Dark Matter in Stars and Planets

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Based on 2010.00015, 2101.12213, + work to appear

w/ Tim Linden, Payel Mukhopadhyay, Juri Smirnov, Natalia Toro

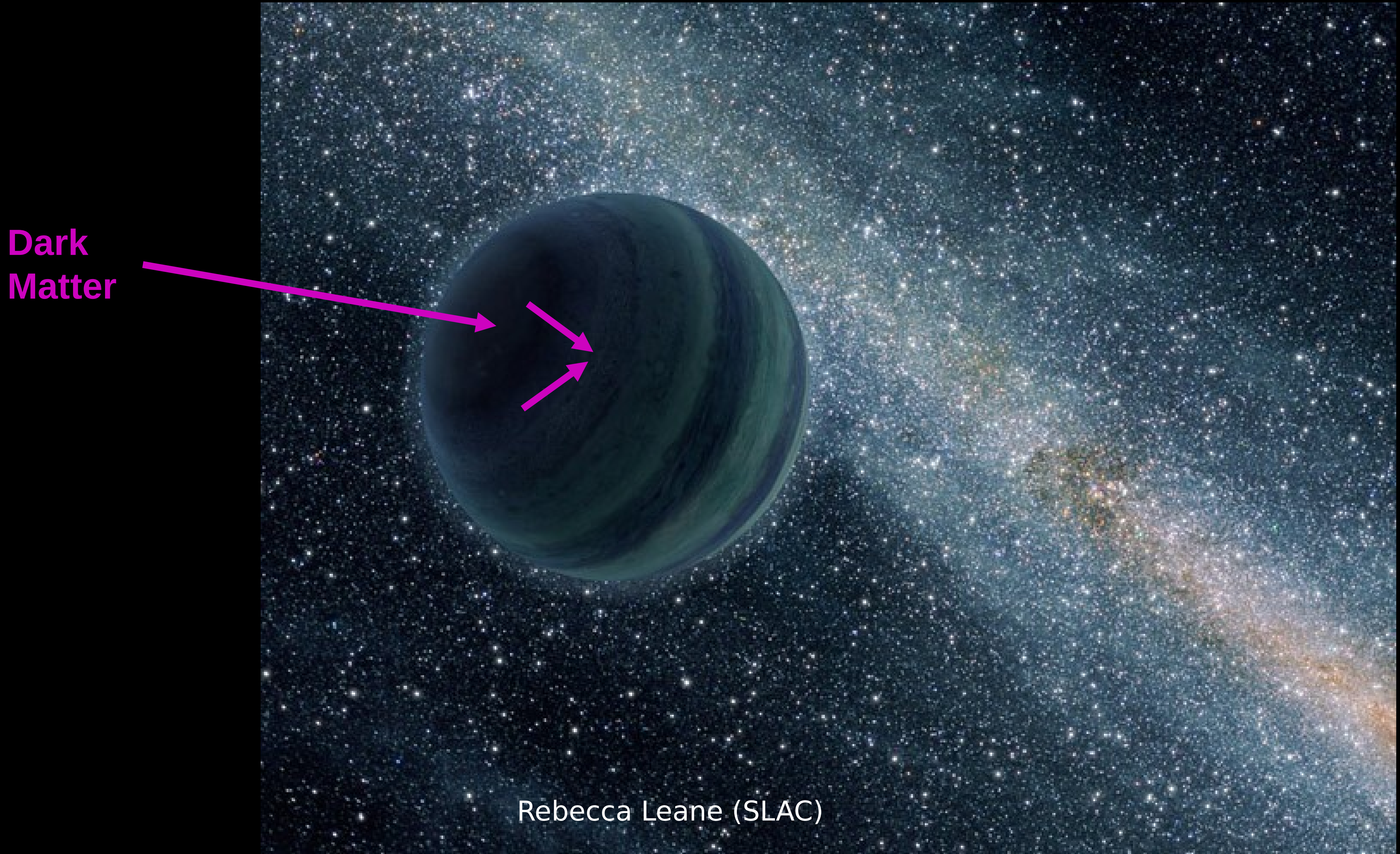
Outline

- 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 *Limits* on Stars and Planets at the Galactic Center
- New analysis of Jupiter in gamma rays

Exoplanets are new, exciting, and powerful detectors of dark matter.

Rebecca Leane (SLAC)

DARK MATTER CAPTURE IN EXOPLANETS



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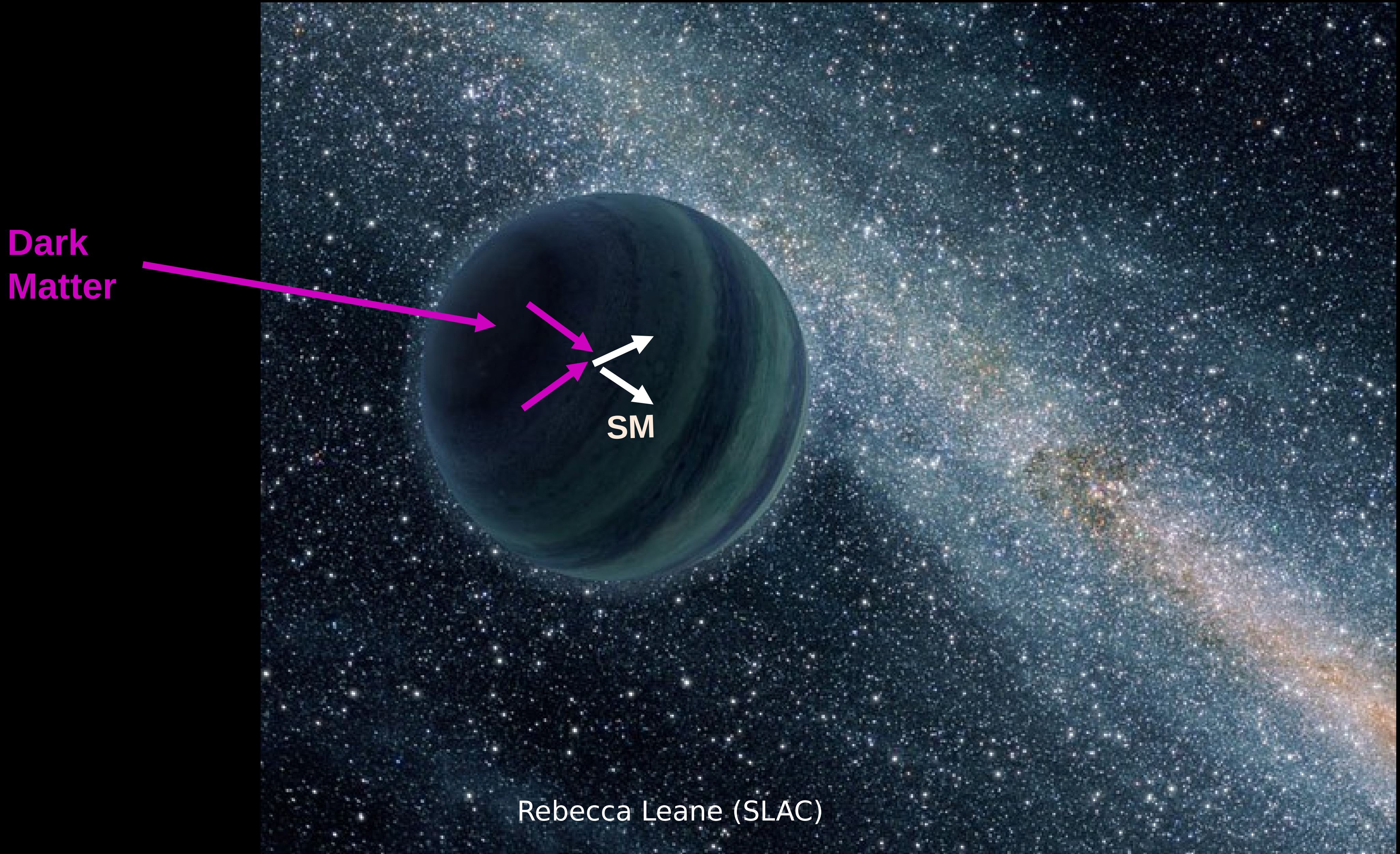
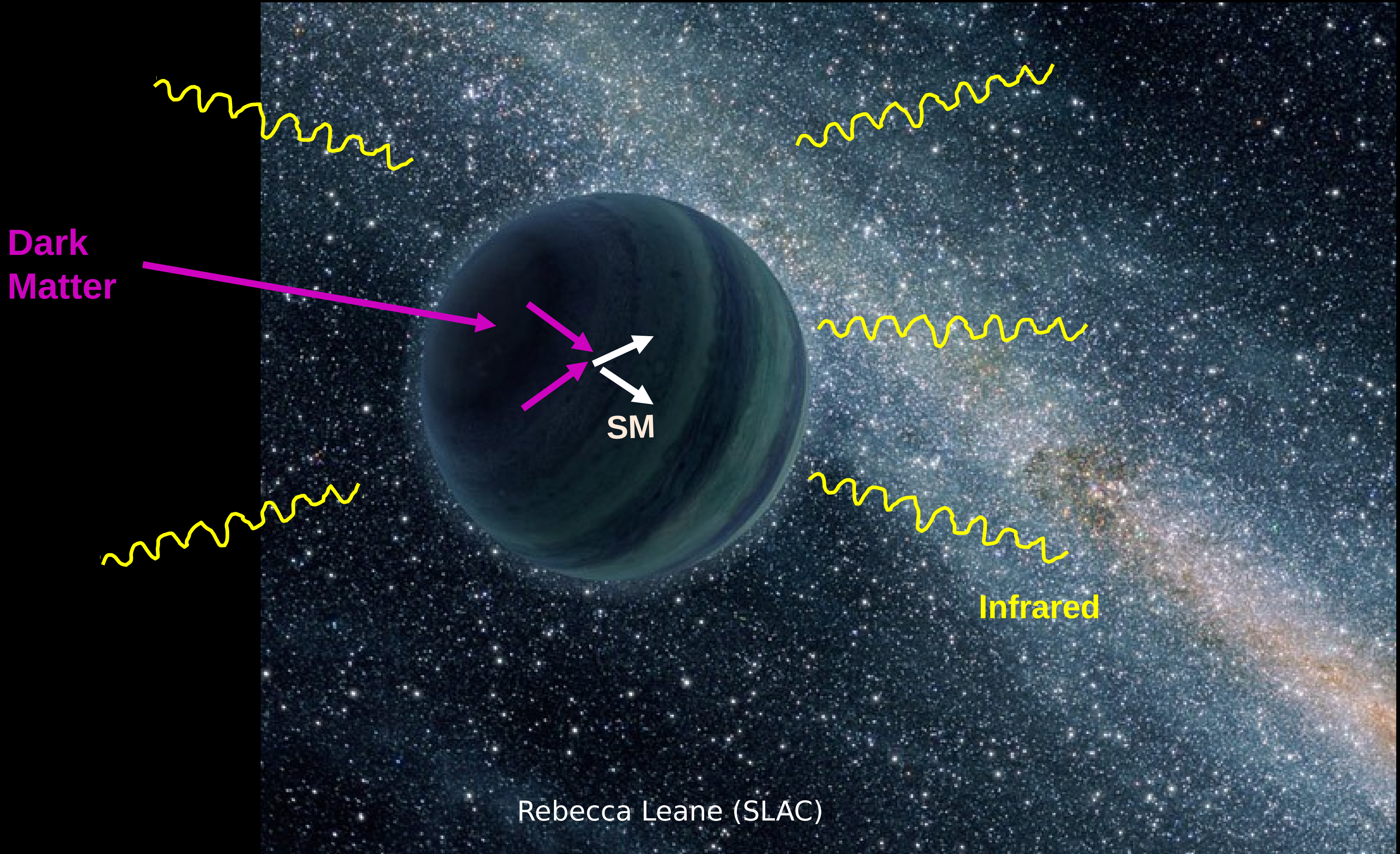


DARK MATTER CAPTURE IN EXOPLANETS



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.

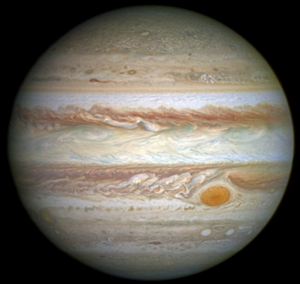
Advantage 2: Statistics

Estimates predict around 300 billion exoplanets in our galaxy!

To date:
4,301 confirmed exoplanets
5,633 exoplanet candidates

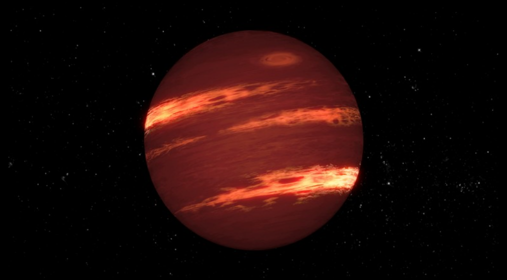
x 1

One Jupiter :(



x 10^11

x 10^11



x 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

+ Easier to detect than neutron stars

+ Easy to find

Exoplanet Search Targets

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}

Brown dwarfs:
Mass: 13 – 75 M_{jup}
Radius: ~1 R_{jup}
Very dense!

Rogue Planets:
Cold and all alone!

Most commonly Jupiter-sized up to brown dwarf sized

Calculating Dark Matter Exoplanet Heating

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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:

$$\Gamma^{\rm tot}_{\rm heat} = \Gamma^{\rm ext}_{\rm heat} + \Gamma^{\rm int}_{\rm heat} + \Gamma^{\rm DM}_{\rm heat} = 4\pi R^2\,\sigma_{\rm SB}\,T^4\,\epsilon$$

- 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

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

<u>Heat power from DM:</u>

- 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

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

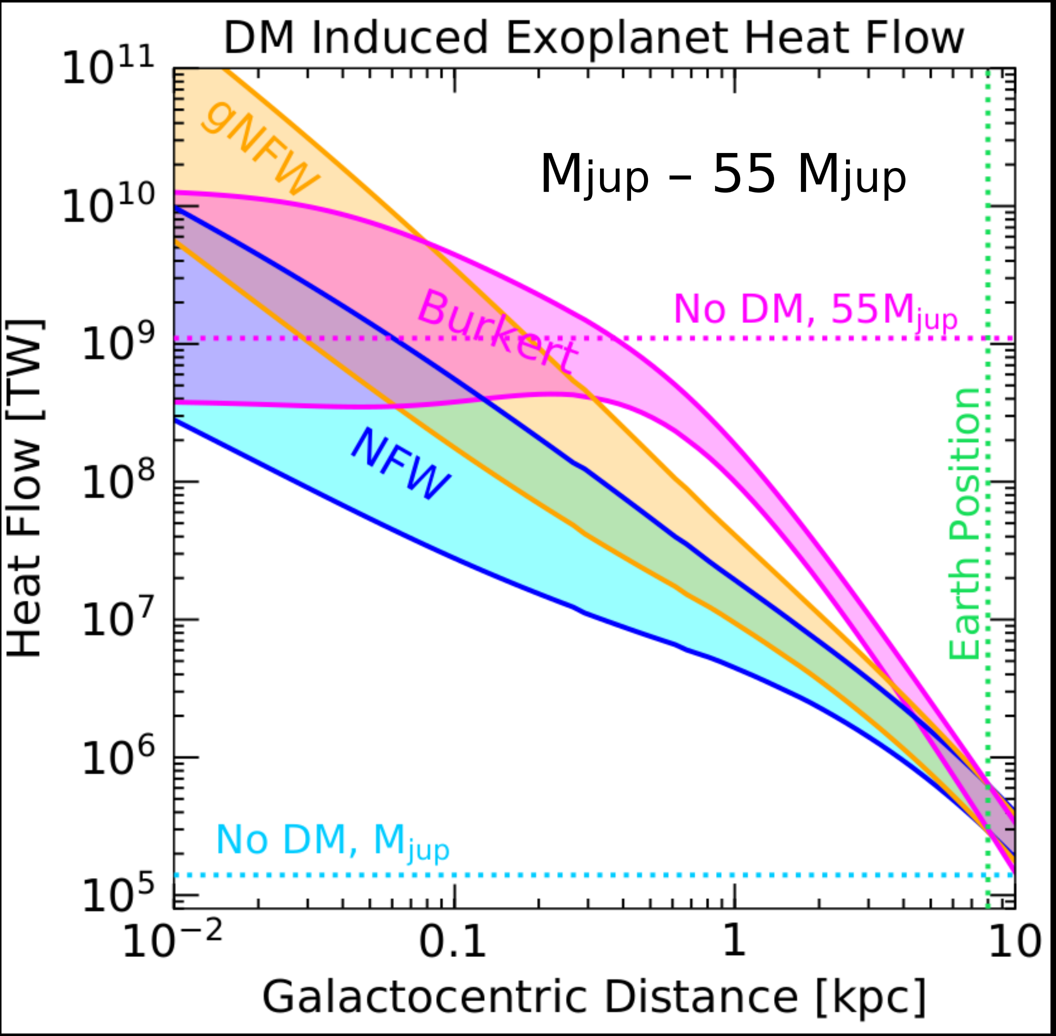
$$\Gamma_{\rm heat}^{\rm DM} = f \, \pi R^2 \rho_\chi(r) \, v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_d(r)^2}\right)$$

DM Heating vs Internal Heat

RKL + Smirnov, 2020

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

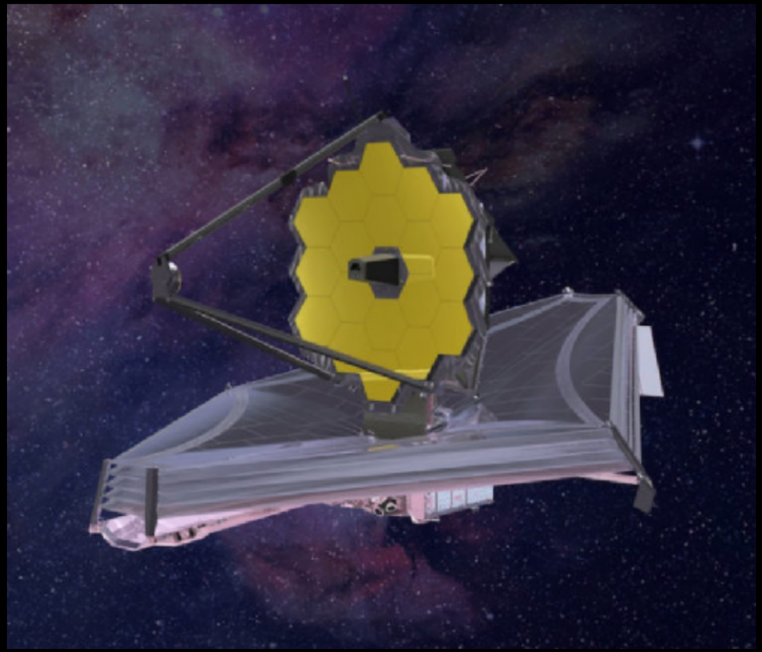
$$\Gamma^{\rm DM}_{\rm heat} = f\, \pi R^2 \rho_\chi(r)\, v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_d(r)^2}\right)$$

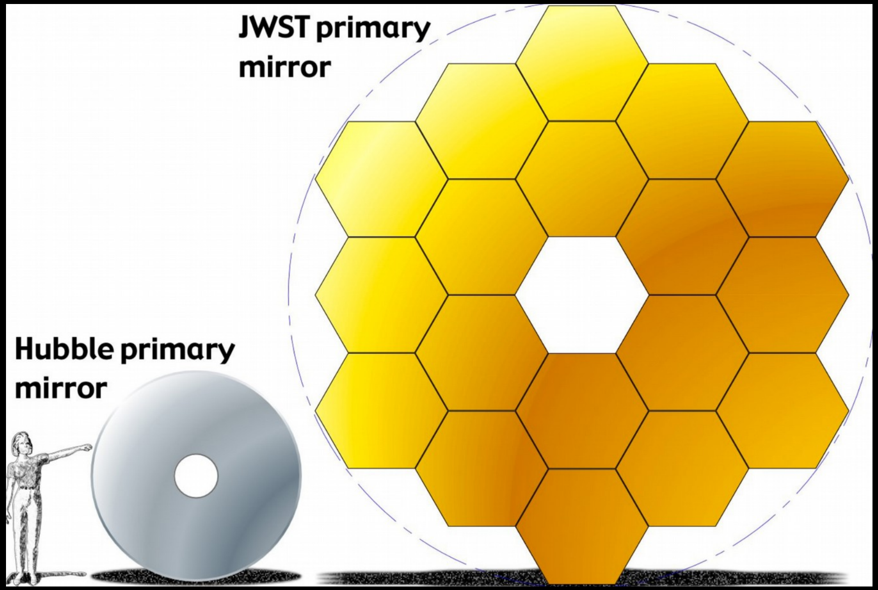


1 parsec = 3.26 light years

Telescope Sensitivity

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



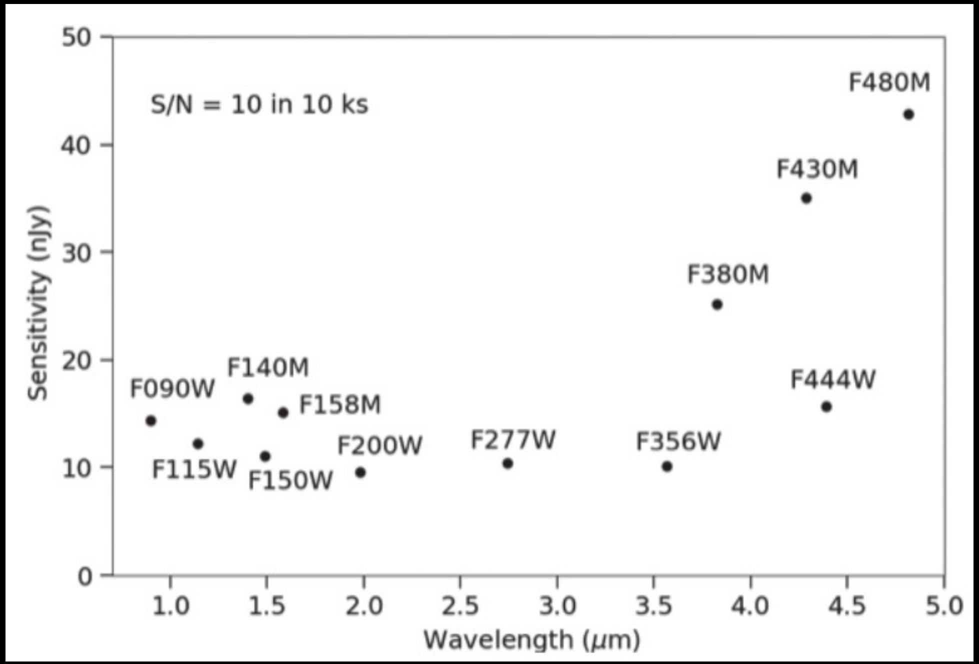


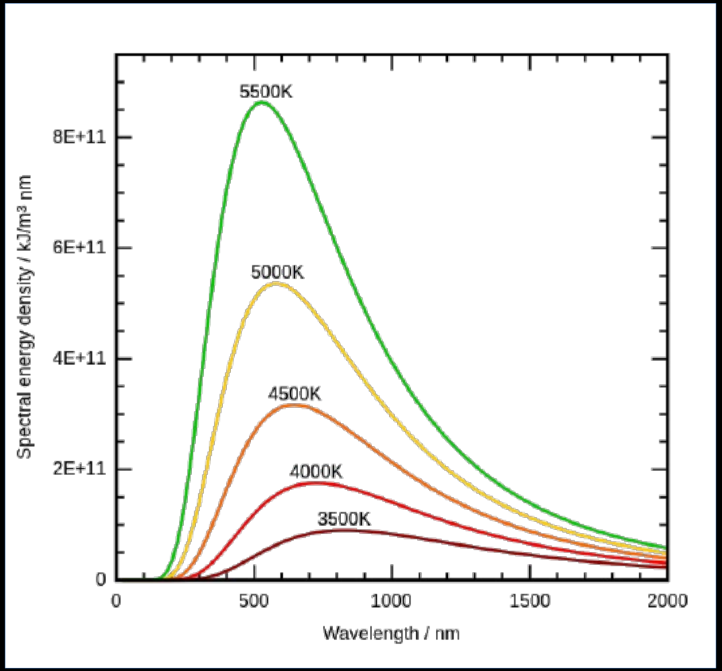
Signal with James Webb

- Can see many stars/planets at once
- Assume exoplanets radiate as a blackbody
  - Assume peak of blackbody temperature sets the sensitivity limit

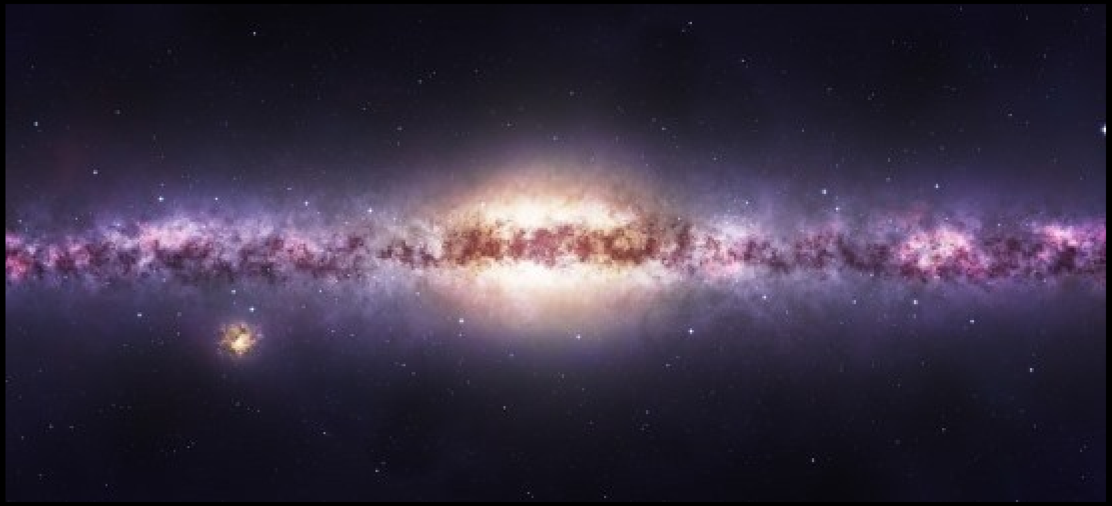
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K
- Mid-Infrared Instrument (MIRI) for T = 100 - 500 K

Won’t need new dedicated searches; can piggyback





Search Challenges



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

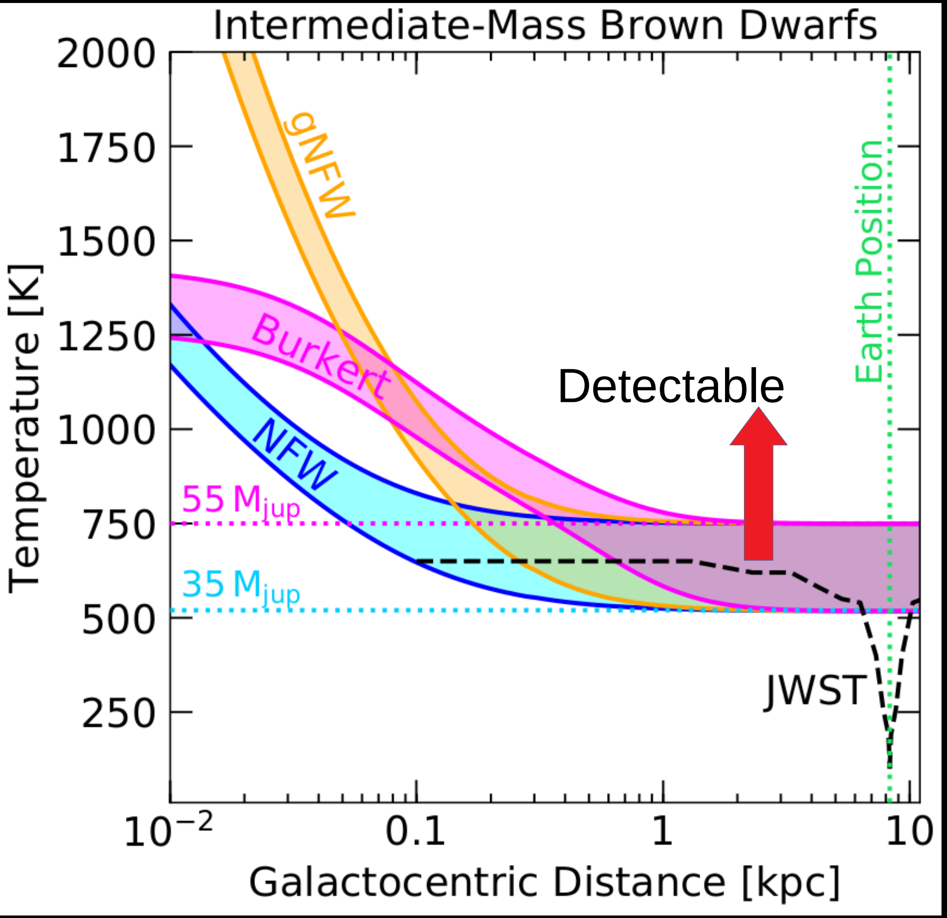
Stellar crowding:
Stars per pixel important, can outshine exoplanet signal

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
- Minimum JWST sensitivity shown is signal to noise of 2, with exposure time of ~day
- Can do 10 SNR in 10^6 seconds on the line shown, + higher temps need less exposure time
- Sensitivity truncates at ~0.1kpc, due to stars per pixel, and dust scattering

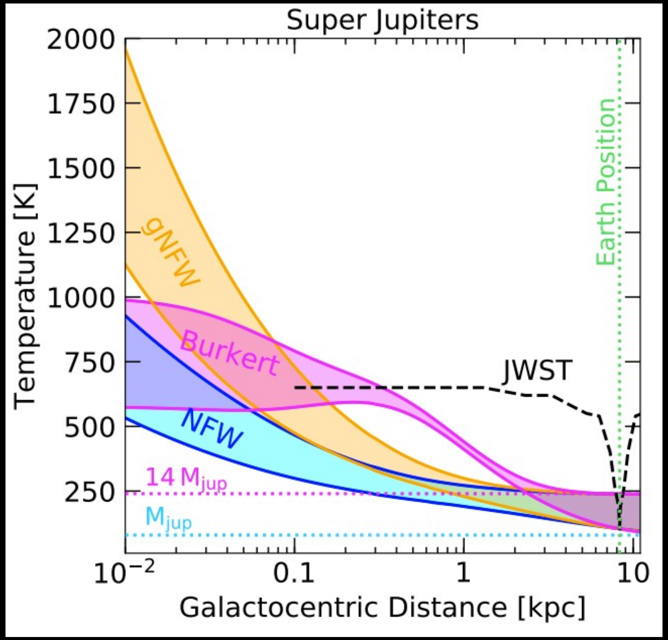
35 Mjup – 55 Mjup



RKL + Smirnov, 2020

Exoplanet masses vs sensitivity

Mjup – 14 Mjup



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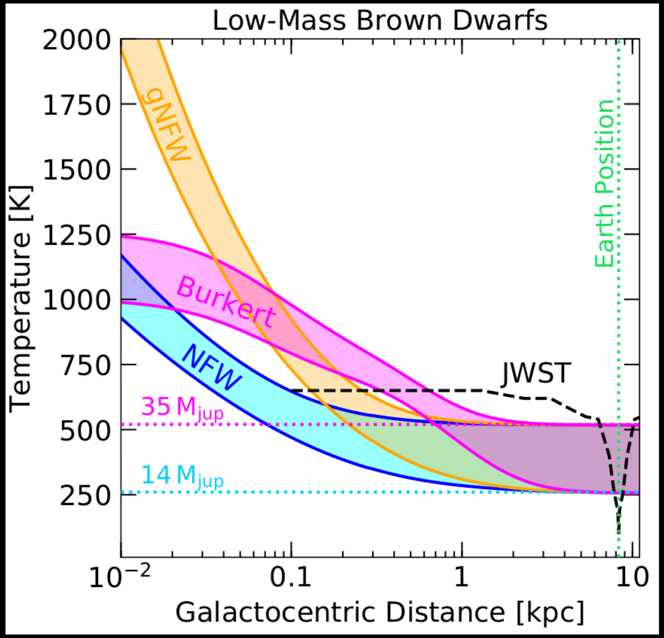

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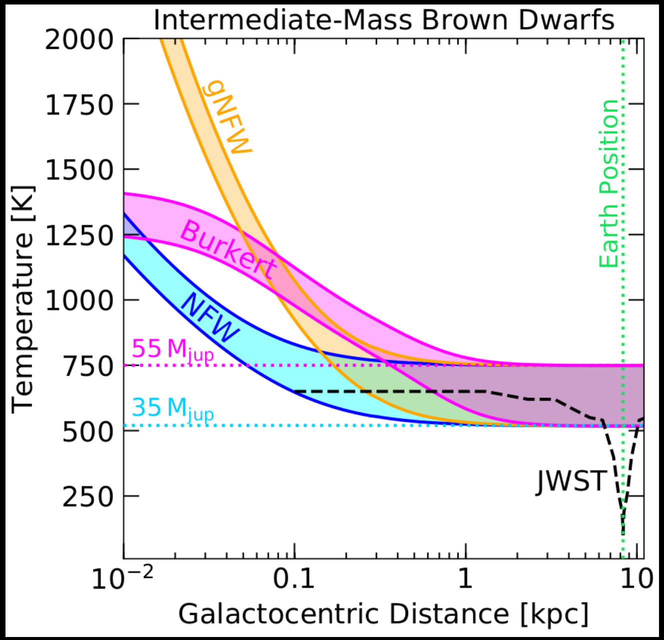

Lower masses:
DM heat > internal heat at all positions

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

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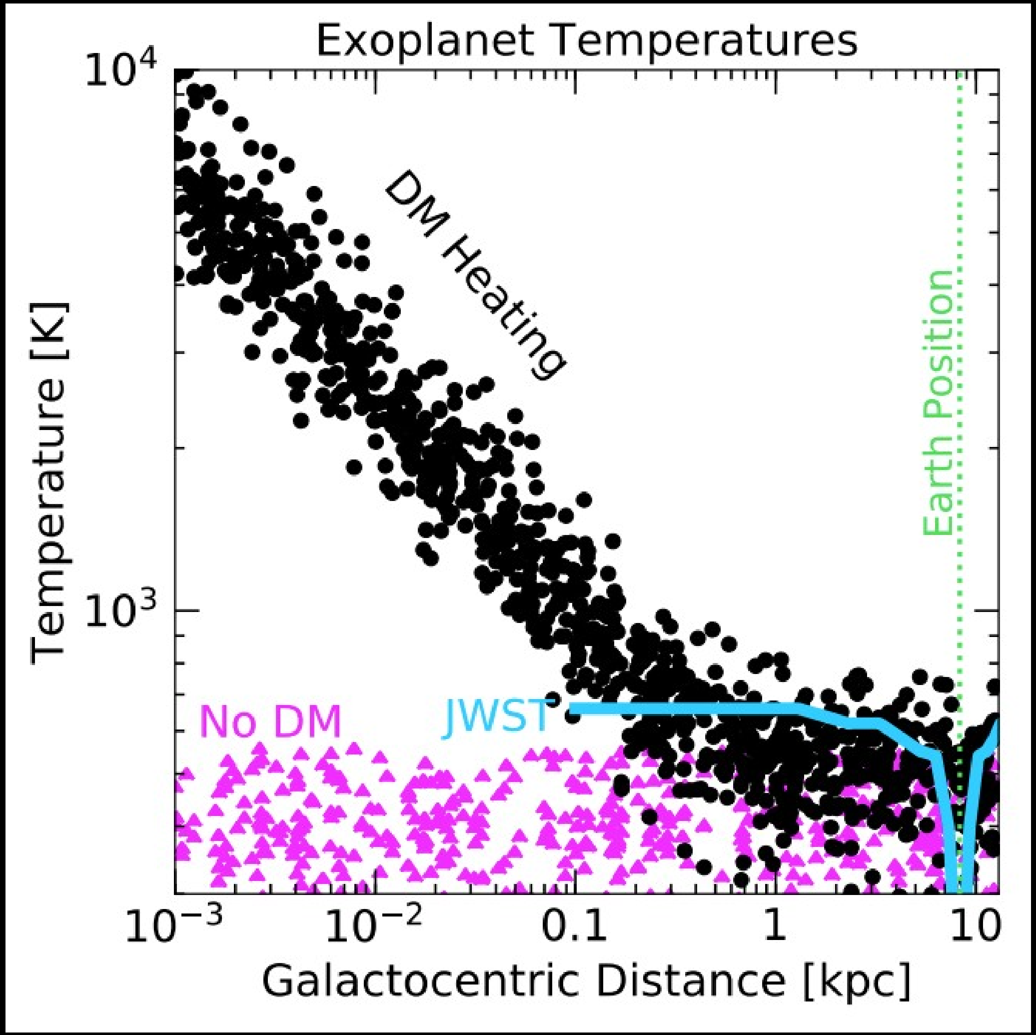
RKL + Smirnov, 2020

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



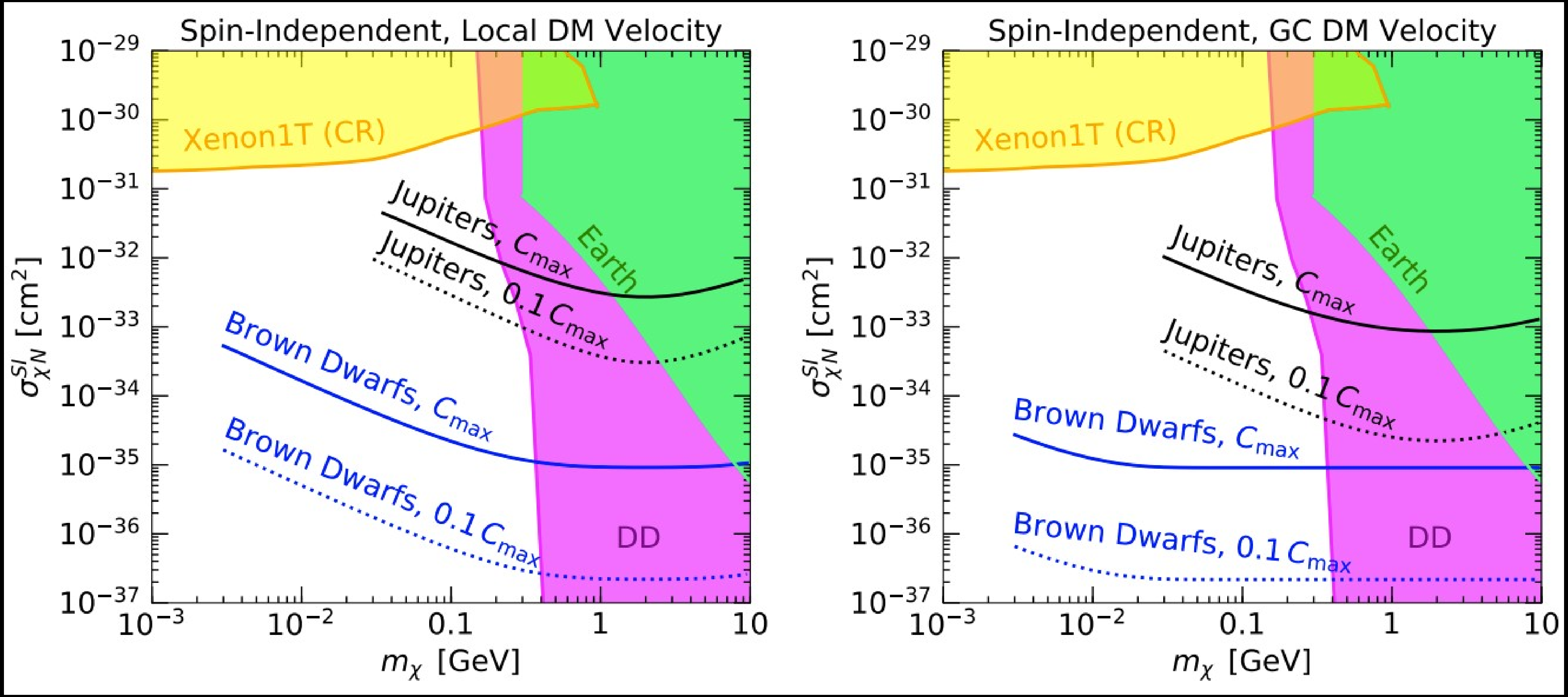
RKL + Smirnov, 2020

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	$\sim$ 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]

- 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

DM scattering cross section sensitivity



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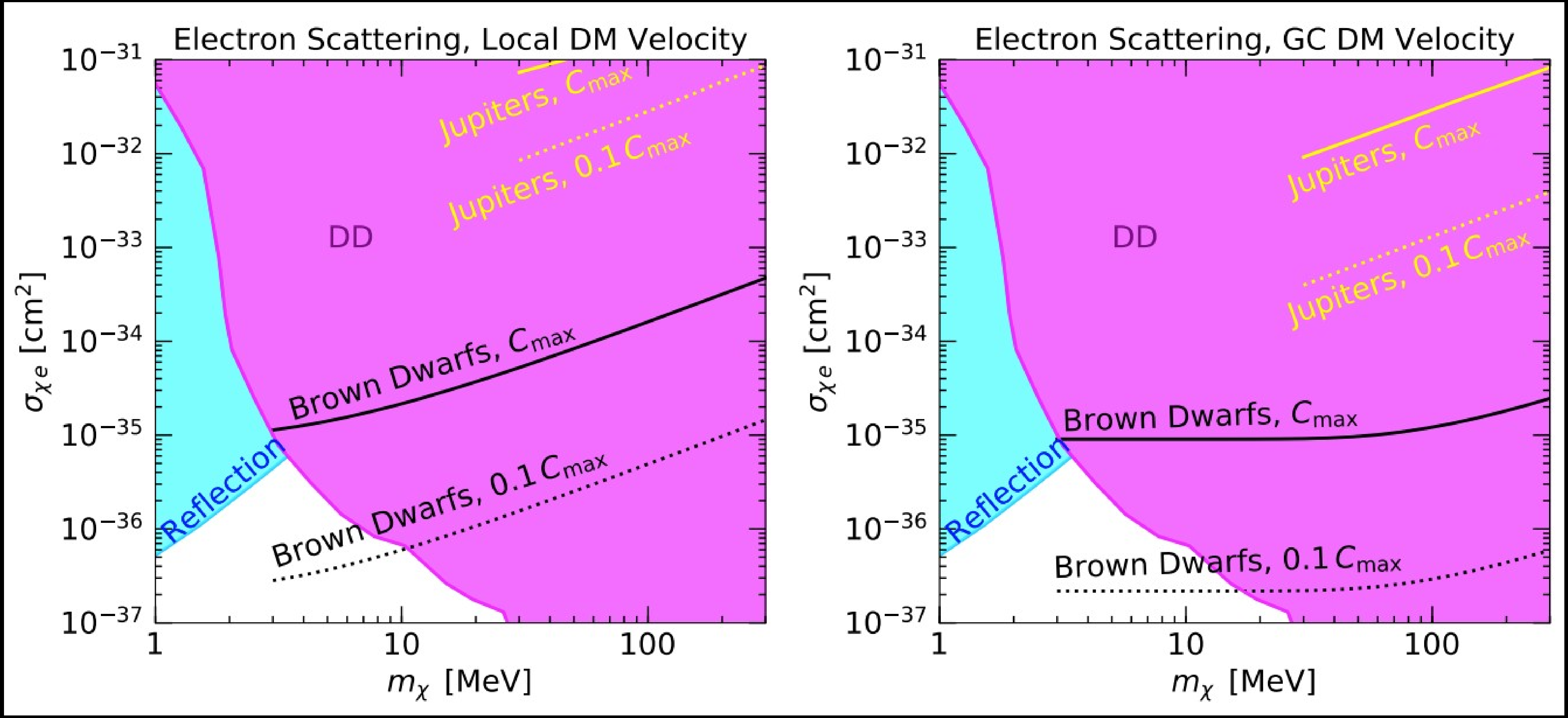

RKL + Smirnov, 2020

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 Searches

with new limits

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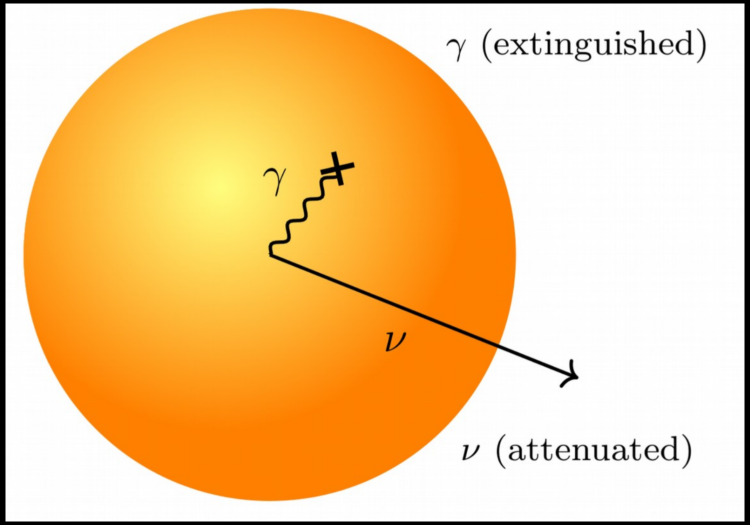
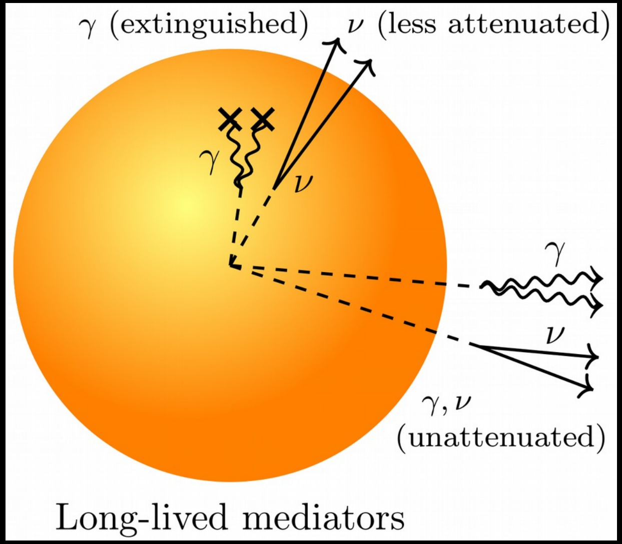
Complementary Searches

Two regimes:

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



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



Complementary Searches

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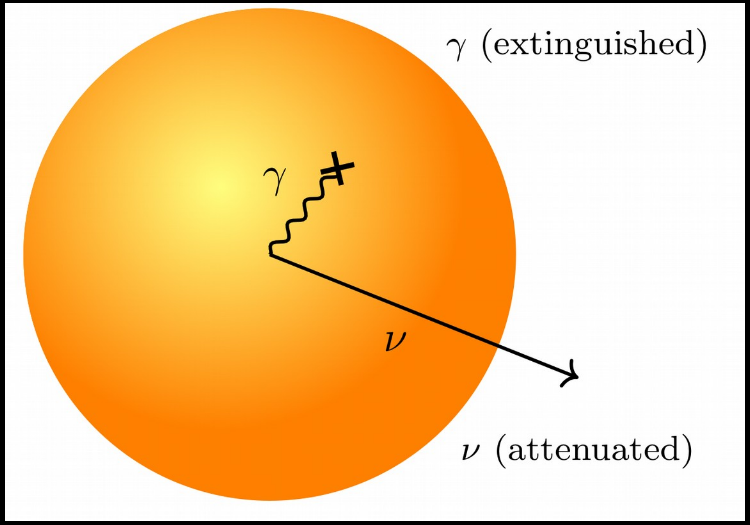

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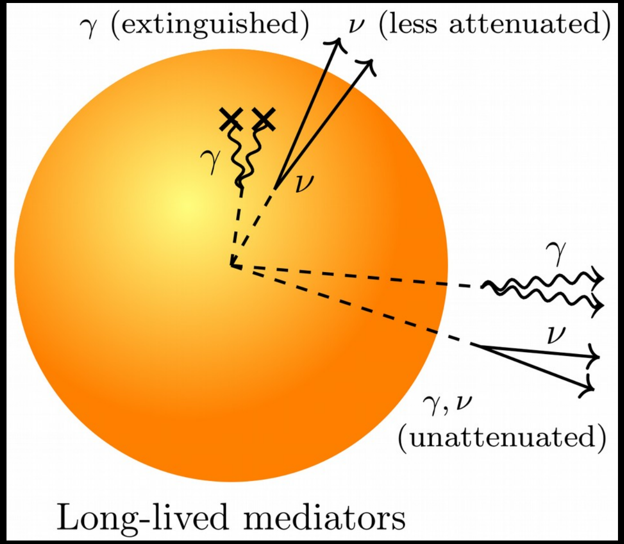
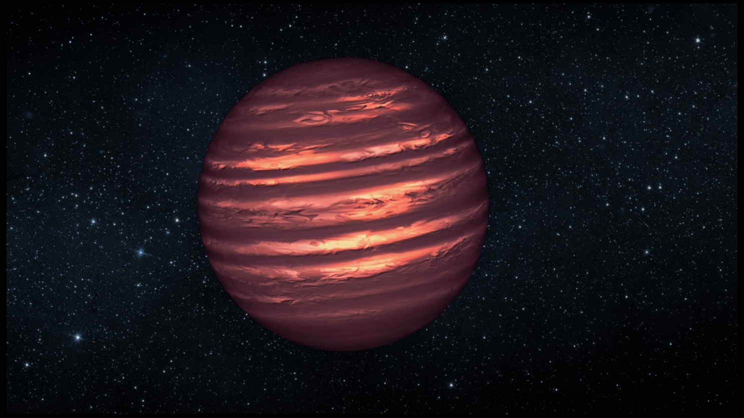
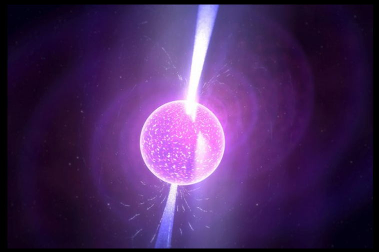
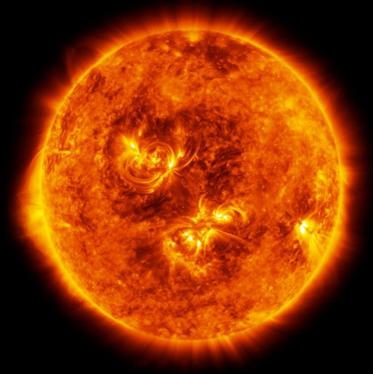
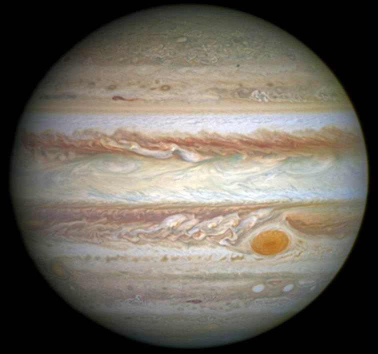


Optimal Celestial Target?

- Radius: Larger amount of DM captured, larger annihilation signal
- Core Temperature: Gives kinetic energy to DM, if high, more evaporation
- Density: Lower cross section sensitivities

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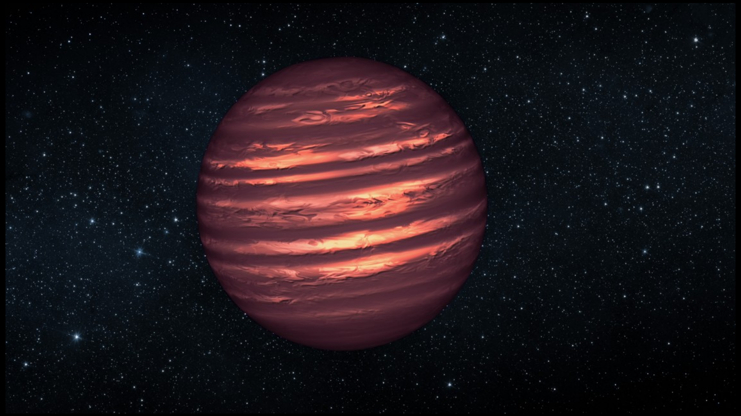
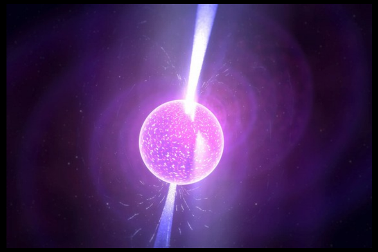


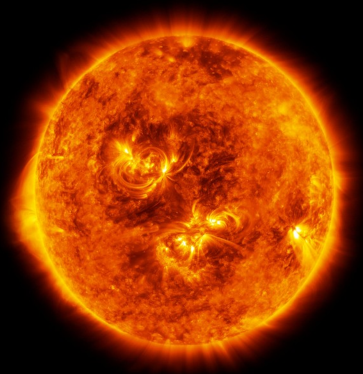
Brown Dwarf

BIG
Cold
Dense



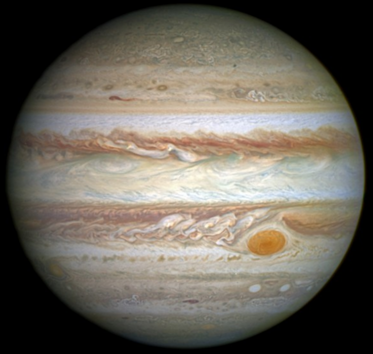
Neutron Star

Small
Cold
Ultra-dense



Sun

BIG
Hot



Jupiter

BIG
Cold

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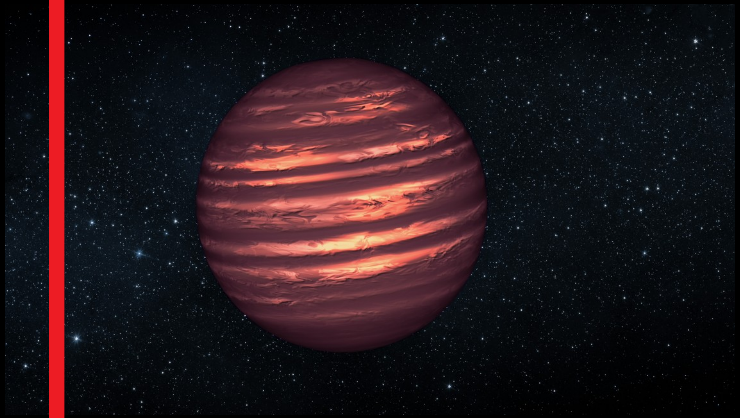
Optimal Celestial Target?



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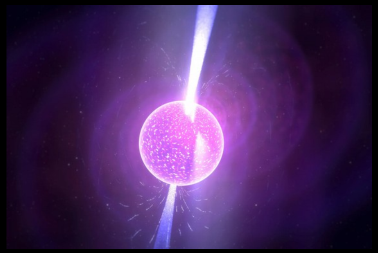

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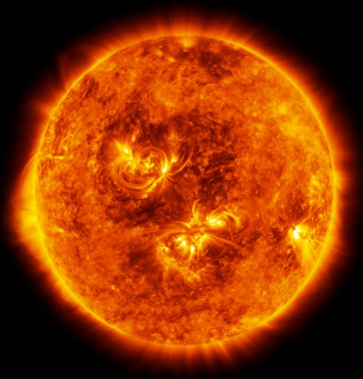

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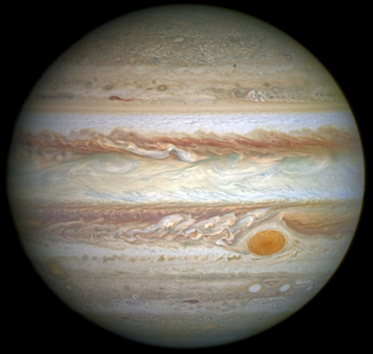


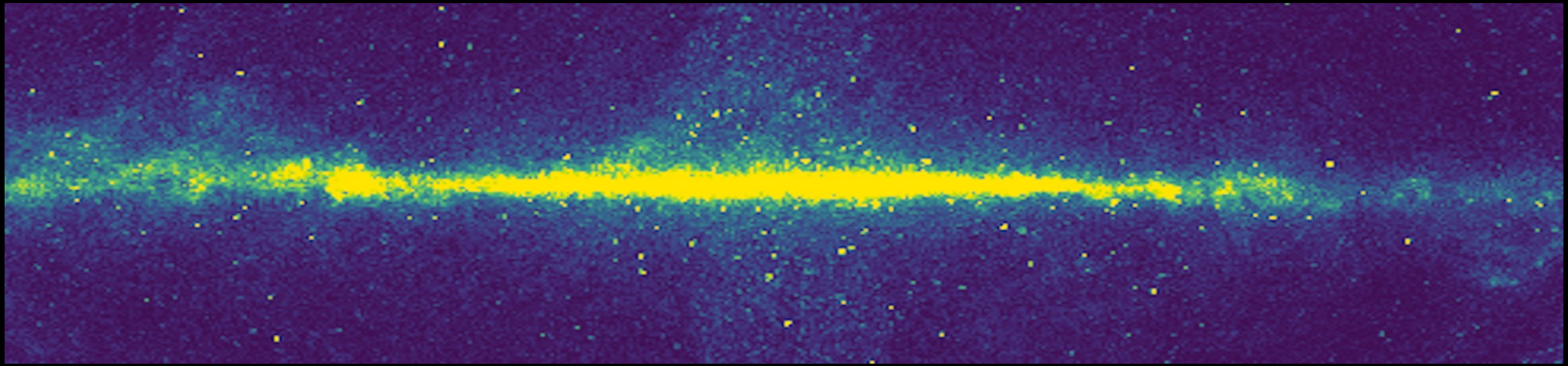
Jupiter

BIG
Cold

Galactic Center Population Signal

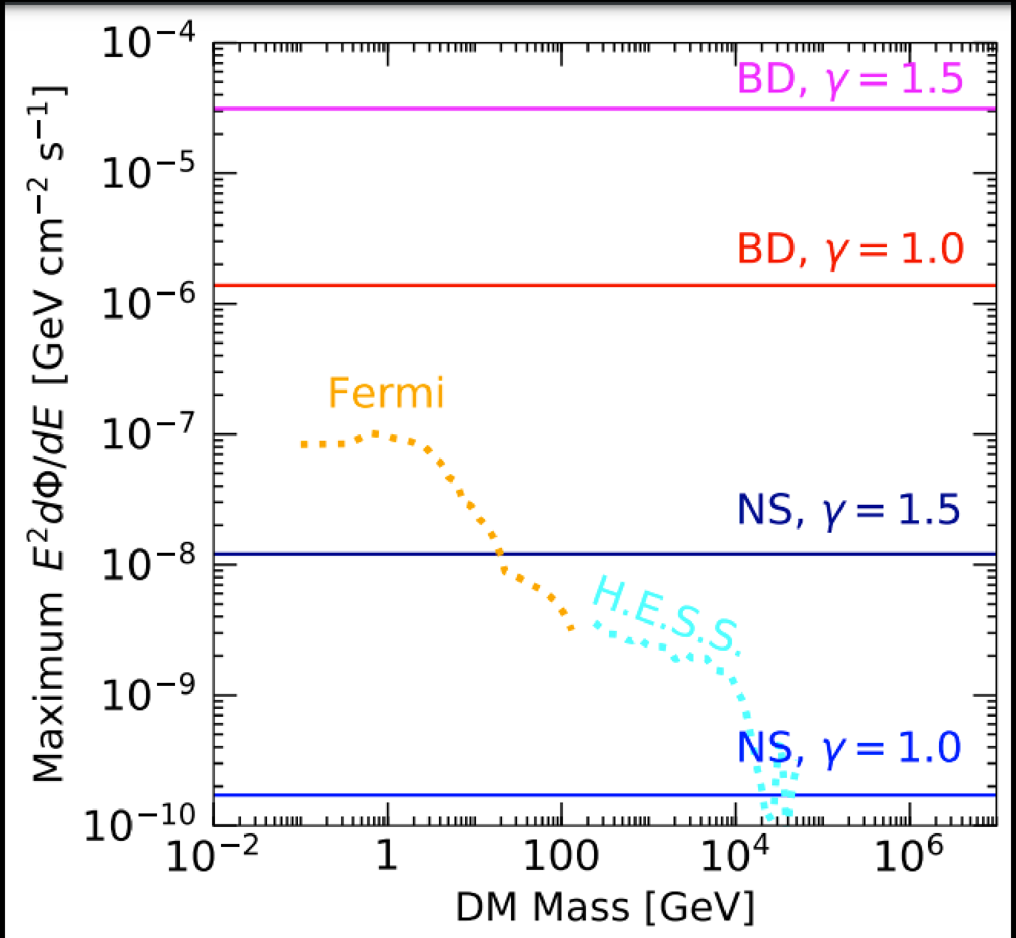
- Use all the neutron stars, all the brown dwarfs
- Large population in the Galactic Center, DM density high: large rate!

- Our new signal follows matter density: DM density * stellar density
  - DM Halo annihilation scales with DM density squared



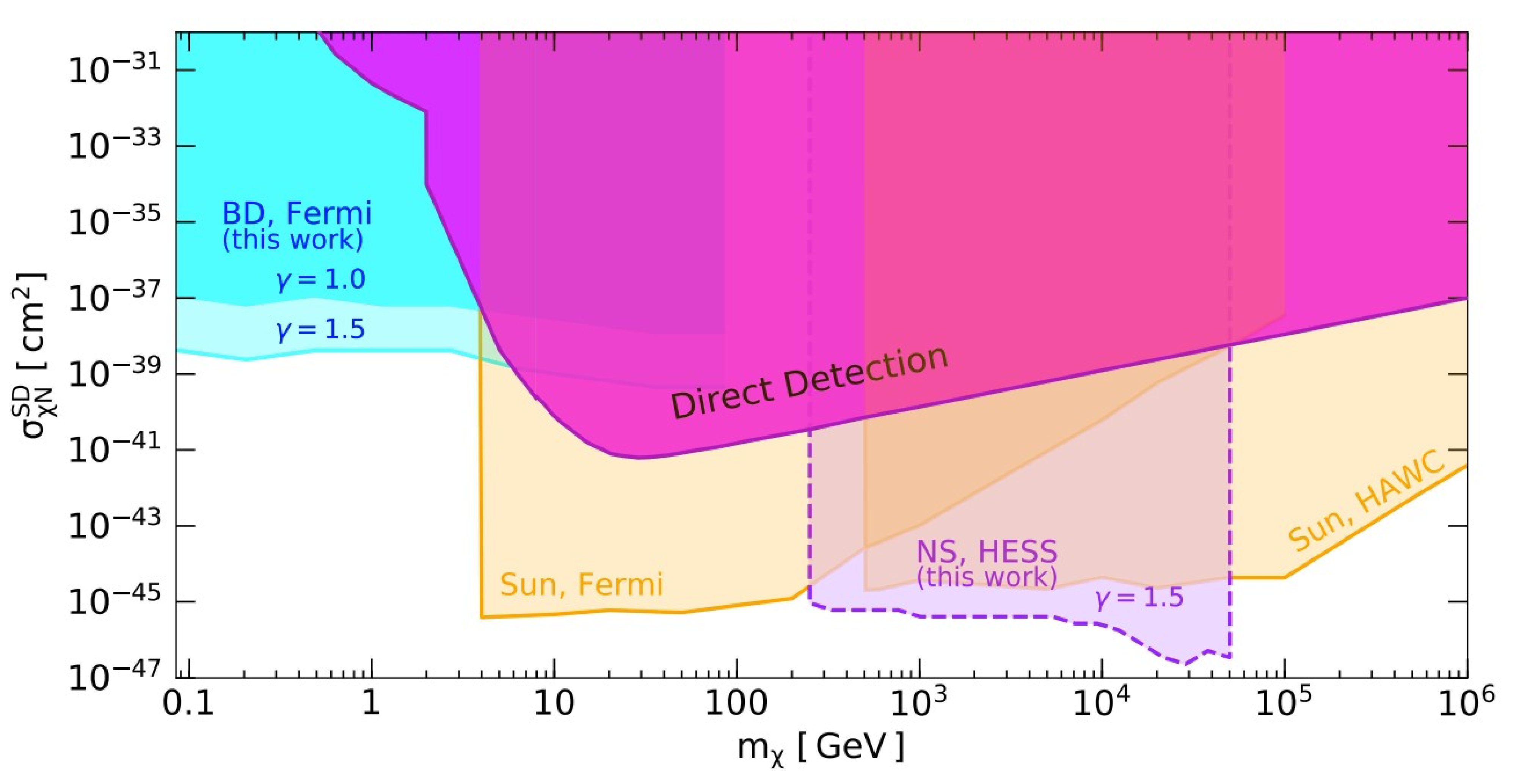
Galactic Center Population Signal

- 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!



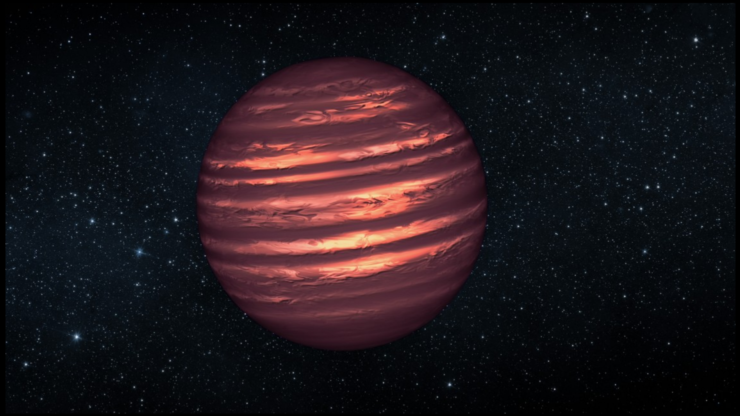
RKL, Linden, Mukhopadyay, Toro, 2021

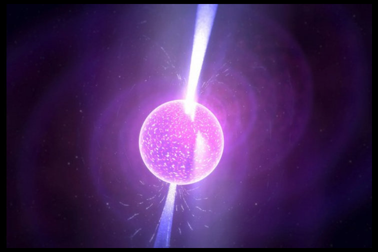
New Limits w/ Brown Dwarfs and Neutron Stars

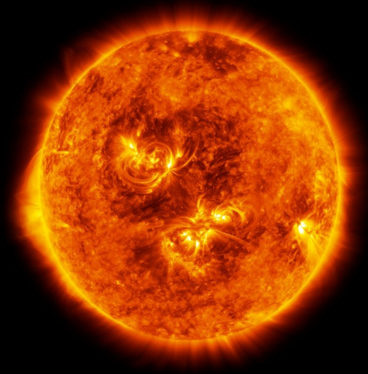


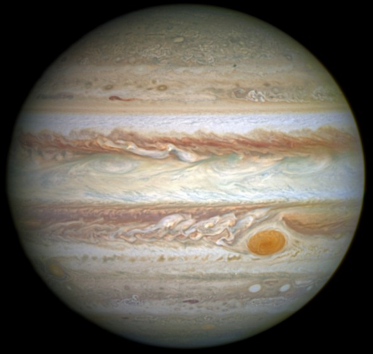
RKL, Linden, Mukhopadyay, Toro, 2021

Optimal Celestial Target?









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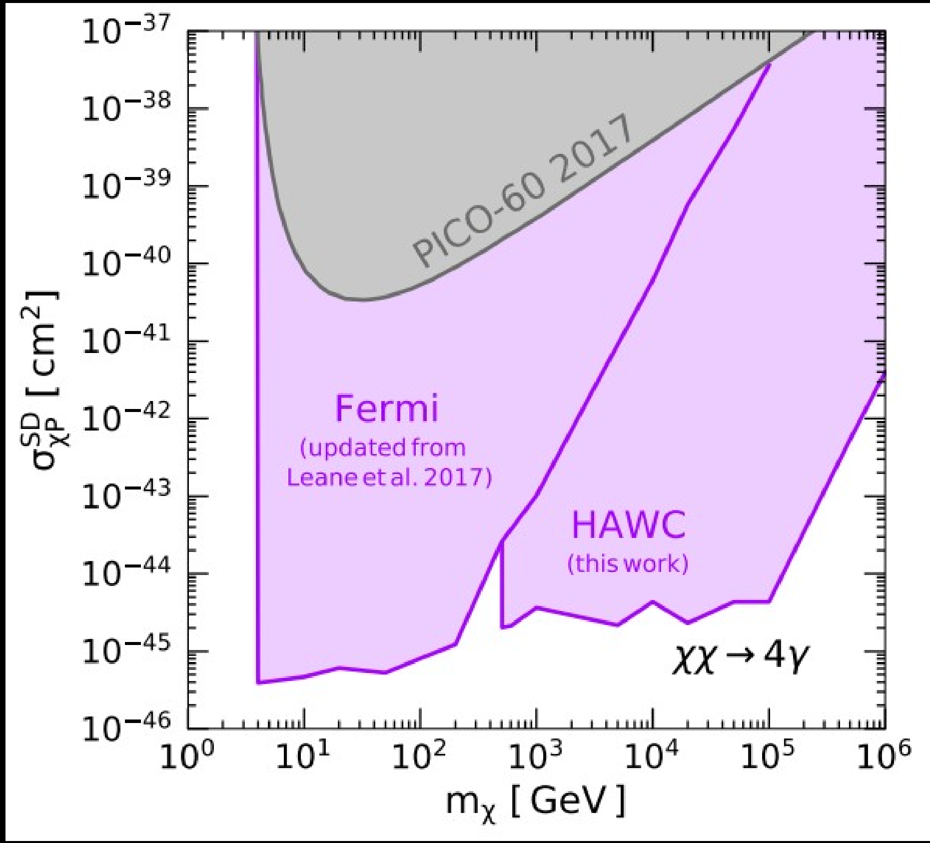
Solar System Objects

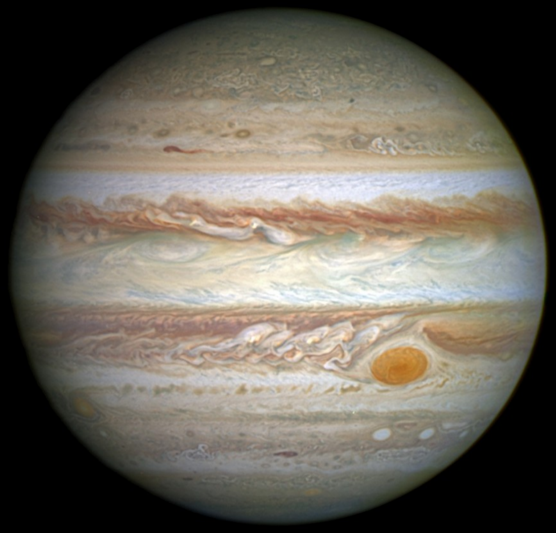


Sun

Long-Lived Mediator Limits

RKL, Ng, Beacom (PRD '17)

RKL + HAWC Collaboration (PRD '18)



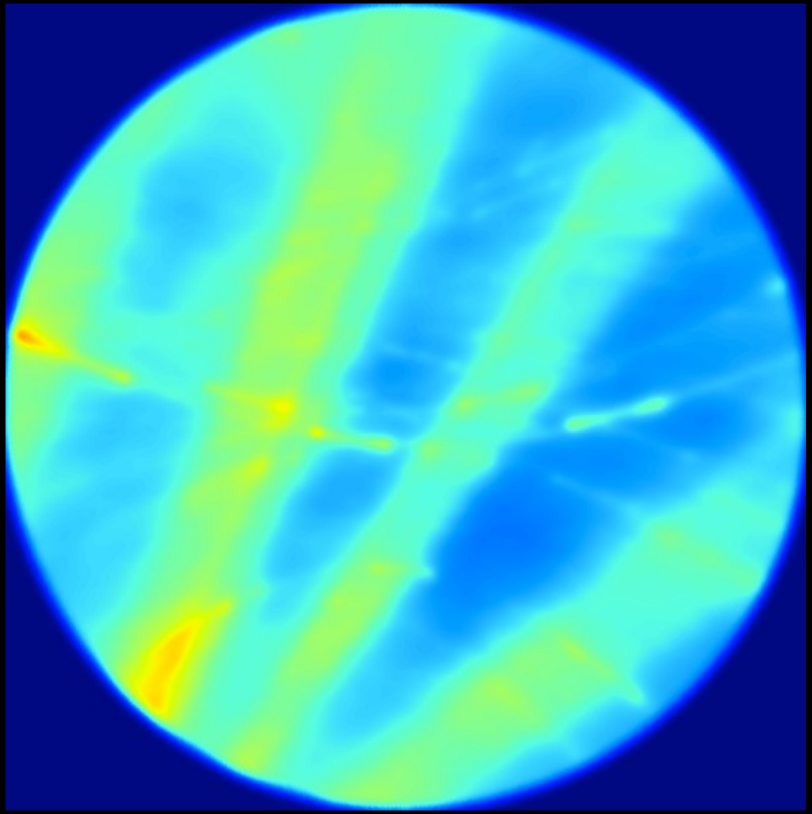
What about Jupiter?

Cooler than the Sun:
MeV-DM mass sensitivity!

Jupiter in Gamma Rays

RKL, Linden (to appear)

- Never measured in gamma rays!
- We perform first search using publicly available Fermi Telescope data



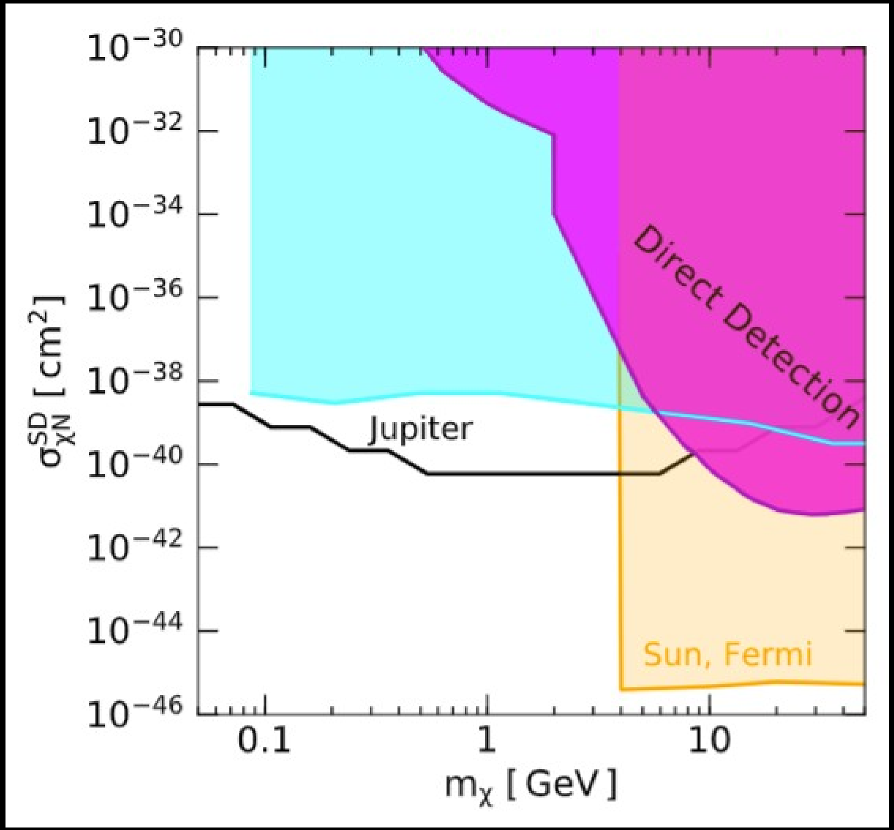
Nothing there :(

PRELIMINARY

Jupiter in Gamma Rays

RKL, Linden (to appear)

- Never measured in gamma rays!
- We perform first search using publicly available Fermi Telescope data
- Can set limits on DM annihilation to long-lived particle scenario
- Plot assumes long-lived particles decay directly into gamma rays



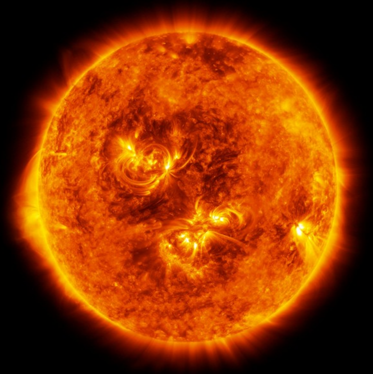
PRELIMINARY

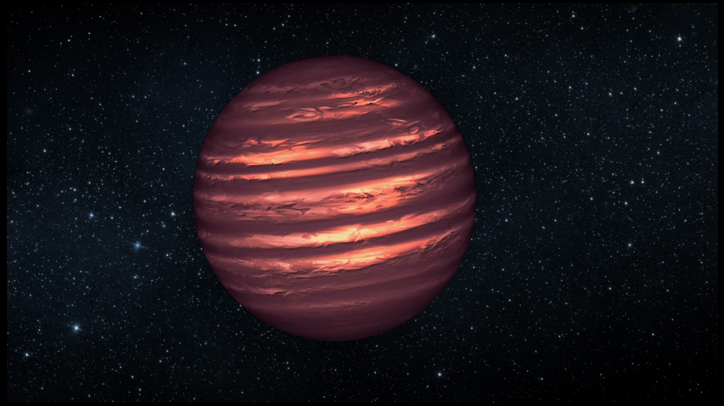
Summary: Long-lived particles

- Complementary searches for sub-GeV DM in celestial bodies:
  - DM annihilation to long-lived mediators:

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

    + Search for gamma rays from Jupiter, new sub-GeV limits





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

DM Equilibrium and Evaporation

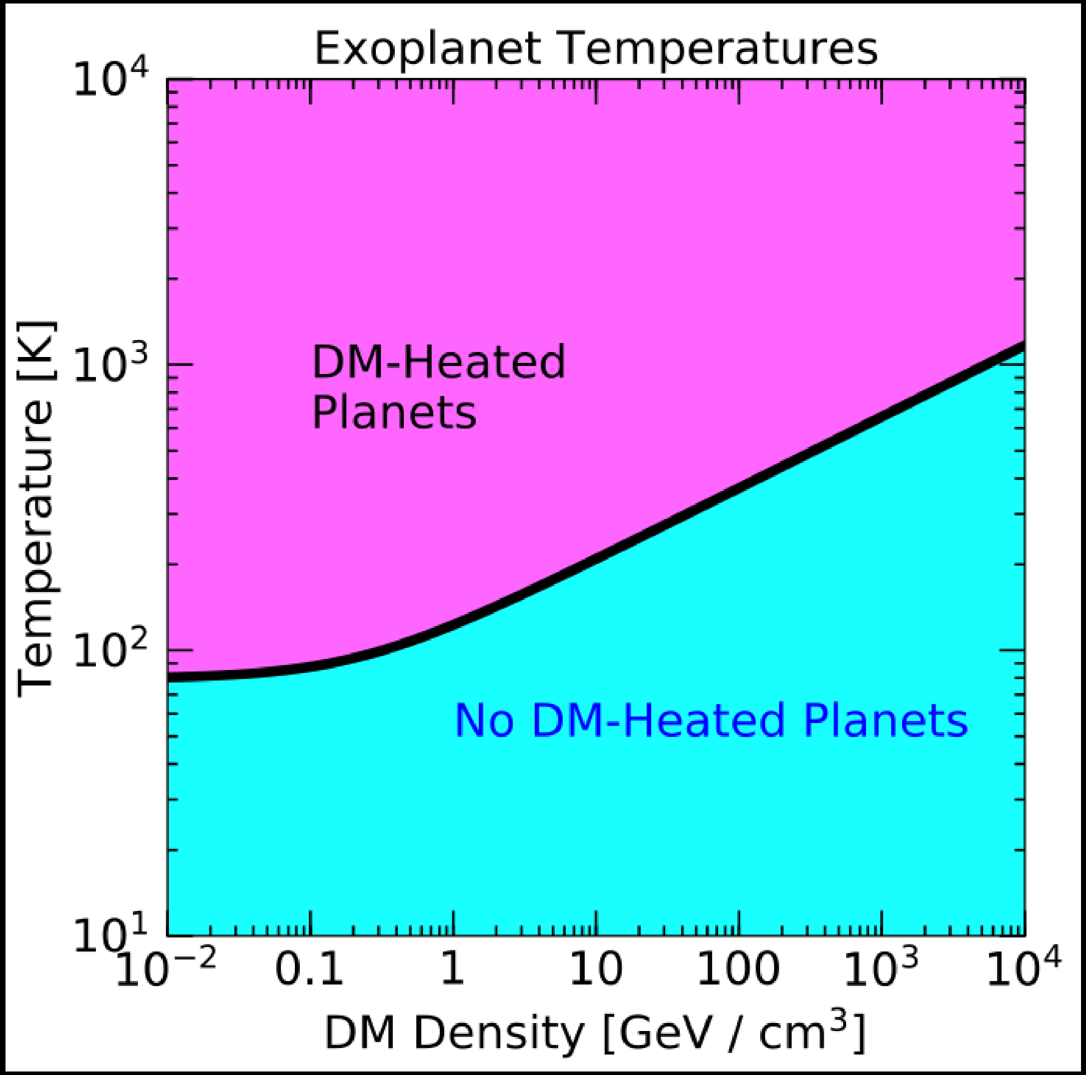
- For maximal rate, want DM scattering and annihilation to be in equilibrium
  - Find DM reaches equilibrium by 1-10 Gigayears

- 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:

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

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

Deviations: DM-overdensities

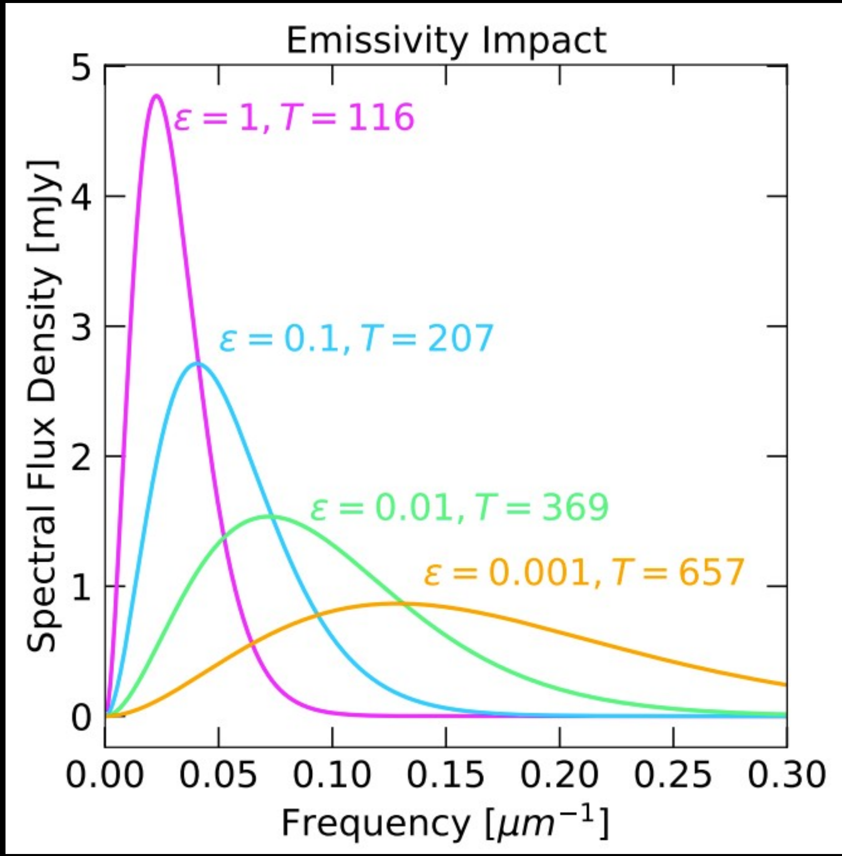


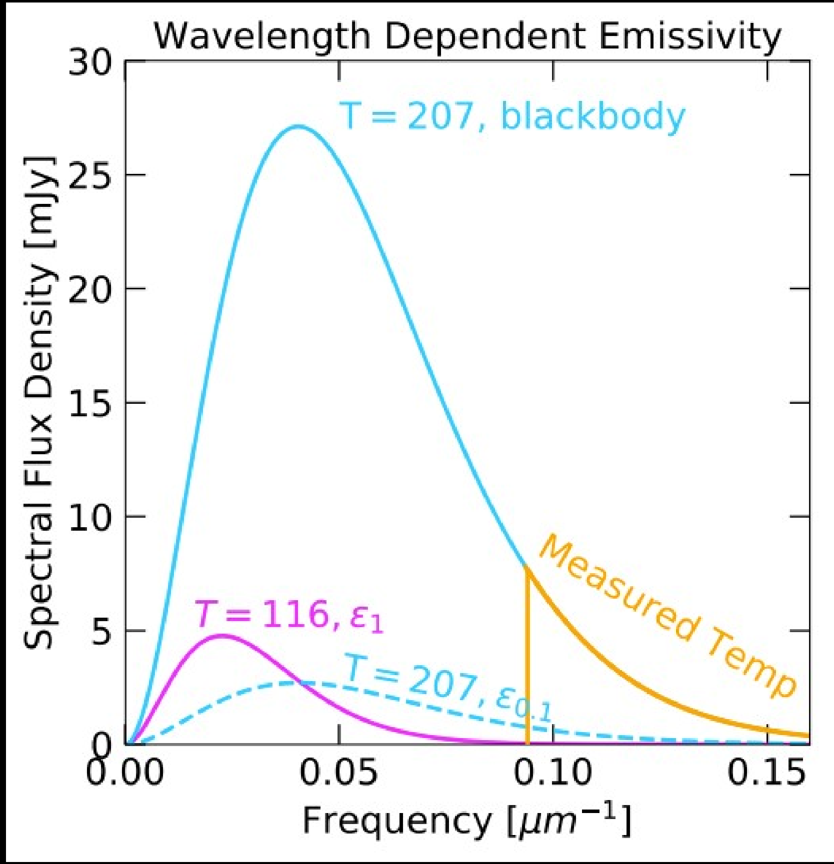
Rebecca Leane (SLAC)

Deviations: Non-Blackbody Spectra

Atmosphere effects can cause deviations from a blackbody

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

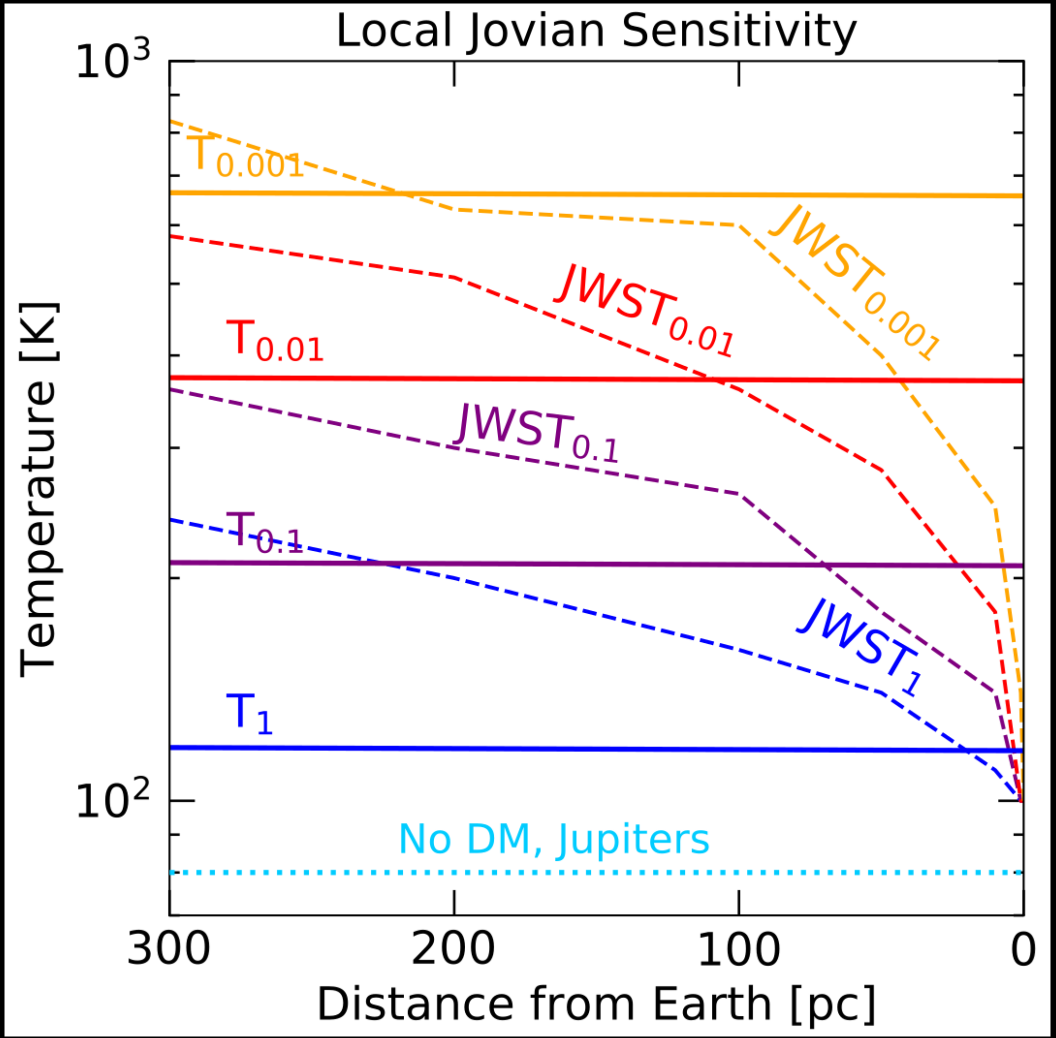




Rebecca Leane (SLAC)

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

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

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

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

Here v_d is the velocity dispersion, $v_N = v_{\rm esc}\left(1 - \langle z\rangle\beta\right)^{-N/2}$ 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

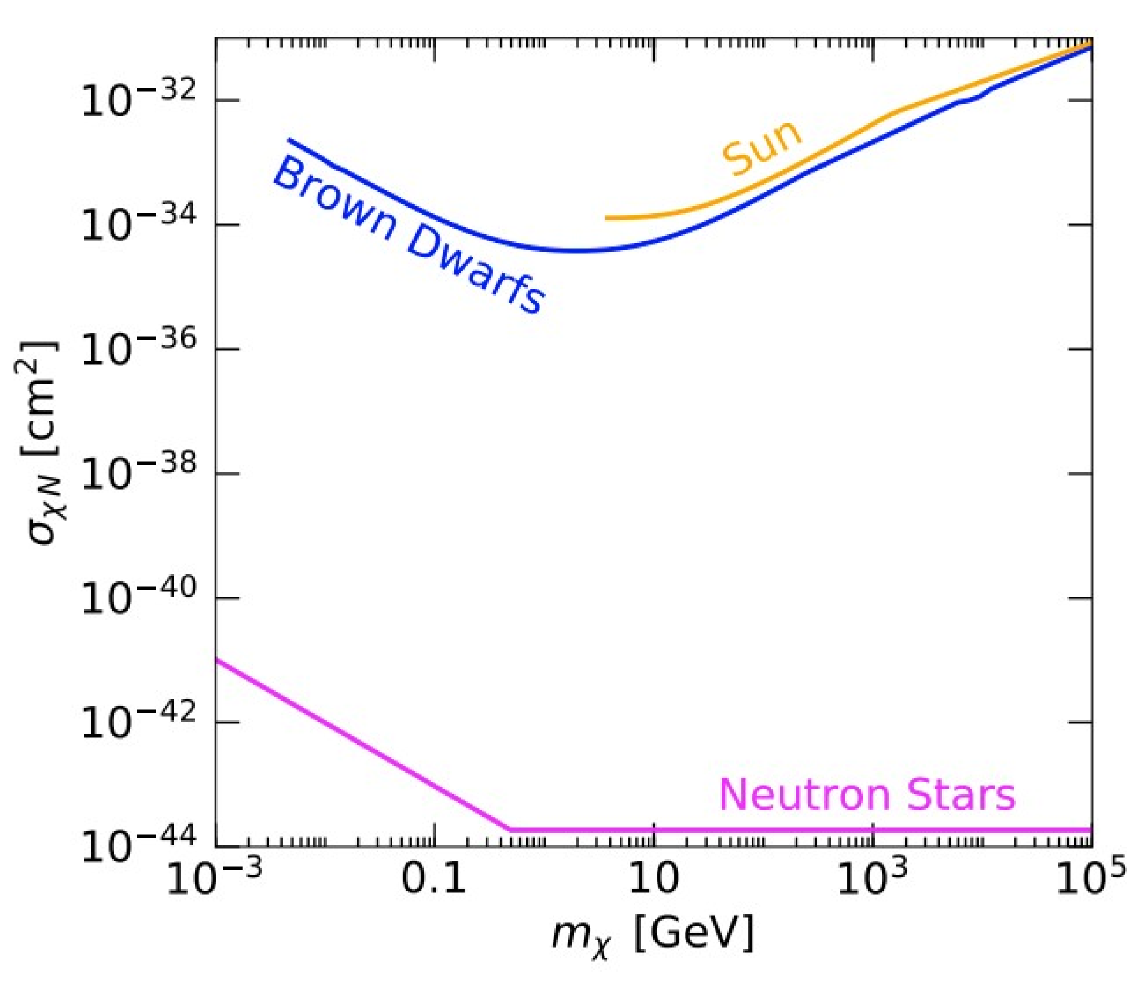
$$p(N,\tau) = \frac{2}{\tau^2}\left(N_s + 1 - \frac{\Gamma(N_s+2,\tau)}{N_s!}\right)$$

$$\tau = \frac{3}{2}\frac{\sigma}{\sigma_{\rm sat}}$$

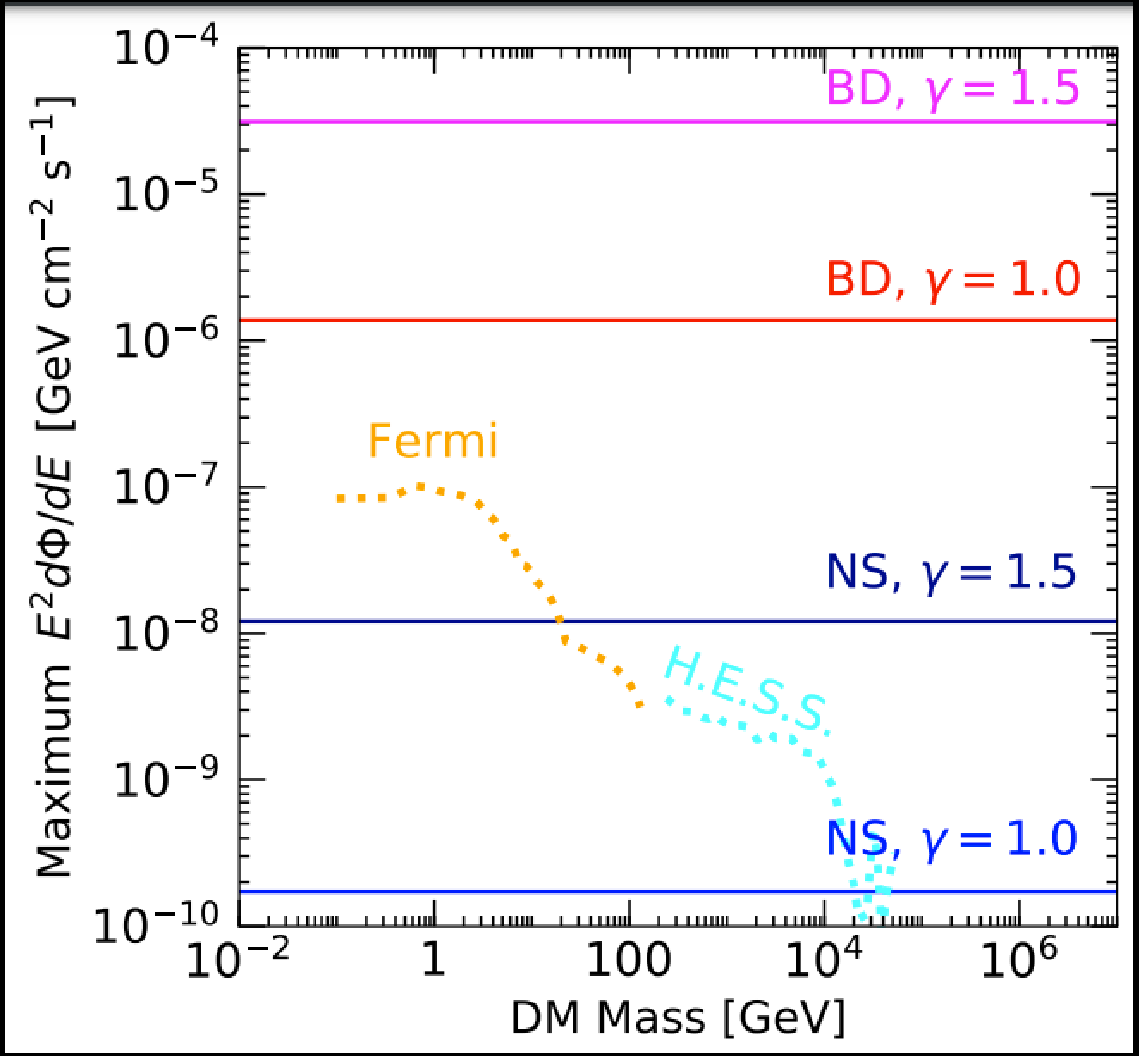
$$\sigma_{\rm sat} = \pi R^2 / N_{\rm SM}$$

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

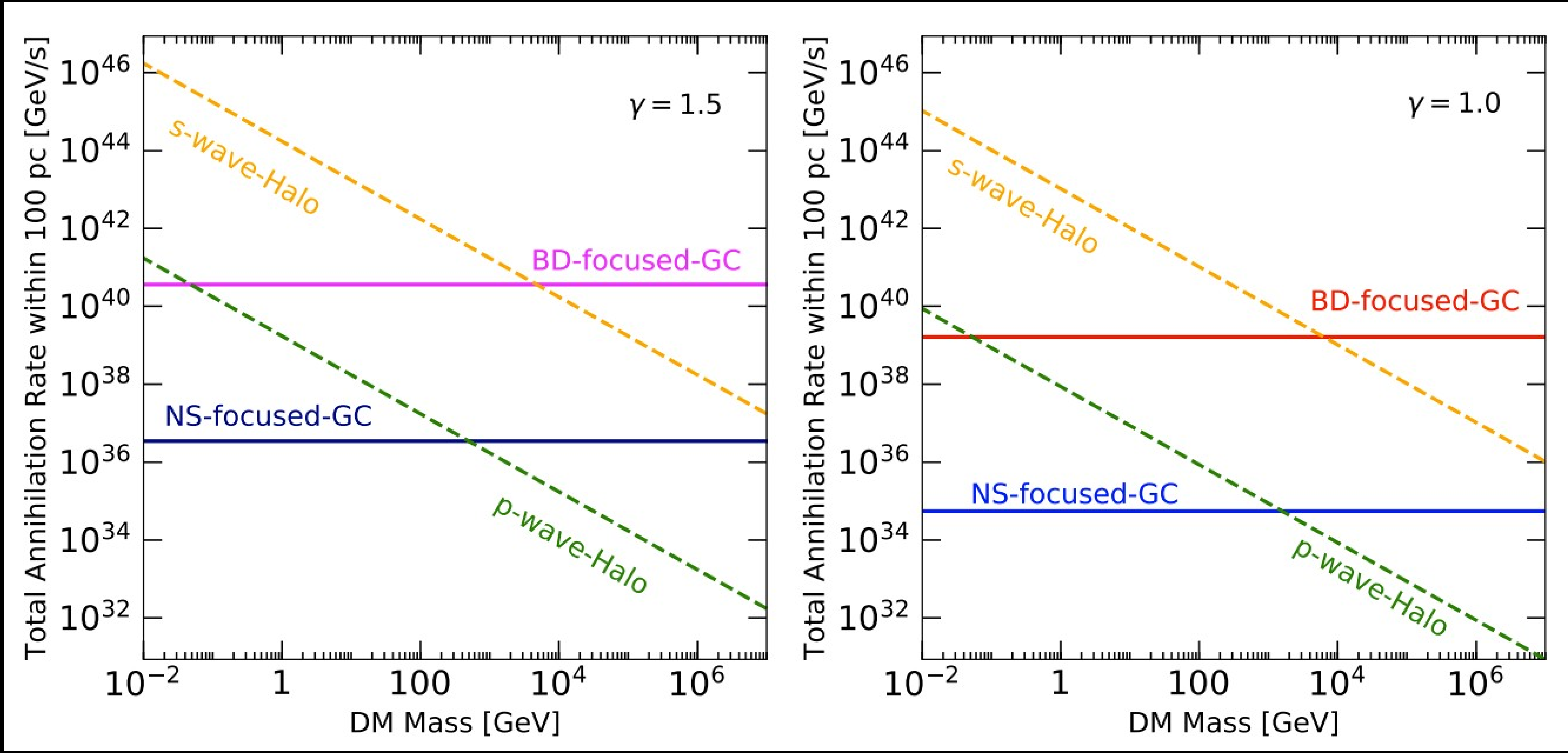
$$\sigma_{\chi A}^{\rm SI} = \sigma_{\chi N}^{\rm SI}\left(\frac{\mu(m_A)}{\mu(m_N)}\right)^2\left[Z + \frac{a_n}{a_p}(A - Z)\right]^2$$



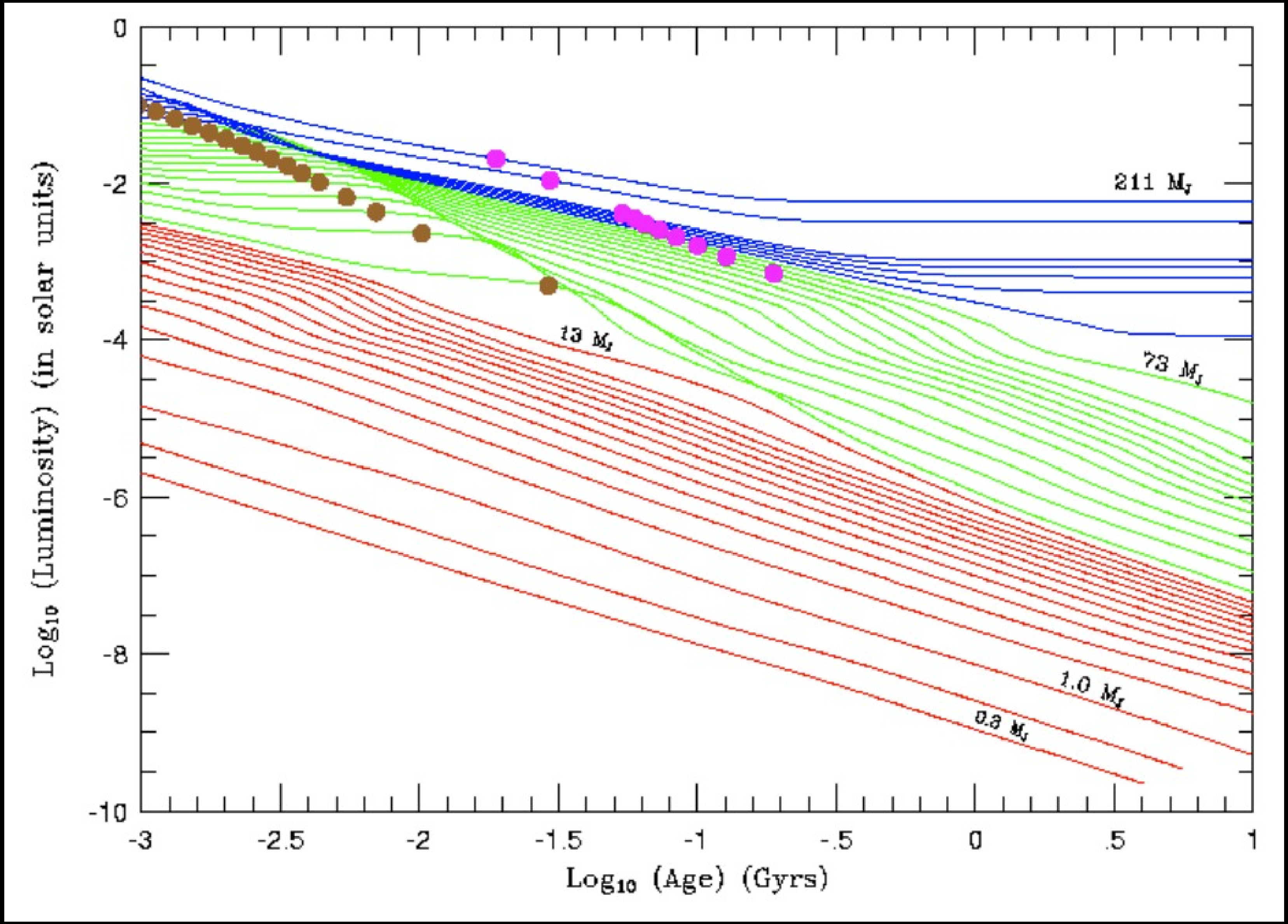
Sun
Brown Dwarfs
Neutron Stars
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
$\sigma_{\chi N}$ [cm^2]
10^{-3}
0.1
10
10^3
10^5
m_χ [GeV]



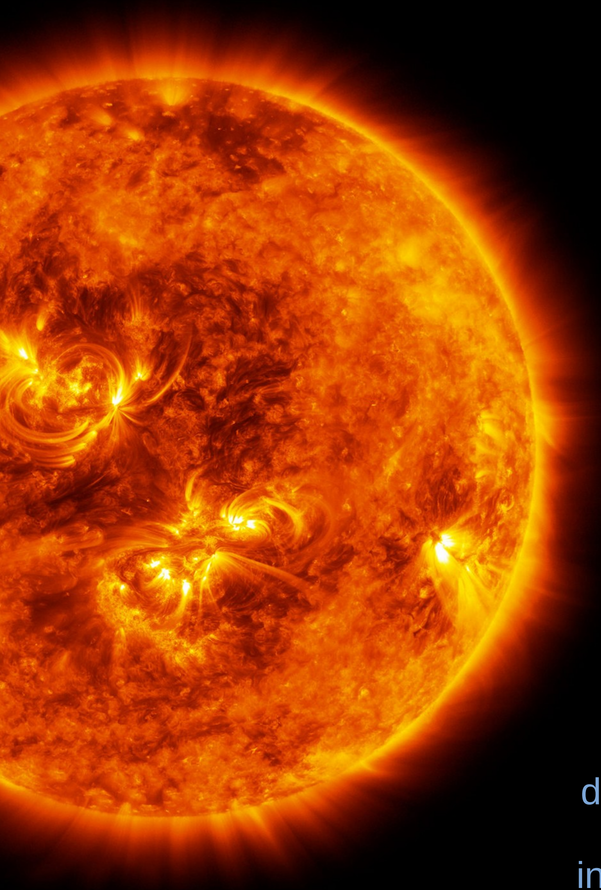
BD, $\gamma = 1.5$
BD, $\gamma = 1.0$
Fermi
NS, $\gamma = 1.5$
H.E.S.S.
NS, $\gamma = 1.0$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Maximum $E^2 d\Phi/dE$ [GeV cm^{-2} s^{-1}]
10^{-2}
1
100
10^4
10^6
DM Mass [GeV]


Total Annihilation Rate within 100 pc [GeV/s]
10^{46}
10^{44}
10^{42}
10^{40}
10^{38}
10^{36}
10^{34}
10^{32}
$\gamma = 1.5$
s-wave-Halo
BD-focused-GC
NS-focused-GC
p-wave-Halo
10^{-2}
1
100
10^{4}
10^{6}
DM Mass [GeV]
Total Annihilation Rate within 100 pc [GeV/s]
$\gamma = 1.0$
s-wave-Halo
BD-focused-GC
NS-focused-GC
p-wave-Halo
DM Mass [GeV]

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

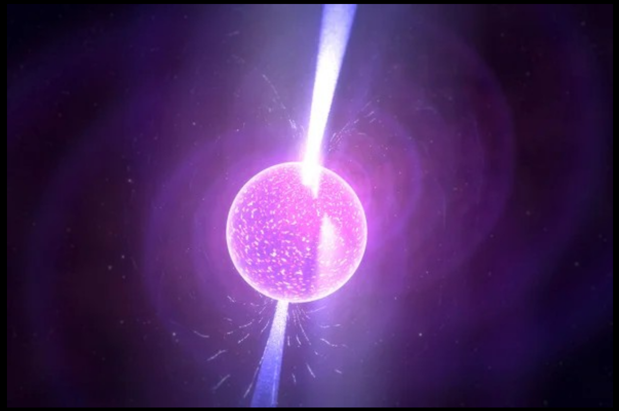
Impact on magnetic fields? Volcanoes?

Jupiter

DM heat anomaly?

Uranus

DM limits from temperature

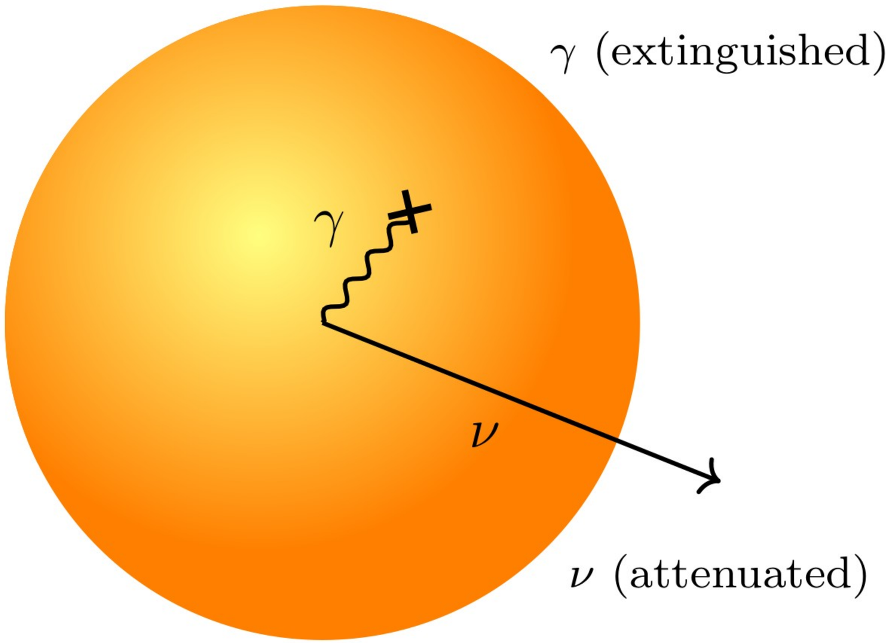


Neutron Stars

DM heating, infrared telescopes

White Dwarfs

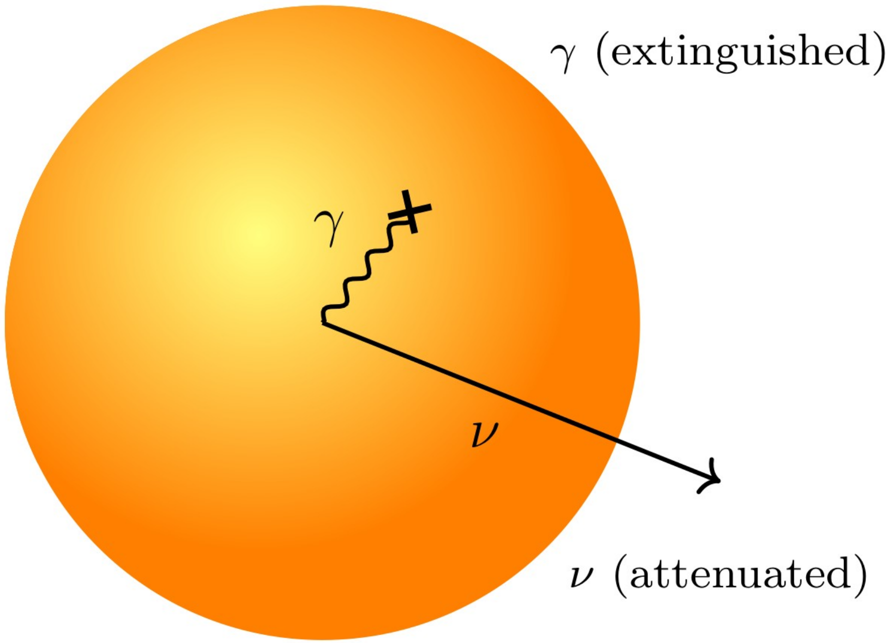
DARK MATTER IN THE SUN



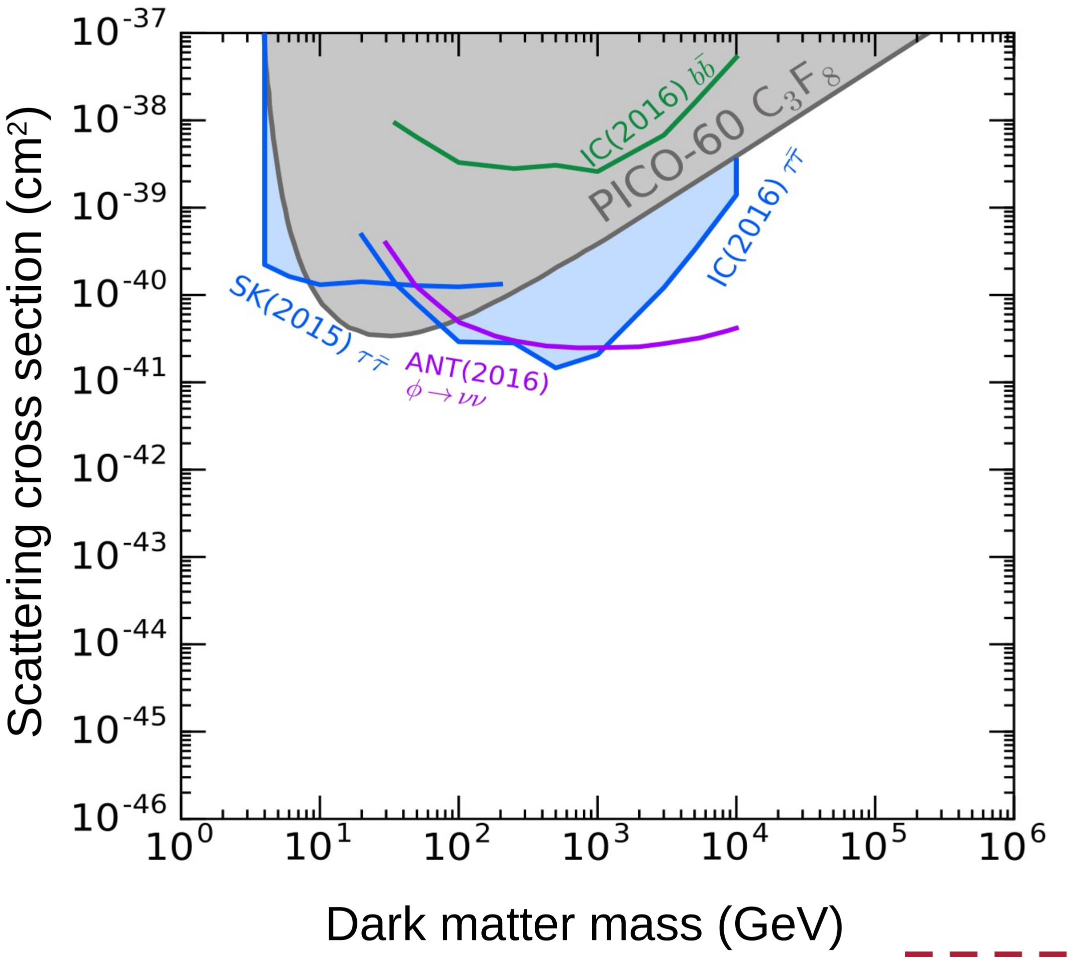
Evolution of dark matter number density

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

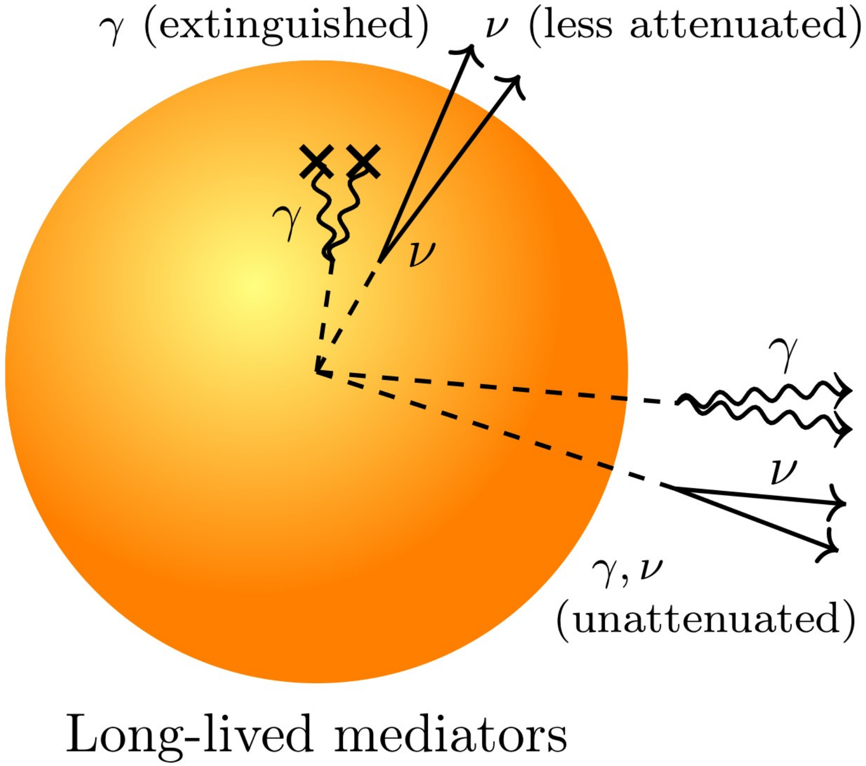
DARK MATTER IN THE SUN



Limits from neutrinos, standard scenario

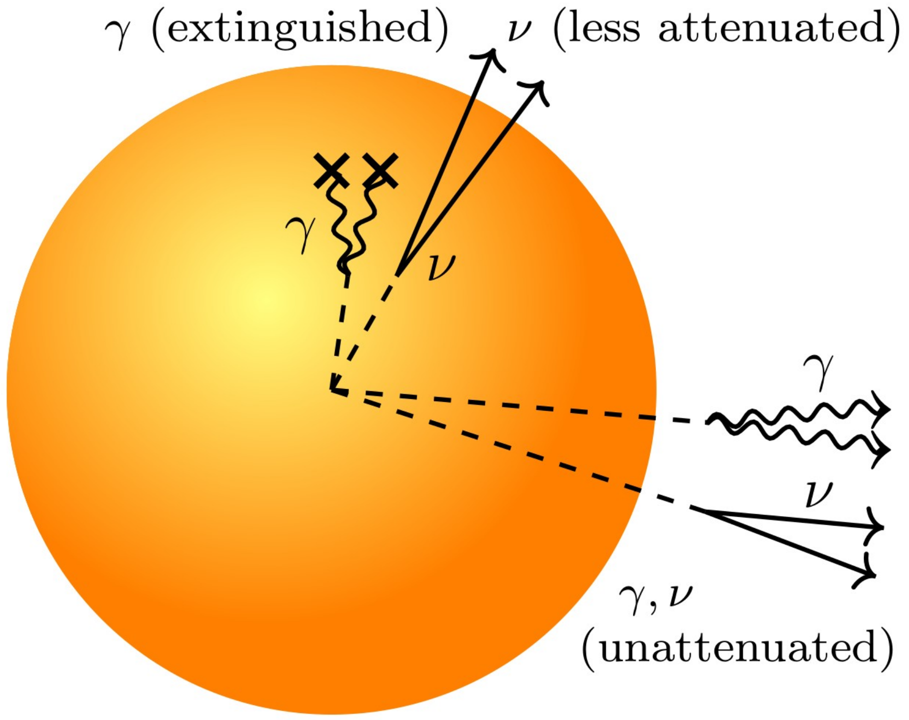


LONG-LIVED SIGNAL BOOST:



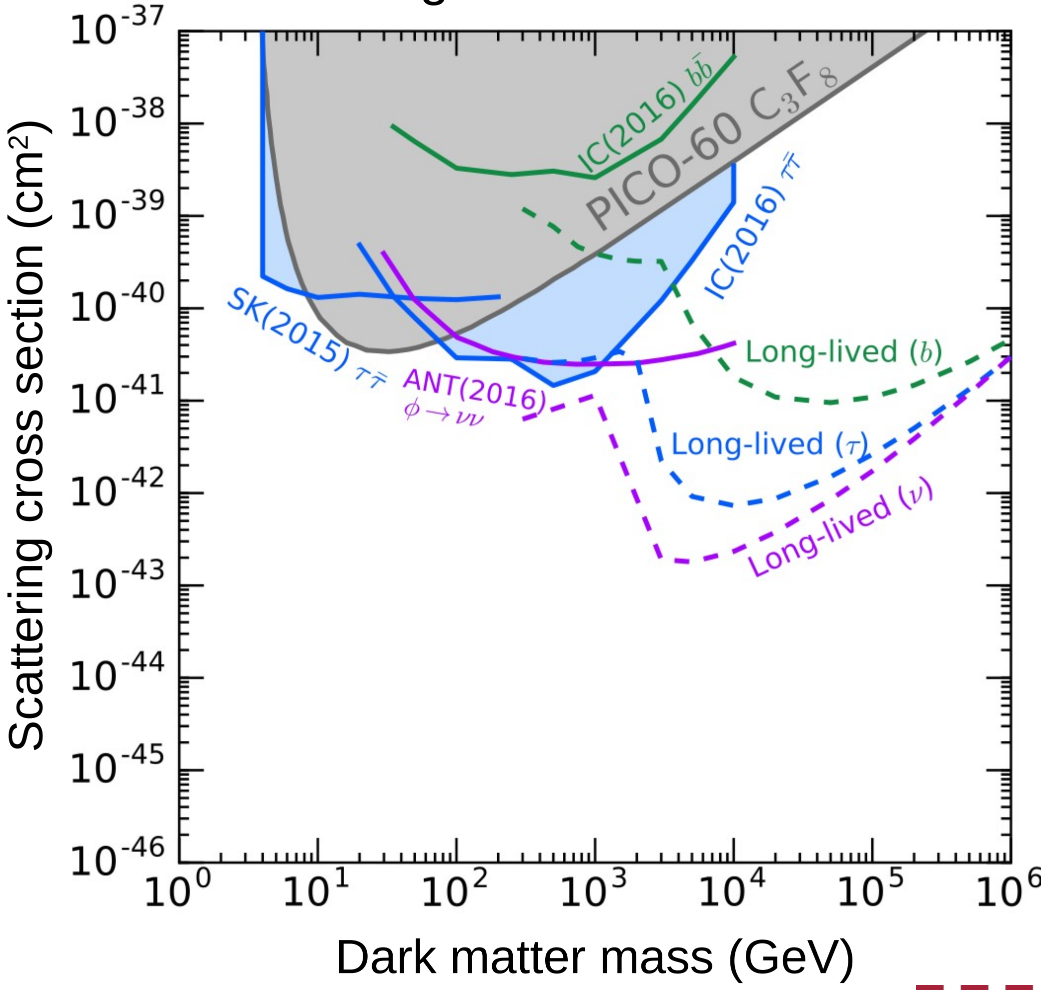
Schuster, Toro, Yavin (PRD ‘10)
Batell, Pospelov, Ritz, Shang (PRD ‘10)
Meade, Nussinov, Papucci, Volansky (JHEP ‘10)

LONG-LIVED SIGNAL BOOST: NEUTRINOS



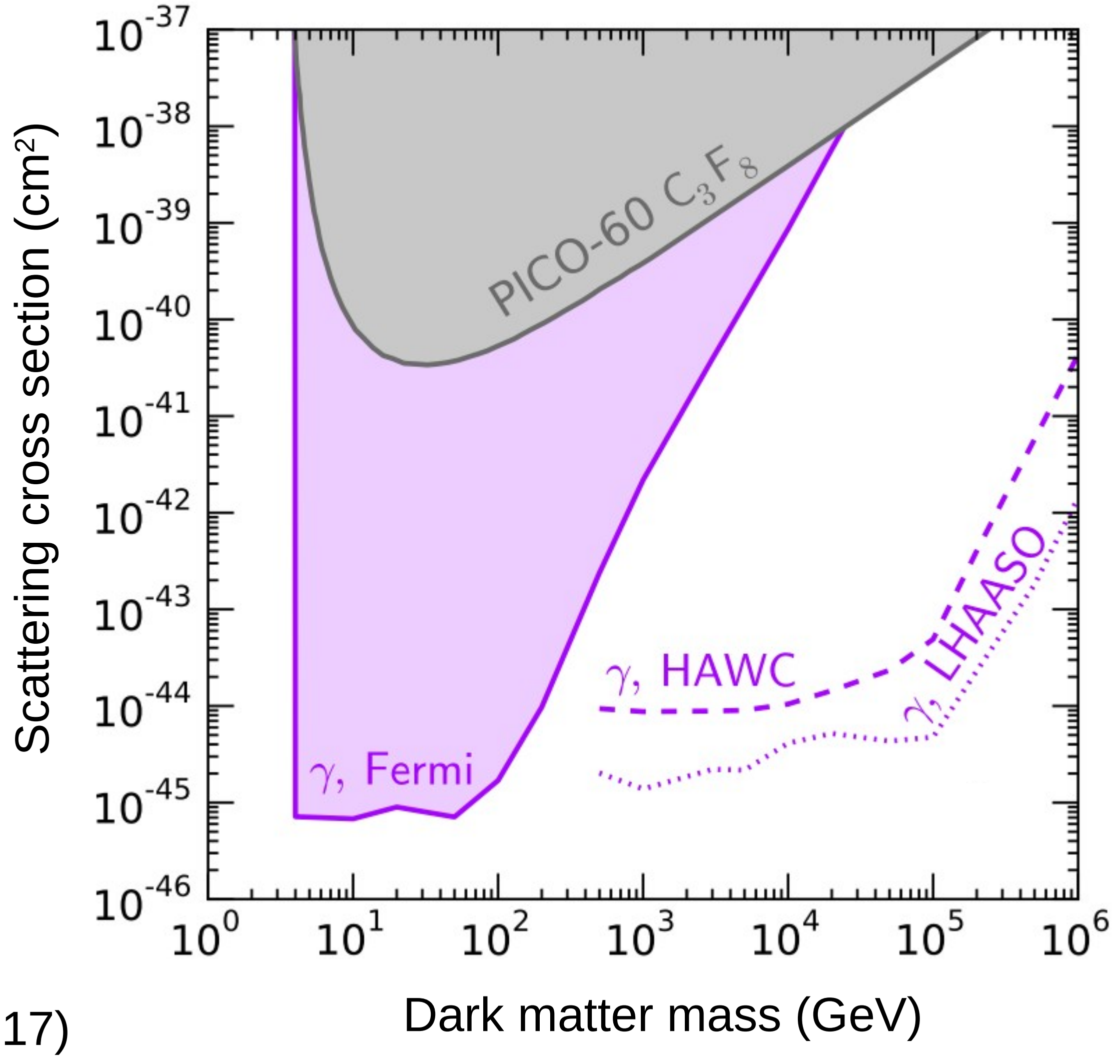
Long-lived mediators

Long-lived mediators



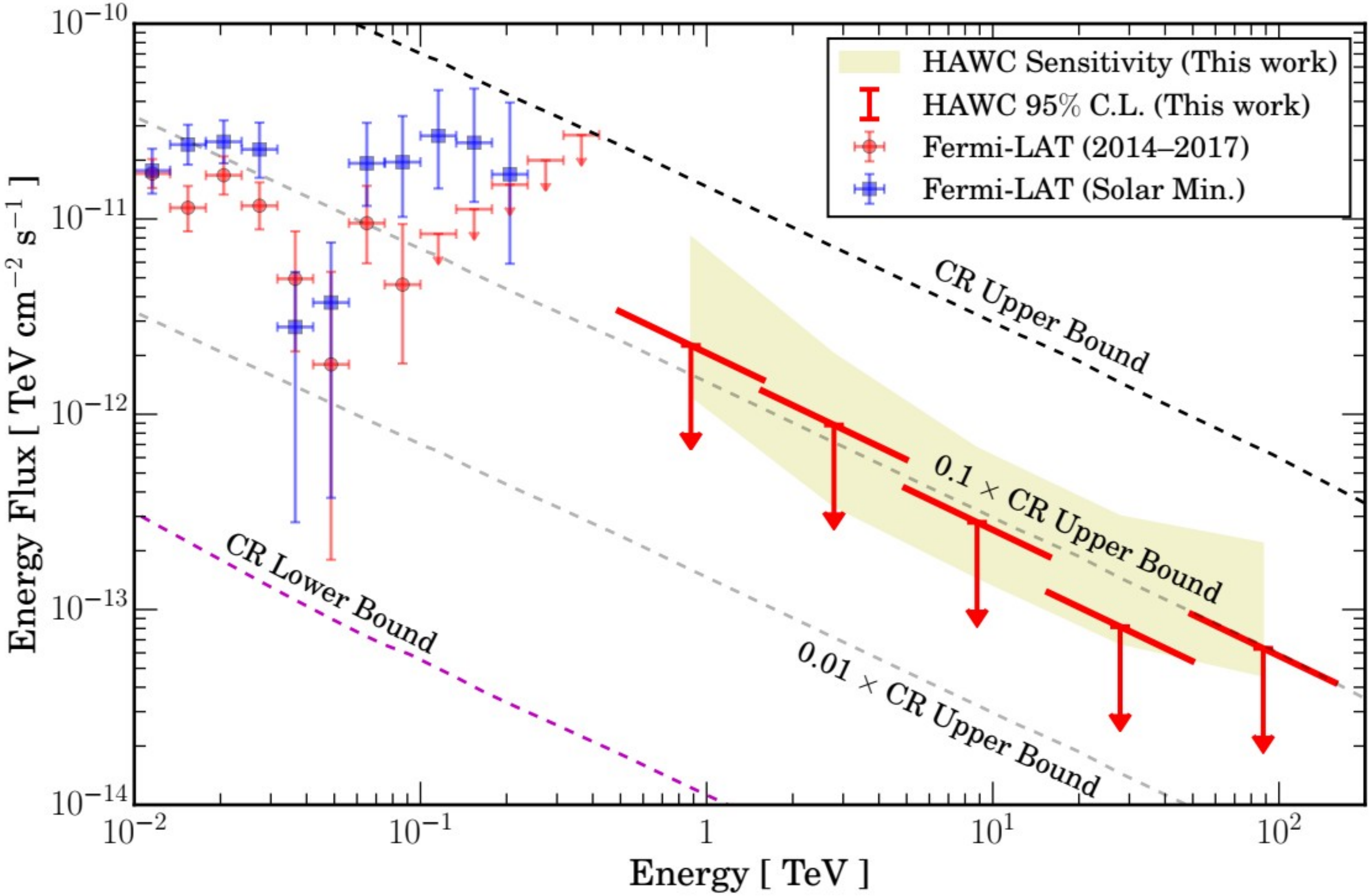
RL, Ng, Beacom (PRD '17)

LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)

NEW LIMITS WITH HAWC



HAWC Collaboration + **RL** (PRD ‘18)

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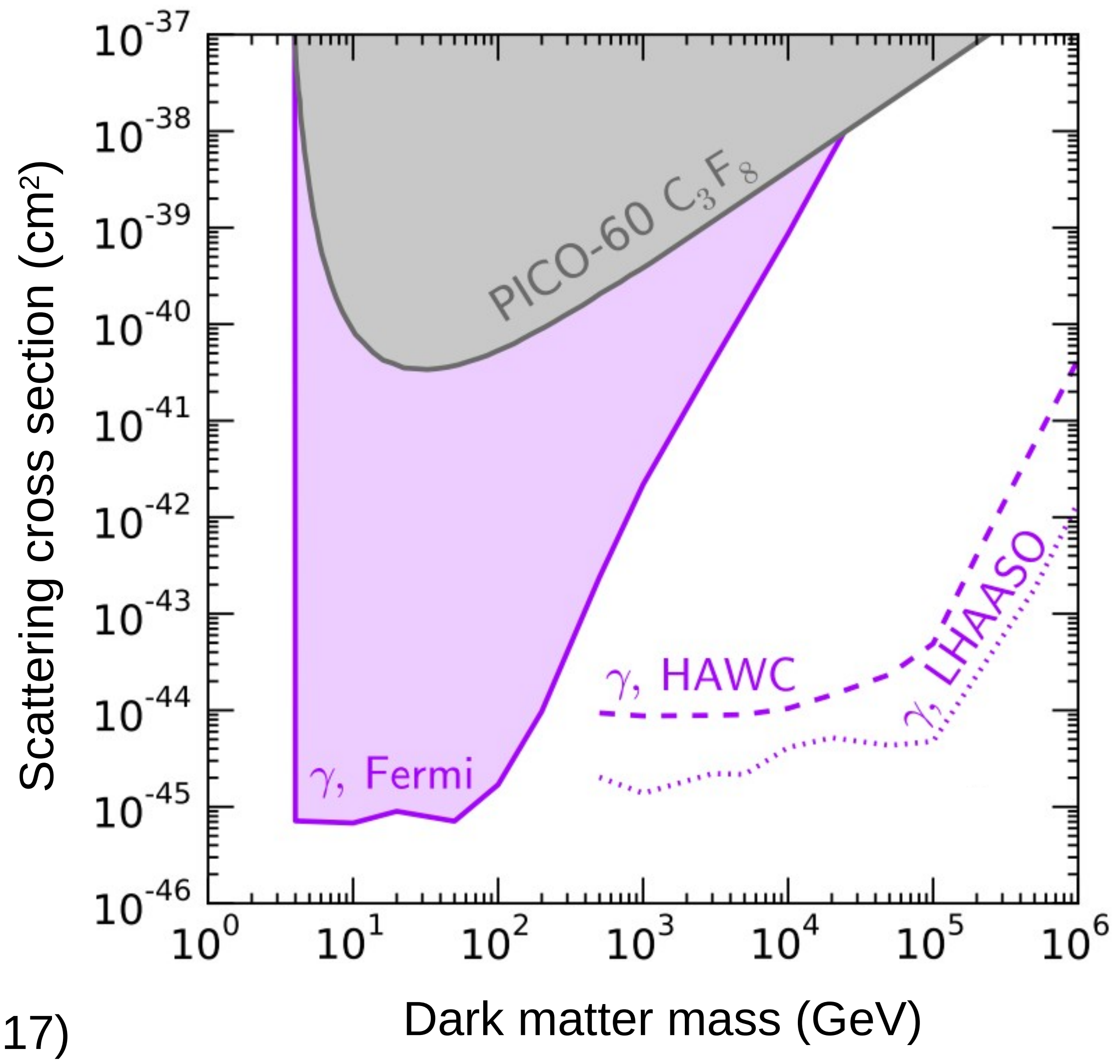
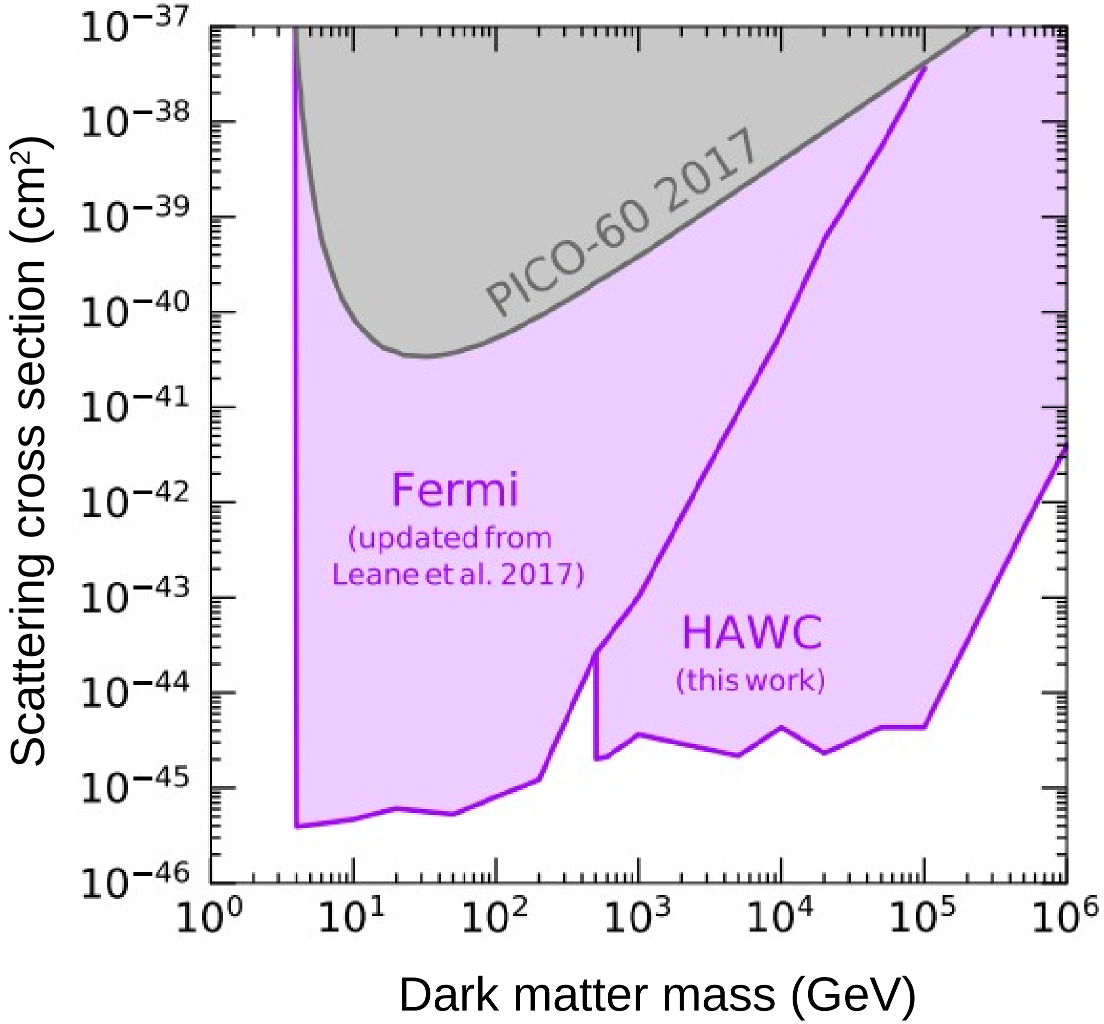
LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)

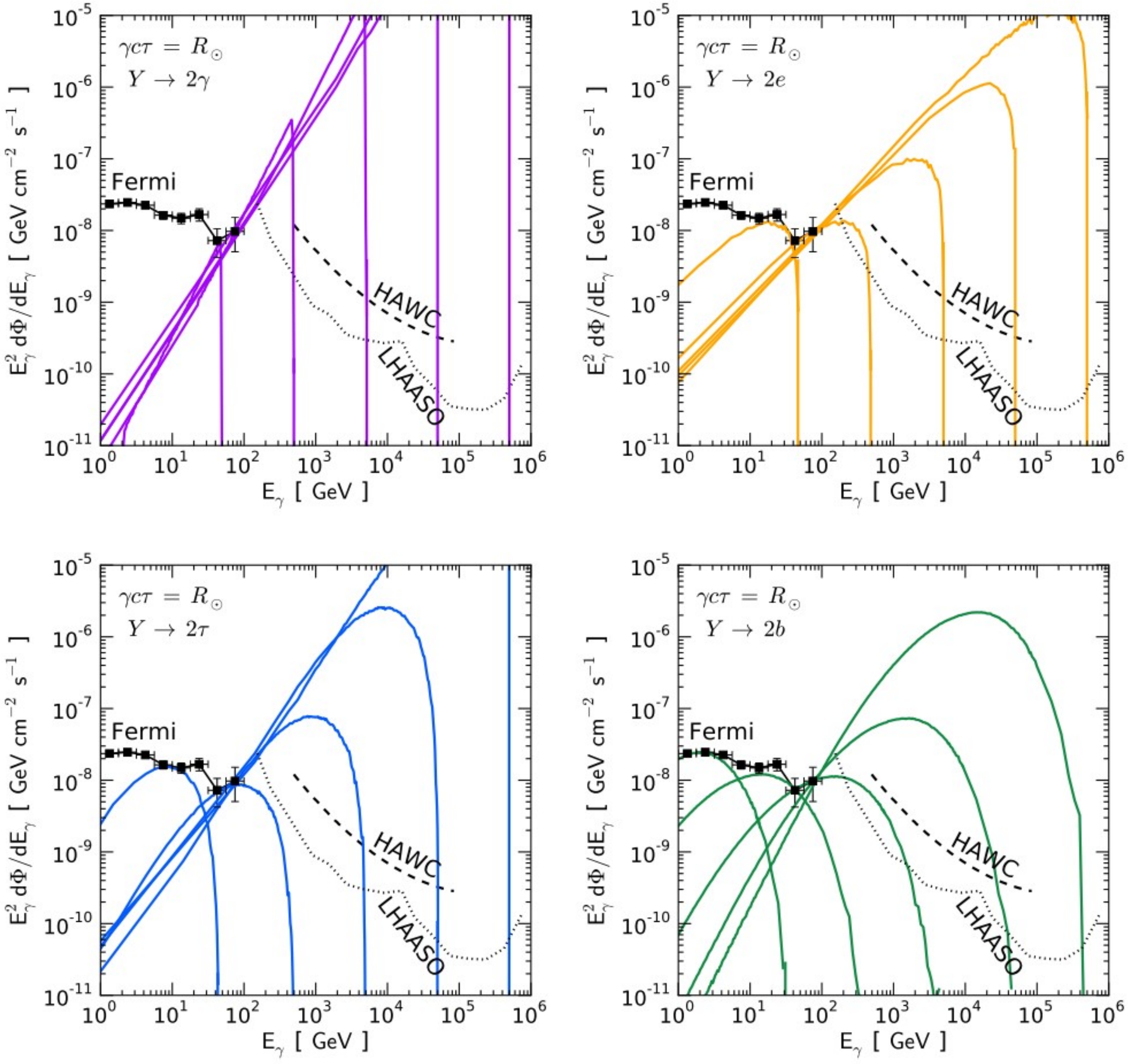
NEW LIMITS WITH FERMI AND HAWC



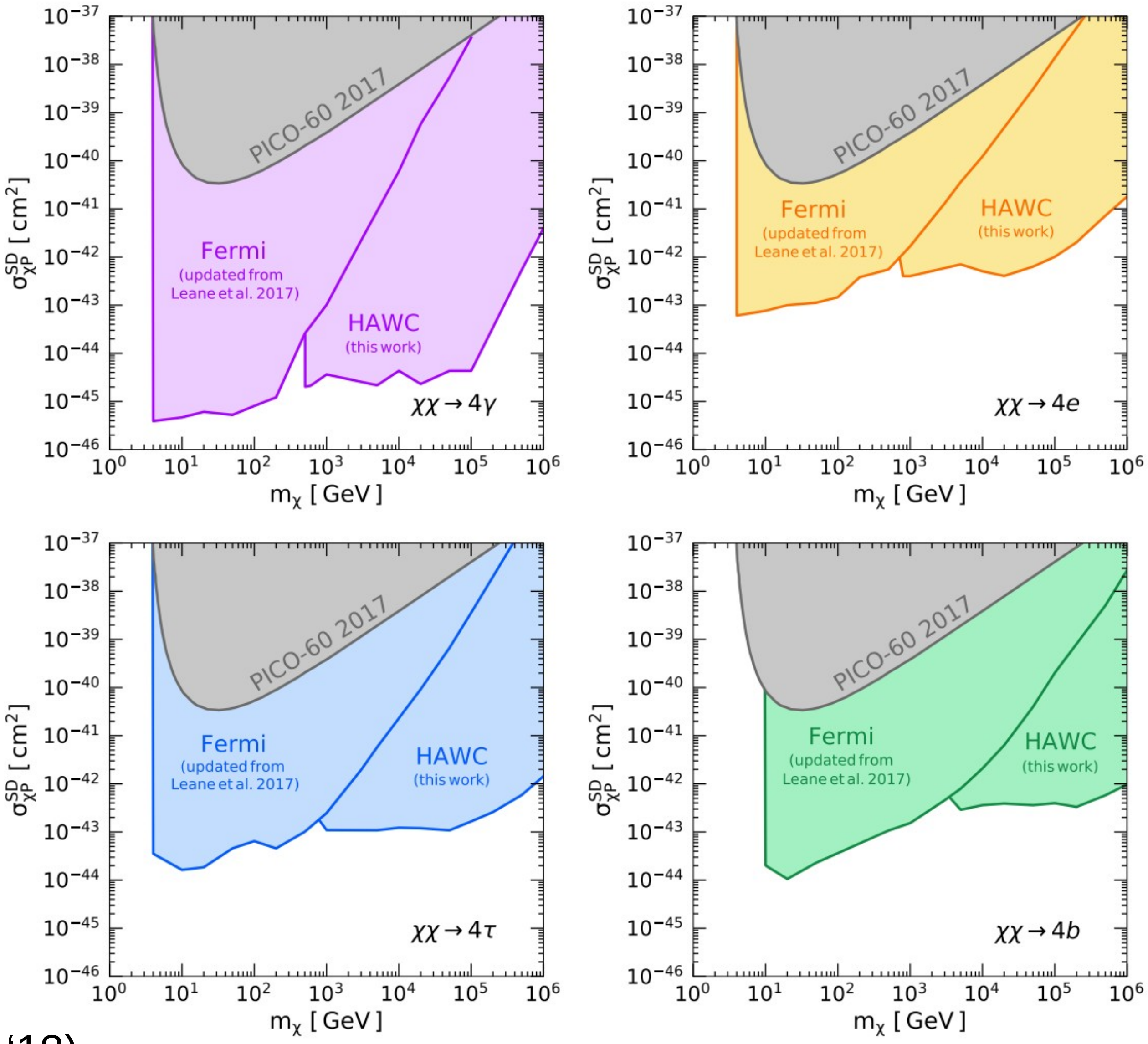
HAWC Collaboration + **RL** (PRD '18)

SOLAR DARK MATTER LIMITS

RL, Ng, Beacom (PRD ‘17)

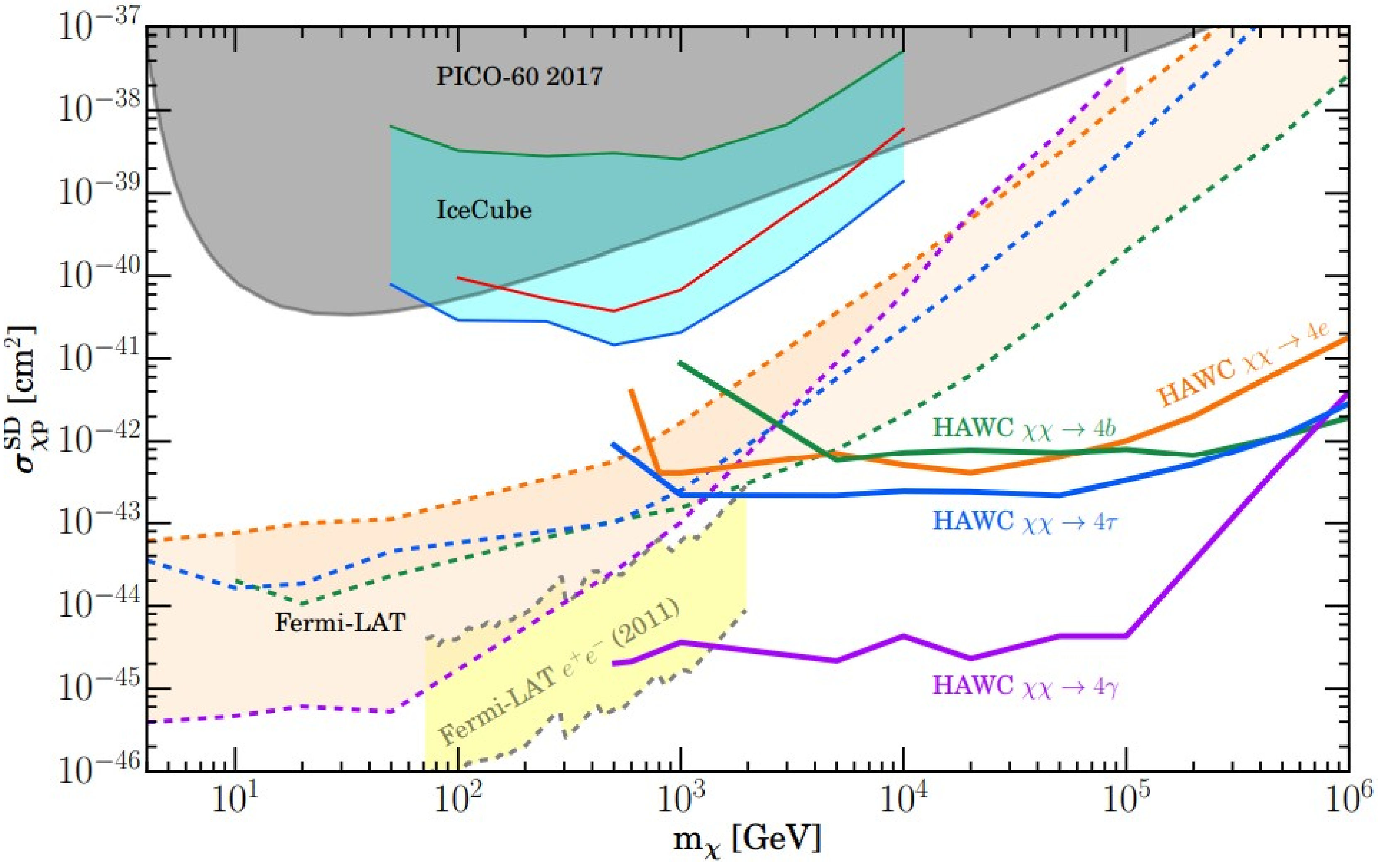


SOLAR DARK MATTER LIMITS: UPDATED



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

SOLAR DARK MATTER LIMITS: ALL



HAWC Collaboration + **RL** (PRD in press ‘18)