DETECTING DARK MATTER IN CELESTIAL BODIES

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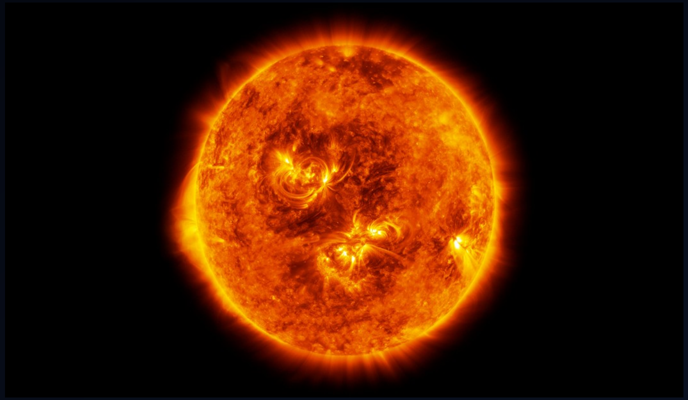
JUNE 28TH 2021

Outline

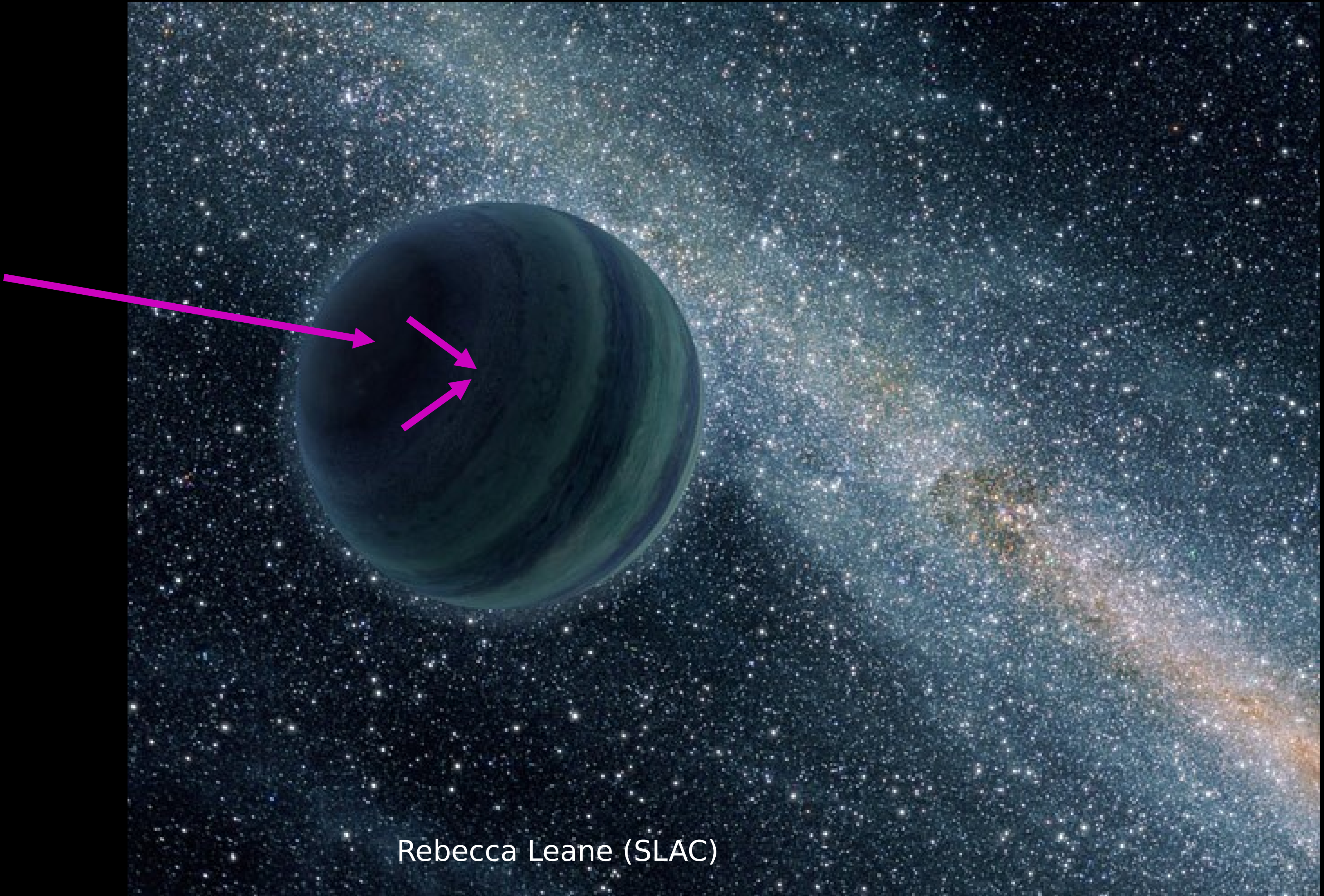
- DM capture in celestial objects
- Ideal properties of celestial objects
- Search locations

- Heating Searches
  - Telescopes, new technologies
  - Earth, White Dwarfs, Neutron Stars, Exoplanets
- Neutrino and Gamma-Ray Searches
  - Telescopes, new technologies
  - Sun, Jupiter, populations of celestial bodies

- Interesting things I don't have time to mention



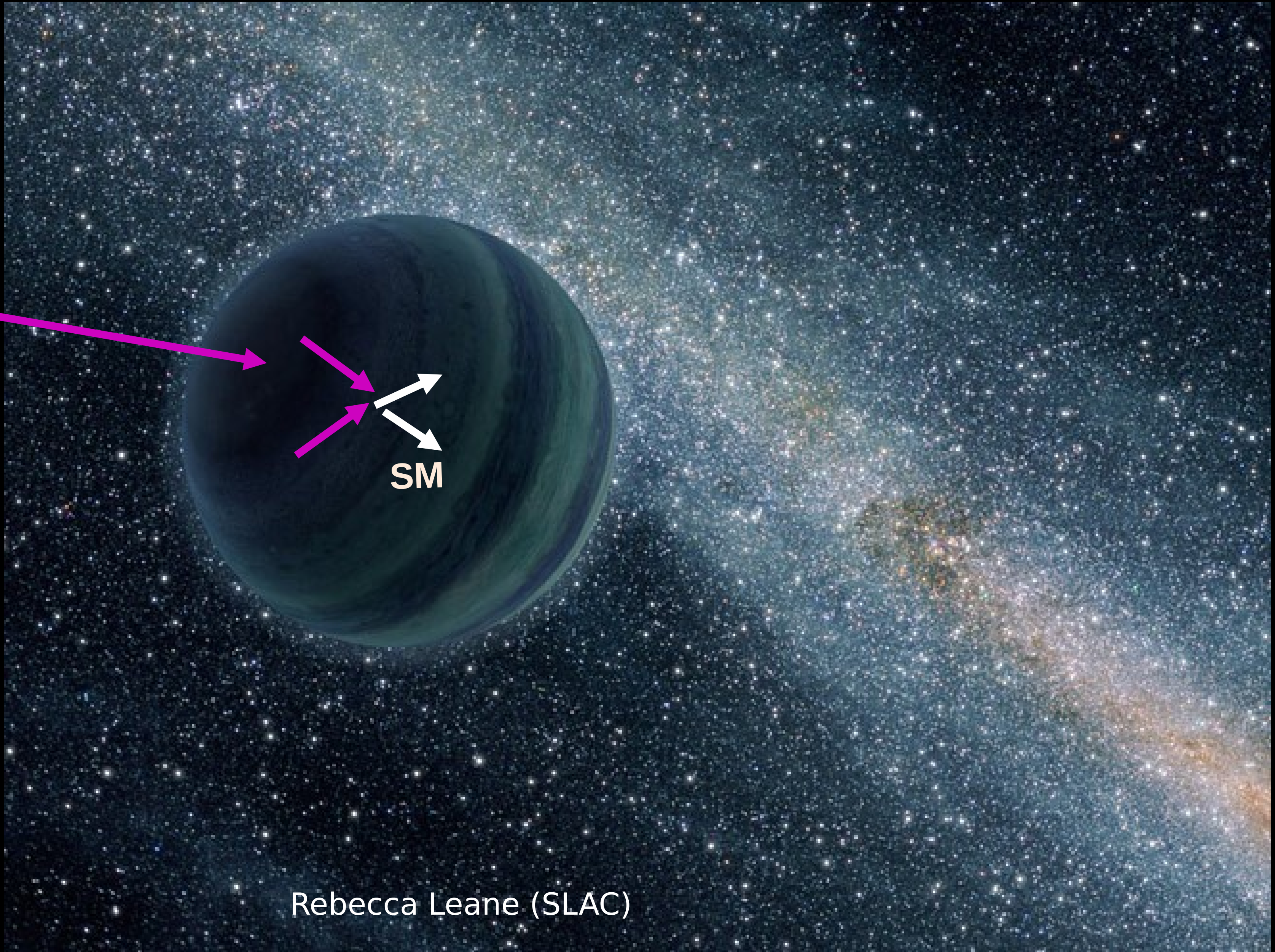
DM capture in celestial bodies



Dark Matter

Steigman, Sarazin,
Quintana, Faulkner 1978
Press, Spergel 1985
Gould 1987
Griest, Seckel 1987

DM capture in celestial bodies



Steigman, Sarazin, Quintana, Faulkner 1978
Press, Spergel 1985
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Griest, Seckel 1987

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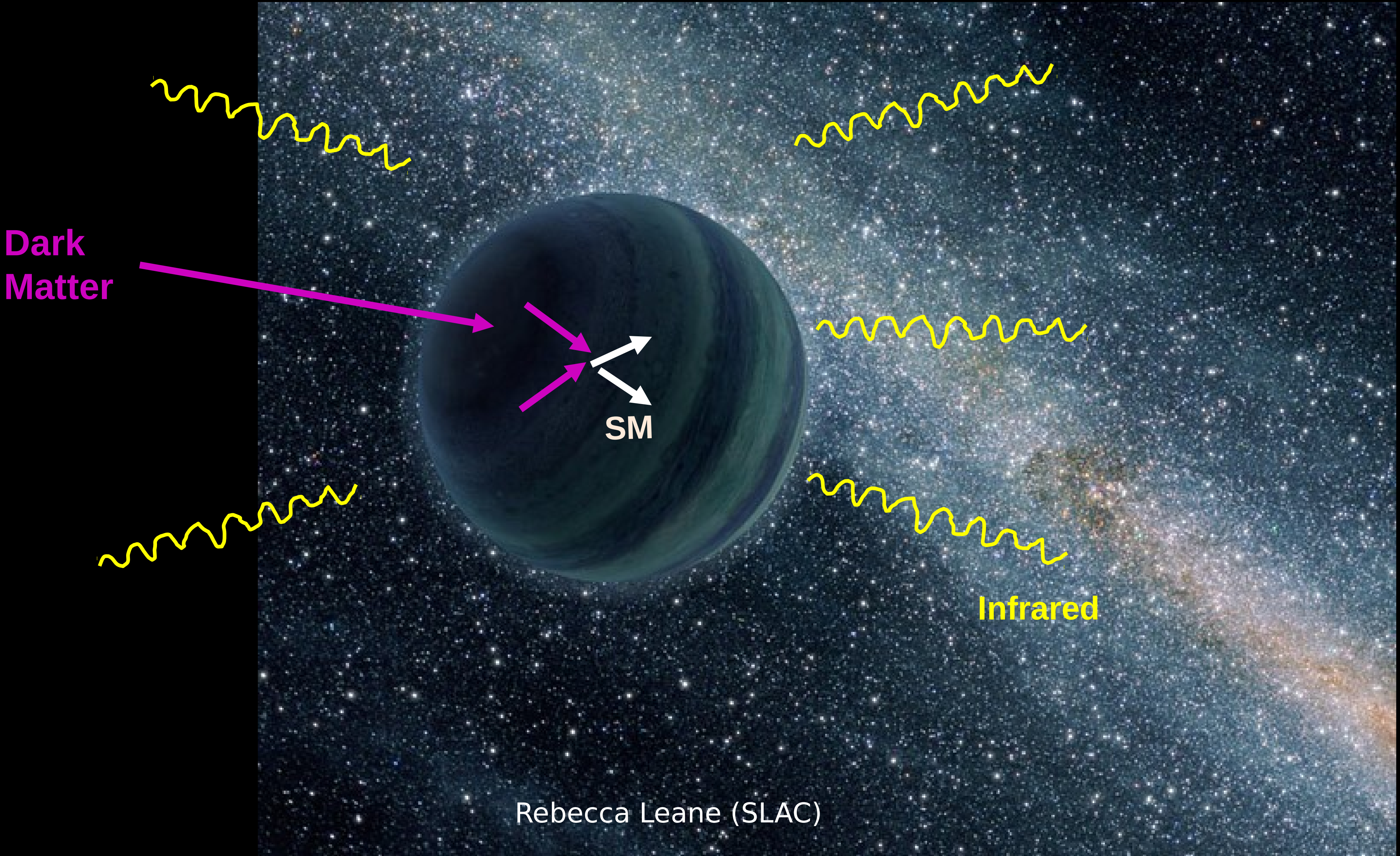
DM capture in celestial bodies



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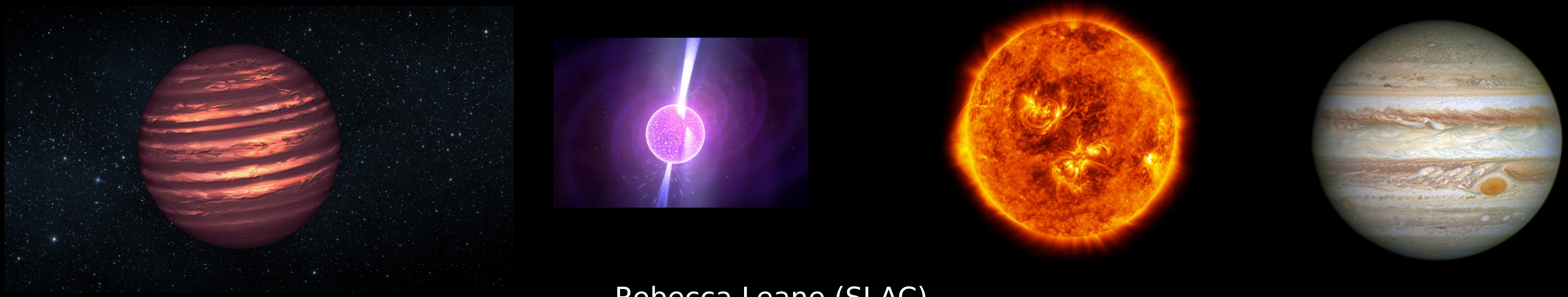
Optimal Celestial Target?

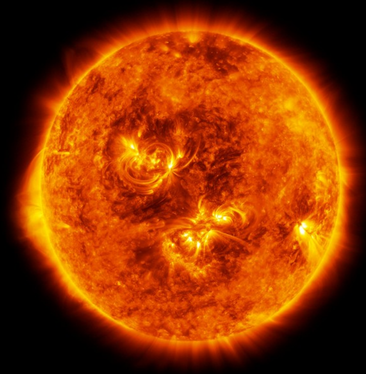
- Radius: Larger amount of DM captured, larger annihilation signal
- Density: Optical depth → lower cross section sensitivities
- Core temperature: Gives kinetic energy to DM, if high, more evaporation (internal heat source?)



Optimal Celestial Target + Location

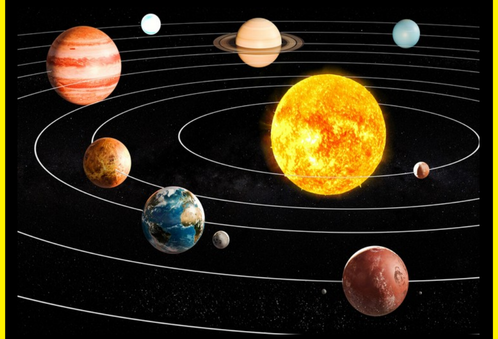
Signal detectability matters!

- Telescope sensitivity to a given flux size?
  - If larger amount of DM captured, larger annihilation signal
  - Further away → 1/R^2 suppression
  - Larger objects easier to detect further away
- Background expectation?



Search Locations

Local Position



Age: ~5 Gyr
Distance: ~100 pc

DM density/velocity:
~0.4 GeV/cm^3
~230 km/s

Globular Clusters

Age: ~12 Gyr
Distance: 2 kpc

DM density/velocity*:
~100 GeV/cm^3, 2 pc
~10 km/s

Galactic Center

Age: ~8 Gyr (varies)
Distance: 8 kpc

DM density/velocity*:
~100 GeV/cm^3, 0.1kpc
~30-100 km/s

Best features:

- ✓ High DM density
- ✓ Low DM velocity
- ✓ Close proximity
- ✓ Old environment
- ✓ Low dust

Recap so far

- Lots of celestial objects: unique temperatures, radii, and densities
  - Different objects optimal for different cross sections or DM masses
- Variety of search locations
  - Beneficial environment features: DM density, velocity, proximity, age
- Variety of DM signatures in celestial objects
  - Now will consider DM heating, for many objects and locations!

Dark Matter Annihilation:
Heating

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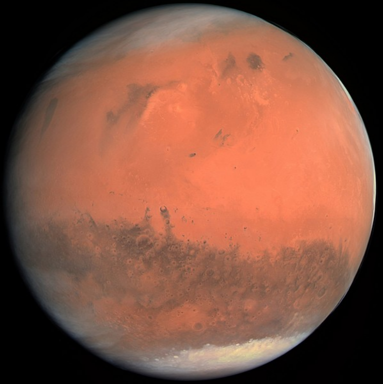
Good heating candidates

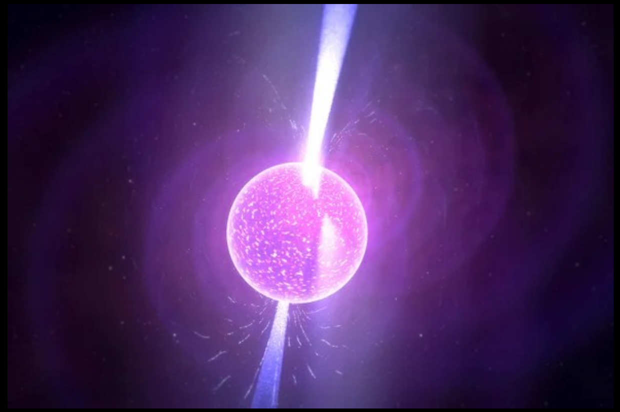
Earth

Mars

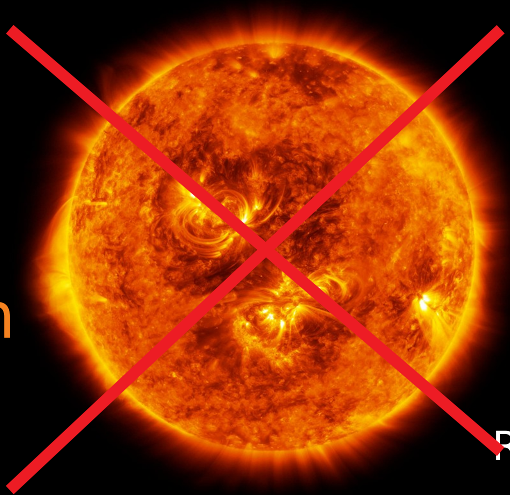


Jupiter

Neutron Stars



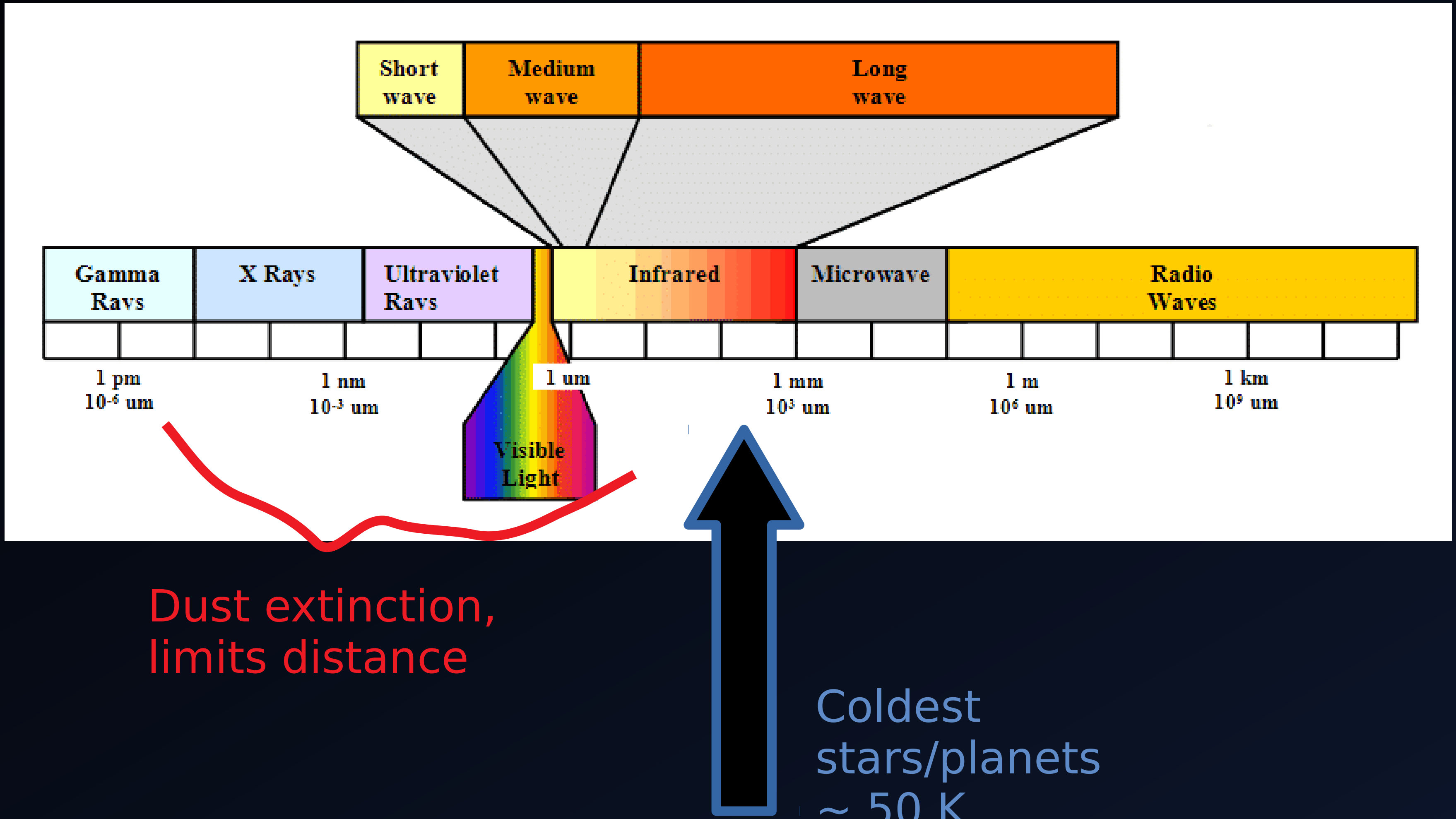
NOT GOOD:
Sun, other main sequence stars



Exoplanets

White Dwarfs

Detecting Dark Matter Heating



Dust extinction,
limits distance

Coldest
stars/planets
~ 50 K

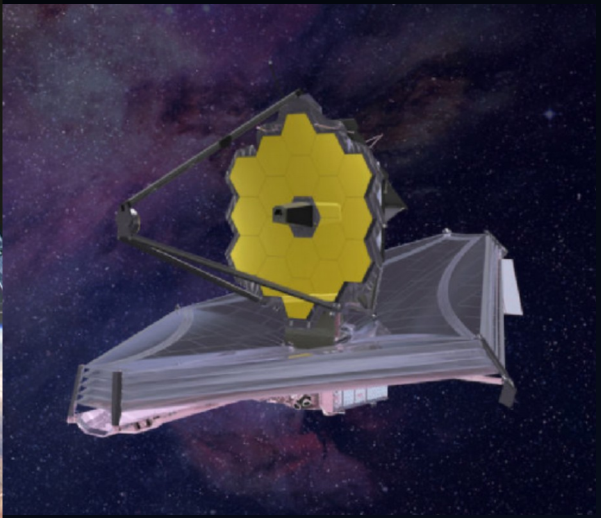
Detecting Dark Matter Heating

Hubble

Near-infrared
Optical
Ultraviolet

~0.12-2 microns

Data obtained
~31 years elapsed

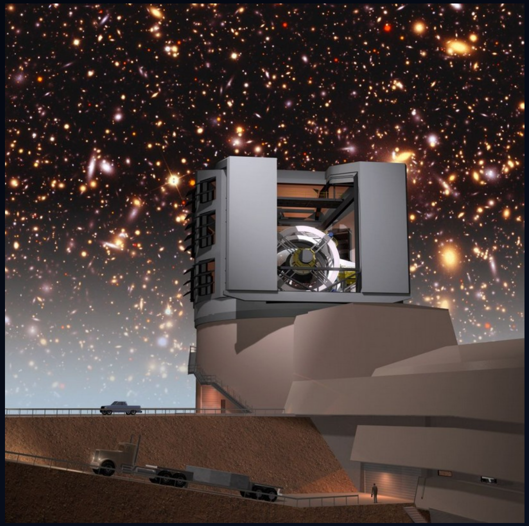


Webb

Full Infrared
Optical

~0.5 – 28 microns

Awaiting Data
Launch 2021

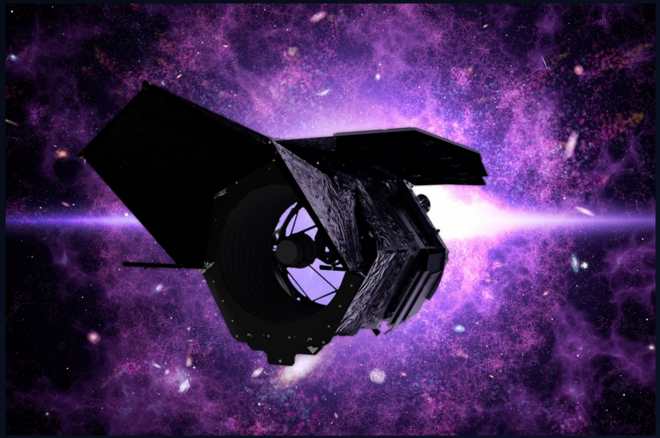


Rubin

Near-infrared
Optical

~0.32–1.06 microns

Awaiting Data
First light 2022/23



Roman

Near-infrared
Optical

~0.5 – 2 microns

Awaiting Data
Launch 2025

EARTH

Freese 1985
Krauss, Srednicki, Wilczek 1986
Gaisser, Steigman, Tilav 1986
Gould 1987, 1988, 1991, 1992
Gould, Frieman, Freese 1989
Gould, Alam 2001
Starkman, Gould, Esmailzadeh, Dimopoulos 1990
Mack, Beacom, Bertone 2007
Bramante, Buchanan, Goodman, Lodhi 2019
Acevedo, Bramante, Goodman,
Kopp, Opferkuch 2020

+ more

Category: Rocky planet
Core temp: ~10^3 K
Escape Velocity: ~11 km/s

EARTH

Available data: **20,000 bore holes drilled throughout crust**

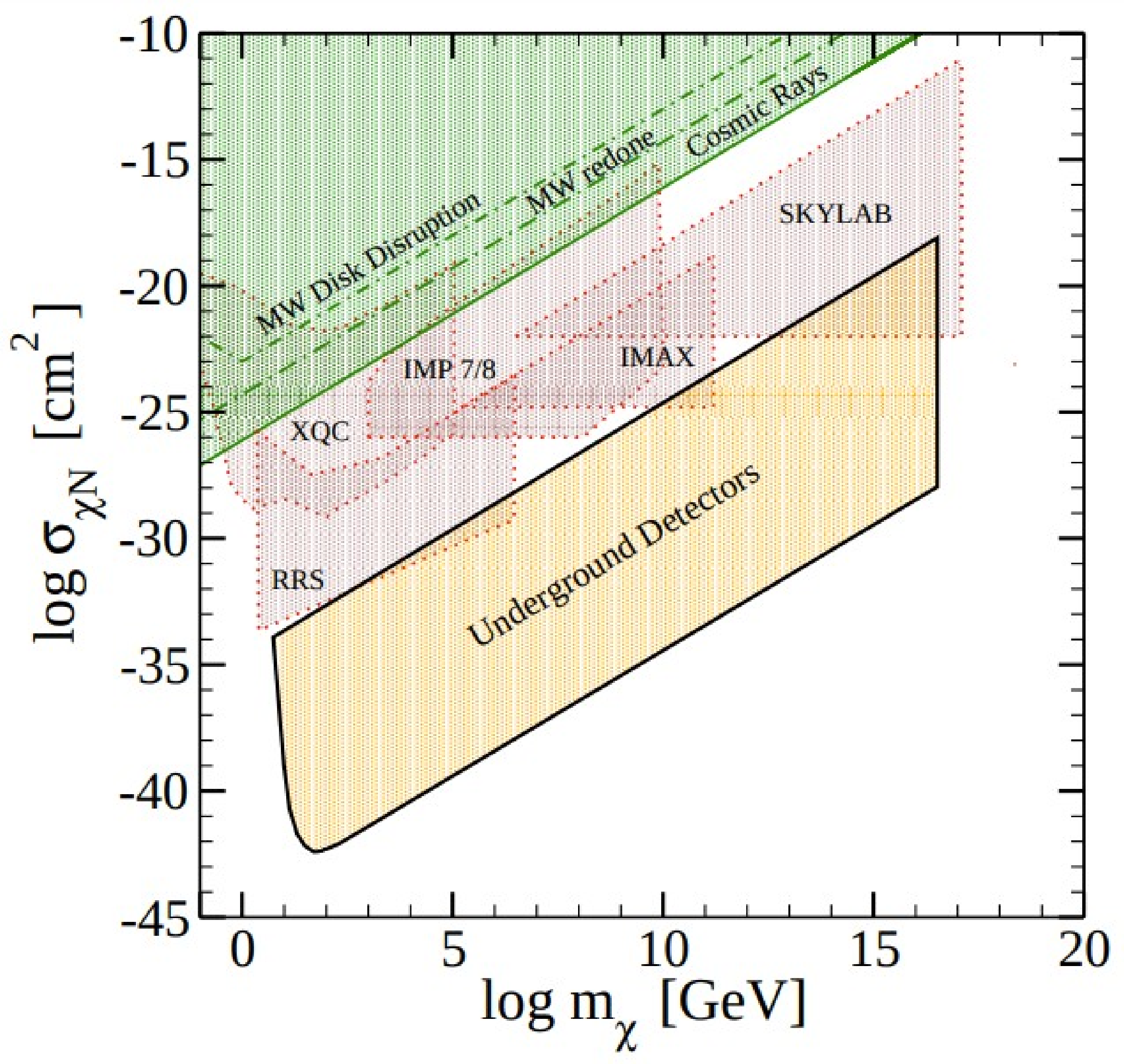
+ Geologists extensively studied Earth’s internal heat

+ Temperature gradient in borehole is recorded, multiplied by the thermal conductivity of the relevant material yields a heat flux

Benefits:
+ Systematics low
+ Best proximity
+ Data now

Limitation: Higher DM evaporation mass

EARTH



Mack, Beacom, Bertone 0705.4298

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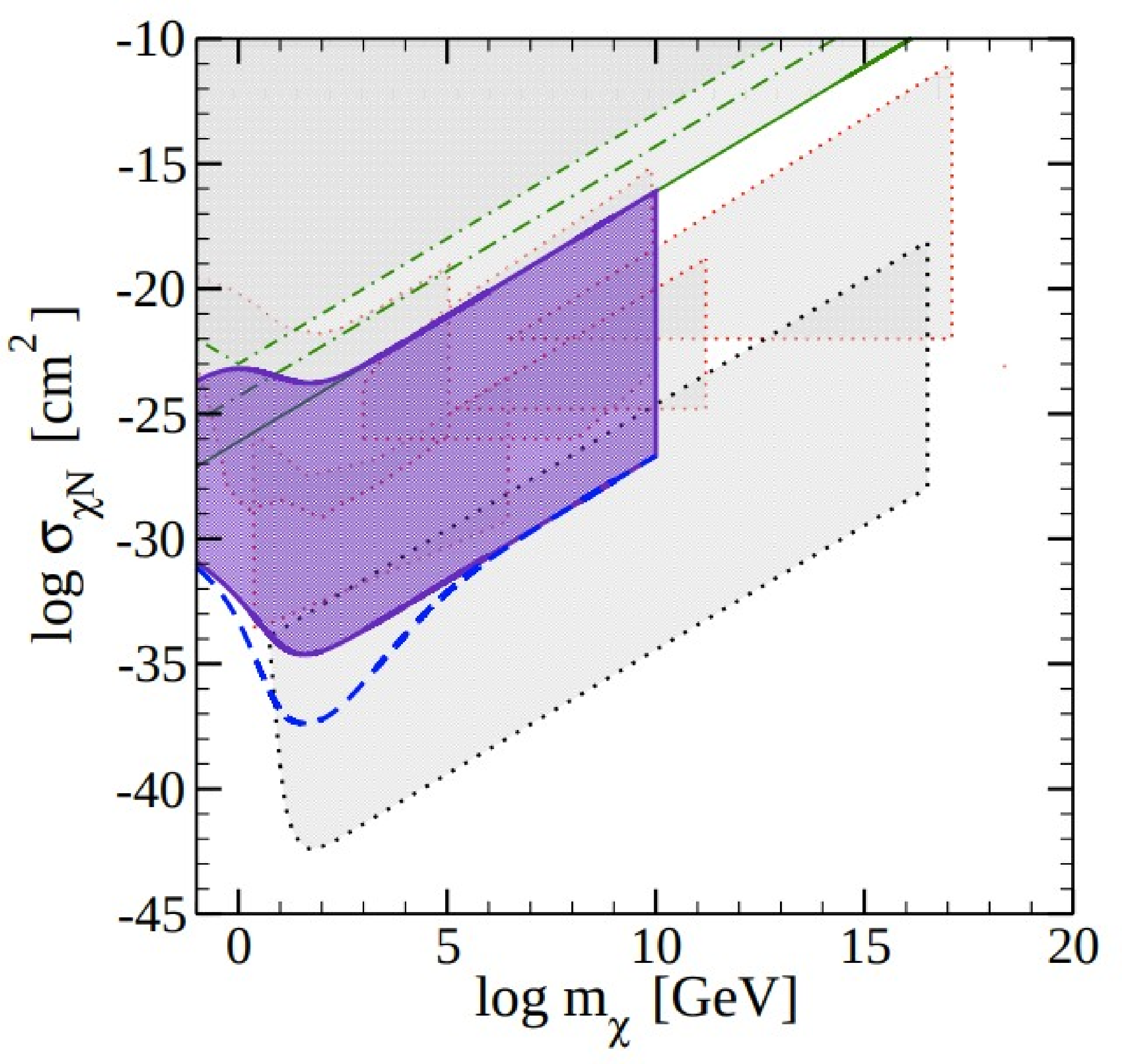
EARTH



Mack, Beacom, Bertone 0705.4298

See also Bramante, Buchanan, Goodman, Lodhi 1909.11683 (incl Mars)

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WHITE DWARFS

Moskalenko, Wai, 2006, 2007
Bertone, Fairbairn 2007
McCullough, Fairbairn 2010
Hooper, Spolyar, Vallinotto, Gnedin 2010
Amaro-Seoane, Casanellas, Schoedel, Davidson, Cuadra 2015
Bramante 2015
Graham, Rajendran, Varela 2015
Graham, Janish, Narayan, Rajendran, Riggins, 2018
Dasgupta, Gupta, Ray 2019
Acevedo, Bramante 2019
Horowitz 2020
Panotopoulos, Lopes 2020
Curtin, Setford, 2020
Bell, Busoni, Ramirez-Quezada, Robles, Virgato 2021

Composition: Mostly Carbon + Oxygen
Mass: ~1 Solar mass
Radius: ~1 Earth radius
Escape velocity: ~10^3 km/s

Origin: Collapse of main sequence stars w/ mass less ~8-10 solar mass, supported against grav collapse by electron degeneracy pressure

WHITE DWARFS

Available data: **Hubble measurements of Messier 4 globular cluster**

Limitations:

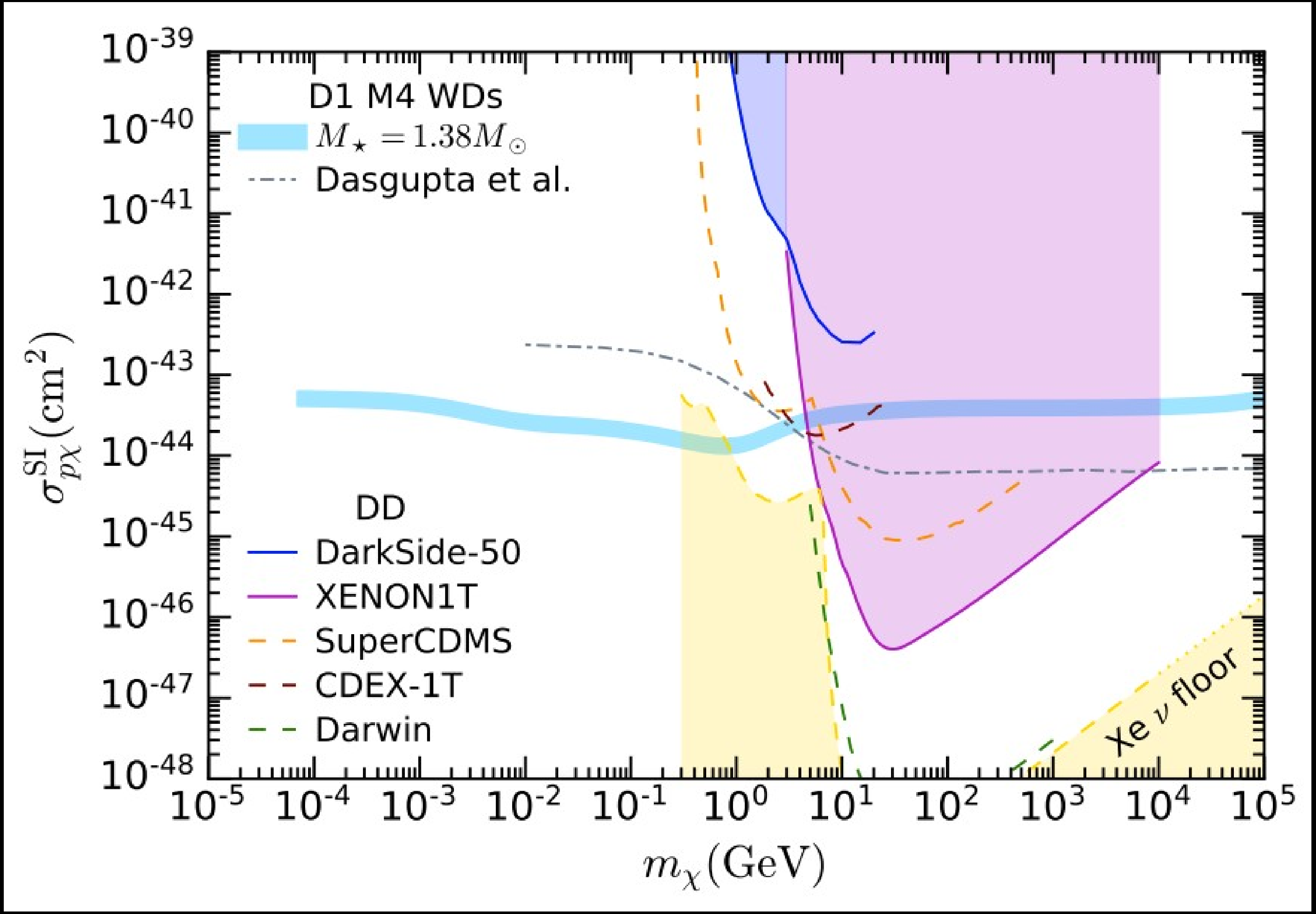
+ High surface temperature, want high DM density locations
+ DM density NOT known for M4
+ Candidates needed for Galactic Center

Benefits:

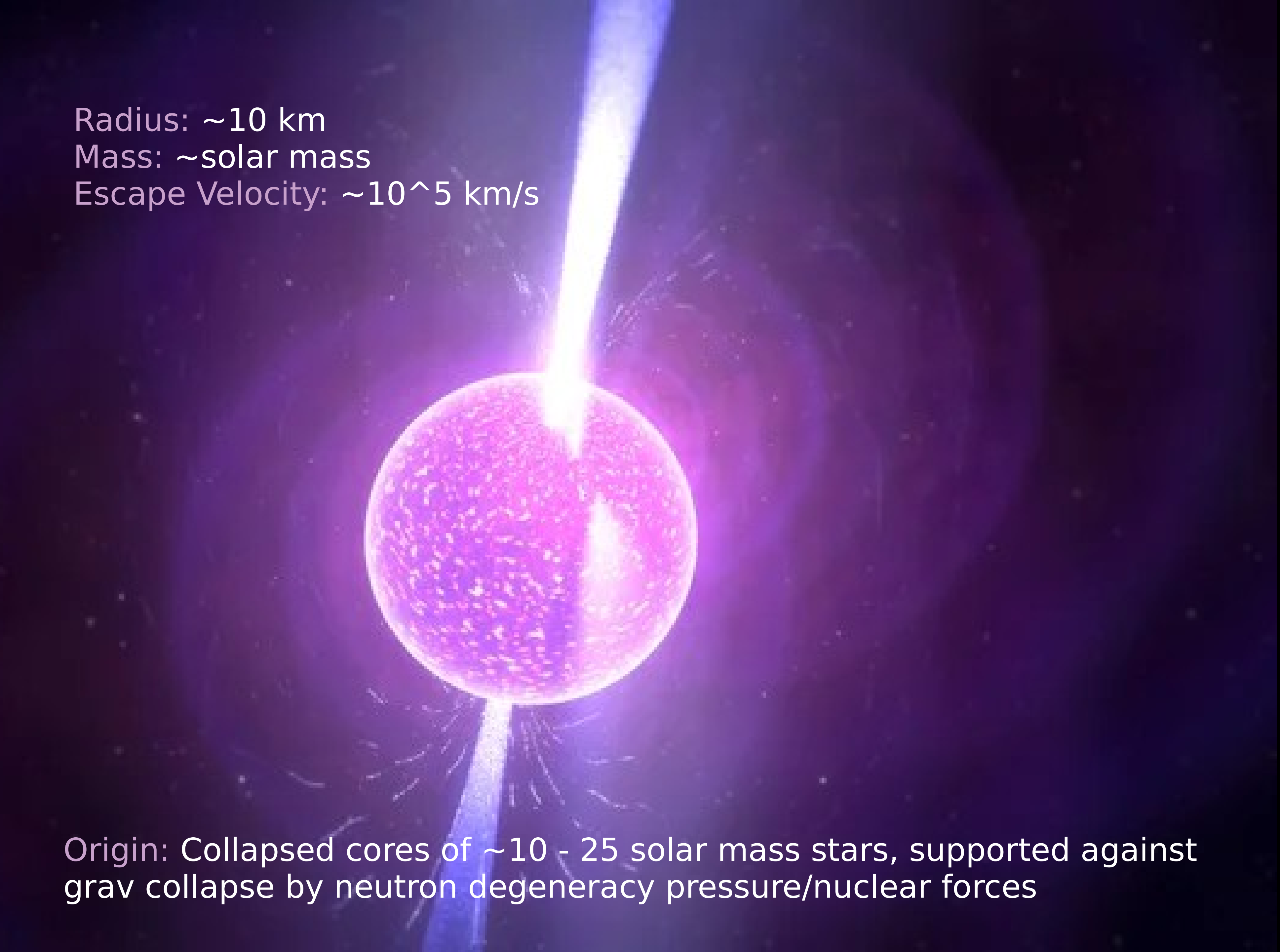
+ Do exist in globular cluster cores
+ M4 data now!
+ Low evaporation masses
+ Better cross section sensitivity than Earth

WHITE DWARFS

Bell, Busoni, Ramirez-Quezada, Robles, Virgato 2021



NEUTRON STARS



Radius: ~10 km
Mass: ~solar mass
Escape Velocity: ~10^5 km/s

Origin: Collapsed cores of ~10 - 25 solar mass stars, supported against grav collapse by neutron degeneracy pressure/nuclear forces

Gould, Draine, Romani, Nussinov 1989
Goldman, Nussinov 1989
Starkman, Gould, Esmailzadeh, Dimopoulos 1990
Bertone, Fairbairn 2007
Kouvaris 2007
Gonzalez, Reisenegger 2010
Kouvaris, Tinyakov 2011
McDermott, Yu, Zurek 2011
Bramante, Fukushima, Kumar 2013
Bell, Melatos, Petraki 2013
Bramante, Linden 2014
Bertoni, Nelson, Reddy 2014
Bramante, Elahi 2015
Baryakhtar, Bramante, Li, Linden, Raj 2017
Bramante, Delgado, Martin 2017
Raj, Tanedo, Yu 2017
Chen, Lin 2018
Jin, Gao 2018
Garani, Genolini, Hambye 2018
Acevedo, Bramante, Leane, Raj 2019
Hamaguchi, Nagata, Yanagi 2019
Camargo, Queiroz, Sturani 2019
Joglekar, Raj, Tanedo, Yu 2019
Garani, Heeck 2019
Bell, Busoni, Robles 2019
Keung, Marfatia, Tseng 2020
Bell, Busoni, Robles 2020
Bai, Berger, Korwar, Orlofsky 2020
Bell, Busoni, Motta, Robles, Thomas, Virgato 2020
Leane, Linden, Mukhopadhyay, Toro 2021

+ even more

NEUTRON STARS

Available data:

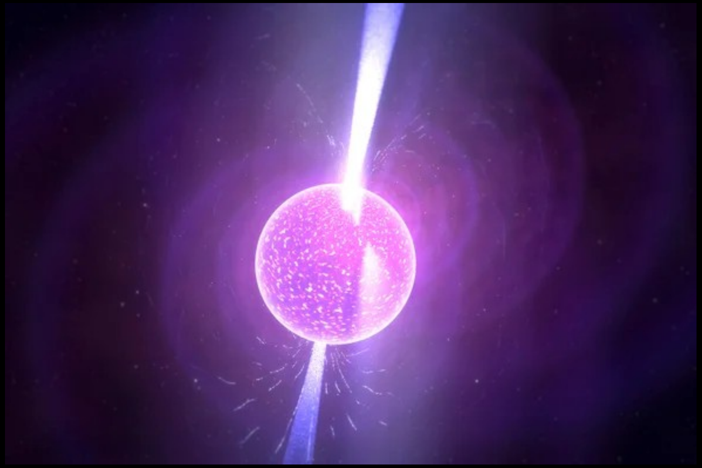
None yet, potentially use upcoming infrared telescopes

Limitations:

+ NS are small, so need to use target close by
+ No yet known candidates
+ Exposure times required can be large

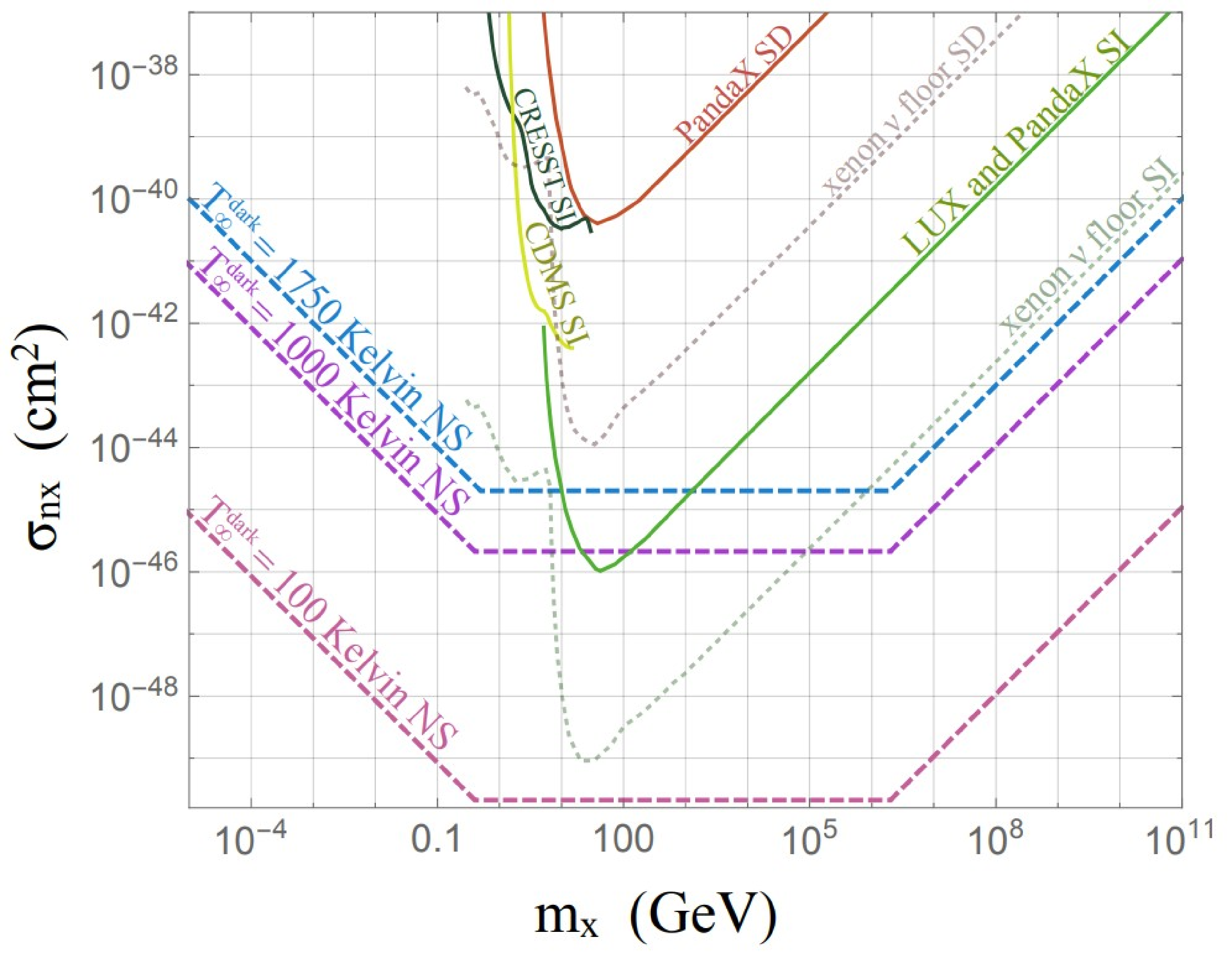
Benefits:

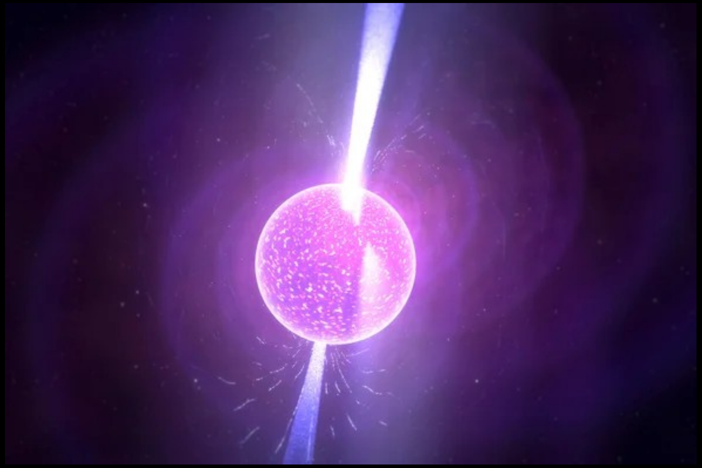
+ Kinetic heating boost in rate
+ Superior cross section sensitivity
+ Broad class of particle models
+ Low evaporation masses



NEUTRON STARS

Baryakhtar, Bramante, Li, Linden, Raj 2017





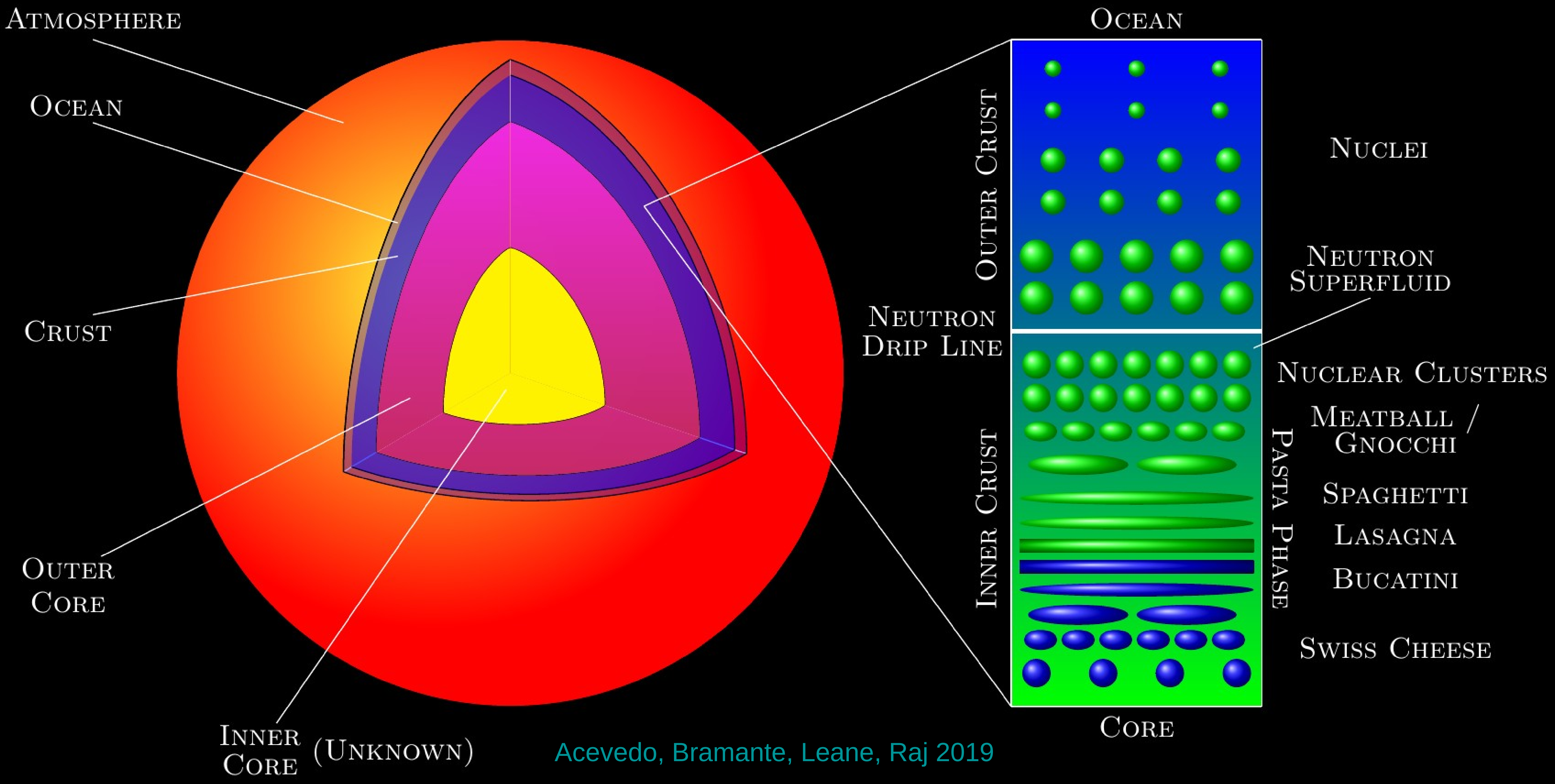
See also Bell, Busoni, Motta, Robles, Thomas, Virgato 2020

NEUTRON STAR INTERIORS?

- Neutron stars usually estimated to be a degenerate core of neutrons
- Core could be exotic (i.e. uds matter, meson/hyperon condensates)
  Dark matter scattering with such phases can be suppressed
- Dark matter interactions might be density dependent
- Further into the neutron star, less and less is understood

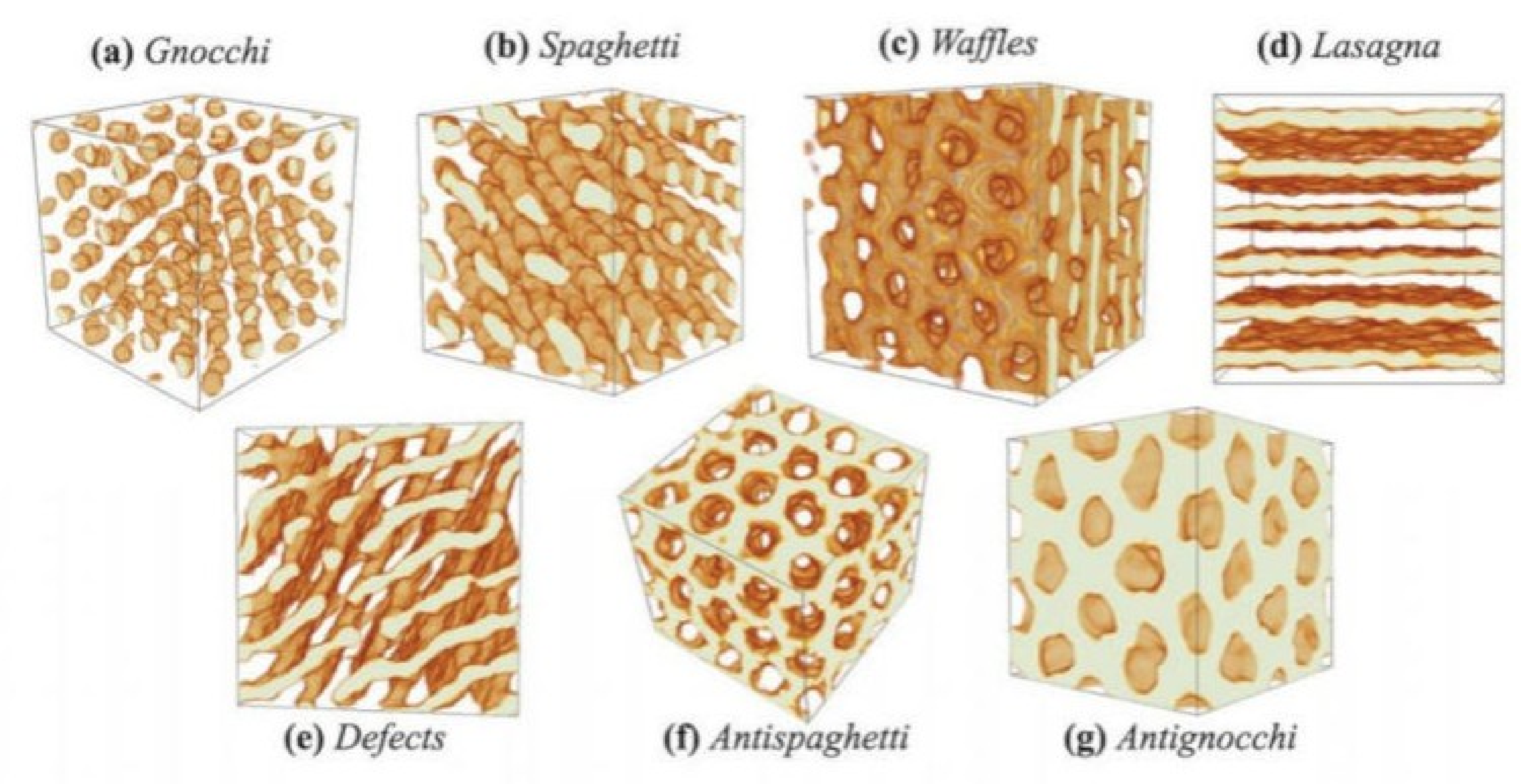
No imperial knowledge of NS interiors – but crust best understood!

INSIDE NEUTRON STARS



Acevedo, Bramante, Leane, Raj 2019

NUCLEAR PASTA



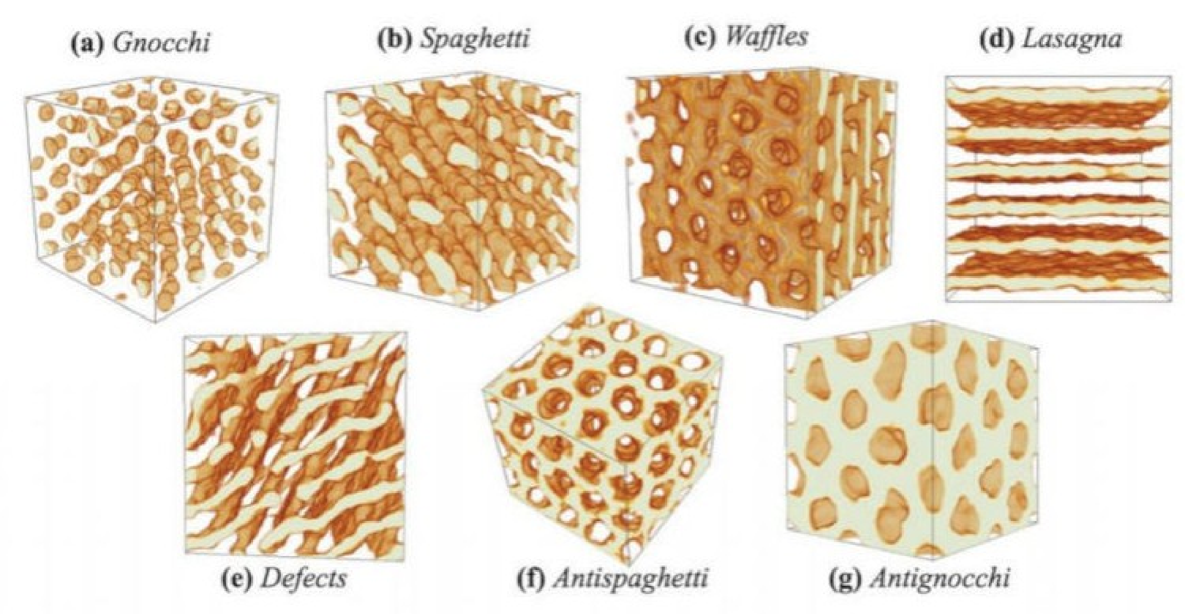
Caplan, Schneider, Horowitz ‘18

THE PASTA COMMUNITY

\+ Pasta impacts properties of neutron stars and core collapse supernovae

\+ Neutrino interactions: impacts neutrino opacity in supernovae

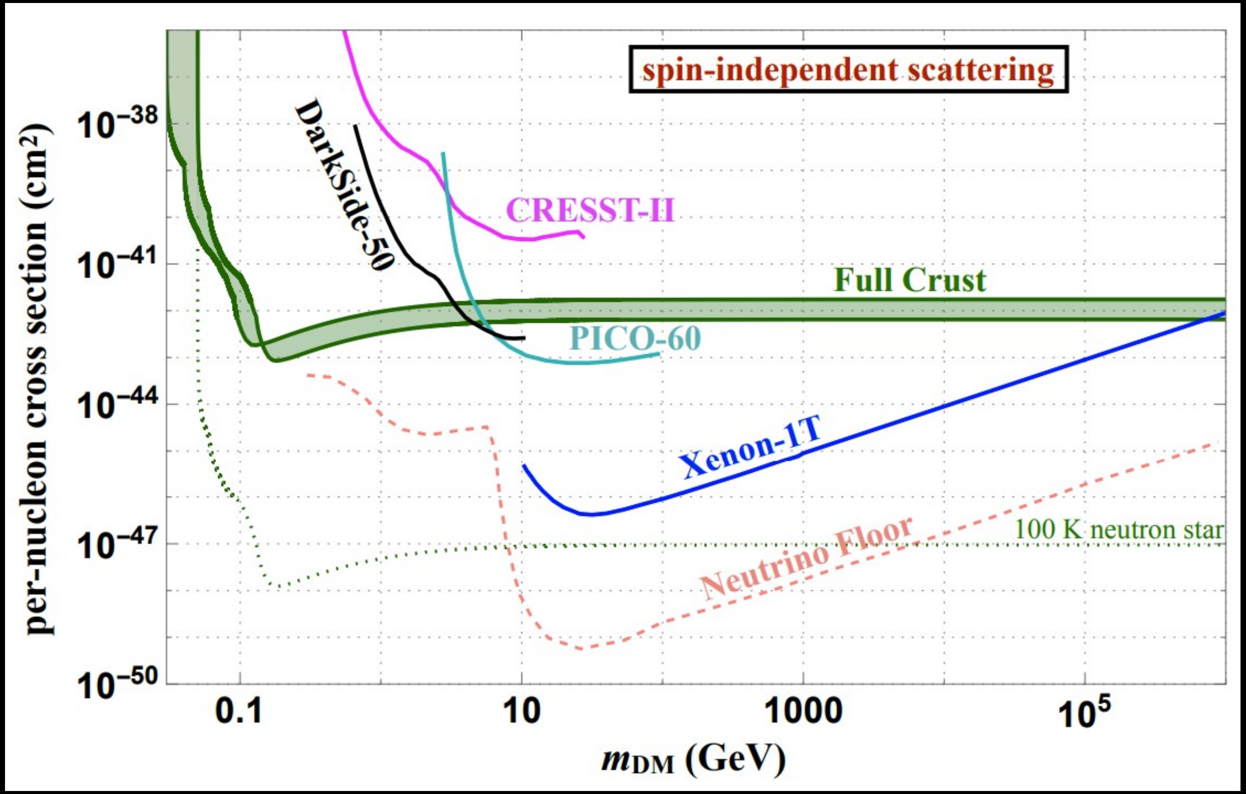
\+ Electron interactions: impact shear viscosity, thermal and electrical conductivity



Caplan, Schneider, Horowitz ‘18

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

PASTA CAN BEAT DIRECT DETECTION



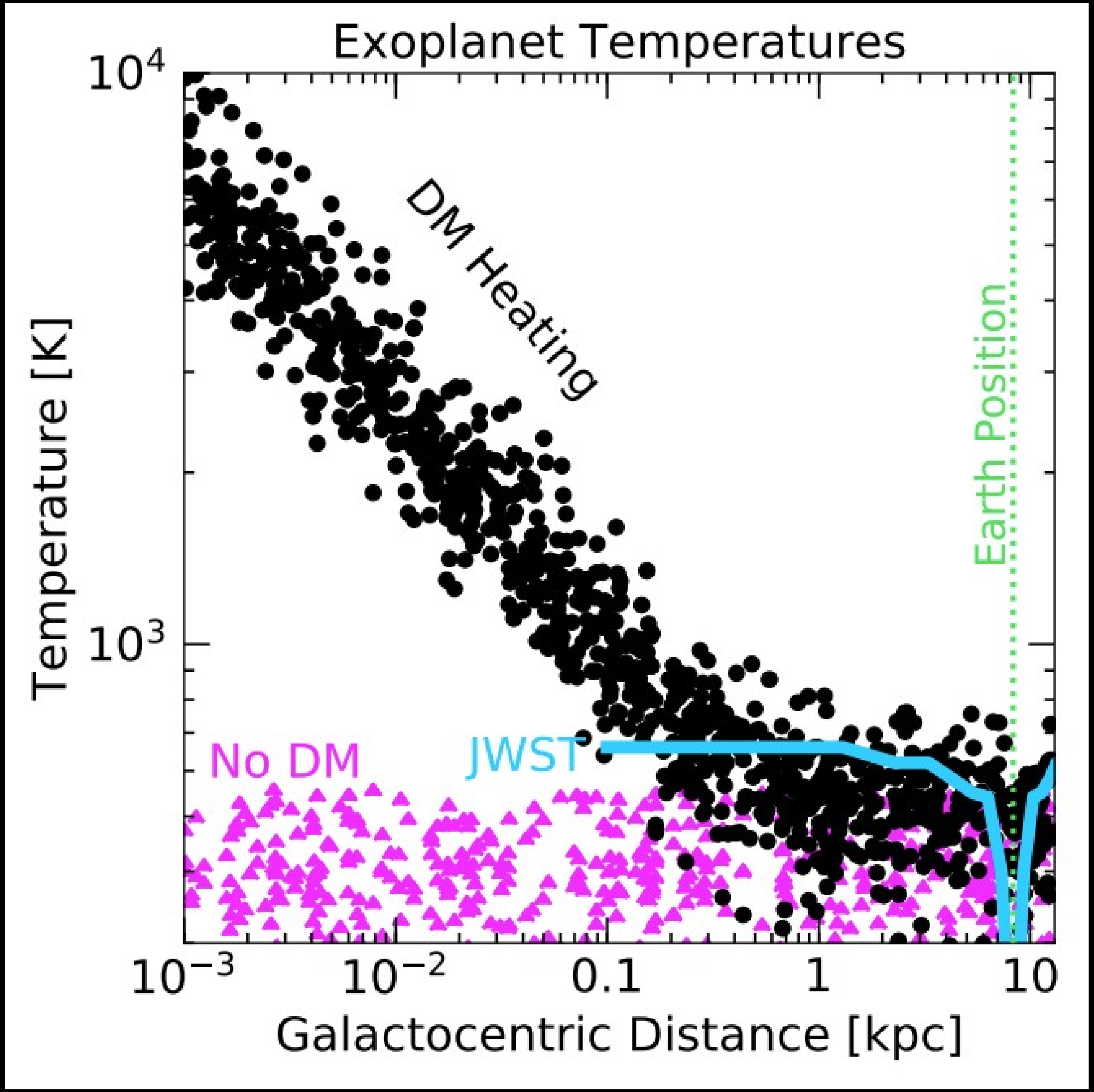
Acevedo, Bramante, Leane, Raj, 2019

Low + high masses, velocity suppressed, spin-dependent, inelastic DM

EXOPLANETS

Adler 2009
Hooper, Steffen 2011
Leane, Smirnov 2020

EXOPLANETS



Leane + Smirnov, 2020

Exoplanets can potentially be used to map the Galactic DM density

EXOPLANETS

Available data:

Little yet, use upcoming infrared telescopes

Limitations:

+ Having enough acceptable candidates
+ Not robustly known interiors
+ Cooling systematics

Benefits:

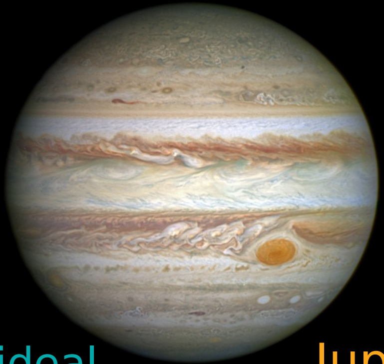
+ Exploding exoplanet program+telescope technologies
+ Large statistics
+ Some candidates already exist
+ Cold (good signal over background)
+ Large radii, easier to detect than NS
+ Low evaporation masses
+ Potential probe of DM density profile

Leane + Smirnov, 2020

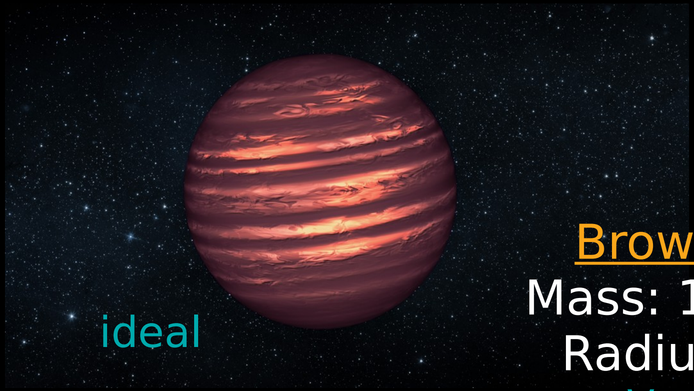
Exoplanet Search Targets


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

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:

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

- 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

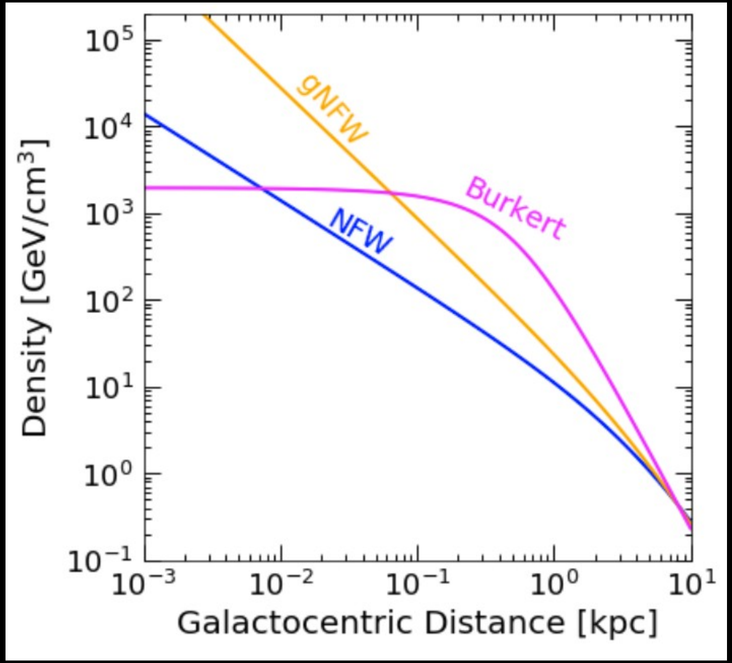
Calculating Exoplanet Temperatures

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

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

Heat power from DM:

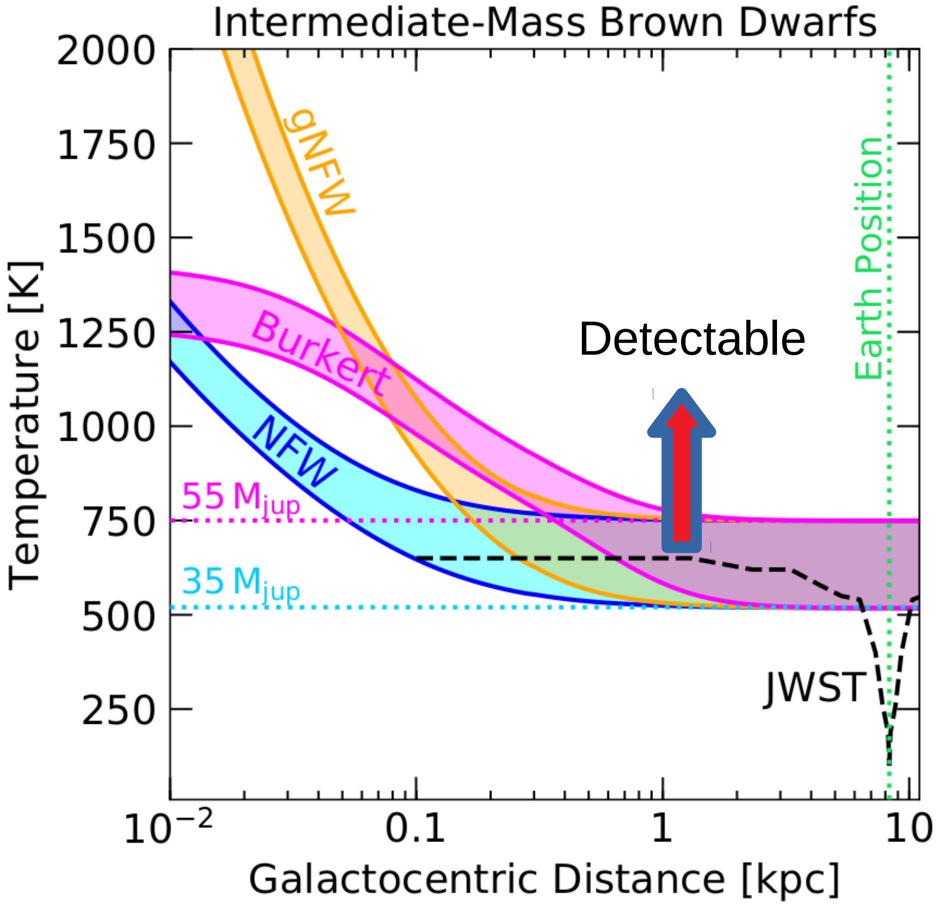
- DM density throughout Galaxy
- DM halo velocity
- Exoplanet escape velocity



Exoplanet temperatures vs sensitivity

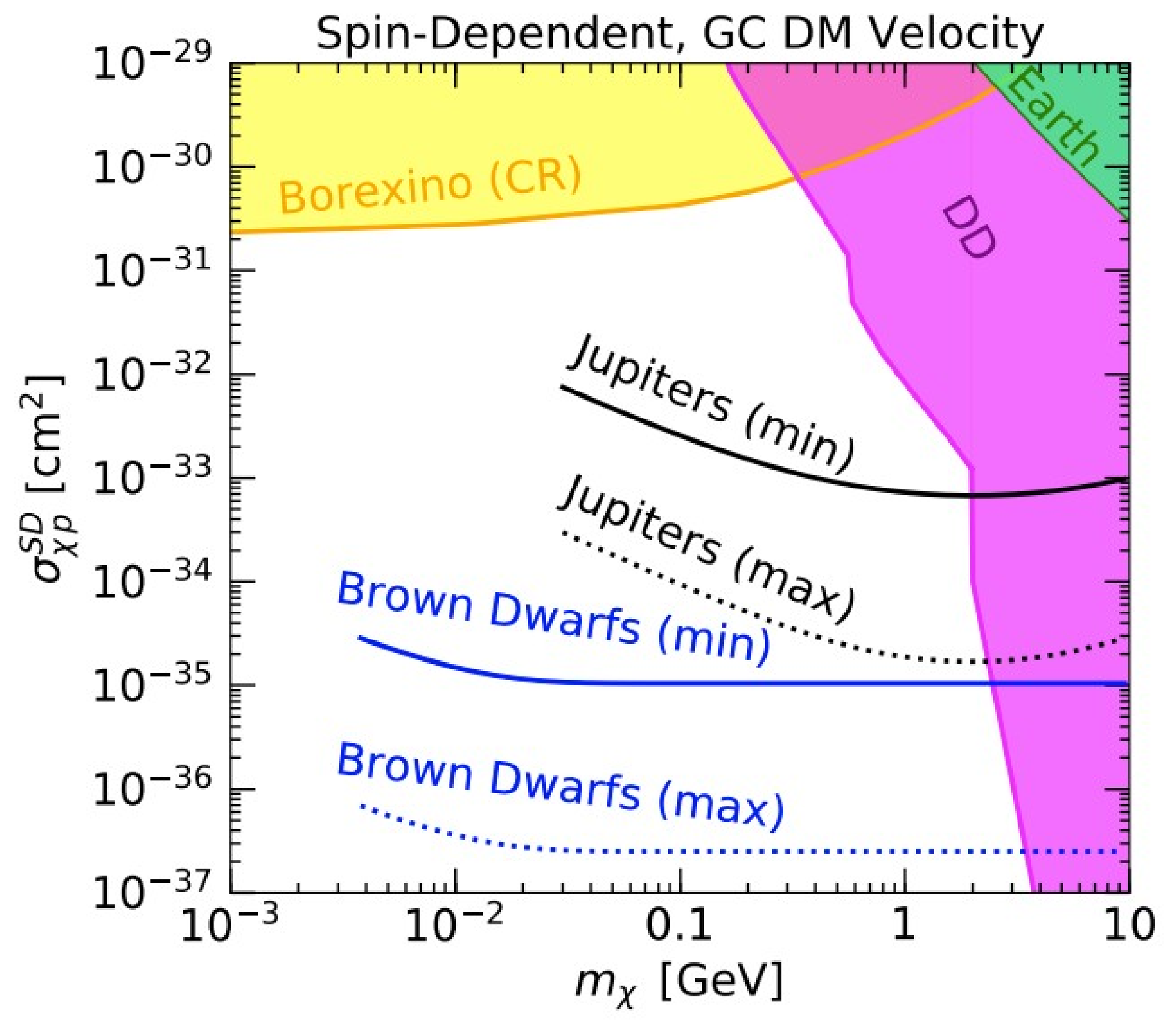
- NFW, gNFW, Burkert are DM profiles, shaded area is exoplanet mass range
- Sensitivity truncates at ~0.1kpc, due to stars per pixel, and dust scattering

35 Mjup – 55 Mjup



Leane + Smirnov, 2020

Exoplanet cross section sensitivity

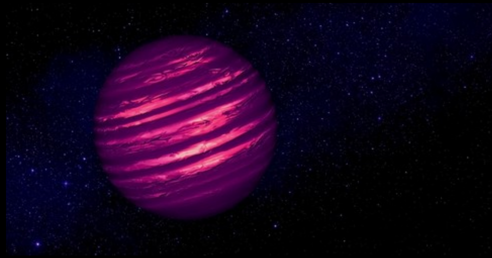


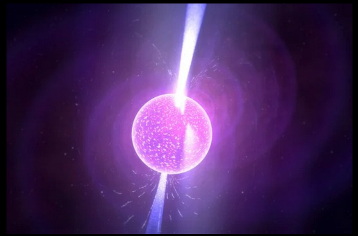
Leane + Smirnov, 2020

Actions for successful discovery/exclusion

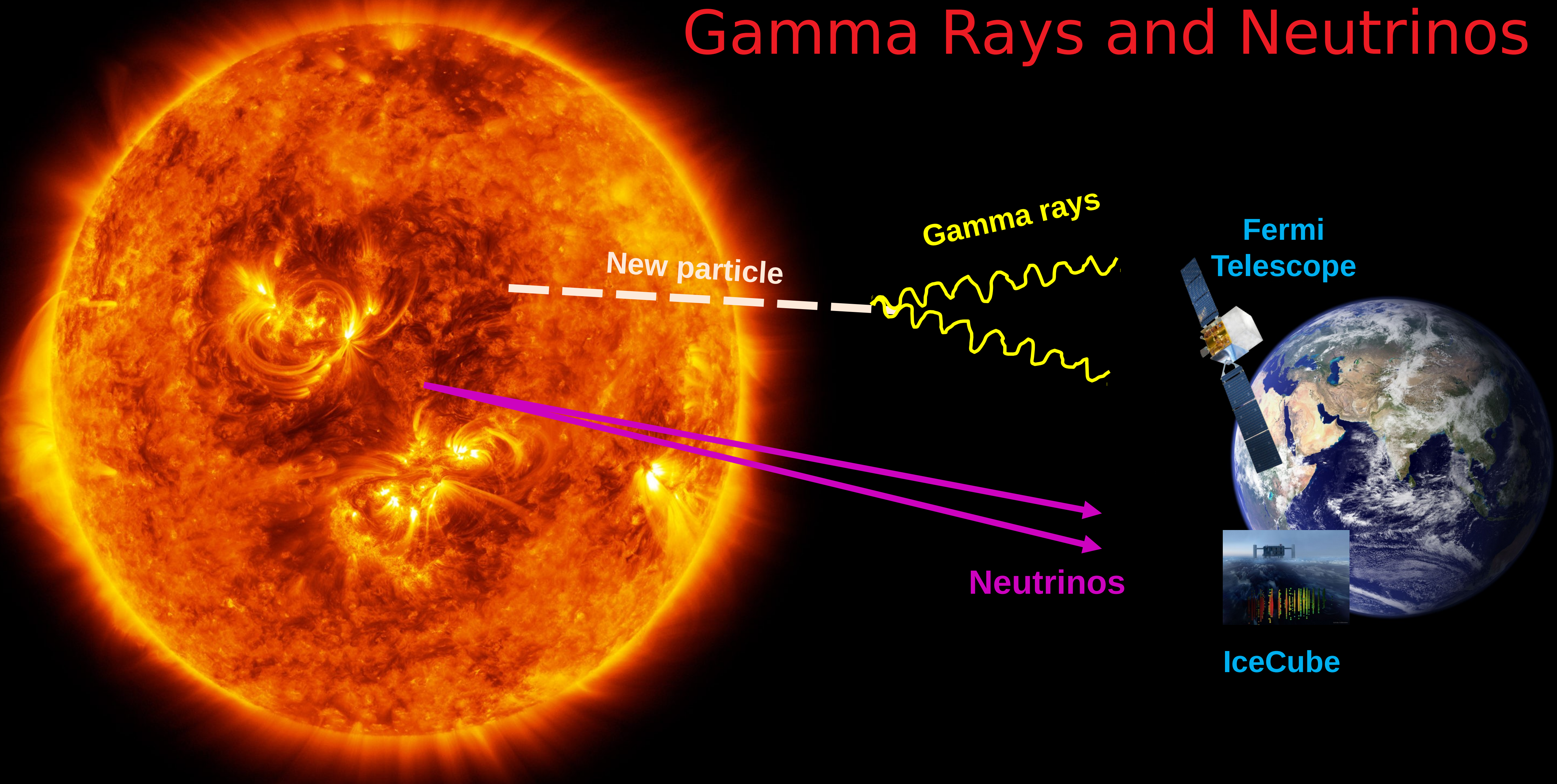
- Successful launch with JWST

- Exoplanets:
  - Large statistical sample obtained to overcome systematics
  - Detailed studies of atmosphere effects including DM
- Neutron stars:
  - Find a candidate close by and old enough! (FAST radio search)
  - Enough observing time granted
- White dwarfs:
  - Understand astrophysical uncertainties in clusters
  - More candidates





Dark Matter Annihilation:
Gamma Rays and Neutrinos



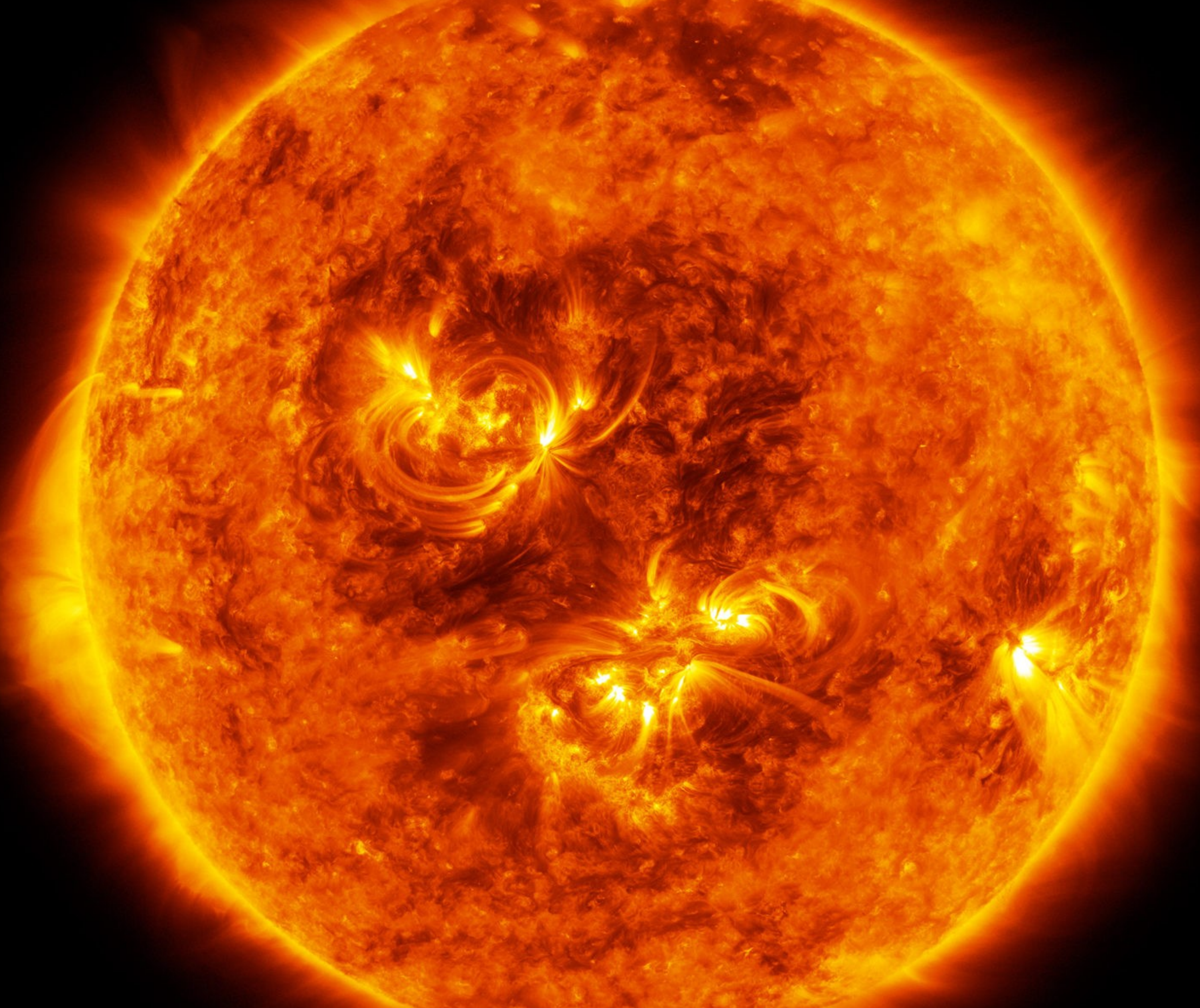
New particle

Gamma rays

Neutrinos

Fermi Telescope

IceCube



THE SUN

Press, Spergel 1985

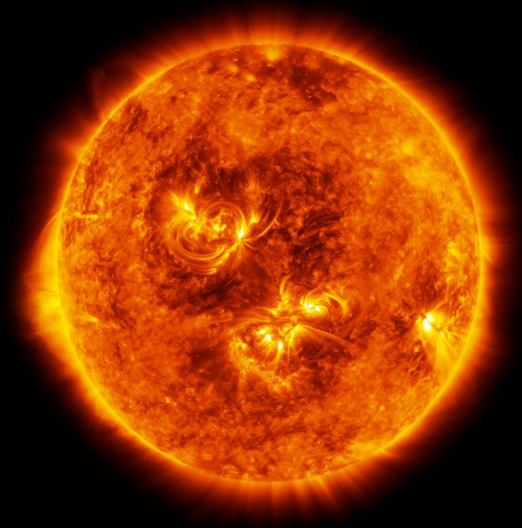
Krauss, Freese, Press, Spergel 1985

Silk, Olive, Srednicki, 1985

Stats: Hot, big, close

Escape velocity: 615 km /s

THE SUN



Available data:
Gamma-ray data (e.g. Fermi, HAWC)
Neutrino data (e.g. SuperK, IceCube)

Limitations:

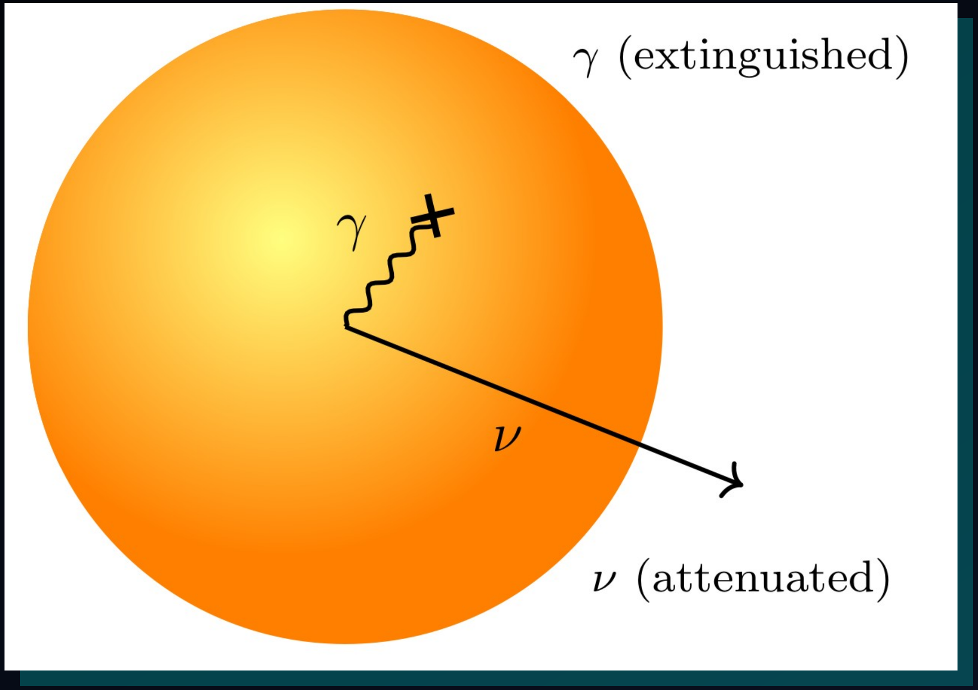
+ Hot
+ Higher DM evaporation (~GeV mass)

Benefits:

+ Huge
+ Proximity
+ Excellent data

THE SUN

- DM can be captured by scattering with solar matter, then annihilate to neutrinos



THE SUN

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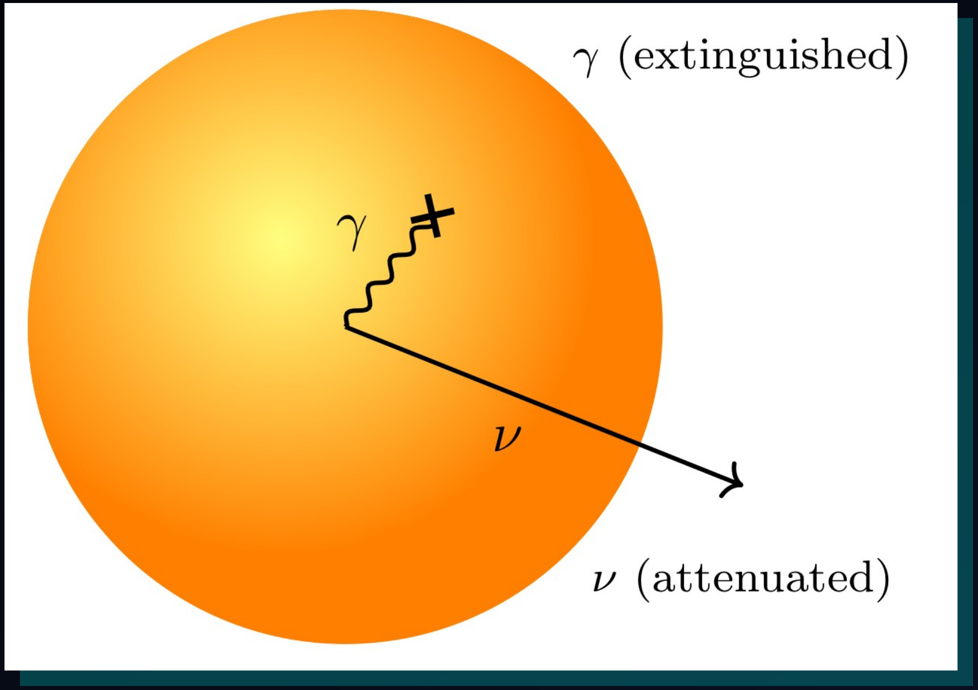
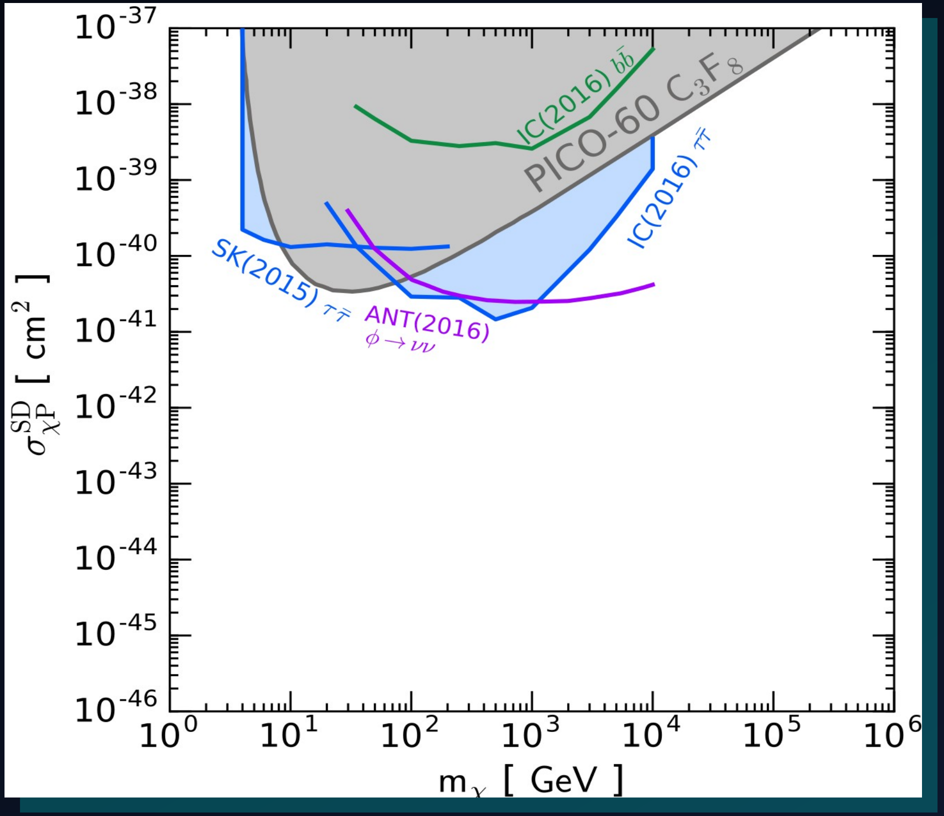
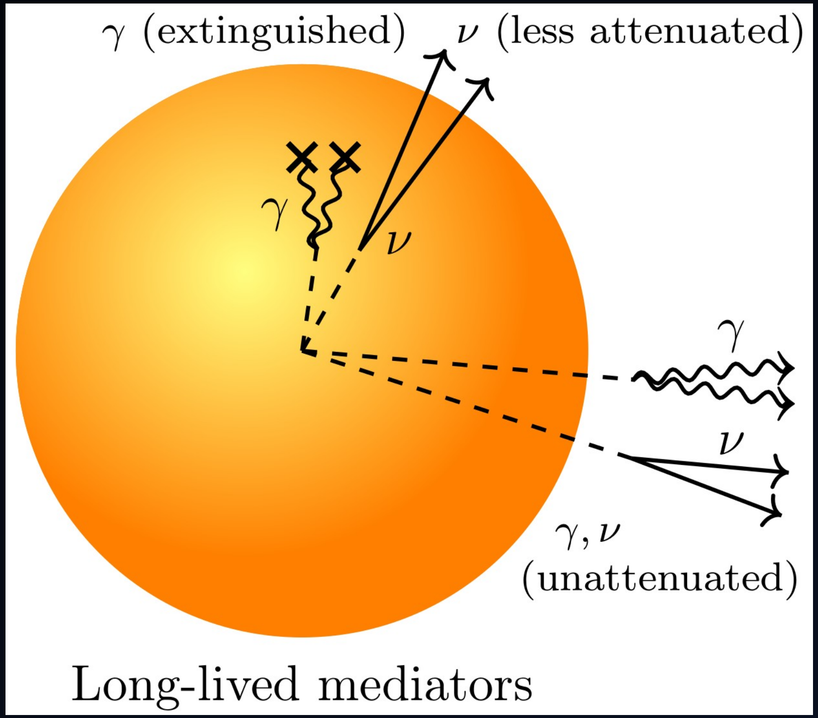




THE SUN

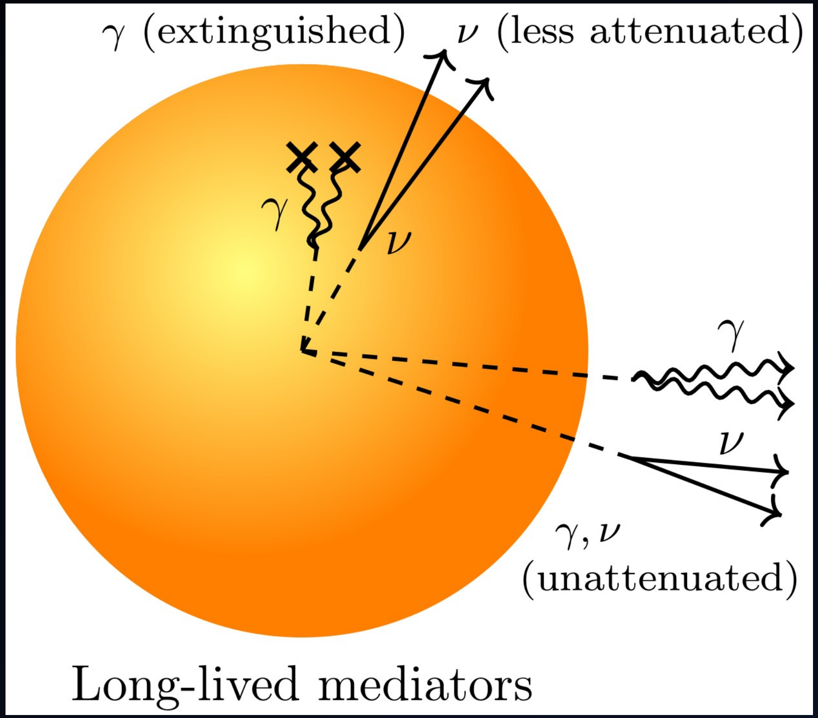
- DM can be captured by scattering with solar matter
- If DM annihilates to long-lived particles, neutrino signal is boosted

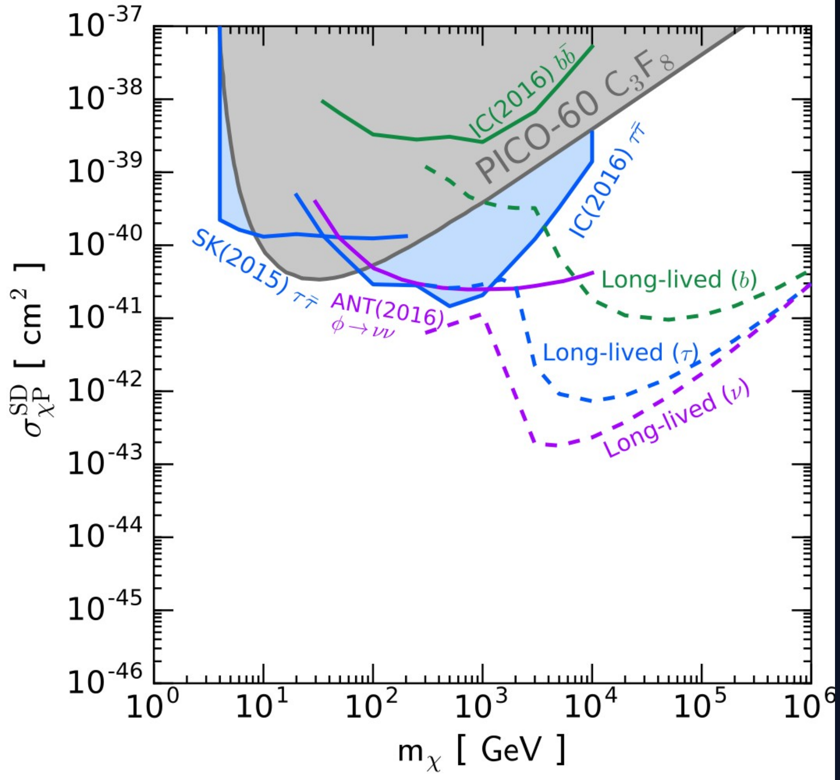


Schuster+ ‘10
Batell+ ‘10
Meade+ ‘10

THE SUN

- DM can be captured by scattering with solar matter
- If DM annihilates to long-lived particles, neutrino signal is boosted

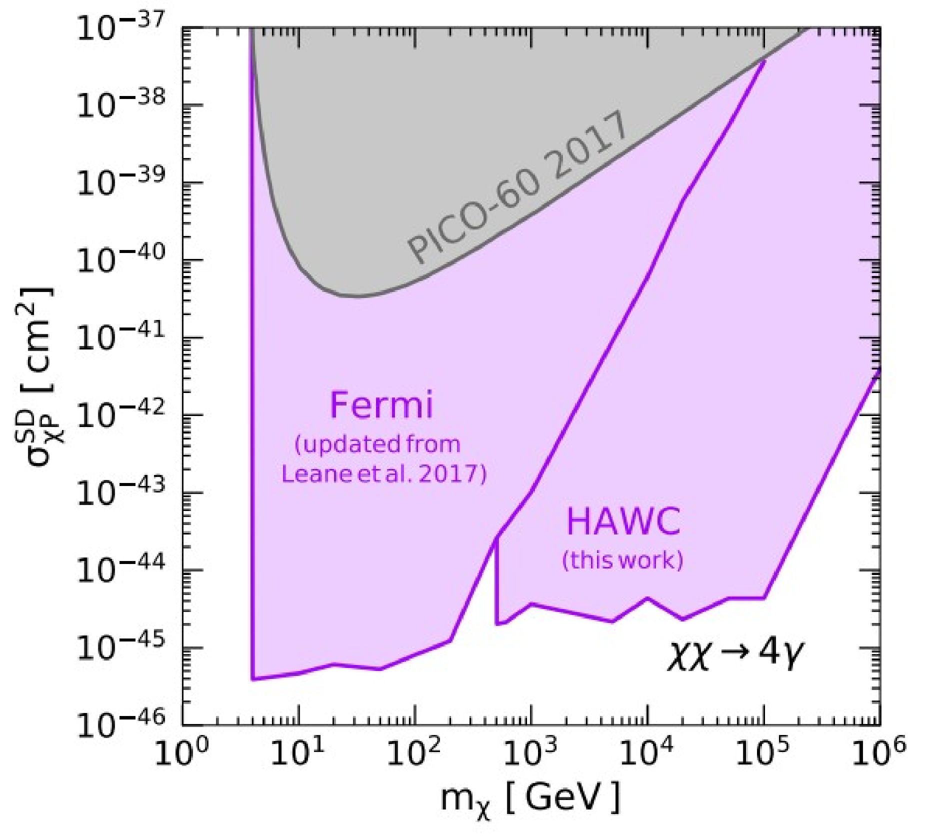




Leane, Ng, Beacom, 2017

THE SUN

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



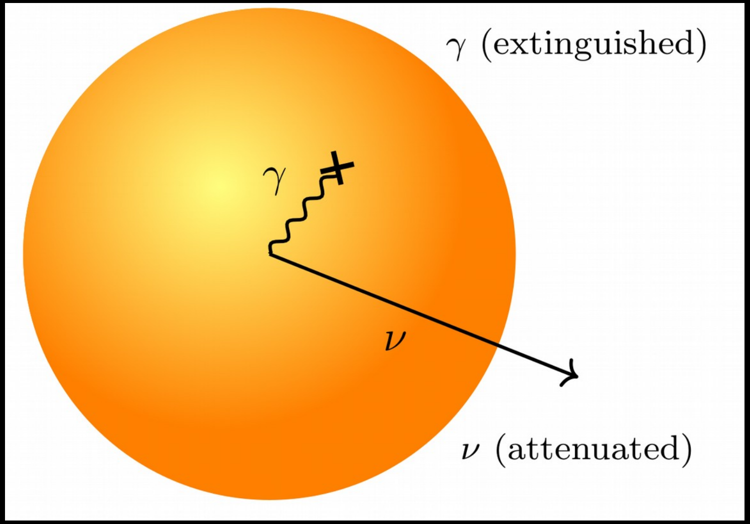
Leane, Ng, Beacom (PRD '17)
Leane + HAWC Collaboration (PRD '18 a,b)

Rebecca Leane (SLAC)

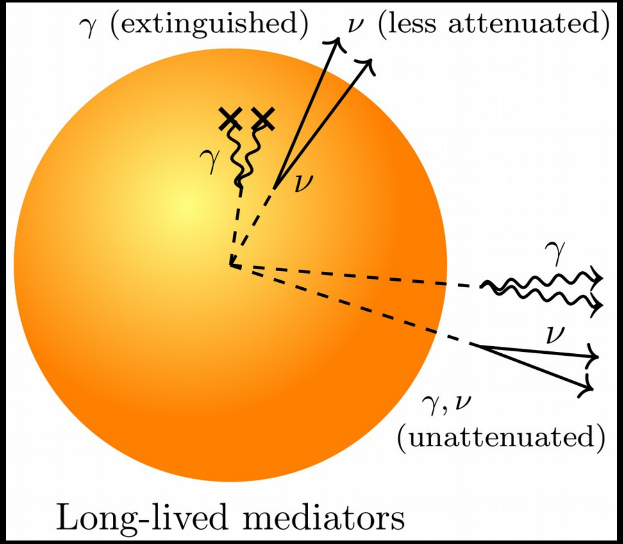
A Complementary Search

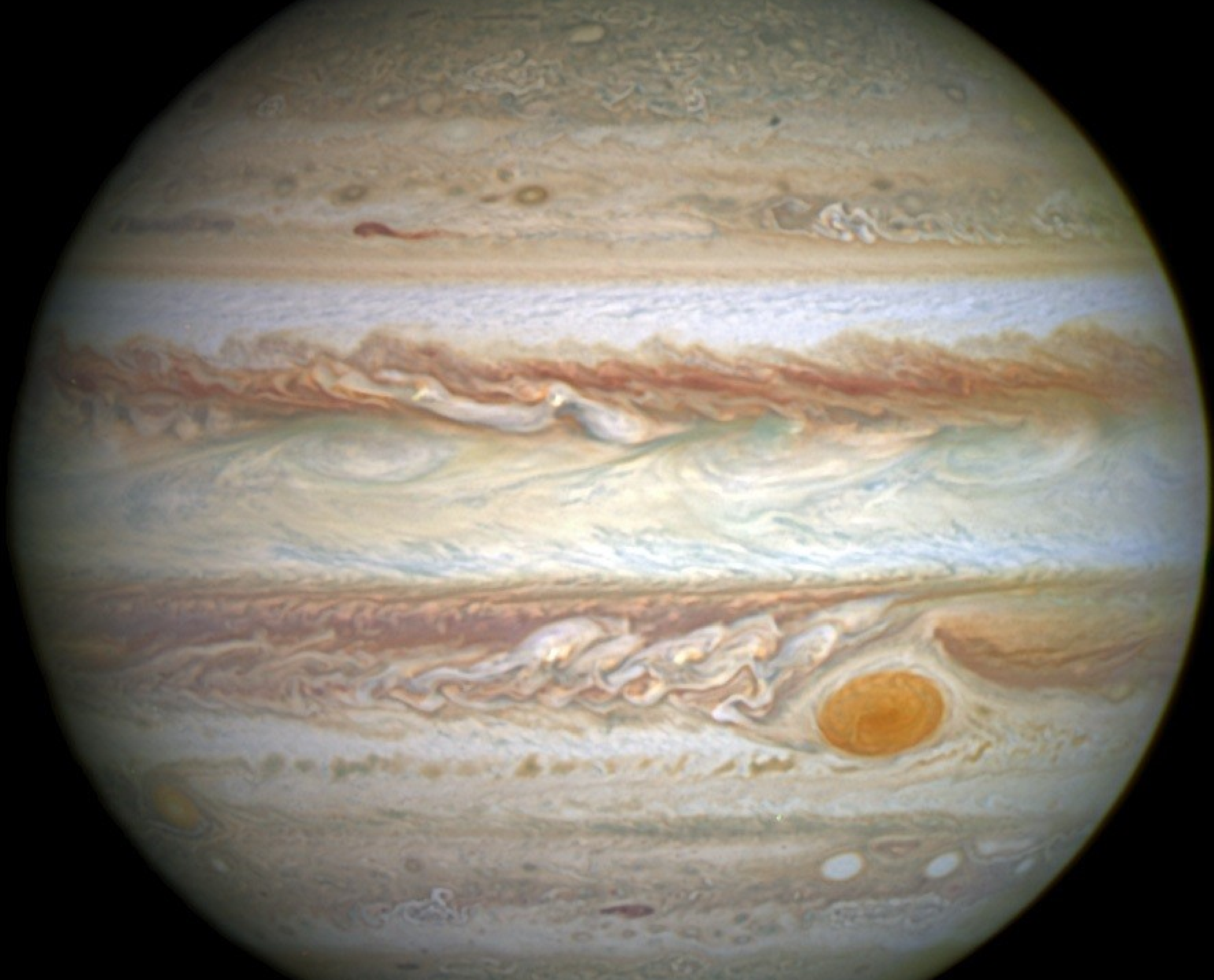
Two regimes:

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



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





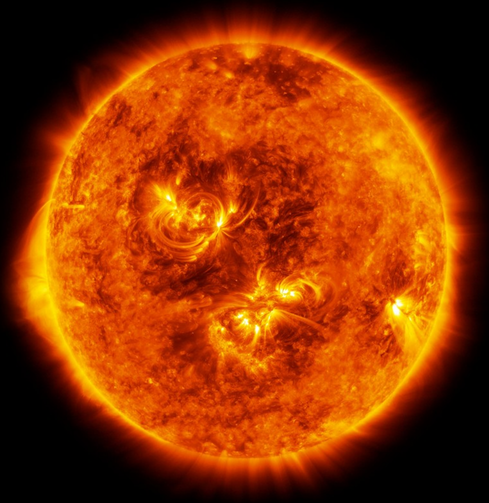
JUPITER

Kawasaki, Murayama, Yanagida 1992

Adler 2009

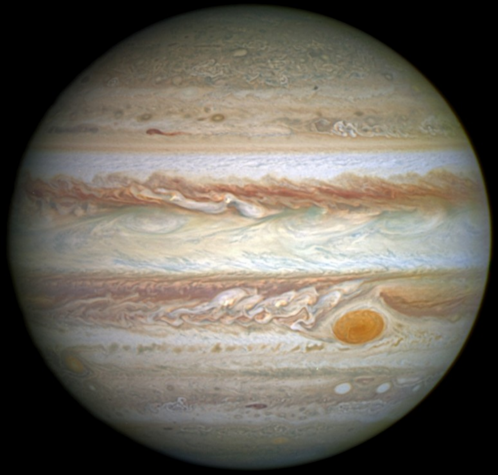
Leane, Linden 2021

Why Jupiter?



Sun

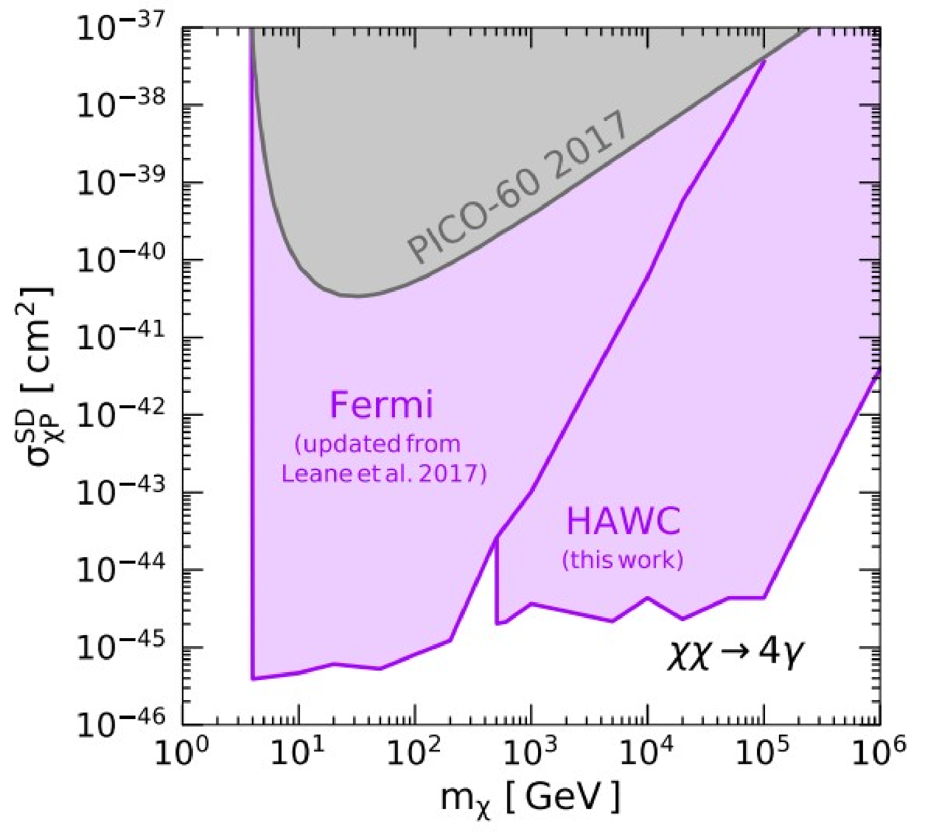
BIG
Hot



Jupiter

BIG
Cold

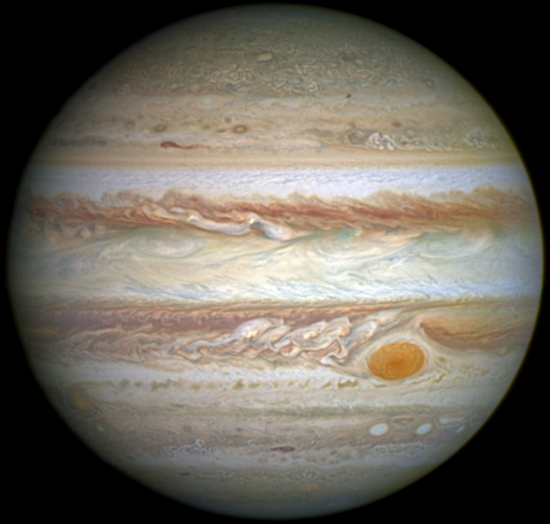
Solar Comparison



Sun

Long-Lived Mediator Limits

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



Jupiter

Cooler than the Sun:
MeV-DM mass sensitivity!

Jupiter in Gamma Rays

What does Jupiter look like in gamma rays?
No one has ever really checked!

- Use Fermi Gamma-Ray Space Telescope
- Analyze 12 years of Fermi data, 10 MeV – 10 GeV

Leane, Linden, 2021

Jupiter in Gamma Rays

What does Jupiter look like in gamma rays?
No one has ever really checked!

If we find gammas, they could be from:

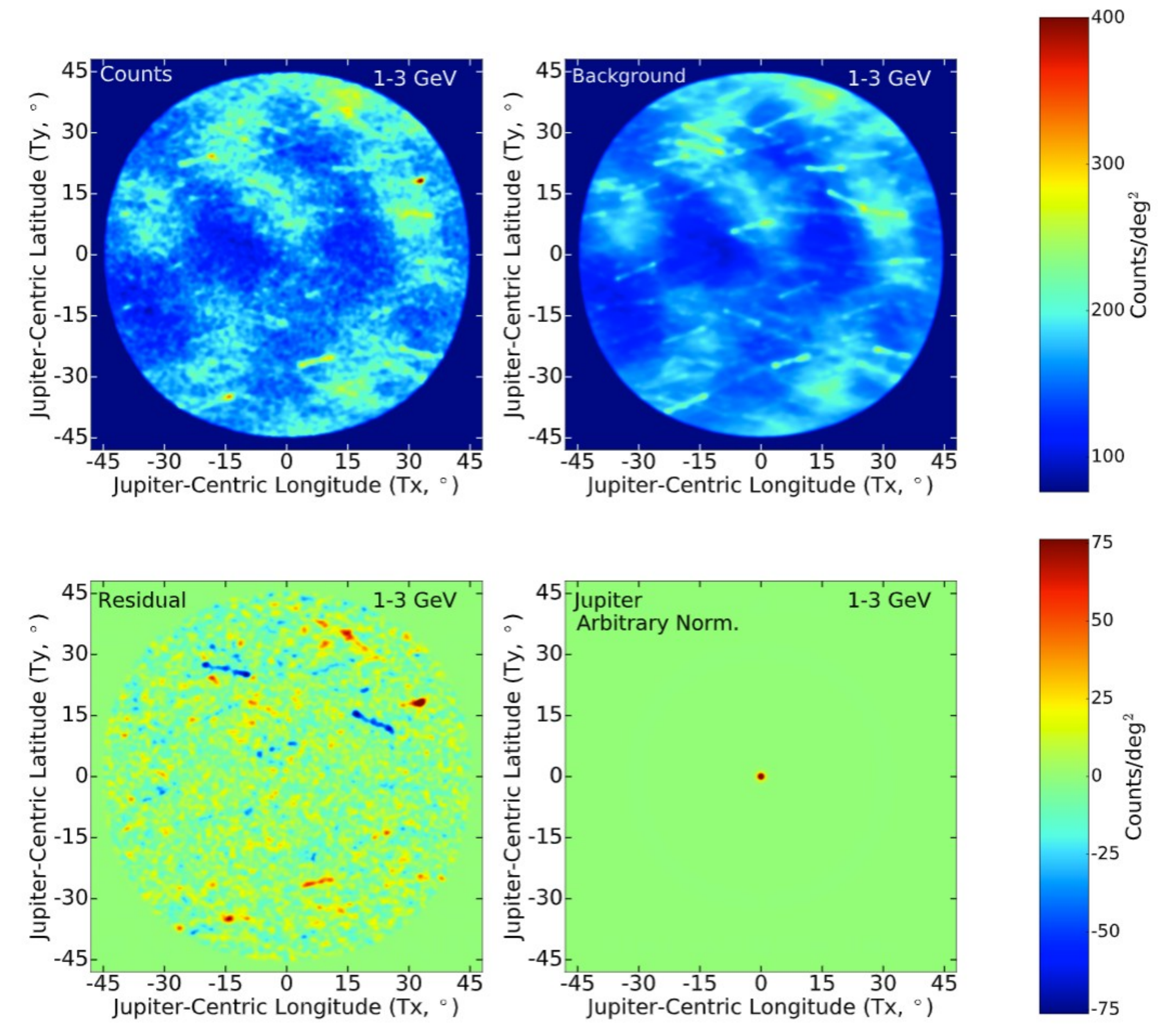
+ acceleration of cosmic rays in Jovian magnetic fields

+ interaction of cosmic rays with Jupiter's atmosphere

...or something exotic (dark matter)!

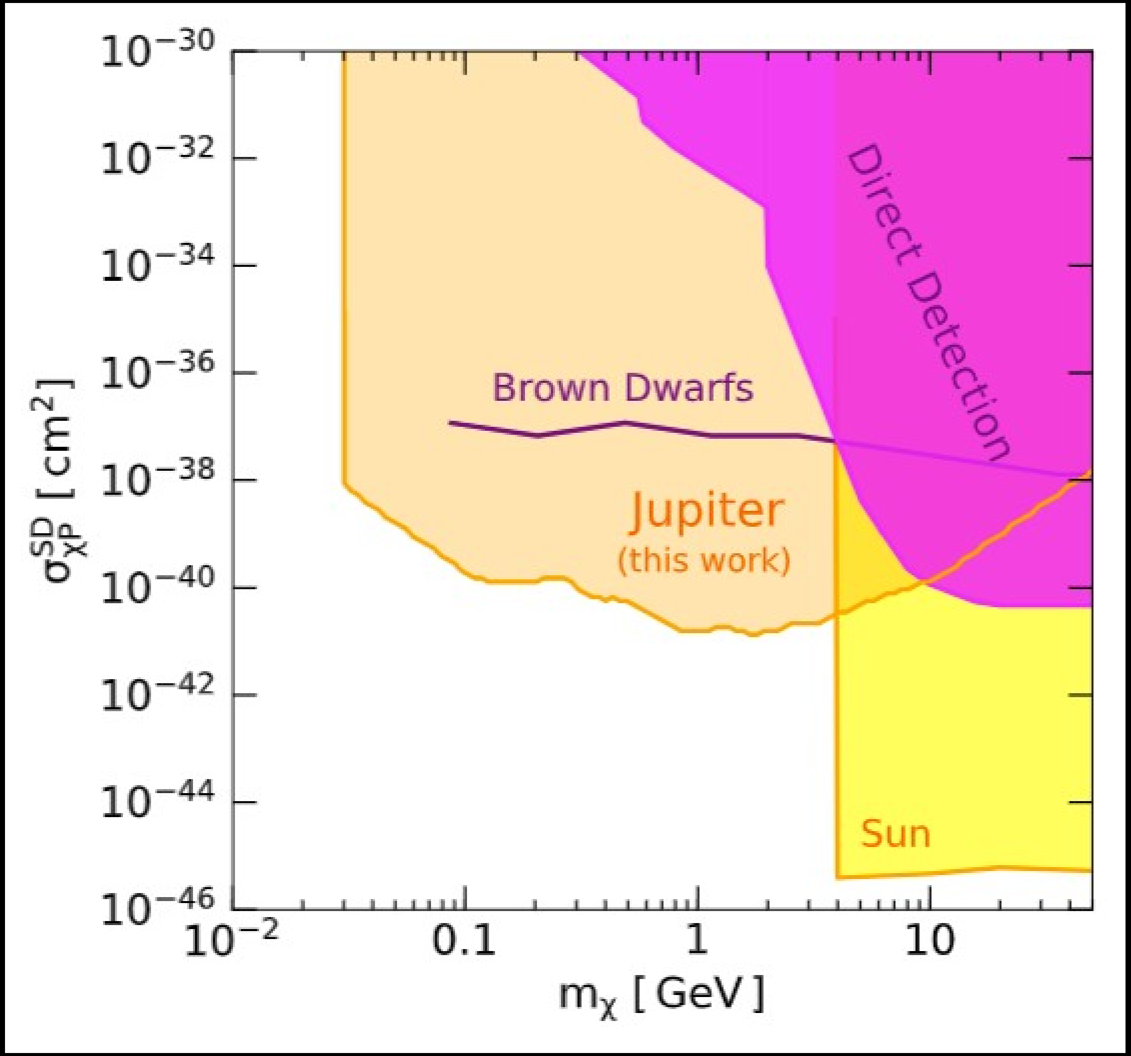
Leane, Linden, 2021

Jupiter in Gamma Rays



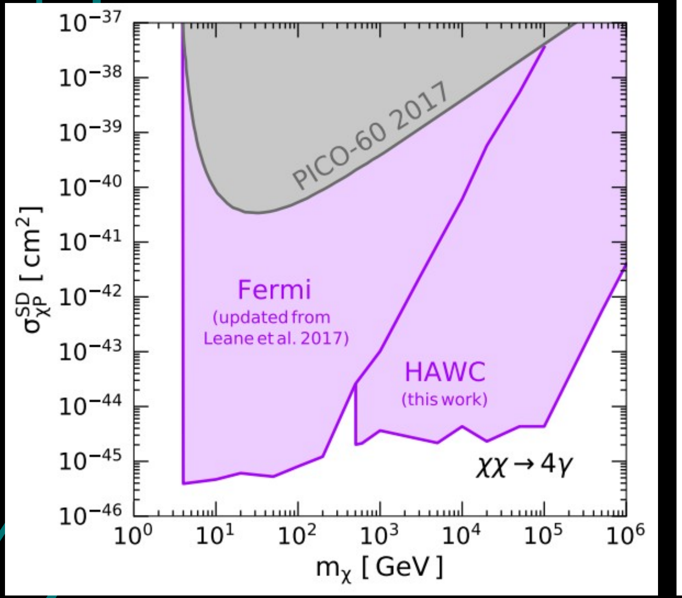
Leane, Linden, 2021

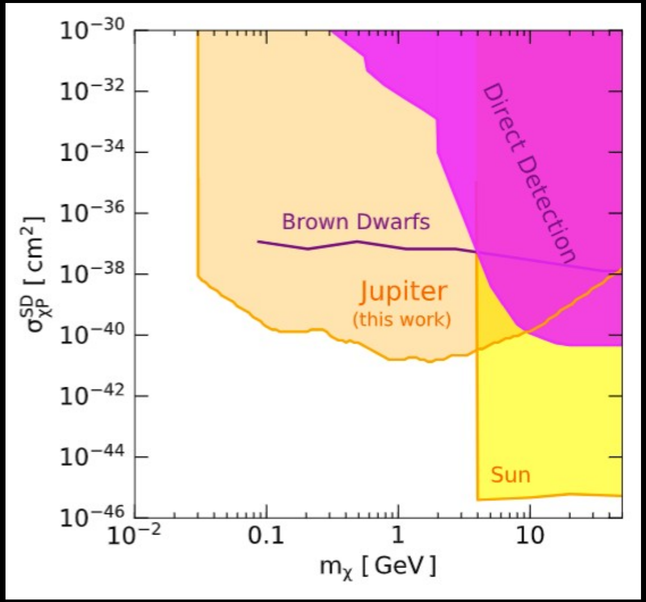
New dark matter limits



Leane, Linden, 2021

Optimal Celestial Target?





Sun

Leane, Ng, Beacom 2017
Leane + HAWC Collaboration 2018

Jupiter

Leane, Linden 2021

?

Neutron Star

?

Brown Dwarf

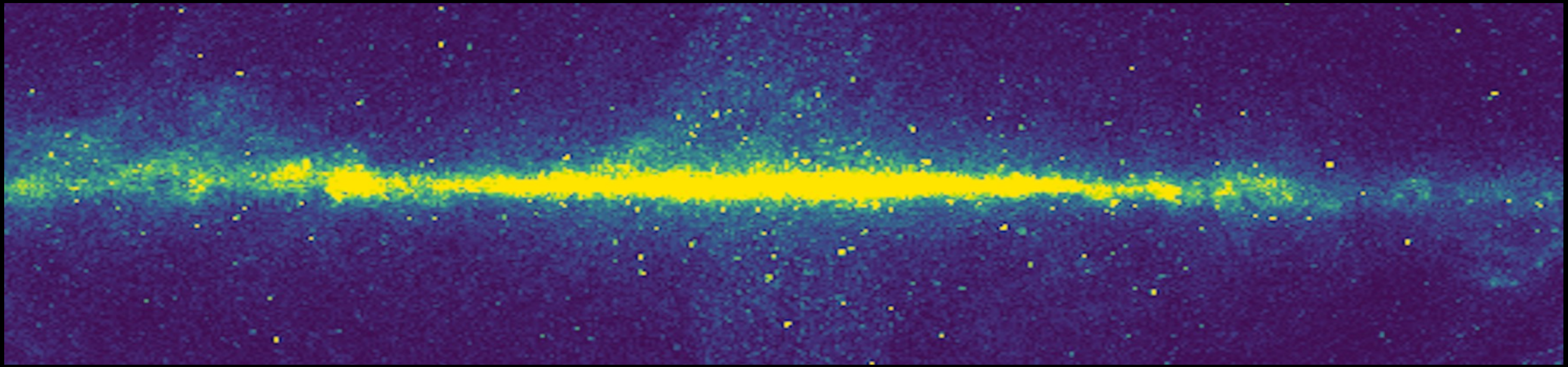
Long-Lived Mediator Limits

Rebecca Leane (SLAC)

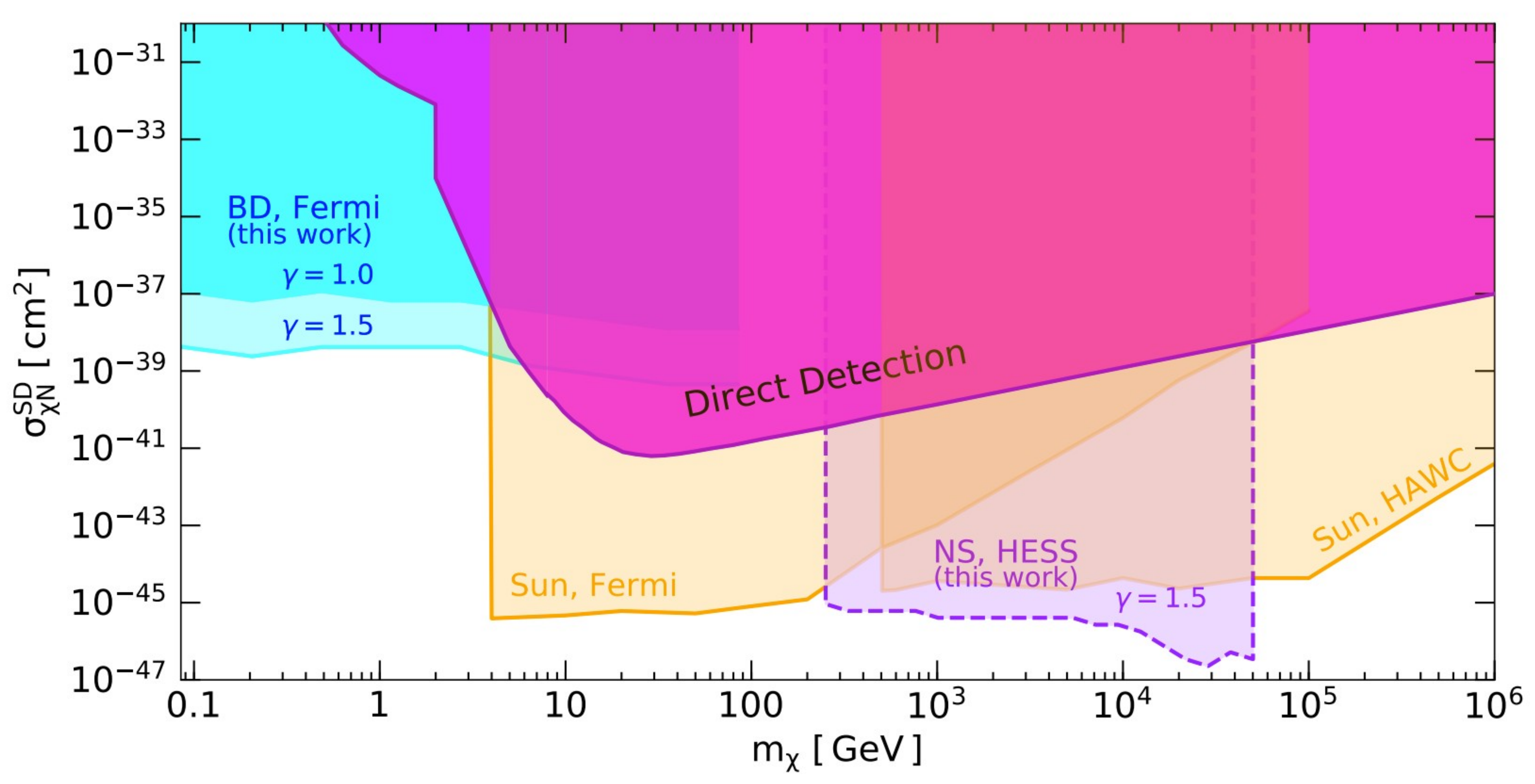
Galactic Center Population Signal

- 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



New Limits w/ Brown Dwarfs and Neutron Stars



Leane, Linden, Mukhopadyay, Toro 2021

Interesting things I didn’t mention…

- EoS effects on NSs, gravitational waves

Panotopoulos, Lopes 2017
Ellis et al 2018

- DM in Pop III stars

Freese, Spolyar, Aguirre 2008
Freese, Gondolo, Sellwood, Spolyar 2008

- Stellar evolution effects

Taoso et al 2010
Frandsen, Sarkar 2010
Zentner, Hearin 2011

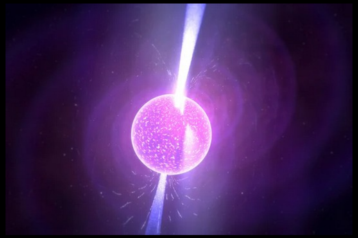
- Creation of black holes, destruction of stars

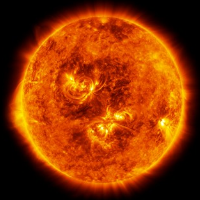
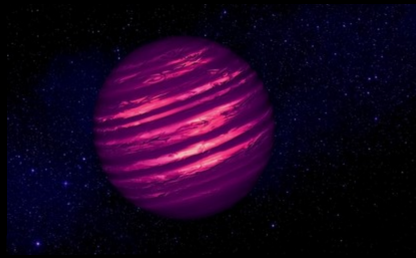
Gould, Draine, Romani, Nussinov 1989

- Evaporation of black holes, neutrinos

Acevedo, Bramante, Goodman, Kopp, Opferkuch 2020

Summary

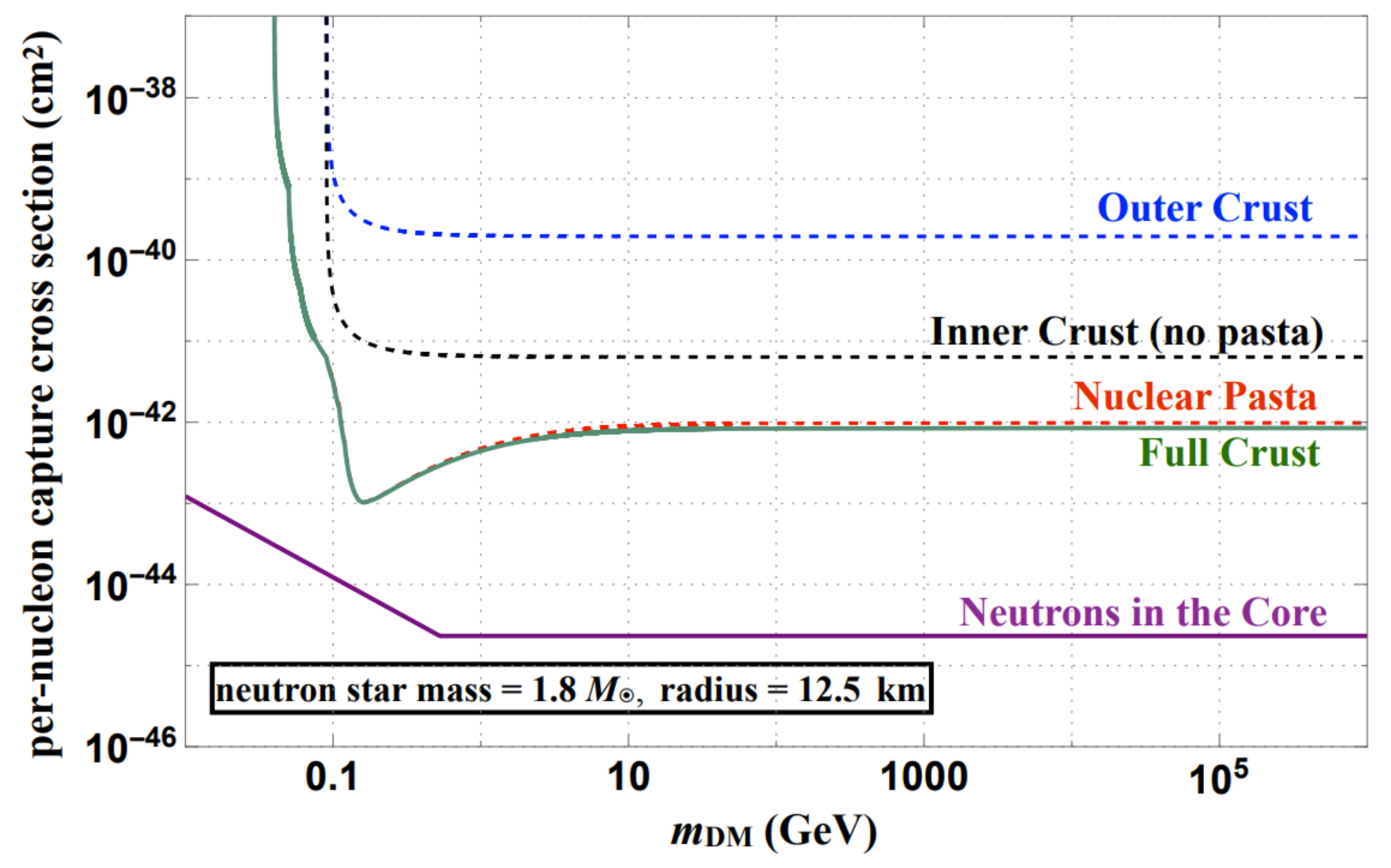


- Celestial bodies are playgrounds for discovering DM!
- Heating and neutrino/gamma-ray detection possible
- Earth, Sun, and Jupiter now already have strong constraints
- Exoplanets, Planets, White Dwarfs and Neutron Stars may provide new DM sensitivities
- New technologies and searches coming soon, also, hopefully DM!

EXTRA SLIDES

DARK MATTER – NEUTRON STAR INTERACTIONS



$T_\infty^{\rm crust} = 1620$ K

Acevedo, Bramante, Leane, Raj, 2019

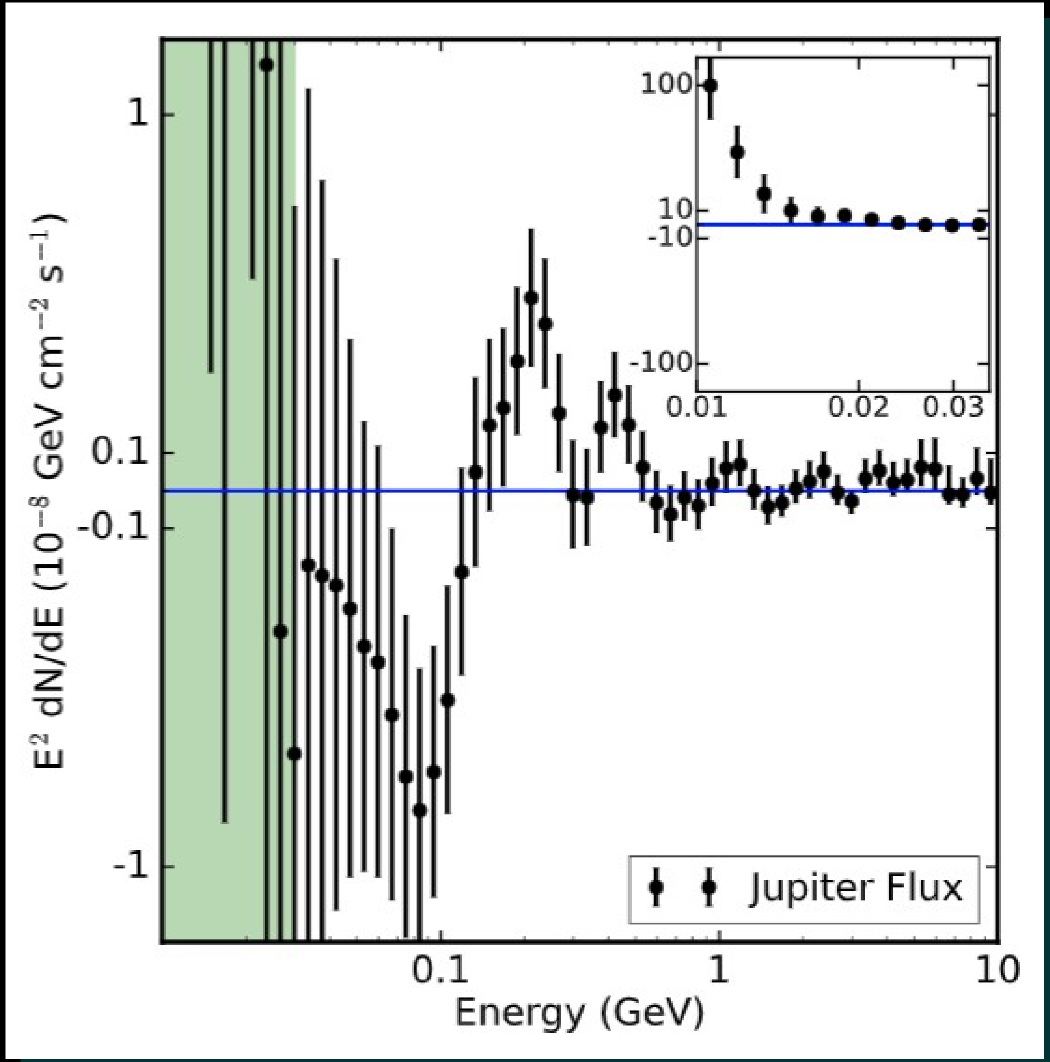
Rebecca Leane (SLAC)

Jupiter Flux Limits

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

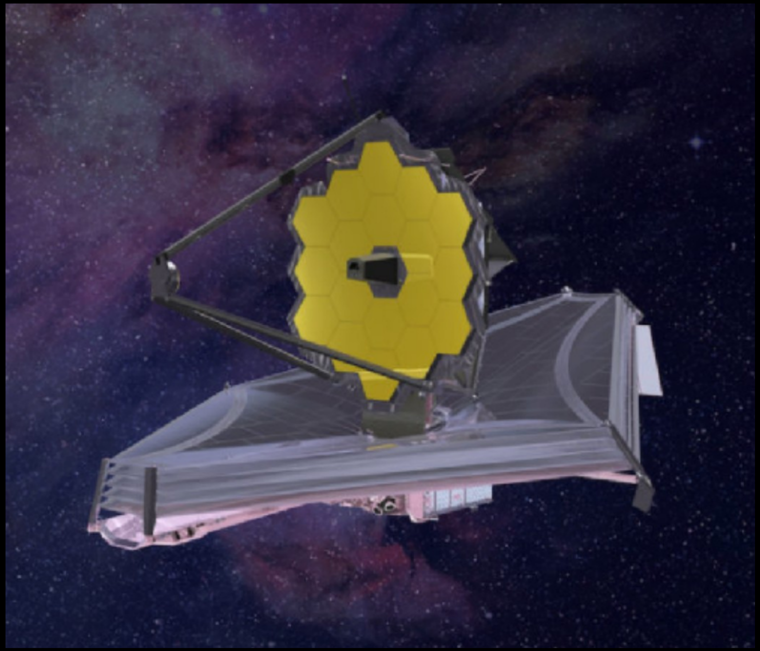
\+ In low energy bins, “5σ” excess, but important systematics not there

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

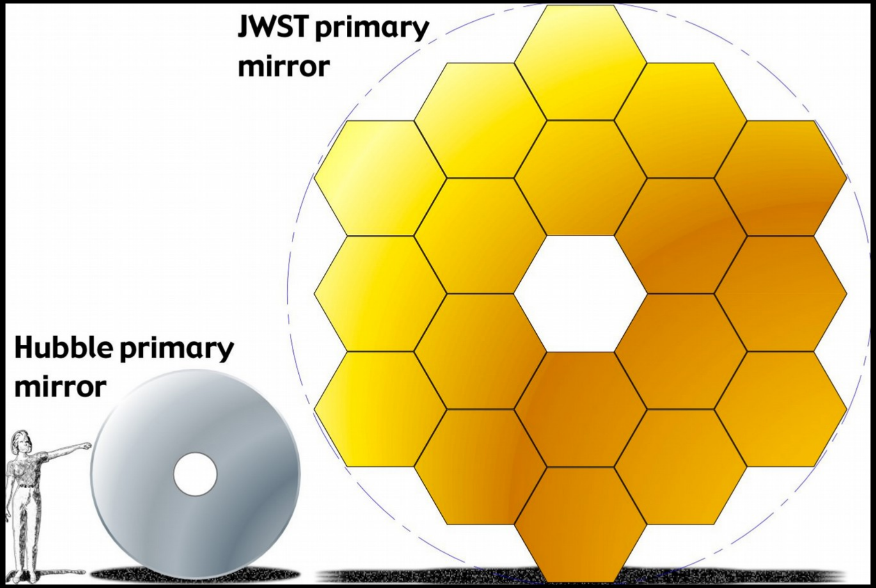


Leane, Linden, 2021

Telescope Sensitivity



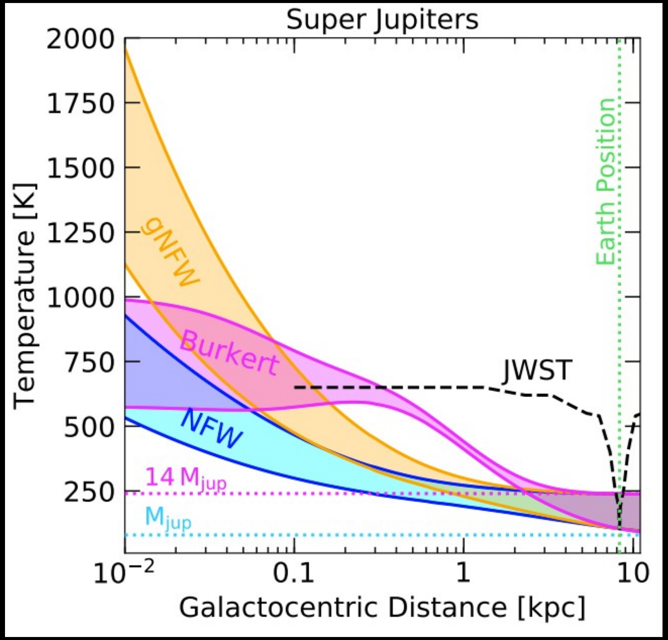
- Use James Webb Space Telescope (planned launch Oct 2021)
- Infrared sensitivity (~0.5 – 28 microns)
- Has many instruments and filters, relevant choice for maximum sensitivity depends on peak wavelength



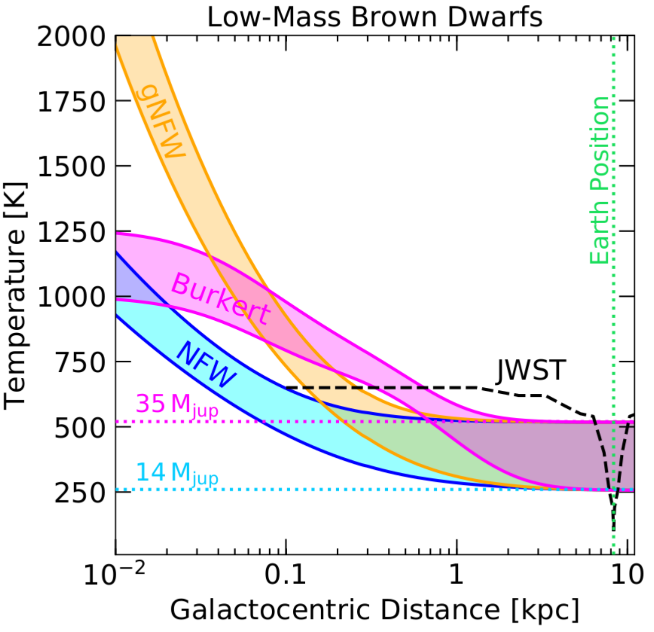
Rebecca Leane (SLAC)

Exoplanet masses vs sensitivity

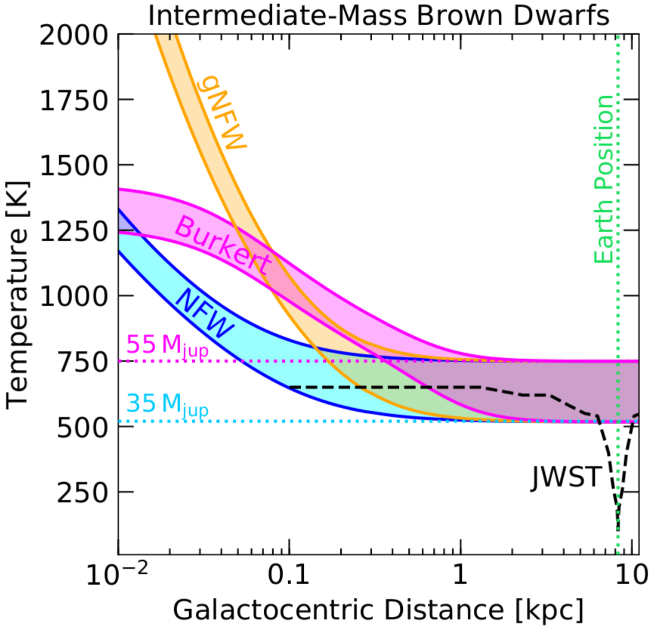
Mjup – 14 Mjup



14 Mjup – 35 Mjup



35 Mjup – 55 Mjup

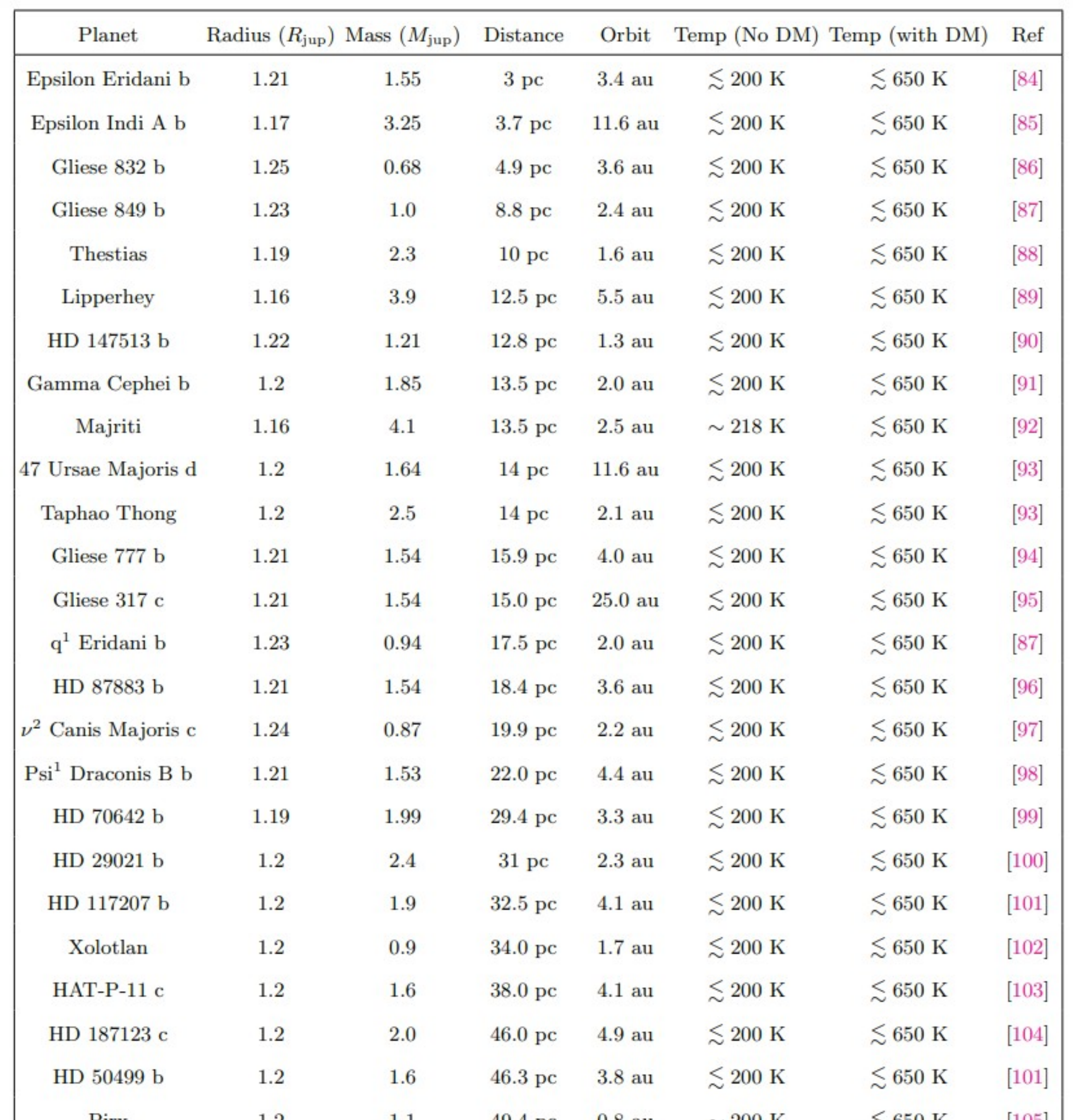


Lower masses:
DM heat > internal heat at all positions

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

Rebecca Leane (SLAC)

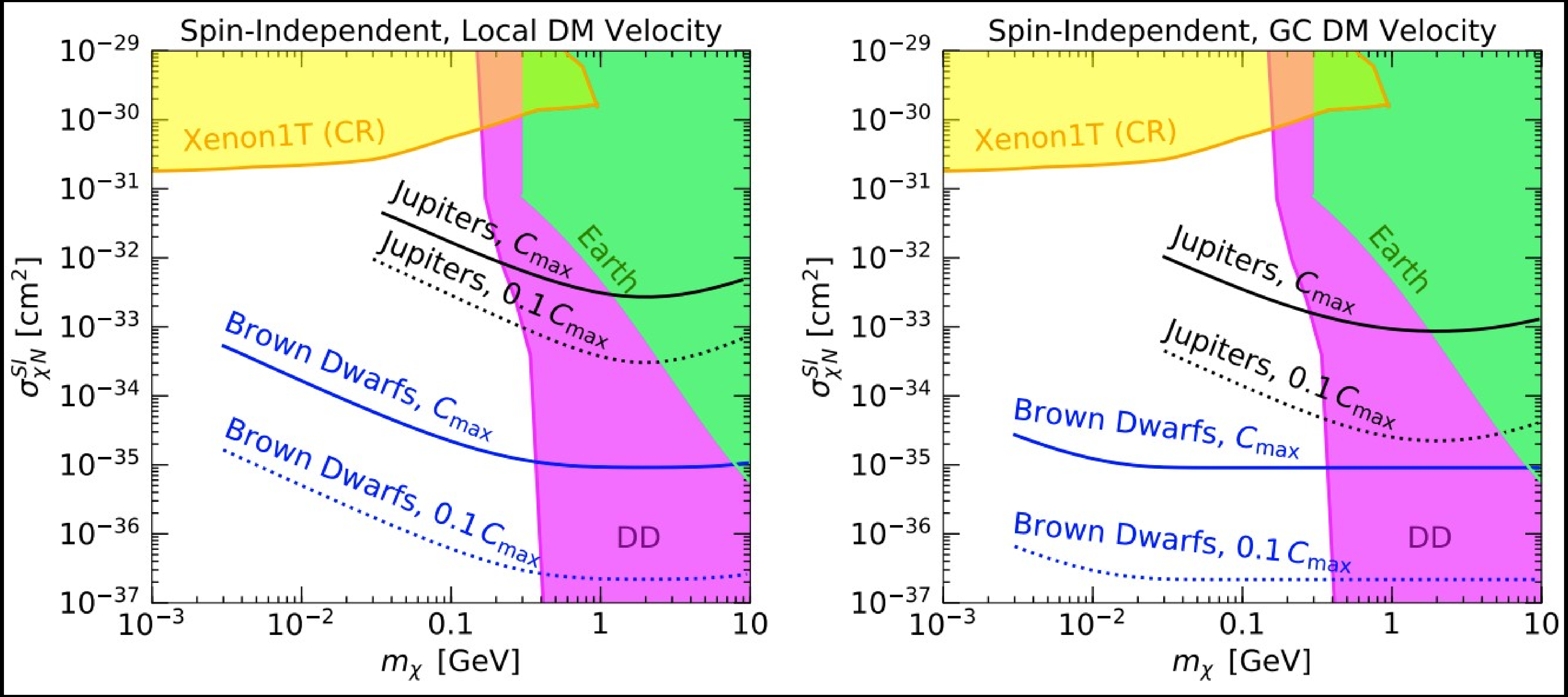
Prospects for these searches?



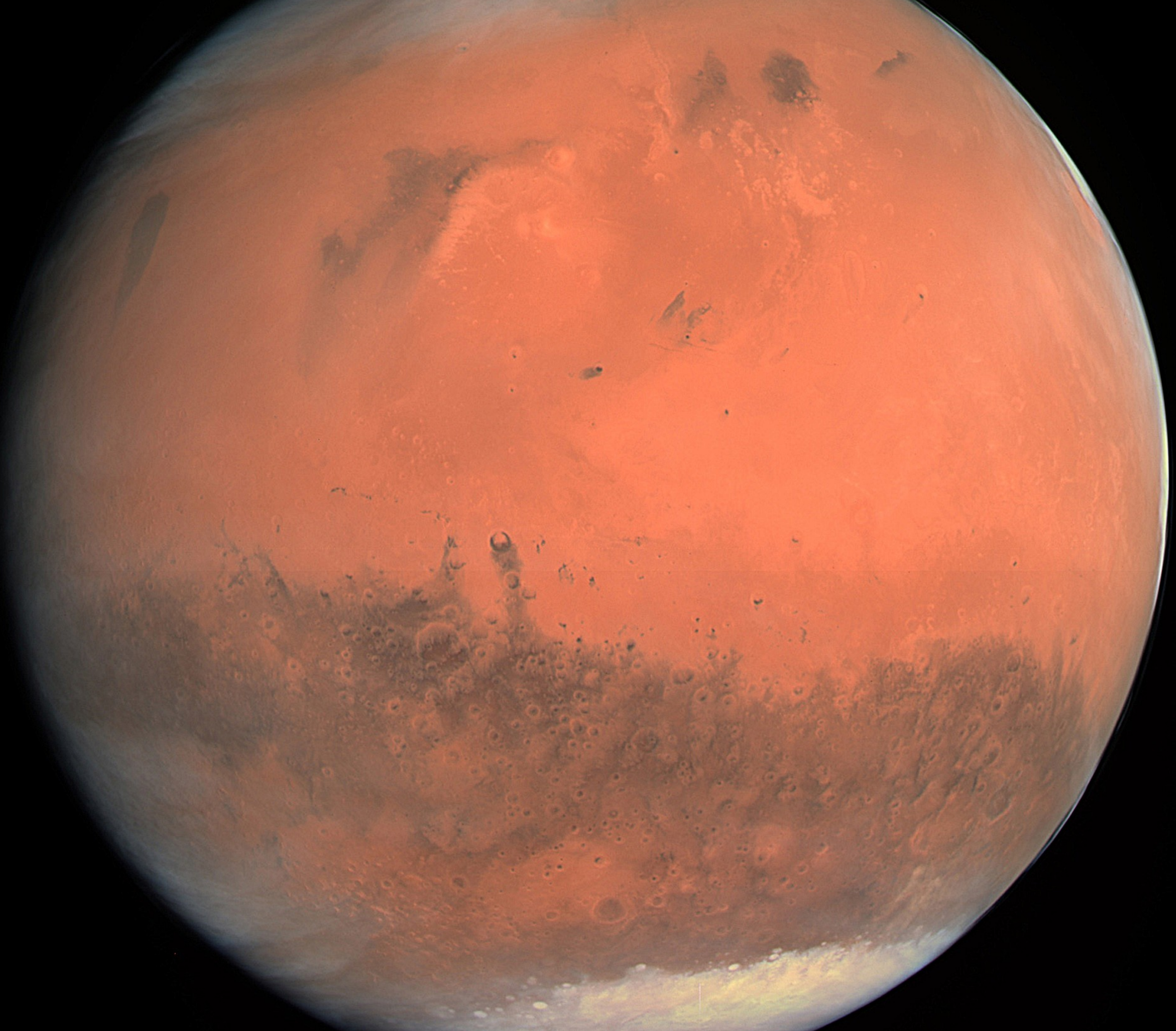
Planet	Radius (R_{jup})	Mass (M_{jup})	Distance	Orbit	Temp (No DM)	Temp (with DM)	Ref
Epsilon Eridani b	1.21	1.55	3 pc	3.4 au	$\lesssim 200$ K	$\lesssim 650$ K	[84]
Epsilon Indi A b	1.17	3.25	3.7 pc	11.6 au	$\lesssim 200$ K	$\lesssim 650$ K	[85]
Gliese 832 b	1.25	0.68	4.9 pc	3.6 au	$\lesssim 200$ K	$\lesssim 650$ 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]

- 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



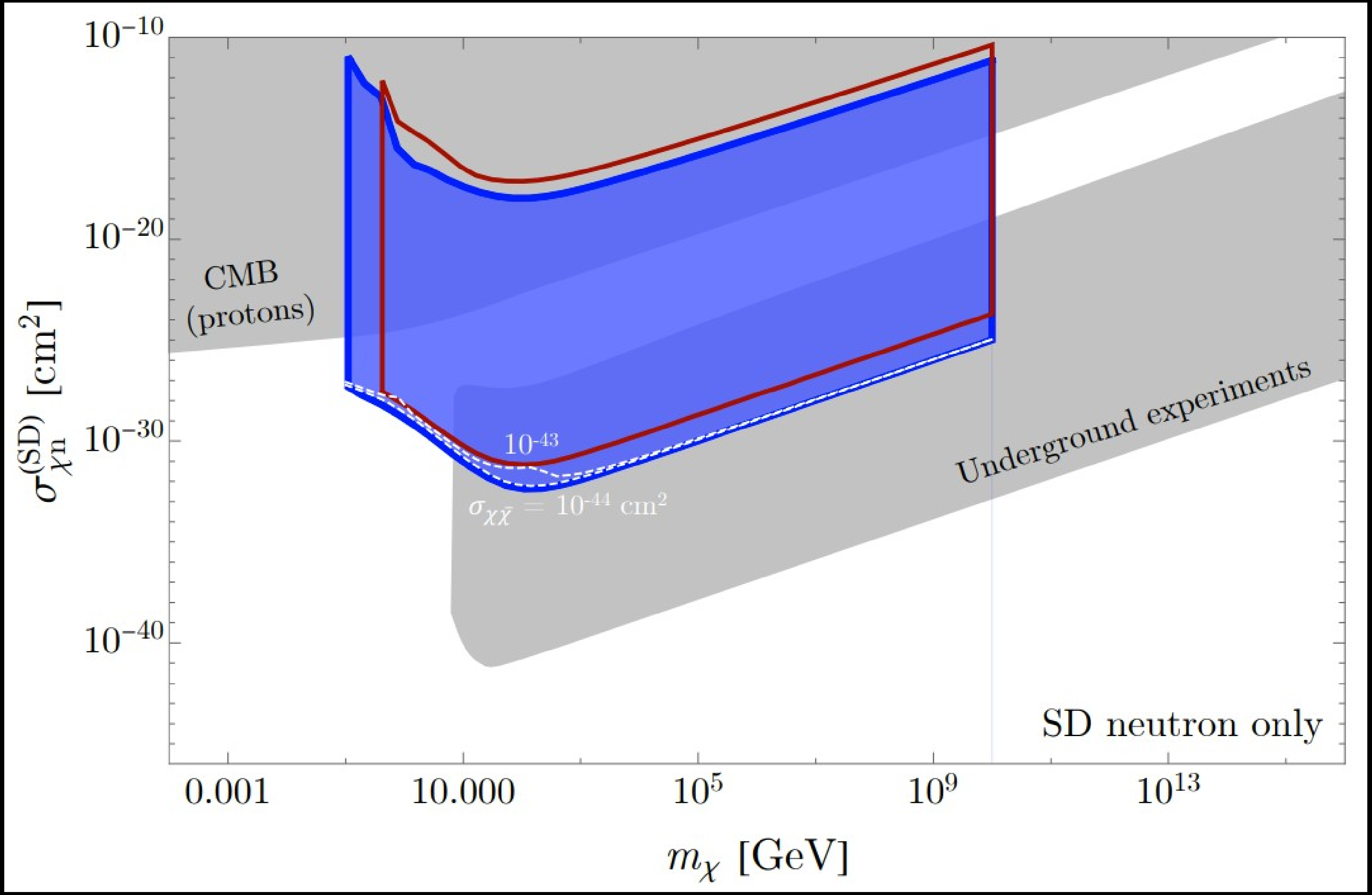
RKL + Smirnov, 2020



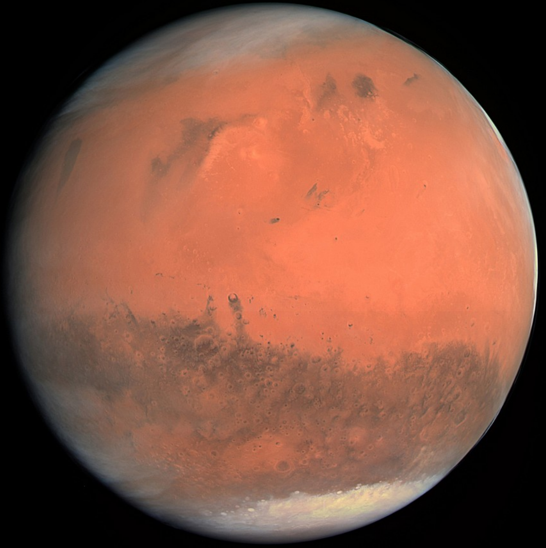
MARS

Bramante, Buchanan,
Goodman, Lodhi 2019

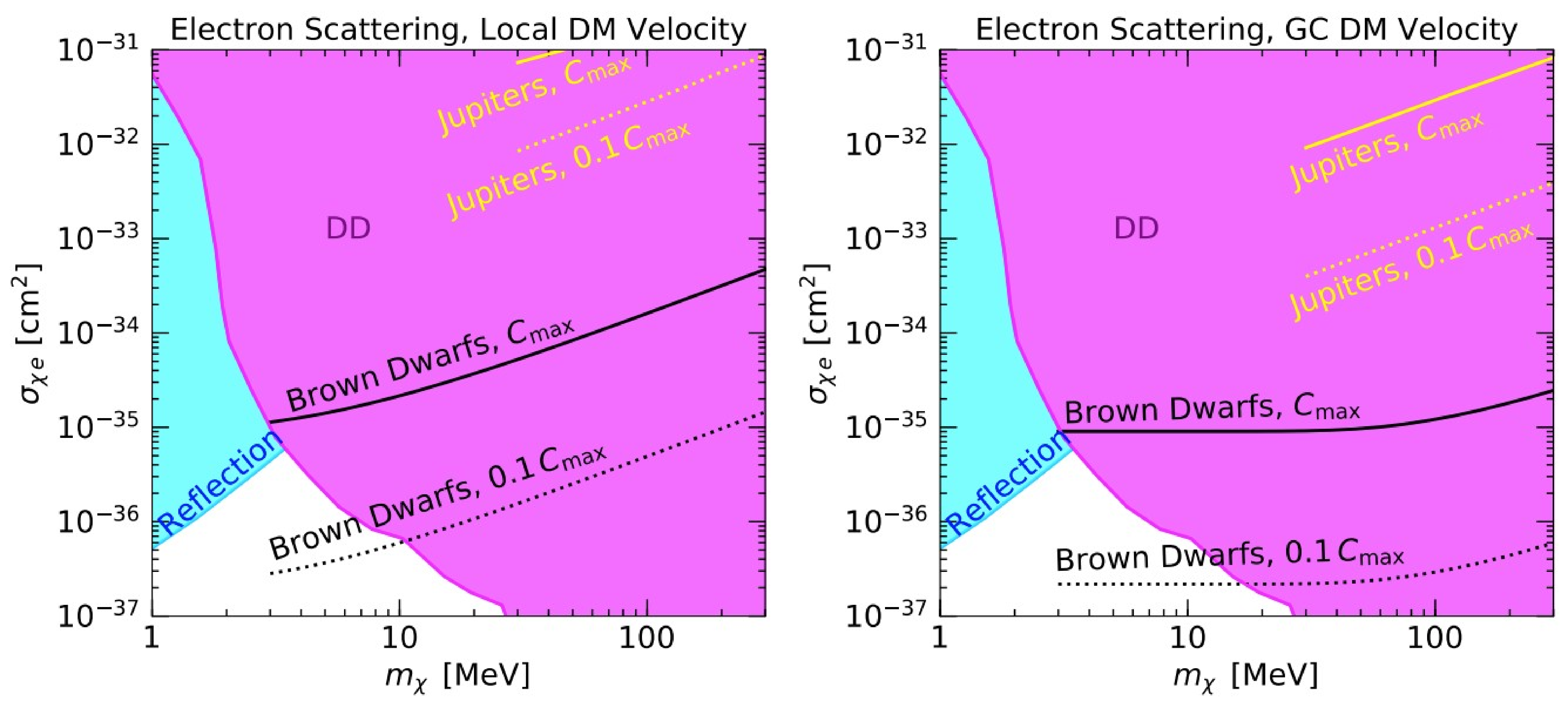
MARS



Bramante, Buchanan,
Goodman, Lodhi
1909.11683



DM scattering cross section sensitivity



RKL + Smirnov, 2020

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

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

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

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

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

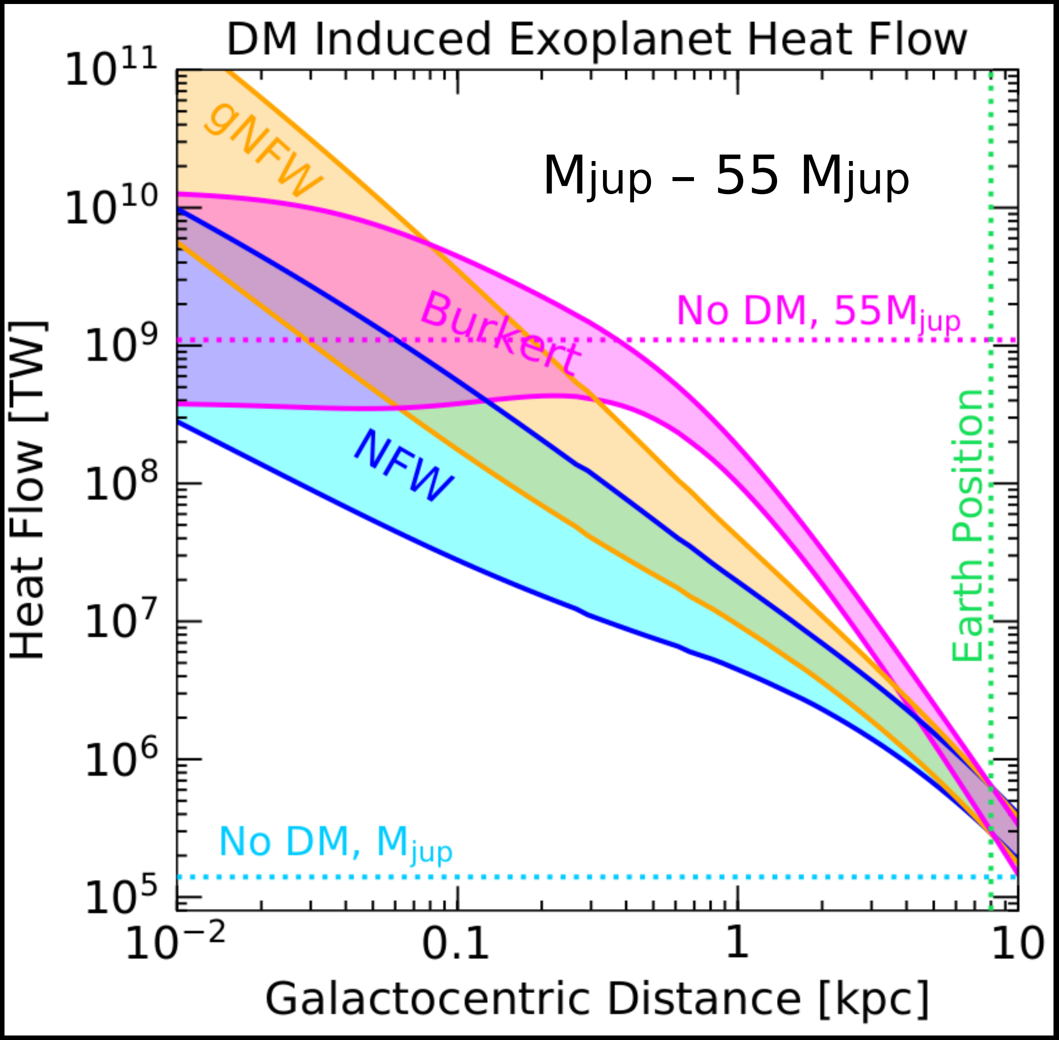
$$\boxed{\Gamma_{\rm heat}^{\rm DM} = f \, \pi R^2 \rho_\chi(r) \, v_0 \left(1 + \frac{3}{2} \frac{v_{\rm esc}^2}{v_d(r)^2}\right)}$$

DM Heating vs Internal Heat

RKL + Smirnov, 2020

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

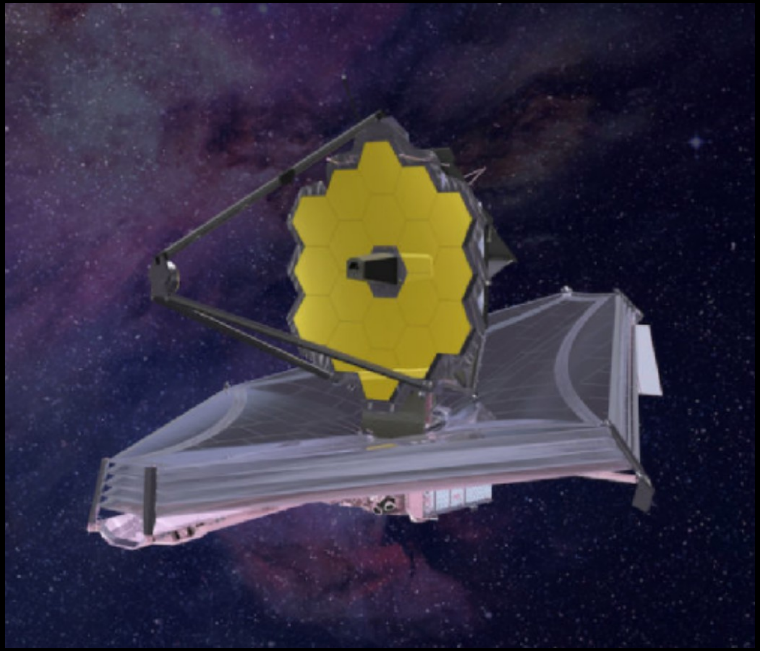
$$\Gamma^{\rm DM}_{\rm heat} = f\,\pi R^2 \rho_\chi(r)\,v_0\left(1+\frac{3}{2}\frac{v_{\rm esc}^2}{v_d(r)^2}\right)$$

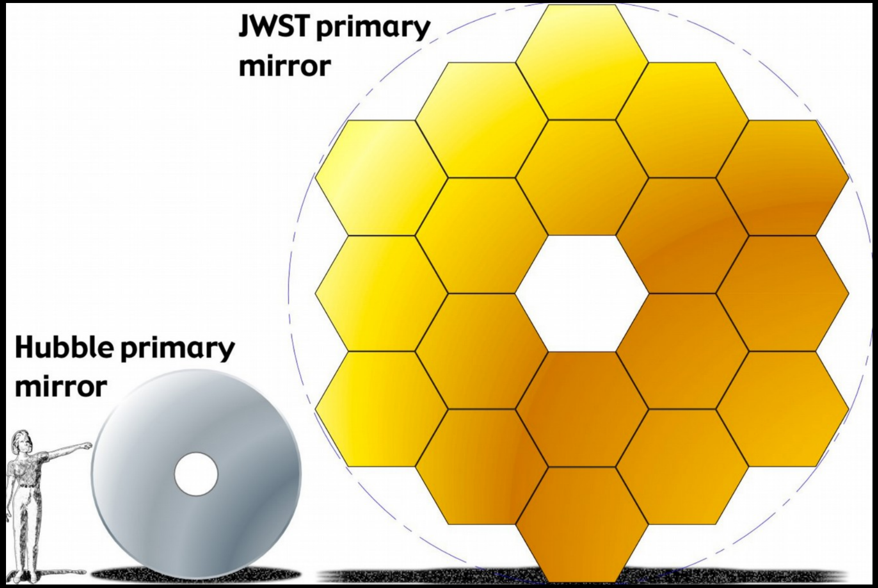


1 parsec = 3.26 light years

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



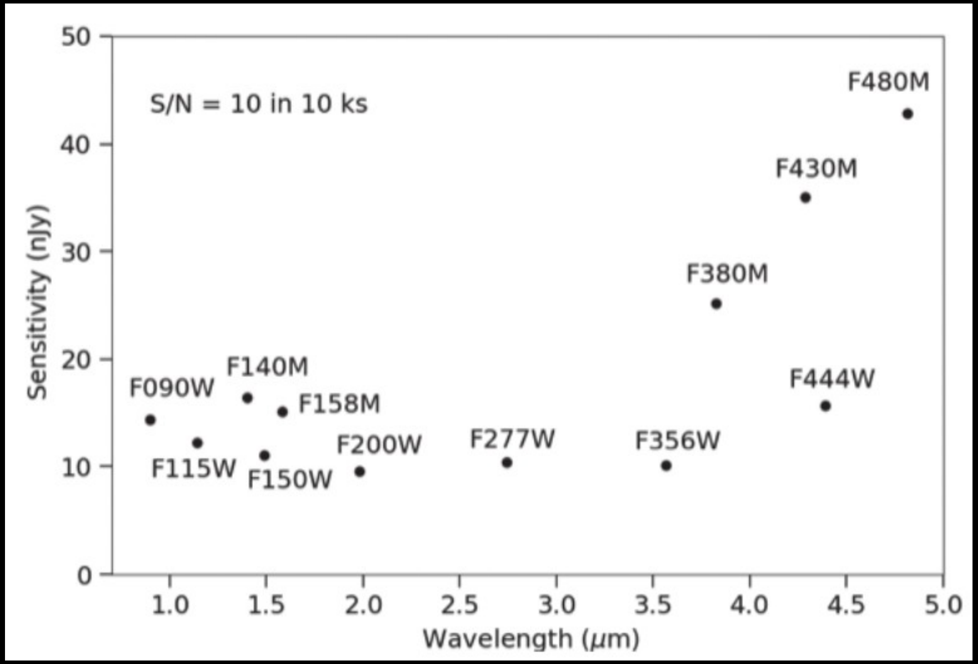


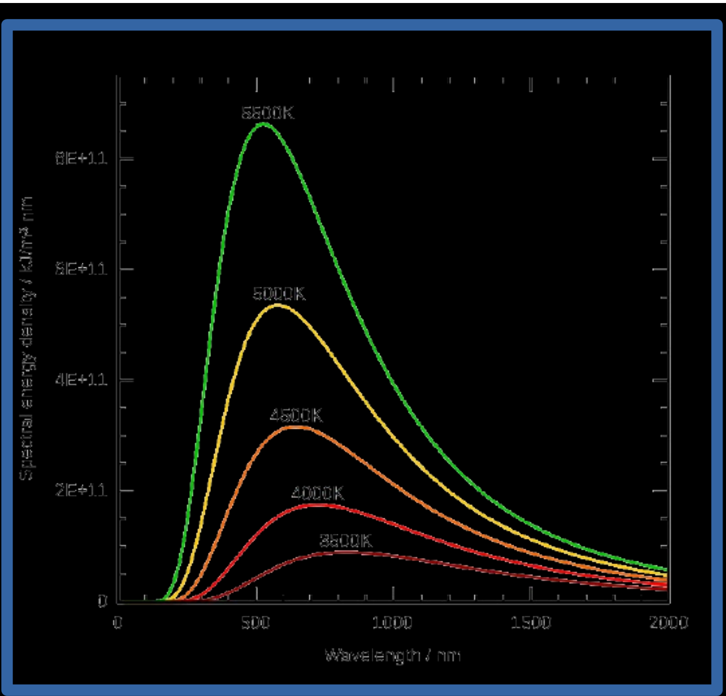
Signal with James Webb

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

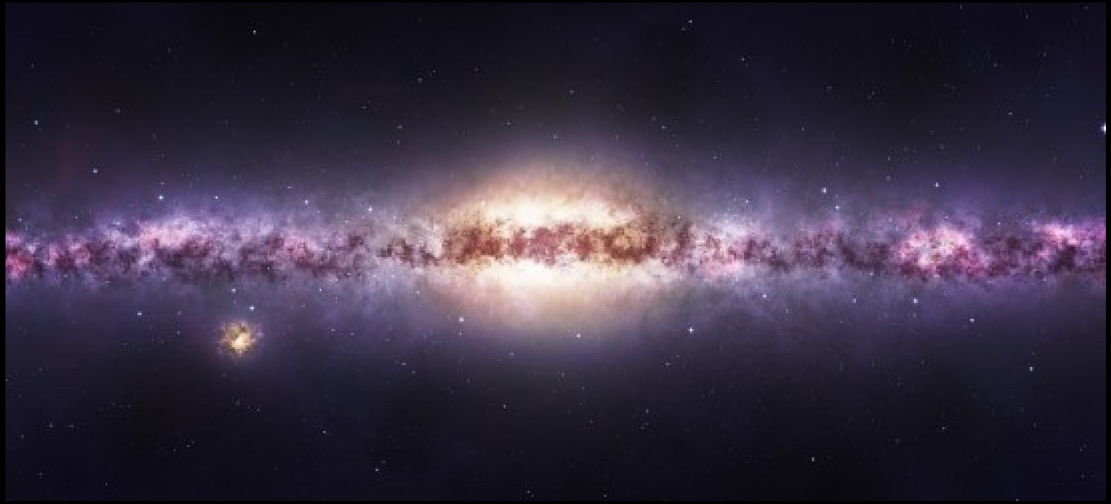
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K
- Mid-Infrared Instrument (MIRI) for T = 100 - 500 K

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)

DM Equilibrium and Evaporation

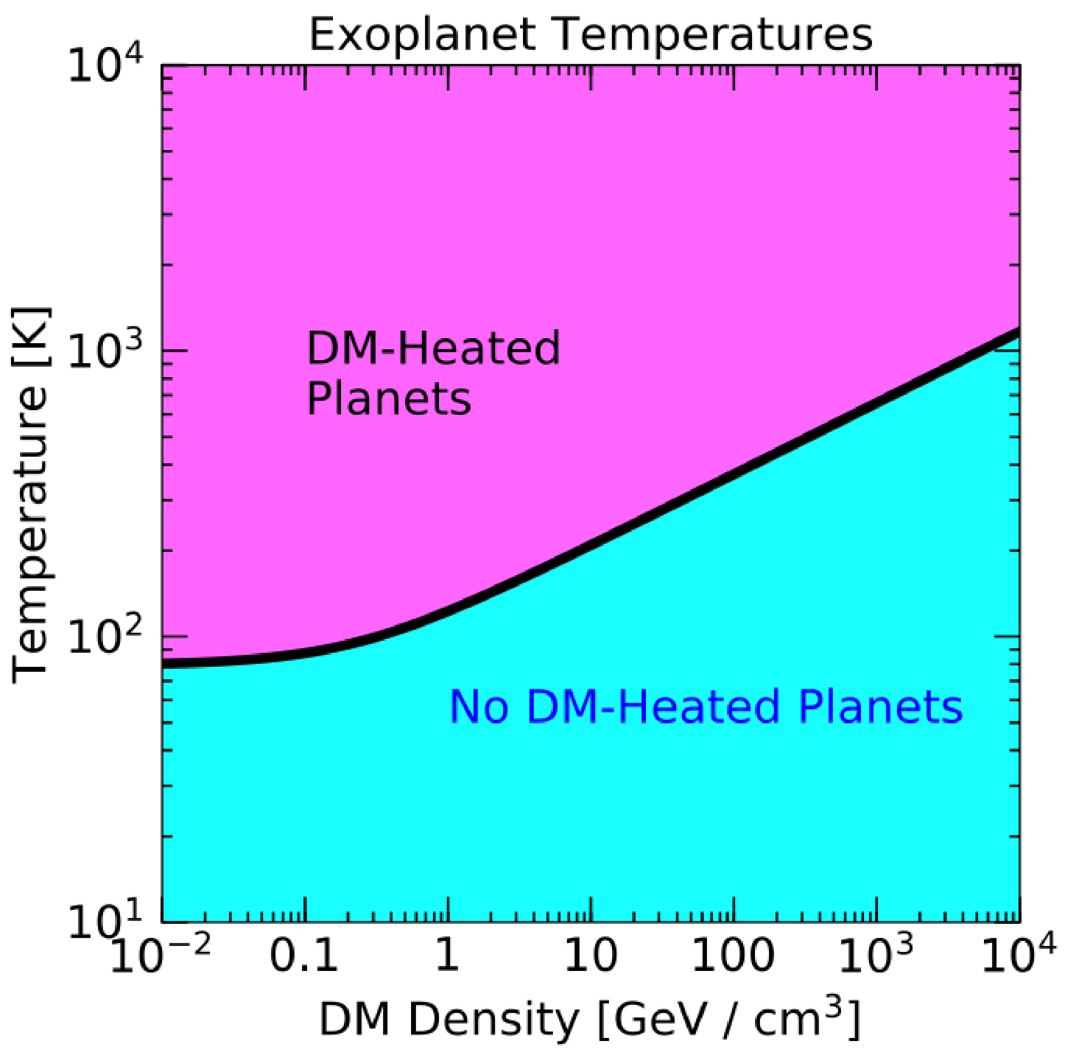
- For maximal rate, want DM scattering and annihilation to be in equilibrium
  - Find DM reaches equilibrium by 1-10 Gigayears

- 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

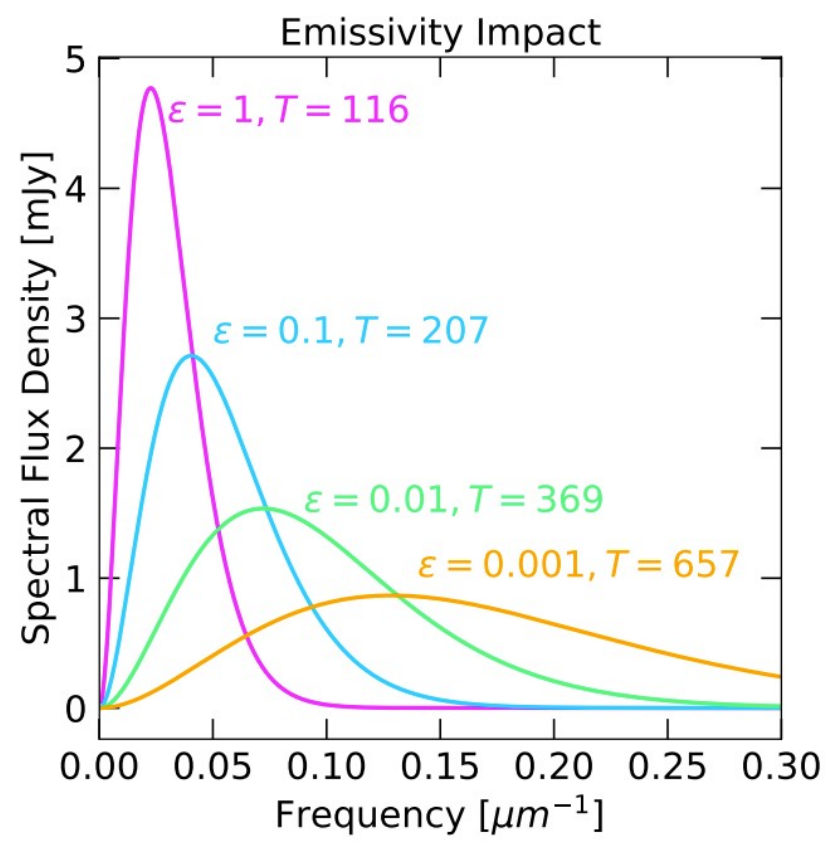


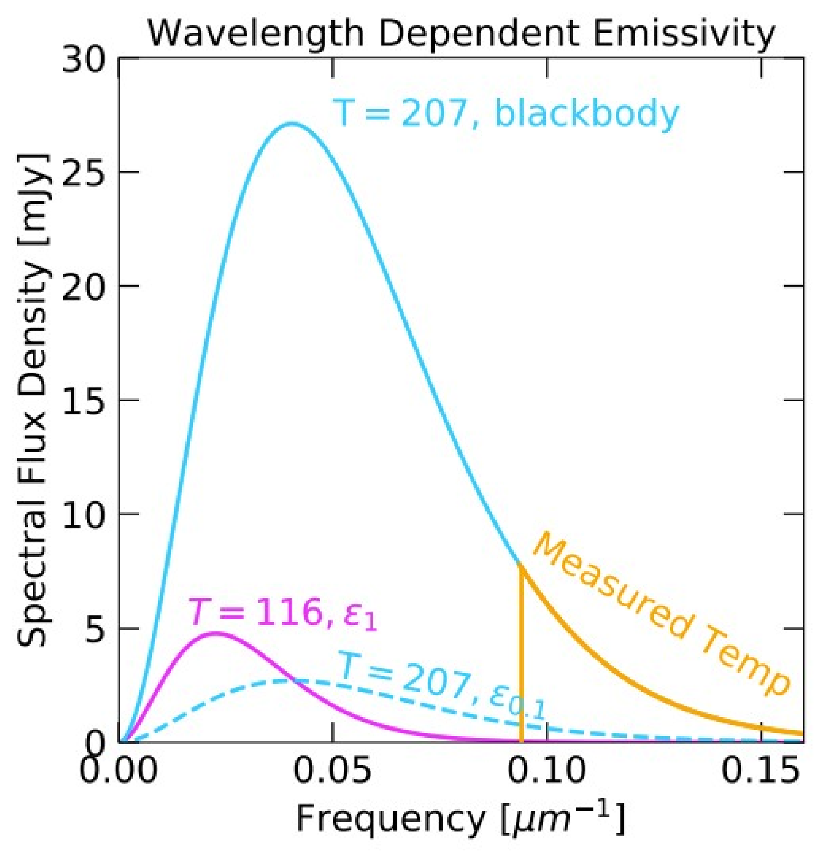
Rebecca Leane (SLAC)

Deviations: Non-Blackbody Spectra

Atmosphere effects can cause deviations from a blackbody

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



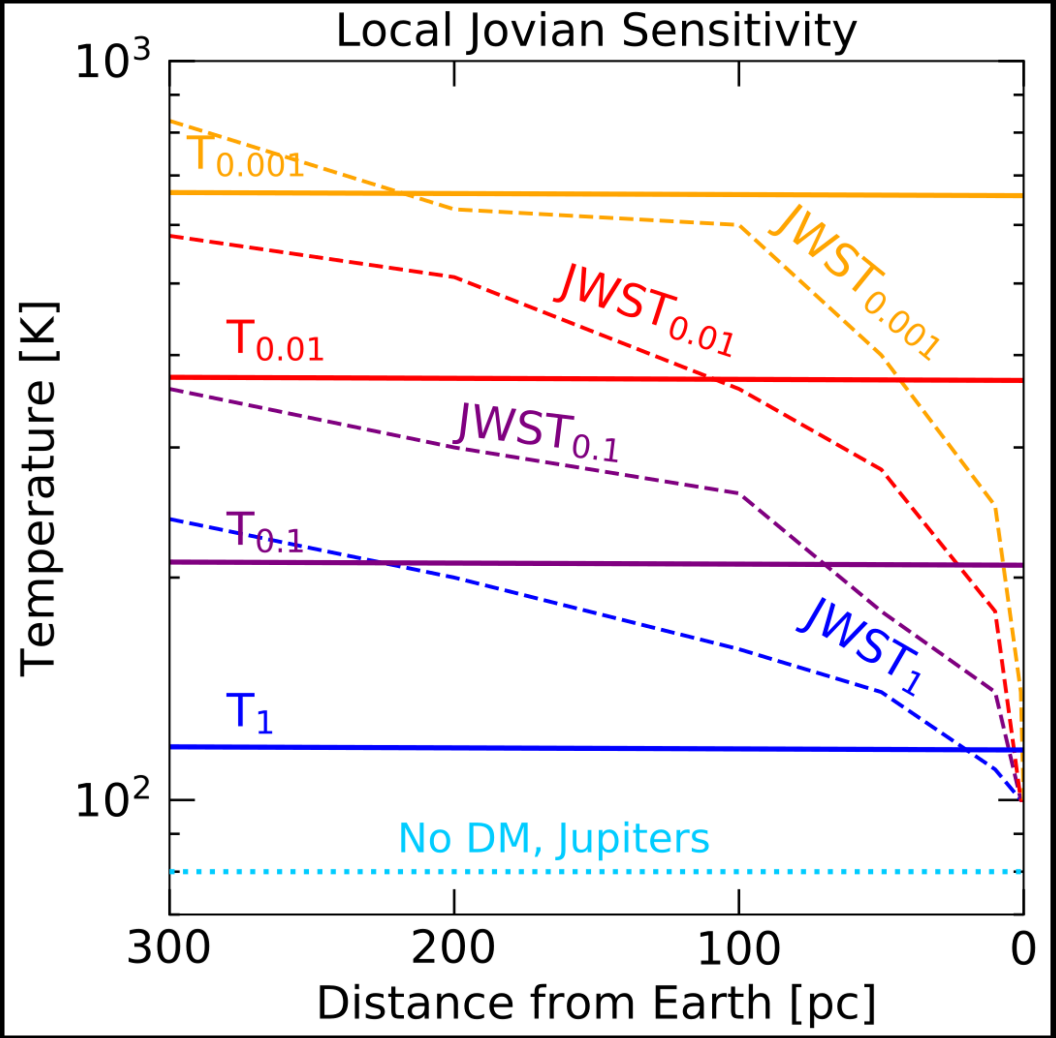


Local DM-Heated Exoplanet Search

- 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

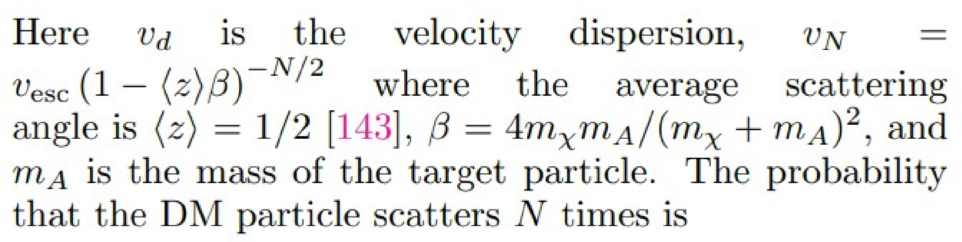

Local Jovian Sensitivity

DM scattering cross section sensitivity

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

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

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



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

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

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

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

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

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

AGE – COOLING CURVES