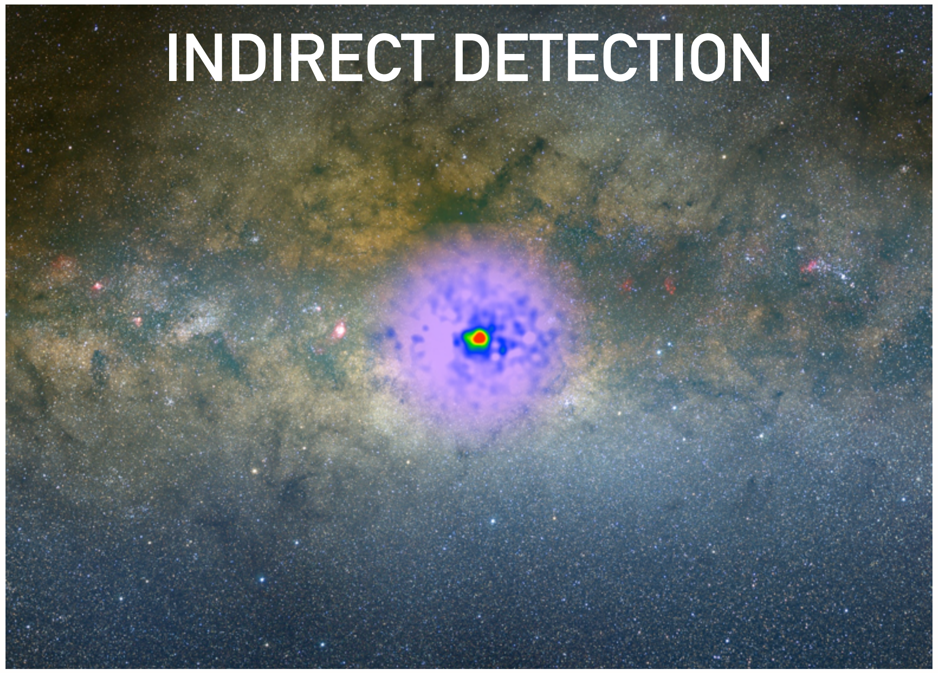
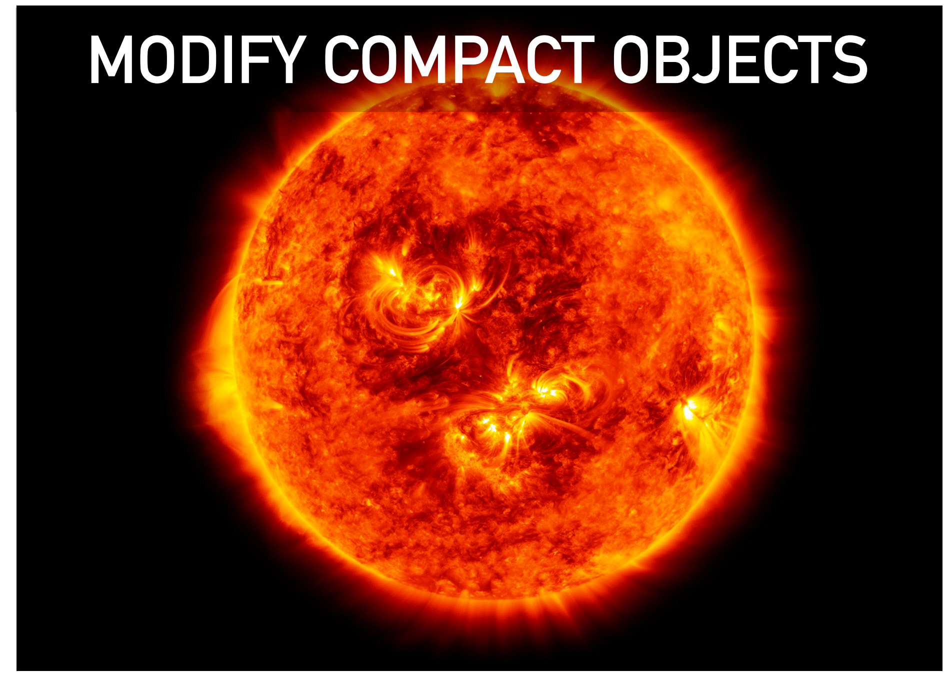
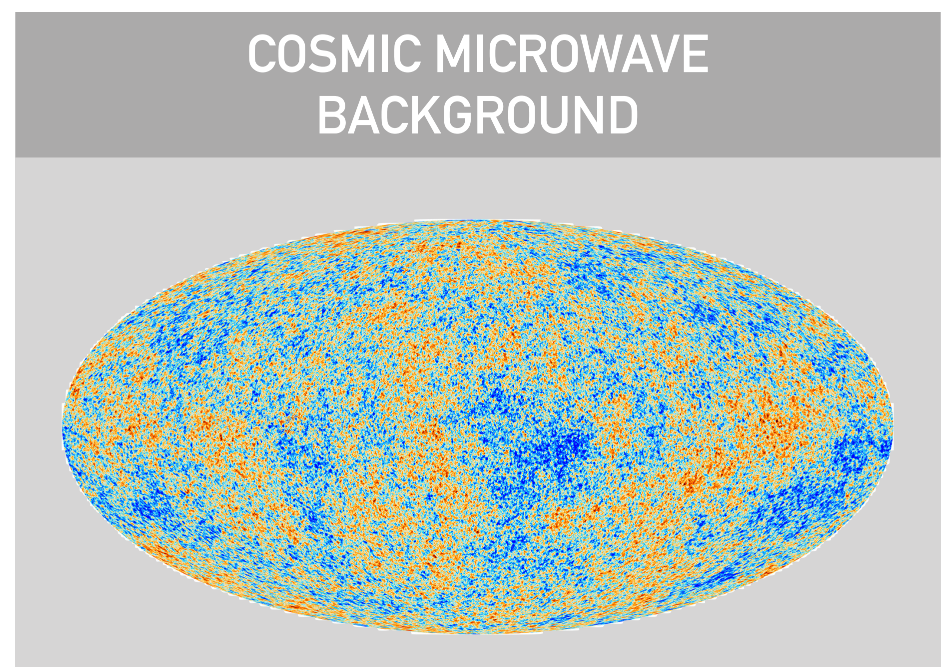
Astrophysical Probes of Dark Matter

NICK RODD | SNOWMASS THEORY FRONTIER | 25 FEBRUARY 2022

Astro Probes of Dark Matter

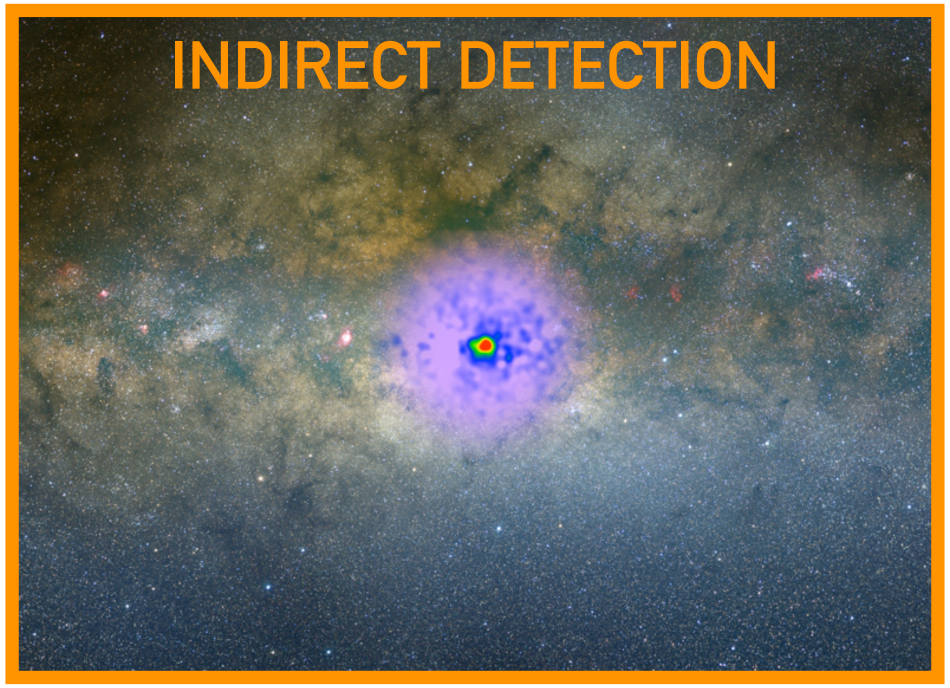






Disclaimer: incomplete list - see TF09 "Astrophysical Probes of Dark Matter" w/ Kim Boddy, Mariangela Lisanti, Sam McDermott, Christoph Weniger

Astro Probes of Dark Matter



Today's focus:

X-ray and γ-ray indirect detection

Disclaimer: again very incomplete - e.g. neutrino DM searches with IceCube, charged cosmic-rays with AMS-02, radio searches for axion DM

Indirect Detection

Dark matter decay flux

$$\Phi = \frac{1}{4\pi m_{\rm DM}\tau} \int dE \, \frac{dN}{dE} \times \int ds \rho_{\rm DM}(s)$$

Dark Matter flux the experiments can detect [photons/cm^2/s/sr]

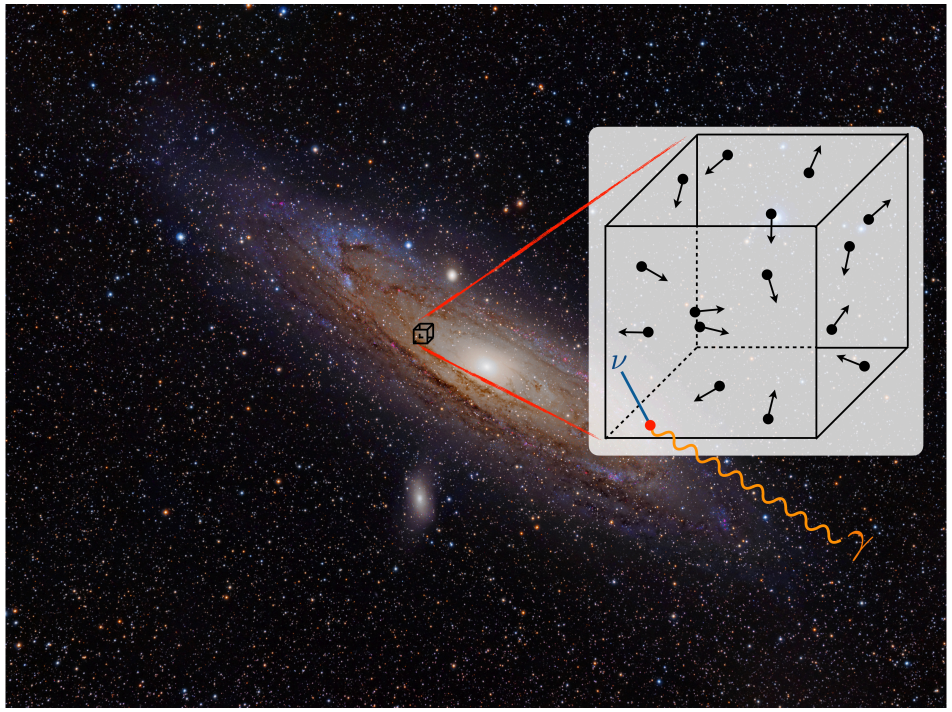
Equivalent for annihilation

$$\Phi = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \int dE \frac{dN}{dE} \times \int ds \rho_{\rm DM}^2(s)$$

Indirect Detection

Where are these decays occurring?

$$\Phi = \frac{1}{4\pi m_{\mathrm{DM}}\tau} \int dE\, \frac{dN}{dE} \times \int ds\, \rho_{\mathrm{DM}}(s)$$



Equivalent for annihilation

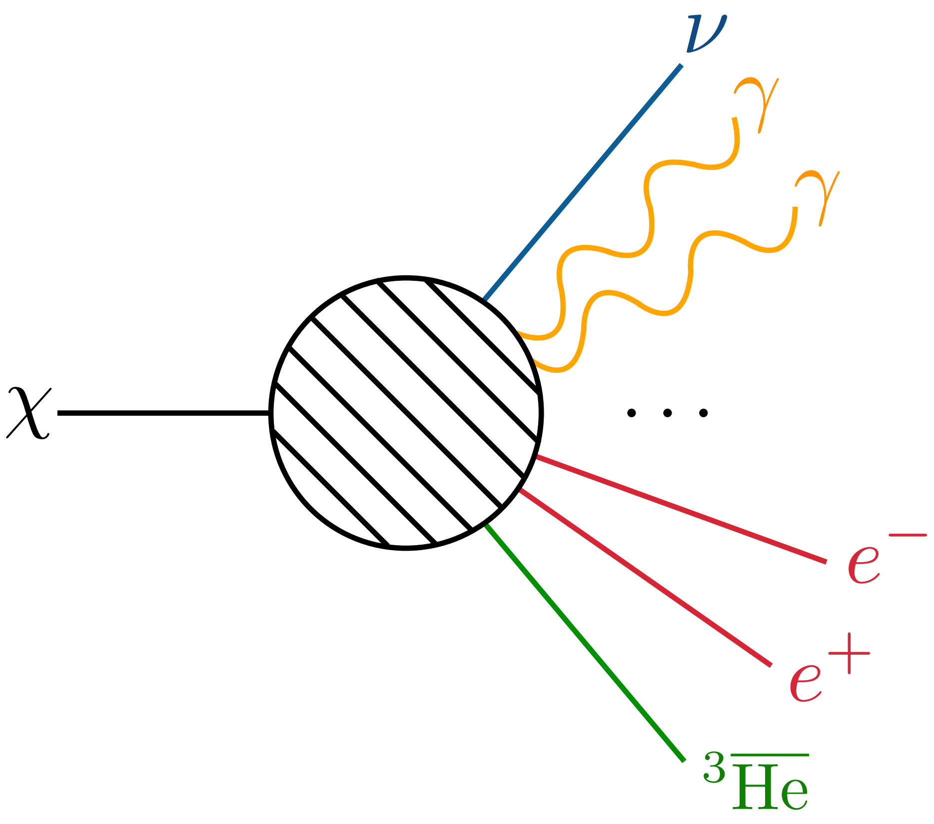
$$\Phi = \frac{\langle \sigma v \rangle}{8\pi m_{\mathrm{DM}}^2} \int dE \frac{dN}{dE} \times \int ds \rho_{\mathrm{DM}}^2(s)$$

Indirect Detection

What emerges from the decay?

$$\Phi = \frac{1}{4\pi m_{\rm DM}\tau} \int dE \, \frac{dN}{dE} \times \int ds \rho_{\rm DM}(s)$$

$$\frac{dN}{dE} = \frac{1}{\Gamma_0}\frac{d\Gamma}{dE}$$



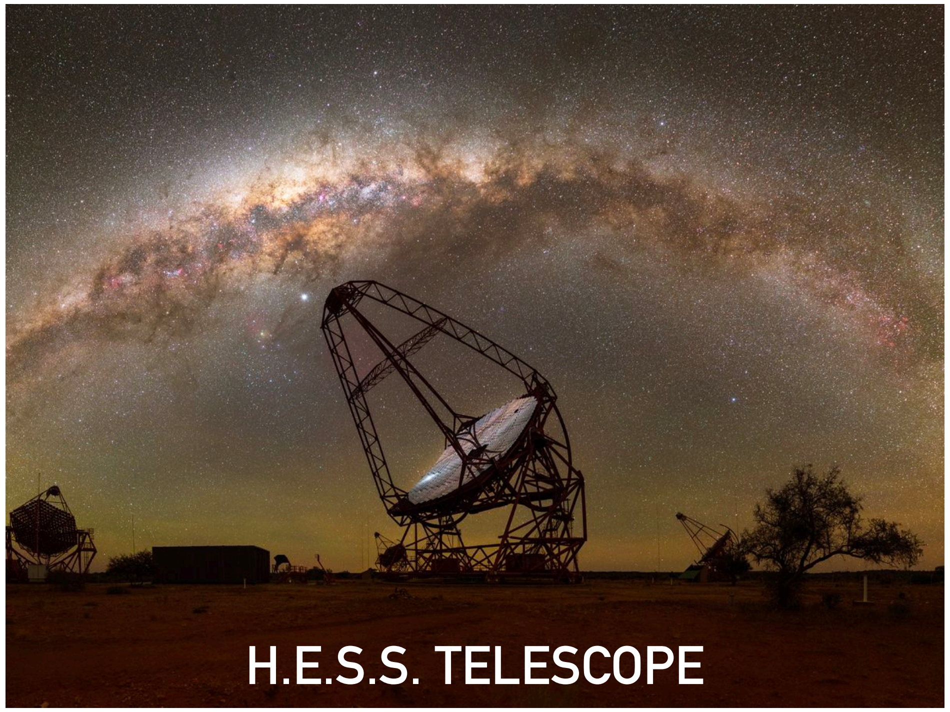
Equivalent for annihilation

$$\Phi = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \int dE \frac{dN}{dE} \times \int ds \rho_{\rm DM}^2(s)$$

Indirect Detection

Can we detect them?

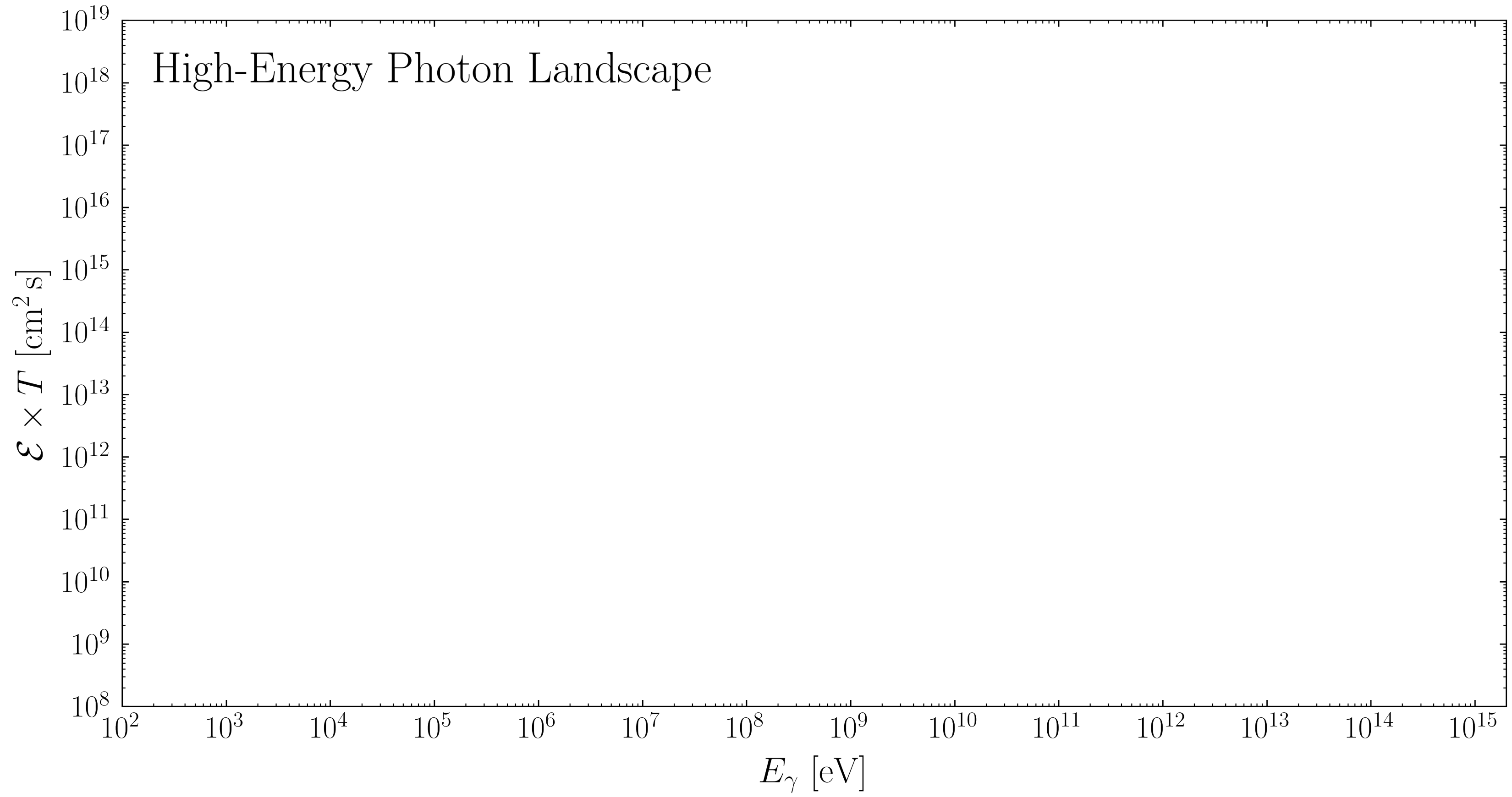
$$\Phi = \frac{1}{4\pi m_{\rm DM}\tau}\int dE\,\frac{dN}{dE} \times \int ds \rho_{\rm DM}(s)$$



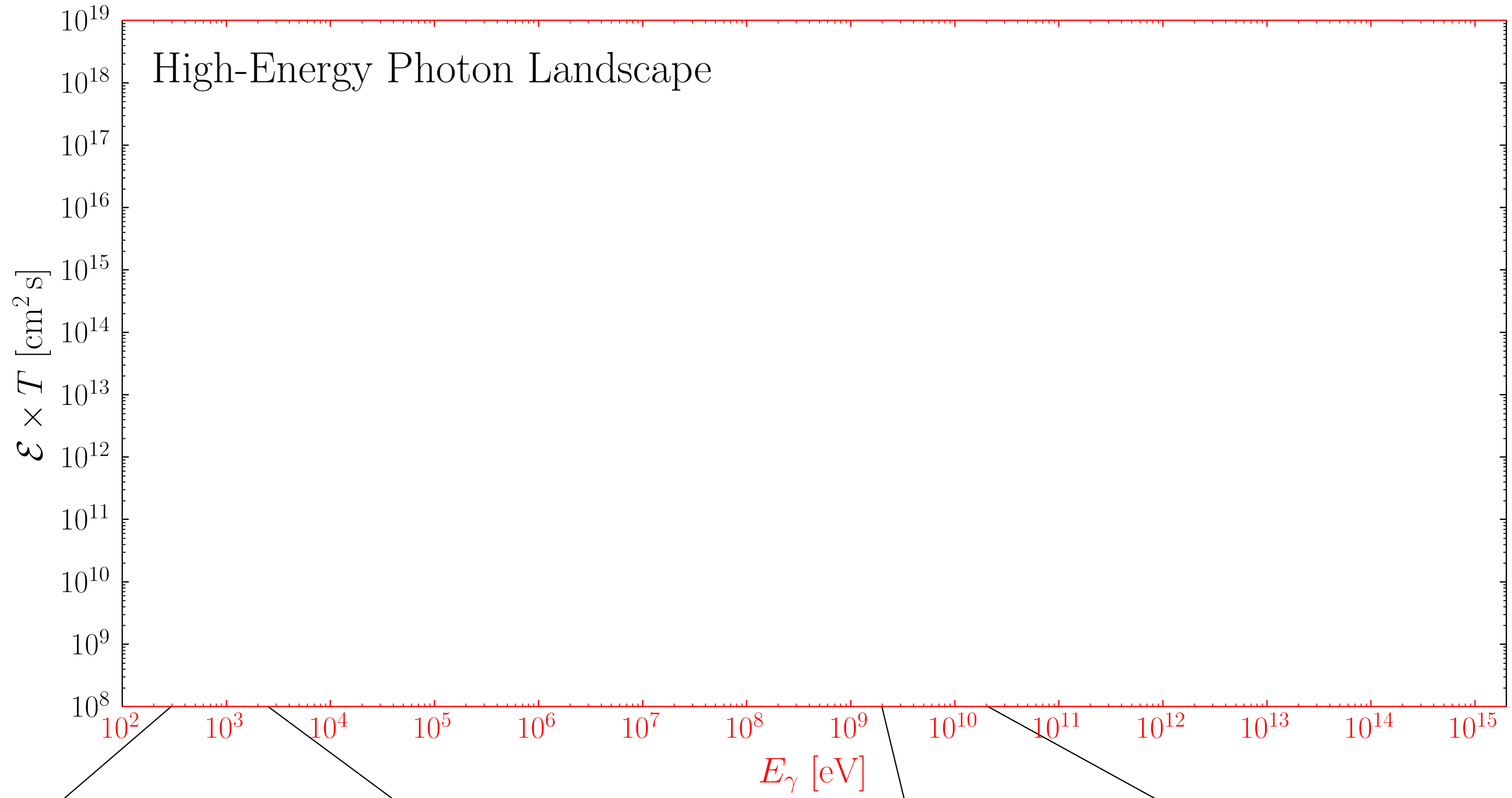
Equivalent for annihilation

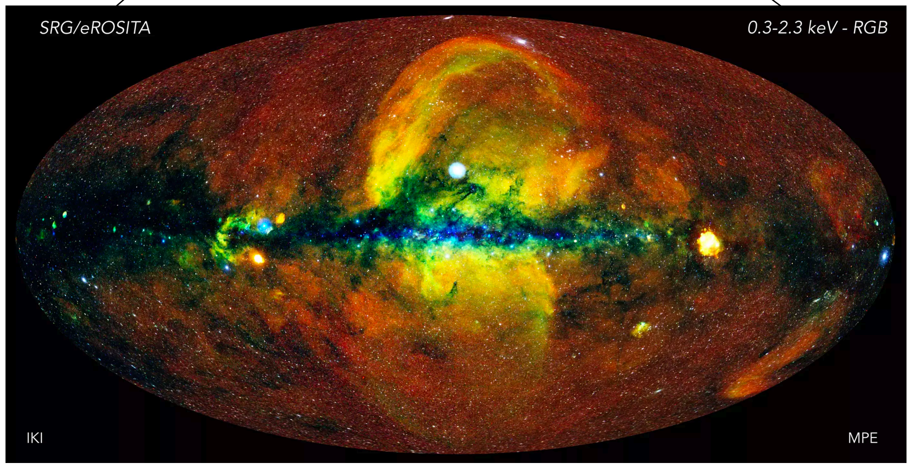
$$\Phi = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2}\int dE\,\frac{dN}{dE} \times \int ds \rho_{\rm DM}^2(s)$$

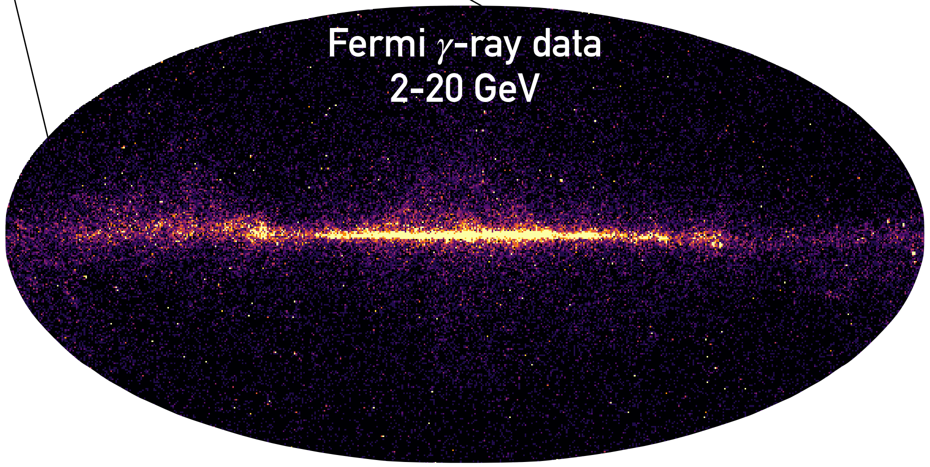
Experimental Landscape



Experimental Landscape







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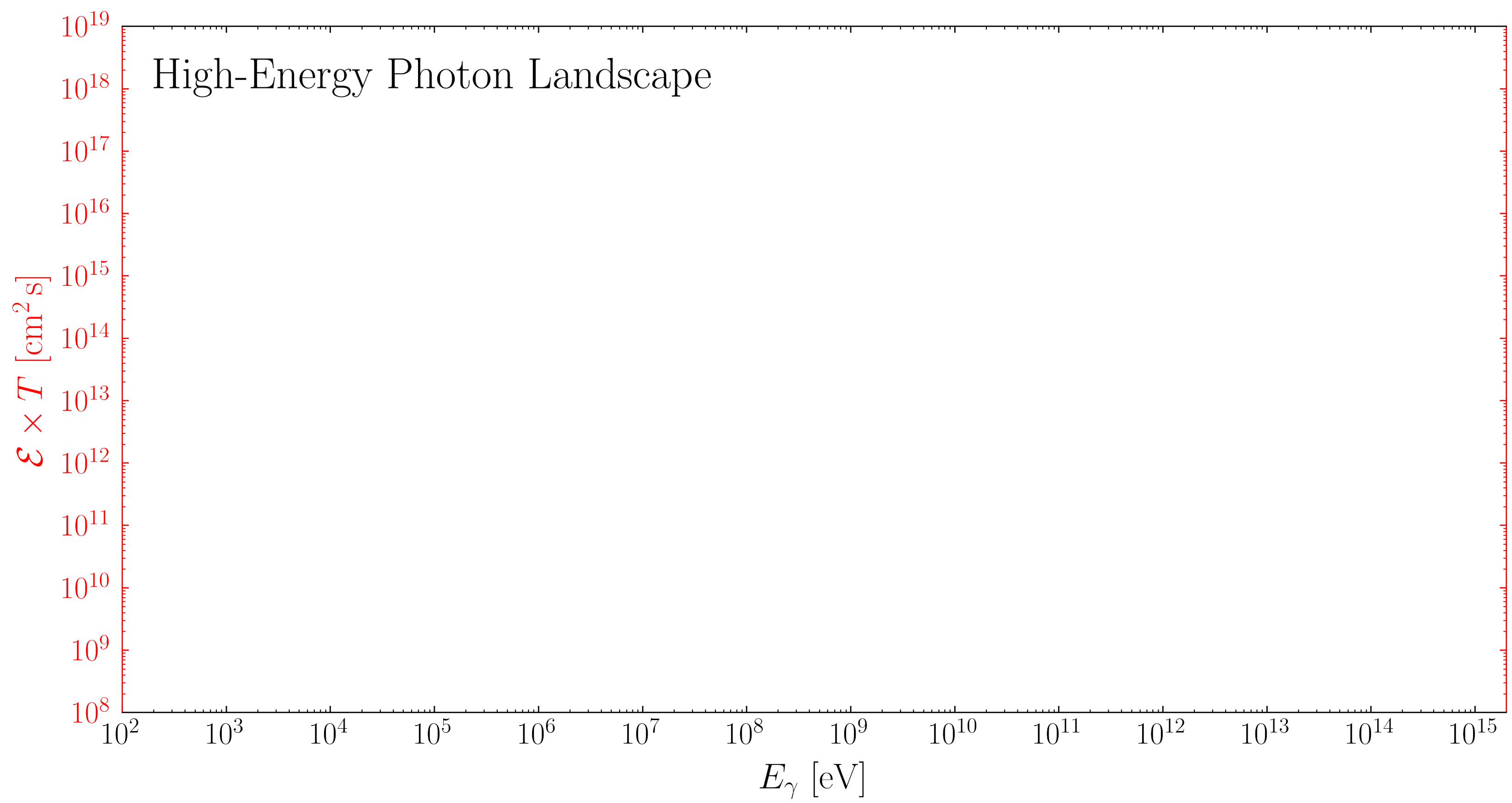


$$\mathcal{E} = \text{effective area}$$

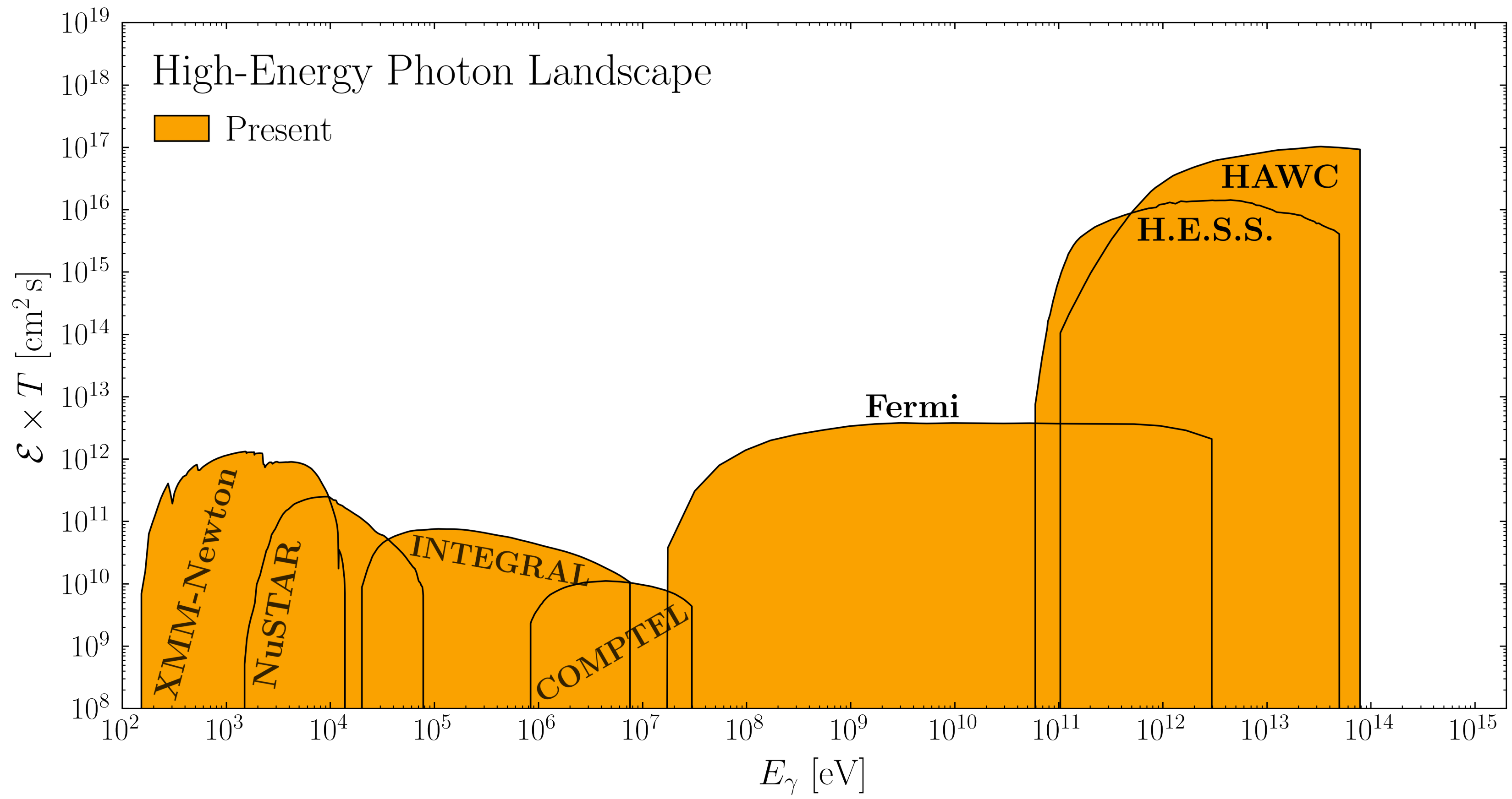
$$T = \text{observation time}$$

$$\Phi \times (\mathcal{E} \times T) \sim \#\text{ of detected photons}$$

Disclaimer: one of many ways to compare instruments; cf. energy/spatial resolution

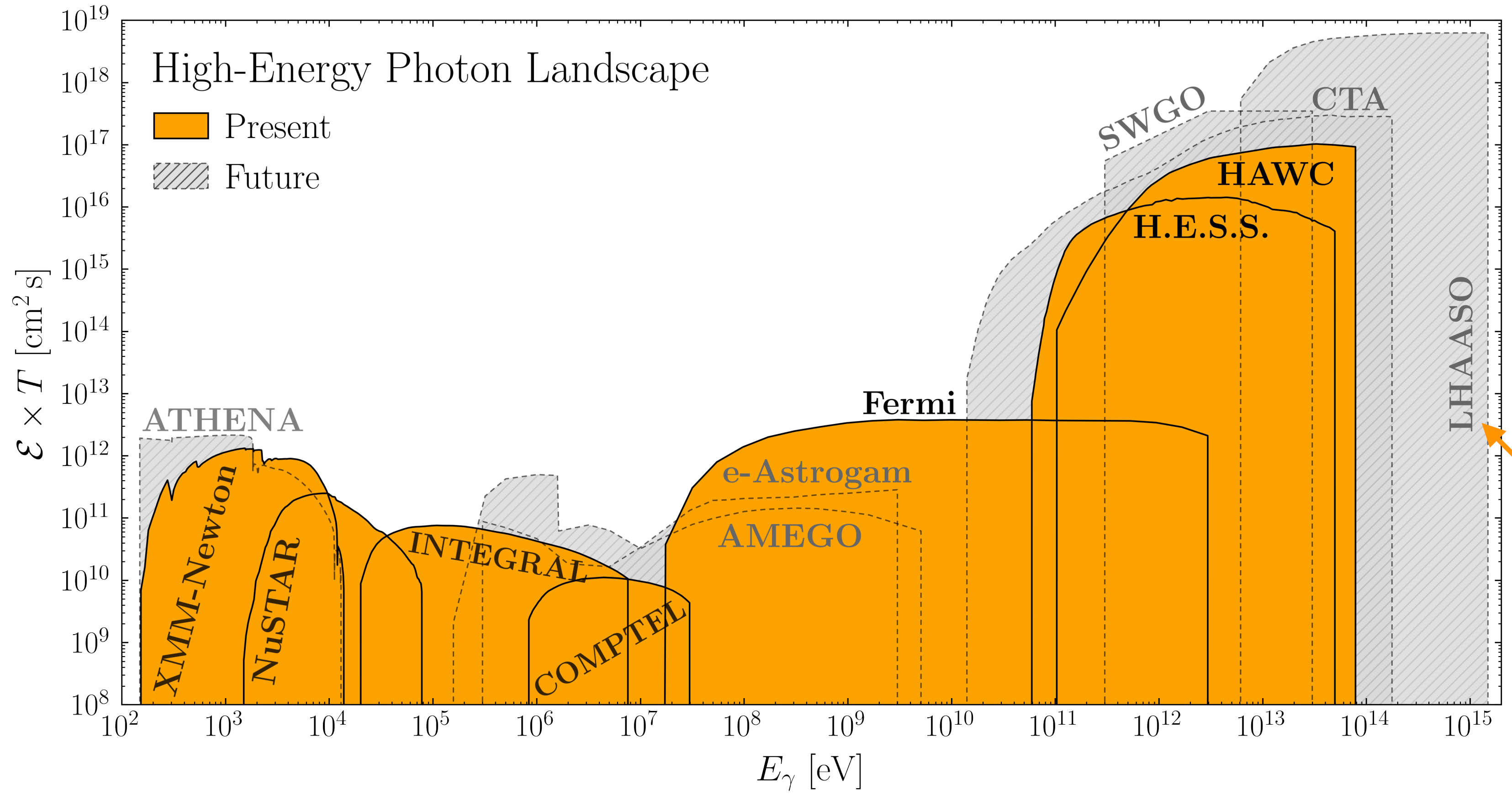
INDIRECT DETECTION

Experimental Landscape



Disclaimer: incomplete list - see e.g. CF07 "The Future of Gamma-Ray Experiments in the MeV-EeV Range"

Experimental Landscape



Partial array recently detected photons > PeV [Cao+ 2021]

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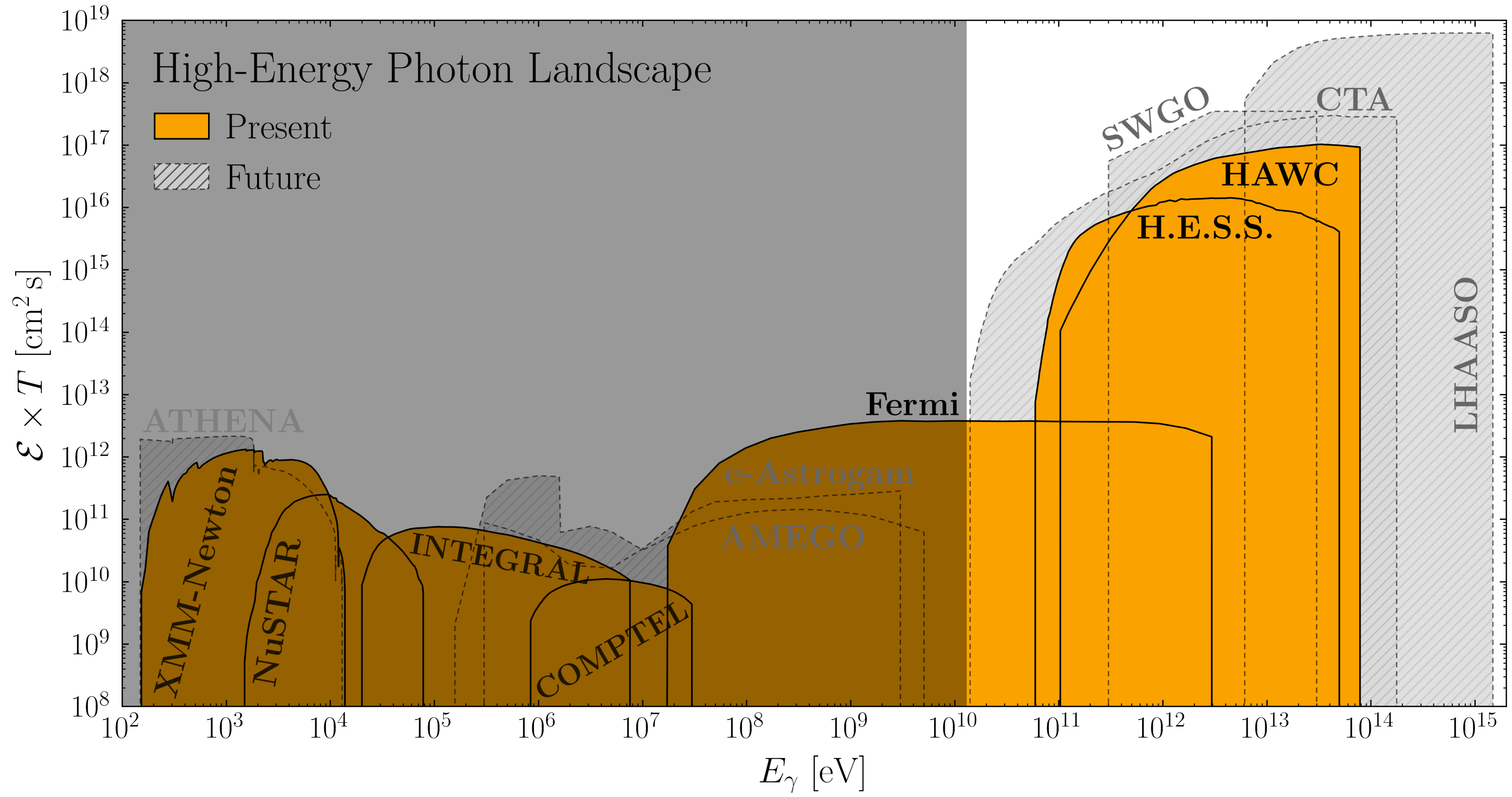
Experimental Landscape

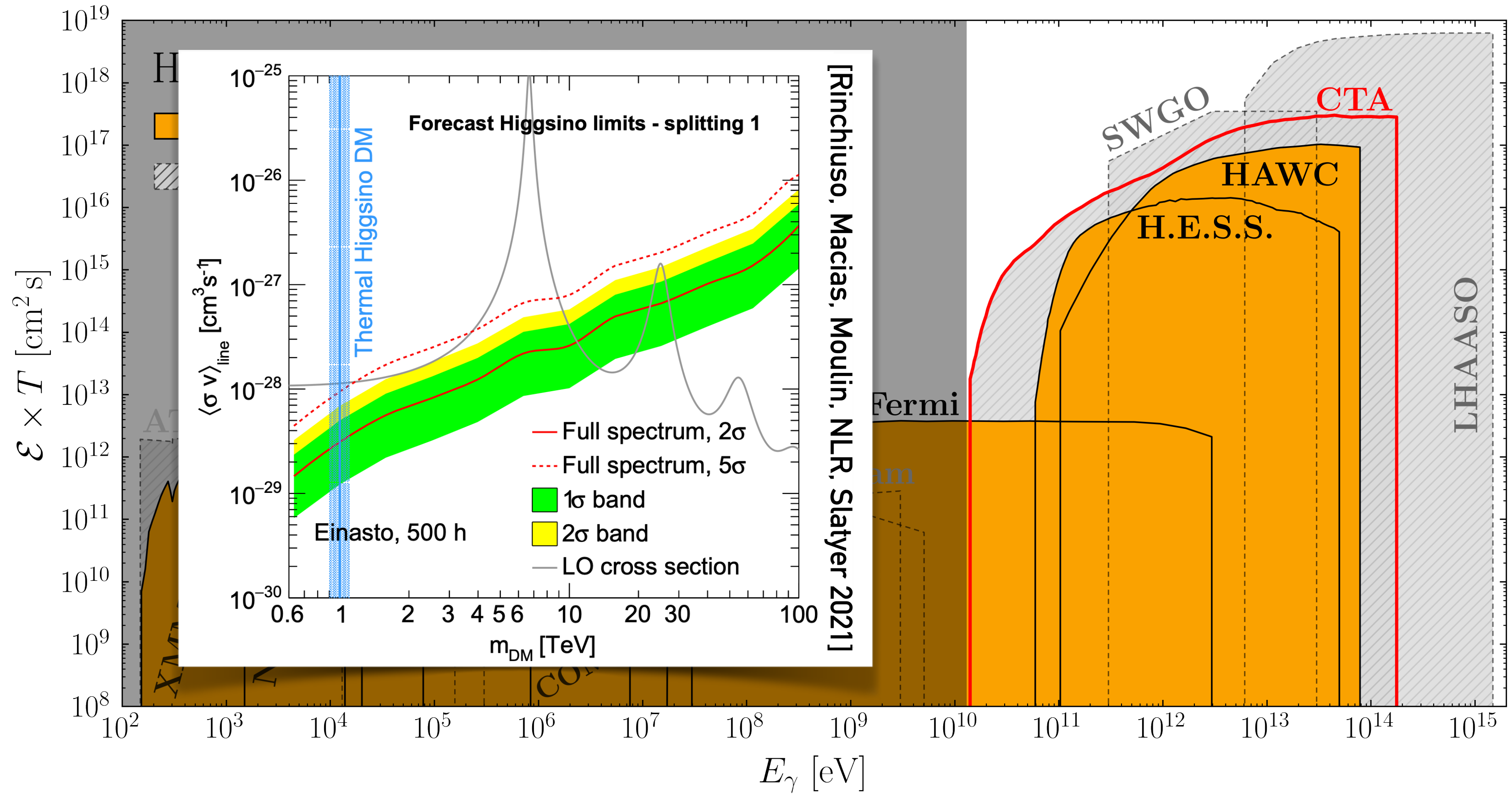


High Energies: dramatic improvement within ten years

Theory Mandate

reliable predictions at these energies

Experimental Landscape

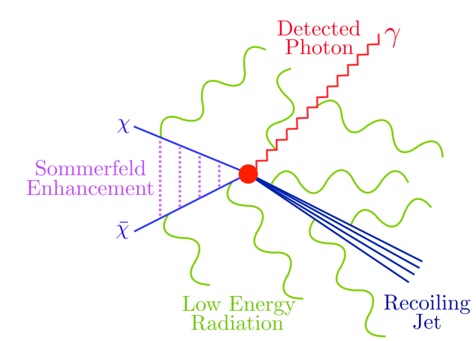


CTA could discover or exclude the thermal Higgsino

BUT: missing corrections from the cross talk of $m_{\rm DM}$ and m_W could be $\mathcal{O}(1)$

Significant progress achieved for the Wino

[Bauer, Cohen, Hill, Solon 2015], [Ovanesyan, Slatyer, Stewart 2015], [Baumgart, Rothstein, Vaidya 2015], [Baumgart, Vaidya 2016], [Ovanesyan, NLR, Slatyer, Stewart 2017], [Baumgart, Cohen, Moult, NLR, Slatyer, Solon, Stewart, Vaidya 2018], [Beneke, Broggio, Hafner, Vollmann 2018], [Baumgart, Cohen, Moulin, Moult, Rinchiuso, NLR, Slatyer, Stewart, Vaidya 2019], [Beneke, Broggio, Hafner, Urban, Vollmann 2019], [Beneke, Hasen, Urban, Vollmann 2020]



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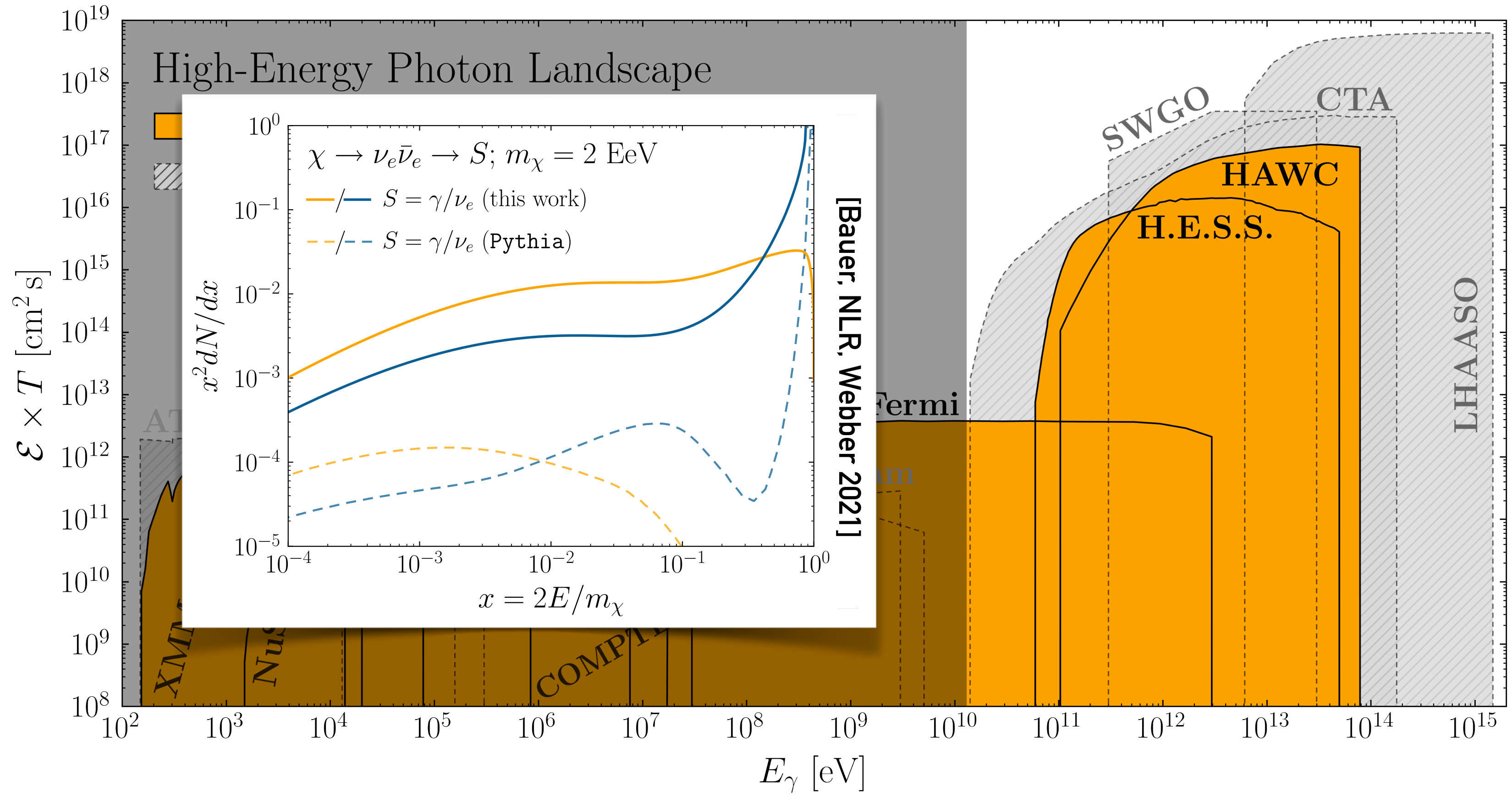
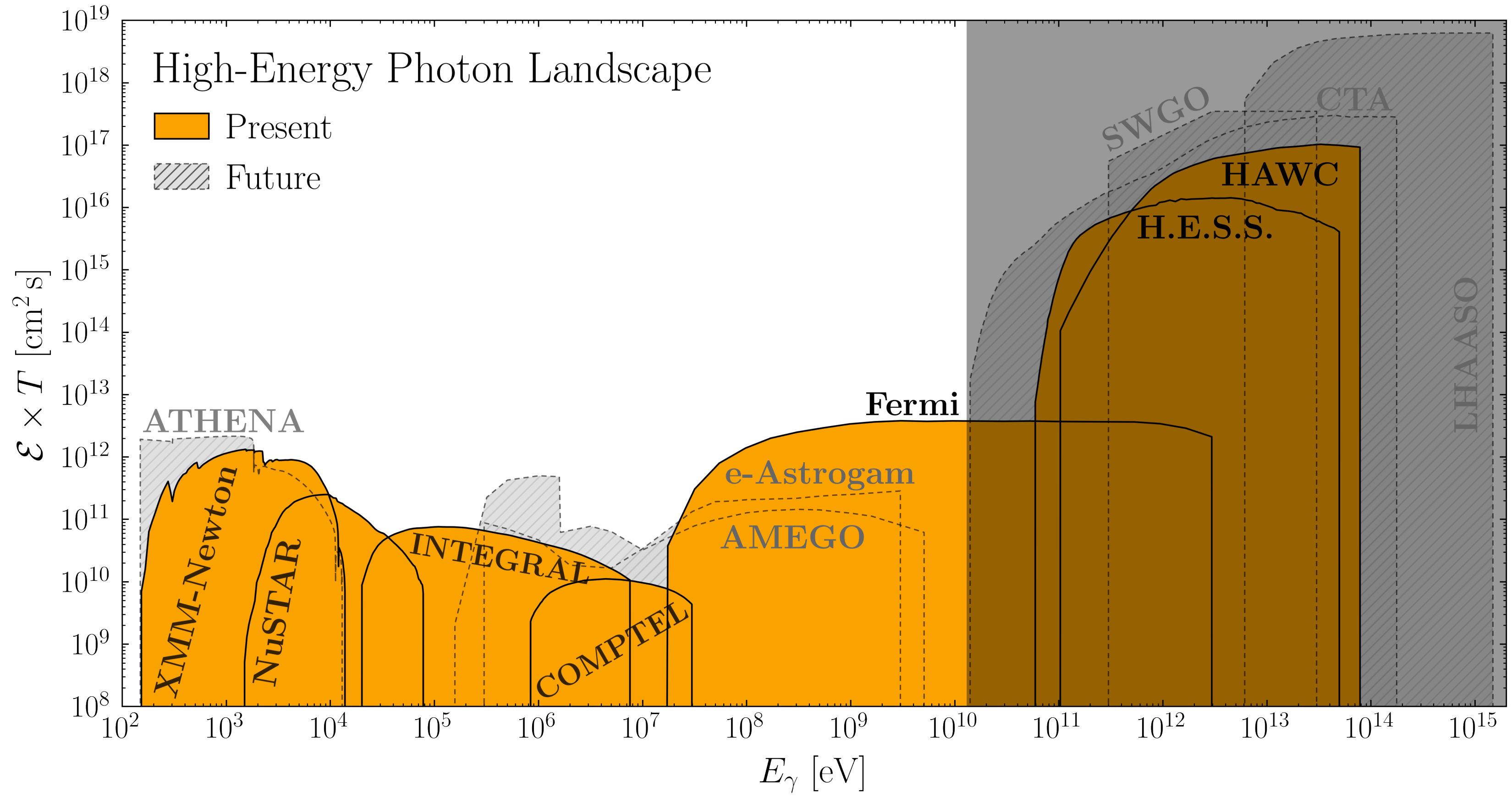


Electroweak effects are broadly important for heavy dark matter

Same ideas relevant for a 100 TeV collider
e.g. [Chen, Han, Tweedie 2017], [Bauer, Ferland, Webber 2017], [Manohar, Waalewijn 2018], [Bauer, Provasoli, Webber 2018]

See also CF01 “Ultra-heavy particle dark matter”

Experimental Landscape



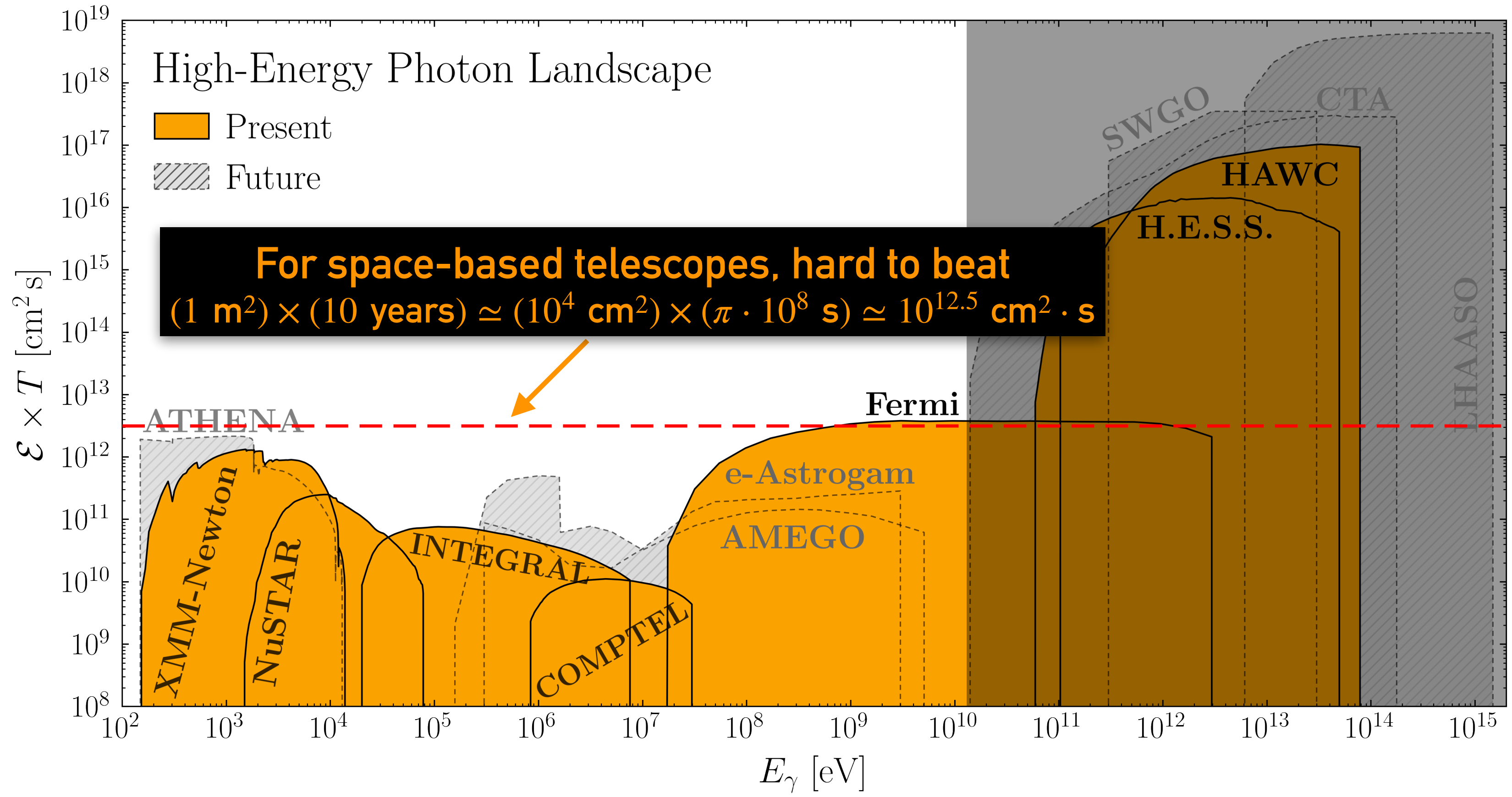
Low Energies: best* anticipated datasets already on disk

Theory Mandate

maximize the discovery potential of existing data

*again there are other ways to compare instruments, there will be improvements in e.g. energy resolution

Experimental Landscape



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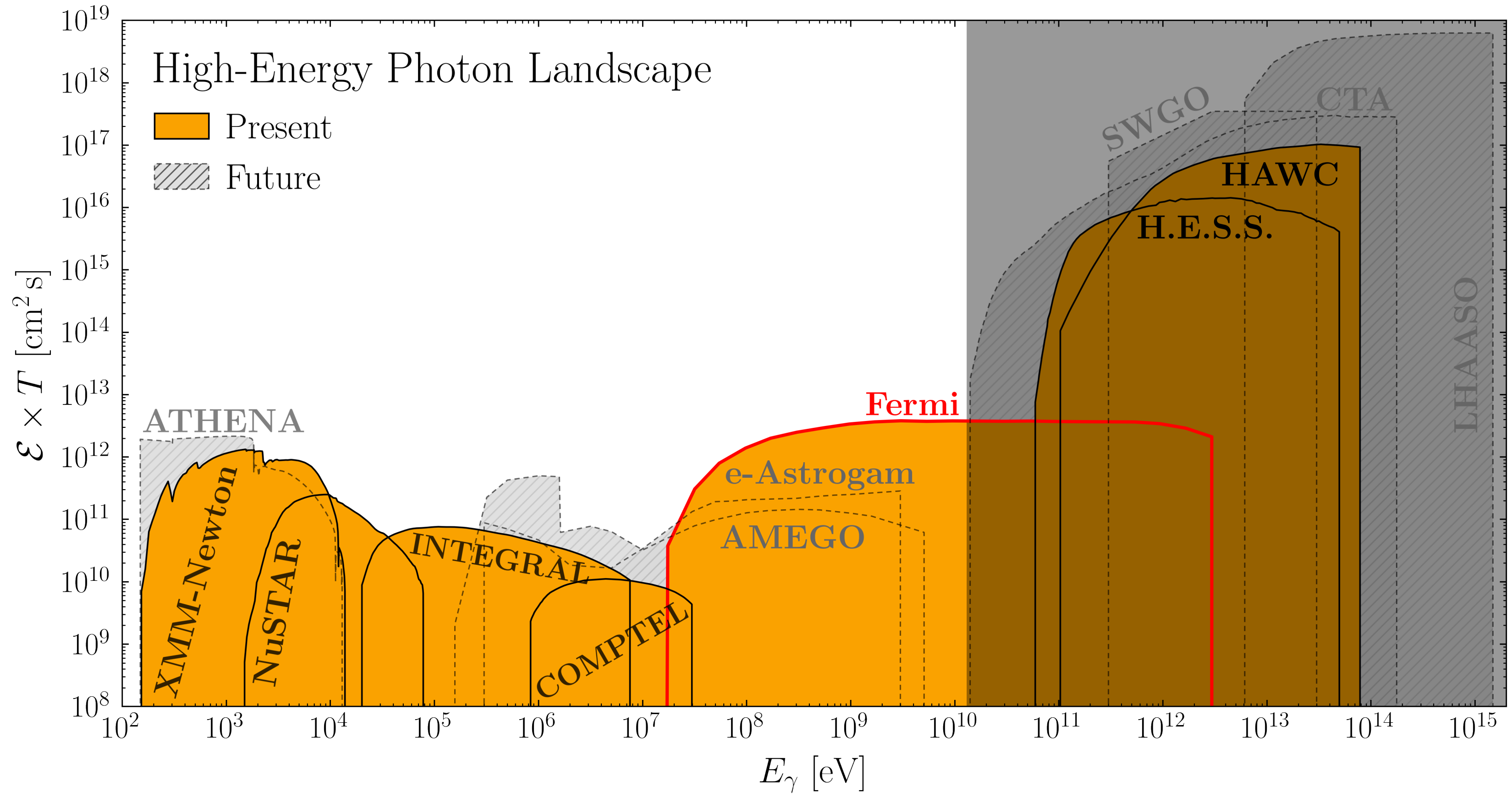
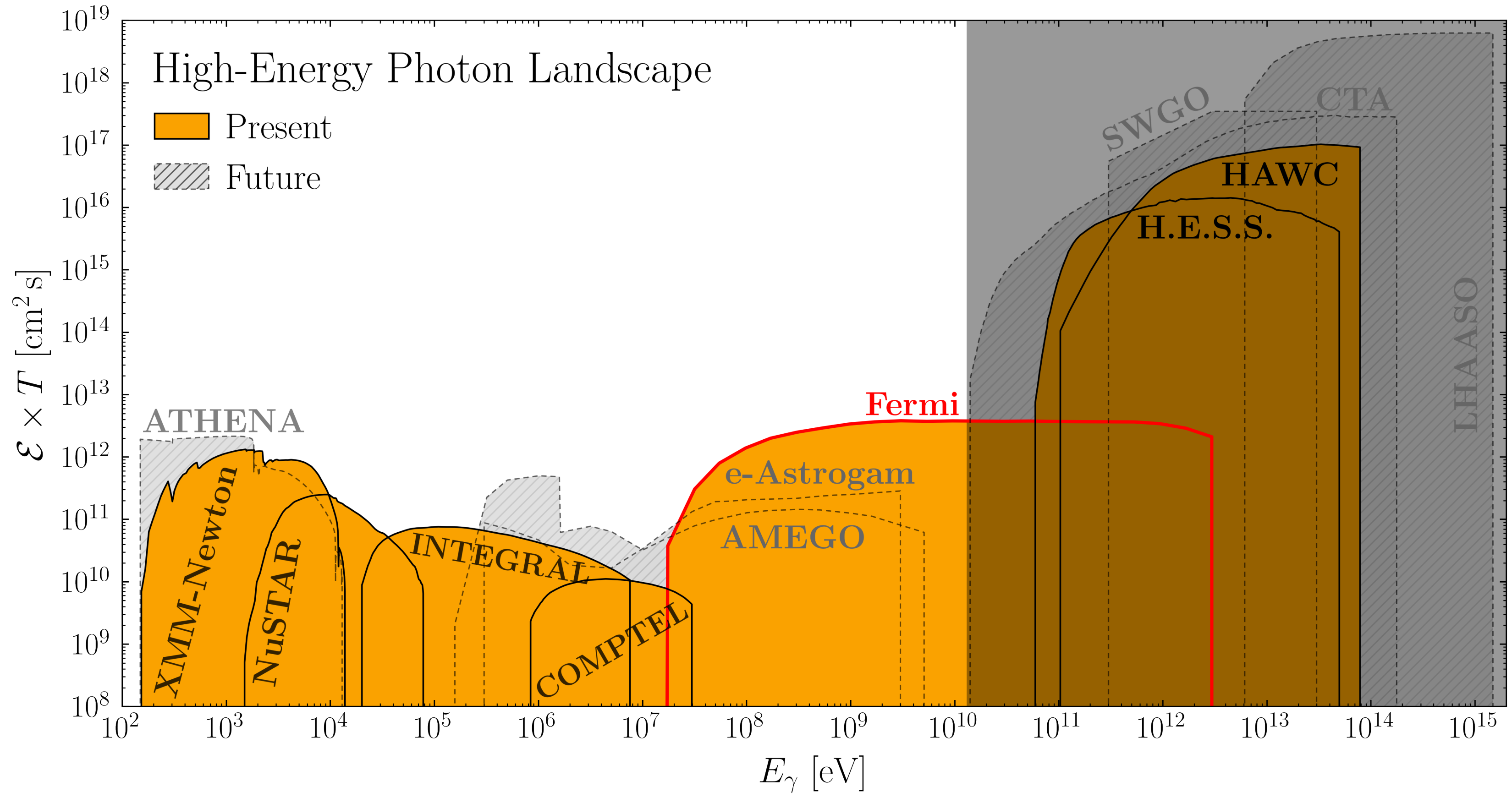


See also CF01 "Puzzling Excesses and How to Resolve Them"

Experimental Landscape



Galactic Center Excess

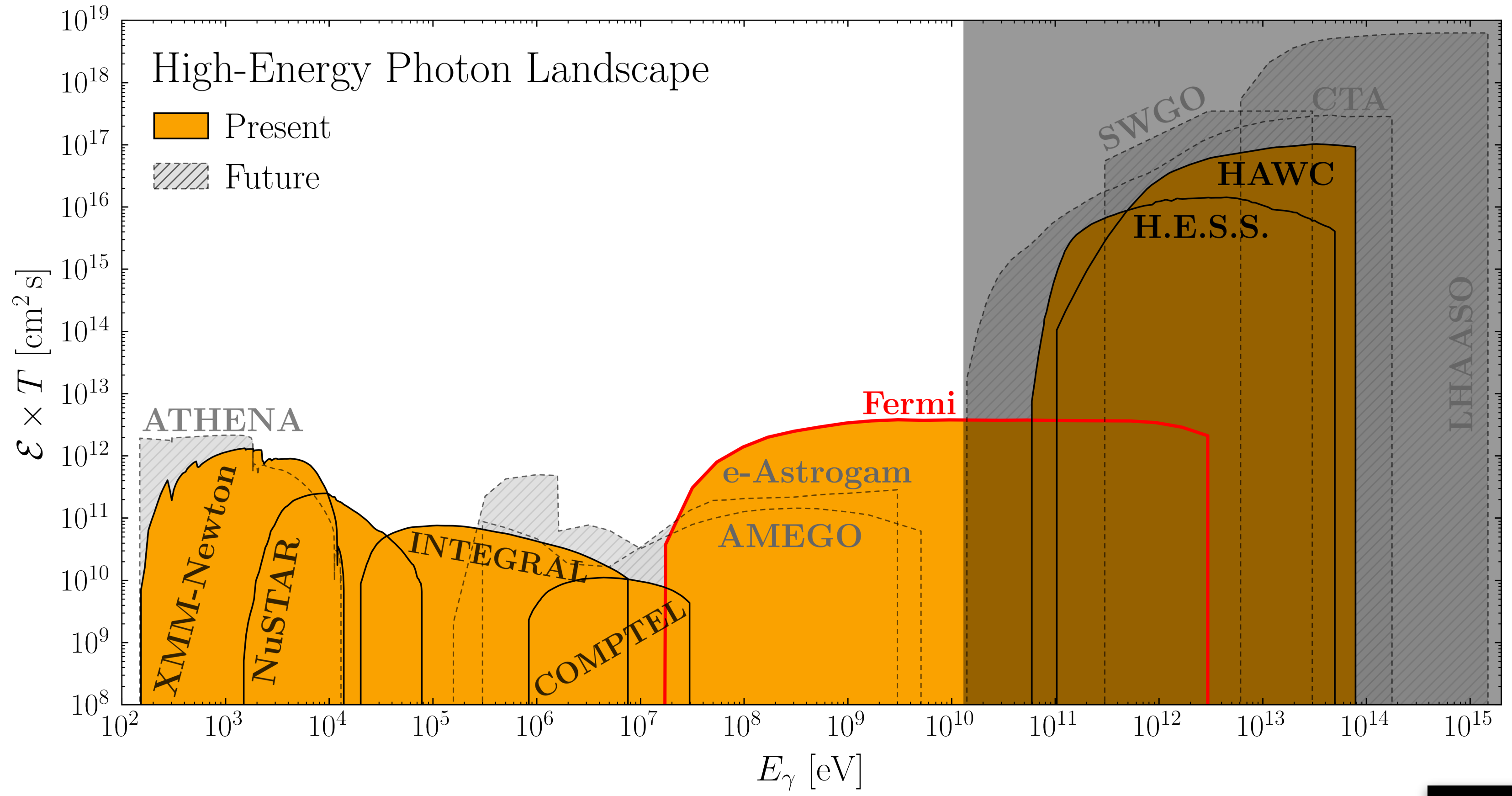
Pre 2019: originates from an unresolved point-sources

[Lee, Lisanti, Safdi, Slatyer, Xue 2016], [Bartels, Krishnamurthy, Weniger 2016]

That conclusion could originate from a systematic uncertainty

[Leane, Slatyer 2019, 2020a, 2020b]

Experimental Landscape

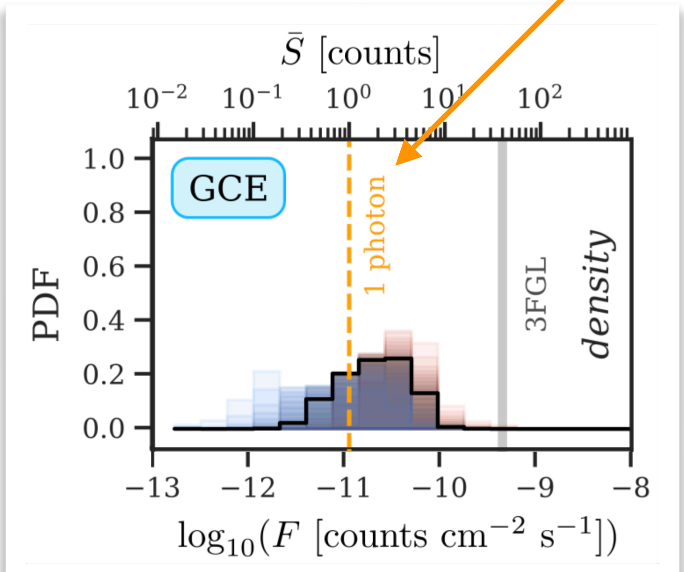


Galactic Center Excess

Active effort to improve existing methods and develop new tools

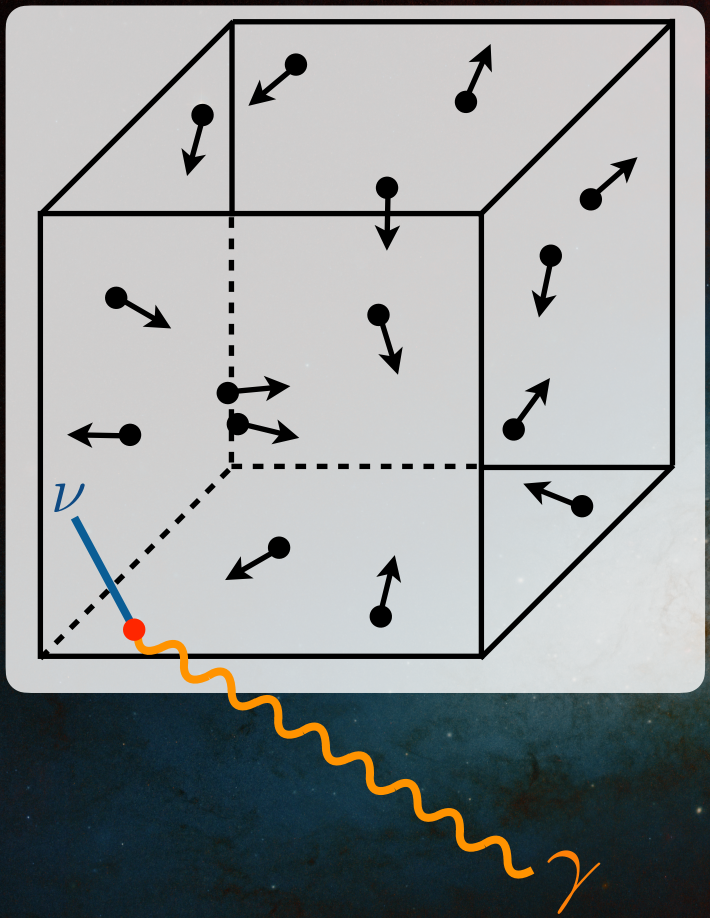
e.g. [Buschmann, NLR, Safdi, Chang, Mishra-Sharma, Lisanti, Macias 2020a, b], [Zhong, McDermott, Cholis, Fox 2020], [List, NLR, Lewis, Bhat 2020], [Mishra-Sharma, Cranmer 2020], [Calore, Donato, Manconi 2021], [Di Mauro 2021], [Collin, NLR, Erjavec, Perez 2021], [List, NLR, Lewis 2021], [Mishra-Sharma, Cranmer 2021], [Cholis, Zhong, McDermott, Surdutovich 2021]

Machine learning approach finds sources well below conventional thresholds

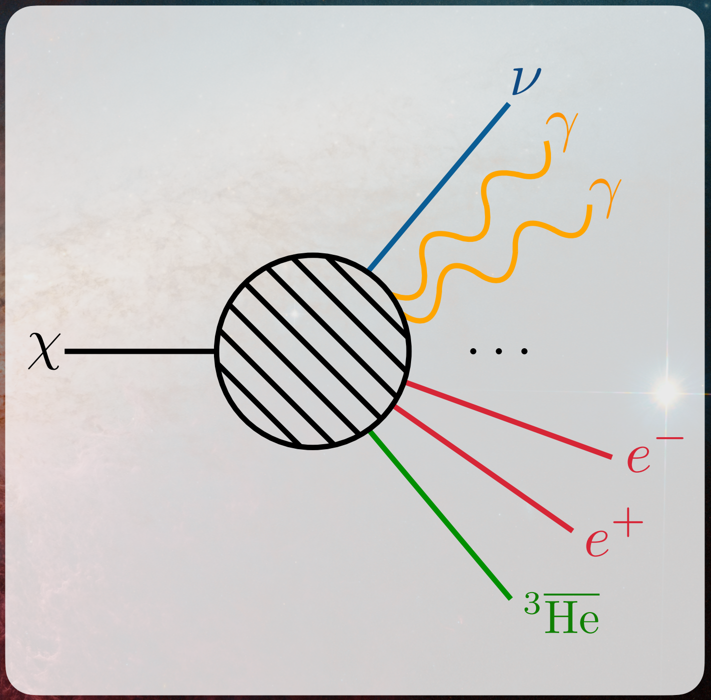


Conclusion

Astrophysics



Particle Physics

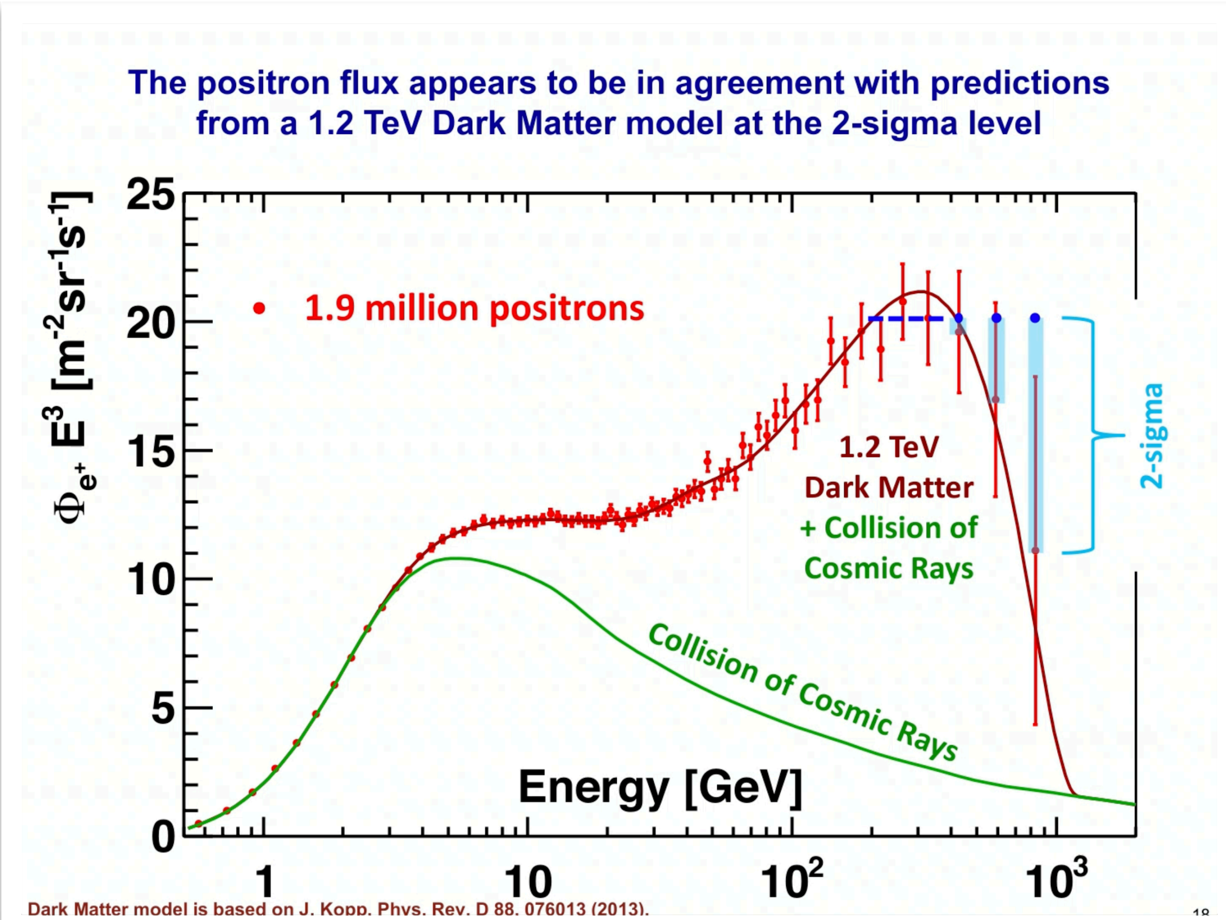


Theory will play a key role in realizing the exciting decade ahead for indirect detection

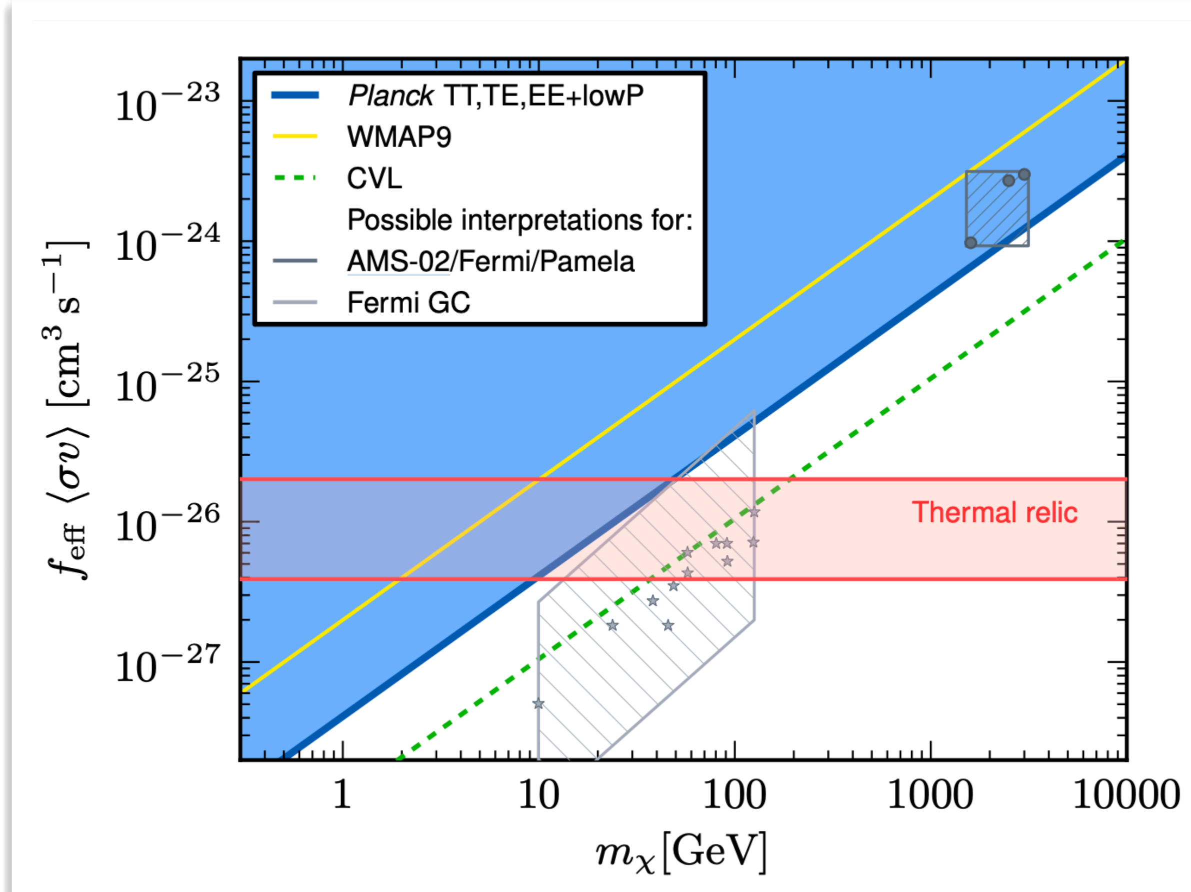
Backup Slides

Positron Fraction

Cutoff observed, as predicted by DM, but that interpretation remains challenged by CMB measurements (alternative is nearby pulsars or supernova remnants)



[Sam Ting "Latest Results from the AMS Experiment on the International Space Station" 2018]



[Planck 2016]

Antihelium Events

Still large uncertainties in the production rate, both from conventional sources and dark matter

$^{3}\overline{\mathrm{He}}$

To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$.

All eight events are in the helium mass region.

All eight events are clean single-track events without additional hits.

All eight events are in the momentum range < 100 GeV/c (where the momentum resolution is better than 10%).

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Observations on $^{4}\overline{\mathrm{He}}$

1. We have two $^{4}\overline{\mathrm{He}}$ events with a background probability of 3×10^{-3}.
2. Continuing to take data through 2024 the background probability for $^{4}\overline{\mathrm{He}}$ would be $2\mathrm{x}10^{-7}$, i.e., greater than 5-sigma significance.
3. The $^{3}\mathrm{He}/^{4}\mathrm{He}$ ratio is 10-20% yet $^{3}\overline{\mathrm{He}}/^{4}\overline{\mathrm{He}}$ ratio is 300%. More data will resolve this mystery.

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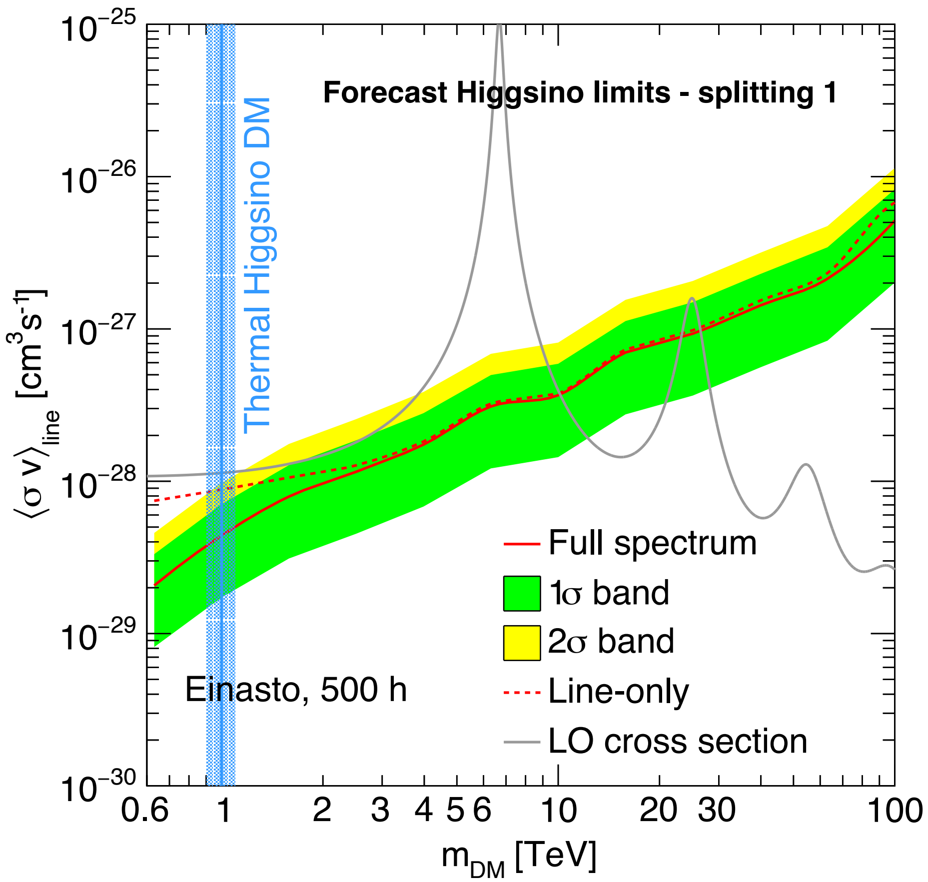
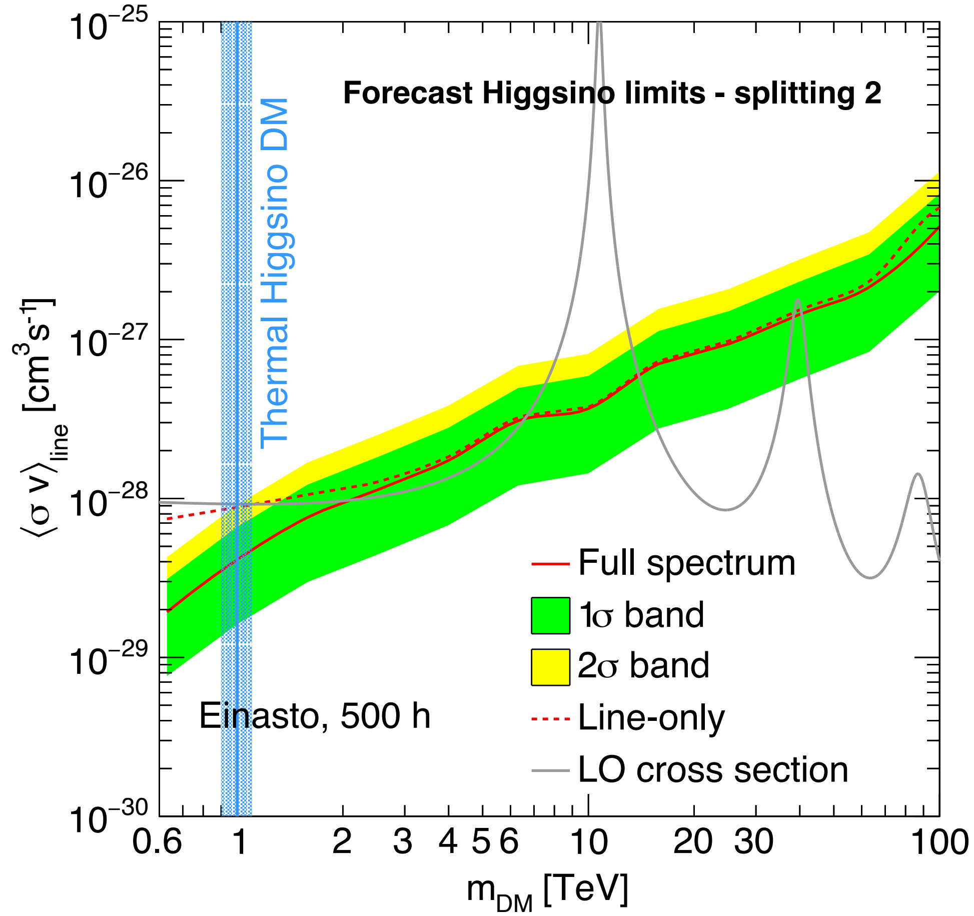
[Sam Ting “Latest Results from the AMS Experiment on the International Space Station“ 2018]

For more details see TF09 “Astrophysical Probes of Dark Matter”

Higgsino Limits



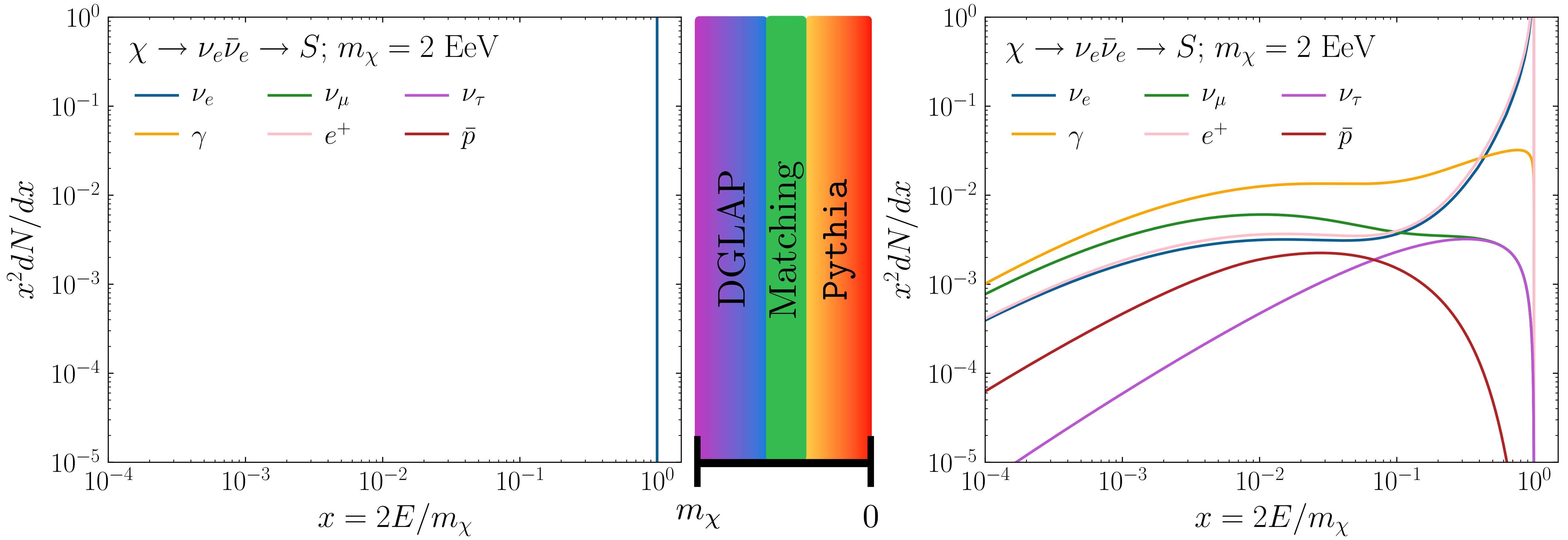
$$\delta m_N = 200 \text{ keV}$$
$$\delta m_+ = 350 \text{ MeV}$$



$$\delta m_N = 2 \text{ GeV}$$
$$\delta m_+ = 480 \text{ MeV}$$

[Rinchiuso, Macias, Moulin, NLR, Slatyer 2021]

Heavy Dark Matter Spectra



[Bauer, NLR, Webber 2021]

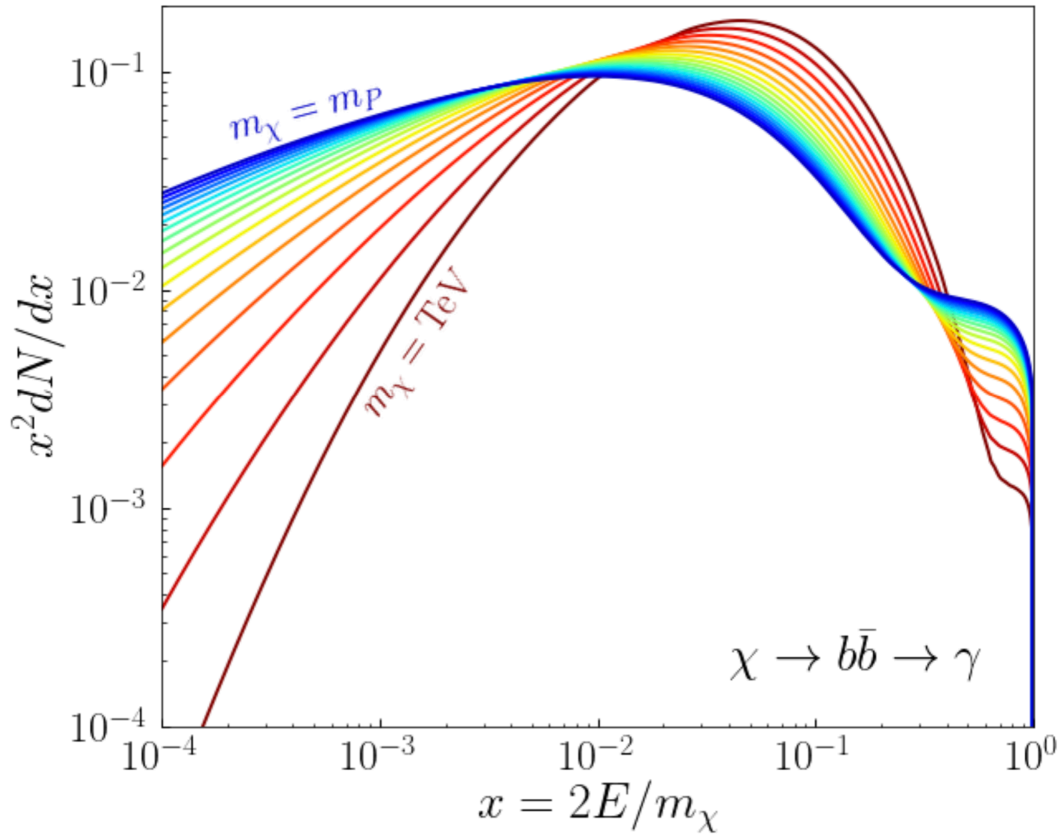
Heavy Dark Matter Spectra

README.md

HDMSpectra

Dark Matter Spectra from the Electroweak to the Planck Scale

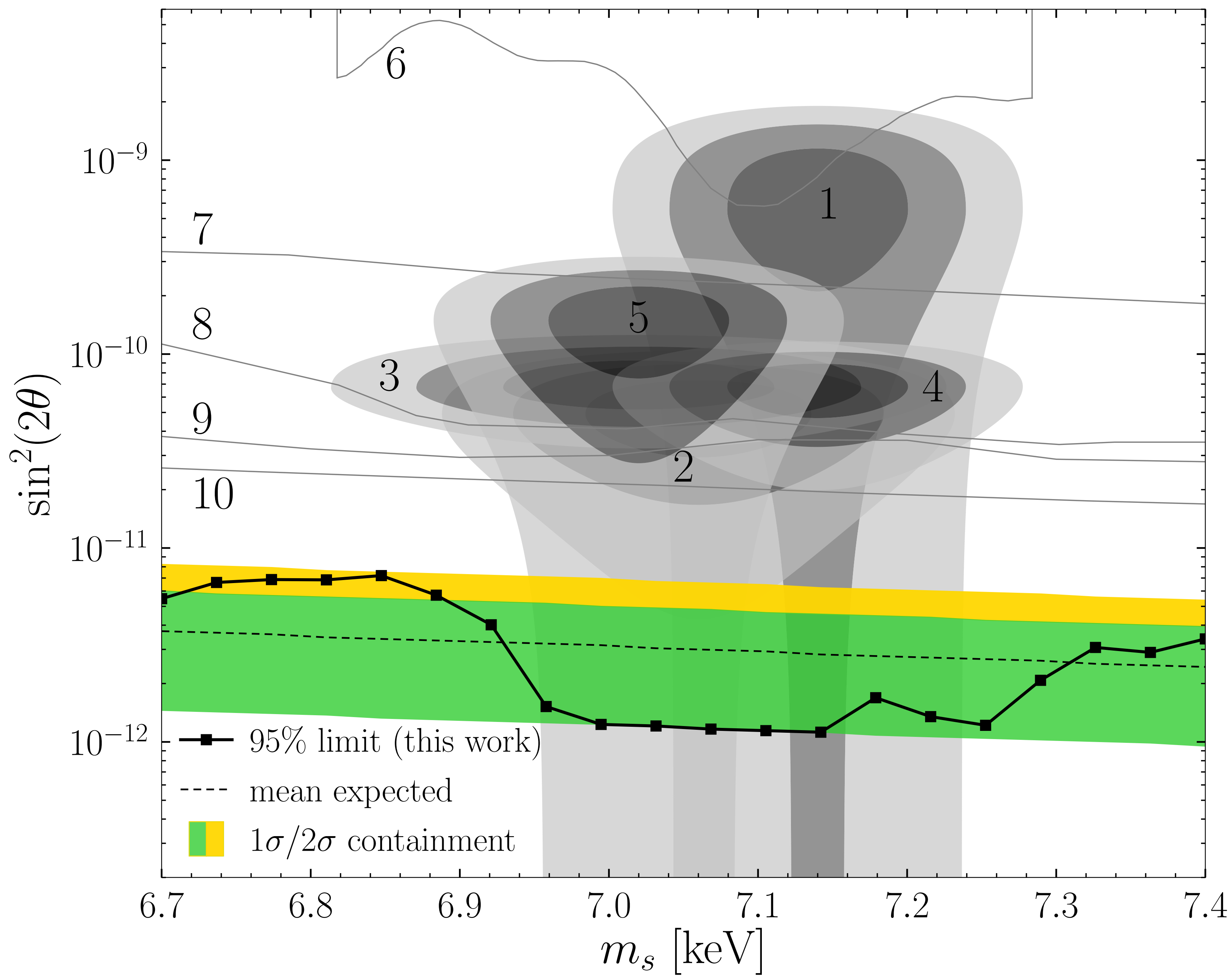
License MIT arXiv 2007.15001



Adopted by IceCube [Liu+ JCAP 2020]

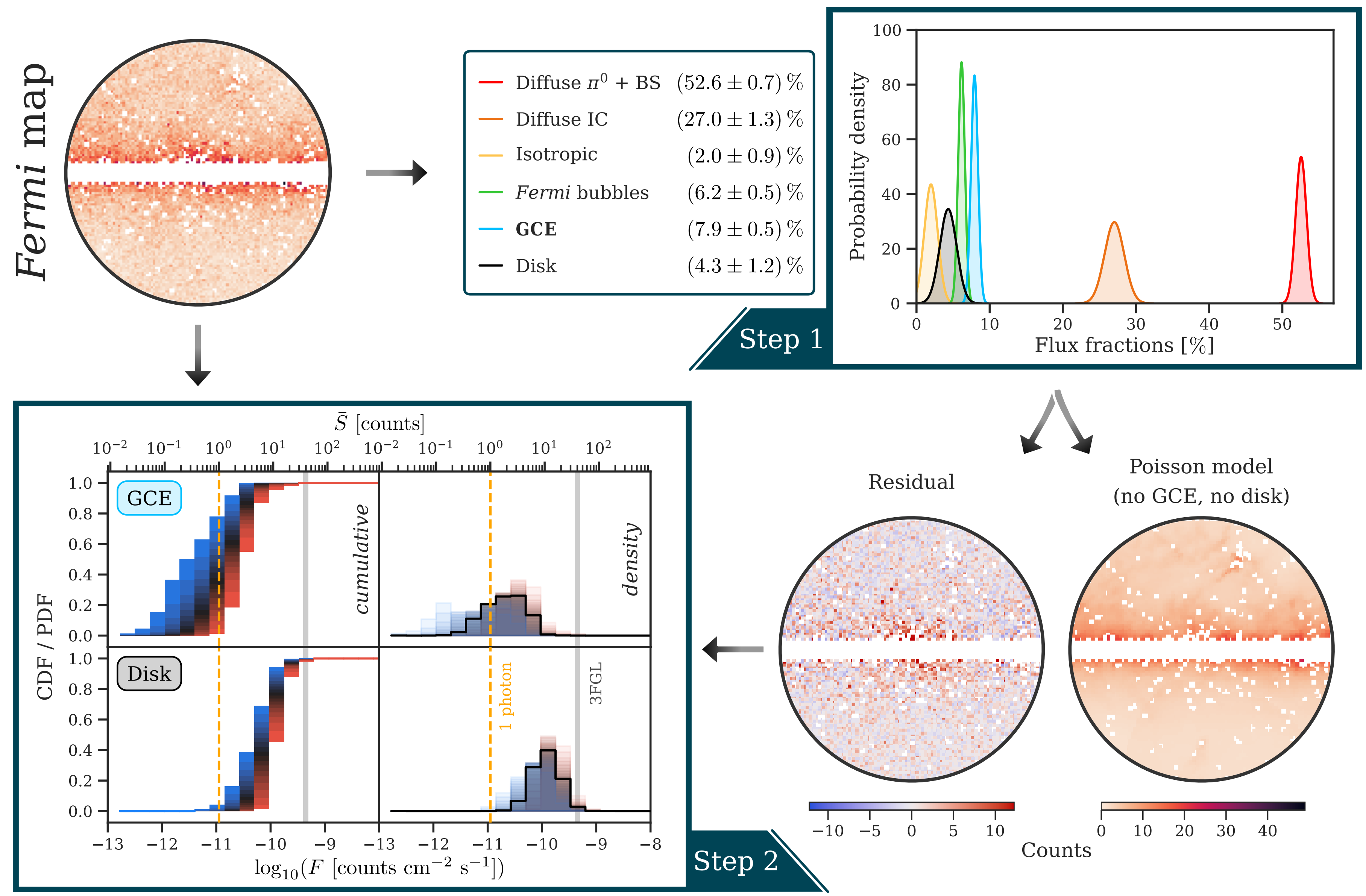
[Bauer, NLR, Webber 2021]

Excluding the 3.5 keV line



[Dessert, NLR, Safdi 2020]

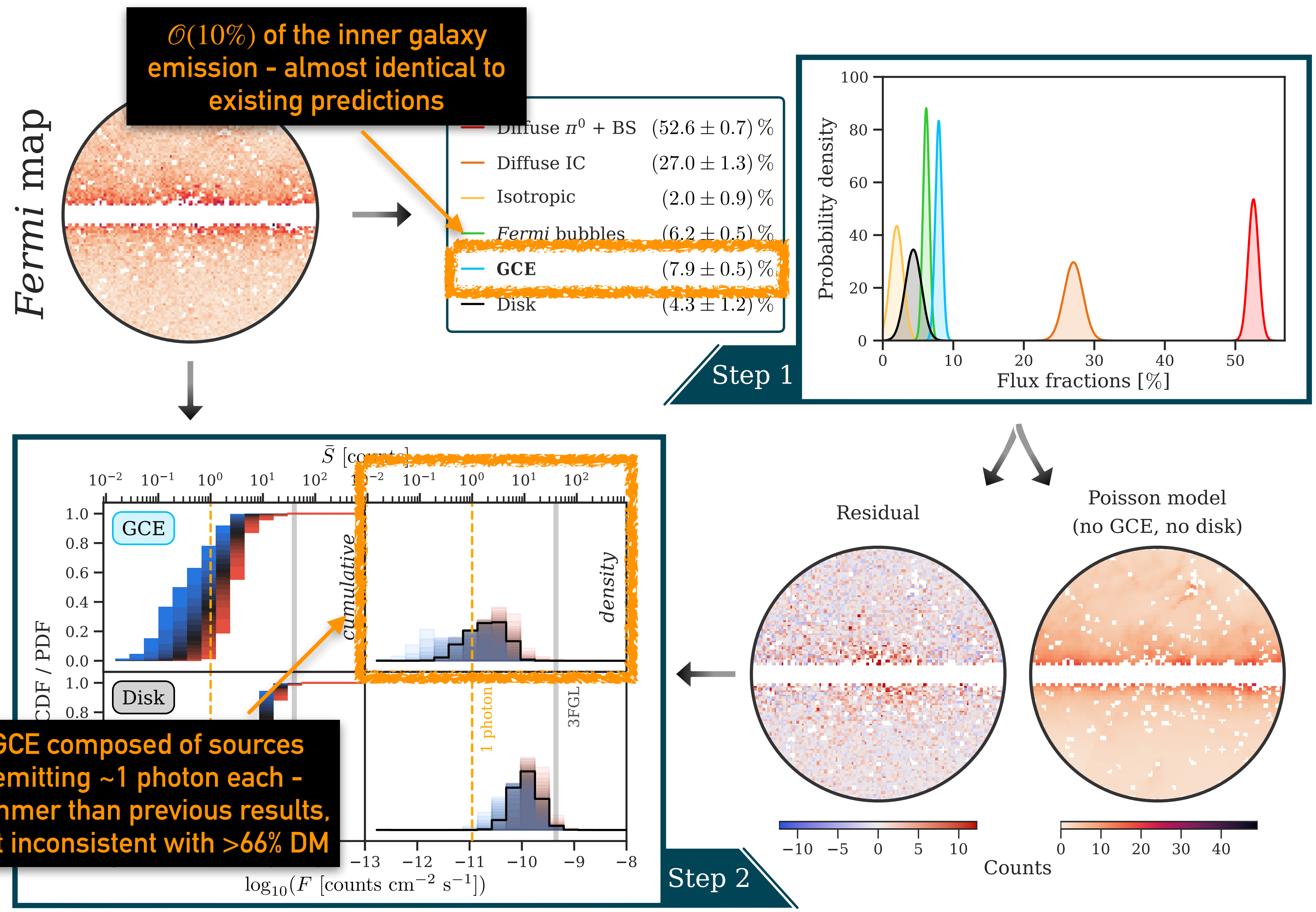
Machine Learning for the GCE



[List, NLR, Lewis 2021]

See also [List, NLR, Lewis, Bhat 2020], [Mishra-Sharma, Cranmer 2020, 2021]

Machine Learning for the GCE



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