Gamma-Ray Searches for Dark Matter in Celestial Bodies

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BAPTS
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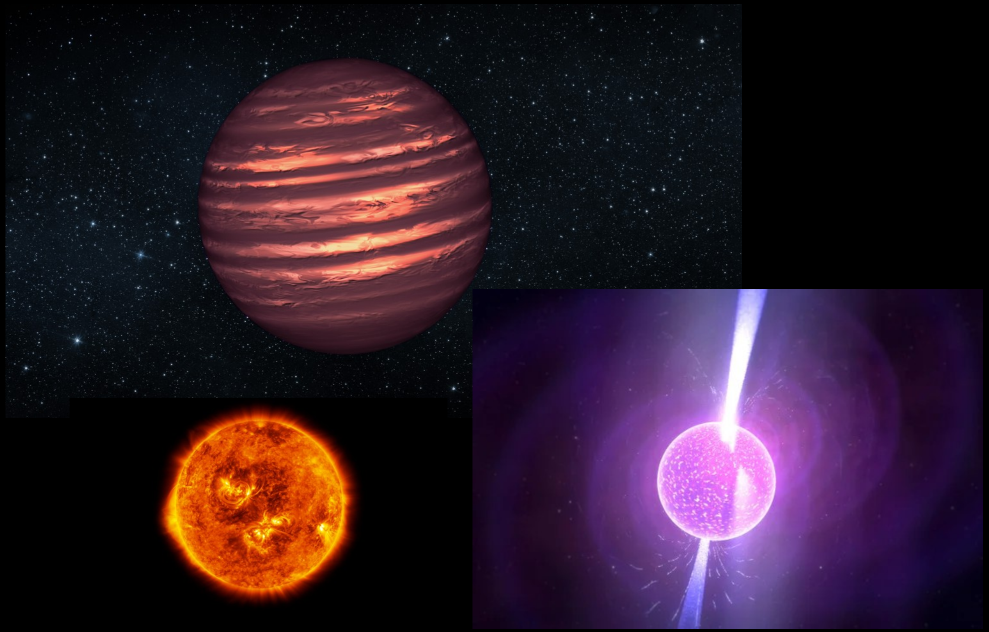
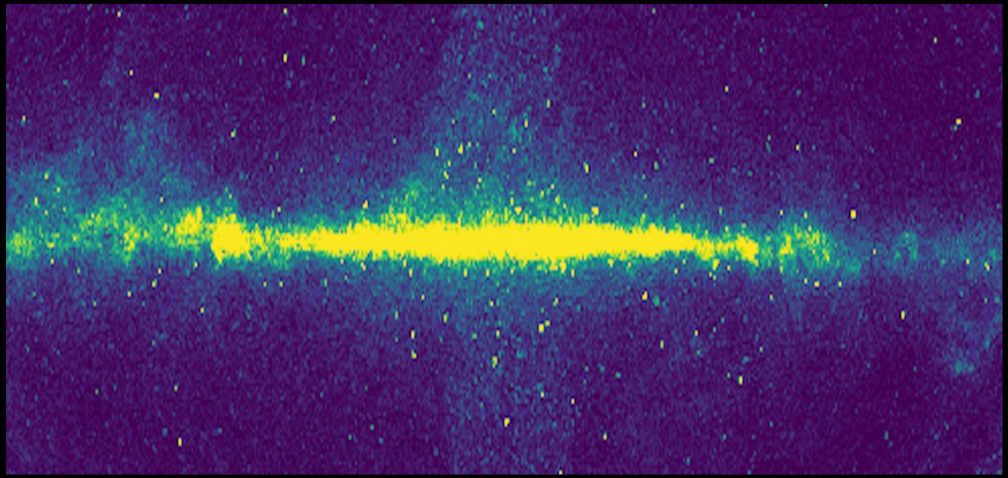
Based on 2101.12213 + 2104.02068
w/ Tim Linden, Payel Mukhopadhyay, Natalia Toro

Finding Particle Dark Matter



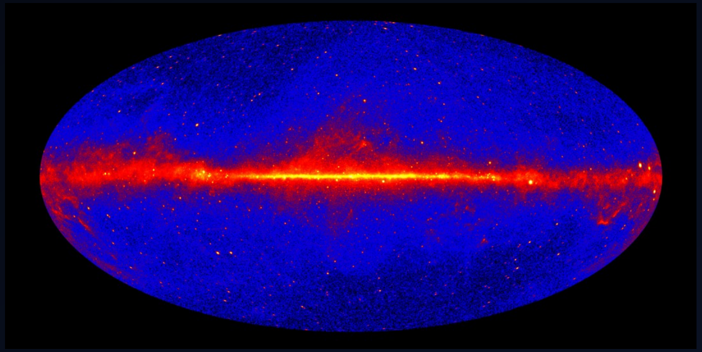
New searches with
astrophysical systems



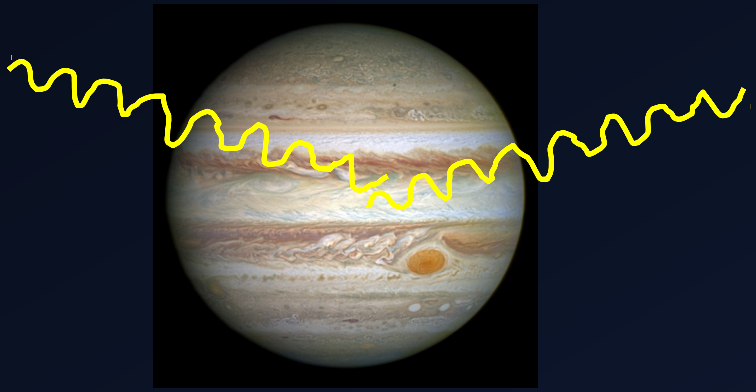
Use **astrophysical datasets**
to discover new particles

New Gamma-Ray Searches

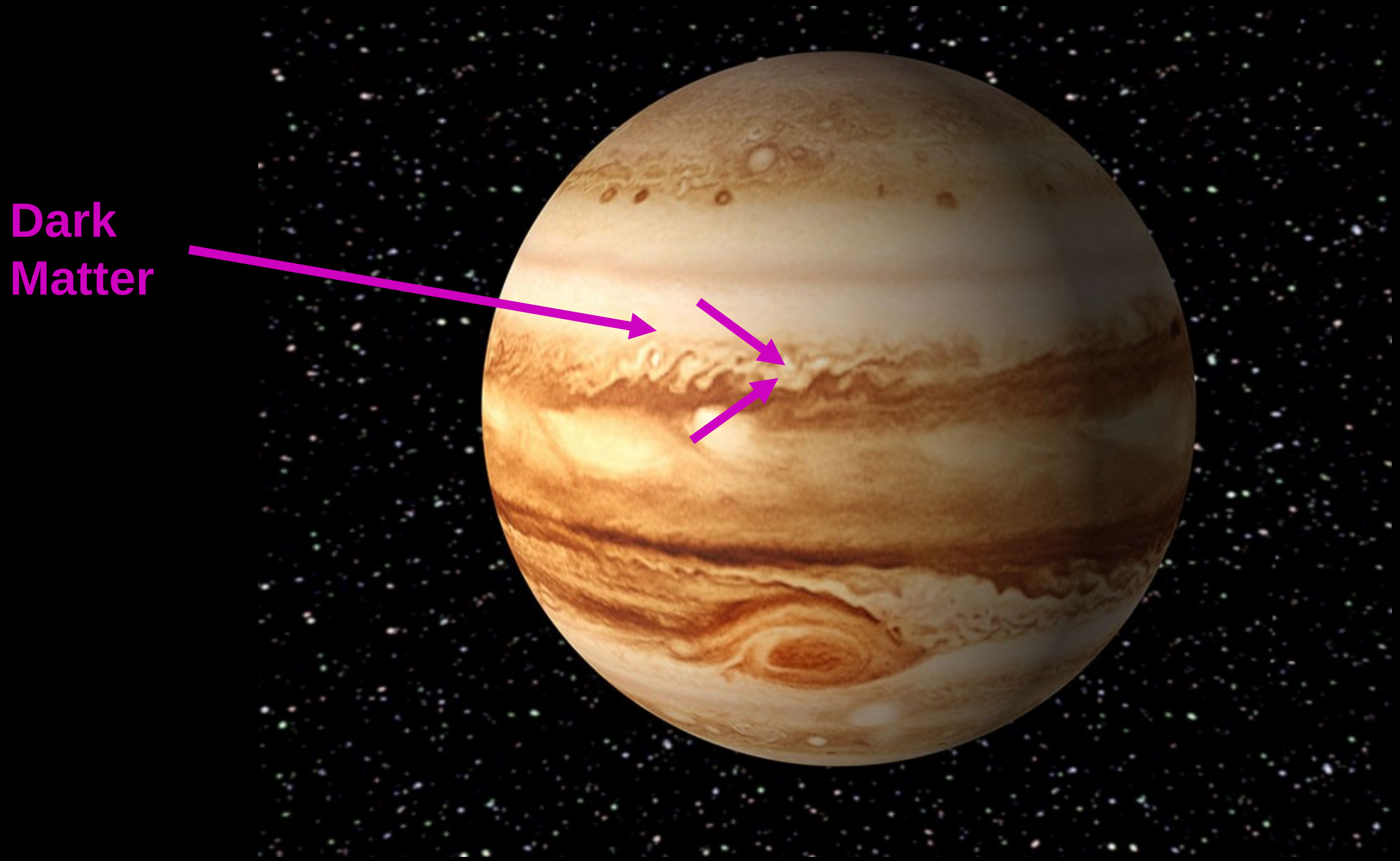
- Traditional indirect detection:
  - Look for annihilation or decay products in dark matter halos



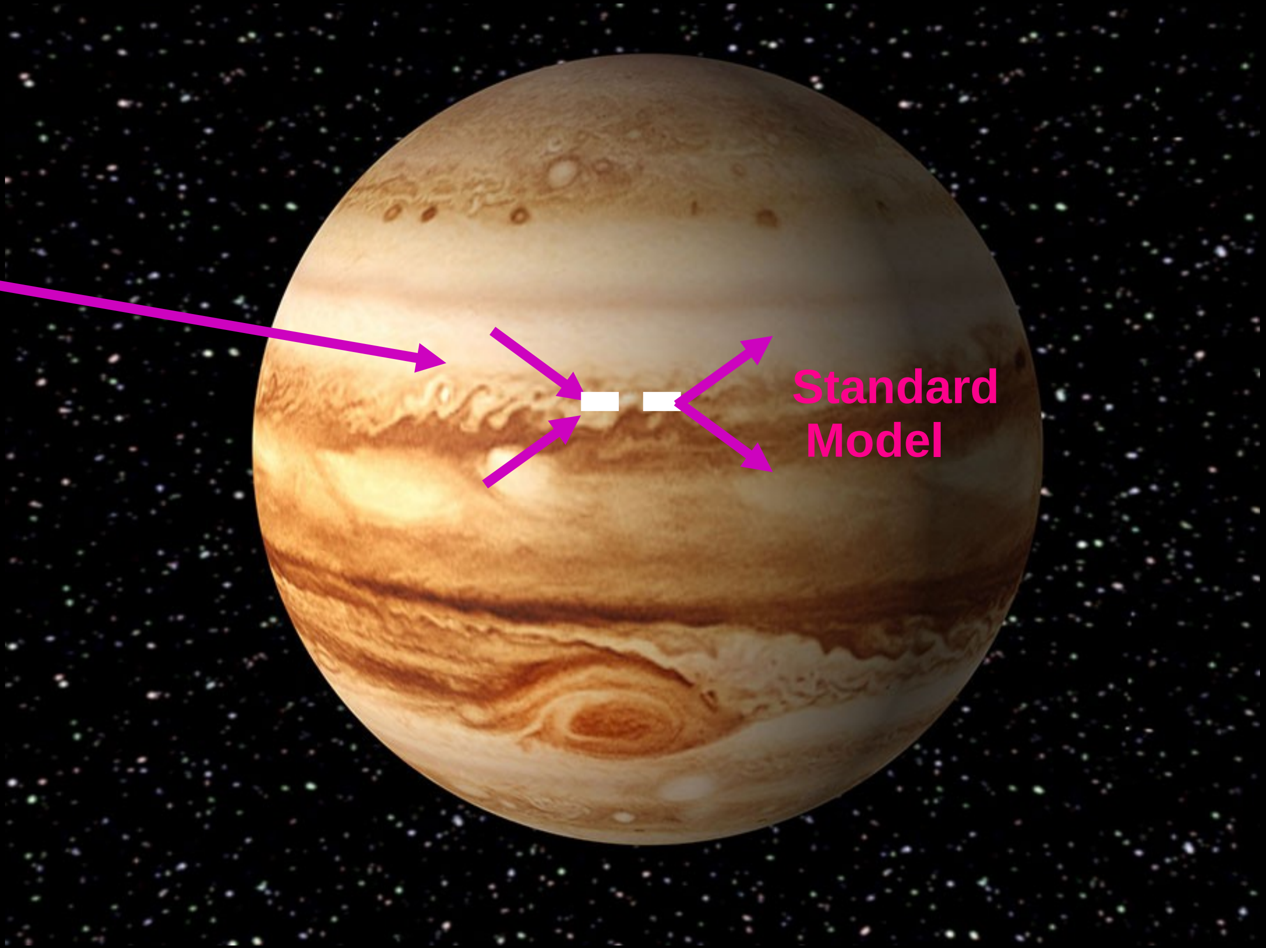
- Alternate signal:
  - Gamma rays from celestial objects!



Dark matter signals



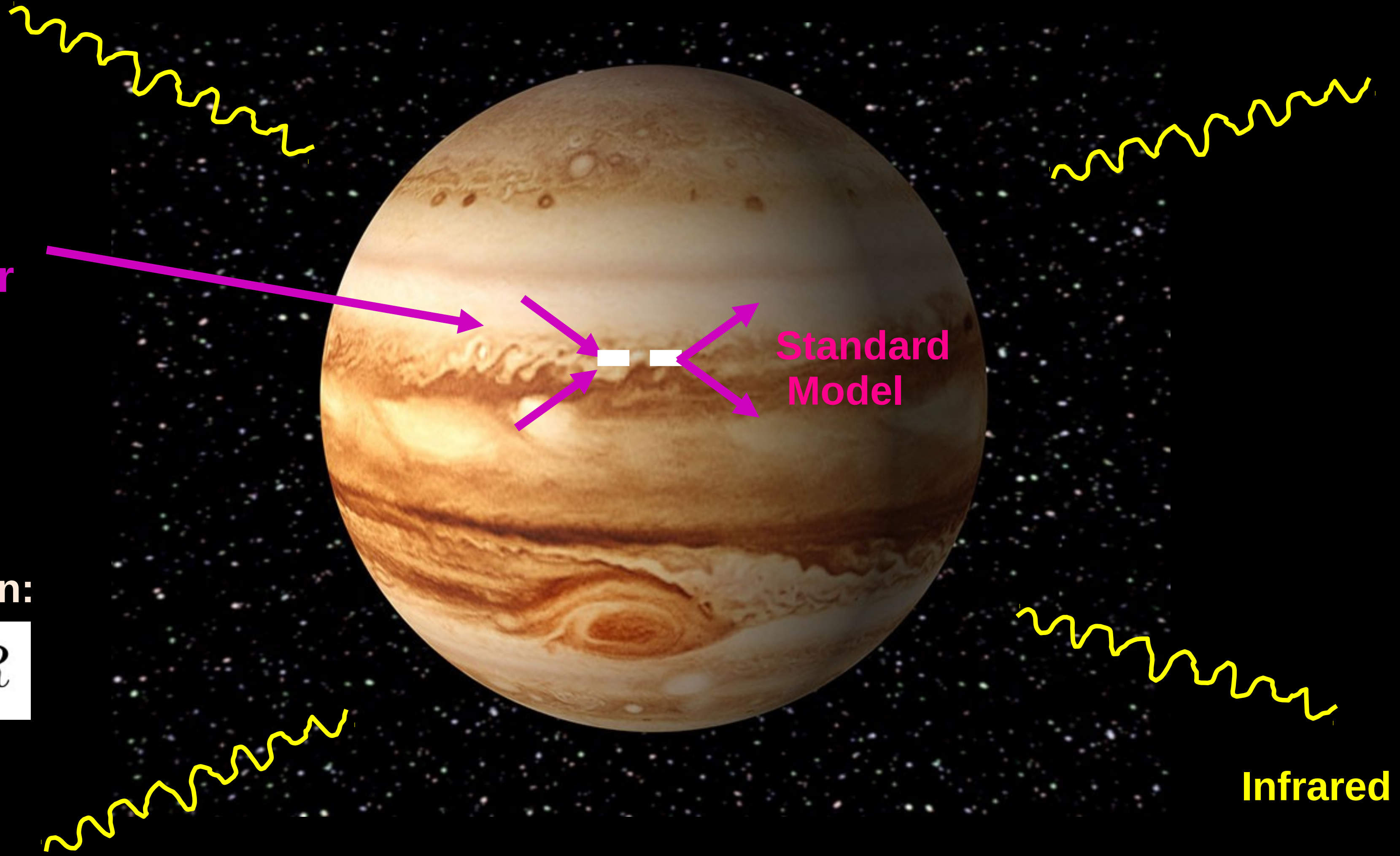
Dark matter signals



Assumption:

$$\gamma c \tau < R$$

Dark matter signals

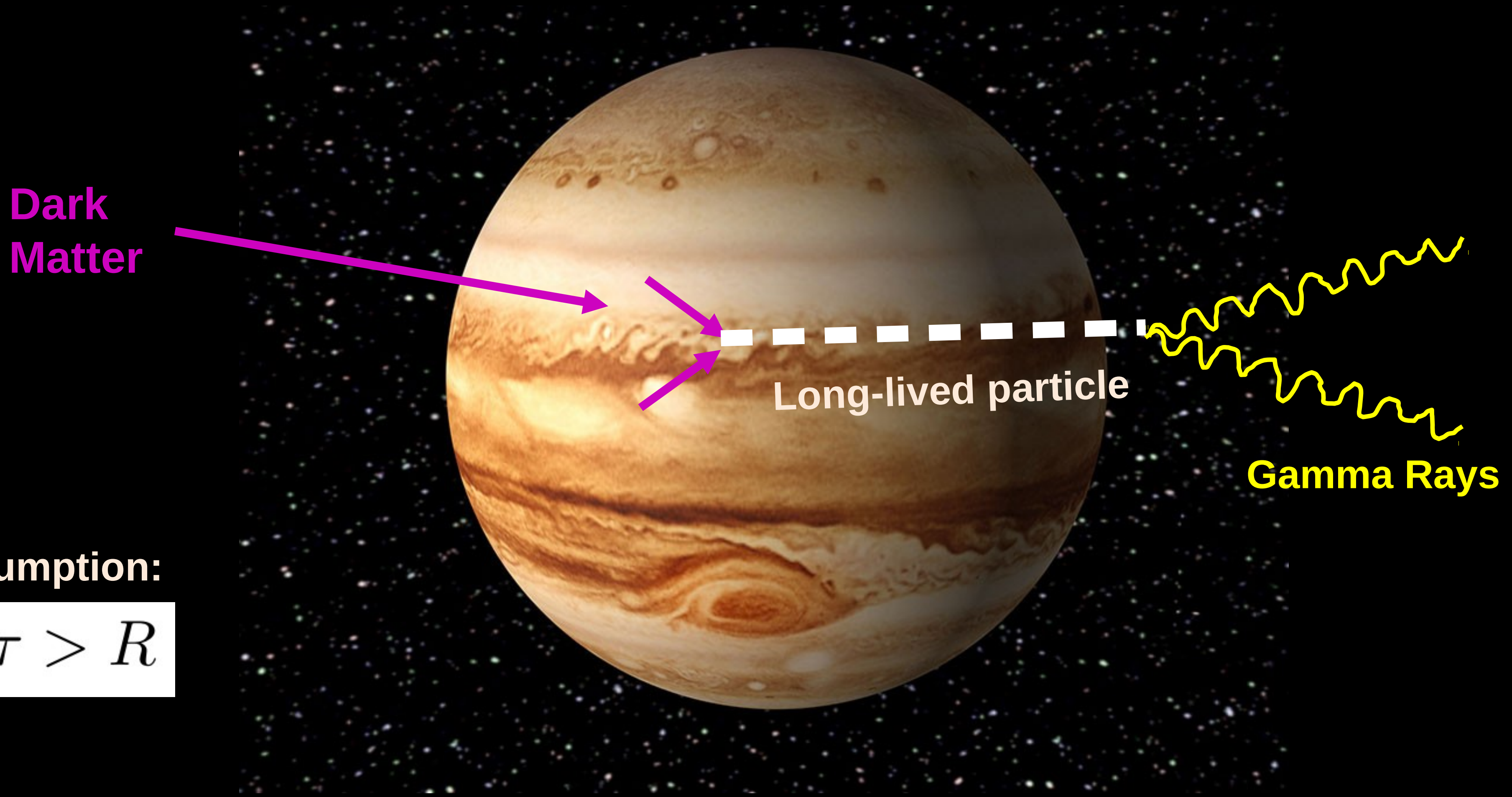


Assumption:

$$\gamma c \tau < R$$

Data next 5 - 10 years

Dark matter signals



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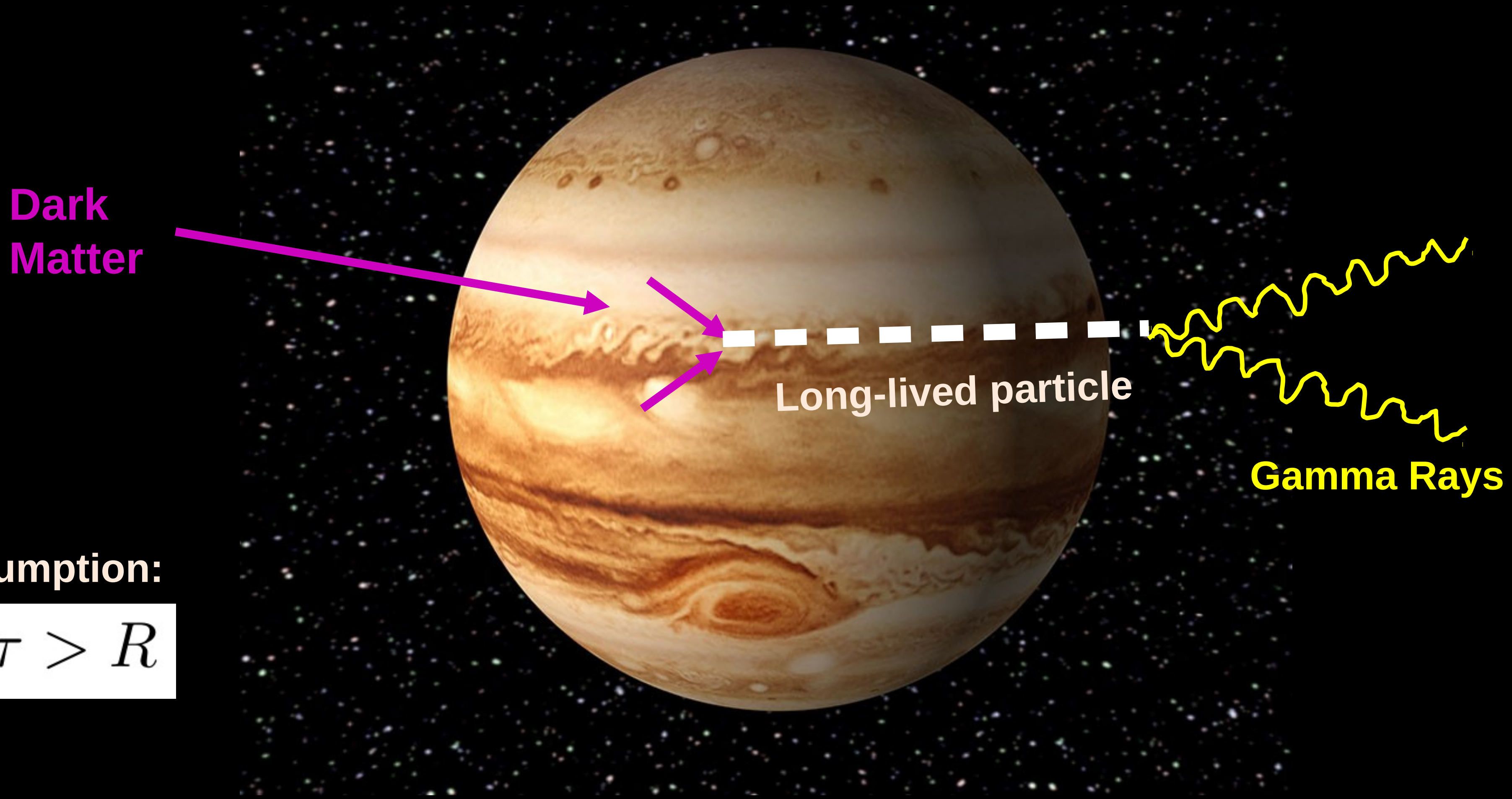
Dark matter signals



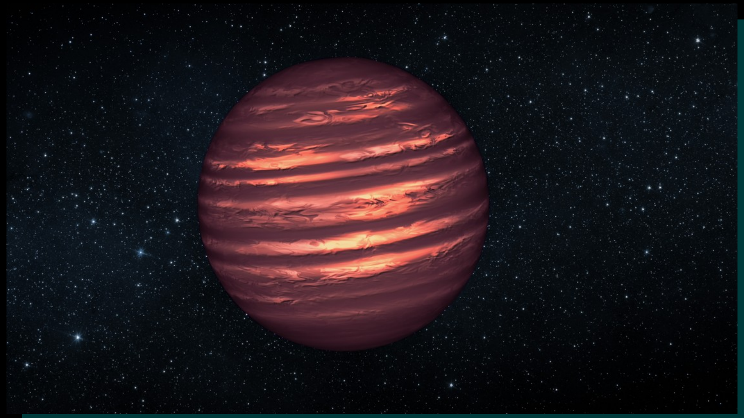
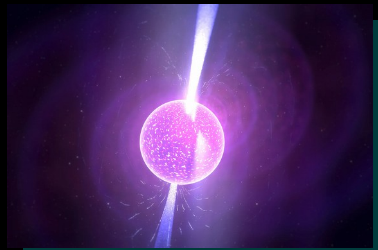
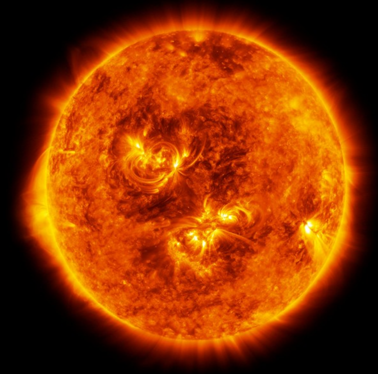
Assumption:

$$\gamma c\tau > R$$

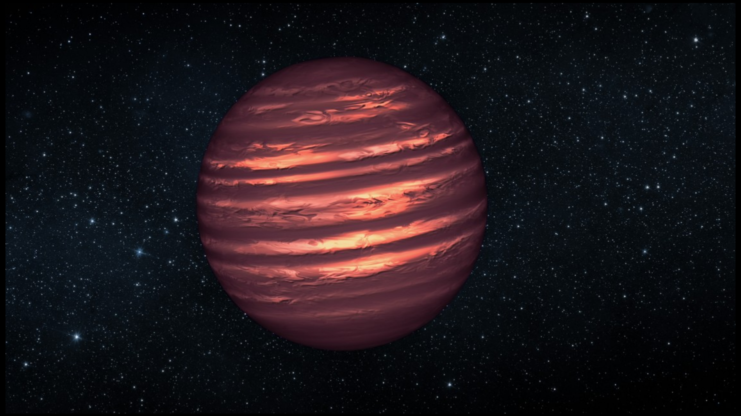
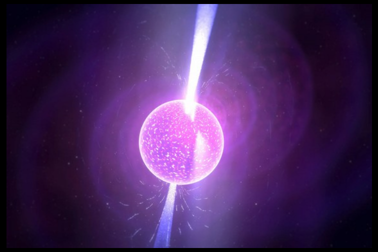
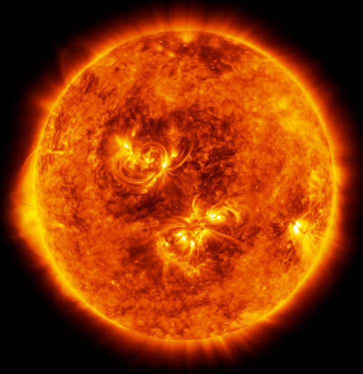
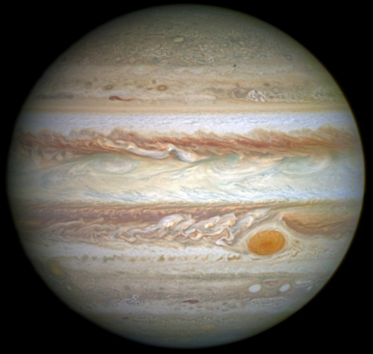
Fermi-LAT, HAWC, HESS gamma-ray data available now

Optimal Celestial Target?

- Radius: Larger amount of DM captured, larger annihilation signal
- Density: Easier to trap DM, sensitivity to weaker interactions
- Core temperature: Higher temperature gives more kinetic energy to DM, can kick out the DM (not good!)

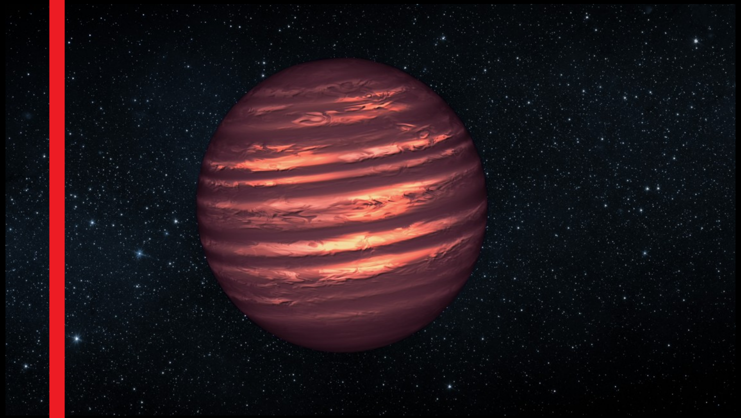





Optimal Celestial Target?

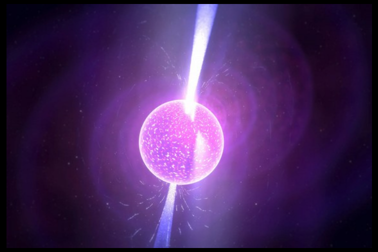
Brown Dwarf	Neutron Star	Sun	Jupiter
BIG	Small	BIG	BIG
Cold	Cold	Hot	Cold
Dense	Ultra-dense		

Optimal Celestial Target?



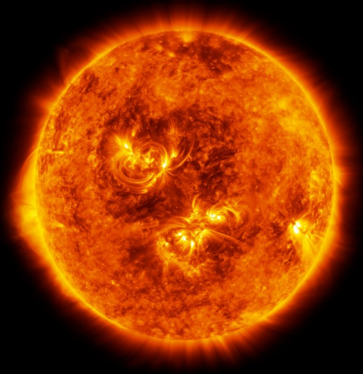
Brown Dwarf

BIG
Cold
Dense



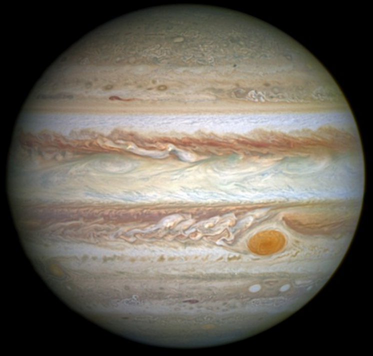
Neutron Star

Small
Cold
Ultra-dense



Sun

BIG
Hot

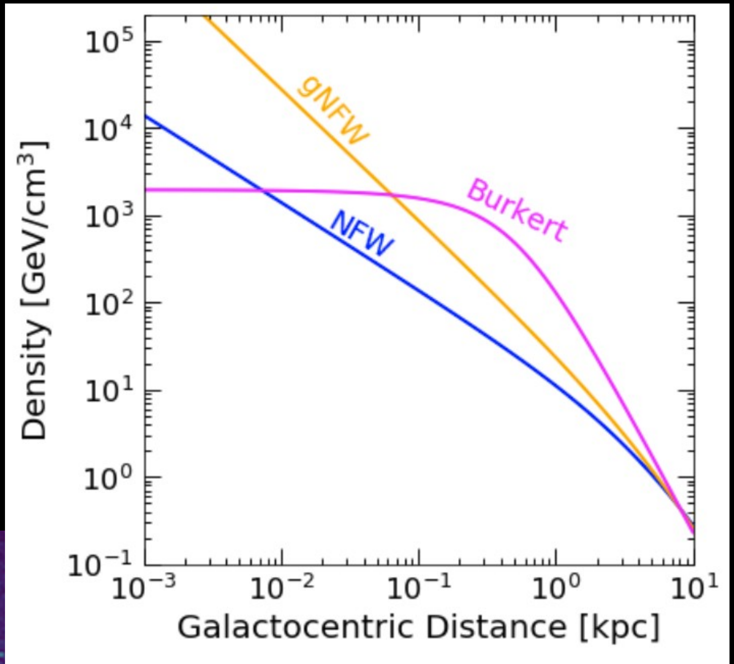


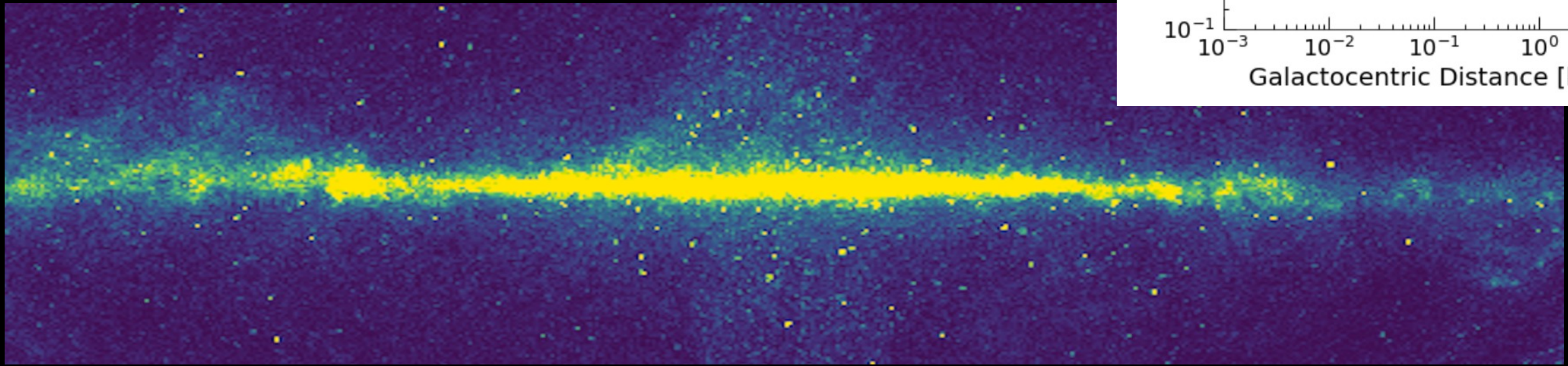
Jupiter

BIG
Cold

Galactic Center Signal

- Galactic Center benefits:
  - High DM density
  - Lower DM velocity
  - Lots of neutron stars and brown dwarfs present





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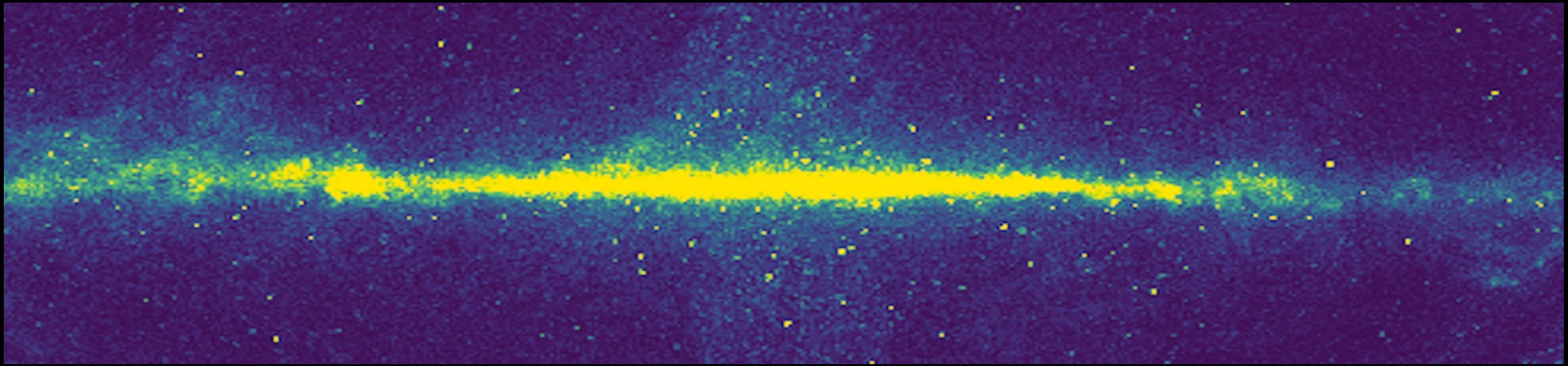
Galactic Center **Population** Signal

Use all the neutron stars, all the brown dwarfs

Indirect detection flux with celestial objects!



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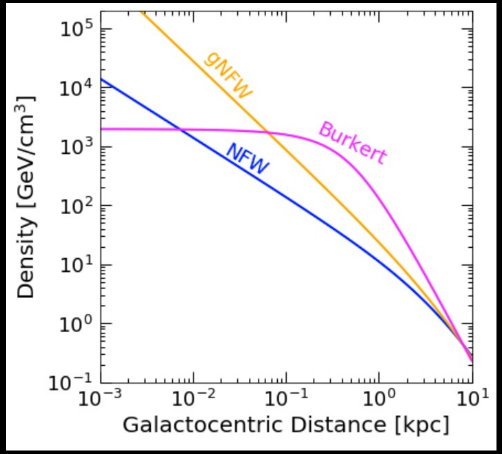
Comparison with Halo Annihilation

Halo

Annihilation Scaling: $\Gamma_{\rm halo} \propto \frac{\langle \sigma_A v \rangle \, n_\chi^2}{2}$



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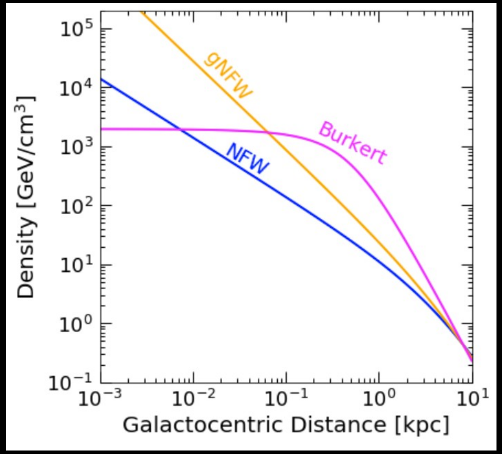
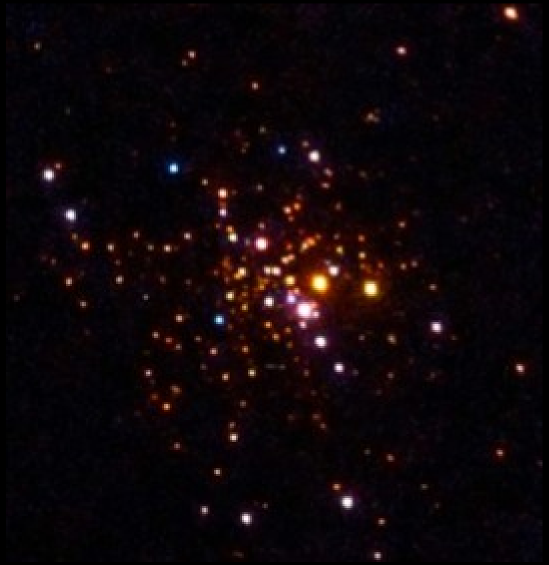


Celestial-body population



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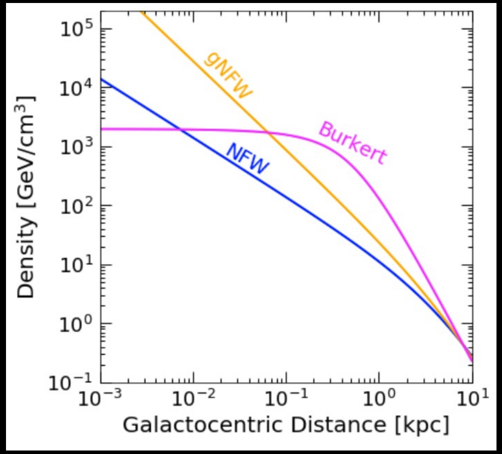
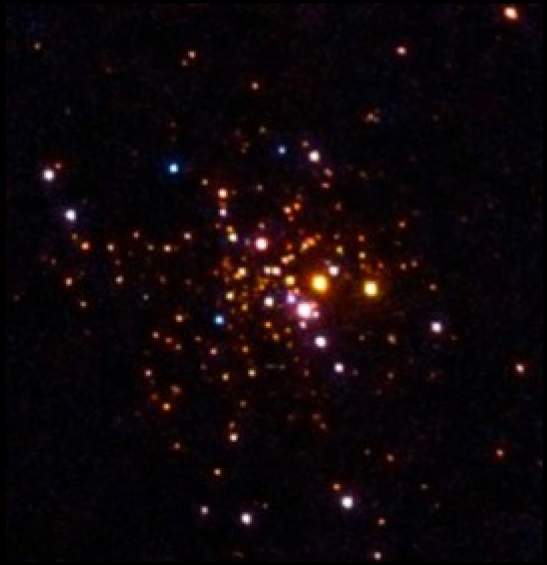


Celestial-body population

Max capture rate: $$C_{\rm max} = \pi R^2 n_\chi(r) v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{\overline{v}(r)^2}\right) \xi(v_p, \overline{v}(r)),$$



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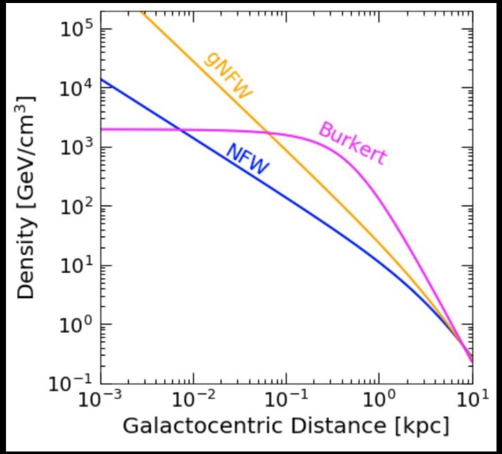

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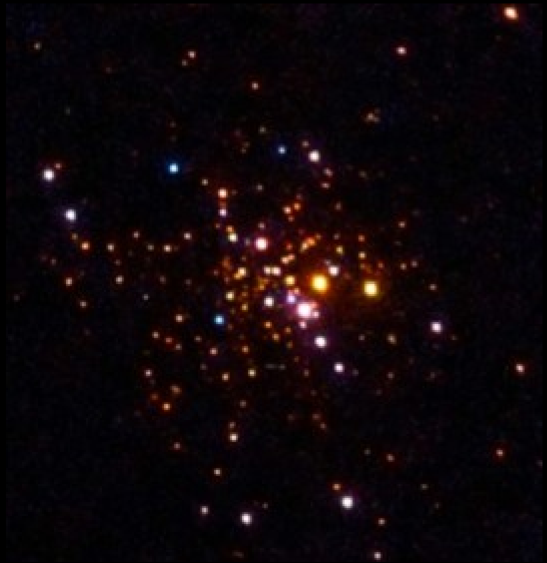
Population capture rate: $C_{\rm BD/NS,tot} = 4\pi \int_{r_1}^{r_2} r^2\, n_{\rm BD/NS}\, C\, dr$



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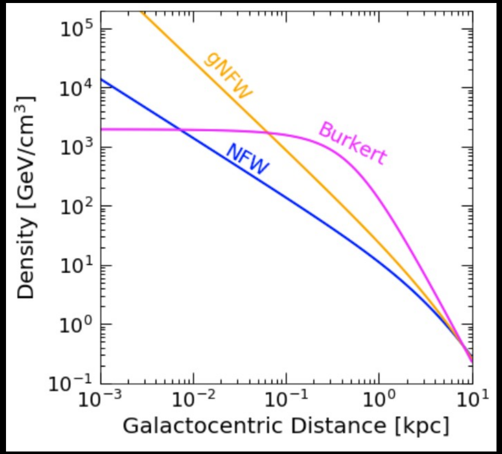

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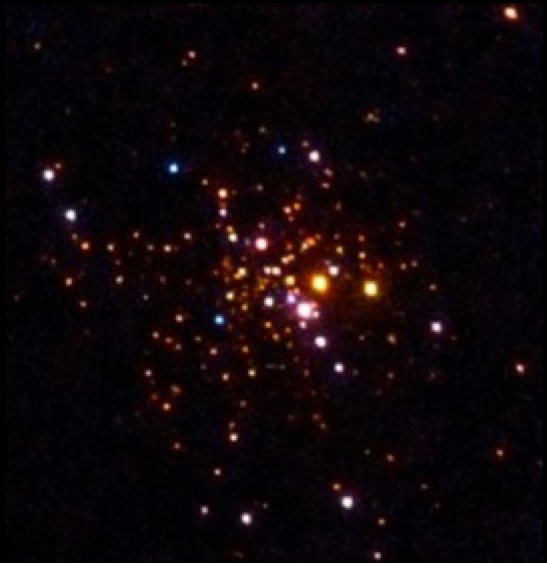

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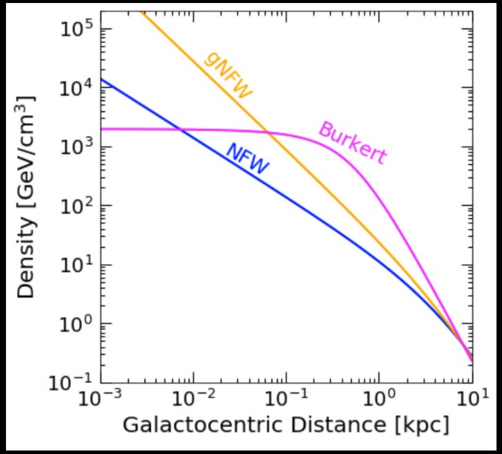

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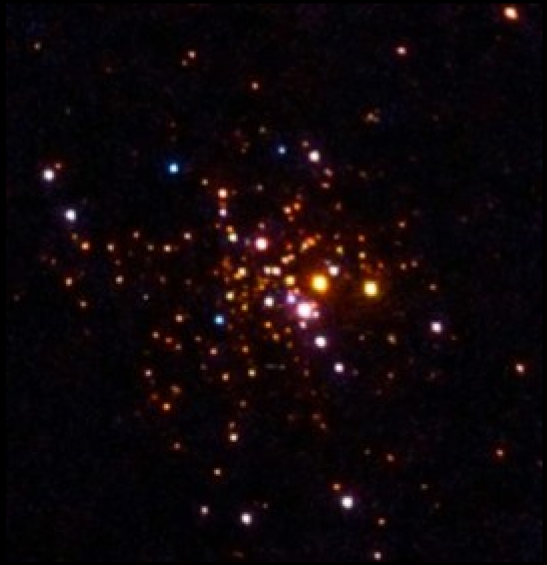


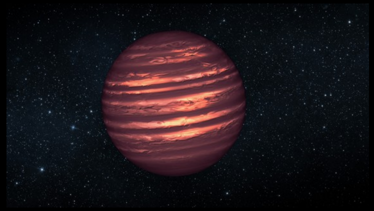
RKL, Linden, Mukhopadyay, Toro, 2021

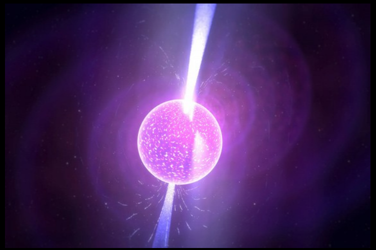
Comparison with Halo Annihilation

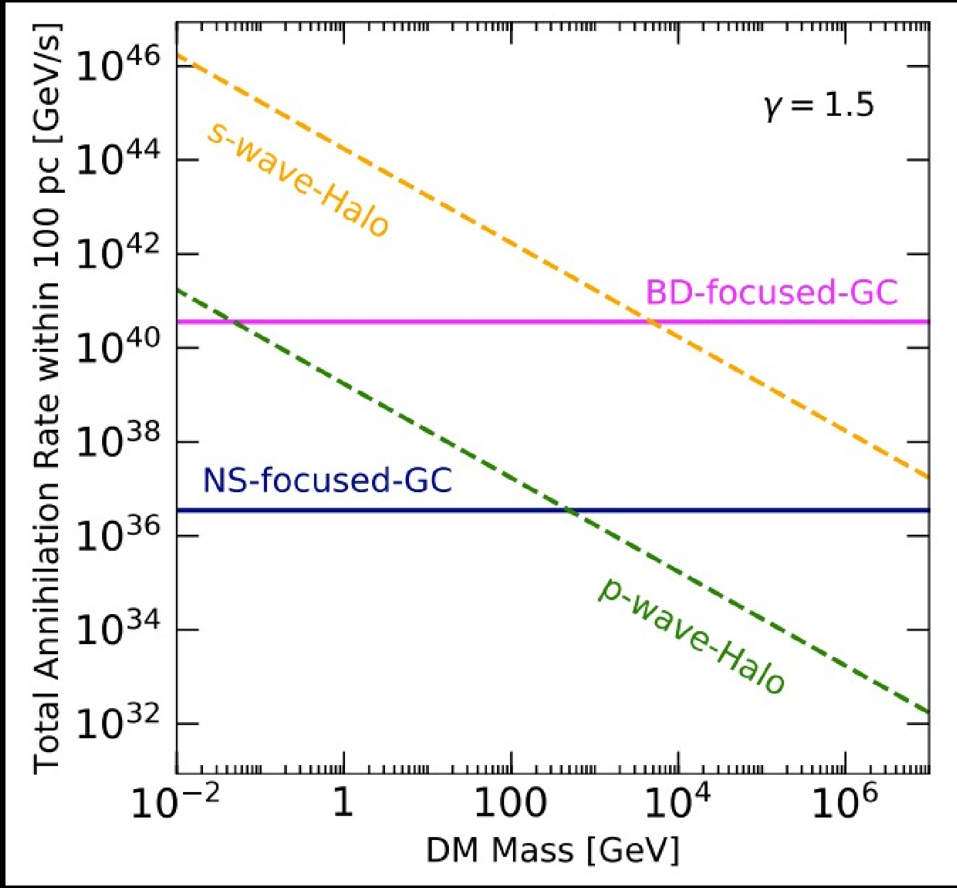
- Signal morphology:
  DM density squared,
  vs DM density*stellar density

- Celestial-body “focused” annihilation
  “focuses” rate above halo levels

- Only s-wave detectable in the halo,
  and only for lighter DM masses







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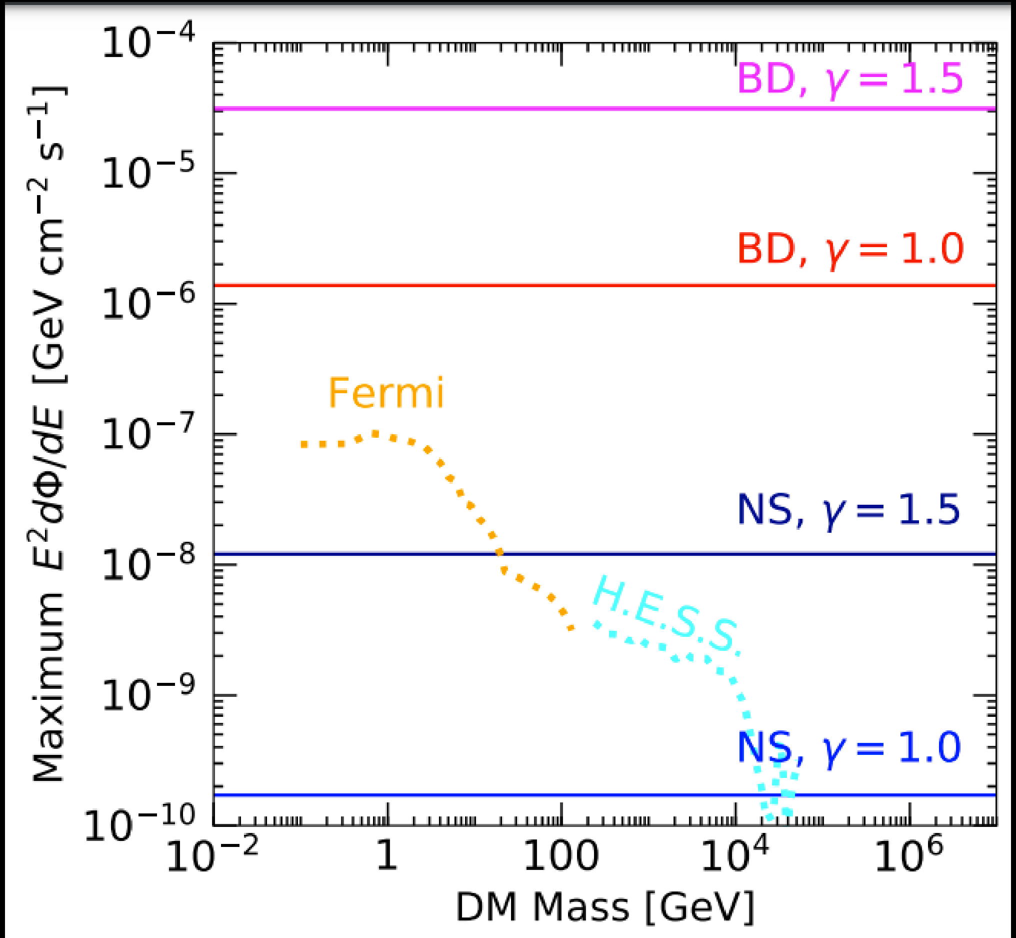
Gamma-ray population detectability

- Detectability: compare with known gamma-ray data
  - Use Fermi and H.E.S.S. data for Galactic Center
  - No model assumptions on mediator, other than must escape
  - Brown dwarfs very large signal!



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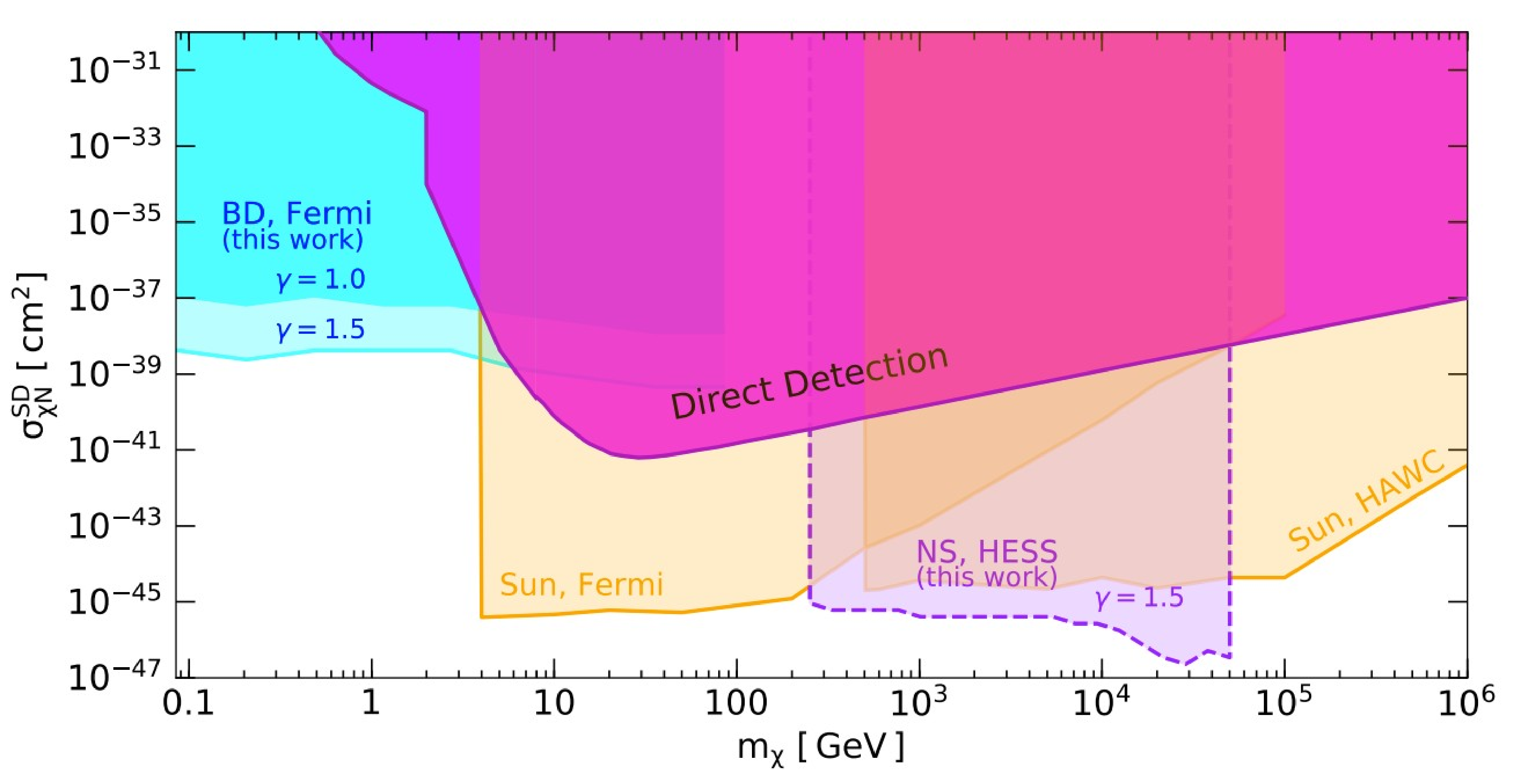
New Limits w/ Brown Dwarfs and Neutron Stars



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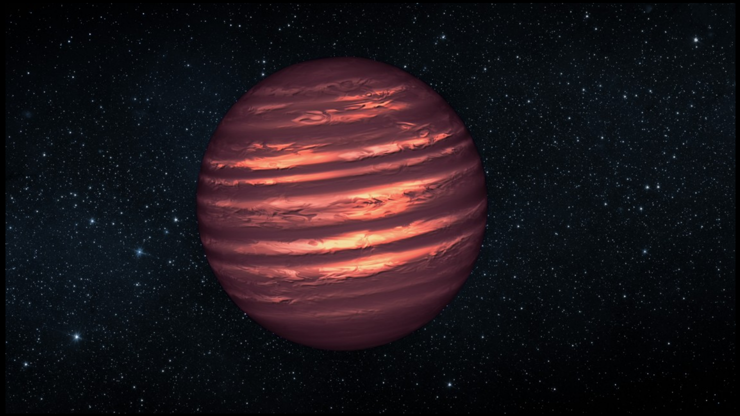
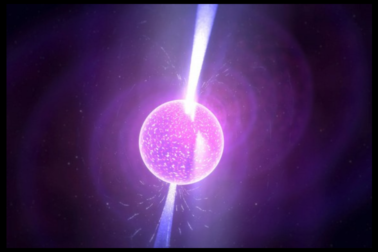
Optimal Celestial Target?



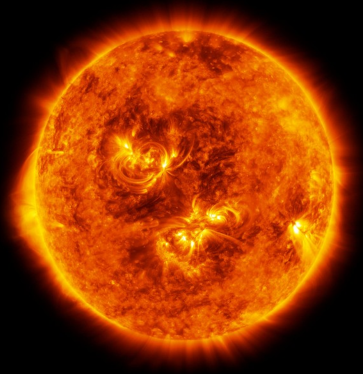
Brown Dwarf

BIG
Cold



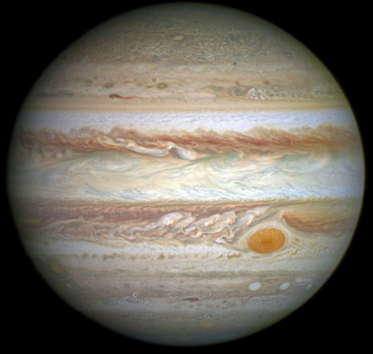
Neutron Star

Small
Cold



Sun

BIG
Hot



Jupiter

BIG
Cold

THE SUN

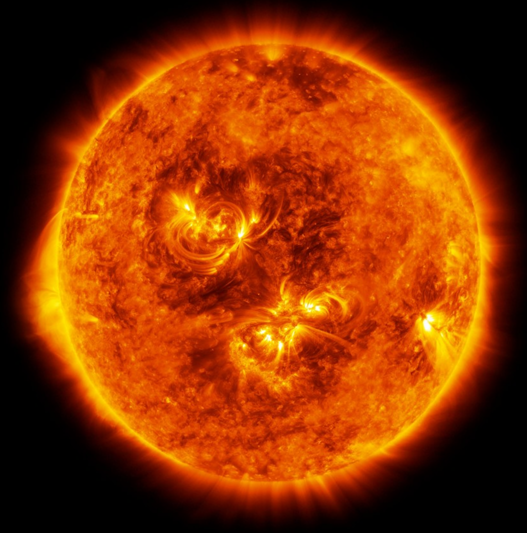
Available data:
Fermi, HAWC

Limitations:

+ Hot
+ Higher DM evaporation (~GeV mass)

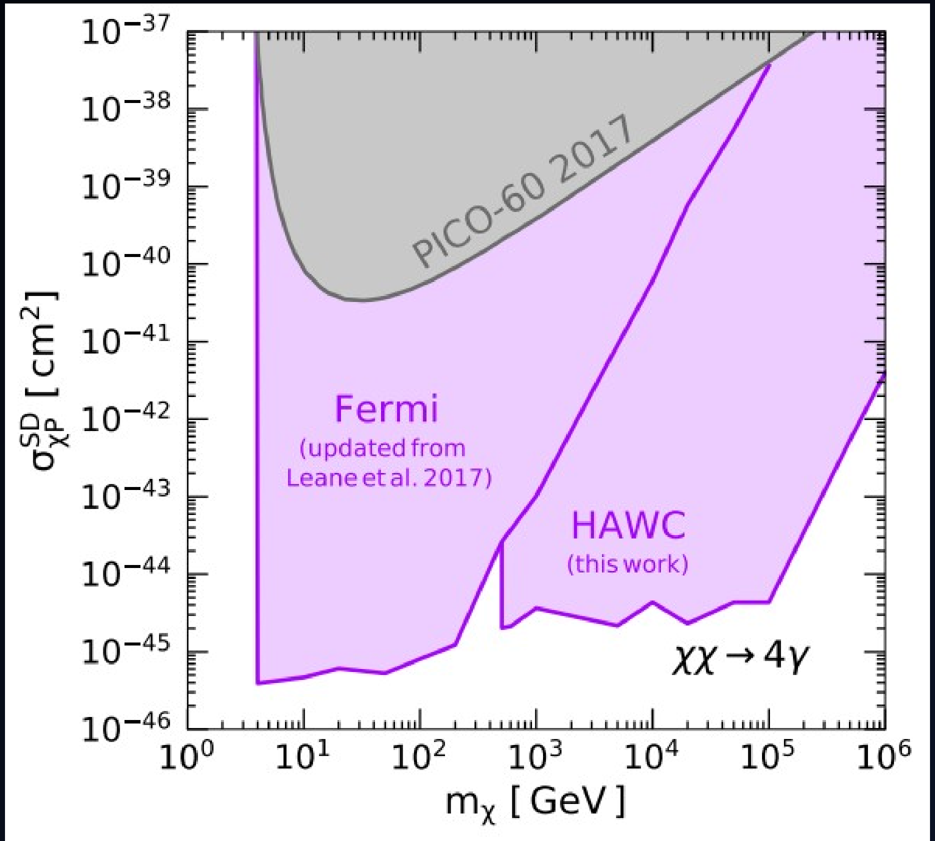
Benefits:

+ Huge
+ Proximity
+ Excellent data

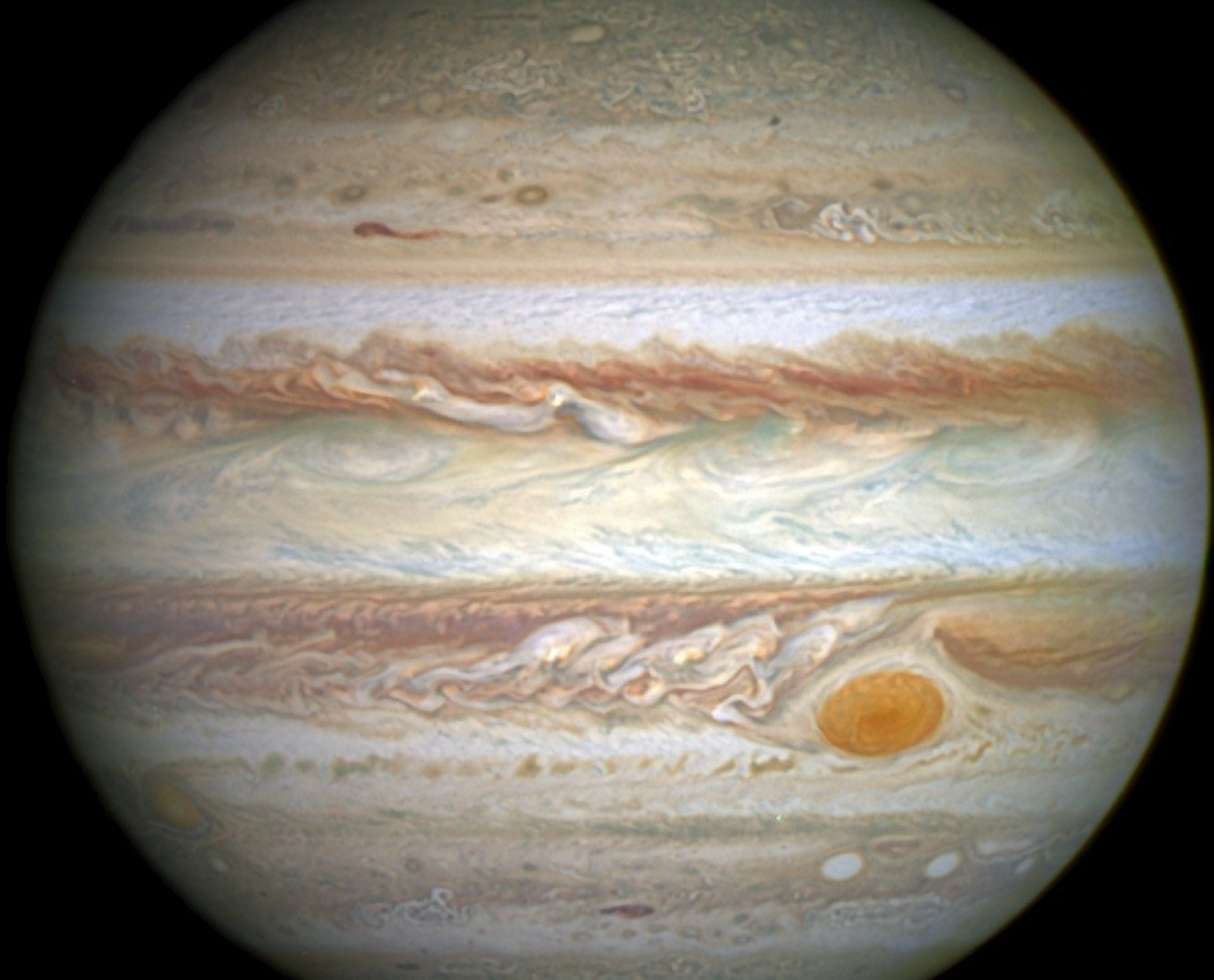


THE SUN

- Long-lived particle scenario, excellent gamma-ray sensitivity



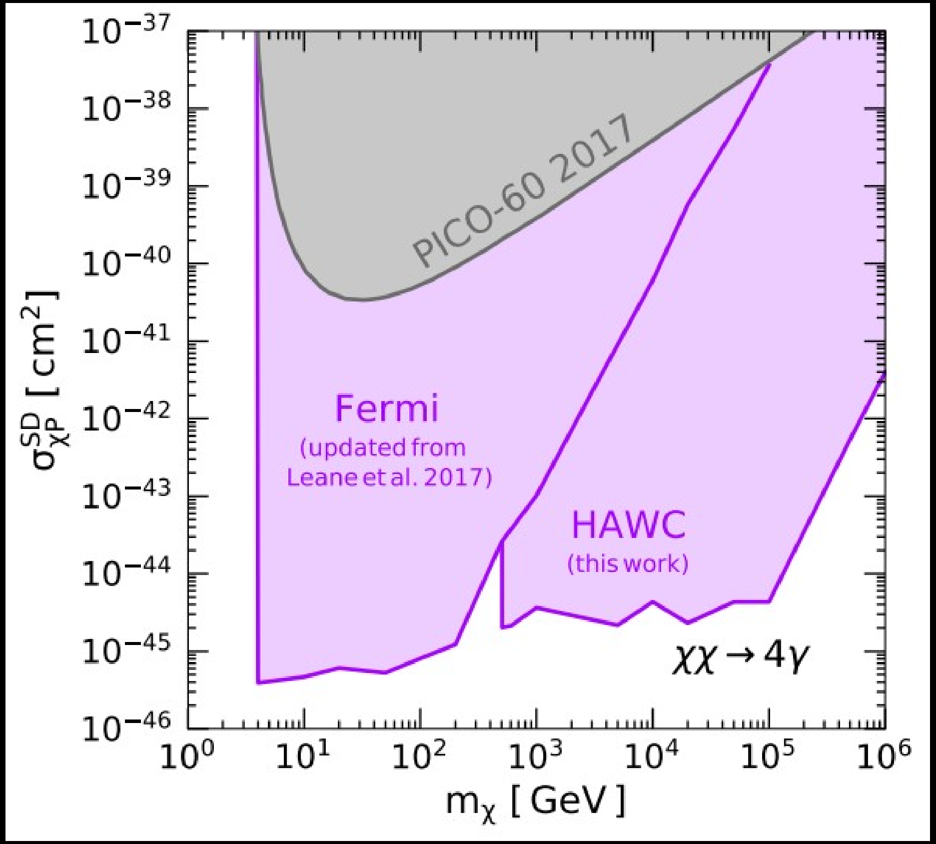
Leane, Ng, Beacom (PRD '17)
Leane + HAWC Collaboration (PRD '18 a,b)



JUPITER

Leane, Linden 2021

Why Jupiter?

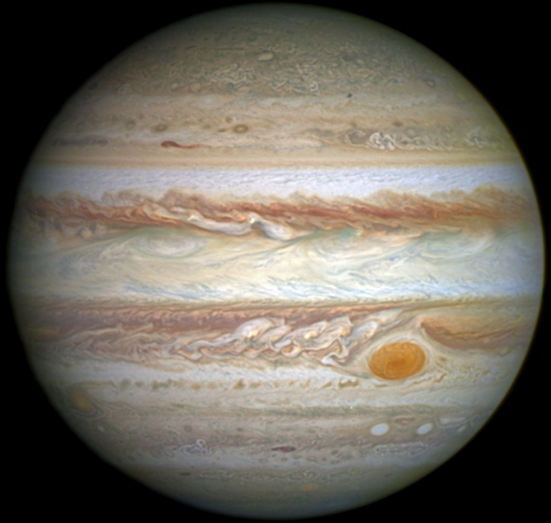


Sun

Long-Lived Mediator Limits

Leane, Ng, Beacom (PRD ‘17)

Leane + HAWC Collaboration (PRD ‘18)



Jupiter

Cooler than the Sun:
MeV-DM mass sensitivity!

Jupiter in Gamma Rays

What does Jupiter look like in gamma rays?
No one had ever really checked!

If we find gammas, they could be from:

+ acceleration of cosmic rays in Jovian magnetic fields

+ interaction of cosmic rays with Jupiter’s atmosphere

...or something exotic (dark matter)!

Fermi Analysis of Jupiter

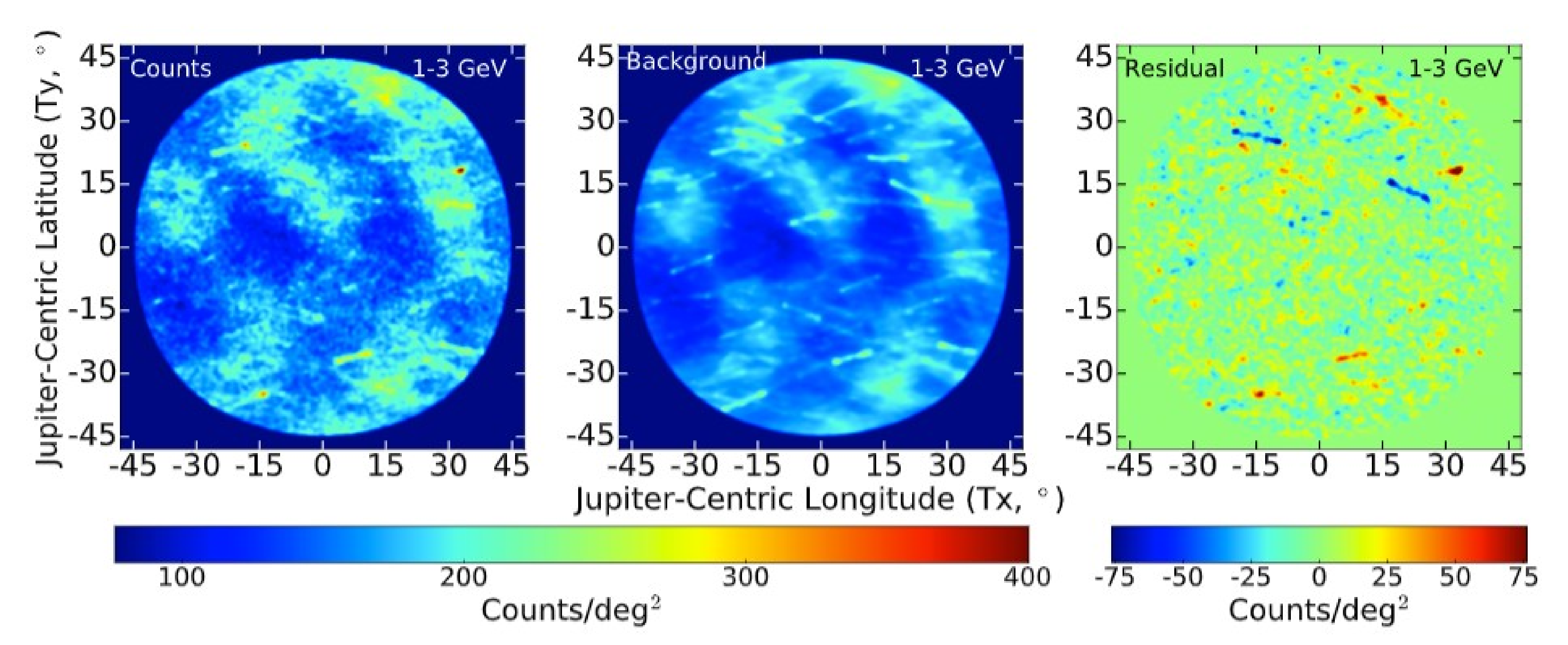
+ Analyze 12 years of Fermi data, 10 MeV – 10 GeV

+ Select photons within 45 degrees of Jupiter’s orbit

+ Data-driven background model from Jupiter orbit when it is not there

+ Subtract “on” and “off” map events

Jupiter in Gamma Rays



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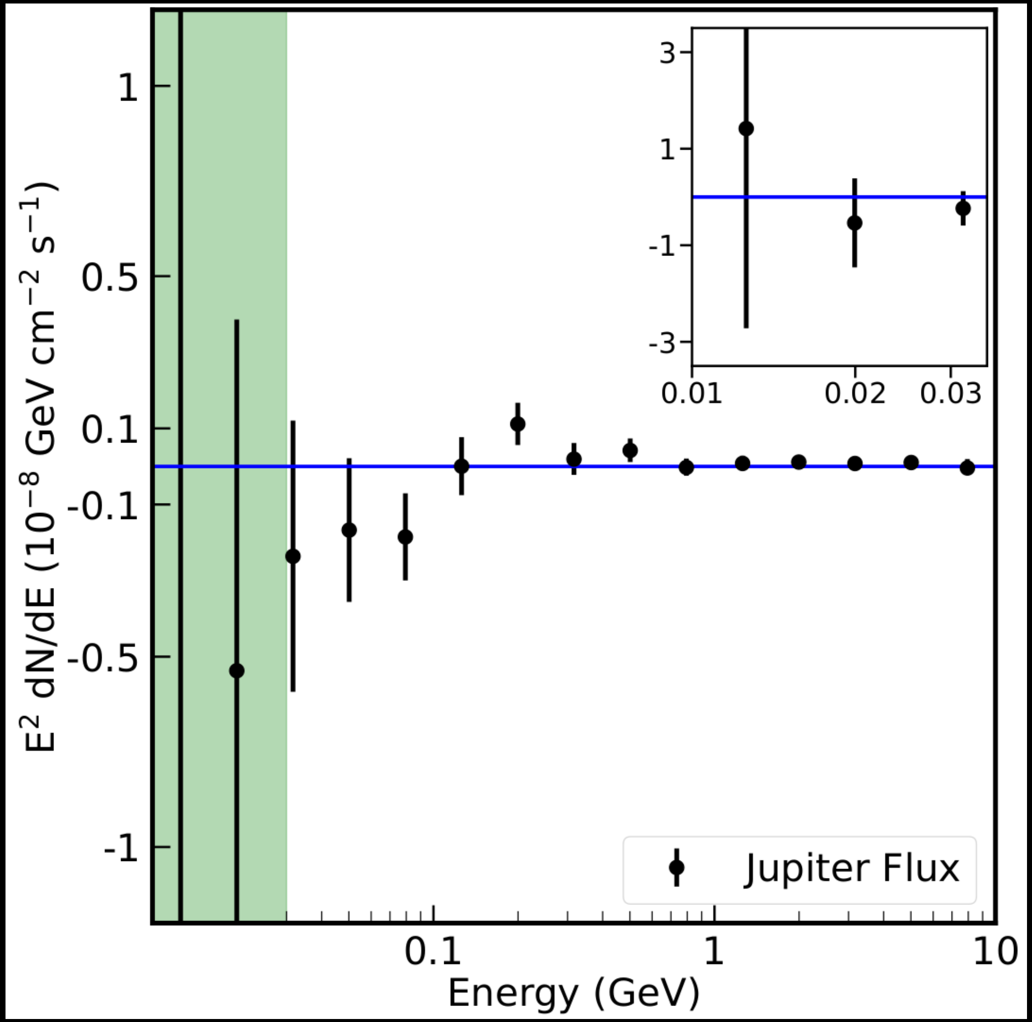
Jupiter Gamma-Ray Flux Limits

+ For range of power-law spectra, statistical sig of Jupiter emission never exceeds ~1.5σ

+ In low energy bins, larger excess, but important systematics not there

+ Motivates follow-up with MeV telescopes: AMEGO, e-ASTROGAM



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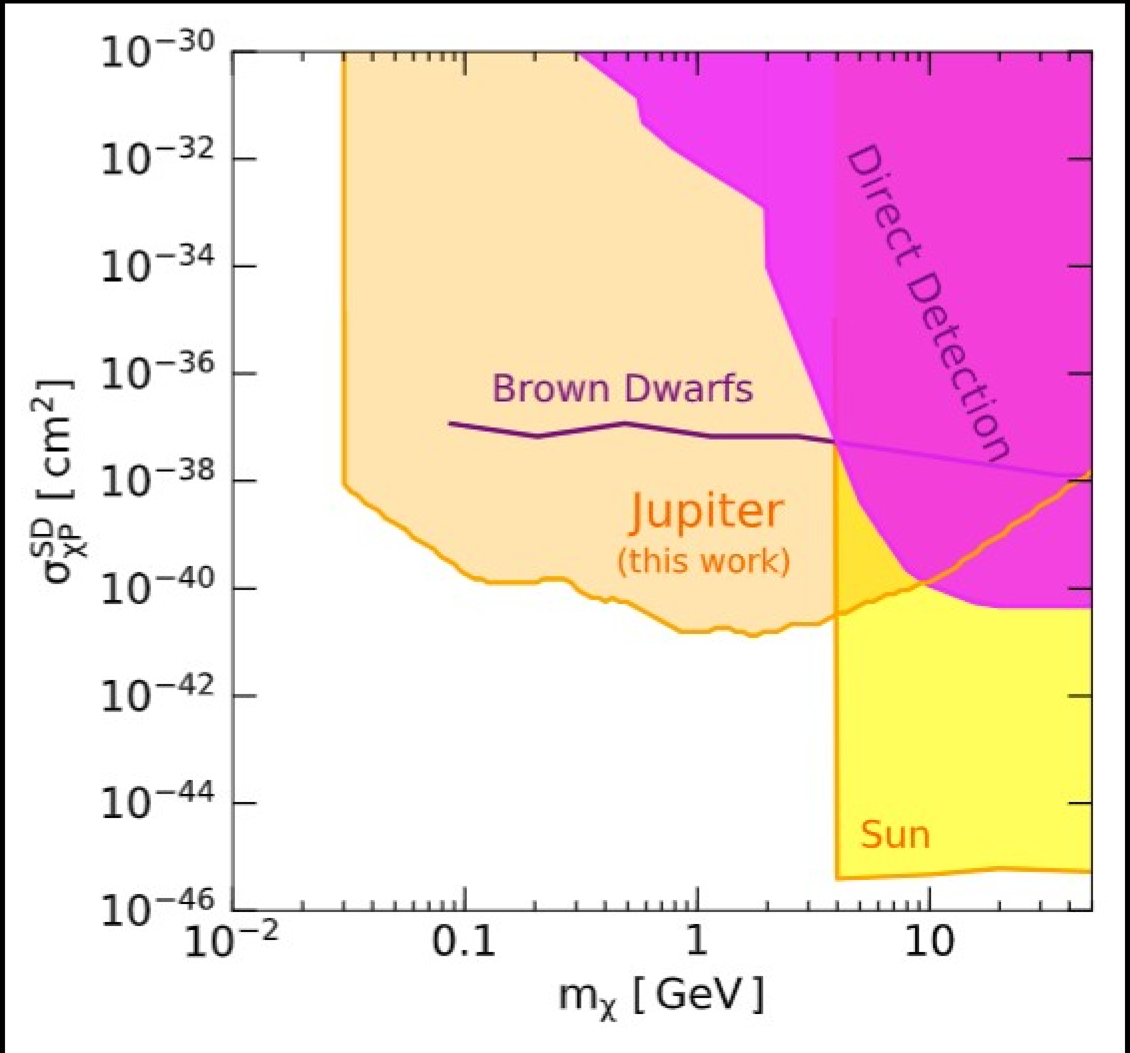
New dark matter limits

Some assumptions:

+ direct decay to gammas,
(but other final states possible)

+ mediator decay length > Jupiter radius

+ equilibrium



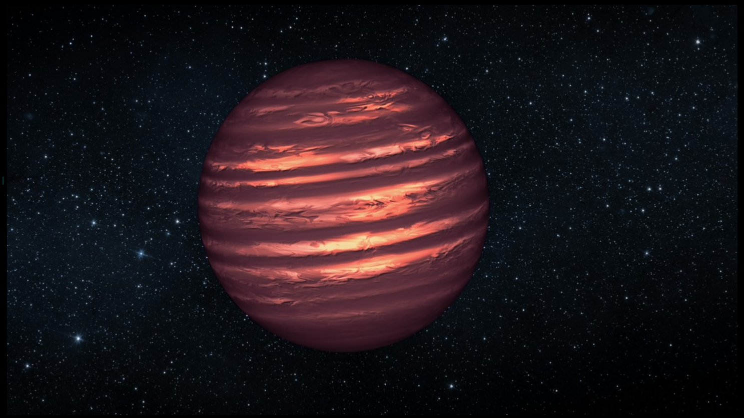
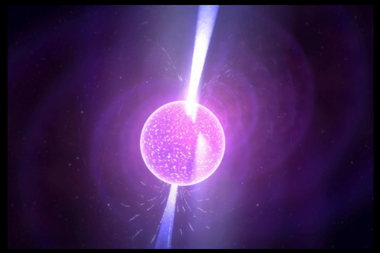
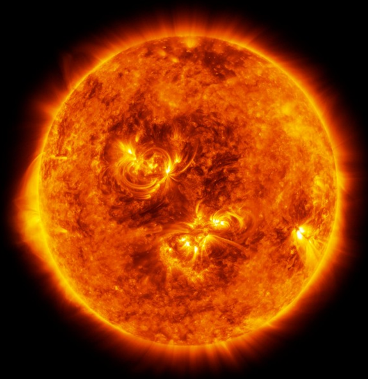
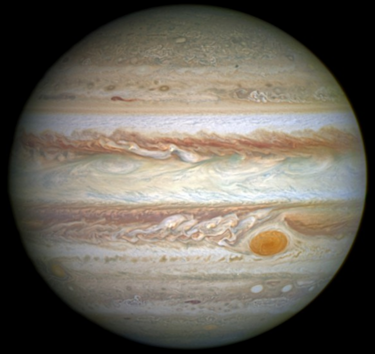
Leane + Linden '21

Summary

- New gamma-ray searches for sub-GeV DM in celestial bodies:

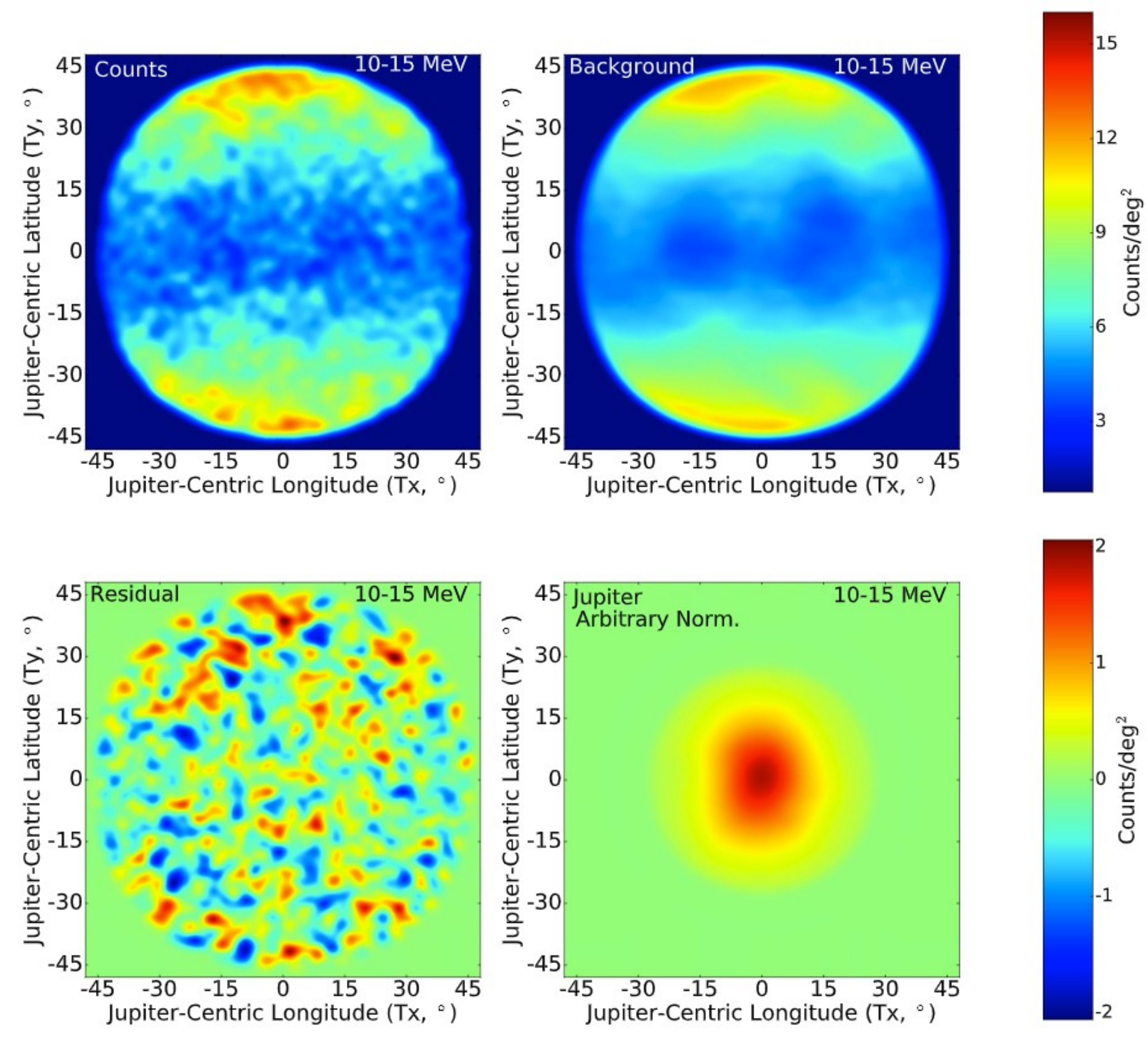
  + Search for gamma rays, powered by Galactic Center population of brown dwarfs or neutron stars, new sub-GeV DM limits

  + Search for gamma rays from Jupiter, new sub-GeV DM limits, motivates follow up with MeV gamma-ray telescopes

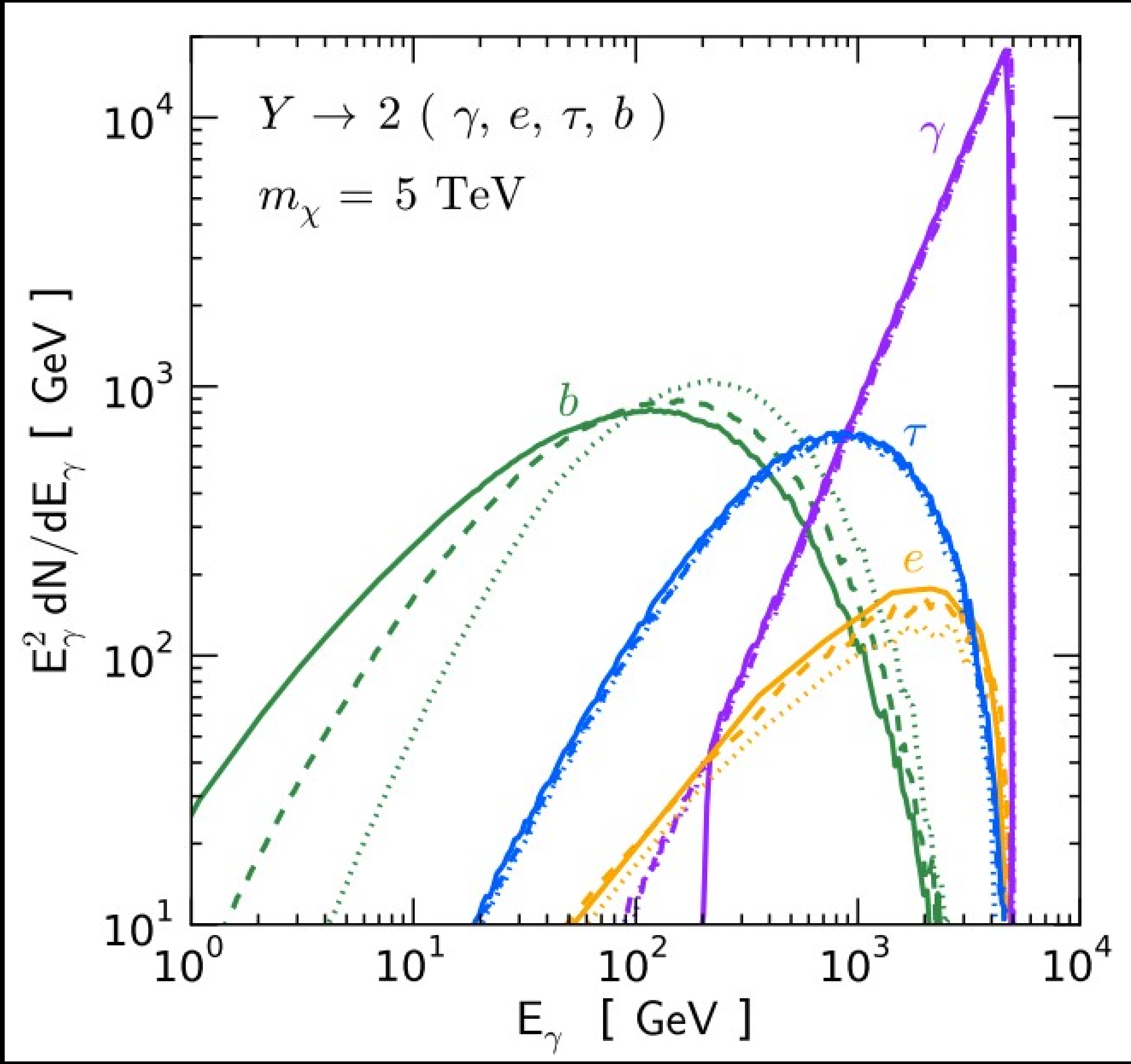





EXTRA SLIDES

Jupiter in Gamma Rays



Leane + Linden '21



Rebecca Leane (SLAC)