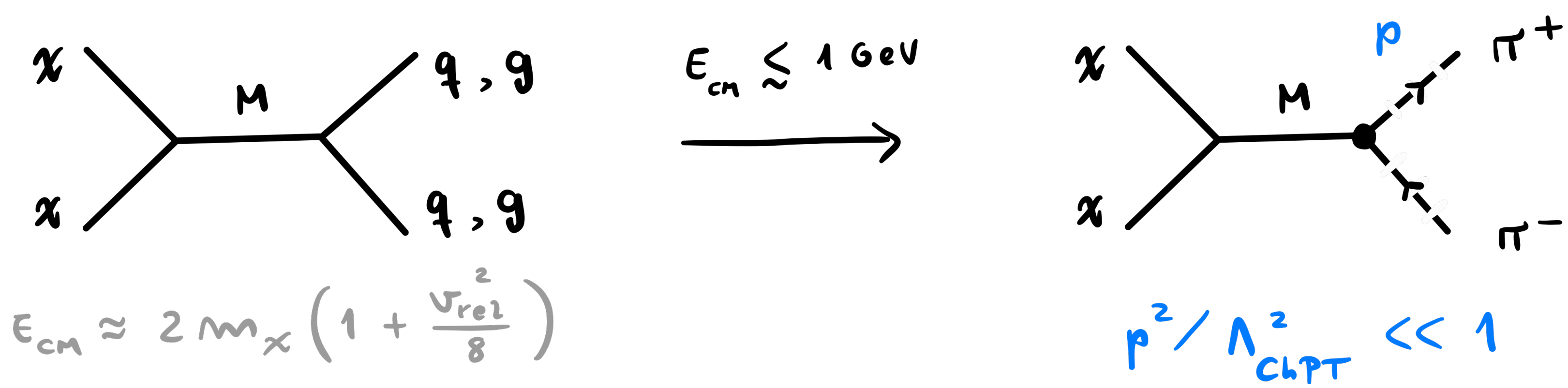
- To compute the self-annihilation of LDM into mesons, we use Chiral Perturbation Theory (ChPT), an EFT valid up to a scale $\Lambda_{ChPT} = 4\pi f_\pi \sim 1$GeV



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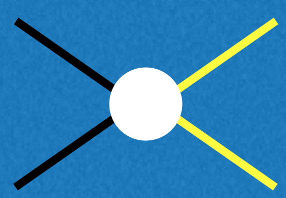

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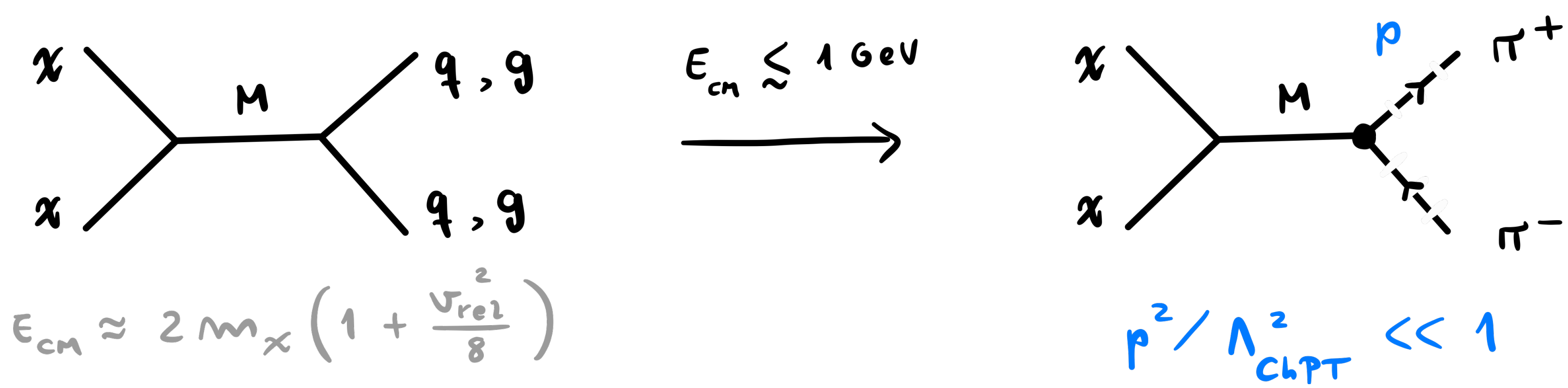

We use the **hazma** package to precisely compute spectra for the indirect detection of light dark matter

Hazma: a python toolkit for studying indirect detection of sub-GeV dark matter
Coogan, Morrison, Profumo arXiv:1907.11846

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Typical new physics framework: $U(1)'$ portal models

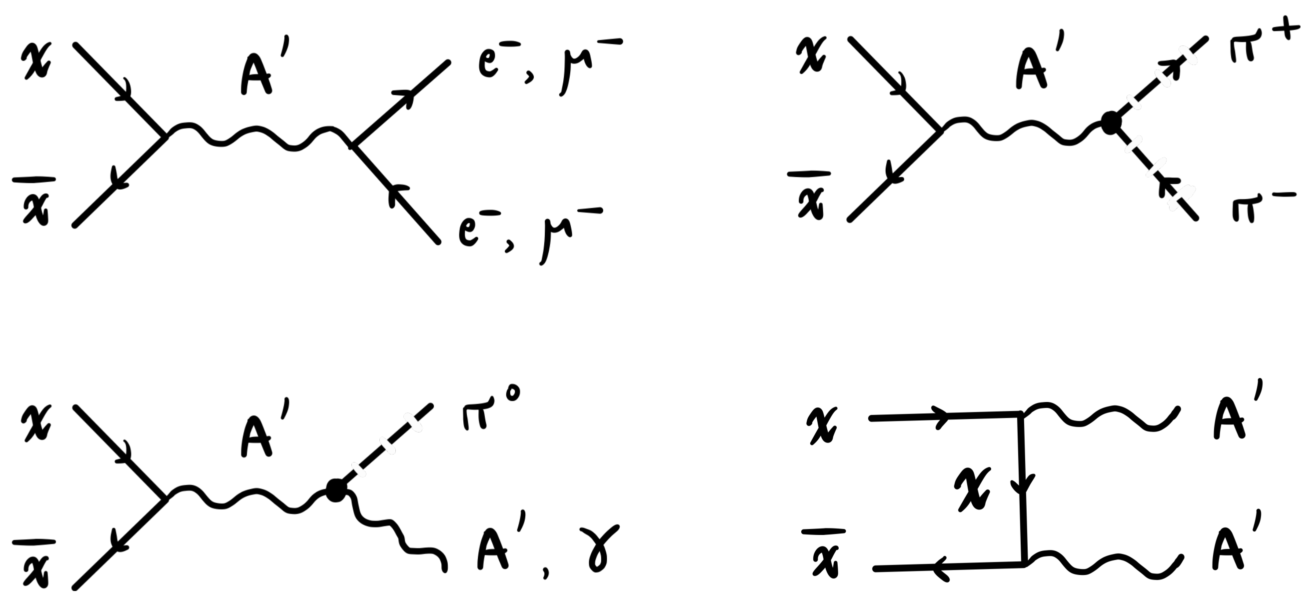
ordinary matter
(Standard Model)

vector mediator: A'

new non-grav. interaction: $U(1)'$

dark matter
Dirac fermion: χ

$$\mathscr{L} \supset -m_\chi \bar{\chi}\chi + \frac{m_{A'}}{2} A'_\mu A'^\mu + V_\chi \bar{\chi}\gamma^\mu \chi A'_\mu + \sum_f V_f \bar{f}\gamma^\mu f A'_\mu$$

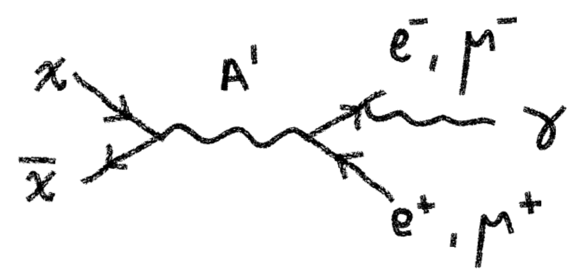


Cosme, **Dutra**, Godfrey, Gray
arXiv:2104.13937

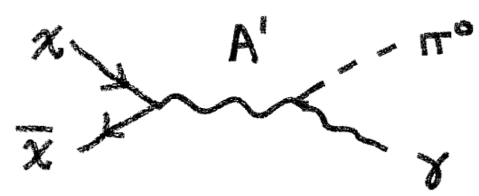
γ-ray spectra from LDM in U(1)' portals

$$\left.\frac{d\Phi_\gamma}{dE_\gamma}\right|_{\chi\bar{\chi}} = \frac{1}{16\pi}\frac{\langle\sigma v\rangle}{m_\chi^2}\sum_f B_f\frac{dN_\gamma^f}{dE_\gamma}\int d\Omega\int_{los} dl\,\rho_\chi^2(r(l,\psi))$$

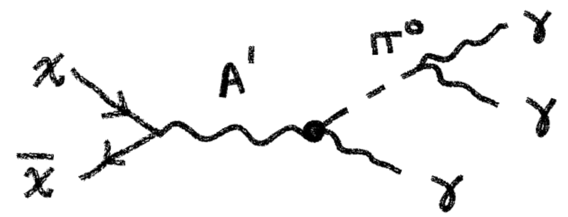
Particle physics — Astrophysics



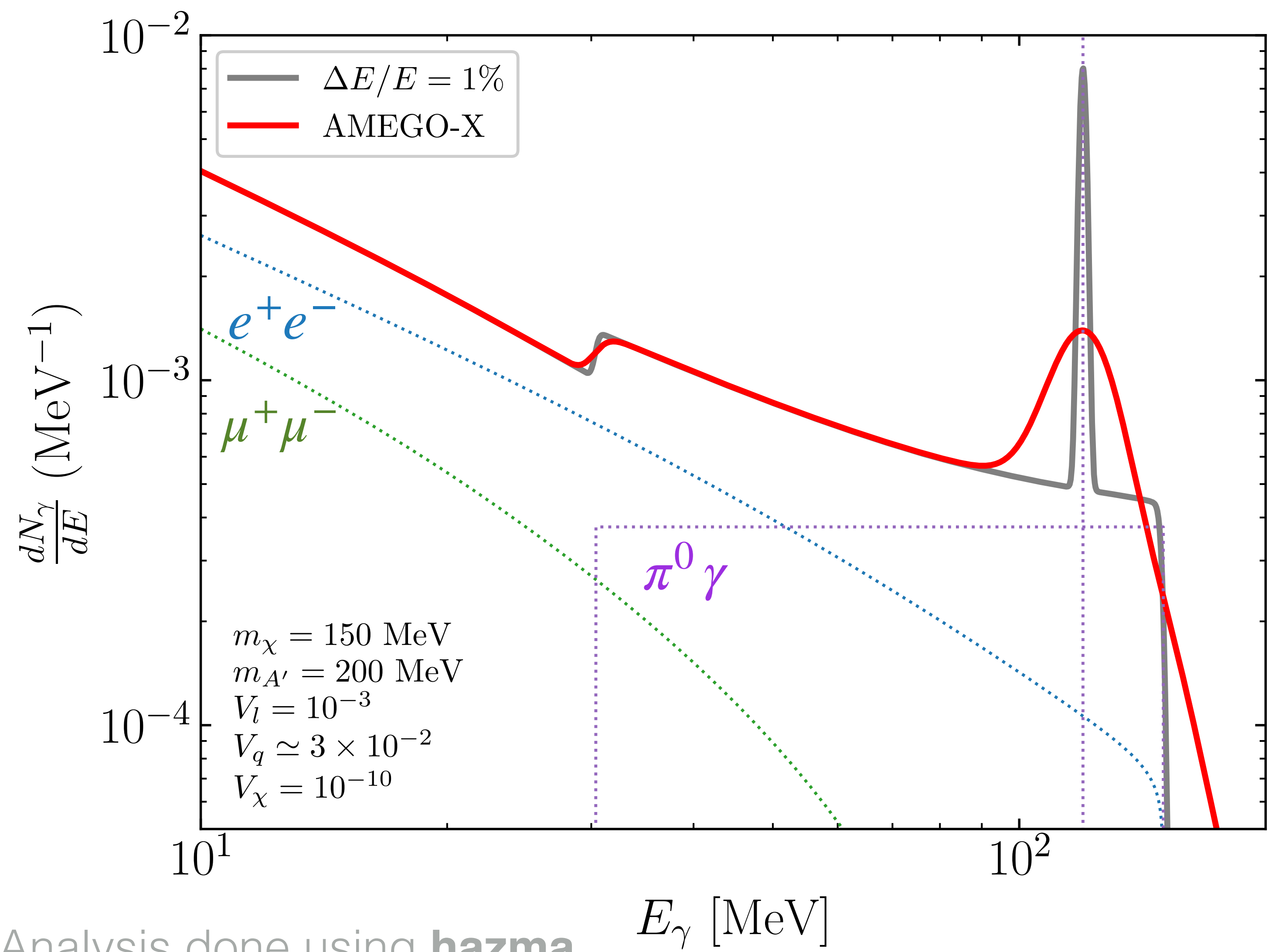
continuum



line



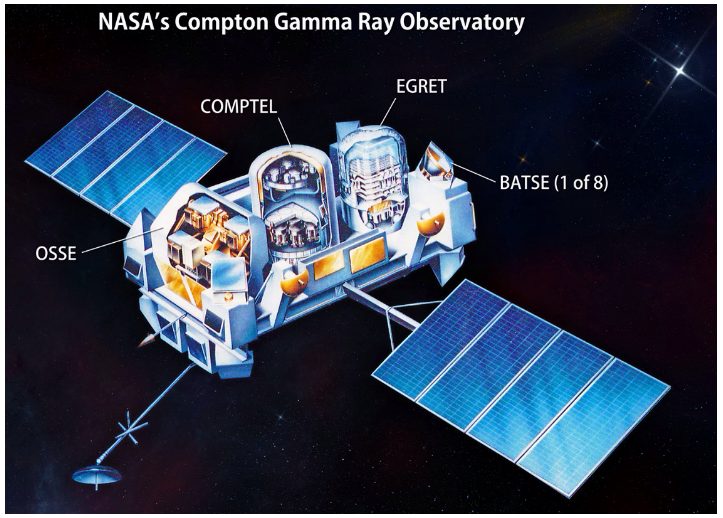
box



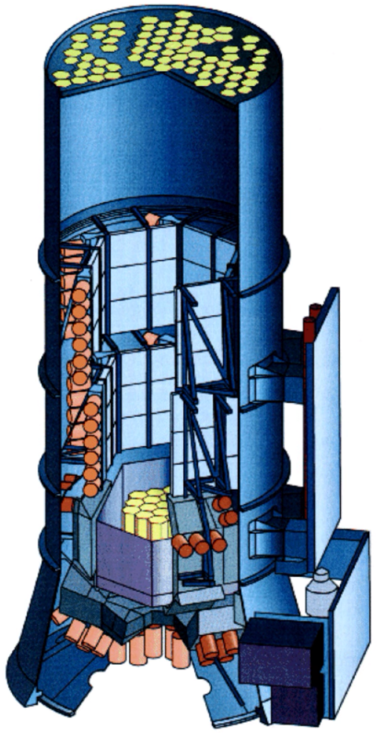
Analysis done using **hazma**
(see arXiv:1907.11846)

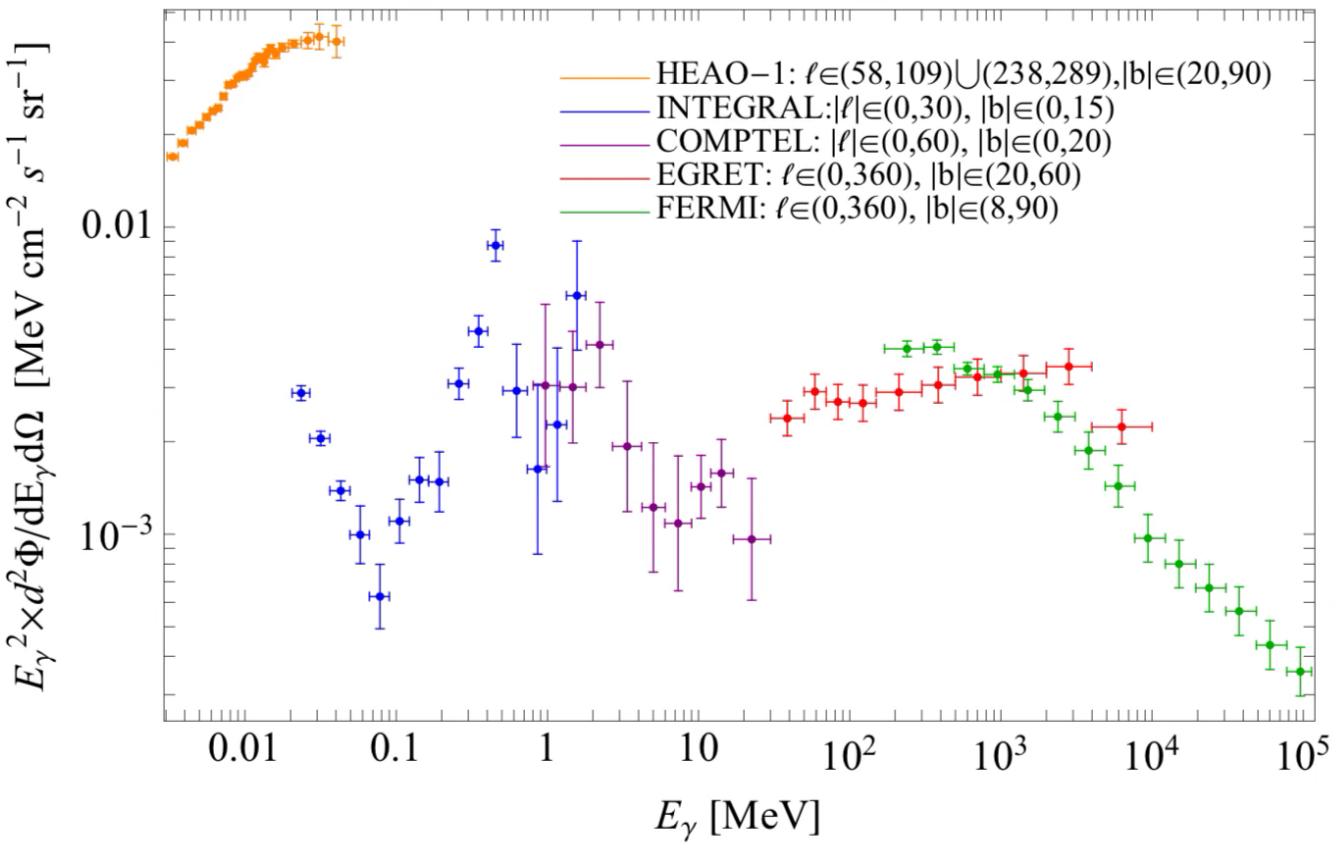
Current limits

COMPTEL: 1991 - 2000



INTEGRAL/SPI: 2002 - present





Essig+
arXiv:1309.4091

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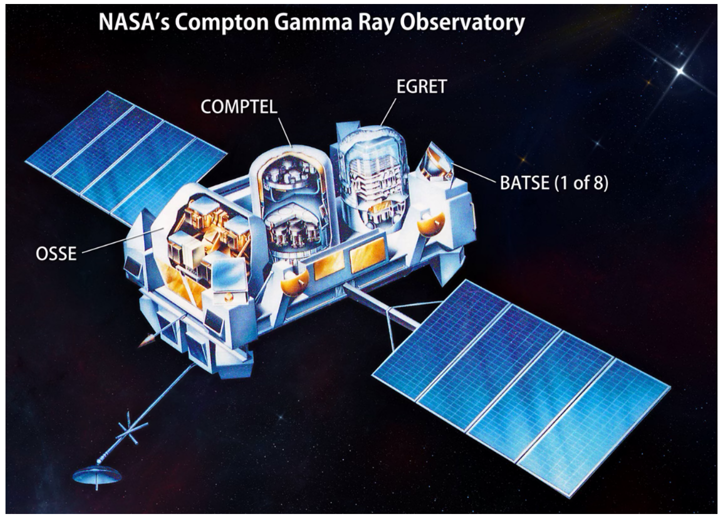

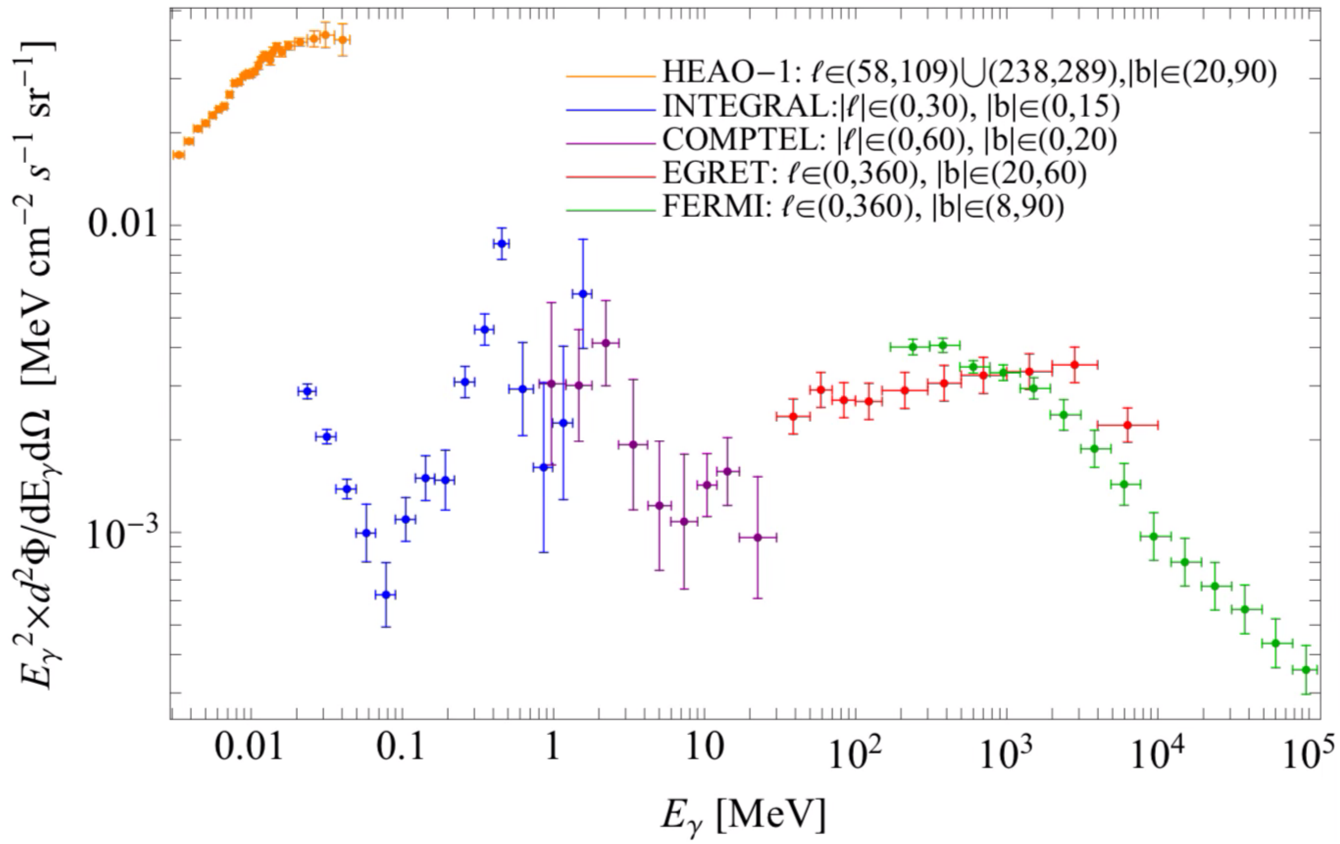

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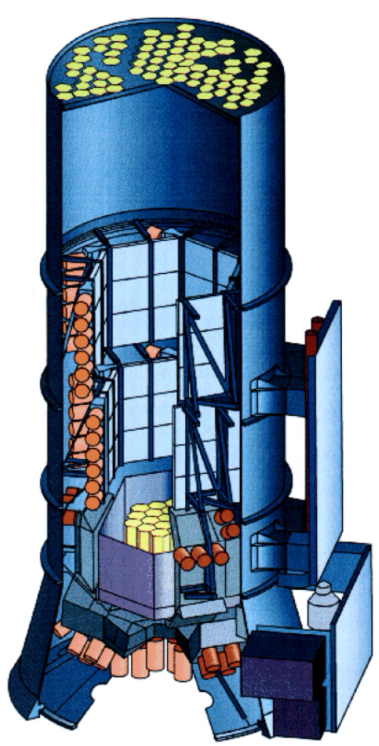
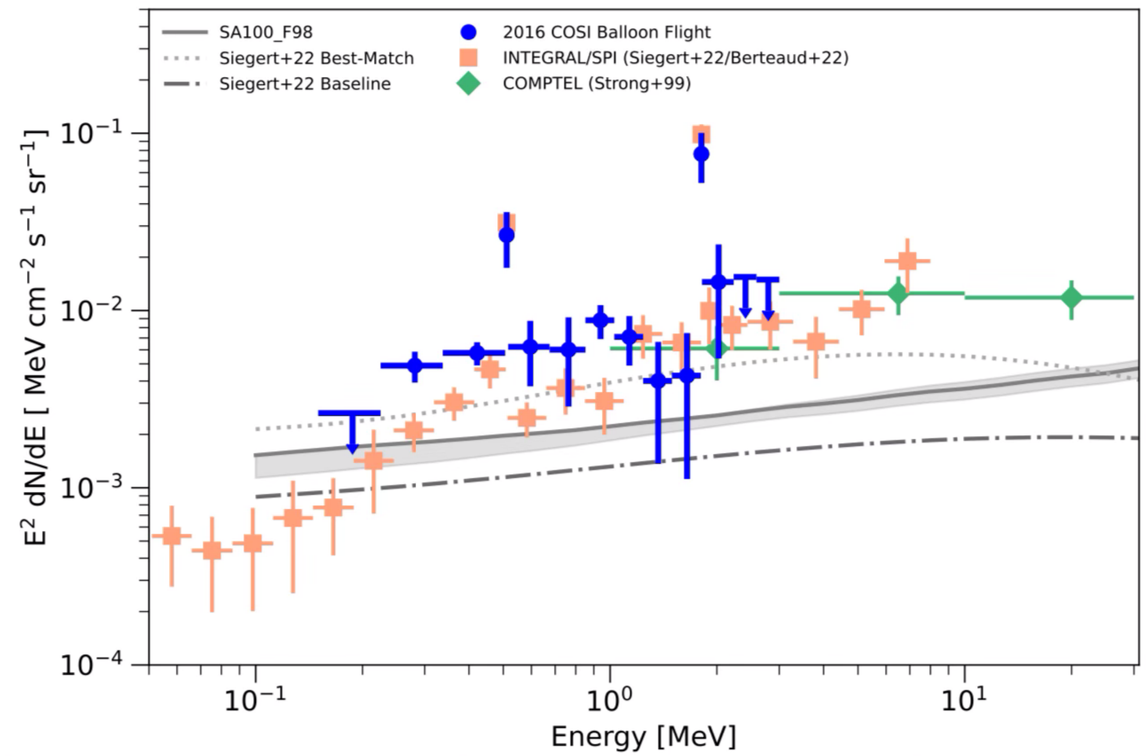
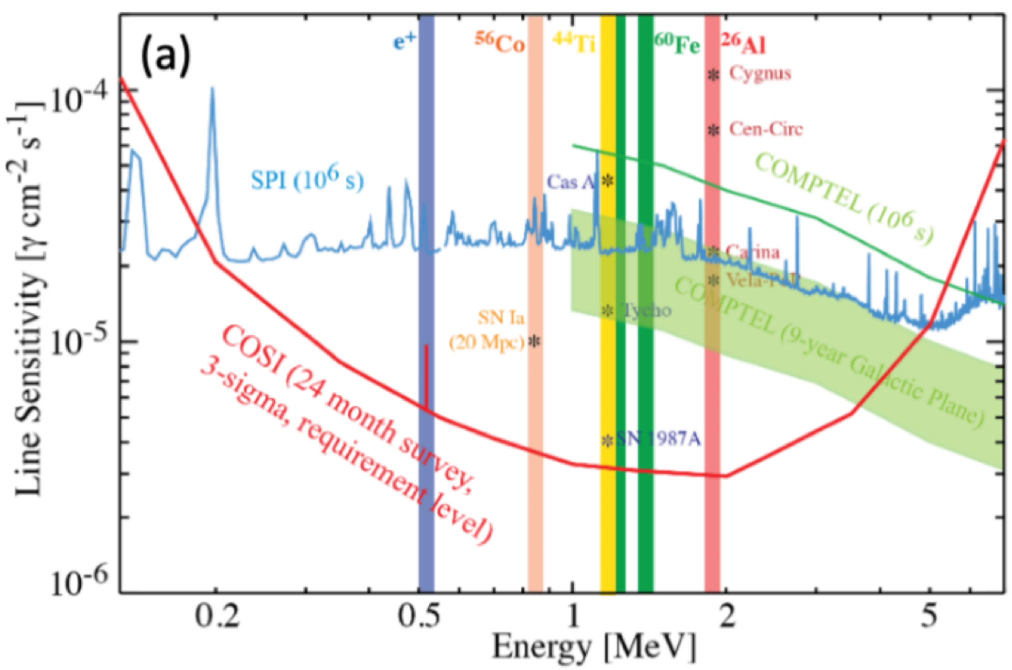


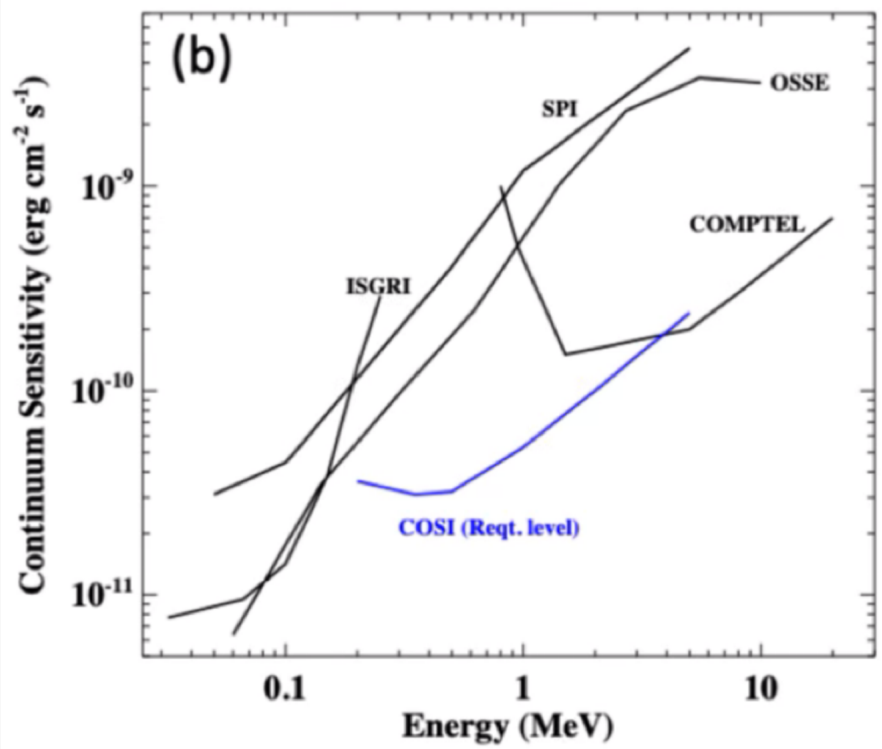
COSI balloon flights:
2014, 2016

Karwin+
arXiv:2310.12206



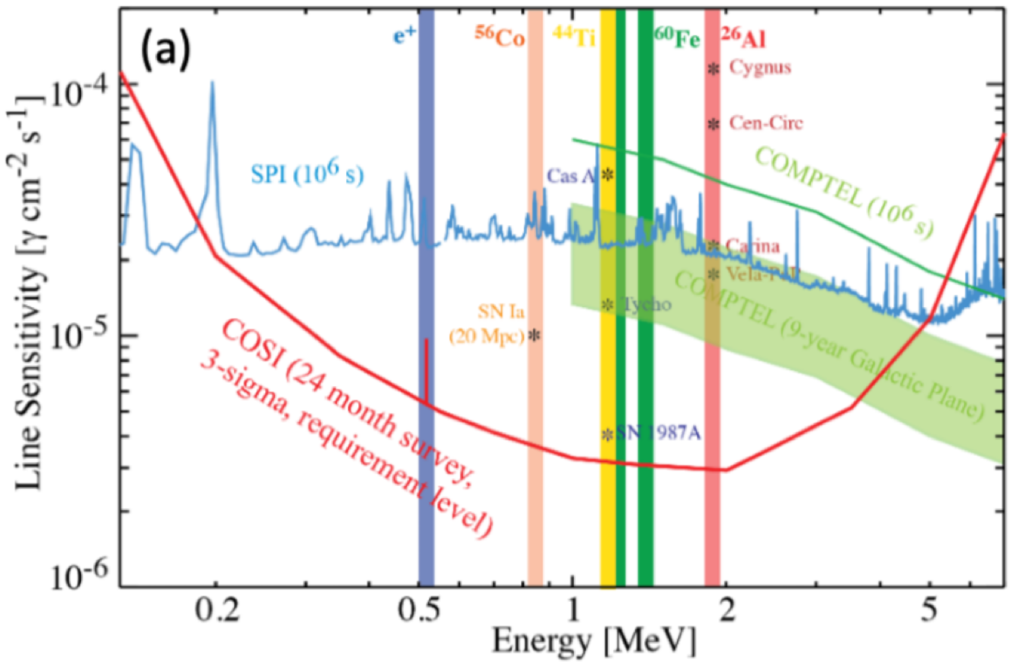
Discovery reach (or future limits...)

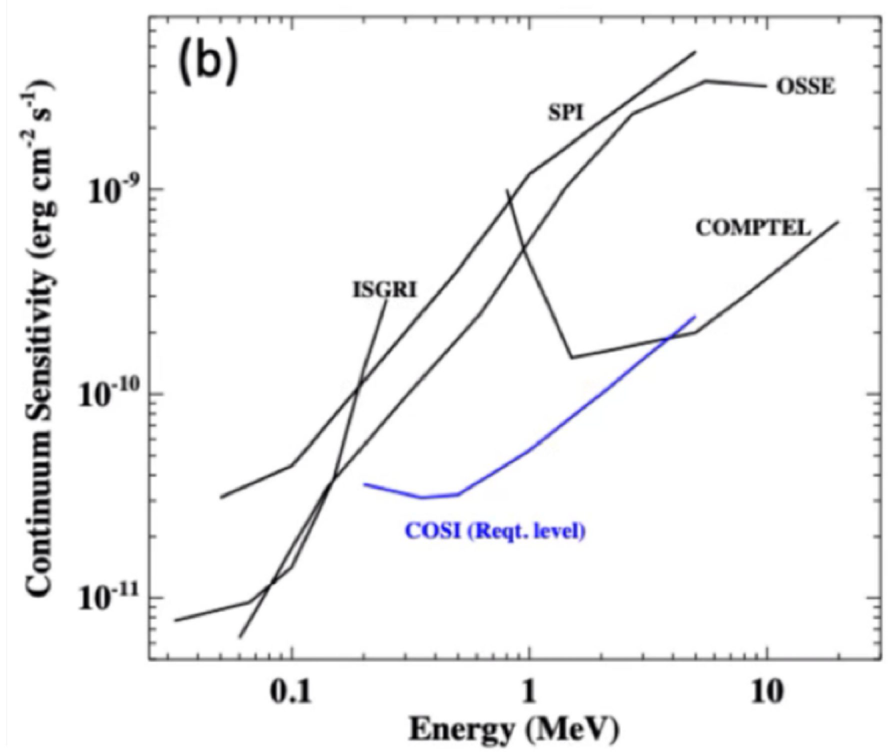




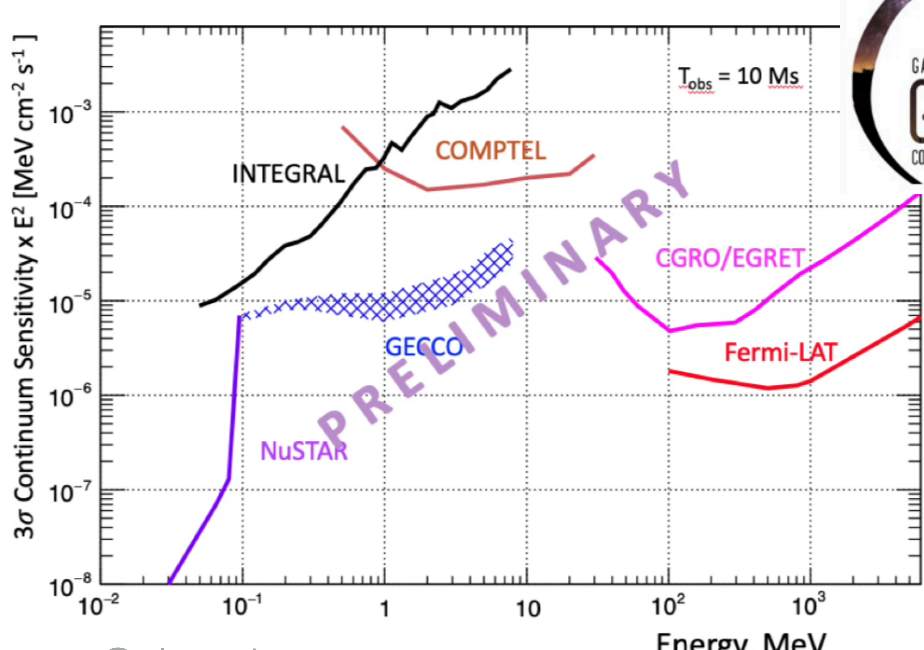
Tomsick+
arXiv:2308.12362

Discovery reach (or future limits...)

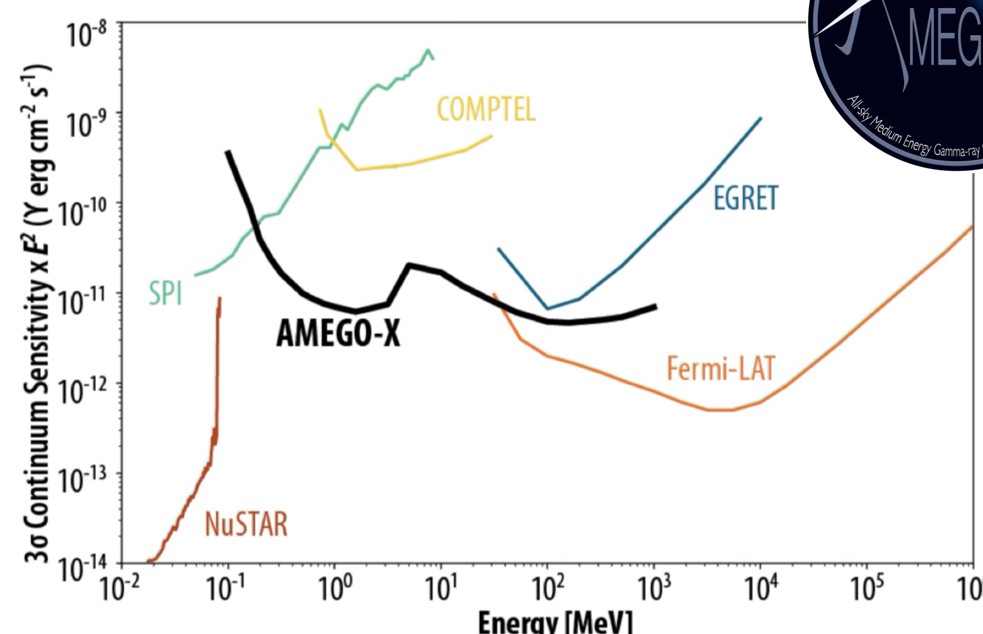




Tomsick+
arXiv:2308.12362

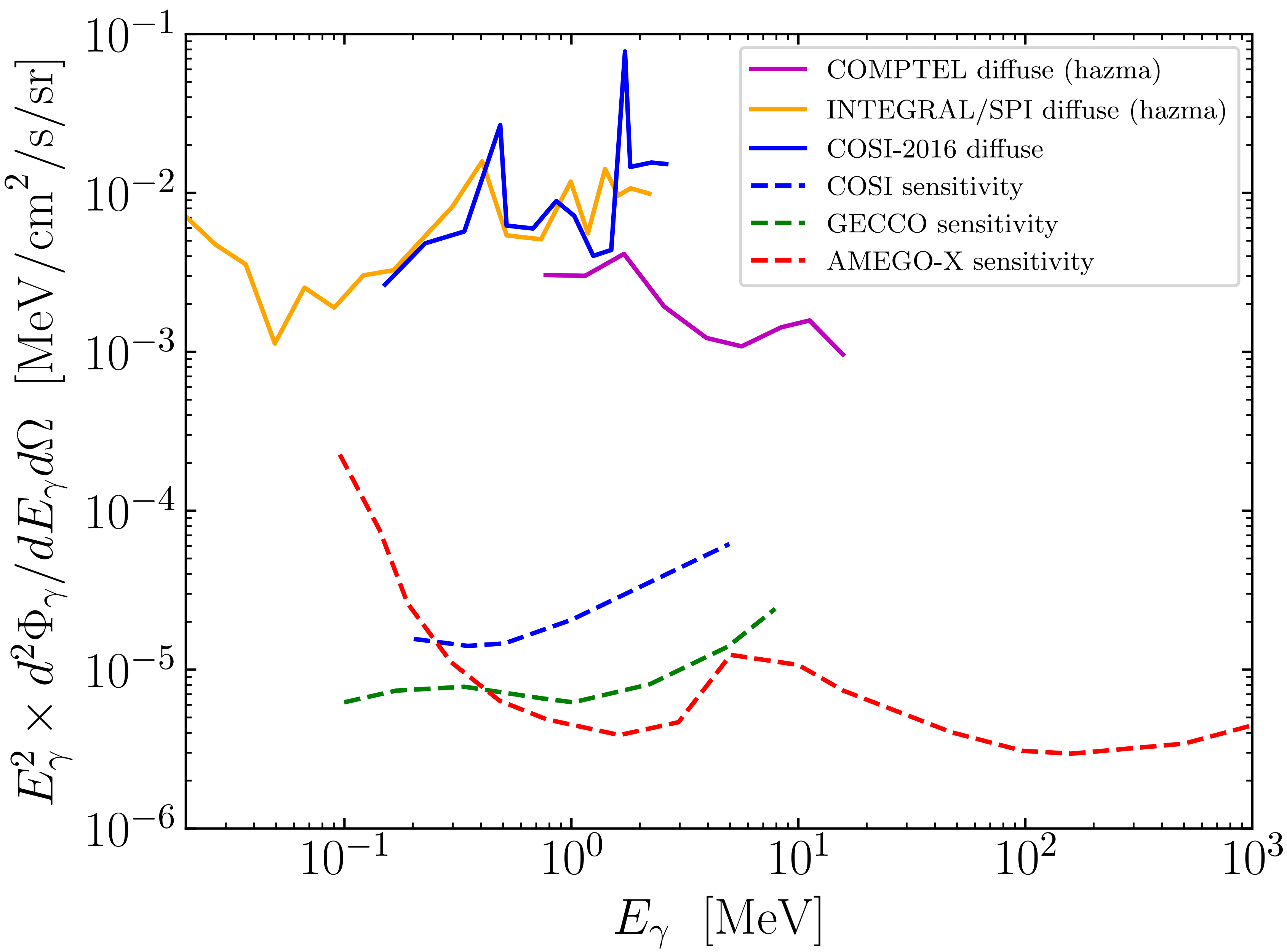


Orlando+
arXiv:2112.07190



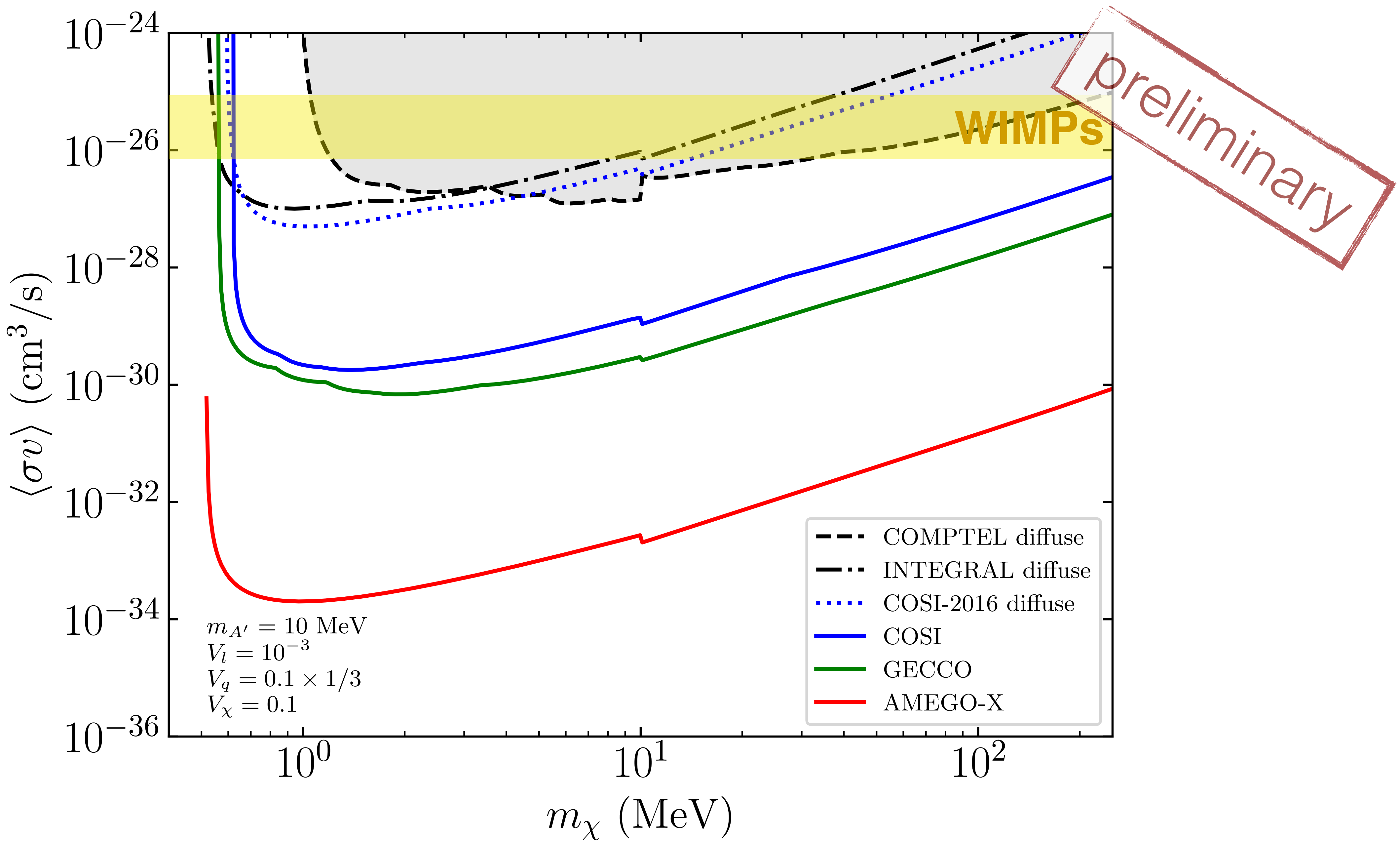
Caputo+
arXiv:2208.04990

Observed/observable γ-ray fluxes



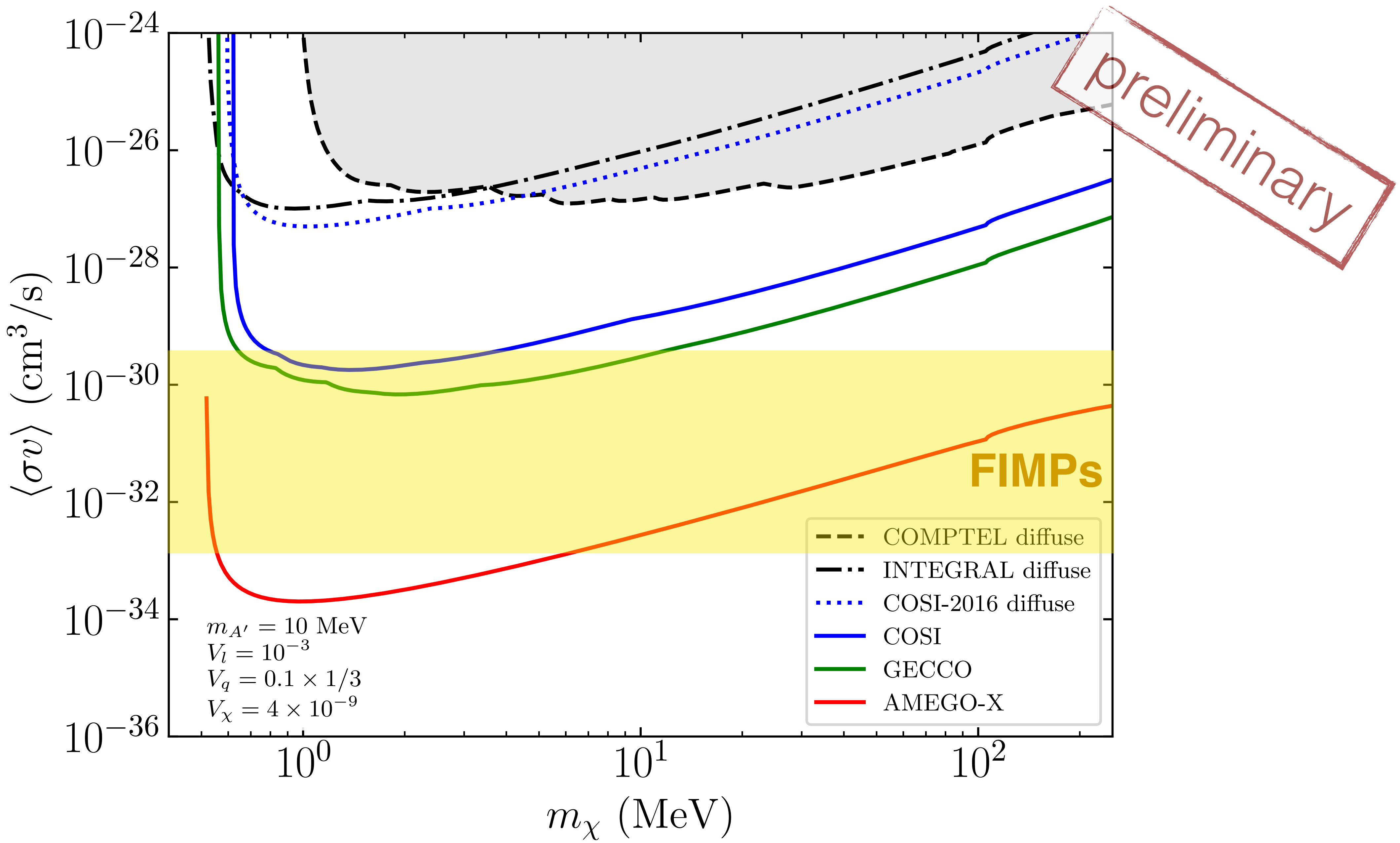
Excluded region in the DM parameter space: $\Phi^{(i)}{}_\gamma|^{DM} > \Phi^{(i)}{}_\gamma|^{obs} + 2\sigma^{(i)}$

Limits on the freeze-out parameter space



- A new part of the LDM parameter space might have been probed by the COSI balloon 46-days flight in 2016;

Limits on the freeze-in parameter space



- A new part of the LDM parameter space might have been probed by the COSI balloon 46-days flight in 2016;
- In the next decade, we will probe LDM well beyond the WIMP paradigm with γ rays!

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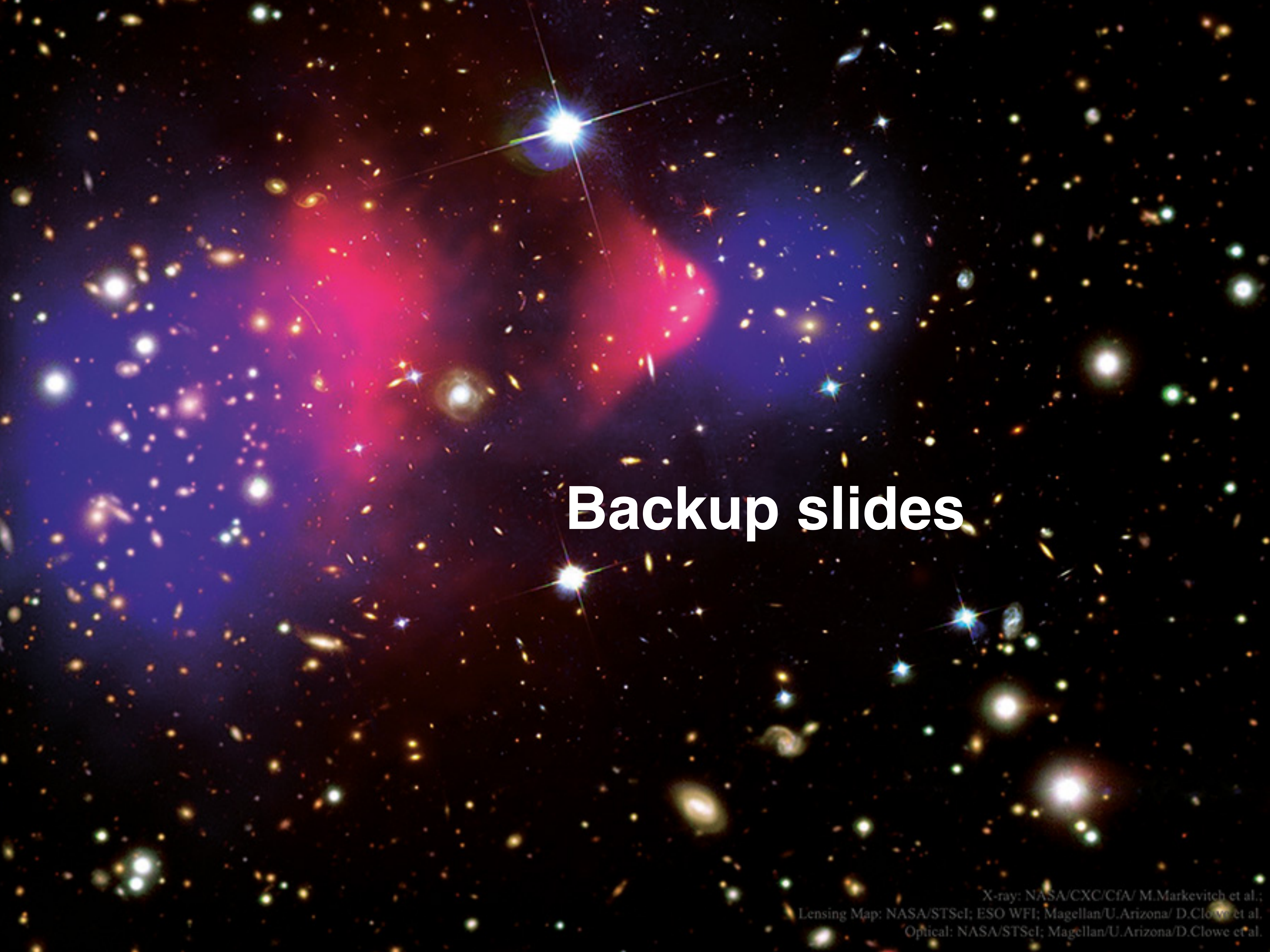
Conclusions

- The **nature of dark matter** (DM) is one of the main open questions in fundamental science and is necessarily part of new physics;
- An indirect detection signal of DM in gamma rays wold give us invaluable insights into the nature of dark matter, as it would tell us its **mass scale** and potentially the **annihilation channel(s)**;
- We can use the **2016 COSI balloon flight** data to probe the physics of light dark matter;
- Future MeV gamma-ray telescopes, such as **COSI, GECCO**, and **AMEGO-X**, could **discover DM** or set **leading constraints** on what the DM new physics could be.

Thank you!

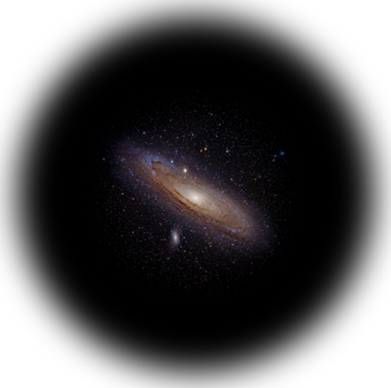

Backup slides
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Introduction: Evidence for dark matter

based on all the evidence we have, dark matter is most likely made of gravitationally interacting **particles**

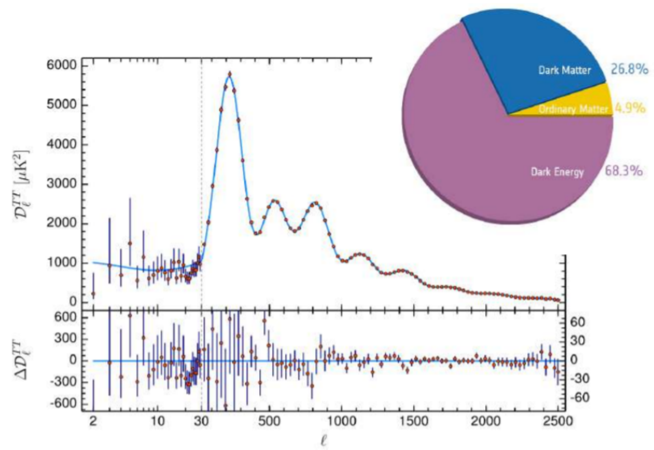
Astrophysics: most of the matter in the universe is *dark matter* - it does not interact with light as ordinary matter

- Stability of galaxy clusters
- Stability of disk galaxies
- Rotation curves
- Merging galaxy clusters



Cosmology: ordinary matter alone cannot form structures - one needs the gravitational potential of *dark matter*

- BBN
- CMB
- Structure formation

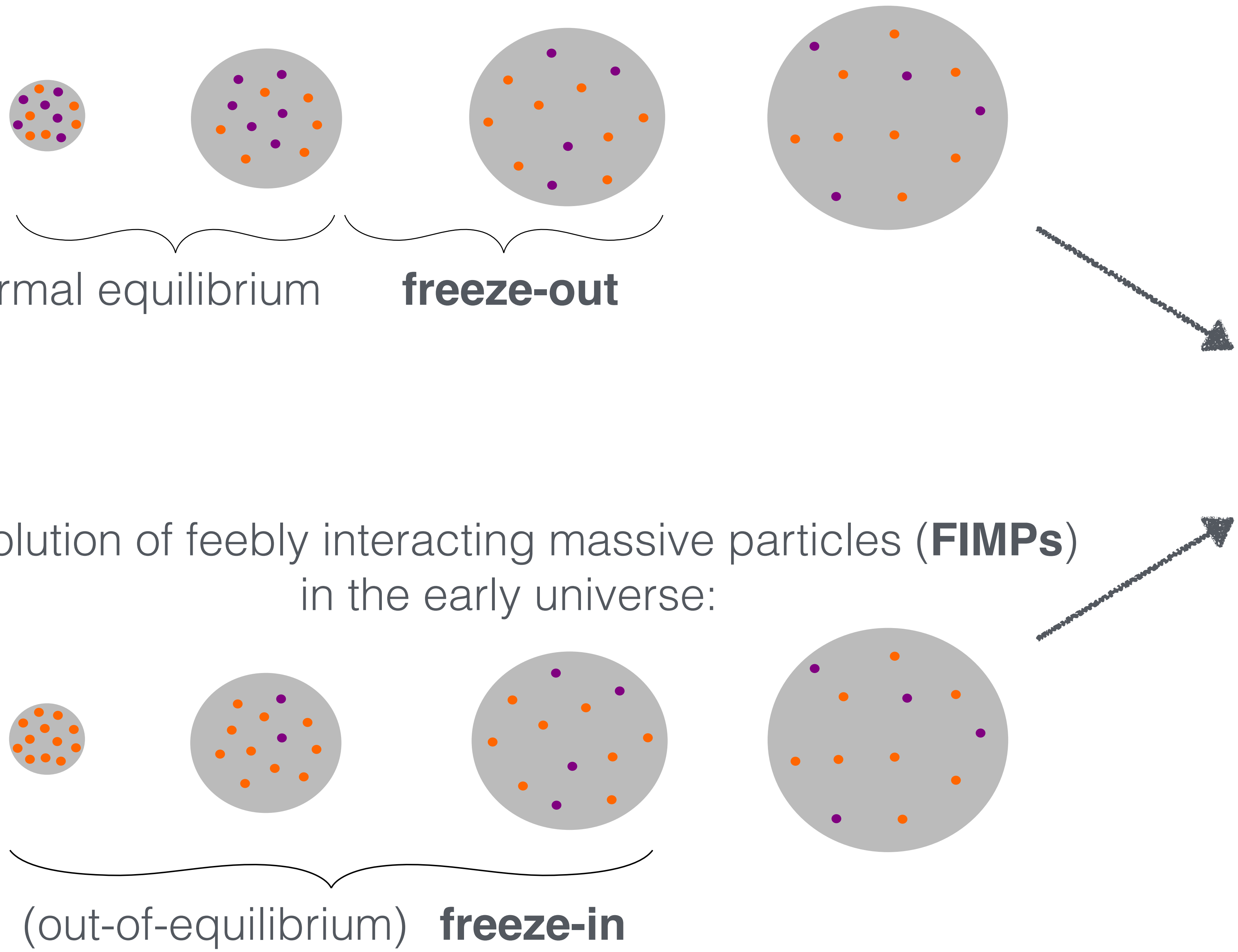


A sucessful dark matter (DM) candidate must have mass and couplings providing the **DM relic density** as inferred by the Planck satellite (27% of the cosmic energy today)

We tipically need to assume DM-SM **non-gravitational interactions**

DM genesis: Freeze-out and Freeze-in

Evolution of weakly interacting massive particles (**WIMPs**)
in the early universe:



Evolution of feebly interacting massive particles (**FIMPs**)
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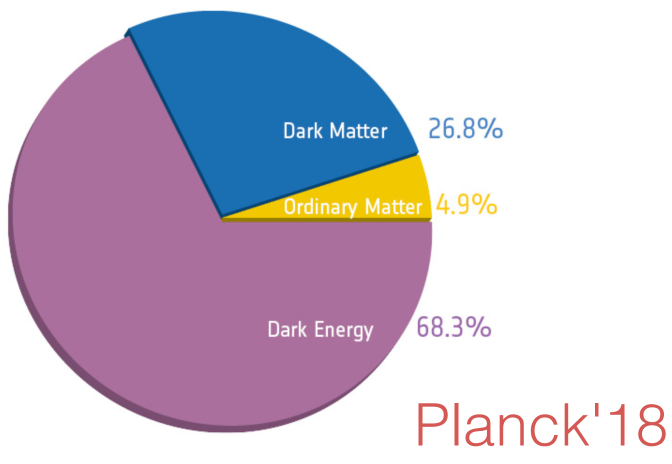
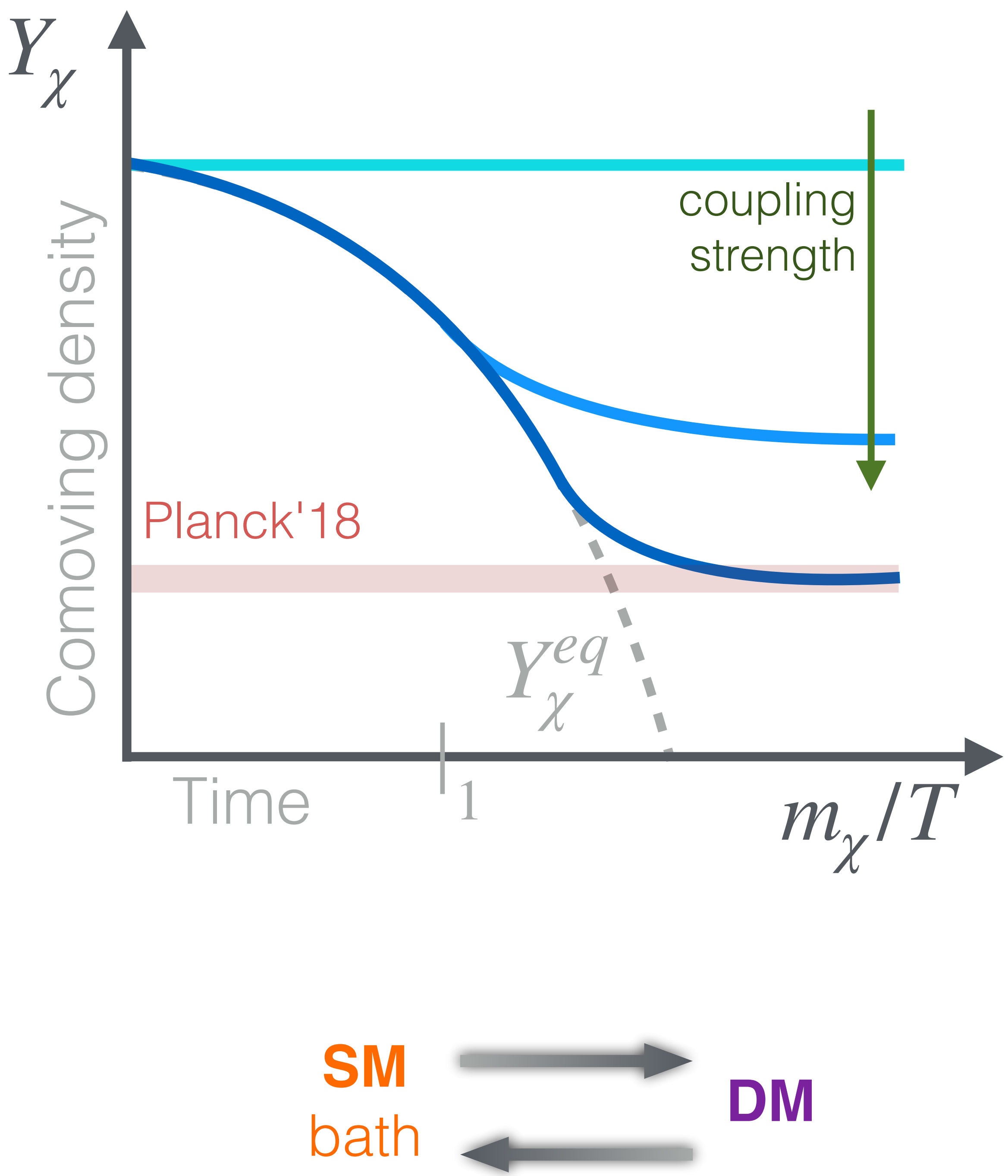
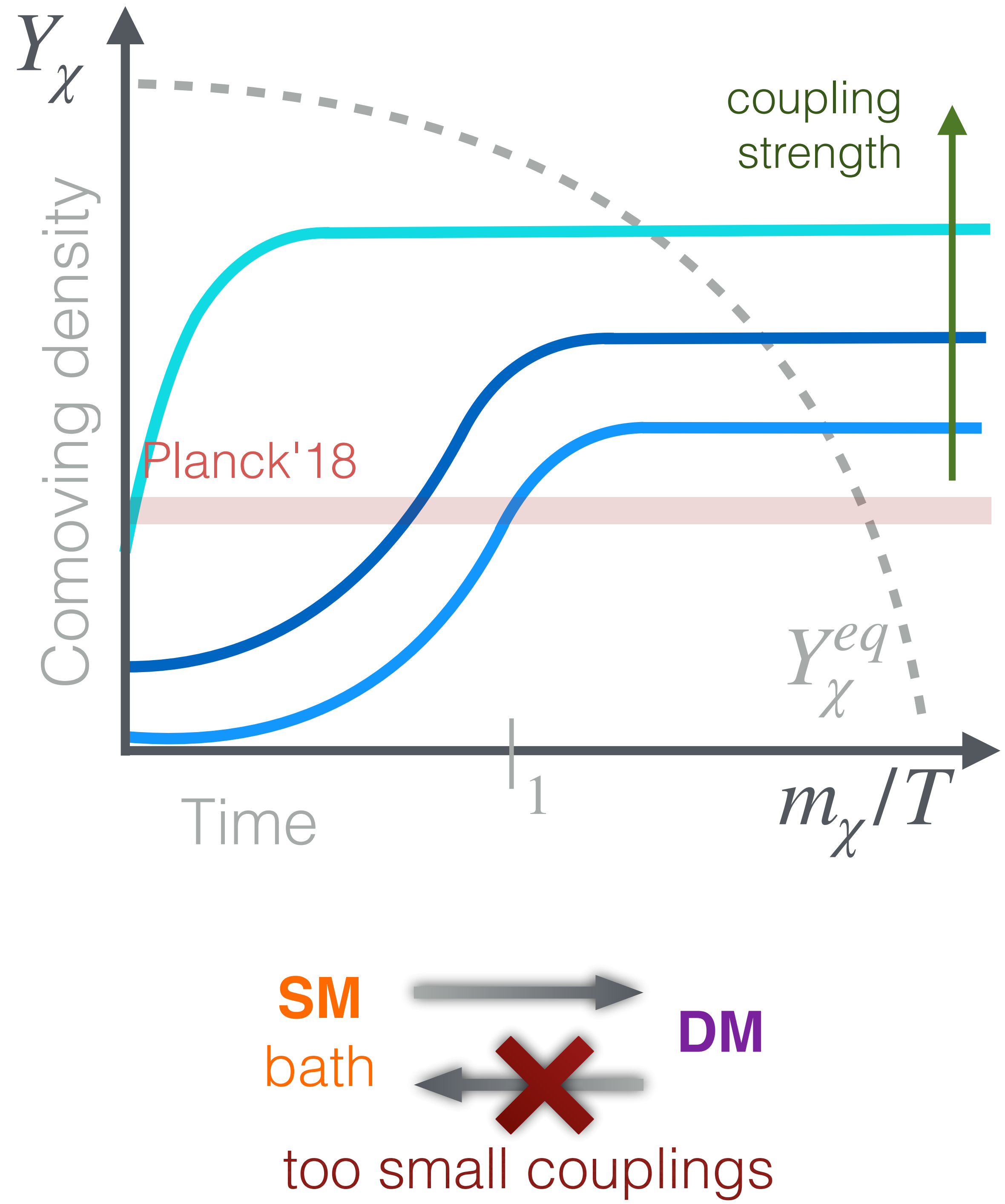


Relic abundance: Freeze-out and Freeze-in

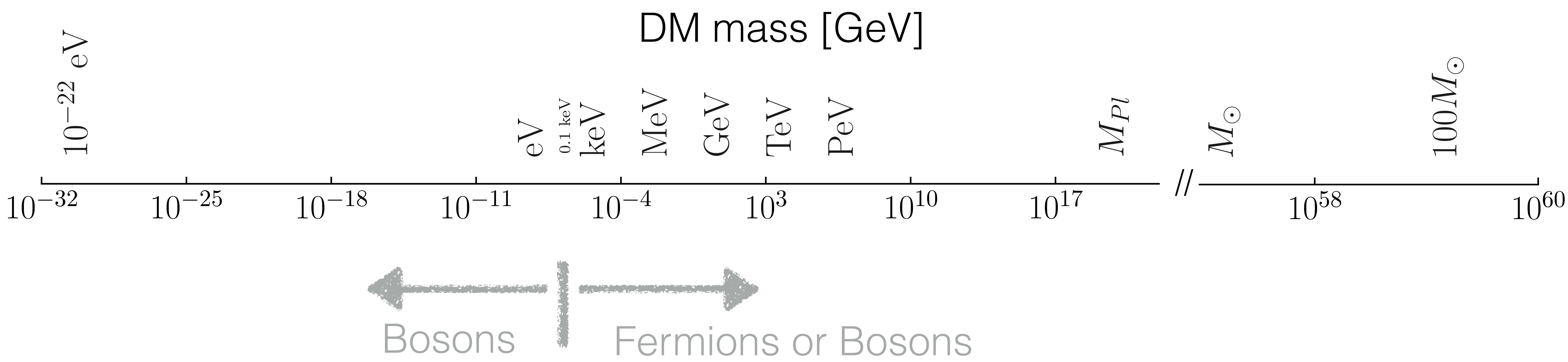
freeze-out of WIMPs



freeze-in of FIMPs



The nature of DM particles



Tremaine and Gunn, 1979:

We can place a **model-independent lower bound on the mass of fermionic DM** that can be compressed within astrophysical objects (e.g., dwarf spheroidal galaxies), by using the **Pauli exclusion principle.**

This is another reason why SM neutrinos cannot be DM.

$$m_{fermionic\,DM} \gtrsim 0.1 \text{ keV}$$

Alvey et al. (2020)
arXiv:2010.03572

The nature of DM particles

Dark matter particles behave more like **waves** or like **localized particles**?

Einstein, 1905:

Photons carry momentum: $p = |\vec{p}\,| = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$

de Broglie, 1924:

Matter fields (e.g., electrons, neutrons) have an associated *wavelength*: $\lambda_{dB} \equiv \frac{h}{p}$

Schrödinger, 1926:

Derivation of a wave equation for matter fields, the Schrödinger equation!

DM particles may exhibit a wave-like behavior
if their **de Broglie wavelength** is **larger than the average inter-particle separation**
within an astrophysical object;
In this case, it can be described as a set of classical waves

The nature of DM particles

$$\lambda_{dB} \equiv \frac{h}{p} = \frac{2\pi\hbar}{mv} \sim \begin{cases} 1.5\ \text{pm} \left(\frac{1\,\text{GeV}}{m_{DM}}\right)\left(\frac{250\,\text{km/s}}{v_{DM}}\right) \\ 1500\ \text{pm} \left(\frac{1\,\text{MeV}}{m_{DM}}\right)\left(\frac{250\,\text{km/s}}{v_{DM}}\right) \\ 1.5\ \text{km} \left(\frac{10^{-6}\,\text{eV}}{m_{DM}}\right)\left(\frac{250\,\text{km/s}}{v_{DM}}\right) \end{cases}$$

picometer: $pm = 10^{-12} m$

$v_{DM} \sim 250$ km/s: velocity dispersion of DM in the Galactic halo

$$N_{dB} = n_{DM}\lambda_{dB}^3 = \frac{\rho_{DM,\odot}}{m_{DM}}\lambda_{dB}^3 \gg 1 \Rightarrow \text{wave-like DM}$$

DM local density:
$\rho_{DM,\odot} = 0.3 - 0.4$ GeV/cm^3
$\sim 0.01\, M_\odot$/pc^3

$$m_{Wave-like\,DM} \lesssim 30 \text{ eV}$$

Hui (2021)
arXiv:2101.11735

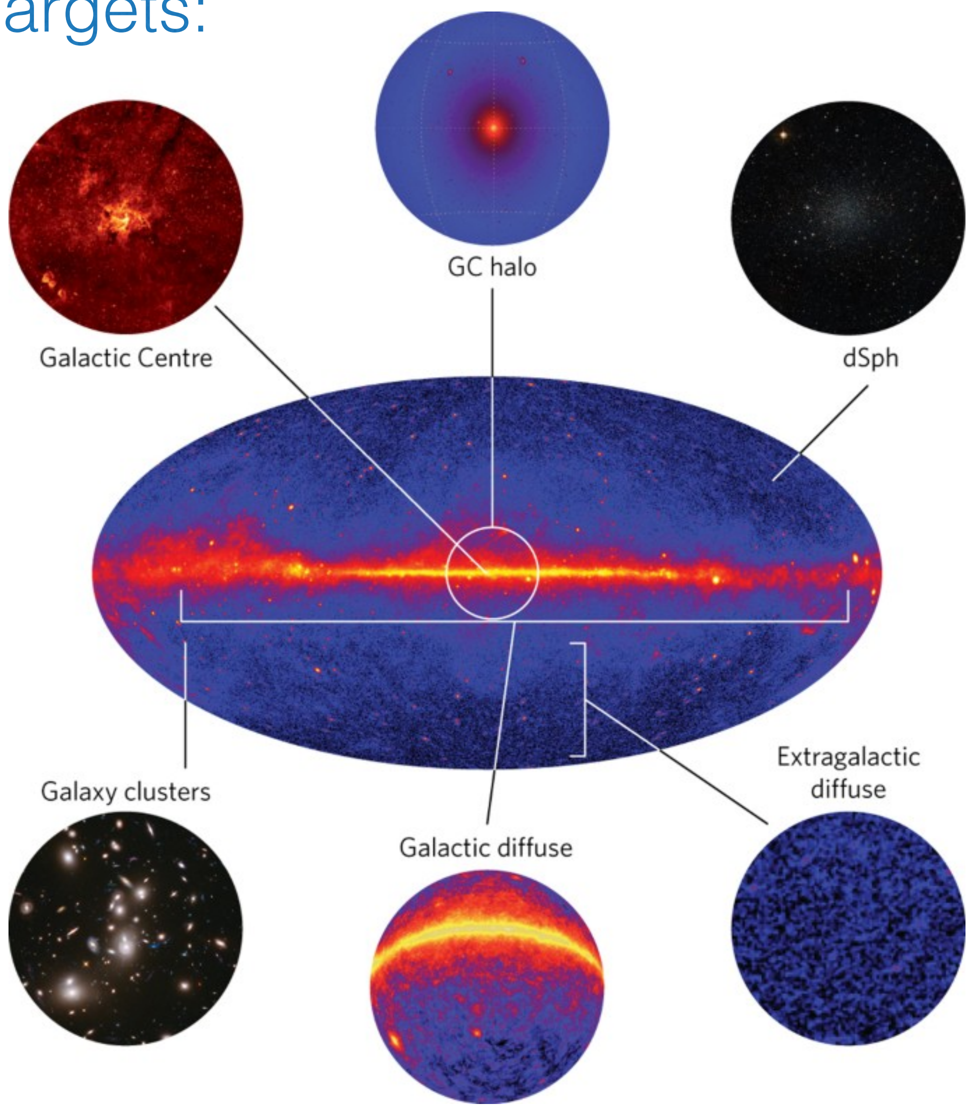
MeV γ-rays from light dark matter

Differential γ-ray flux from DM annihilation:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \theta_{obs})\Big|_{\chi\bar{\chi}} = \frac{\Delta\Omega}{4\pi}\bar{J}(\theta_{obs})\frac{\langle\sigma v\rangle}{2 f_{DM} m_{DM}^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}(E_\gamma)$$

Astrophysics Particle physics

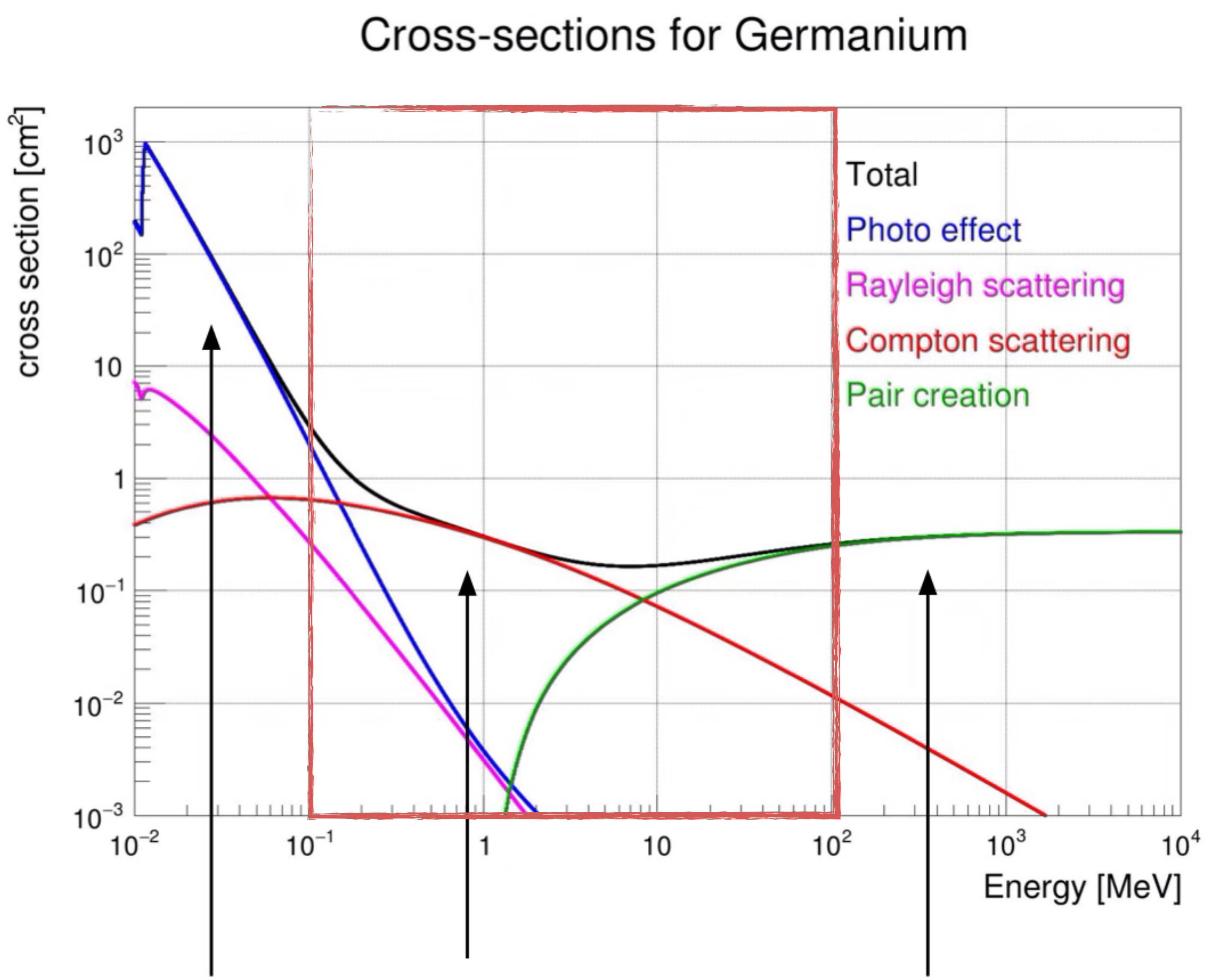
Targets:



$$\bar{J}(\theta_{obs}) \equiv \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{los} ds\, \rho_{DM}^2(r(s,\Omega))$$

$$\rho_{DM}^2(r)\,|^{NFW} = \rho_s \frac{r_s}{r}\left(1 + \frac{r}{r_s}\right)^{-2}$$

The 'MeV gap'

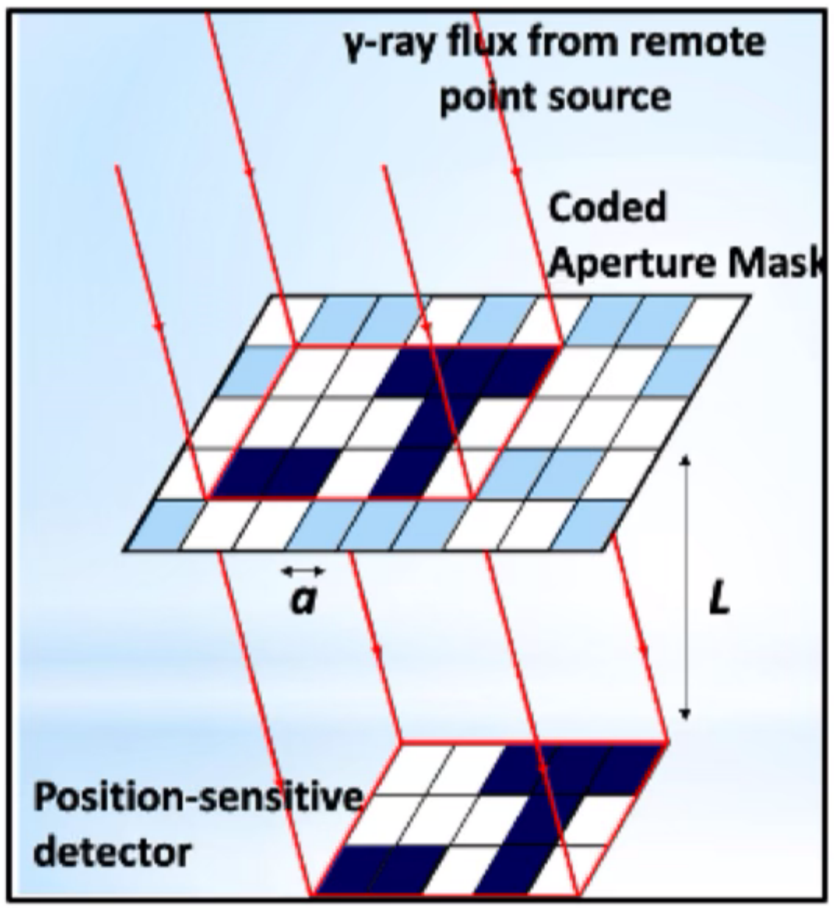


Full photon absorption (NuSTAR, etc.)

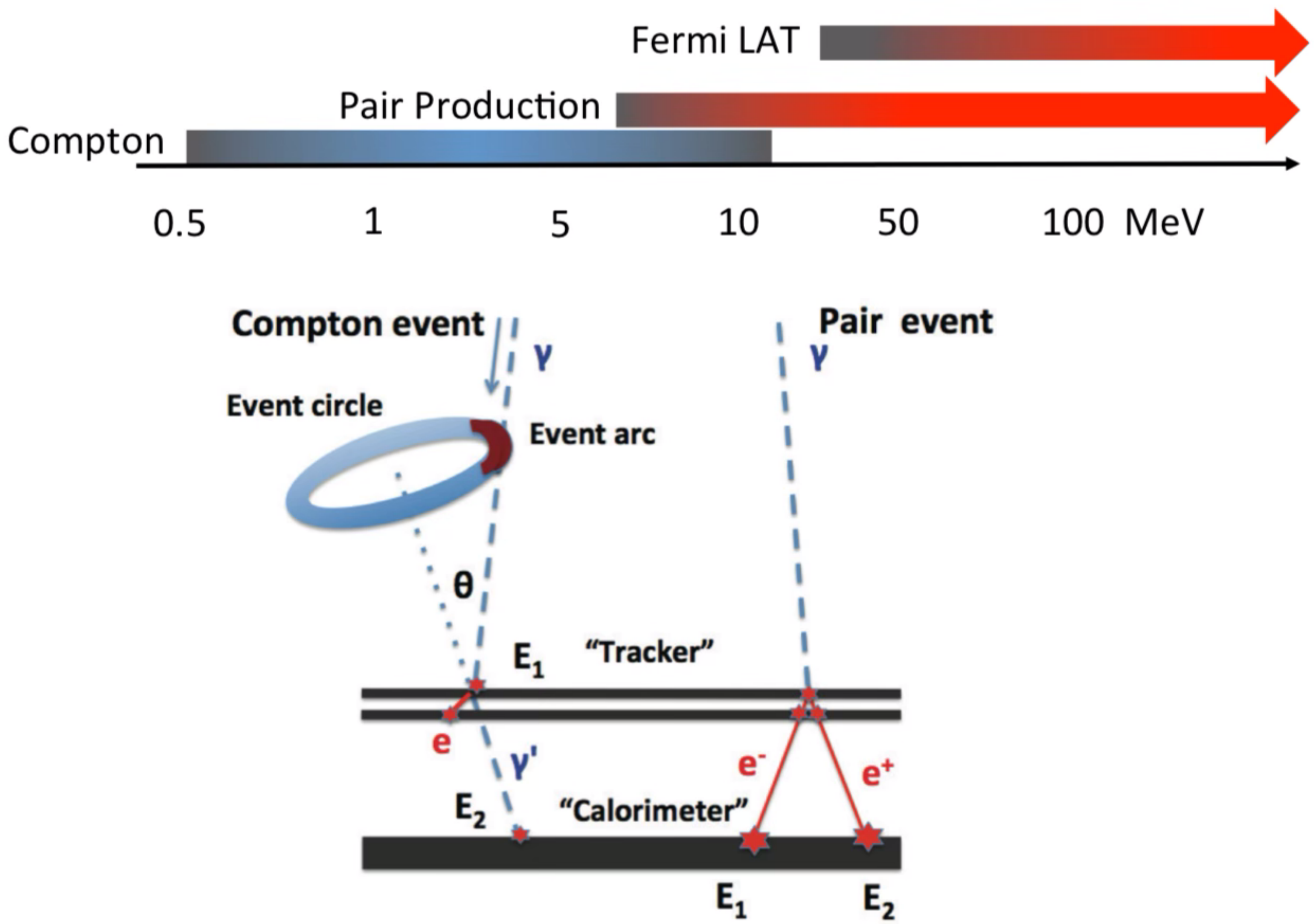
Compton telescopes (COMPTEL, **COSI**)

Pair creation telescopes (Fermi/LAT)

Compton, Coded mask, and Pair telescopes

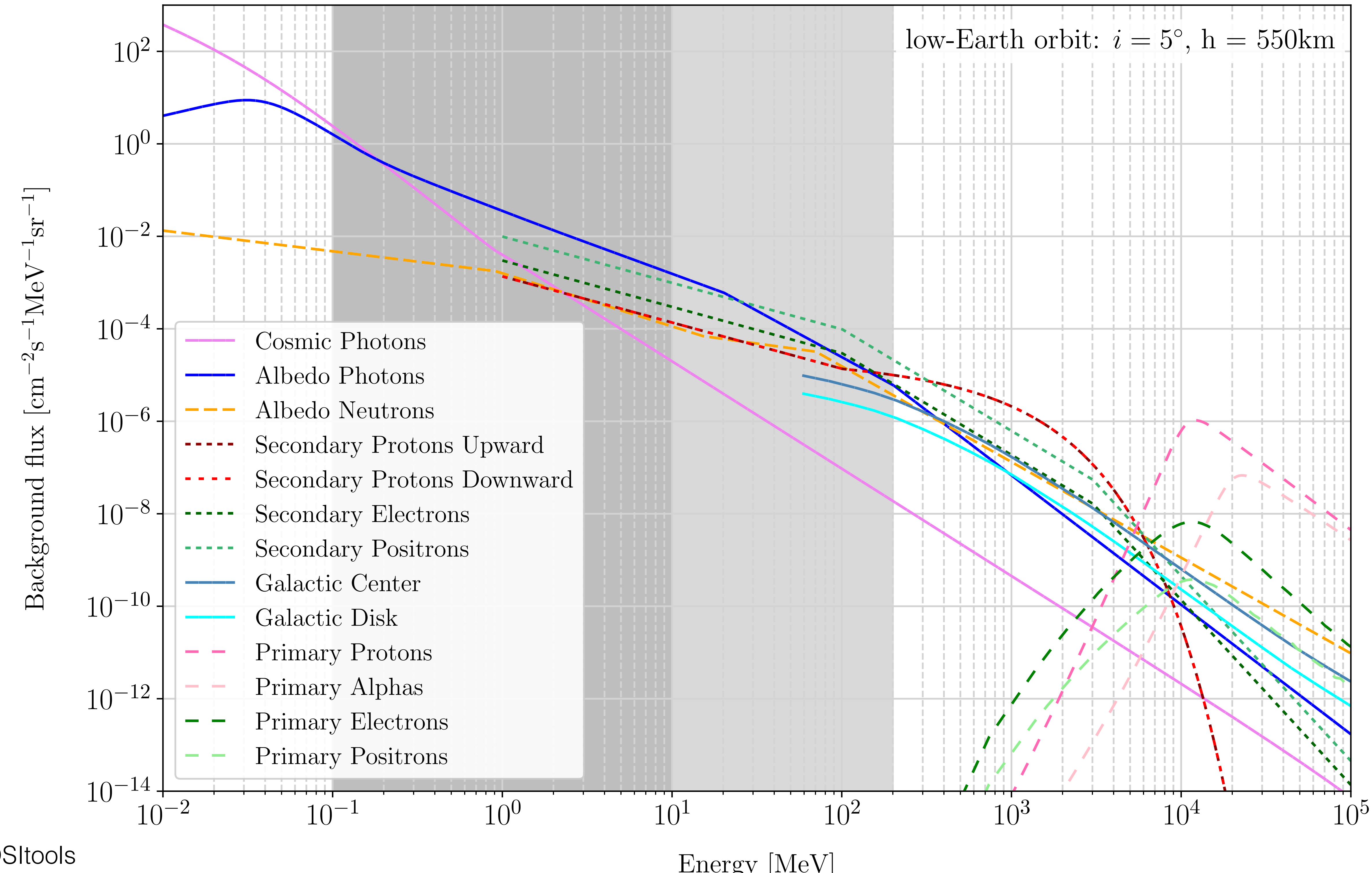


A. Moiseev 38th ICRC 2023



J. McEnery FSGO 2016

Background for low-Earth orbit telescopes



COSItools
Background for a gamma-ray satellite on a low-Earth orbit
Cumani et al. arXiv:1902.06944