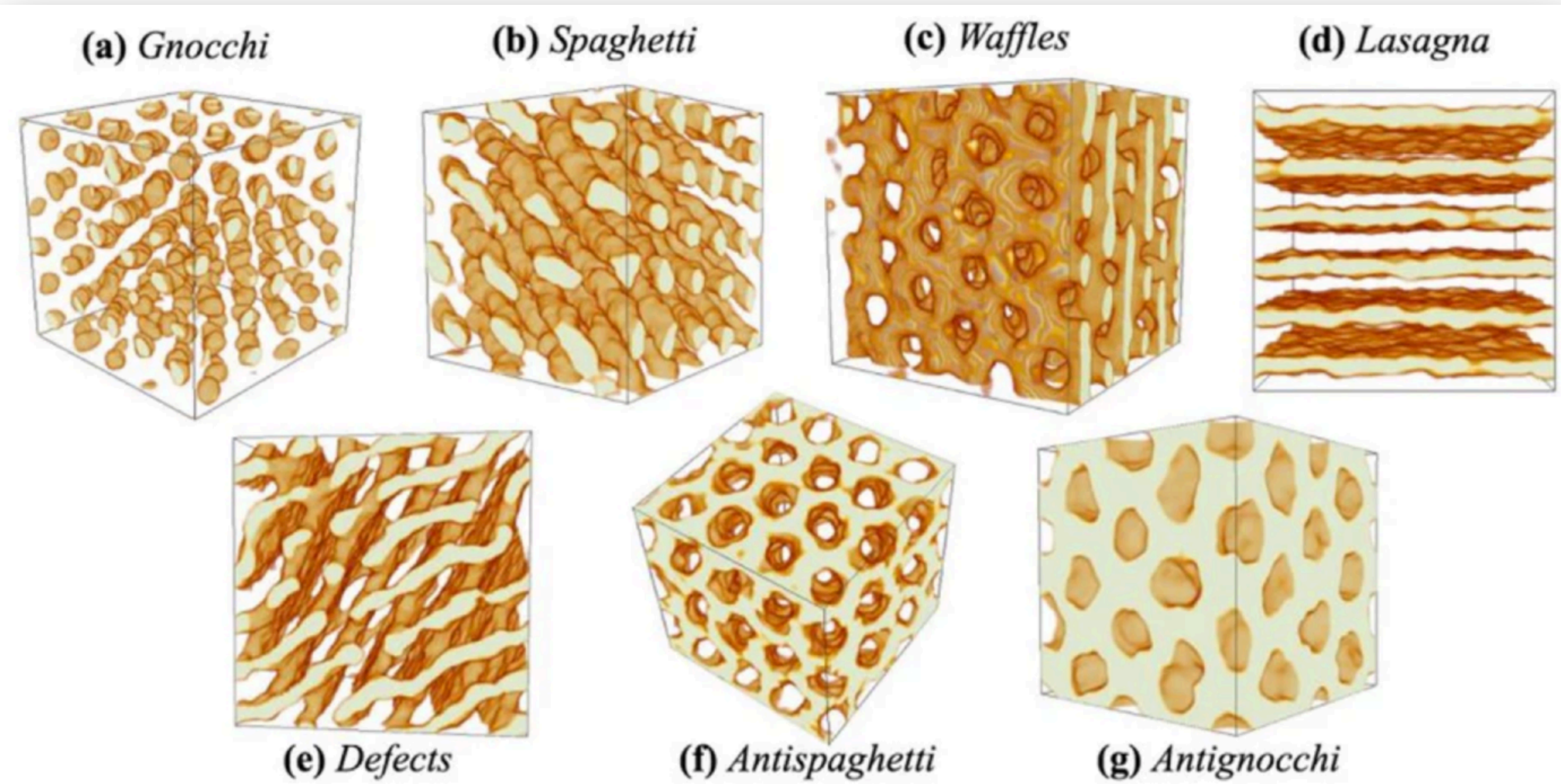
Discovering Dark Matter by Reheating Pasta

Nirmal Raj
TRIUMF



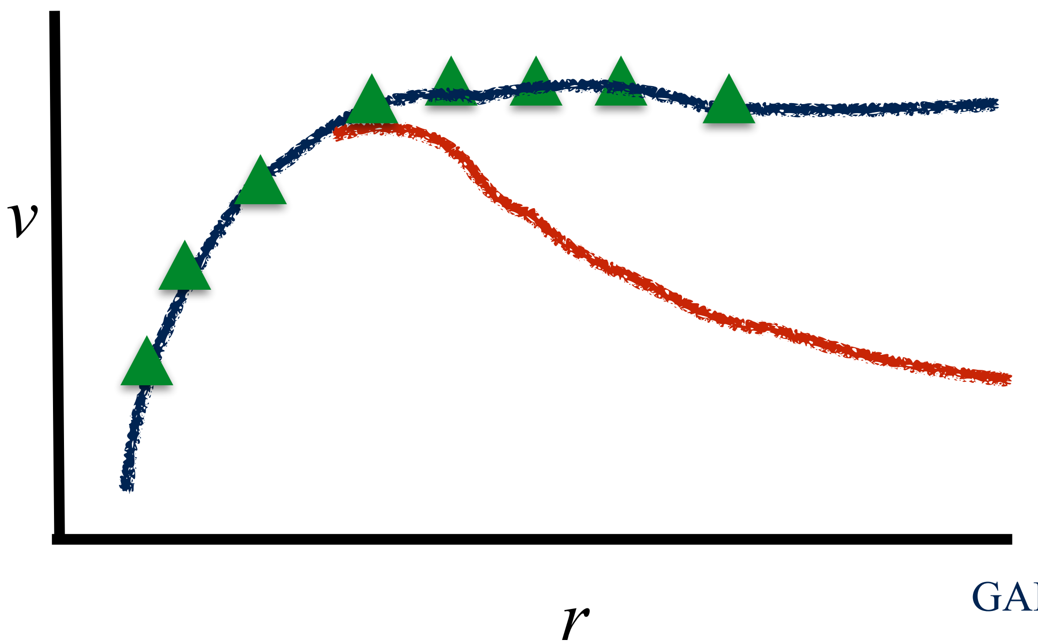
with
Javier Acevedo,
Joe Bramante,
Rebecca Leane

1911.06334,
accepted at JCAP

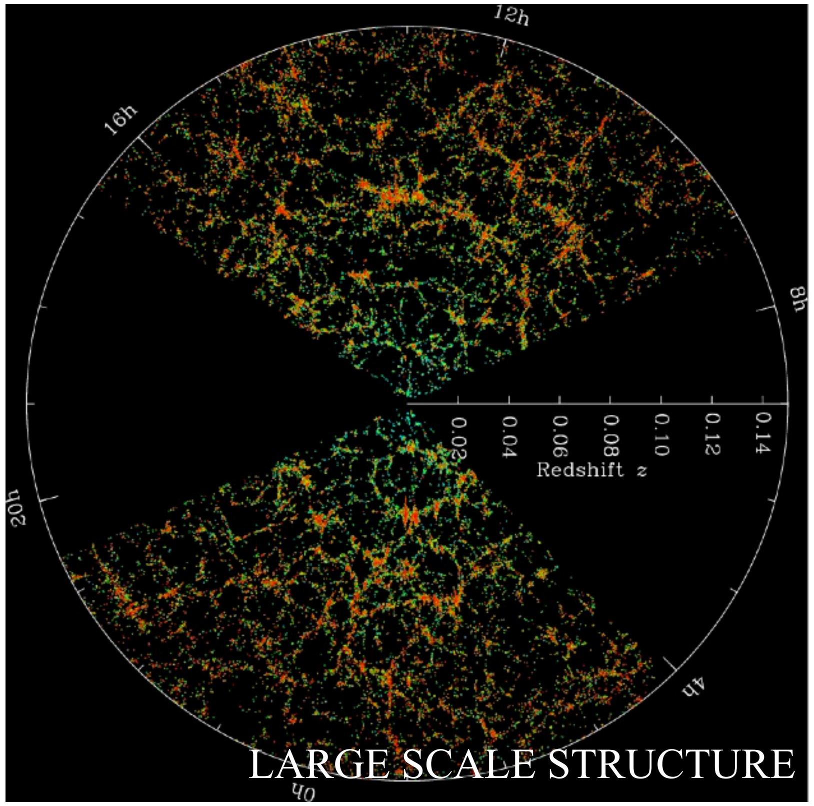
based partly on collaborations with
Masha Baryakhtar | Aniket Joglekar | Shirley Li
Tim Linden | Flip Tanedo | Hai-Bo Yu

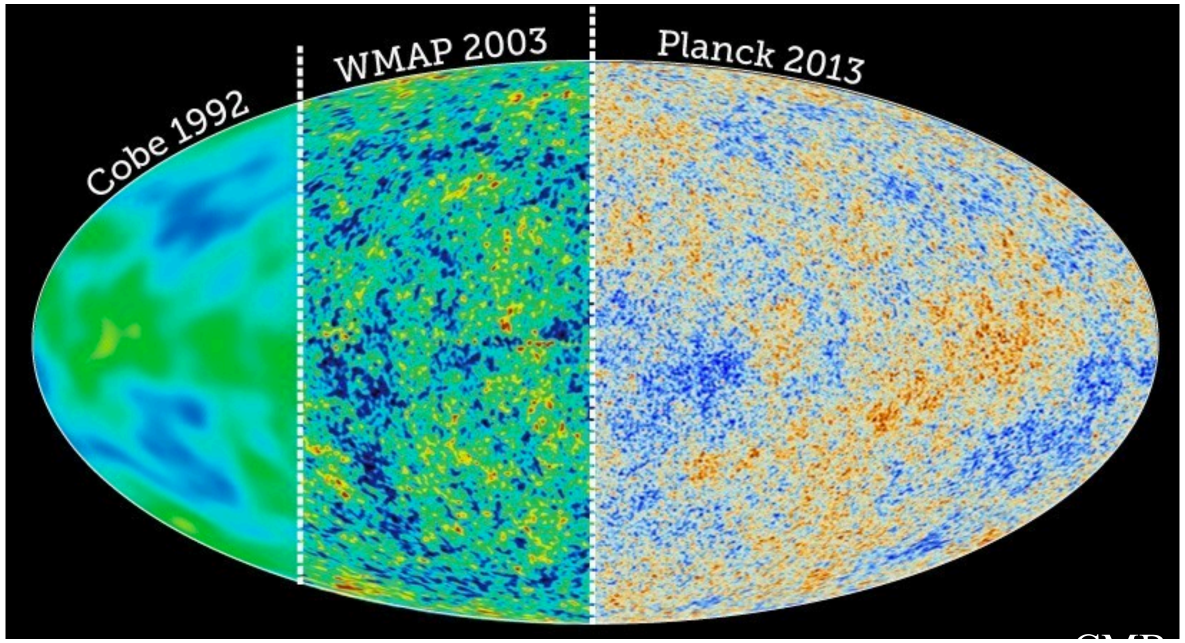
11 Mar 2020, New Techniques for Dark Matter Discovery, TRIUMF

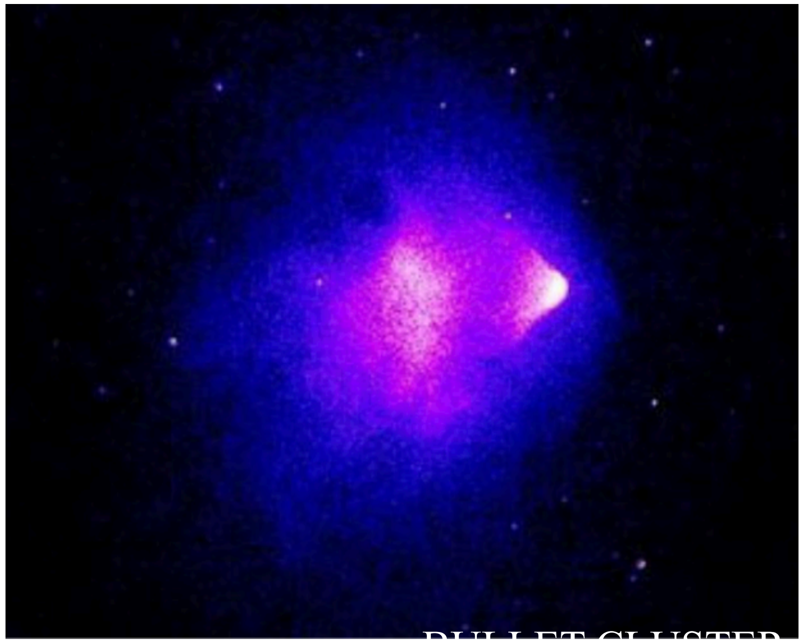
Dark reality



GALACTIC ROTATION

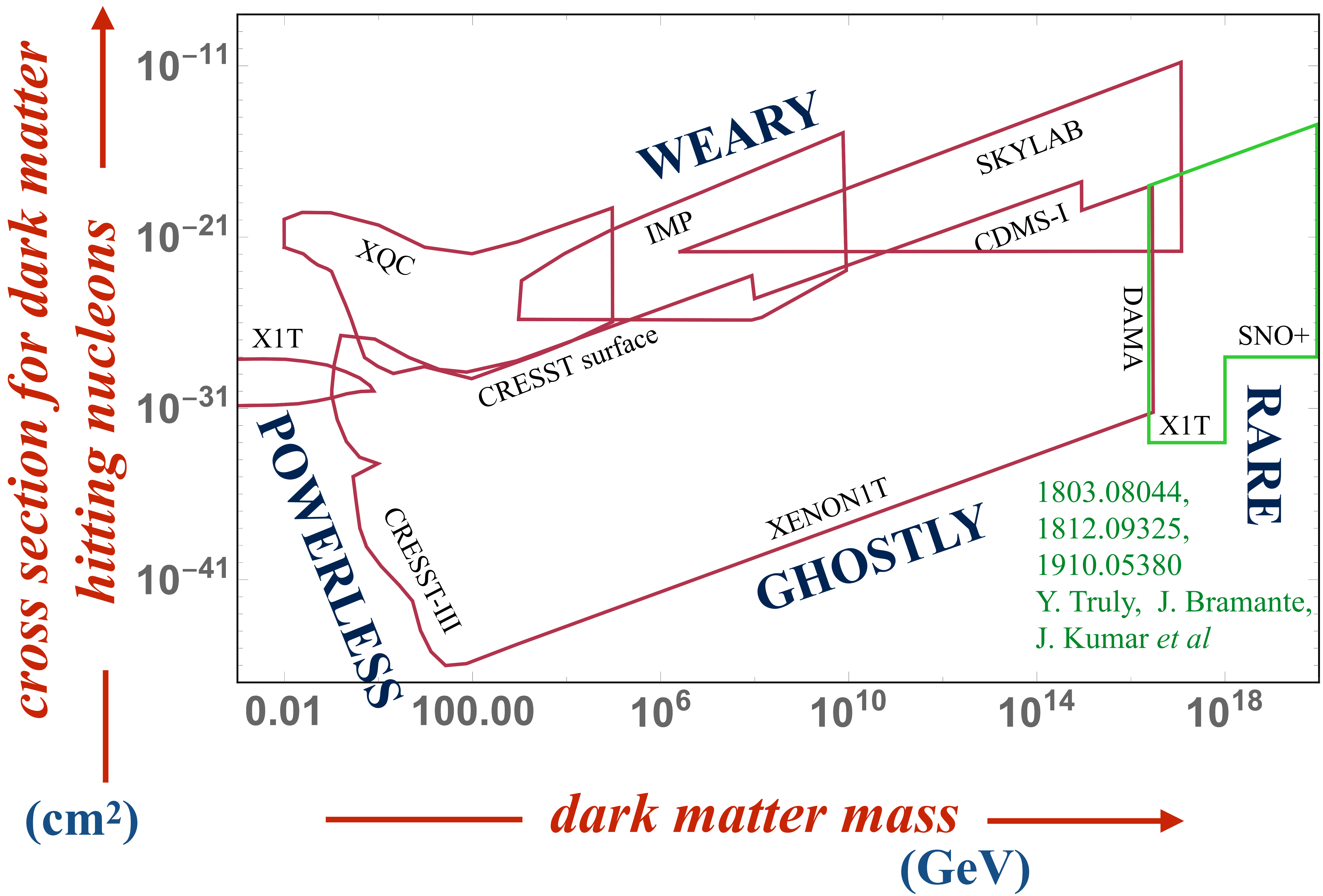






Can we detect its putative non-gravitational interactions?

Earth-bound searches



A proposal

$$L \propto \boxed{(\gamma - 1) m_{\rm DM}}$$

kinetic heating of neutron stars

M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *119, 131801 (2017)*

A proposal

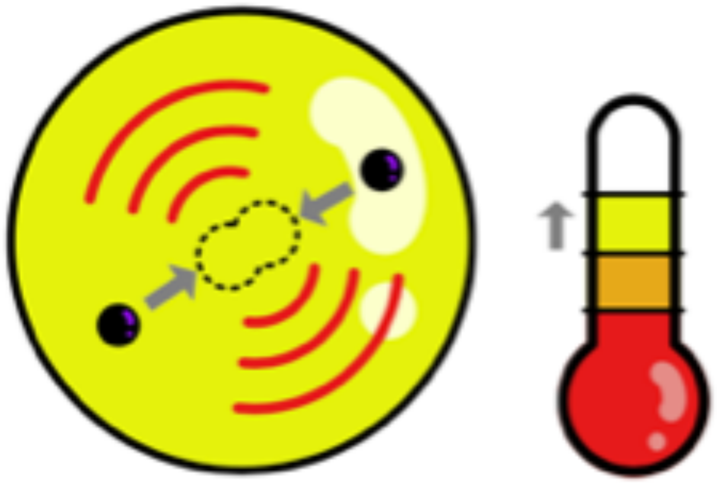
$$L \propto (\gamma - 1) m_{\rm DM} + m_{\rm DM}$$

kinetic heating

+ annihilation

Minimum signature

Possible bonus



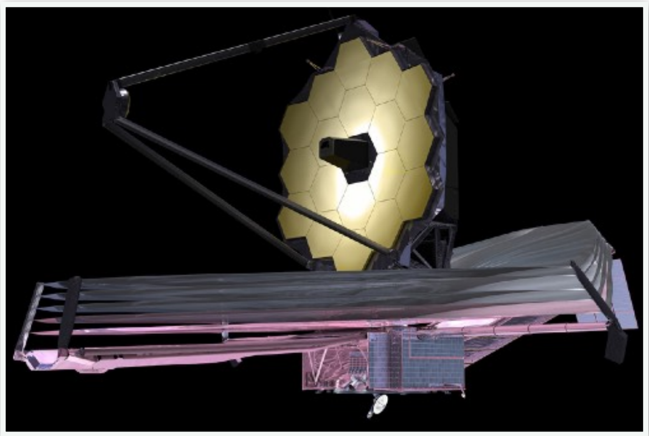
M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**

Phys.Rev.Lett. *119, 131801 (2017)*

Observation prospects

	kinetic heating	+ annihilation
(1.5 solar mass, 10 km star)	1750 K	2480 K

telescope time for 2σ sensitivity



James Webb

$$10^5 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4 \qquad 9 \times 10^3 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$$

Thirty Meter

$$7 \times 10^4 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4 \qquad 2 \times 10^3 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$$

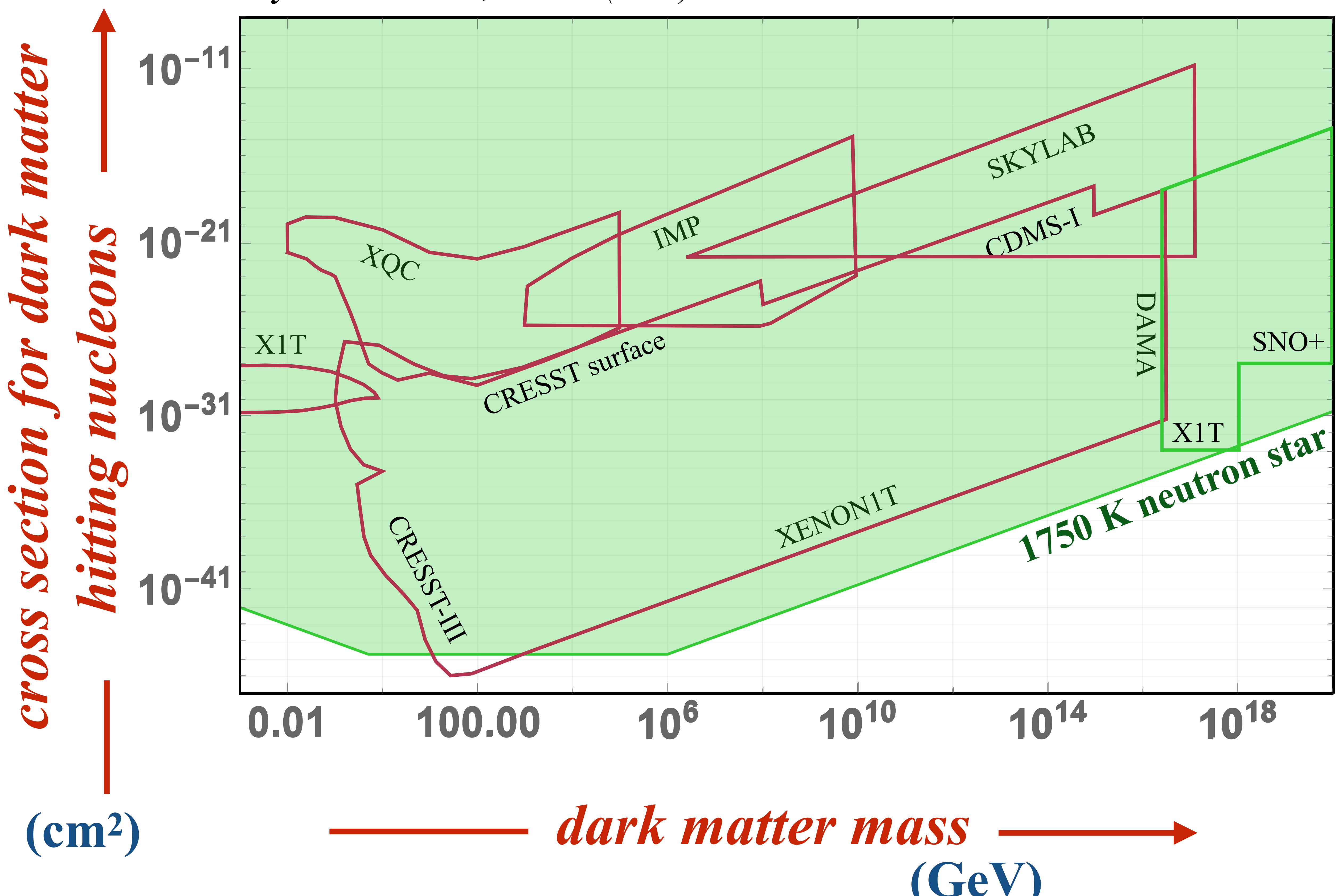
M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *119, 131801 (2017)*

Annihilation saves observation time (= $$)
by a factor of >10!

Increase in acreage

M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**

Phys.Rev.Lett. *119, 131801 (2017)*



What happened next

particle model interpretations

nucleon targets

32. **Neutron stars at the dark matter direct detection frontier**
Nirmal Raj (Notre Dame U.), Philip Tanedo, Hai-Bo Yu (UC, Riverside). Jul 28, 2017. 6 pp.
Published in **Phys.Rev. D97 (2018) no.4, 043006**

26. **Reheating neutron stars with the annihilation of self-interacting dark matter**
Chian-Shu Chen (Tamkang U.), Yen-Hsun Lin (Taiwan, Natl. Cheng Kung U.). Apr 10, 2018. 16 pp.
Published in **JHEP 1808 (2018) 069**

21. **Heating up Neutron Stars with Inelastic Dark Matter**
Nicole F. Bell, Giorgio Busoni, Sandra Robles (Melbourne U.). Jul 8, 2018. 20 pp.
Published in **JCAP 1809 (2018) 018**

2. **Heating neutron stars with GeV dark matter**
Wai-Yee Keung (Illinois U., Chicago), Danny Marfatia (Hawaii U.), Po-Yan Tseng (IPAP, Seoul & Yonsei U.). Jan 24, 2020. 24 pp.
e-Print: arXiv:2001.09140 **[hep-ph] |** PDF

18. **New Analysis of Neutron Star Constraints on Asymmetric Dark Matter**
Raghuveer Garani, Yoann Genolini, Thomas Hambye (Brussels U.). Dec 20, 2018. 42 pp.
Published in **JCAP 1905 (2019) 035**

lepton targets

15. **Capture of Leptophilic Dark Matter in Neutron Stars**
Nicole F. Bell (Melbourne U.), Giorgio Busoni (Heidelberg, Max Planck Inst.), Sandra Robles (Melbourne U.). Apr 22, 2019. 26 pp.
Published in **JCAP 1906 (2019) 054**

9. **Dark matter interactions with muons in neutron stars**
Raghuveer Garani (Brussels U.), Julian Heeck (UC, Irvine). Jun 24, 2019. 8 pp.
Published in **Phys.Rev. D100 (2019) no.3, 035039**

Julian's talk

4. **Relativistic capture of dark matter by electrons in neutron stars**
Aniket Joglekar (UC, Riverside), Nirmal Raj (TRIUMF), Philip Tanedo, Hai-Bo Yu (UC, Riverside). Nov 29, 2019. 6 pp.
UCR-TR-2019-FLIP-NCC-1701-B
e-Print: **arXiv:1911.13293 [hep-ph] | PDF**

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astronomy

17. **Detecting Dark Matter with Neutron Star Spectroscopy**
Daniel A. Camargo, Farinaldo S. Queiroz, Riccardo Sturani (IIP, Brazil). Jan 16, 2019. 22 pp.
Published in **JCAP 1909 (2019) no.09, 051**

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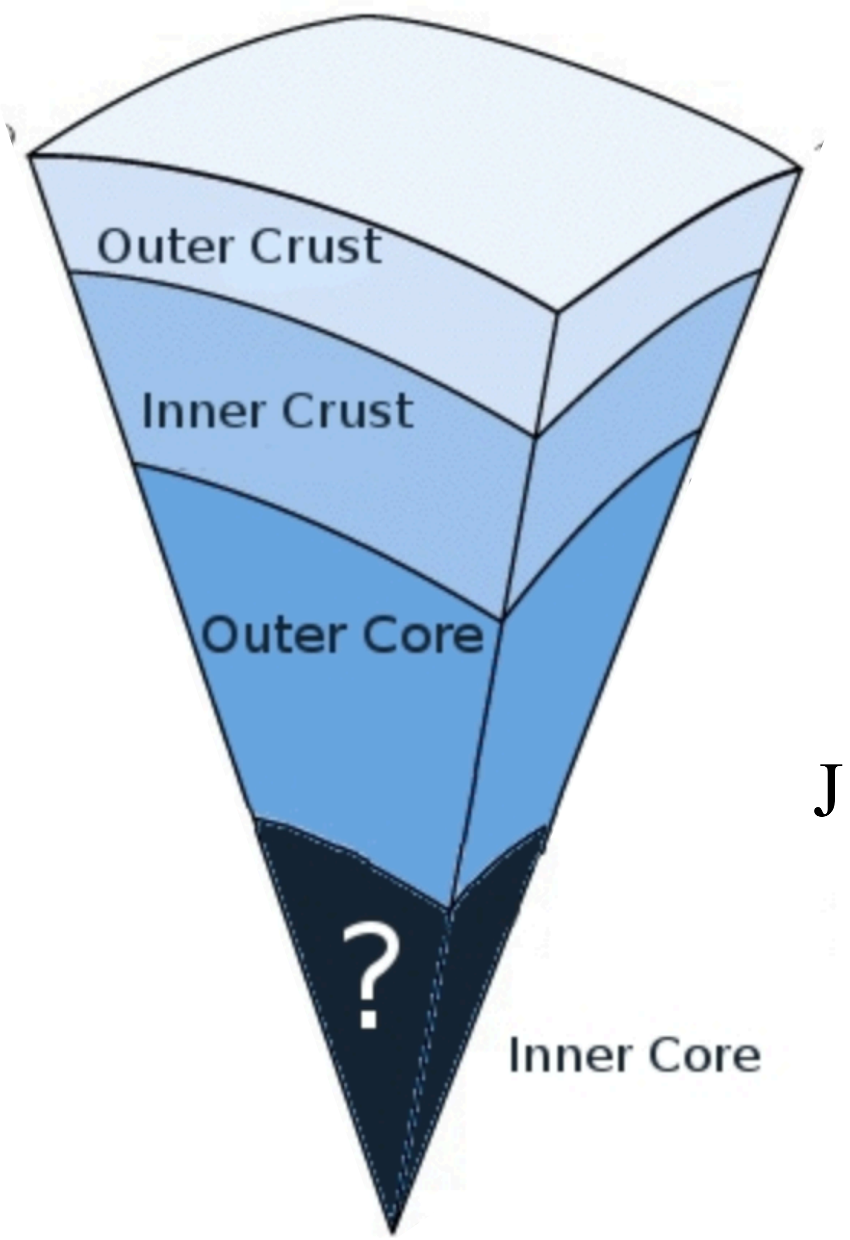
nuclear astrophysics

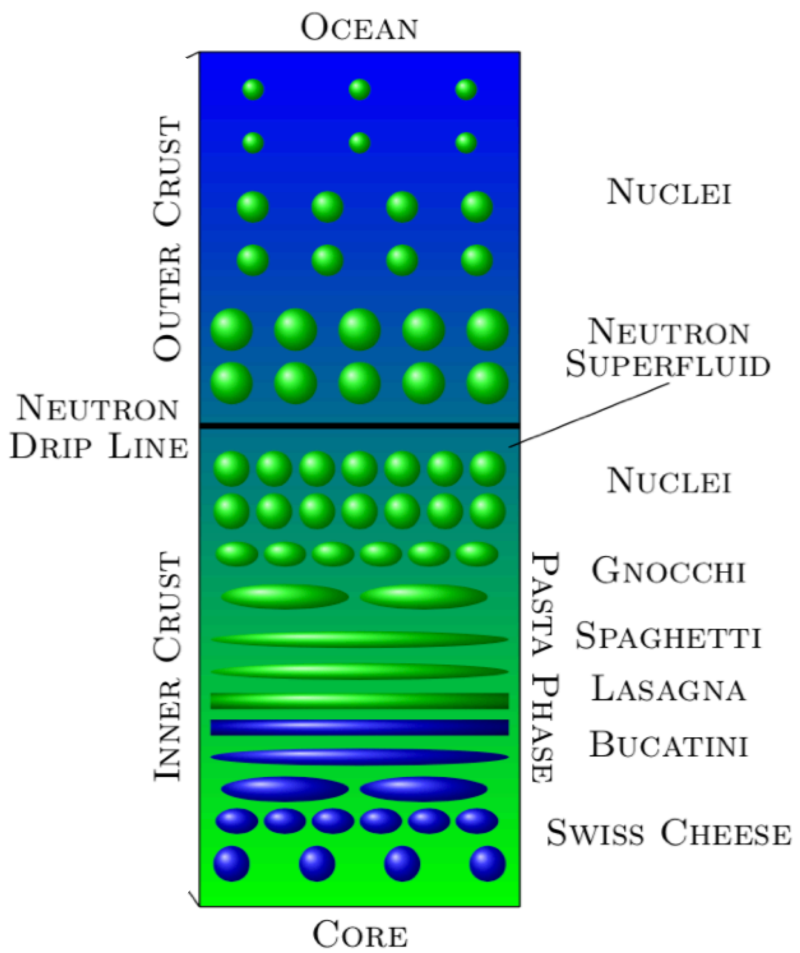
11. **Dark Matter Heating vs. Rotochemical Heating in Old Neutron Stars**
Koichi Hamaguchi (Tokyo U. & Tokyo U., IPMU), Natsumi Nagata, Keisuke Yanagi (Tokyo U.). May 8, 2019. 6 pp.
Published in **Phys.Lett. B795 (2019) 484-489**

BUT

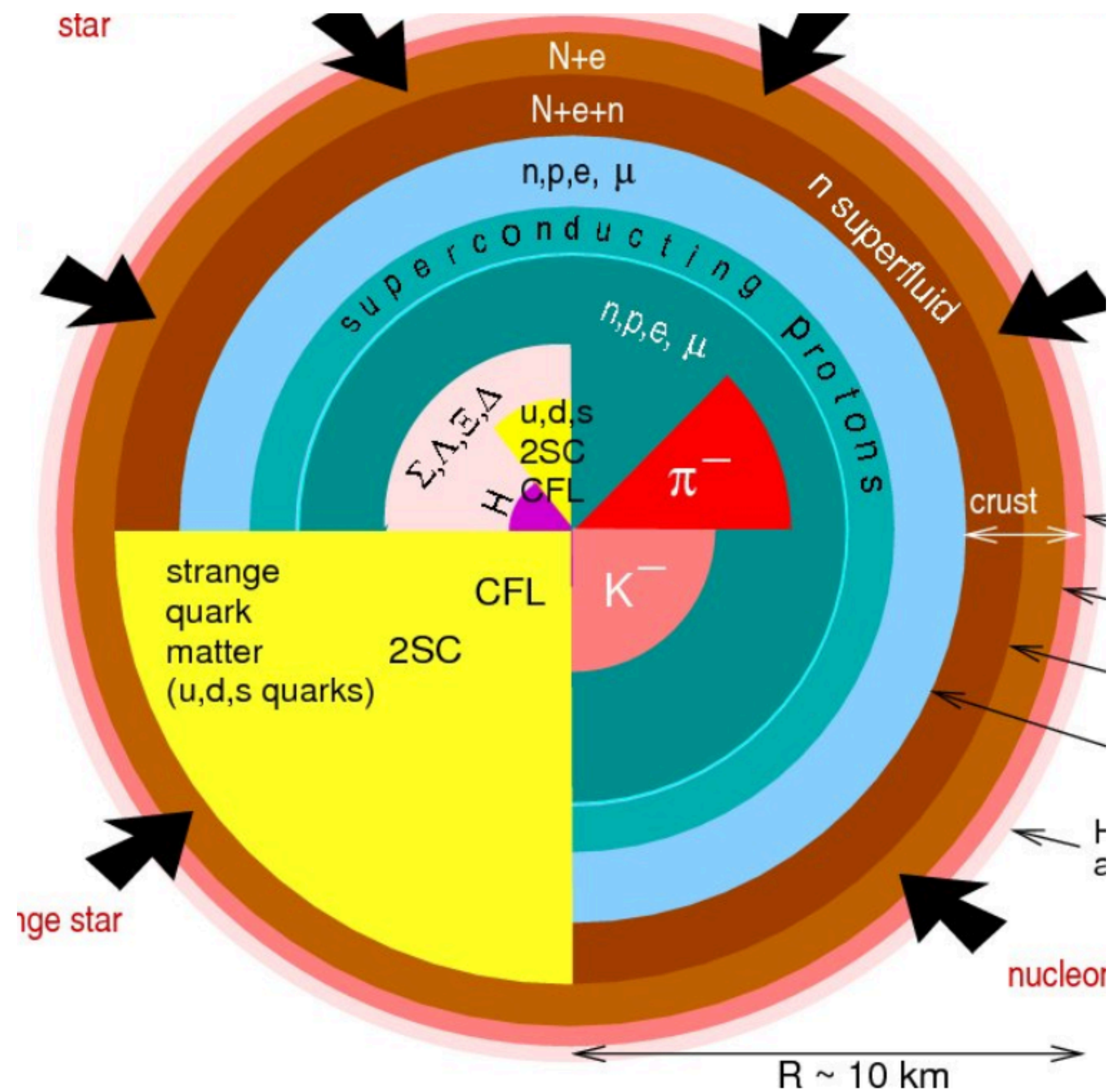


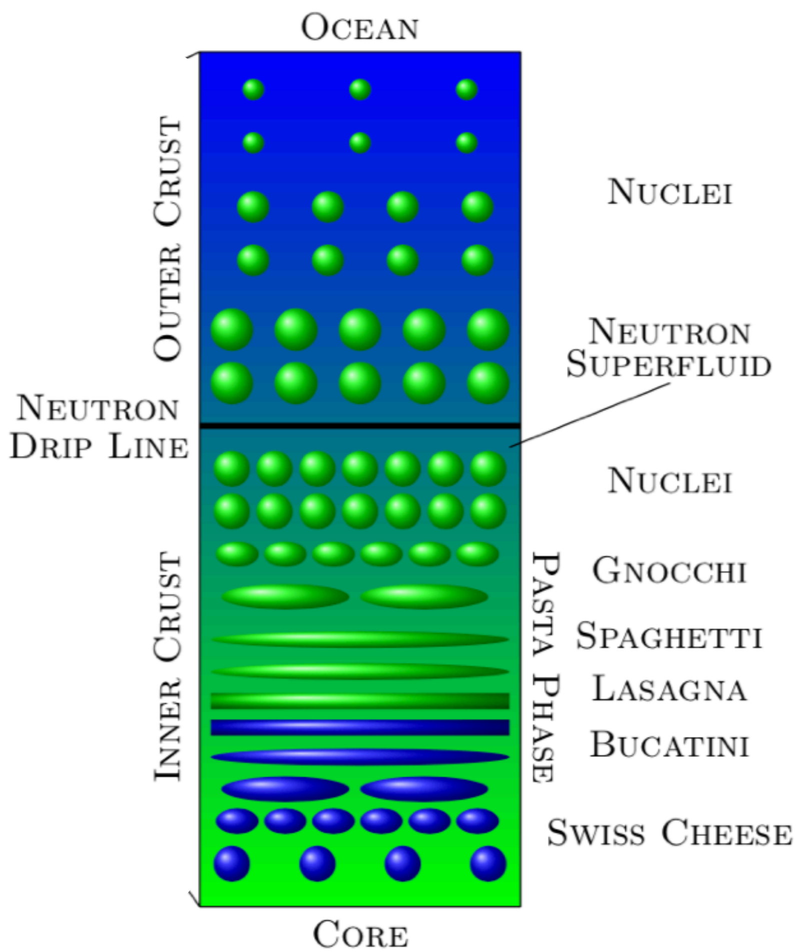
Are we barking down the wrong stellar region?

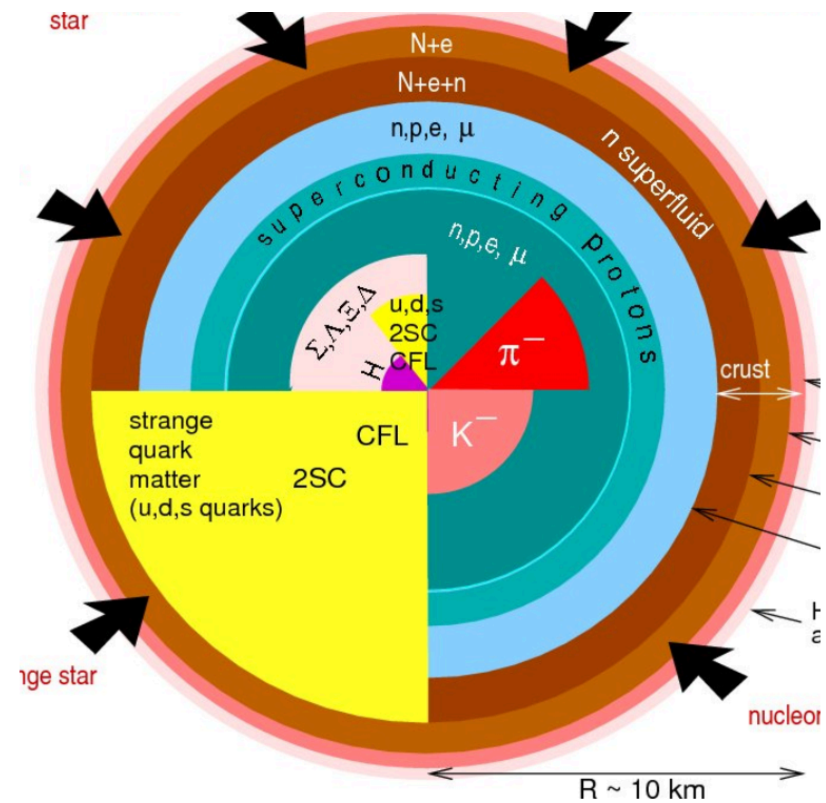
J Acevedo, J Bramante, R Leane, **N R**; 1911.06334

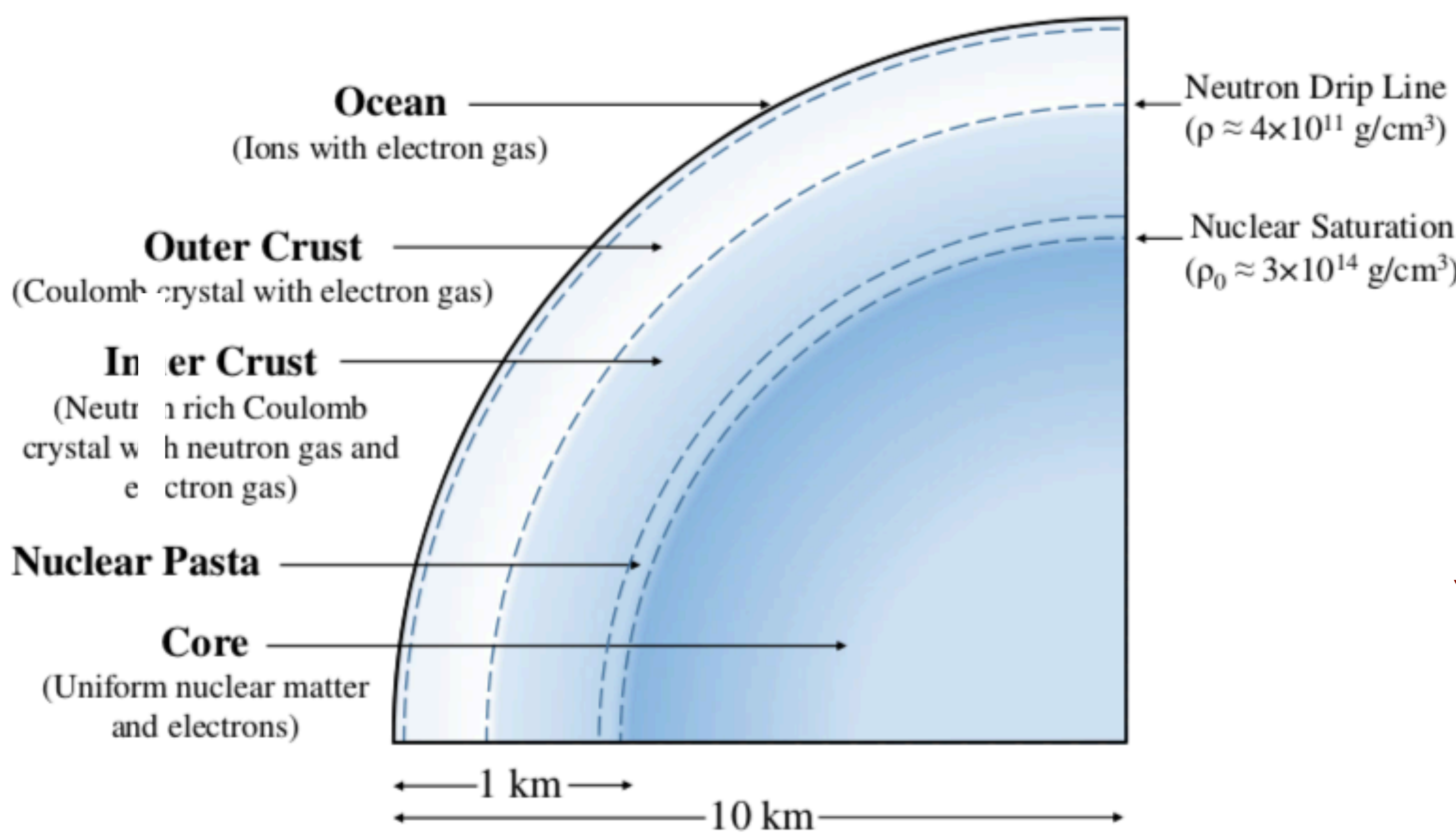


structure of the crust,
better understood than core









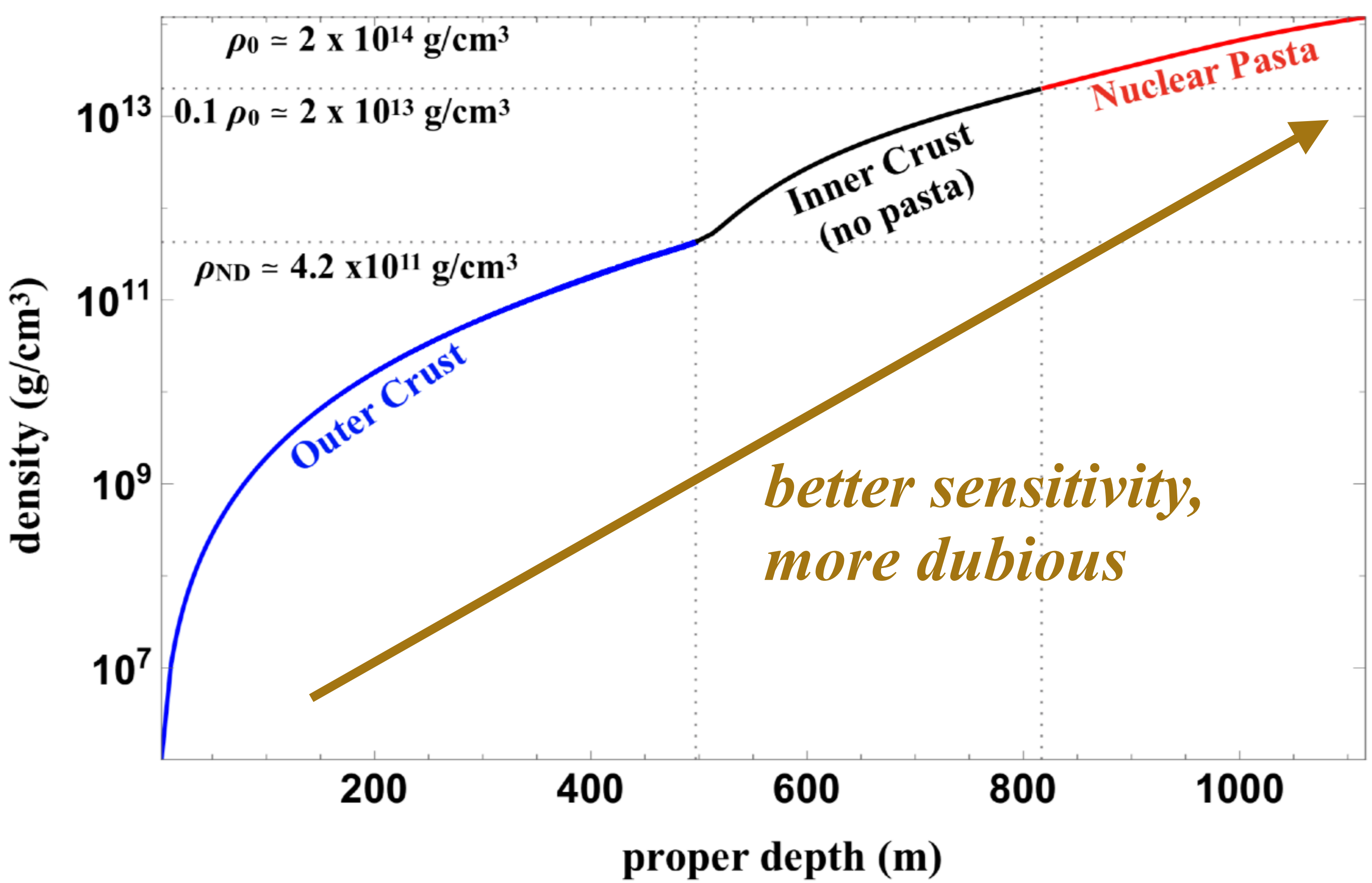
deeper =>
knowledge of structure
more uncertain

[Caplan, Horowitz, *RevModPhys 2017*]

Climbing down the layers

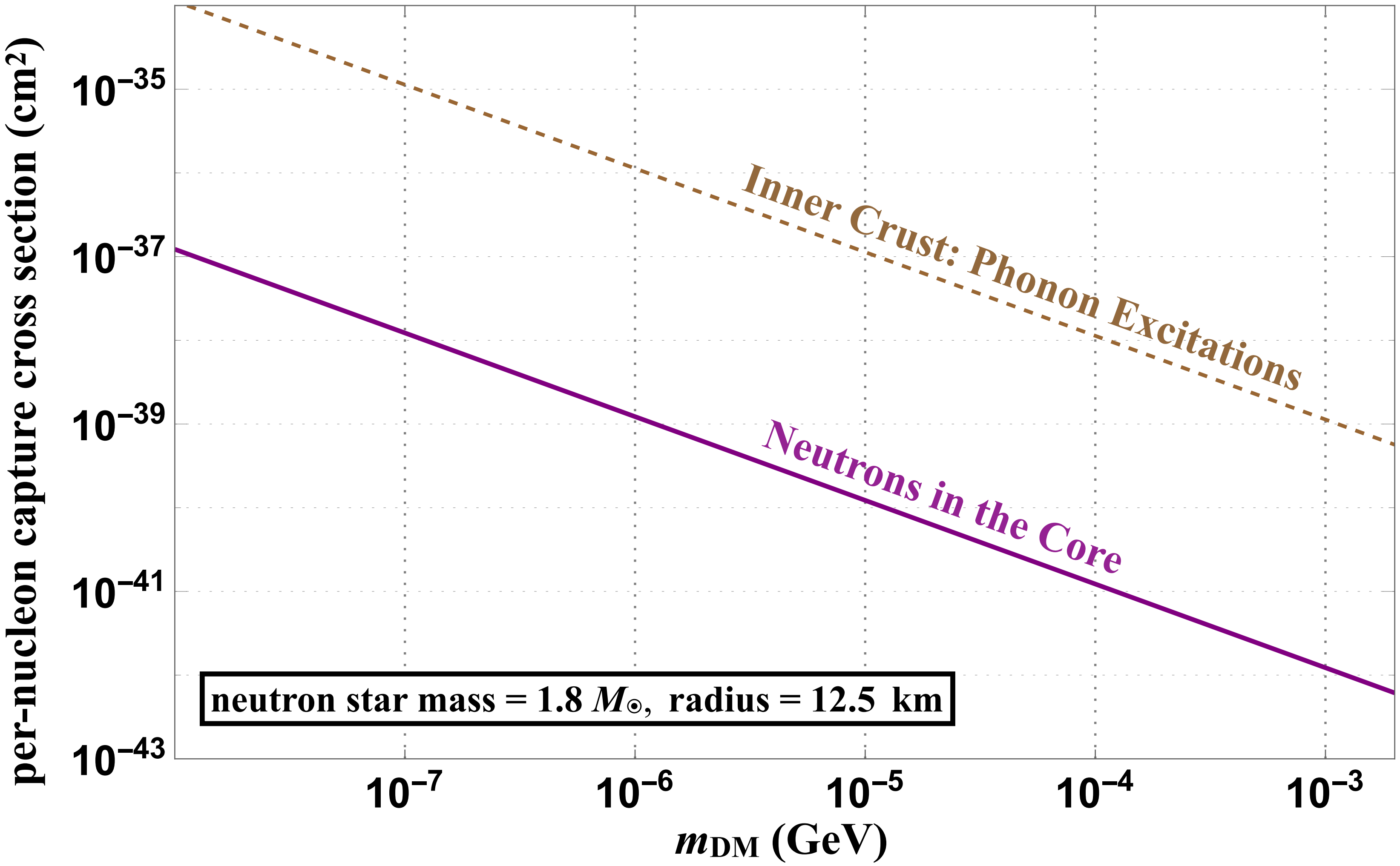
deeper =>
knowledge of structure
more uncertain

worthwhile to investigate capability of every layer to capture dark matter



J Acevedo, J Bramante, R Leane, **N R**; 1911.06334

Crust vs low mass dark matter



capture by exciting single superfluid phonon:

energy deposited > halo KE

[q x phonon speed ~ $m_{DM}\, v_{esc}$ x 0.04 c]   [$m_{DM}\,(10^{-3}\, c)^2$]

$$\sigma_{\rm phonon}(q) = S_{\rm phonon}(q)\sigma_{{\rm n}\chi}$$

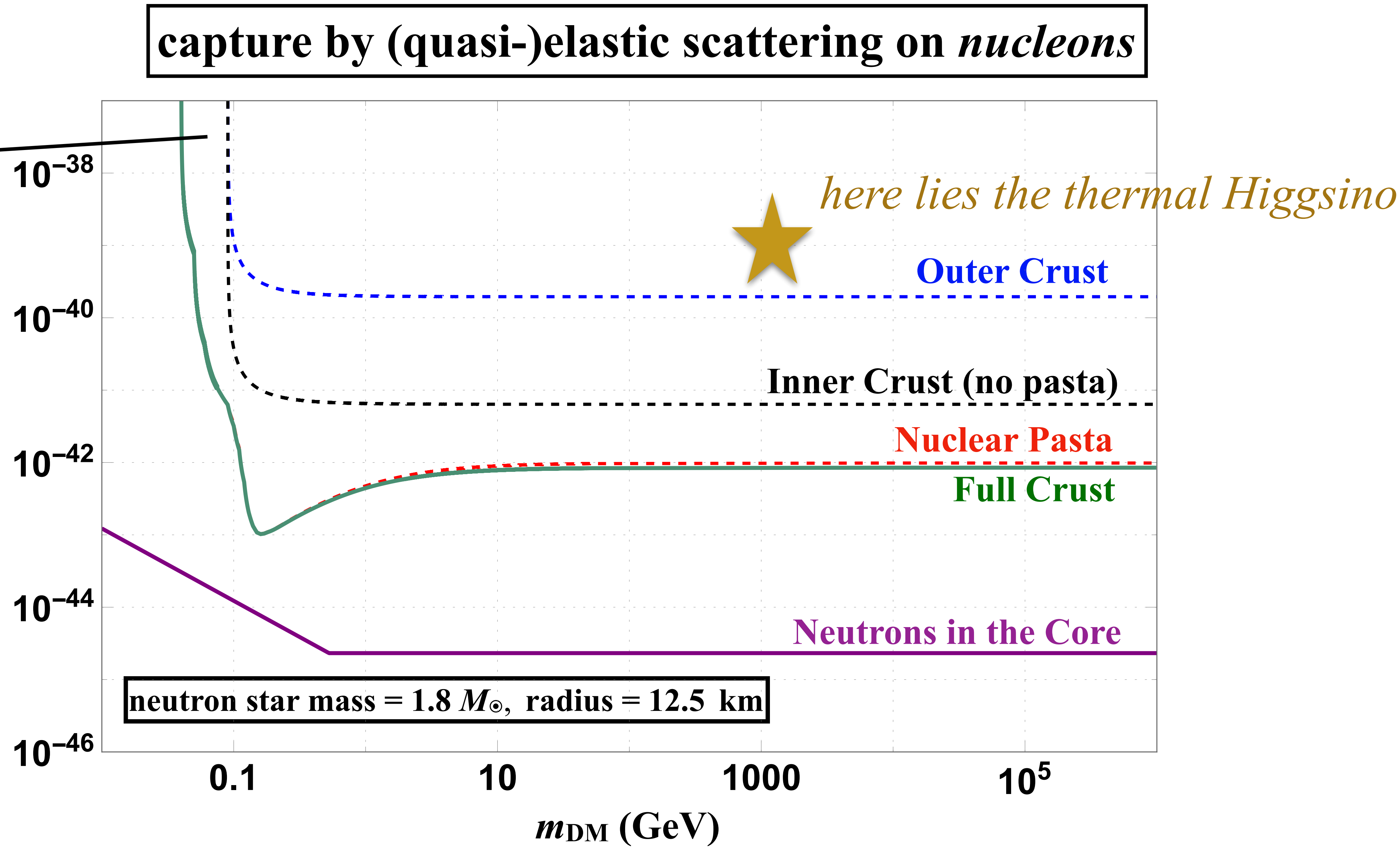
↓

q/ (2m_n x phonon speed)

J Acevedo, J Bramante, R Leane, **N R**; 1911.06334

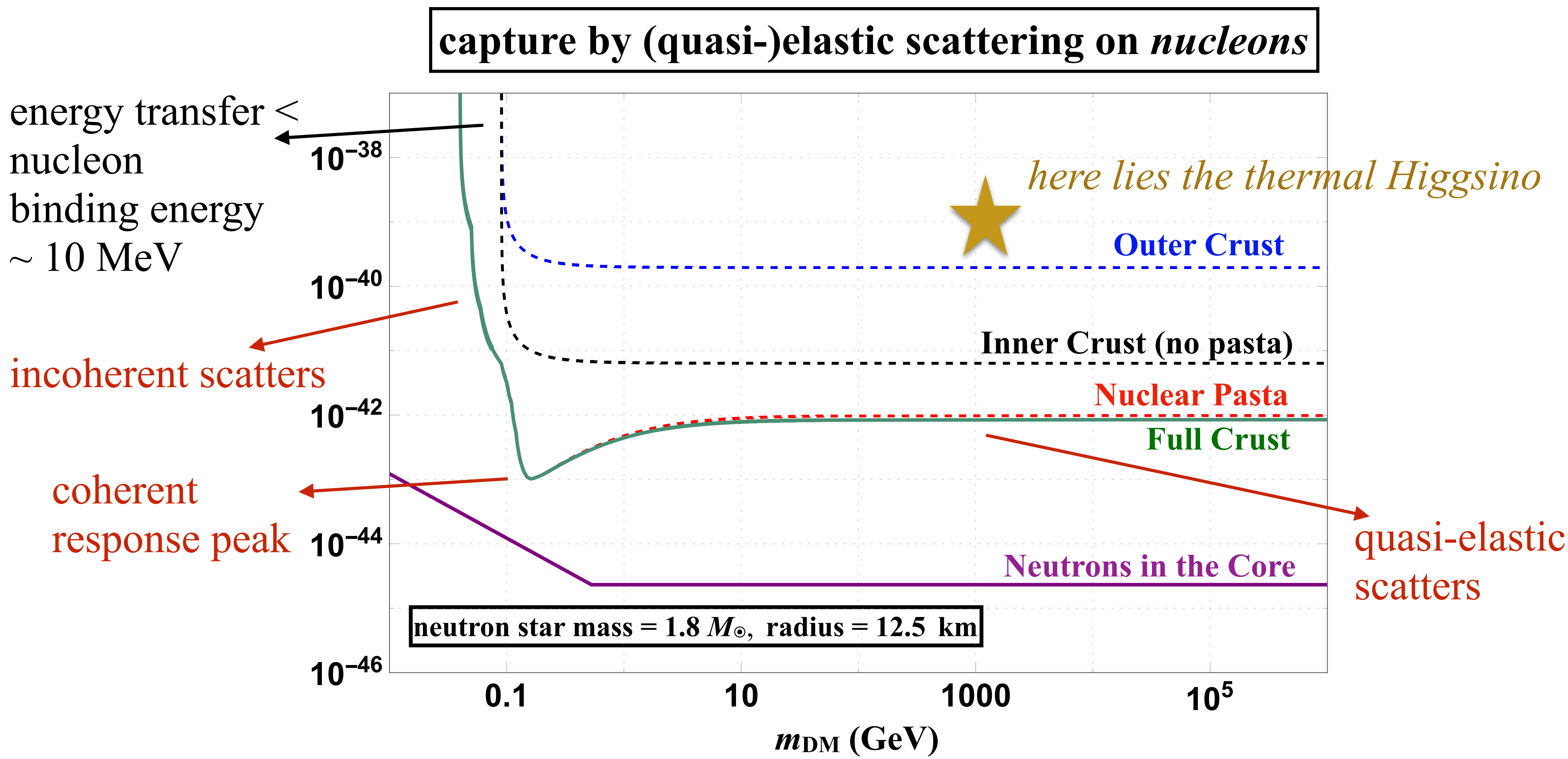
Crust vs WIMPs & heavier dark matter

energy transfer < nucleon binding energy ~ 10 MeV



J Acevedo, J Bramante, R Leane, **N R**; 1911.06334

Crust vs WIMPs & heavier dark matter



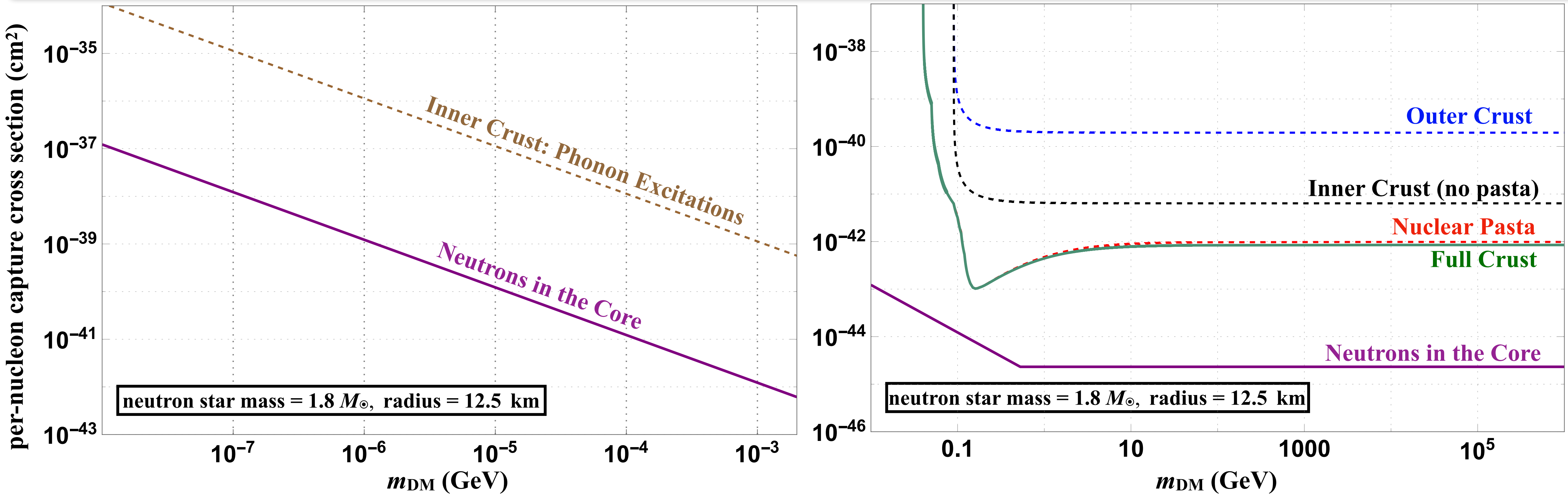
capture by pasta:

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

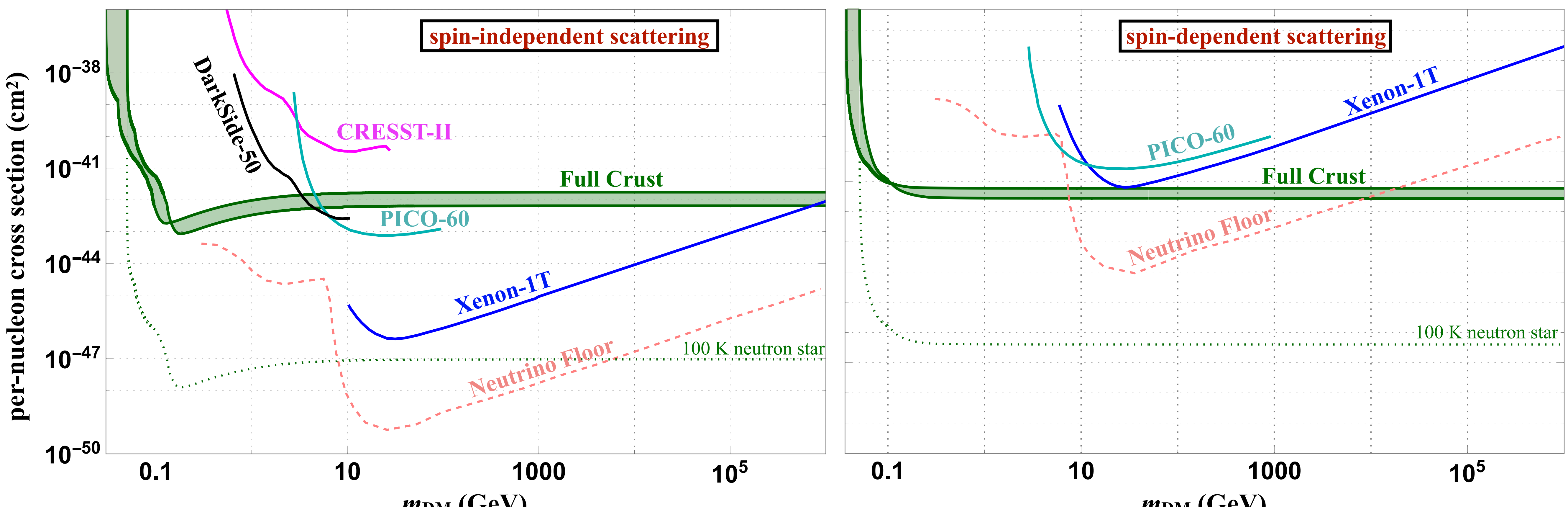
response function describing correlations among *nucleons* in pasta

J Acevedo, J Bramante, R Leane, **N R**; 1911.06334

Neutron star crust vs Earth crust



versus direct detection:



Annihilations

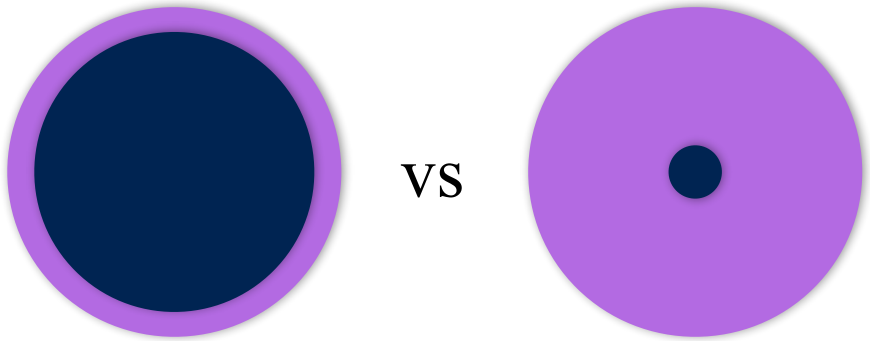
Annihilation saves observation time (= $$) by a factor of >10!

But how much annihilation is guaranteed?

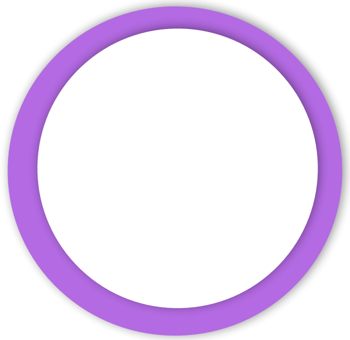
<u>Asymmetric</u> — none
<u>p-wave</u> — very suppressed

Does DM even thermalize with the star?

Affects DM spatial distribution, hence annihilation rate:



If DM only touches **crust**, star effectively **hollow shell:**



Would the DM cloud filling it annihilate efficiently?

Annihilations

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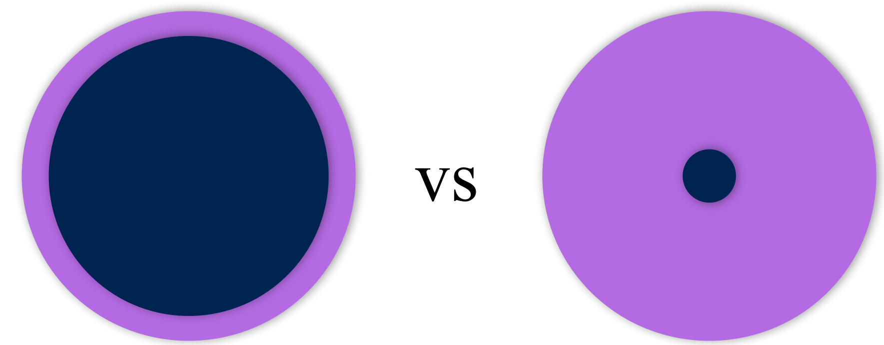

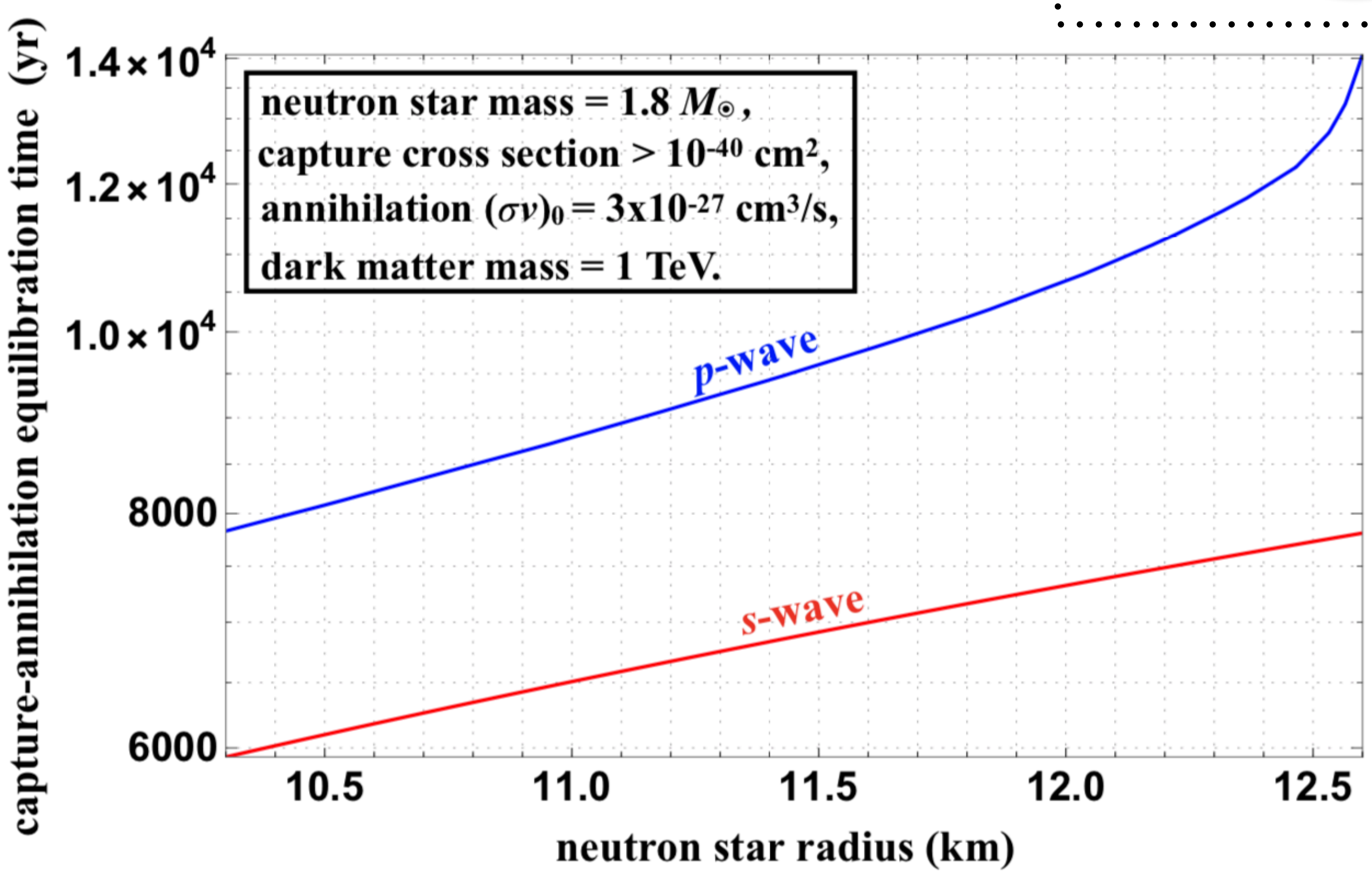

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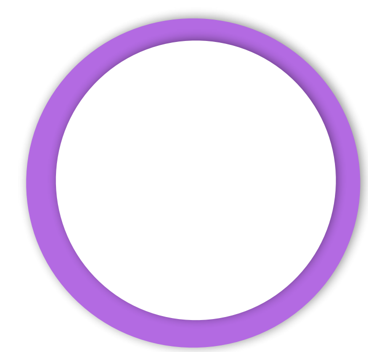


Would the DM cloud filling it annihilate efficiently?

Takeaways

- Dark kinetic heating of neutron stars via scattering on *non-relativistic* **nucleonic** or *ultra-relativistic* **electronic** targets, in the *less-understood* **core** or *fail-safe* **crust**, seriously advances direct detection frontiers.
  - Capture in the crust depends on

    kinematics
    - phonon excitation for sub-MeV masses
    - quasi-elastic nucleon scattering for masses > 100 MeV

    dynamics
    - larger cross section => upper layers
    - resonant enhancement due to pasta structure near 100 MeV mass

  - Pasta is the best trap (densest layer) for masses > 100 MeV

- Exoplanet observers like James Webb and Thirty Meter Telescope can unmask the heating signal with a day's exposure.

Thank you!

Questions?

Observation prospects

Radio telescopes
(design: pulsar discovery)

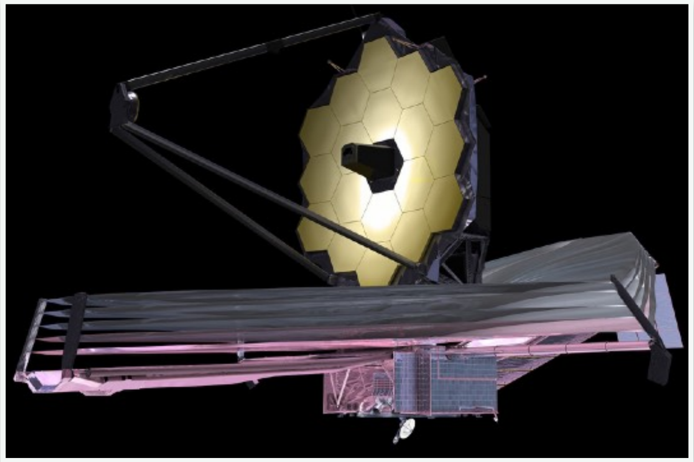
Infrared telescopes
(design: exoplanet atmosphere study)


CHIME

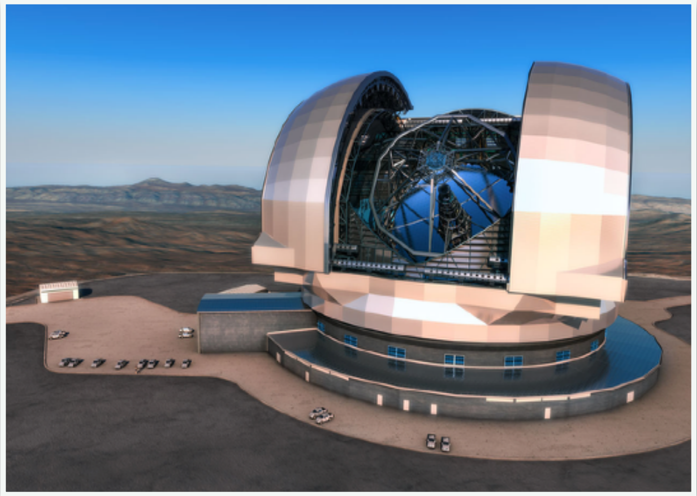

FAST

100 old, cold neutron stars
in the local 50 pc.

O. Blaes, P. Madau (1993)


James Webb

2021


European Extremely Large

2025


Thirty Meter

2027

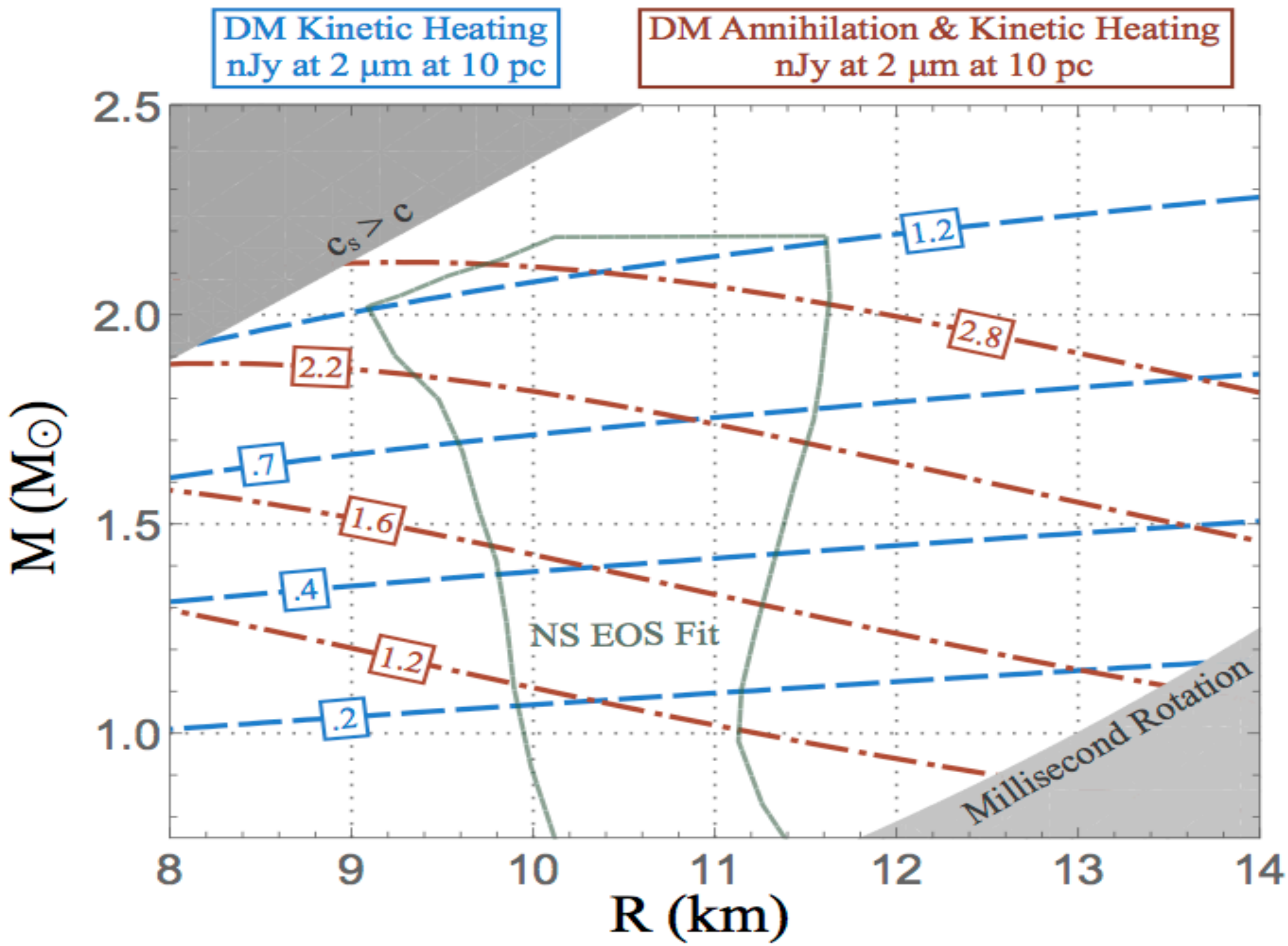
Brightness diagnosis

$$L \propto (\gamma - 1)m_{\mathrm{DM}} + m_{\mathrm{DM}}$$

$$\left(\gamma = \frac{1}{\sqrt{1 - 2GM/R}}\right)$$

kinetic heating

+ annihilation



Telling between crust-only and core heating