Detecting Dark Matter in Exoplanets

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Caltech
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Based on 2010.00015 w/ Juri Smirnov

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

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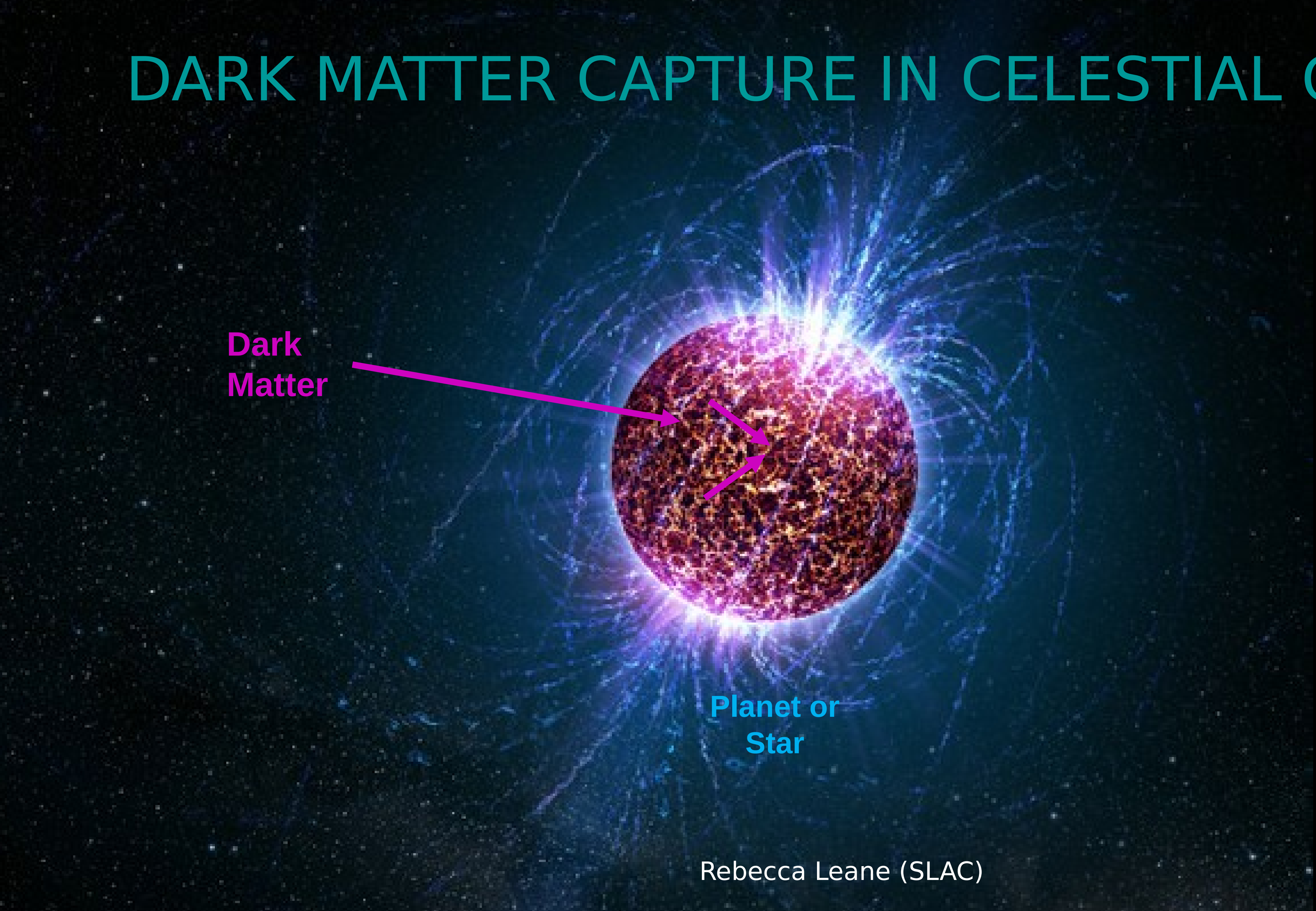
Outline

- Dark Matter Accumulation in Stars and Planets
- 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

DARK MATTER CAPTURE IN CELESTIAL OBJECTS



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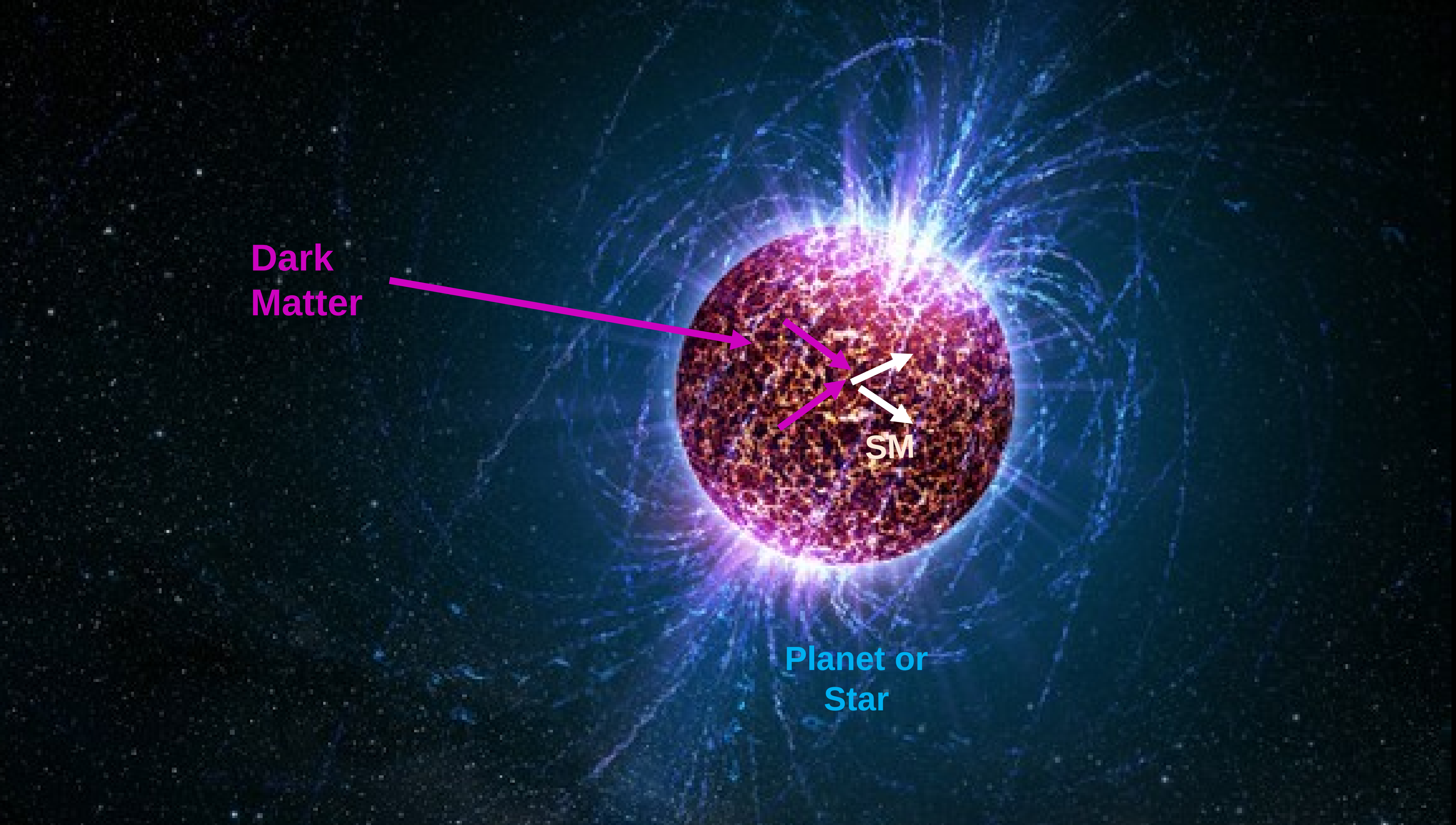

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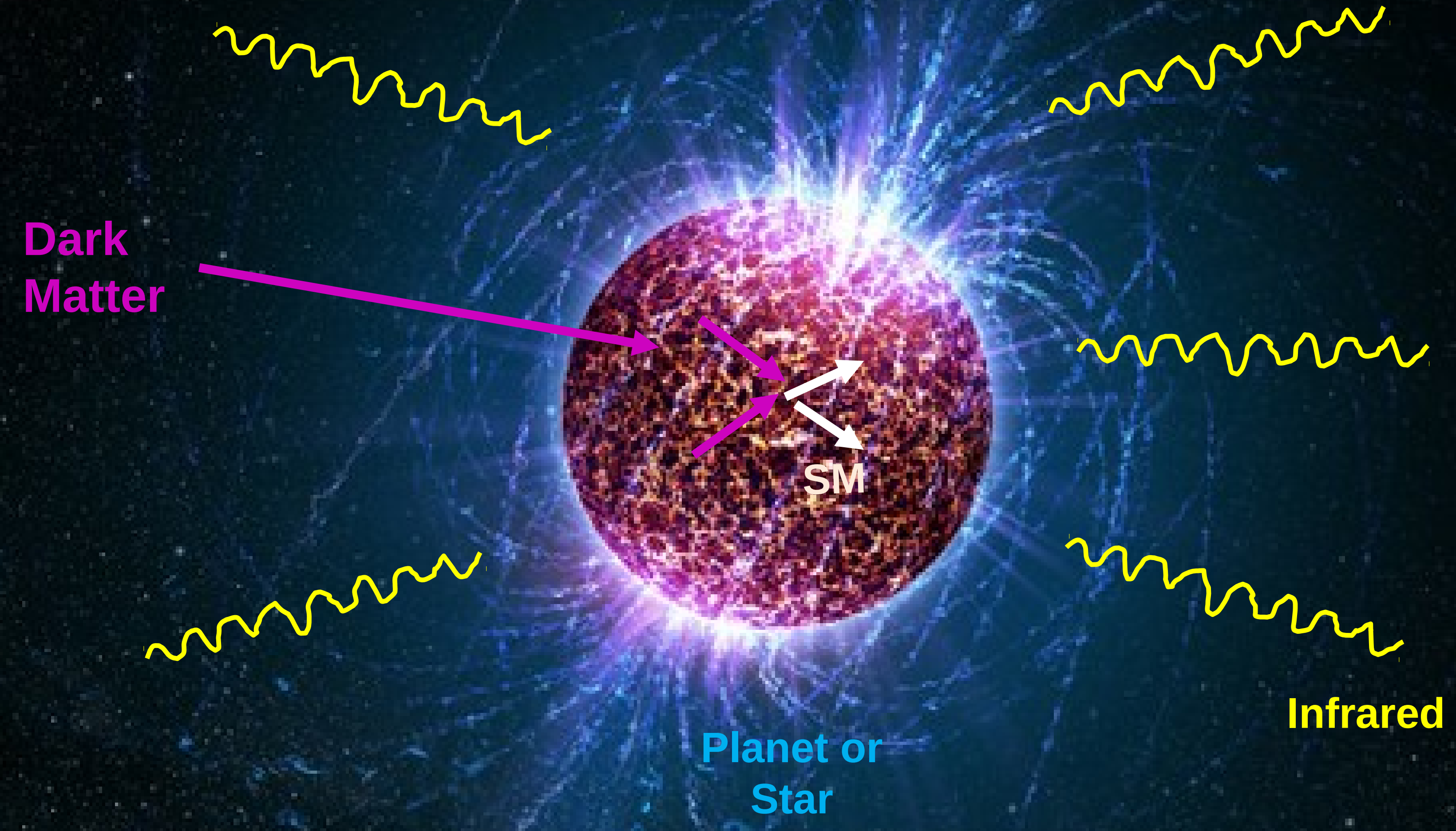

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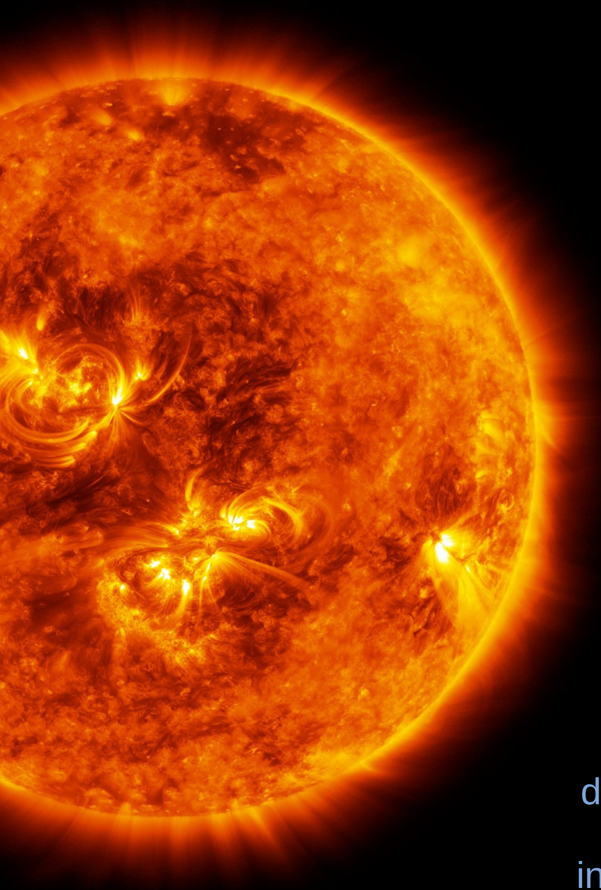
DARK MATTER IN CELESTIAL OBJECTS



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

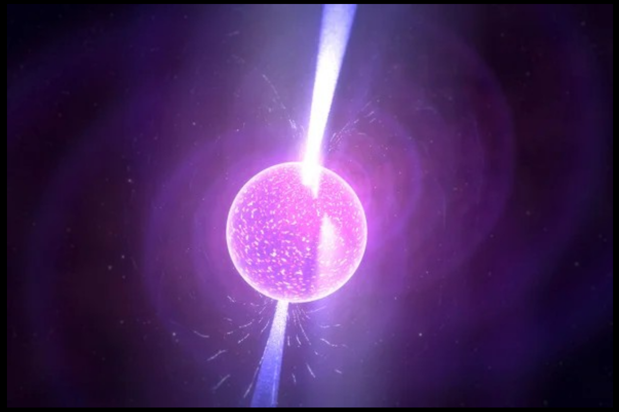
Impact on magnetic fields? Volcanoes?

Jupiter

DM heat anomaly?

Uranus

DM limits from temperature



Neutron Stars

DM heating, infrared telescopes

White Dwarfs

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What about *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

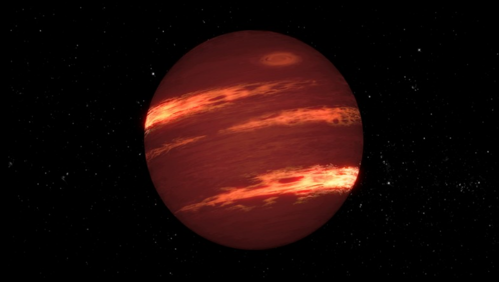
Estimates predict around 300 billion exoplanets in our galaxy!

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

x 10^11

x 10^11

x 1



x 10^11

One Jupiter :(

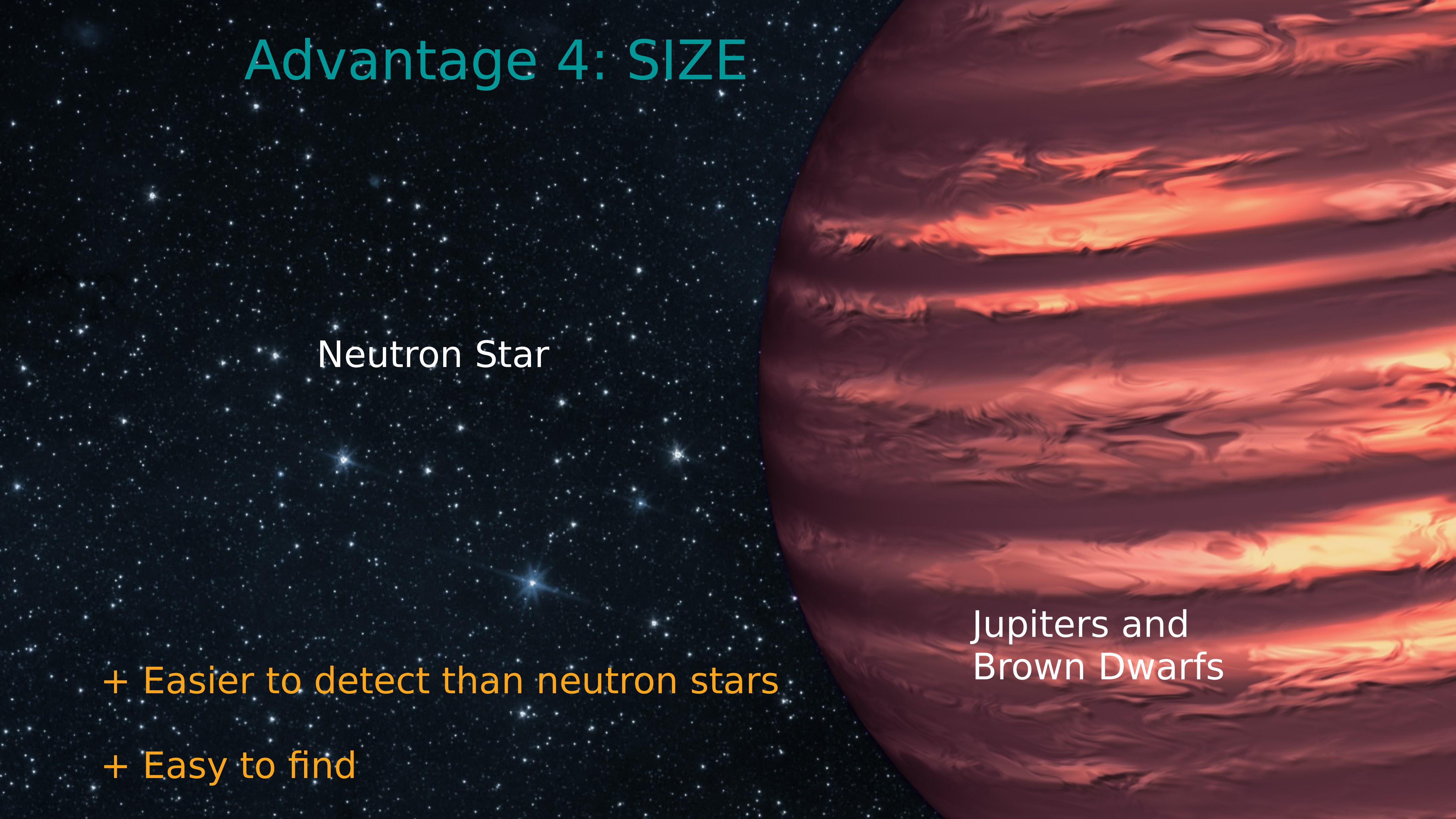
Billions of Exoplanets! :)

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

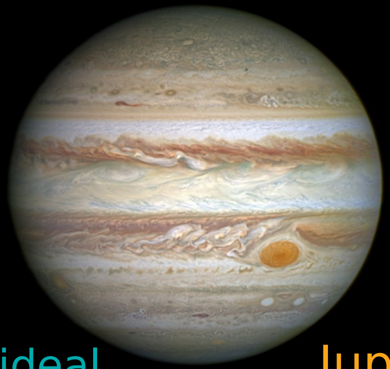


+ Easier to detect than neutron stars

+ 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:

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

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

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

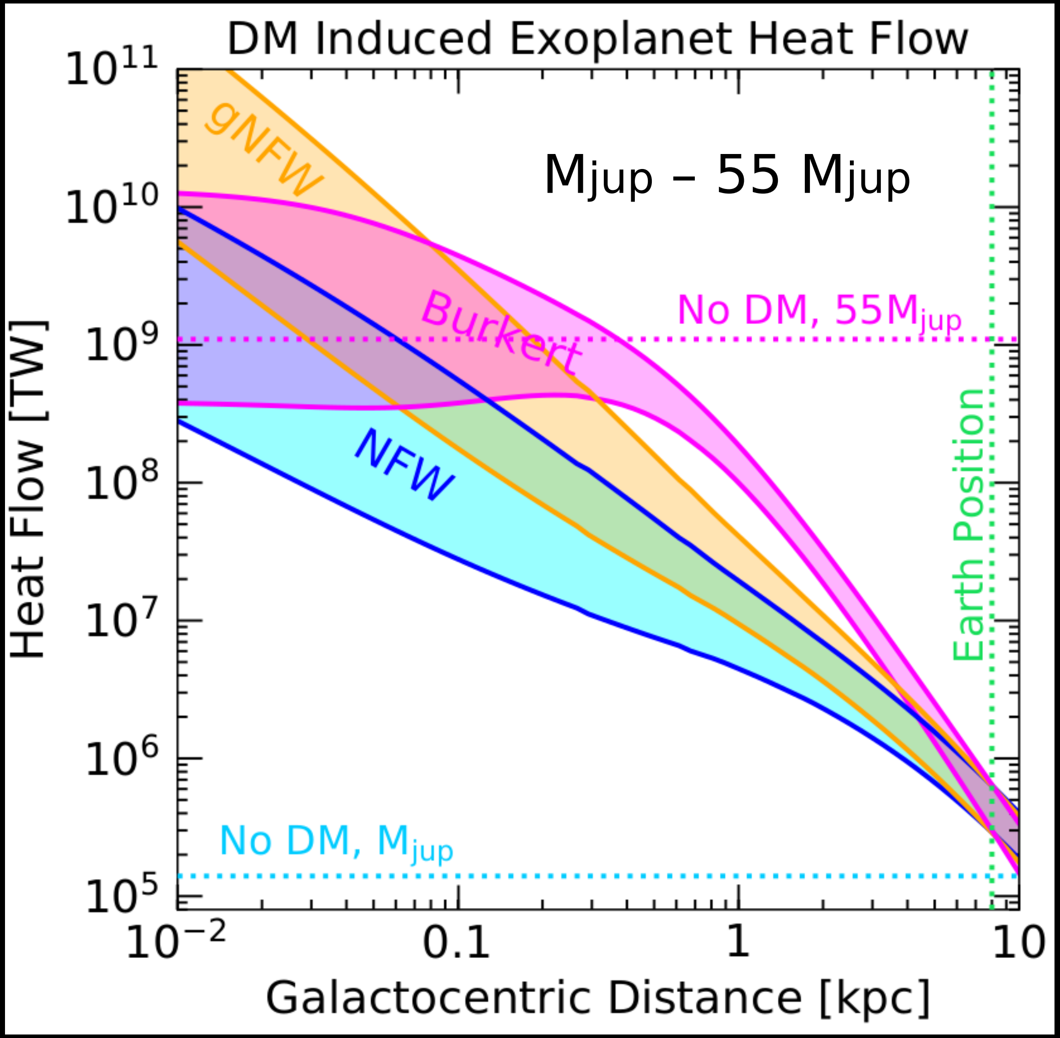
$$v_{\rm esc}^2 = 2 G_N M/R$$

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

DM Heating vs Internal Heat

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

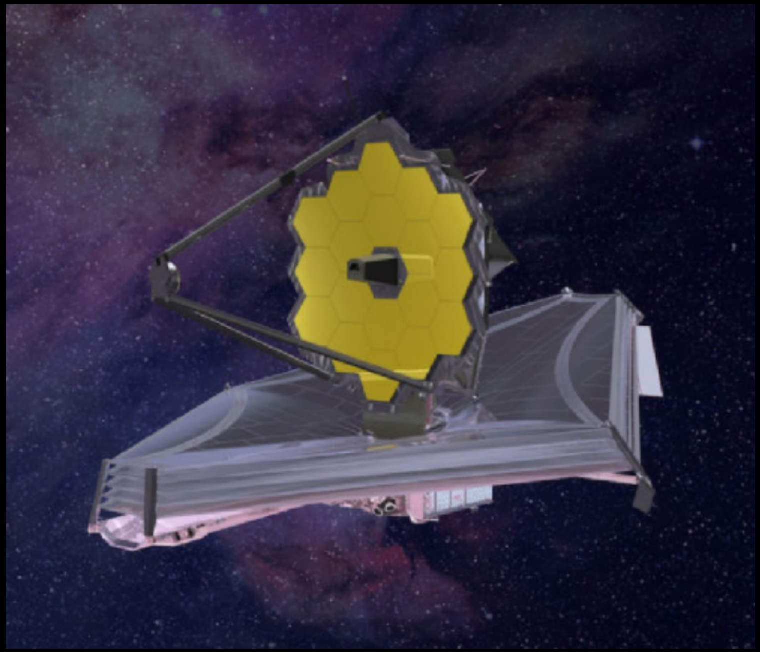
$$\Gamma_{\rm heat}^{\rm DM} = f \, \pi R^2 \rho_\chi(r) \, v_0 \left(1 + \frac{3}{2} \frac{v_{\rm esc}^2}{v_d(r)^2}\right)$$

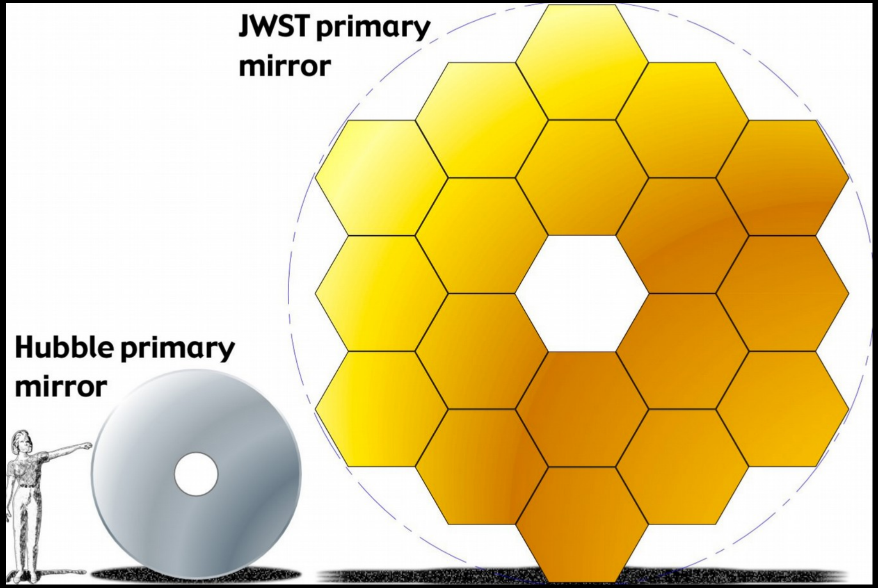


1 parsec = 3.26 light years

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



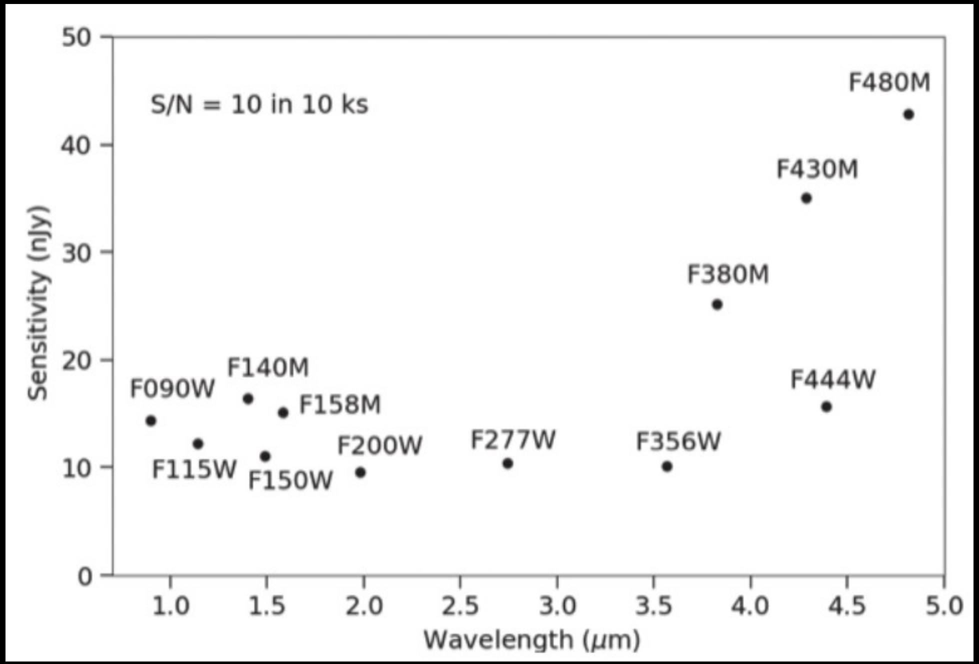


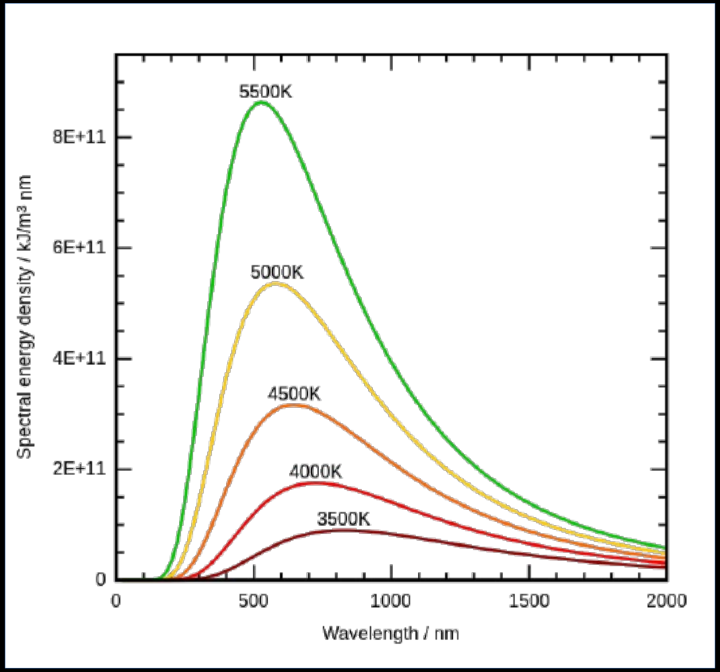
Signal with James Webb

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

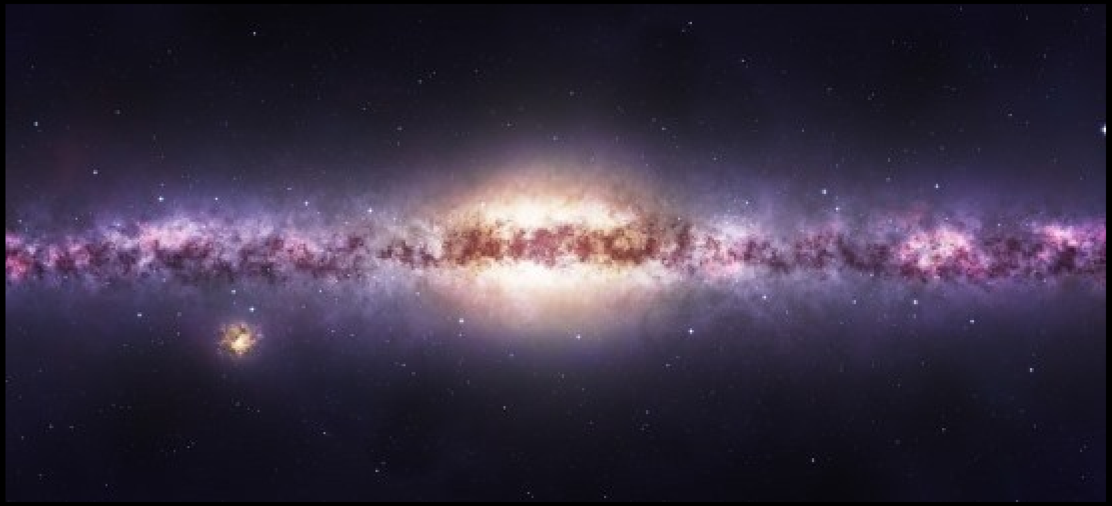
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K
- Mid-Infrared Instrument (MIRI) for T = 100 - 500 K

Won’t need new dedicated searches; can piggyback





Search Challenges



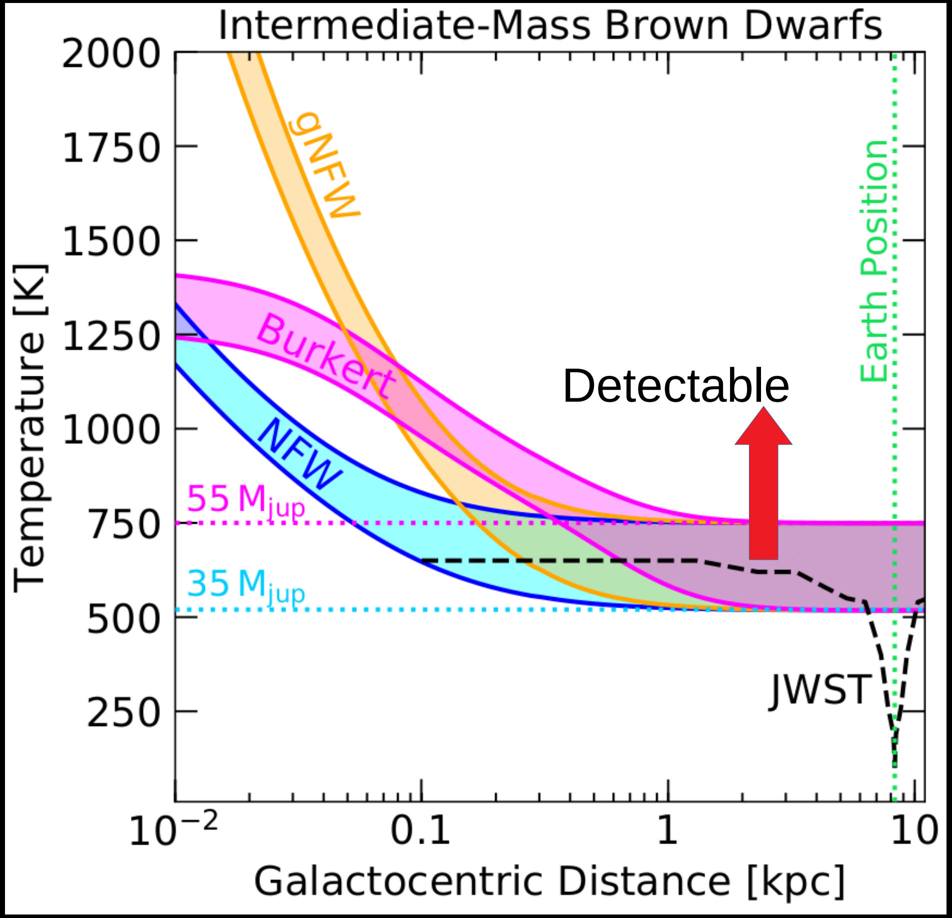
Dust backgrounds:
Rescatter some wavelengths, which can reduce intensity and shift spectrum peaks

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

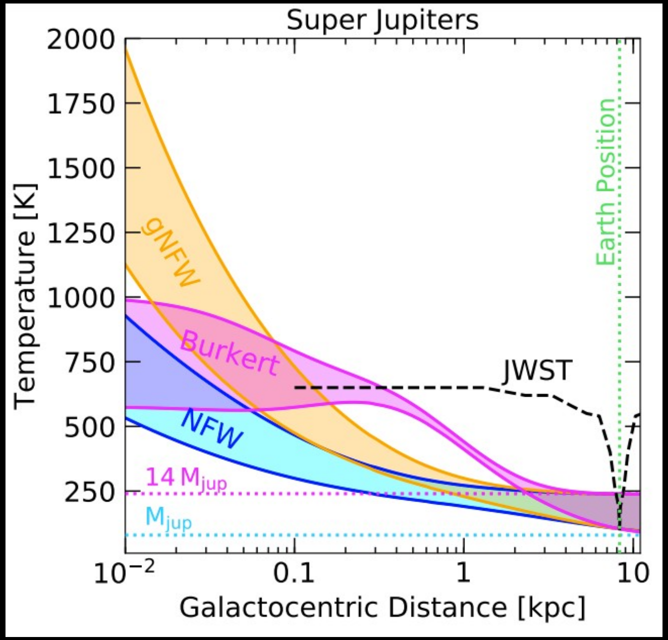
- NFW, gNFW, Burkert are DM profiles, shaded area is exoplanet mass range
- Minimum JWST sensitivity shown is signal to noise of 2, with exposure time of ~day
- Can do 10 SNR in 10^6 seconds on the line shown, + higher temps need less exposure time
- Sensitivity truncates at ~0.1kpc, due to stars per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



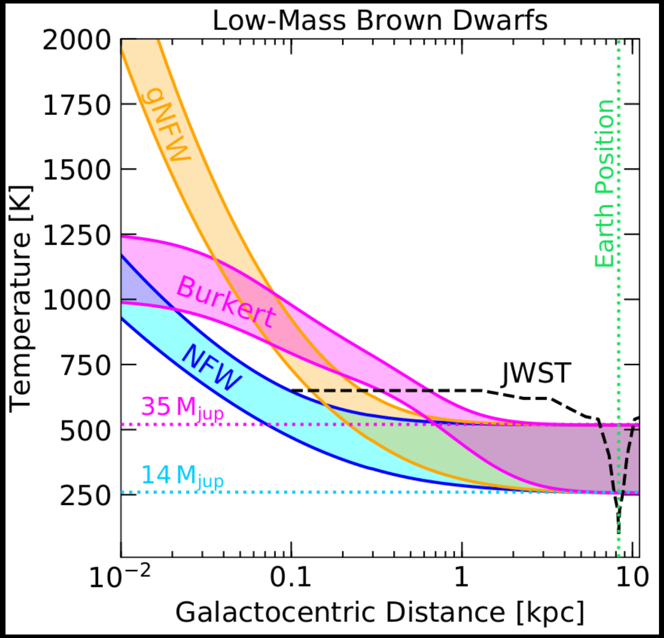
35 Mjup – 55 Mjup

Exoplanet masses vs sensitivity

Mjup – 14 Mjup



14 Mjup – 35 Mjup



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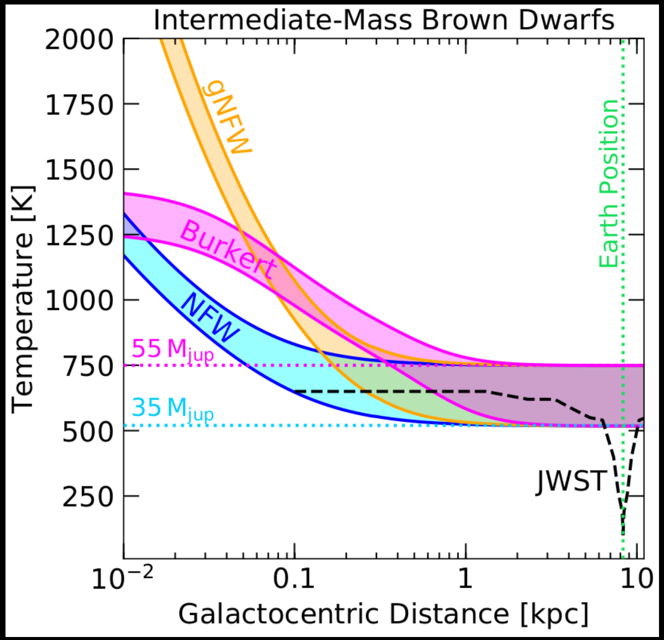


Lower masses:
DM heat > internal heat at all positions

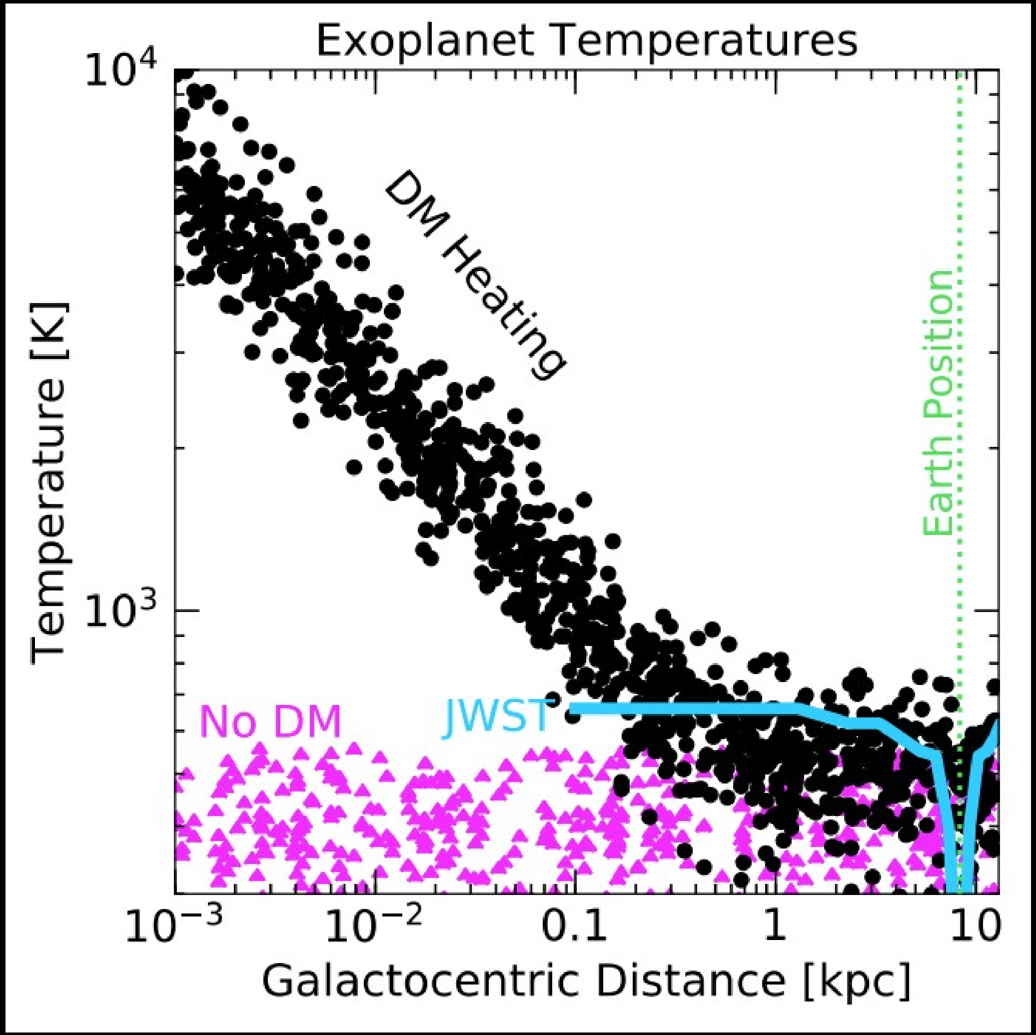
Higher masses:
Strongest signal towards Galactic Center, local DM heating signal difficult to outperform internal heat

New DM Search with Exoplanets

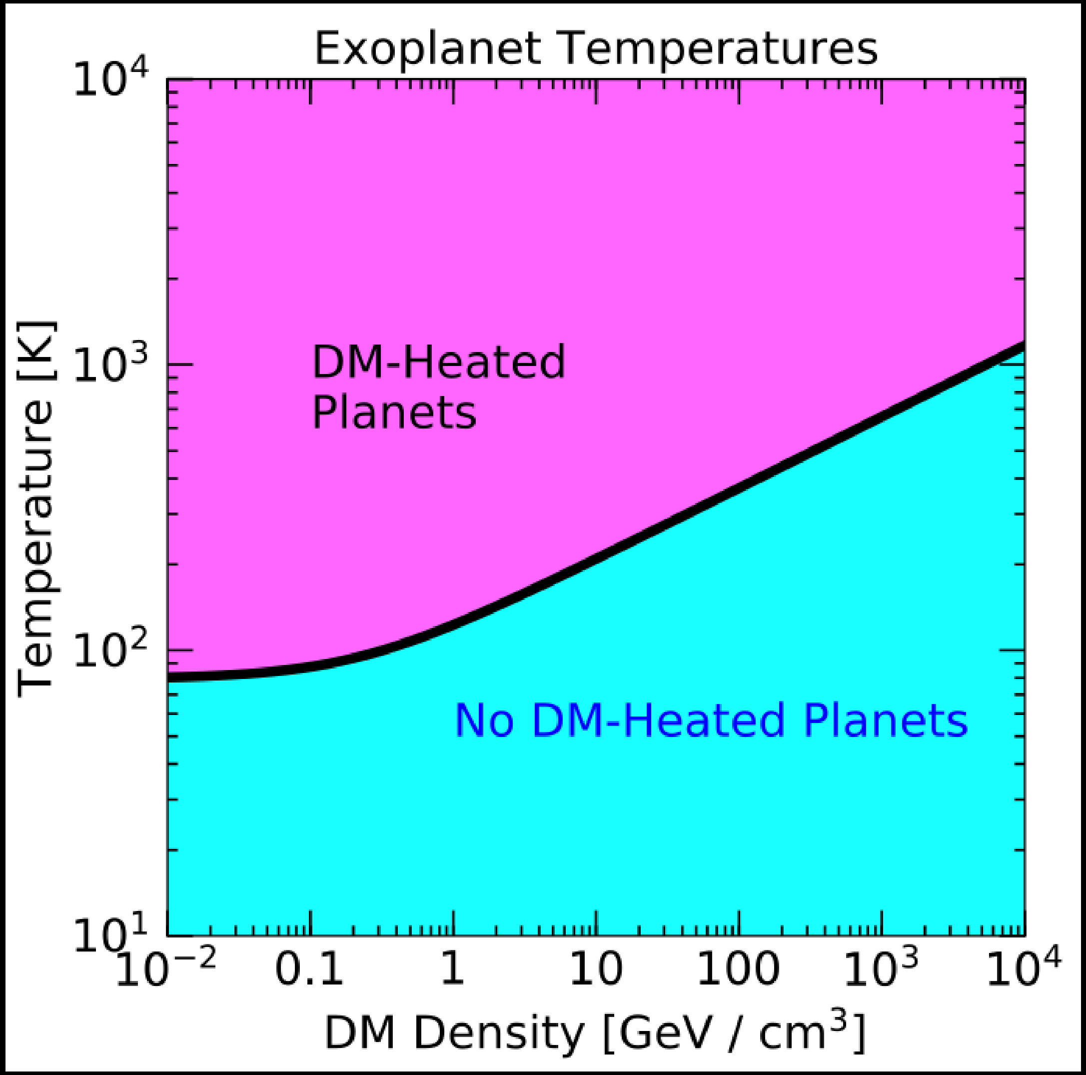
- Mock distribution of exoplanets with masses 20 − 50 Jupiters, gNFW profile, with and without DM heating

- 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



Deviations: DM-overdensities



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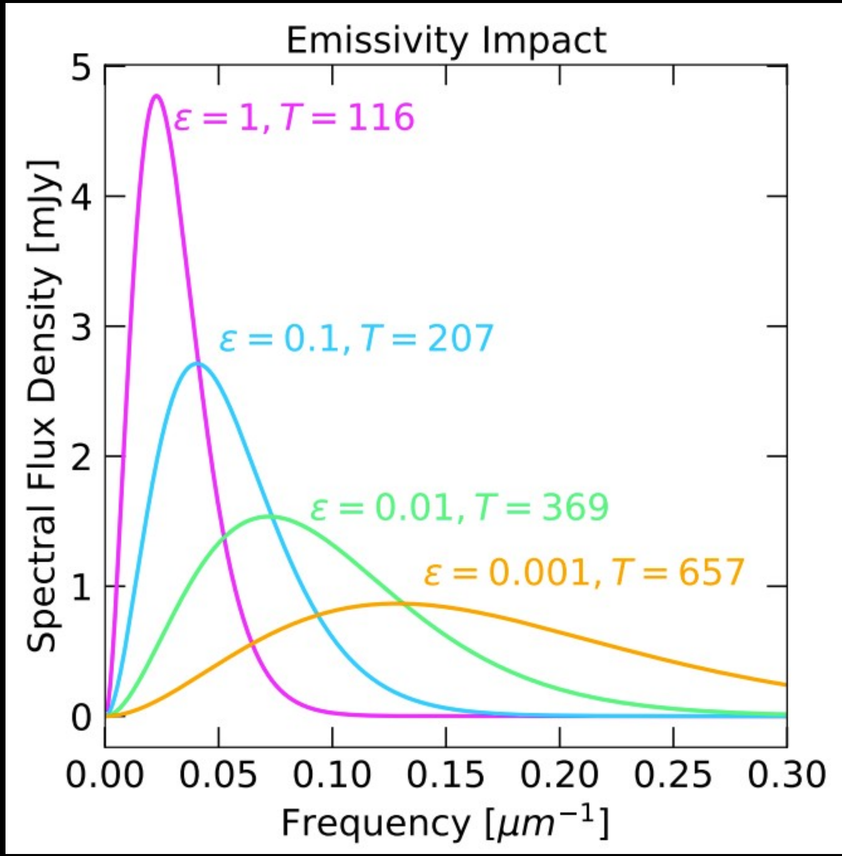
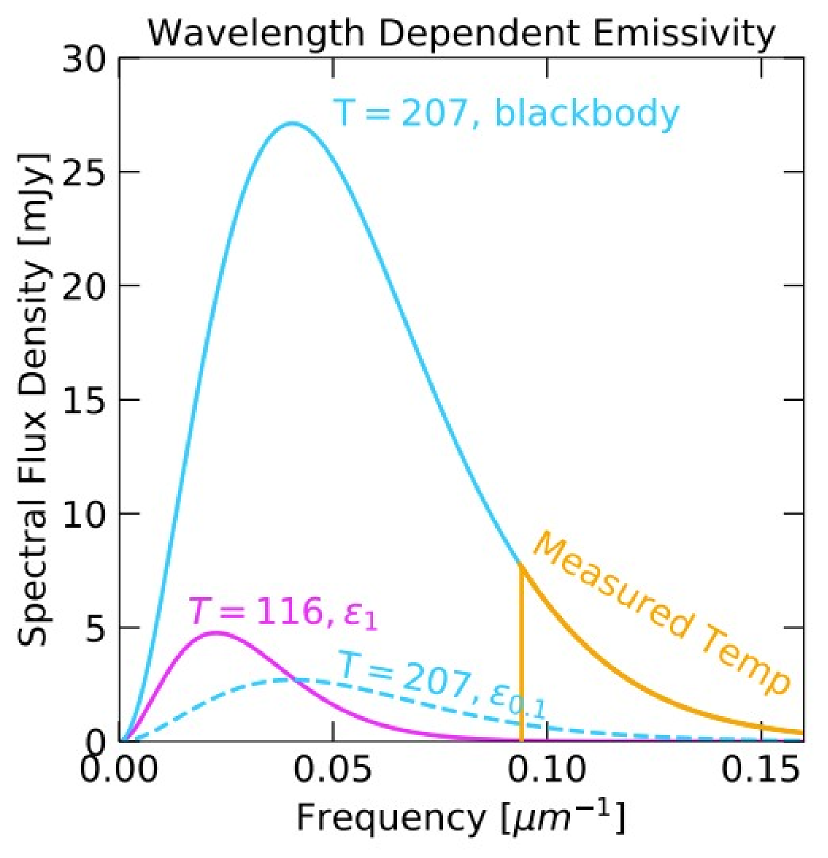
Deviations: Non-Blackbody Spectra

Atmosphere effects can cause deviations from a blackbody

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





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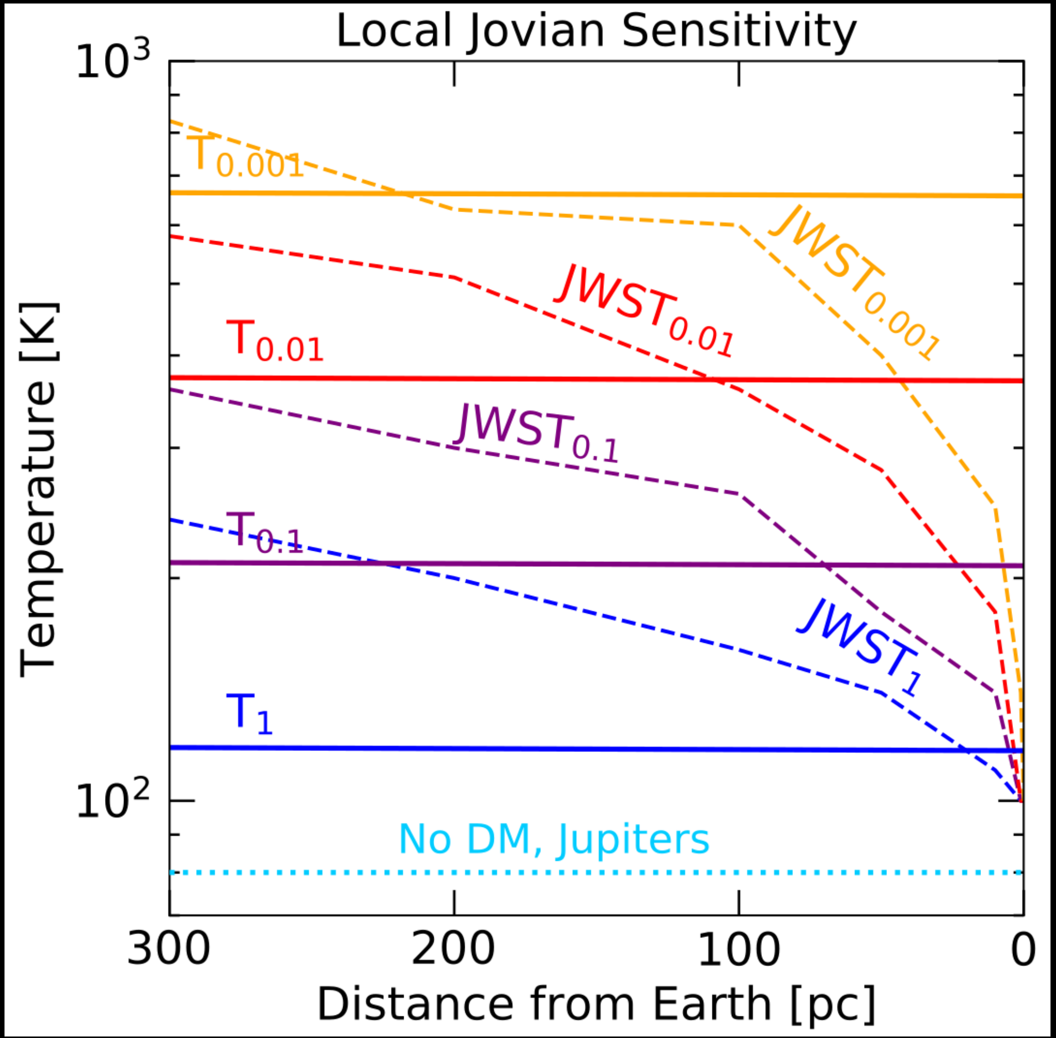
Local DM-Heated Exoplanet Search

- 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



Prospects for these searches?

Planet	Radius ($R_{\rm jup}$)	Mass ($M_{\rm jup}$)	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]
$\rm Psi^1$ 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]
Pirx	1.2	1.1	[illegible]	0.8 au	$\sim$ 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

- To relate the DM heat flow with scattering cross sections, need to find the range of parameters where a fraction f of the DM particles passing through the planet is gravitationally captured

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

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

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

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

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

Bramante et al (2017)

- Given these gaseous planets are mostly hydrogen; assume hydrogen spheres when calculating limits

DM Equilibrium and Evaporation

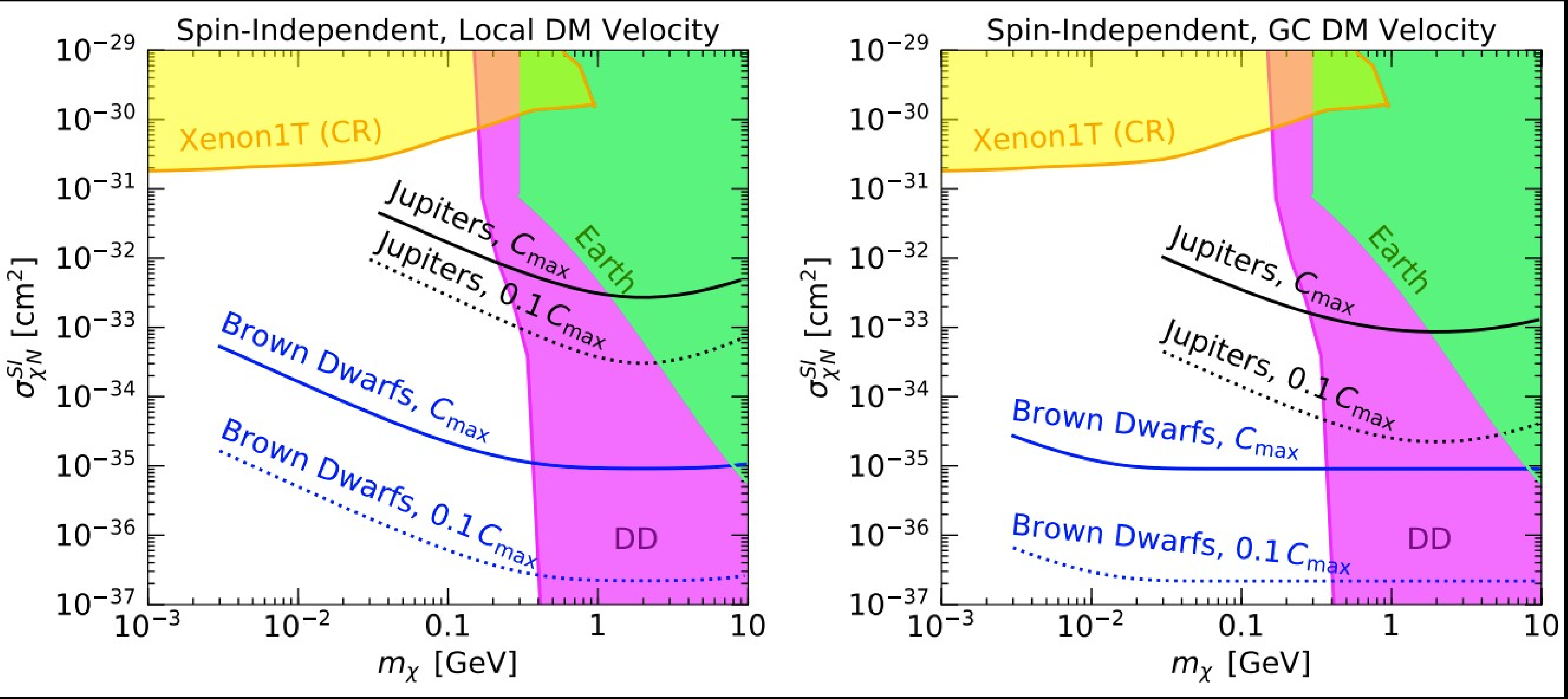
- For maximal rate, want DM scattering and annihilation to be in equilibrium
  - Find DM reaches equilibrium by 1-10 Gigayears

- 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:

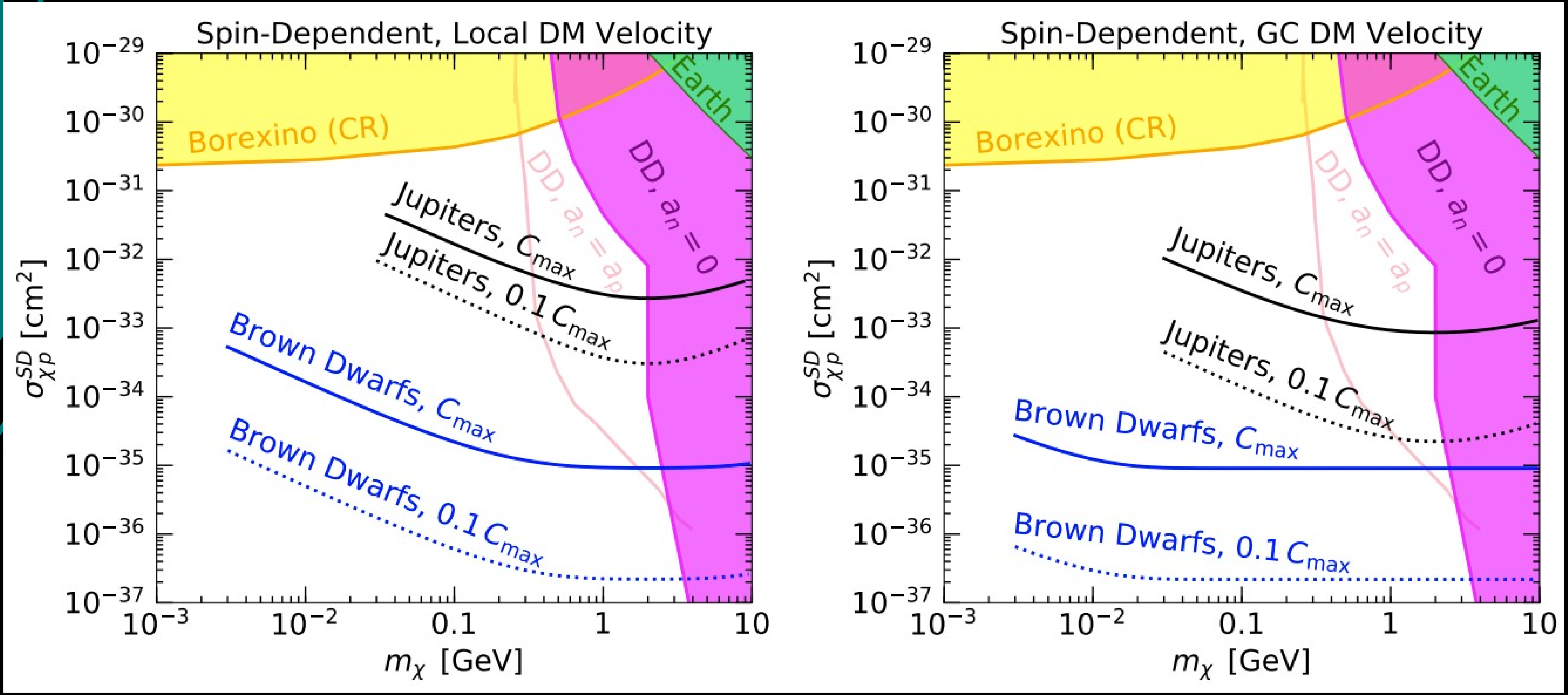
$$E_{\rm DM}^{\rm kin} = \frac{3}{2}T(r) < \frac{G_N M(r) m_\chi}{2r}$$

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

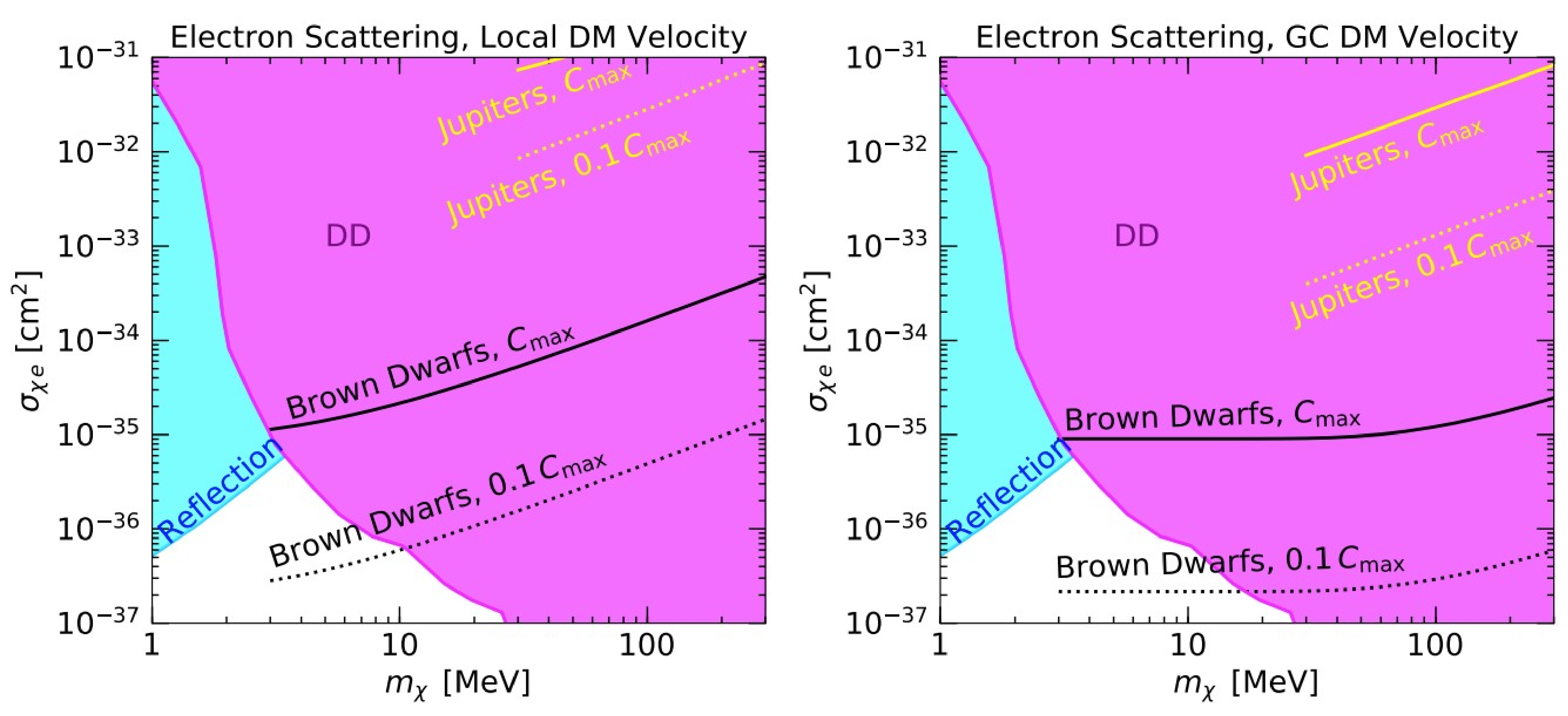
DM scattering cross section sensitivity



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*

Summary

- 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
  - Potential sensitivity to overdensities
- 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 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

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

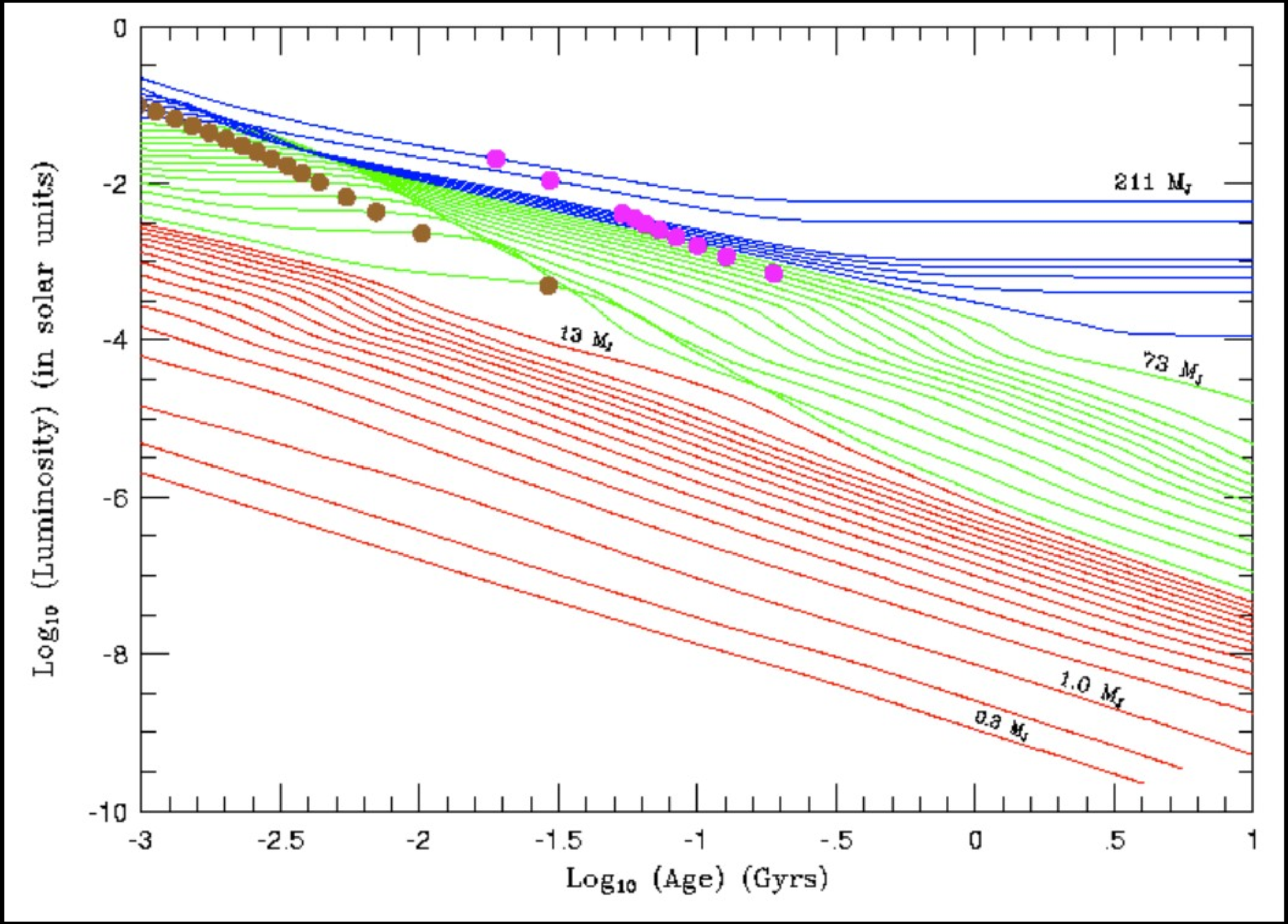
$$\tau = \frac{3}{2}\frac{\sigma}{\sigma_{\rm sat}}$$

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

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

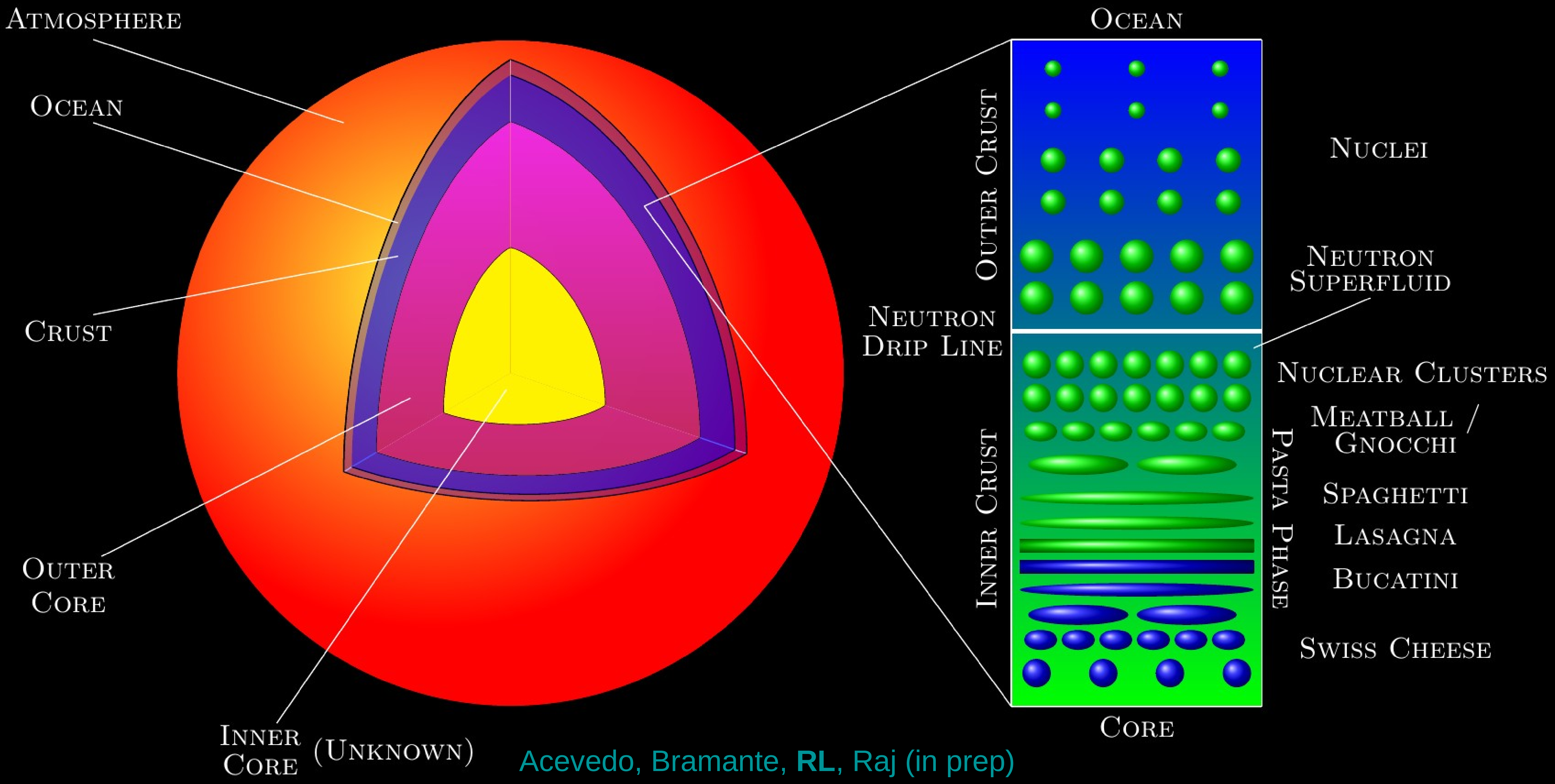
$$\sigma_{\chi A}^{\rm SI} = \sigma_{\chi N}^{\rm SI}\left(\frac{\mu(m_A)}{\mu(m_N)}\right)^2\left[Z + \frac{a_n}{a_p}(A - Z)\right]^2$$

AGE – COOLING CURVES



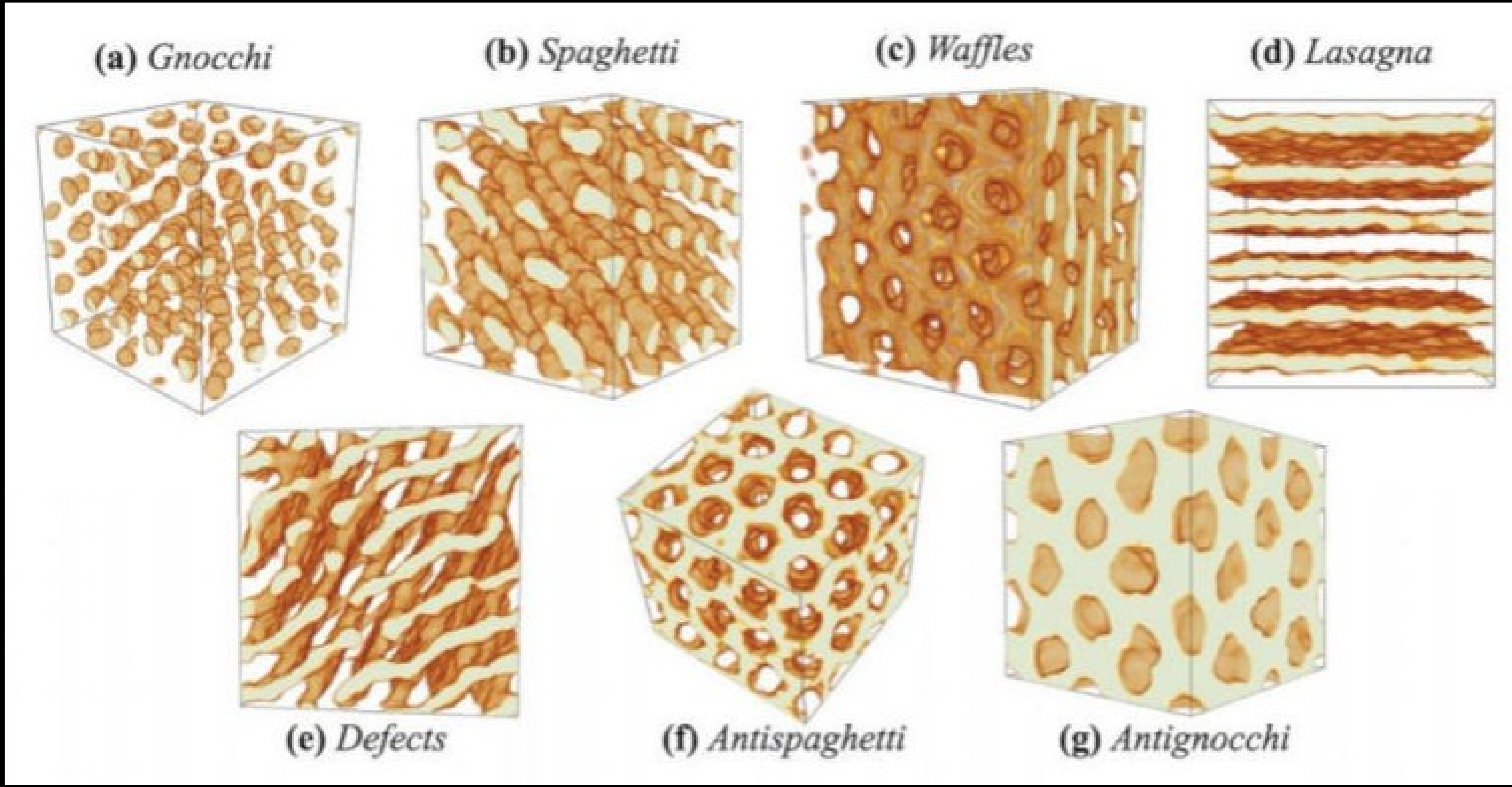
Other ways than accumulation to get lots of DM into celestial objects?

INSIDE NEUTRON STARS



Acevedo, Bramante, **RL**, Raj (in prep)

NUCLEAR PASTA



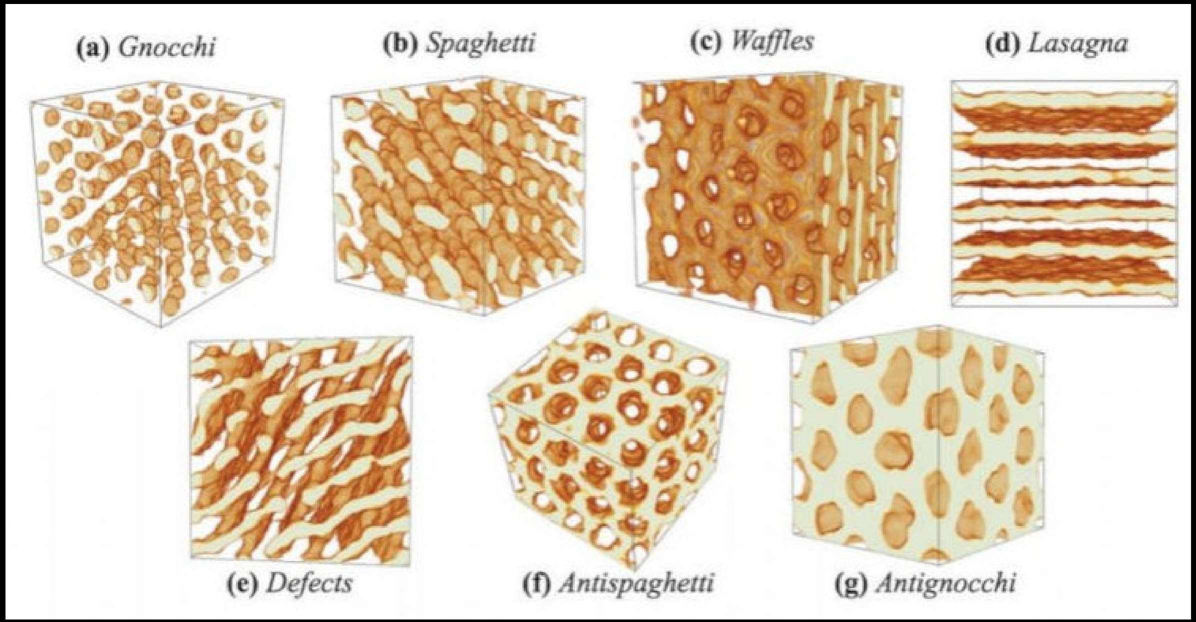
Caplan, Schneider, Horowitz ‘18

THE PASTA COMMUNITY

+ Pasta impacts properties of neutron stars and core collapse supernovae

+ Neutrino interactions: impacts neutrino opacity in supernovae

+ Electron interactions: impact shear viscosity, thermal and electrical conductivity



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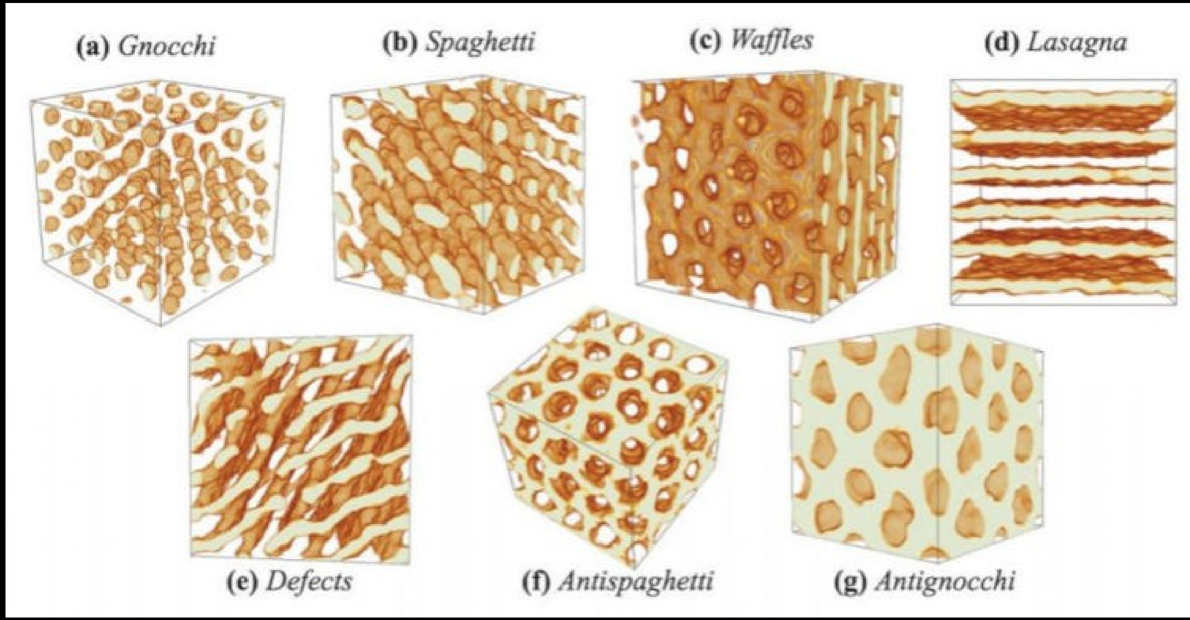
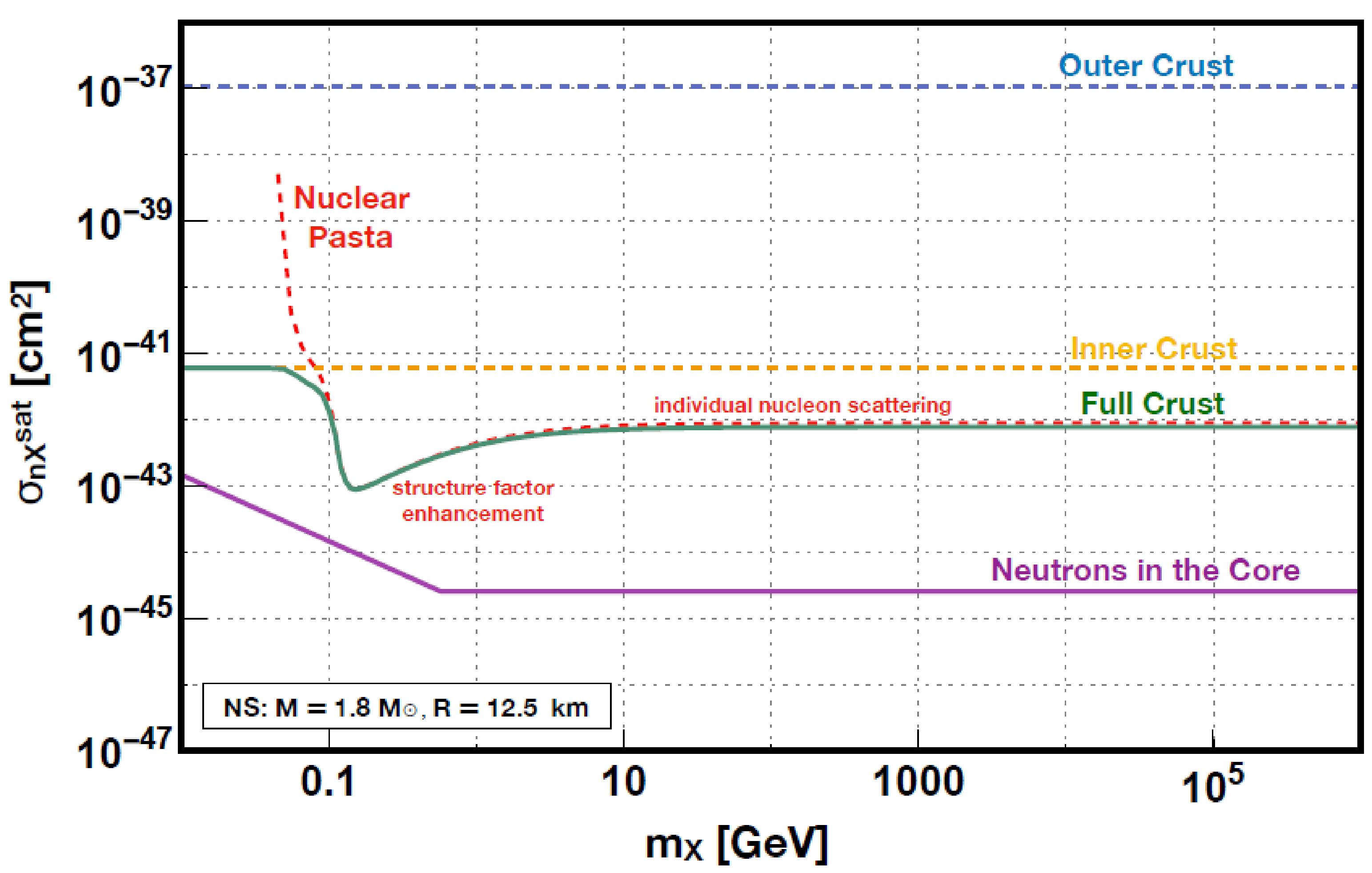


Caplan, Schneider, Horowitz '18

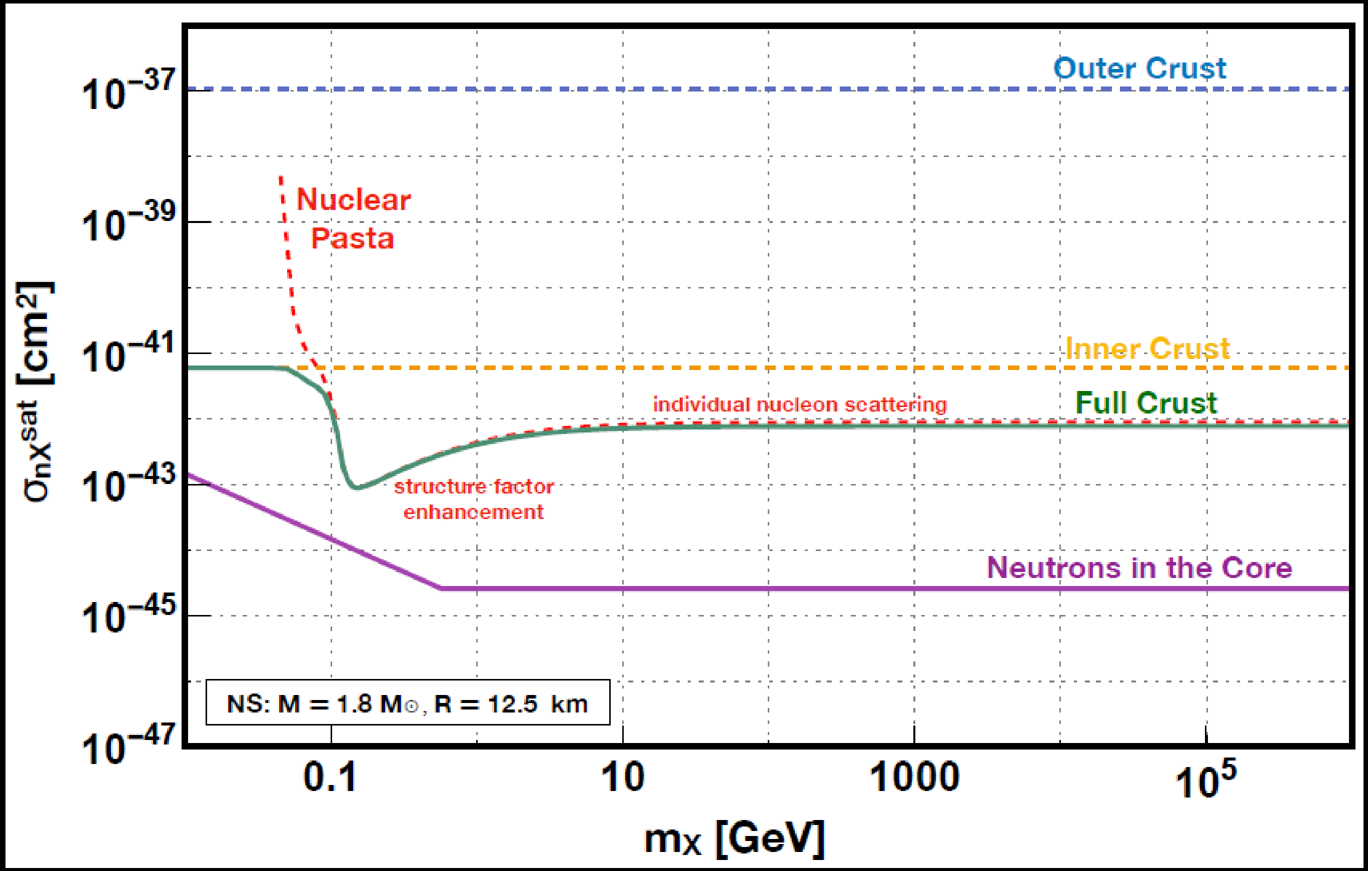
Use known response functions from simulations to calculate dark matter scattering with pasta!

DARK MATTER – NEUTRON STAR INTERACTIONS



Acevedo, Bramante, **RL**, Raj (in prep)

PASTA BEATS DIRECT DETECTION



- Low masses
- High masses
- Velocity suppressed
- Spin-dependent
- Inelastic DM (Higgsinos!)

Acevedo, Bramante, **RL**, Raj (in prep)

DARK MATTER - PASTA INTERACTIONS

+ Use known response functions from simulations, takes into account coherence of neutrons at different densities and temperatures

$$\sigma_{\mathrm{pasta}}(q) = S_{\mathrm{pasta}}(q)\ \sigma_{\mathrm{n}\chi}$$

Acevedo, Bramante, **RL**, Raj (in prep)

DARK MATTER CAPTURE

$$E_{\rm DM} = m_{\rm DM}(\gamma - 1)$$

$$\dot{M}_{\rm DM} = \rho_{\rm DM} v_{\rm halo} \times \pi b_{\rm max}^2 \times f$$

$$N_{\rm scatters} = \int_{\rm crust} n_{\rm T} \sigma_{{\rm T}\chi} dz$$

$$\frac{dP}{dz} = g_s \rho$$

$$N_{\rm scatters} = \frac{1}{g_s} \int_{\rm crust} n_{\rm T} \sigma_{{\rm T}\chi} \frac{1}{\rho} \frac{dP}{d\rho} d\rho$$

Acevedo, Bramante, **RL**, Raj (in prep)

CRUST SCATTERING

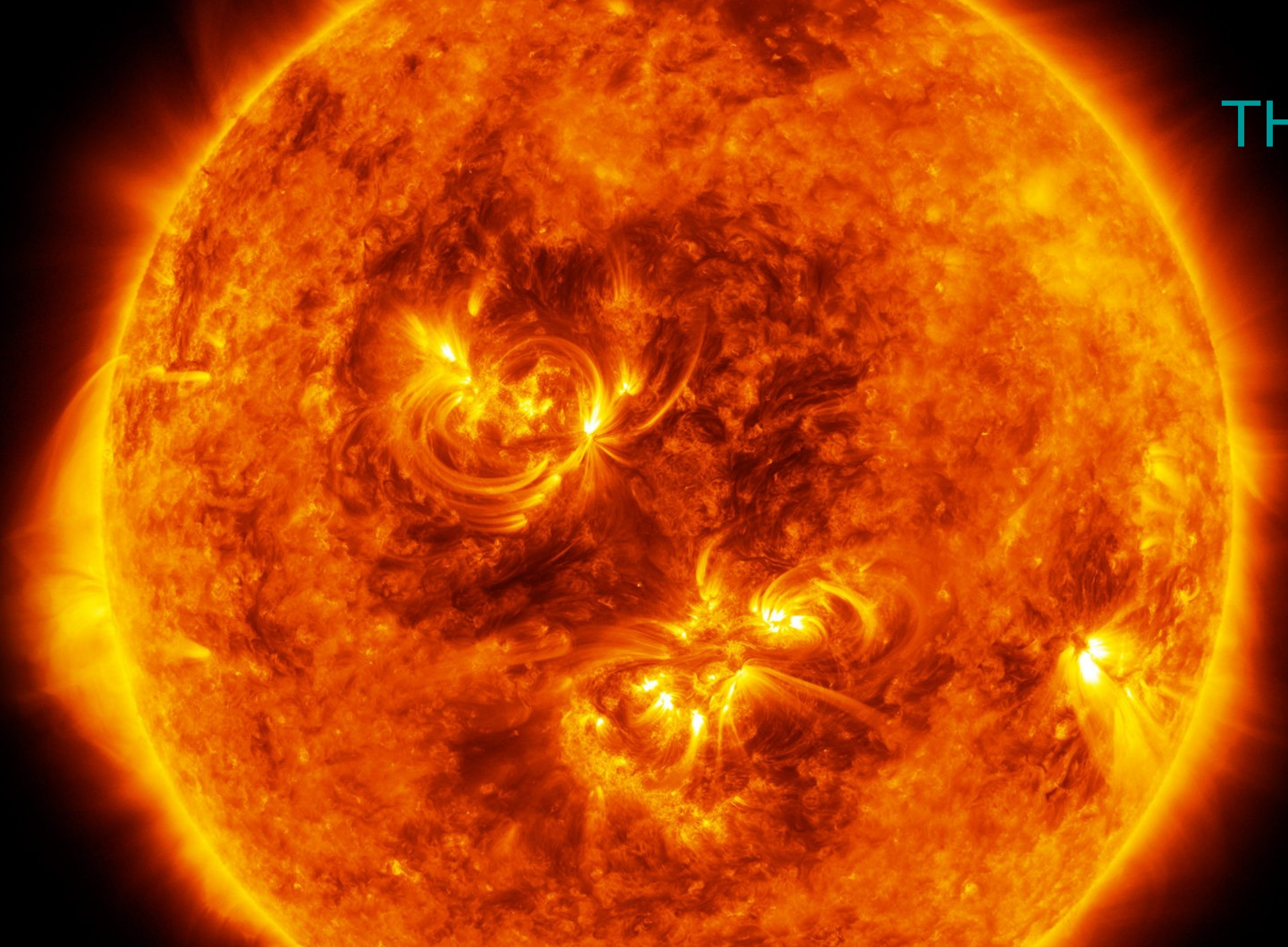
$$\sigma_{T\chi}(q) = \left(\frac{\mu_{T\chi}}{\mu_{n\chi}}\right)^2 A^2 F^2(q) S_T(q) \sigma_{n\chi}$$

+ F (q) captures the loss of coherence over a nucleus
  Suppresses $\sigma_{T\chi}$ for the de Broglie wavelength q^{-1} < nuclear radius.

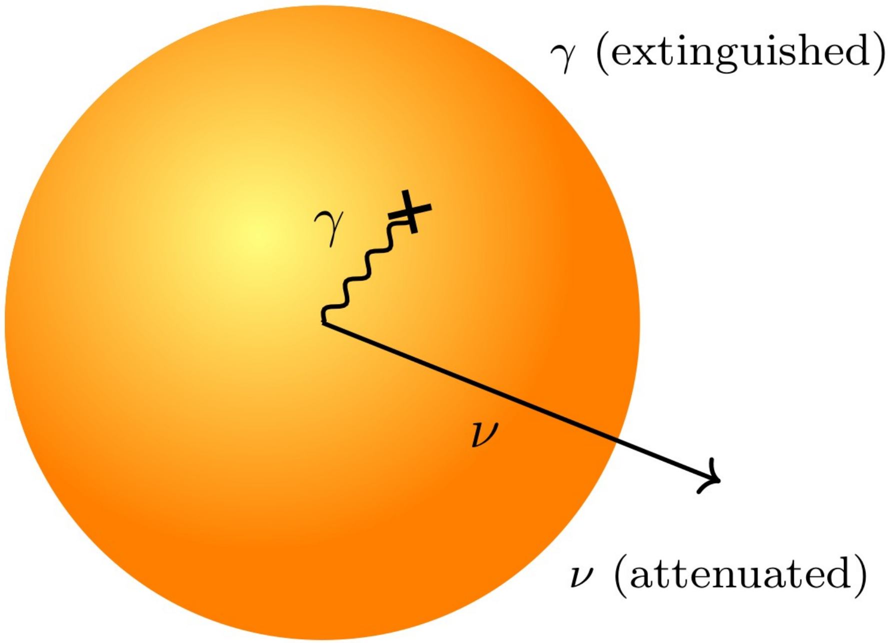
+ S T (q) accounts for coherence among the relative amplitudes of dark matter scattering on multiple nuclei.
  Suppresses the cross section for q^{-1} > nuclear separation

Acevedo, Bramante, **RL**, Raj (in prep)

THE SUN



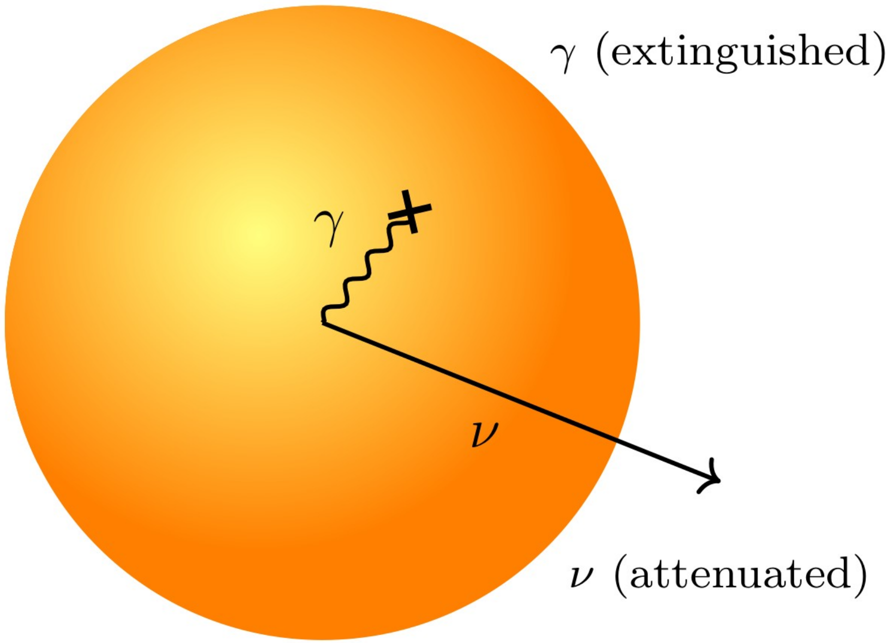
DARK MATTER IN THE SUN



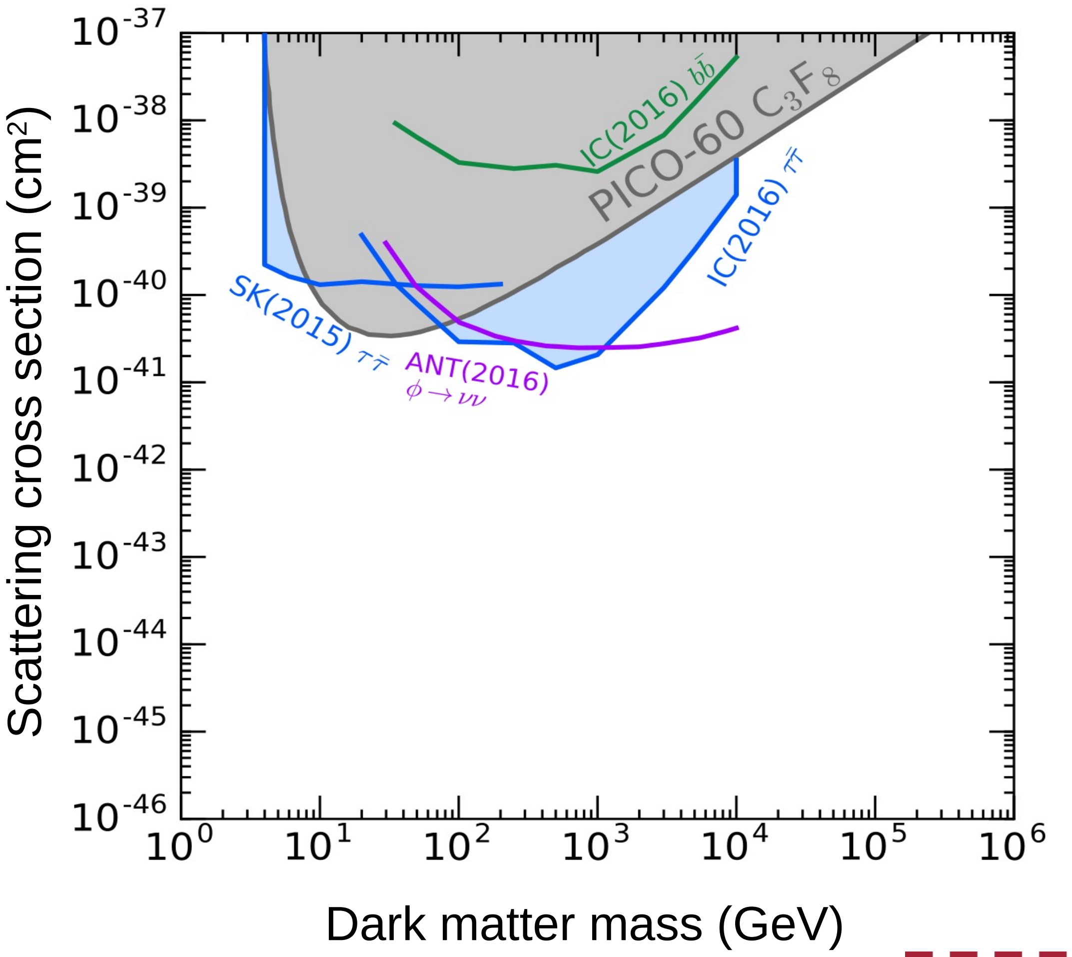
Evolution of dark matter number density

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

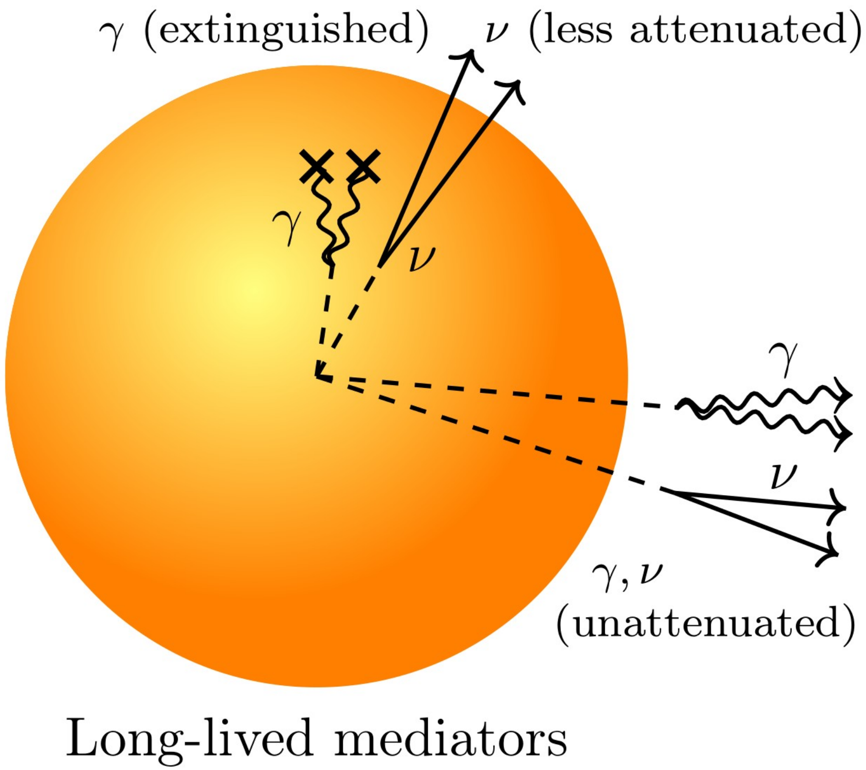
DARK MATTER IN THE SUN



Limits from neutrinos, standard scenario

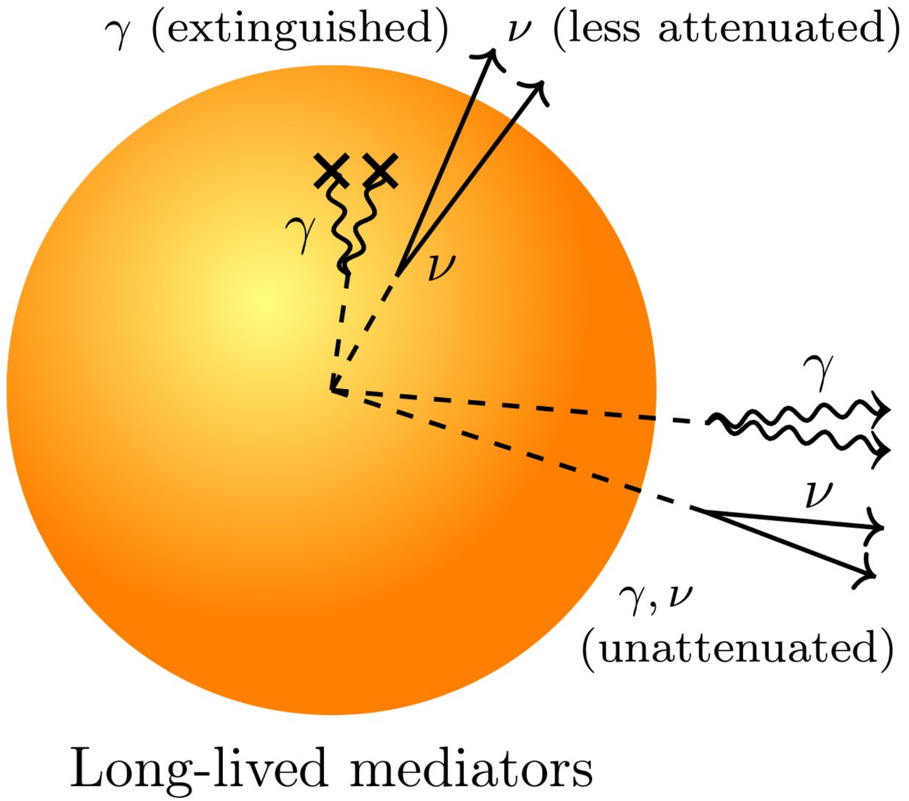


LONG-LIVED SIGNAL BOOST:

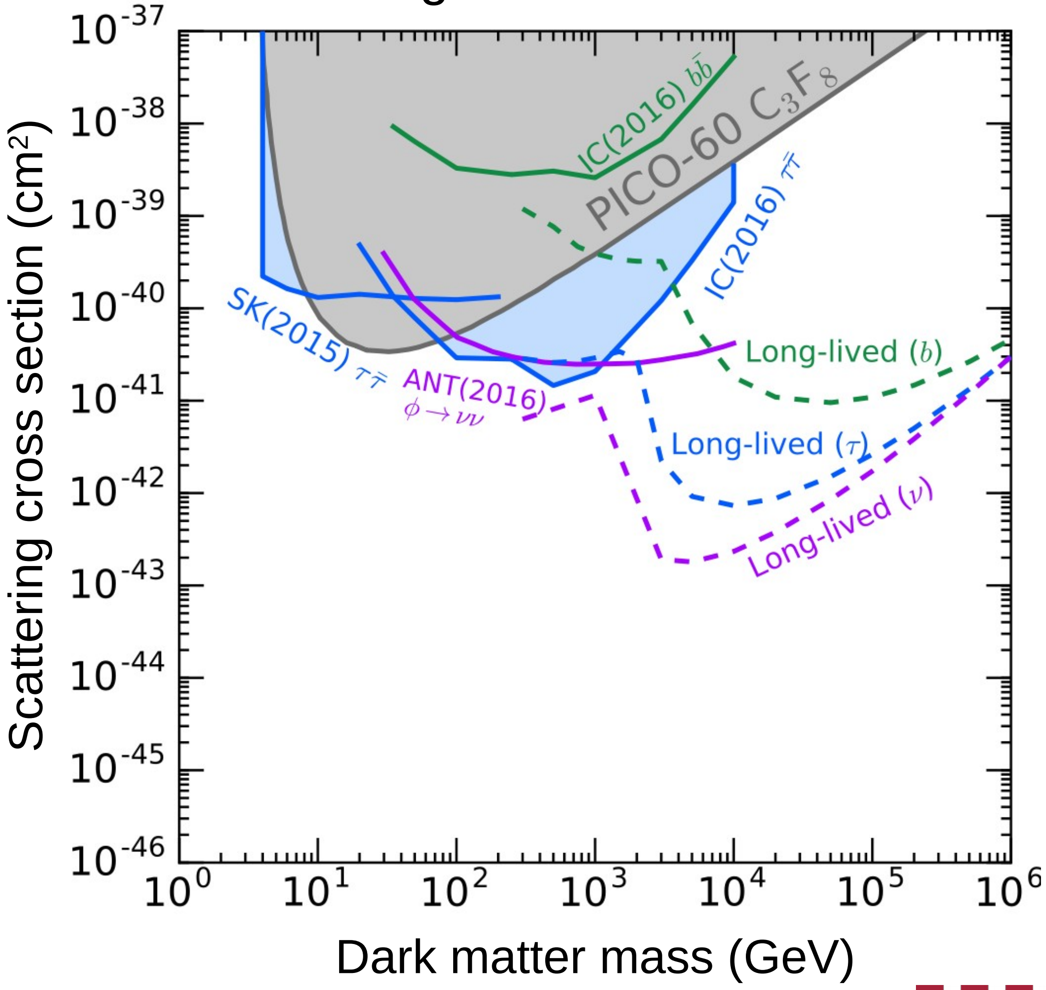


Schuster, Toro, Yavin (PRD ‘10)
Batell, Pospelov, Ritz, Shang (PRD ‘10)
Meade, Nussinov, Papucci, Volansky (JHEP ‘10)

LONG-LIVED SIGNAL BOOST: NEUTRINOS

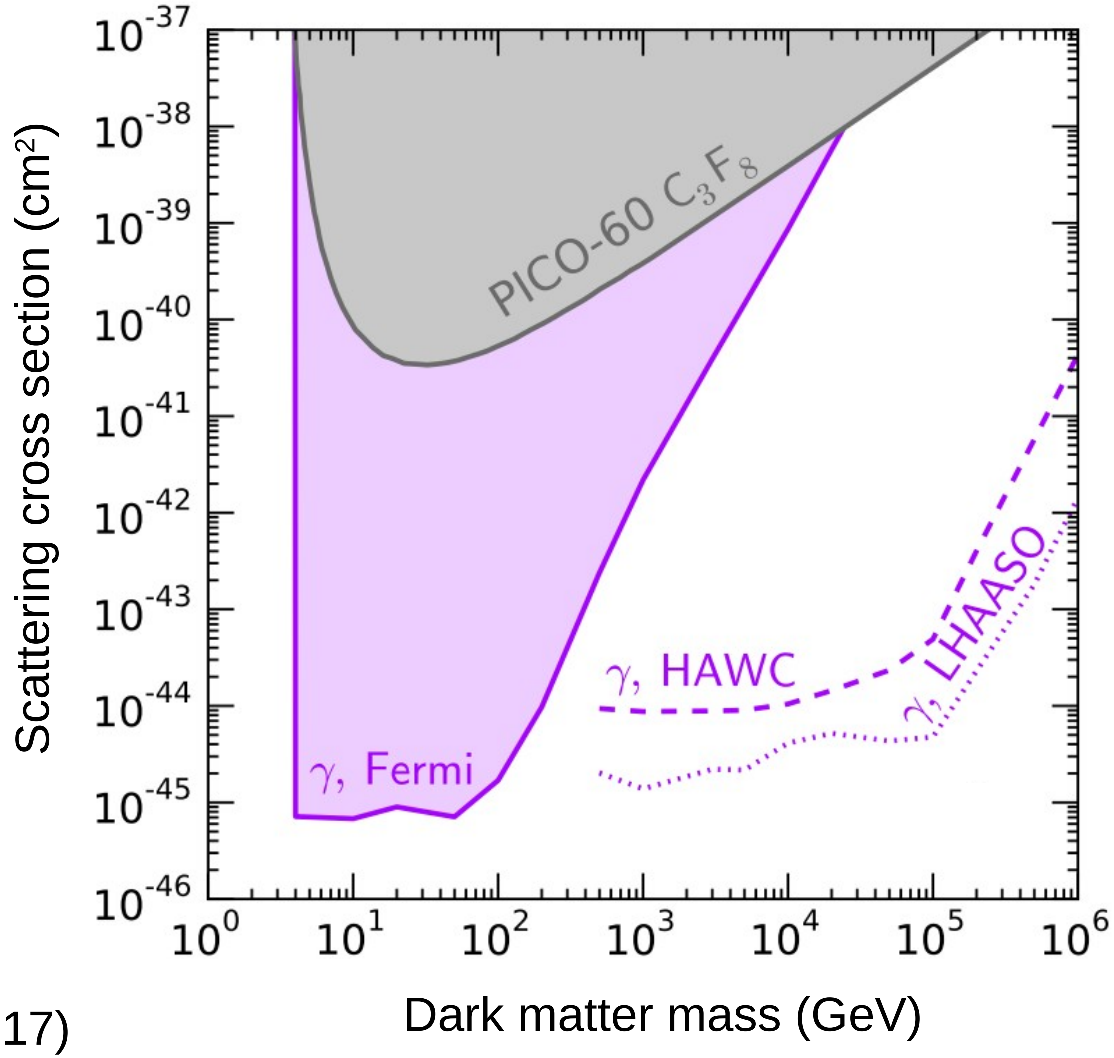


Long-lived mediators



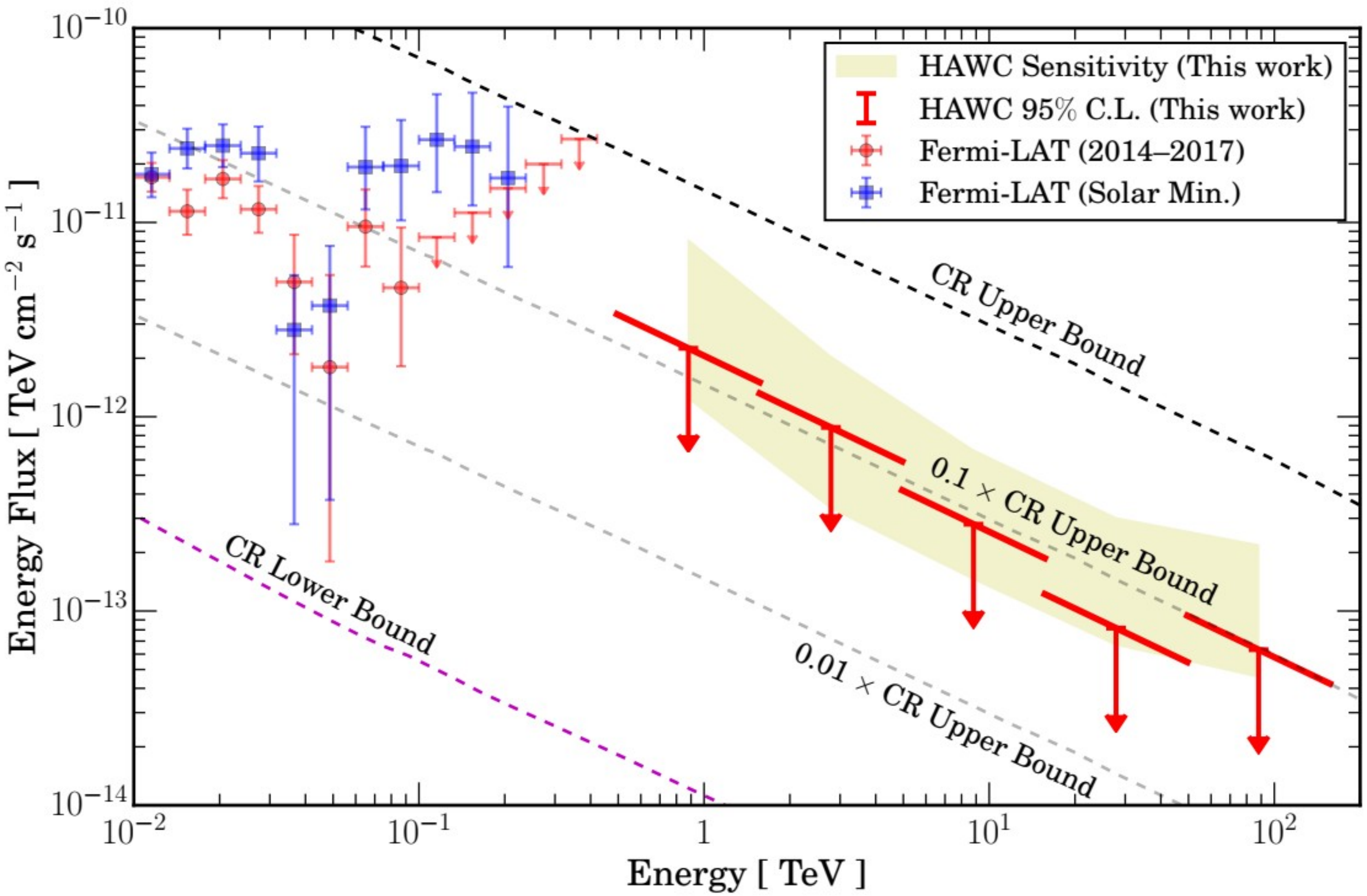
RL, Ng, Beacom (PRD ‘17)

LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)

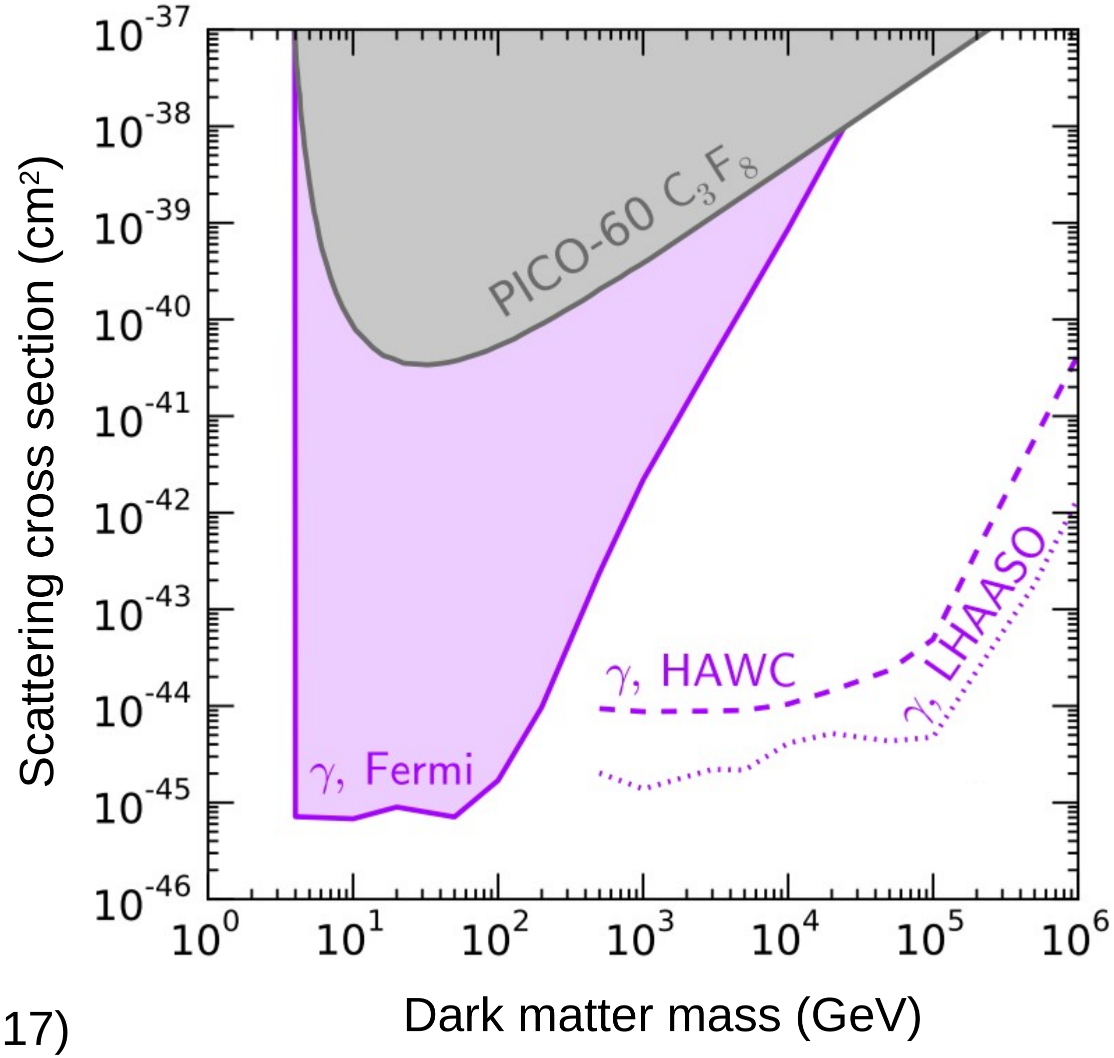
NEW LIMITS WITH HAWC



HAWC Collaboration + **RL** (PRD ‘18)

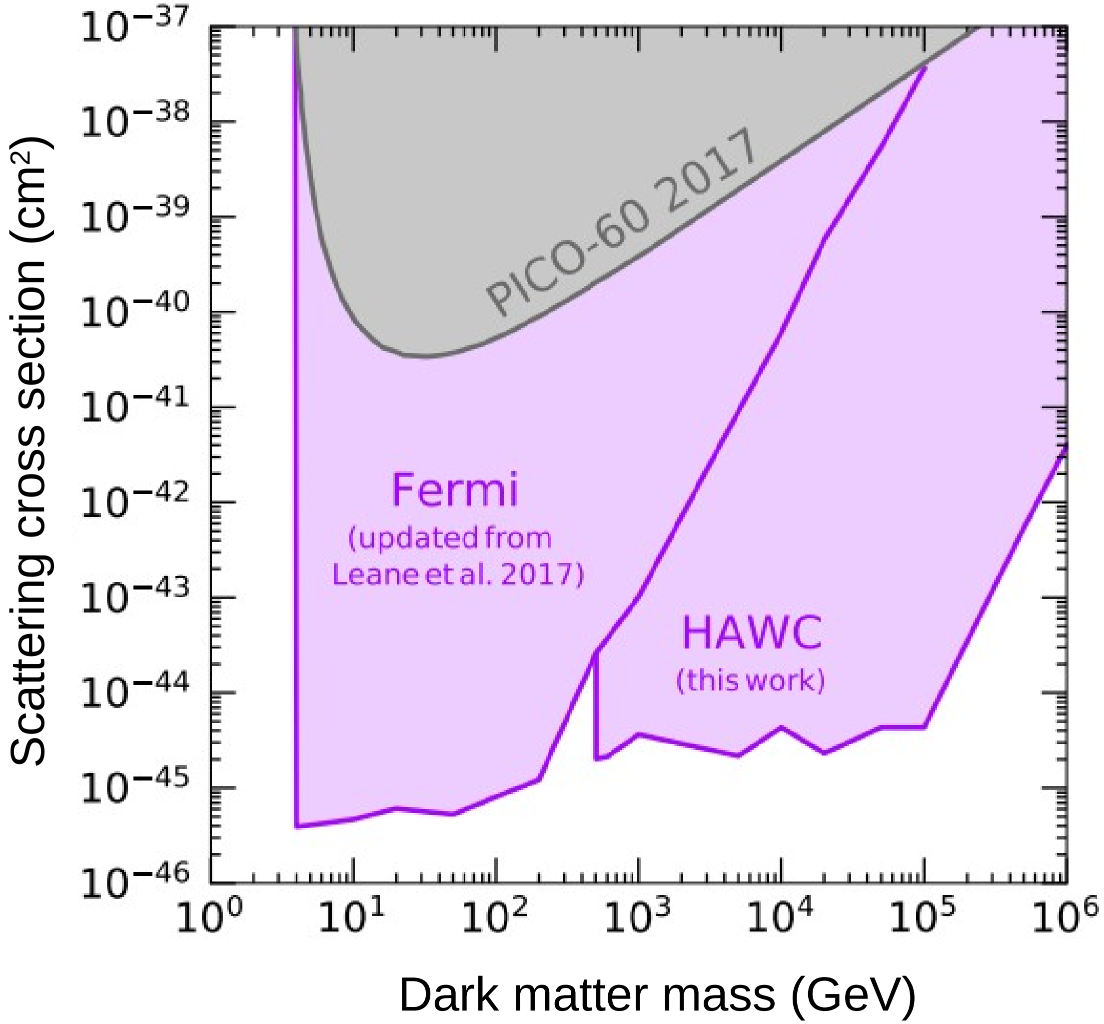
HAWC Collaboration + **RL** (PRD ‘18)

LONG-LIVED SIGNAL BOOST: GAMMA RAYS



RL, Ng, Beacom (PRD '17)

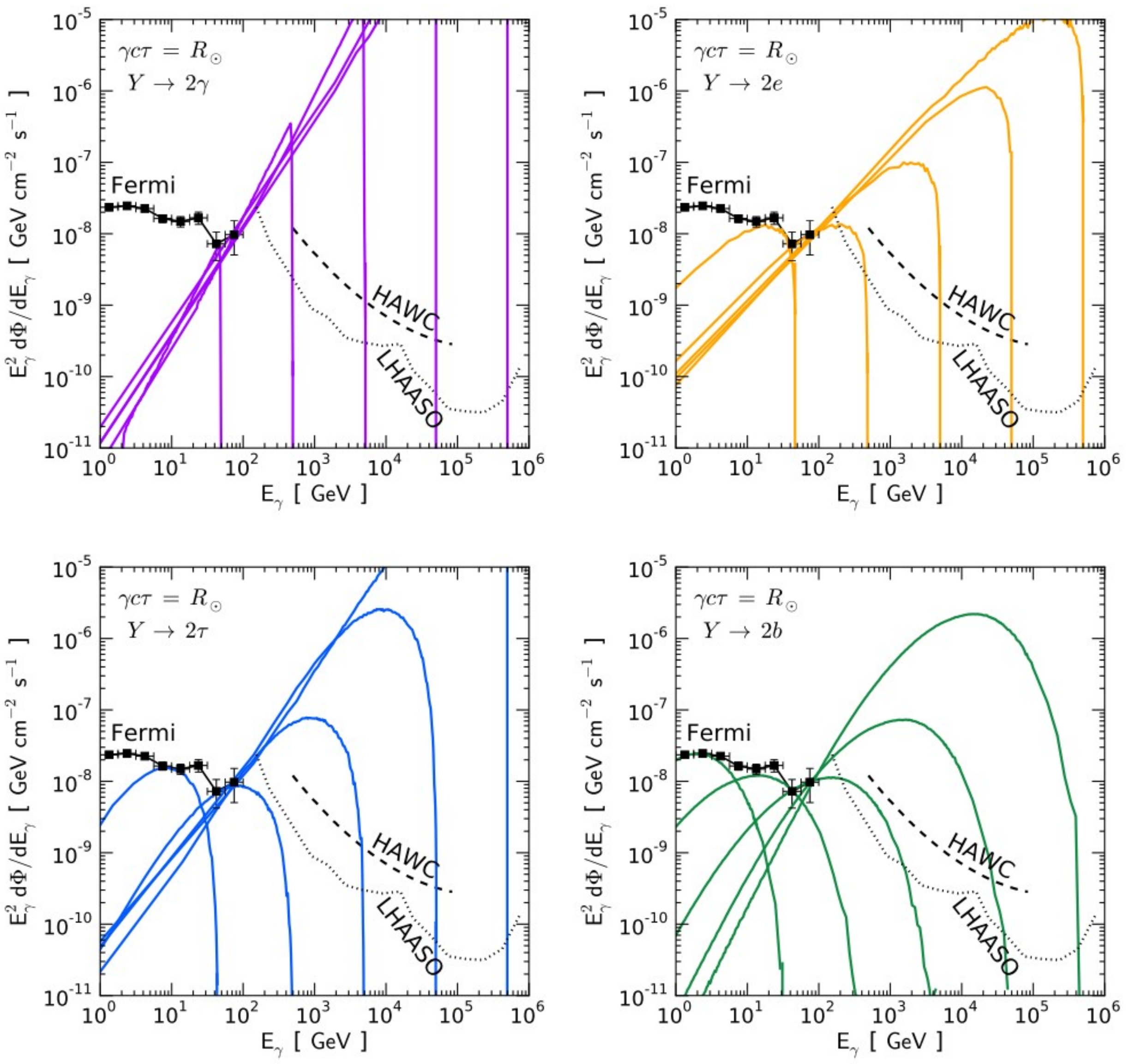
NEW LIMITS WITH FERMI AND HAWC



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

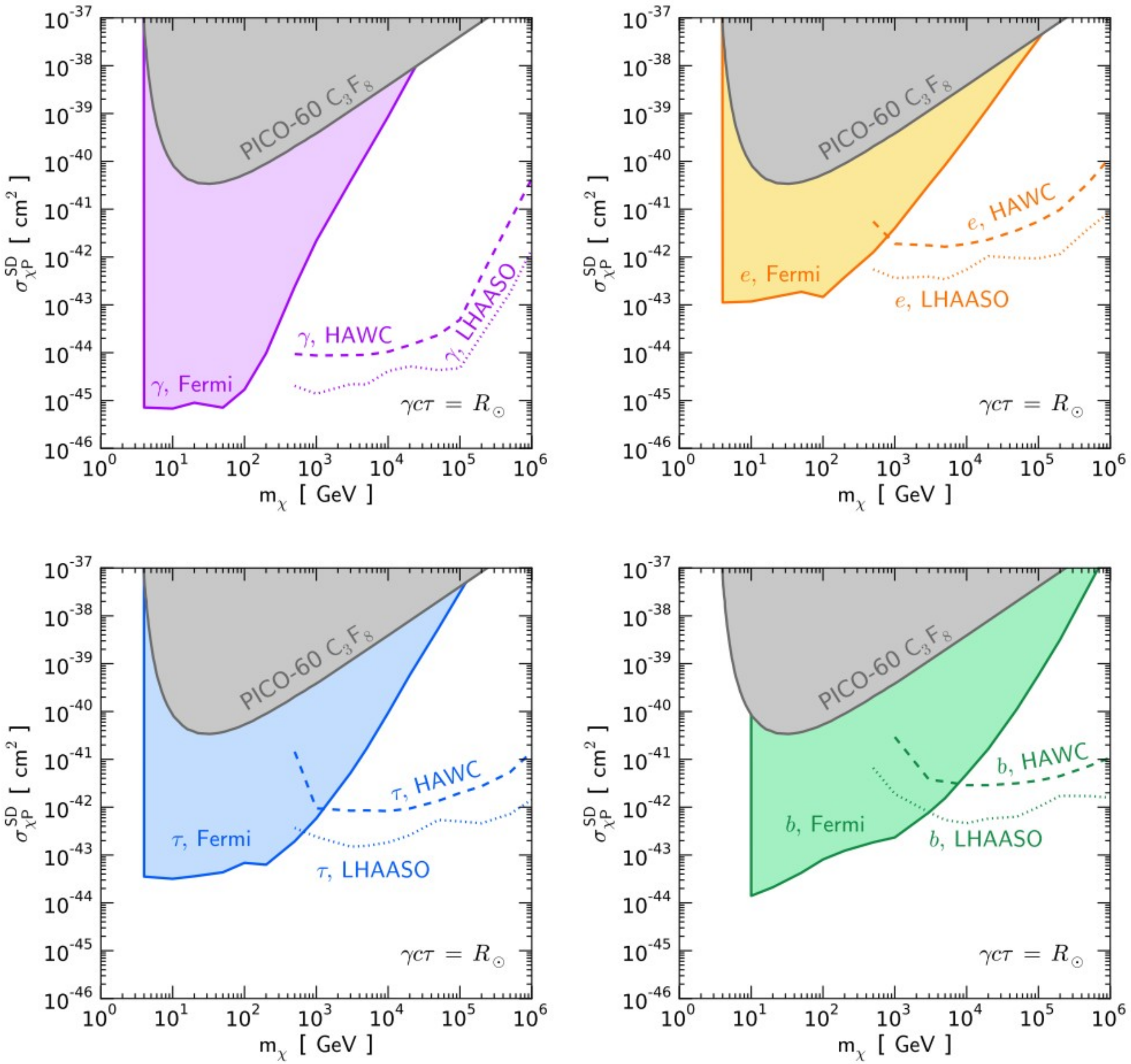
SOLAR DARK MATTER LIMITS

RL, Ng, Beacom (PRD '17)

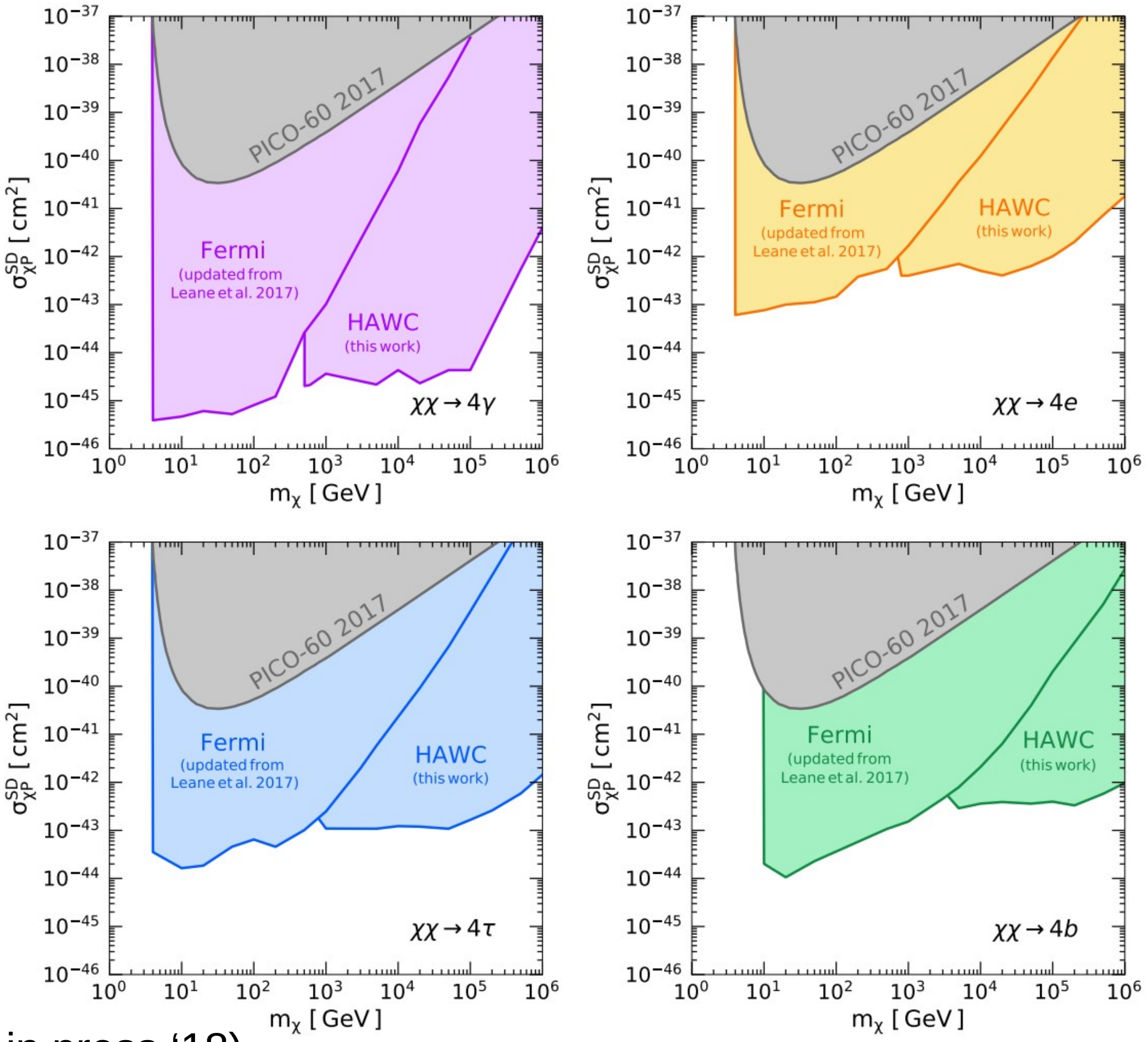


SOLAR DARK MATTER LIMITS

RL, Ng, Beacom (PRD '17)

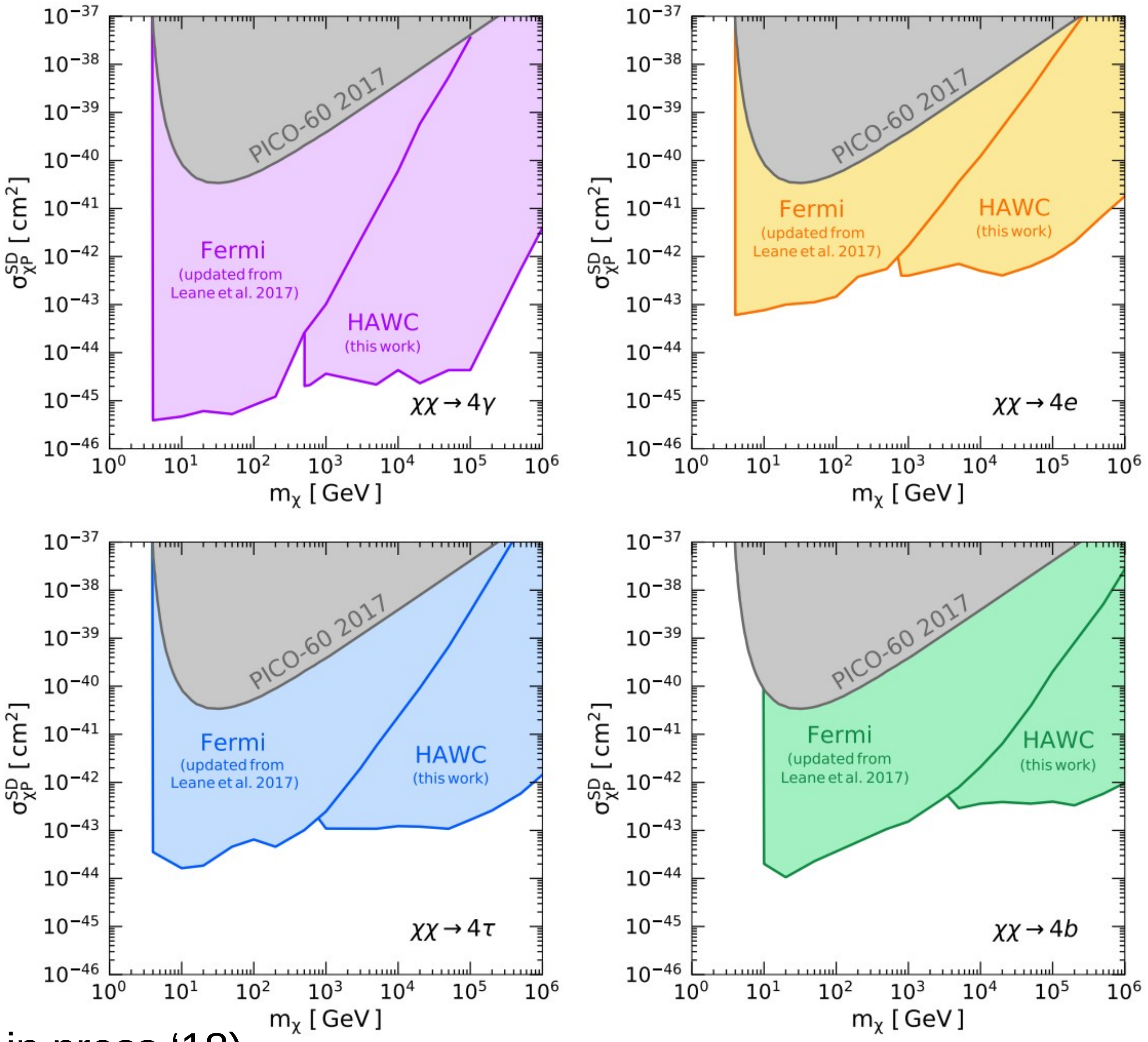


SOLAR DARK MATTER LIMITS: UPDATED



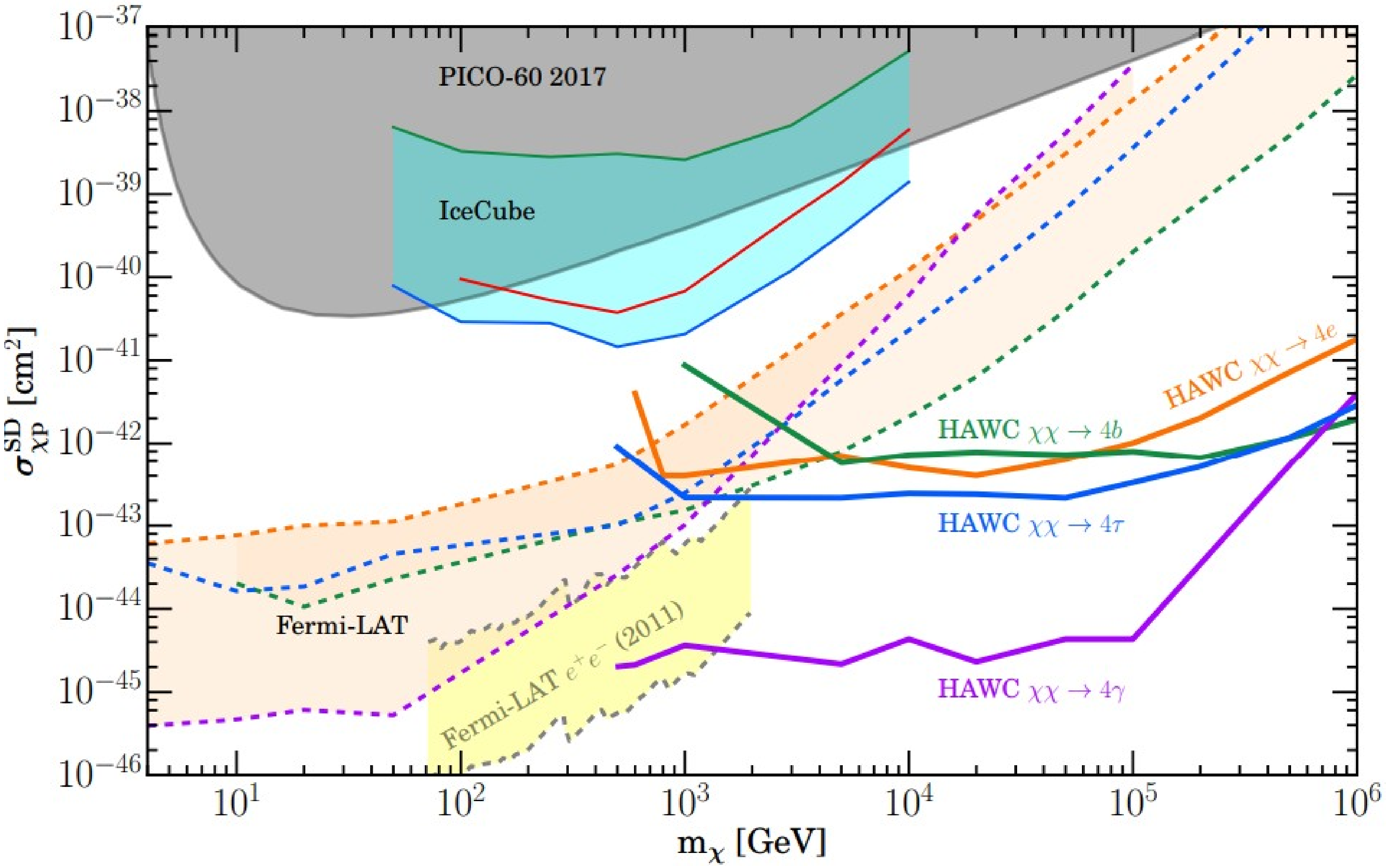
HAWC Collaboration + **RL** (PRD in press ‘18)

SOLAR DARK MATTER LIMITS: UPDATED



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

SOLAR DARK MATTER LIMITS: ALL



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