GAMMA-RAY SEARCHES FOR DARK MATTER

REBECCA LEANE
SLAC NATIONAL ACCELERATOR LABORATORY

IDM 2022, VIENNA, AUSTRIA
JULY 21ST 2022

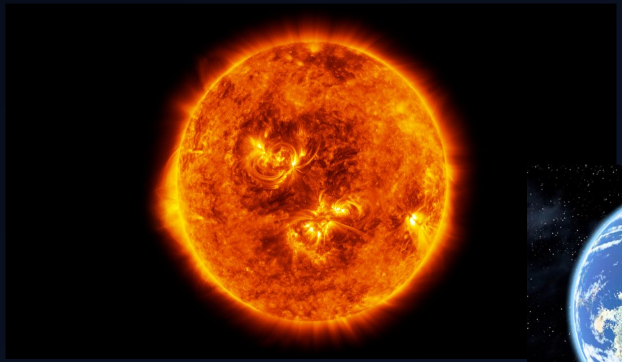
Why indirect detection is exciting

- Universe has been running experiments <u>for us</u> over very long time scales
- Can uniquely access specific scales: long decay lengths, smaller couplings, high energies
- Dark matter in its natural habitat
  - Well defined target rates

Outline

- Traditional Indirect Detection
  - Ingredients for Searches
  - Gamma Ray Instruments
    - Now and future, sensitivities
  - Combining constraints

- New Astrophysical Searches
  - DM in astrophysical objects
  - Gamma-ray signals

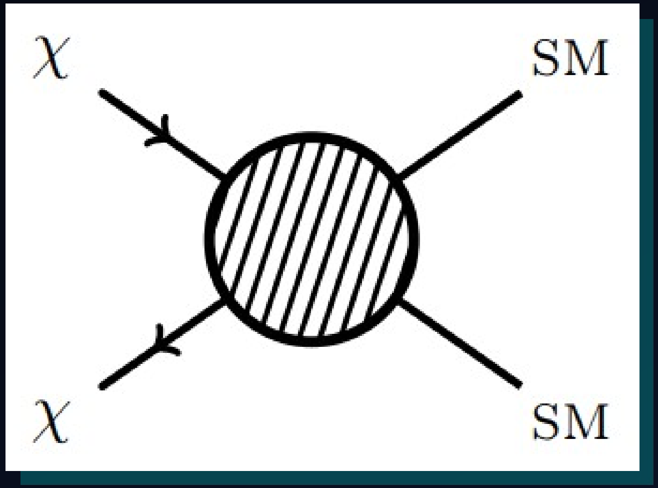


Ingredients for Indirect Searches

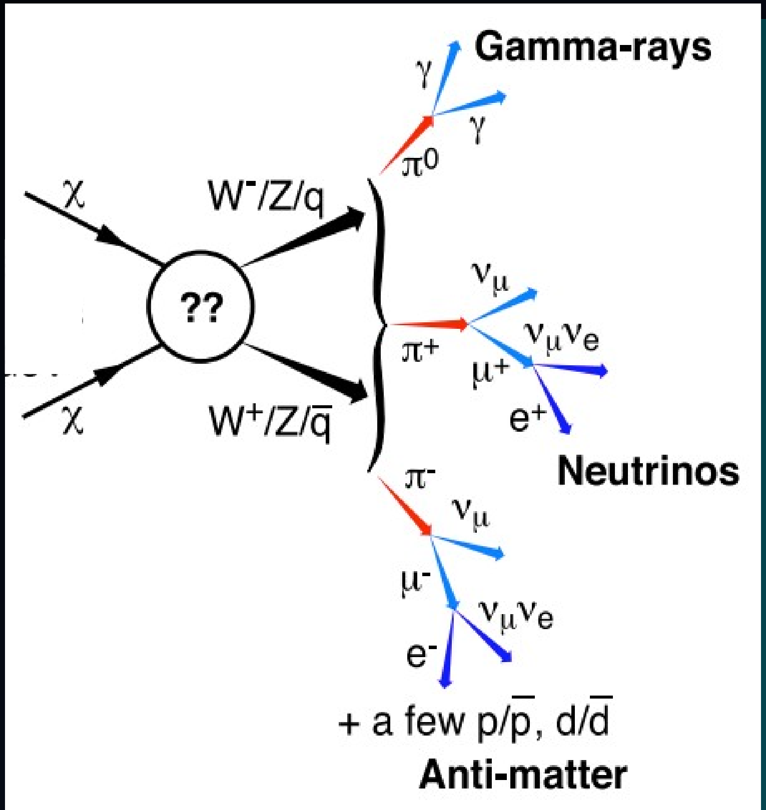
Rebecca Leane

Ingredient #1: DM Interaction Rate

- DM annihilation or decay rate
- Particle model dependent, usually fixed by relic abundance

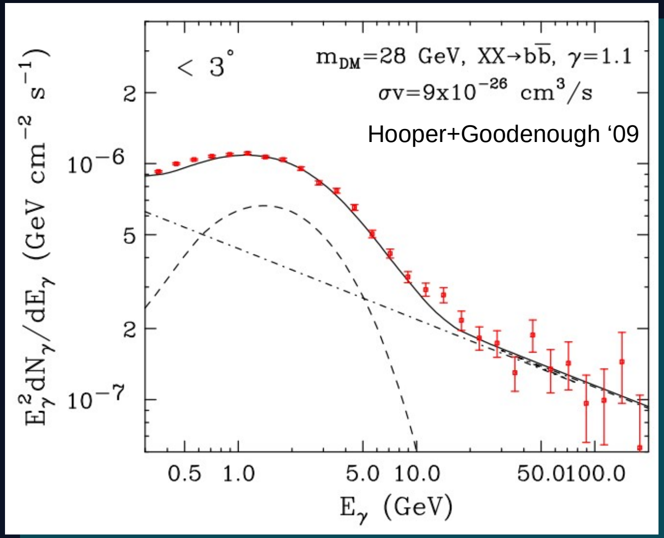


Ingredient #2: Energy Spectrum



Baltz et al 0806.2911

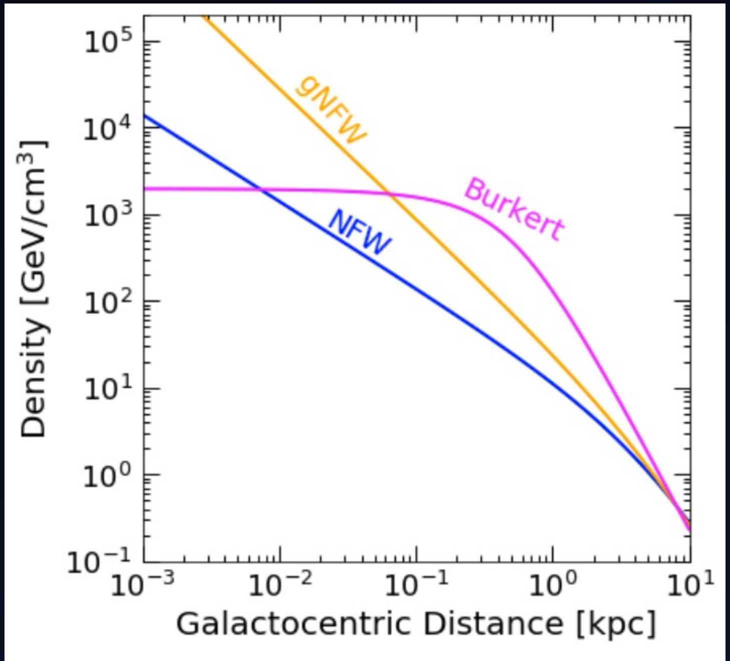
- Also driven by particle physics model
- Shape depends on:
  - branching ratios to final SM states
  - boosts of particles



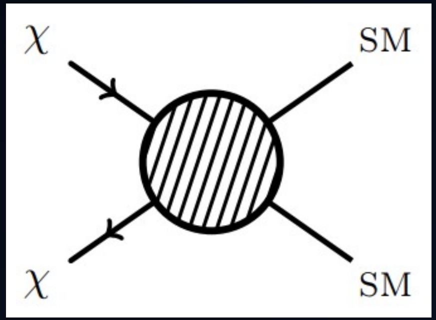
Ingredient #3: DM Density+Distribution

- Line of sight integral over DM density
  - J-factor (annihilation)
  - D-factor (decay)

- DM density profiles not well-known
  - large uncertainties



Indirect Detection Ingredients



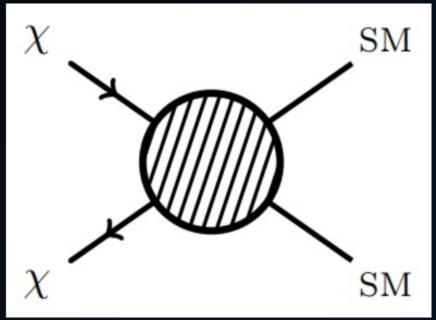
Particle Physics

Astrophysics

(Gamma rays: straight propagation!)

$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a\, d\ell.$$

Indirect Detection Ingredients



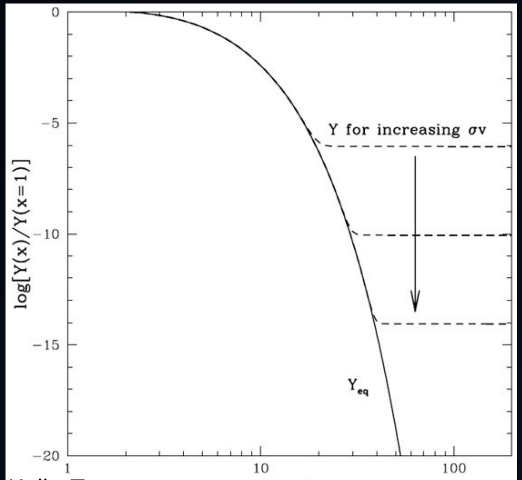
Particle Physics

Astrophysics

(Gamma rays: straight propagation!)

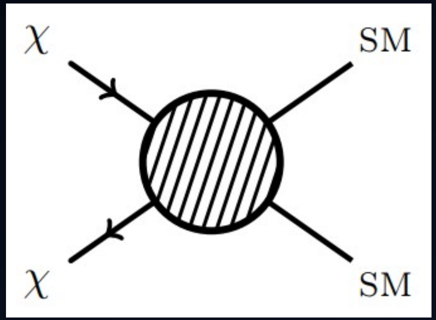
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a \, d\ell.$$

Annihilation cross section



Kolb+Turner

Indirect Detection Ingredients



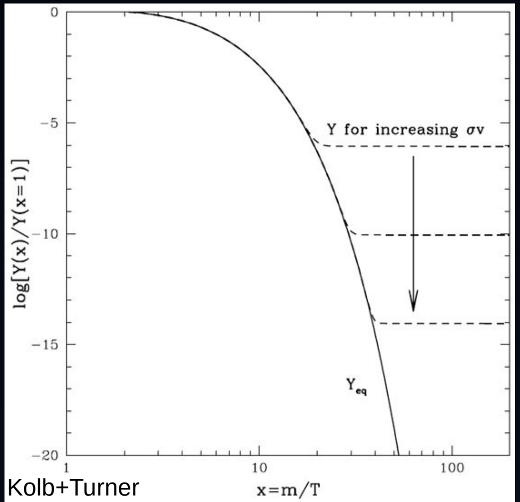
Particle Physics   Astrophysics

(Gamma rays: straight propagation!)

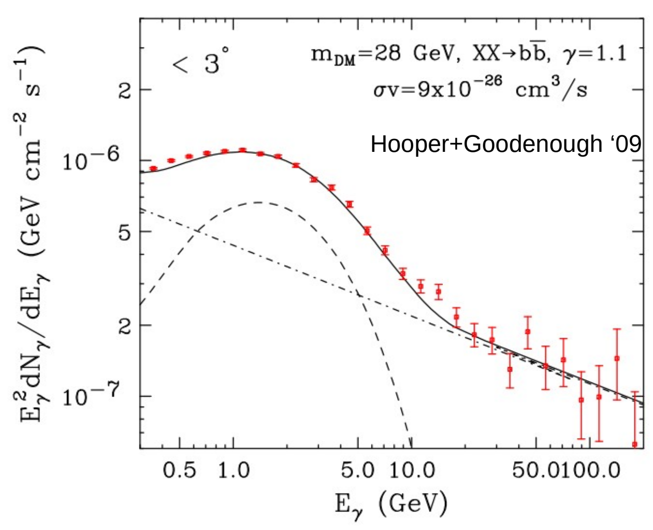
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a\, d\ell.$$

Annihilation cross section

Energy spectrum

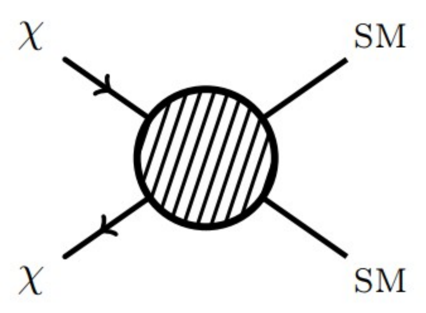


Kolb+Turner



Hooper+Goodenough '09

Indirect Detection Ingredients



Particle Physics | Astrophysics

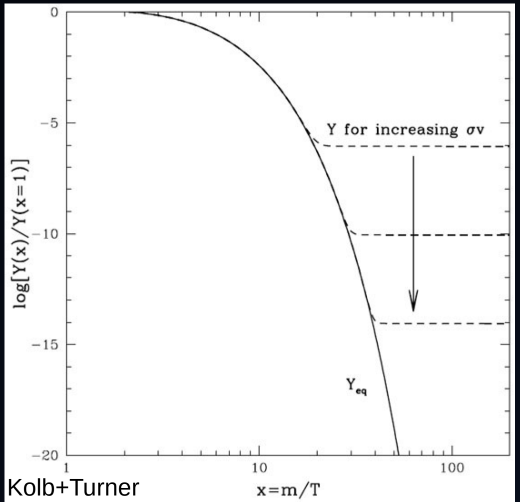
(Gamma rays: straight propagation!)

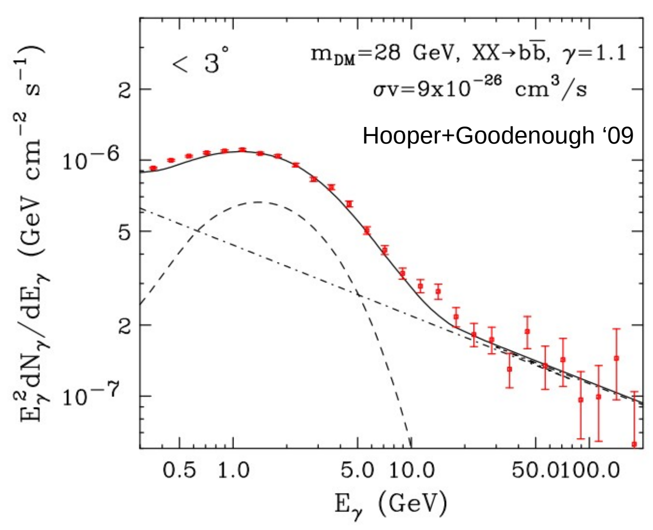
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a} \frac{dN}{dE} \int \rho[r,(\ell,\phi)]^a \, d\ell.$$

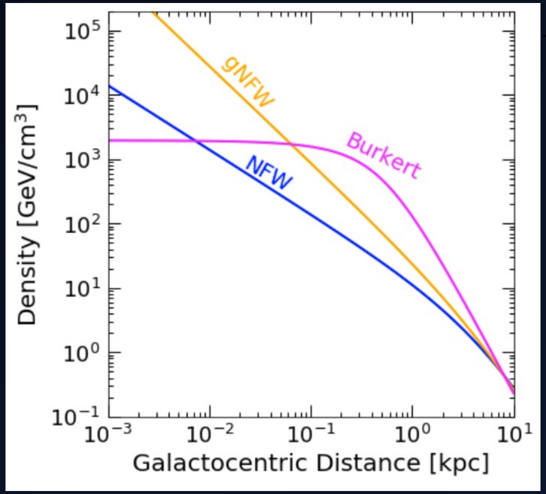
Annihilation cross section

Energy spectrum

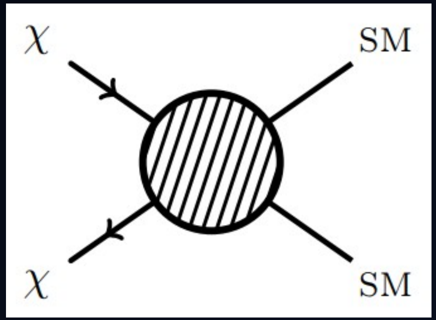
"J factor", DM density







Indirect Detection Ingredients



Particle Physics

Astrophysics

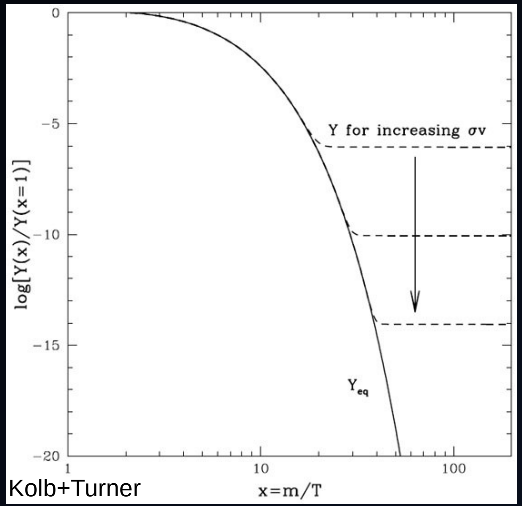
(Gamma rays: straight propagation!)

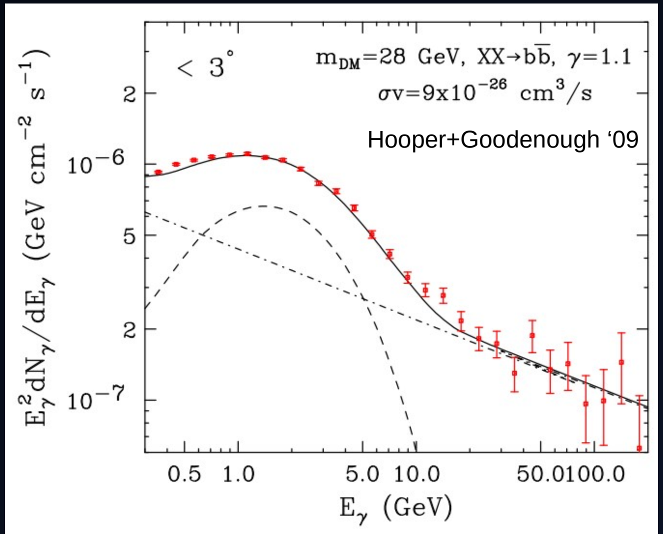
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a \, d\ell.$$

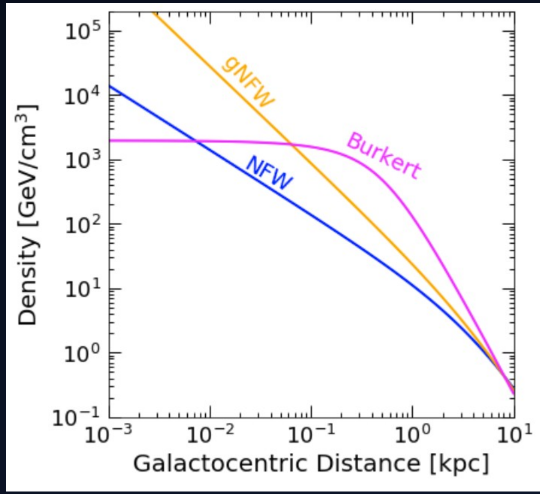
“J factor”, DM density

Annihilation cross section

Energy spectrum

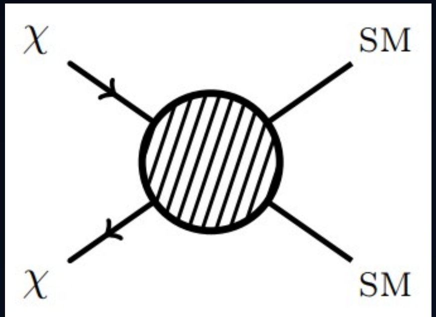






Look where this is large!

Indirect Detection Ingredients



Particle Physics

Astrophysics

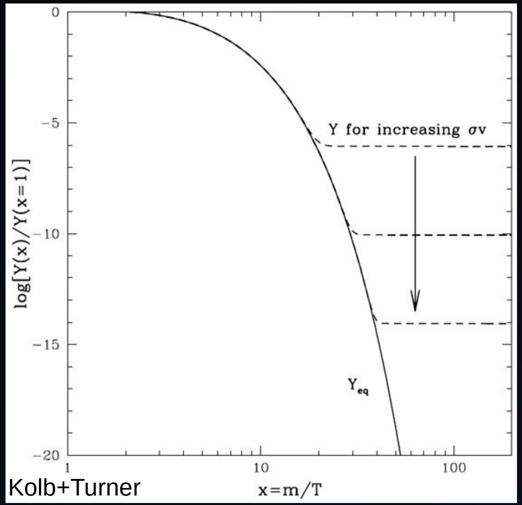
(Gamma rays: straight propagation!)

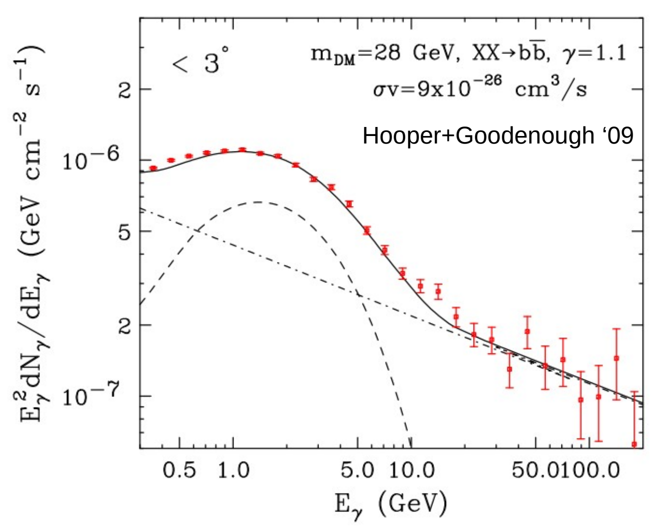
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a \, d\ell$$

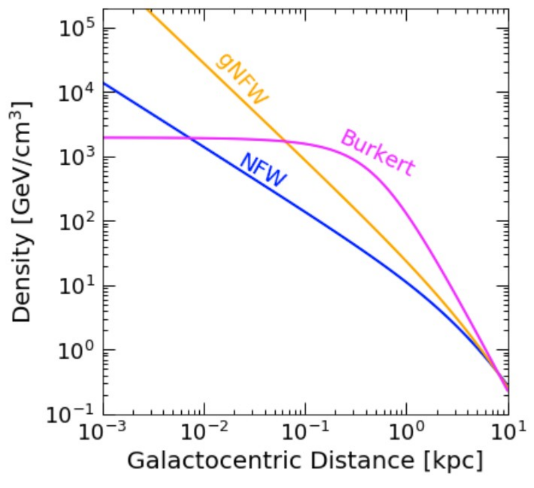
“J factor”, DM density

Annihilation cross section

Energy spectrum







Look where this is large!

...or places with low background!

Gamma-ray Instruments:
Sensitivity and Future Goals

Rebecca Leane

High energy gamma rays: now

Fermi

Space based

~10 MeV – 1 TeV

Data recording
~13 years elapsed

HAWC,
LHAASO

Water Cherenkov

~100 GeV-100 TeV

Data recording
~5 years elapsed

VERITAS,
HESS, MAGIC

Imaging atmospheric
Cherenkov telescopes

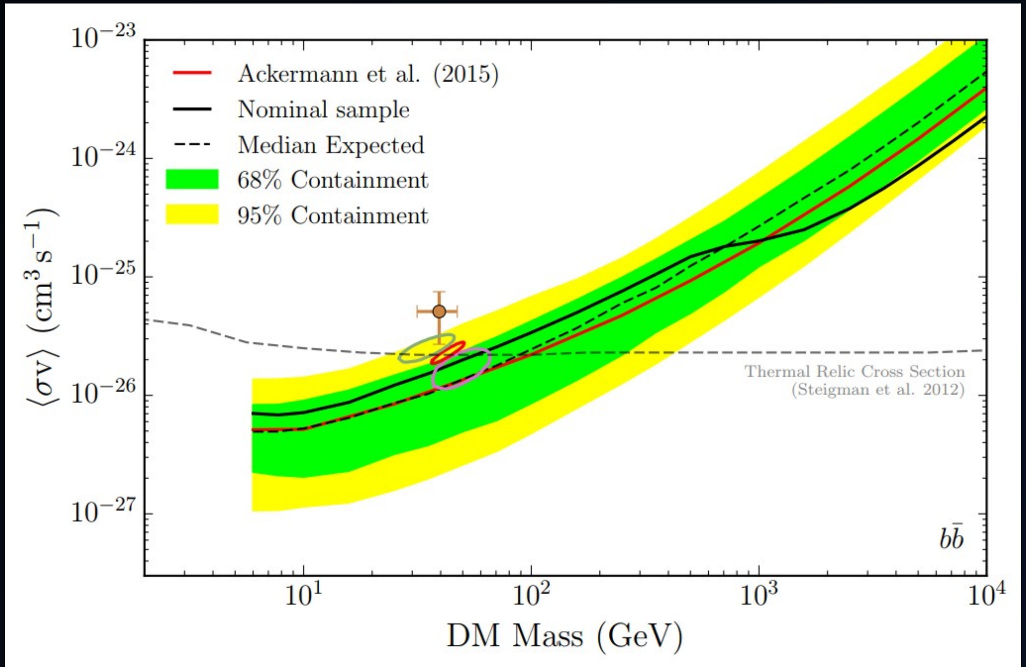
~10 GeV–100 TeV

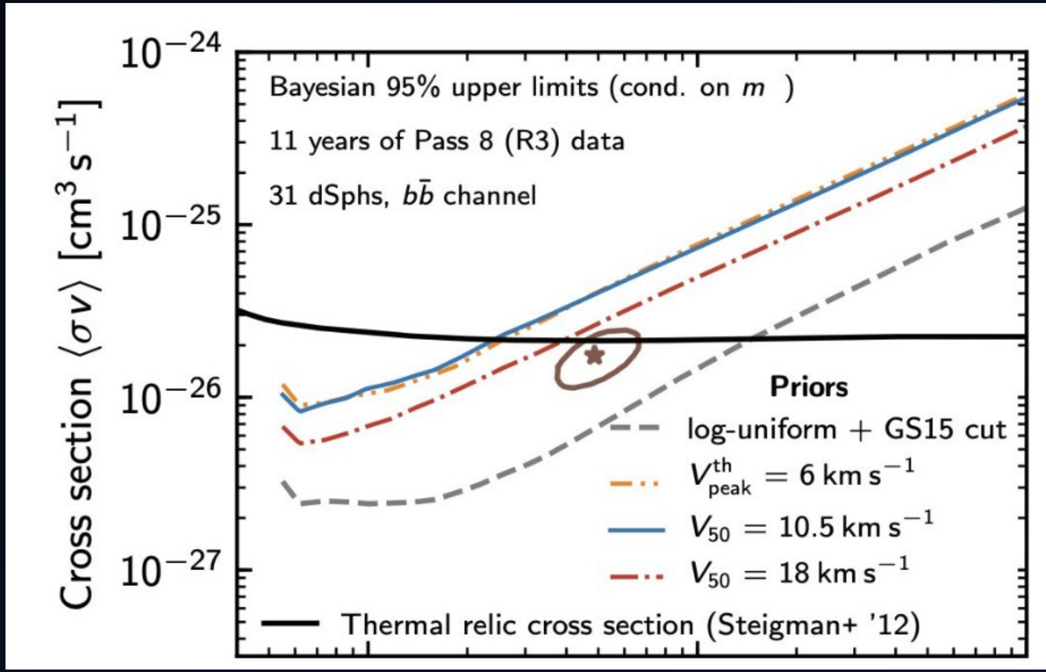
Data recording
~17 years elapsed

Signals from Dwarf Spheroidal Galaxies

- Generally strongest probe, but keep in mind systematics!

Ando+, '20





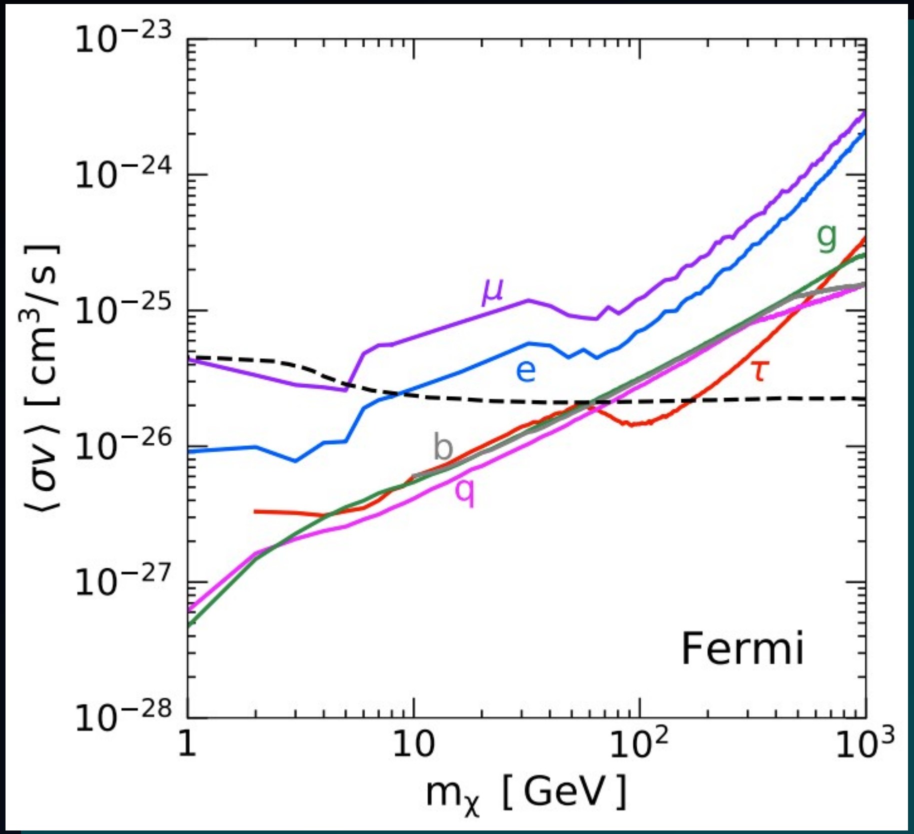
Ackermann+, '16

DM density uncertainties weaken limits further

See also Chang, Necib '20

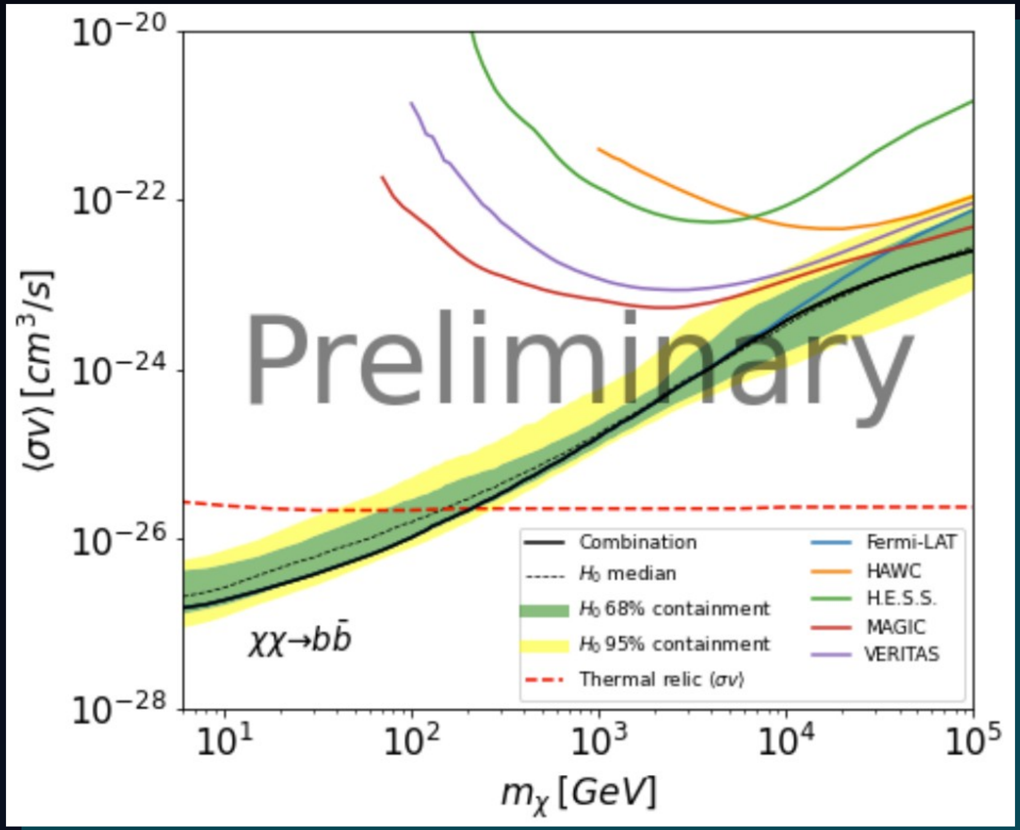
High energy gamma rays: dwarfs

Fermi



RL et al, 2018
(See also Fermi Collab 2016)

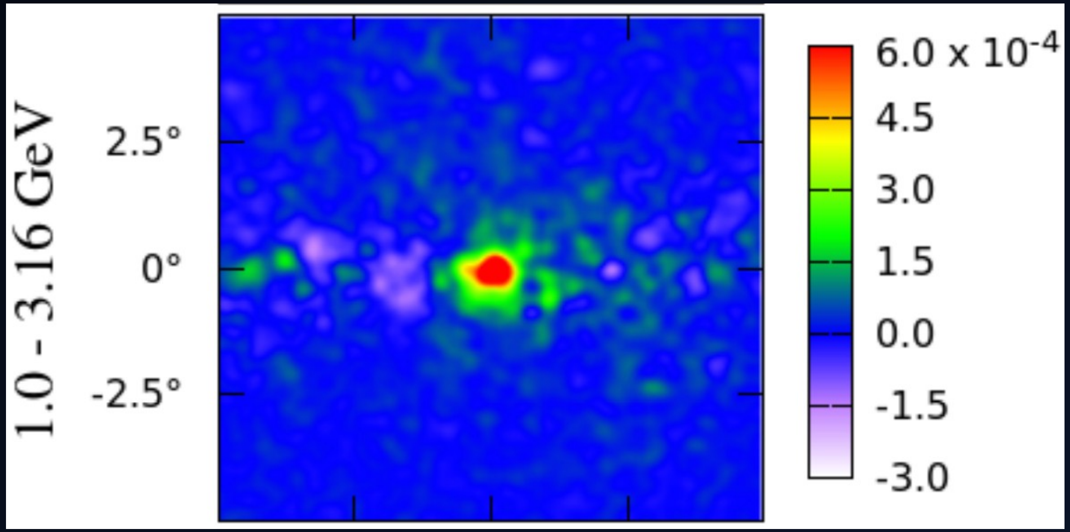
Fermi + HAWC + HESS + MAGIC + VERITAS



Armand et al, Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS Collaborations (2021)

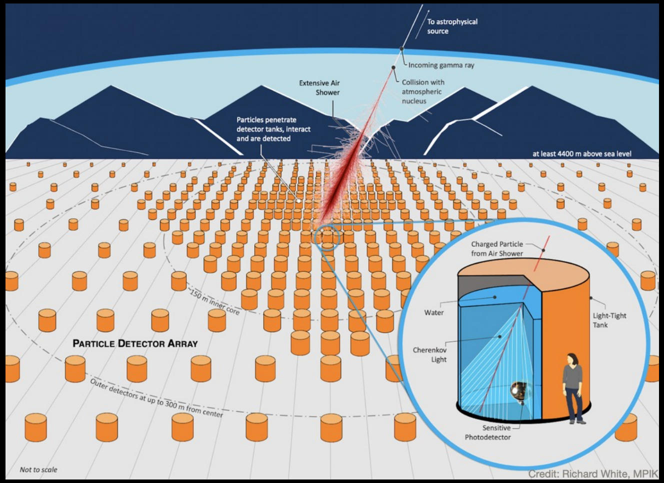
Fermi: Galactic Center Excess

- Statistically significant excess in gamma-rays peaked at a few GeV
- Presents with features consistent with DM: intensity, morphology, spectrum
- Origin currently unknown!
  - See Dan Hooper's talk today
  - GCE parallel talks today:
    - Mattia Di Mauro
    - Ilias Cholis
    - Oscar Macias
    - Florian List



Daylan, et al. (2014)

High energy gamma rays: future



SWGO

Water Cherenkov

~100 GeV-1 PeV

In R&D

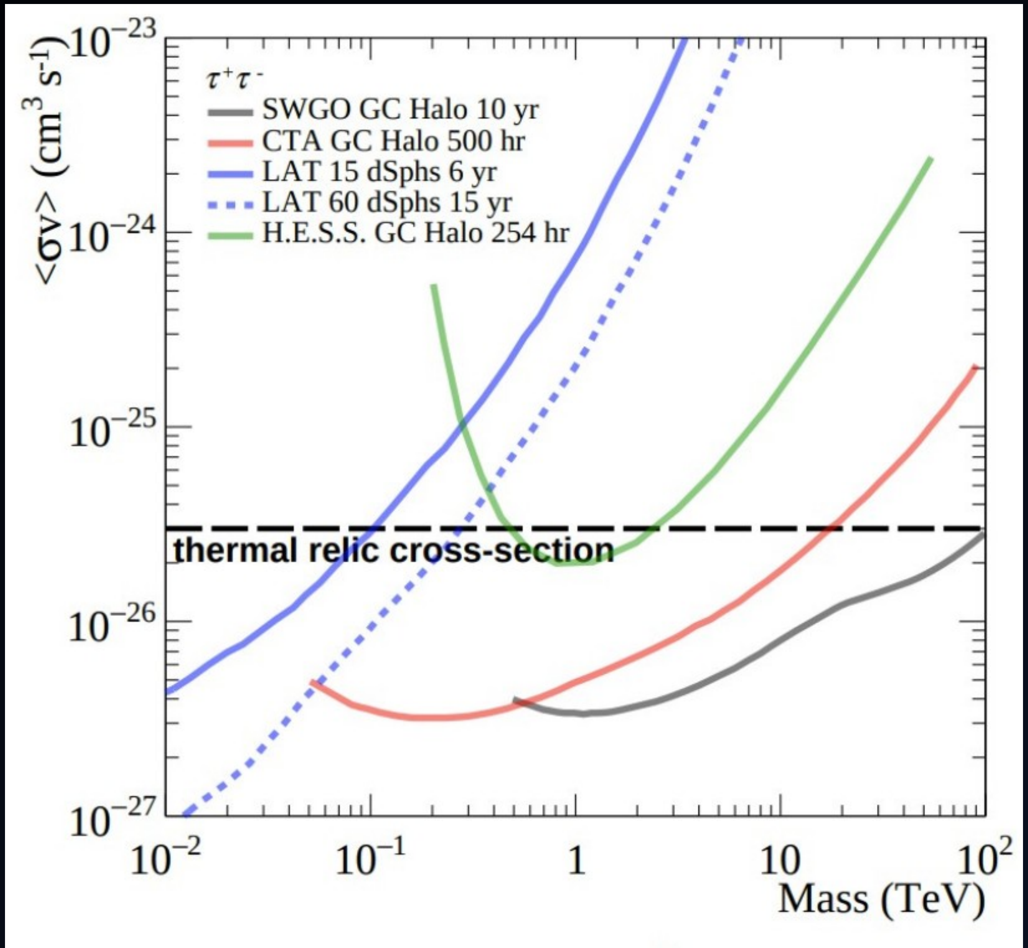
Cherenkov Telescope Array (CTA)

Imaging atmospheric Cherenkov telescope

~20 GeV–300 TeV

Planned ~2024

High energy gamma rays: future



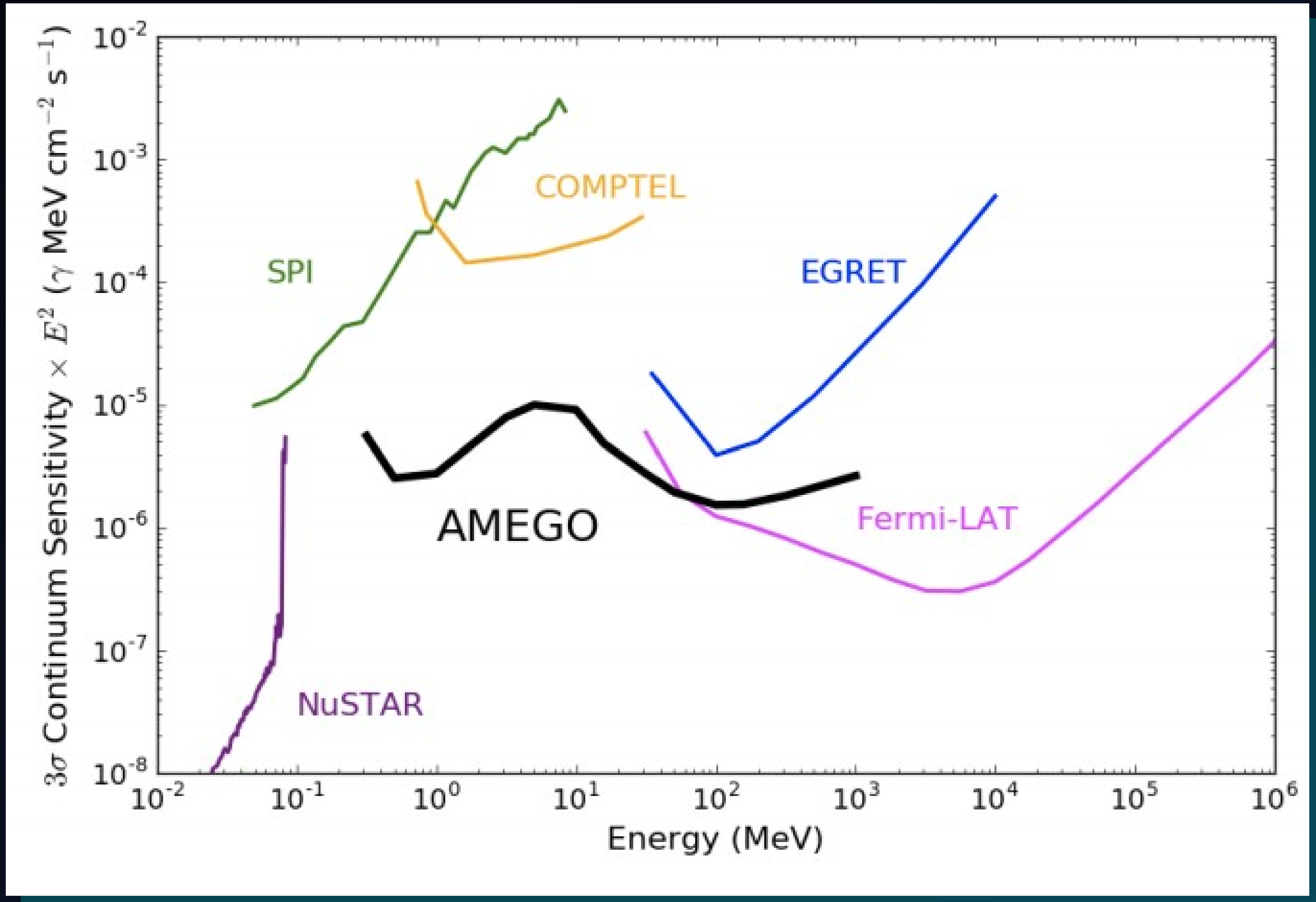
Viana+, 2019

Strong potential to probe much of thermal relic target

Solid probe of ultra-heavy DM

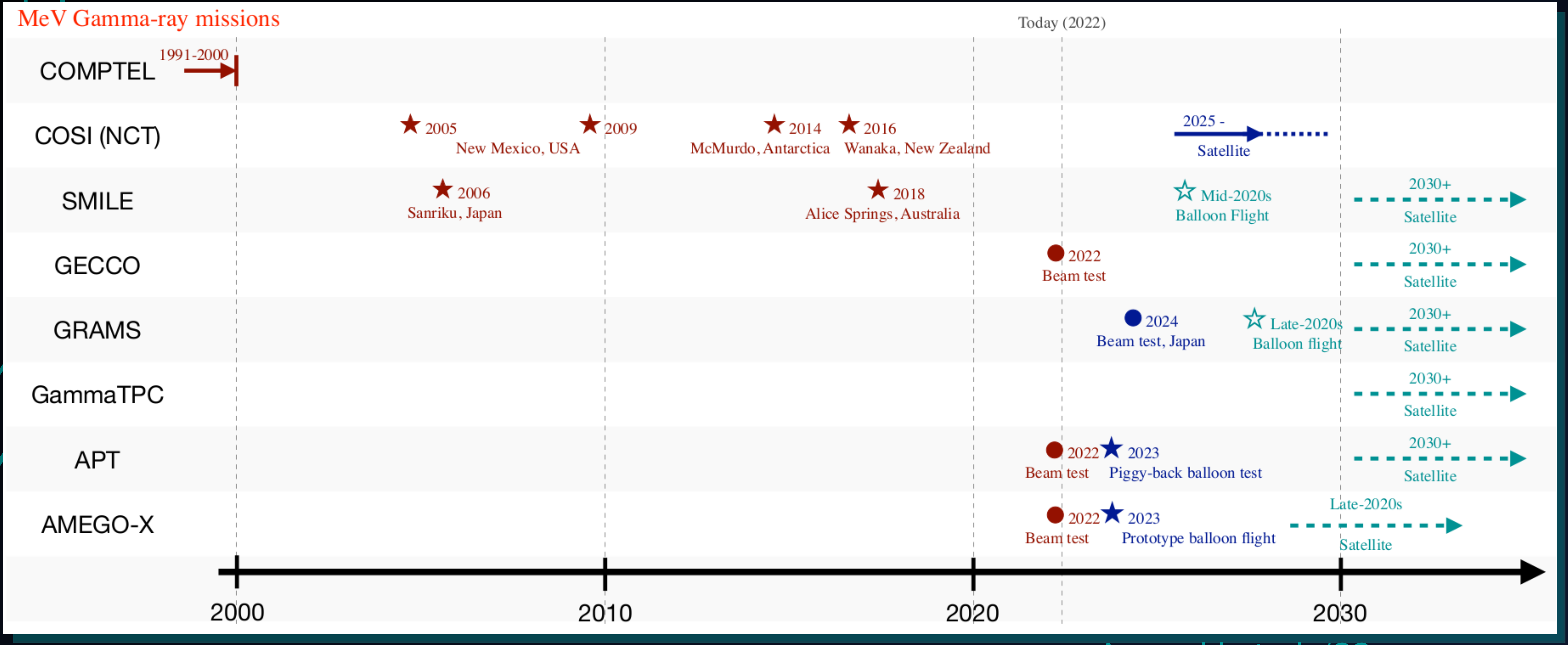
Closing the MeV gap

- Last major experiment in the ~MeV gamma-ray band was COMPTEL, 1991-2000
- Closing this gap is important for:
  - providing greater sensitivity to light DM in the MeV-GeV mass range
  - enabling data-driven studies of backgrounds



AMEGO collab, '19

Closing the MeV gap



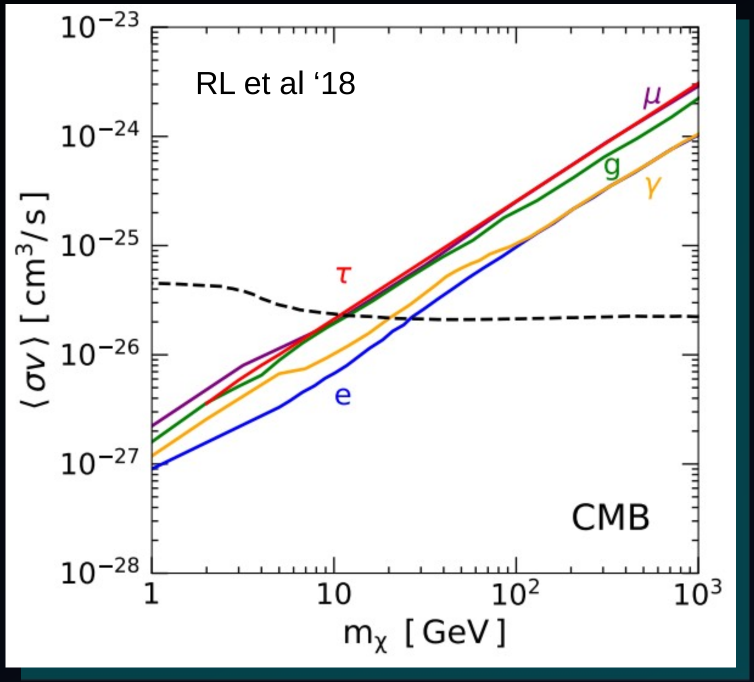
Aramaki et al, ‘22

Combining searches

Rebecca Leane

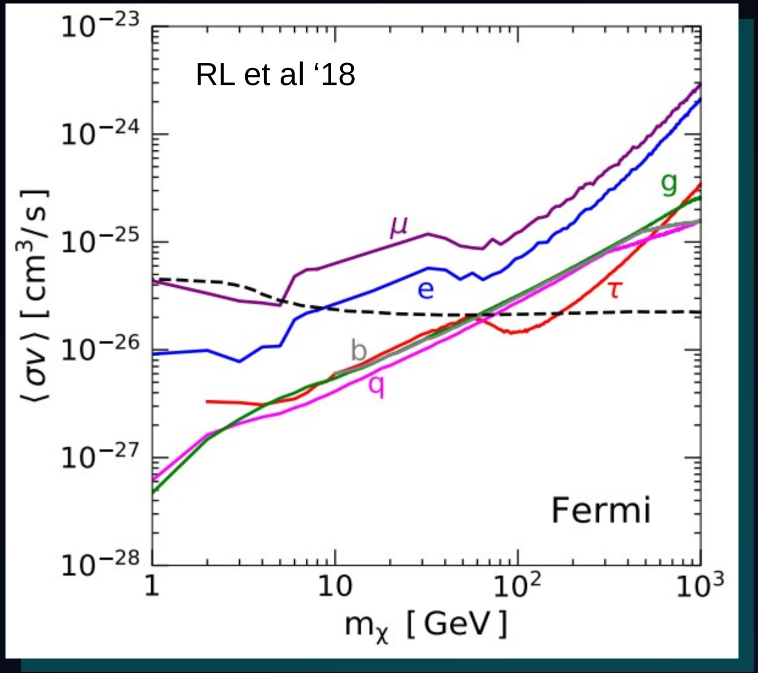
Complementarity: cornering WIMPs

Strongest low mass



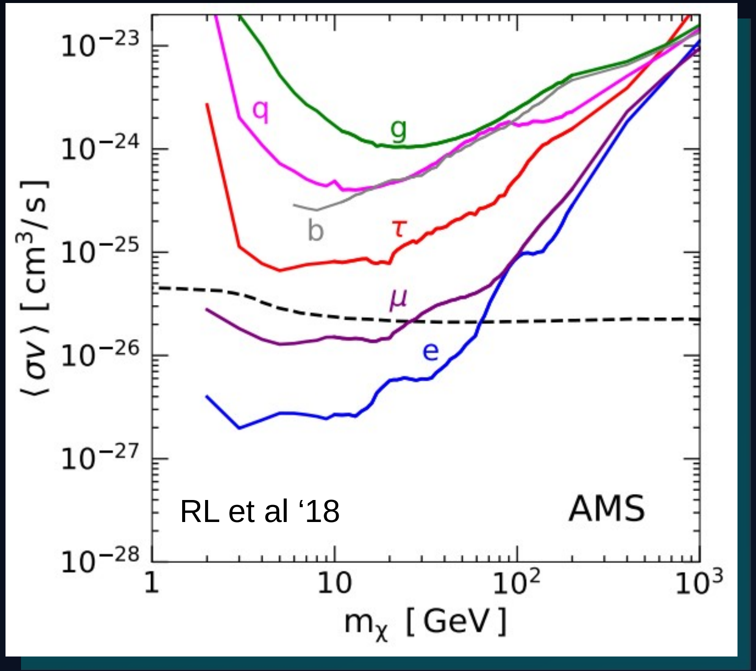
Also see Slatyer '15

Strongest for hadrons



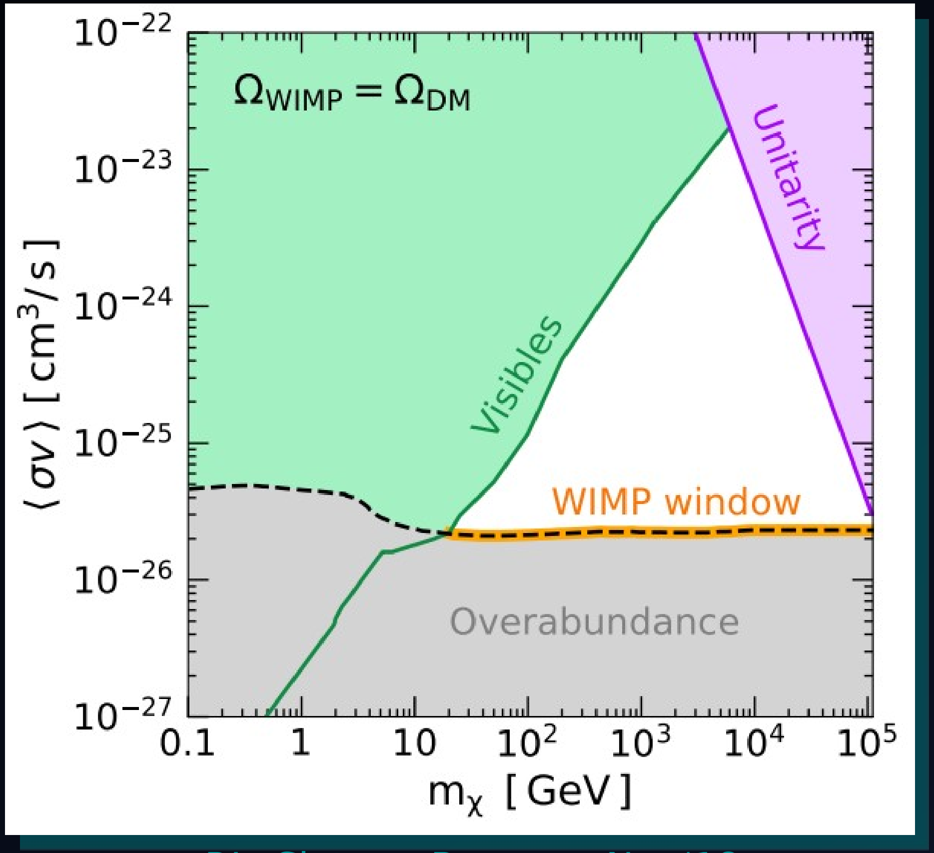
Also see Fermi Collab '16

Strongest for leptons



Also see AMS collab '14

Complementarity: cornering WIMPs



RL, Slatyer, Beacom, Ng, '18

WIMP is not dead!

Use all possible final states, combine strongest limits

S-wave 2→2 thermal DM to visible states: mass greater than ~20 GeV

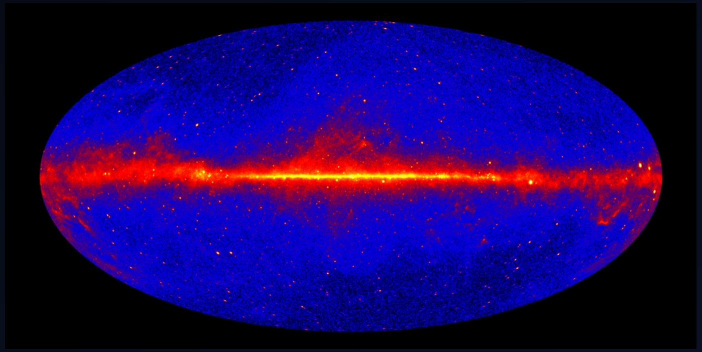
Vital to push through this window

New gamma-ray searches

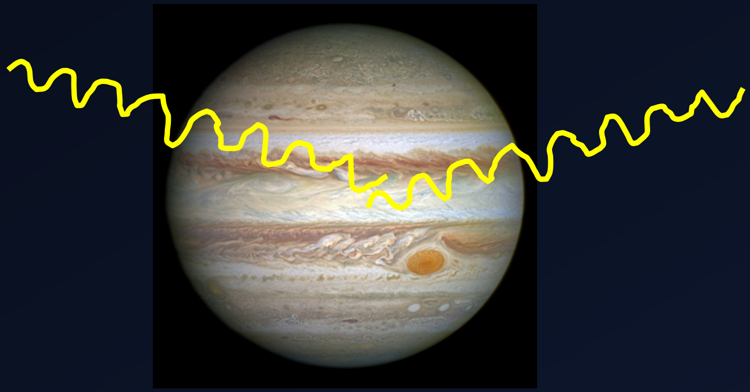
Rebecca Leane

New Gamma-Ray Searches

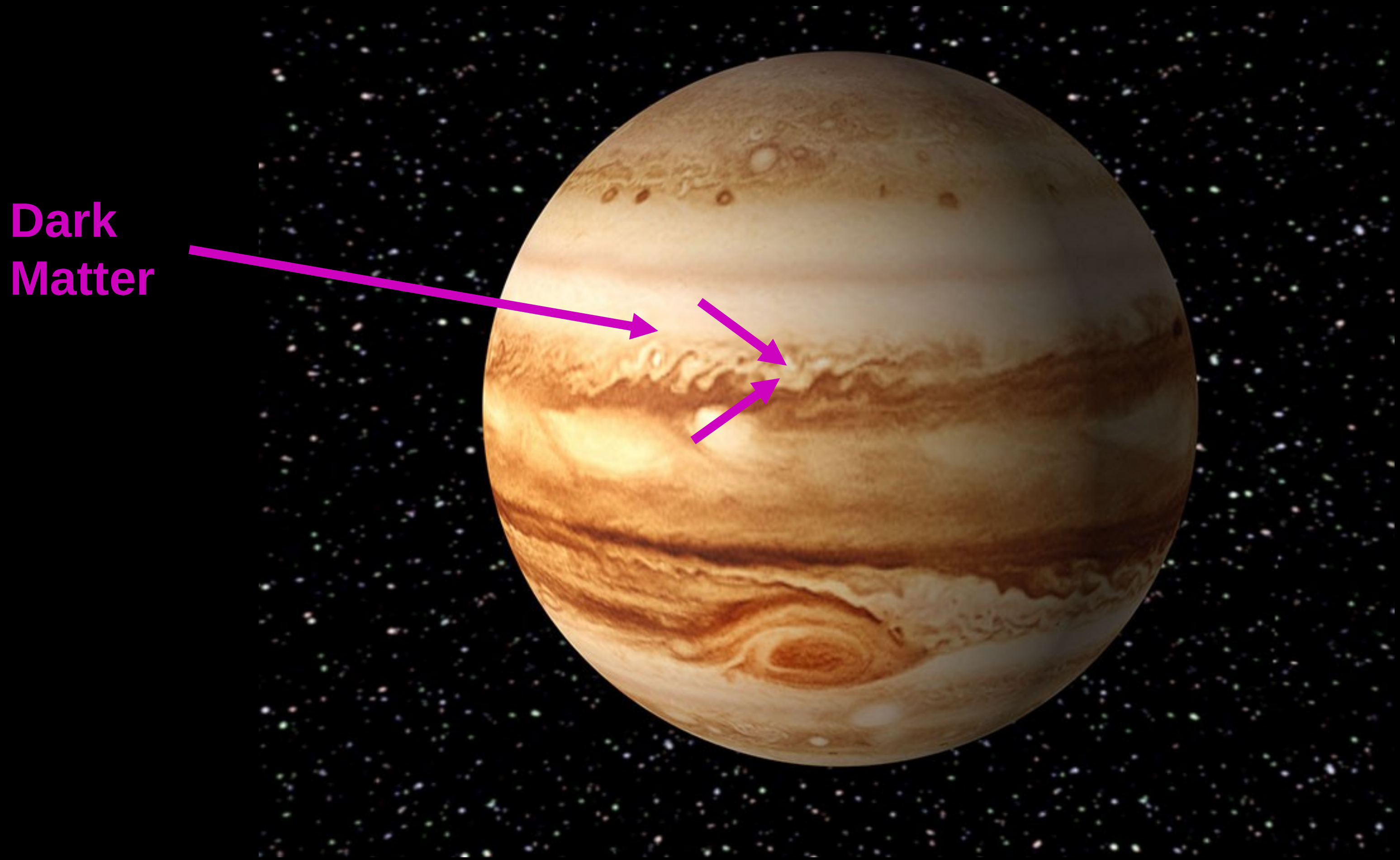
- Traditional indirect detection:
  - Look for annihilation or decay products in dark matter halos



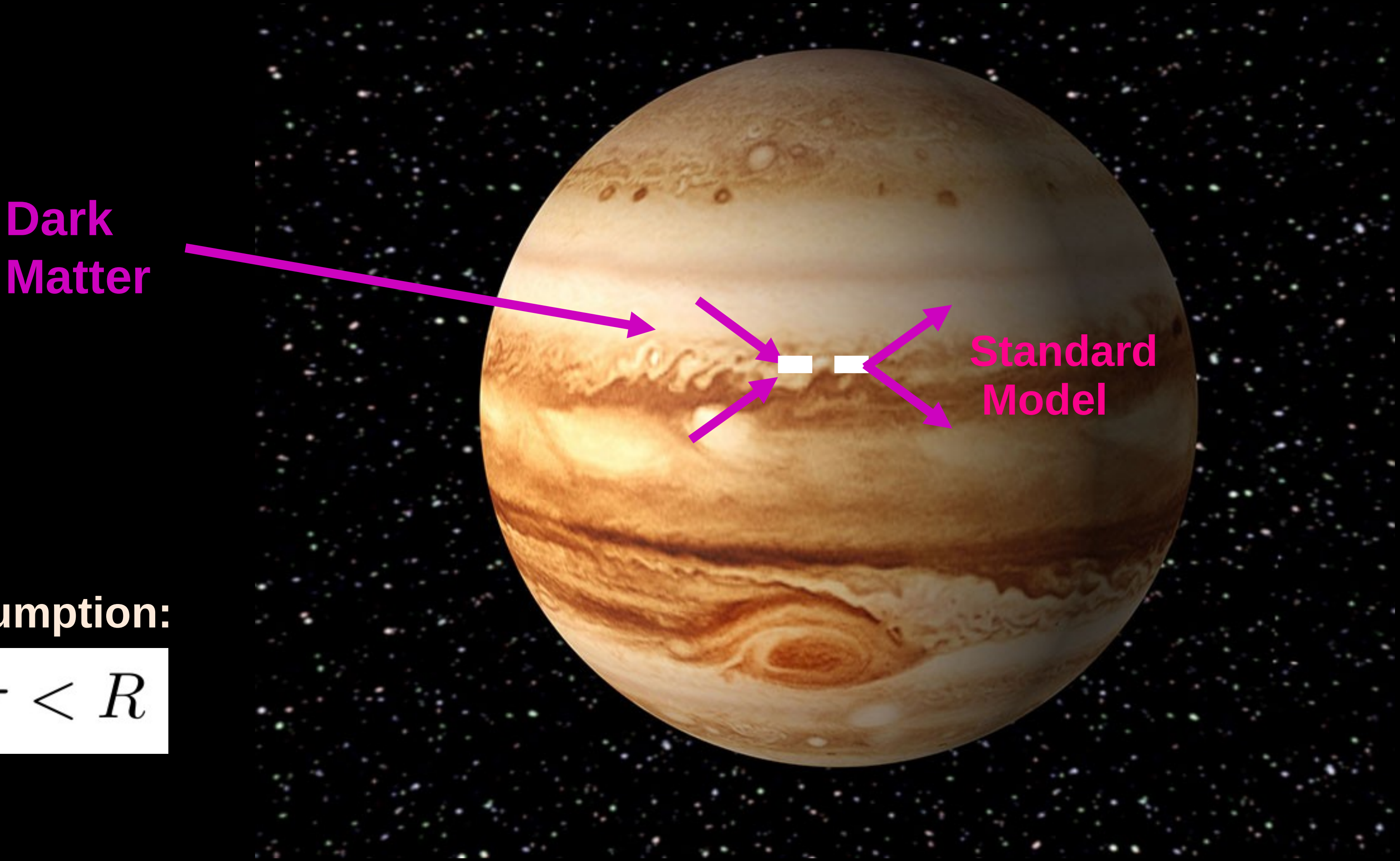
- Alternate signal:
  - Gamma rays from celestial objects!



Dark matter signals



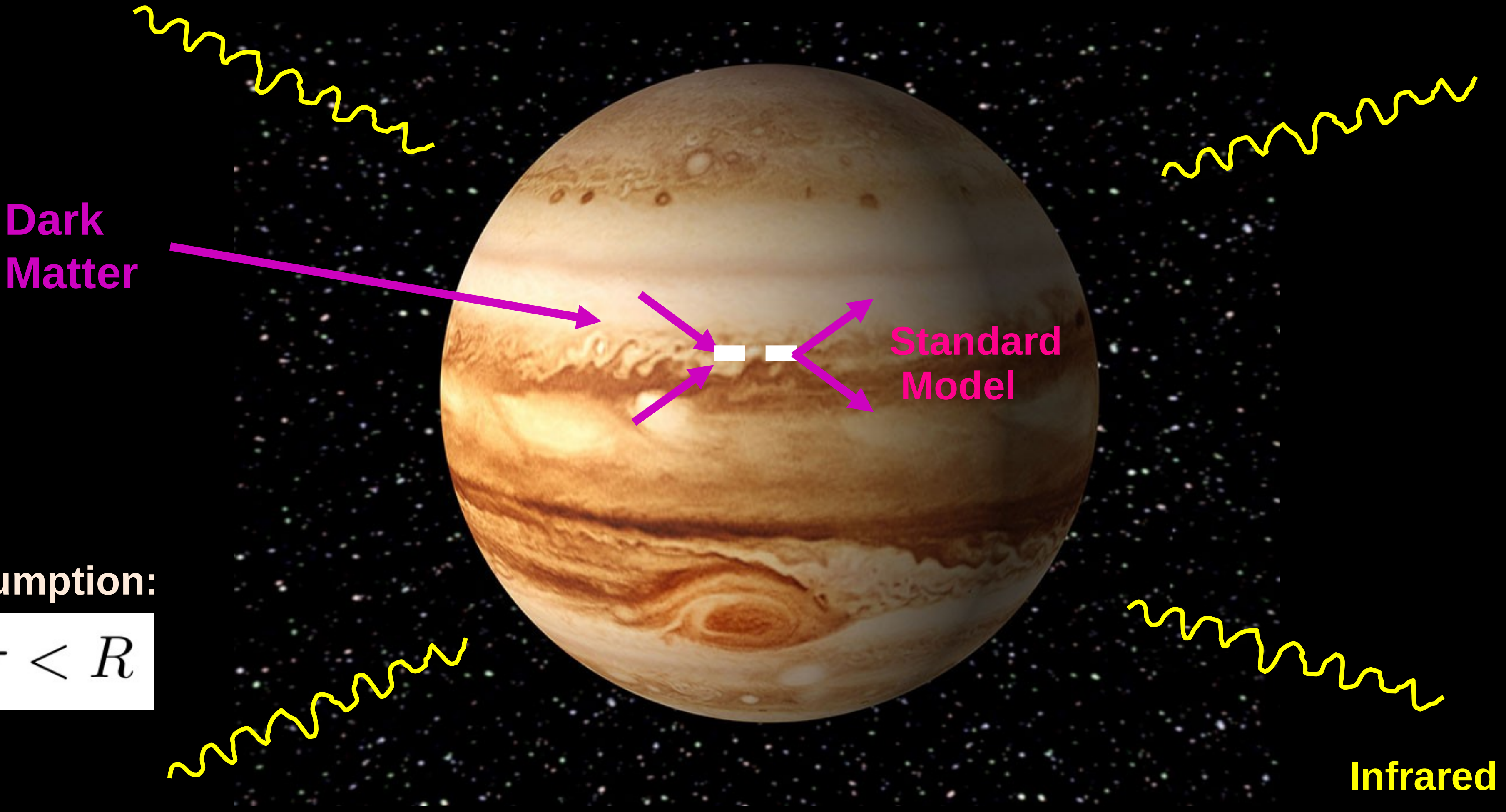
Dark matter signals



Assumption:

$$\gamma c\tau < R$$

Dark matter signals

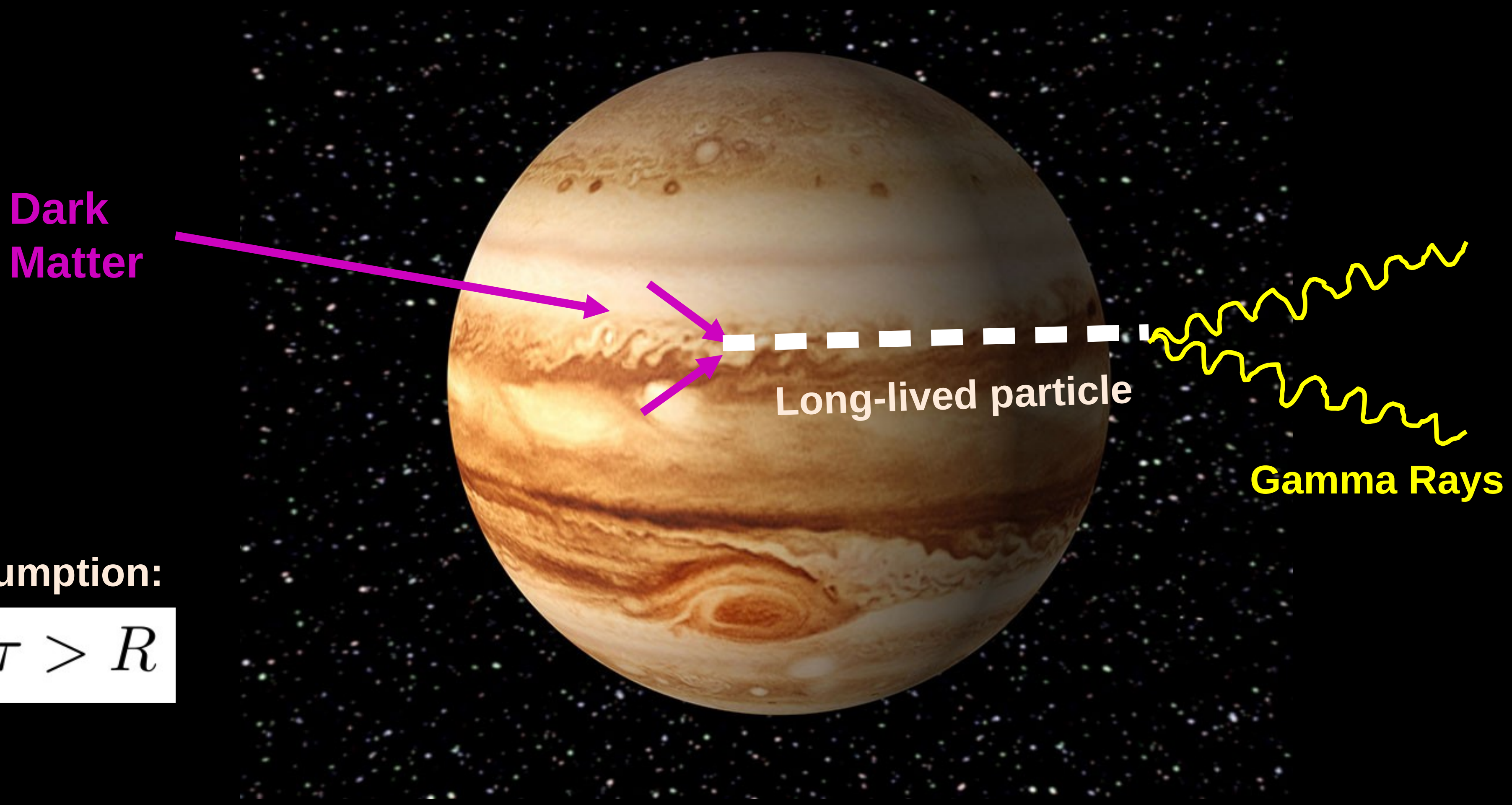


Assumption:

$$\gamma c\tau < R$$

Data next 5 - 10 years

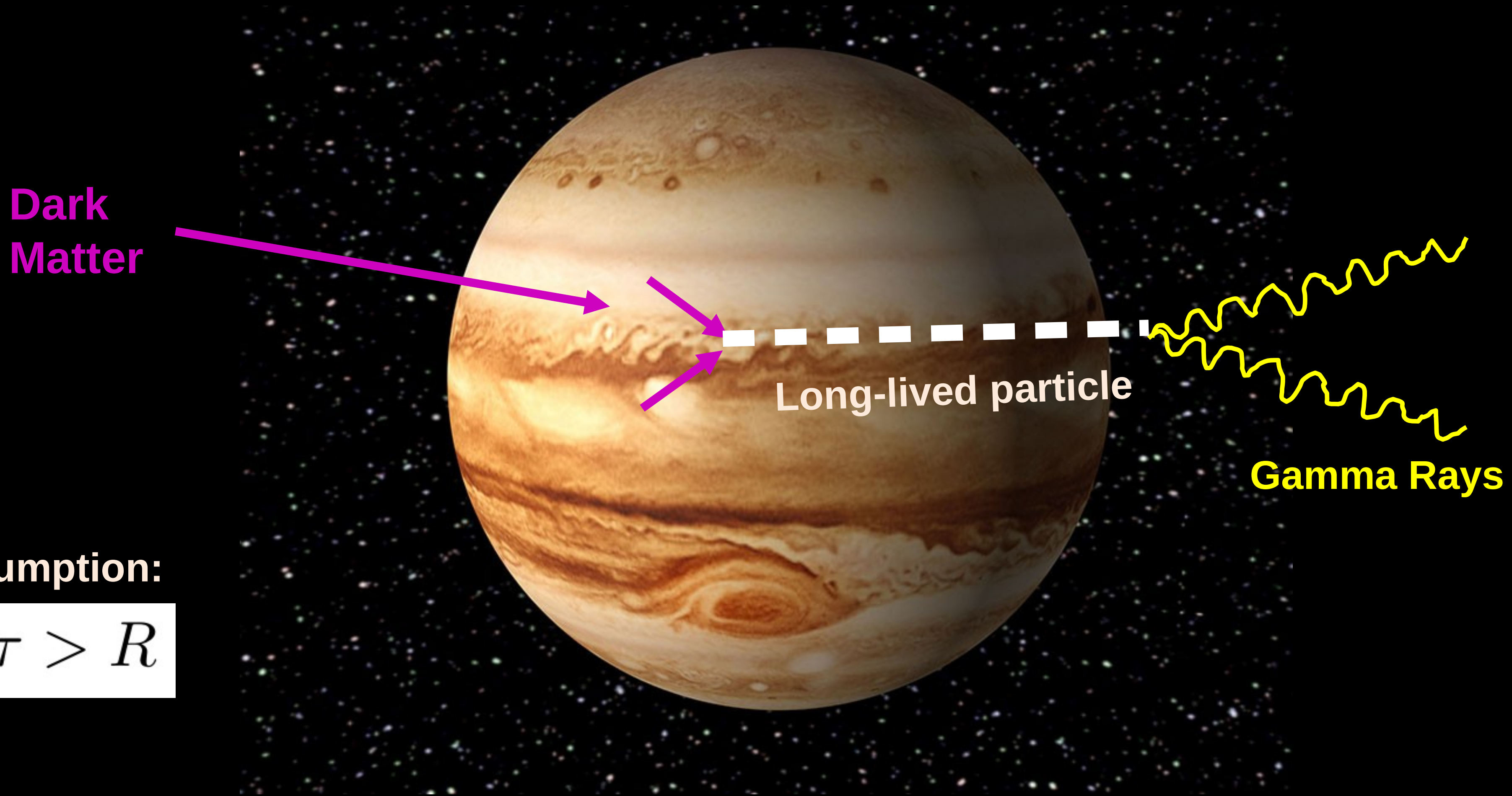
Dark matter signals



Assumption:

$$\gamma c \tau > R$$

Dark matter signals



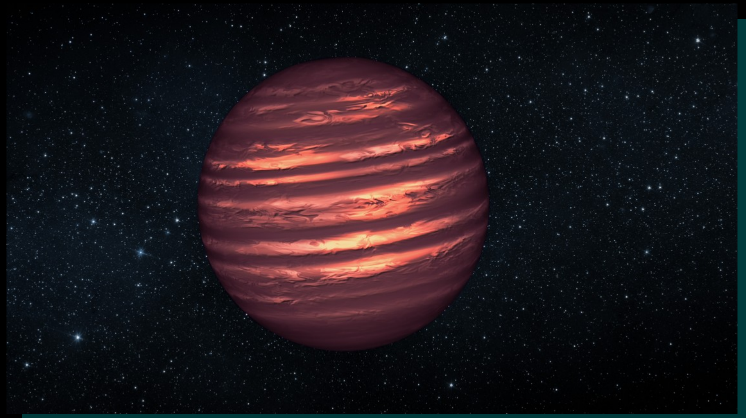
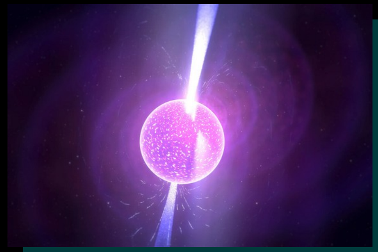
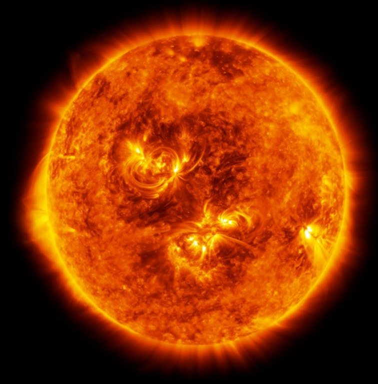
Assumption:

$$\gamma c\tau > R$$

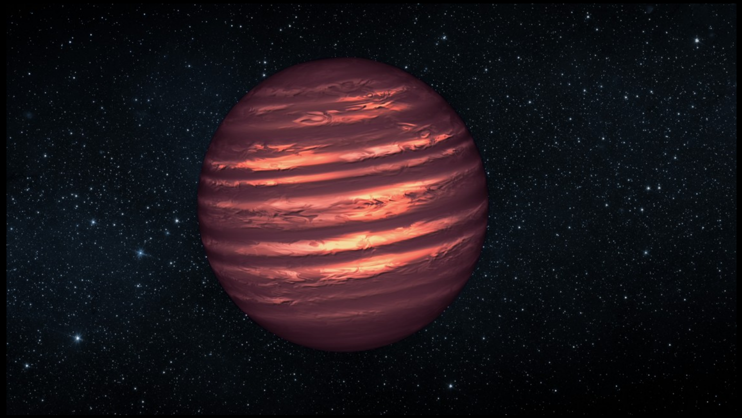
Fermi-LAT, HAWC, HESS gamma-ray data available now

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!)

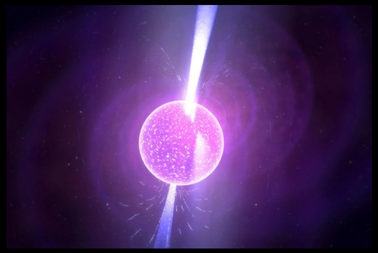





Optimal Celestial Target?



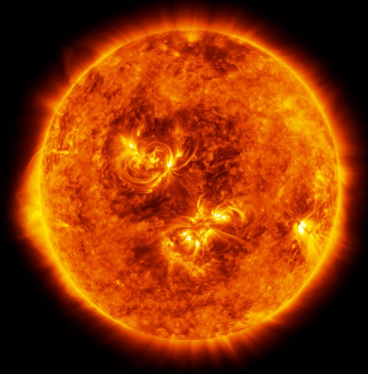
Brown Dwarf

BIG
Cold
Dense



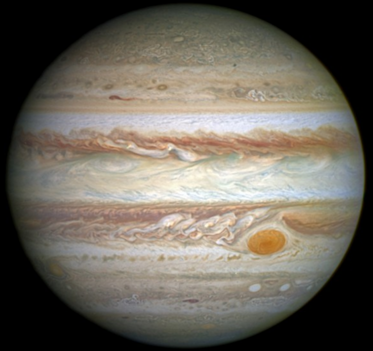
Neutron Star

Small
Cold
Ultra-dense



Sun

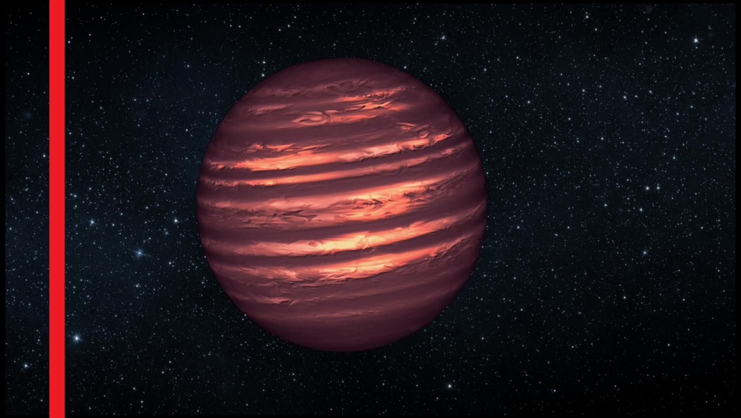
BIG
Hot



Jupiter

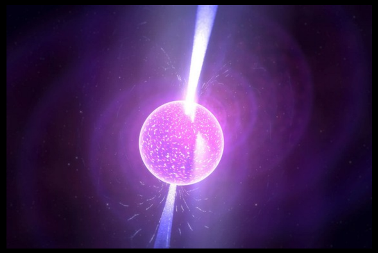
BIG
Cold

Optimal Celestial Target?



Brown Dwarf

BIG
Cold
Dense

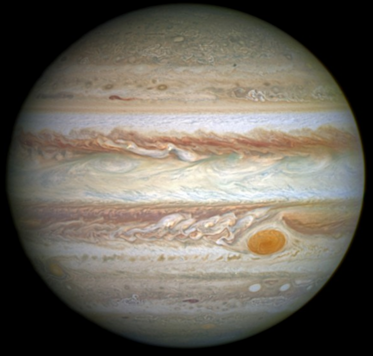


Neutron Star

Small
Cold
Ultra-dense

Sun

BIG
Hot

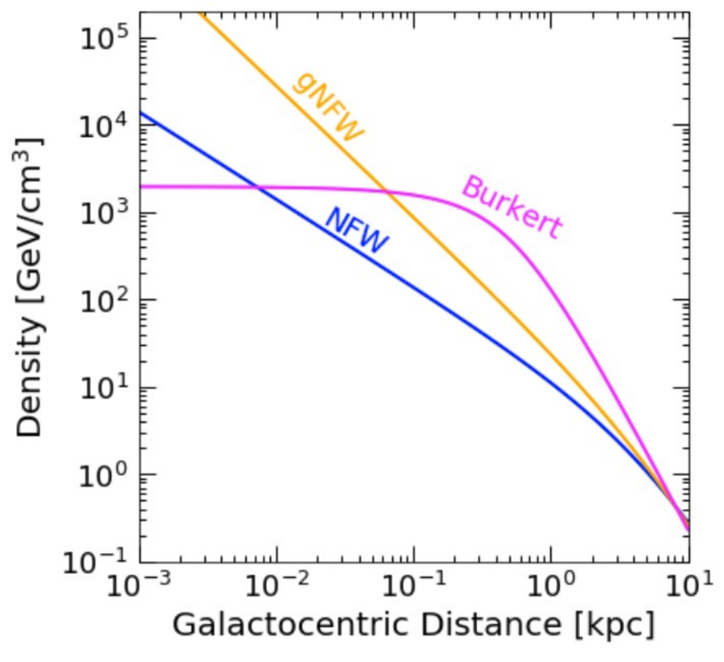


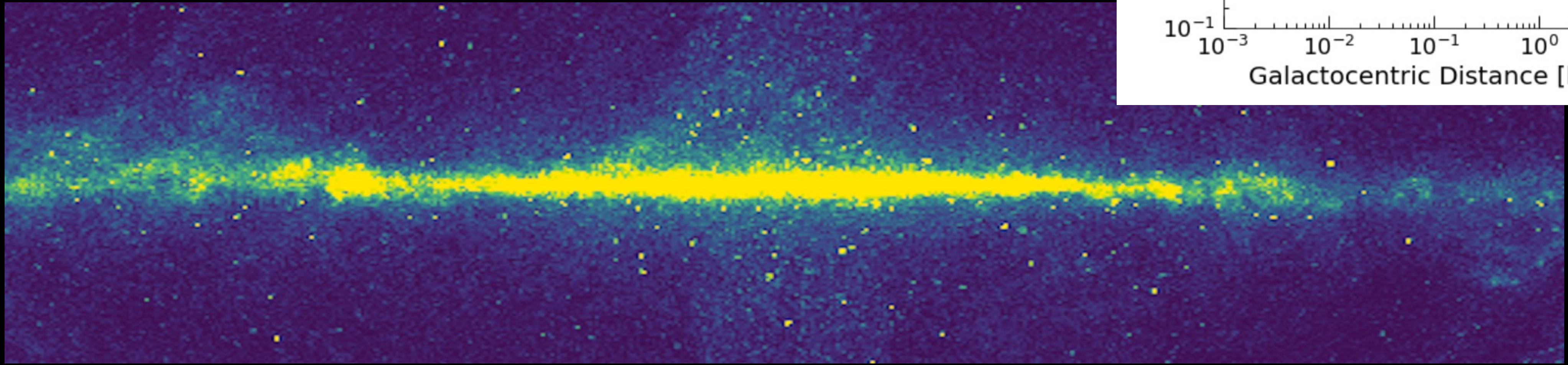
Jupiter

BIG
Cold

Galactic Center Signal

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



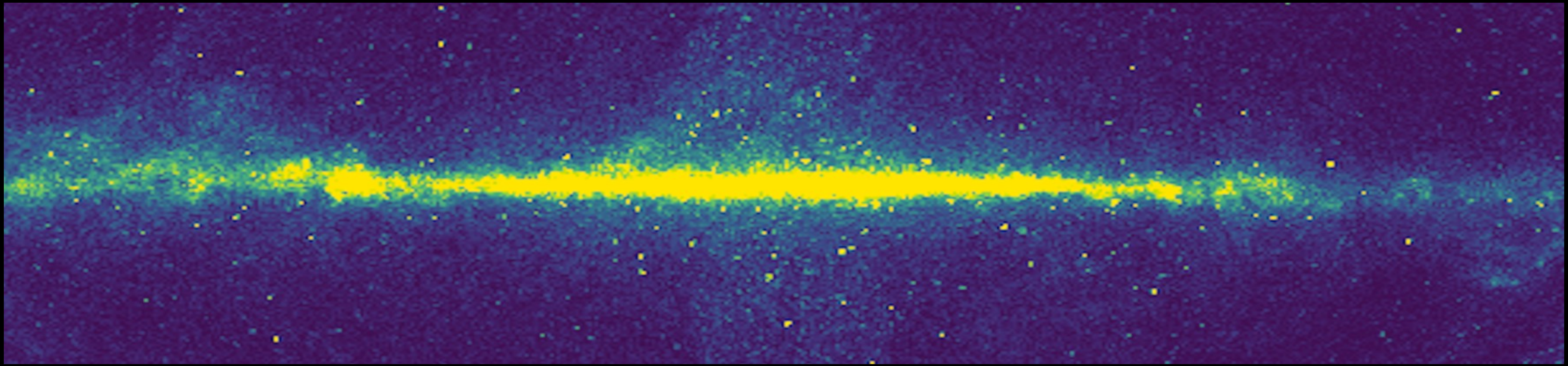


Rebecca Leane (SLAC)

Galactic Center **Population** Signal

Use all the neutron stars, all the brown dwarfs

Indirect detection flux with celestial objects!



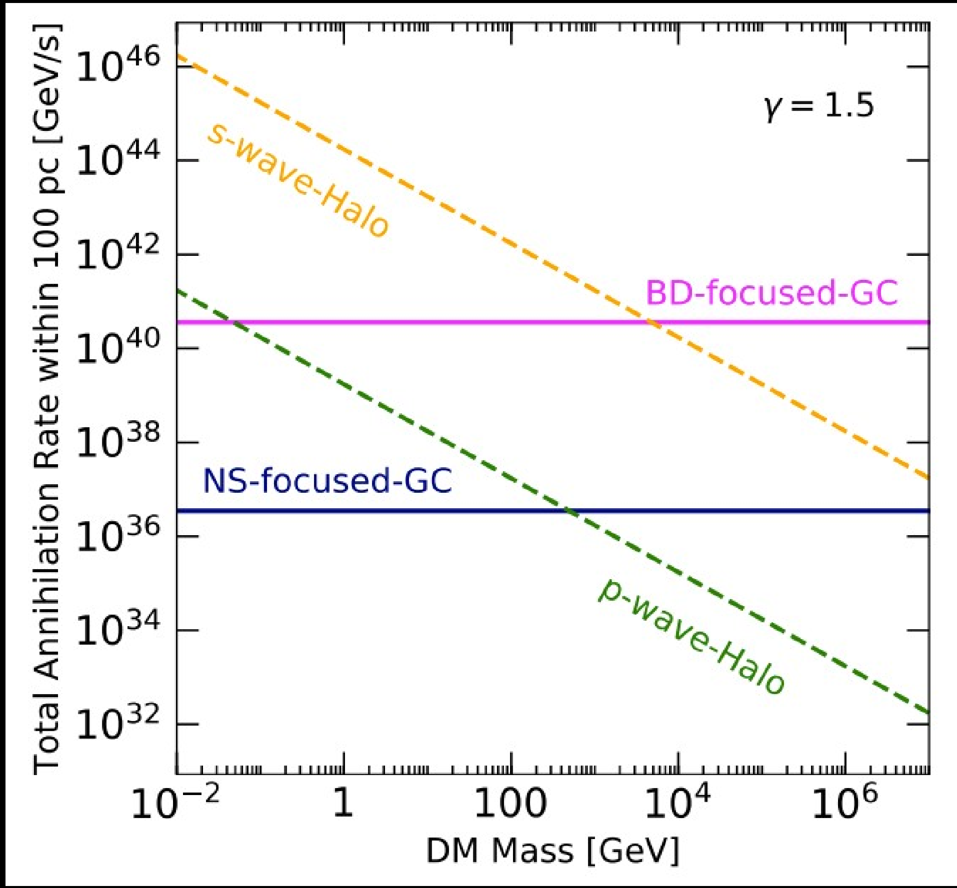
RL, Linden, Mukhopadyay, Toro, 2021

Comparison with Halo Annihilation

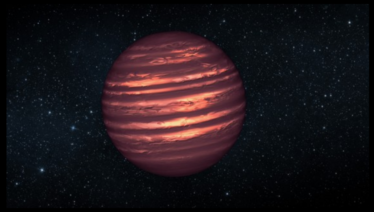
- Signal morphology:
  DM density squared,
  vs DM density*stellar density

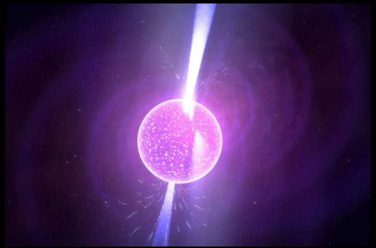
- Celestial-body "focused" annihilation
  "focuses" rate above halo levels

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



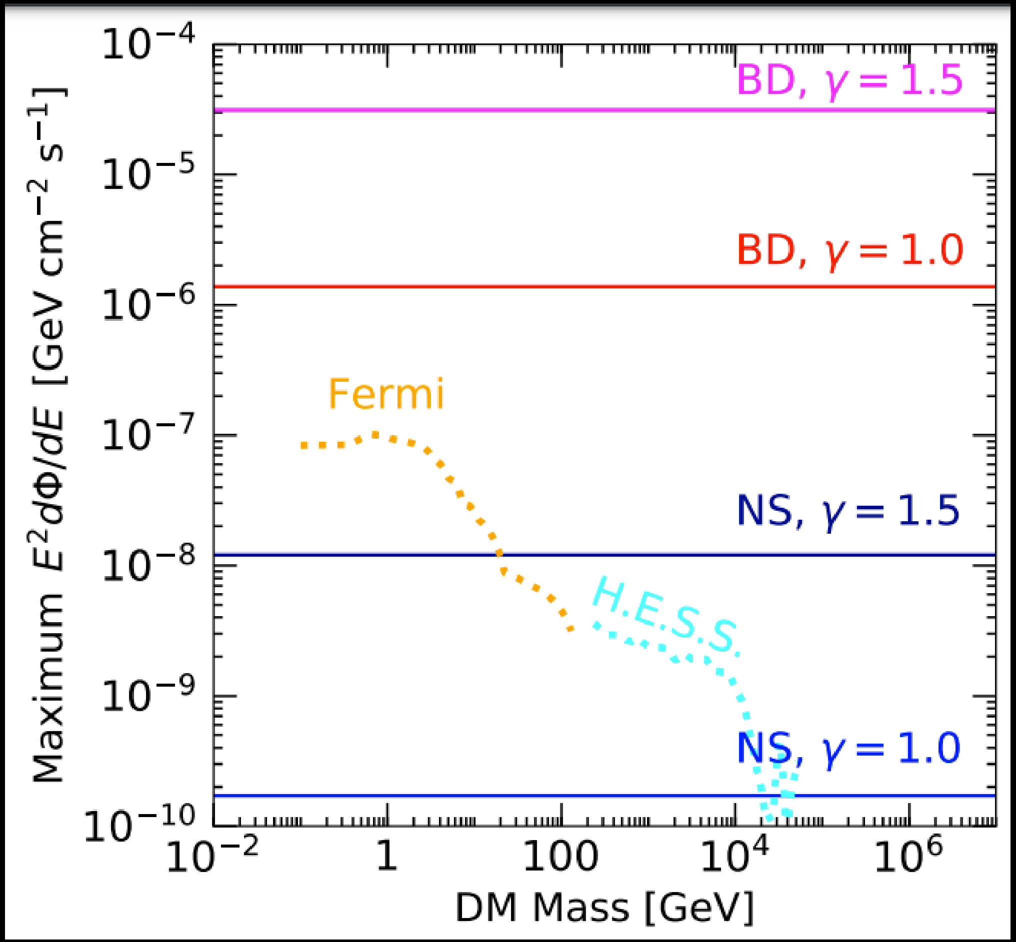
RL, Linden, Mukhopadyay, Toro, 2021





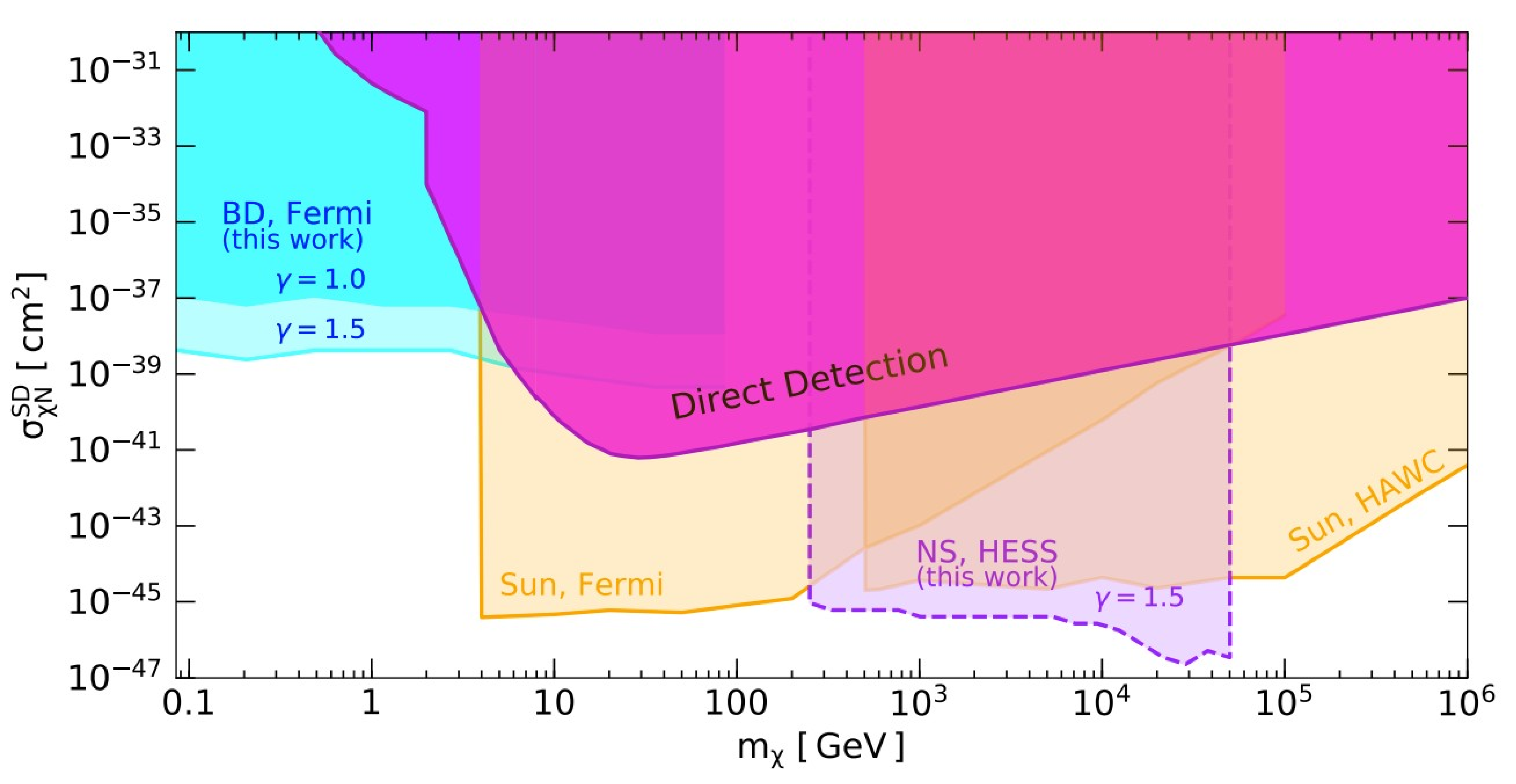
Gamma-ray population detectability

- 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!



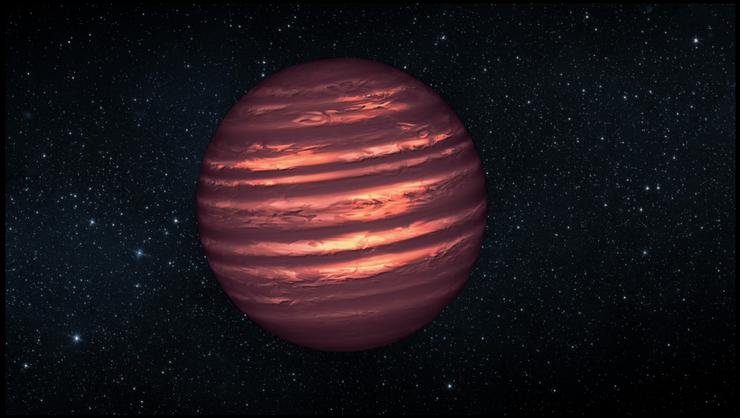
RL, Linden, Mukhopadyay, Toro, 2021

New Limits w/ Brown Dwarfs and Neutron Stars



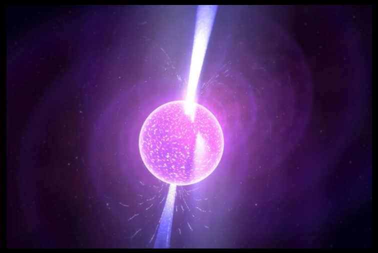
RL, Linden, Mukhopadyay, Toro, 2021

Optimal Celestial Target?



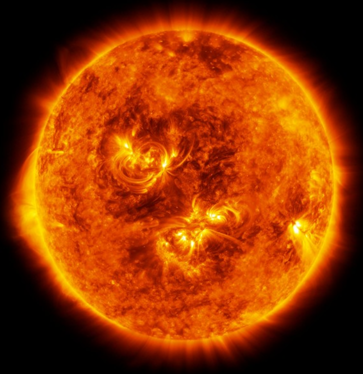
Brown Dwarf

BIG
Cold



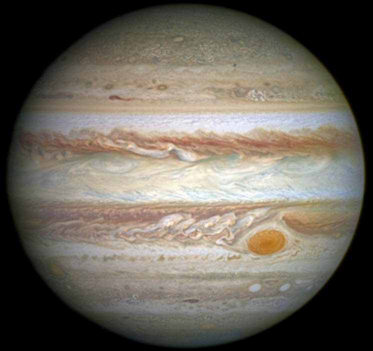
Neutron Star

Small
Cold



Sun

BIG
Hot



Jupiter

BIG
Cold

THE SUN

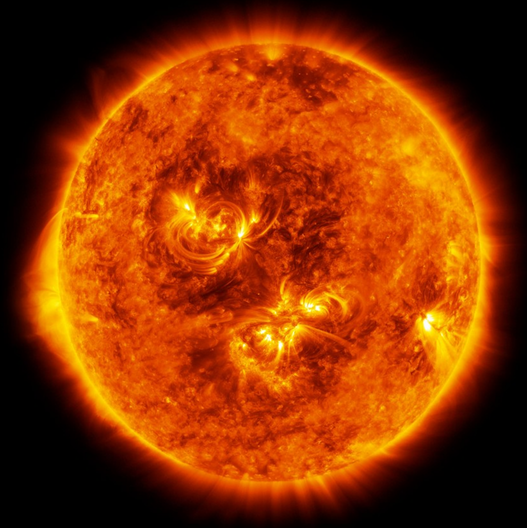
Available data:
Fermi, HAWC

Limitations:

+ Hot
+ Higher DM evaporation (~GeV mass)

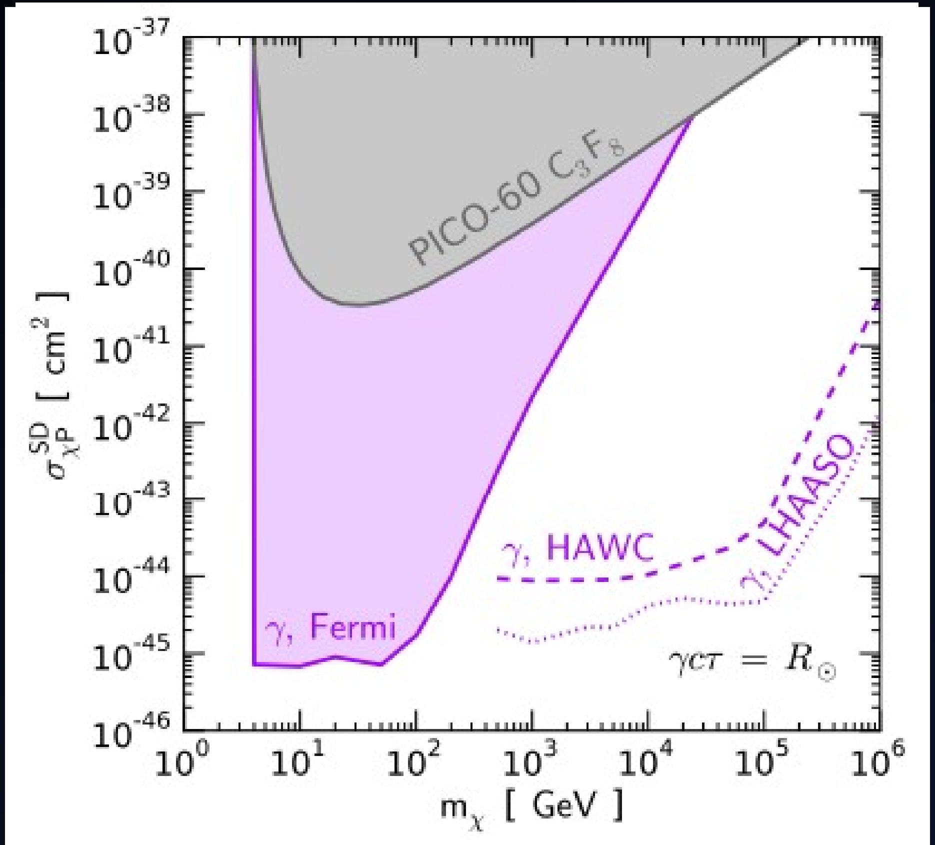
Benefits:

+ Huge
+ Proximity
+ Excellent data



THE SUN

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

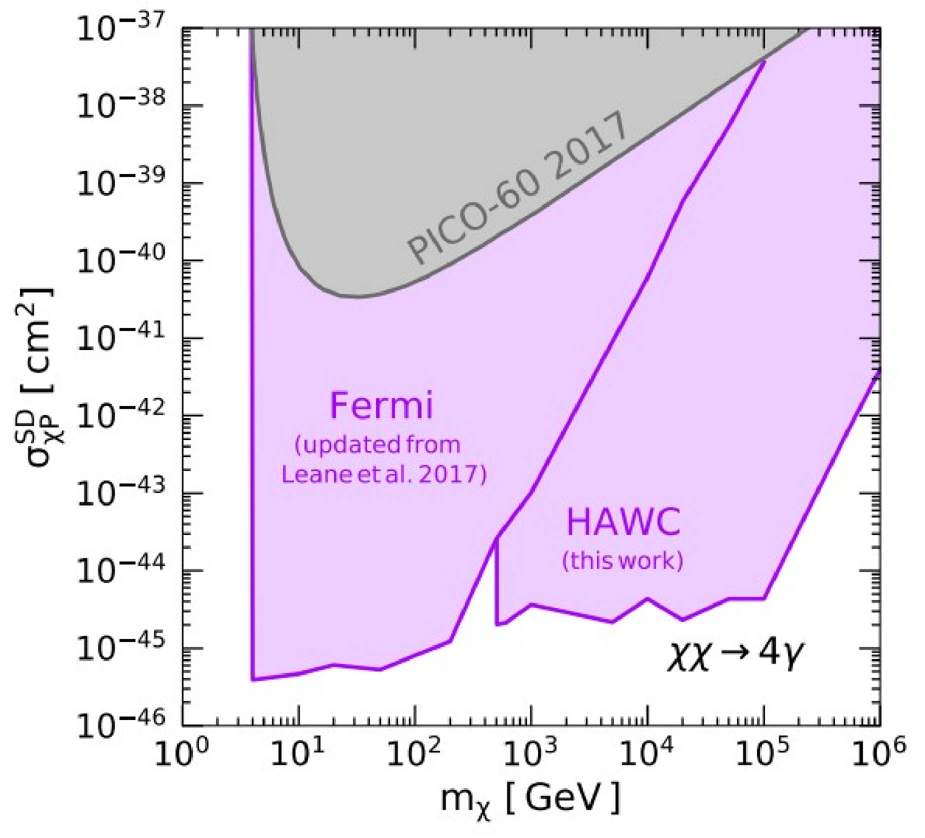


Leane, Ng, Beacom (PRD '17)
Leane + HAWC Collaboration (PRD '18 a,b)

<u>See earlier:</u>
Schuster, Toro, Weiner, Yavin '10
Batell, Pospelov, Ritz, Shang '10
Meade, Nussinov, Pappuci, Volansky '10

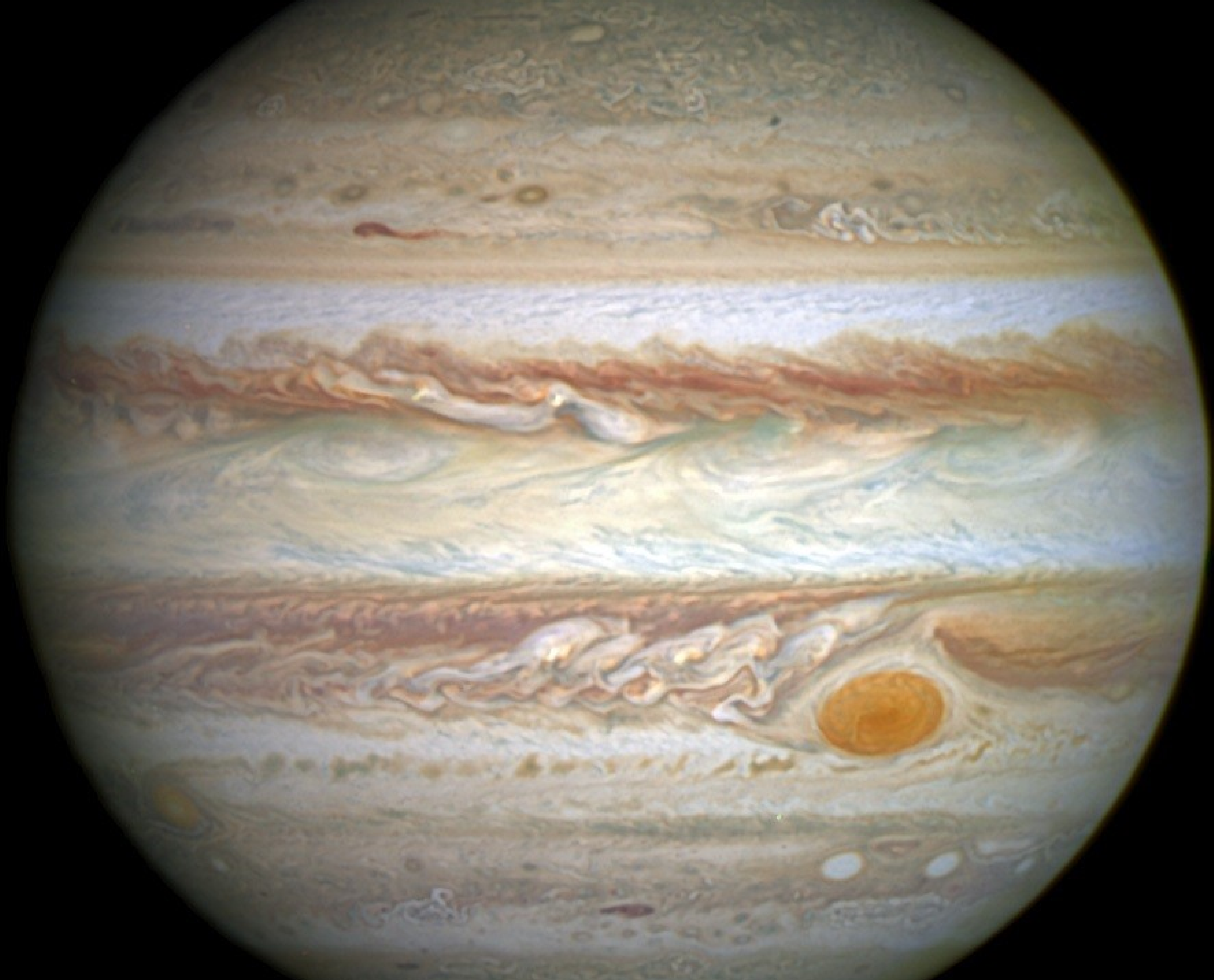
THE SUN

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



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

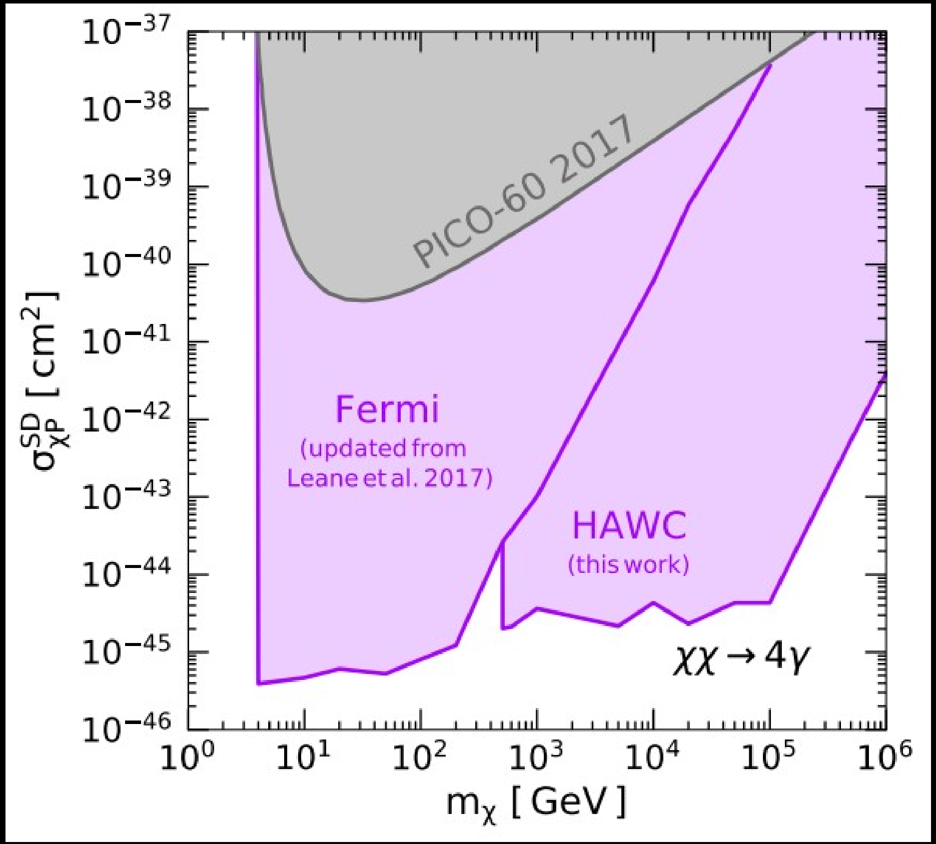
See earlier:
Schuster, Toro, Weiner, Yavin ‘10
Batell, Pospelov, Ritz, Shang ‘10
Meade, Nussinov, Pappuci, Volansky ‘10



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

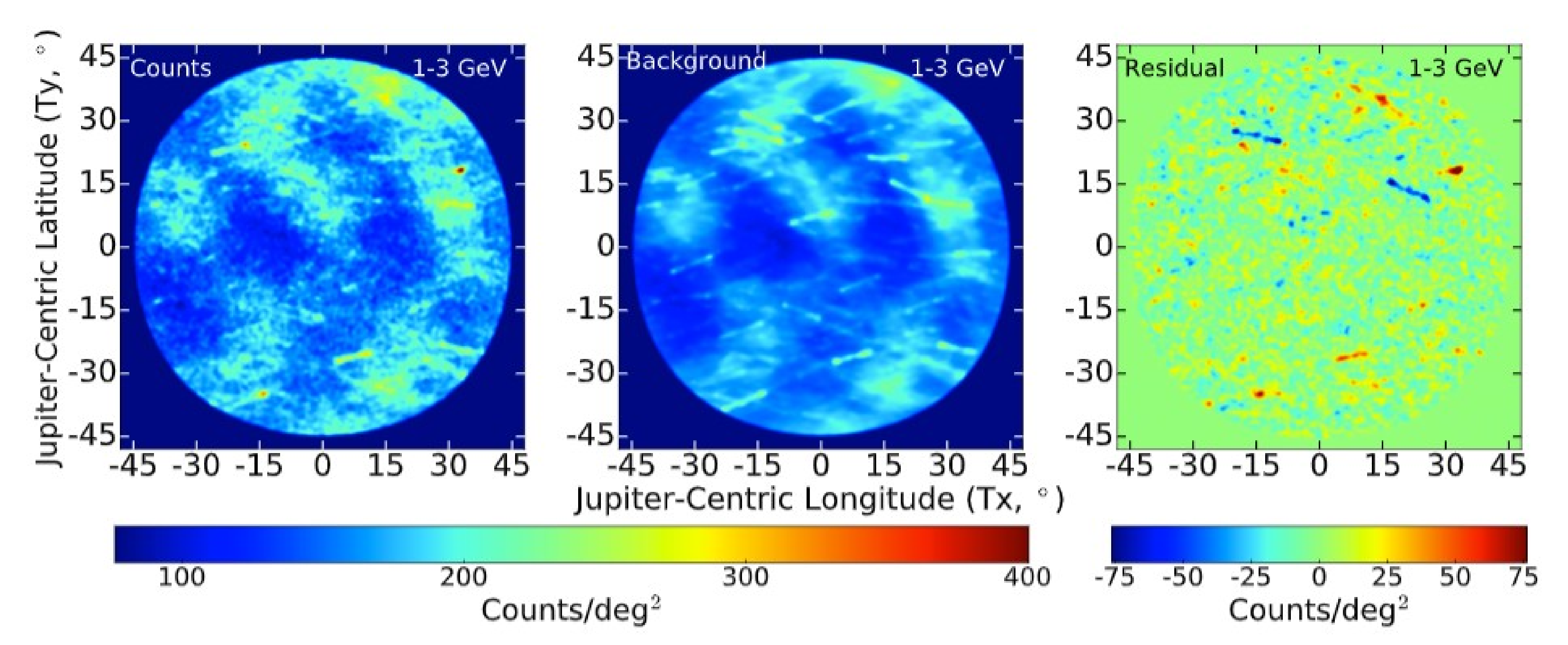
+ interaction of cosmic rays with Jupiter's atmosphere

...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



Leane + Linden '21

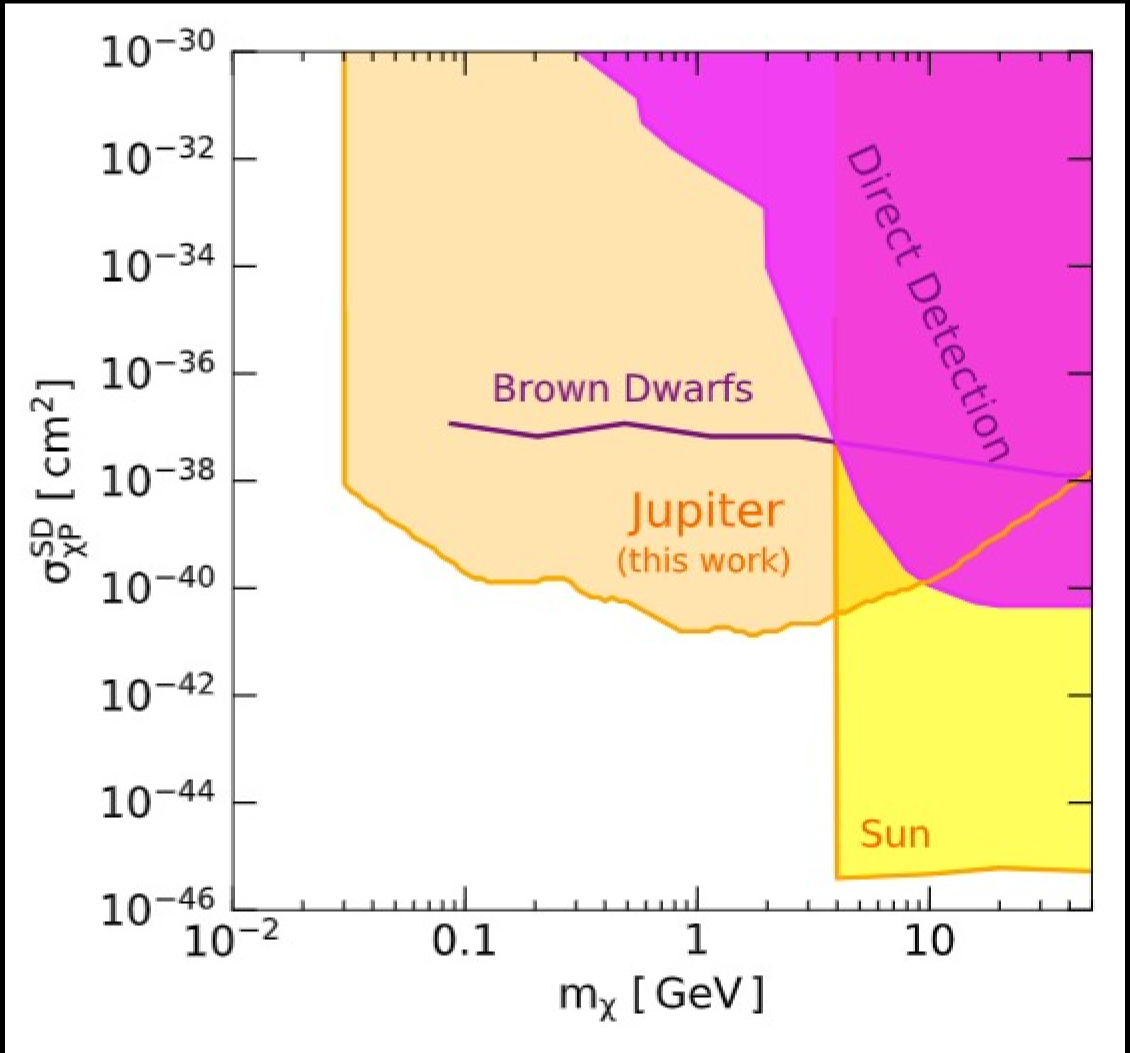
New dark matter limits

Some assumptions:

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

+ mediator decay length > Jupiter radius

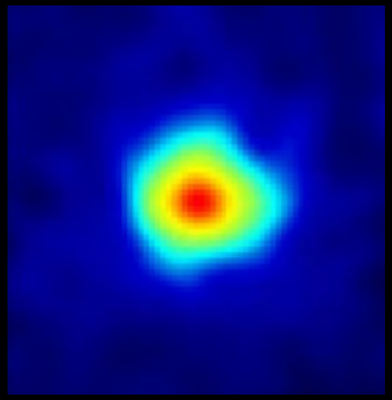
+ equilibrium

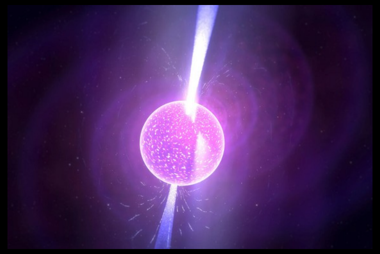


Leane + Linden '21

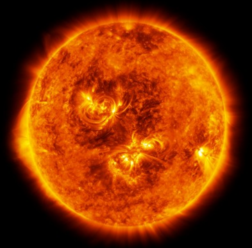
Summary and Outlook

- Dark matter unknown, key goal of our community
- Indirect detection probes a wide range of wavelengths and multi-messenger data
  - Dark matter in its natural habitat
  - Gamma rays: important role probing WIMP window



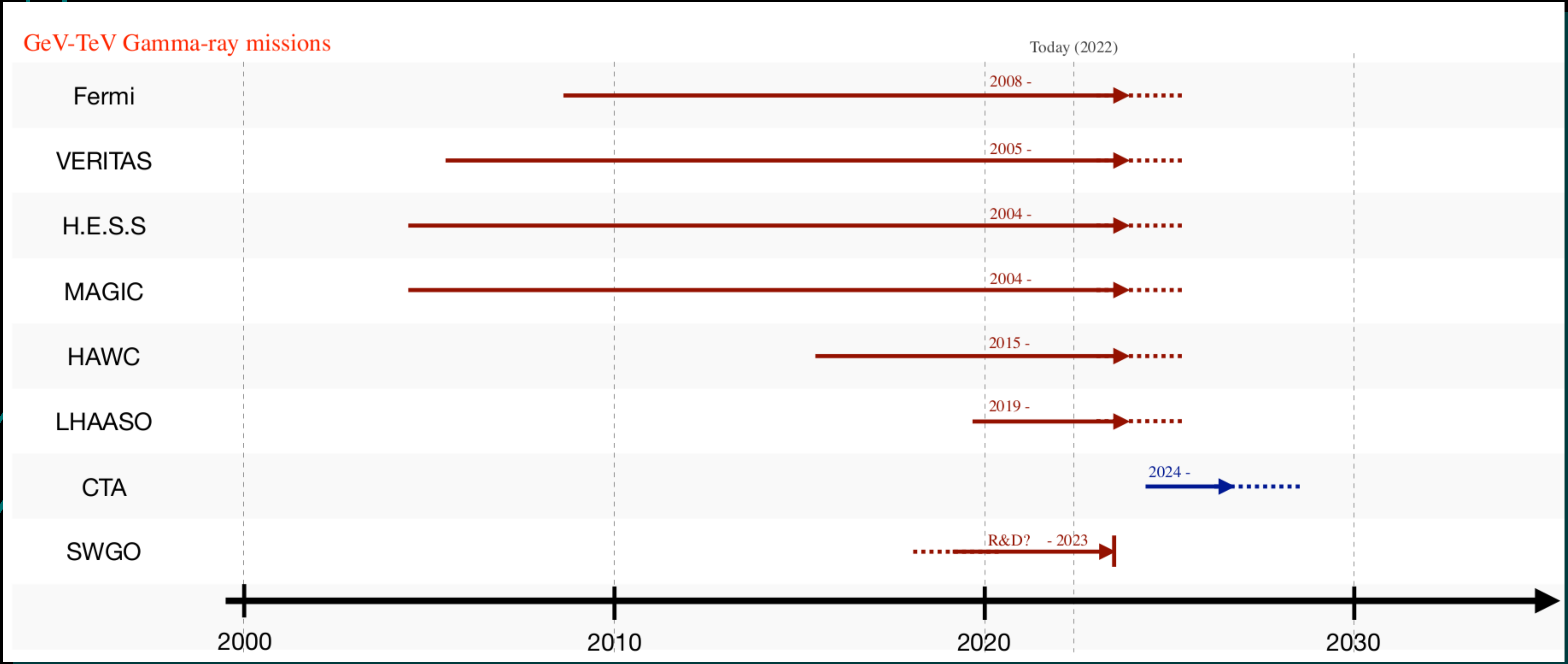


- Already have gamma-ray excess at Galactic Center



- Many excellent telescopes, upcoming SWGO, CTA
- New astrophysical searches with gamma-rays strong probe of DM properties

EXTRA SLIDES

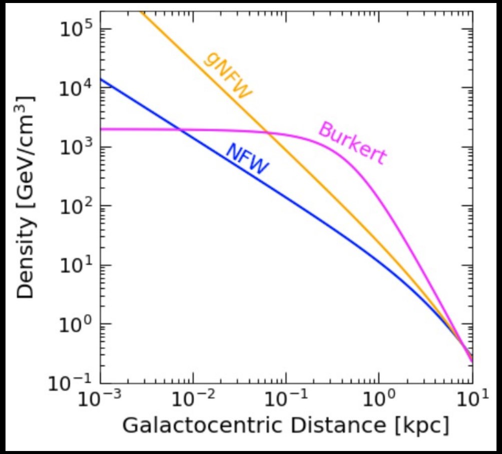


Aramaki et al, ‘22

Comparison with Halo Annihilation

Halo

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

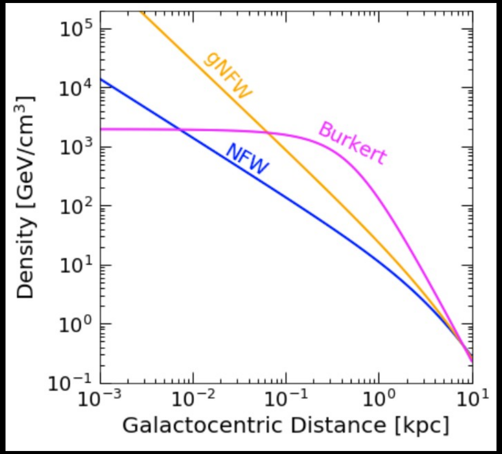


RKL, Linden, Mukhopadyay, Toro, 2021

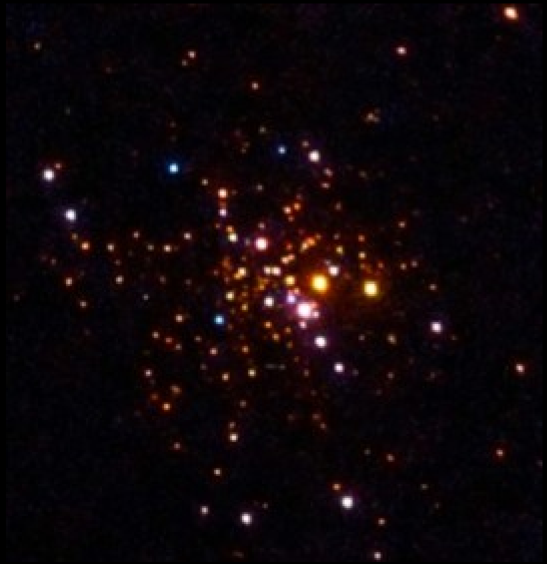
Comparison with Halo Annihilation

Halo

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

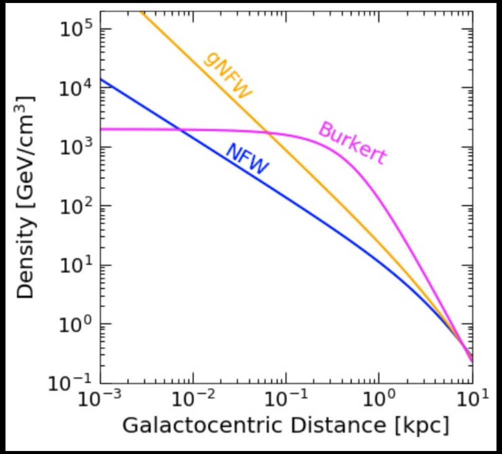


Celestial-body population



RKL, Linden, Mukhopadyay, Toro, 2021

Comparison with Halo Annihilation

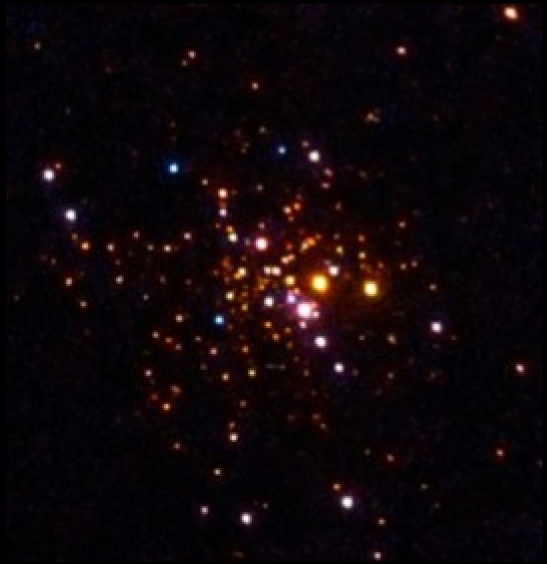


Halo

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

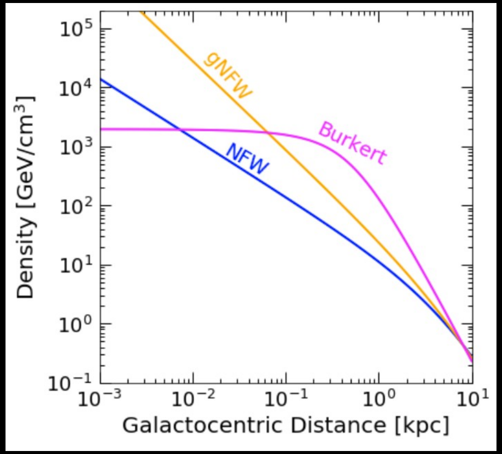
Celestial-body population

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



RKL, Linden, Mukhopadyay, Toro, 2021

Comparison with Halo Annihilation



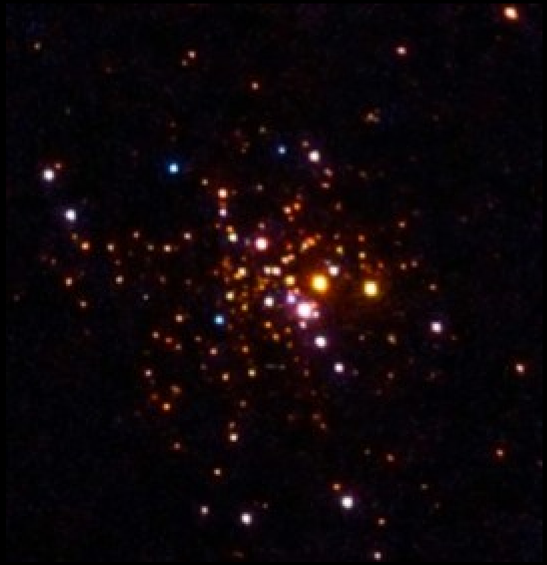
Halo

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

Celestial-body population

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

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

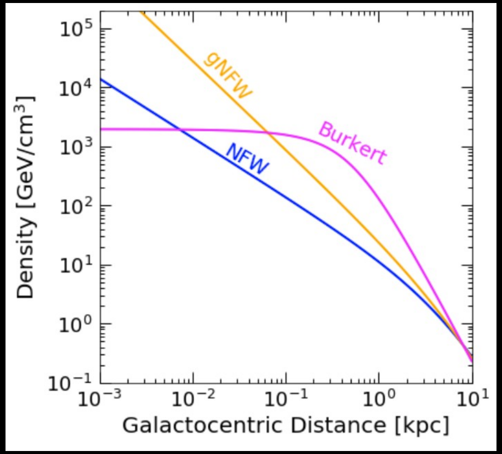


RKL, Linden, Mukhopadyay, Toro, 2021

Comparison with Halo Annihilation

Halo

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

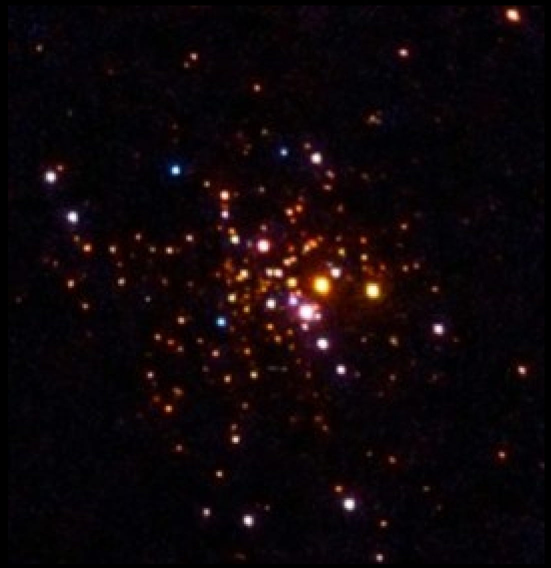


Celestial-body population

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

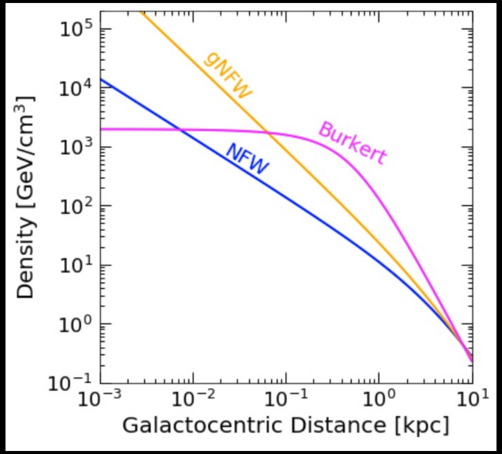
Population capture rate: $C_{\text{BD/NS,tot}} = 4\pi \int_{r_1}^{r_2} r^2 \, n_{\text{BD/NS}} \, C \, dr$

Annihilation/Capture equilibrium: $\Gamma_{\text{ann}} = \frac{\Gamma_{\text{cap}}}{2}$



RKL, Linden, Mukhopadyay, Toro, 2021

Comparison with Halo Annihilation



Halo

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

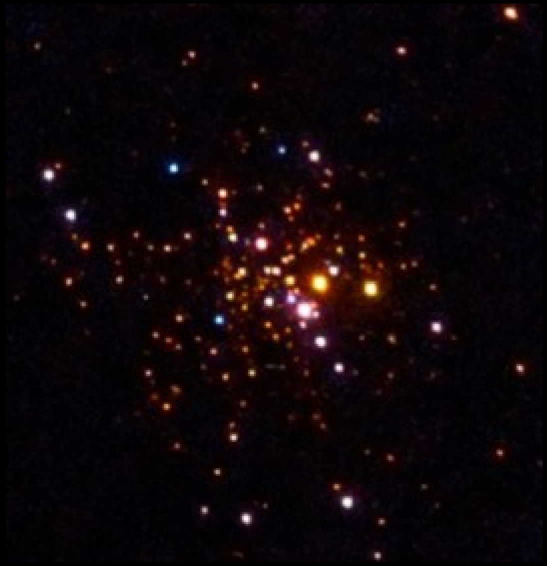
Celestial-body population

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

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

Annihilation/Capture equilibrium: $\Gamma_{\rm ann} = \frac{\Gamma_{\rm cap}}{2}$

Annihilation Scaling: $\Gamma_{\rm ann} \propto n_\chi n_{\rm BD/NS}$



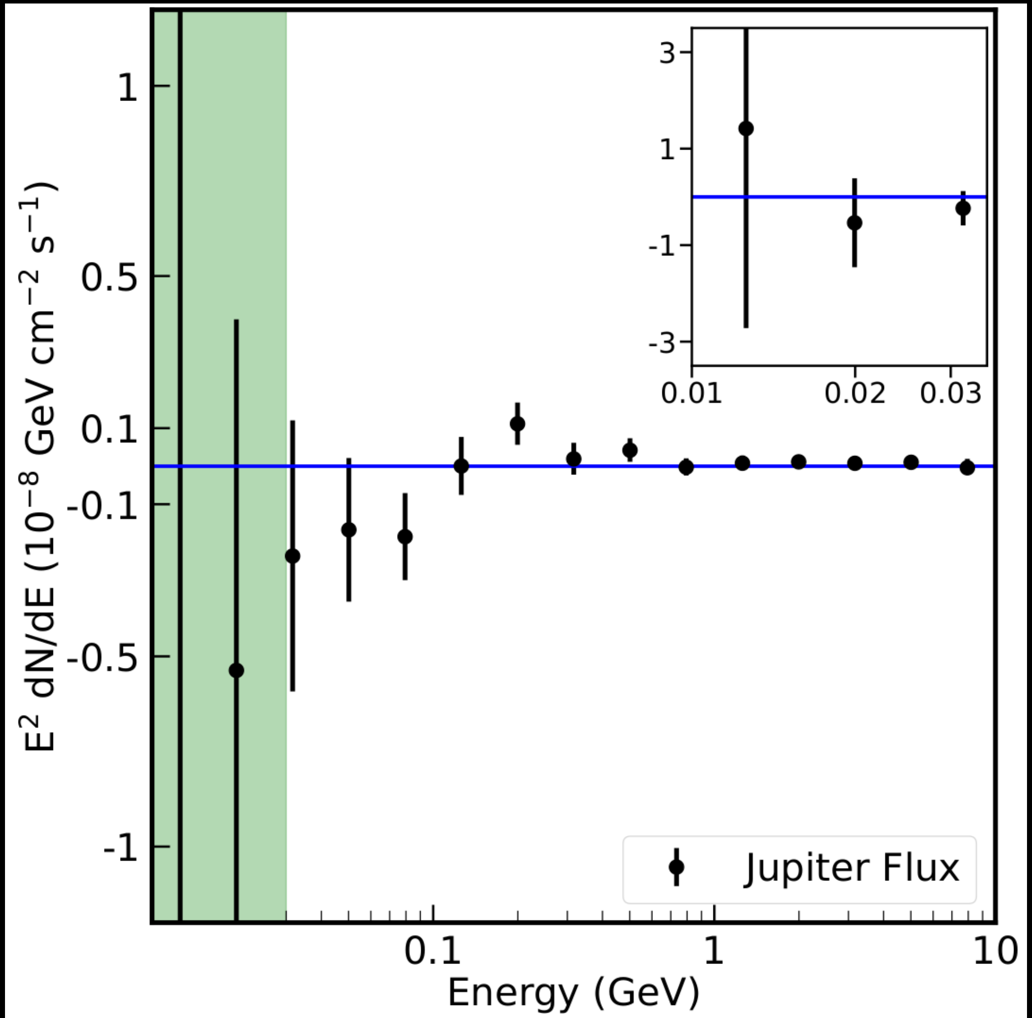
RKL, Linden, Mukhopadyay, Toro, 2021

Jupiter Gamma-Ray Flux Limits

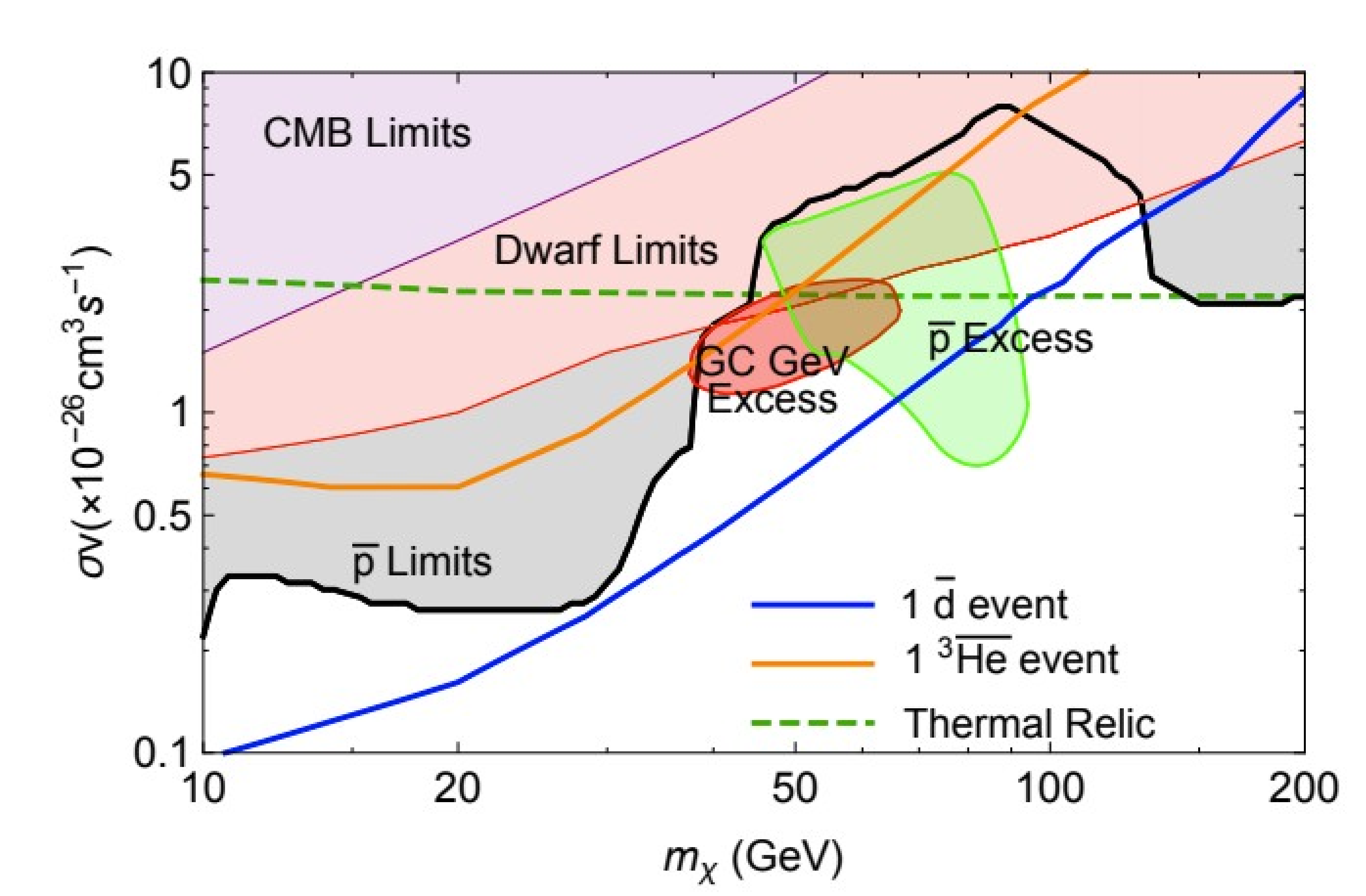
+ For range of power-law spectra, statistical sig of Jupiter emission never exceeds ~1.5σ

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

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

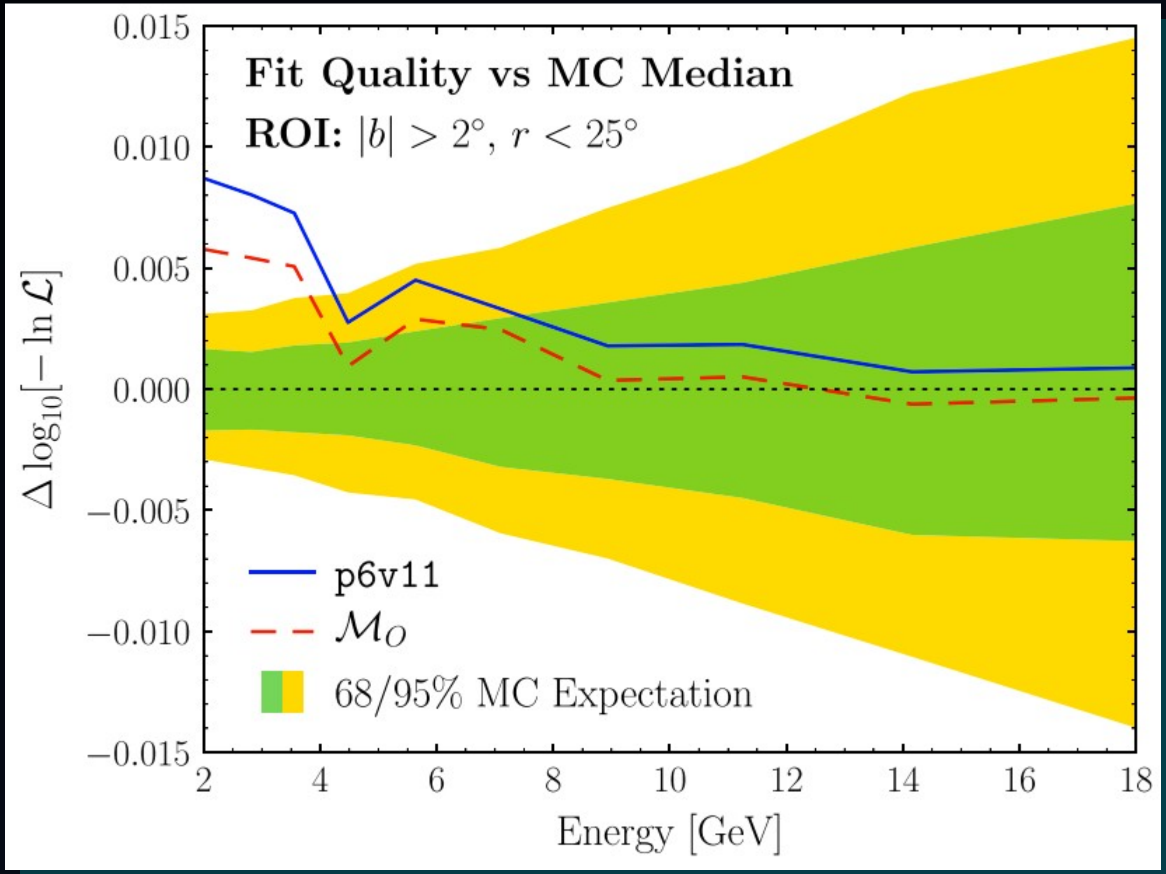


Leane + Linden '21



CMB Limits
Dwarf Limits
GC GeV Excess
p̄ Excess
p̄ Limits
1 d̄ event
1 ³He̅ event
Thermal Relic
σv(×10⁻²⁶cm³s⁻¹)
mχ (GeV)
10
5
1
0.5
0.1
10
20
50
100
200

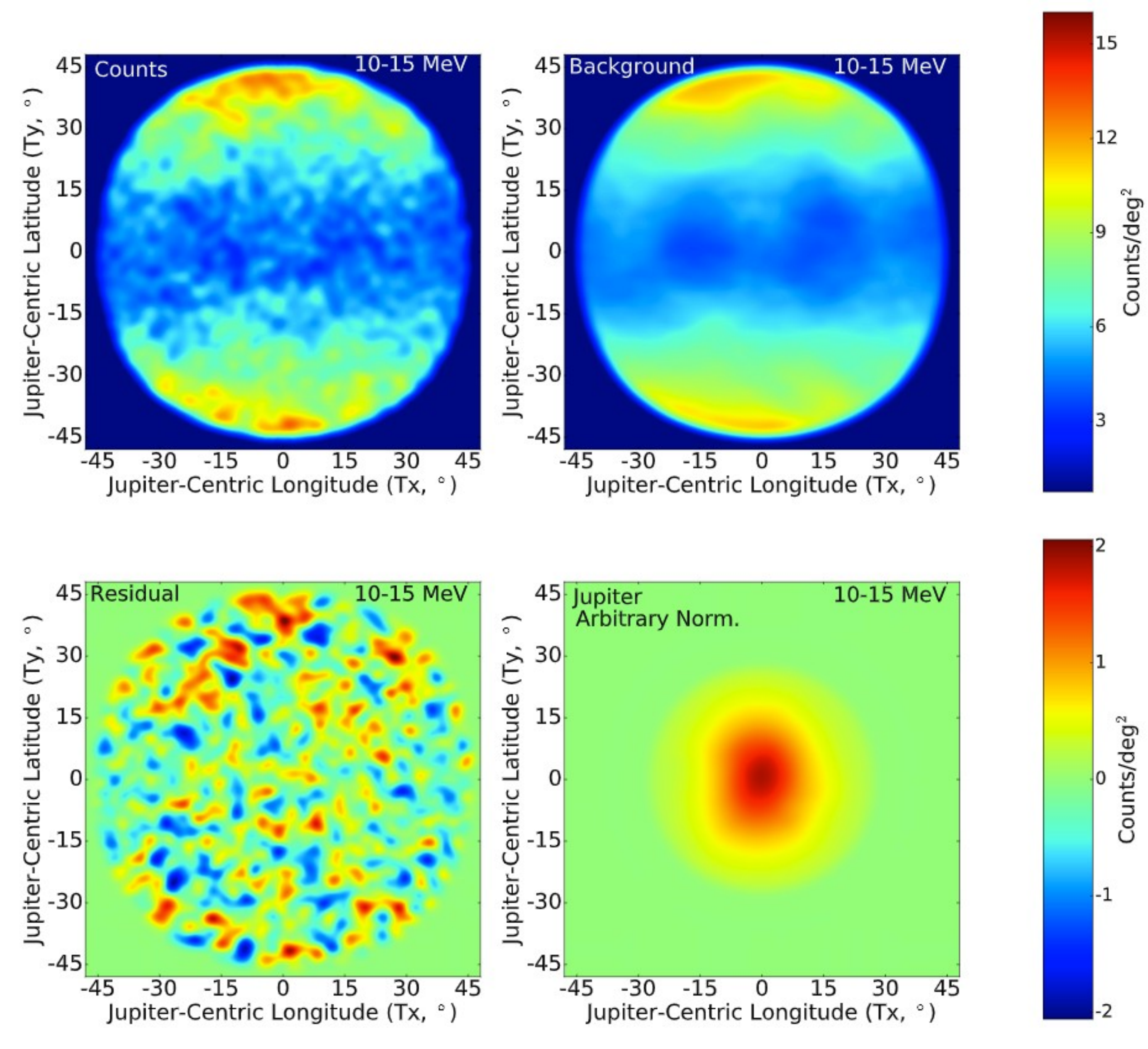
Key Point: All diffuse models are not good



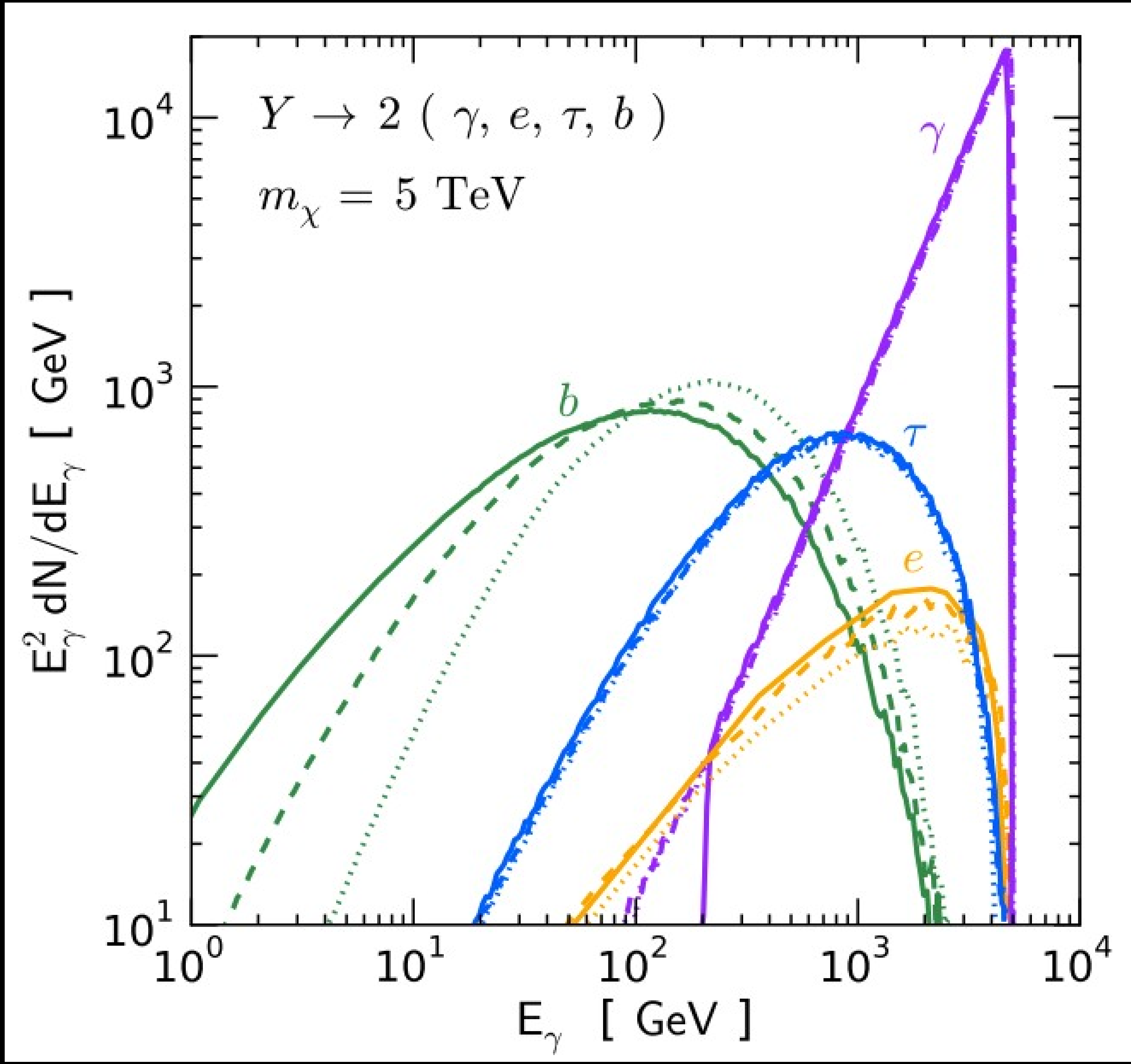
Buschmann+, '20

- Even the best diffuse models are far from good fits to the data
- Fitting to real data, and simulating based on best-fit parameters, does not return likelihoods expected within Poisson noise
- There is clearly a systematic here
- Better diffuse models are key to moving forward

Jupiter in Gamma Rays



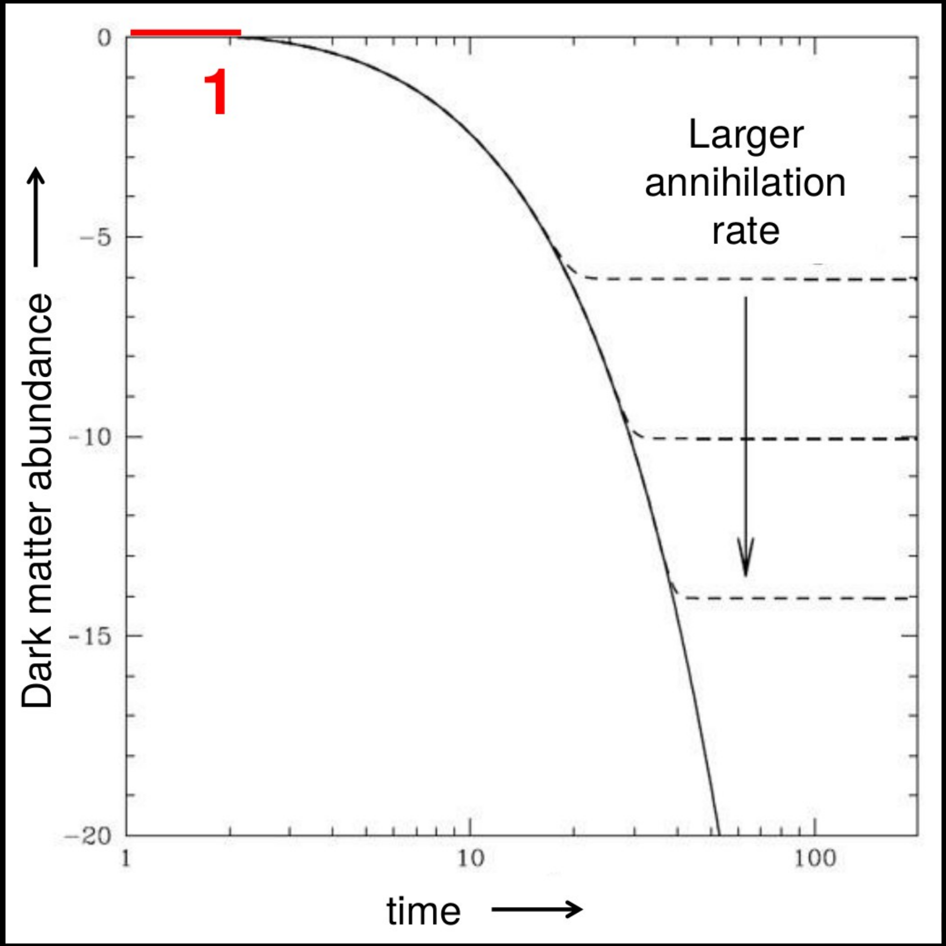
Leane + Linden ‘21



Rebecca Leane (SLAC)

Ingredient #1: DM Interaction Rate

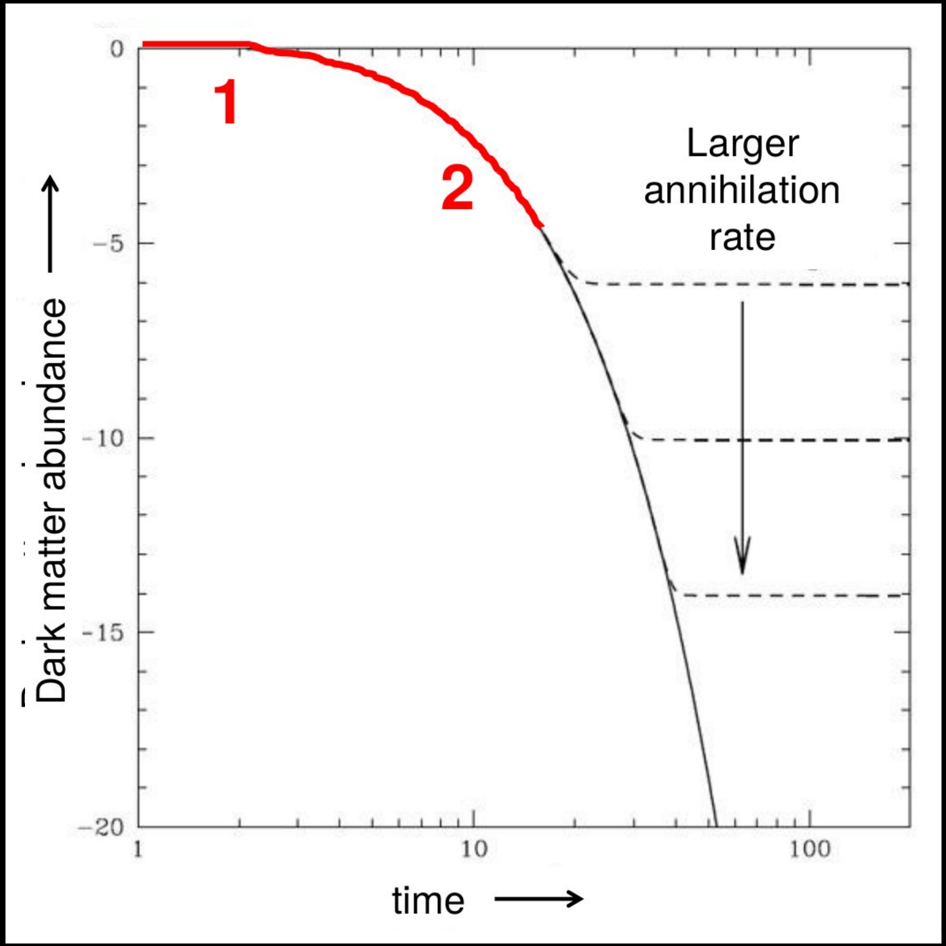
1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM



Ingredient #1: DM Interaction Rate

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

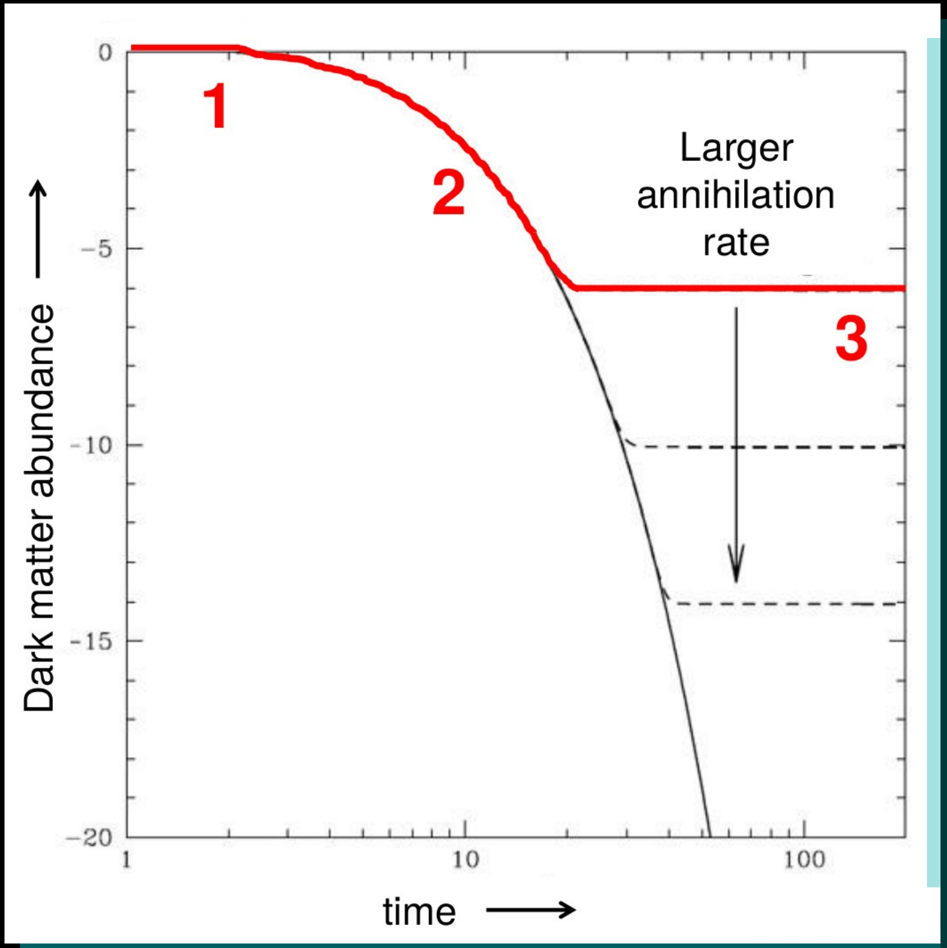


Ingredient #1: DM Interaction Rate

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

3) Universe expands too fast.
No more annihilations.
DM abundance is set.



Predicts a particular annihilation rate for dark matter.