


# EXOPLANETS AS SUB-GEV DM DETECTORS

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BASED ON 2010.00015 w/ JURI SMIRNOV  
+WORK TO APPEAR w/ T. LINDEN, P. MUKHOPADHYAY, N. TORO



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

# Outline

- Why Exoplanets?
- New Search for Dark Matter in 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

# DARK MATTER CAPTURE IN EXOPLANETS

**Dark  
Matter**



Rebecca Leane (SLAC)



# DARK MATTER CAPTURE IN EXOPLANETS

Dark  
Matter

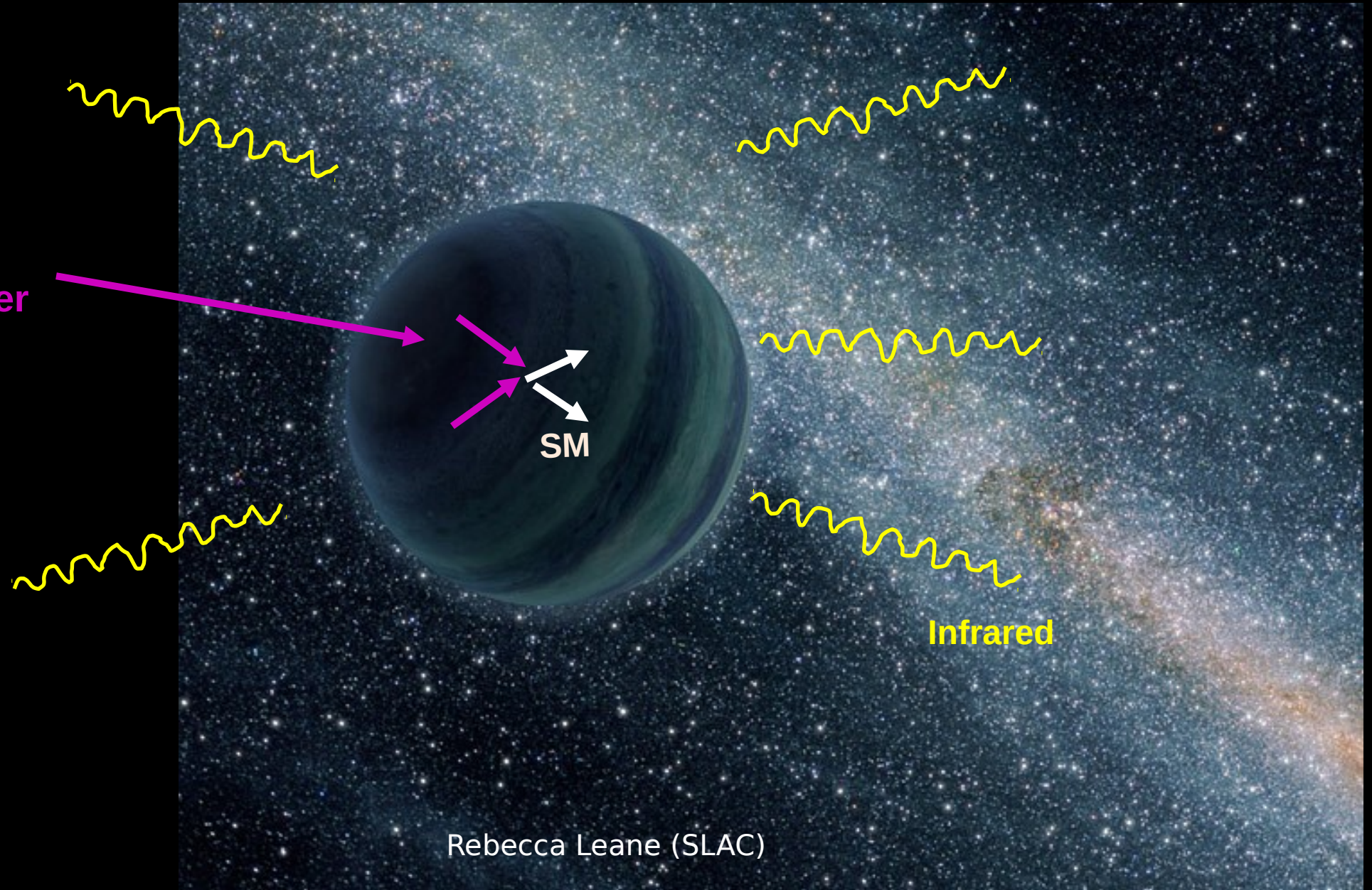


Rebecca Leane (SLAC)



# DARK MATTER CAPTURE IN EXOPLANETS

Dark  
Matter



Infrared

Rebecca Leane (SLAC)



# *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

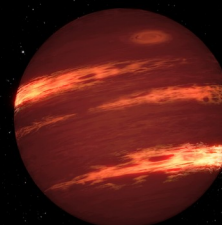
5,633 exoplanet candidates



$\times 10^{11}$



$\times 10^{11}$



$\times 10^{11}$



$\times 1$

One Jupiter :(

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
- + Easy to find



# Exoplanet Search Targets



Not ideal

## Earths + Super Earths:

Mass: 0.001– 0.01  $M_{\text{jup}}$

Radius:  $\sim 0.1 - 1 R_{\text{jup}}$



ideal

## Jupiters + Super Jupiters:

Mass: 1 – 13  $M_{\text{jup}}$

Radius:  $\sim 1 R_{\text{jup}}$



ideal

## Brown dwarfs:

Mass: 13 – 75  $M_{\text{jup}}$

Radius:  $\sim 1 R_{\text{jup}}$

Very dense!



ideal

## 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:

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

- 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

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

## 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

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

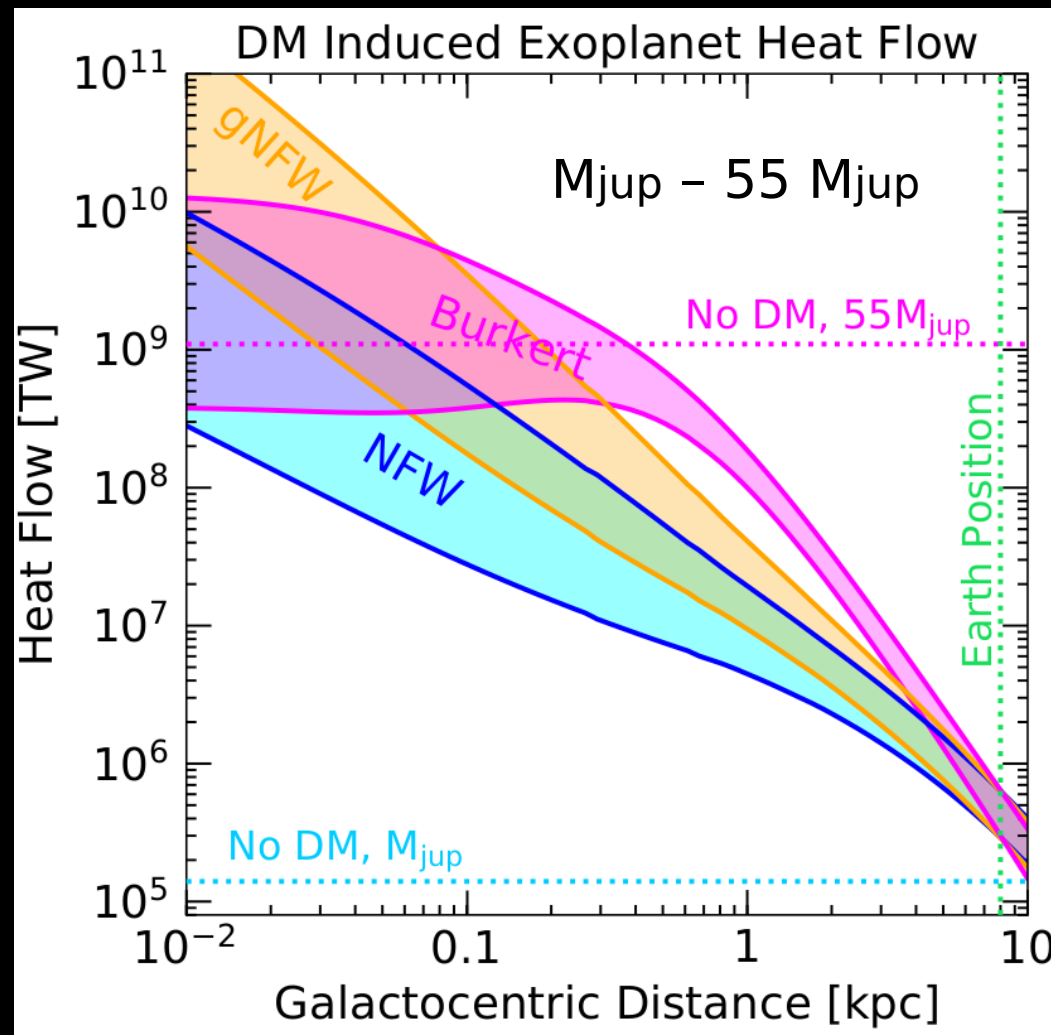
$$v_{\text{esc}}^2 = 2G_N M/R$$

# DM Heating vs Internal Heat

RKL + Smirnov, 2020

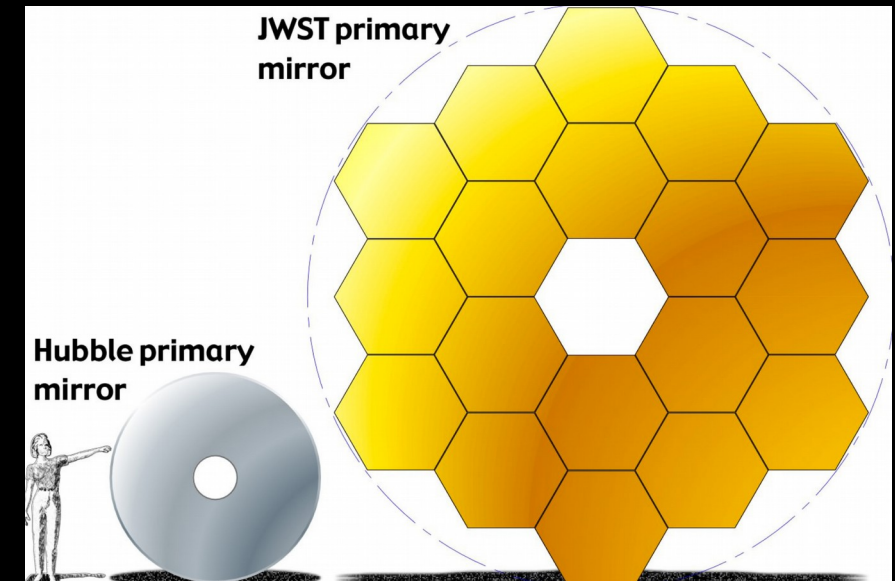
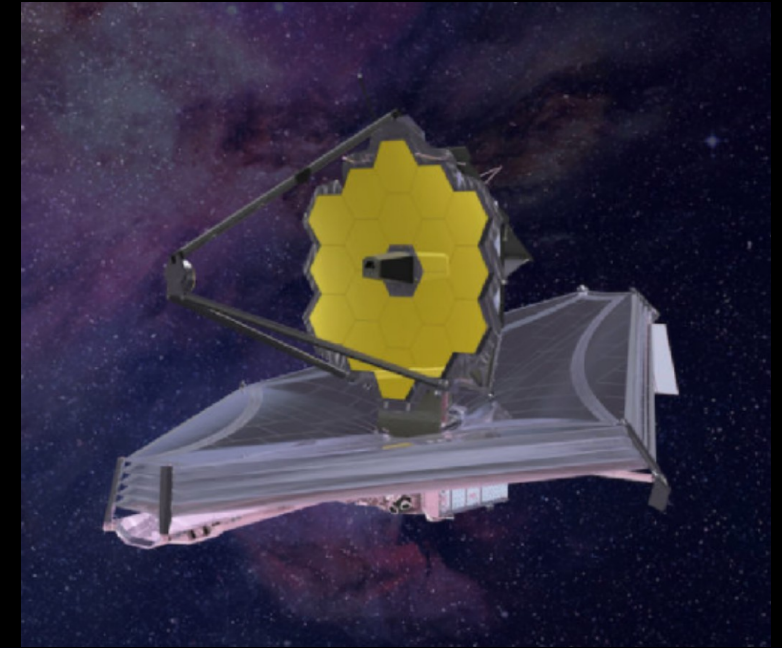
$$\Gamma_{\text{heat}}^{\text{tot}} = \Gamma_{\text{heat}}^{\text{ext}} + \Gamma_{\text{heat}}^{\text{int}} + \Gamma_{\text{heat}}^{\text{DM}} = 4\pi R^2 \sigma_{\text{SB}} T^4 \epsilon$$

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



# 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

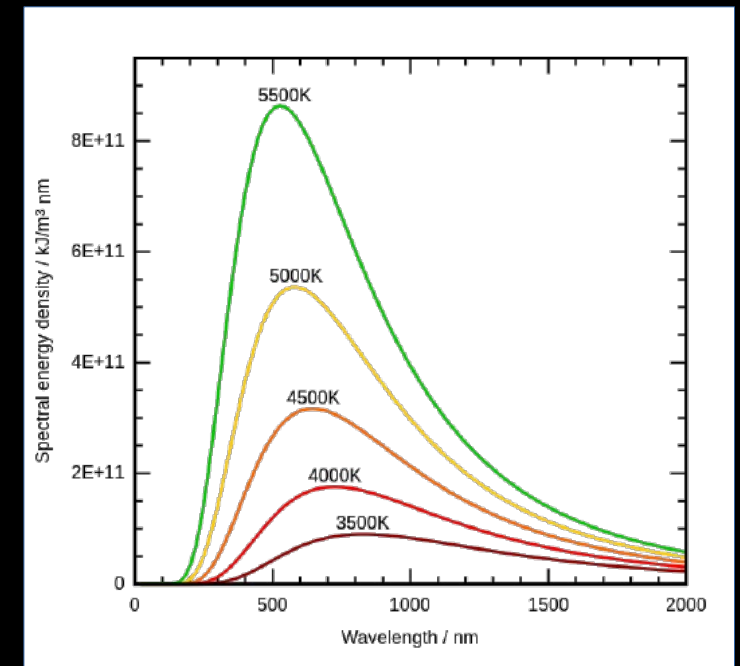
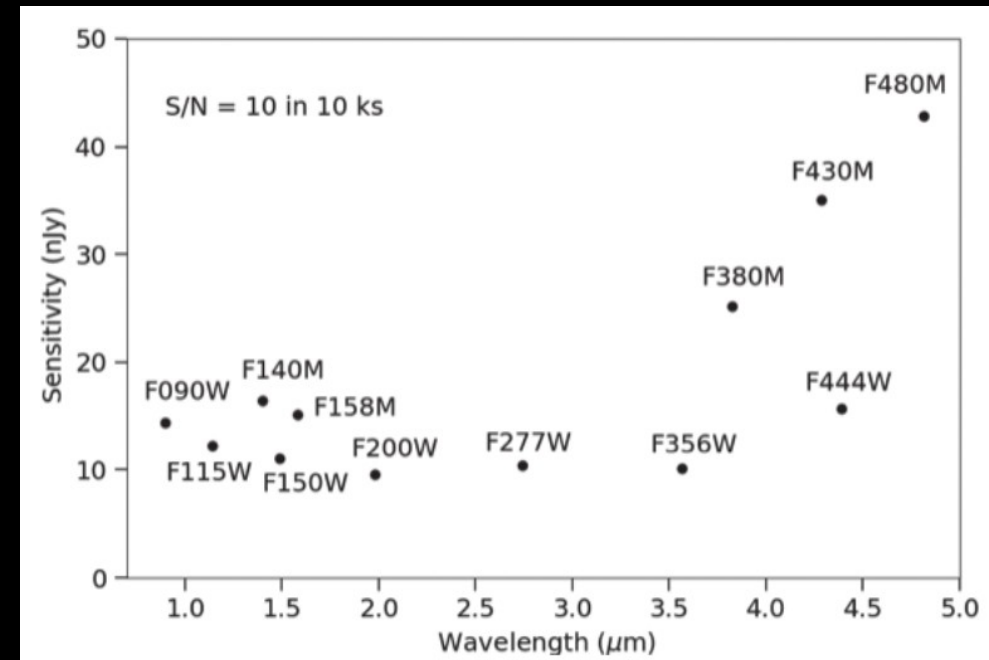




# Signal with James Webb

- 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



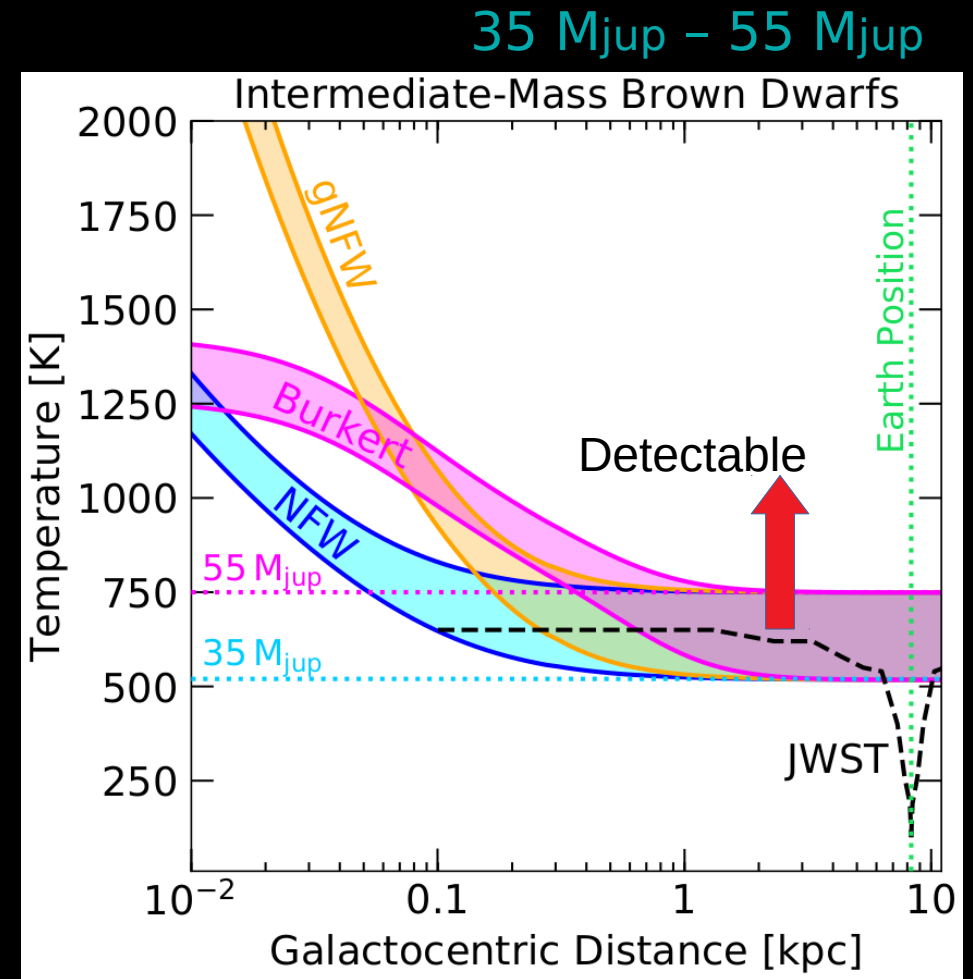
## Stellar crowding:

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

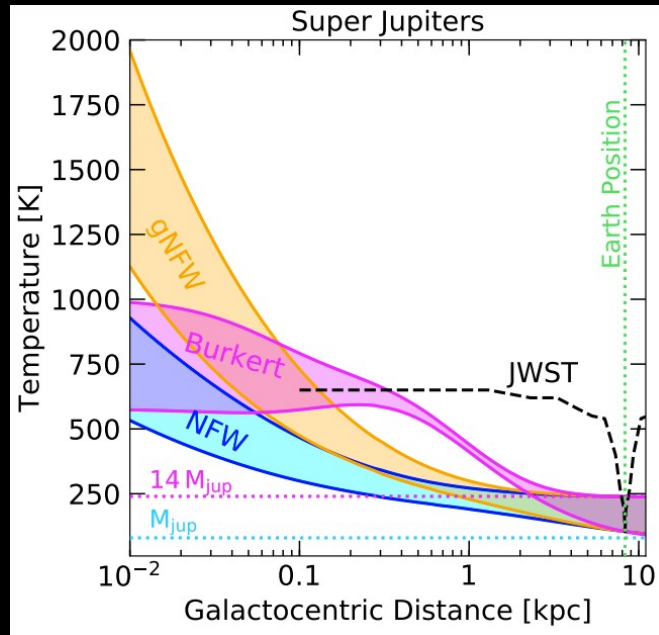


RKL + Smirnov, 2020

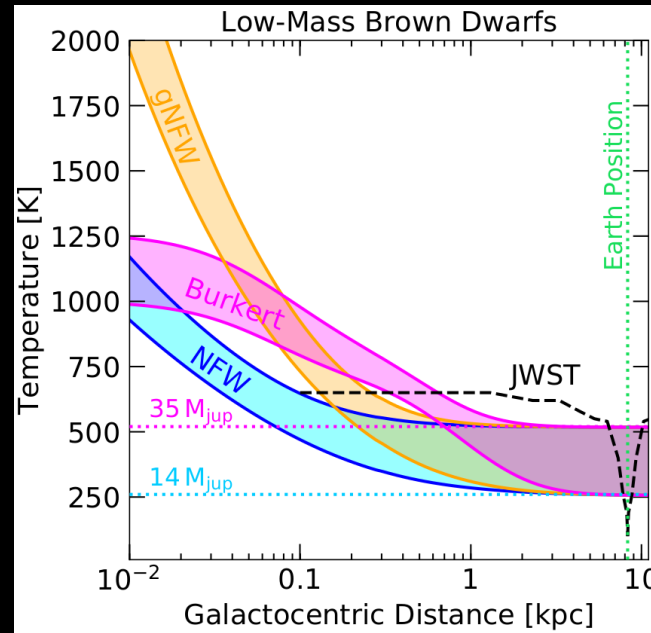


# Exoplanet masses vs sensitivity

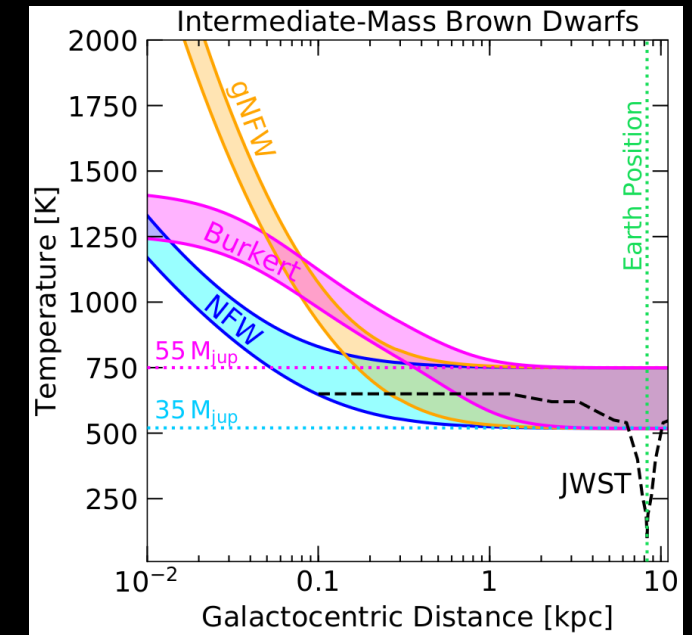
$M_{\text{jup}} - 14 M_{\text{jup}}$



$14 M_{\text{jup}} - 35 M_{\text{jup}}$



$35 M_{\text{jup}} - 55 M_{\text{jup}}$

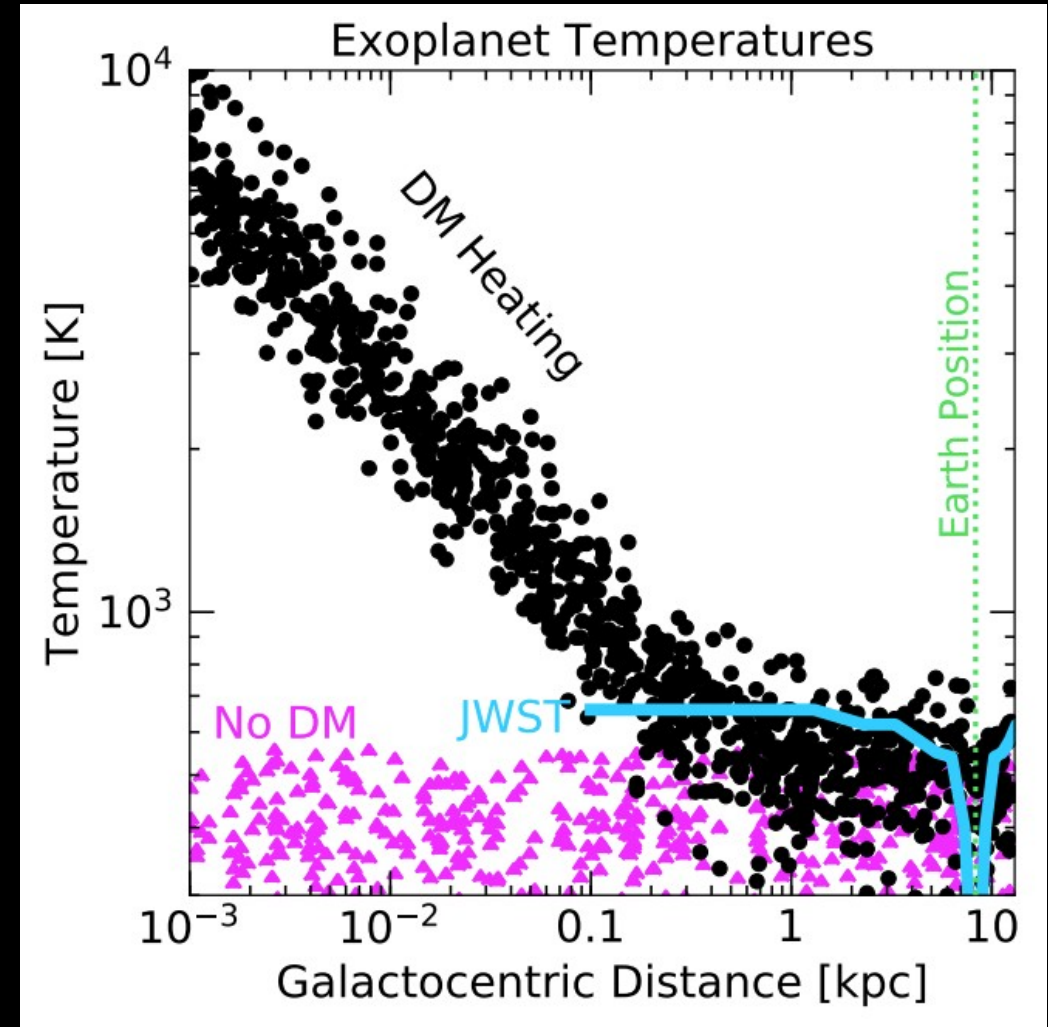


**Lower masses:**  
DM heat > internal  
heat at all positions

**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



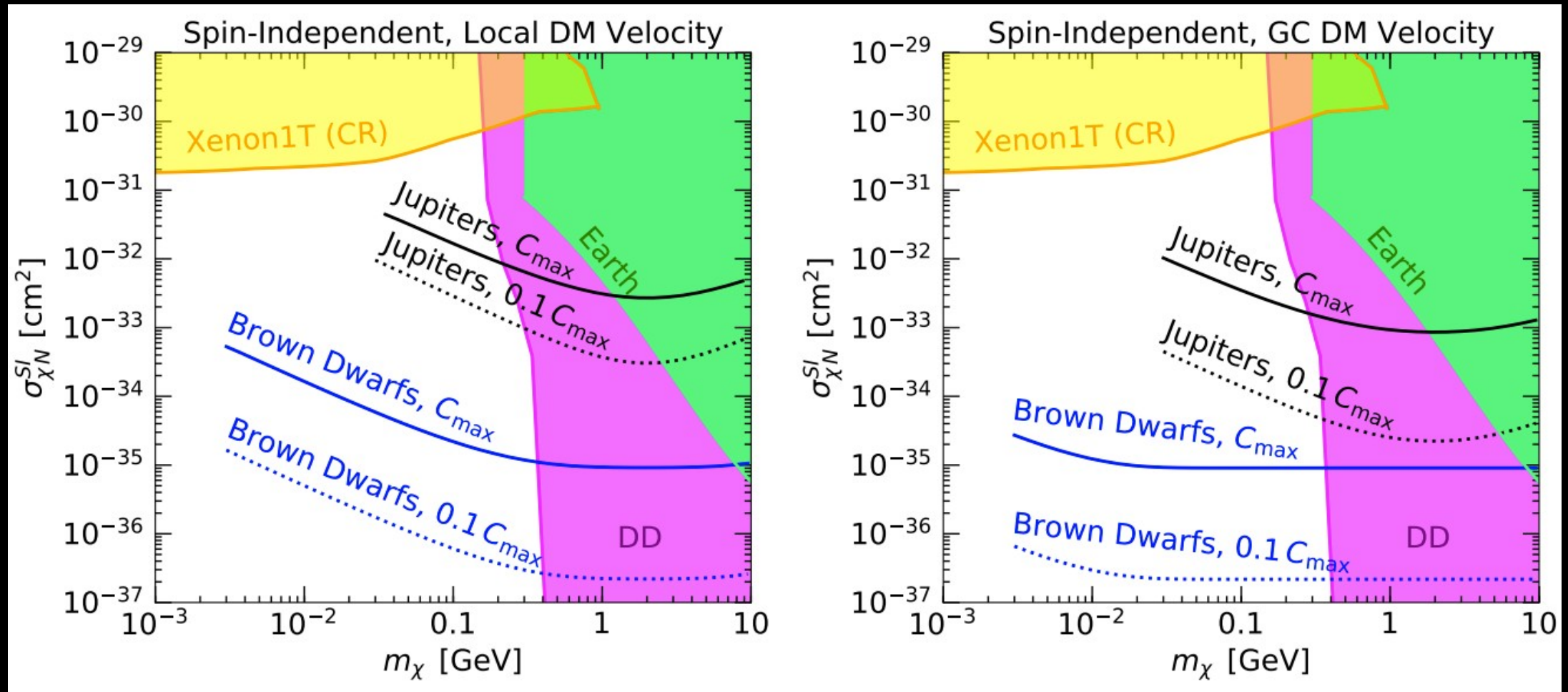
RKL + Smirnov, 2020

# Prospects for these searches?

Planet	Radius ( $R_{\text{jup}}$ )	Mass ( $M_{\text{jup}}$ )	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 <sup>1</sup> 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]
$\nu^2$ Canis Majoris c	1.24	0.87	19.9 pc	2.2 au	$\lesssim 200$ K	$\lesssim 650$ K	[97]
Psi <sup>1</sup> 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]
Barnard's Star b	1.2	1.1	49.4 pc	0.8 au	$\lesssim 200$ K	$\lesssim 650$ K	[105]

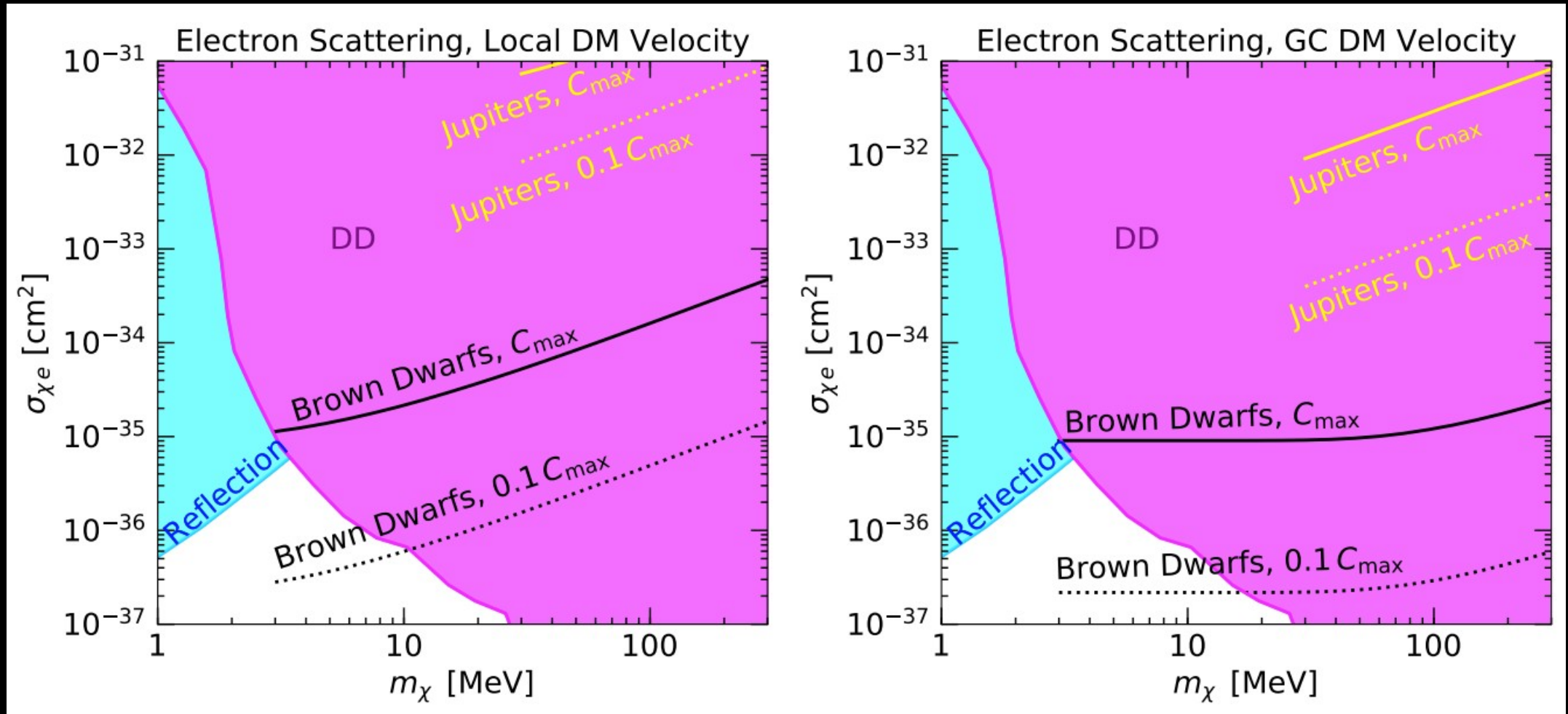
- Many candidates already exist!
- Gaia may be able to see up to around 90,000 planets within 100 pc (local search)
- WFIRST/Roman expects to detect least several thousand exoplanets in the inner galaxy

# DM scattering cross section sensitivity





# DM scattering 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\*



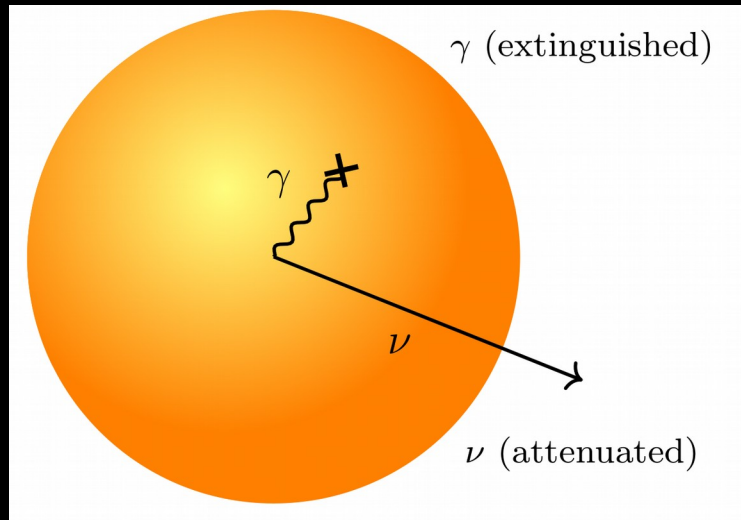
# A Complementary Search with new limits

Rebecca Leane (SLAC)

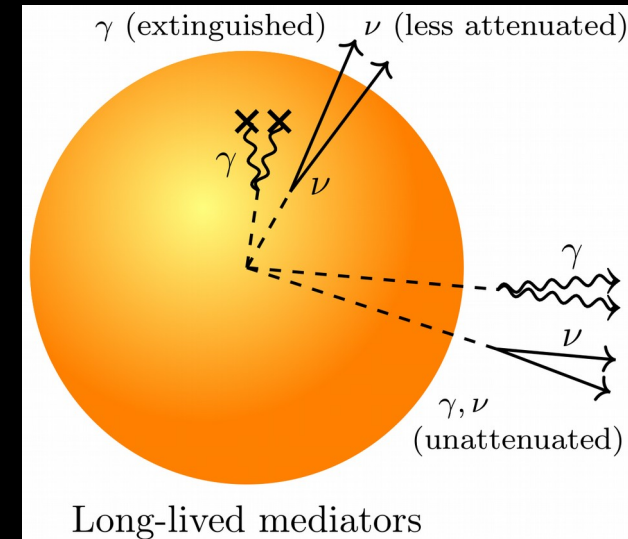
# A Complementary Search

Two regimes:

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

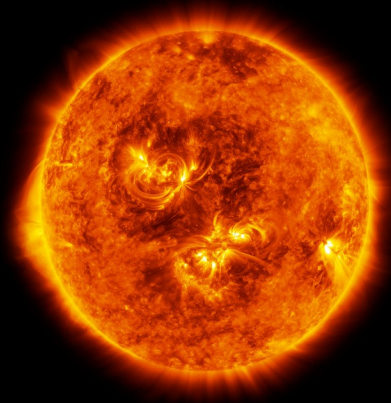


- 2. DM annihilates to **long-lived mediators**  
→ *escapes* planets!

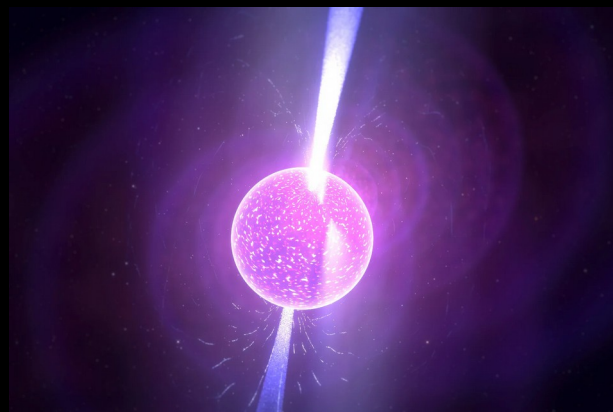




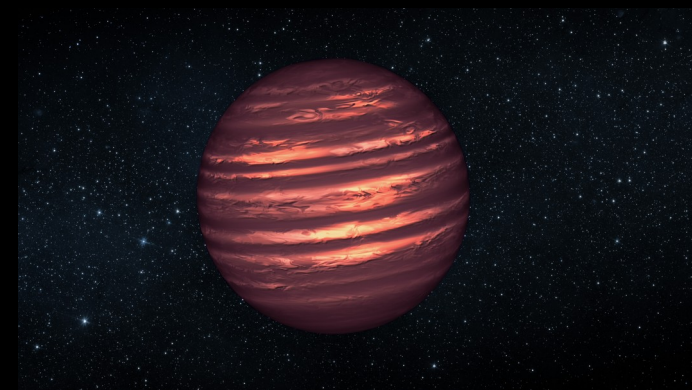
# Optimal Celestial Target?



Sun  
BIG + Hot

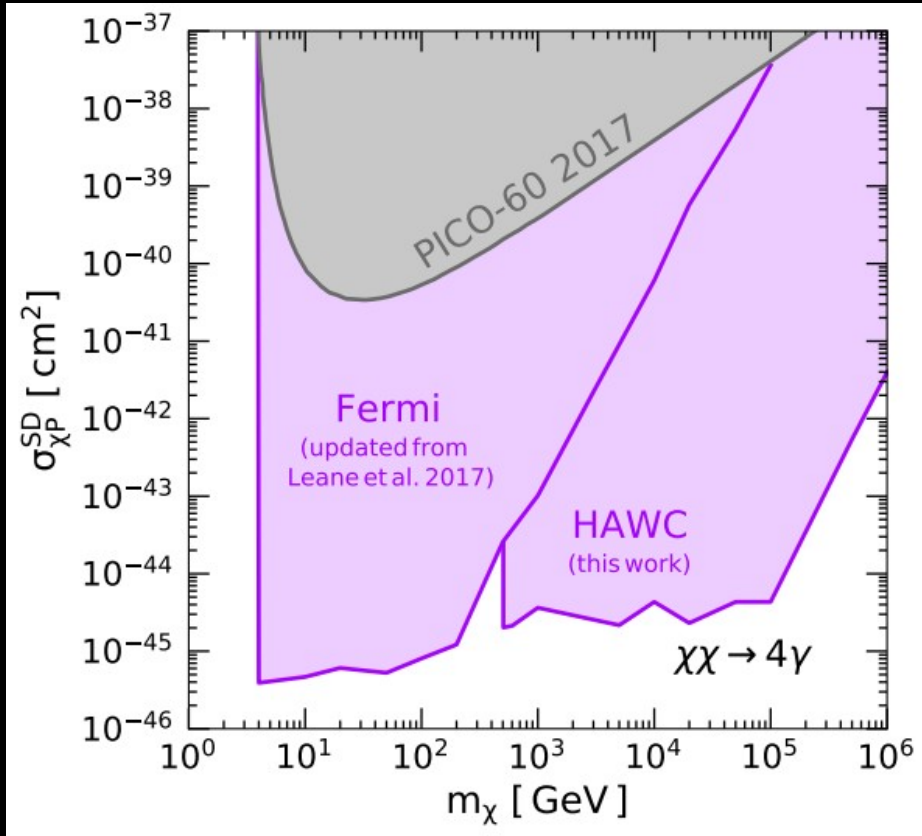


Neutron Star  
Small + Cold



Brown Dwarf  
BIG + Cold

# Optimal Celestial Target?



Sun

Long-Lived Mediator Limits

**RKL**, Ng, Beacom (PRD '17)

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

?

Neutron Star

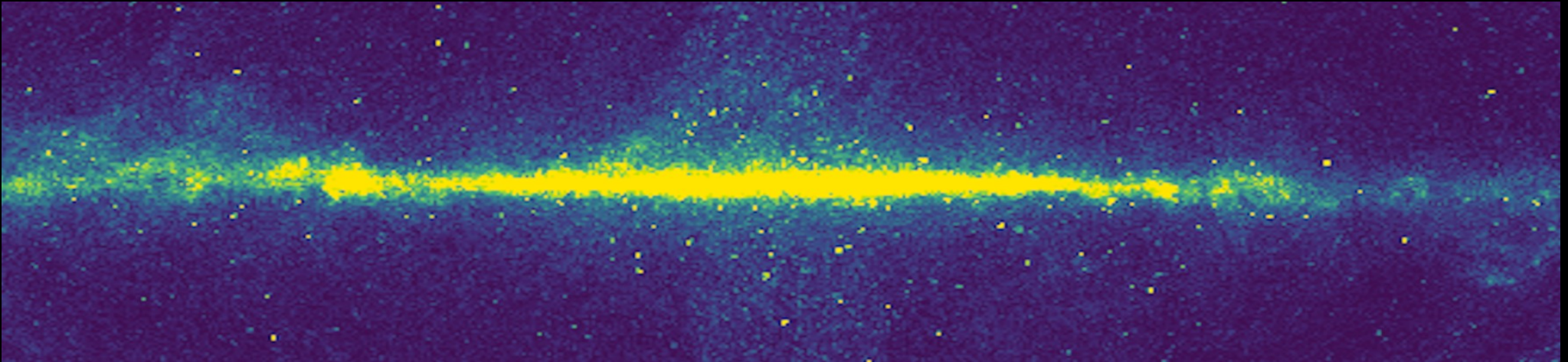
?

Brown Dwarf

Long-Lived Mediator Limits

# Galactic Center Population Signal

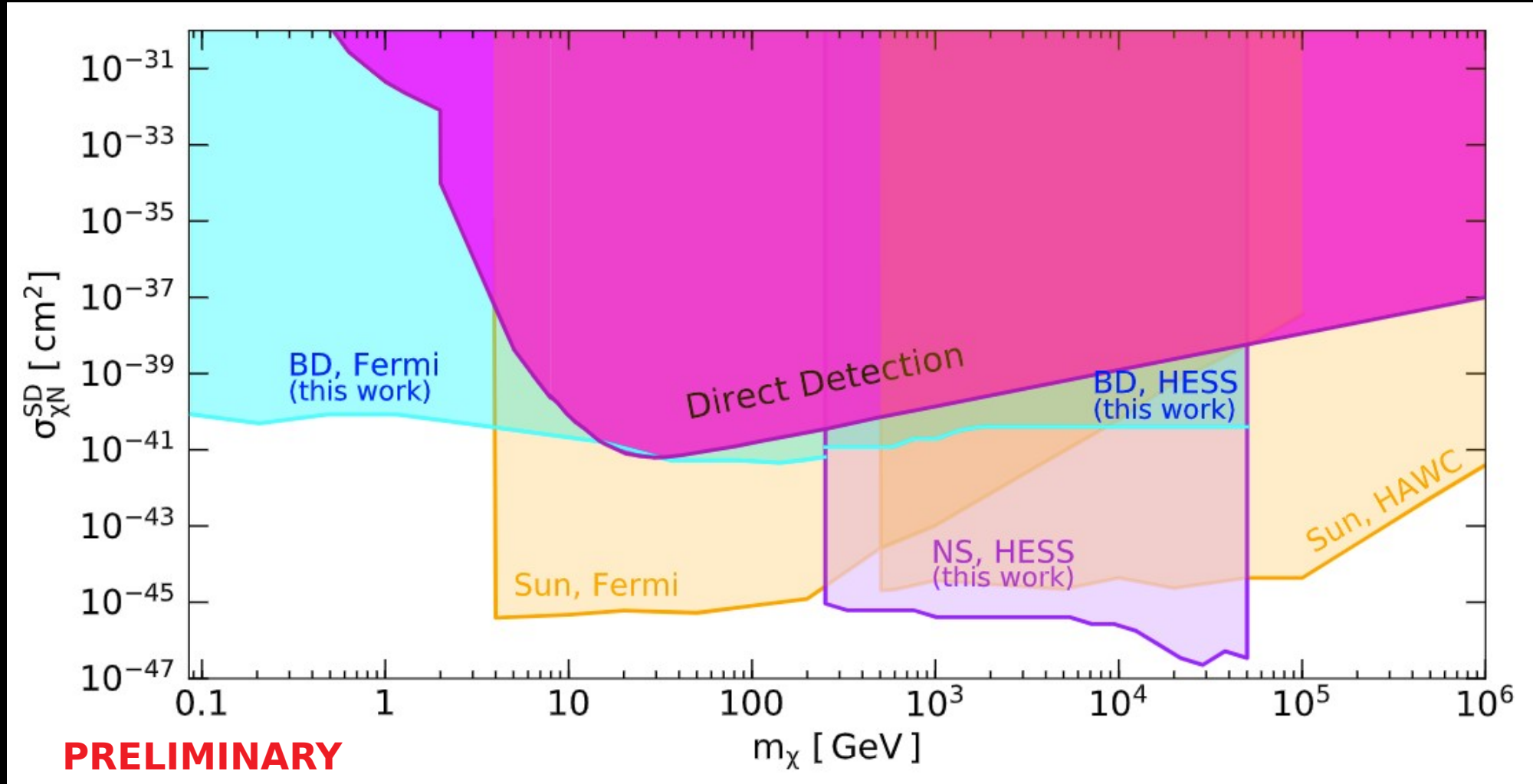
- Use **all** the neutron stars, **all** the brown dwarfs
  - Compare with Fermi and H.E.S.S. data for Galactic Center
  - No model assumptions on mediator, other than must escape
- Our new signal follows matter density: DM density \* stellar density
  - DM Halo annihilation scales with DM density squared



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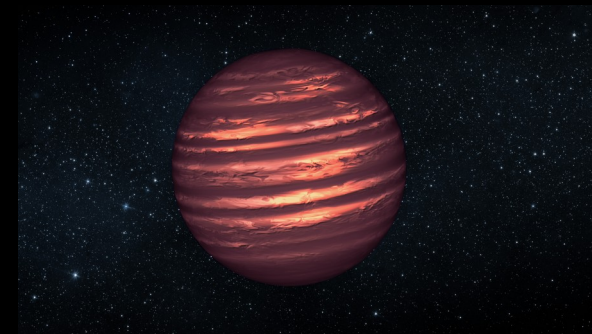


# New Limits w/ Brown Dwarfs and Neutron Stars



RKL, Linden, Mukhopadhyay, Toro (to appear)

# Summary



- Two searches for sub-GeV DM in celestial bodies:
  - One for 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**
  - One for DM annihilation to short lived mediators:  
Search for DM heated exoplanets, measure temperatures with upcoming James Webb Telescope, **new sub-GeV sensitivities**

# 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!





The image features a solid black background. In the top-left corner, there are several thin, parallel lines in a light blue or cyan color, forming a series of nested L-shapes. Similarly, in the bottom-right corner, there are several thin, parallel lines in the same color, forming a series of nested L-shapes that mirror the ones in the top-left.

EXTRA SLIDES

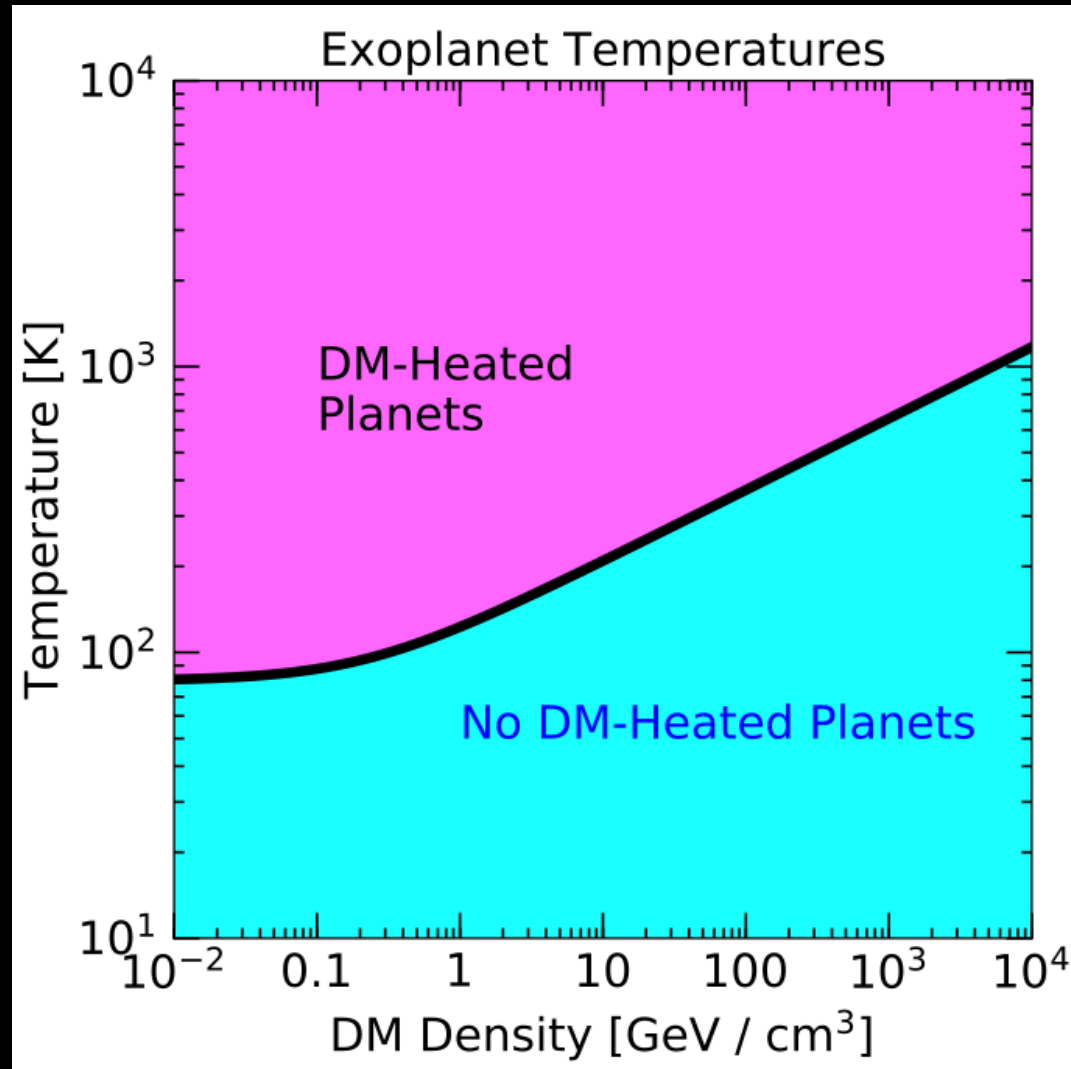
# DM Equilibrium and Evaporation

- 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:

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

- Evaporation occurs for  $\sim 4$  MeV DM mass in brown dwarfs,  $\sim 30$  MeV DM mass in Jupiters

# Deviations: DM-overdensities

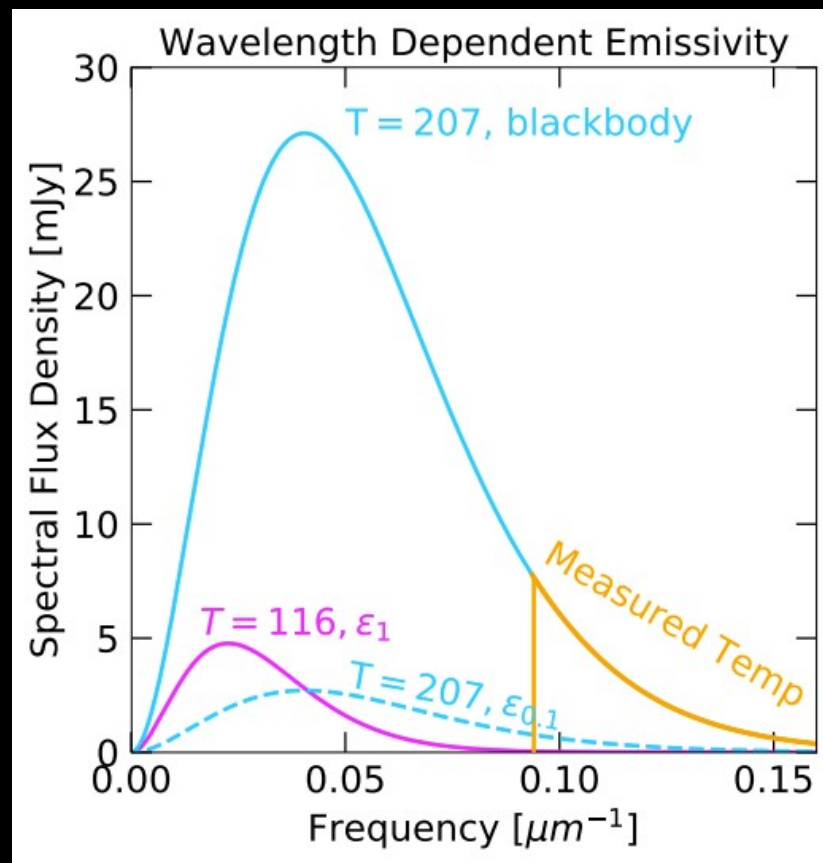
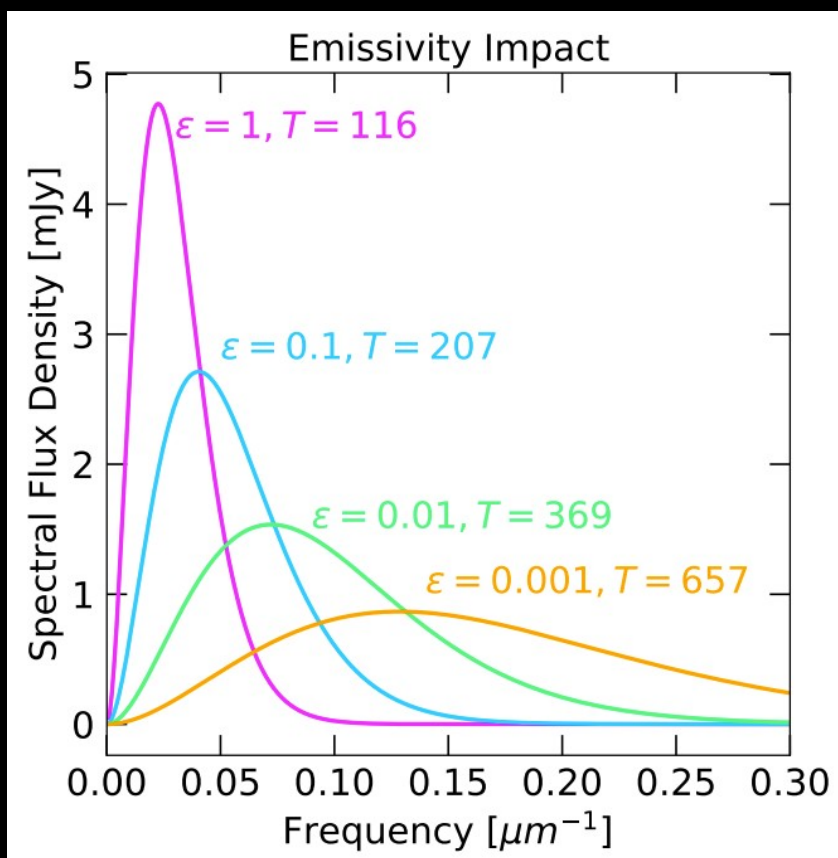


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# Deviations: Non-Blackbody Spectra

Atmosphere effects can cause deviations from a blackbody

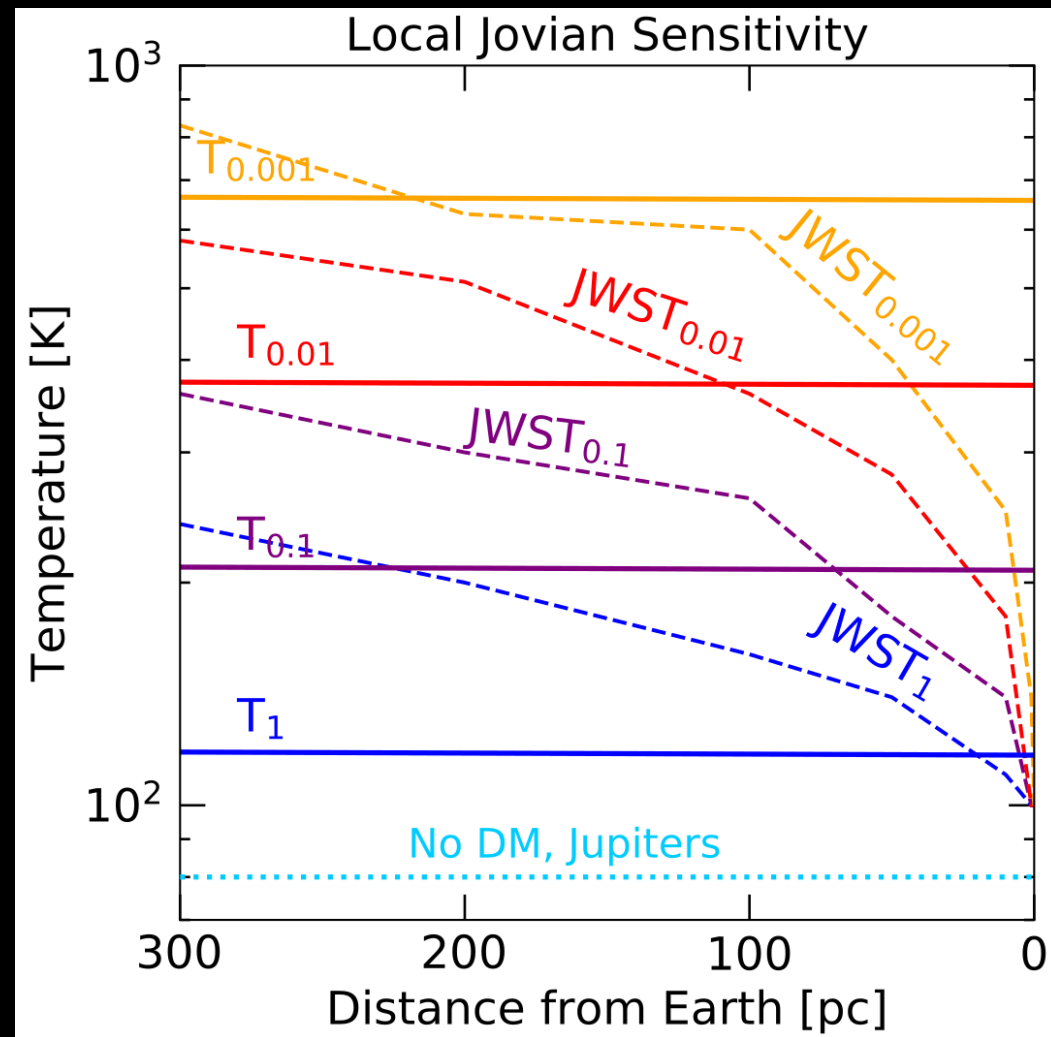
$$B(\nu, T) = \frac{2\nu^3 \epsilon}{\exp\left(\frac{2\pi\nu}{k_b T}\right) - 1}$$





# 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

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

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

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

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

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

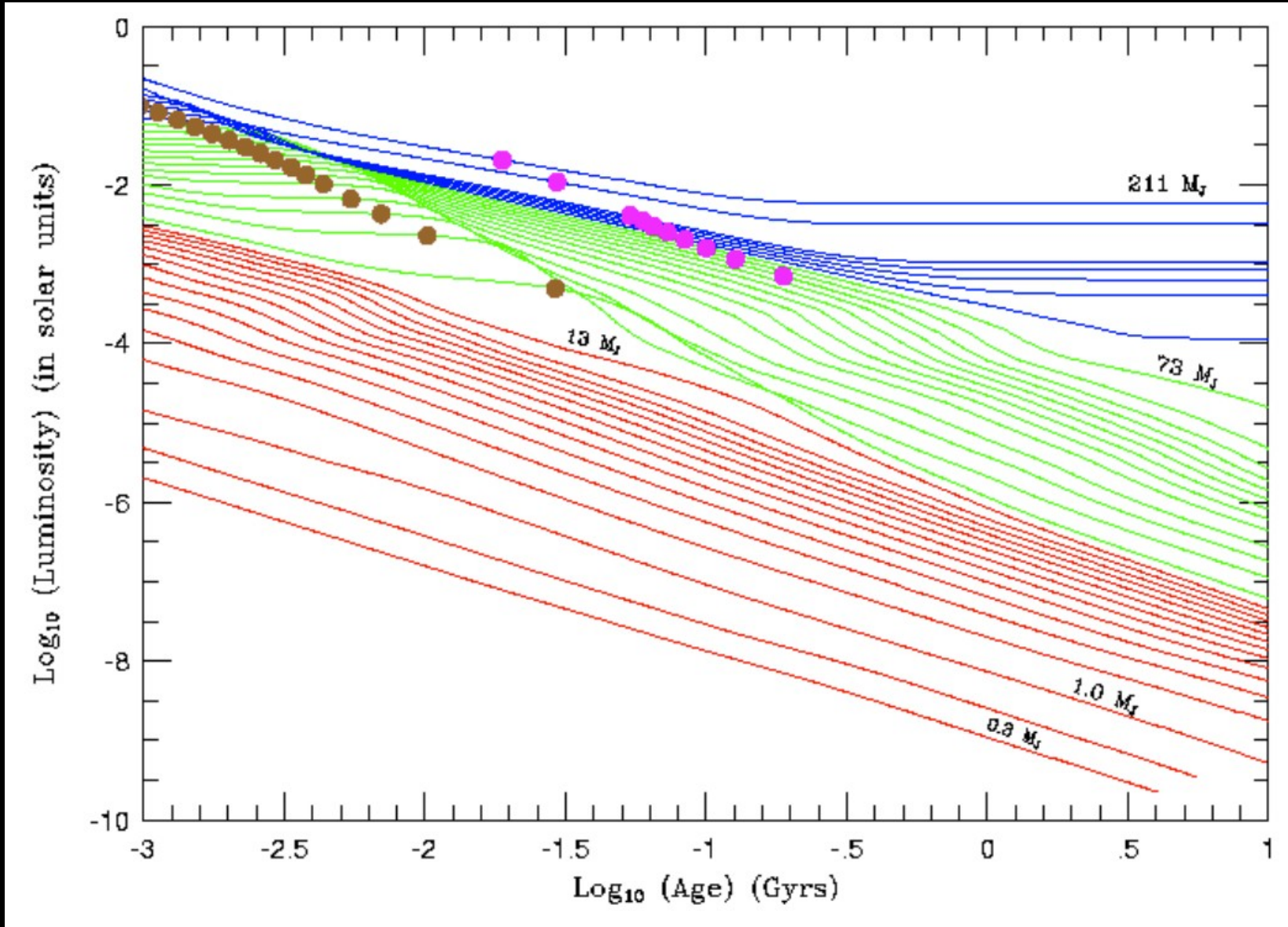
$$\tau = \frac{3}{2} \frac{\sigma}{\sigma_{\text{sat}}}$$

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

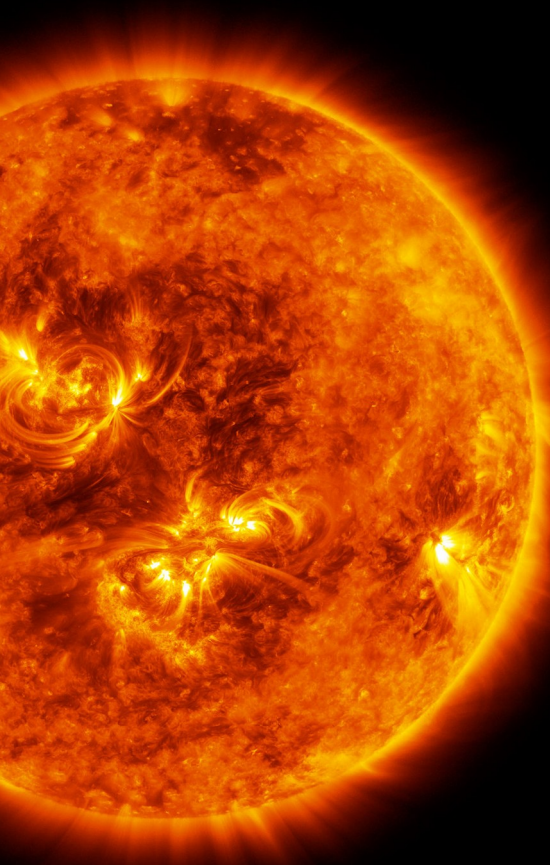
$$\sigma_{\chi A}^{\text{SD}} = \sigma_{\chi N}^{\text{SD}} \left( \frac{\mu(m_A)}{\mu(m_N)} \right)^2 \frac{4(J+1)}{3J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2$$

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

# 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



Impact on  
magnetic fields?  
Volcanoes?



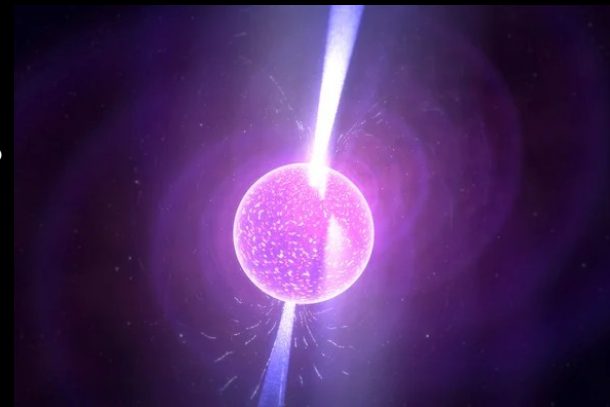
Jupiter

DM heat  
anomaly?



Uranus

DM limits from  
temperature



Neutron Stars

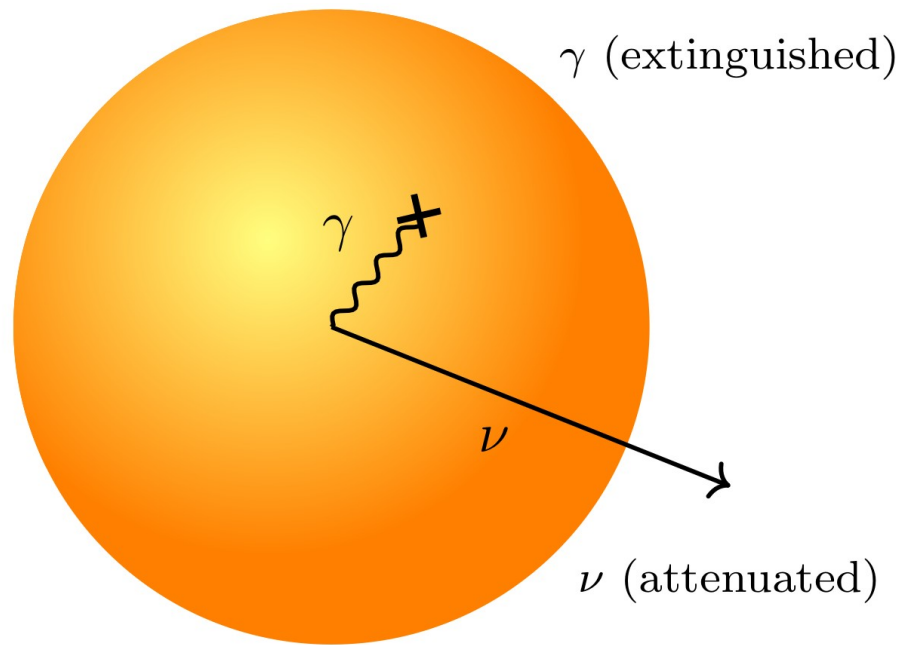
DM heating, infrared  
telescopes



White Dwarfs



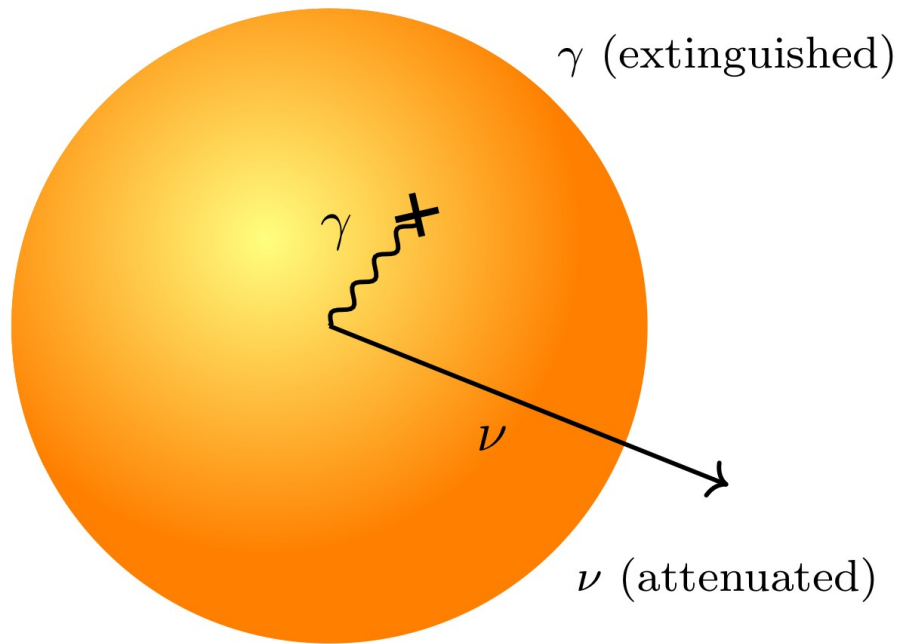
# DARK MATTER IN THE SUN



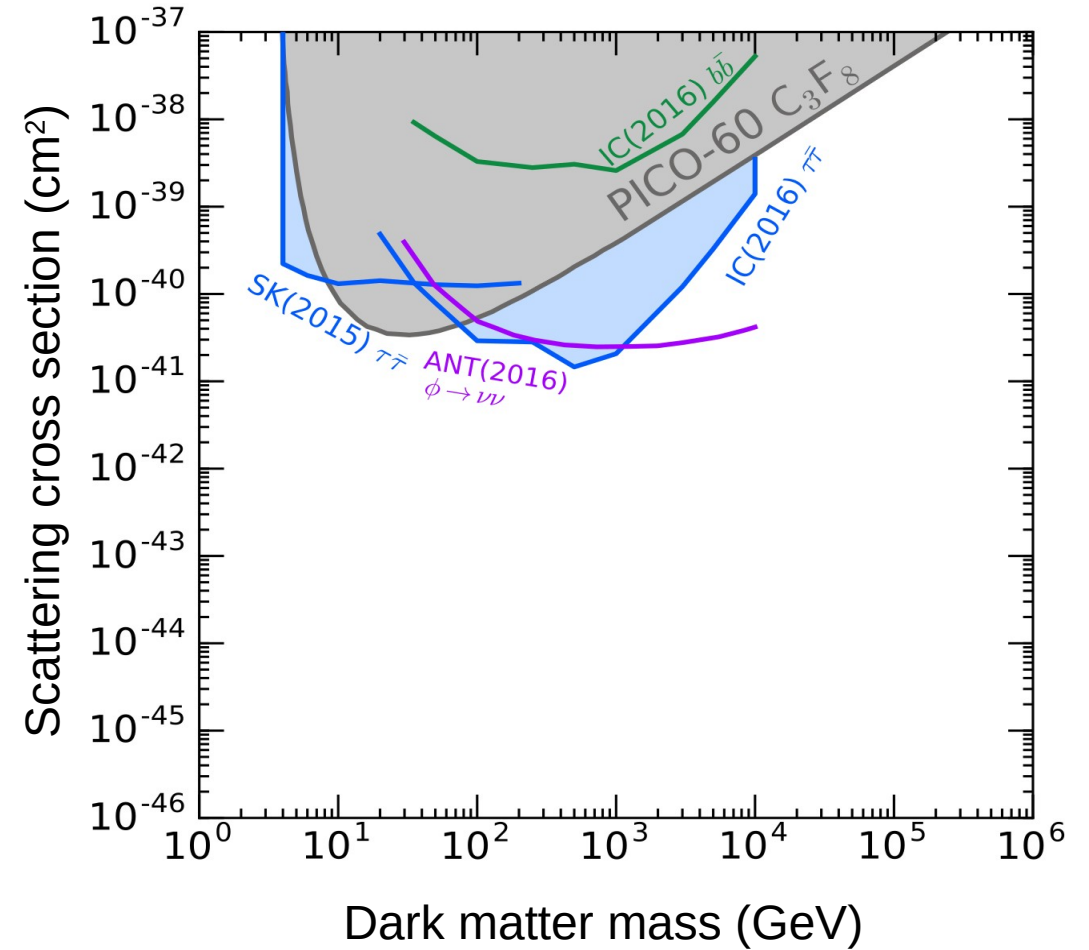
Evolution of dark matter number density

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

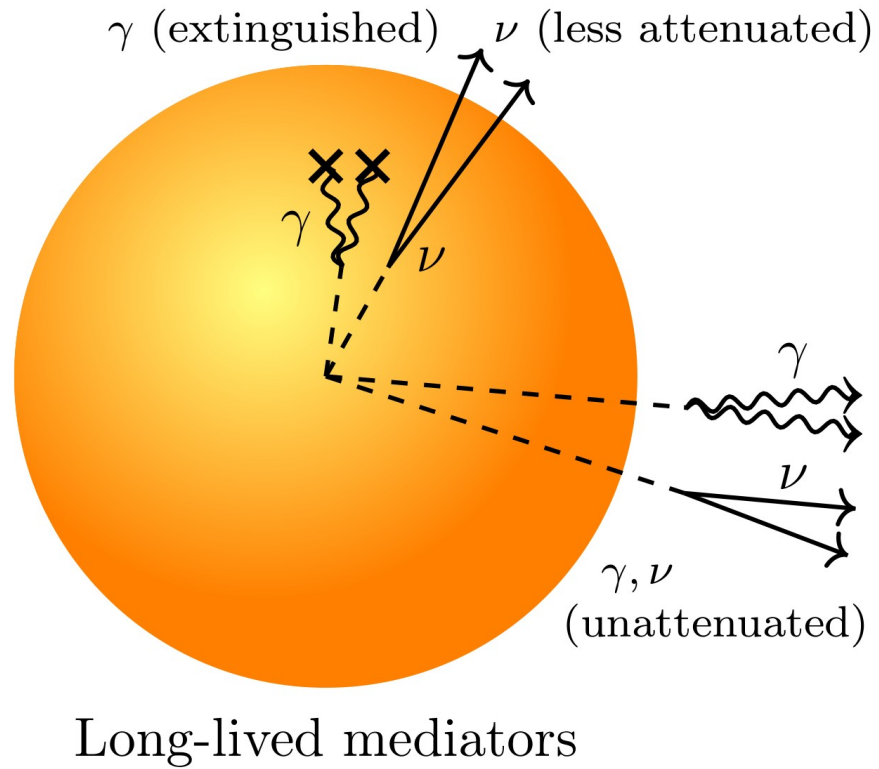
# DARK MATTER IN THE SUN



Limits from neutrinos, standard scenario



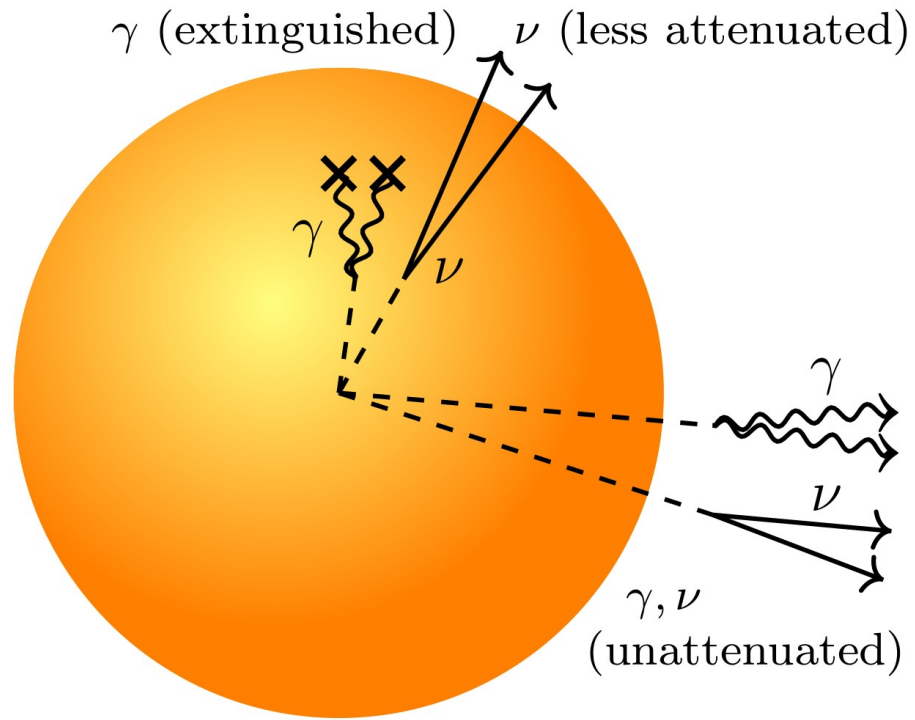
# LONG-LIVED SIGNAL BOOST:



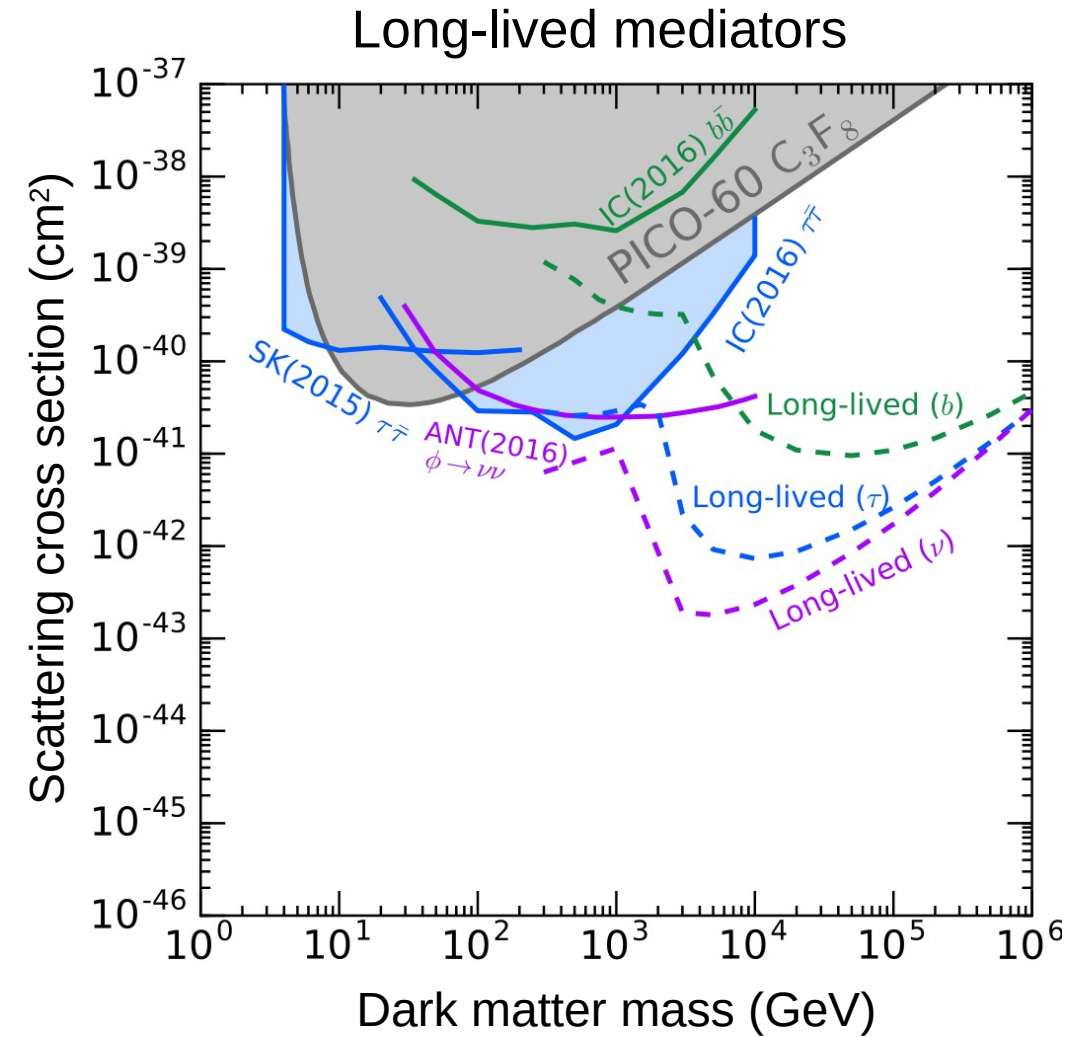
Schuster, Toro, Yavin (PRD '10)  
Batell, Pospelov, Ritz, Shang (PRD '10)  
Meade, Nussinov, Papucci, Volansky (JHEP '10)



# LONG-LIVED SIGNAL BOOST: NEUTRINOS

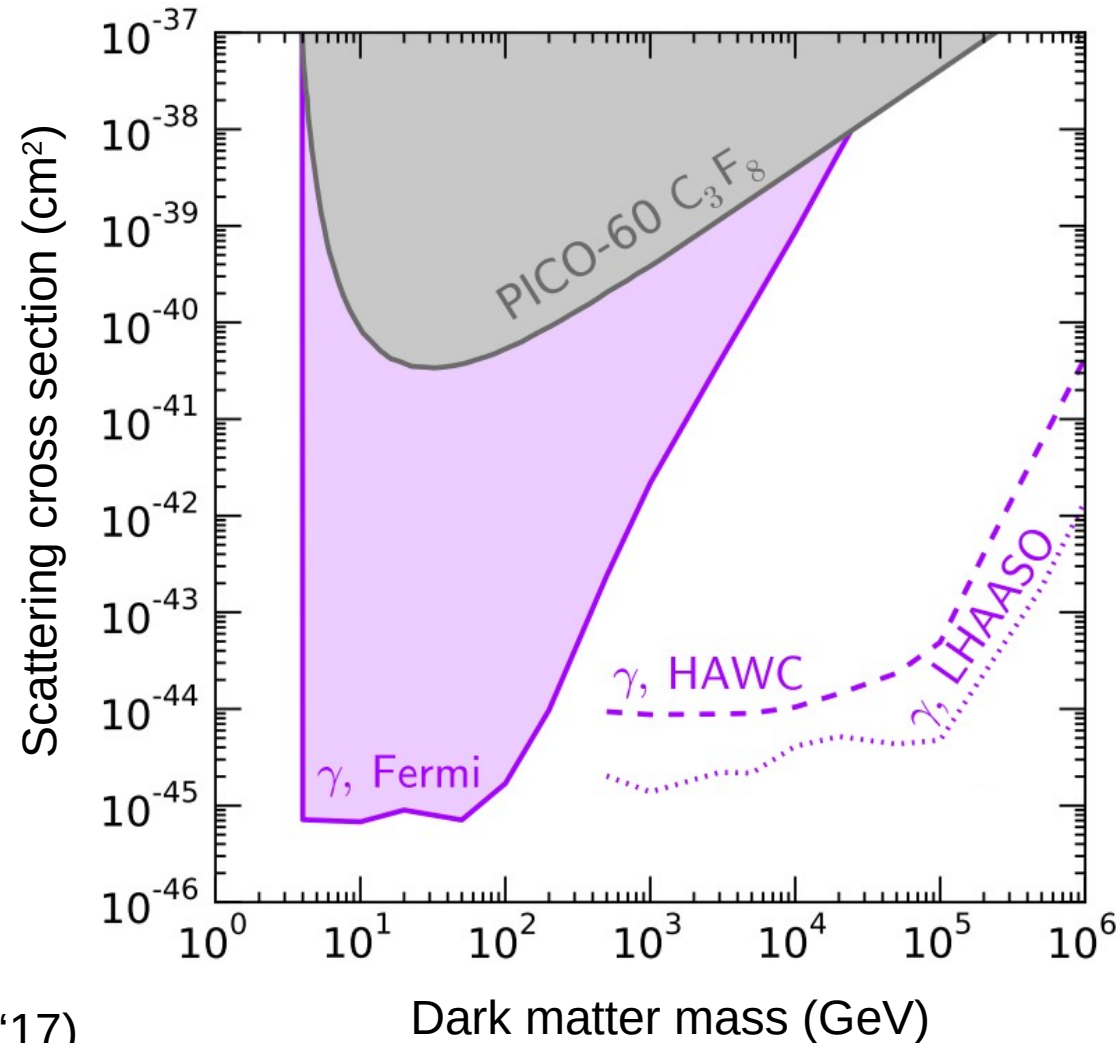


Long-lived mediators





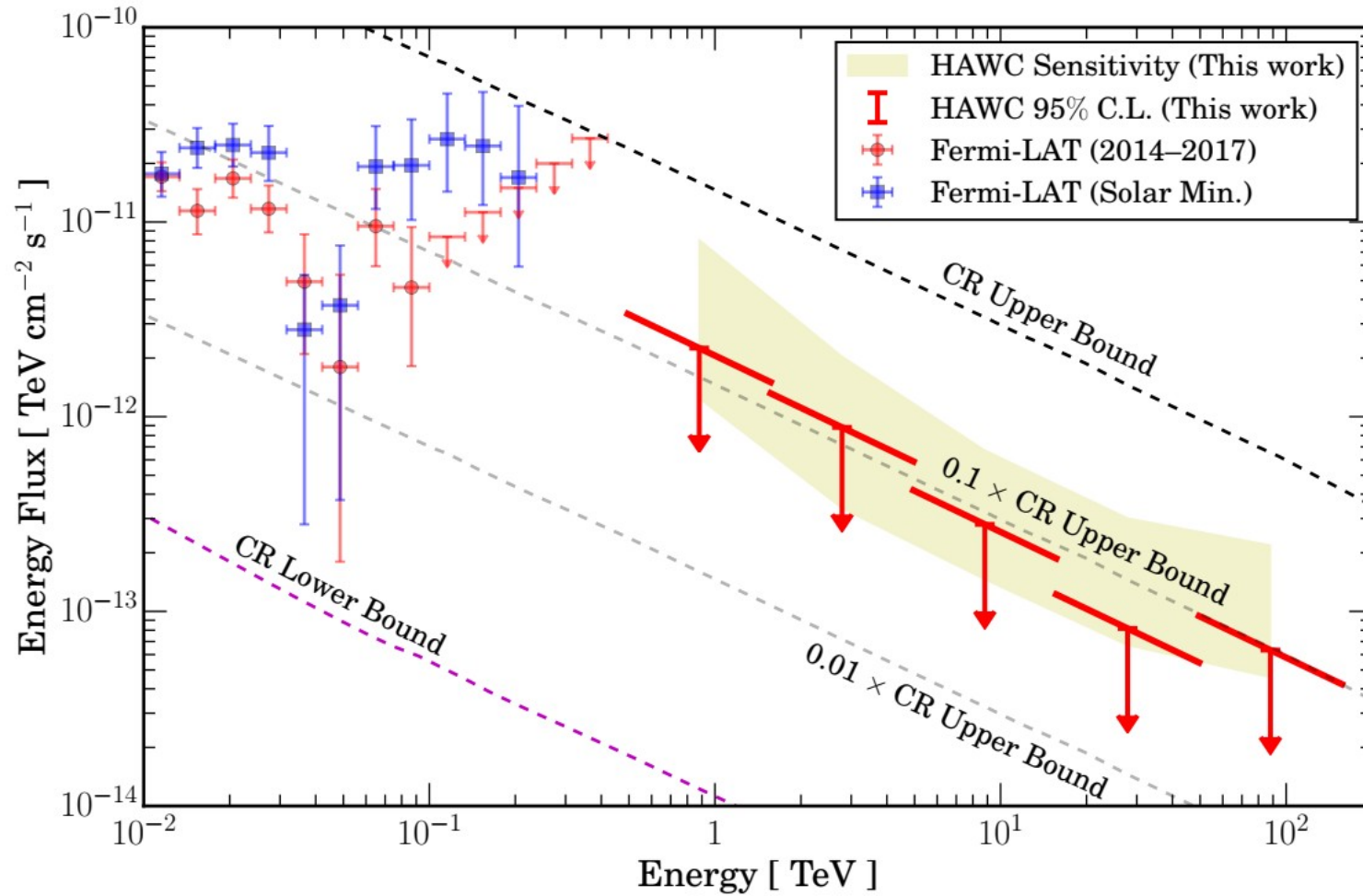
# LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)



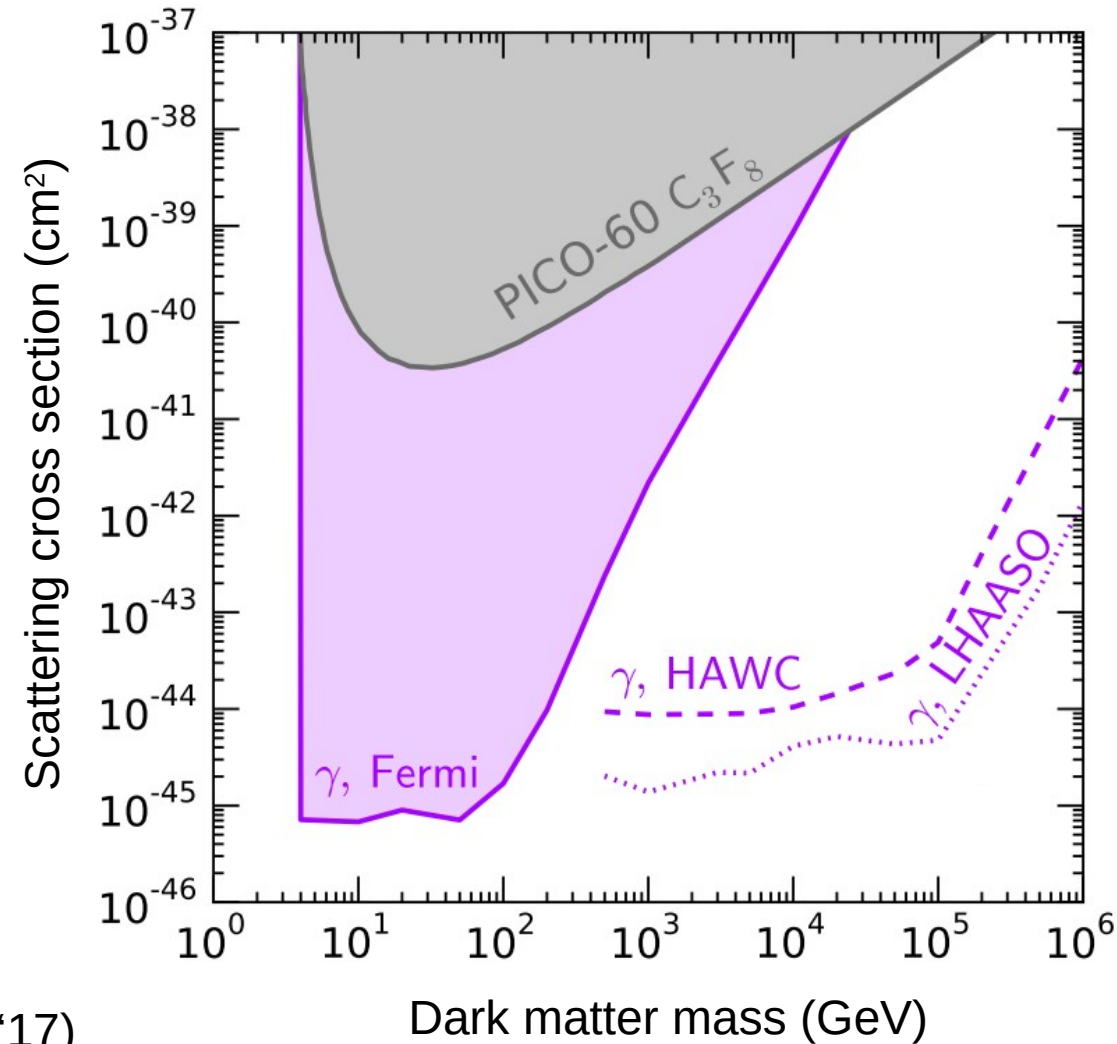
# NEW LIMITS WITH HAWC



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

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

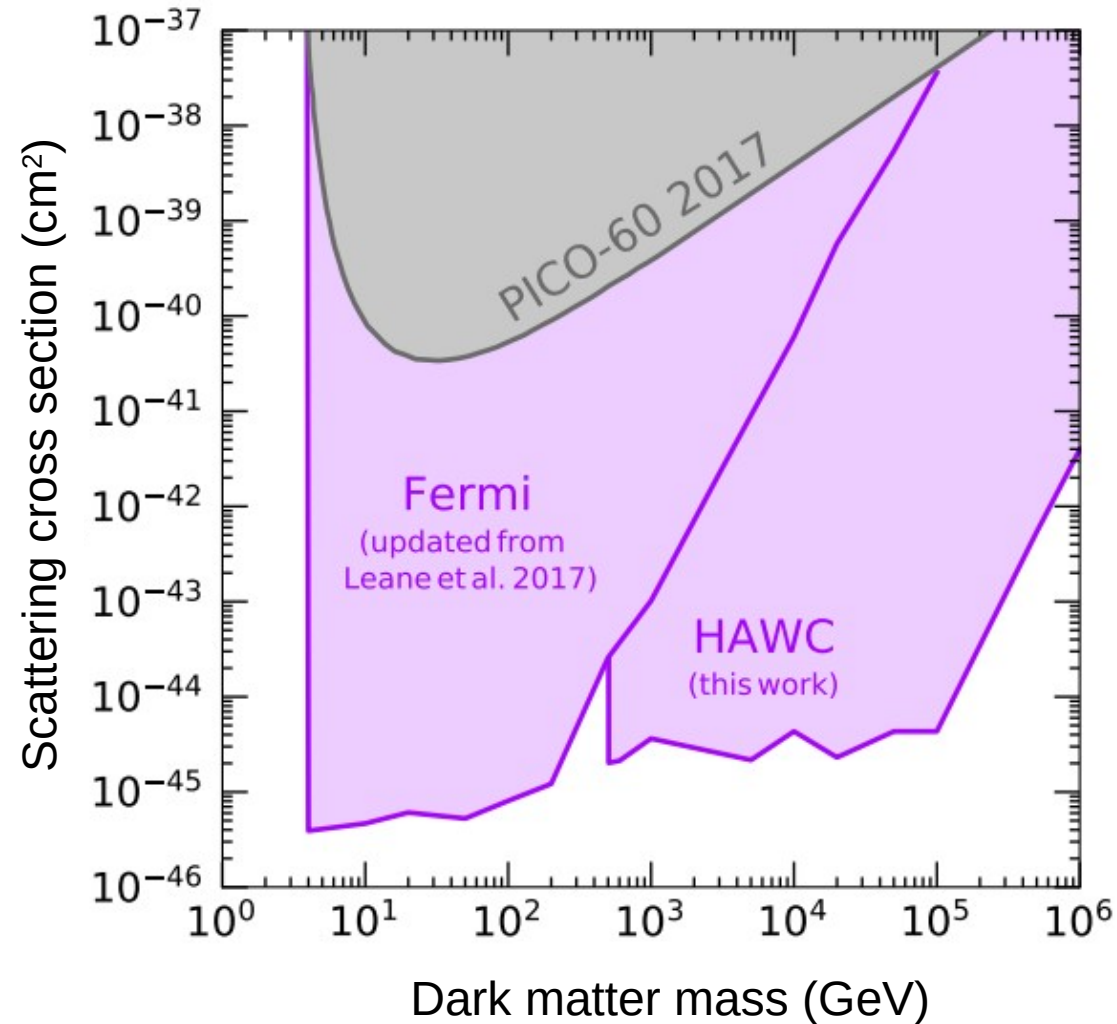
# LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)



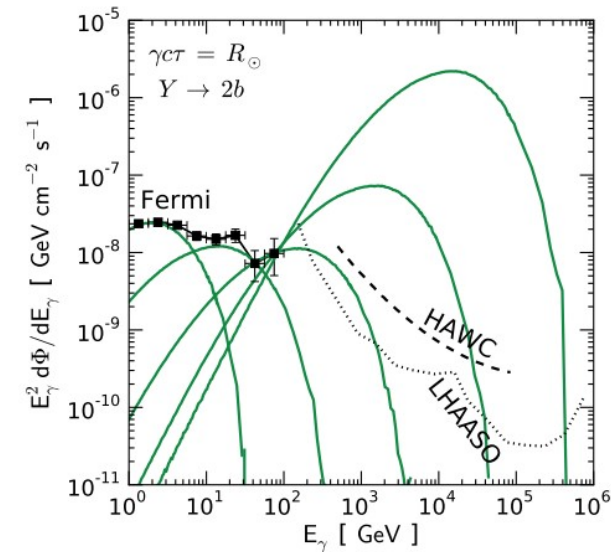
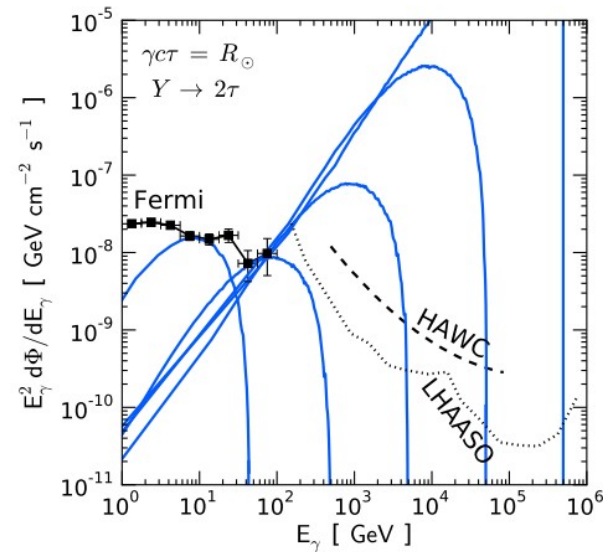
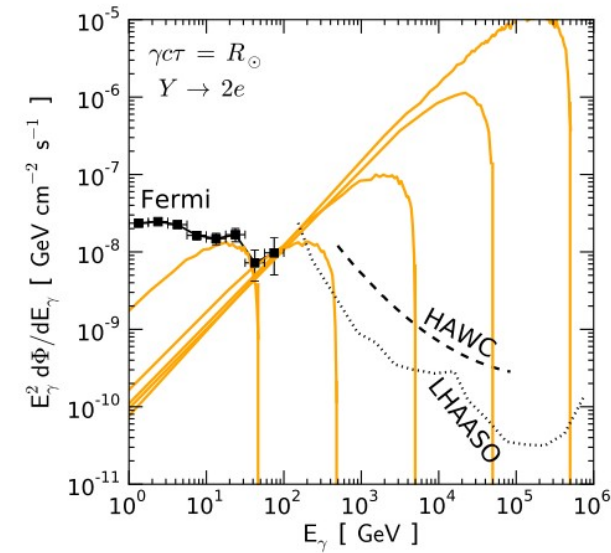
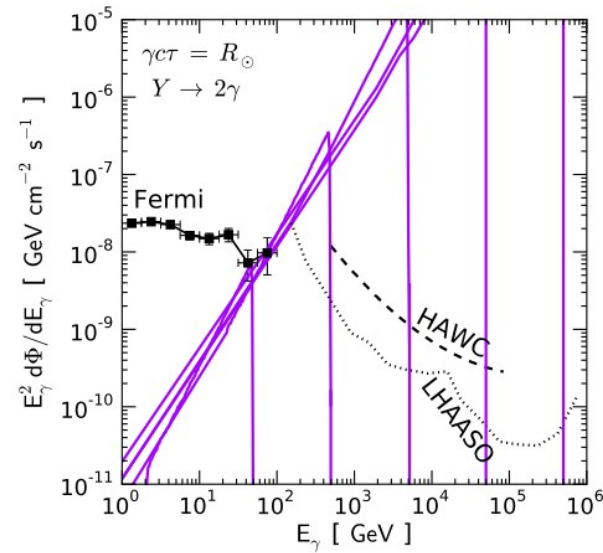
# NEW LIMITS WITH FERMI AND HAWC



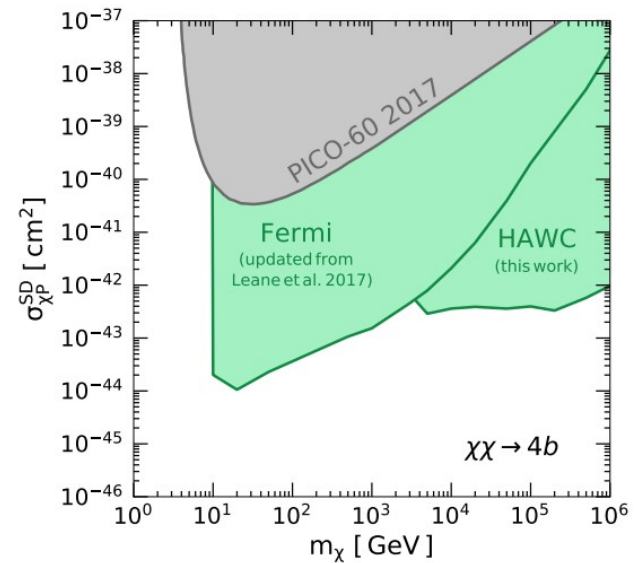
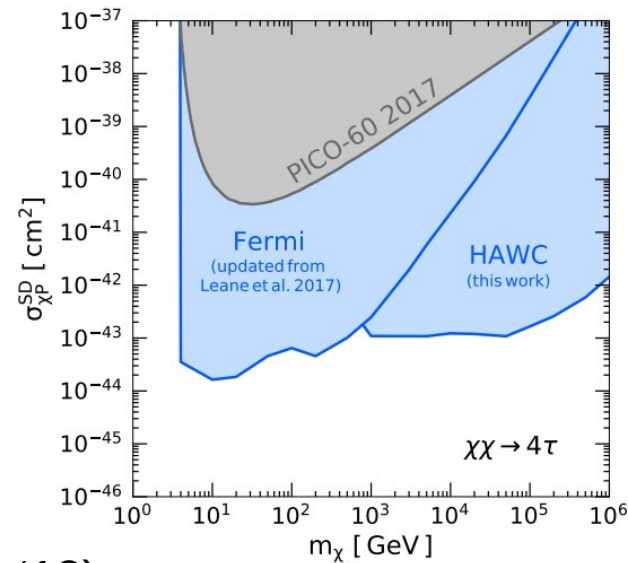
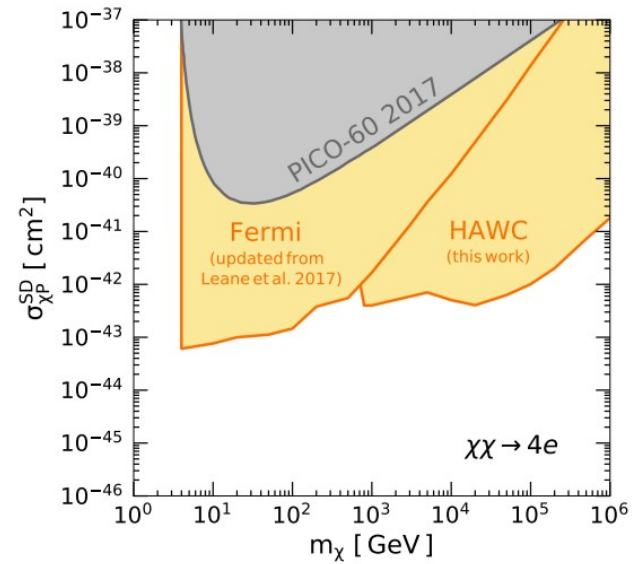
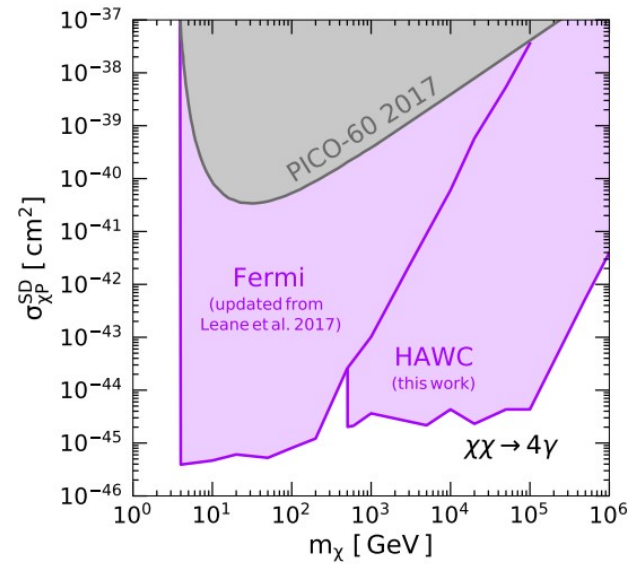


# SOLAR DARK MATTER LIMITS

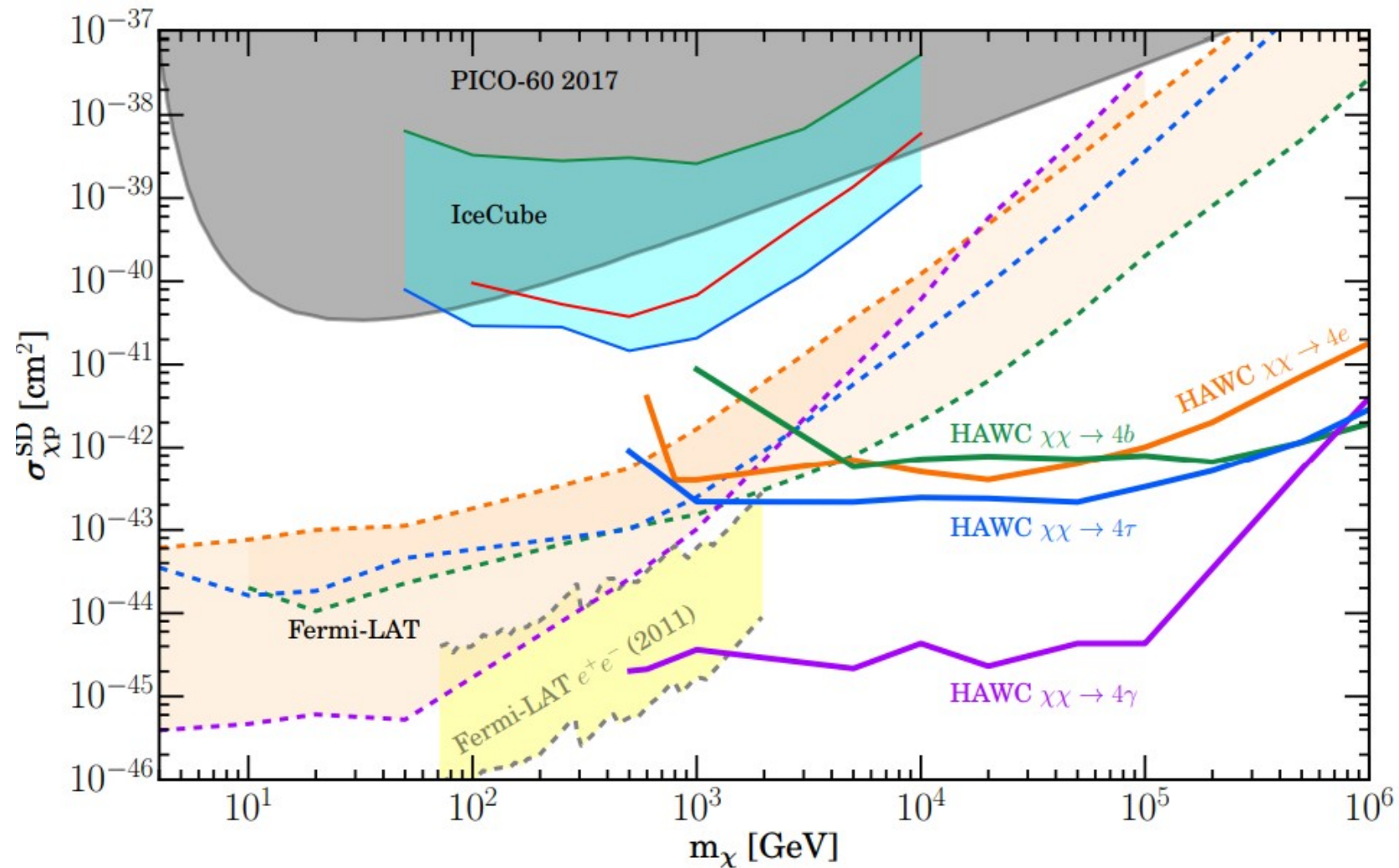
RL, Ng, Beacom (PRD '17)



# SOLAR DARK MATTER LIMITS: UPDATED



# SOLAR DARK MATTER LIMITS: ALL



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

