# Detecting Dark Matter in Exoplanets

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3rd South American DM Workshop, ICTP-SAIFR
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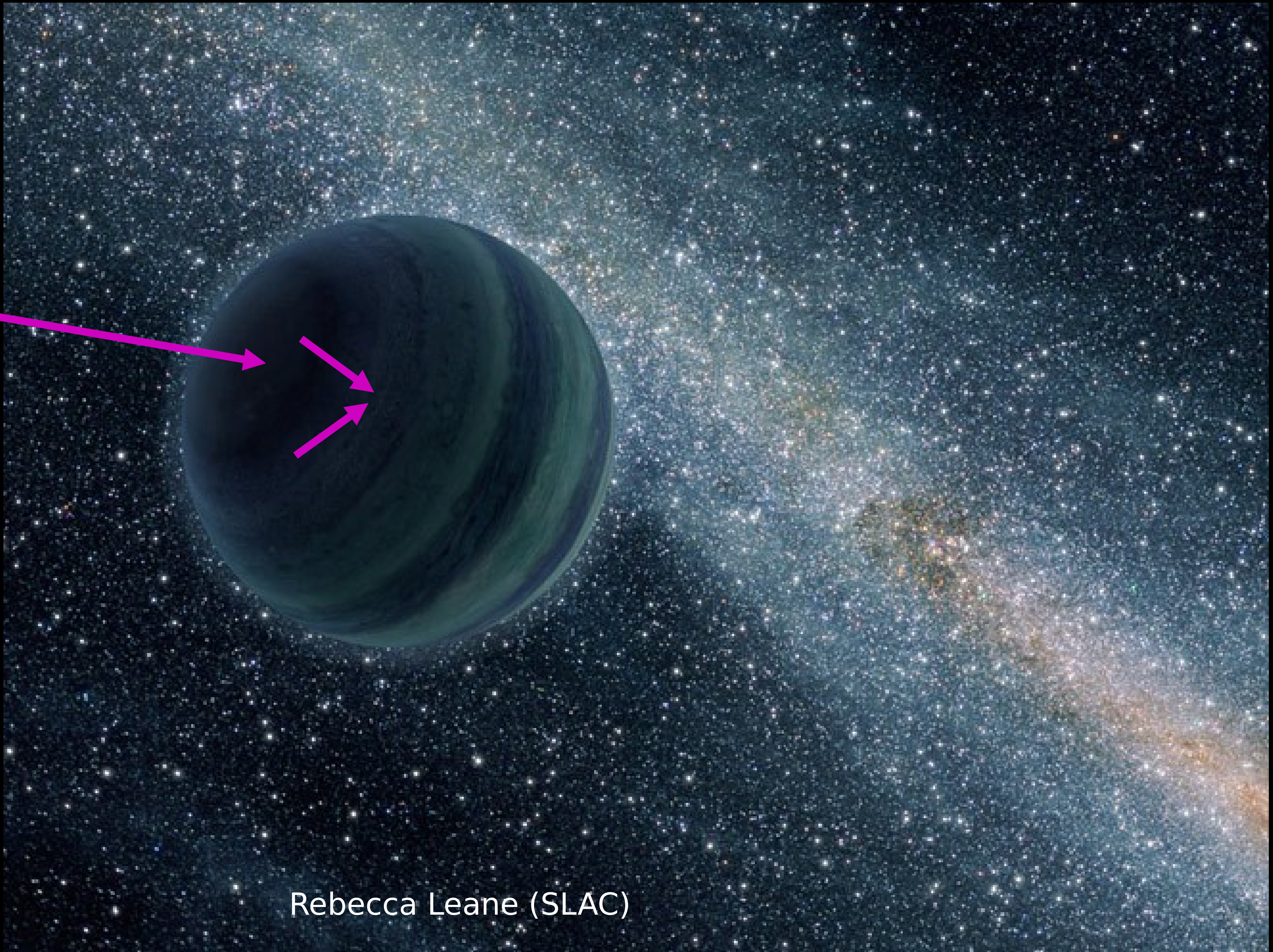
Based on 2010.00015 w/ Juri Smirnov

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

Rebecca Leane (SLAC)

# DARK MATTER CAPTURE IN EXOPLANETS

Dark Matter



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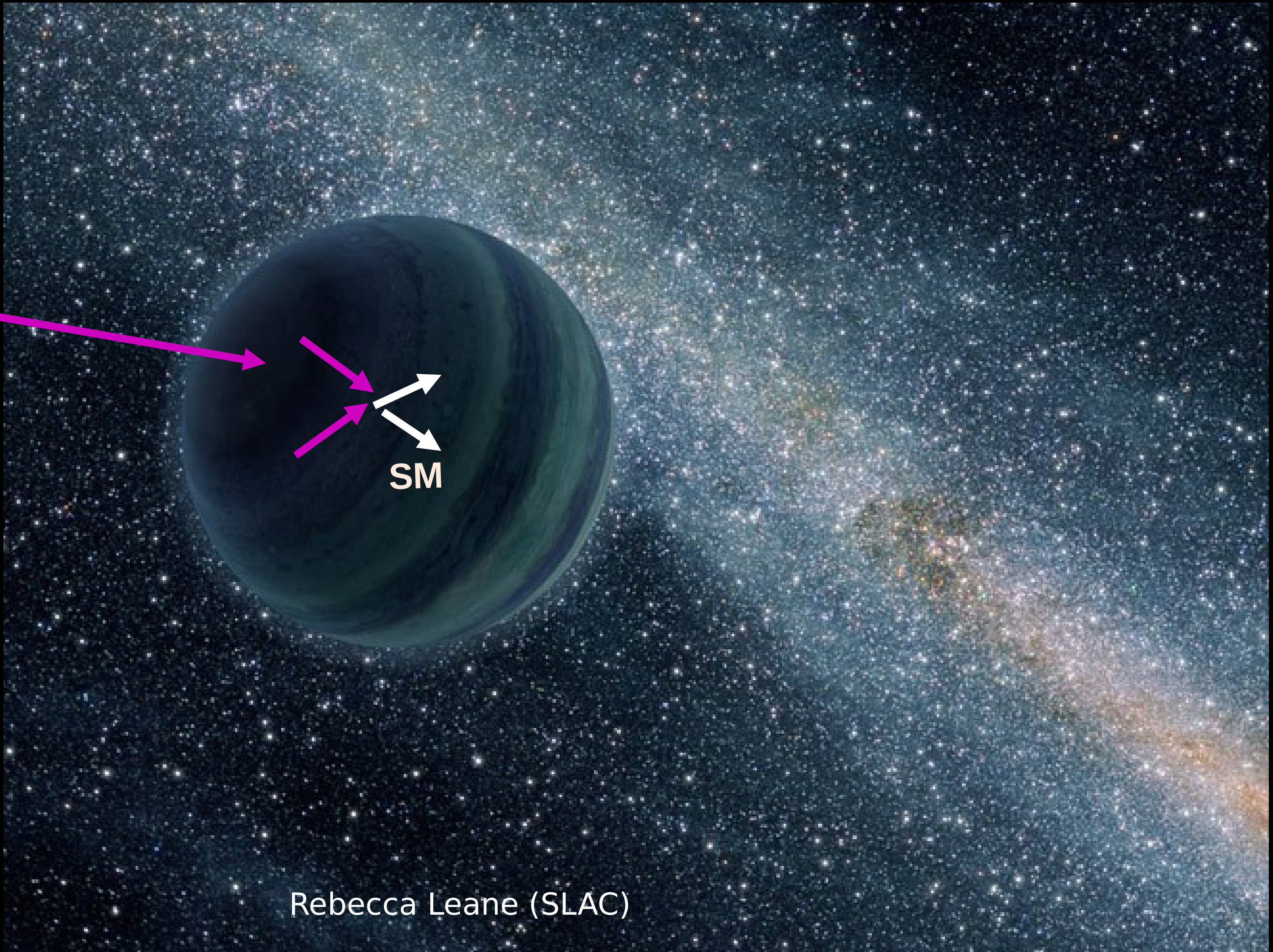


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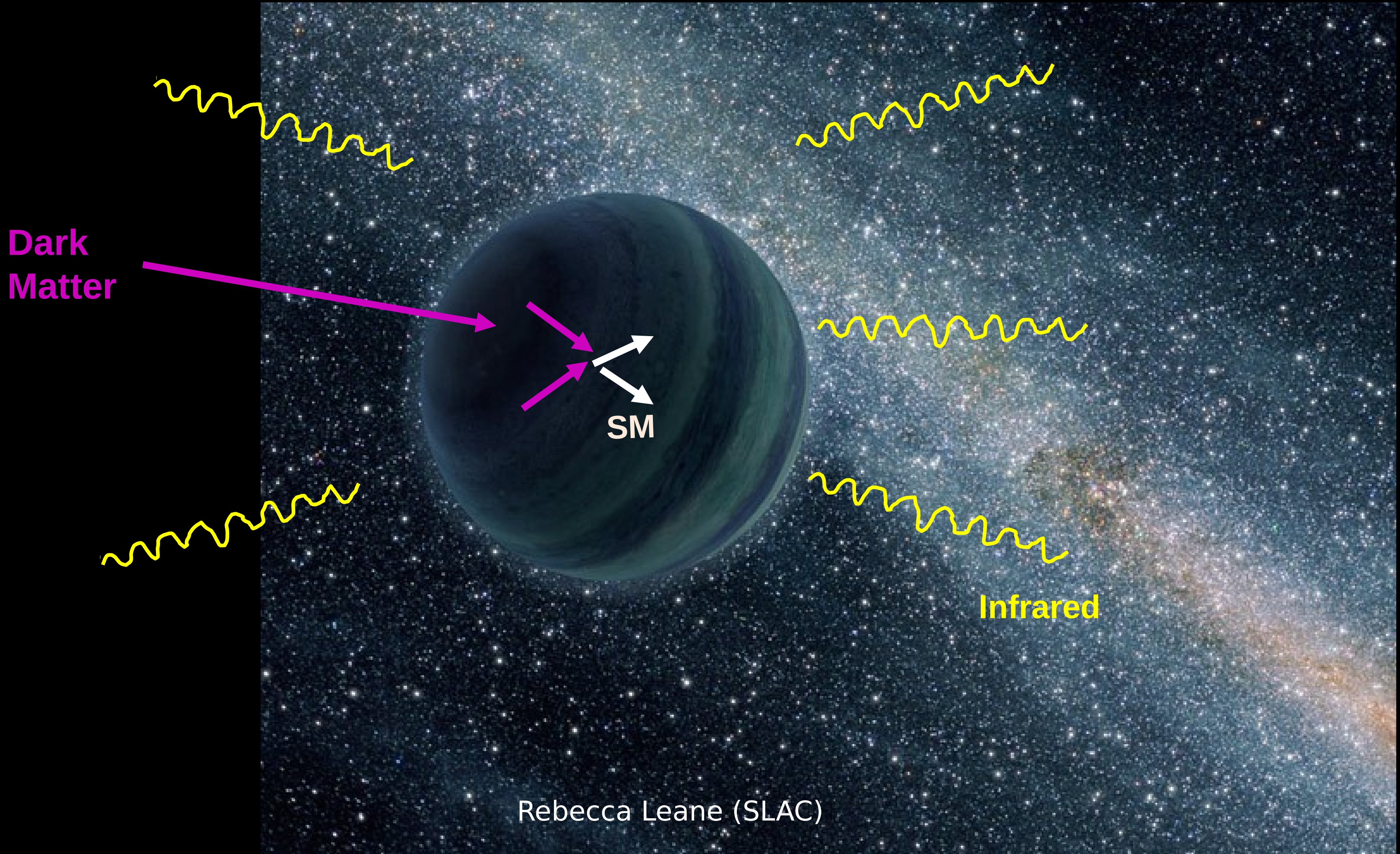


# *Why* Exoplanets?

Rebecca Leane (SLAC)

# 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.

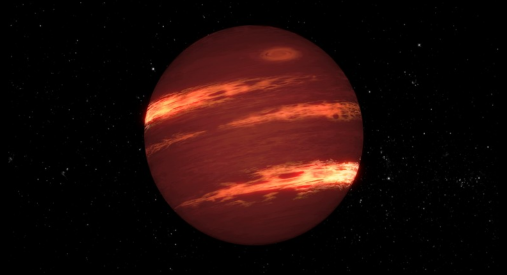
# Advantage 2: Statistics

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 $10^{11}$

x 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


**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 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

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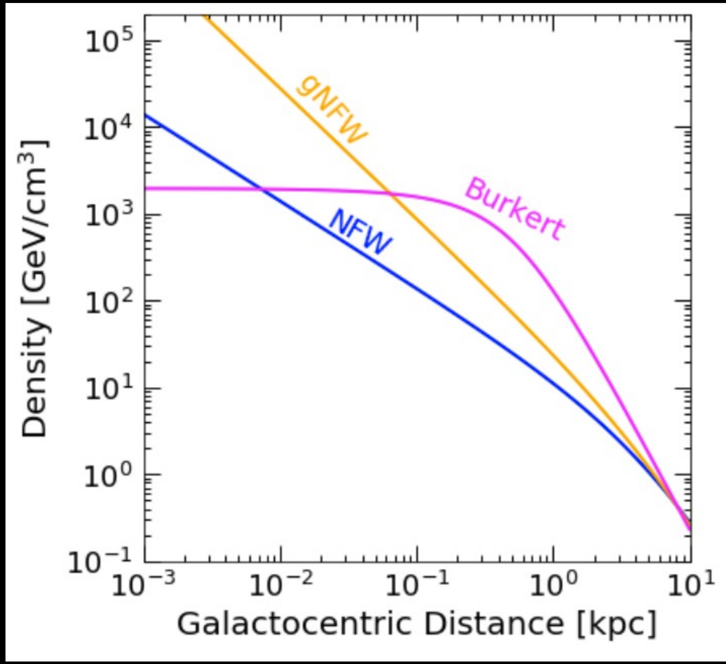
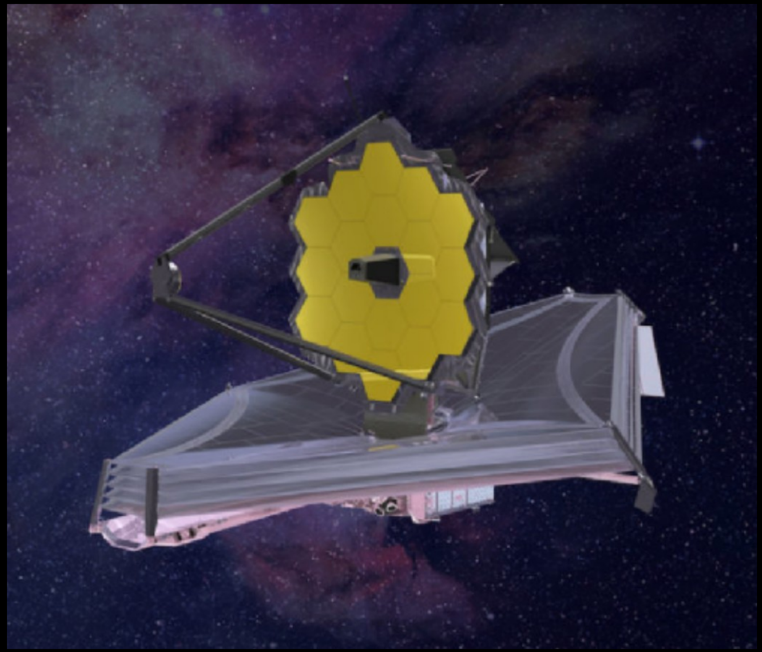
Heat power from DM:

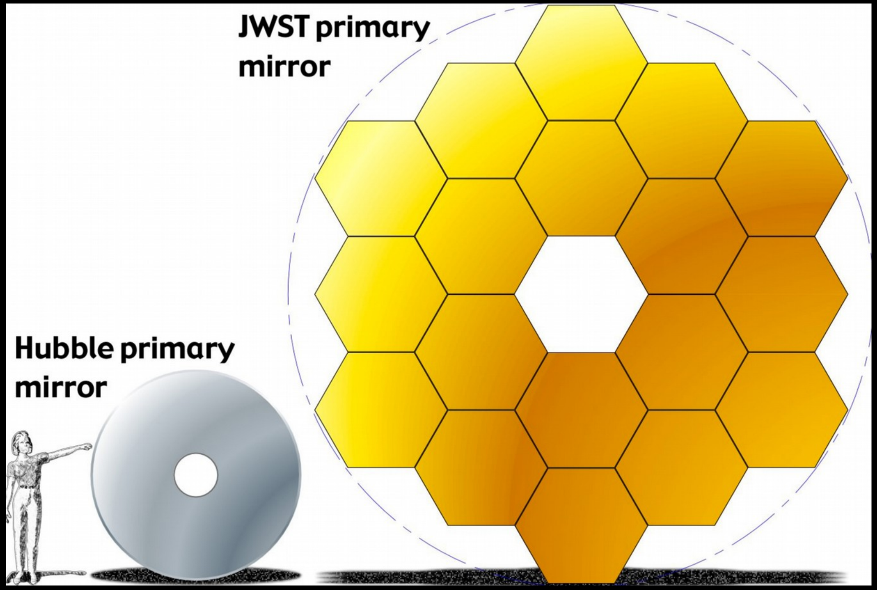
- DM density throughout Galaxy
- DM halo velocity
- Exoplanet escape velocity



# Telescope Sensitivity

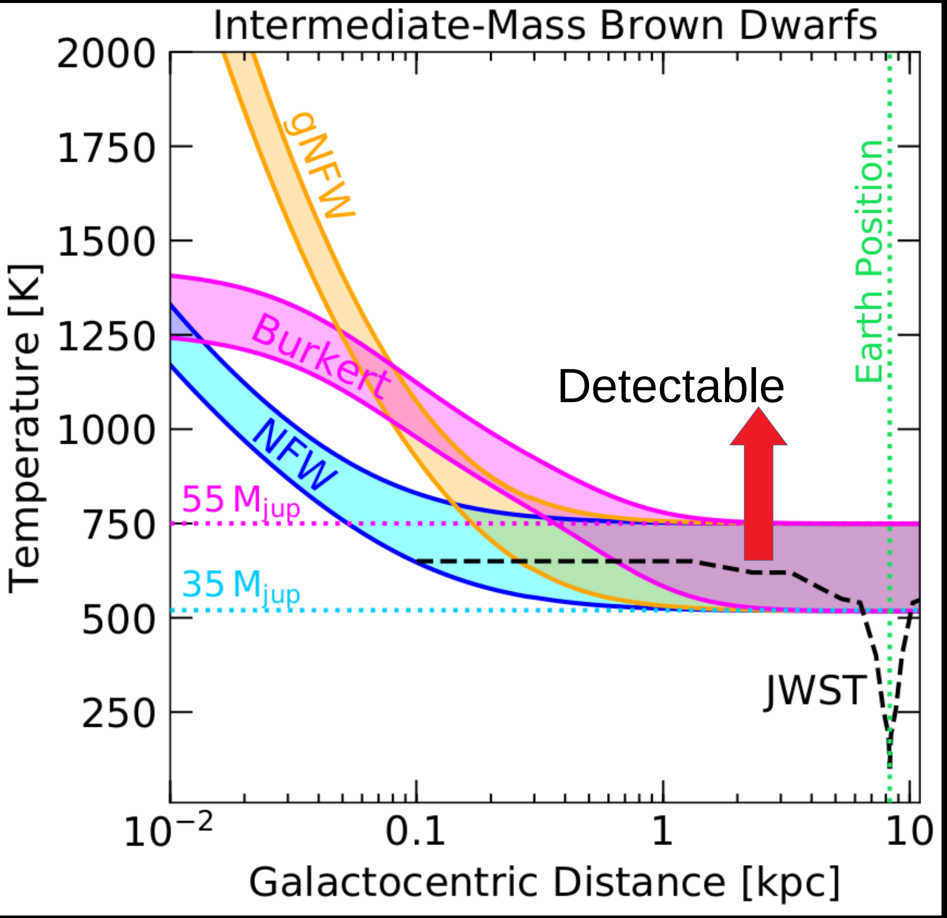
- Use James Webb Space Telescope (planned launch Oct 2021)
- Infrared sensitivity (~0.5 – 28 microns)
- Has many instruments and filters, relevant choice for maximum sensitivity depends on peak wavelength





# Exoplanet temperatures vs sensitivity

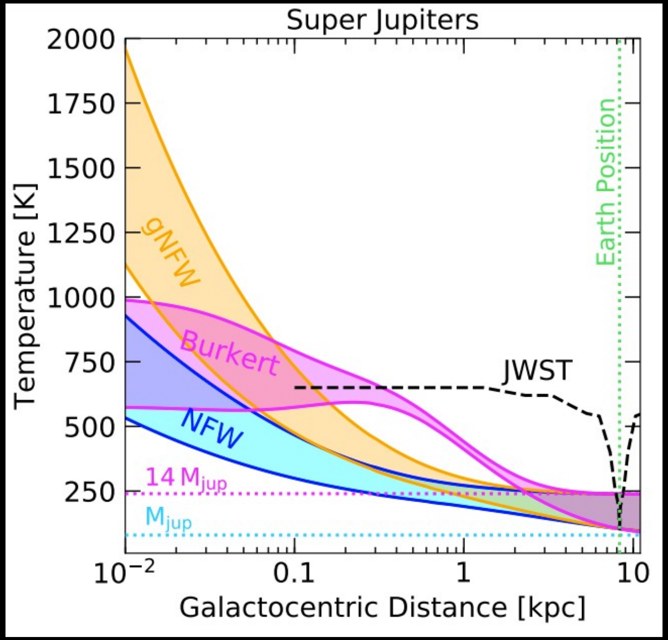
- NFW, gNFW, Burkert are DM profiles, shaded area is exoplanet mass range
- Minimum JWST sensitivity shown is signal to noise of 2, with exposure time of ~day
- Sensitivity truncates at ~0.1kpc, due to stars per pixel, and dust scattering



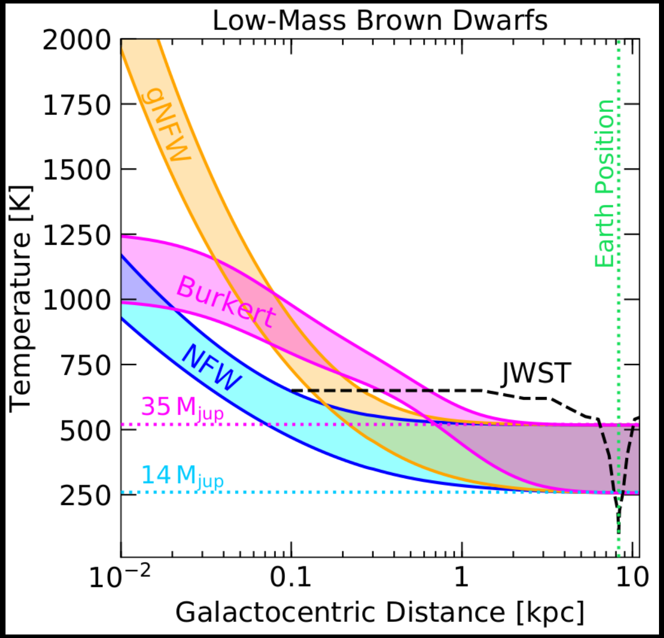

35 Mjup – 55 Mjup

# Exoplanet masses vs sensitivity

Mjup – 14 Mjup




14 Mjup – 35 Mjup

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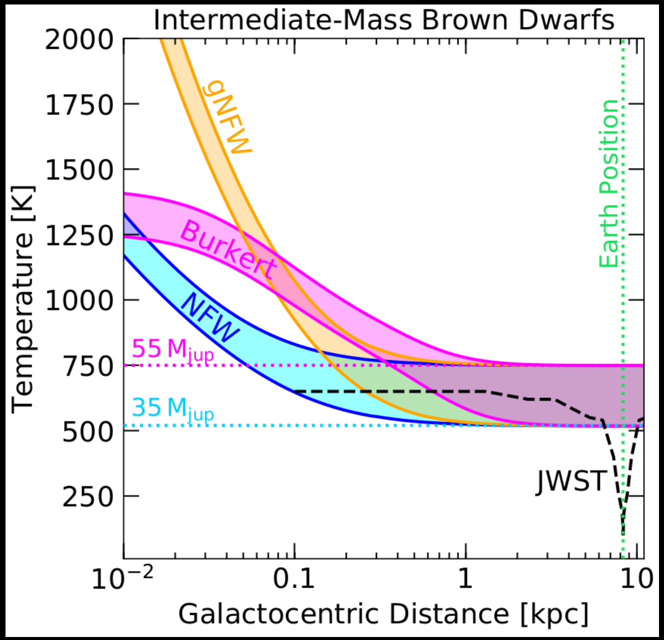
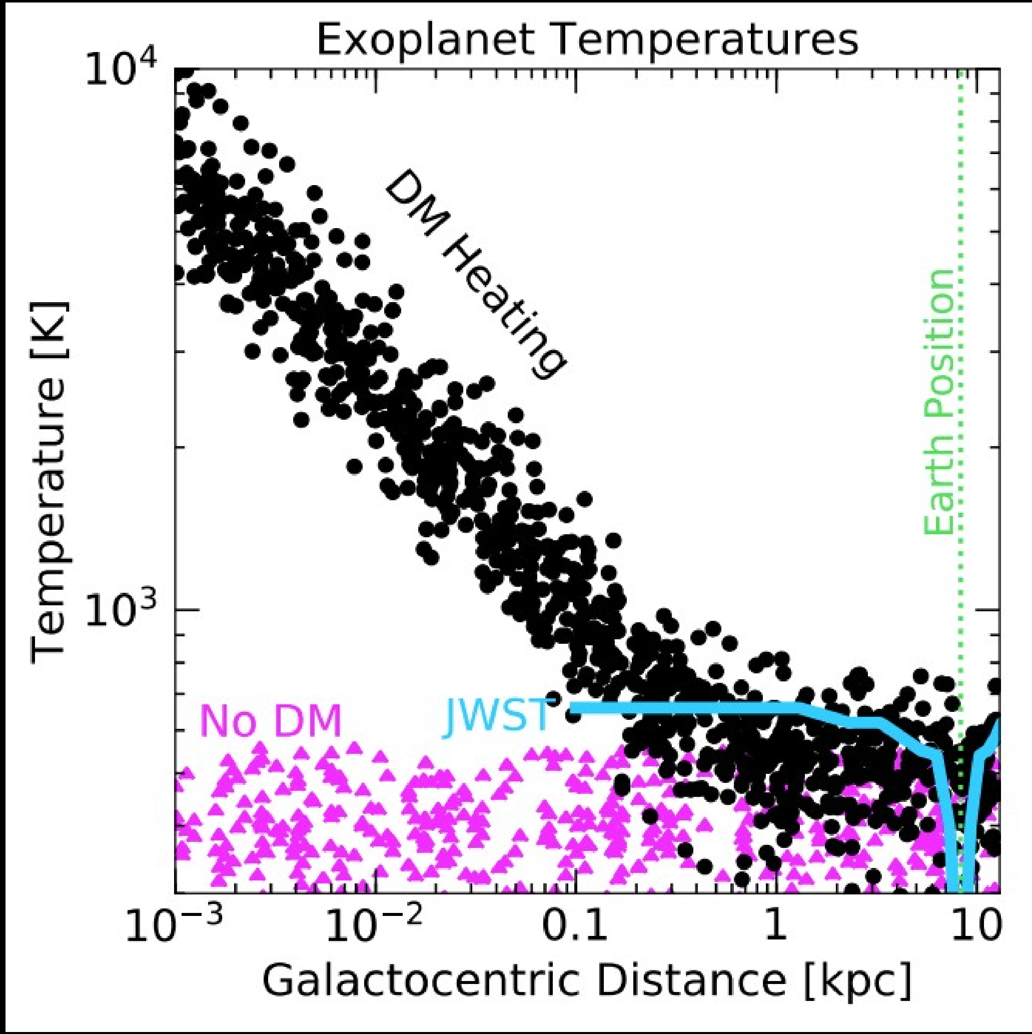



**Lower masses:**
DM heat > internal heat at all positions

**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

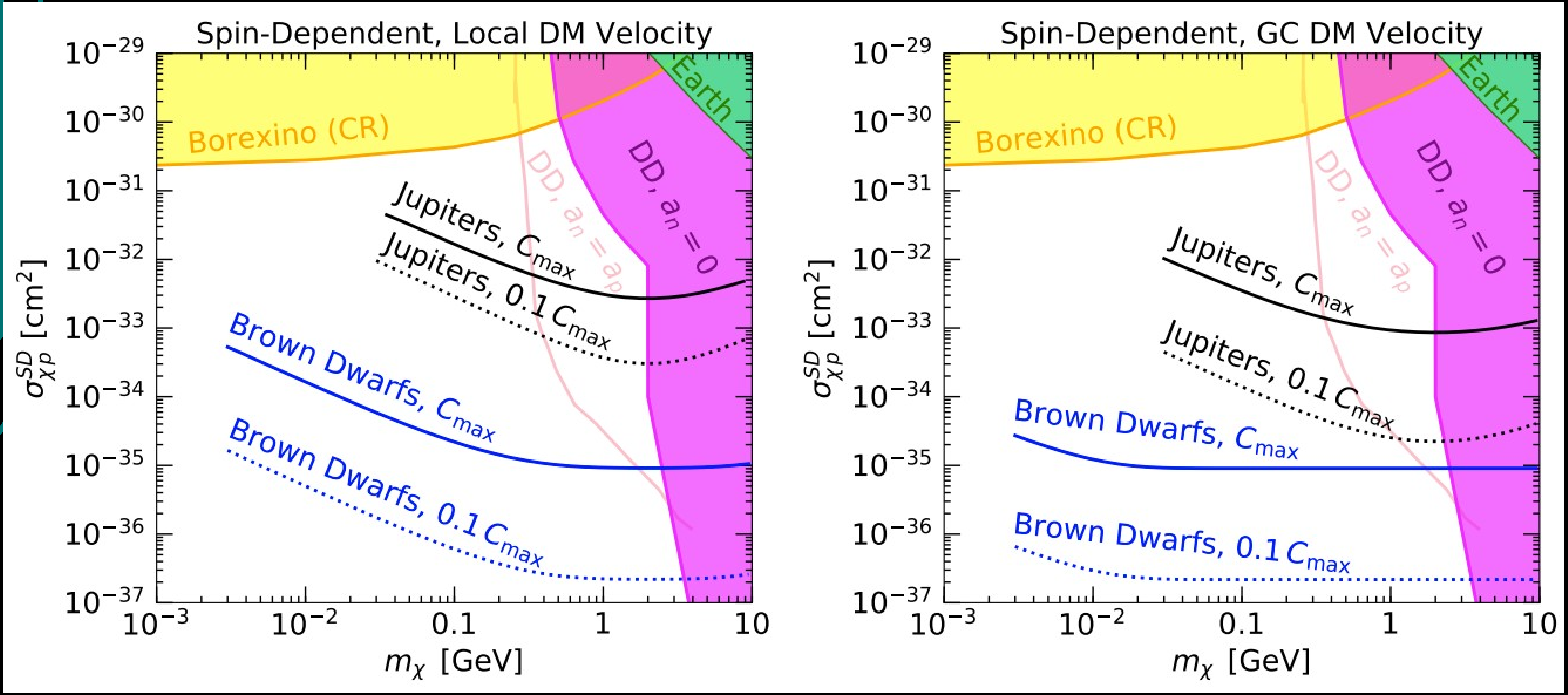


# Prospects for these searches?

| 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] |
| $\nu^2$ 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 the inner galaxy

# DM scattering cross section sensitivity



# Summary

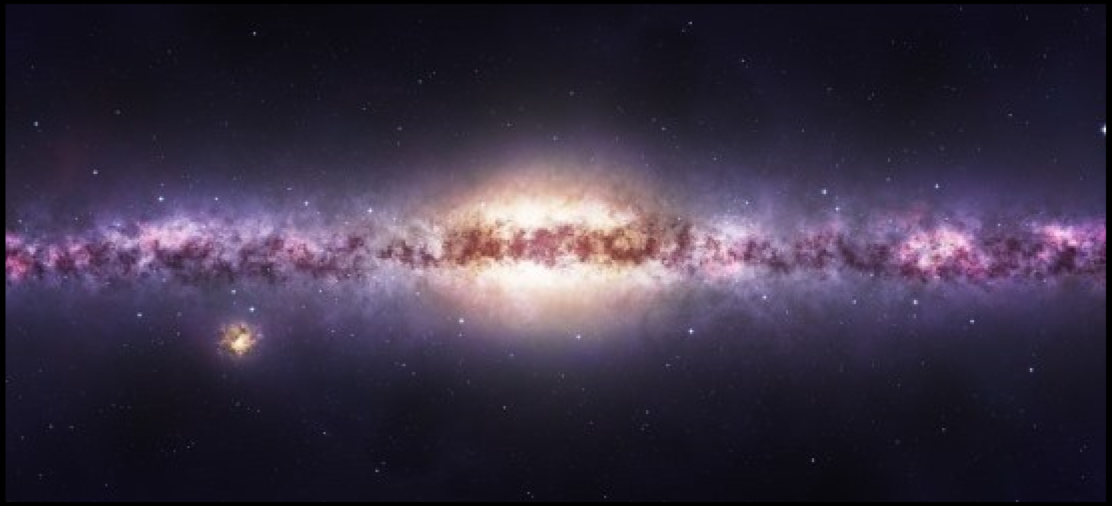
- The exoplanet program is rapidly accelerating, lots of new surprises and discoveries inevitable
- Examined how exoplanets can be used to discover DM, due to overheating from captured DM
  - Old, cold Jupiters and brown dwarfs ideal
- Actionable discovery or exclusion searches with new infrared telescopes
  - 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

# 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*

# Search Challenges



Dust backgrounds:

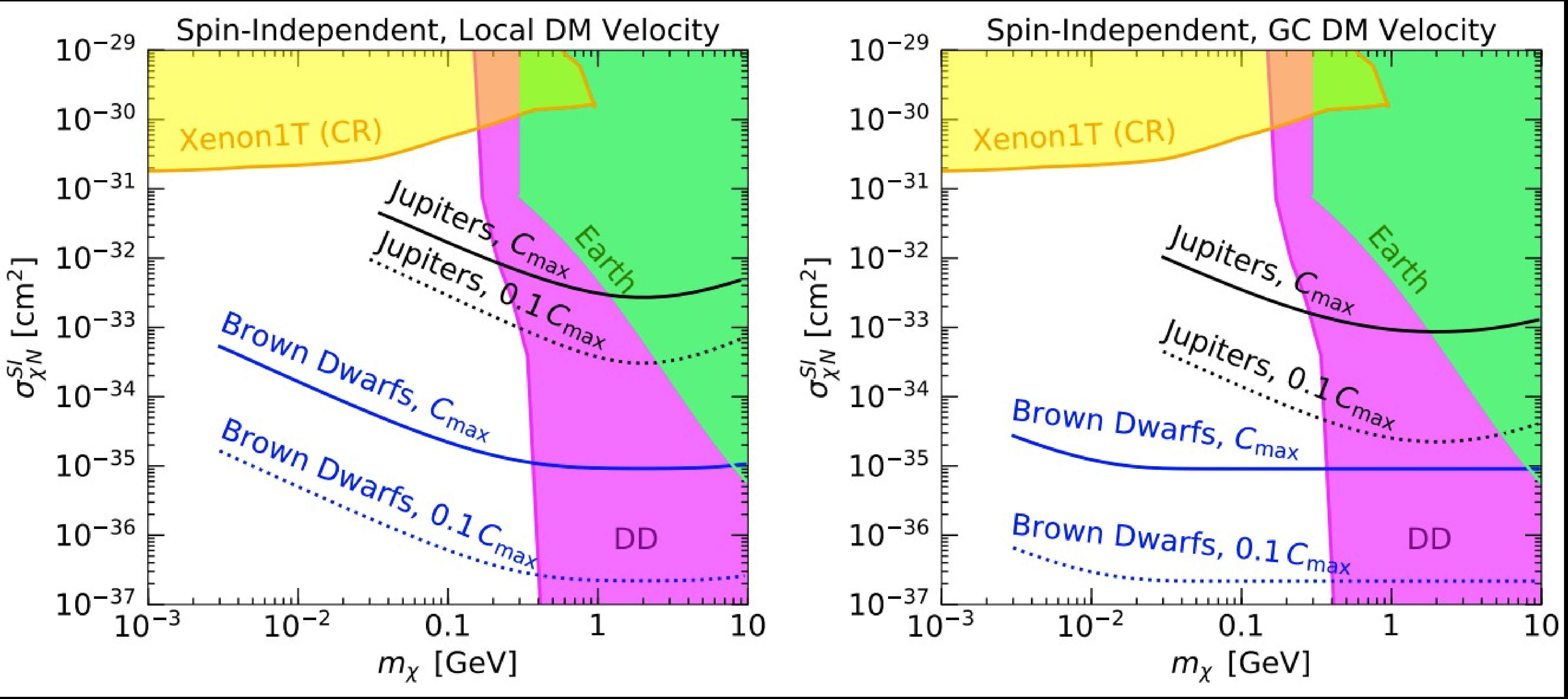
Rescatter some wavelengths, which can reduce intensity and shift spectrum peaks

Stellar crowding:

Stars per pixel important, can outshine exoplanet signal

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

# DM scattering cross section sensitivity



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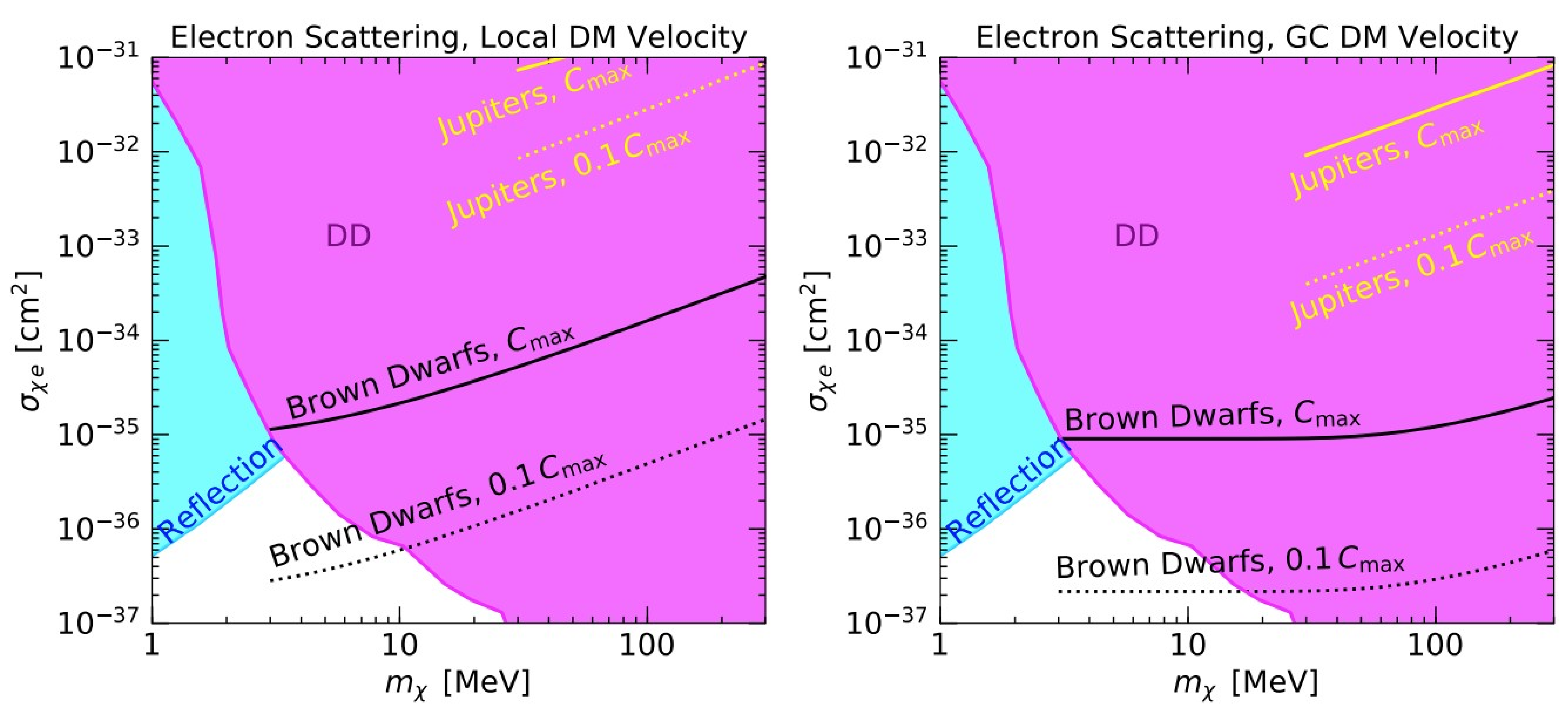

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<u>Heat power from DM:</u>

- DM density throughout Galaxy:

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

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

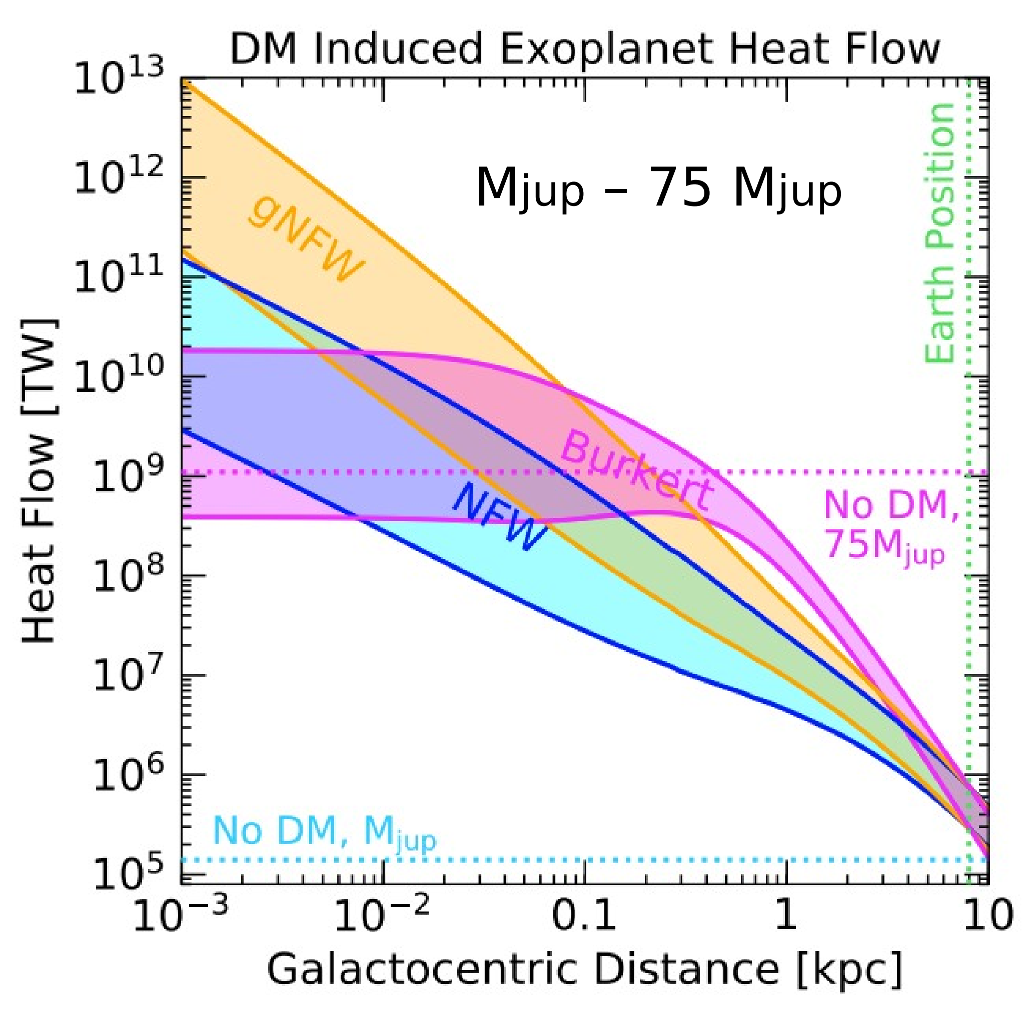
$$v_{\rm esc}^2 = 2 G_N M / R$$

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

# DM Heating vs Internal Heat

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

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

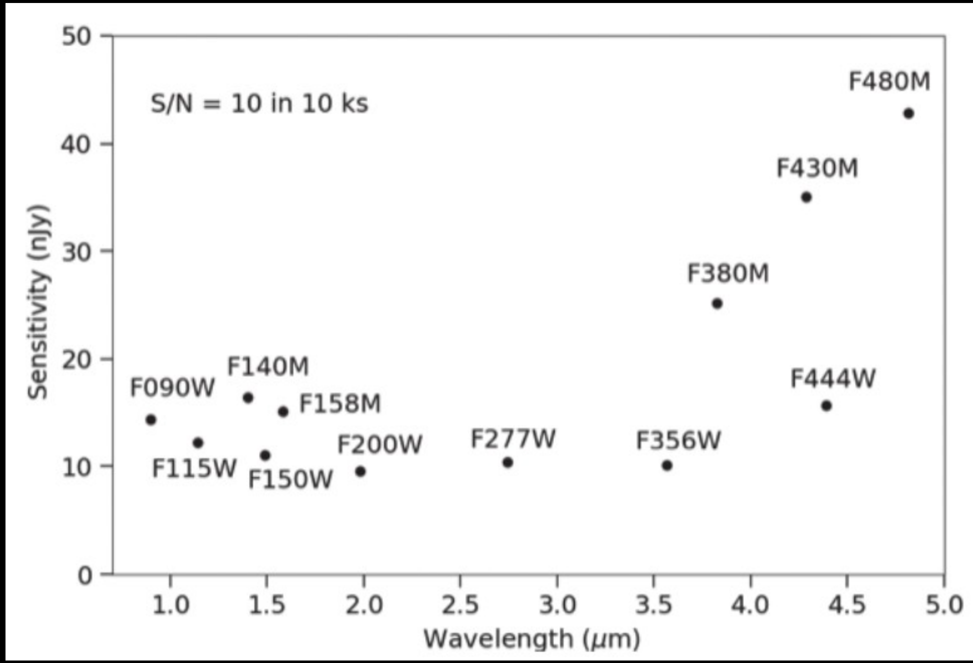


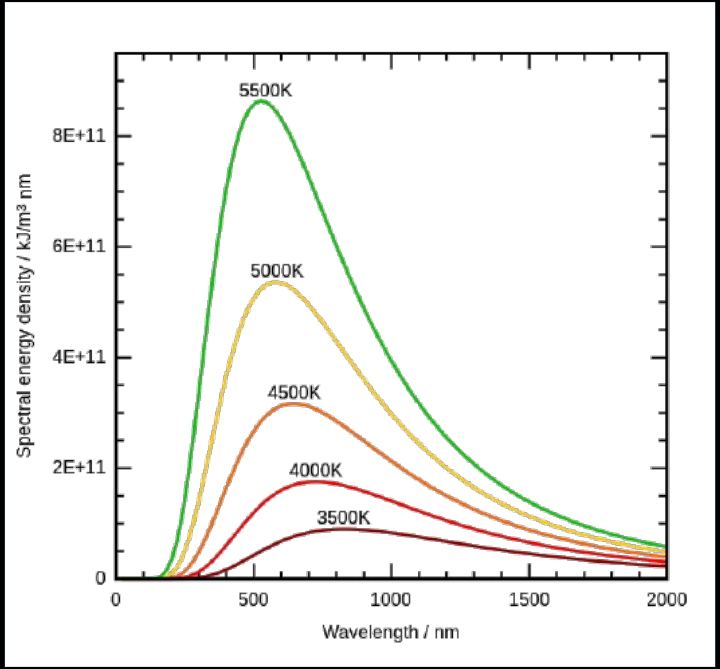

1 parsec = 3.26 light years

# 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

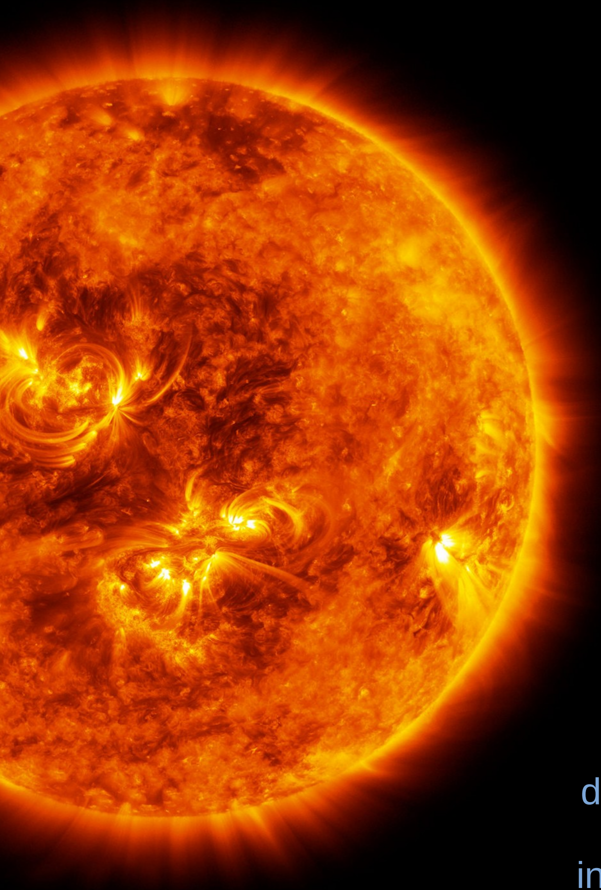
- Near-Infrared Imager and Slitless Spectrometer (NIRISS) for T > 500 K
- Mid-Infrared Instrument (MIRI) for T = 100 - 500 K




Won't need new dedicated searches; can piggyback

# 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

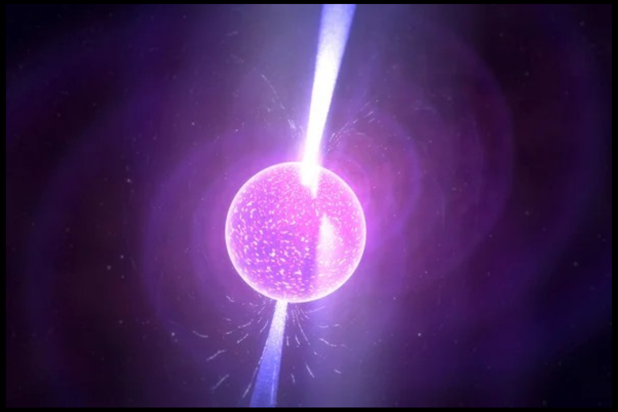
Impact on
magnetic fields?
Volcanoes?

Jupiter

DM heat
anomaly?

Uranus

DM limits from
temperature

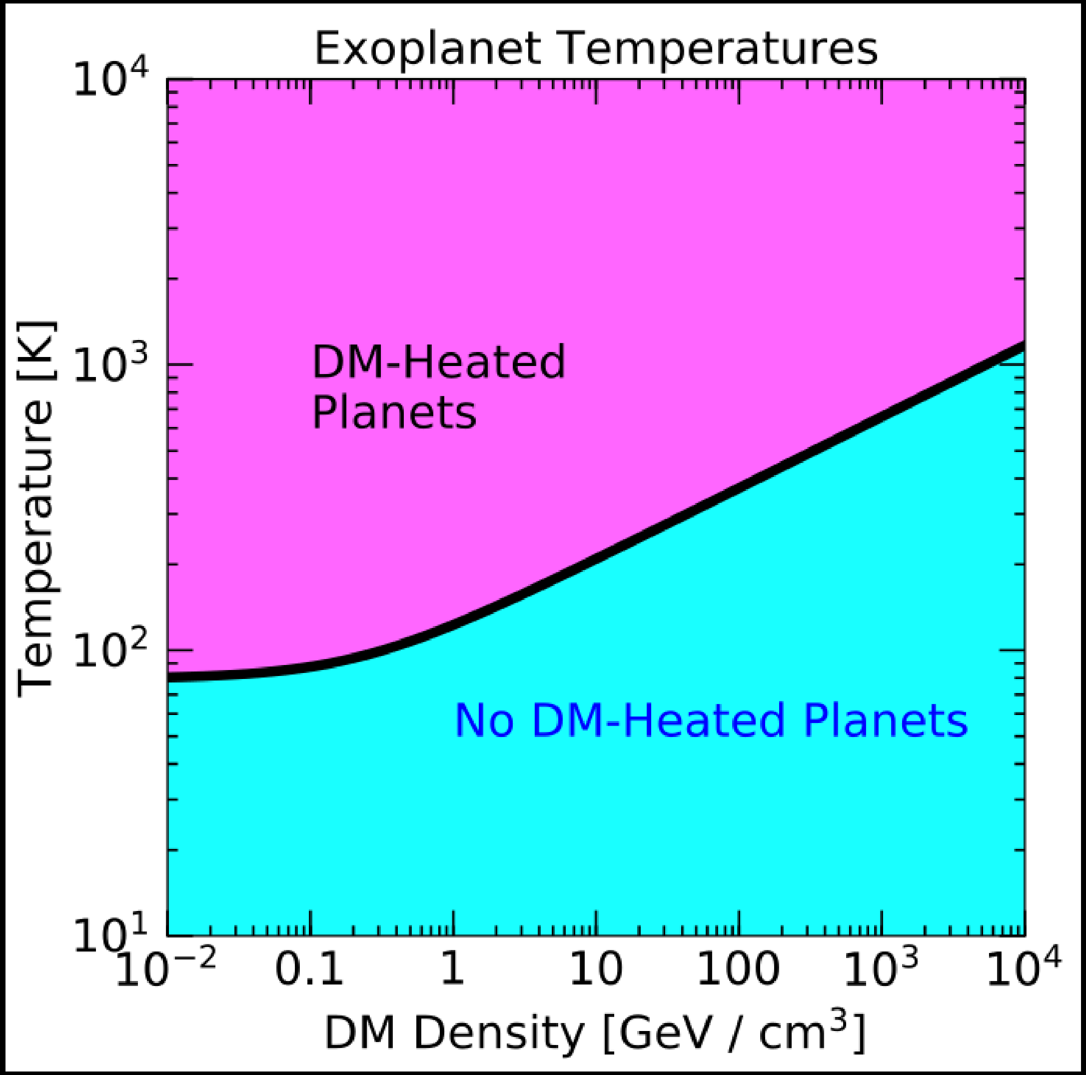


Neutron Stars

DM heating, infrared
telescopes

White Dwarfs

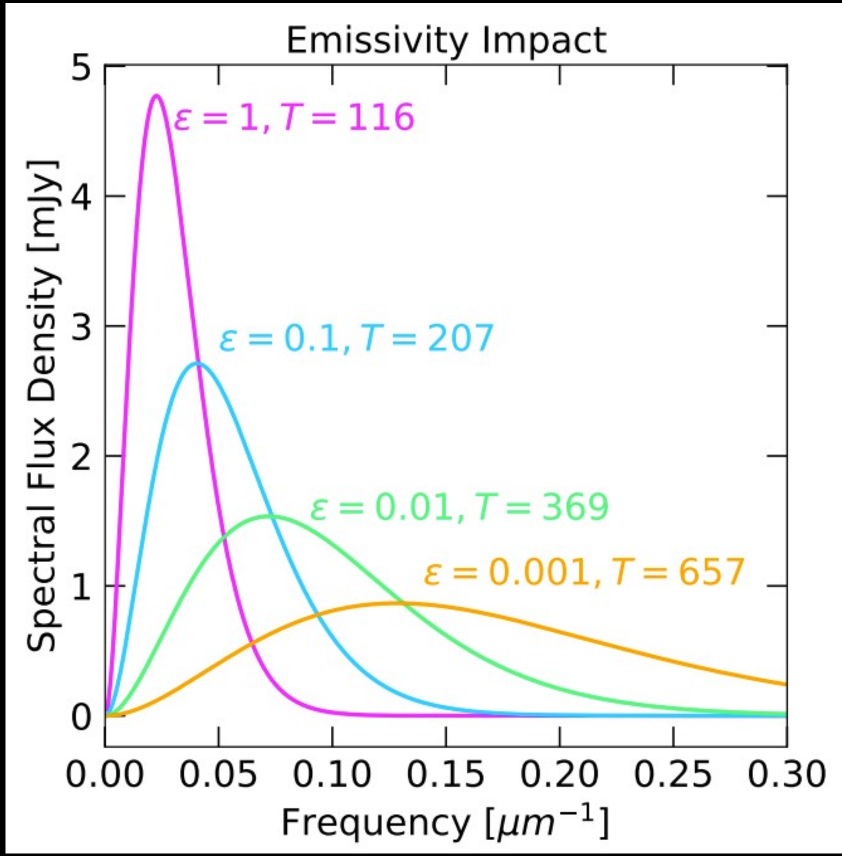
# Deviations: DM-overdensities

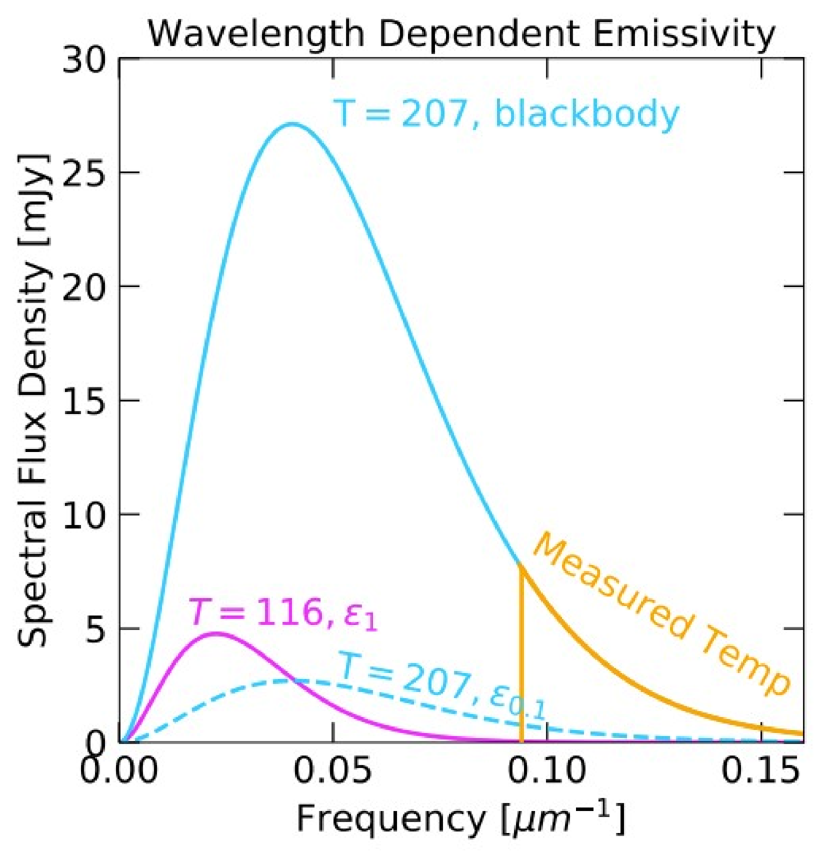


# Deviations: Non-Blackbody Spectra

Atmosphere effects can cause deviations from a blackbody

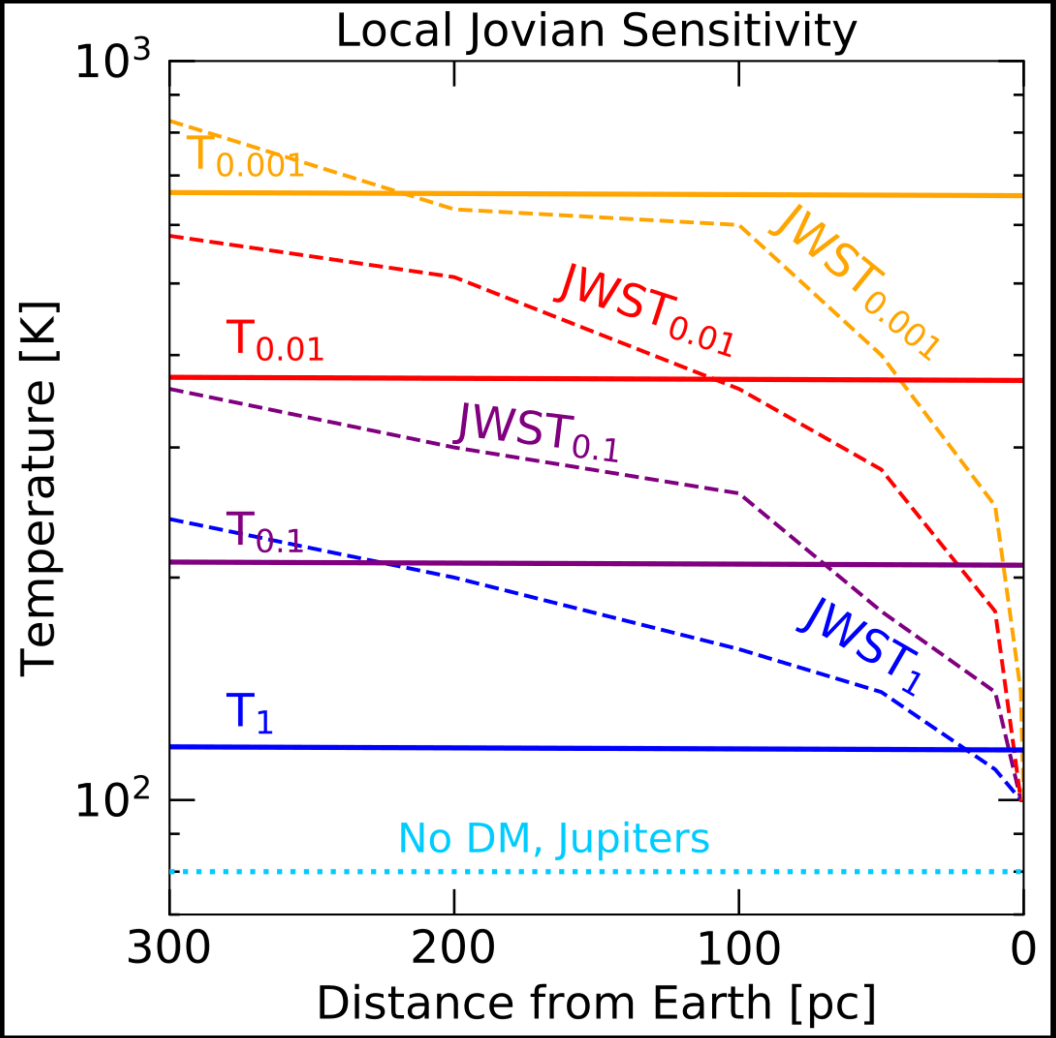
$$B(\nu, T) = \frac{2\nu^3 \epsilon}{\exp\left(\frac{2\pi\nu}{\mathrm{k_b T}}\right) - 1}$$



# 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



# 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:

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

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

# DM scattering cross section sensitivity

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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