

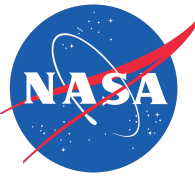


Probing sub-GeV and MeV Dark Matter

With Future Gamma-ray Instruments

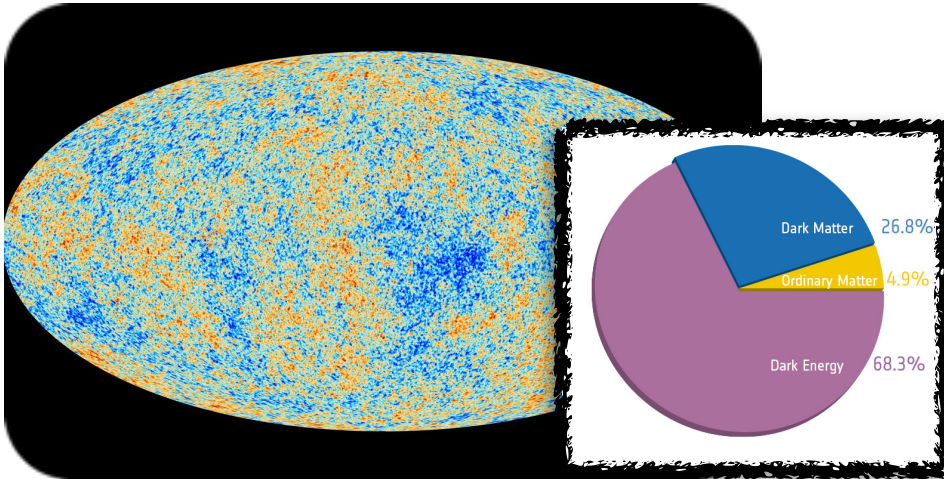
R. Caputo
UMD/NASA/GSFC

VHEPU 2018

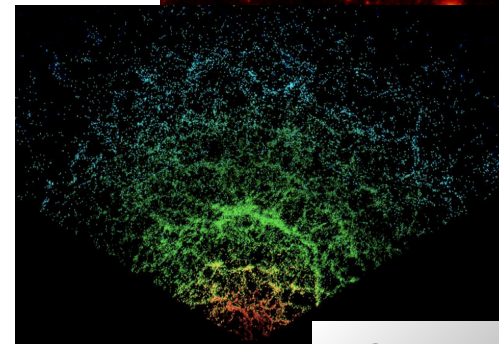
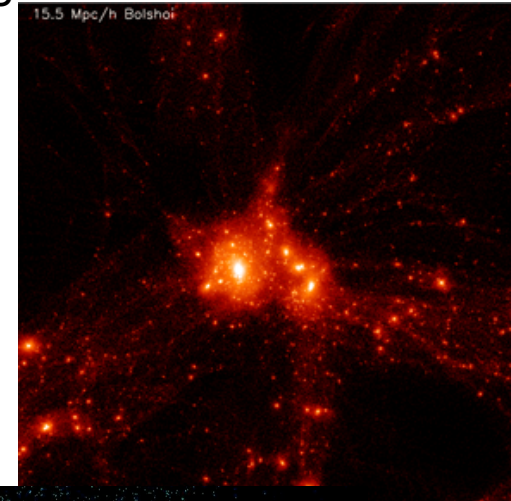


What Do We Know about Dark Matter?

Cosmic Microwave Background



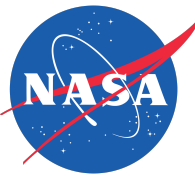
Large Scale Structure



Sloan DSS



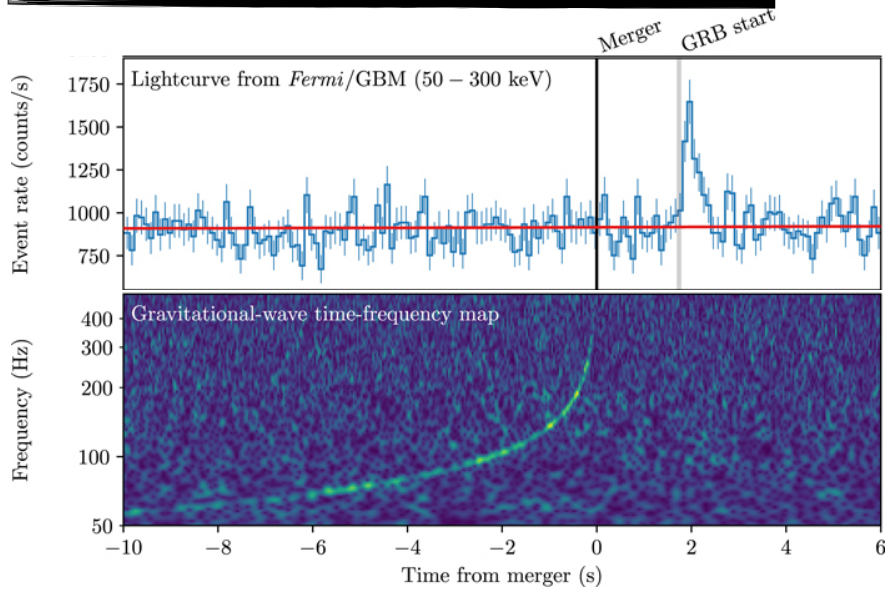
Lensing/The Bullet Cluster



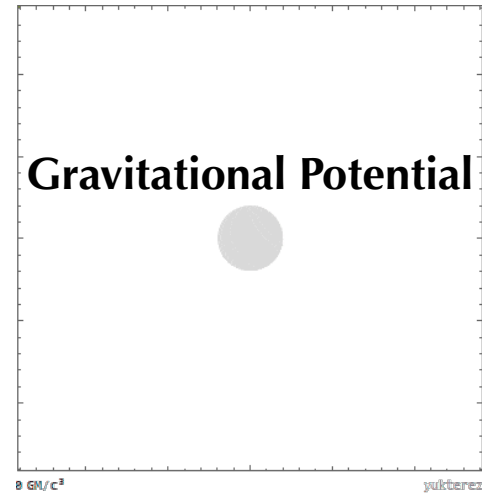
Modified Gravity

GW170817/GRB170817A

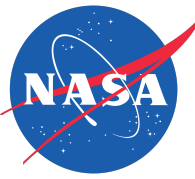
Test of Weak Equivalence principle



ApJ, 848:L13, 2017



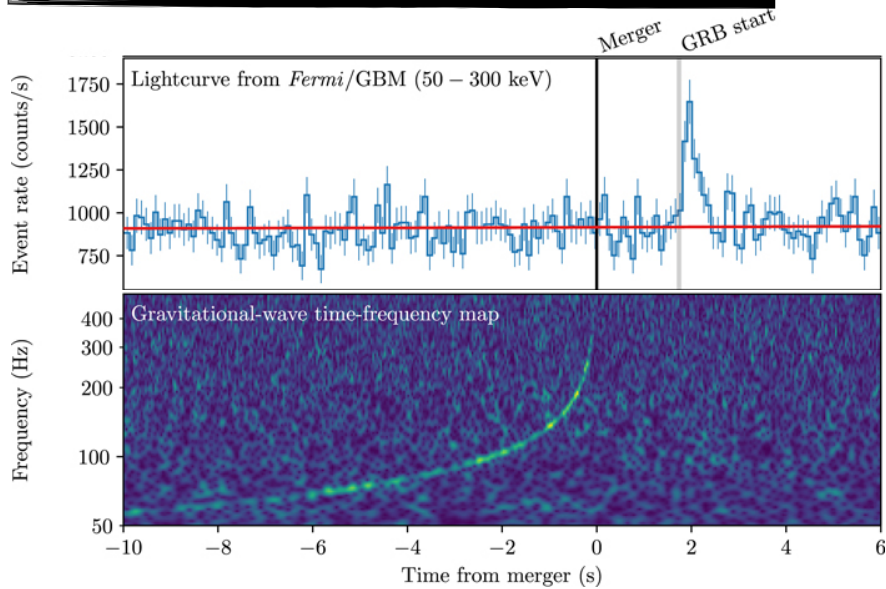
Boran et al., PRD 97, 041501 (2018),



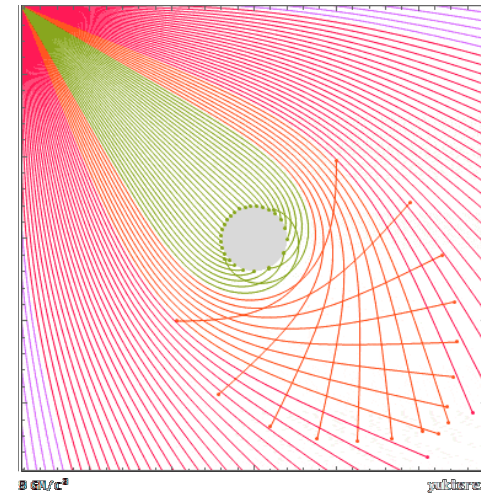
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Test of Weak Equivalence principle

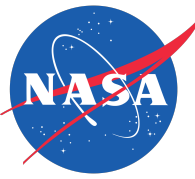


ApJ, 848:L13, 2017



Gravitational Potential

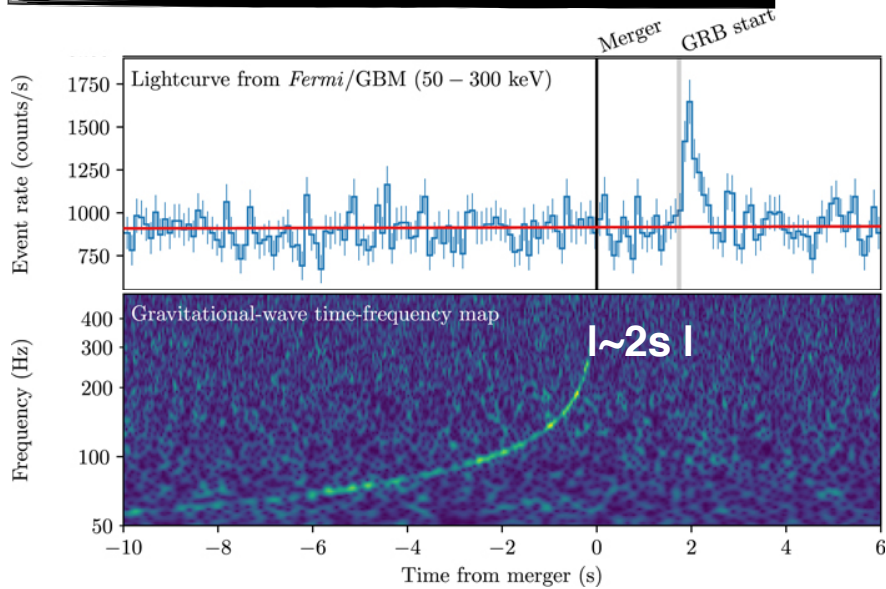
Borah et al., *PRD* 97, 041501 (2018),



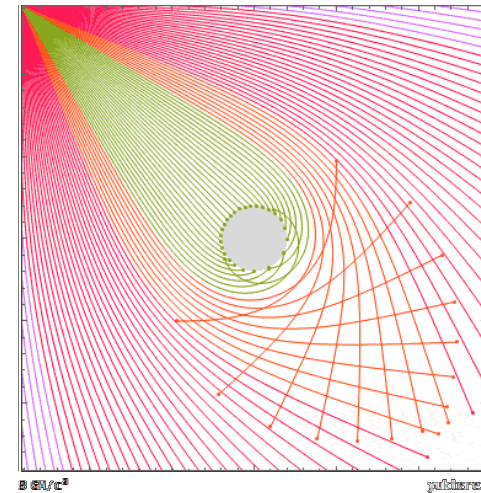
Modified Gravity

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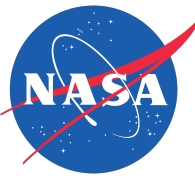
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Gravitational Potential

Borah et al., PRD 97, 041501 (2018),

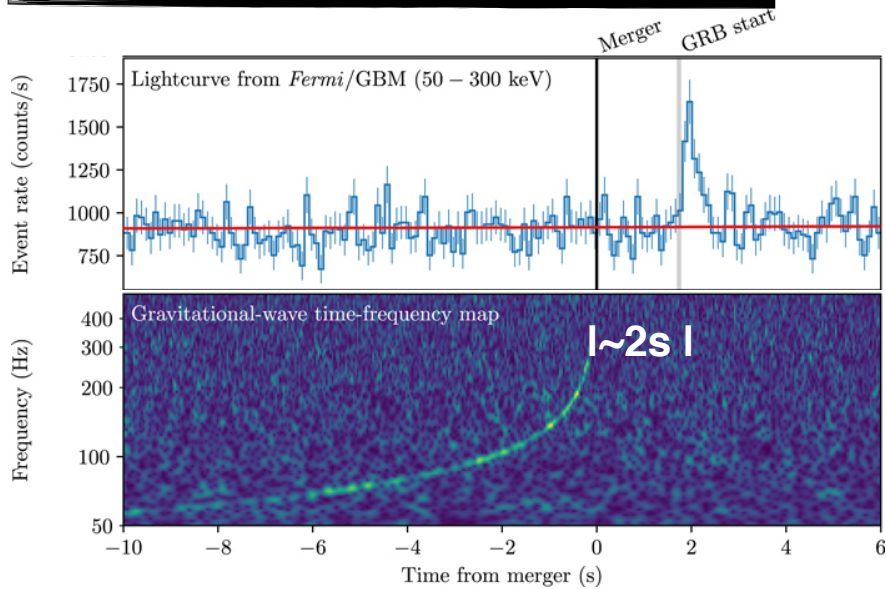
Gravitons and photons travel in space-time in the same way



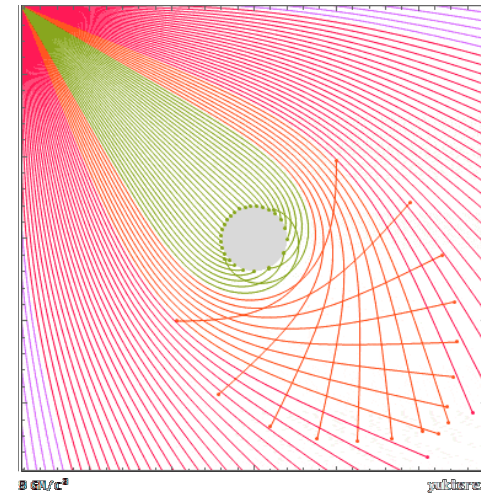
Modified Gravity

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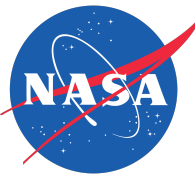


Gravitational Potential

Borah et al., PRD 97, 041501 (2018),

Gravitons and photons travel in space-time in the same way

*SN1987a found the same thing for neutrinos and photons



Dark Matter Model Predictions

Weakly Interacting Massive Particles*

Lower bounds:

~10 GeV if mediated by Weak force
(Lee-Weinberg bound)

~few MeV limited # neutrinos -
thermal relic (Ho & Scherrer)

Upper bounds:

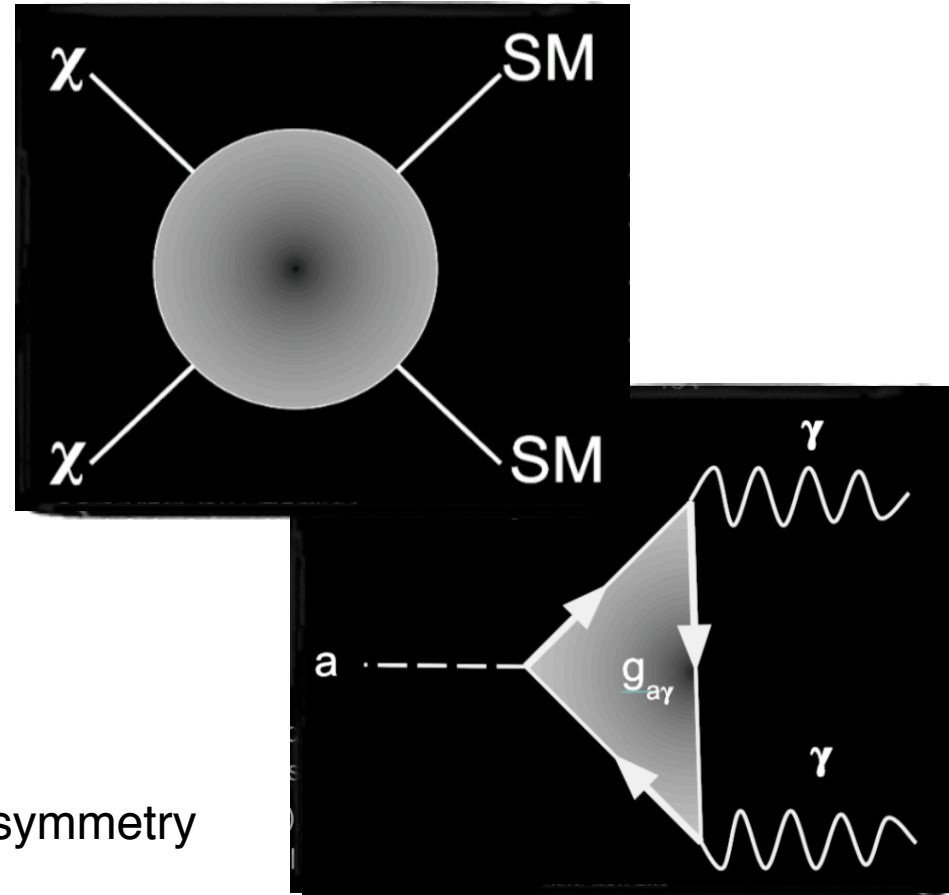
~120 TeV (Unitarity bound)

QCD Axions

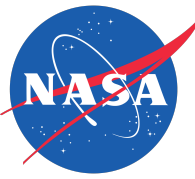
Bounds:

~ 10^{-5} - 10^{-3} eV

Axion-like particles (WISPs) - any U(1) symmetry
breaking



*See talks by A. Albert and E. Moulin in next session



Dark Matter Annihilation

How low (in mass) can you go?

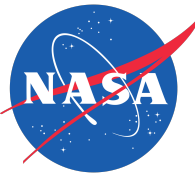
$\chi\chi \rightarrow \gamma\gamma$: Accessible at all energies

$\chi\chi \rightarrow \gamma\pi^0$: Accessible if $\sqrt{\text{COM}}$ interaction $> m_{\pi^0}$

$\chi\chi \rightarrow \pi^0\pi^0$: Accessible if $\sqrt{\text{COM}}$ interaction $> 2m_{\pi^0}$

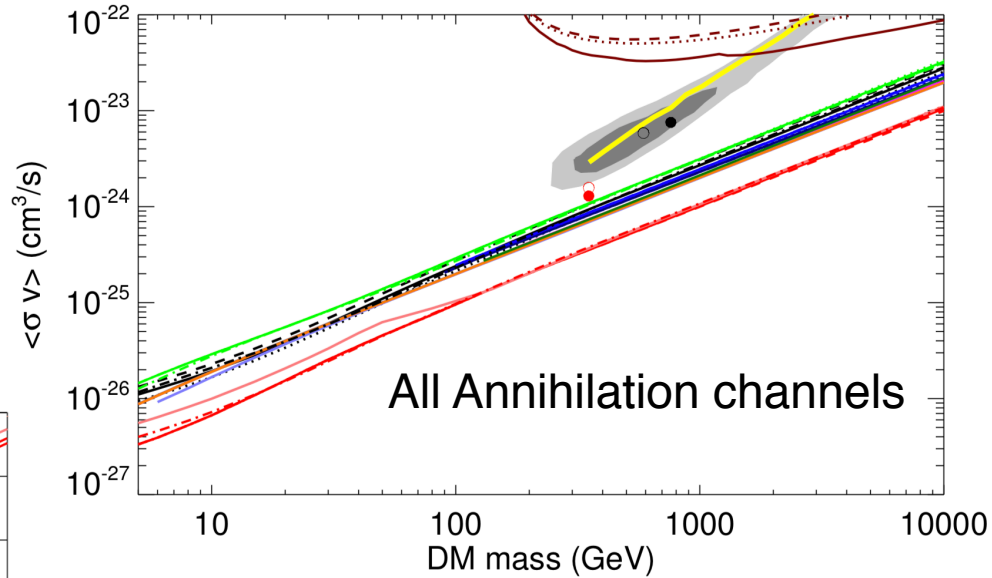
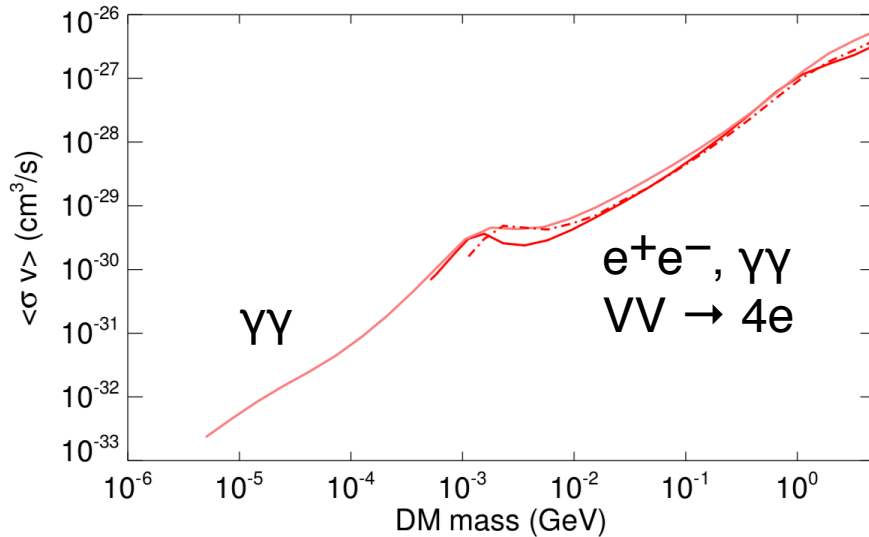
$\chi\chi \rightarrow \bar{\ell}\ell$: Accessible if $\sqrt{\text{COM}}$ interaction $> m_{\ell}$

$\chi\chi \rightarrow \phi\phi$ and $\phi \rightarrow e^+e^-$: Additional mediators,
cascade annihilation



Dark Matter Annihilation Limits from CMB

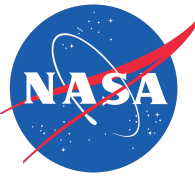
Light Dark Matter Annihilation more constrained than heavier Dark Matter



Weak-Scale cross sections constrained

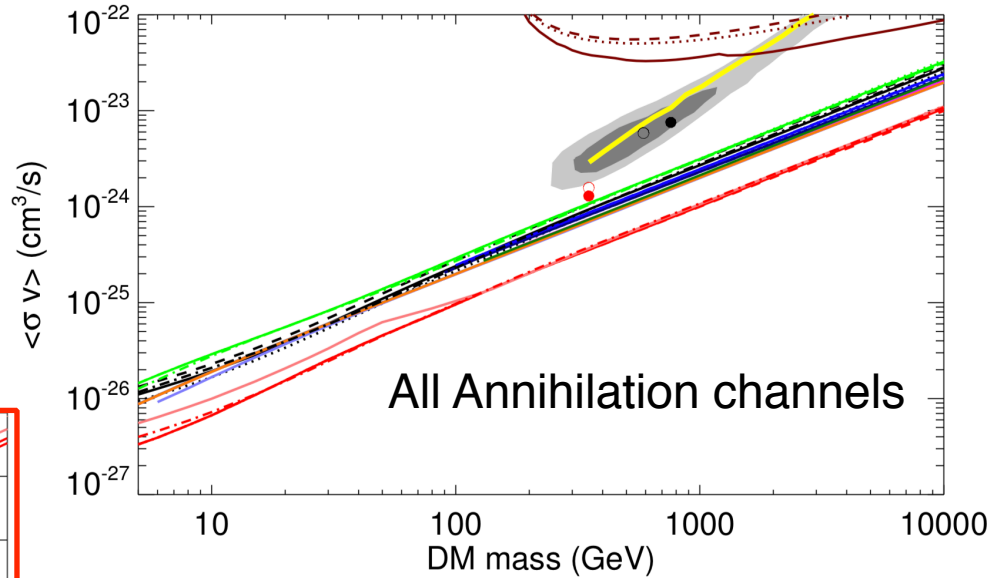
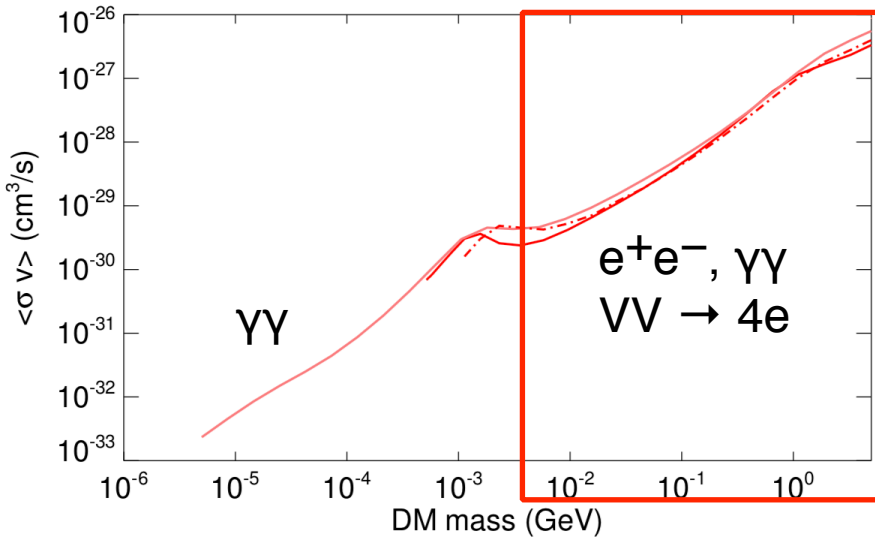
s-wave constraints can be avoided if p-wave (velocity dependent) annihilation

Slatyer 2016



Dark Matter Annihilation Limits from CMB

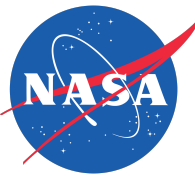
Light Dark Matter Annihilation more constrained than heavier Dark Matter



Weak-Scale cross sections constrained

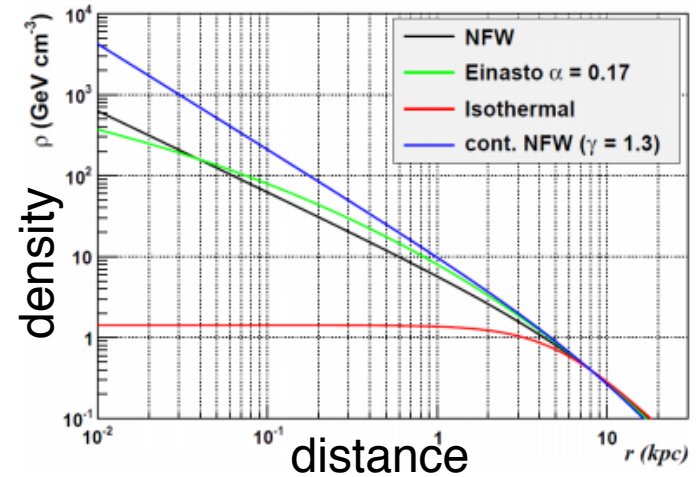
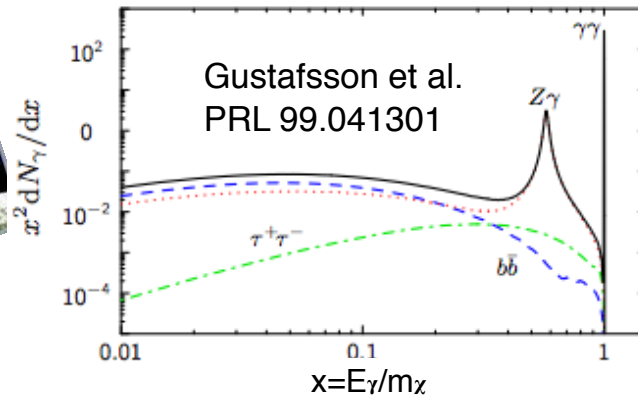
s-wave constraints can be avoided if p-wave (velocity dependent) annihilation

Slatyer 2016



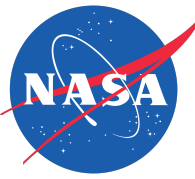
Indirect Searches: γ -rays

Observed = Particle Properties \times Astrophysics Properties



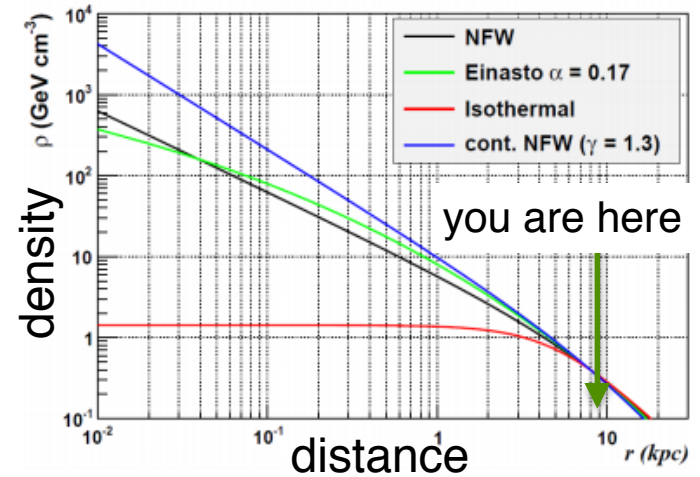
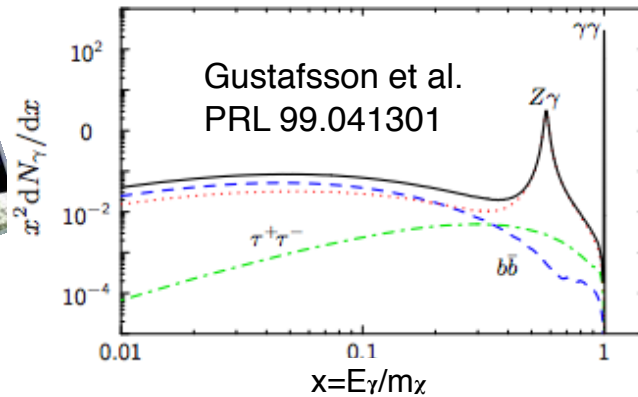
$$\Phi_{\gamma}(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{\chi} v \rangle}{2m_{\chi}^2} N_{\gamma}(E) \times J(\psi)$$

cross section \rightarrow $\langle \sigma_{\chi} v \rangle$
 mass \rightarrow $2m_{\chi}^2$
 photons \rightarrow $N_{\gamma}(E)$
 J-Factor: $\sim \int \rho^2$
 (solid angle, line of sight) \rightarrow $J(\psi)$



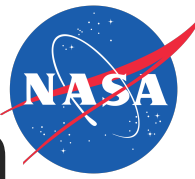
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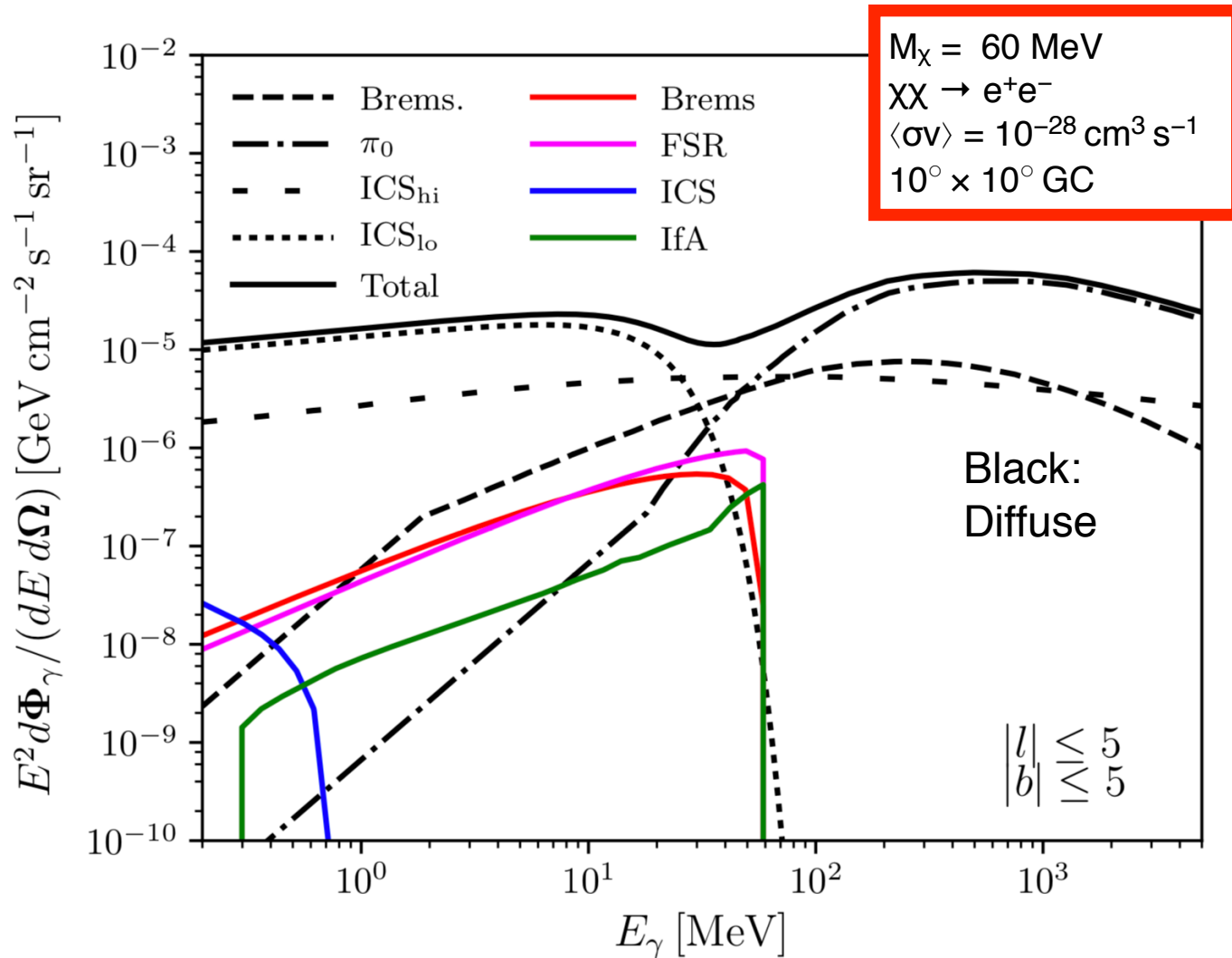


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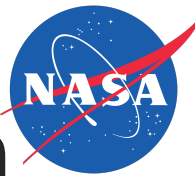
cross section $\rightarrow \langle \sigma_{\chi} v \rangle$
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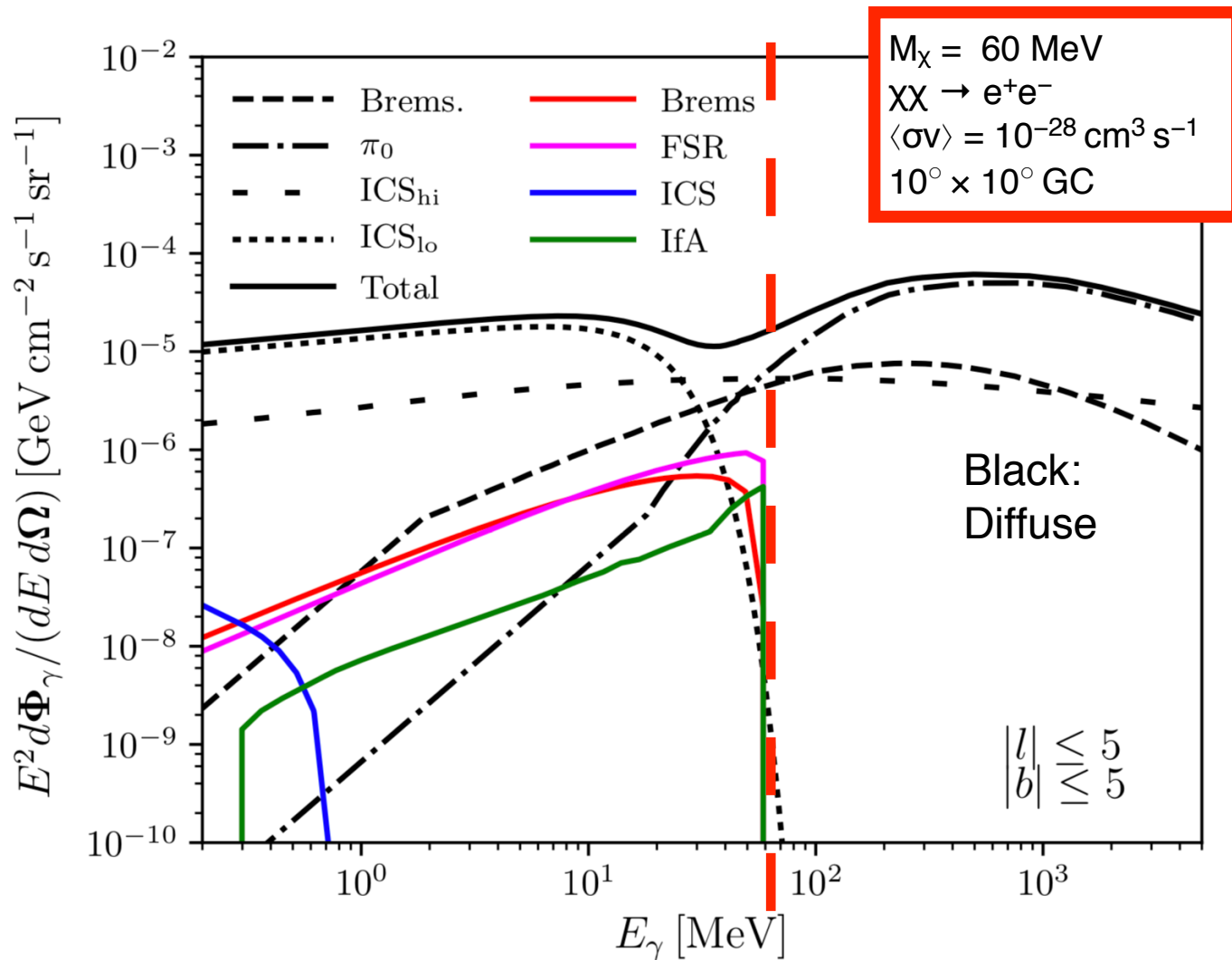
MeV Dark Matter Annihilation



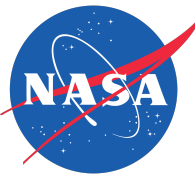
Bartels et al., 2017



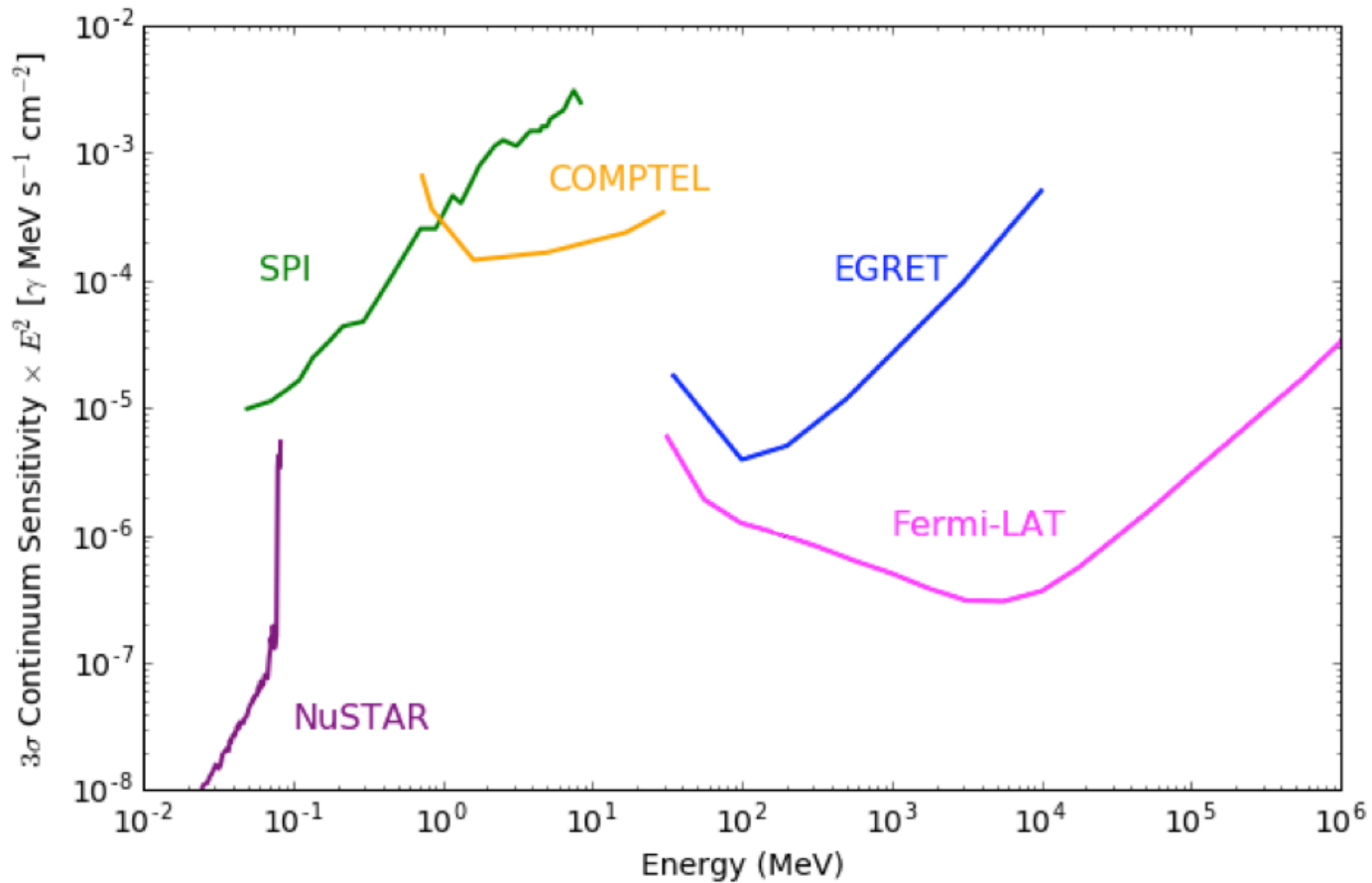
MeV Dark Matter Annihilation



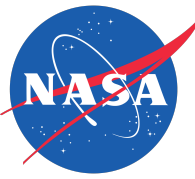
Bartels et al., 2017



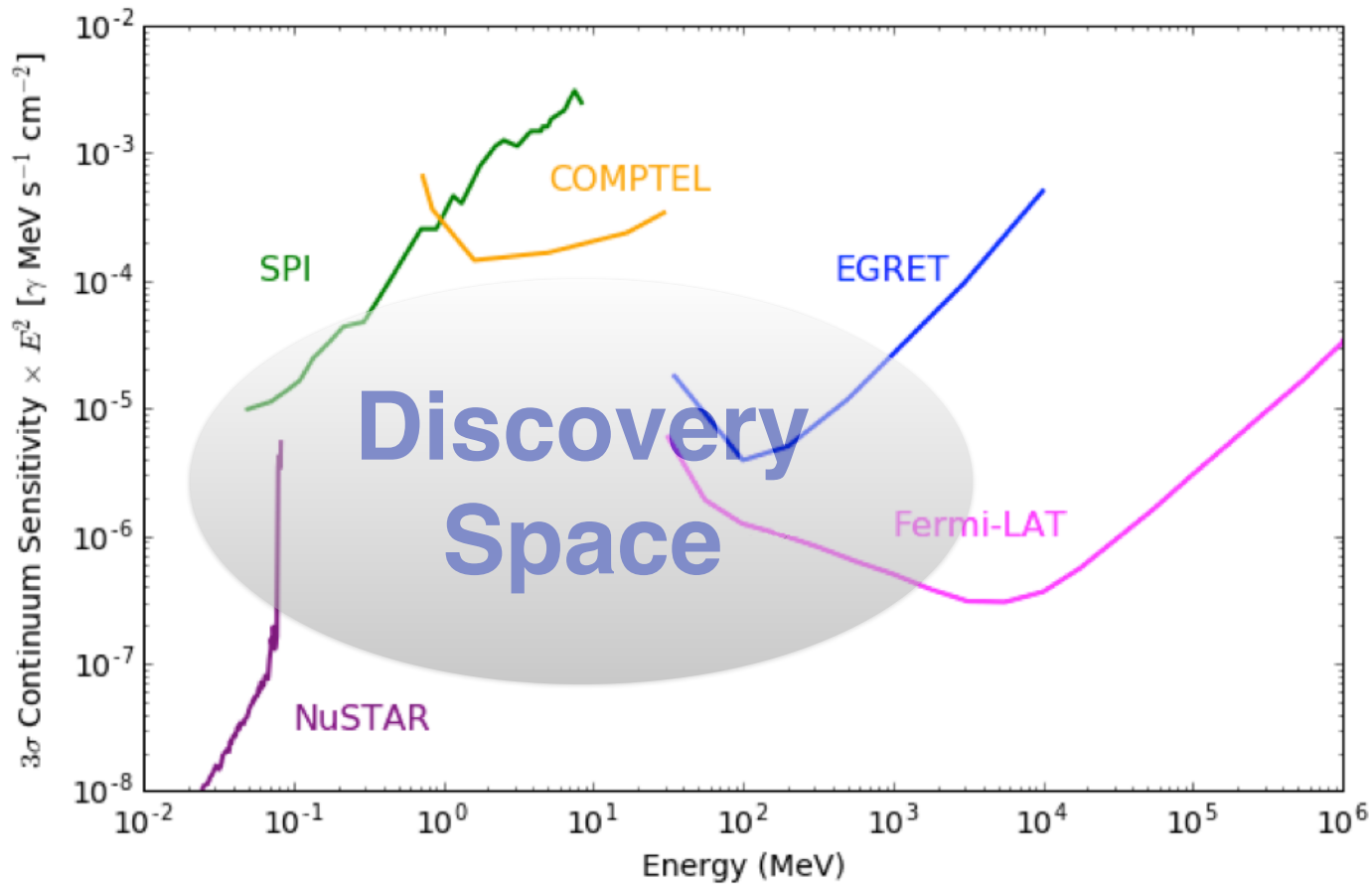
Instrument Sensitivities



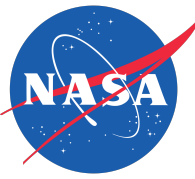
Wide FoV, broad energy range, good energy/angular resolution



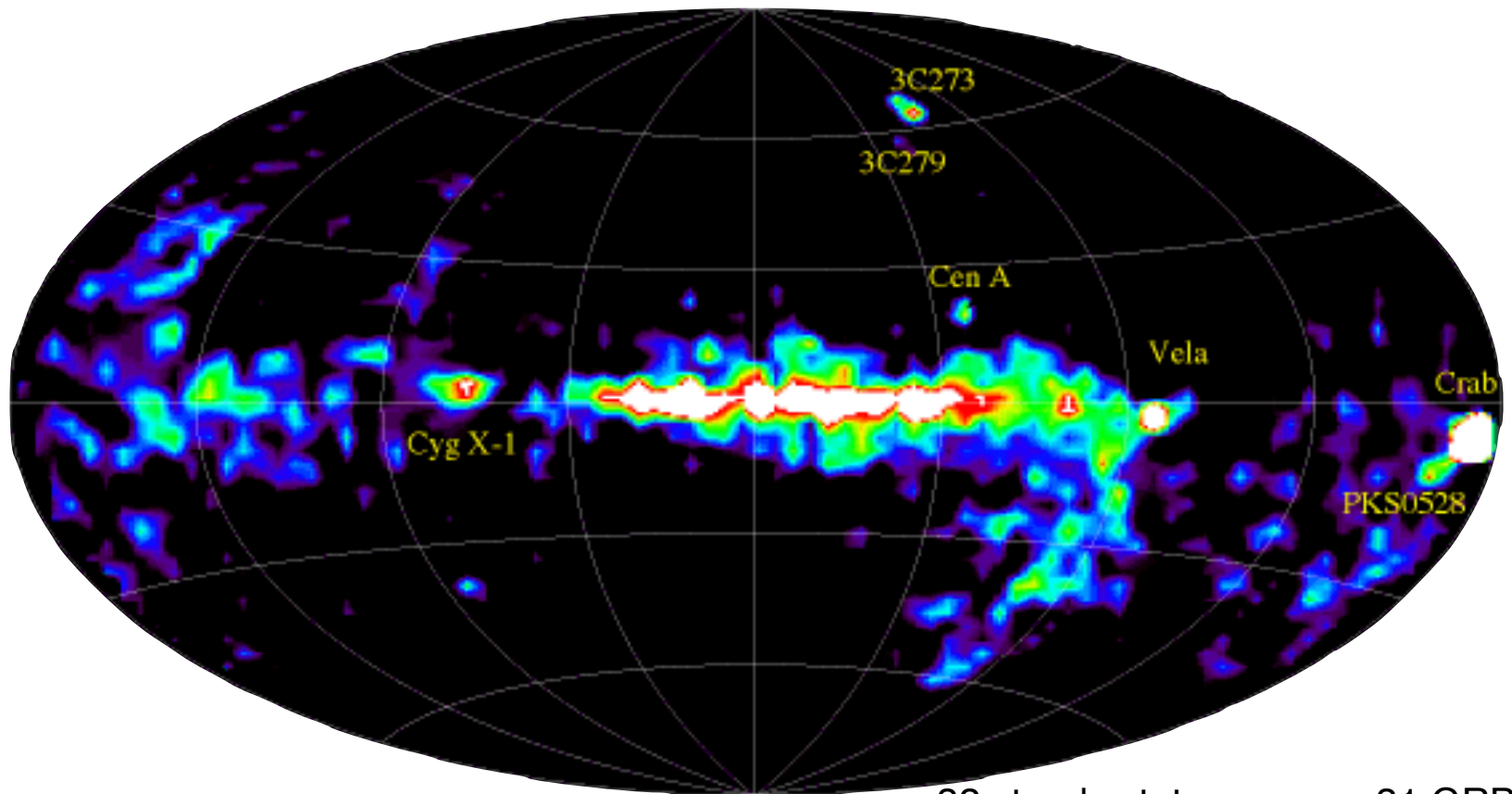
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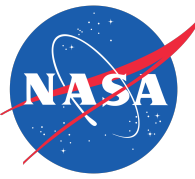


The MeV Band COMPTEL 1-30 MeV



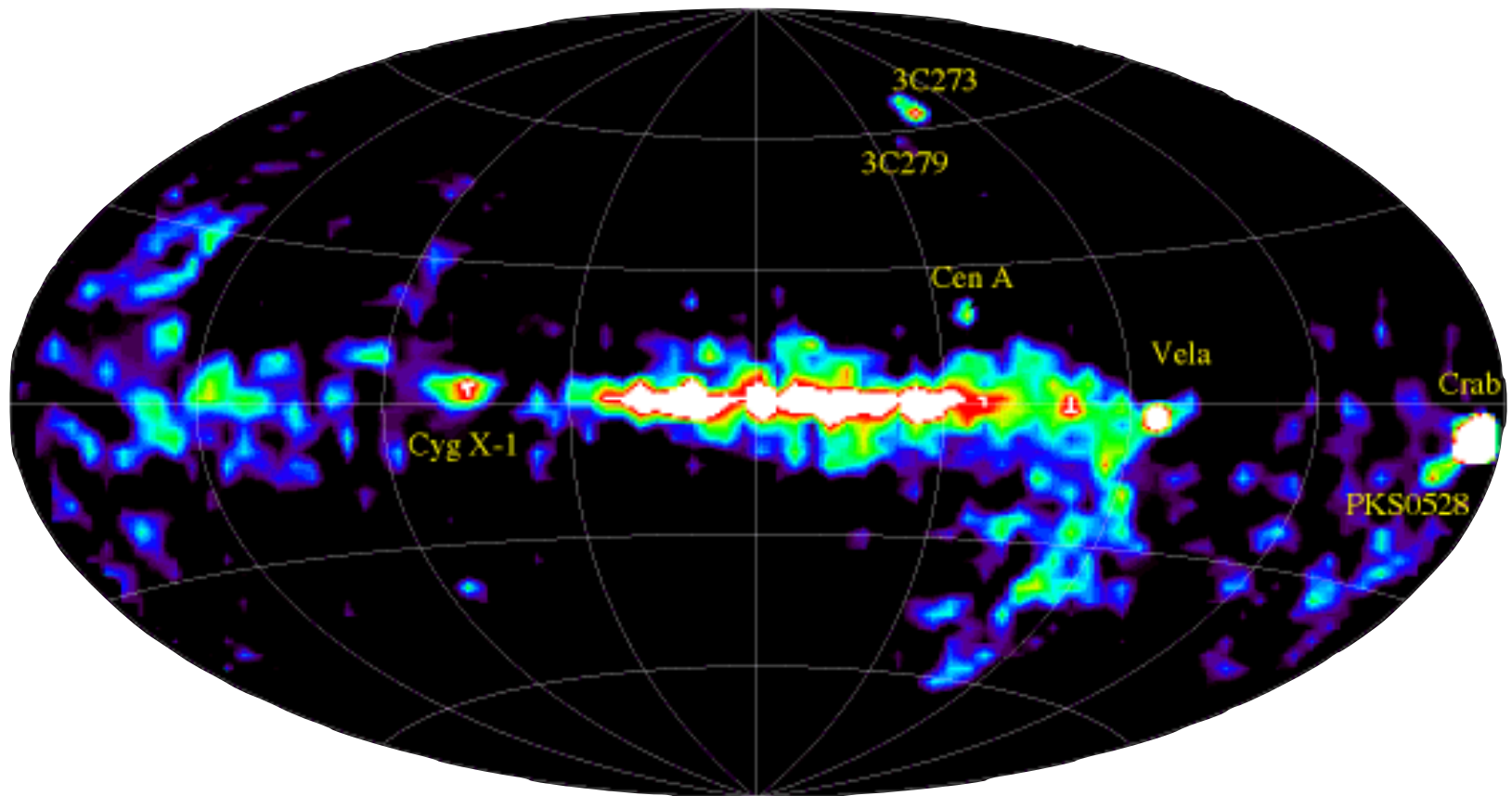
Credit: COMPTEL Collaboration

32 steady state sources, 31 GRBs
(Schoenfelder et al 2000)



The MeV Band

Deeper view: 300keV - >10 GeV



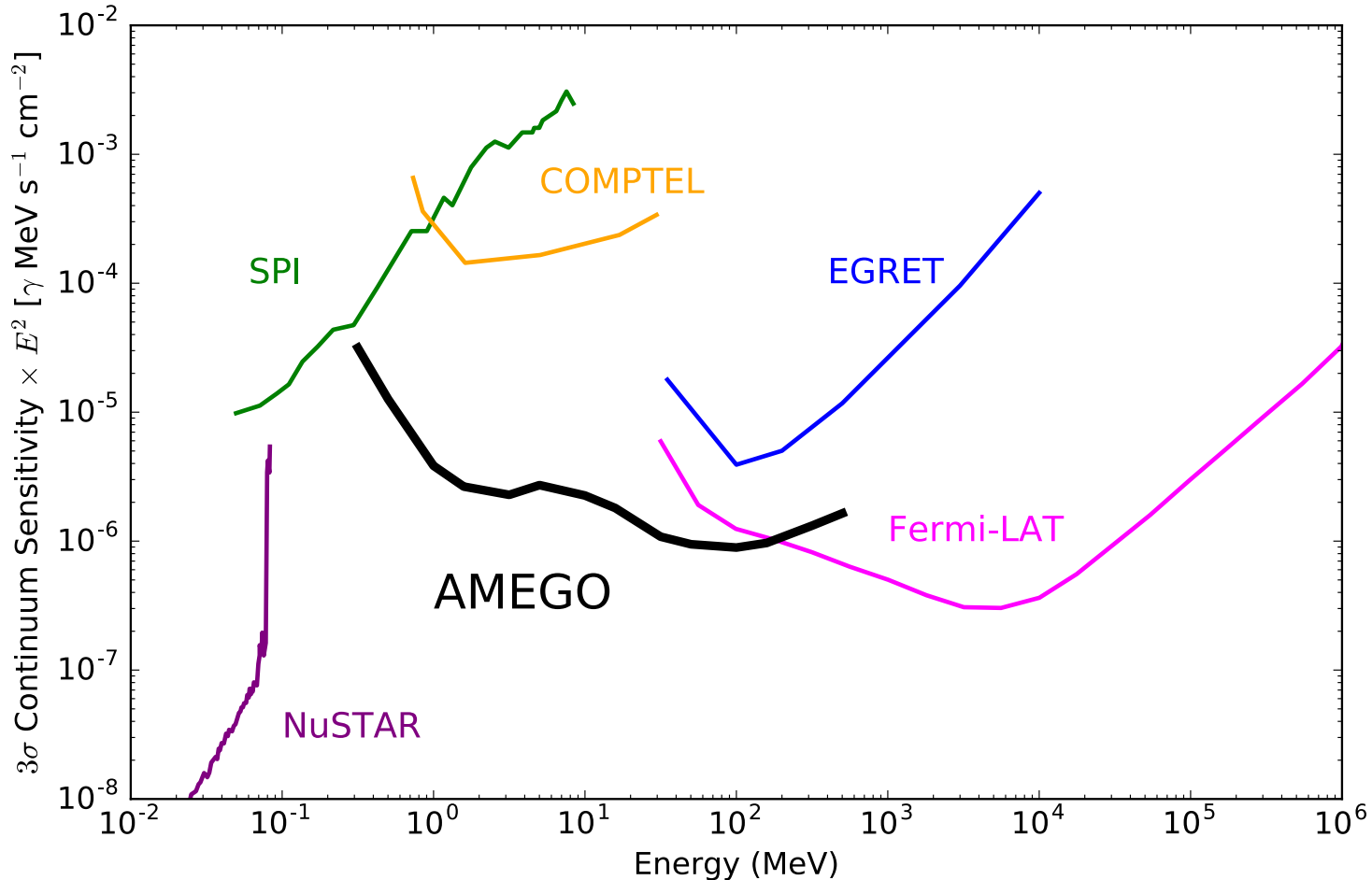
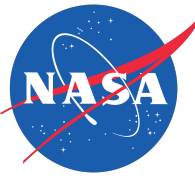
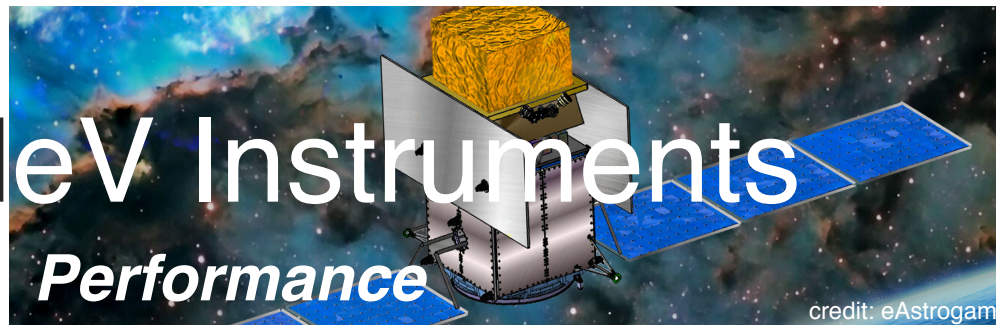
Credit: COMPTEL Collaboration

What lies beyond?



Future MeV Instruments

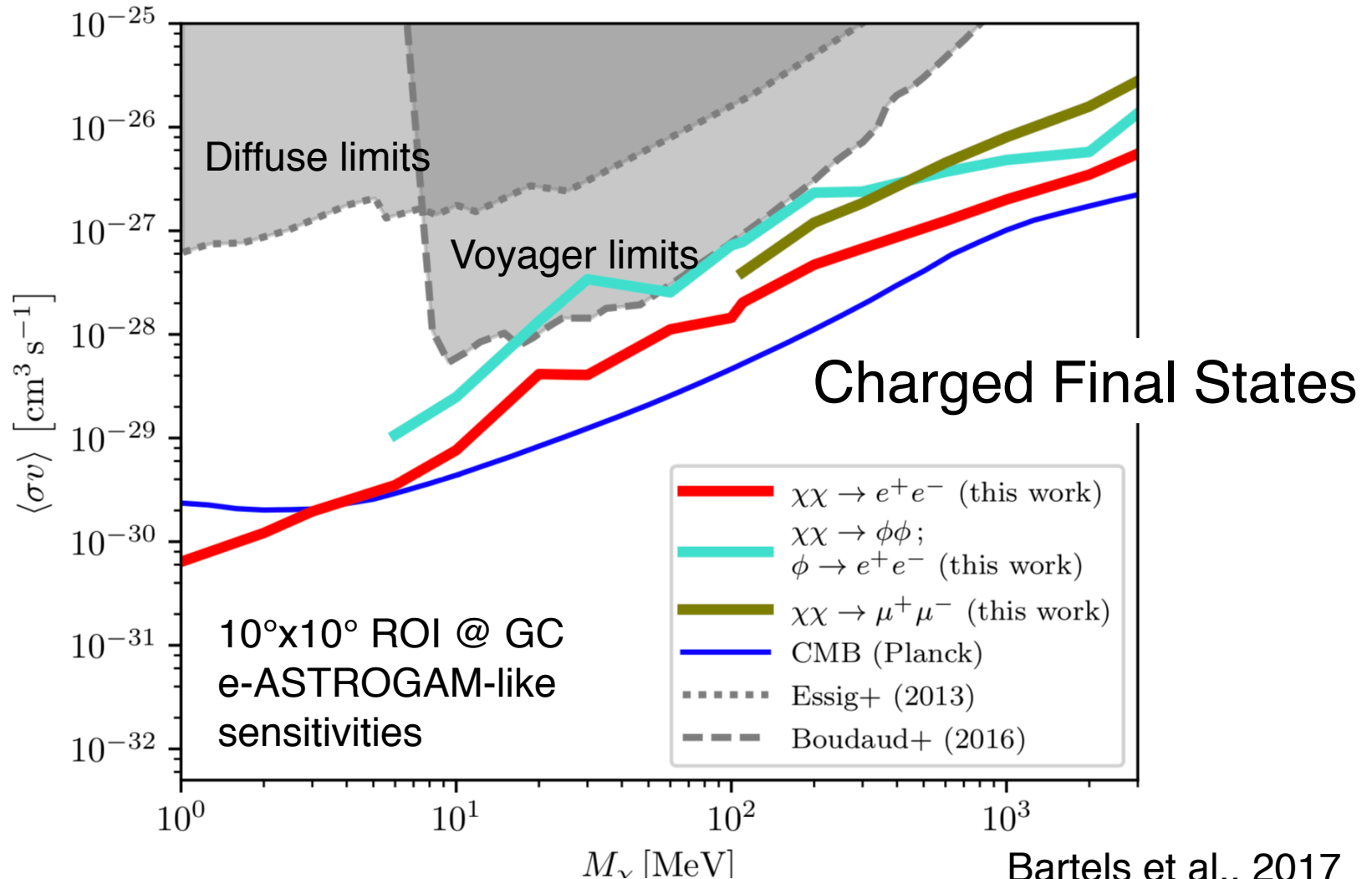
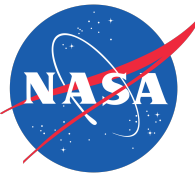
Performance



See talk by J. McEnery Thursday



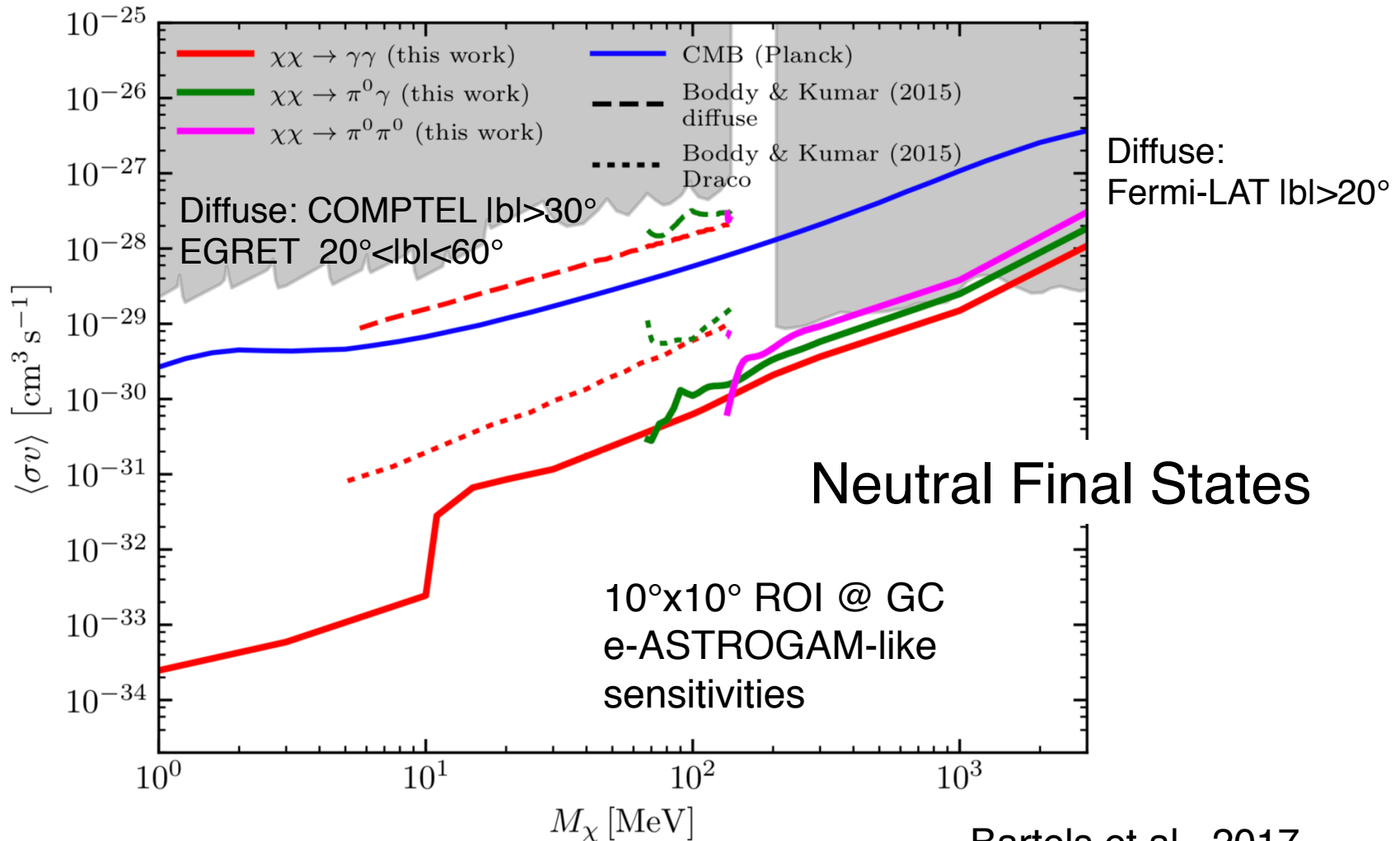
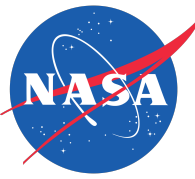
Dark Matter Annihilation Sensitivity



Bartels et al., 2017



Dark Matter Annihilation Sensitivity



Bartels et al., 2017



Probing the Galactic Center Excess

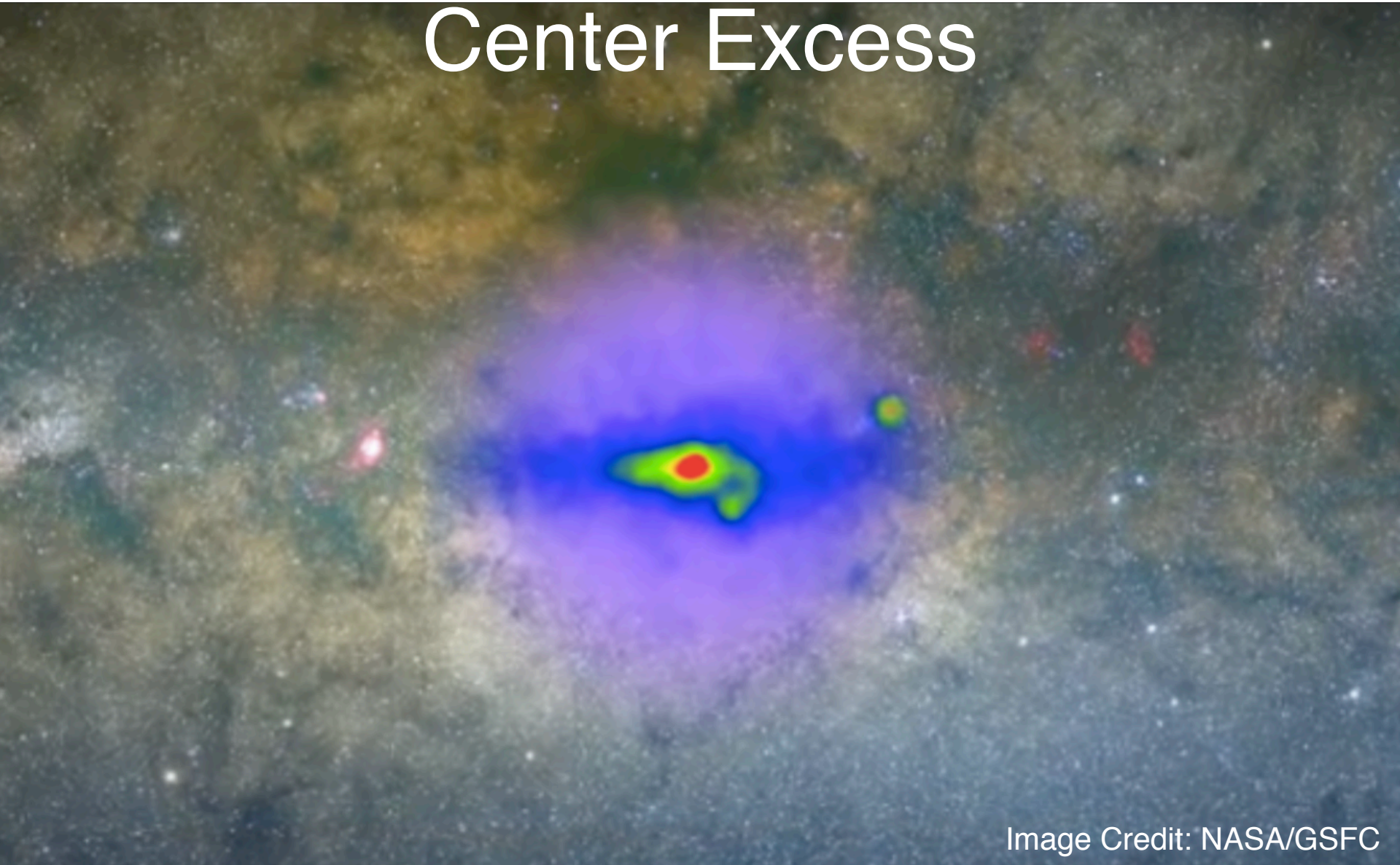
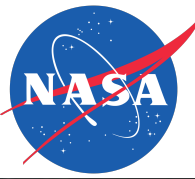
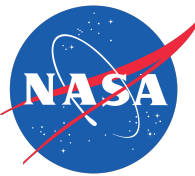


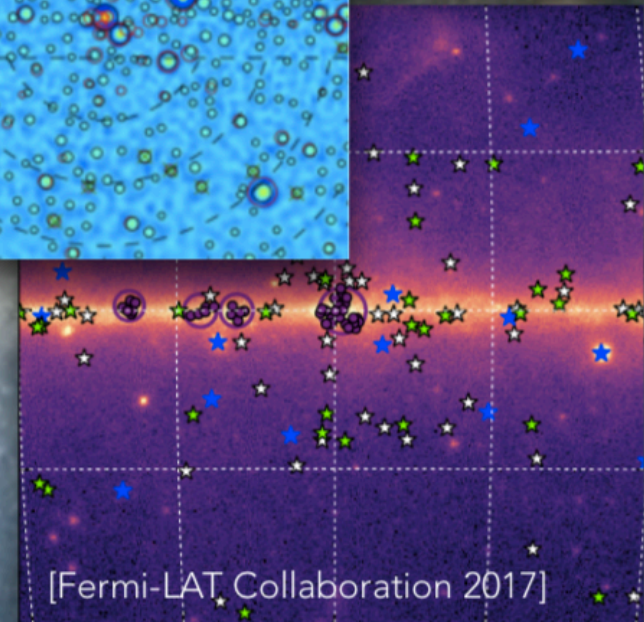
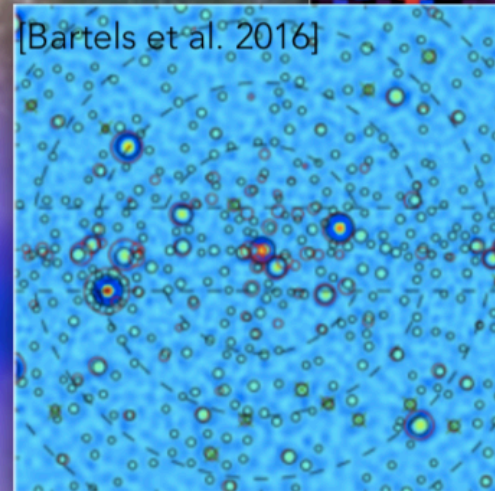
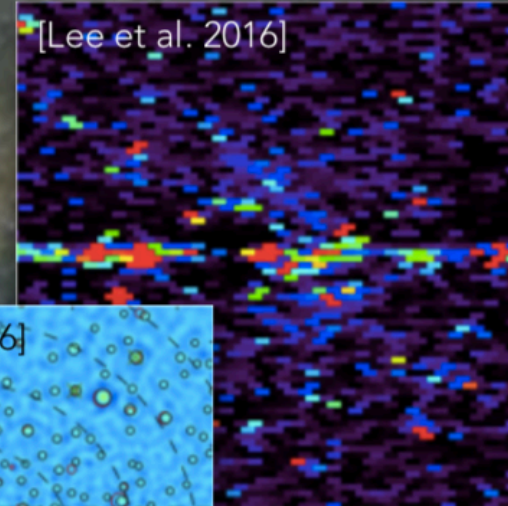
Image Credit: NASA/GSFC



Probing the Galactic Center Excess



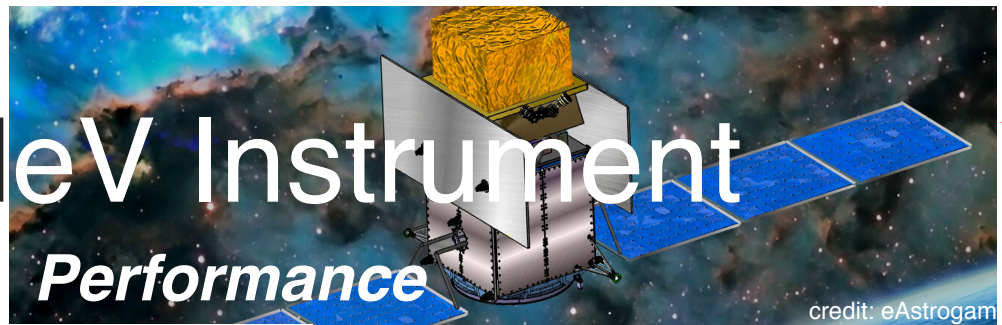
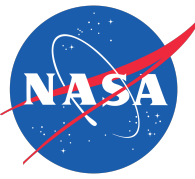
Population of point sources:
Millisecond pulsars



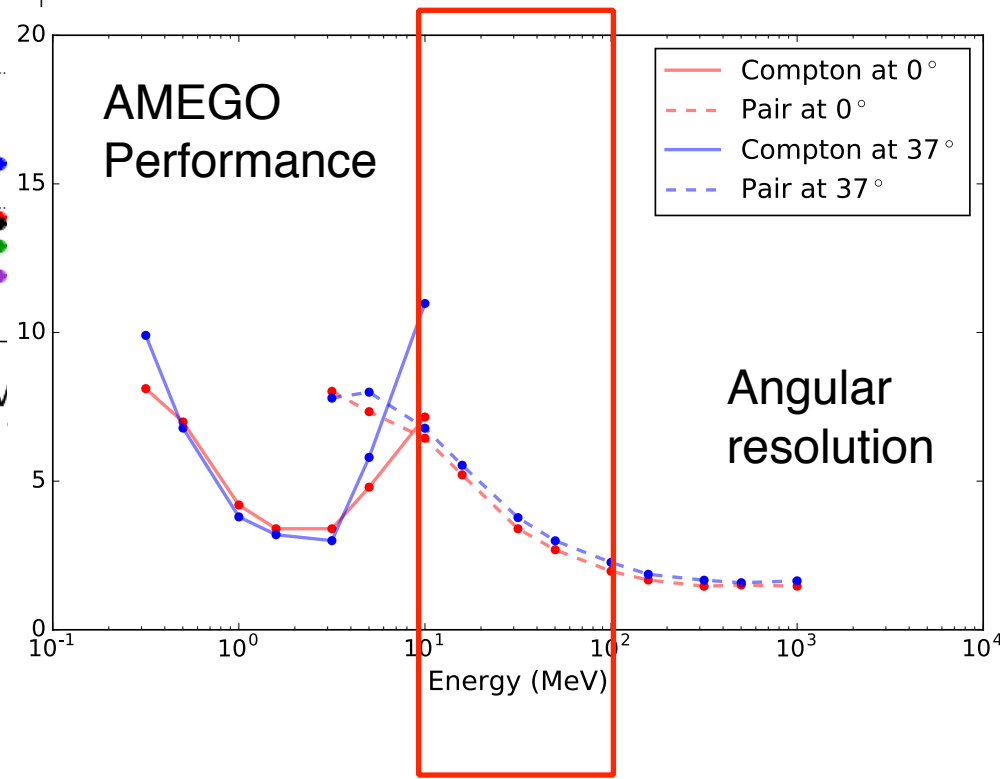
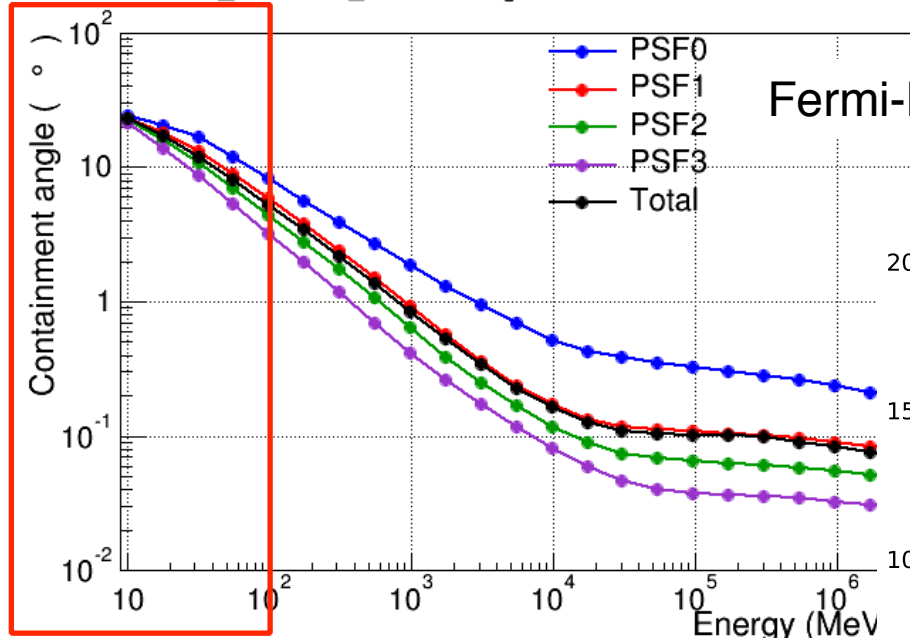
Talk by R. Bartles Monday



Future MeV Instrument Performance

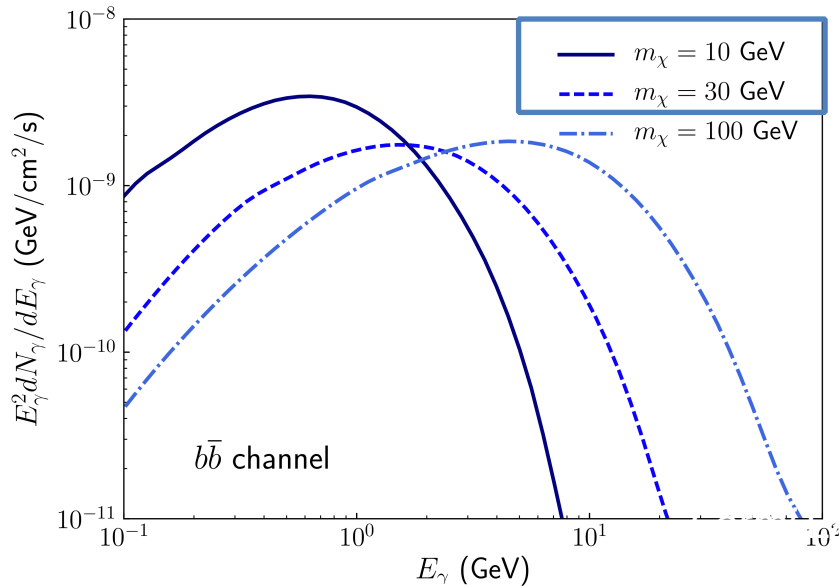
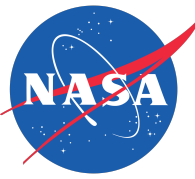


P8R2_SOURCE_V6 acc. weighted PSF 68% containment





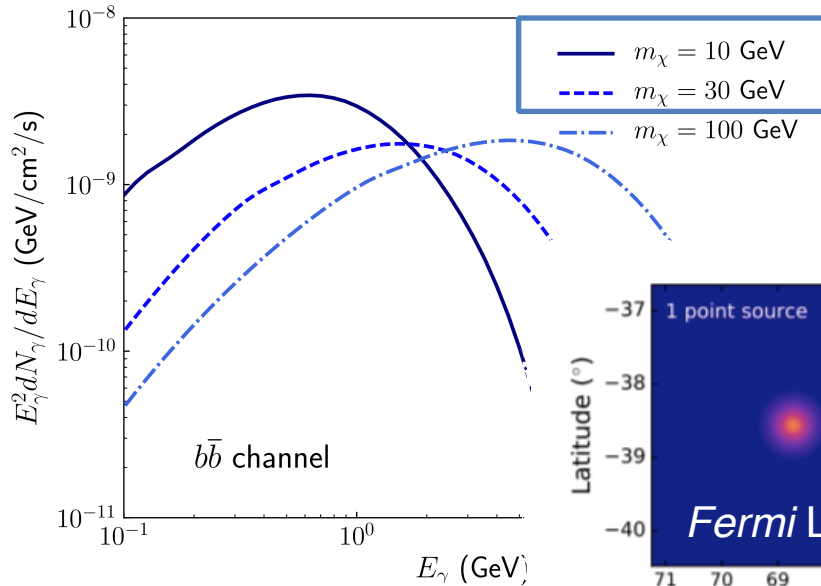
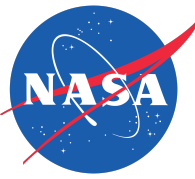
Complementarity in the γ -ray Sky



**Relevant for extended sources
and Galactic Center**

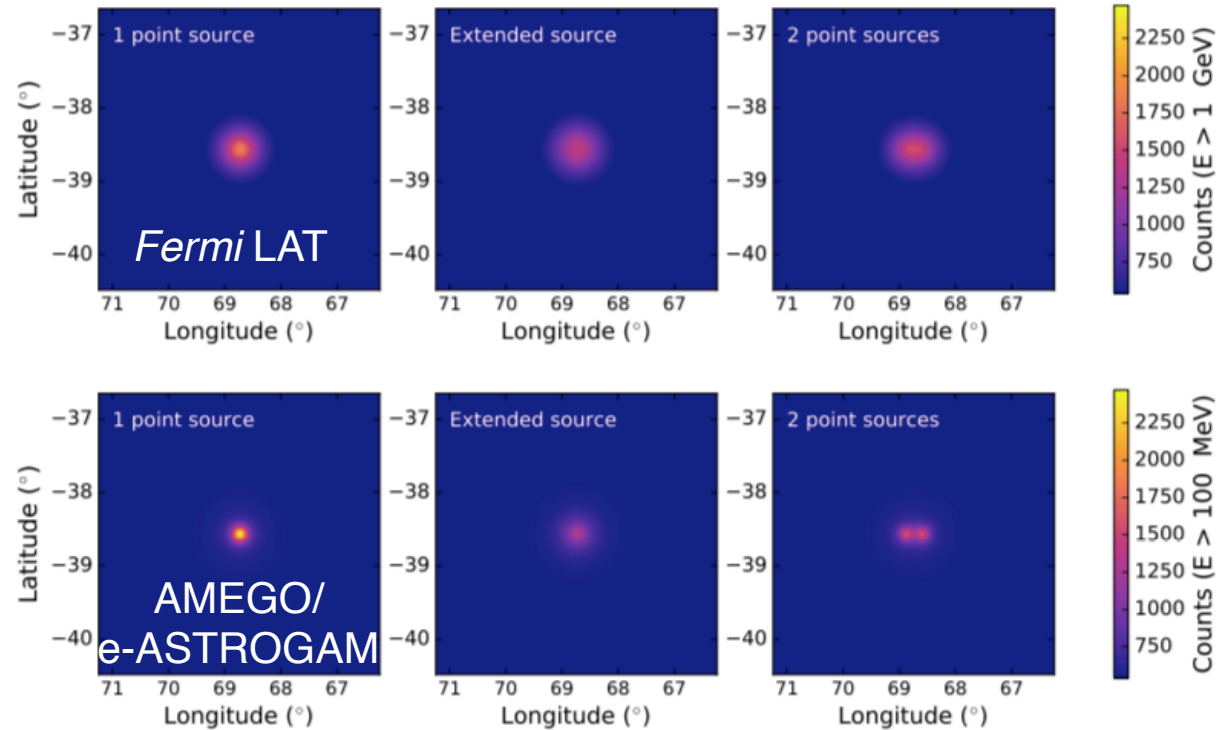


Complementarity in the γ -ray Sky

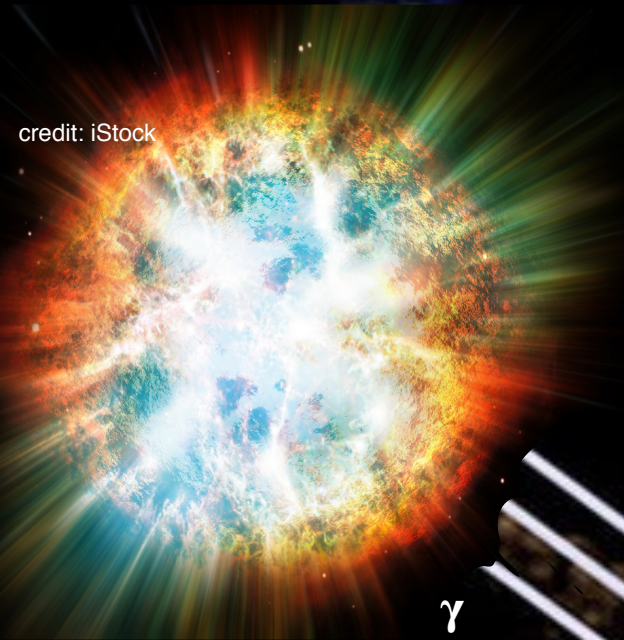


Relevant for extended sources
and Galactic Center

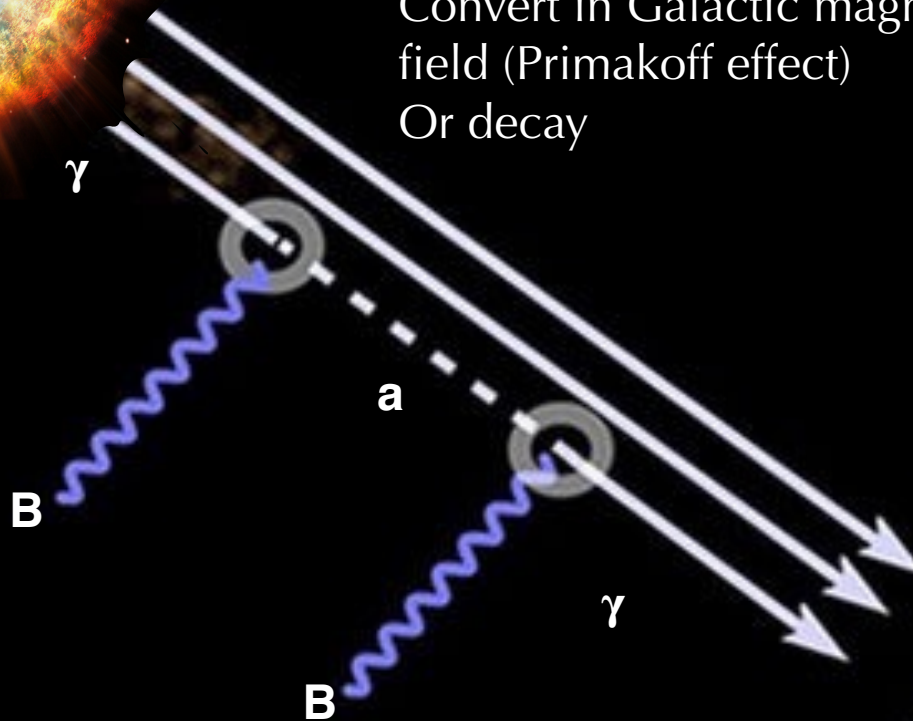
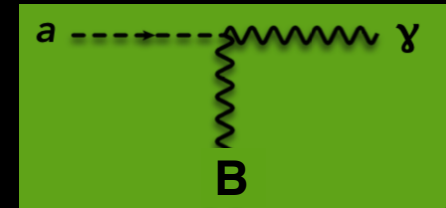
Separated by 0.28°



Axions and Axion-like Particles



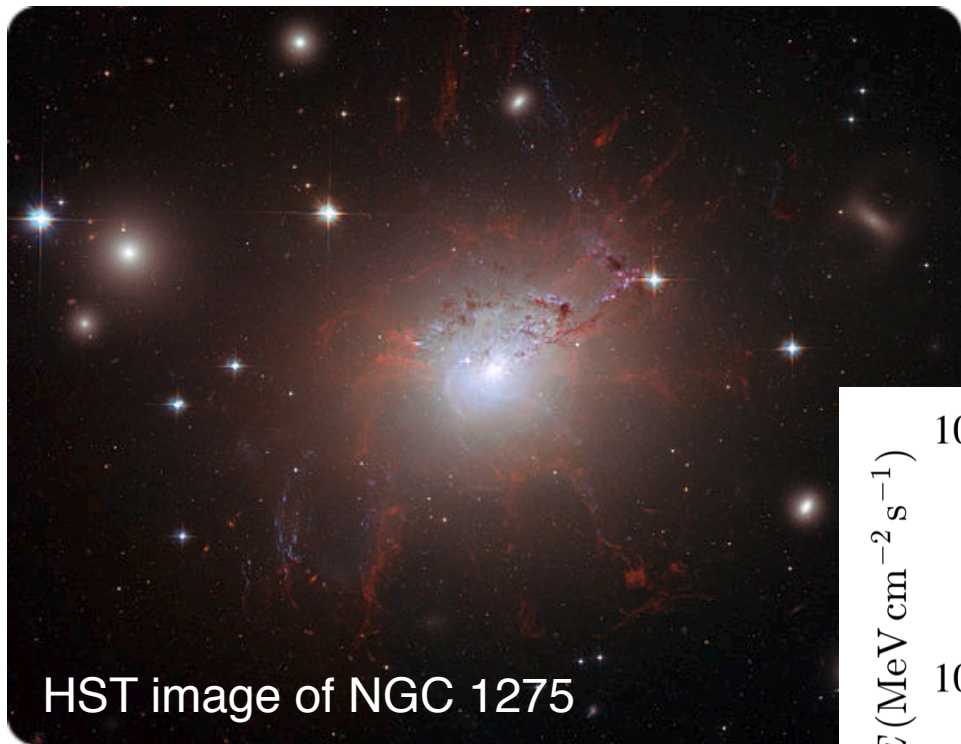
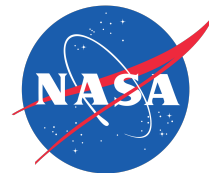
Convert in Galactic magnetic field (Primakoff effect)
Or decay



[Peccei & Quinn 77; Wilczek 78; Weinberg 78;
Preskill et al. 83; Abbott & Sikivie 83; Witten 84;
e.g. Arvanitaki et al. 09; Cicoli et al. 12; Arias et al. 2012;
Raffelt & Stodolsky 1988]



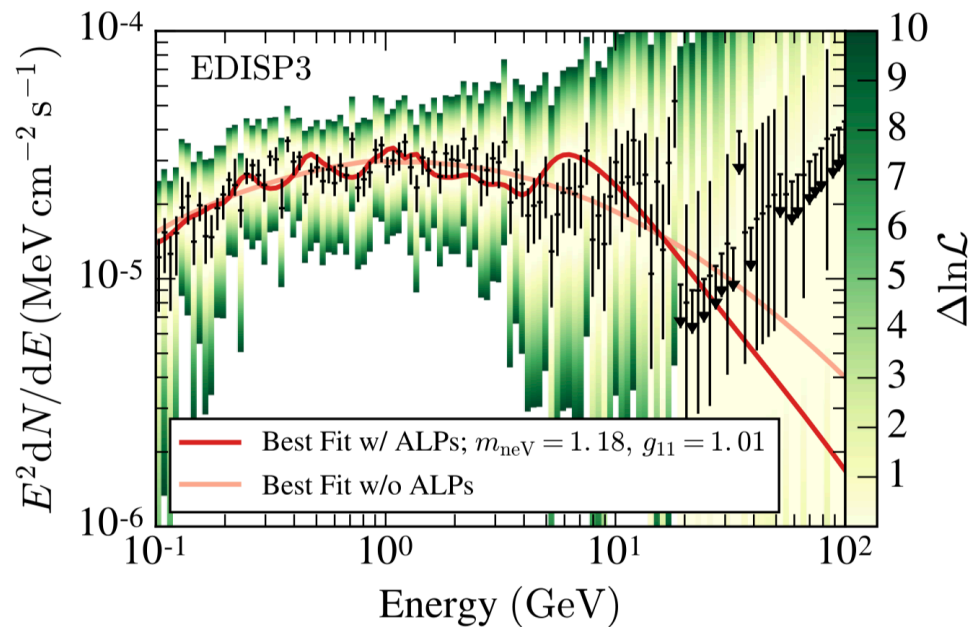
Axion Induced Spectral Modulations



HST image of NGC 1275

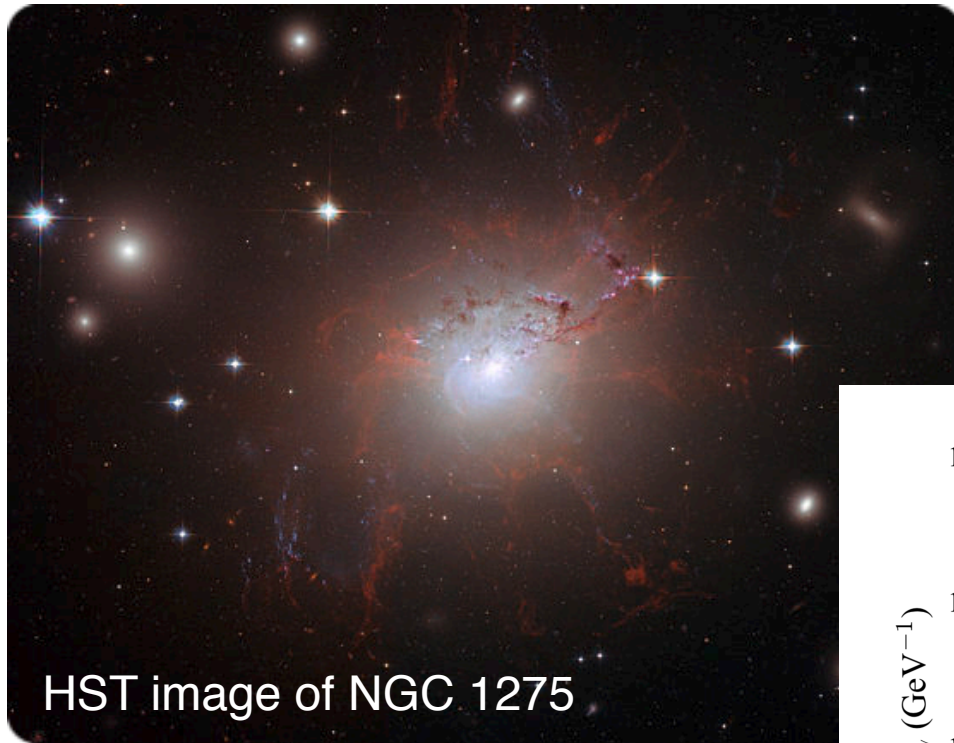
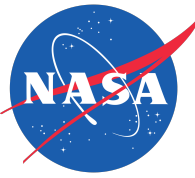
- Central radio galaxy of Perseus cluster
- Bright γ -ray emitter
- Central B field of cluster: $25 \mu\text{G}$

Taylor et al. 2006





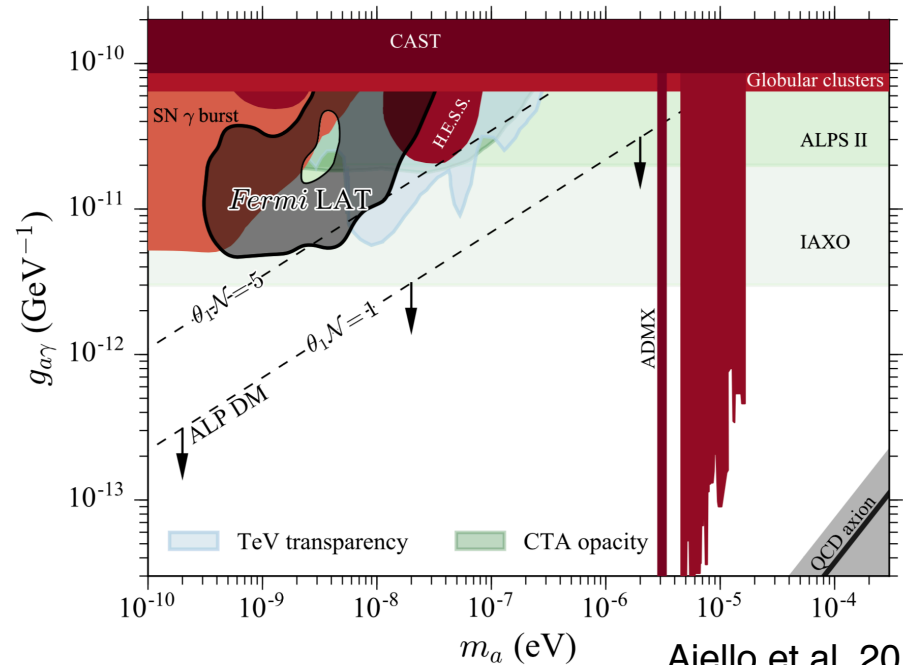
Axion Induced Spectral Modulations



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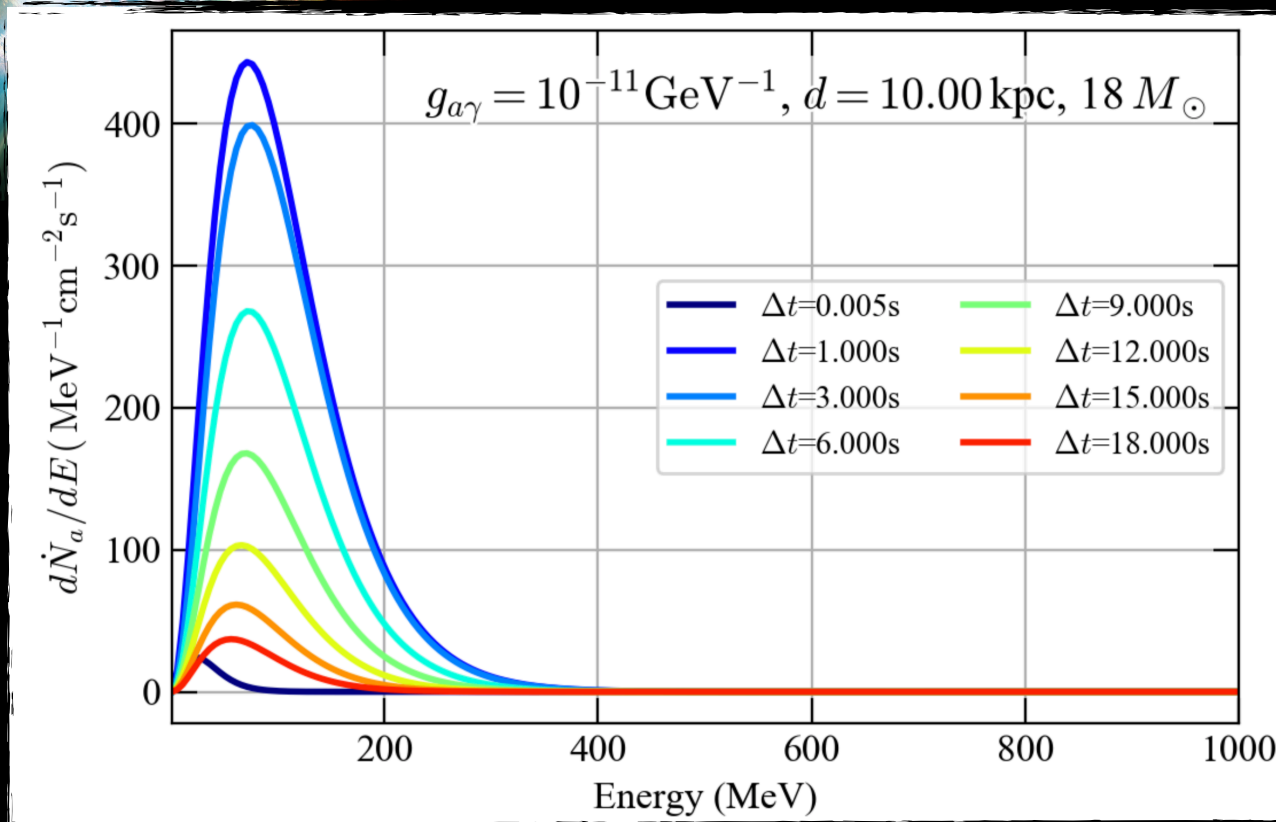
Taylor et al. 2006



Ajello et al. 2016 19

Axions Produced in Core-Collapse Supernovae

credit: iStock



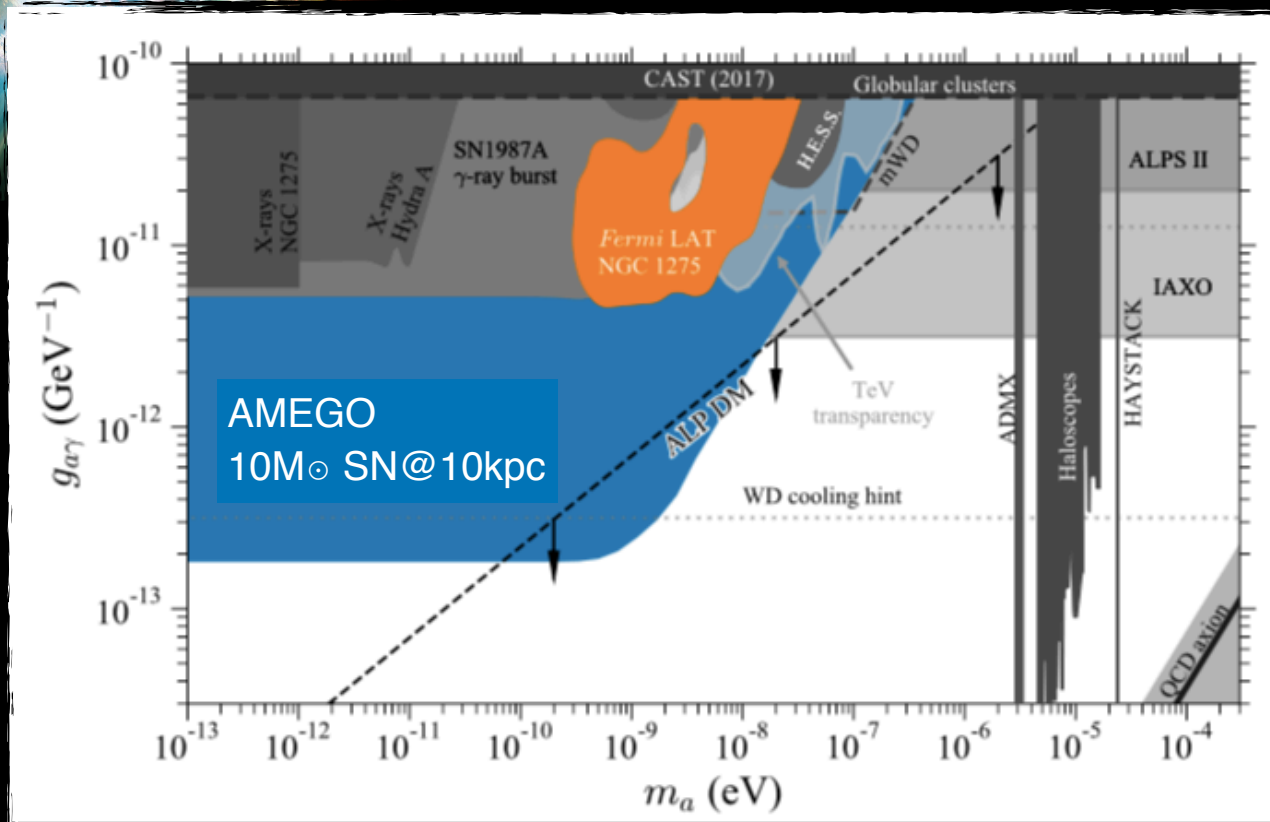
Produced ~10s
with neutrinos

Peak ~60 MeV

Flux $\propto g_{a\gamma}^4$

Axions Produced in Core-Collapse Supernovae

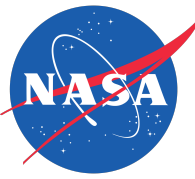
credit: iStock



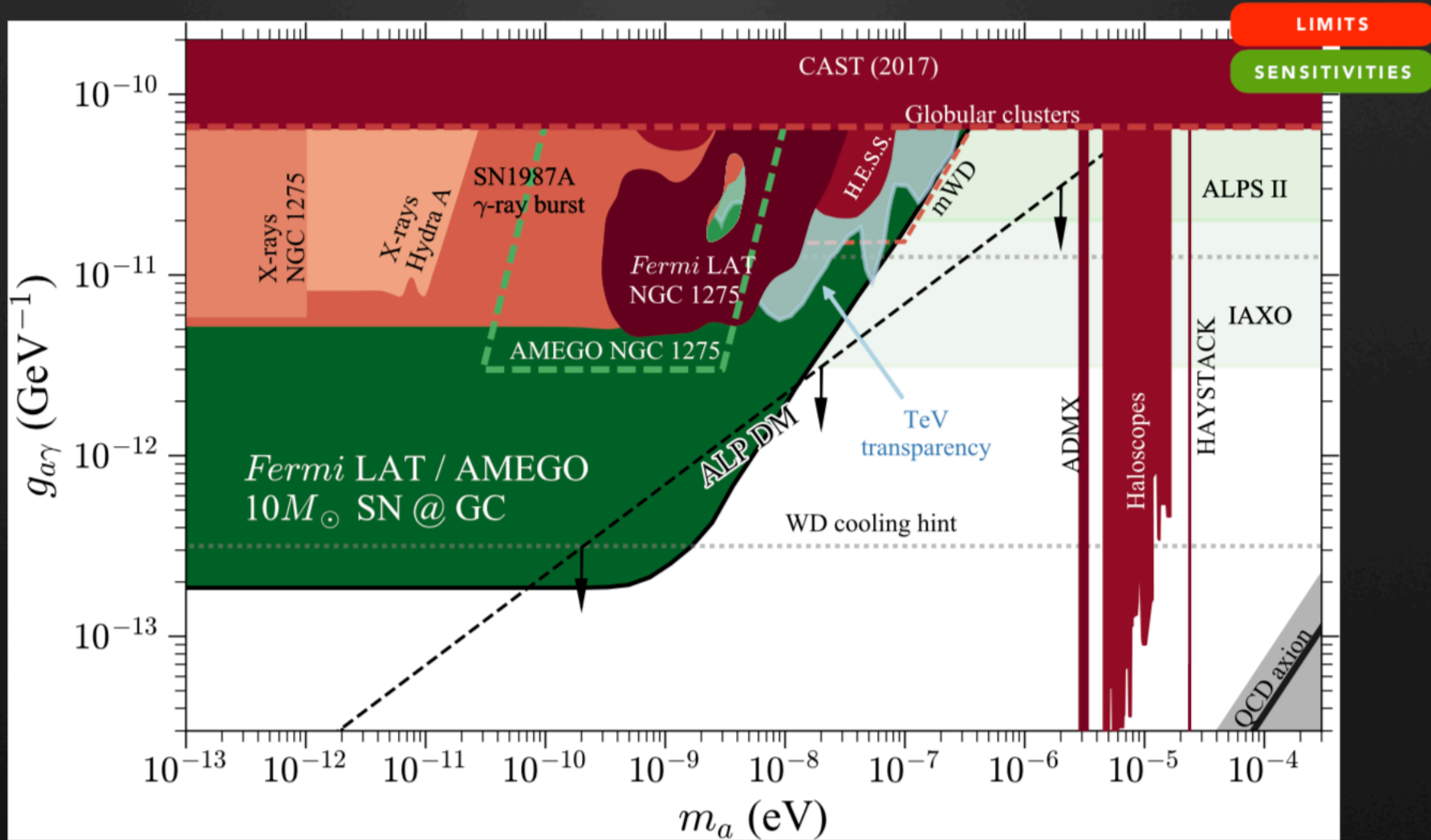
Produced ~10s
with neutrinos

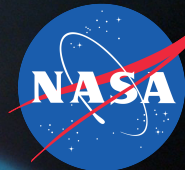
Peak ~60 MeV

Flux $\propto g_{a\gamma}^4$



Axion/ALP Dark Matter Sensitivities



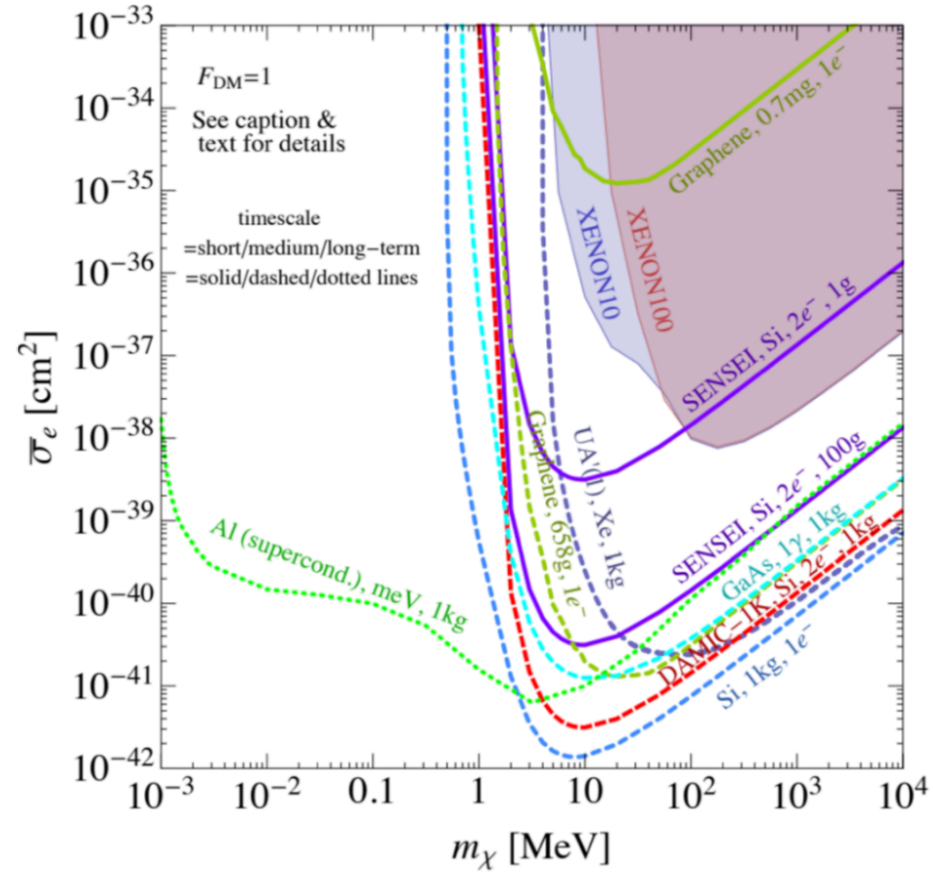
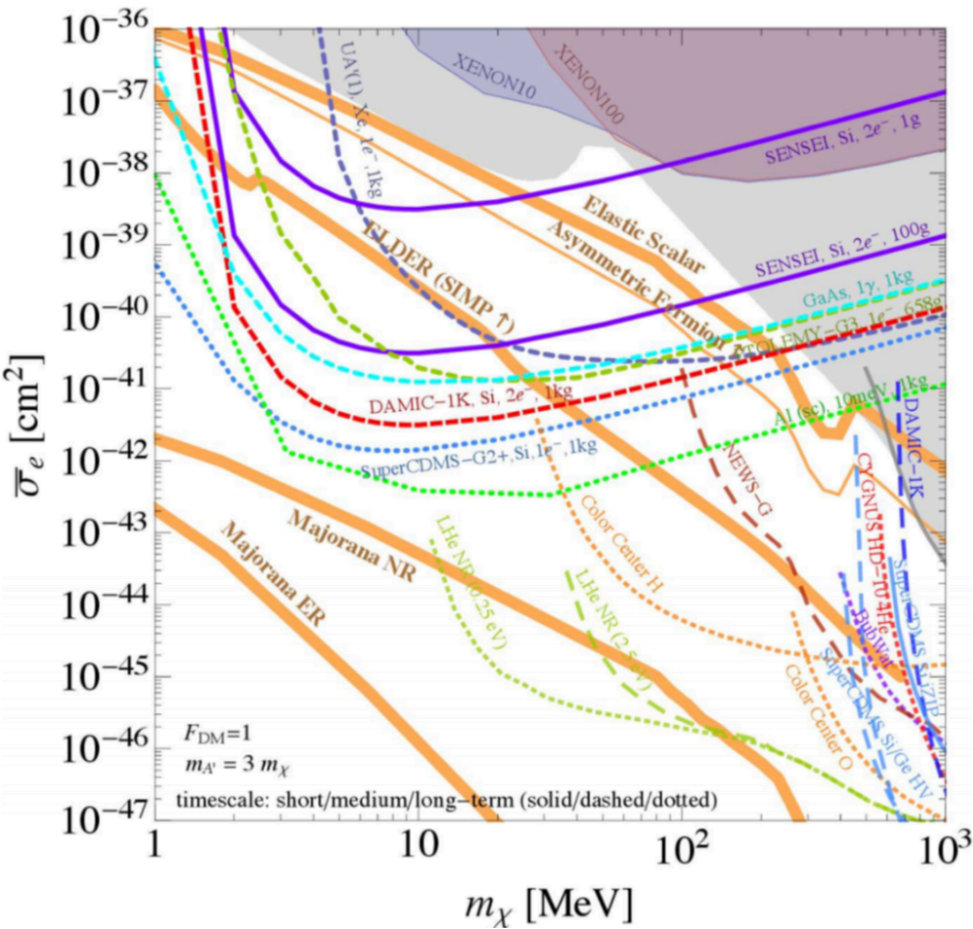
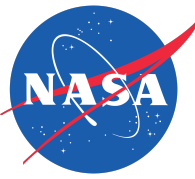


The Future is bright in the MeV band...



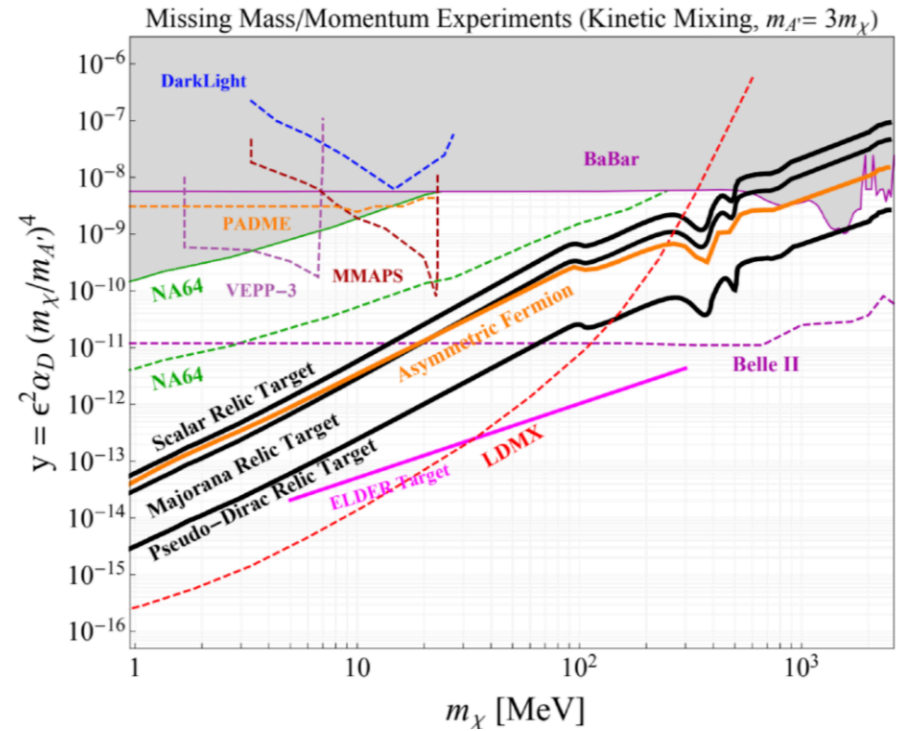
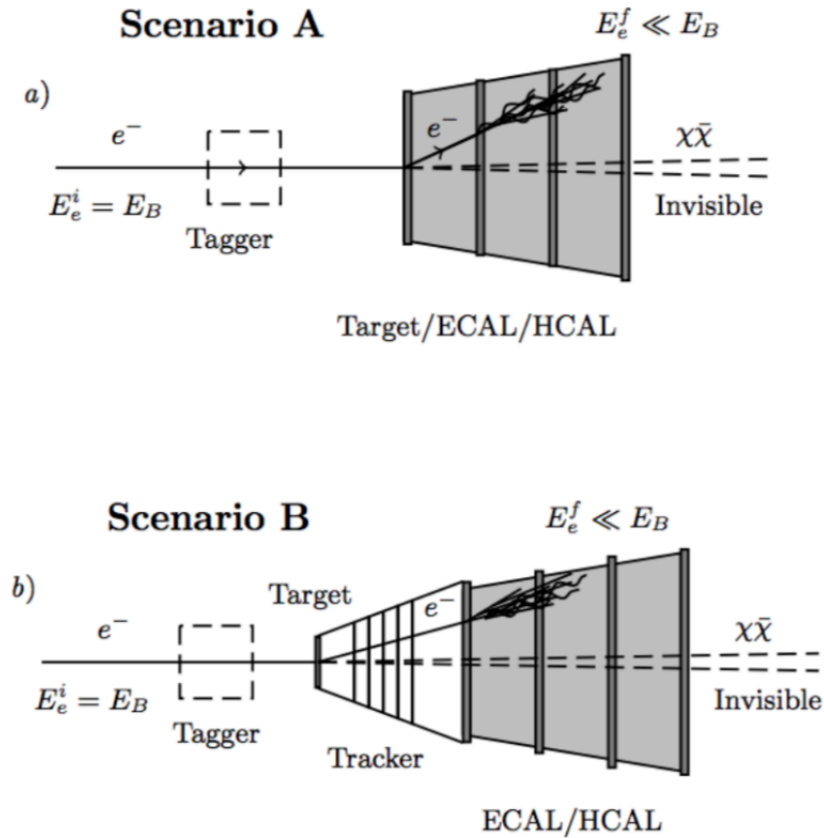
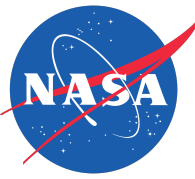


Complementarity: Direct Detection

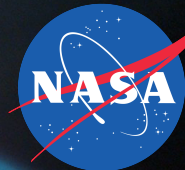




Complementarity: Fixed-Target

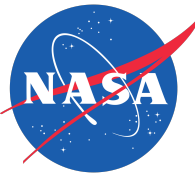


Izaguirre et al. 2015



The Future is bright in the MeV band...

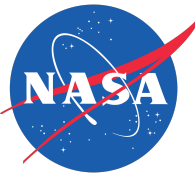
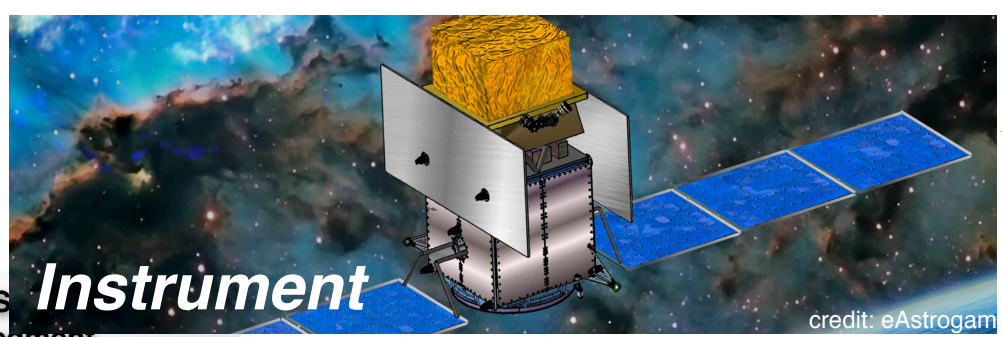
Well motivated discovery space in direct, collider and indirect dark matter searches for broad range of different dark matter candidates



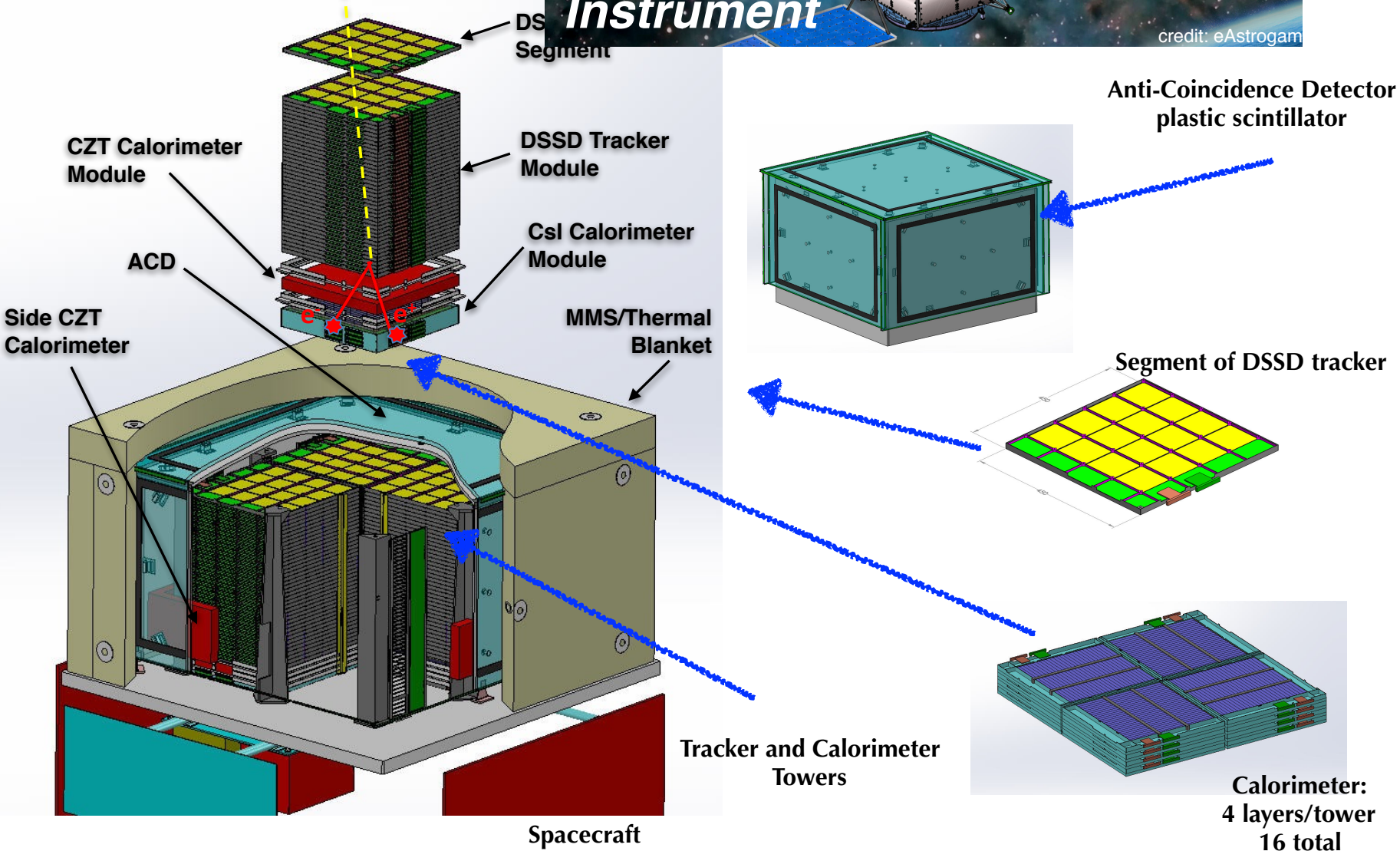
Backups



AMEGO



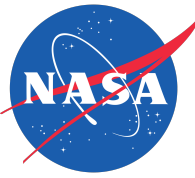
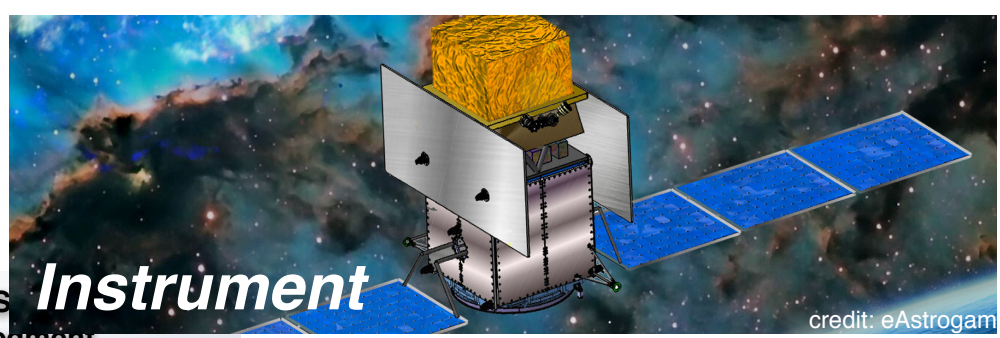
credit: eAstrogam



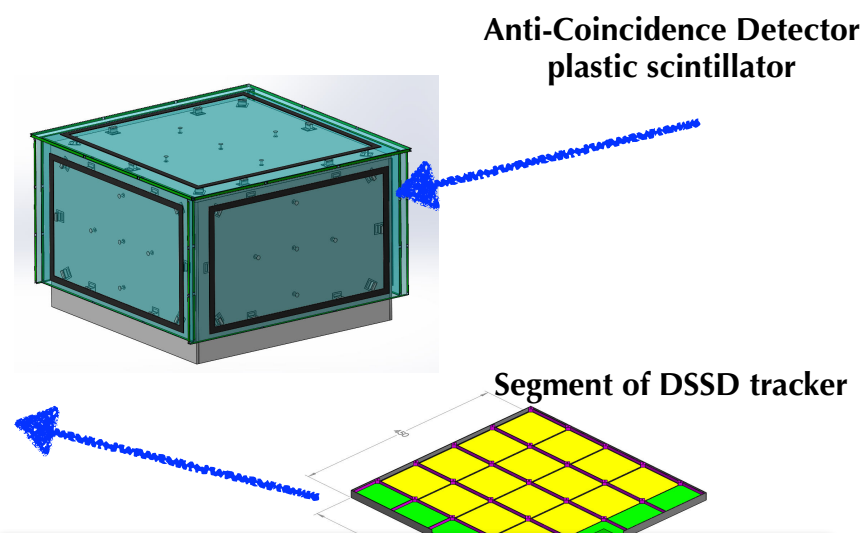
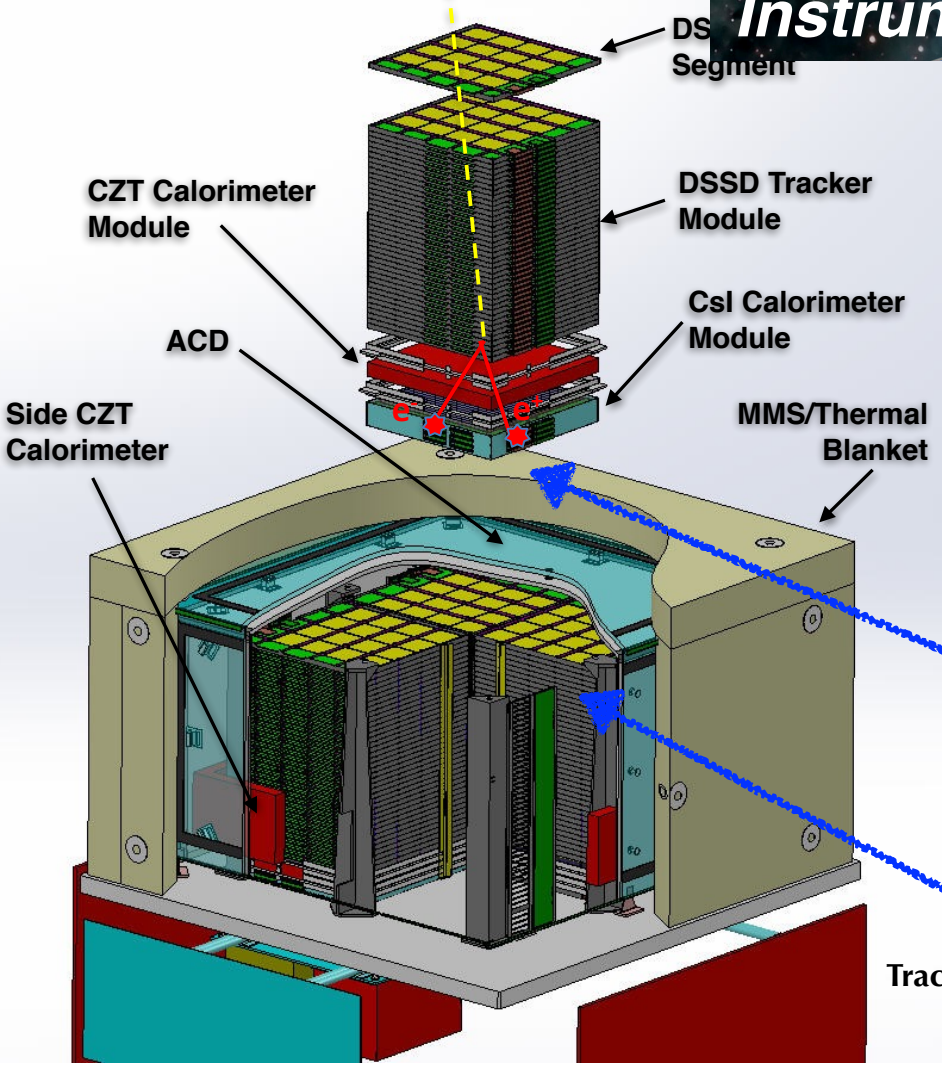
Calorimeter:
4 layers/tower
16 total



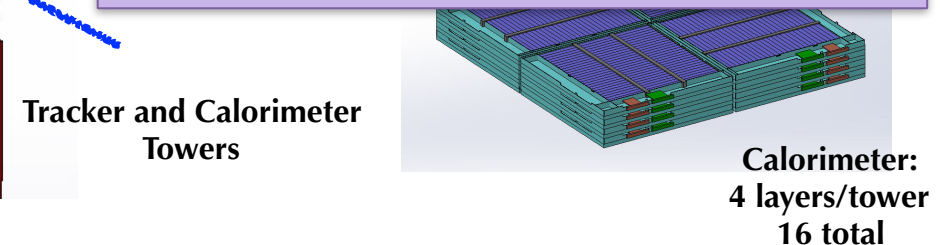
AMEGO



credit: eAstrogam



Sister Instrument:
e-ASTROGAM



Spacecraft