

DETECTING DARK MATTER IN PLANETS

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BASED ON:

2010.00015 w/ JURI SMIRNOV

2104.02068 w/ TIM LINDEN

Outline

- New Search for Dark Matter in Exoplanets
 - Why exoplanets?
 - Calculating the signal
 - Detecting the signal
 - Dark Matter mass and cross section sensitivity
 - Outlook: what's needed next
- New Search and Analysis of Jupiter in Gamma Rays

Dark Matter in Exoplanets

Dark
Matter



Rebecca Leane (SLAC)

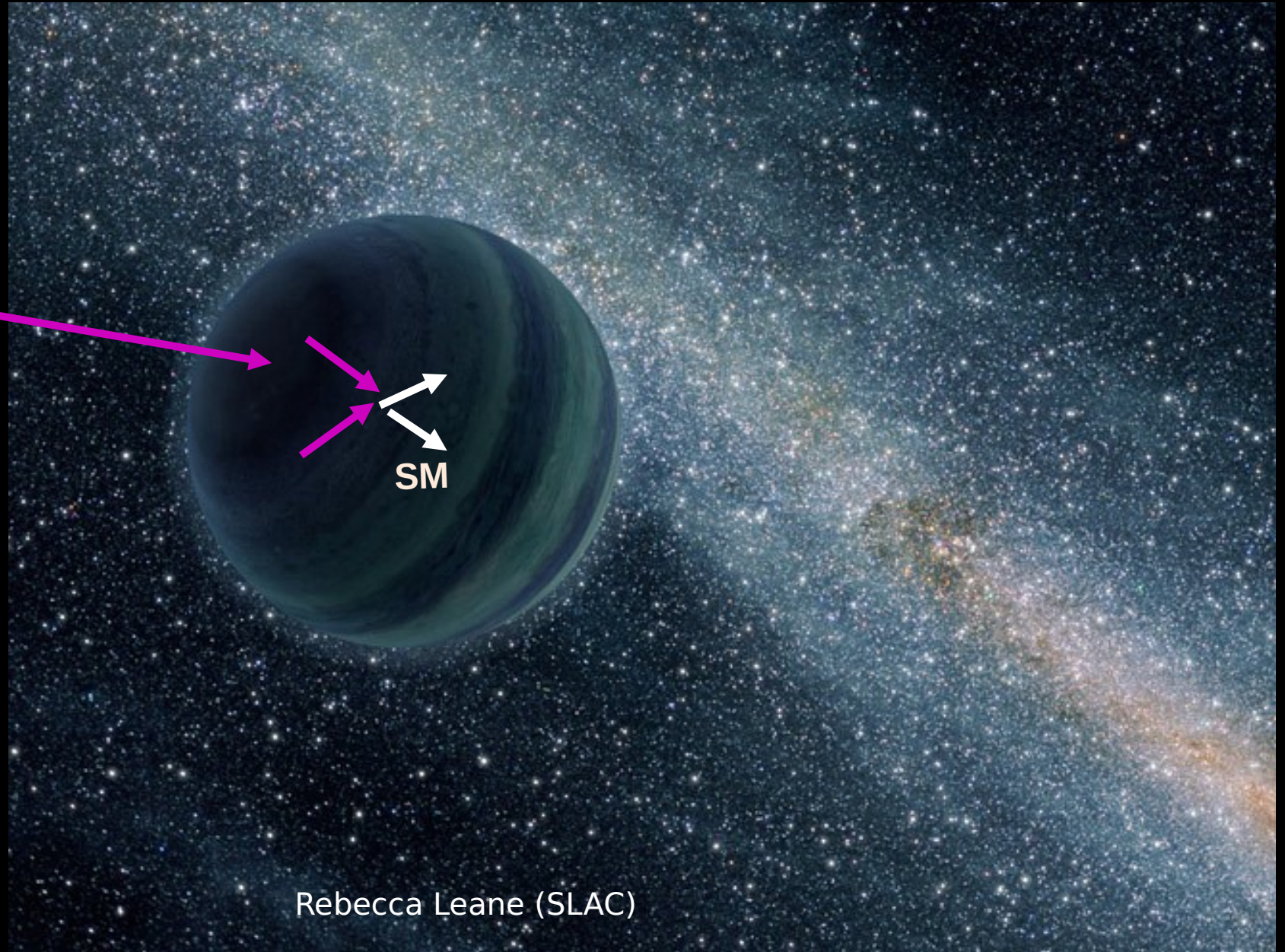
Dark Matter in Exoplanets

Dark
Matter

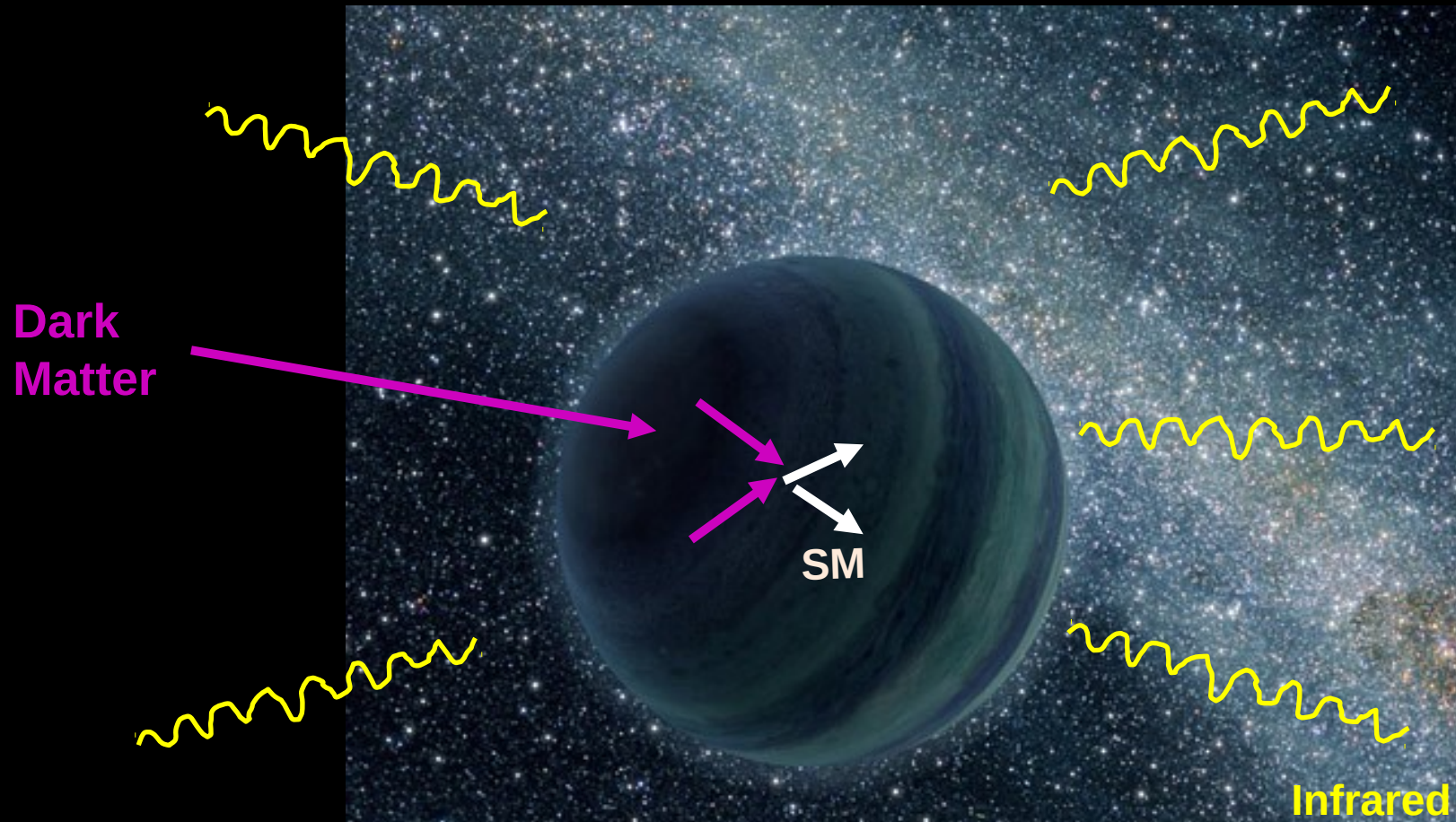


SM

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Dark Matter in Exoplanets



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Why Exoplanets?

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Advantage 1: Exploding Research Program

First exoplanet discovery: 1992
Almost all exoplanets we now know: 2010+
Majority of known exoplanets: **last five years**



Many upcoming telescopes and searches!

James Webb Space Telescope (JWST)
Transiting Exoplanets Survey Satellite (TESS)
Rubin/LSST
Roman/WFIRST
Gaia Spacecraft
Optical Gravitational Lensing Experiment (OGLE)
Two Micron All Sky Survey (2MASS)

Wide-field Infrared Survey Explorer (WISE)
Thirty Meter Telescope (TMT)
Extremely Large Telescope (ELT)
Gaia Near Infra-Red (GaiaNIR)
Large Ultraviolet Optical Infrared Surveyor (LUVOIR)
Habitable Exoplanet Imaging Mission (HabEx)
Origins Space Telescope (OST)

Ample motivation to consider **new ways** this exploding research area can be used to probe new physics.

Advantage 2: Statistics

Estimates predict around **300 billion** exoplanets in our galaxy!

To date:

4,301 confirmed exoplanets
5,633 exoplanet candidates



$\times 10^{11}$

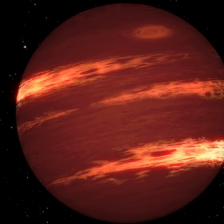


$\times 10^{11}$



$\times 1$

One Jupiter :(



$\times 10^{11}$

Billions of Exoplanets! :)

Advantage 3: Low temperatures

- Exoplanets can be very cold, as they do not undergo nuclear fusion
 - Low temperatures allow for a clearer signal over background for DM heating
- Low core temperatures in part prevent DM evaporation, providing new sensitivity to lighter (sub-GeV) DM

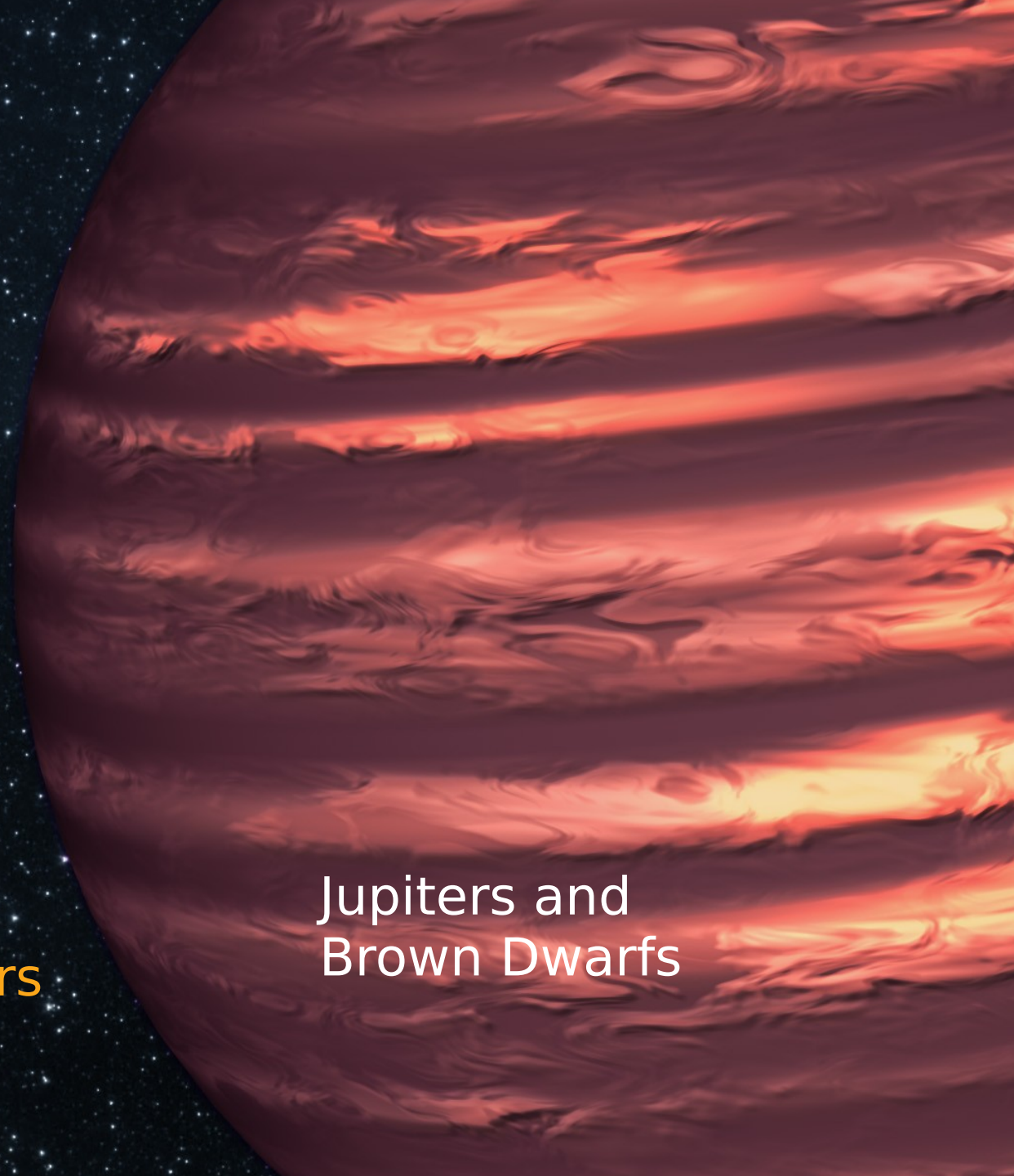


Advantage 4: SIZE

Neutron Star

Jupiters and
Brown Dwarfs

+ Easier to detect than neutron stars



Exoplanet Search Targets

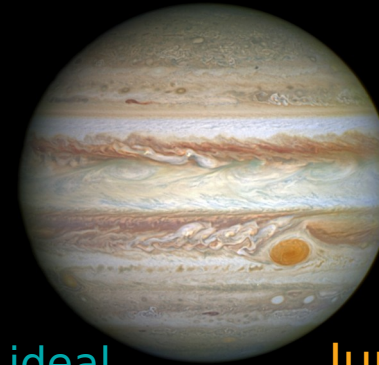


Not ideal

Earths + Super Earths:

Mass: 0.001- 0.01 M_{Jup}

Radius: ~0.1 - 1 R_{Jup}

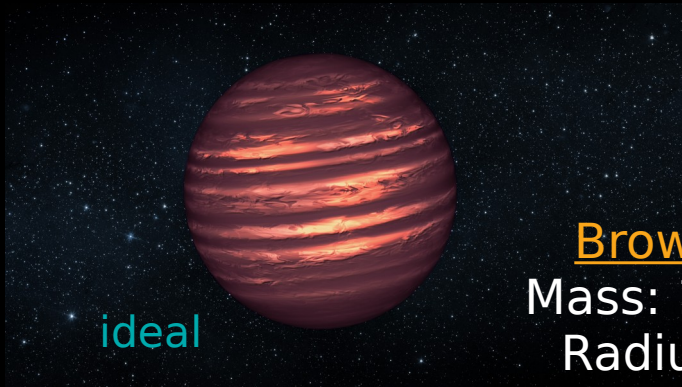


ideal

Jupiters + Super Jupiters:

Mass: 1 - 13 M_{Jup}

Radius: ~1 R_{Jup}



ideal

Brown dwarfs:

Mass: 13 - 75 M_{Jup}

Radius: ~1 R_{Jup}

Very dense!



ideal

Rogue Planets:

Cold and all alone!

Most commonly Jupiter-sized
up to brown dwarf sized



Calculating Dark Matter Exoplanet Heating

Rebecca Leane (SLAC)

Calculating Exoplanet Temperatures

- Contributions to temperature from external heat (i.e. nearby stars), internal heat (e.g. from formation or burning processes), and dark matter:

$$\Gamma_{\text{heat}}^{\text{tot}} = \Gamma_{\text{heat}}^{\text{ext}} + \Gamma_{\text{heat}}^{\text{int}} + \Gamma_{\text{heat}}^{\text{DM}} = 4\pi R^2 \sigma_{\text{SB}} T^4 \epsilon$$

- External heat: assume zero, means we need exoplanets either very far from their host, or not bound at all (rogue planets)
- Internal heat: determined by cooling rate over time, choose old exoplanets (e.g. 1-10 gigayears old) to minimize internal heat

Calculating Exoplanet Temperatures

- Contributions to temperature from external heat (i.e. nearby stars), internal heat (e.g. from formation or burning processes), and dark matter:

$$\Gamma_{\text{heat}}^{\text{tot}} = \Gamma_{\text{heat}}^{\text{ext}} + \Gamma_{\text{heat}}^{\text{int}} + \Gamma_{\text{heat}}^{\text{DM}} = 4\pi R^2 \sigma_{\text{SB}} T^4 \epsilon$$

Heat power from DM:

- DM density throughout Galaxy:

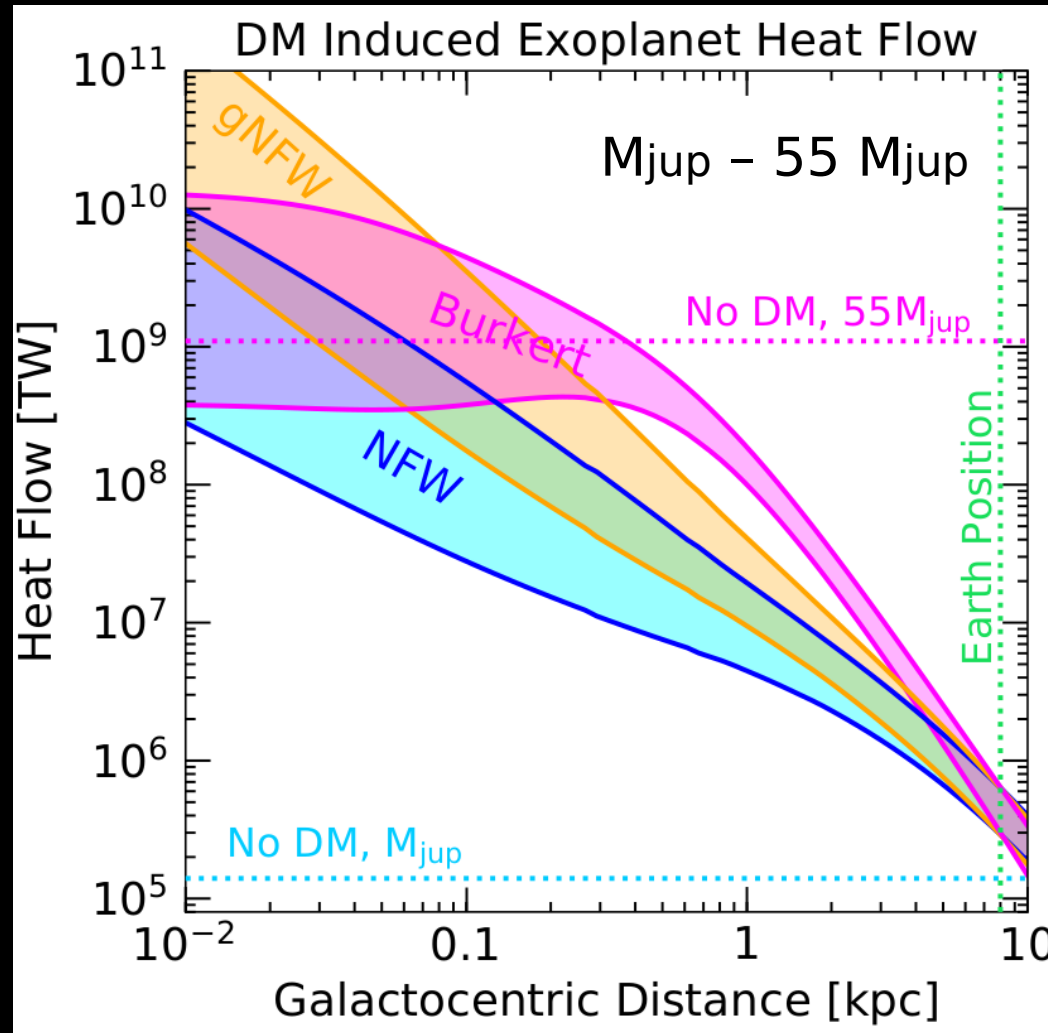
$$\rho_{\chi}(r) = \frac{\rho_0}{(r/r_s)^{\gamma} (1 + (r/r_s))^{3-\gamma}}$$

- Relevant velocities:
 - DM halo velocity
 - Exoplanet escape velocity

$$\Gamma_{\text{heat}}^{\text{DM}} = f \pi R^2 \rho_{\chi}(r) v_0 \left(1 + \frac{3}{2} \frac{v_{\text{esc}}^2}{v_d(r)^2} \right)$$

$$v_{\text{esc}}^2 = 2G_N M/R$$

DM Heating vs Internal Heat



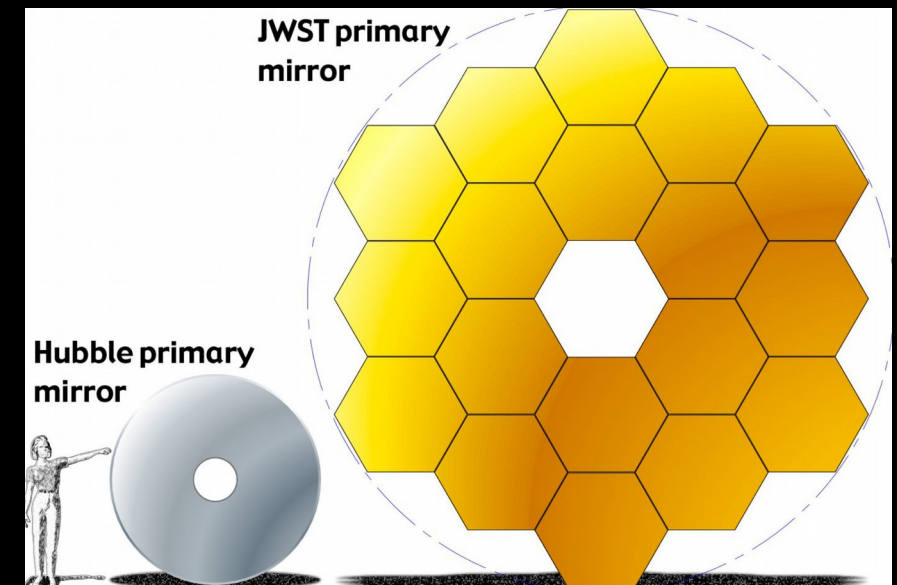
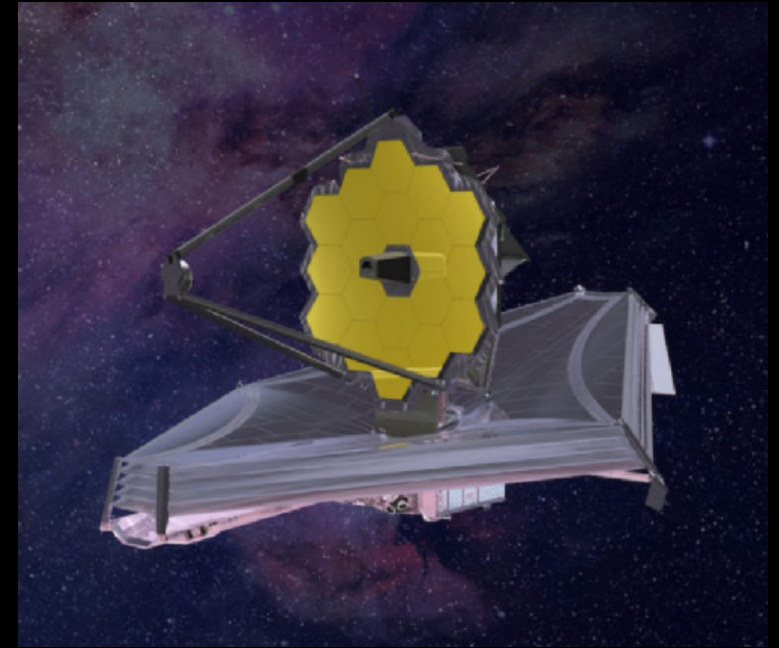
Leane + Smirnov, PRL '21

Rebecca Leane (SLAC)

1 parsec = 3.26 light years

Telescope Sensitivity

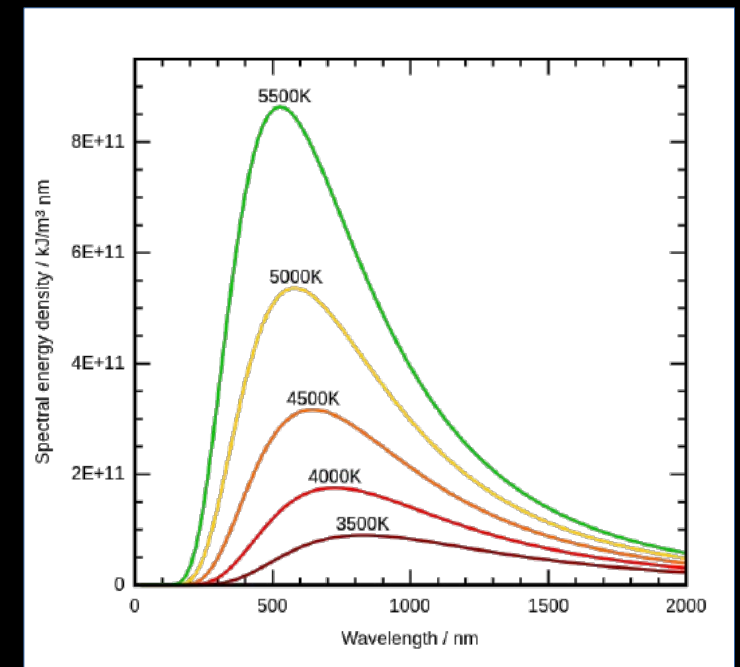
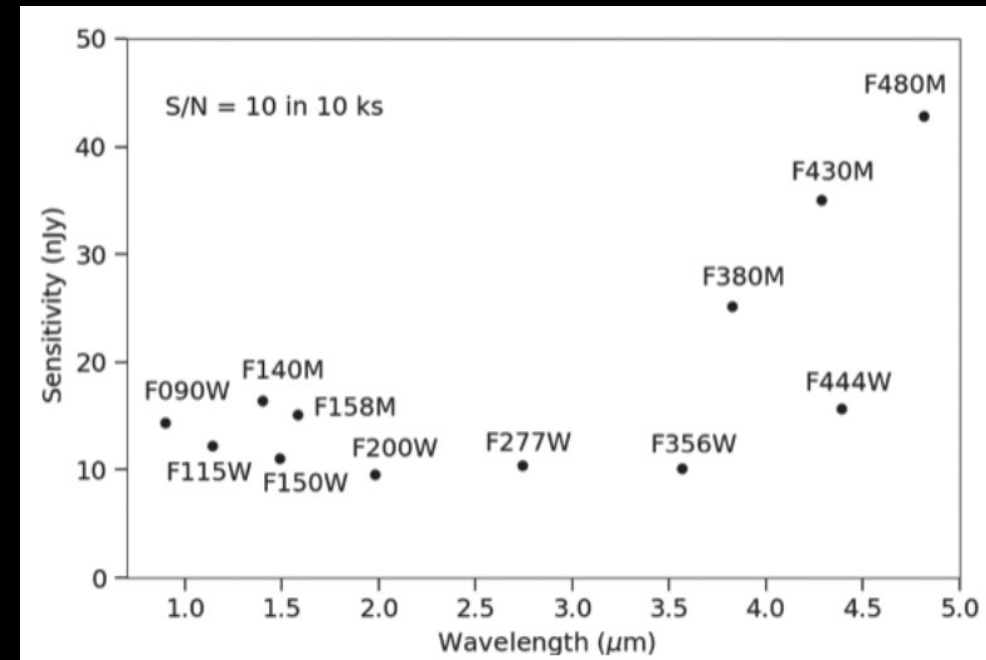
- Use James Webb Space Telescope (planned launch Oct 2021)
- Infrared sensitivity ($\sim 0.5 - 28$ microns)
- Has many instruments and filters, relevant choice for maximum sensitivity depends on peak wavelength



Signal with James Webb

- Can see many stars/planets at once
- Assume exoplanets radiate as a blackbody
 - Assume peak of blackbody temperature sets the sensitivity limit
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for $T > 500$ K
- Mid-Infrared Instrument (MIRI) for $T = 100 - 500$ K

Won't need new dedicated searches; can piggyback



Search Challenges



Dust backgrounds:

Rescatter some wavelengths,
which can reduce intensity and
shift spectrum peaks



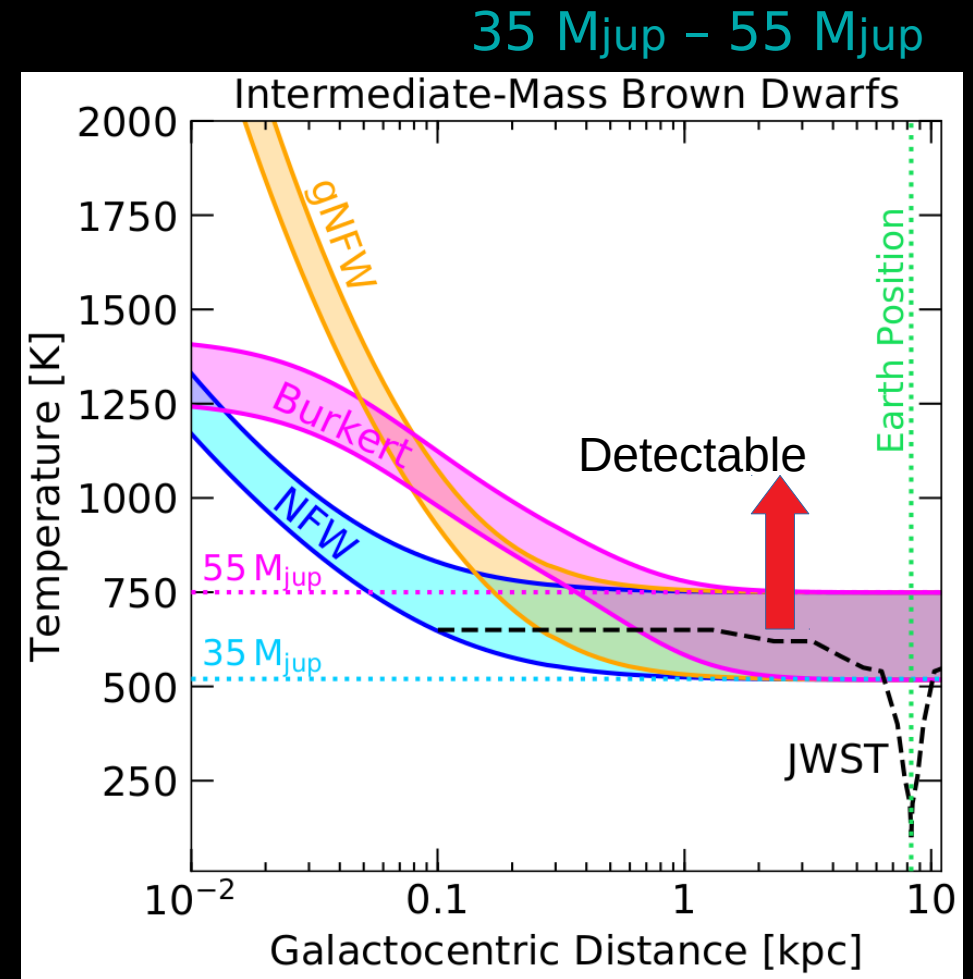
Stellar crowding:

Stars per pixel important, can
outshine exoplanet signal

**Optimal sensitivity is outside 0.1 kpc
(about 1 degree off the plane)**

Exoplanet temperatures vs sensitivity

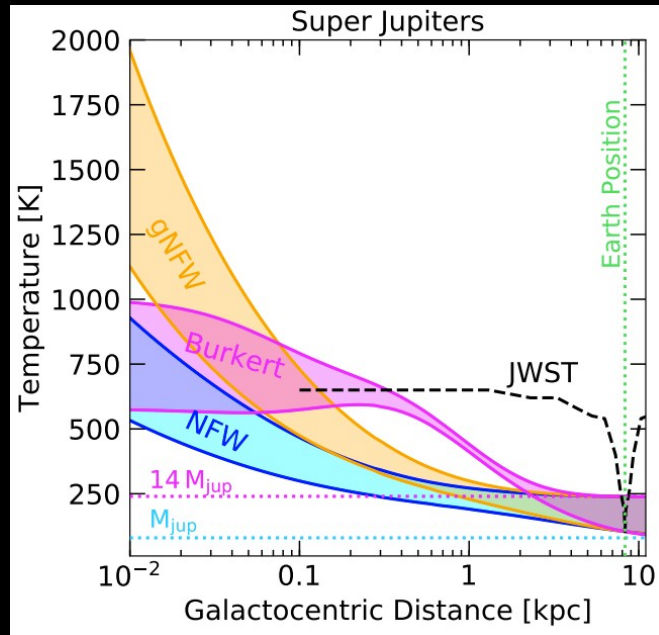
- NFW, gNFW, Burkert are DM profiles, shaded area is exoplanet mass range
- Sensitivity truncates at $\sim 0.1\text{kpc}$, due to stars per pixel, and dust scattering



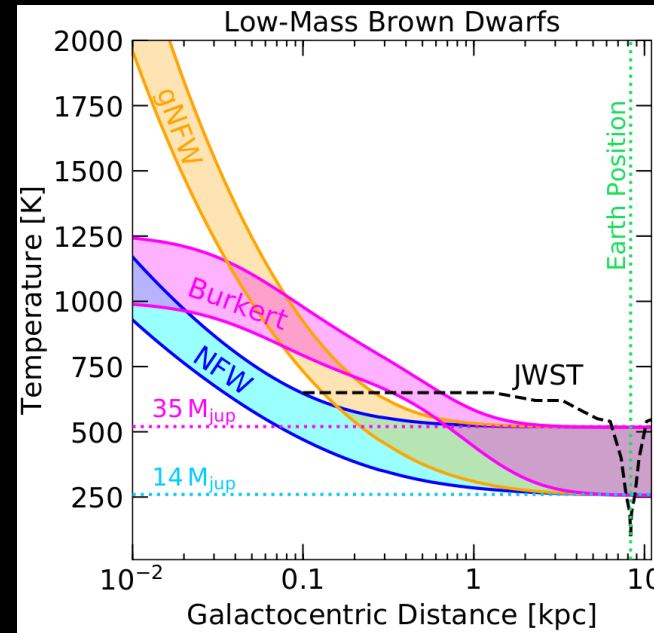
Leane + Smirnov, PRL '21

Exoplanet masses vs sensitivity

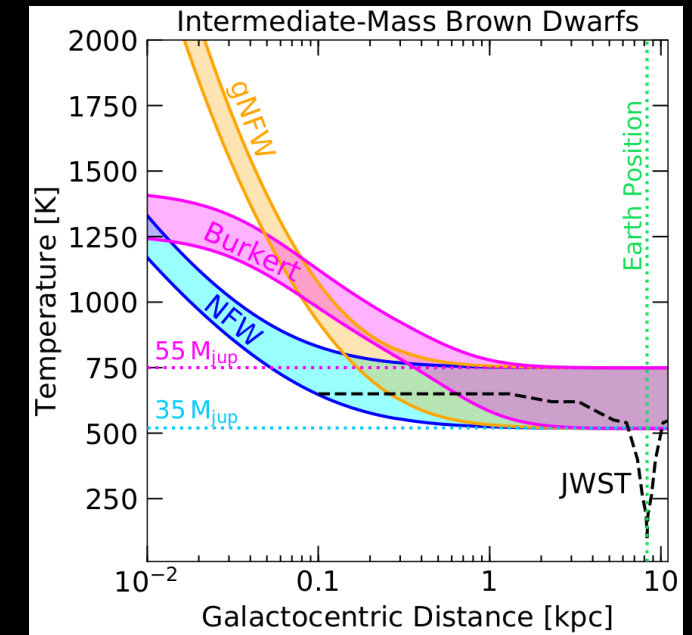
M_{jup} – 14 M_{jup}



14 M_{jup} – 35 M_{jup}



35 M_{jup} – 55 M_{jup}

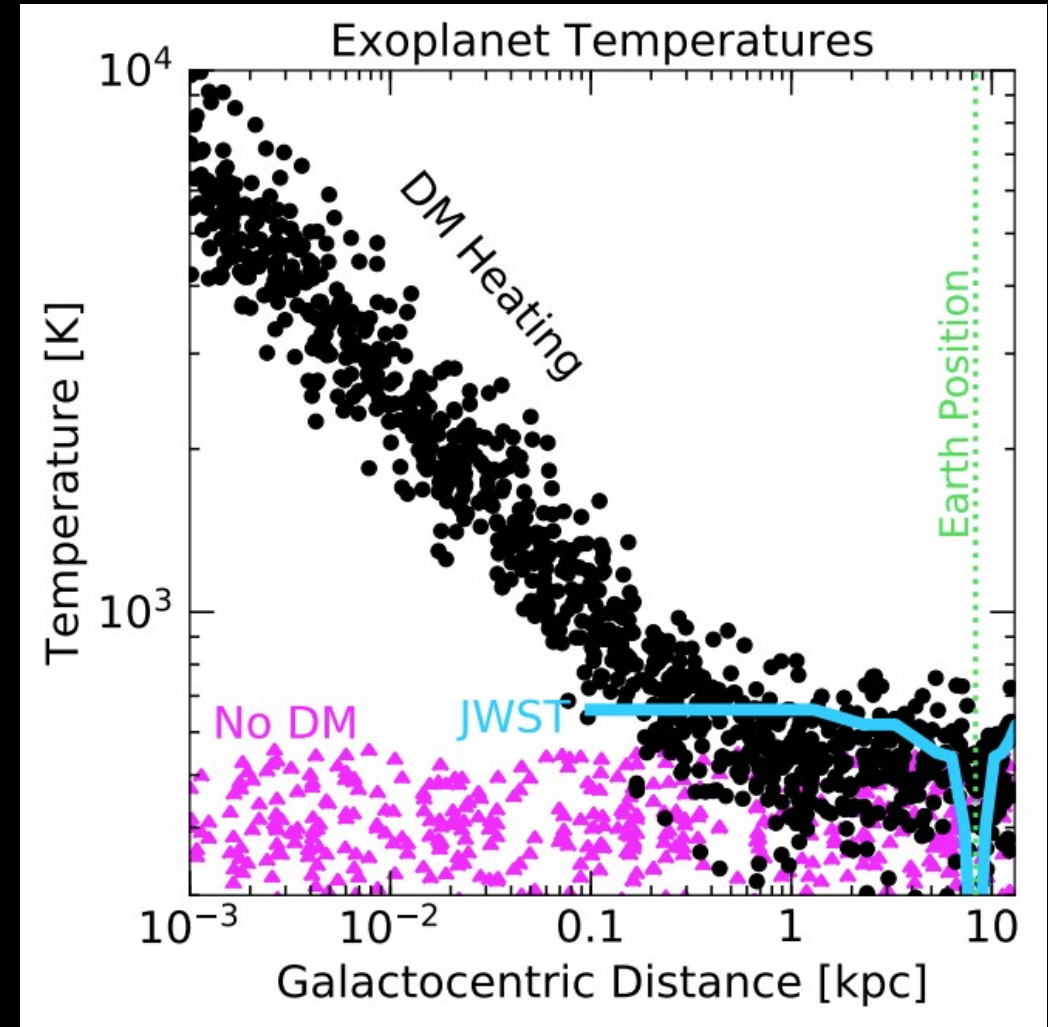


Lower masses:
DM heat > internal
heat at all positions

Higher masses:
Strongest signal towards Galactic
Center, local DM heating signal difficult
to outperform internal heat

New DM Search with Exoplanets

- Mock distribution of exoplanets with masses 20 – 50 Jupiters, gNFW profile, with and without DM heating
- Exoplanets can be used to map the Galactic DM density, given sufficient telescope sensitivity
- Identify exoplanets via other methods (e.g. microlensing) first, follow up with James Webb

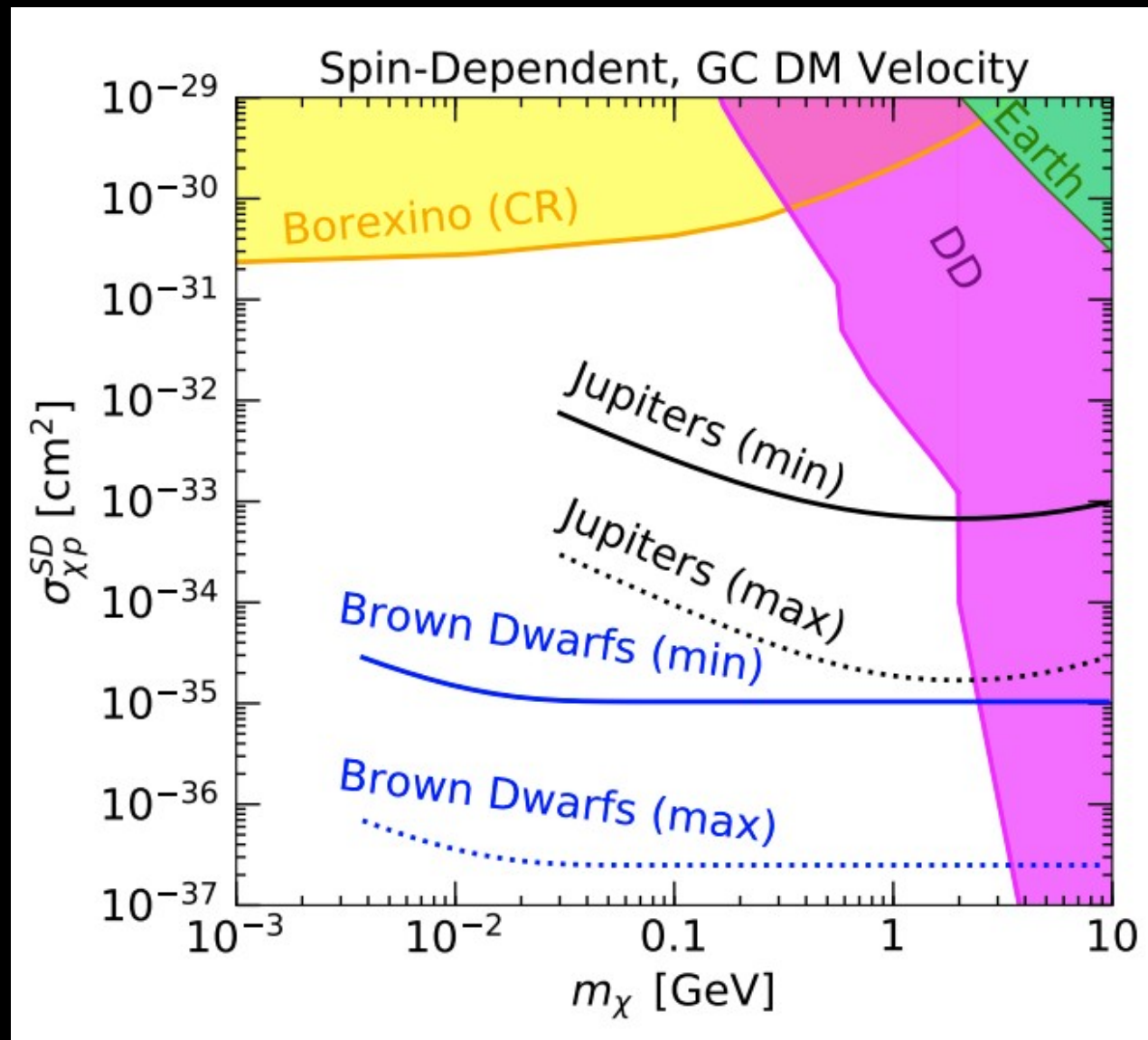


Prospects for these searches?

Planet	Radius (R_{jup})	Mass (M_{jup})	Distance	Orbit	Temp (No DM)	Temp (with DM)	Ref
Epsilon Eridani b	1.21	1.55	3 pc	3.4 au	$\lesssim 200$ K	$\lesssim 650$ K	[84]
Epsilon Indi A b	1.17	3.25	3.7 pc	11.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[85]
Gliese 832 b	1.25	0.68	4.9 pc	3.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[86]
Gliese 849 b	1.23	1.0	8.8 pc	2.4 au	$\lesssim 200$ K	$\lesssim 650$ K	[87]
Thestias	1.19	2.3	10 pc	1.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[88]
Lipperhey	1.16	3.9	12.5 pc	5.5 au	$\lesssim 200$ K	$\lesssim 650$ K	[89]
HD 147513 b	1.22	1.21	12.8 pc	1.3 au	$\lesssim 200$ K	$\lesssim 650$ K	[90]
Gamma Cephei b	1.2	1.85	13.5 pc	2.0 au	$\lesssim 200$ K	$\lesssim 650$ K	[91]
Majriti	1.16	4.1	13.5 pc	2.5 au	~ 218 K	$\lesssim 650$ K	[92]
47 Ursae Majoris d	1.2	1.64	14 pc	11.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[93]
Taphao Thong	1.2	2.5	14 pc	2.1 au	$\lesssim 200$ K	$\lesssim 650$ K	[93]
Gliese 777 b	1.21	1.54	15.9 pc	4.0 au	$\lesssim 200$ K	$\lesssim 650$ K	[94]
Gliese 317 c	1.21	1.54	15.0 pc	25.0 au	$\lesssim 200$ K	$\lesssim 650$ K	[95]
q ¹ Eridani b	1.23	0.94	17.5 pc	2.0 au	$\lesssim 200$ K	$\lesssim 650$ K	[87]
HD 87883 b	1.21	1.54	18.4 pc	3.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[96]
ν^2 Canis Majoris c	1.24	0.87	19.9 pc	2.2 au	$\lesssim 200$ K	$\lesssim 650$ K	[97]
Psi ¹ Draconis B b	1.21	1.53	22.0 pc	4.4 au	$\lesssim 200$ K	$\lesssim 650$ K	[98]
HD 70642 b	1.19	1.99	29.4 pc	3.3 au	$\lesssim 200$ K	$\lesssim 650$ K	[99]
HD 29021 b	1.2	2.4	31 pc	2.3 au	$\lesssim 200$ K	$\lesssim 650$ K	[100]
HD 117207 b	1.2	1.9	32.5 pc	4.1 au	$\lesssim 200$ K	$\lesssim 650$ K	[101]
Xolotlan	1.2	0.9	34.0 pc	1.7 au	$\lesssim 200$ K	$\lesssim 650$ K	[102]
HAT-P-11 c	1.2	1.6	38.0 pc	4.1 au	$\lesssim 200$ K	$\lesssim 650$ K	[103]
HD 187123 c	1.2	2.0	46.0 pc	4.9 au	$\lesssim 200$ K	$\lesssim 650$ K	[104]
HD 50499 b	1.2	1.6	46.3 pc	3.8 au	$\lesssim 200$ K	$\lesssim 650$ K	[101]
Dimos	1.2	1.1	49.4 pc	0.8 au	$\lesssim 200$ K	$\lesssim 650$ K	[105]

- Many candidates already exist!
- Gaia may be able to see up to around 90,000 planets within 100 pc (local search)
- WFIRST/Roman expects to detect least several thousand exoplanets in the inner galaxy

Cross section sensitivity



Actions for successful discovery/exclusion

- Successful launch with JWST
- Large statistical sample obtained to overcome systematics
- Detailed simulations of atmosphere effects including DM
- Simulations of age/cooling curves of Jupiters + Dwarfs
including DM



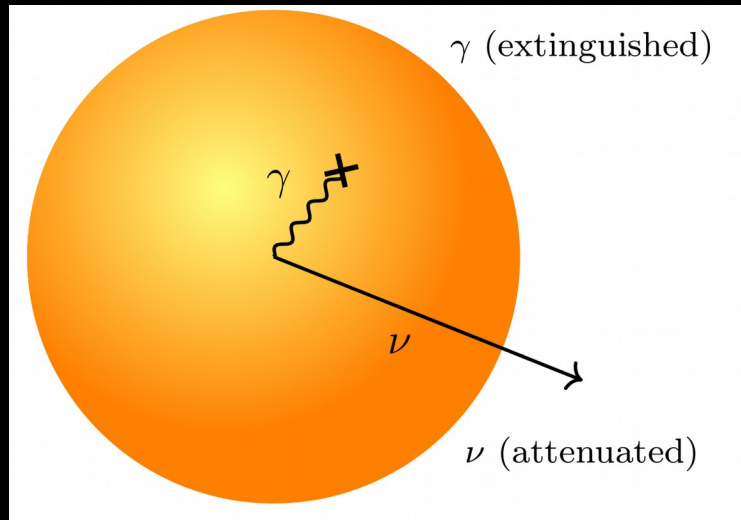
Complementary Search with new limits

Rebecca Leane (SLAC)

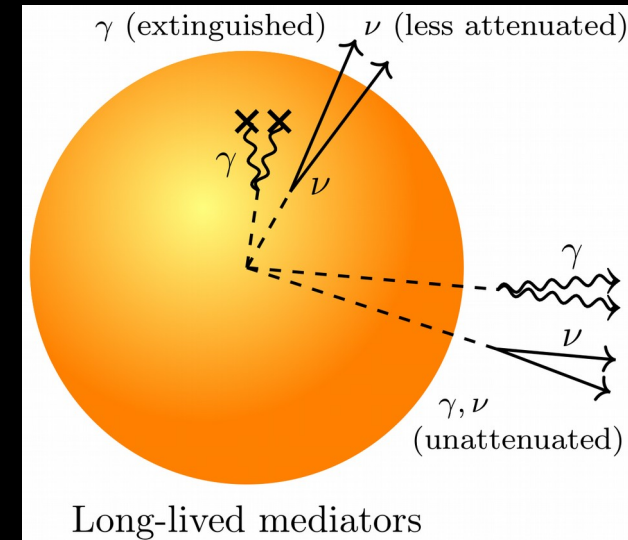
Complementary Searches

Two regimes:

- 1. DM annihilates to **short-lived mediators**
→ heats planets



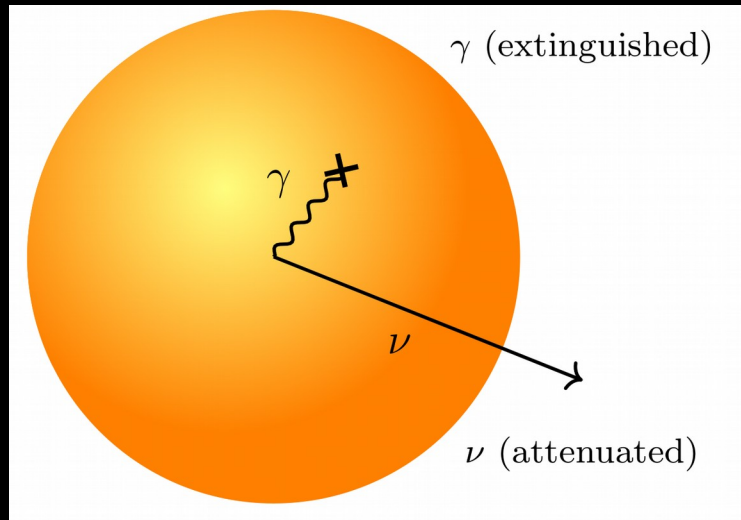
- 2. DM annihilates to **long-lived mediators**
→ *escapes* planets!



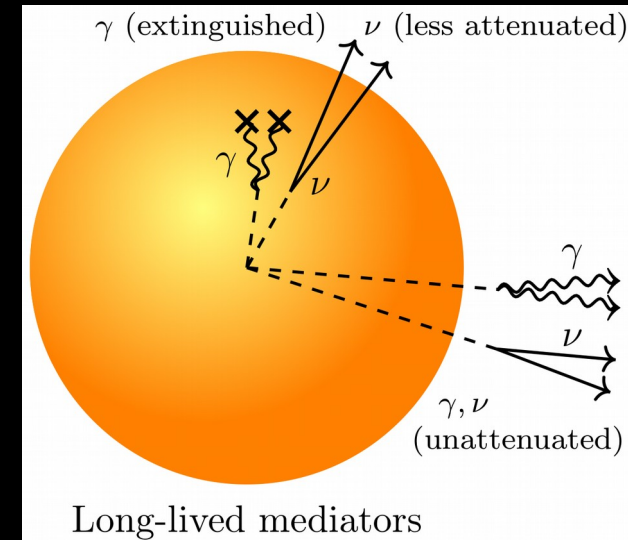
Complementary Searches

Two regimes:

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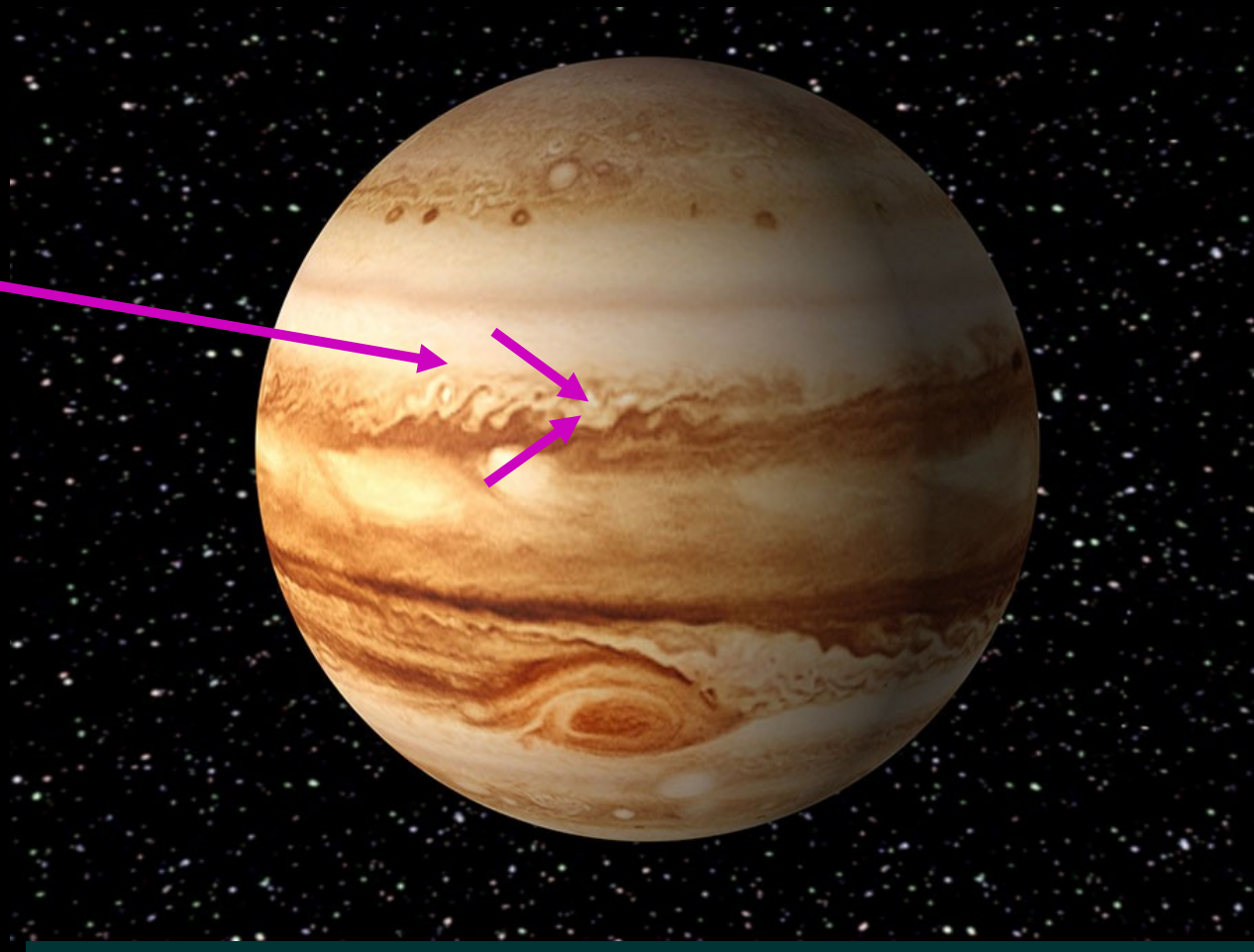


- 2. DM annihilates to **long-lived mediators**
→ *escapes* planets!



Dark Matter in Jupiter

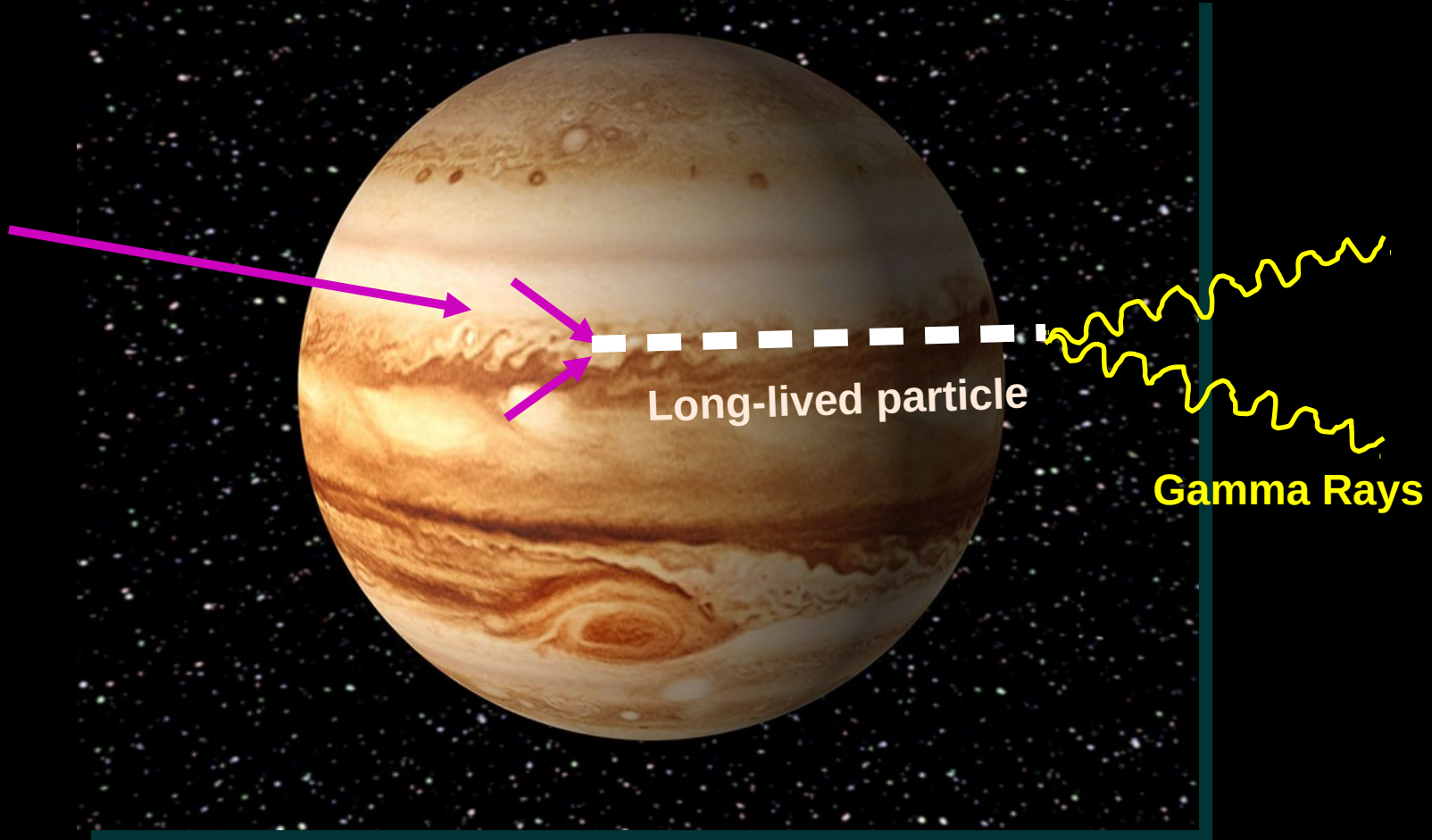
Dark
Matter



Rebecca Leane (SLAC)

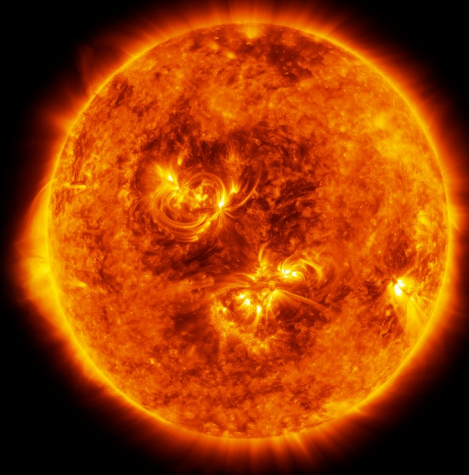
Dark Matter in Jupiter

Dark Matter



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Why Jupiter?



Sun

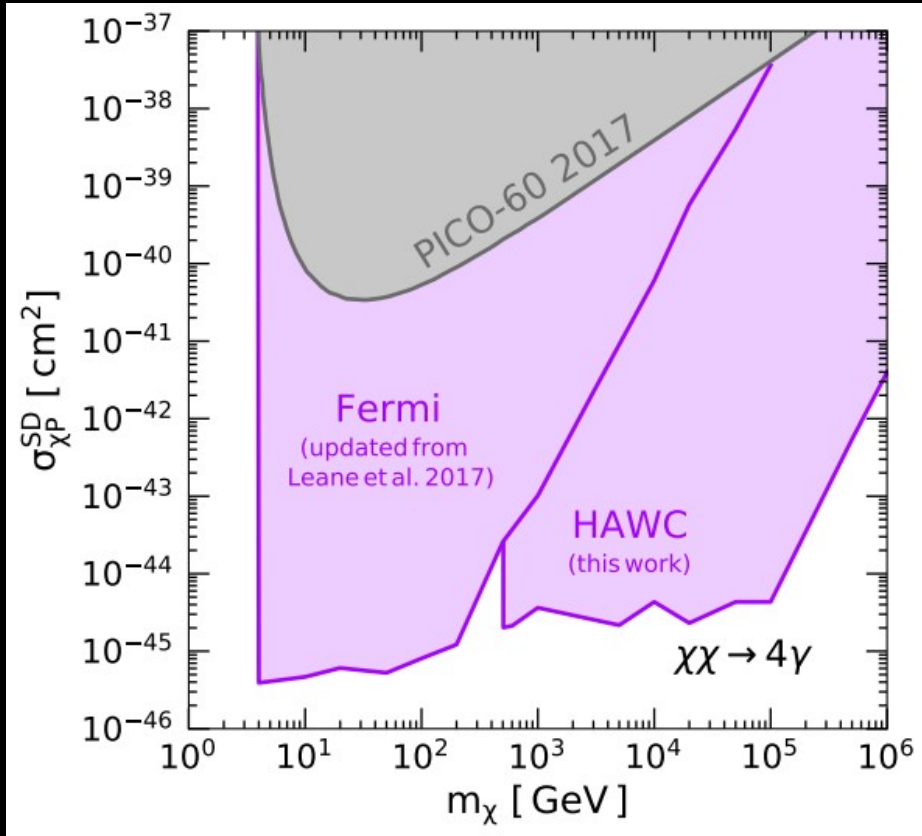
BIG
Hot



Jupiter

BIG
Cold

Solar Comparison



Sun

Long-Lived Mediator Limits

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

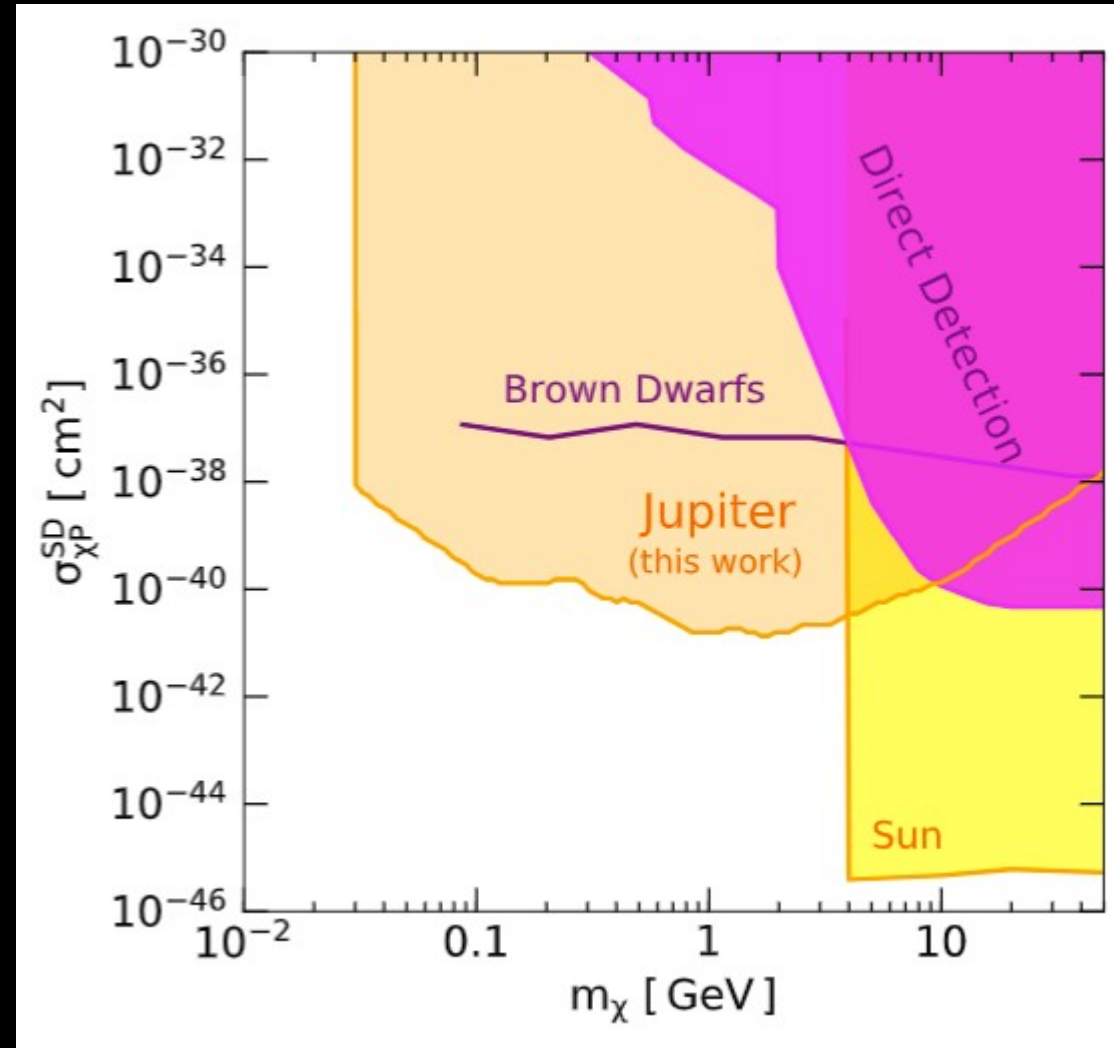


Jupiter

Cooler than the Sun:
MeV-DM mass sensitivity!

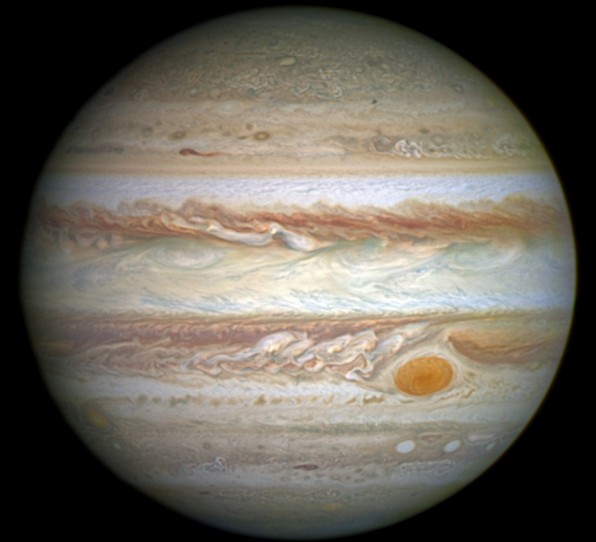
No one ever looked!

New Dark Matter Limits



Summary: Jupiter

- First search for gamma rays from Jupiter
 - No robust evidence, tentative excess at low energies
 - Motivates follow up w/ MeV telescopes
- New DM search with Jovian gamma rays
 - Strong constraints w/ long-lived particles: light masses and small cross sections



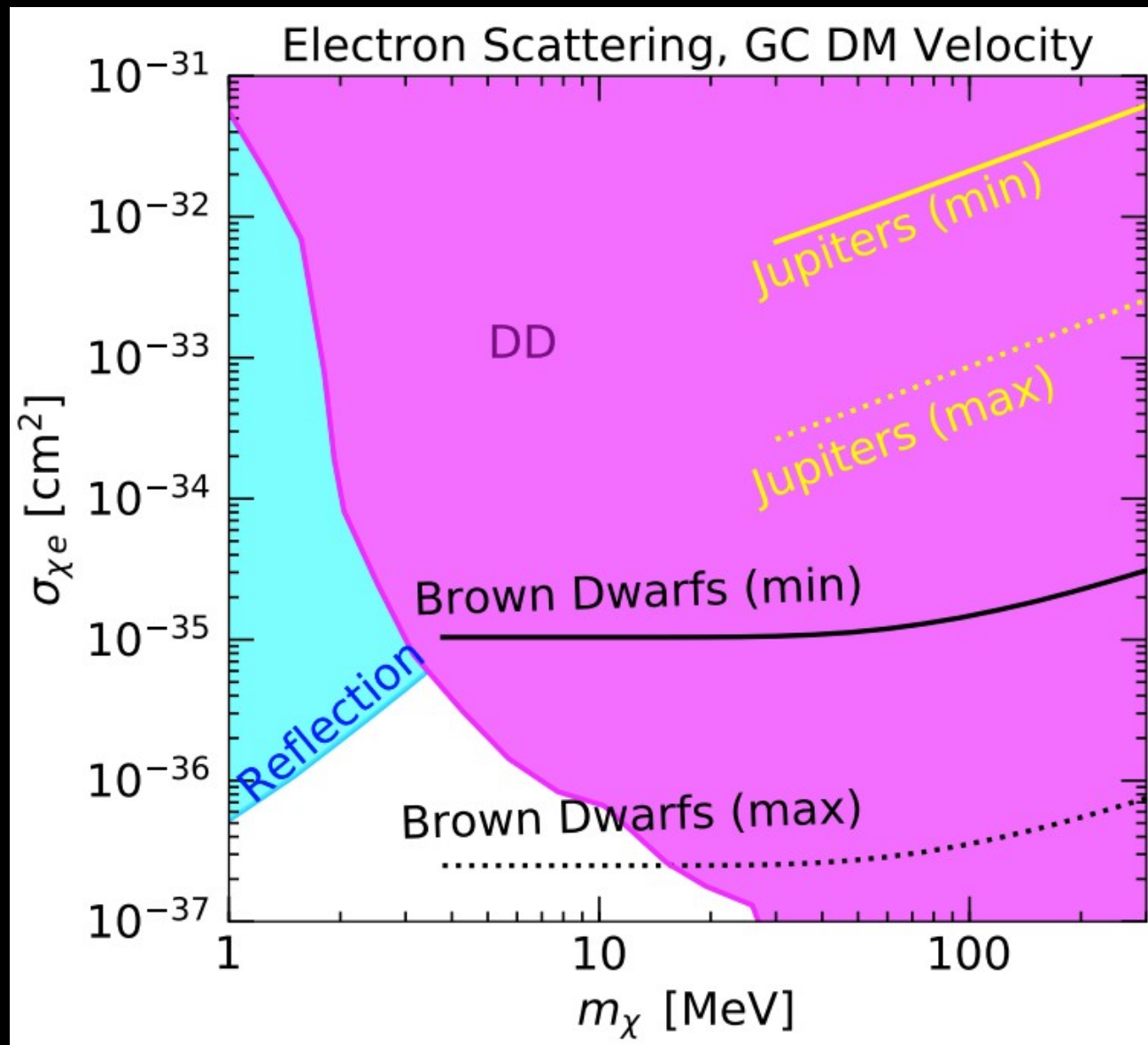
Summary: DM heated exoplanets

- **The exoplanet program is rapidly accelerating**, lots of new surprises and discoveries inevitable
- Examined how exoplanets can be used to discover DM, due to overheating from captured DM
 - Old, cold Jupiters and brown dwarfs ideal
- **Actionable discovery or exclusion searches** with new infrared telescopes
 - Signal traces DM density in the Galaxy
- **New sensitivity to DM parameter space**: DM-proton scattering up to six orders of magnitude stronger than other limits
- **Exciting opportunities** soon to realize search, several telescopes may be informative, new infrared window to Inner Galaxy
 - Oct 2021 James Webb launch!

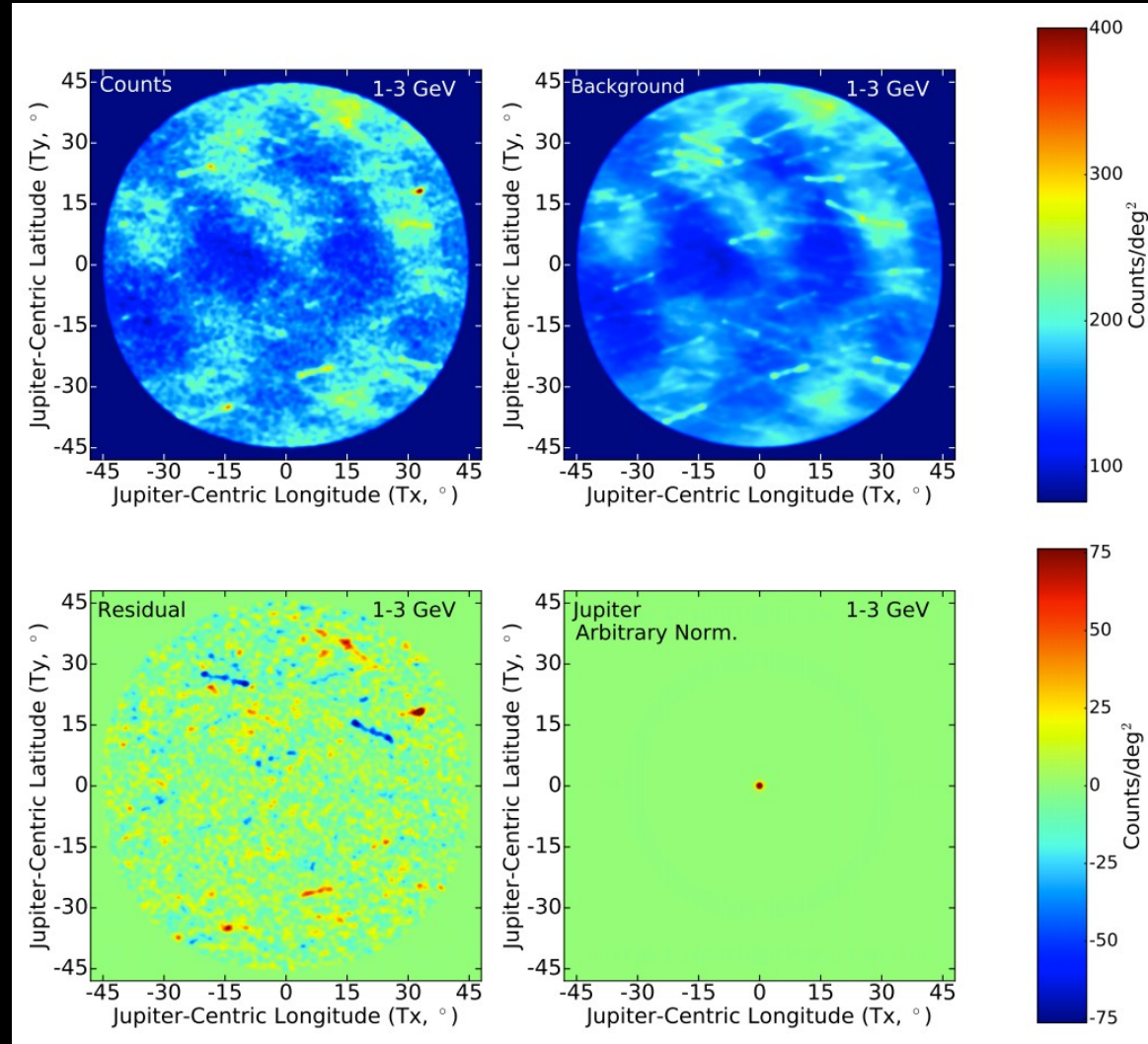


EXTRA SLIDES

Cross section sensitivity

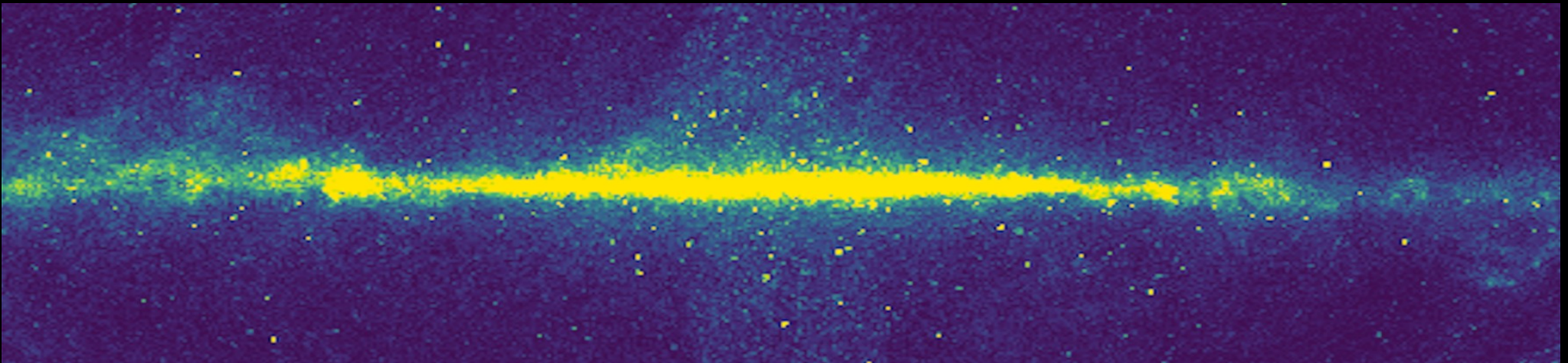


First Jovian Gamma-Ray Measurement



Galactic Center Population Signal

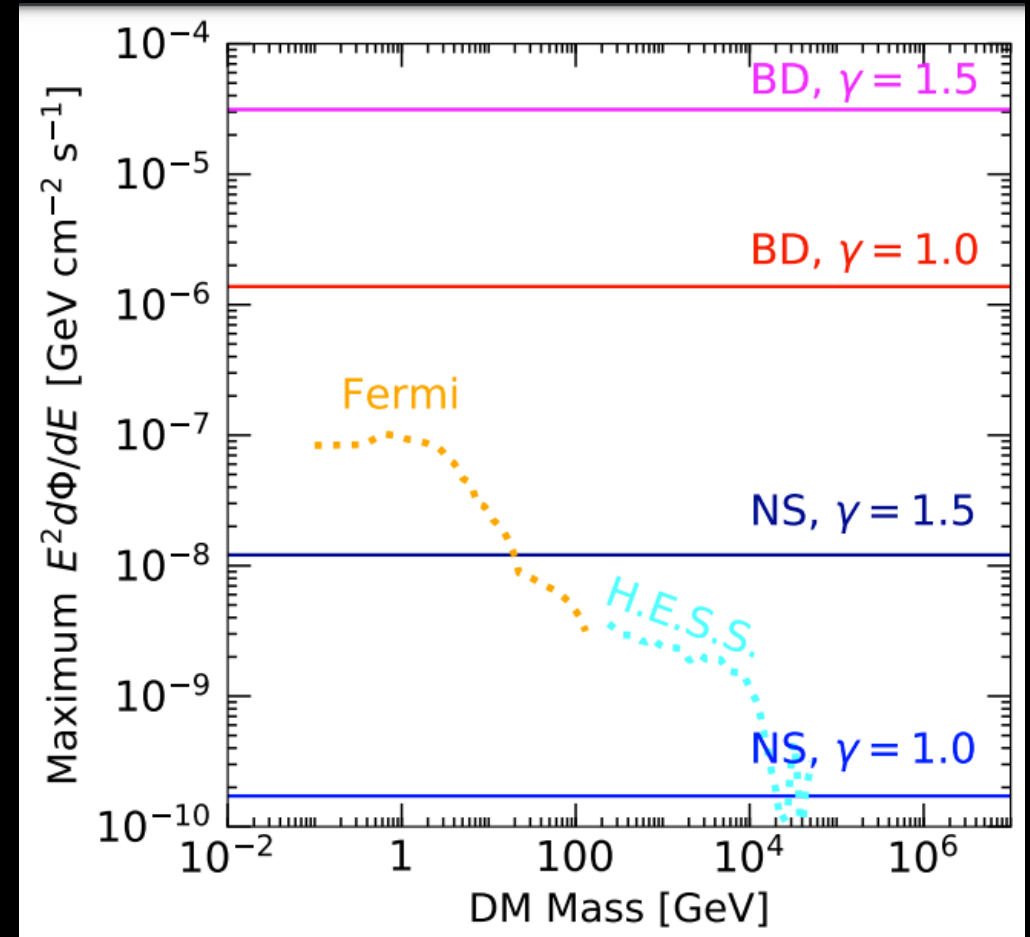
- Use **all** the neutron stars, **all** the brown dwarfs
- Large population in the Galactic Center, DM density high: large rate!
- Our new signal follows matter density: DM density * stellar density
 - DM Halo annihilation scales with DM density squared



Rebecca Leane (SLAC)

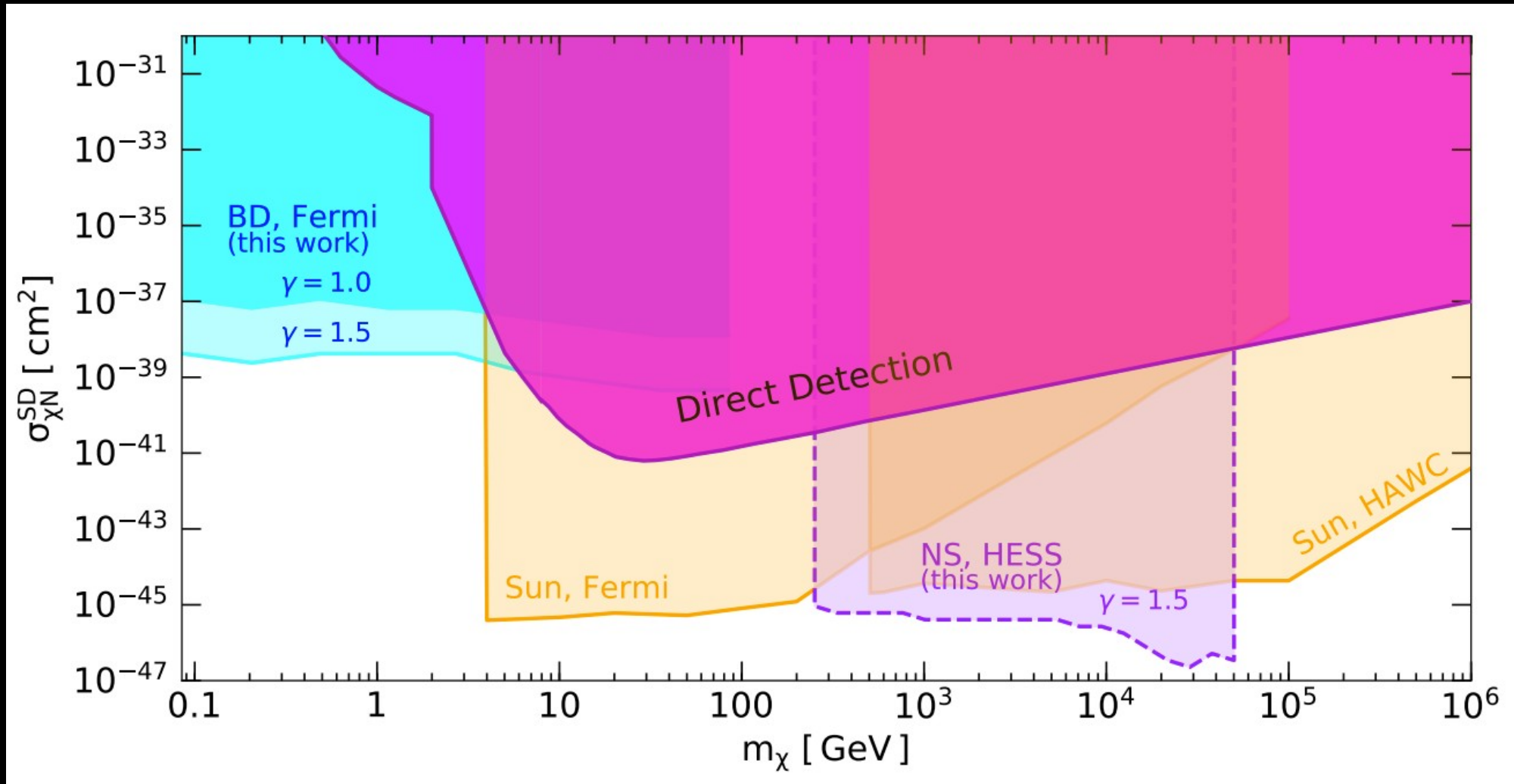
Galactic Center Population Signal

- **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!



RKL, Linden, Mukhopadyay, Toro, 2021

New Limits w/ Brown Dwarfs and Neutron Stars



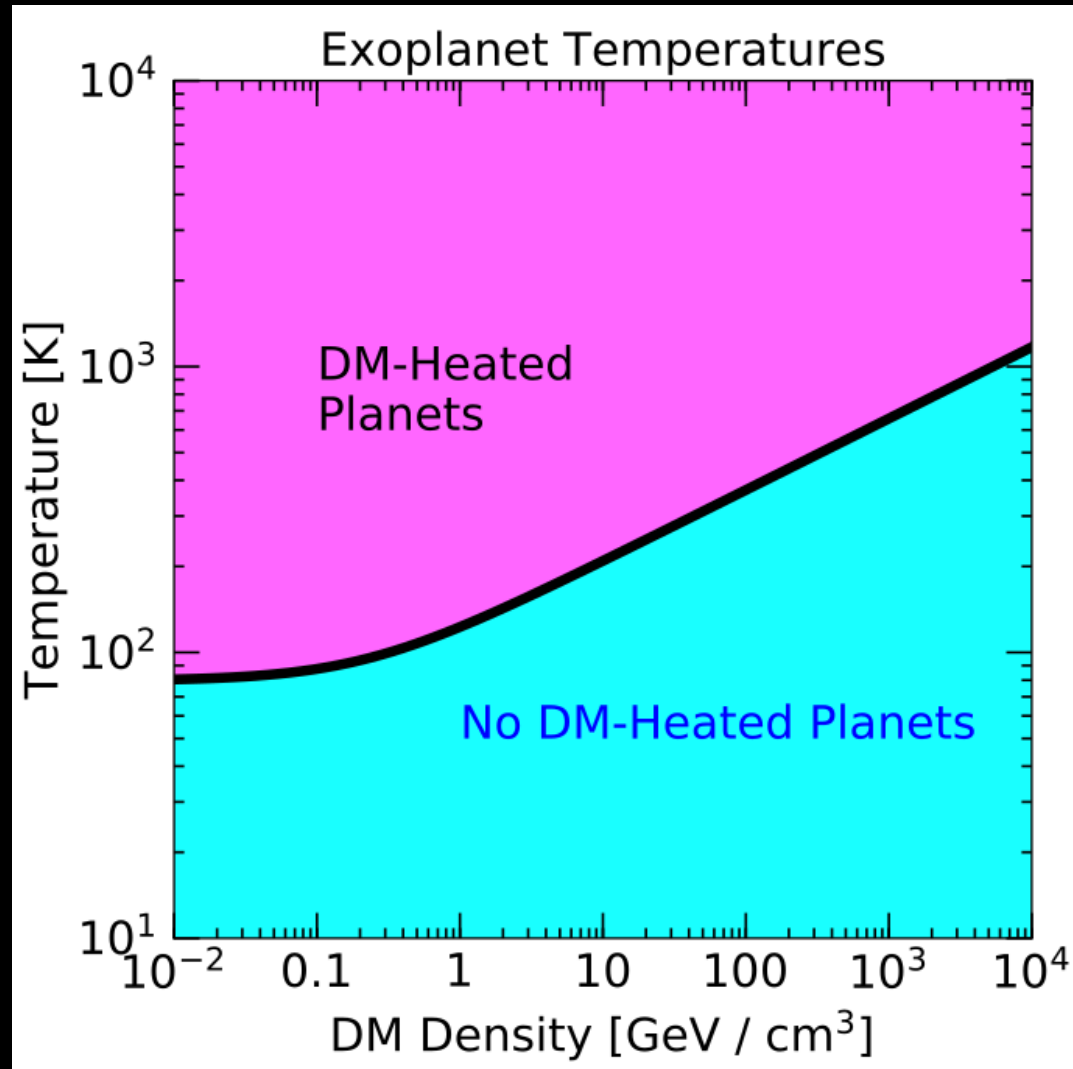
DM Equilibrium and Evaporation

- For maximal rate, want DM scattering and annihilation to be in equilibrium
 - Find DM reaches equilibrium by 1-10 Gigayears
- Lower end of DM mass sensitivity will stop due to DM becoming too light and evaporating out of the planet
 - Using temperature profiles for different exoplanets, find minimum mass, condition to remain bound is:

$$E_{\text{DM}}^{\text{kin}} = \frac{3}{2}T(r) < \frac{G_N M(r)m_\chi}{2r}$$

- Evaporation occurs for ~ 4 MeV DM mass in brown dwarfs, ~ 30 MeV DM mass in Jupiters

Deviations: DM-overdensities

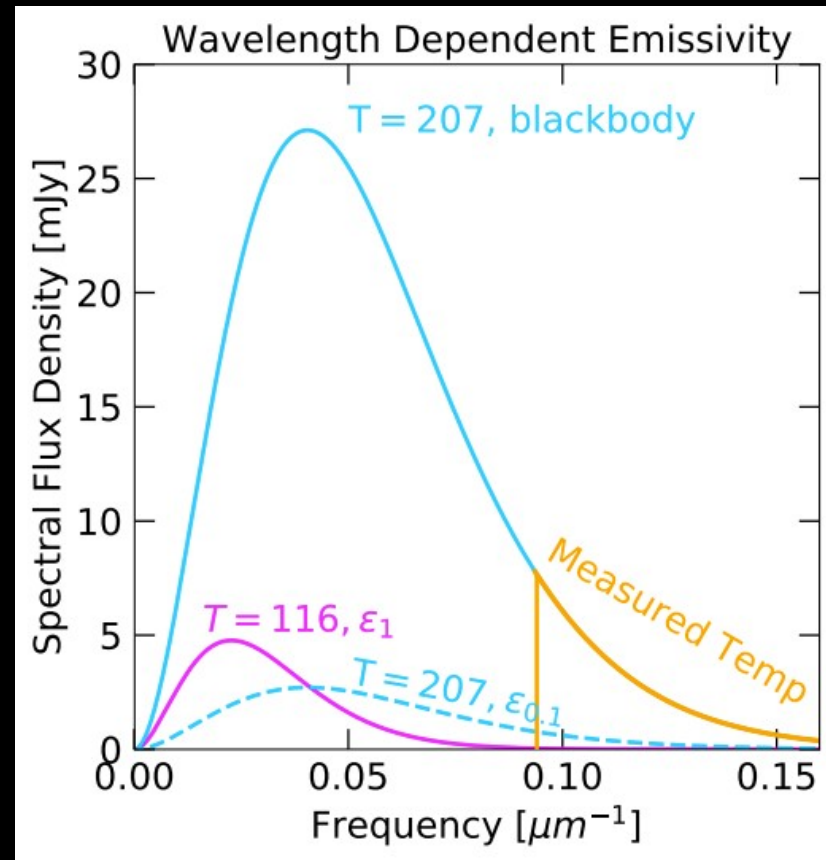
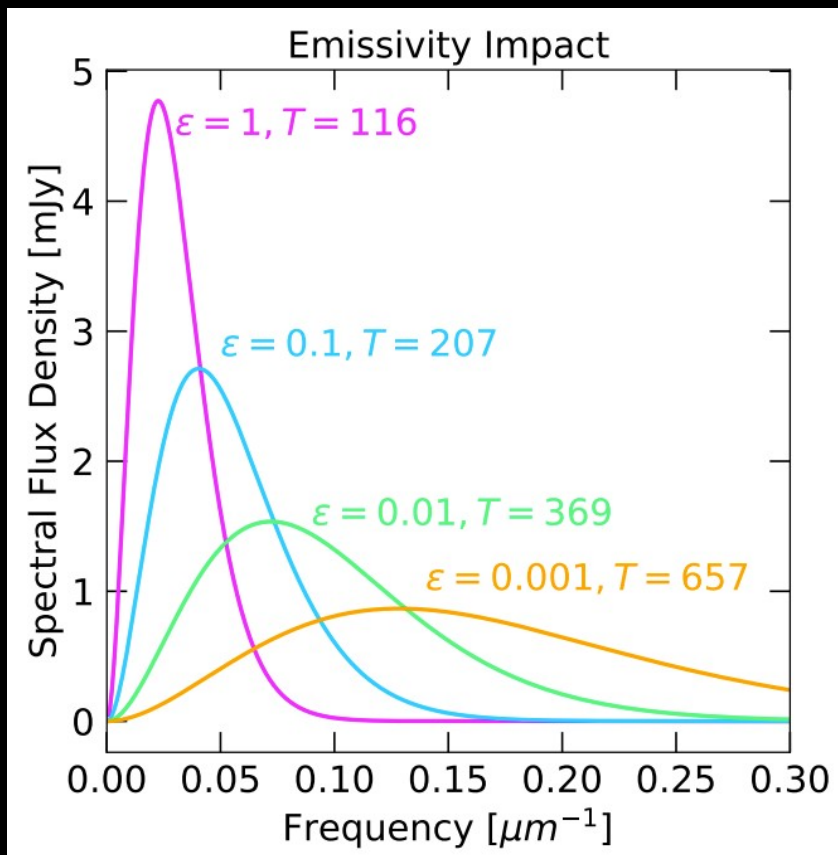


Rebecca Leane (SLAC)

Deviations: Non-Blackbody Spectra

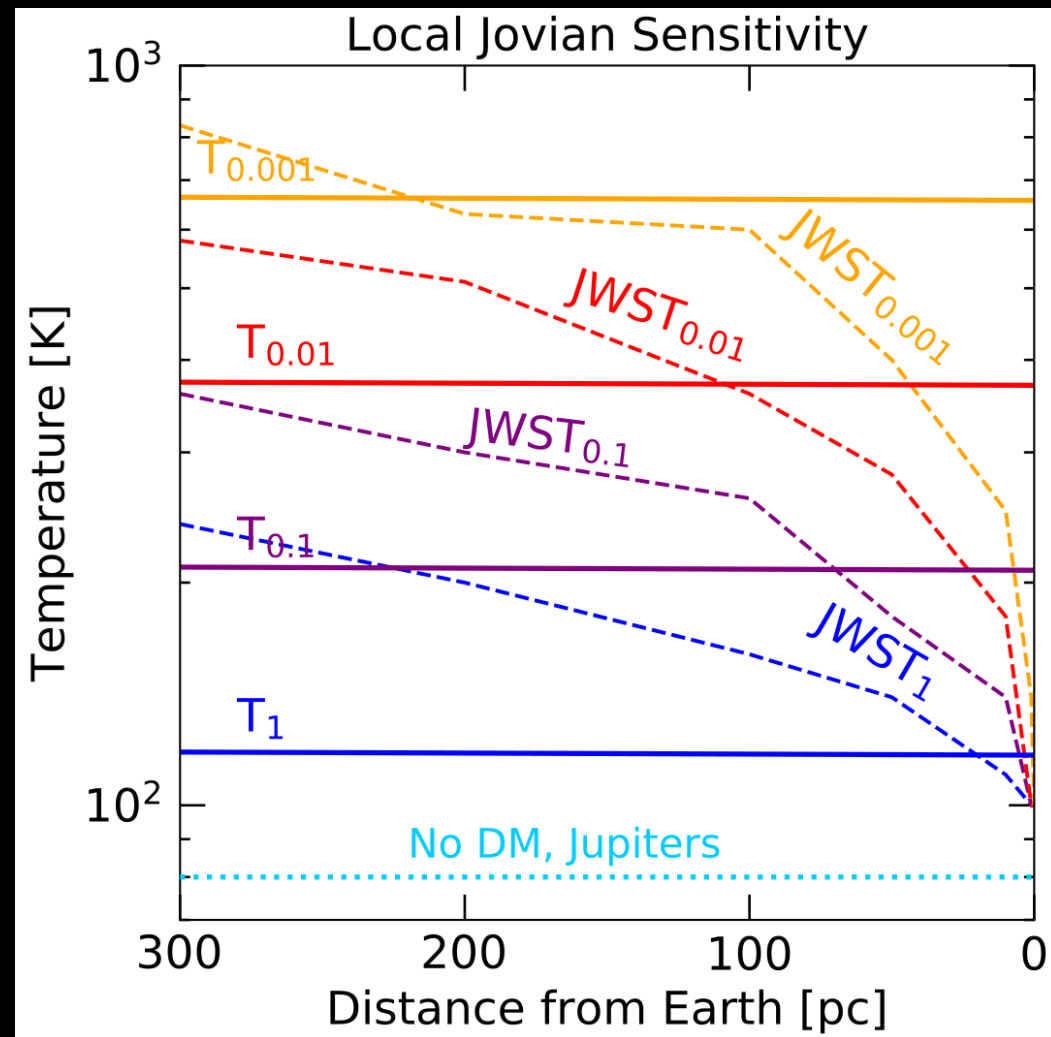
Atmosphere effects can cause deviations from a blackbody

$$B(\nu, T) = \frac{2\nu^3 \epsilon}{\exp\left(\frac{2\pi\nu}{k_b T}\right) - 1}$$



Local DM-Heated Exoplanet Search

- Local fluxes easier to detect, so lower normalization from emissivity isn't a severe penalty
- Allows use of more powerful filters: best JWST filter sensitivity is with higher temps (in this case, higher wavelength peaks)
- Local exoplanets with lower emissivities can extend local sensitivity to DM heating



DM scattering cross section sensitivity

$$f = \frac{C_{\text{cap}}}{C_{\text{max}}} = \sum_{N=1}^{\infty} f_N$$

$$f_N = p(N, \tau) \left[1 - \kappa \exp\left(-\frac{3(v_N^2 - v_{\text{esc}}^2)}{2v_d^2}\right) \right]$$

$$\kappa = \left(1 + \frac{3v_N^2}{2v_d^2}\right) \left(1 + \frac{3v_{\text{esc}}^2}{2v_d^2}\right)^{-1}$$

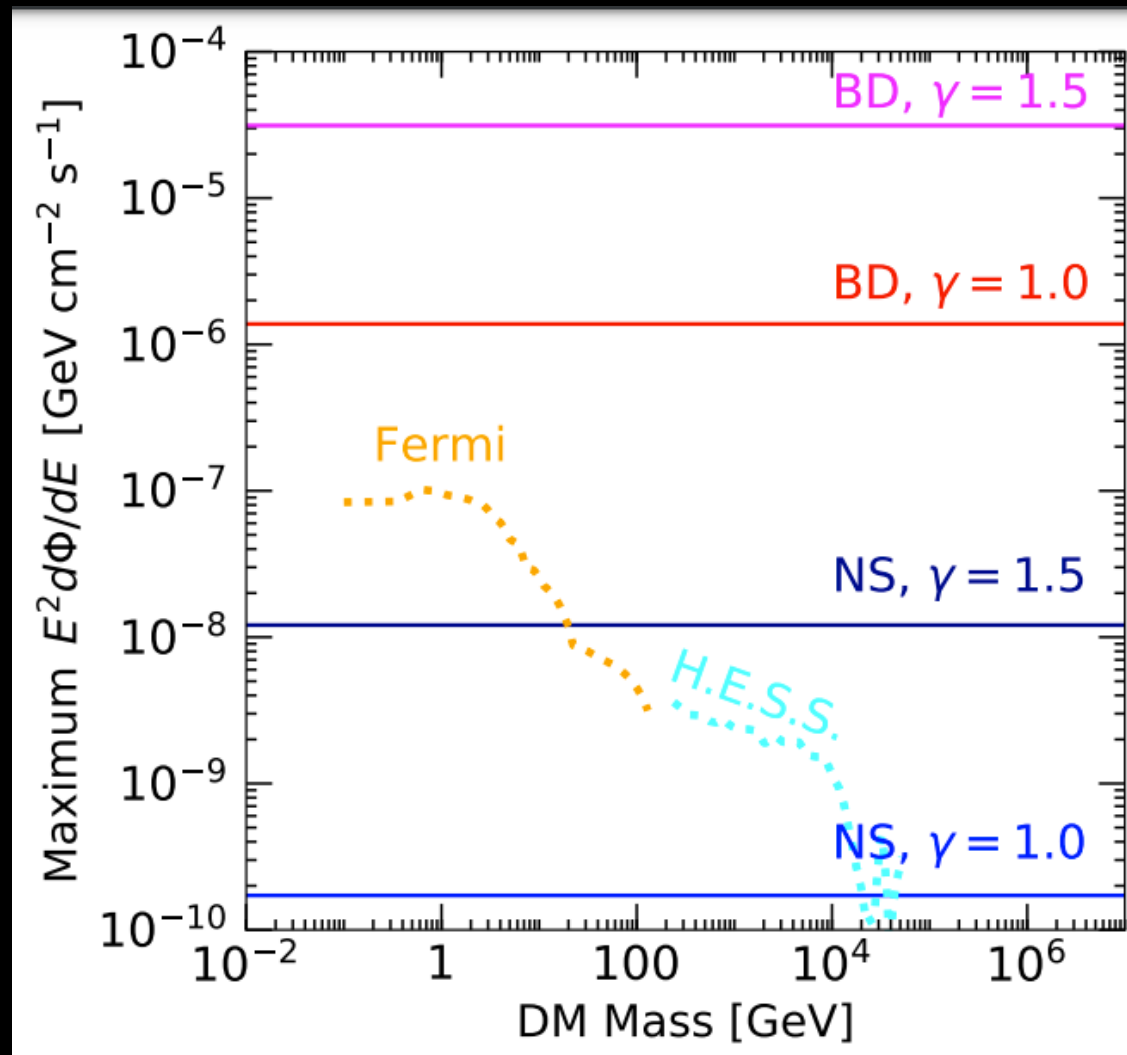
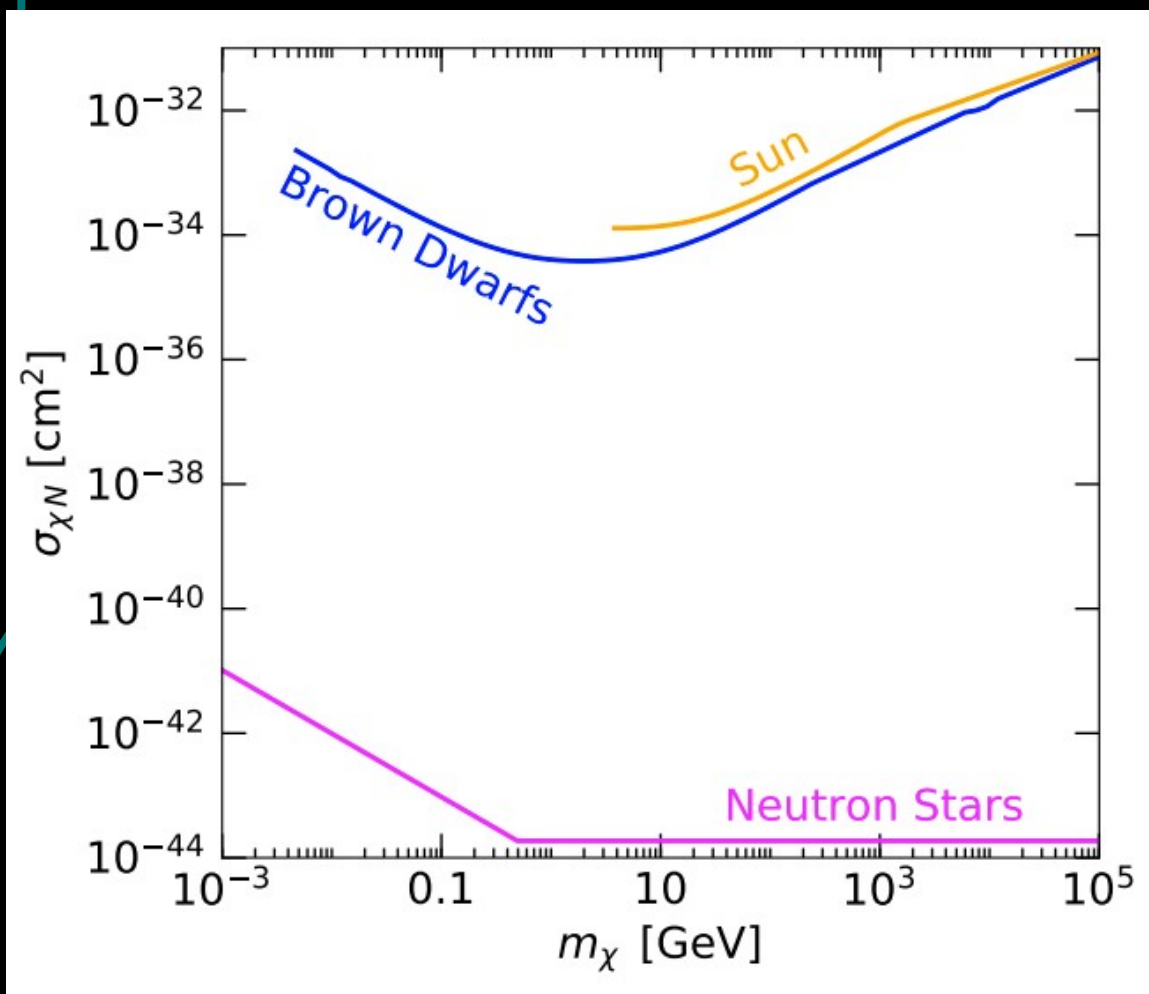
Here v_d is the velocity dispersion, $v_N = v_{\text{esc}}(1 - \langle z \rangle \beta)^{-N/2}$ where the average scattering angle is $\langle z \rangle = 1/2$ [143], $\beta = 4m_\chi m_A / (m_\chi + m_A)^2$, and m_A is the mass of the target particle. The probability that the DM particle scatters N times is

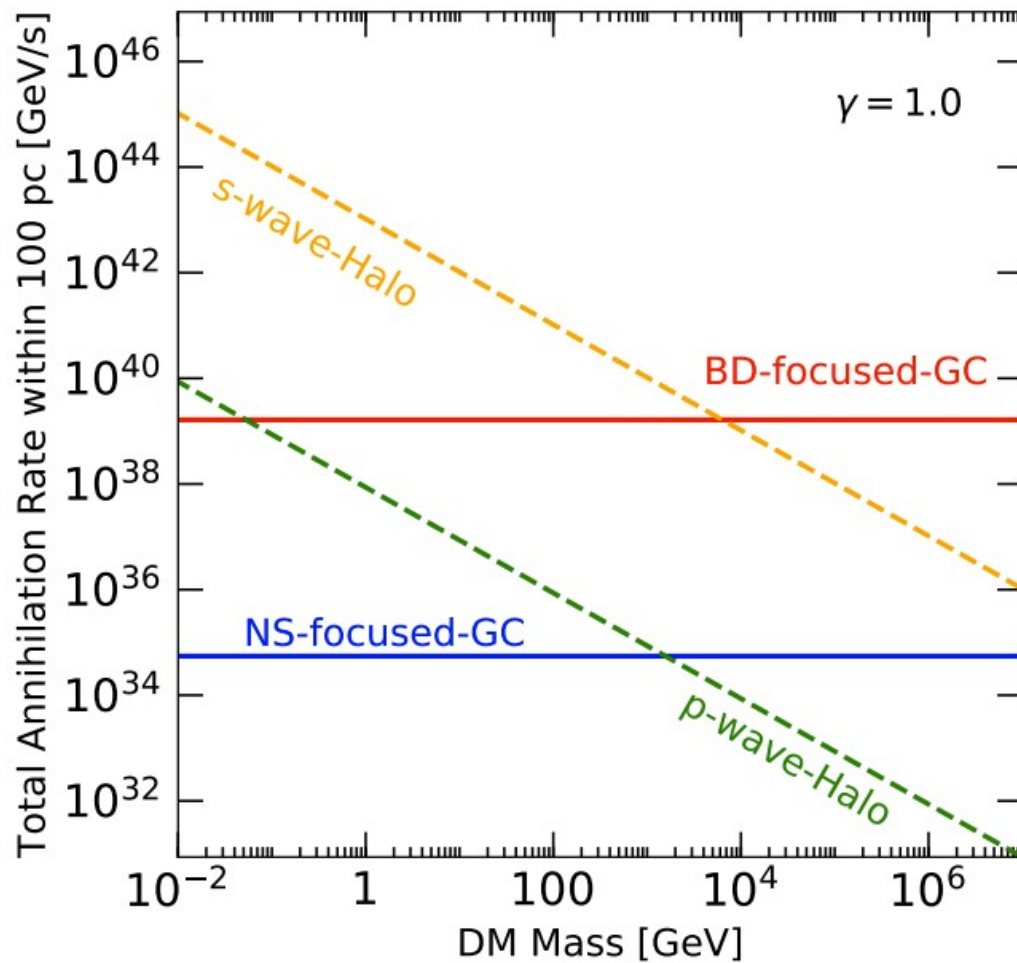
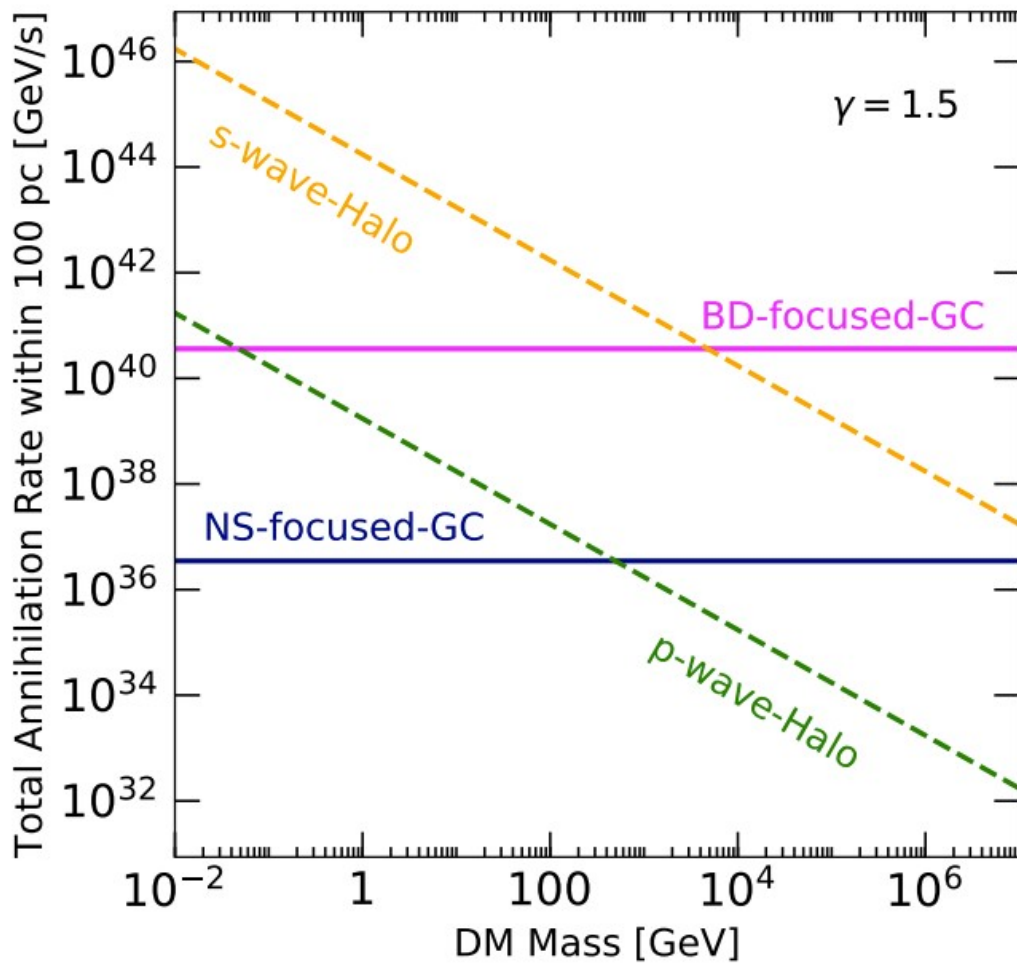
$$p(N, \tau) = \frac{2}{\tau^2} \left(N_s + 1 - \frac{\Gamma(N_s + 2, \tau)}{N_s!} \right) \quad \tau = \frac{3}{2} \frac{\sigma}{\sigma_{\text{sat}}}$$

$$\sigma_{\text{sat}} = \pi R^2 / N_{\text{SM}}$$

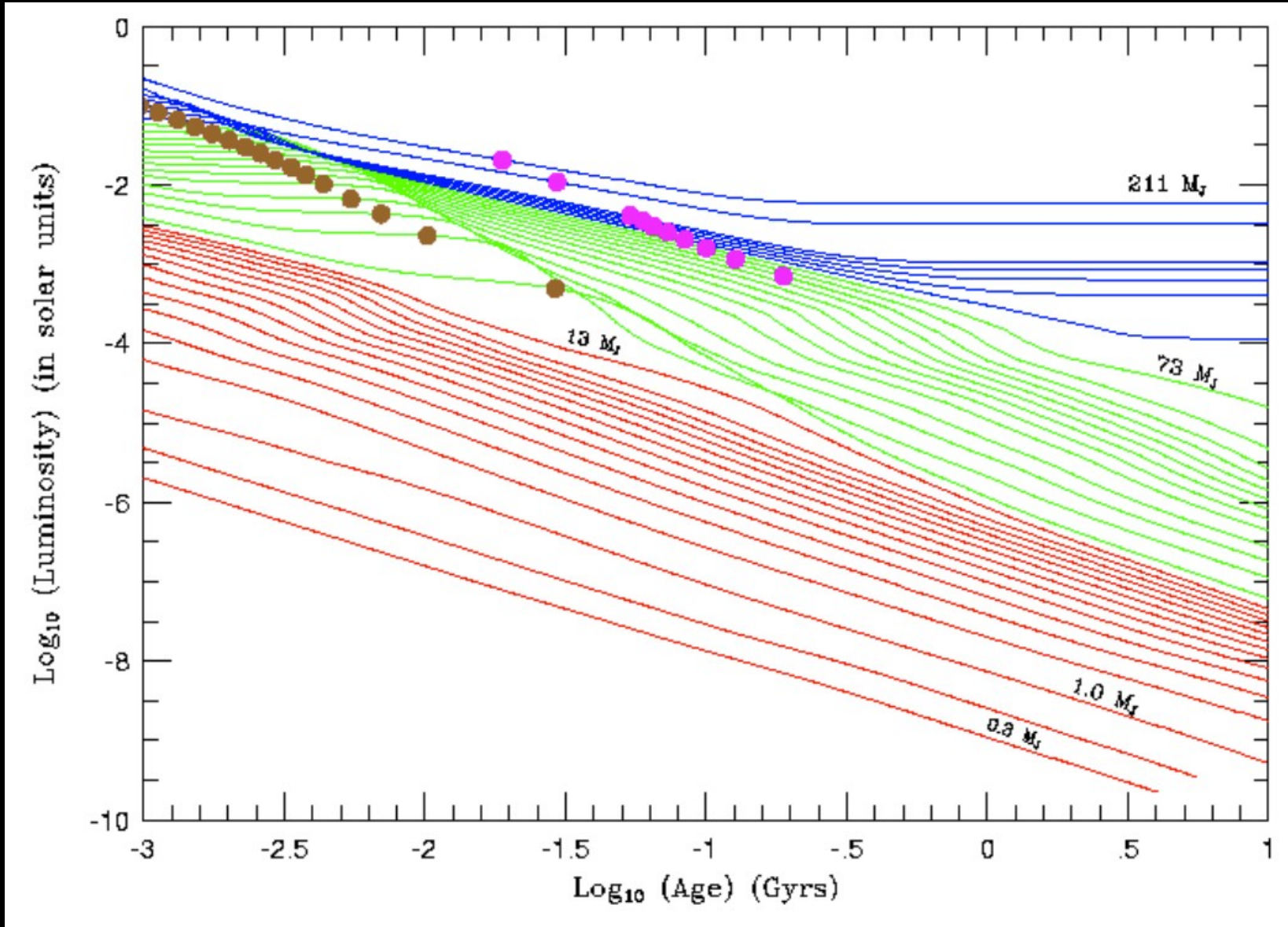
$$\sigma_{\chi A}^{\text{SD}} = \sigma_{\chi N}^{\text{SD}} \left(\frac{\mu(m_A)}{\mu(m_N)} \right)^2 \frac{4(J+1)}{3J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2$$

$$\sigma_{\chi A}^{\text{SI}} = \sigma_{\chi N}^{\text{SI}} \left(\frac{\mu(m_A)}{\mu(m_N)} \right)^2 \left[Z + \frac{a_n}{a_p} (A - Z) \right]^2$$

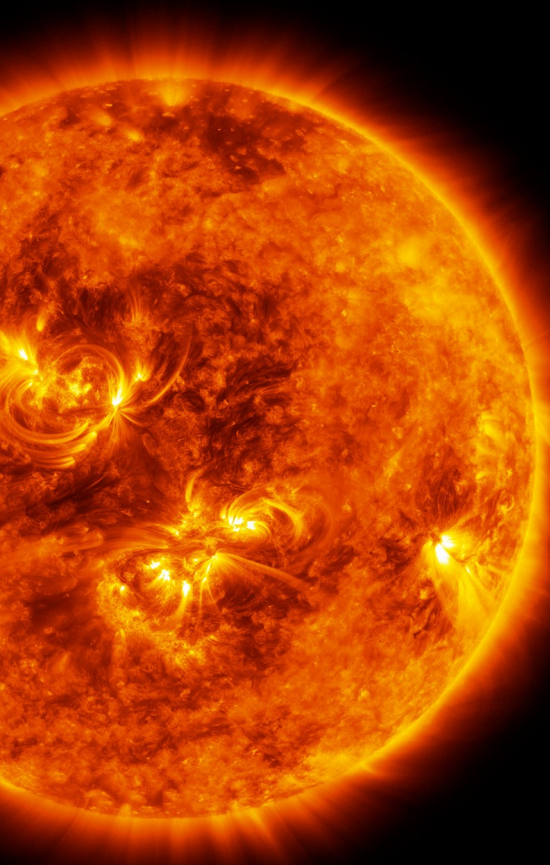




AGE - COOLING CURVES



DARK MATTER IN CELESTIAL OBJECTS



Sun

Neutrinos, long-lived particle decays outside the Sun

Apollo mission data: rock content and heat flux

Luna



Earth

20,000 boreholes drilled kilometers deep into the ground, internal heat measured



Mars

Future Martian mission: more info

Ganymede



Jupiter

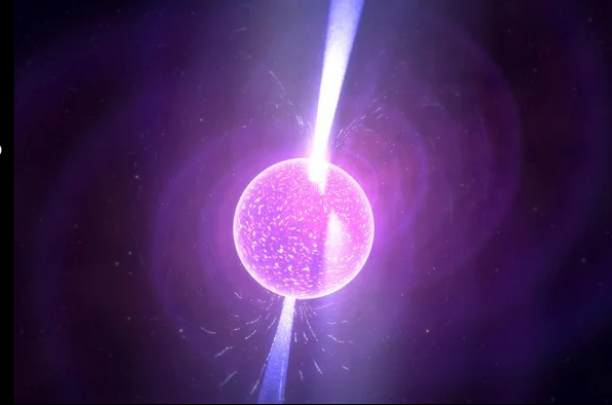
DM heat anomaly?

Impact on magnetic fields? Volcanoes?



Uranus

DM limits from temperature



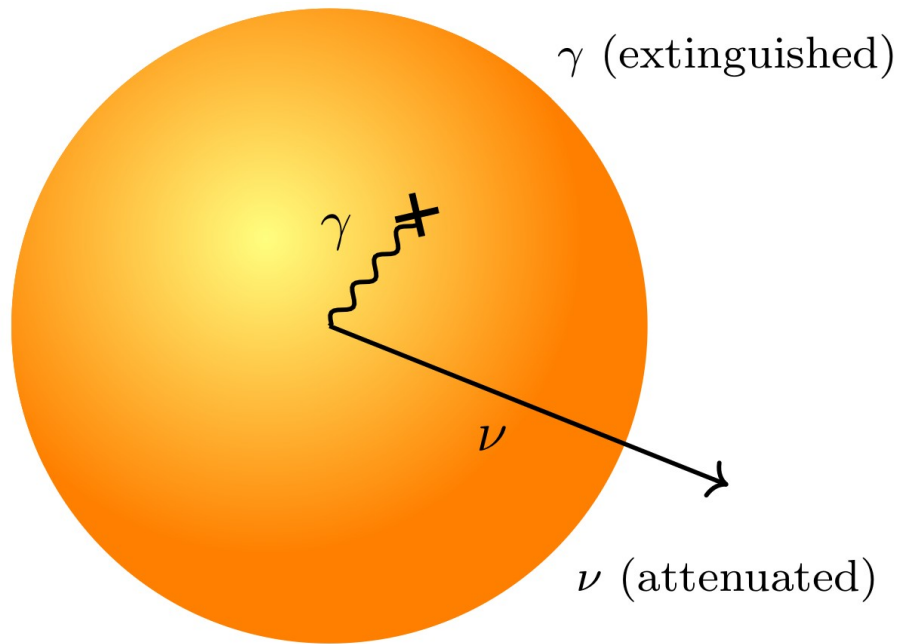
Neutron Stars

DM heating, infrared telescopes



White Dwarfs

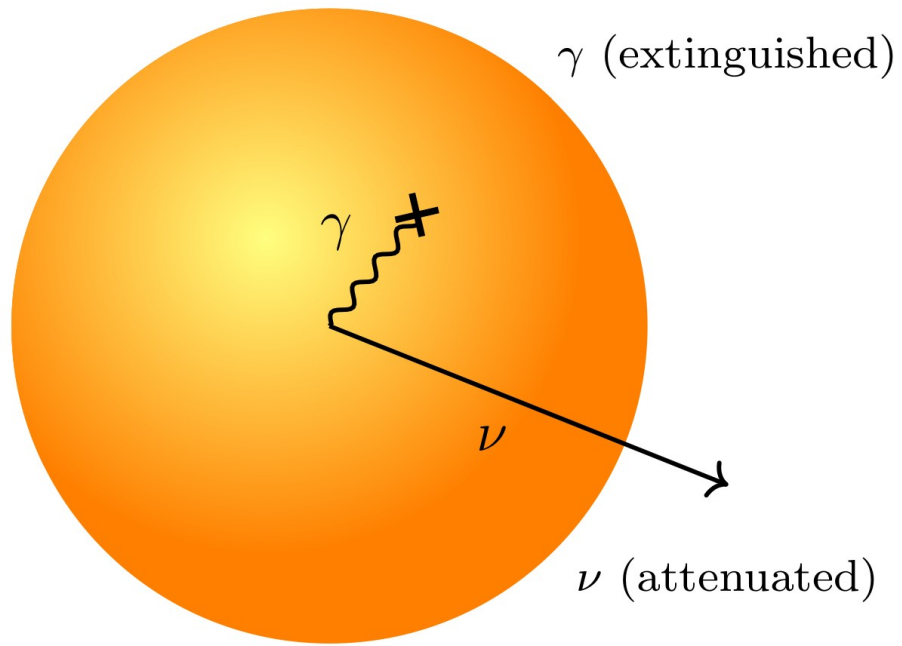
DARK MATTER IN THE SUN



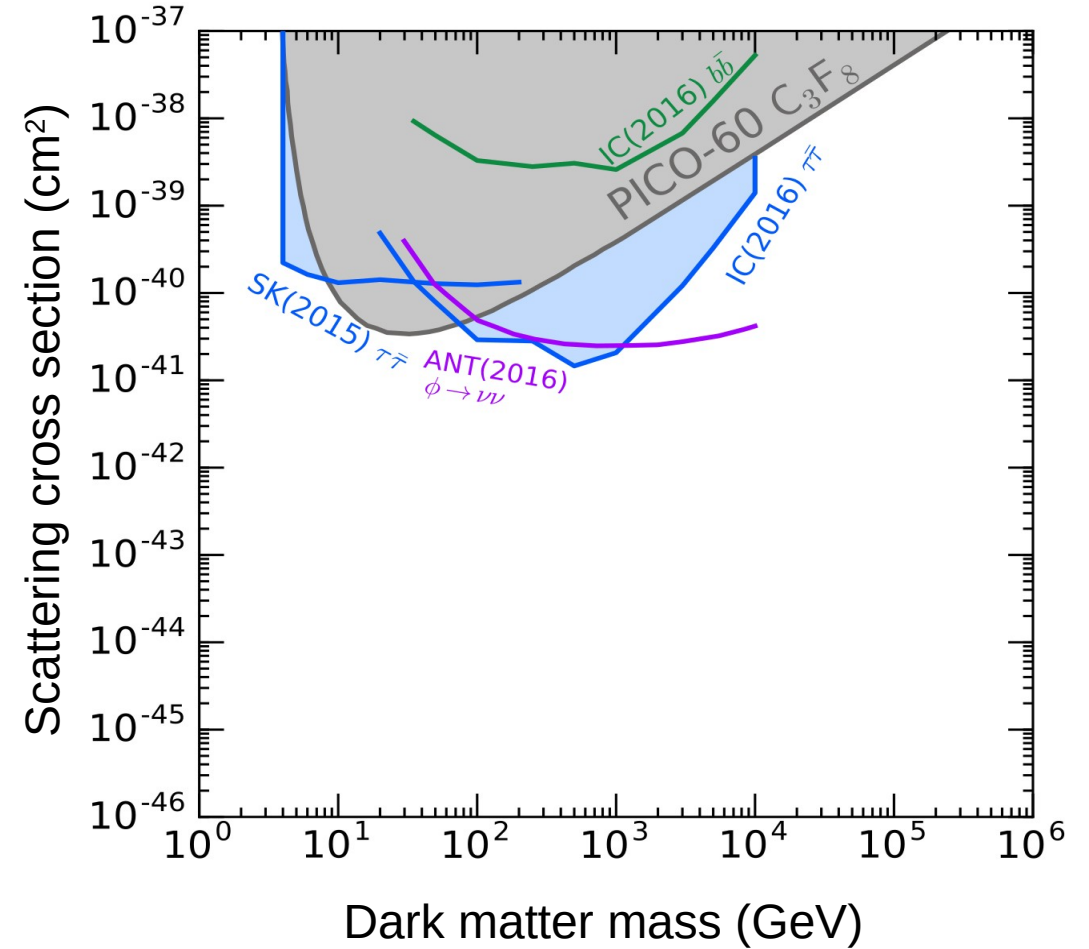
Evolution of dark matter number density

$$\frac{d}{dt} N_\chi = \Gamma_{\text{cap}} - C_{\text{ann}} N_\chi^2$$

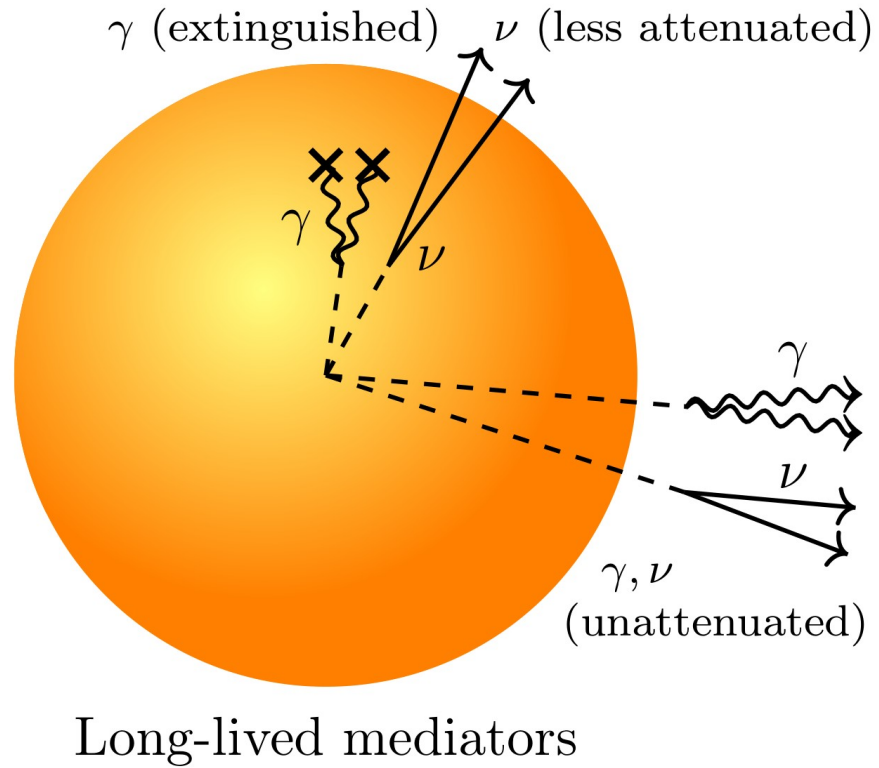
DARK MATTER IN THE SUN



Limits from neutrinos, standard scenario



LONG-LIVED SIGNAL BOOST:



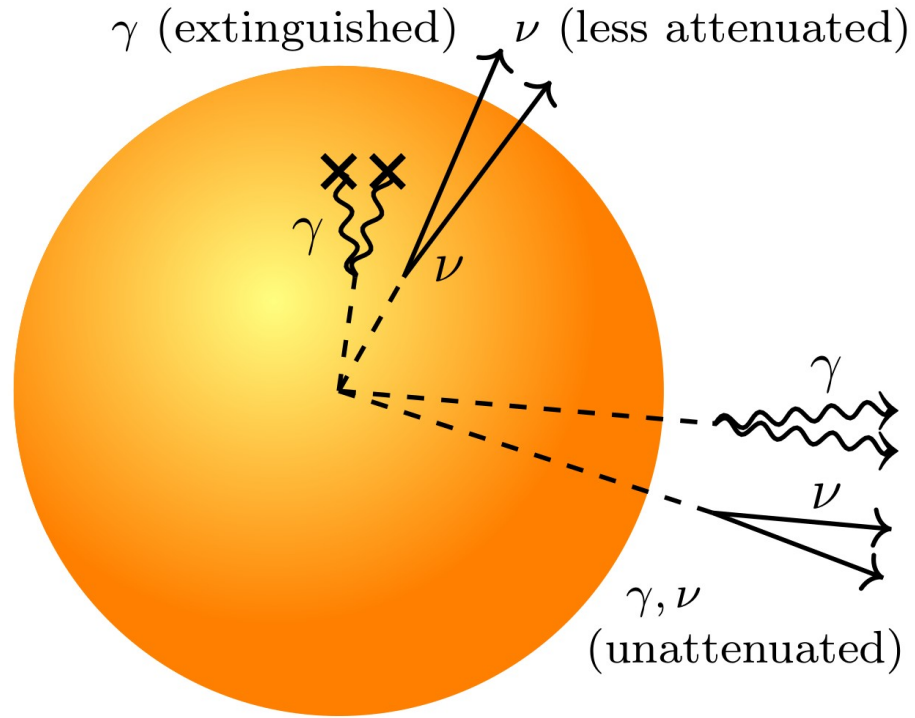
Schuster, Toro, Yavin (PRD '10)

Batell, Pospelov, Ritz, Shang (PRD '10)

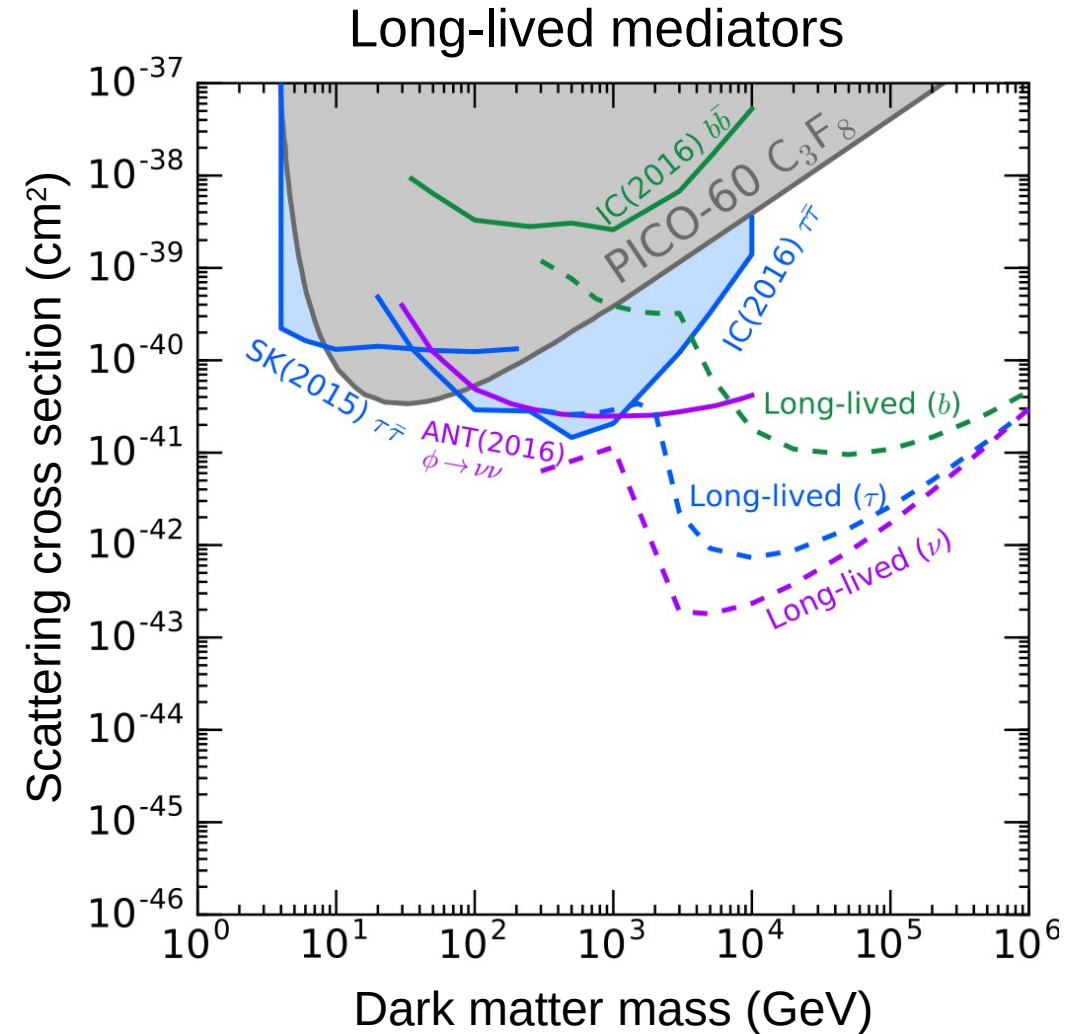
Meade, Nussinov, Papucci, Volansky (JHEP '10)



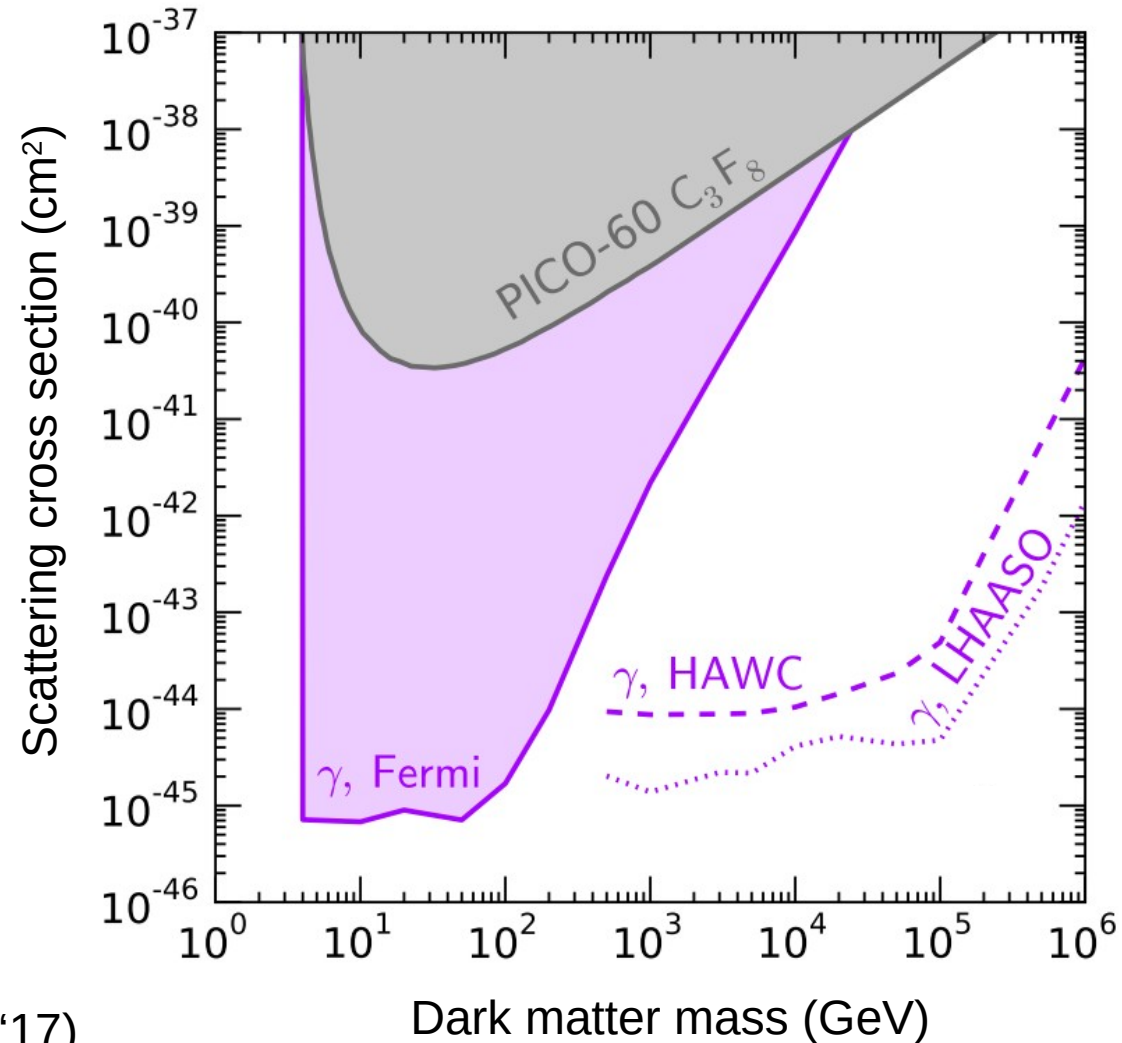
LONG-LIVED SIGNAL BOOST: NEUTRINOS



Long-lived mediators



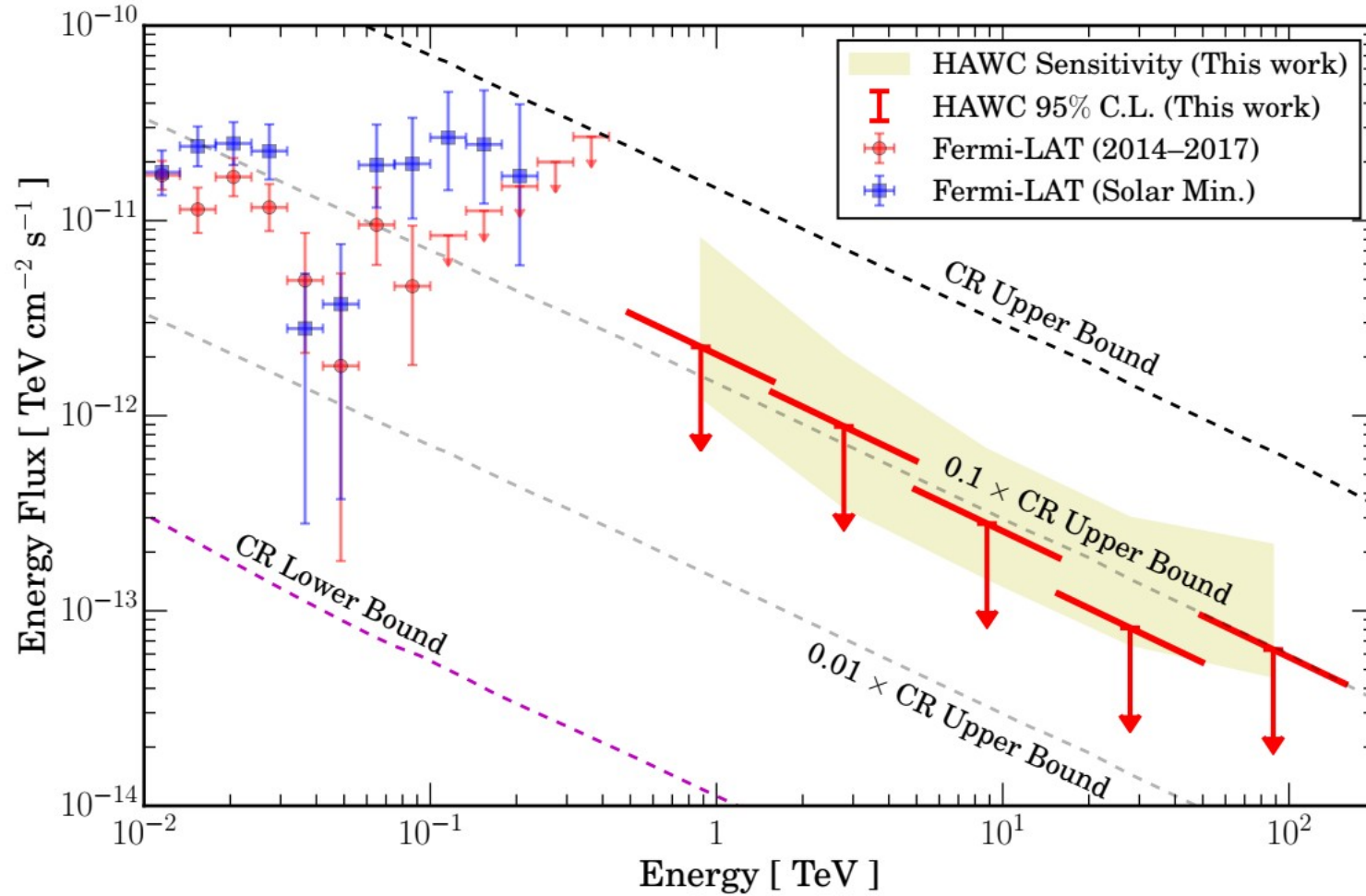
LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)



NEW LIMITS WITH HAWC

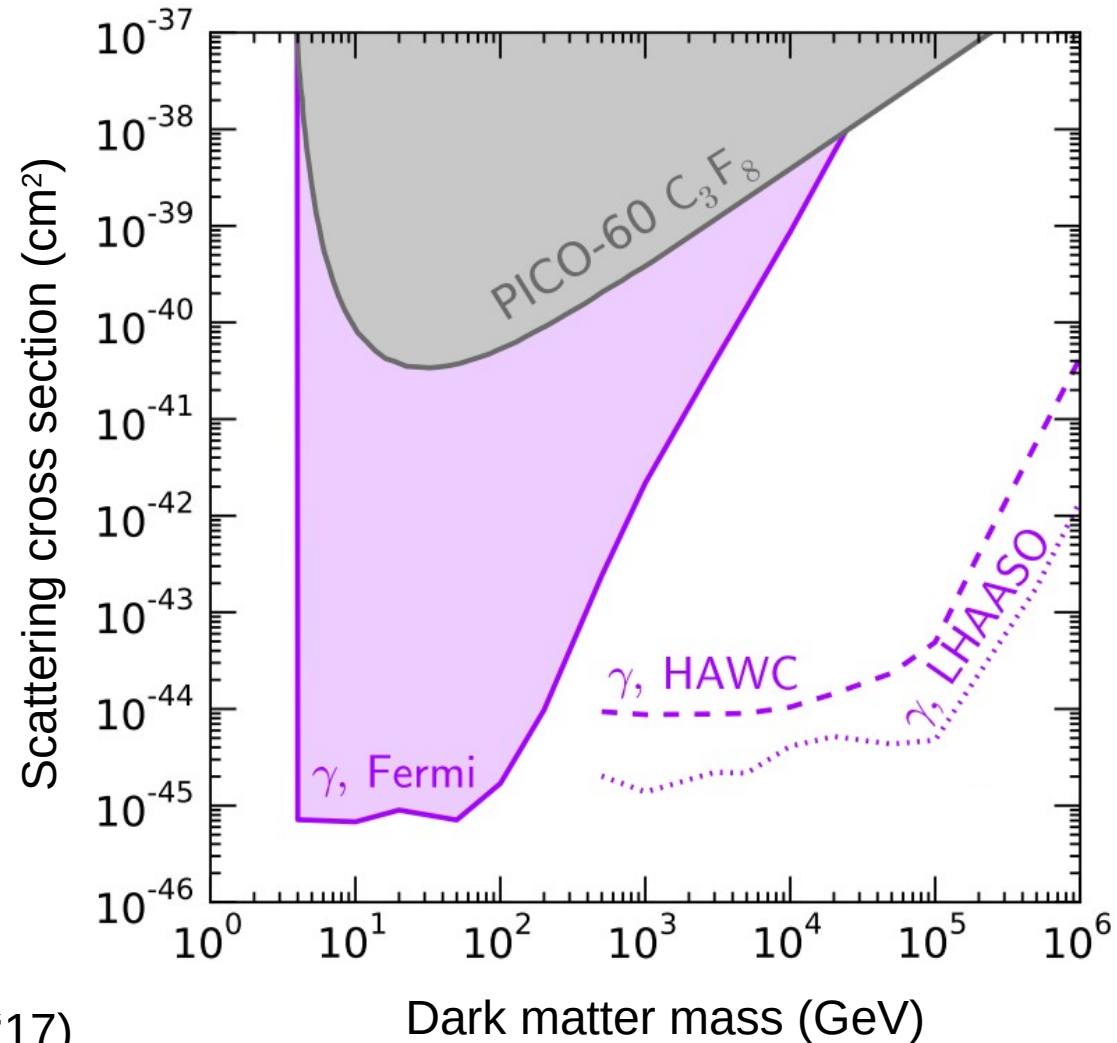


HAWC Collaboration + **RL** (PRD '18)

HAWC Collaboration + **RL** (PRD '18)



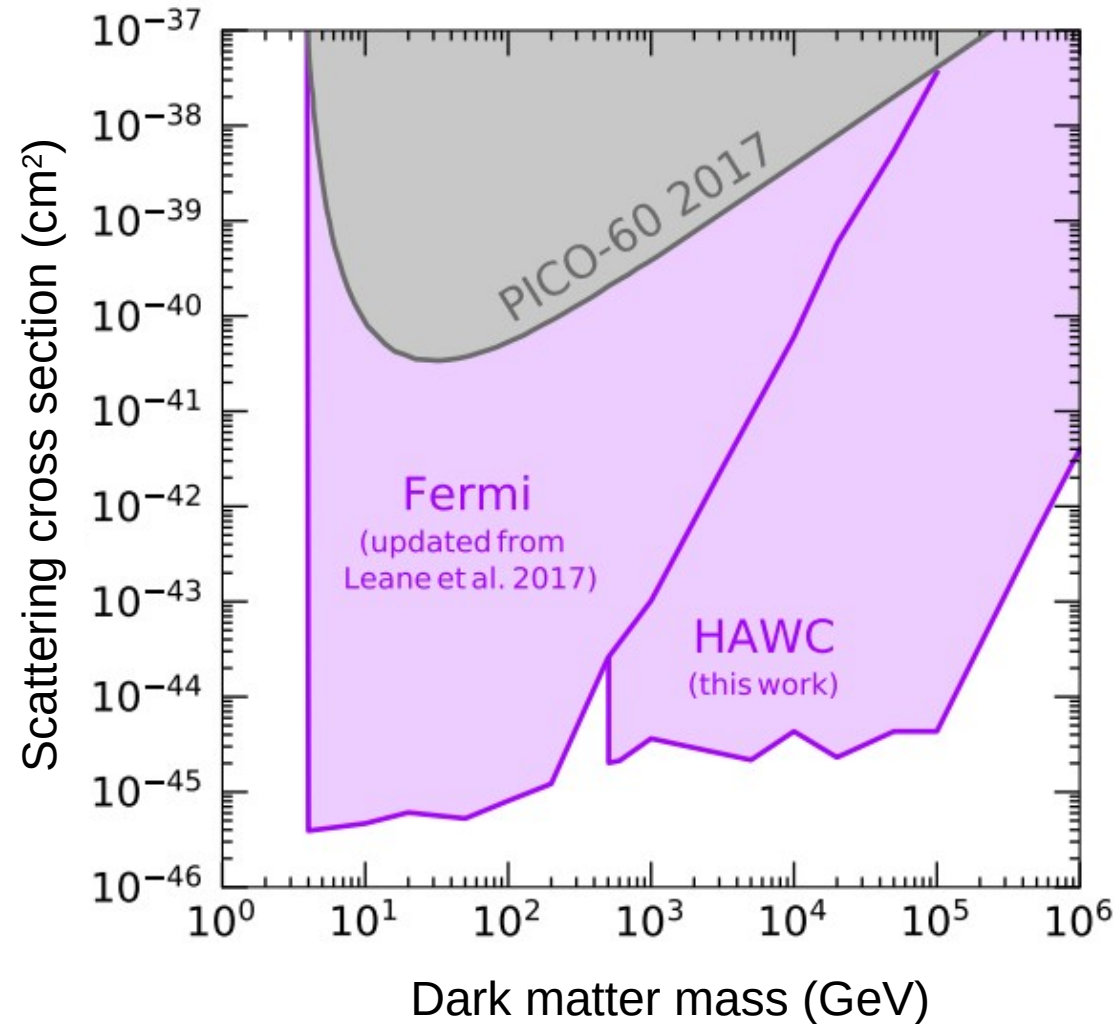
LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)

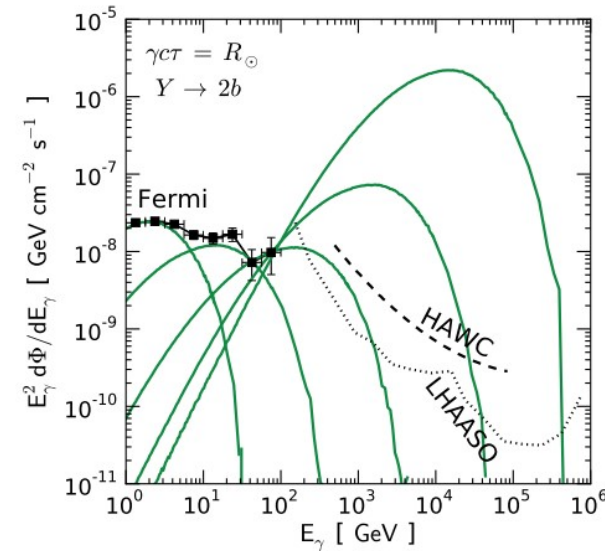
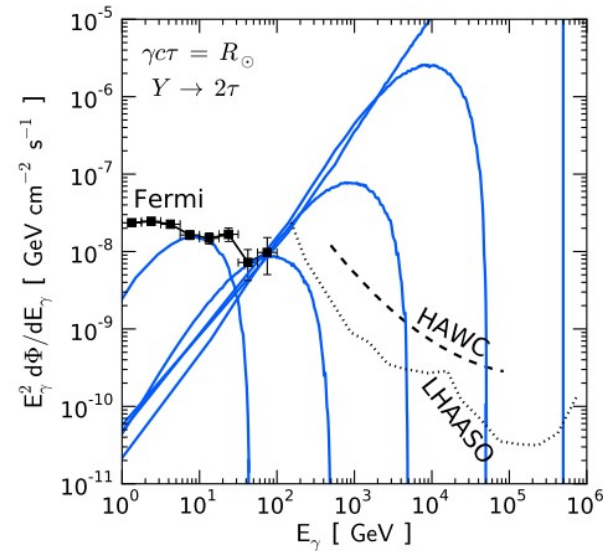
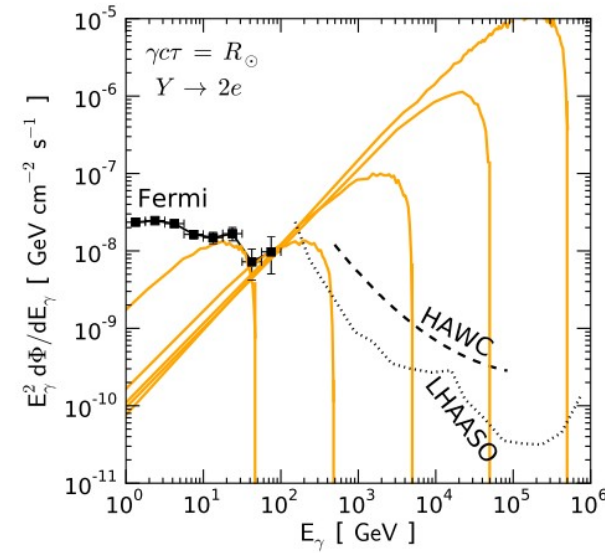
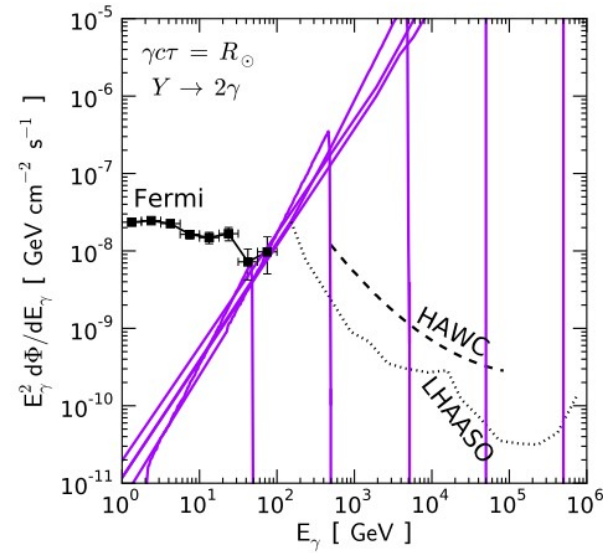


NEW LIMITS WITH FERMI AND HAWC

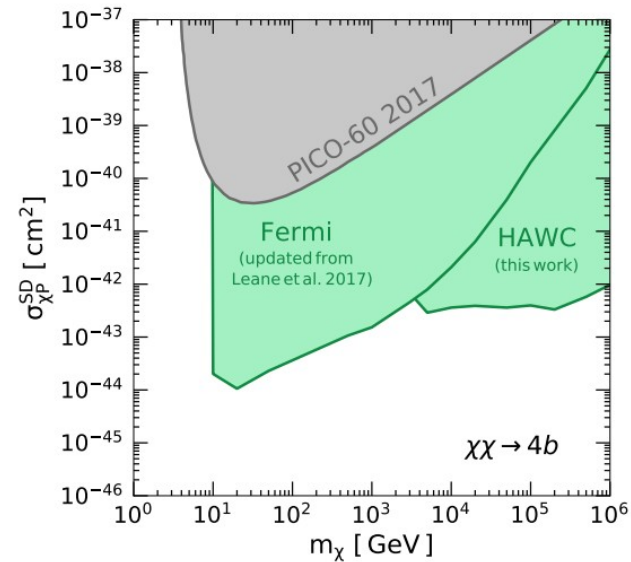
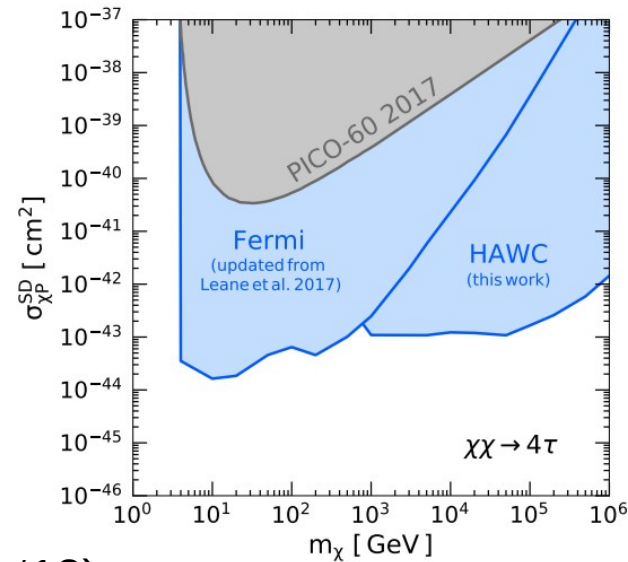
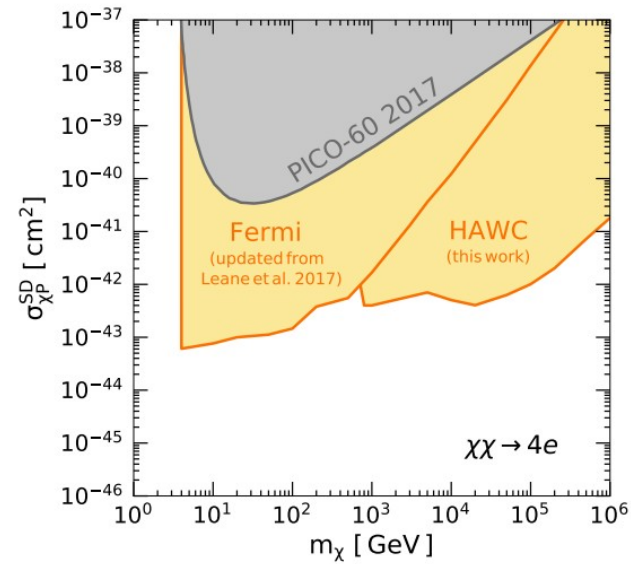
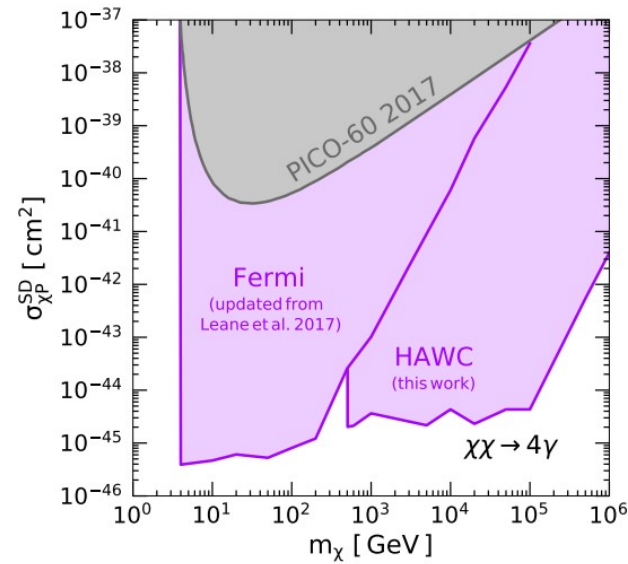


SOLAR DARK MATTER LIMITS

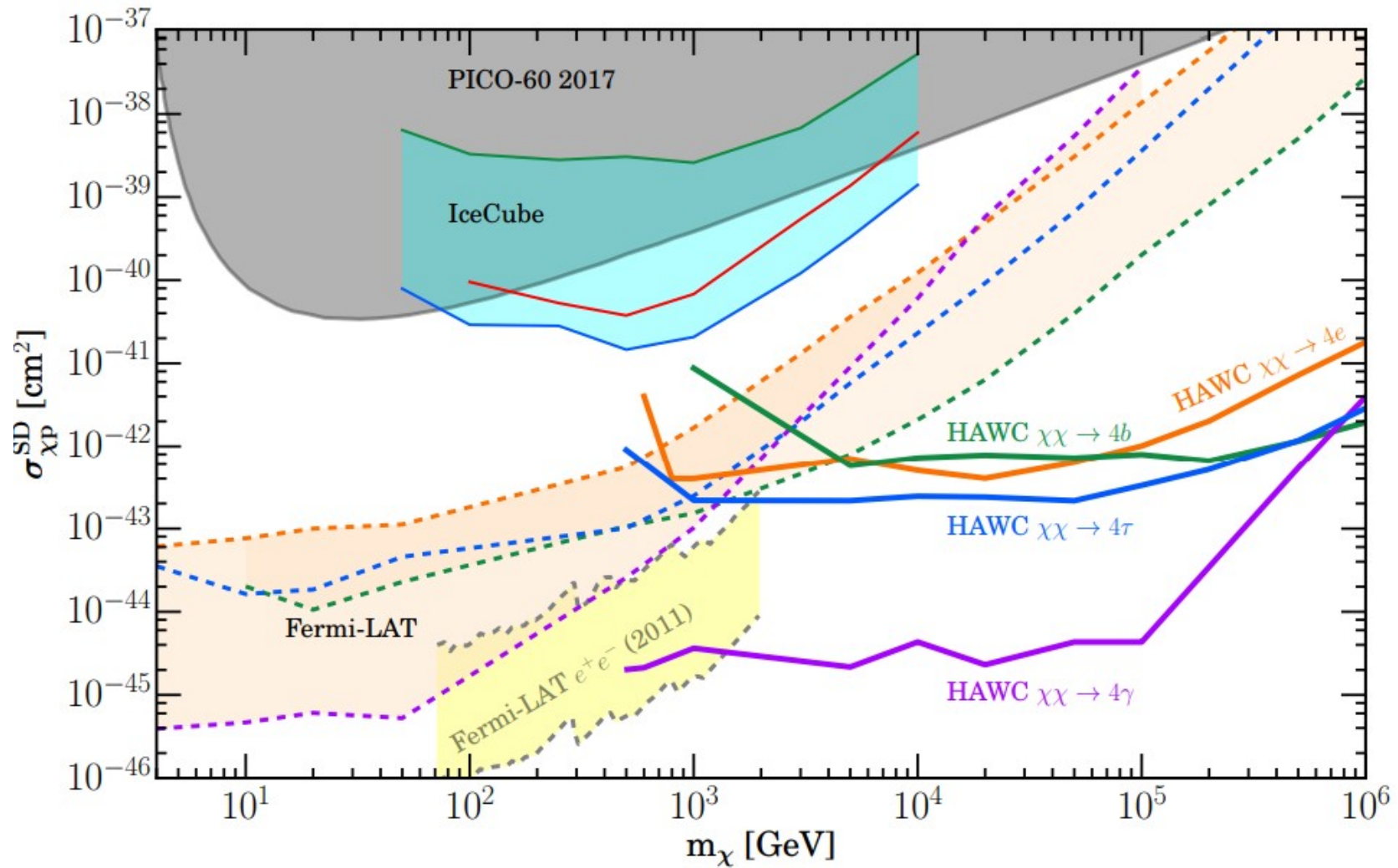
RL, Ng, Beacom (PRD '17)



SOLAR DARK MATTER LIMITS: UPDATED



SOLAR DARK MATTER LIMITS: ALL



HAWC Collaboration + RL (PRD in press '18)

