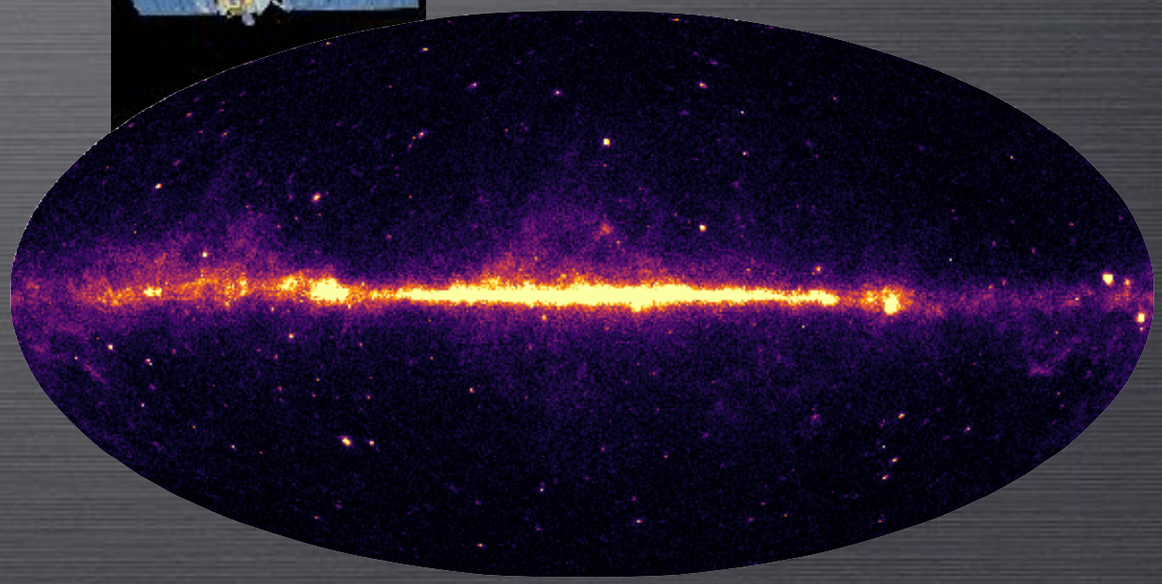
Indirect Detection w/ X-rays & γ-rays

ROSAT: 1990-1999

Fermi: 2008-present

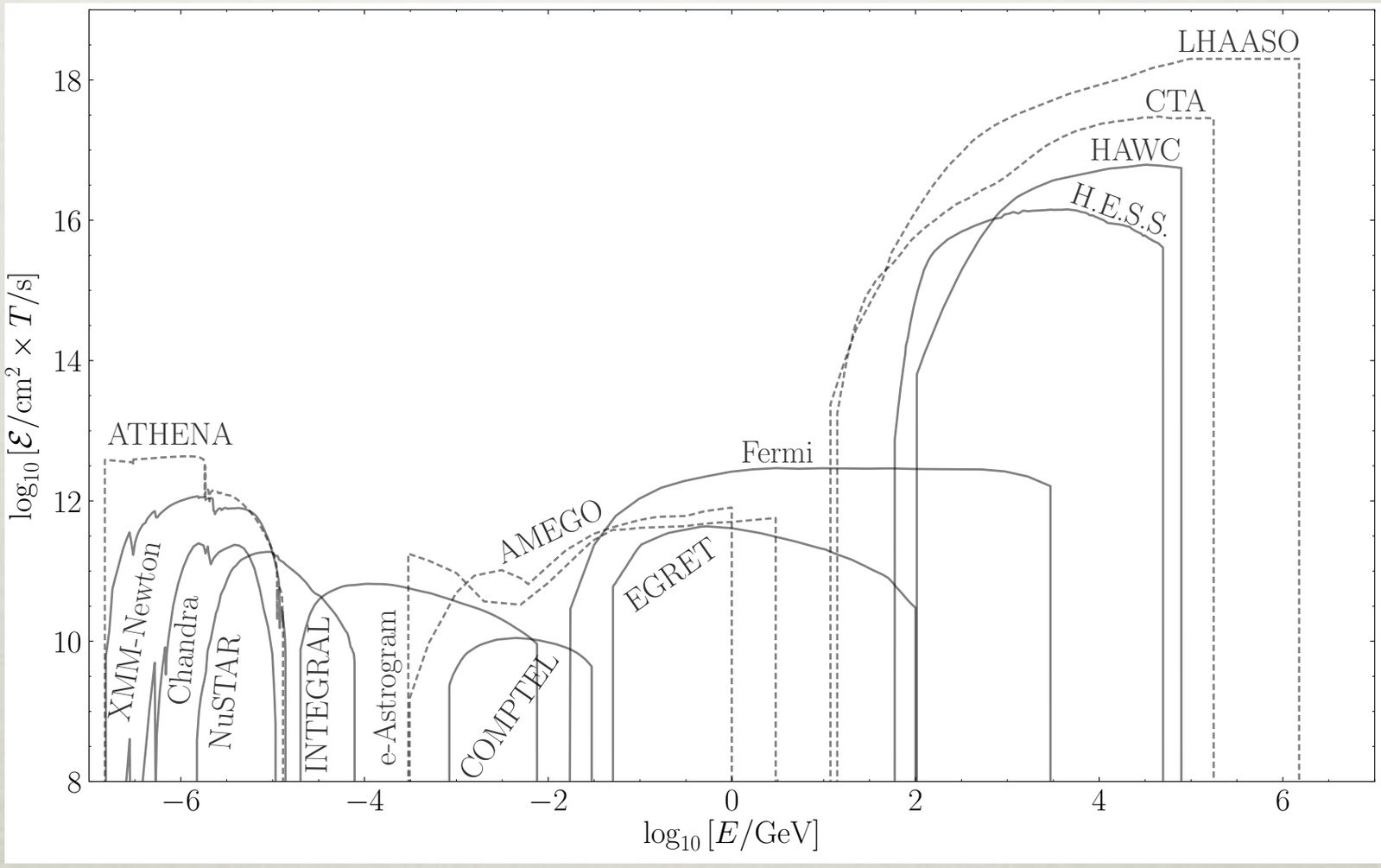


Nick Rodd

GGI, 12 September 2019

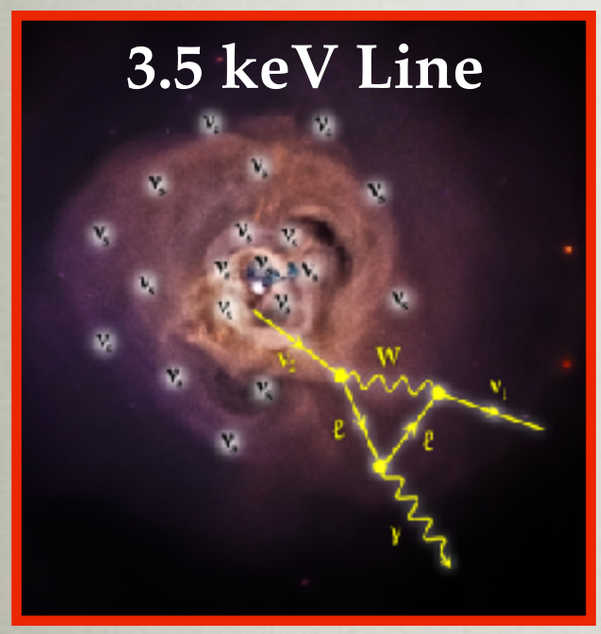
Overview

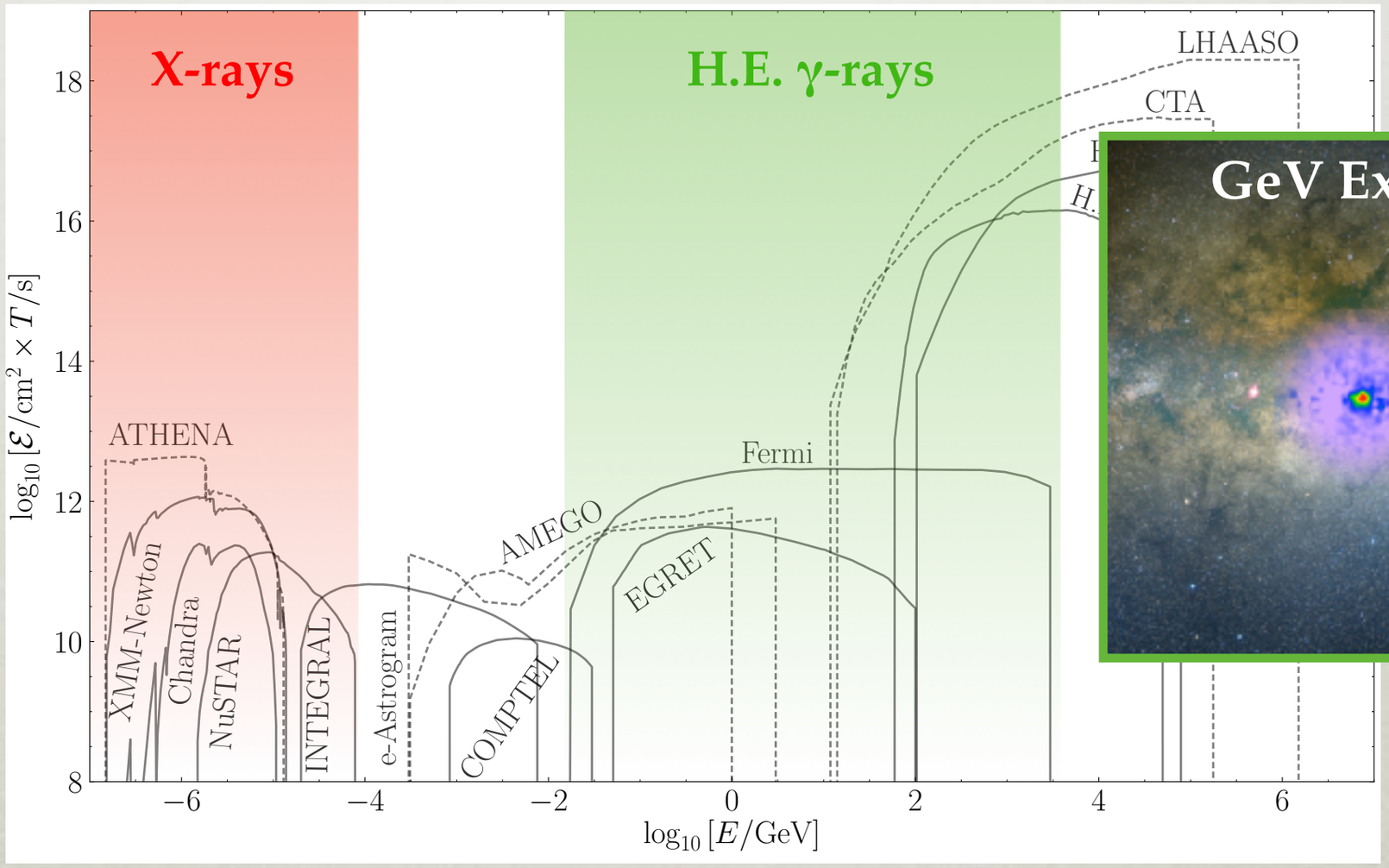
- 1. Landscape of X-ray & γ-ray indirection detection



Overview

- 1. Landscape of X-ray & γ-ray indirection detection
- 2. Status of two anomalies: 3.5 keV line & GeV excess





Images Courtesy of NASA/CXC/SAO/E.Bulbul et al., Overlay: APS/Alan Stonebraker and NASA Goddard/A. Mellinger (Central Michigan Univ.) and T. Linden (Univ. of Chicago)

Overview

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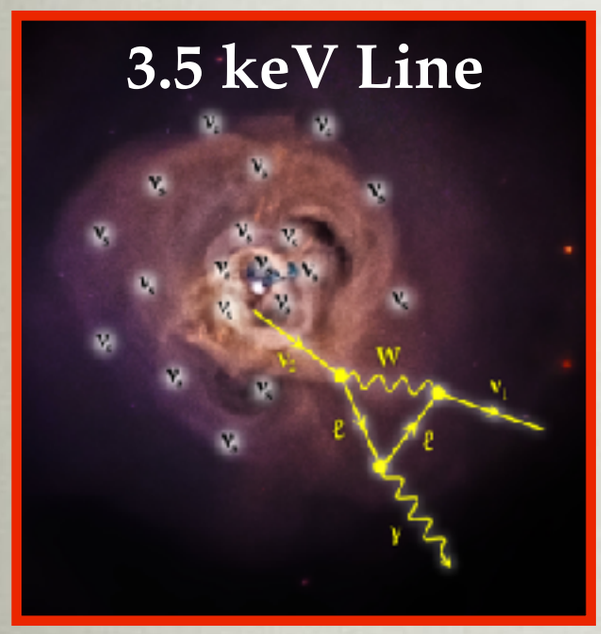
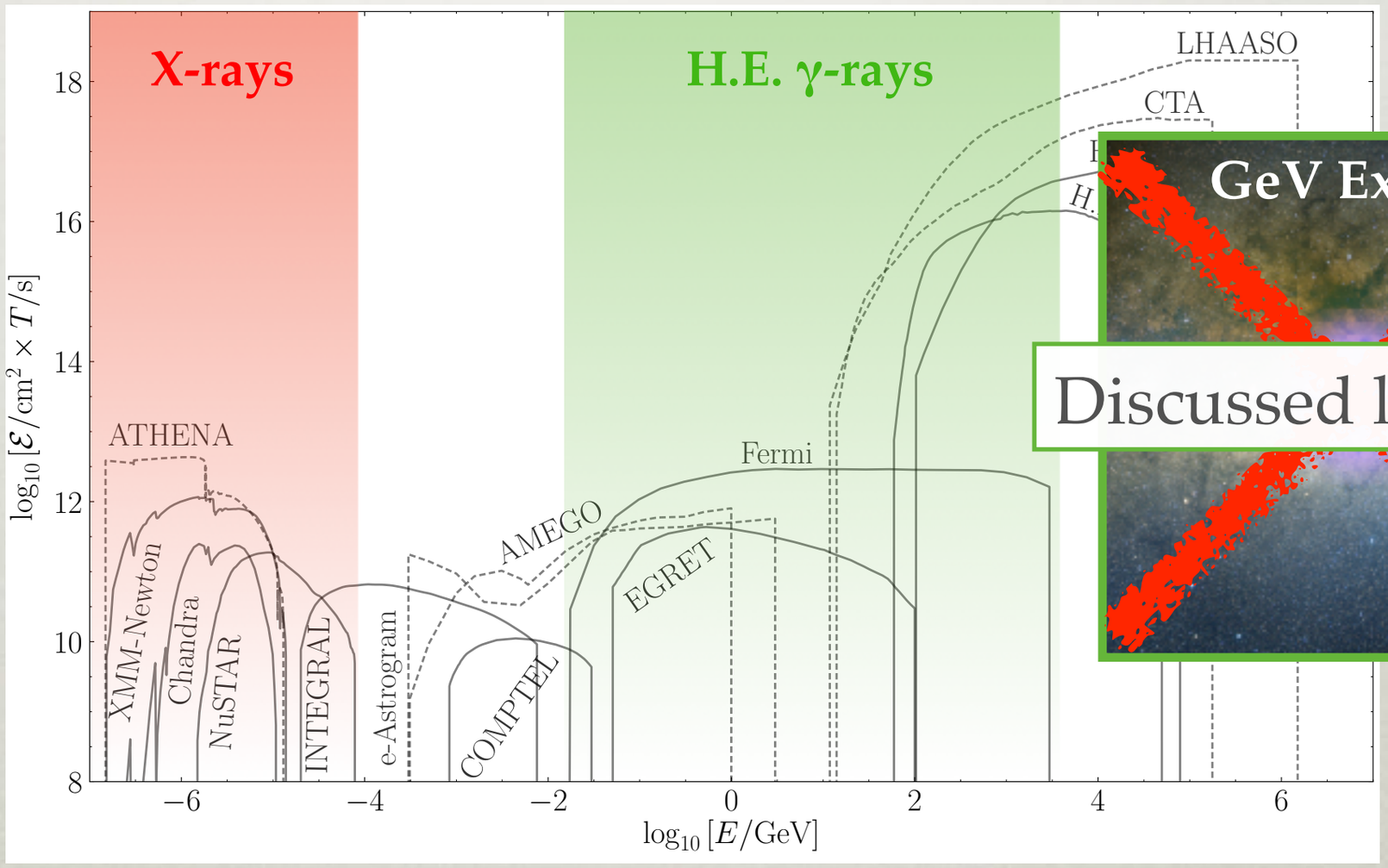
- 2. Status of ~~two~~ one anomalies: 3.5 keV line ~~& GeV excess~~

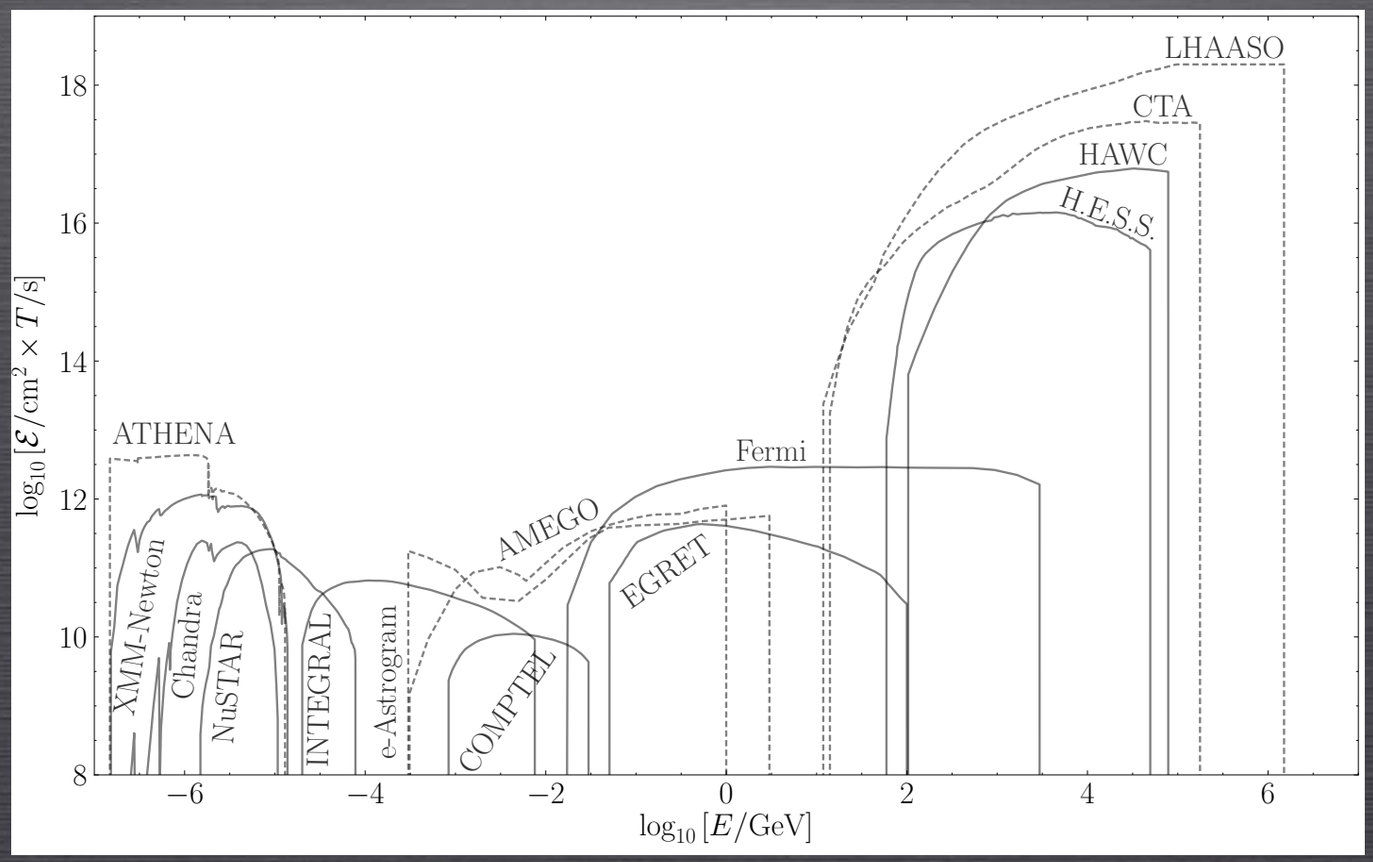




Discussed last week

Images Courtesy of NASA/CXC/SAO/E.Bulbul et al., Overlay: APS/Alan Stonebraker and NASA Goddard/A. Mellinger (Central Michigan Univ.) and T. Linden (Univ. of Chicago)

1. Landscape


LHAASO
CTA
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H.E.S.S.
Fermi
AMEGO
EGRET
ATHENA
XMM-Newton
Chandra
NuSTAR
INTEGRAL
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How do we detect Dark Matter?

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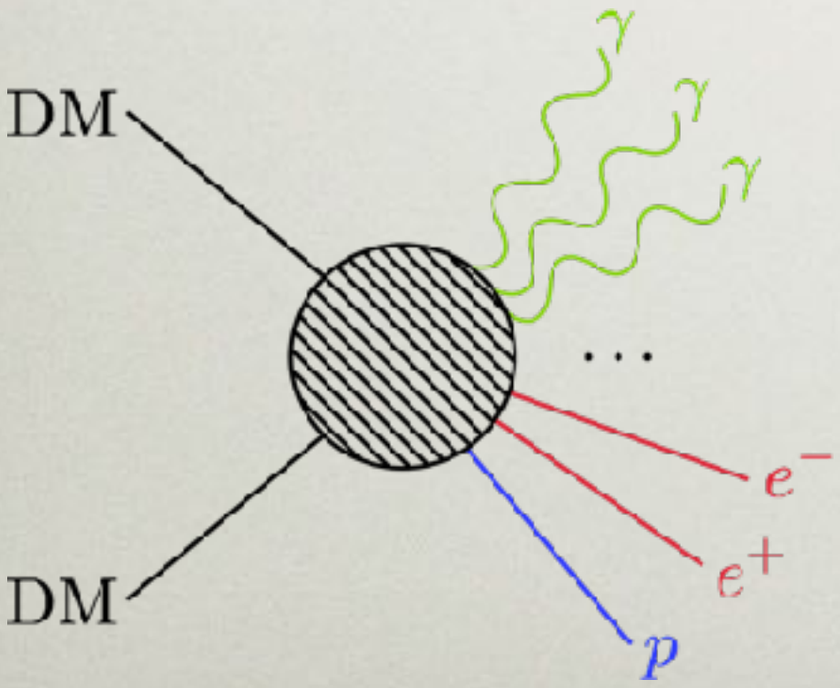
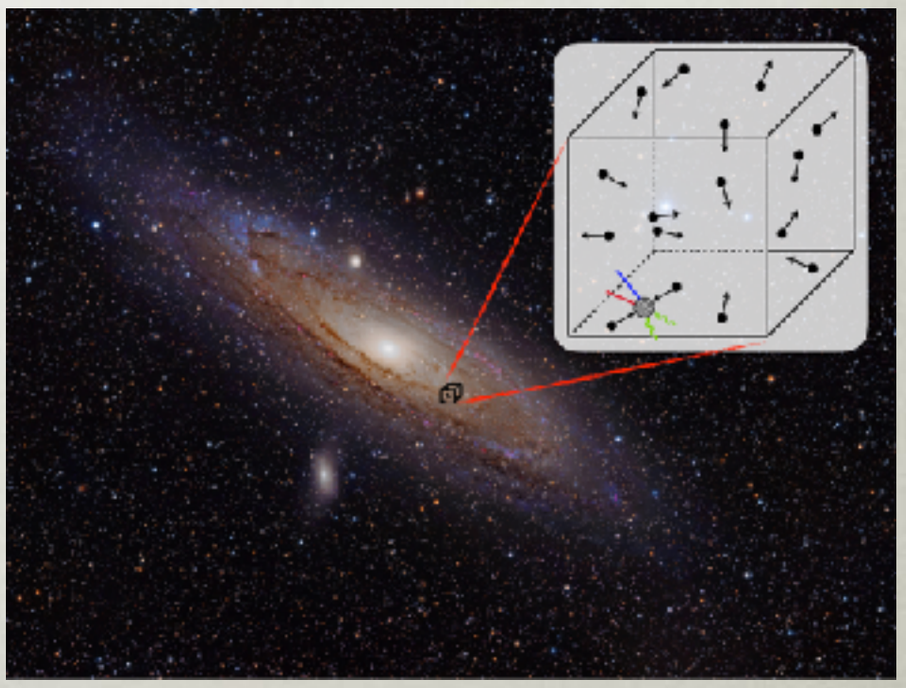
$$\underbrace{\Phi(l,b)}_{\gamma/\mathrm{cm}^2/s} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}}\frac{dN_\gamma}{dE}\,dE}_{\text{“Particle Physics Factor”}} \times \underbrace{\int_{\mathrm{los}}\rho^2_{\mathrm{DM}}(r)\,ds}_{\text{“}J-\text{Factor”}}$$

What are the dark matter interactions?



Where are they occurring?



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$$\langle\sigma v\rangle = 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$m_\chi = 100\ \mathrm{GeV}$$

$$dN_\gamma/dE = 2\delta(E - m_\chi)\ \ (\chi\chi \to \gamma\gamma)$$

$$\Rightarrow \mathrm{PP} \approx 10^{-31}\ \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}^2$$

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e.g. Segue 1 :

$J \approx 10^{20}\ \mathrm{GeV}^2/\mathrm{cm}^5$

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If we had a 1m² space based telescope operate for 10 years:

$$\left(10^{-11}\ \gamma/\mathrm{cm}^2/\mathrm{s}\right) \times \left(10^4\ \mathrm{cm}^2\right) \times \left(10 \times \pi \times 10^7\ \mathrm{s}\right) \approx 30\ \gamma$$

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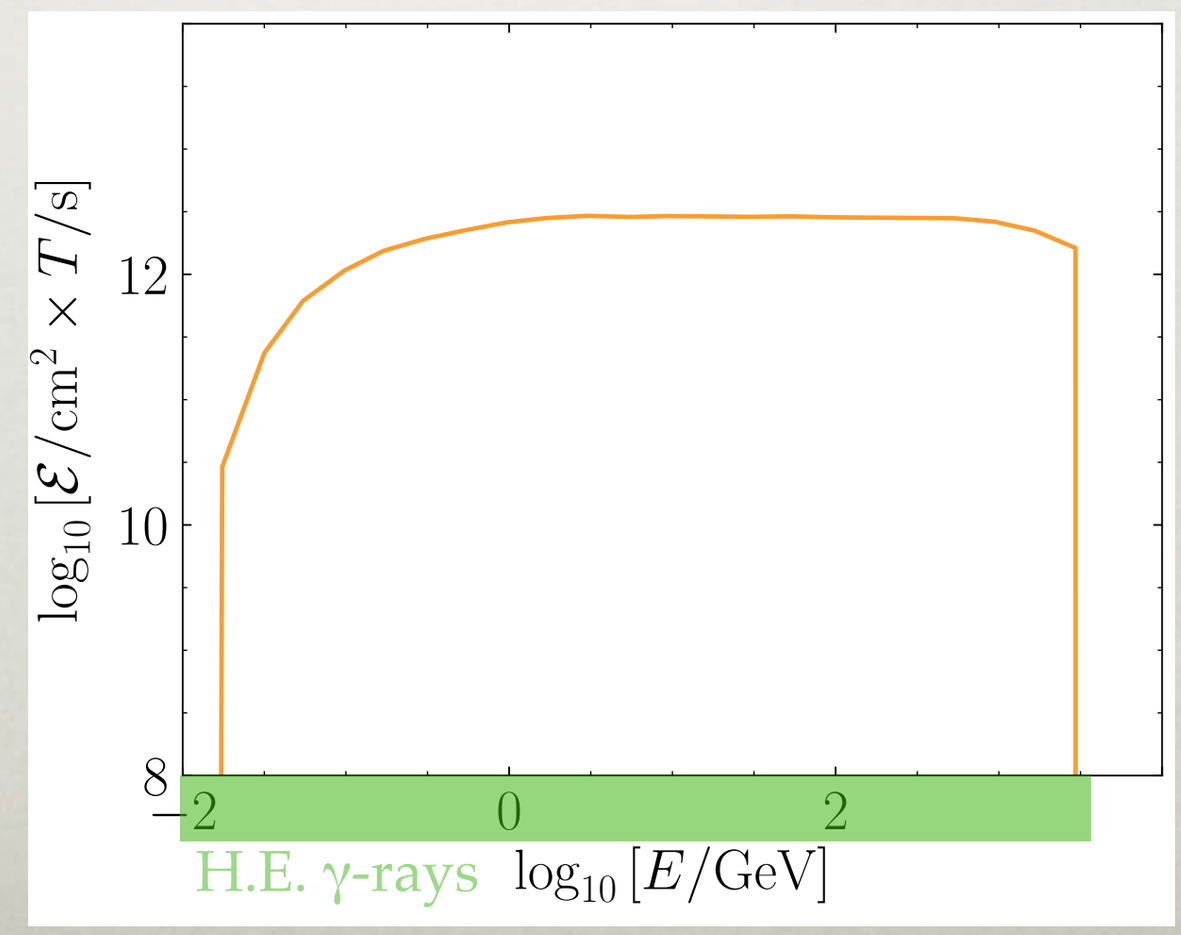
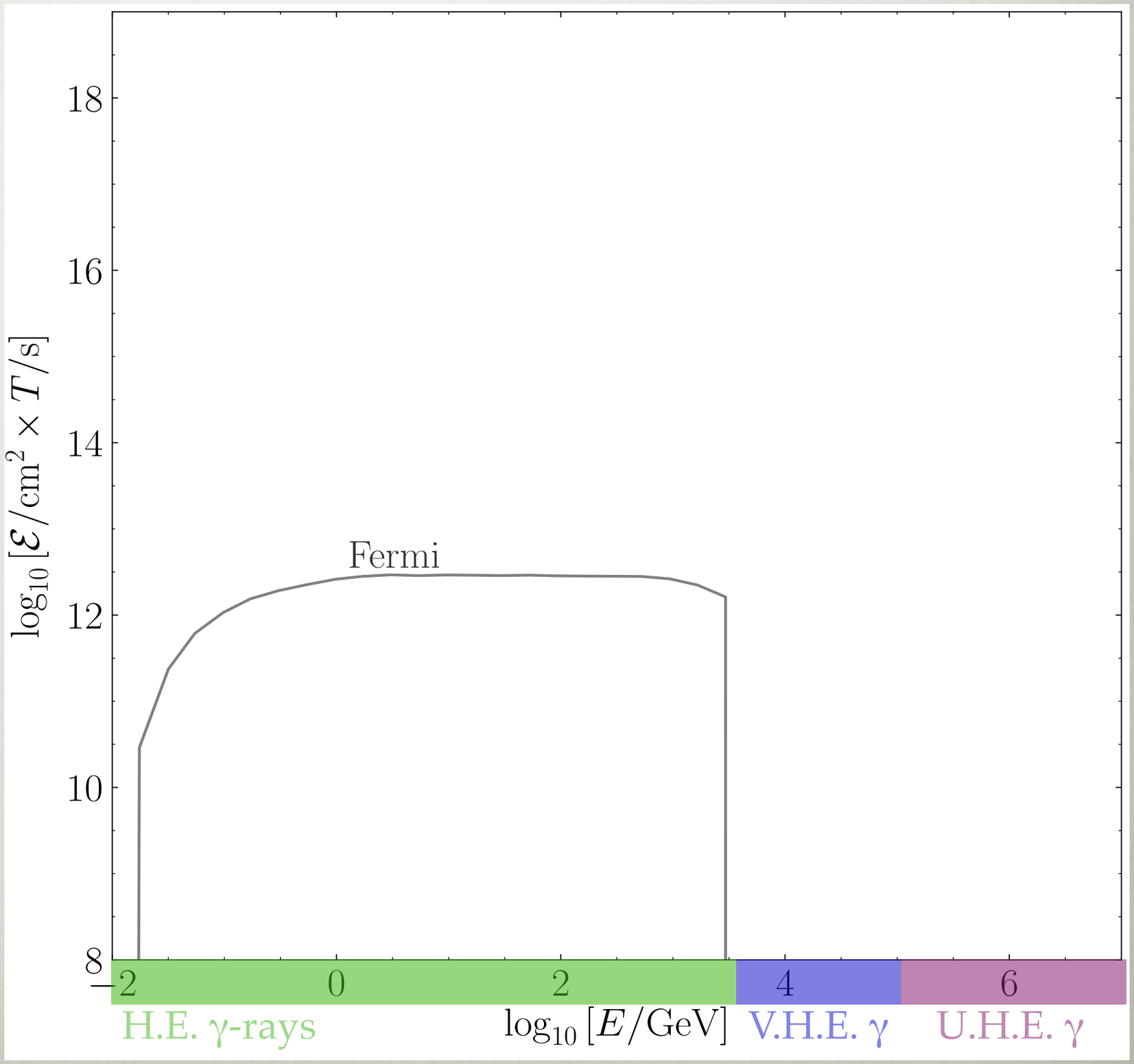
Landscape

Cape Canaveral June 11, 2008



Landscape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H.E. γ-rays
$\log_{10}[E/\mathrm{GeV}]$
V.H.E. γ
U.H.E. γ

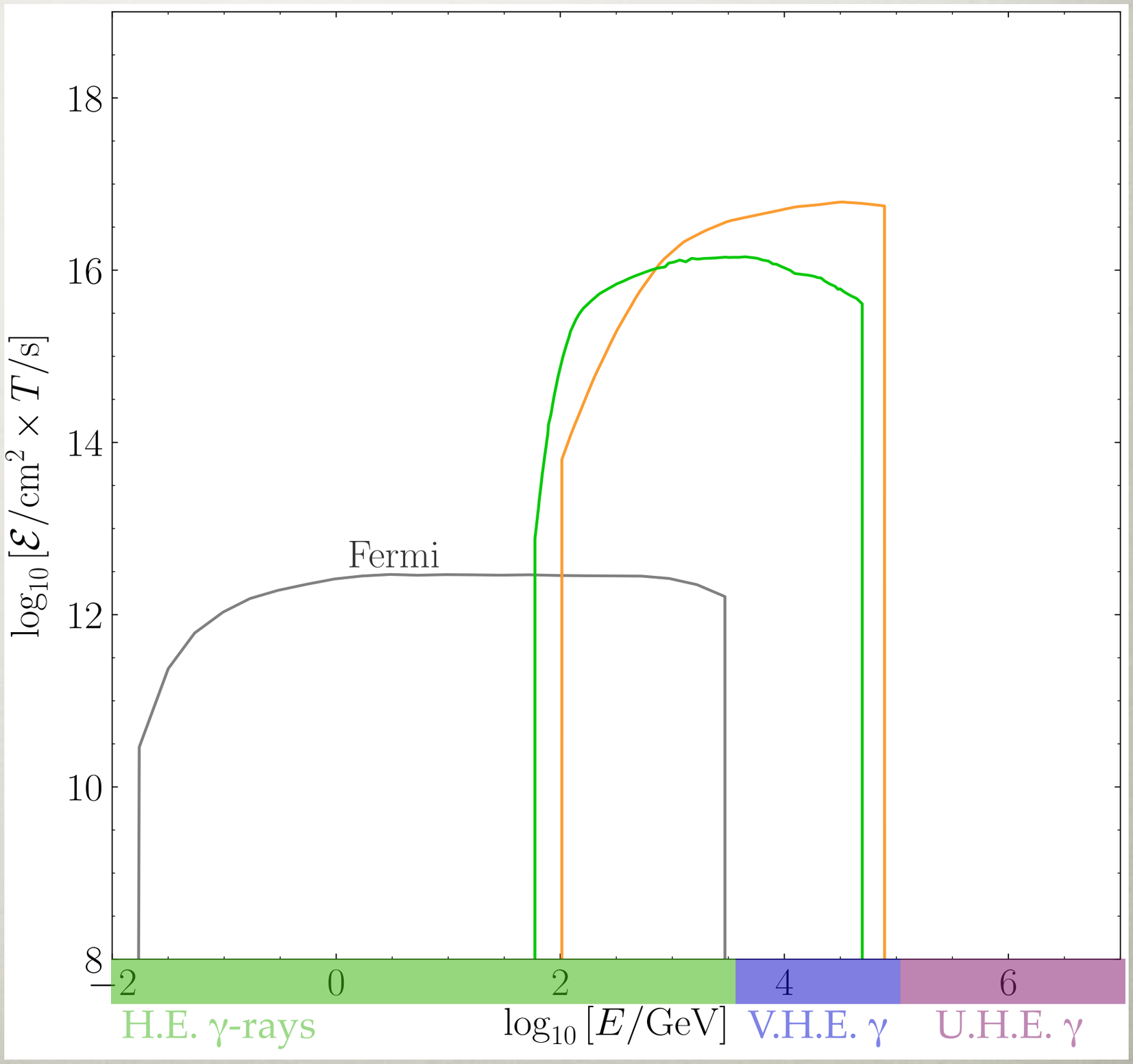
Landscape

HAWC

2015-present

H.E.S.S.

2002-present
(H.E.S.S. II 2012-)

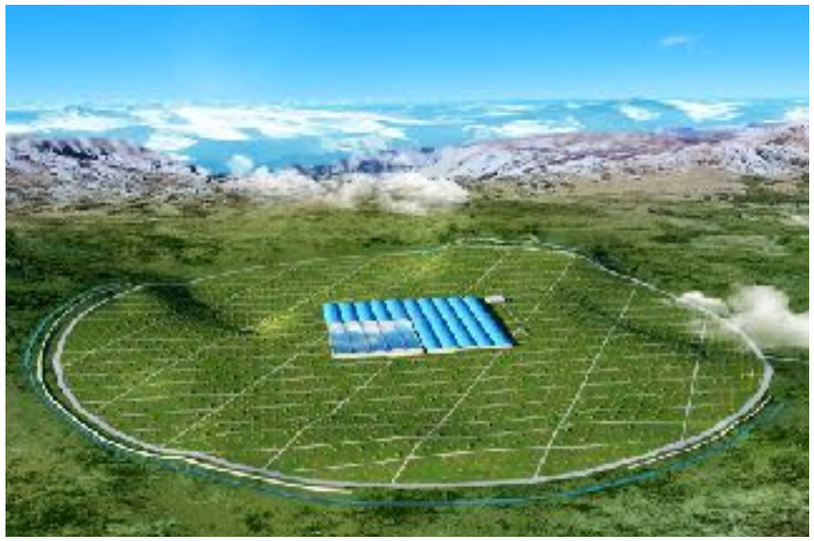


Landscape

LHAASO

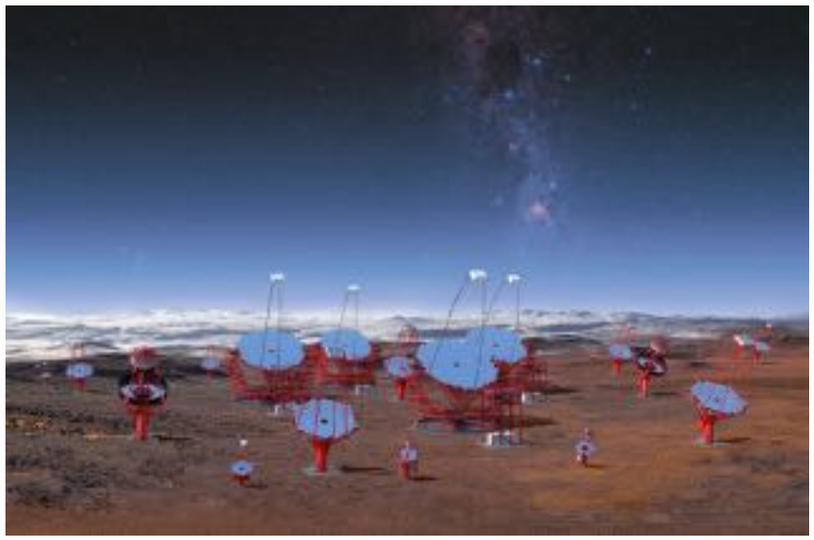
2021?

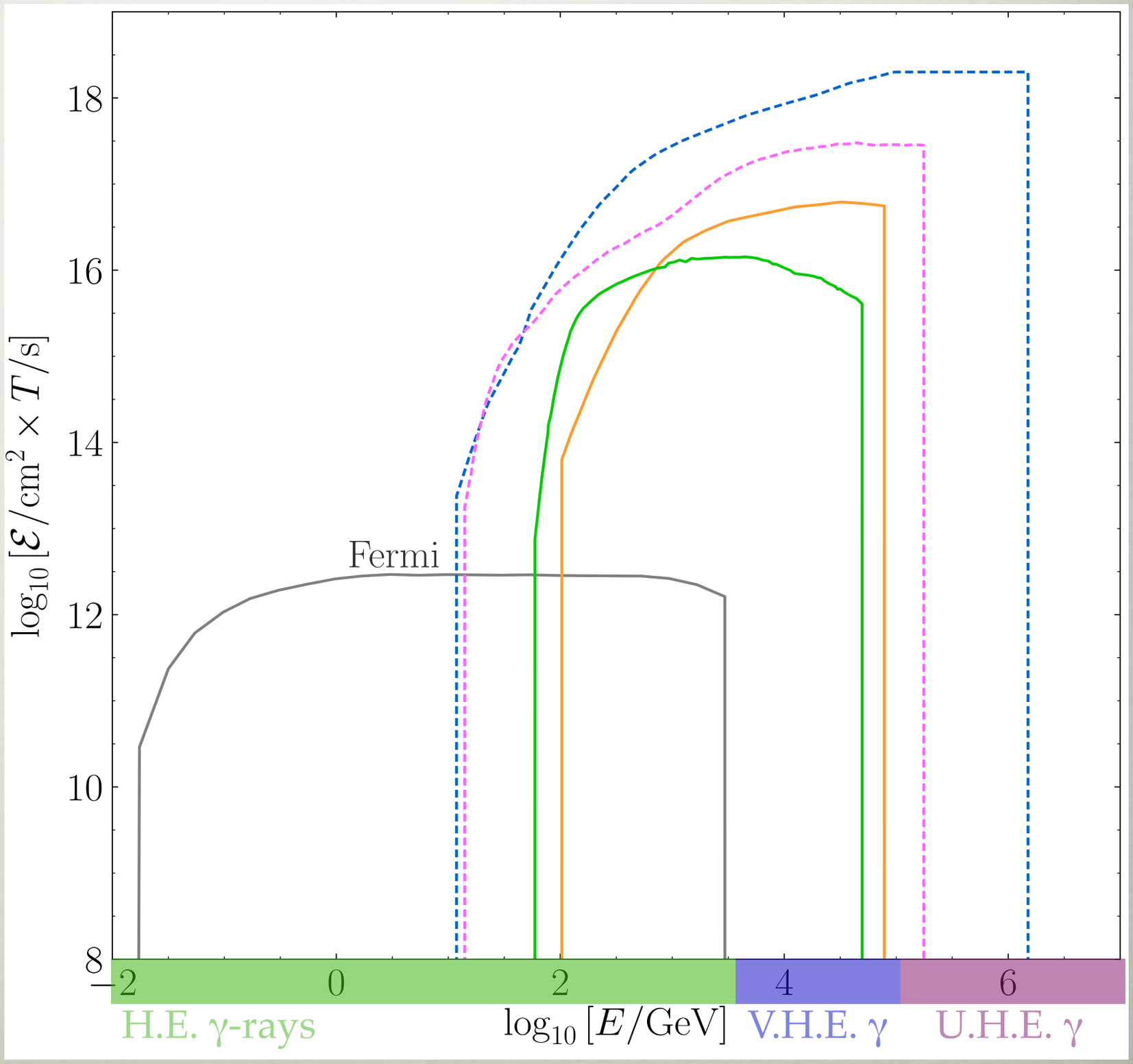
[LHAASO 1905.02773]



CTA

~2025



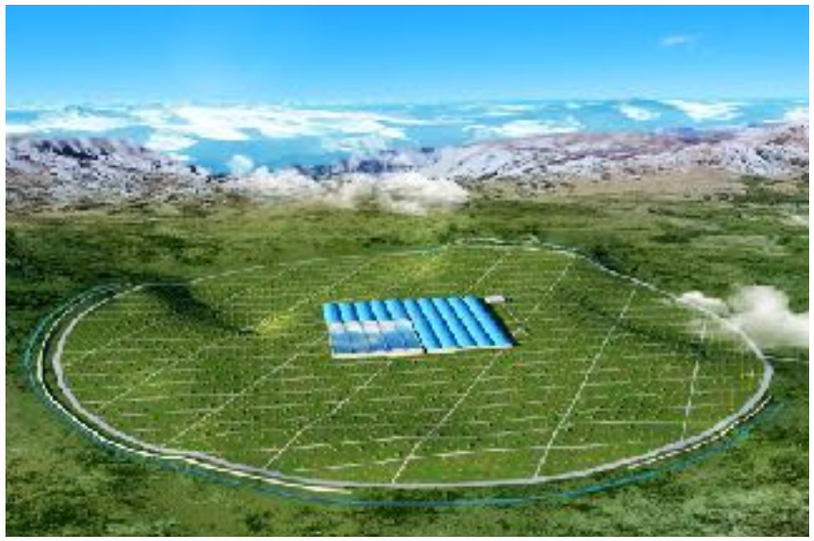


Landscape

LHAASO

2021?

[LHAASO 1905.02773]



CTA

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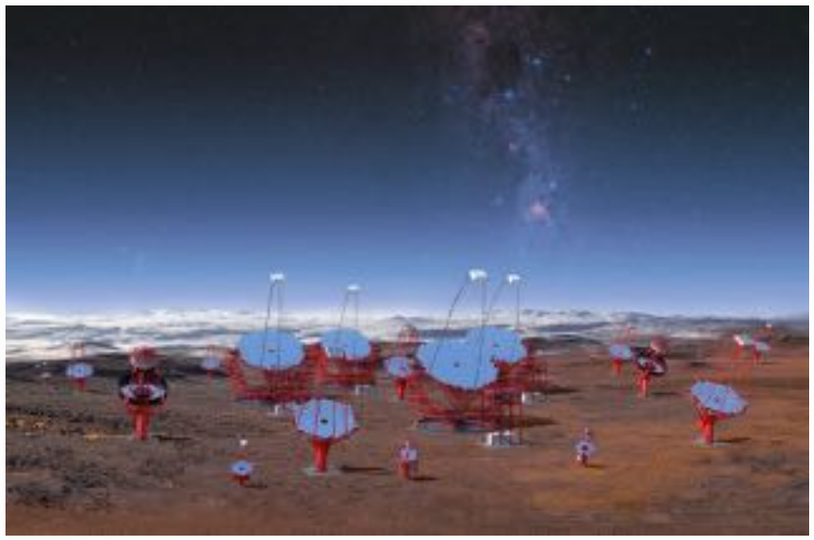
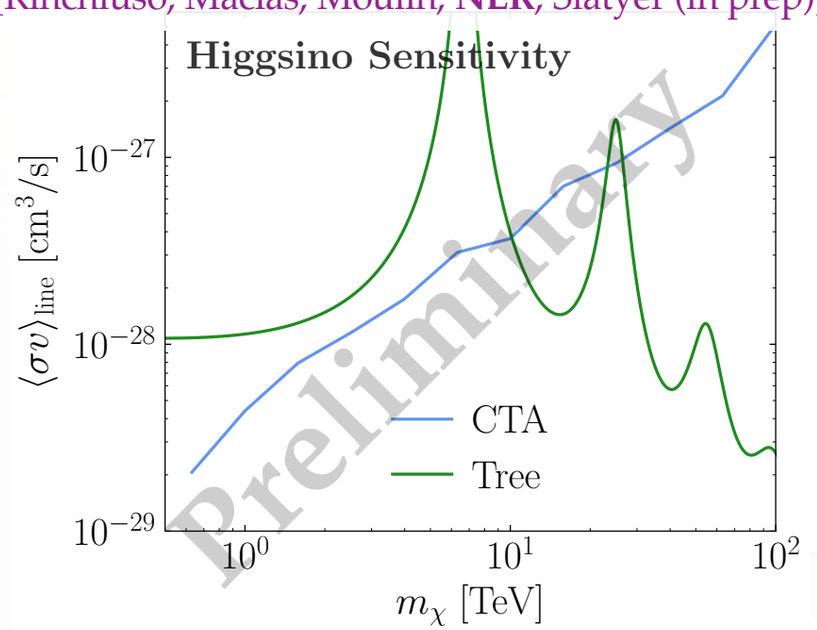
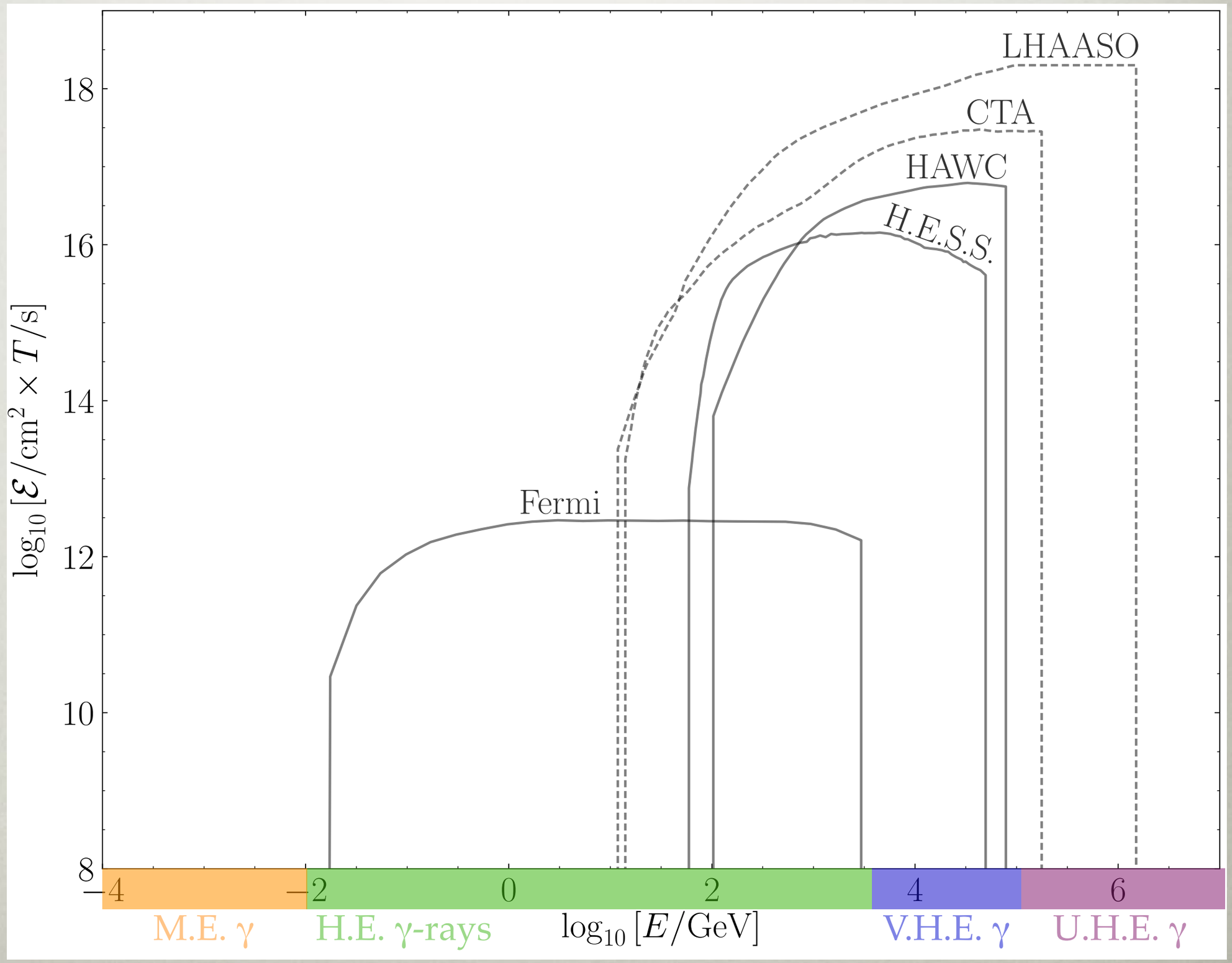


[Rinchiuso, Macias, Moulin, **NLR**, Slatyer (in prep)]



See also [Silverwood+ 1408.4131]; [CTA 1709.07997]

Landscape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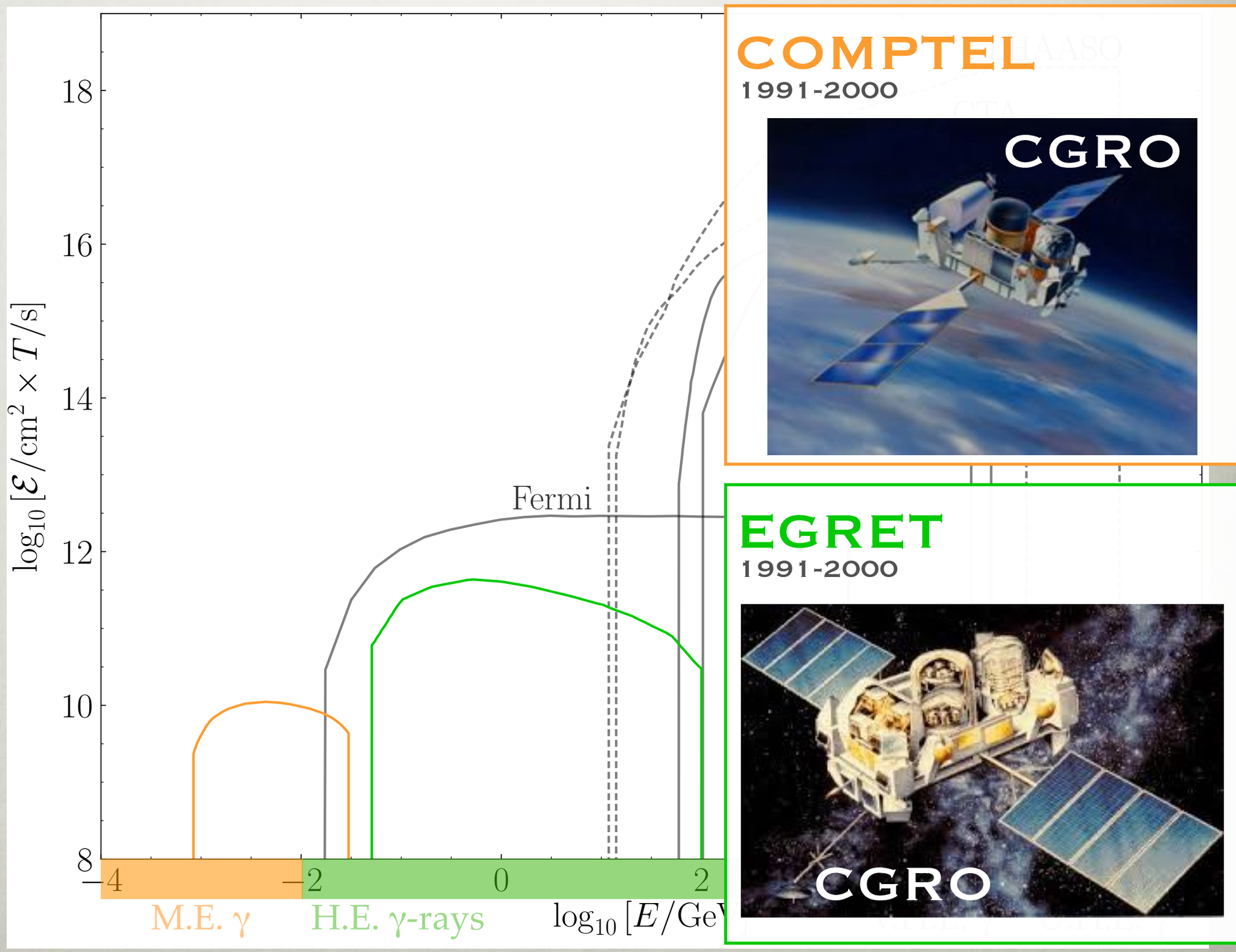
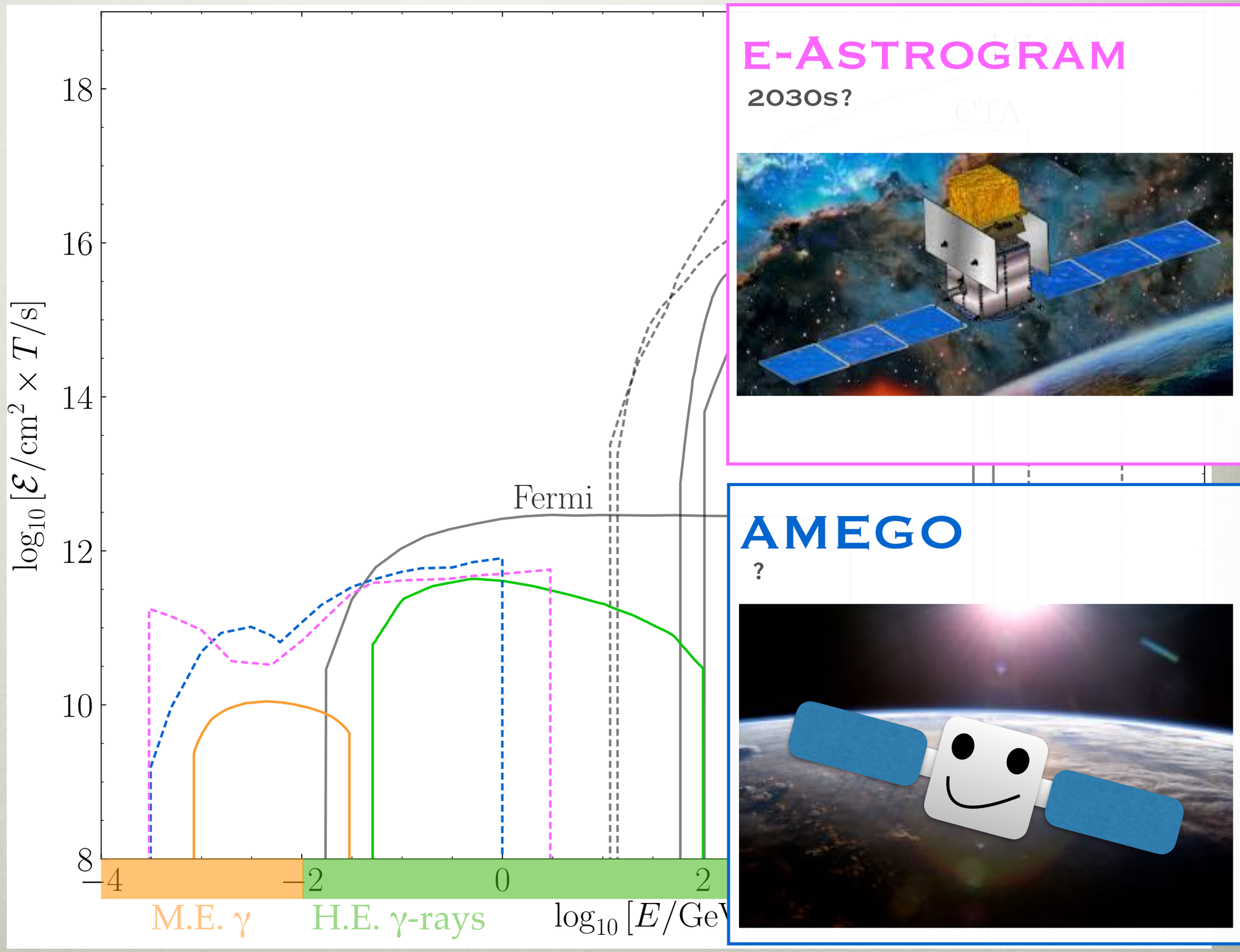
Landscape



COMPTEL
1991-2000

EGRET
1991-2000

Landscape



e-Astrogram

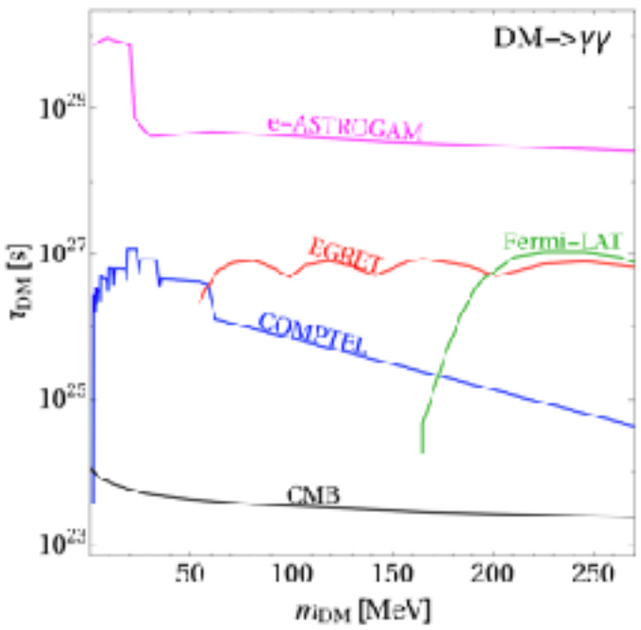
2030s?

AMEGO

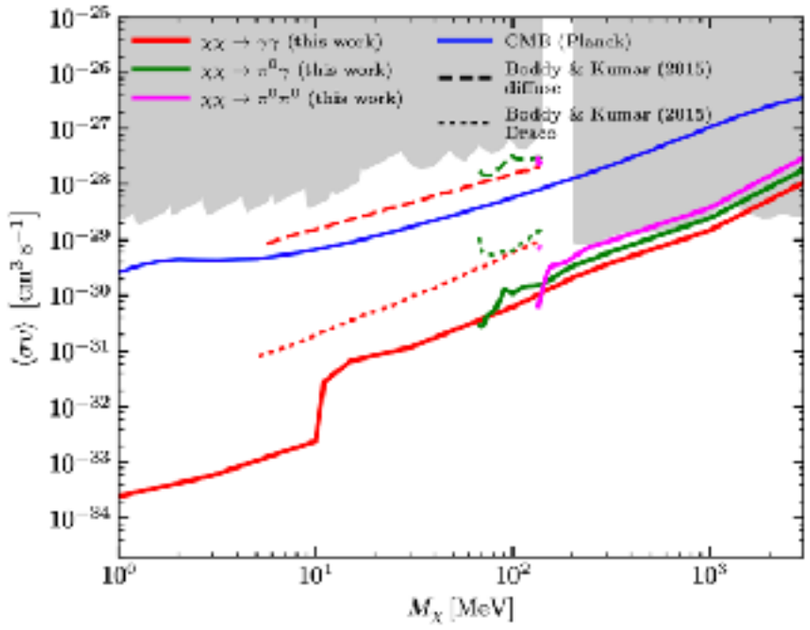
?

Landscape

[e-ASTROGAM 1711.01265]

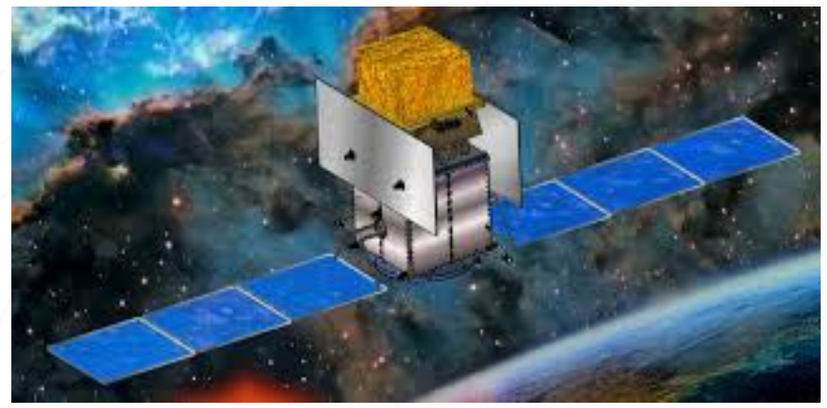


[Bartels, Gaggero, Weniger 1703.02546]

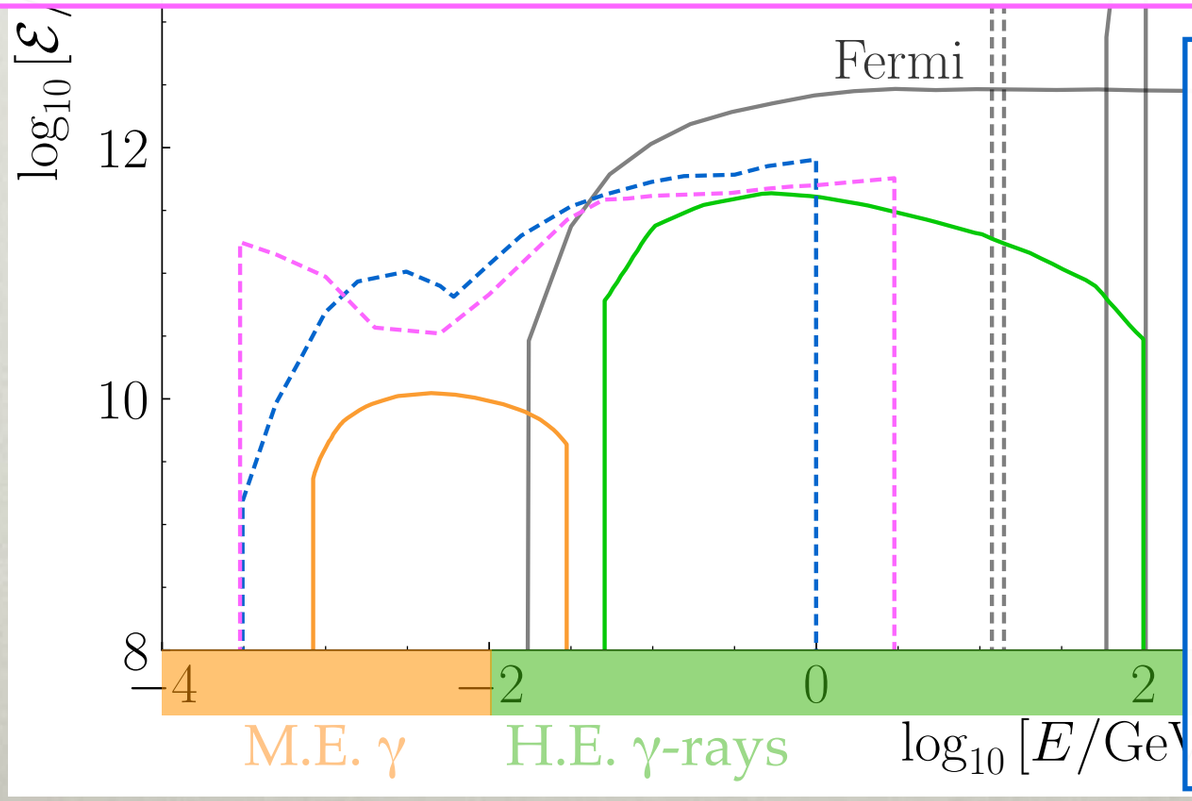


e-Astrogram

2030s?

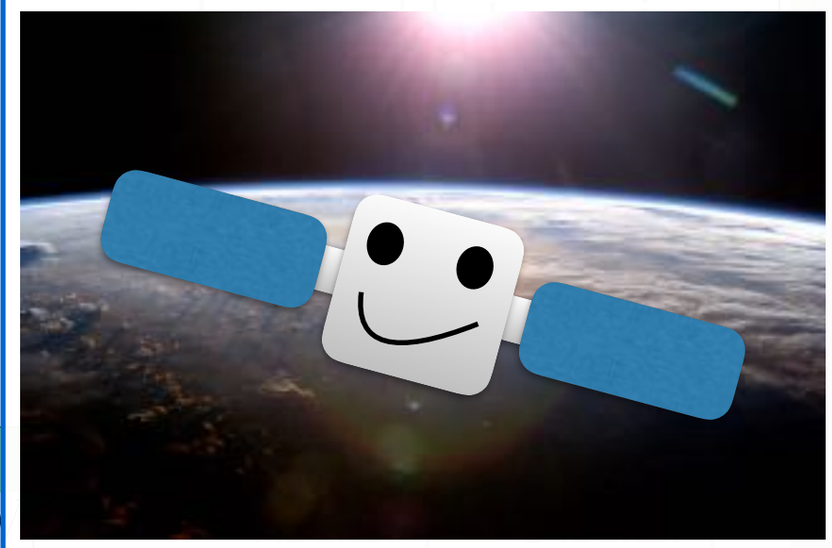


See also:
Caputo+ 1903.05845,
Bringmann+ 1610.04613,
Boddy, Kumar 1504.04024,
Boddy+ 1606.07440,
Kumar 1808.02579,
Coogan+ 1907.11846
…

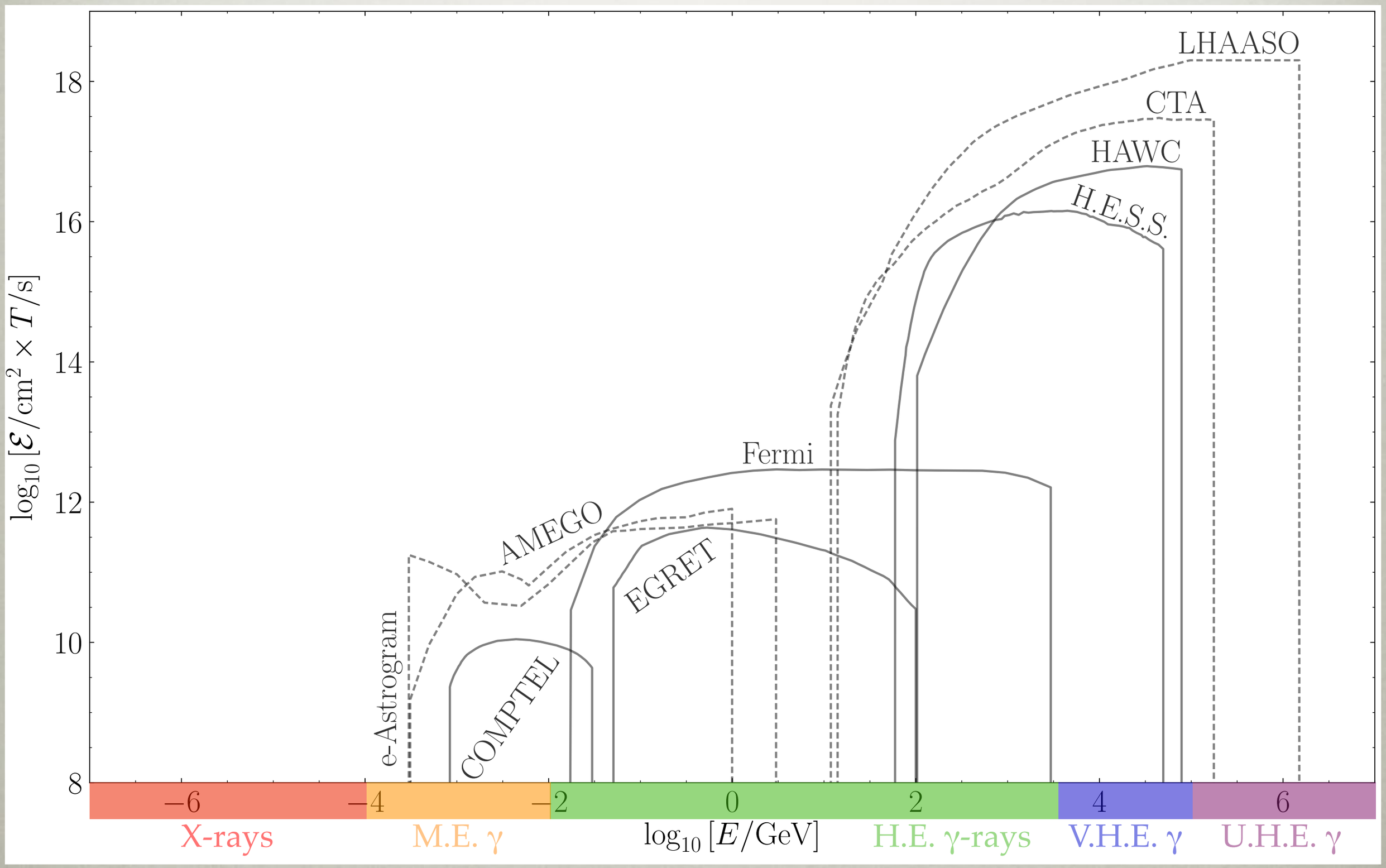


AMEGO

?



Landscape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X-rays
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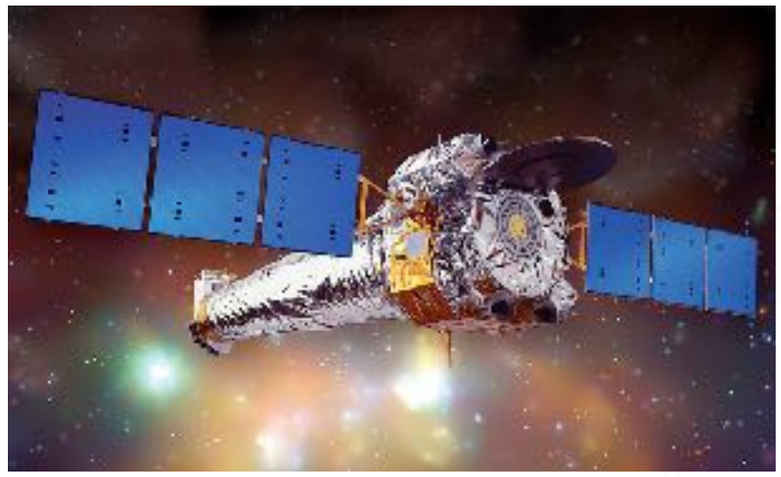
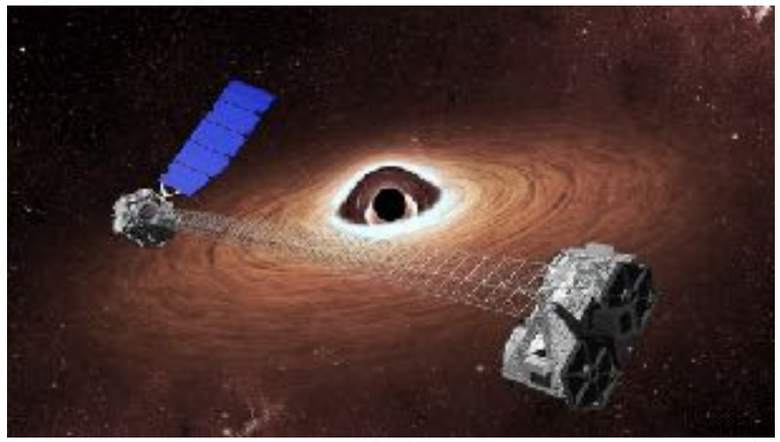
Landscape

XMM-Newton
1999-present

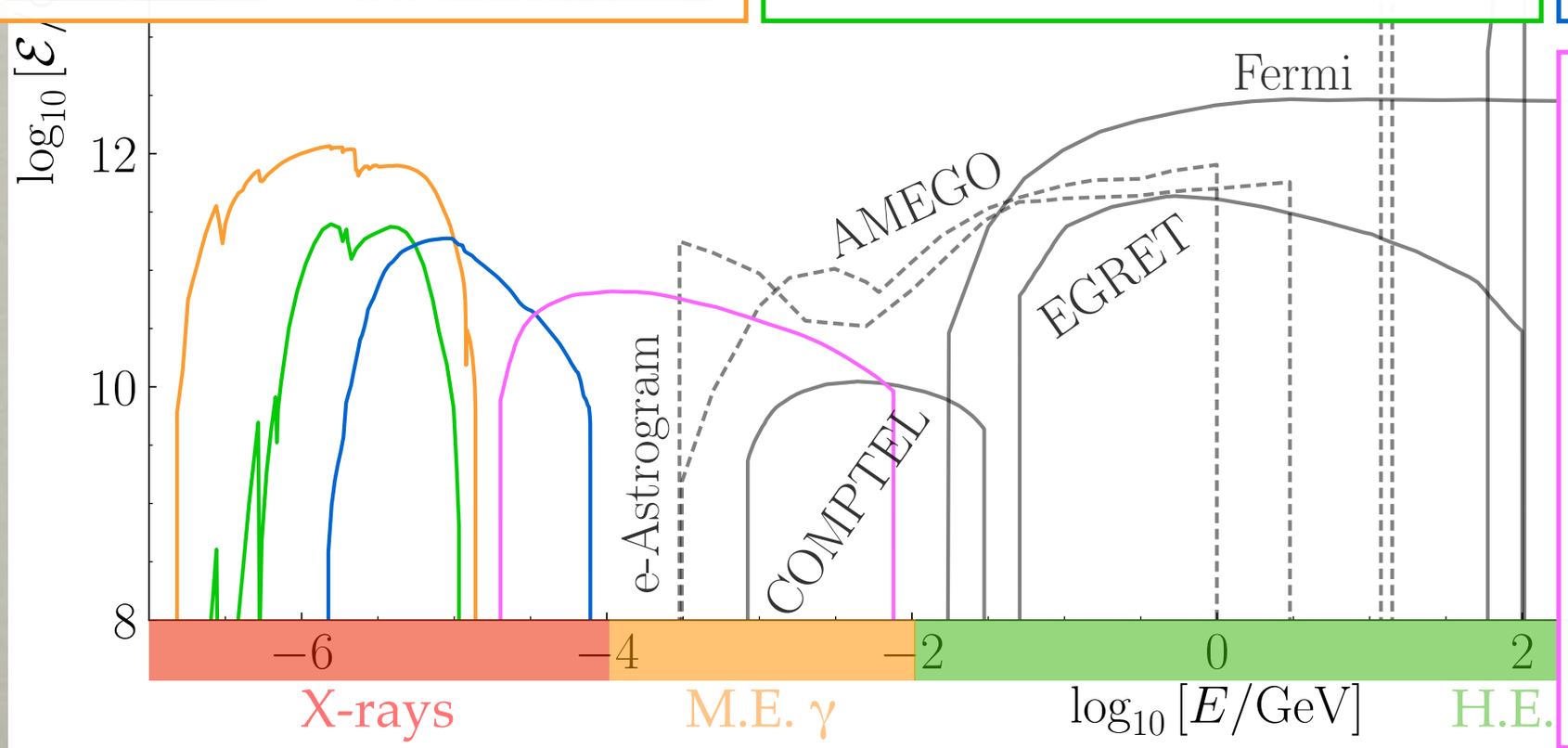
Chandra
1999-present



NuSTAR
2012-present



INTEGRAL
2002-present

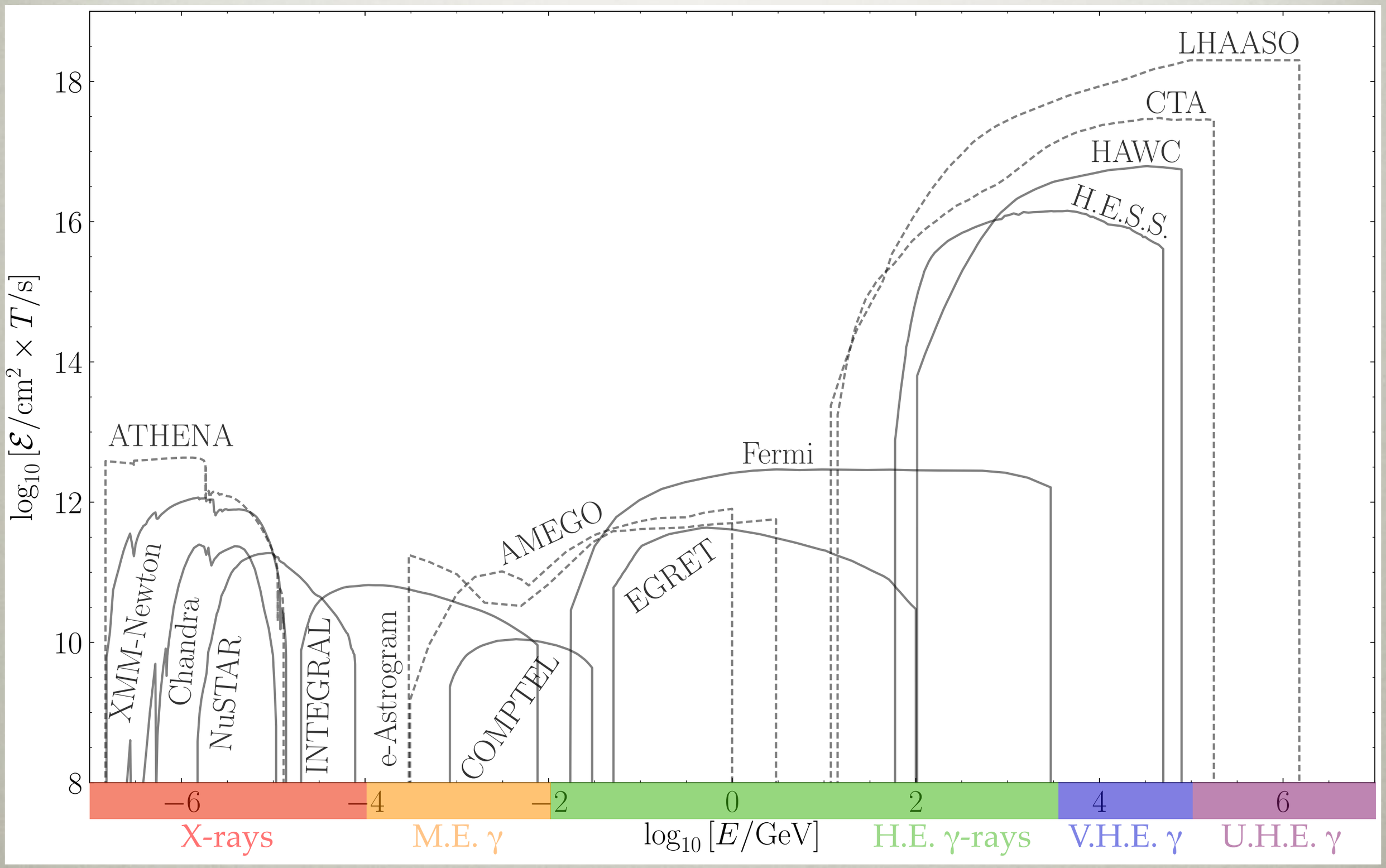


Landscape

ATHENA

~2031

Landscape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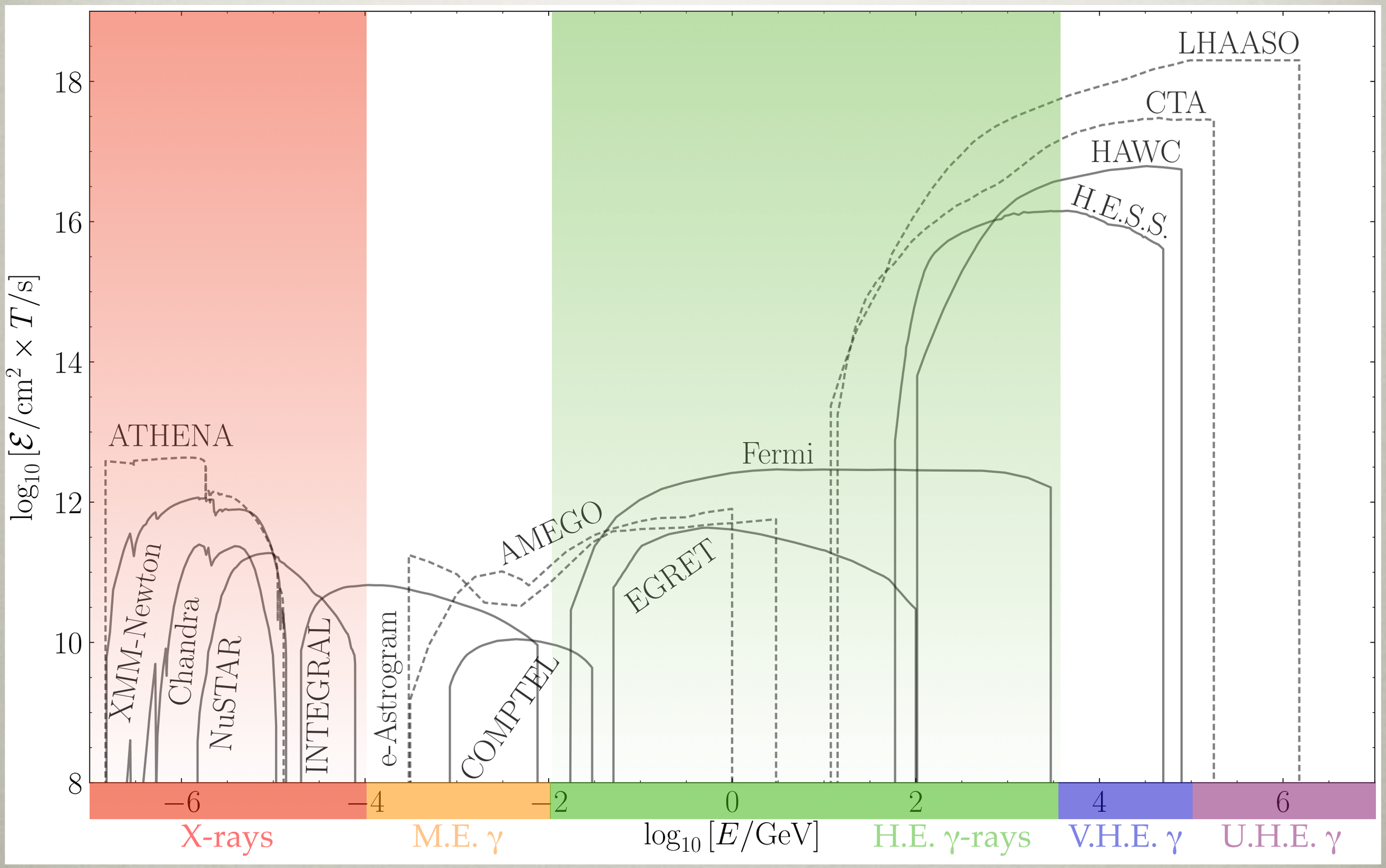
Landscape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H.E. γ-rays
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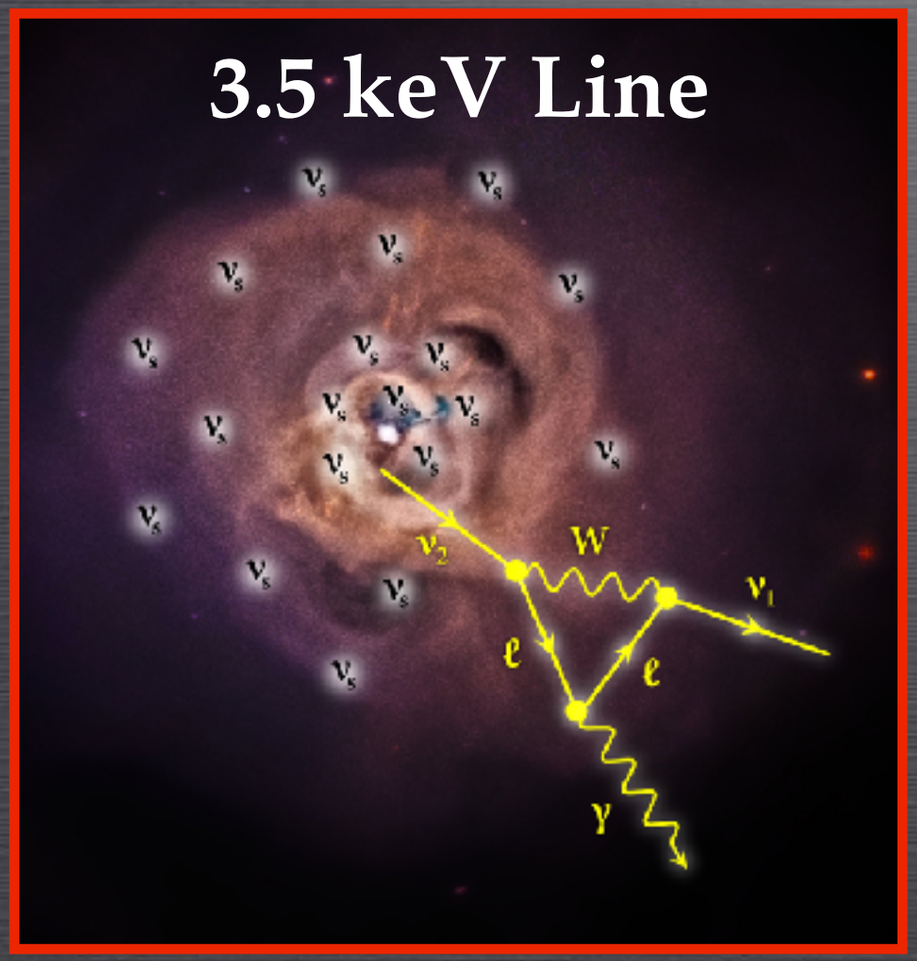
2. Anomalies

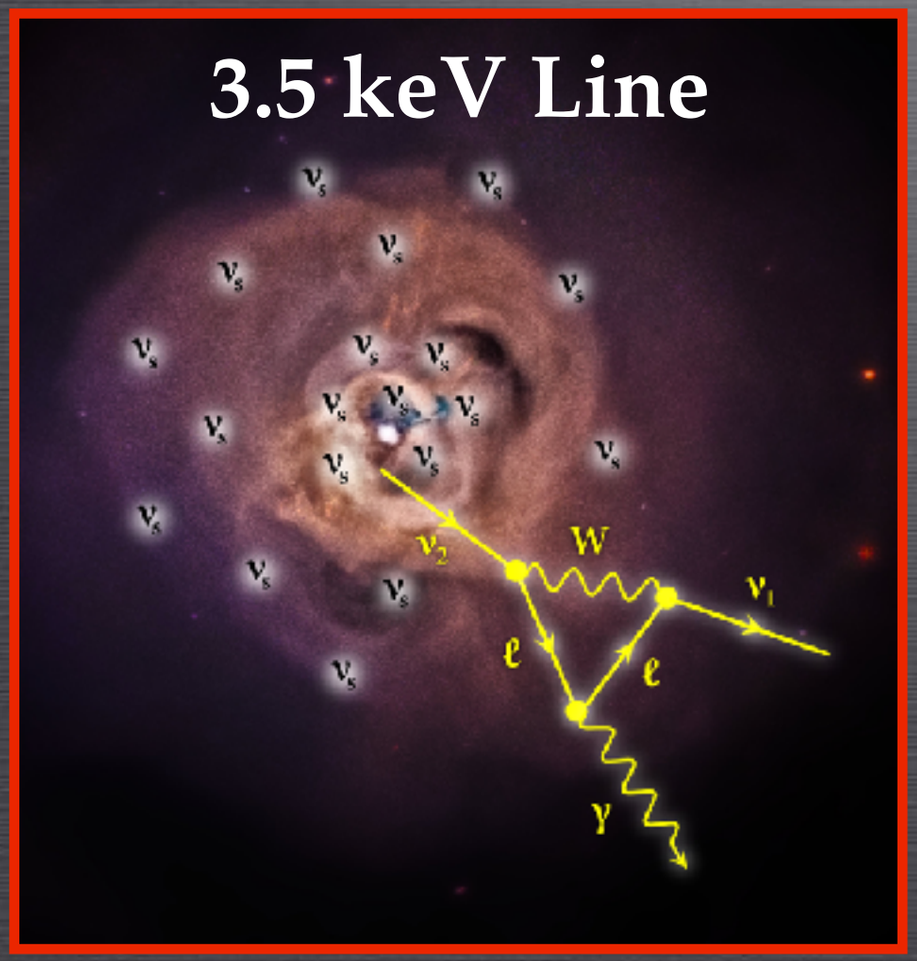
3.5 keV Line



GeV Excess

2. Anomalies

3.5 keV Line



GeV Excess

Status of the 3.5 keV line

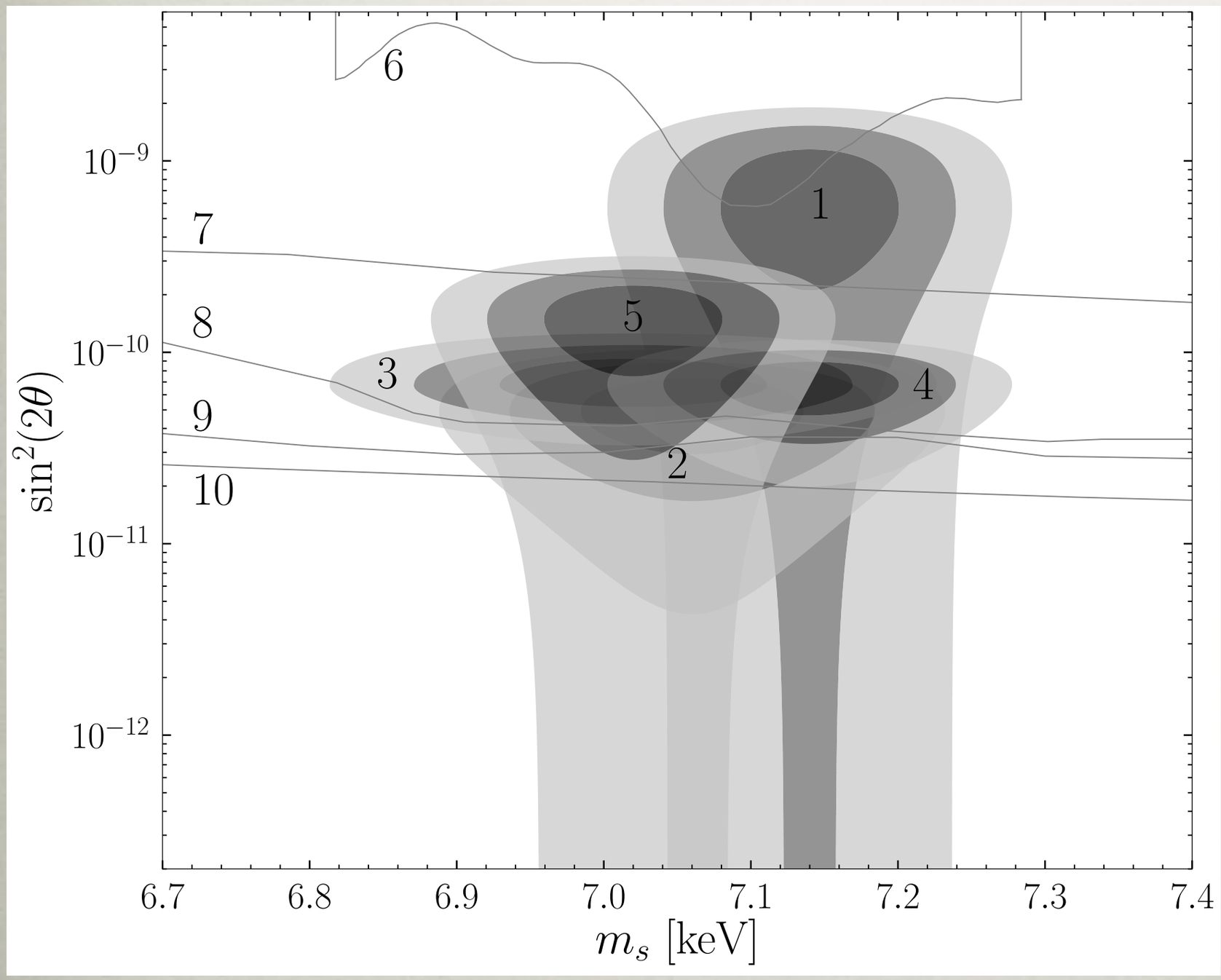
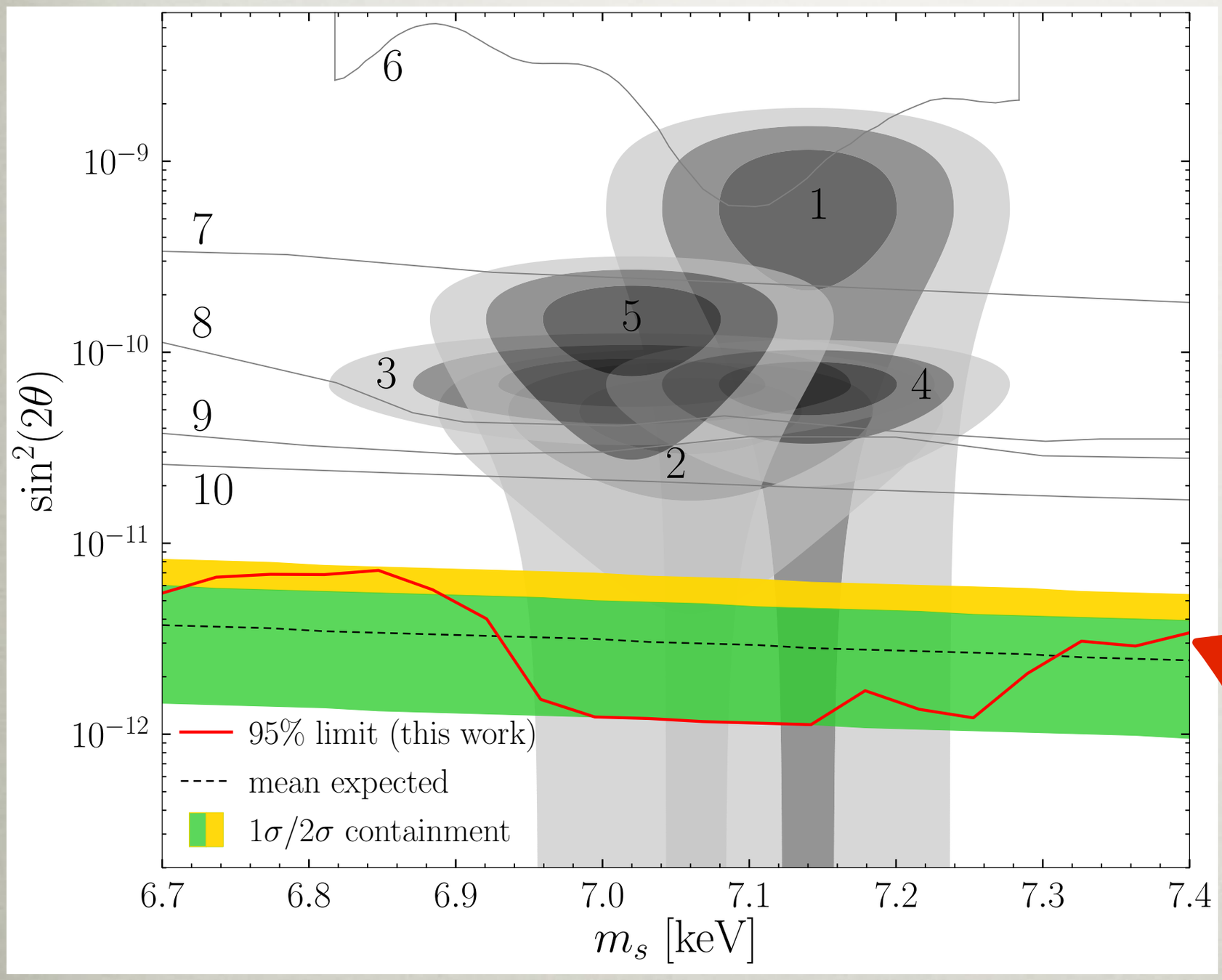


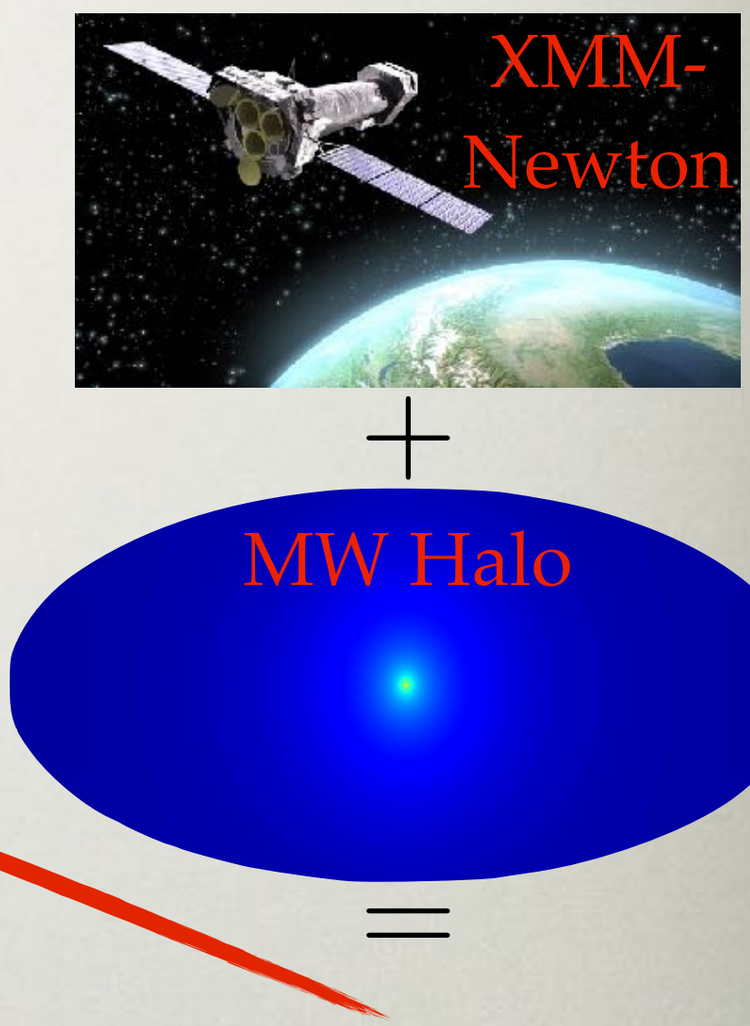
Figure reproduced from [Abazajian 1705.01837]

Legend:

1. [Boyarsky+ 1402.4119] XMM-Newton & Perseus
2. [Boyarsky+ 1402.4119] XMM-Newton & M31
3. [Bulbul+ 1402.2301] XMM-Newton PN & stacked galaxy clusters
4. [Bulbul+ 1402.2301] XMM-Newton MOS & stacked galaxy clusters
5. [Cappelluti+ 1701.07932] Chandra & stacked galaxy clusters
6. [Aharonian+ 1607.07420] Hitomi & Perseus
7. [Tamura+ 1412.1869] Suzaku & Perseus
8. [Malyshev+ 1408.3531] XMM-Newton & stacked dwarfs
9. [Horiuchi+ 1311.0282] Chandra & M31
10. [Anderson+ 1408.4115] Chandra+XMM-Newton & stacked galaxy clusters

Status of the 3.5 keV line





[Dessert, **NLR**, Safdi 1812.06976]

New Strategy

- Expected DM flux

$$\frac{d\Phi}{dE} = \frac{1}{4\pi\, m_s\, \tau}\delta(E - m_s/2) \times \frac{\int_{\mathrm{LoS}} ds \int_{\mathrm{FoV}} d\Omega\, \rho_{\mathrm{DM}}(s,\Omega)}{\int_{\mathrm{FoV}} d\Omega}$$

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- Perseus flux

$$D_{\rm Pers} \approx \frac{1}{\Omega_{\rm XMM}} \frac{M_{\rm Pers}}{d^2_{\rm Pers}} \approx \frac{1}{(10^{-4}\ {\rm sr})} \frac{(10^{15}\ M_\odot)}{(100\ {\rm Mpc})^2} \sim 10^{29}\ {\rm keV/cm^2}$$

- Perseus halo > XMM Field of View, reduces flux by factor of ~3

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- Perseus halo > XMM Field of View, reduces flux by factor of ~3
- What about for the Milky Way?

$$D_{\mathrm{MW}} \approx \int ds\, \rho_{\mathrm{DM}}(s,\Omega) \approx (0.4\ \mathrm{GeV/cm^3}) \times (20\ \mathrm{kpc}) \approx 2 \times 10^{28}\ \mathrm{keV/cm^2}$$

- **Number comparable! Yet more MW we can see than Perseus clusters**

Status of the 3.5 keV line

- **Key observation:** Milky Way halo is bright even away from GC
- Average emission over the XMM-Newton FoV

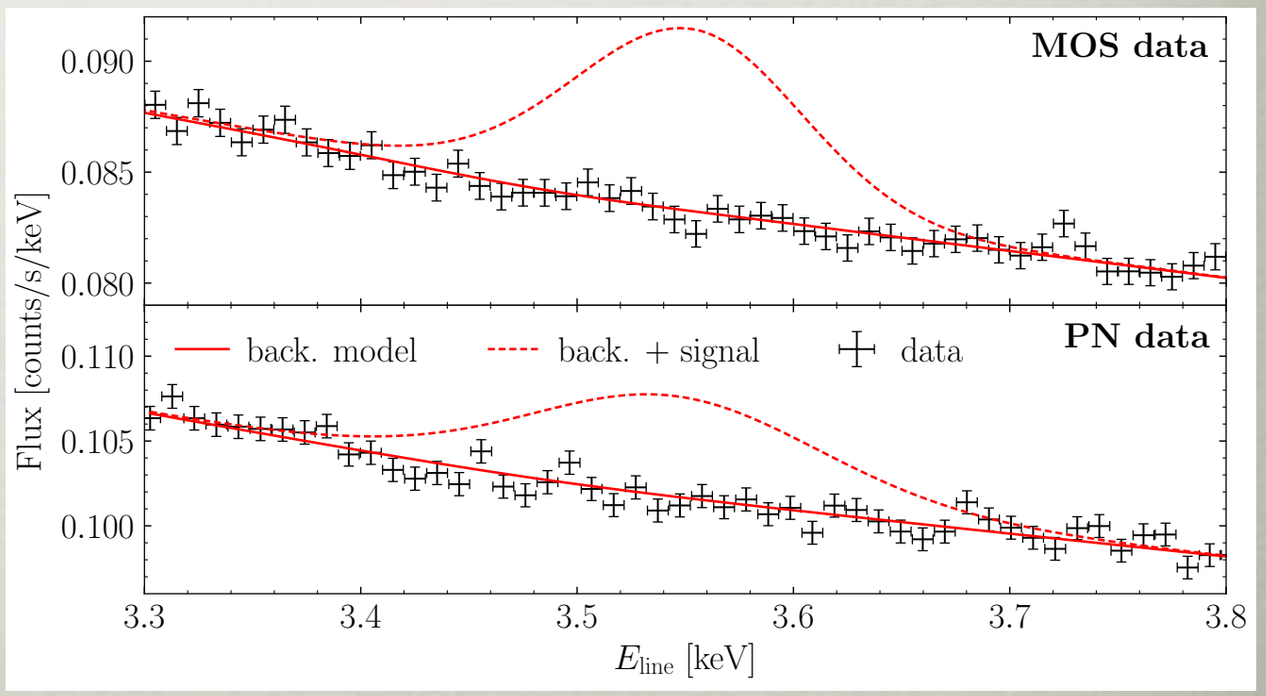
$$D_{\rm Pers} \sim 3 \times 10^{28}\ {\rm keV/cm^2}$$

$$D_{\rm MW}(\psi = 148^\circ) \sim 1 \times 10^{28}\ {\rm keV/cm^2}$$

$$D_{\rm MW}(\psi = 45^\circ) \sim 3 \times 10^{28}\ {\rm keV/cm^2}$$

$\psi_{\rm Pers} = 148^\circ$

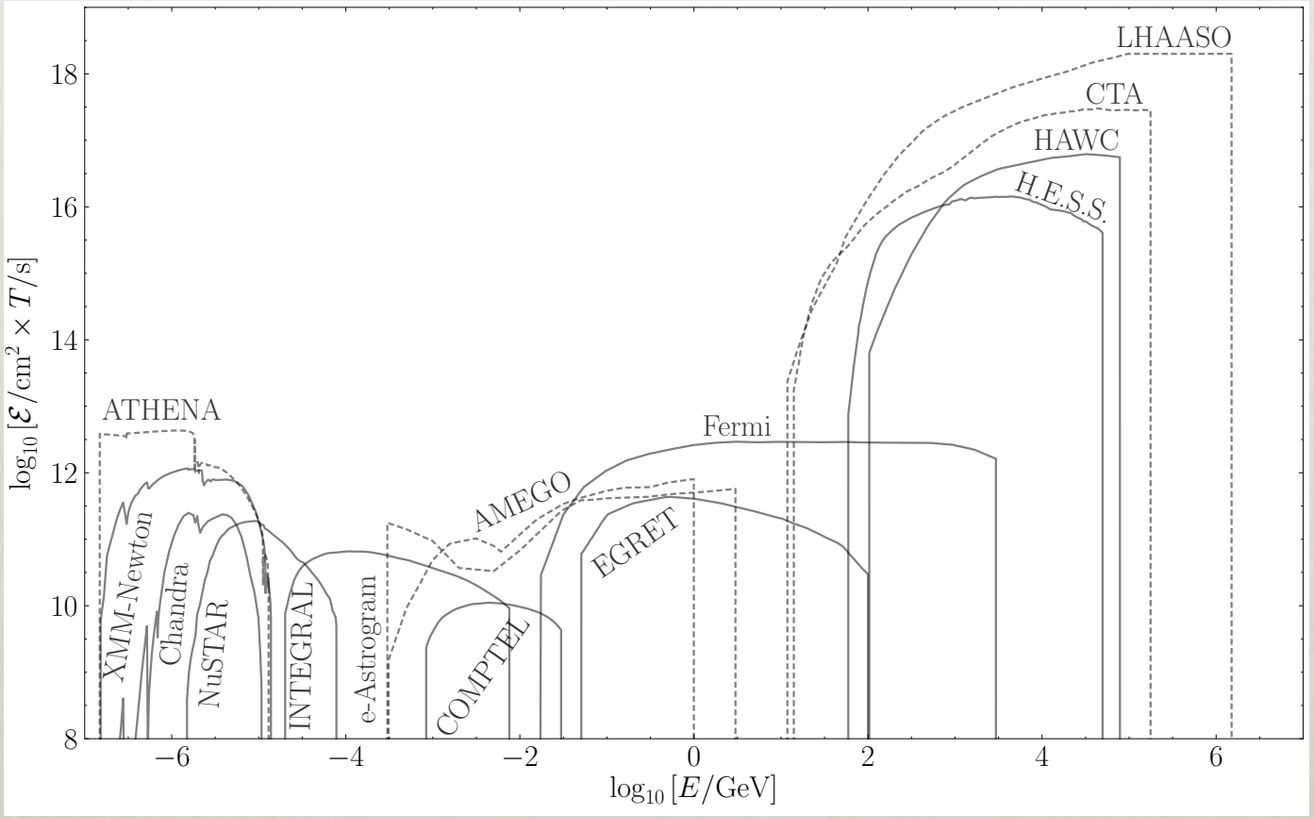
- The line is present in every observation XMM has ever made
- If the line was real, we would have detected it at over 100σ!



[Dessert, **NLR**, Safdi 1812.06976]

Conclusion

- Exciting new experiments coming online in 10-15 years
- Some of the best datasets are already on disk, need to extract all the information we can from them
- DM interpretation of 3.5 keV excess strongly disfavoured
- GeV excess not yet as clear cut!

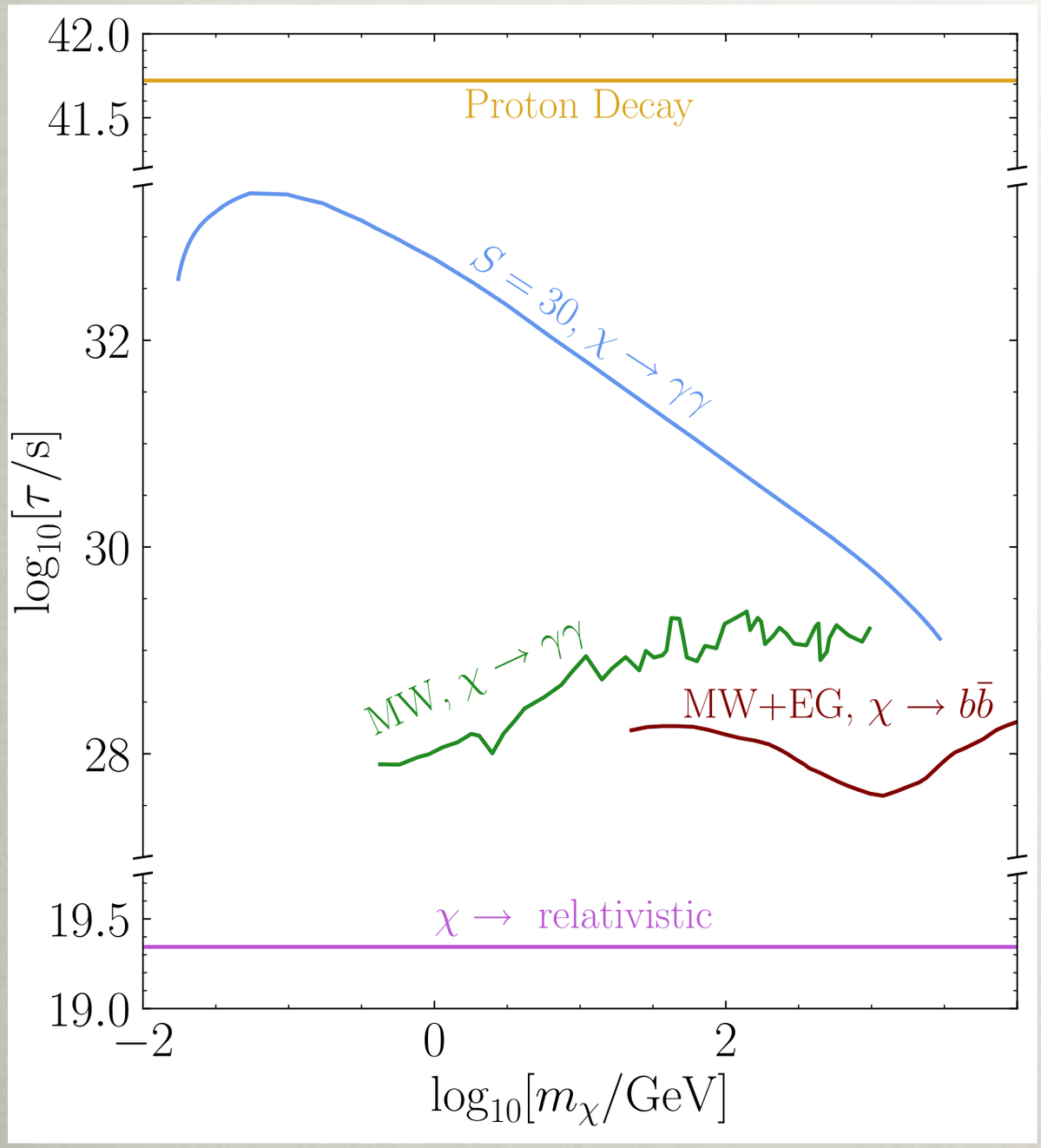


Backup Slides

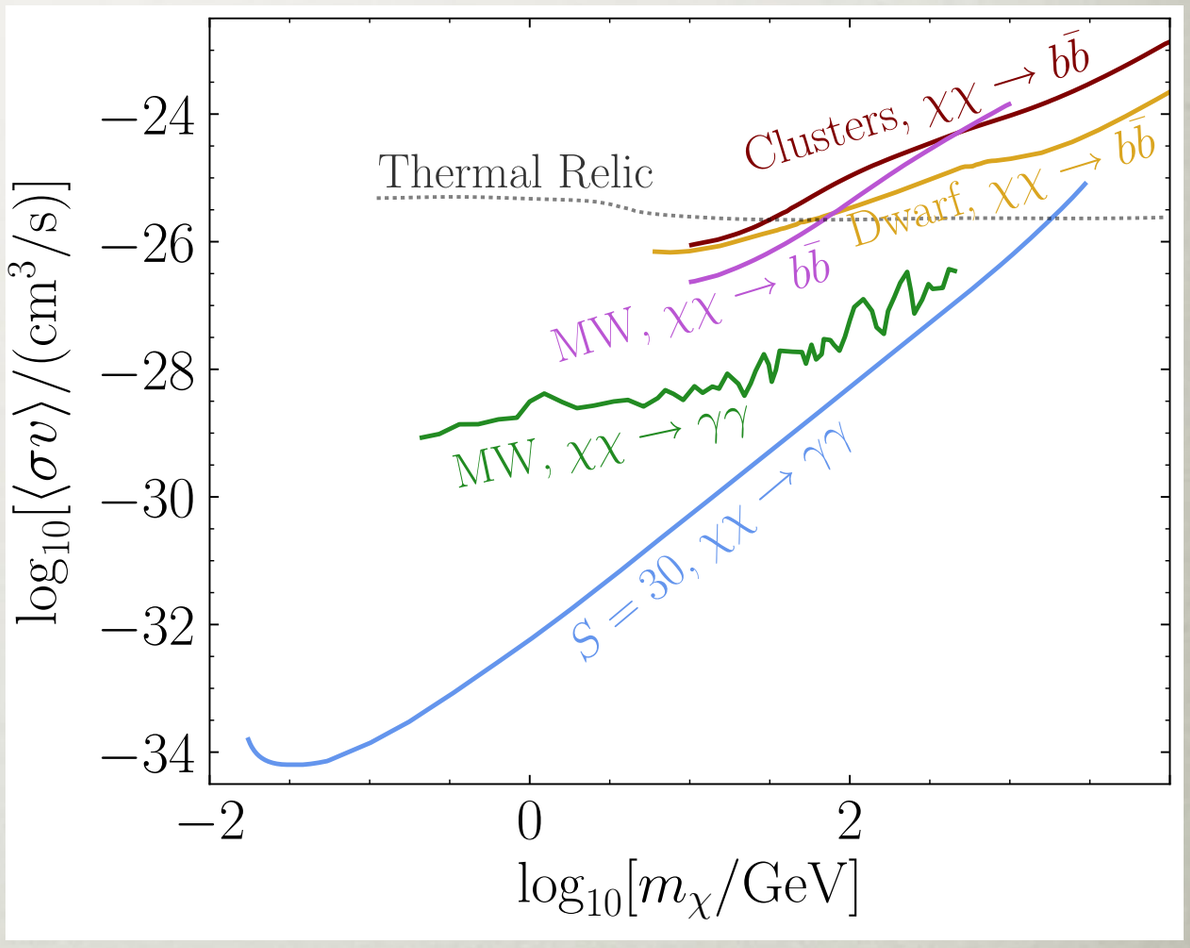
Landscape

(Aside) Fermi Limits

[Super-Kamiokande 1605.03235]



[Gong, Chen 0802.2296]



[Steigman, Dasgupta, Beacom 1204.3622]

Estimated Sensitivity

- What reach should we expect? In the large count limit

$$\mathrm{TS} = 2[\ln \mathcal{L}_S - \ln \mathcal{L}_B] \sim \sigma^2 \sim S^2/B = \Phi_S^2/\Phi_B \times t$$

- Bulbul+ detected line with $\mathrm{TS} \sim 16$ and $t_{\mathrm{Pers}} \sim 320$ ks
- Blank sky observations (BSO) much lower background than Perseus, by selection:

$$\Phi_B^{\mathrm{BSO}}/\Phi_B^{\mathrm{Pers}} \sim 0.02$$

- As the signal is at least as bright starting at 45º, we could reach the same significance using only

$$t_{\mathrm{BSO}} \approx t_{\mathrm{Pers}} \times (\Phi_B^{\mathrm{BSO}}/\Phi_B^{\mathrm{Pers}}) \approx 6 \text{ ks}$$

- With the full ~30 Ms dataset expect

$$\mathrm{TS}_{\mathrm{BSO}} \approx 16 \times (30 \text{ Ms}/6 \text{ ks}) \approx 75,000$$

- **This analysis could detect particle dark matter at over 100σ**

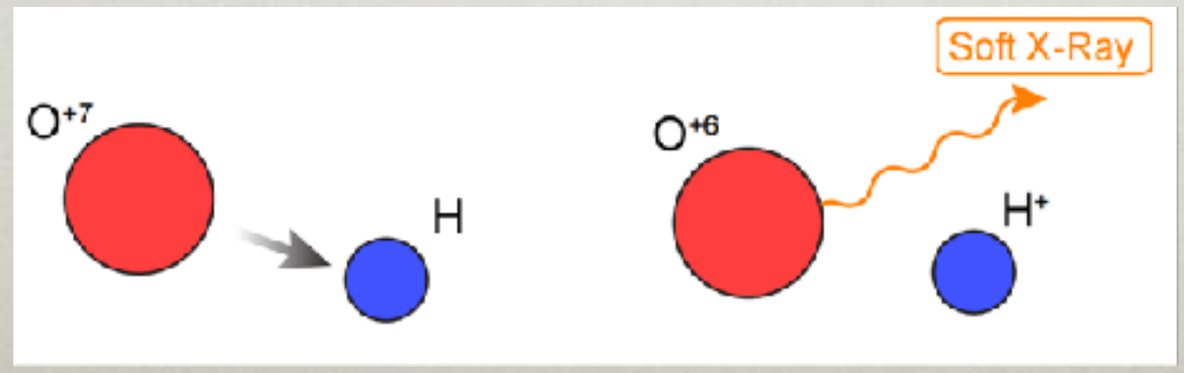
Original Claim

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[3], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2,4], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, USA
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[4] Department of Astronomy, University of Maryland, College Park, MD, USA

[1402.2301]

- Is the line consistent with dark matter?
  - ~scale with cluster mass (see [Lovell+ 1810.05168])
  - No known significant lines nearby, but cluster emission is complex - model 31 known emission lines
- A real line we missed?
  - K XVIII lines at 3.48 and 3.52 keV [Jeltema+Profumo 1408.1699]
  - S XVI charge exchange at 3.5 keV [Gu+ 1511.06557]

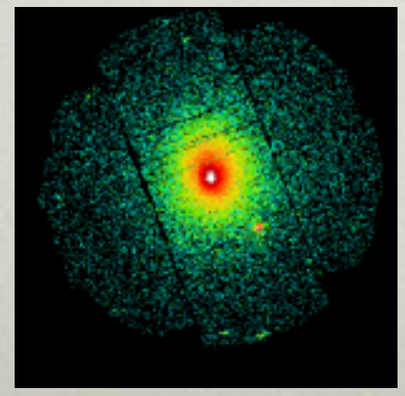


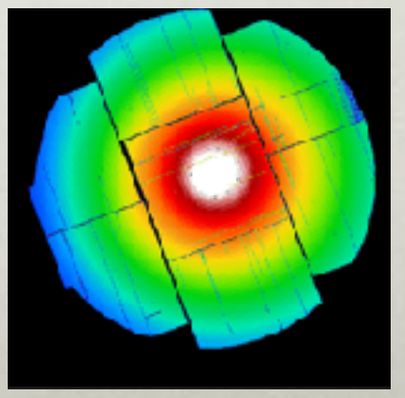
New Strategy

- Strategy motivates using all ~12,000 observations
  - Developed automating tools:

    github.com/nickrodd/XMM-DM
  - Processed all 6,350 obs with $\psi < 90^\circ$
- Apply cuts to restrict this to the best datasets
  - $5^\circ < \psi < 45^\circ$
  - $I_{2-10} < 5 \times I_{2-10}^{\rm CXRB}$
  - Lowest 68% of instrumental background
  - Remove $t_{\rm obs} < 1$ ks
- **1,397 exposures, 752 observations, 30.6 Ms**

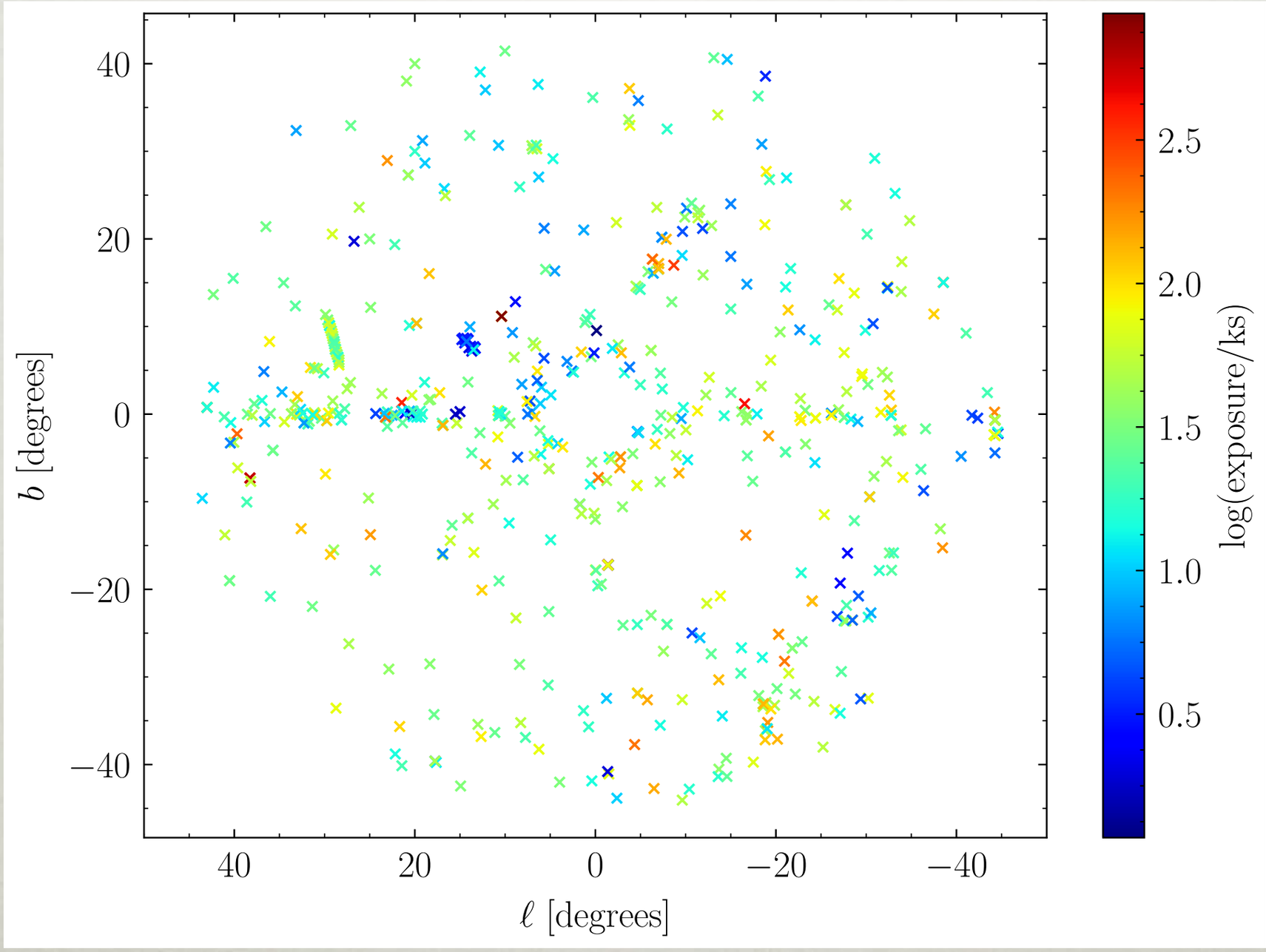
http://nxsa.esac.esa.int

Data: 

Exposure: 

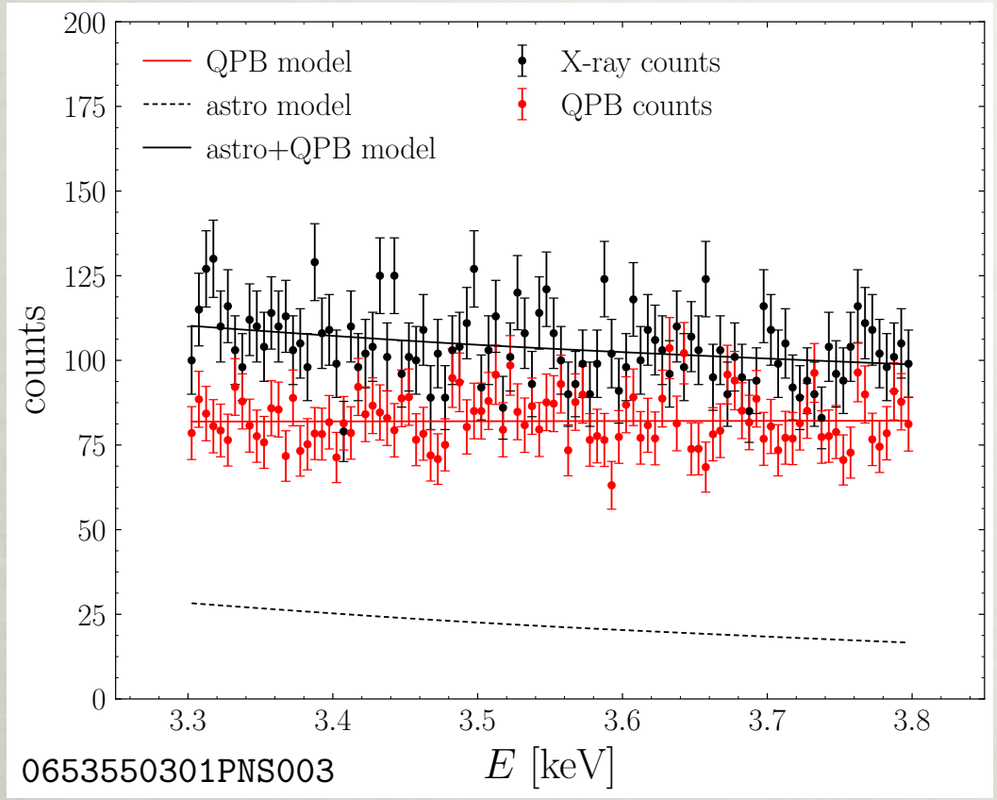
New Strategy

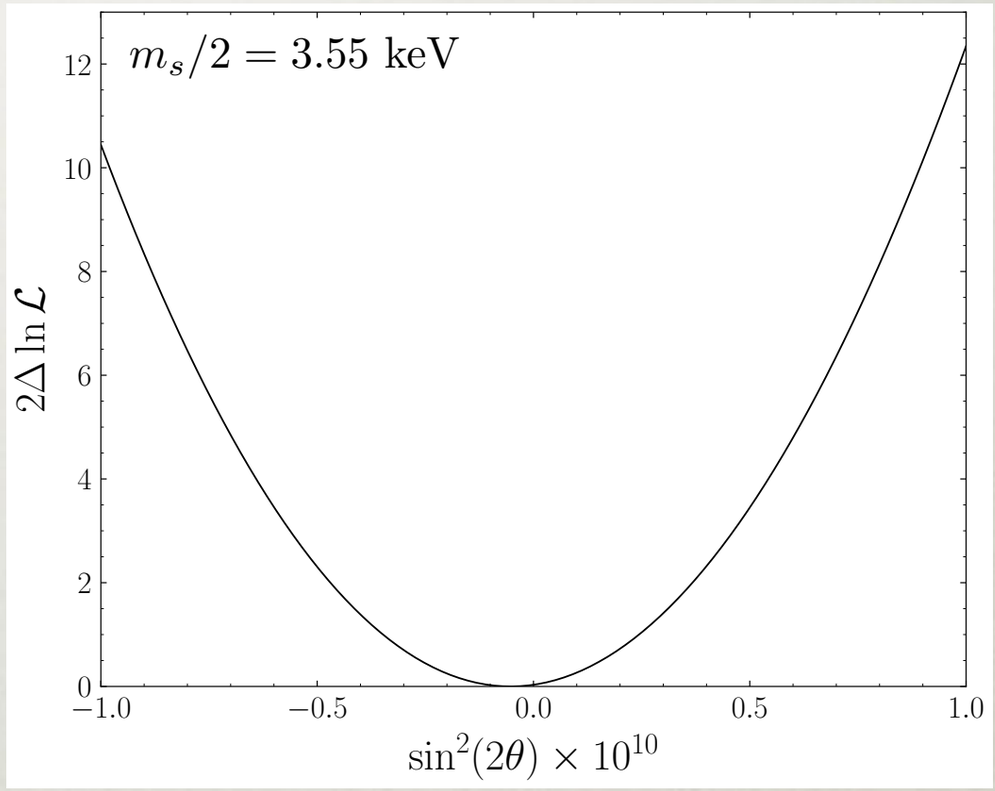
- Exposures well distributed over the region



Profile Likelihood Analysis

- Analyse each exposure using **profile likelihood**
  - Likelihoods are then joined, we do not stack the datasets
  - Use narrow energy window: $m_s/2 \pm 0.25$ keV ($\Delta E_{\rm XMM} \approx 0.1$ keV)
  - Model: astrophysical power-law, instrumental power-law, DM

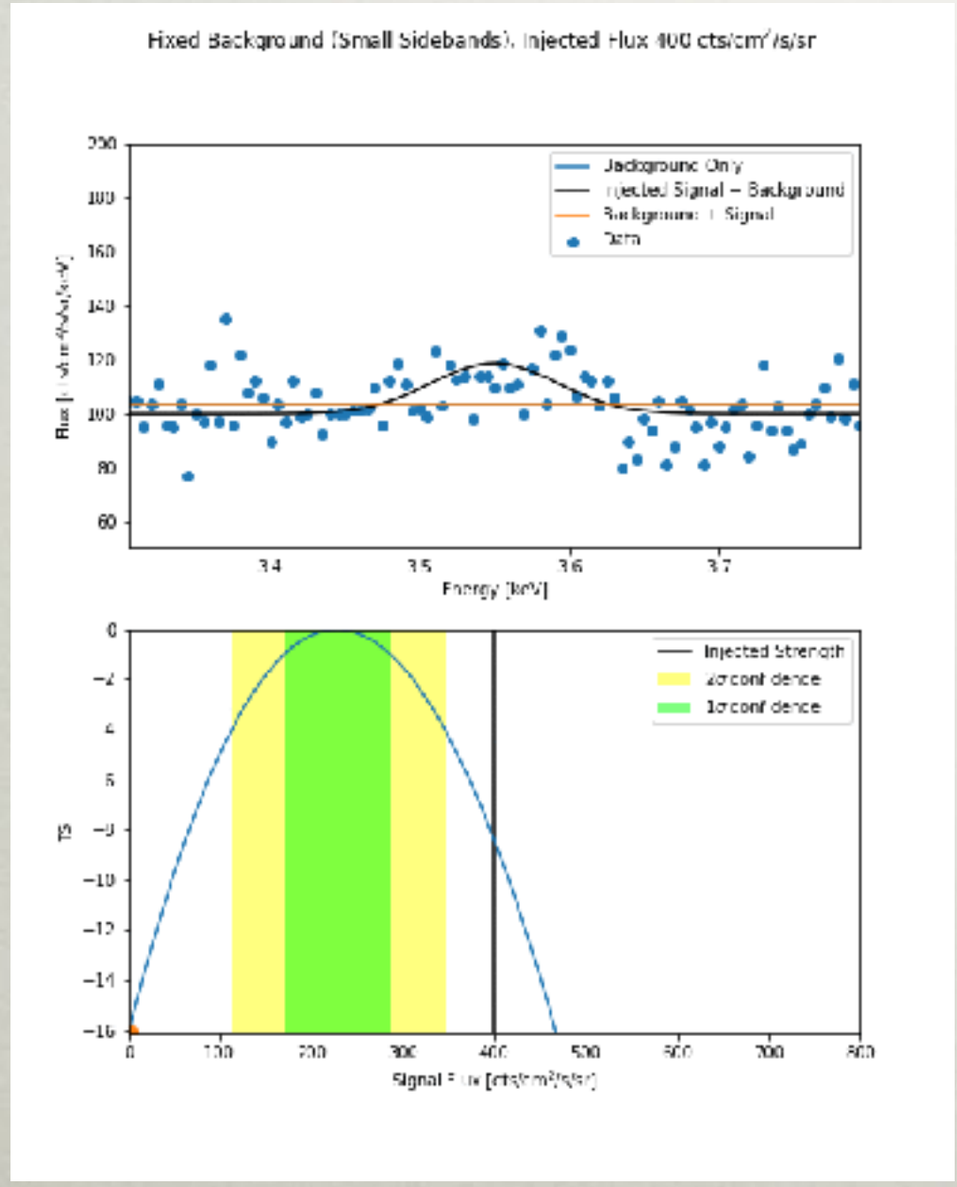


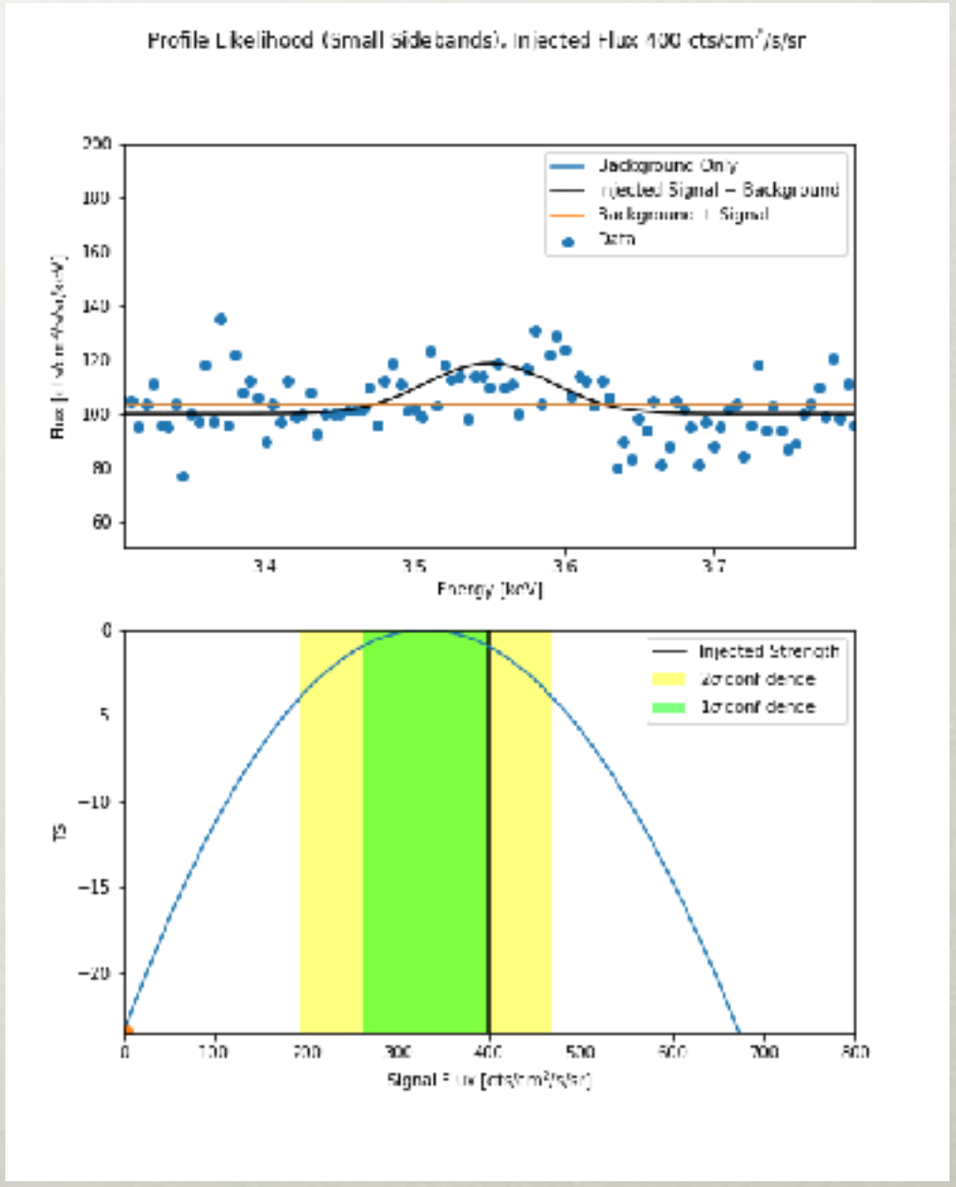


- In detail use Poisson likelihood for counts + Gaussian likelihood for QPB estimates. Instrument response folded into the model prediction

Profile Likelihood Analysis

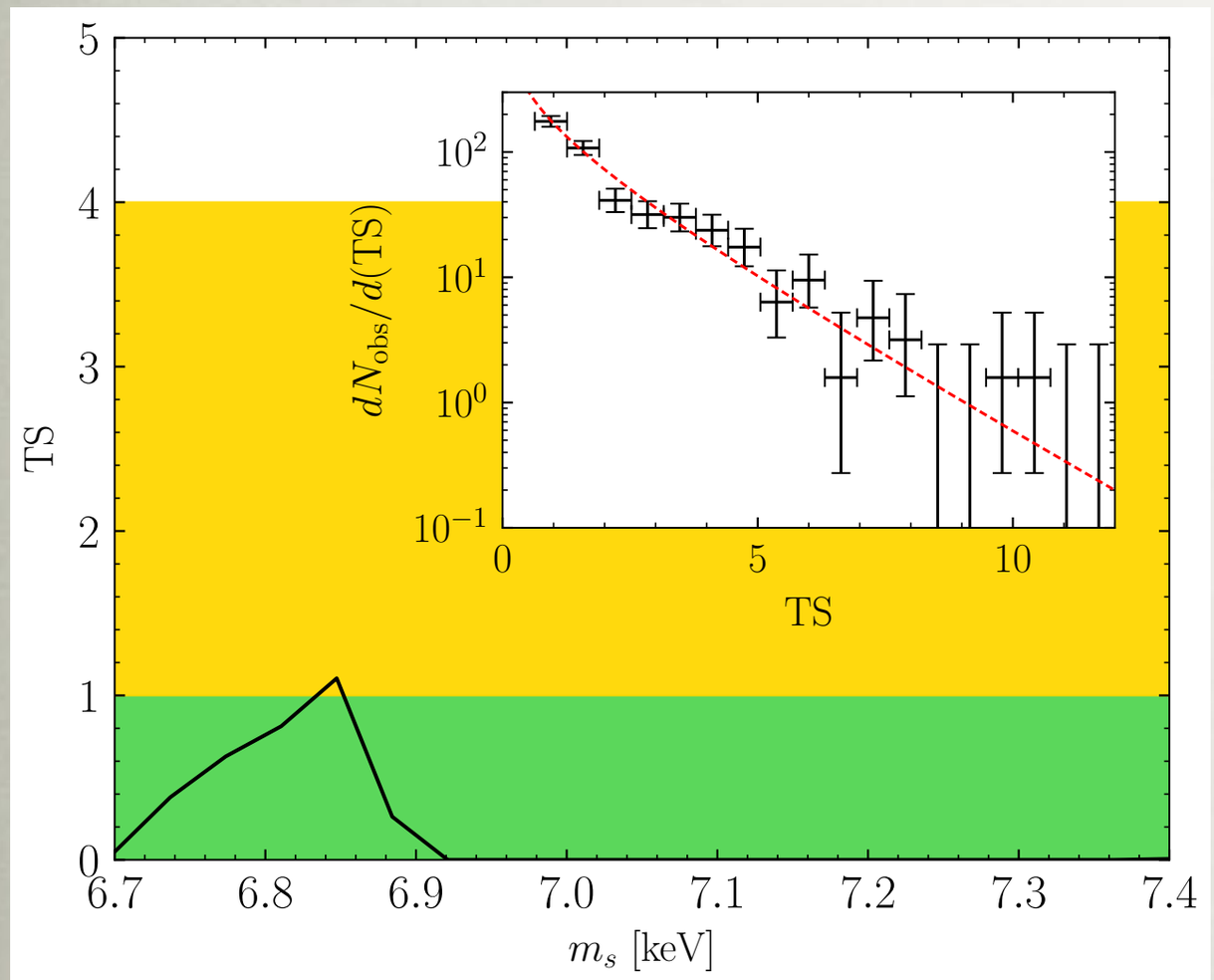
- Nuisance parameters removed using the profile likelihood
- ***The background is refit for every value of the signal***

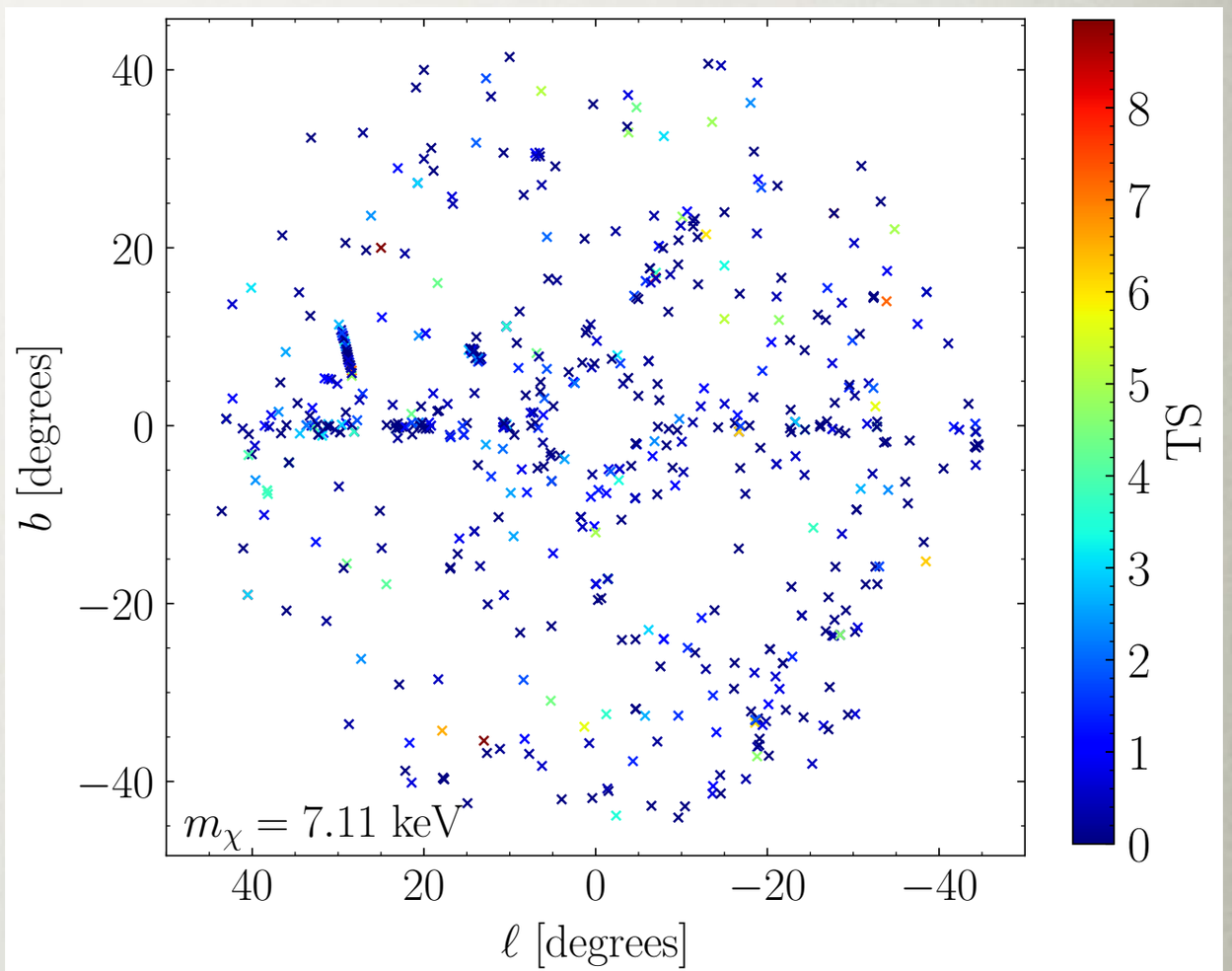




Results

- Calculate the TS for the DM line from the joint profiled likelihood





- **No evidence for a DM decay line**
- Left inset shows the distribution of individual exposures versus a χ^2 distribution under the null, provides a good fit to the data

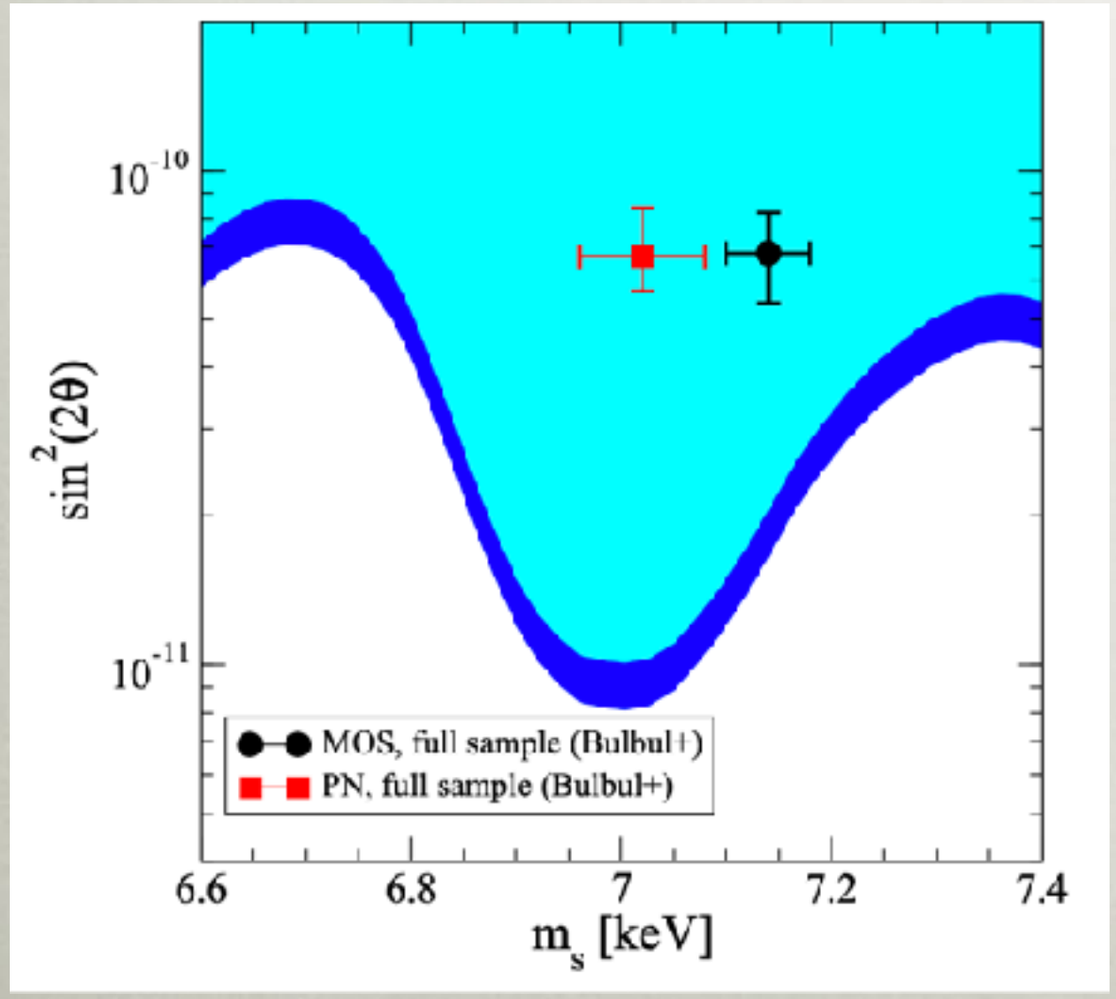
Towards a Definitive Statement

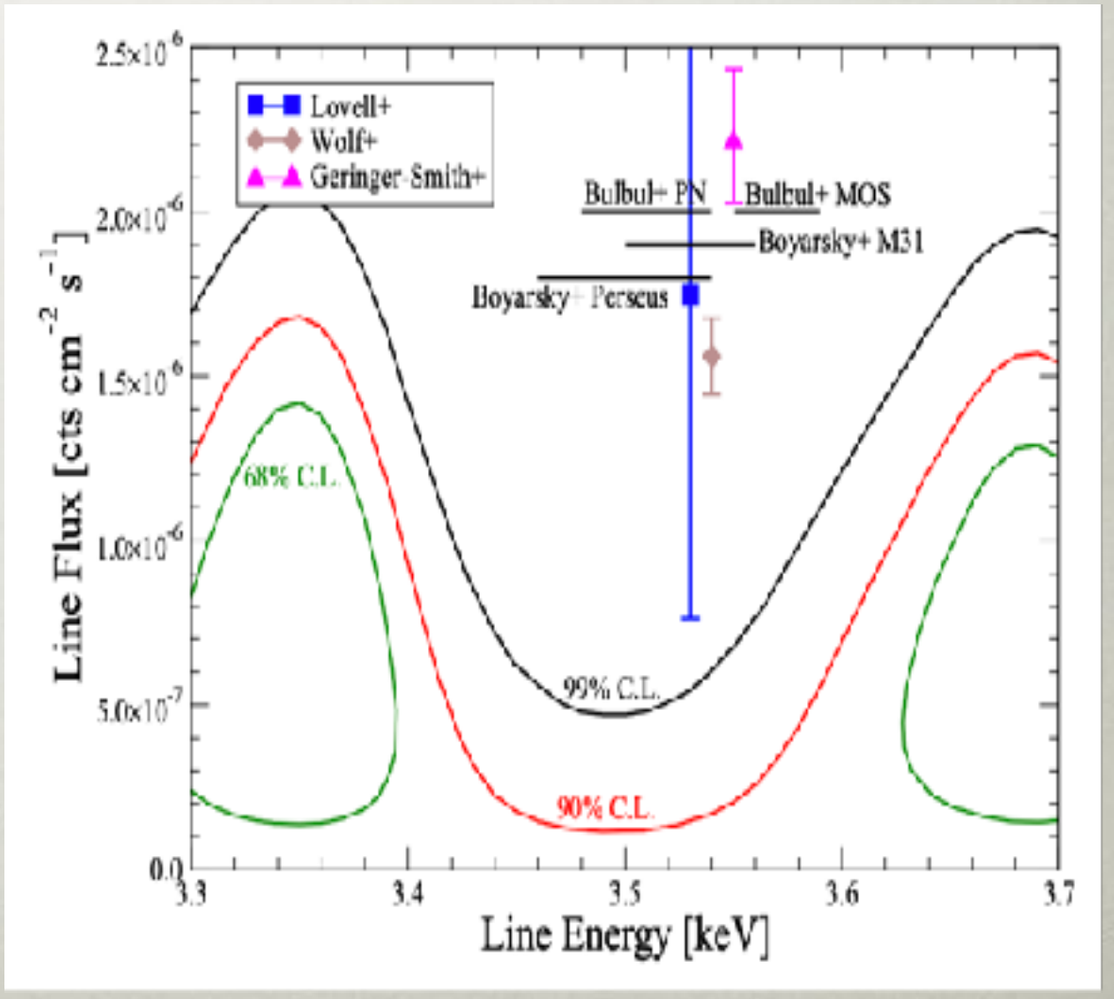
2. Deep observation of dark matter bright object

Deep XMM Observations of Draco rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line

[1512.01239]

Tesla Jeltema[1]* and Stefano Profumo[1]†
[1]*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*





Towards a Definitive Statement

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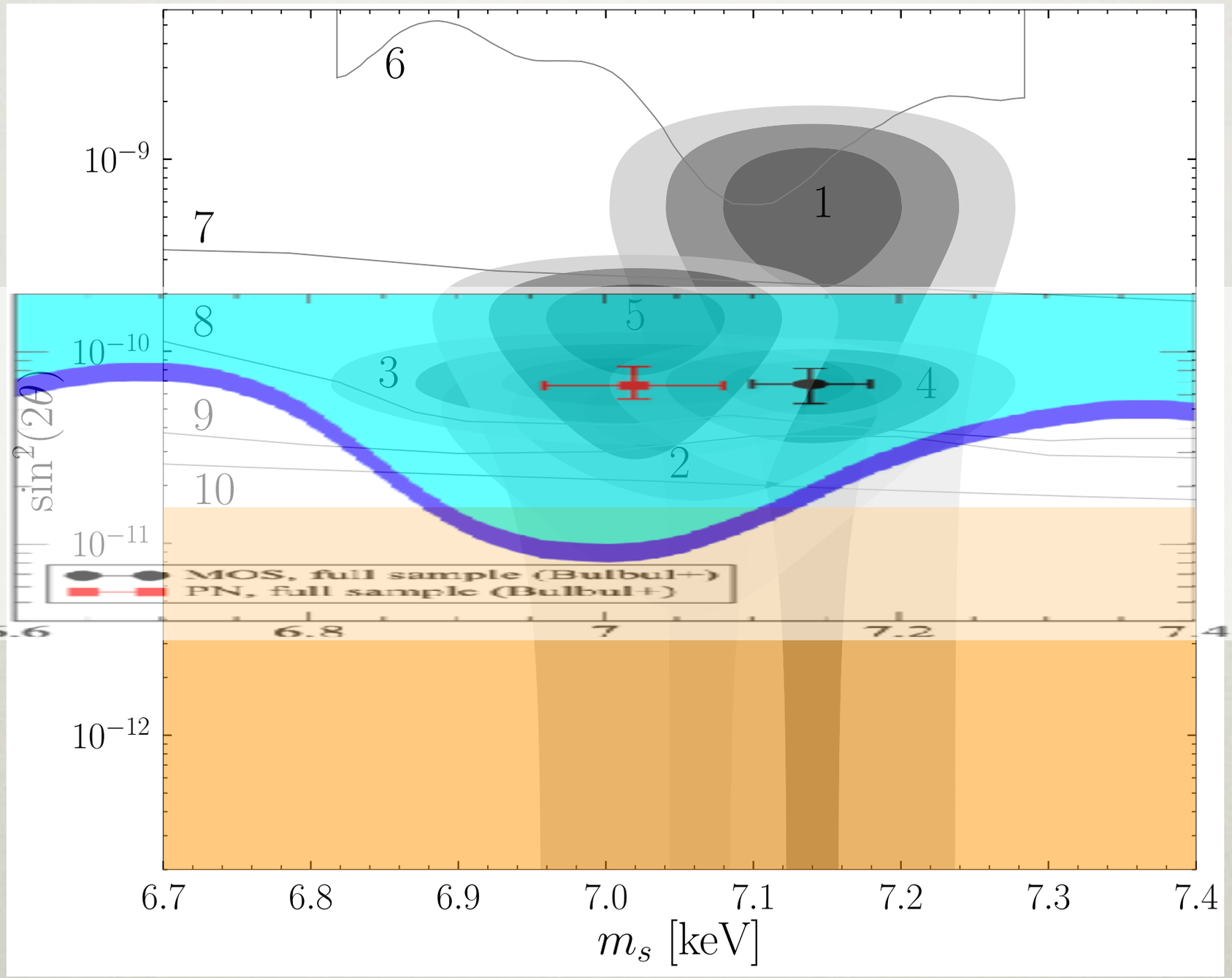


[1512.01239]

Towards a Definitive Statement

2. Deep observation of dark matter bright object

Searching for decaying dark matter in deep *XMM-Newton* observation of the Draco dwarf spheroidal

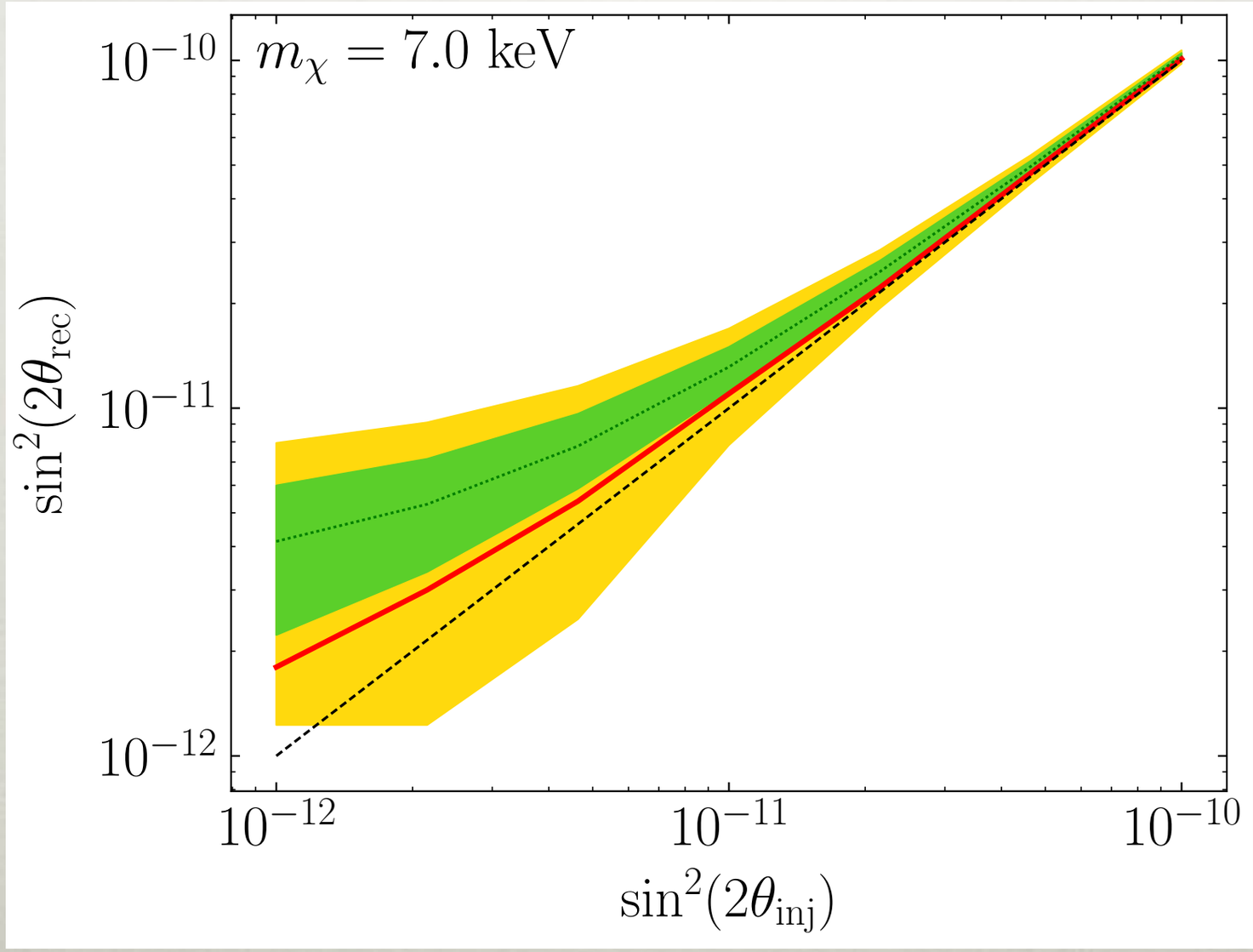
[1512.07217]

Oleg Ruchayskiy,[1,2*] Alexey Boyarsky,[3] Dmytro Iakubovskyi,[2,4] Esra Bulbul,[5] Dominique Eckert,[6] Jeroen Franse,[3,7] Denys Malyshev,[6] Maxim Markevitch,[8] Andrii Neronov[6]

X-ray bright objects, such as galaxies and galaxy clusters. We do not detect a statistically significant emission line from Draco; this constrains the lifetime of a decaying dark matter particle to $\tau > (7-9) \times 10^{27}$ s at 95% CL (combining all three *XMM-Newton* cameras; the interval corresponds to the uncertainty of the dark matter column density in the direction of Draco). The PN camera, which has the highest sensitivity of the three, does show a positive spectral residual (above the carefully modeled continuum) at $E = 3.54 \pm 0.06$ keV with a 2.3σ significance. The two MOS cameras show less-significant or no positive deviations, consistently within 1σ with PN. Our Draco limit on τ is consistent with previous detections in the stacked galaxy clusters, M31 and the Galactic Center within their $1-2\sigma$ uncertainties, but is inconsistent with the high signal from the core of the Perseus cluster (which has itself been inconsistent with the rest of the detections). We conclude that this Draco observation does not exclude the dark matter interpretation of the 3.5 keV line in those objects.

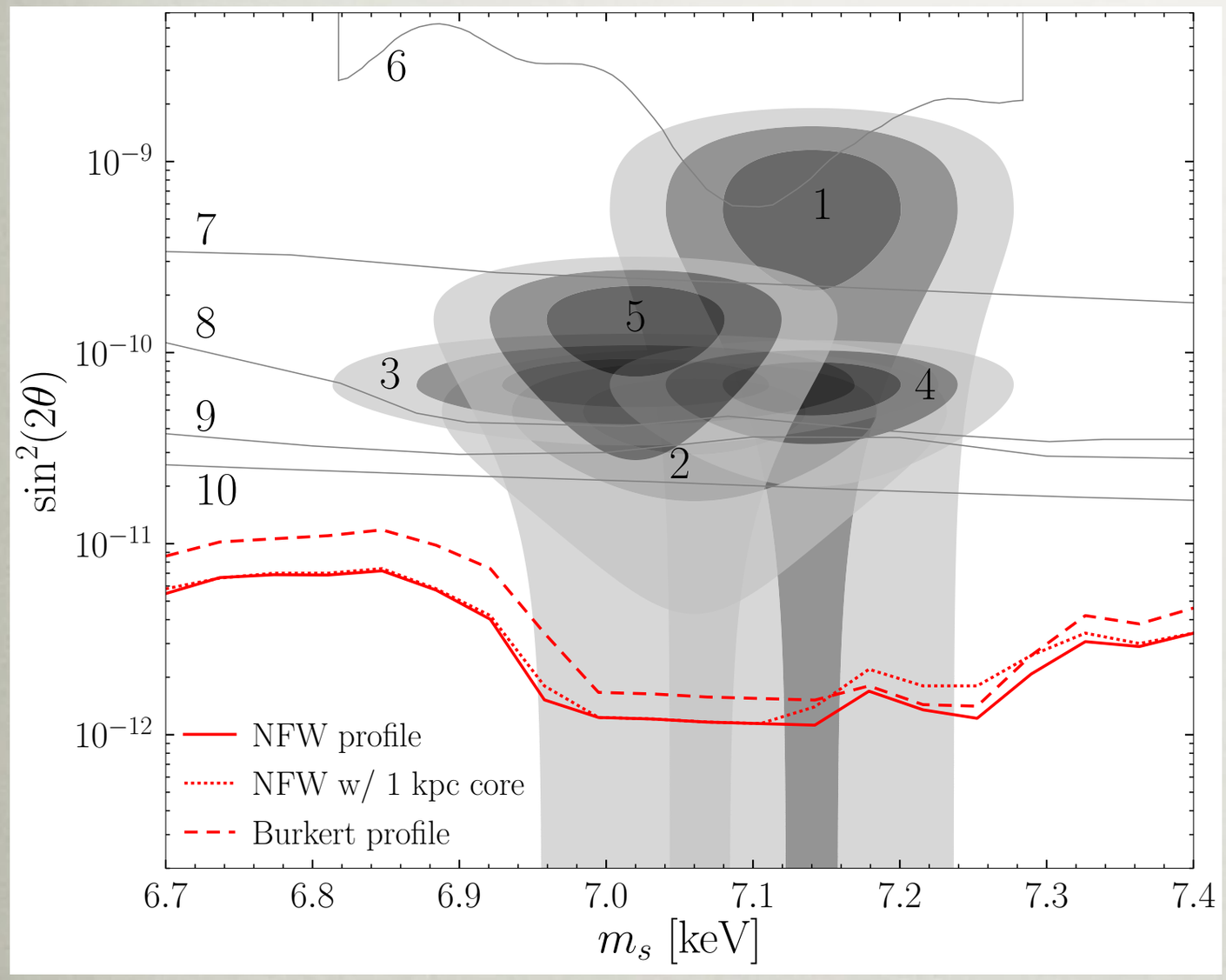
SYSTEMATIC CROSS CHECKS

- The result is controversial, so we have cross checked extensively
- If there was a real signal in the data, would we have excluded it?
- Check by injecting a real signal into the data



SYSTEMATIC CROSS CHECKS

- How dependent are these results on the assumed halo profile?



$$\rho_{\rm local} = 0.4\ {\rm GeV/cm^3}$$

$$r_\odot = 8.127\ {\rm kpc}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{r/r_s\ (1+r/r_s)^2}$$

$$r_s = 20\ {\rm kpc}$$

$$\rho_{\rm Burk}(r) = \frac{\rho_0}{(1+r/r_c)(1+(r/r_c)^2)}$$

$$r_c = 9\ {\rm kpc}$$

SYSTEMATIC CROSS CHECKS

- Is the result strongly dependent upon our cuts?