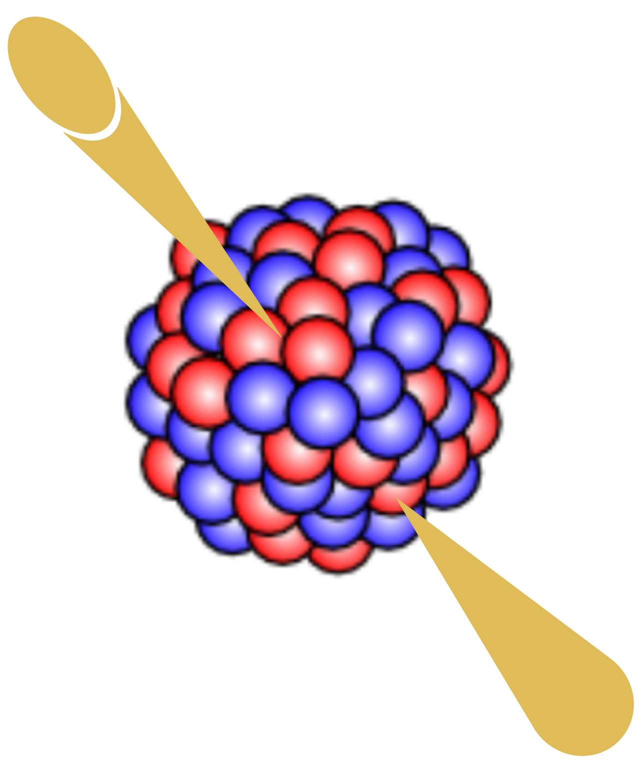
Compact Stars ⇋ Dark Matter

Nirmal Raj

IISc

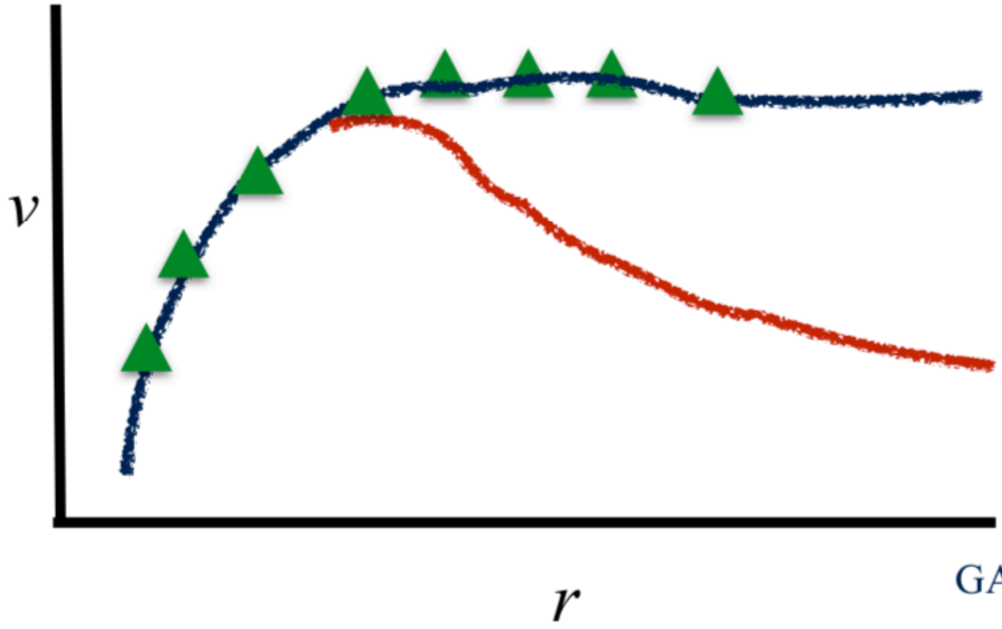
@PhysicsNirmal



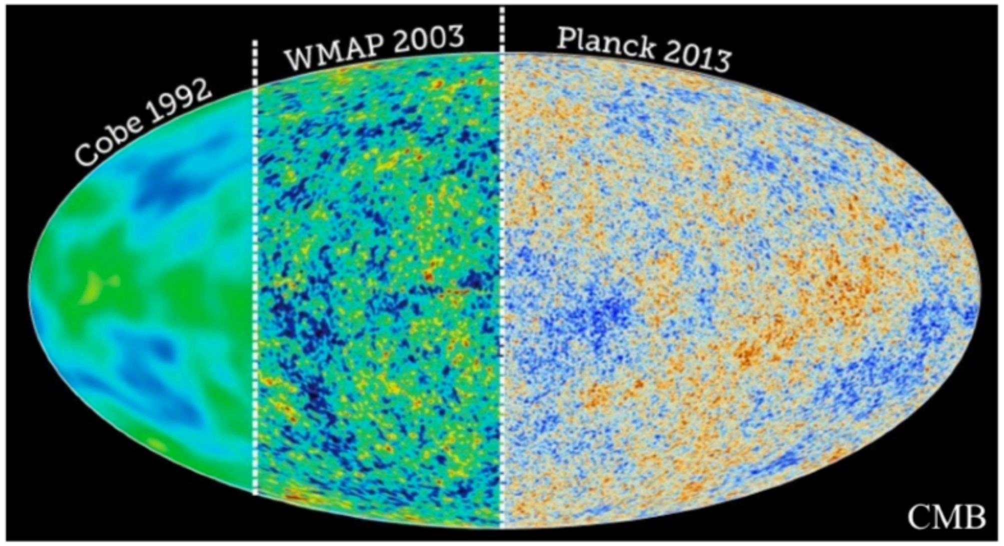
ICHEPAP

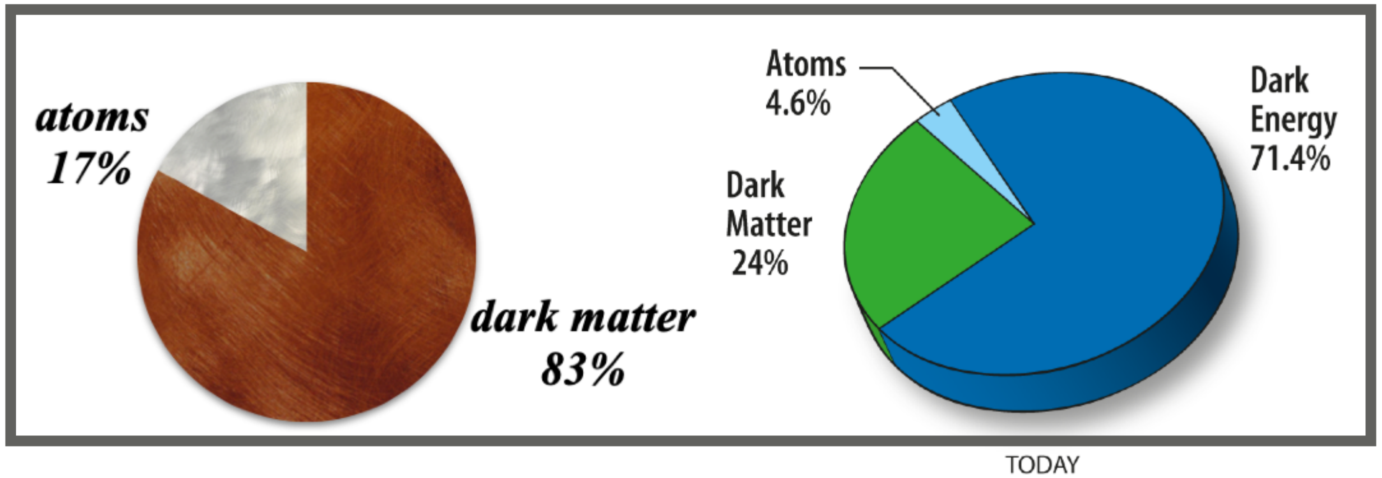
Dec 11 2023

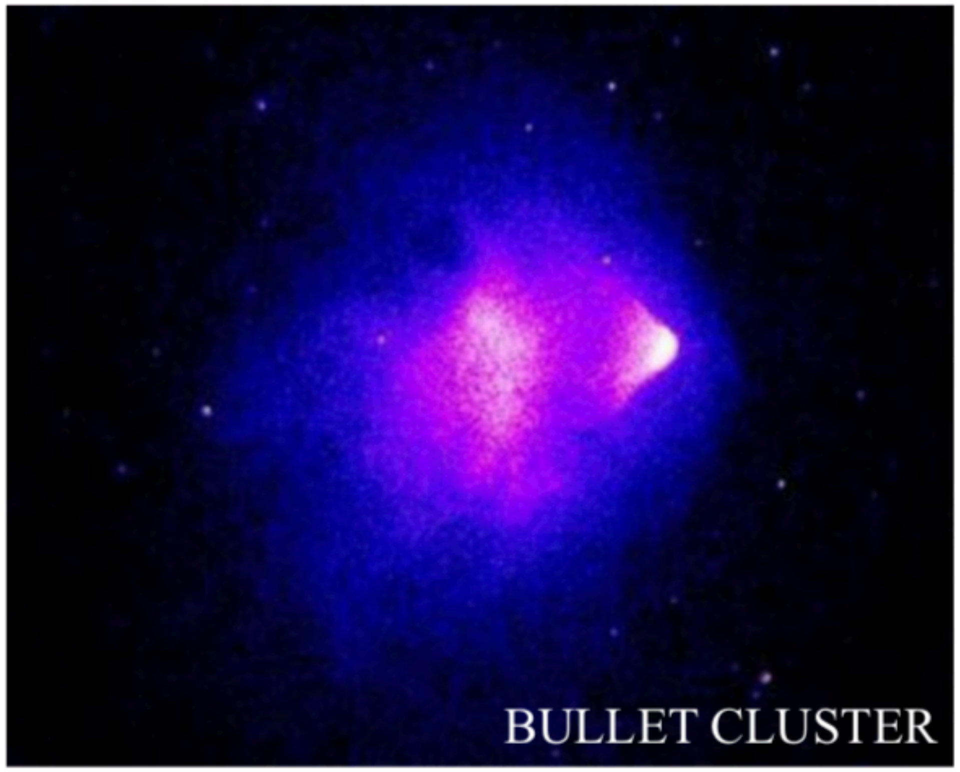
Dark matter exists



GALACTIC ROTATION







Dark possibilities

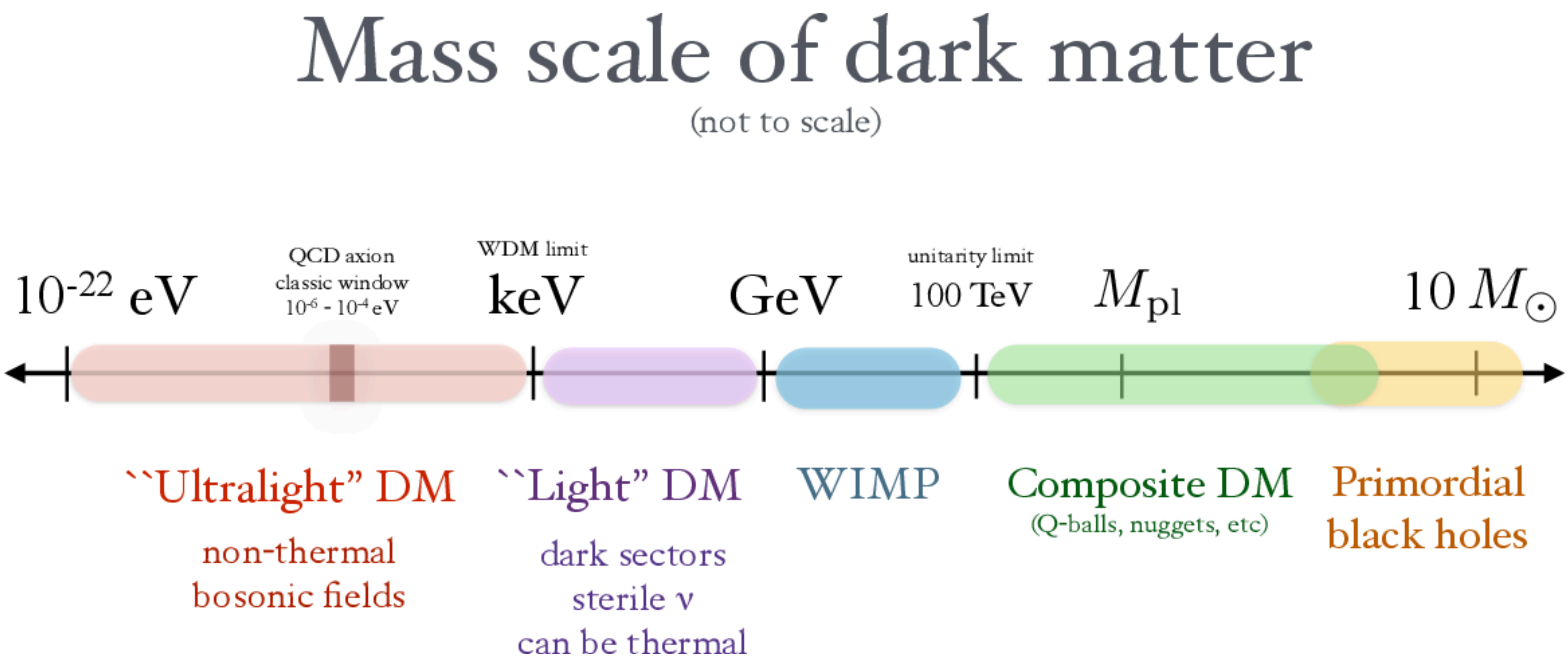
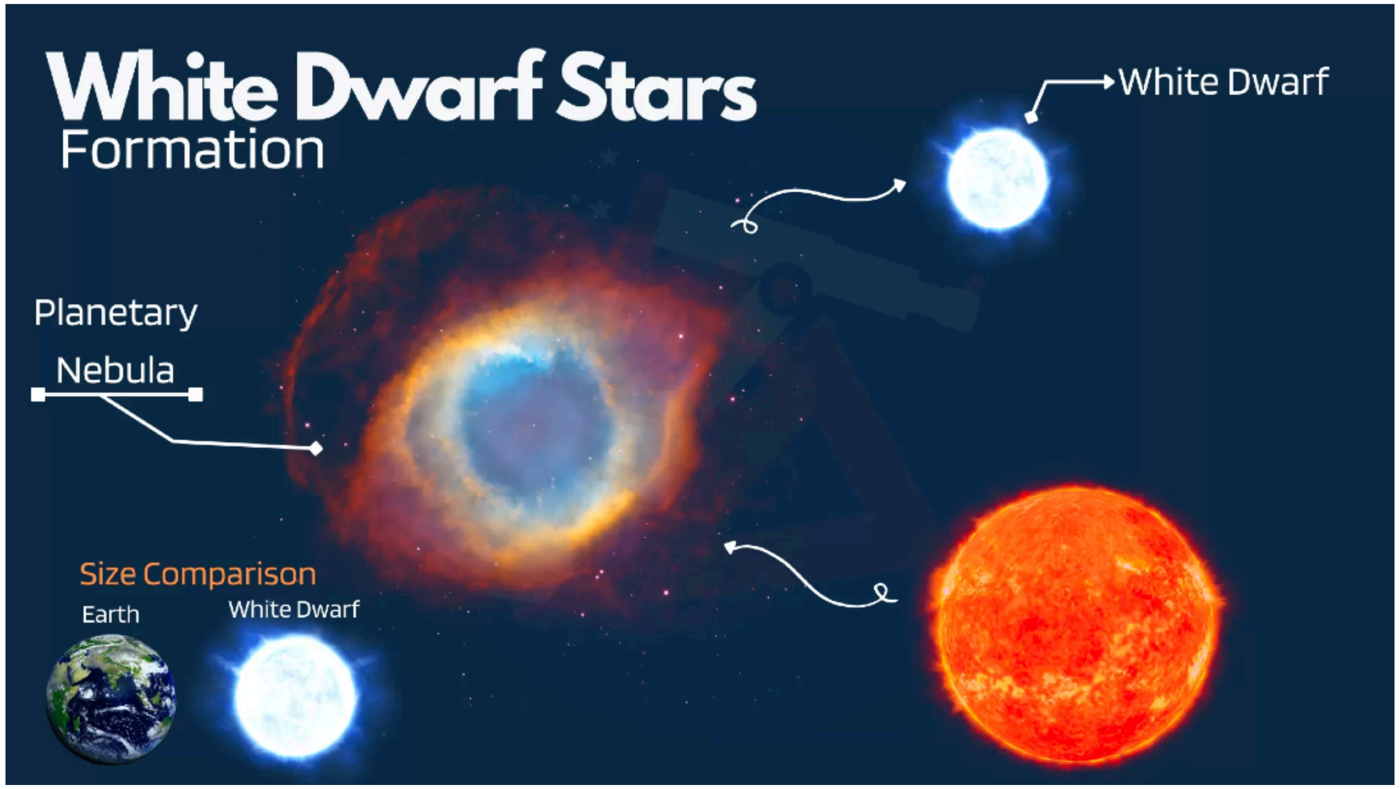
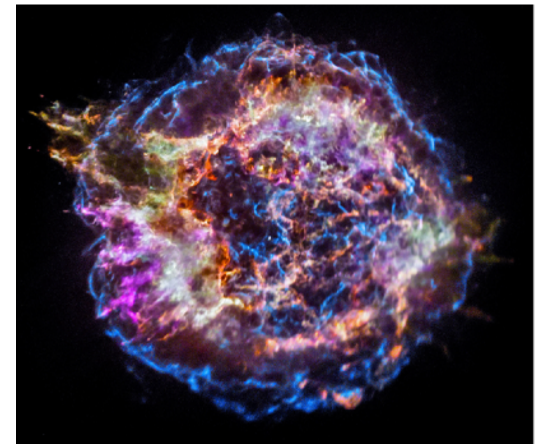


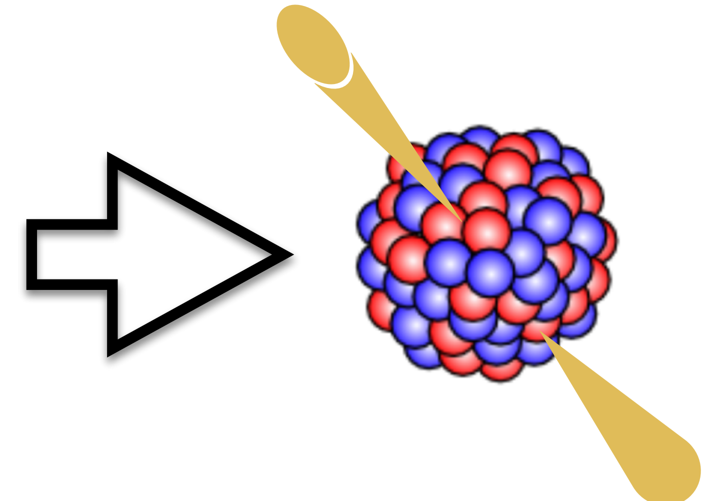
image: Tongyan Lin

Natural laboratories





core-collapse
supernova



neutron star

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

2307.14435

Dark matter in compact stars

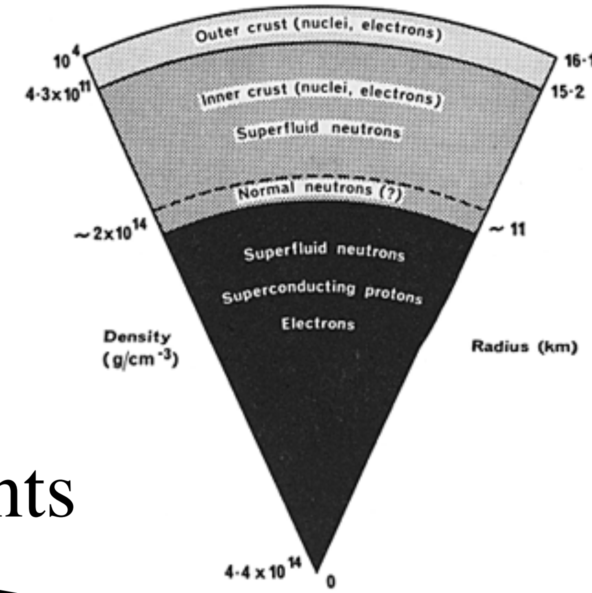
Joseph Bramante [a,b,c], Nirmal Raj [d,*]

[a] *Department of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, Ontario, K7N 3N6, Canada*
[b] *The Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Kingston, Ontario, K7L 3N6, Canada*
[c] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[d] *Centre for High Energy Physics, Indian Institute of Science, C.V. Raman Avenue, Bengaluru 560012, India*

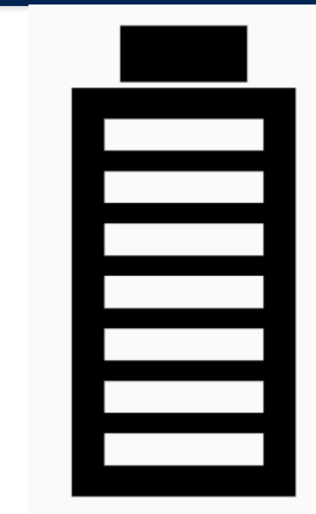
Lab features

- very high densities

  => steep gravitational potentials



- deeply Fermi-degenerate constituents

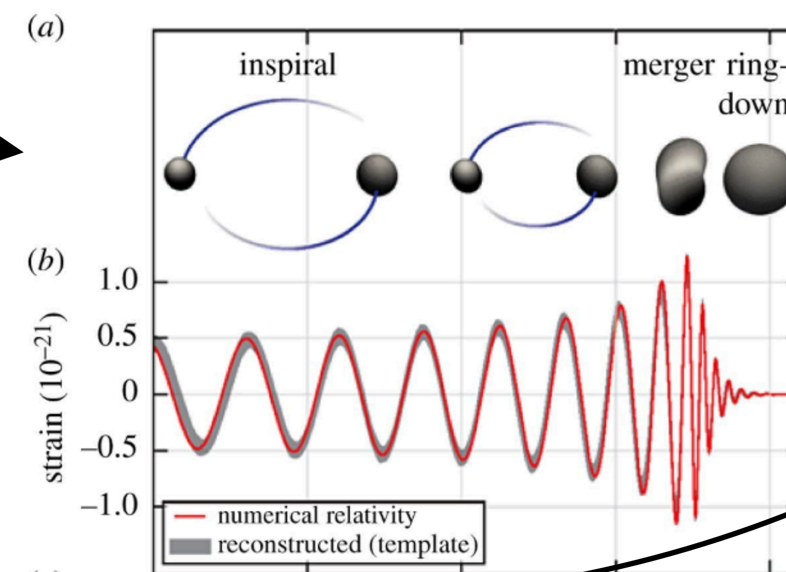


Fermi sea

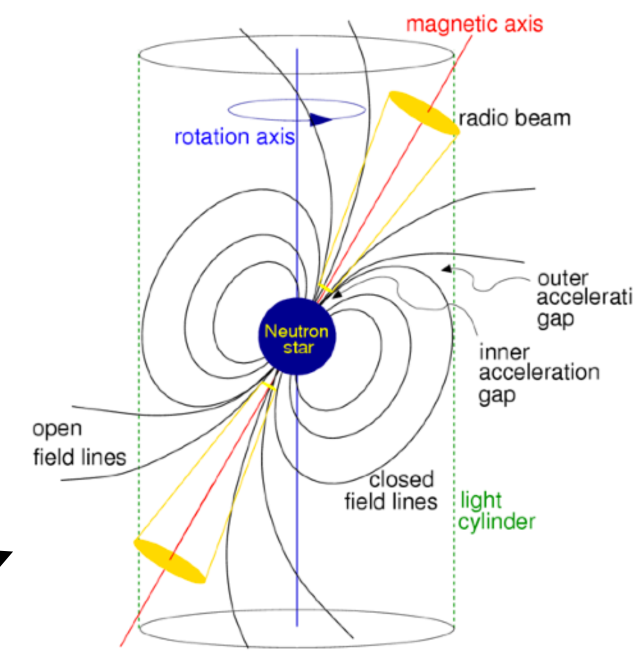
- low stellar temperatures

neutron stars

- powerful gravitational radiation

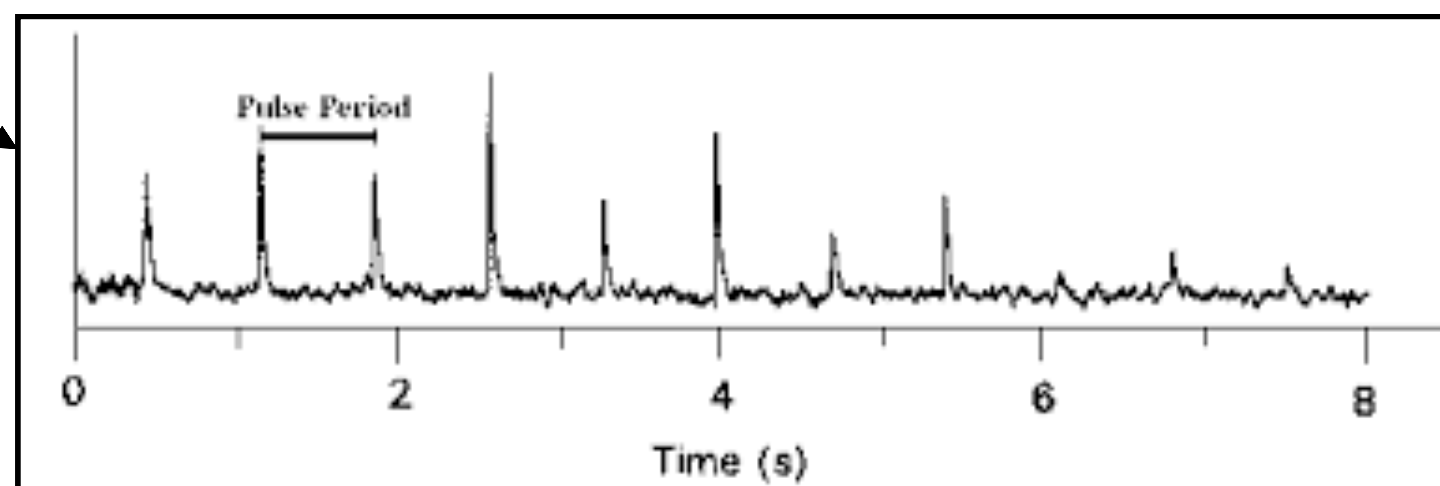


- ultra-strong magnetic fields



- extreme regularity in rotation

  c.f. atomic clocks



- nucleon superfluidity

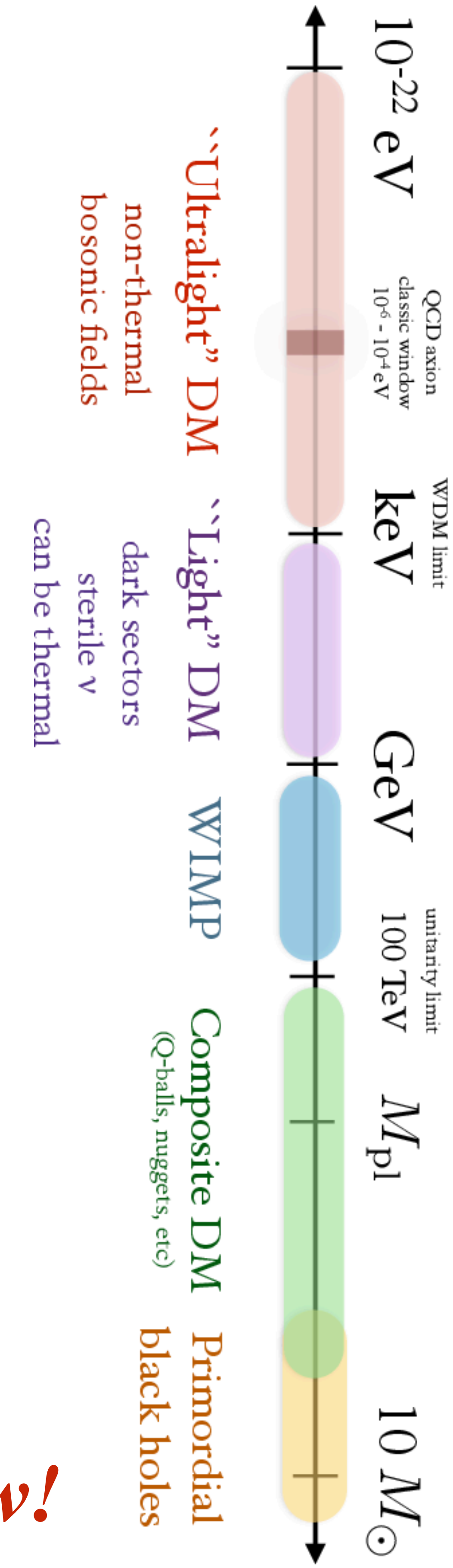
Confront and exploit

- very high densities
  - => steep gravitational potentials
- deeply Fermi-degenerate constituents
- low stellar temperatures

neutron stars

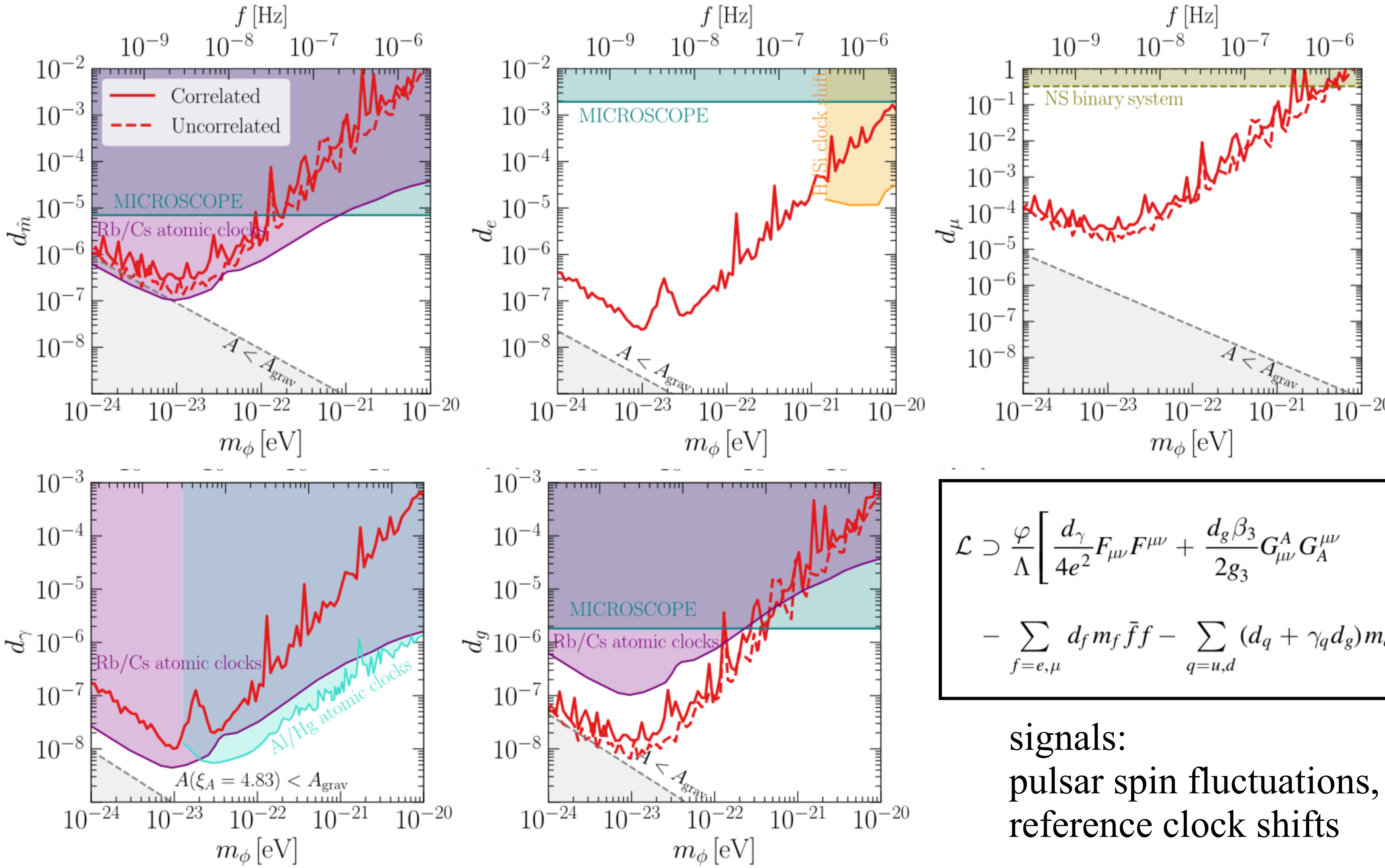
- powerful gravitational radiation
- ultra-strong magnetic fields
- extreme regularity in rotation
  - c.f. atomic clocks
- nucleon superfluidity

VERSUS



hence 446 references in our review!

Ultra-light dark matter vs pulsar timing arrays



$$\mathcal{L} \supset \frac{\varphi}{\Lambda}\left[\frac{d_\gamma}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum_{f=e,\mu} d_f m_f \bar{f}f - \sum_{q=u,d}(d_q+\gamma_q d_g)m_q\bar{q}q\right],$$

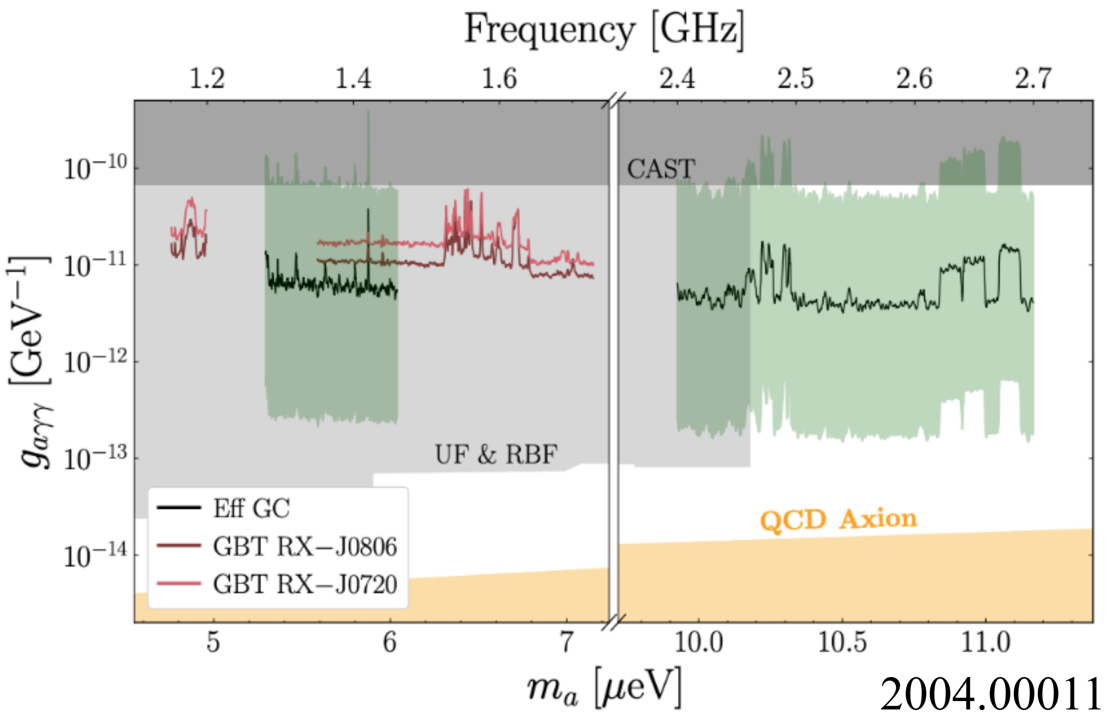
signals:
pulsar spin fluctuations,
reference clock shifts

The Astrophysical Journal Letters, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

The NANOGrav 15 yr Data Set: Search for Signals from New Physics

ALP dark matter vs neutron star radio

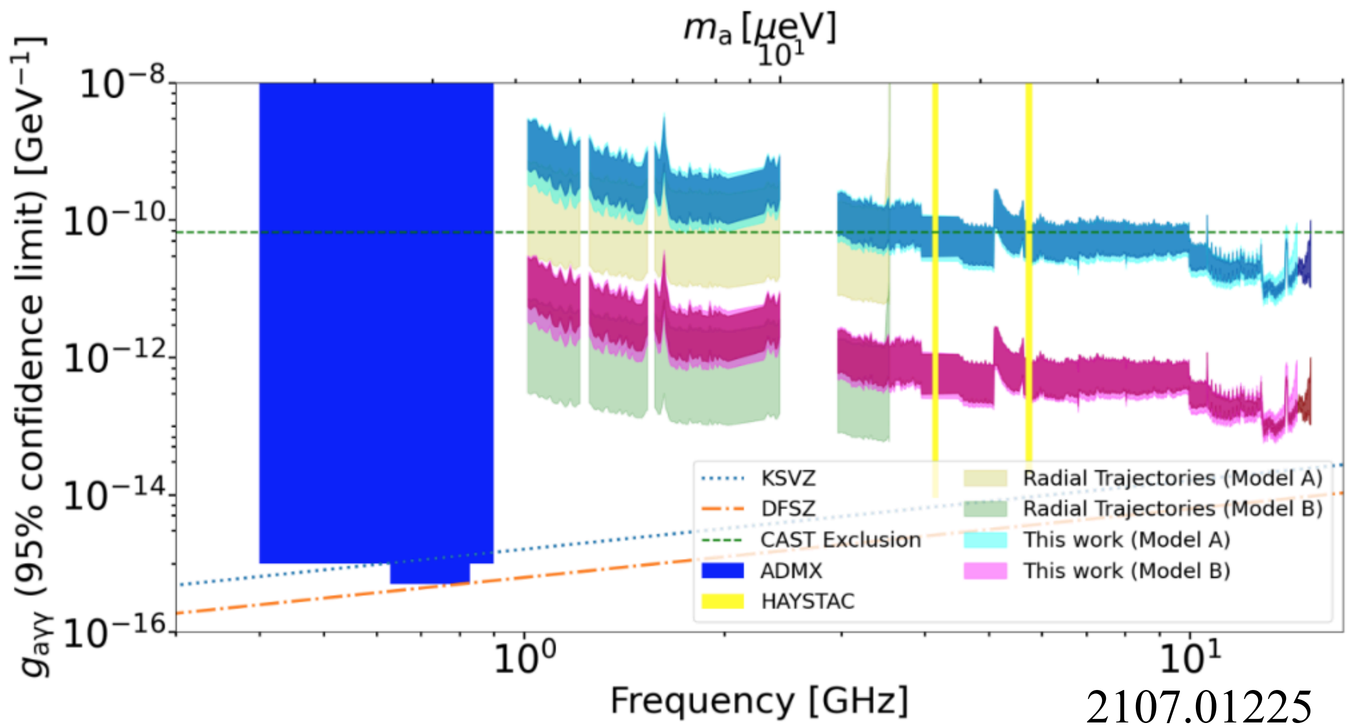
Green Bank & Effelsberg



2004.00011

J. W. Foster, Y. Kahn, O. Macias, Z. Sun, R. P. Eatough, V. I. Kondratiev, W. M. Peters, C. Weniger, B. R. Safdi

Very Large Array



2107.01225

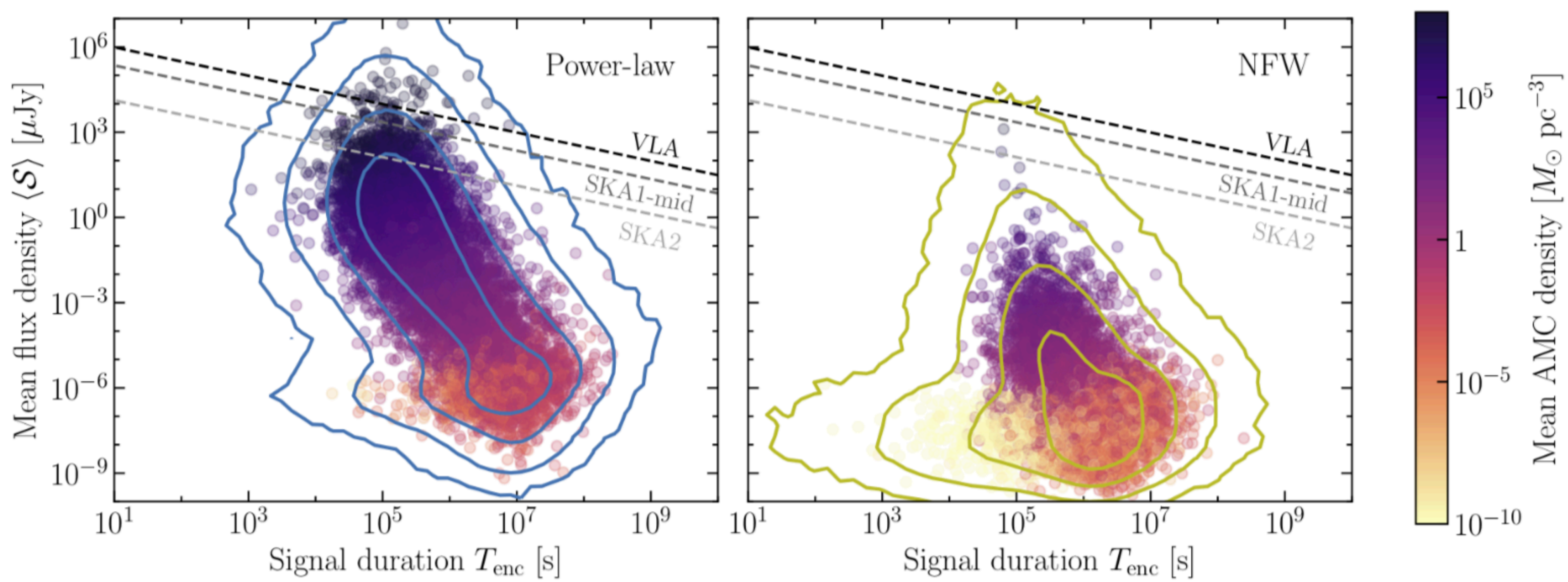
R. A. Battye, J. Darling, J. I. McDonald, S. Srinivasan

$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$$\to -g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

Primakoff conversion in magnetosphere => radio line

T.D.P.Edwards, B.J.Kavanagh, L.Visinelli, C.Weniger 2011.05378



Neutron stars as thermal detectors of “particle” dark matter

fundamental physics

external fire

(“dark kinetic heating”)

PRL **119,** 131801 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos

Masha Baryakhtar,[1] Joseph Bramante,[1] Shirley Weishi Li,[2] Tim Linden,[2] and Nirmal Raj[3]

\+ (with clumped dark matter)

PHYSICAL REVIEW LETTERS **128,** 231801 (2022)

Scattering Searches for Dark Matter in Subhalos: Neutron Stars, Cosmic Rays, and Old Rocks

Joseph Bramante,[1,2,*] Bradley J. Kavanagh,[3,†] and Nirmal Raj[4,‡]

internal fire

(“nucleon Auger effect”)

PHYSICAL REVIEW LETTERS **127,** 061805 (2021)

Neutron Star Internal Heating Constraints on Mirror Matter

David McKeen,[1,*] Maxim Pospelov,[2,3,†] and Nirmal Raj[1,‡]

telescopes

infrared

James Webb (space)

Extremely Large (Chile)

Thirty Meter (Hawai’i?!)

Roman/WFIRST

optical

Rubin/LSST

Dark Energy Survey

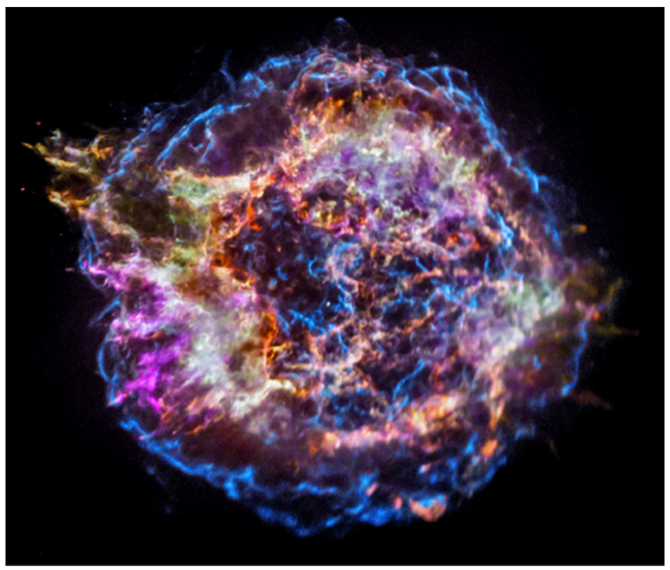
ultraviolet

LUVOIR

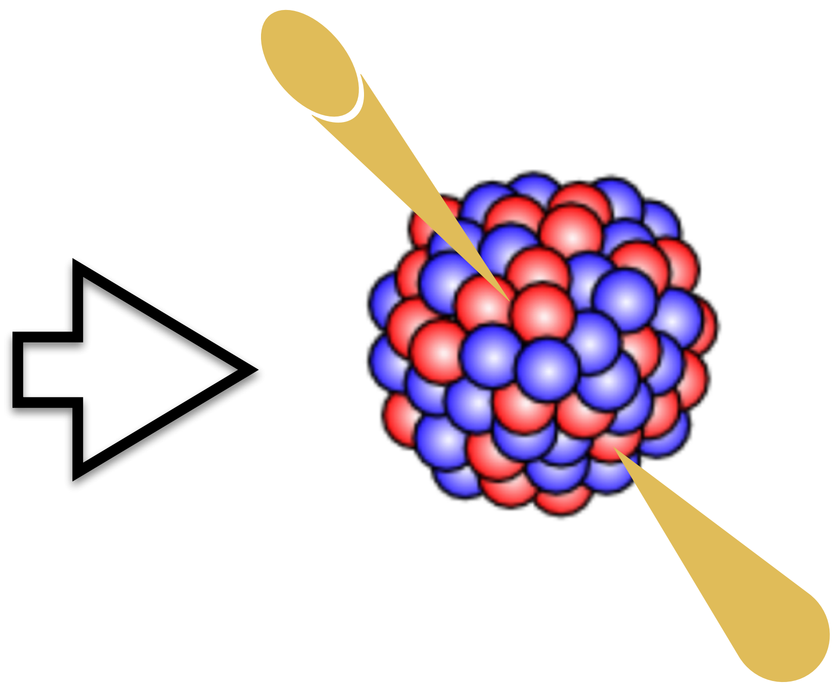
+ radio

FAST, CHIME, uGMRT, SKA, …
to find new pulsars

Use **neutron stars** as scattering targets



core-collapse supernova



neutron star

"detector" properties

diameter: 20 km
density: 10^{15} g/cm^3
temperature: 100-1000 K (if 10^9 yr old)

PRL **119,** 131801 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos

Masha Baryakhtar,[1] Joseph Bramante,[1] Shirley Weishi Li,[2] Tim Linden,[2] and Nirmal Raj[3]

The signature: external fire

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

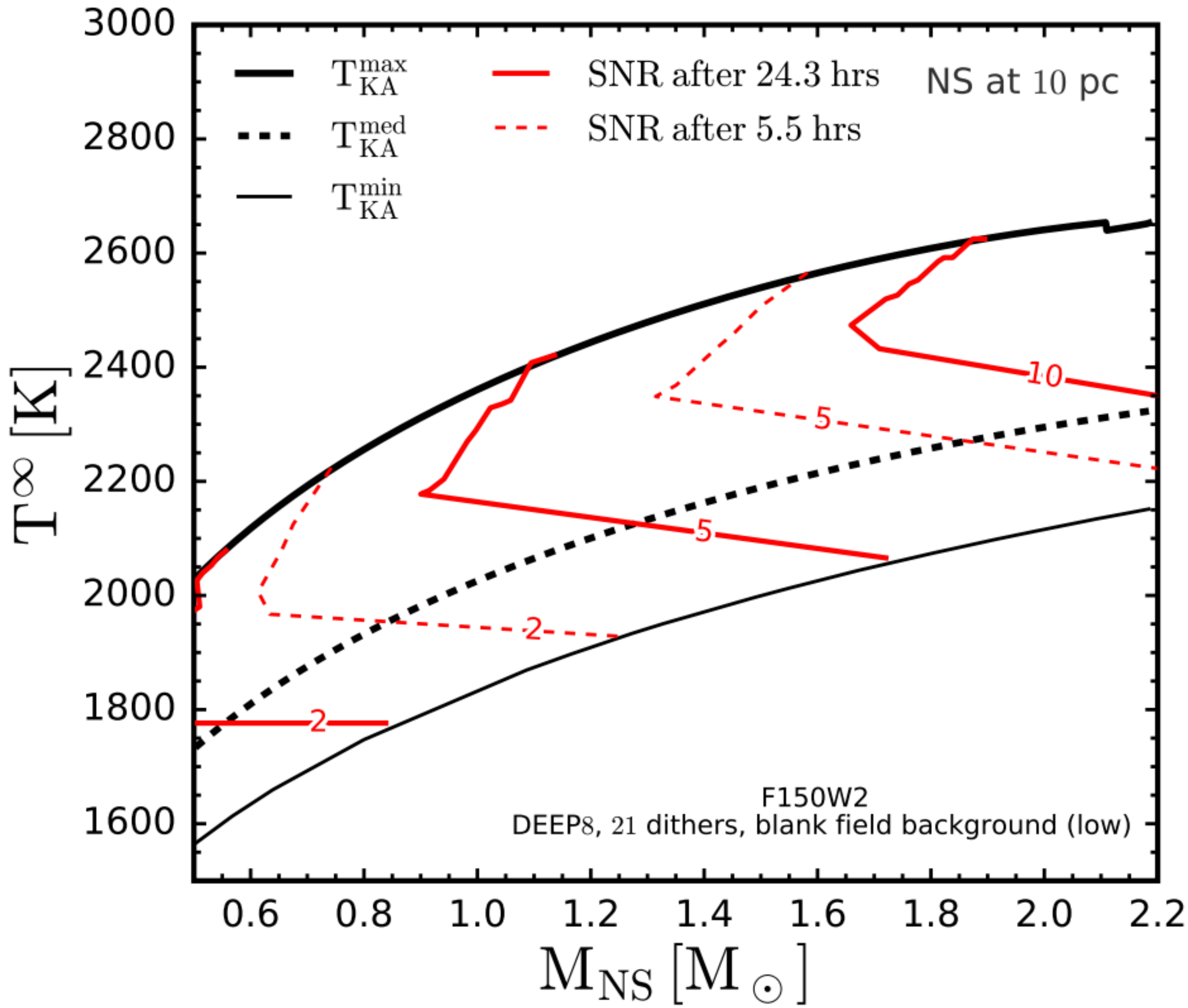
"Dark kinetic heating"

luminosity = kinetic power

(out) (in)

exact analogy: keeping soup hot

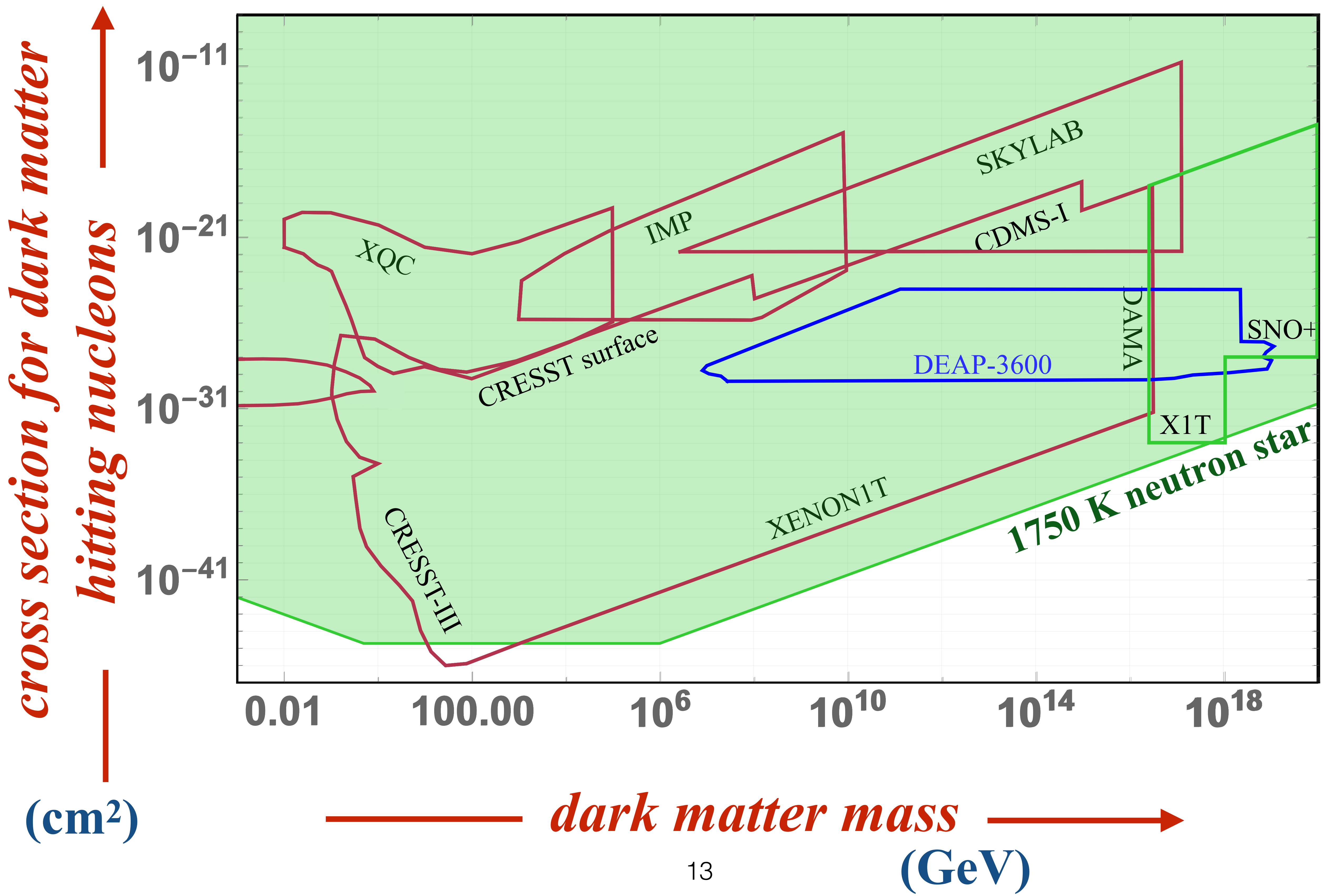
$$C\frac{dT}{dt} = -\,\sigma_{\rm SB}(\text{area})T^4 + \dot{E}_{\rm external}$$



Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope

Shiuli Chatterjee[1,*] Raghuveer Garani[2,†] Rajeev Kumar Jain[3,‡]
Brijesh Kanodia[1,3,§] M. S. N. Kumar[4,¶] and Sudhir K. Vempati[1**]
[1] *Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India*
[2] *INFN Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy*
[3] *Department of Physics, Indian Institute of Science, Bangalore 560012, India*
[4] *Instituto de Astrofísica e Ciências do Espaço, Porto, Rua das Estrelas, s/n, 4150-762, Porto, Portugal*

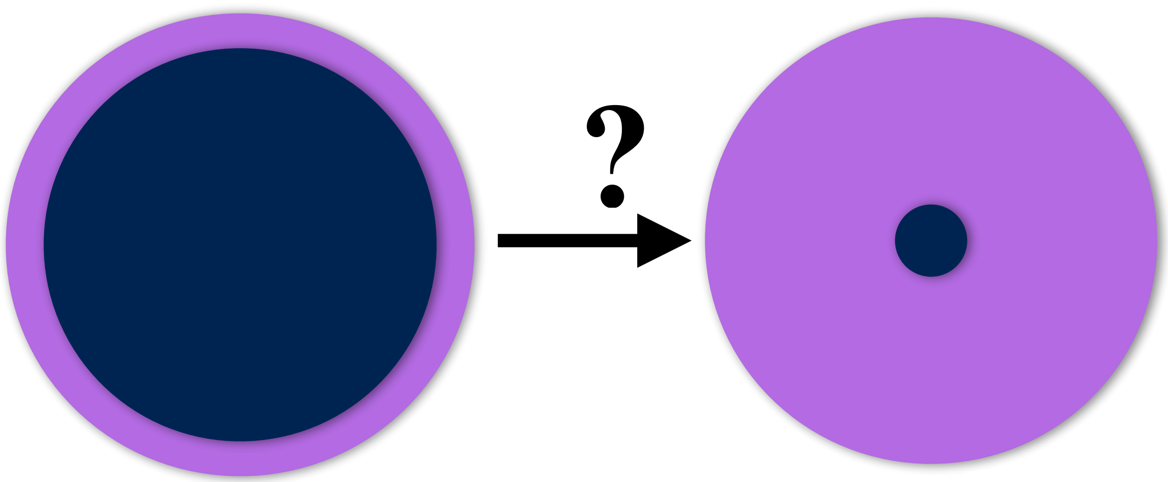
Sensitivities of neutron star direct detector

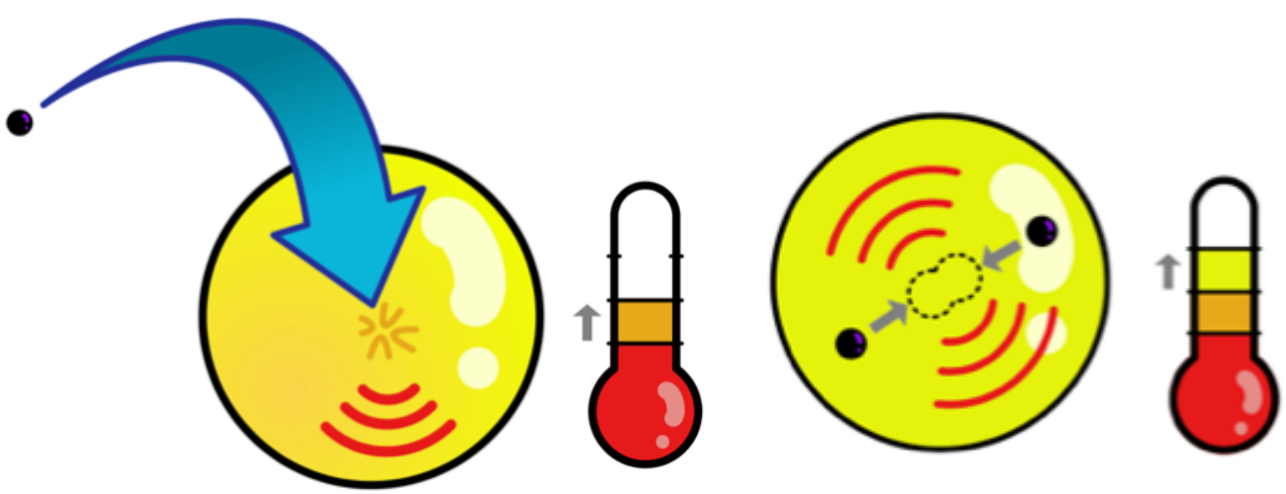


Important variations on a theme

#1 Must we refrigerate dark matter to see its effects?

R. Garani, A. Gupta, **N. Raj**
Phys. Rev. D. (2021)





(answer: yes and no;
highly model-dependent question)

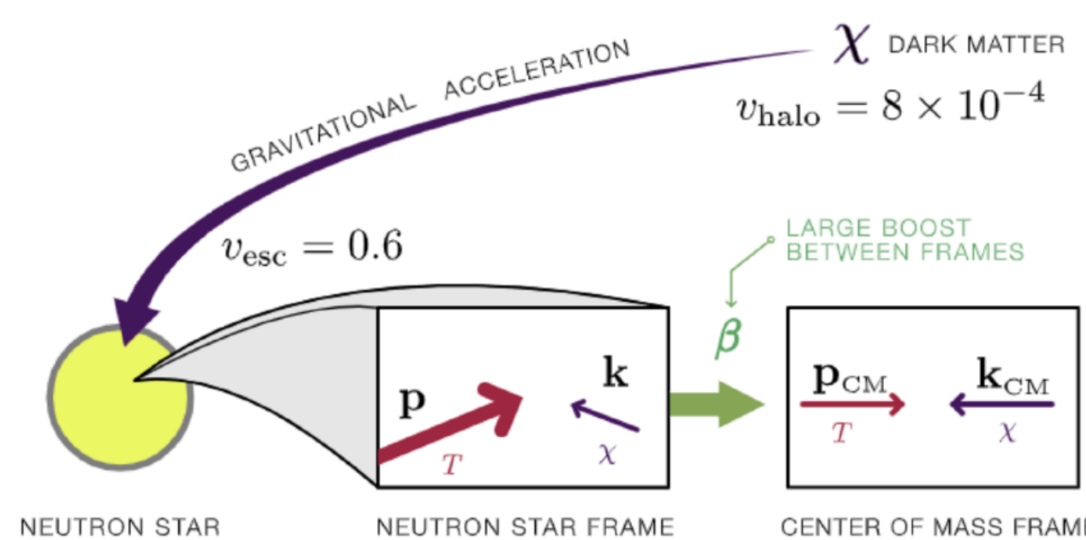
#2 Are we barking down the wrong scattering target?

A. Joglekar, **N. Raj**, *P. Tanedo, H-B. Yu*
Phys. Lett. B (2020) & *Phys. Rev. D* (2020)

species	$\langle Y_T \rangle$	mass (MeV)	$\langle p_F \rangle$ (MeV)
e	0.06	0.51	146
μ	0.02	105.7	50
p	0.07	938.3	160
n	0.93	939.6	373

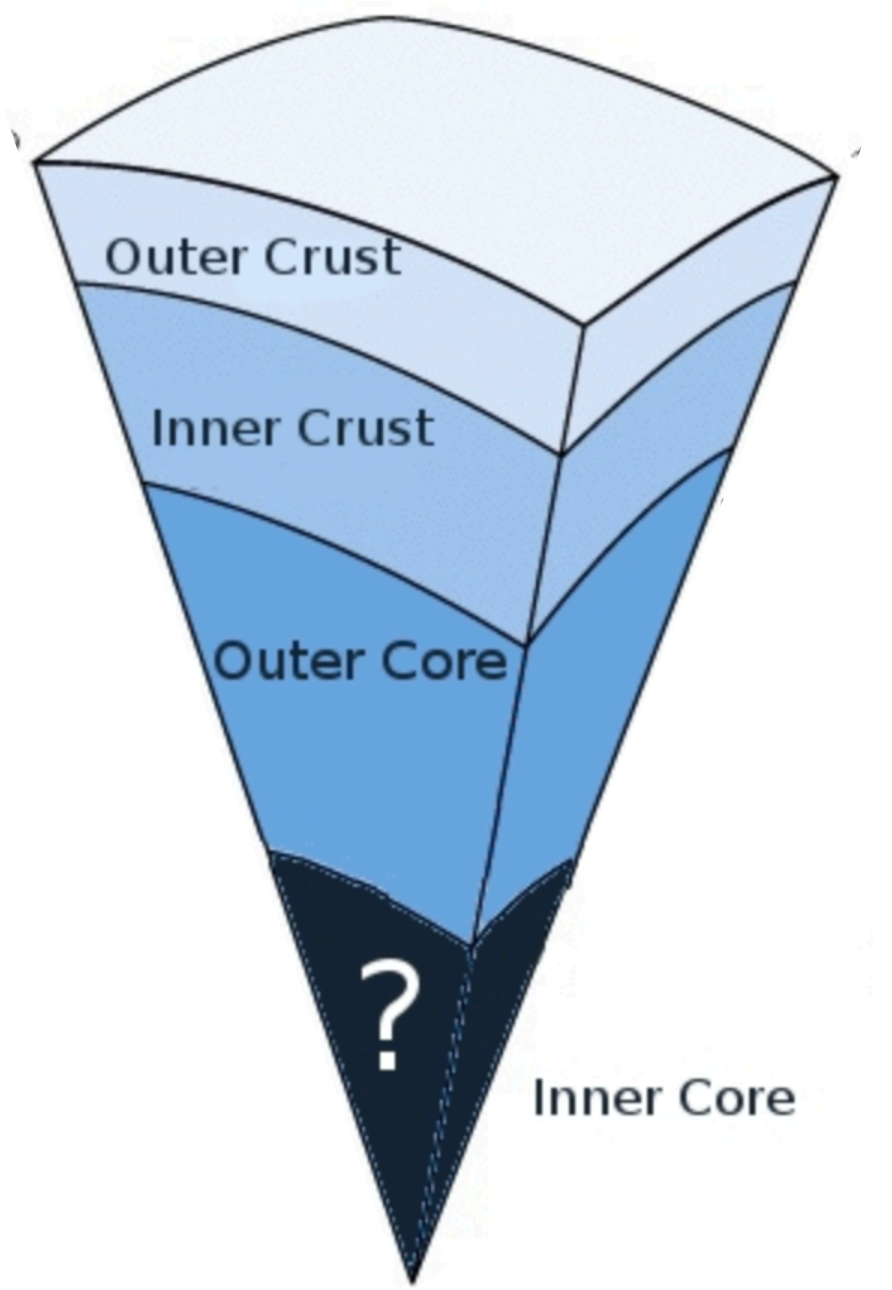
products of β equilibrium

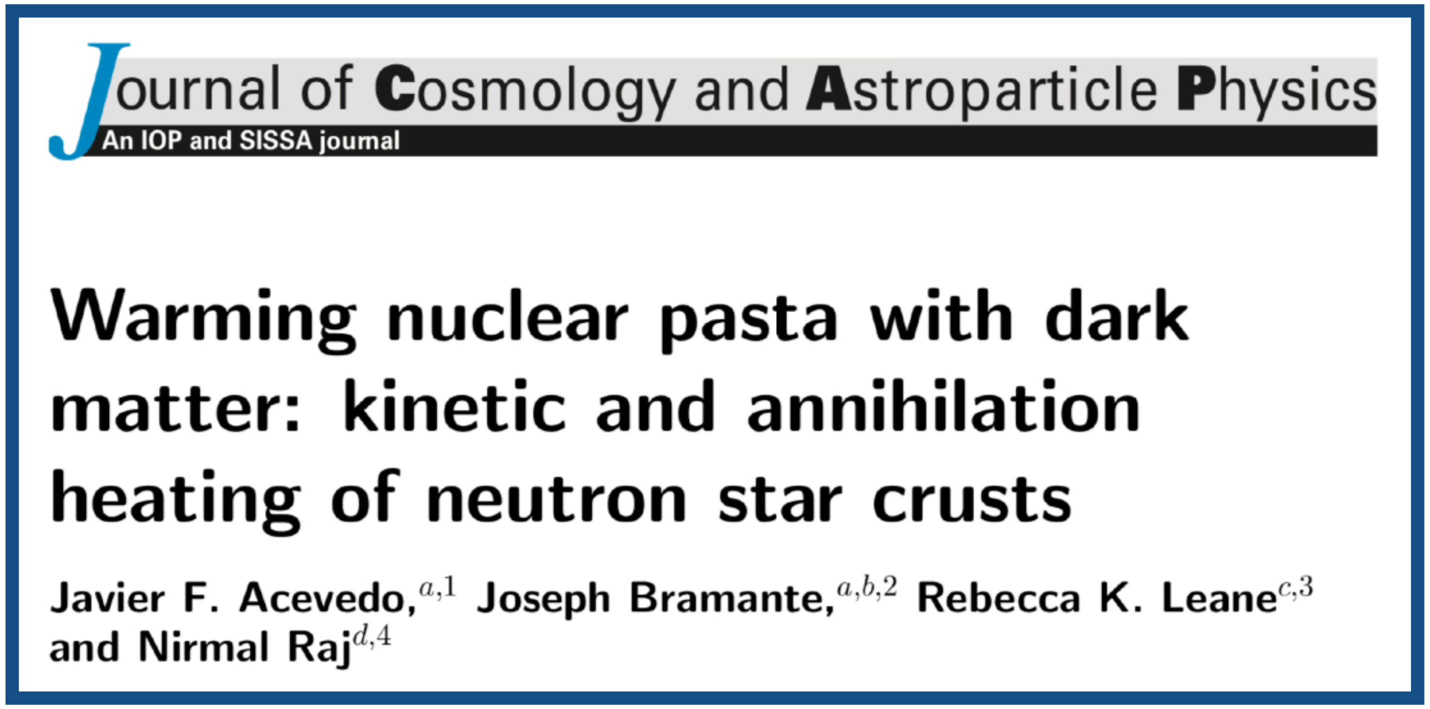
Treat electrons carefully; relativistic in star.



Important variations on a theme

#3 Are we barking down the wrong stellar region?

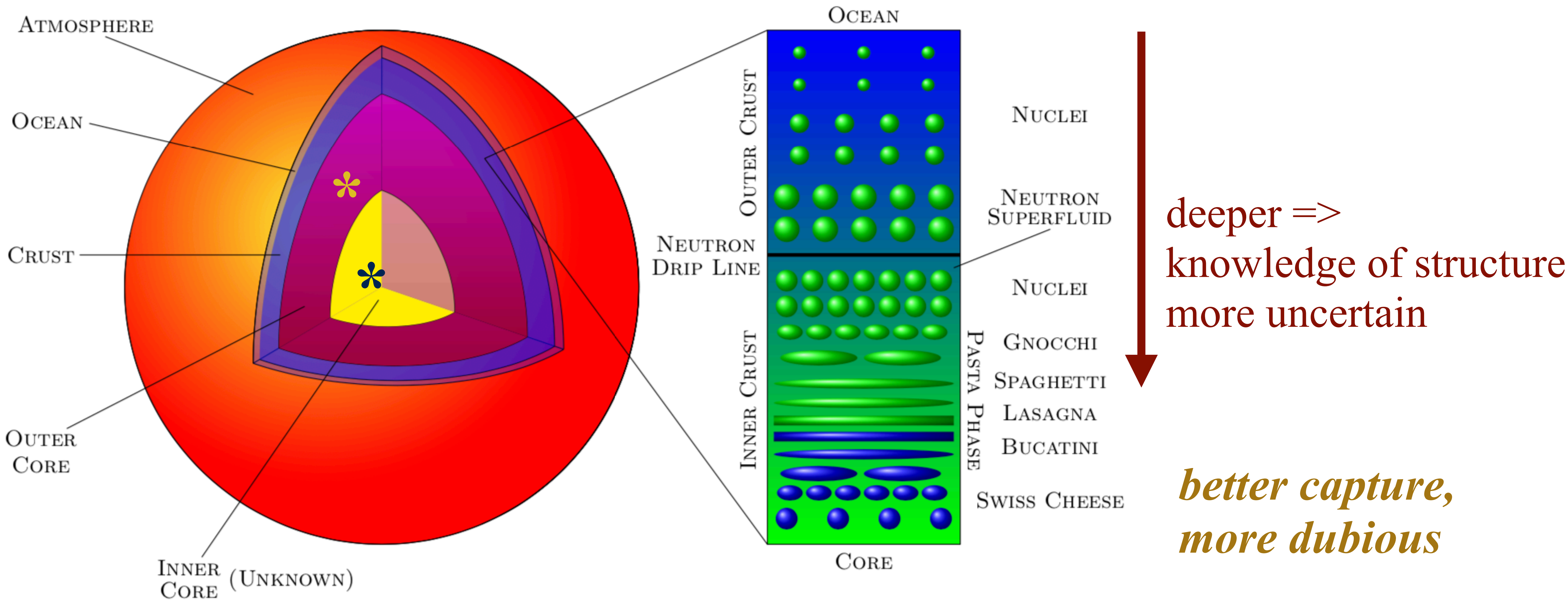



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Warming nuclear pasta with dark matter: kinetic and annihilation heating of neutron star crusts

Javier F. Acevedo,[a,1] Joseph Bramante,[a,b,2] Rebecca K. Leane[c,3] and Nirmal Raj[d,4]

Neutron star structure



* may not be neutrons
(maybe quark matter, meson condensates, etc.)

N Raj, *J Acevedo, J Bramante, R Leane*
JCAP (2020)

Important variations on a theme

#4 Can we catch clumpy dark matter?

PHYSICAL REVIEW LETTERS **128**, 231801 (2022)

Scattering Searches for Dark Matter in Subhalos: Neutron Stars, Cosmic Rays, and Old Rocks

Joseph Bramante,[1,2,*] Bradley J. Kavanagh,[3,†] and Nirmal Raj[4,‡]

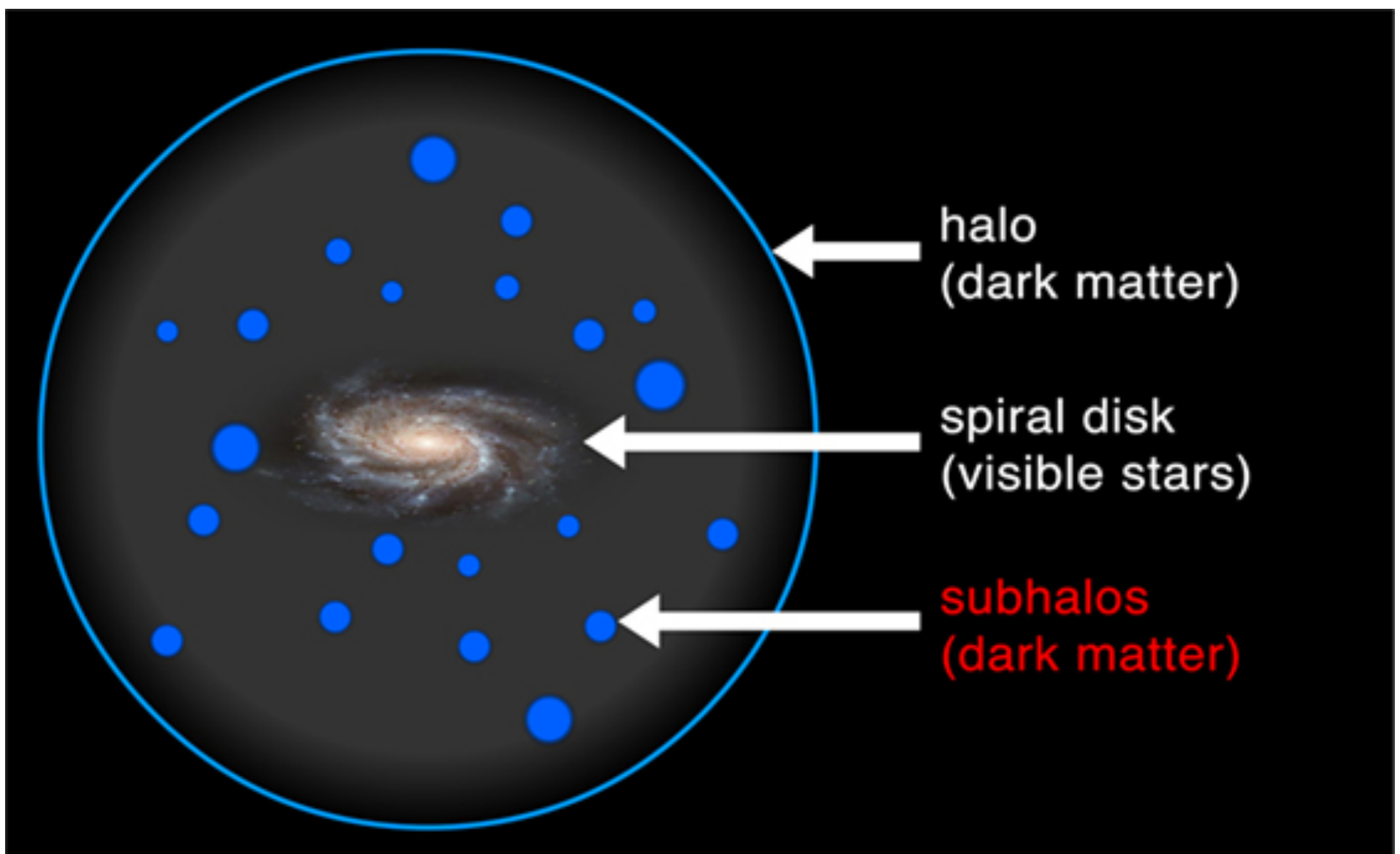


image: astrobites

Is most dark matter clumped?

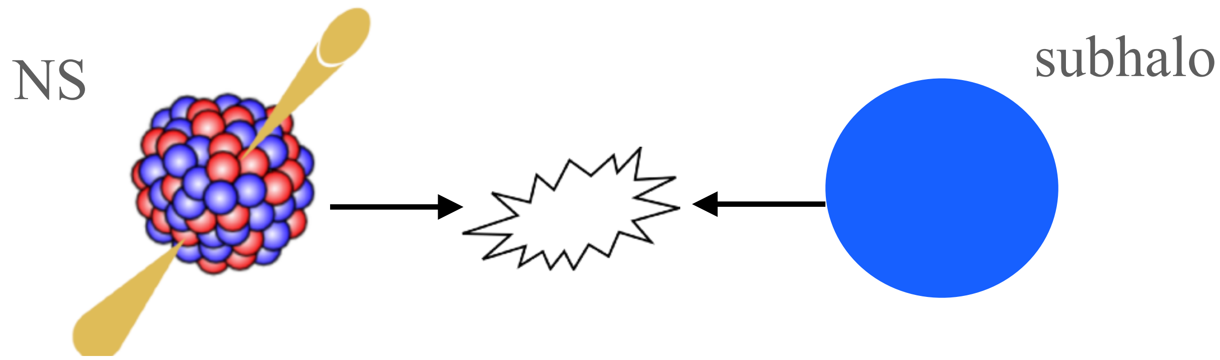
— sub-kpc scale physics unknown

— small scale power enhanced in many cosmologies

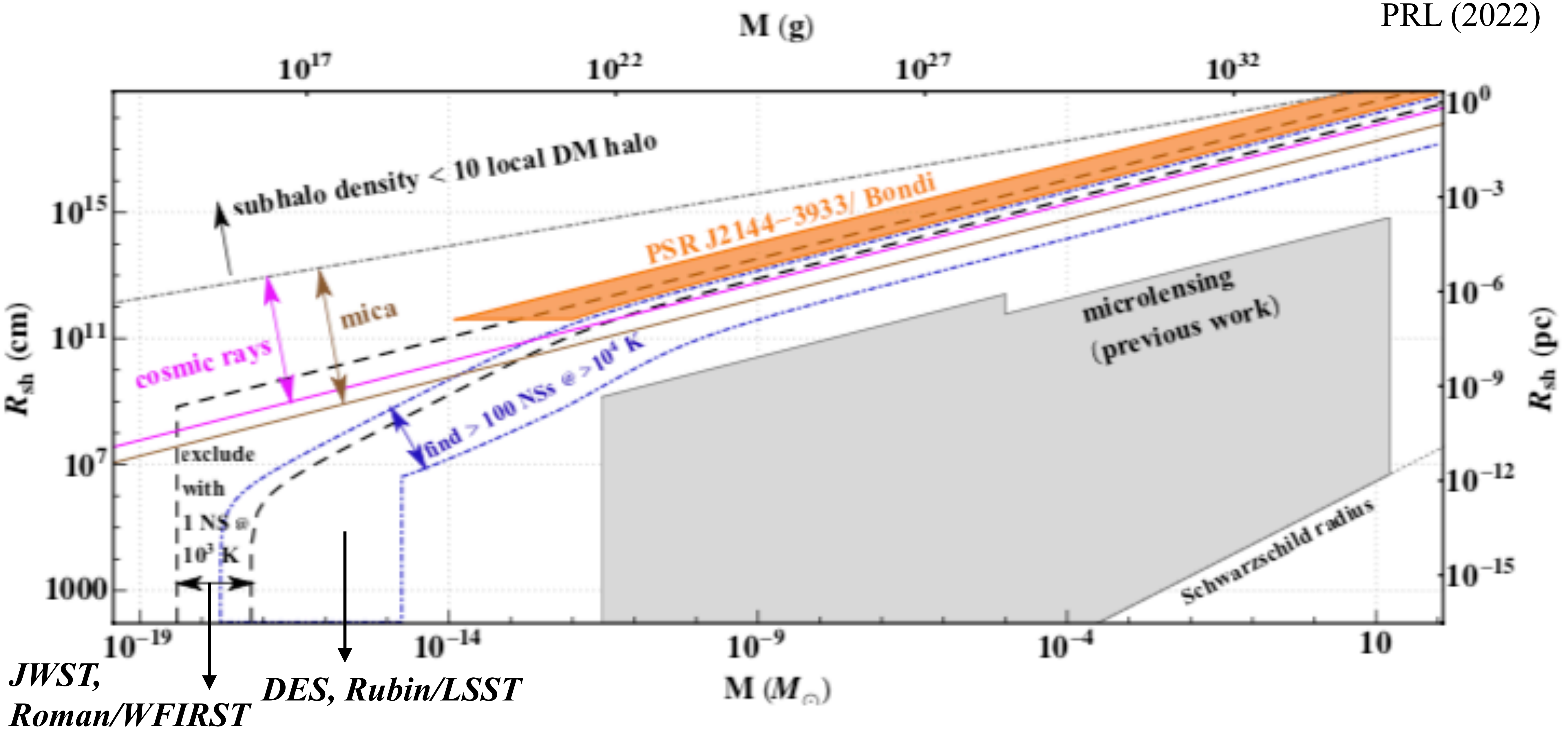
Earth may be in a DM void
=>
underground searches not in play!

Important variations on a theme

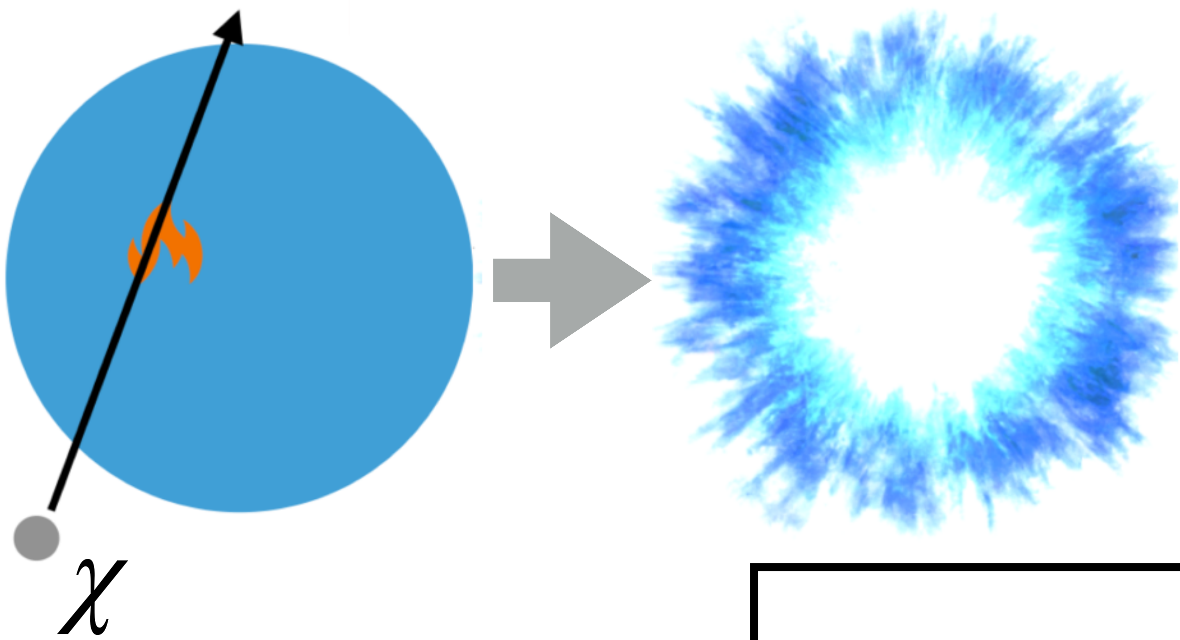
#4 Can we catch clumpy dark matter?



N Raj, *J Bramante, B Kavanagh*
PRL (2022)



And something different



Condition 1 ***ignite it***

$$Q_{\rm dep} \geq M_{\rm crit}(\rho, T_{\rm crit})\bar{c}_p(\rho, T_{\rm crit})T_{\rm crit}$$

Condition 2 ***heat it quick***

$$\dot{Q}_{\rm nuc} > \dot{Q}_{\rm diff}$$

x-ray fountains

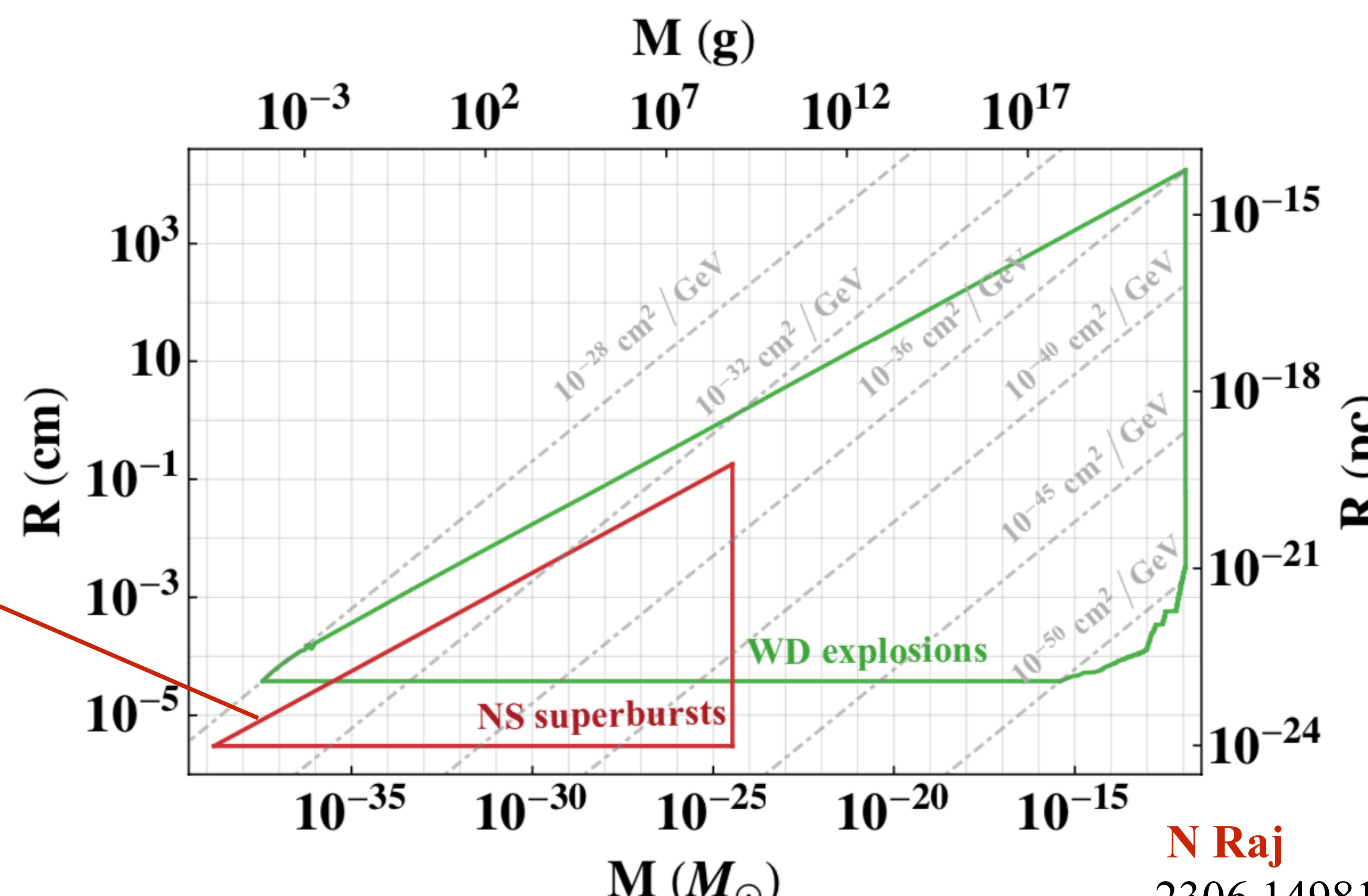
hours-long, $\mathcal{O}(10^{42})$ erg

$10^3 \times$ regular bursts

$\Gamma_{\rm accret} > 0.1\ \dot{M}_{\rm Edding}$

at C "ocean" layer of NS

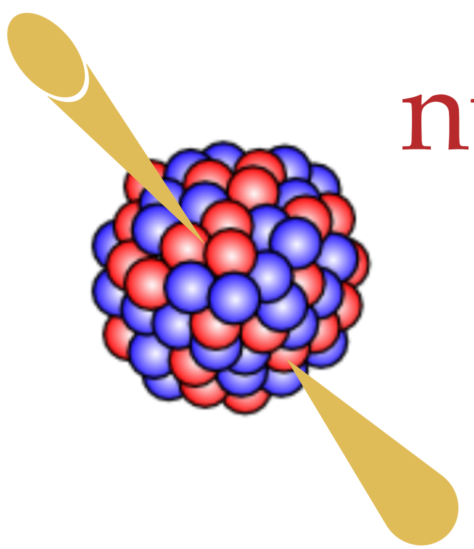
superburst	r (kpc)	$t_{\rm recur}$ (yr)
4U 1820+30	1.2	2.5 [23]
4U 0614+091	11.5	4.8 [28]
GX 17+2	2.4	1 [28]
4U 1636−536	5.3	1 [99]
Ser X−1	5	1 [99]
Aql X−1	5	1 [99]



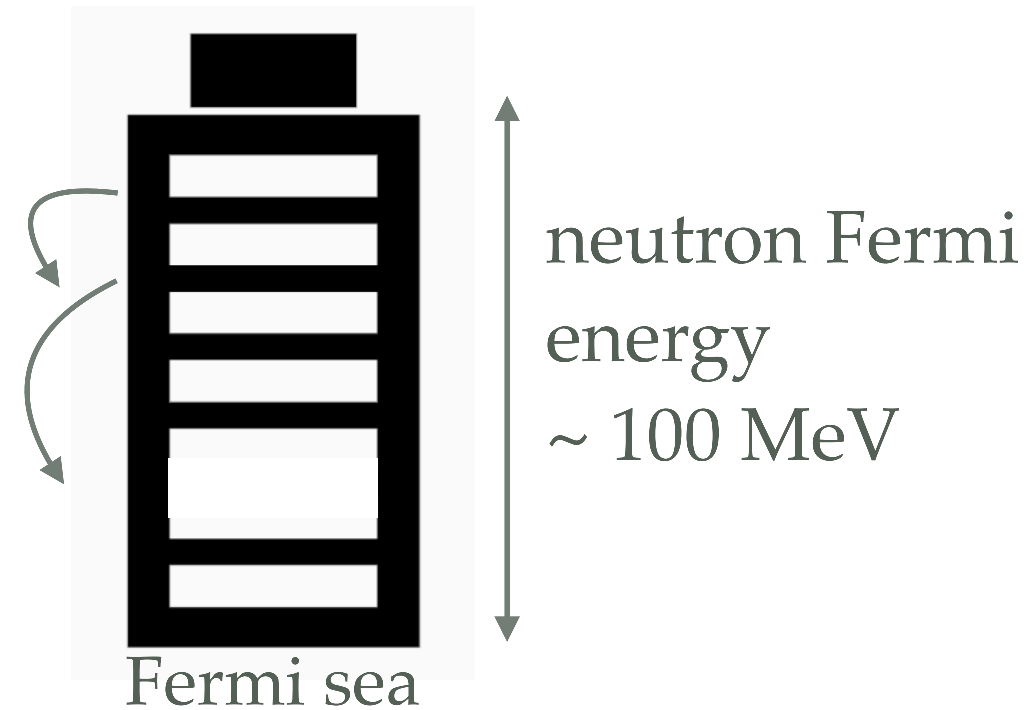
N Raj
2306.14981

Neutron stars = Pauli batteries

new heating mechanism:
nucleon "Auger effect"



$$n \to \chi + \underline{anything}$$
$$n\ n \to n\ \chi$$
$$p\ n \to p\ \chi$$



χ: "dark neutron" that mixes with neutron

10^{57} neutrons
+
10^{56} protons

=>

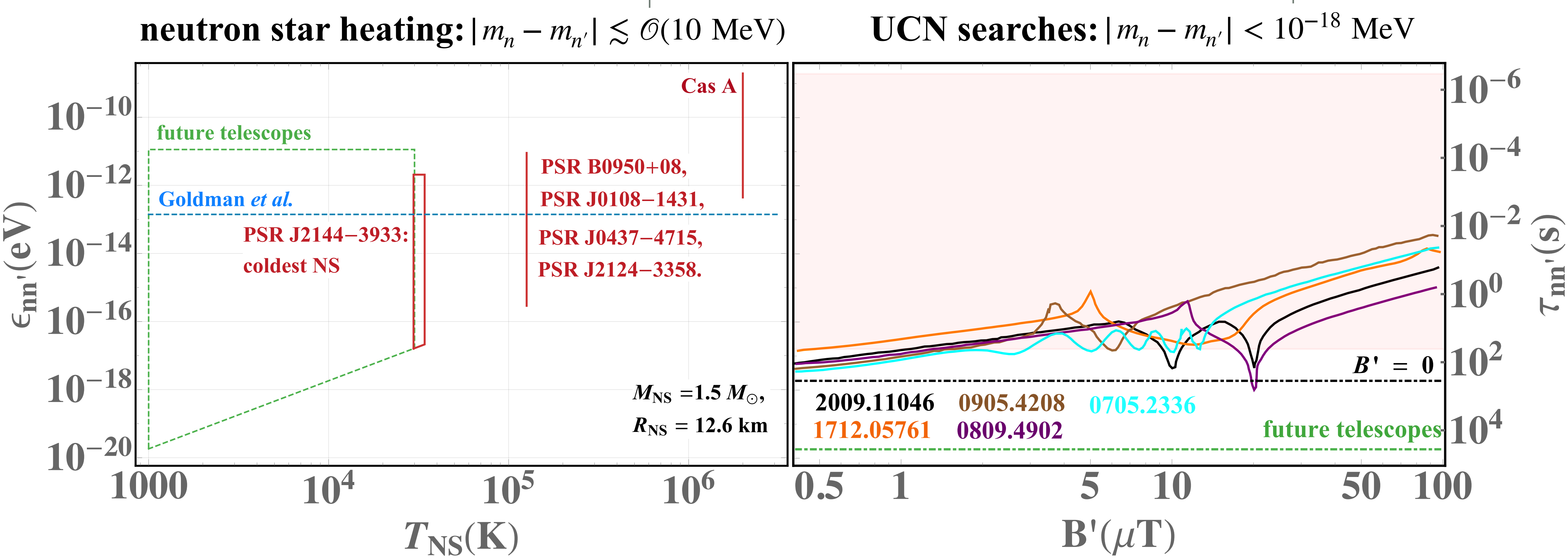
explosive liberation of energy!

PRL 2021 *McKeen, Pospelov,* Raj

Constraints: NS heating

NS energy per baryon

Zeeman from Earth's B field



[hypothetical mirror B field]

Many roads to be built/explored…

topological defect DM

Thorne-Zytkow objects

BEC, BCS states

Type Ia nuclear reaction network

+ *tons more!*

THANK YOU!

QUESTIONS?

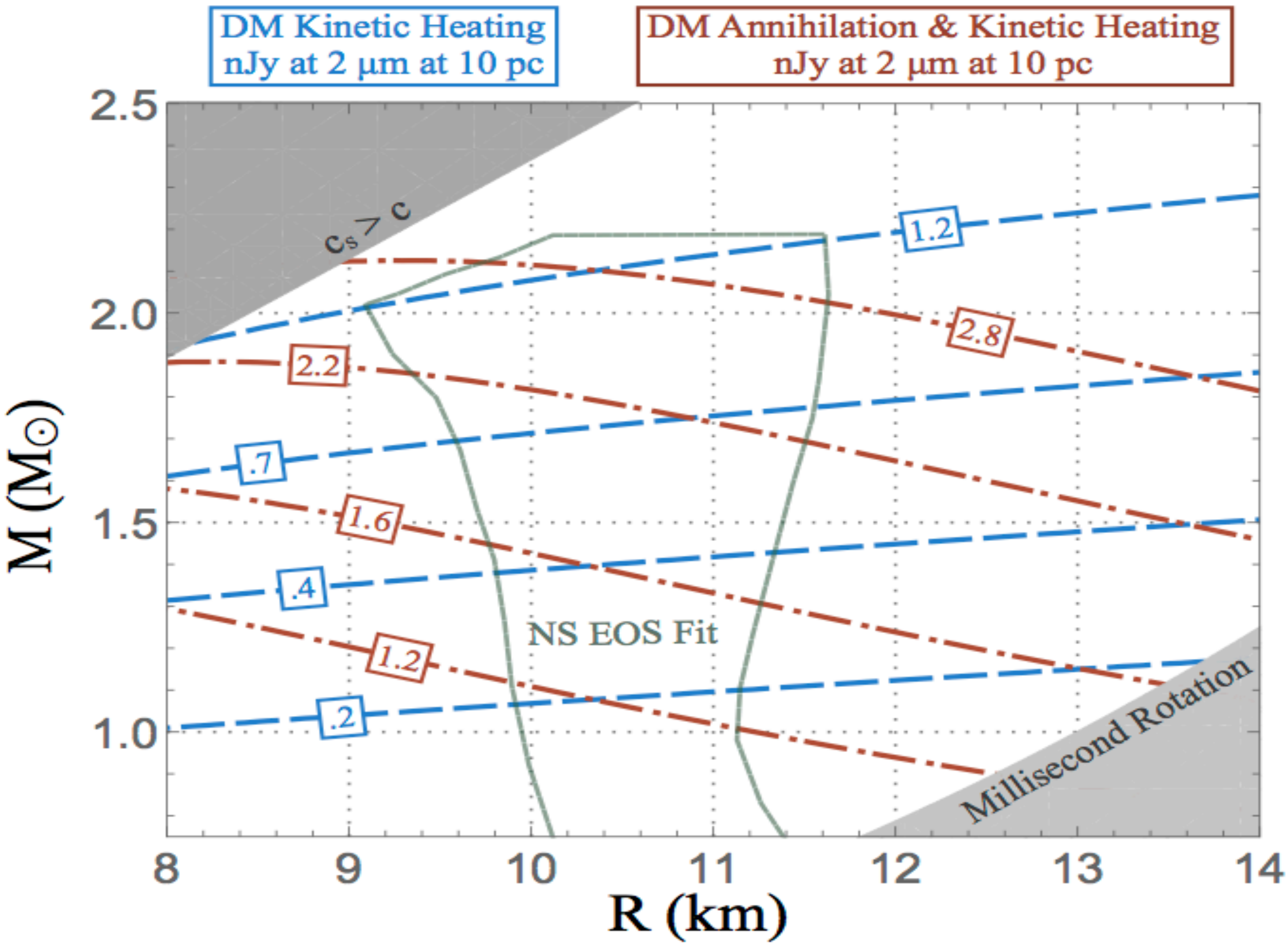
Brightness diagnosis

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

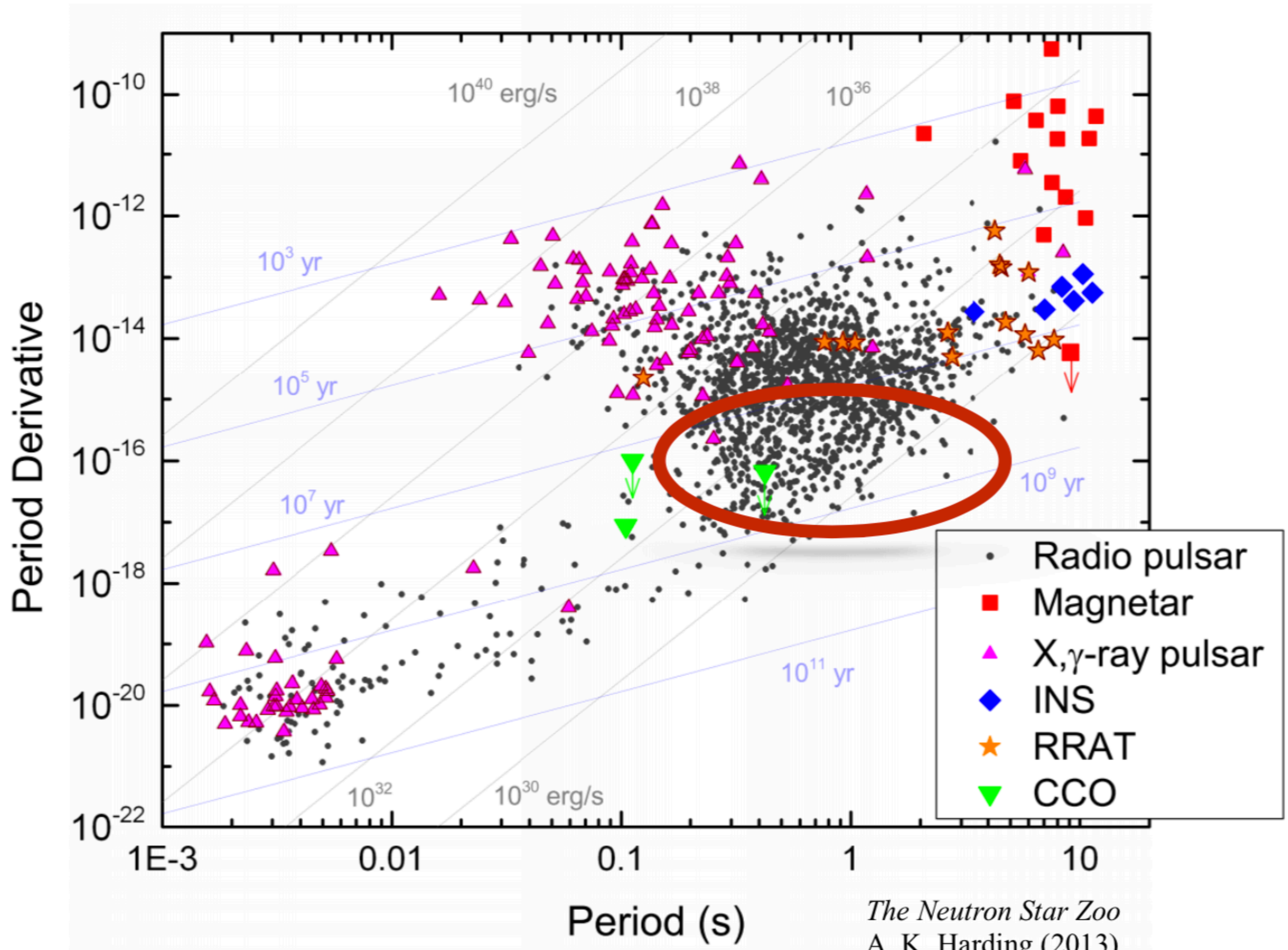
$$\left(\gamma = \frac{1}{\sqrt{1-2GM/R}}\right)$$

kinetic heating

+ annihilation



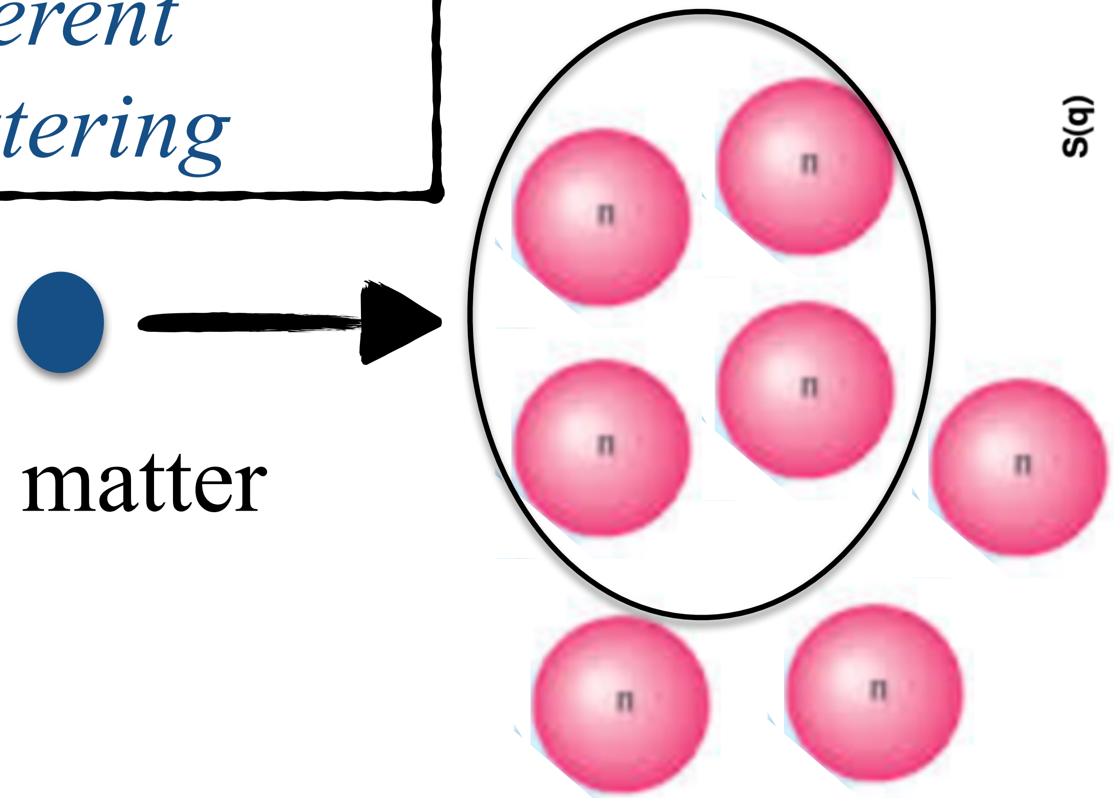
Detection: radio pulsing



The Neutron Star Zoo
A. K. Harding (2013)

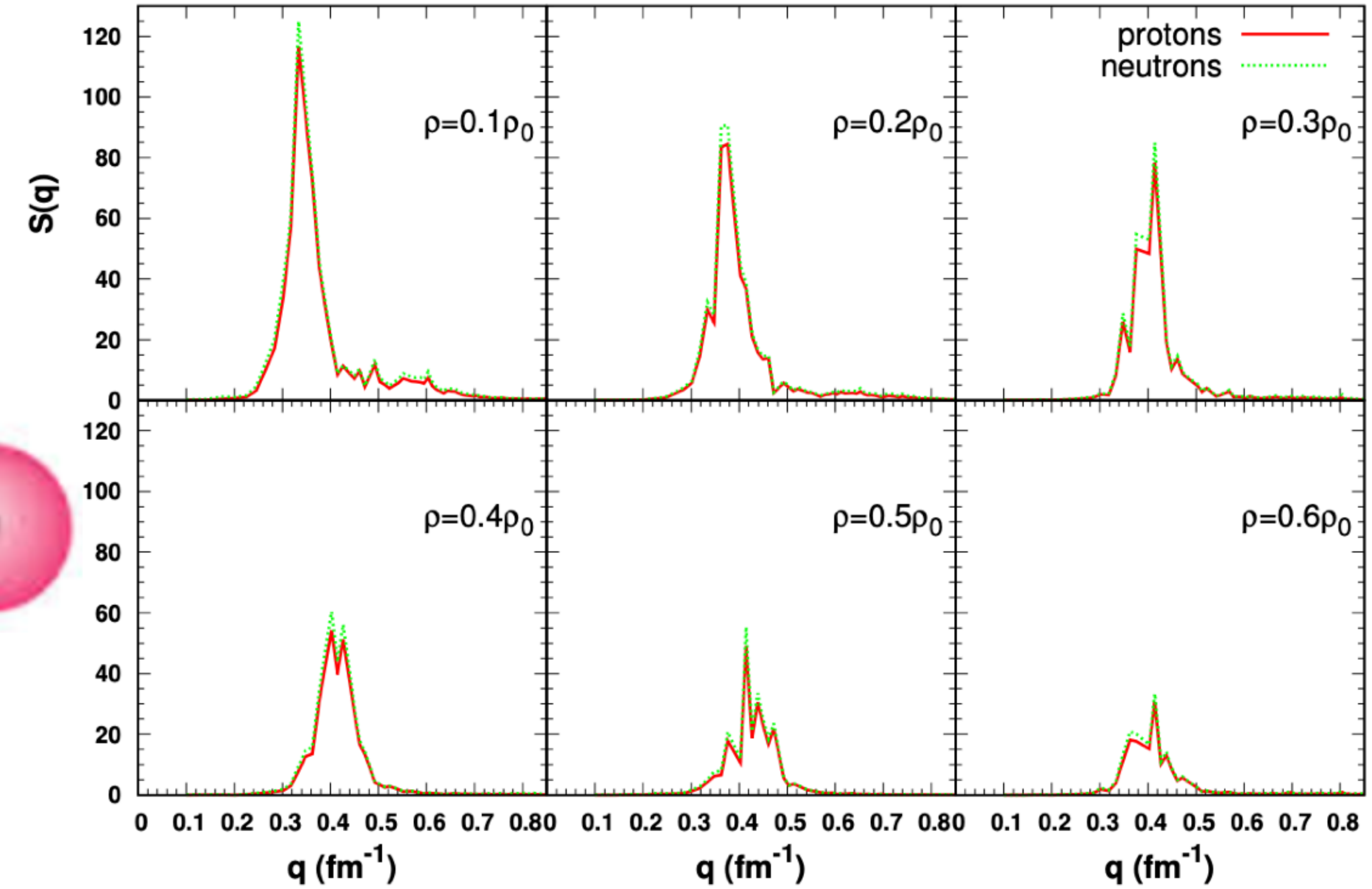
Scattering on pasta

low momenta: coherent scattering



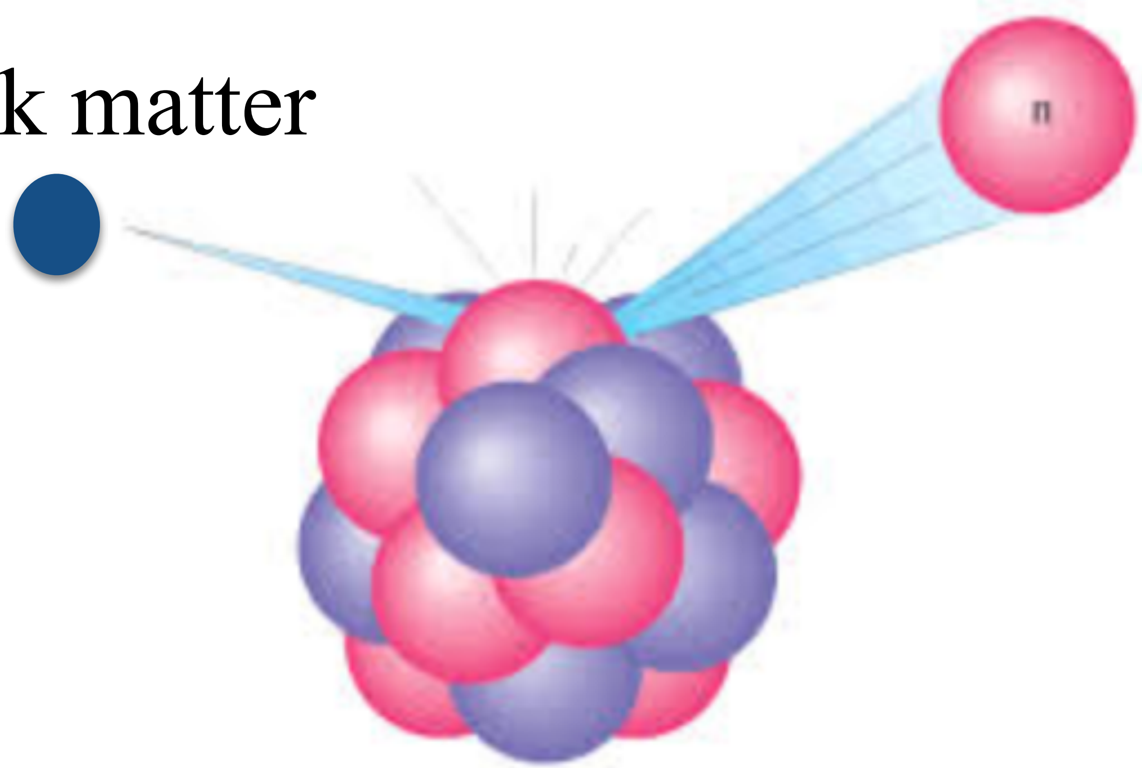
dark matter

response functions Nandi & Schramm (2017)



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

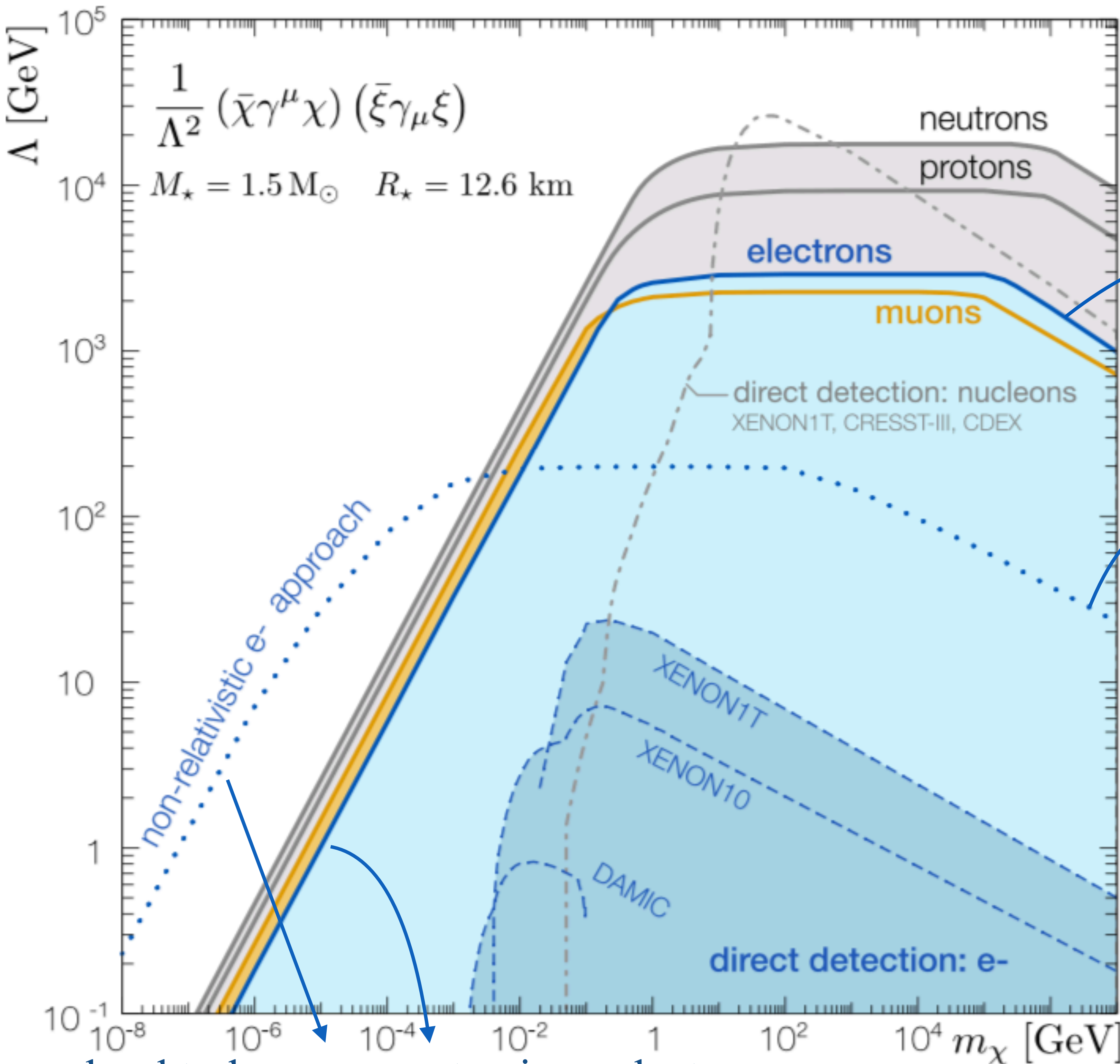
dark matter



high momenta: quasi-elastic scattering

N Raj, *J Acevedo, J Bramante, R Leane*
JCAP (2020)

"Electron star" dark matter detection



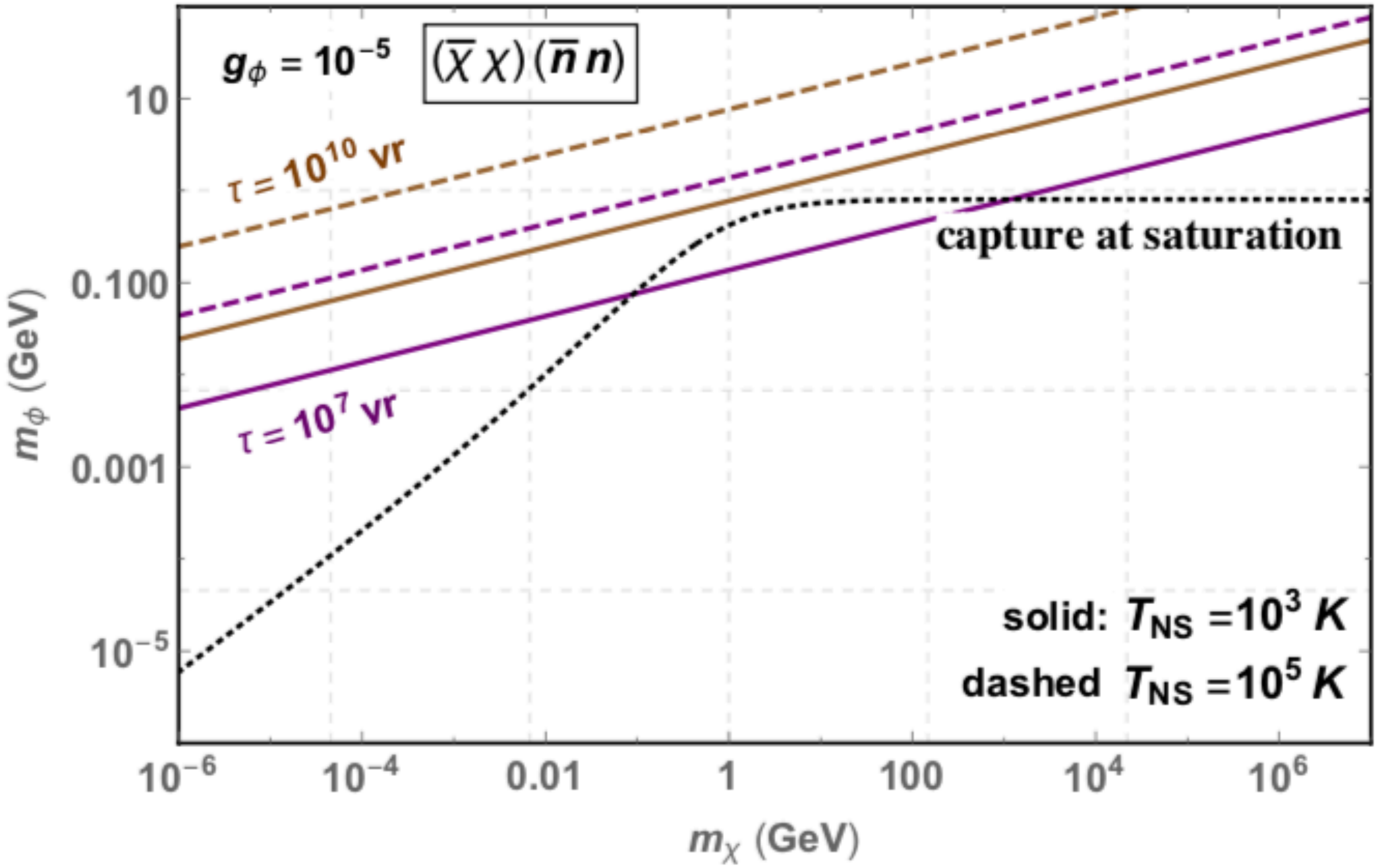
cross section ∝ Fermi energy² [(150 MeV)²]

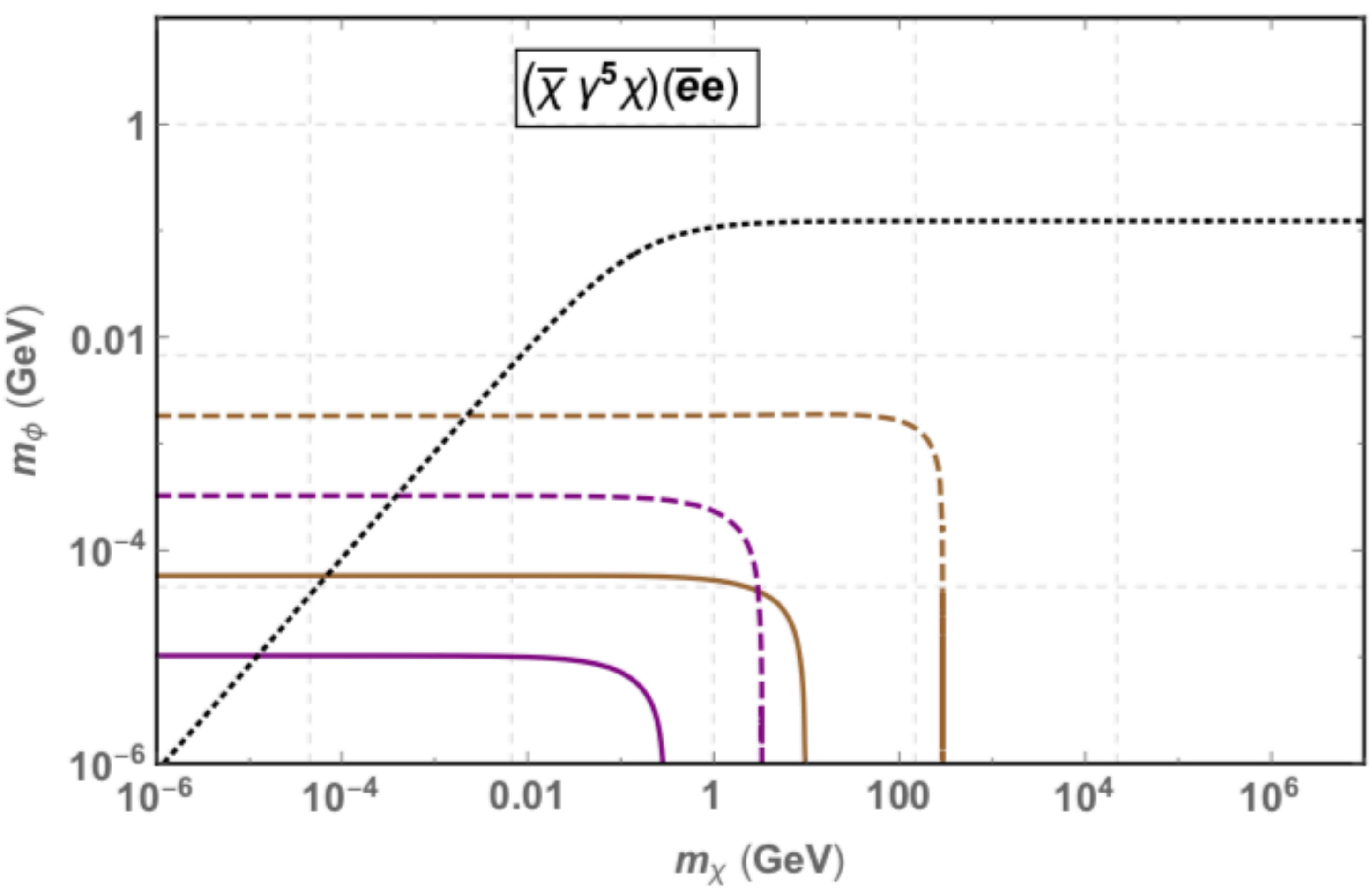
cross section ∝ electron mass² [(0.5 MeV)²]

hard to lose energy to zippy electrons

A Joglekar, **N Raj**, *P Tanedo, H-B. Yu*
Phys. Lett. B (2020) & Phys. Rev. D (2020)

Thermalization vs capture





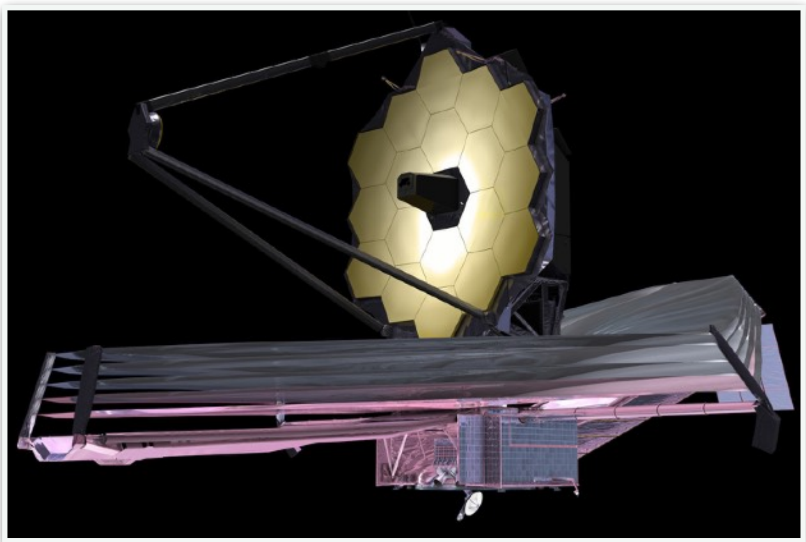
R Garani, A Gupta, **N. Raj**
Phys. Rev. D. (2021)

Detection: infrared telescopes

T = **1750 Kelvin** (infrared emission)

backup

Peak wavelength: $1.65\ \mu\mathrm{m}$



James Webb

Thirty Meter

	James Webb	Thirty Meter
Imager	NIRCam	IRIS
Filter	F200W	K-band
	$1.75 - 2.2\ \mu\mathrm{m}$	$2.0 - 2.4\ \mu\mathrm{m}$
Observ. time for 2σ sensitivity	$10^5\ \mathrm{sec}\left(\frac{d}{10\mathrm{pc}}\right)^4$	$7\times10^4\ \mathrm{sec}\left(\frac{d}{10\mathrm{pc}}\right)^4$

Dark neutrons: an introduction

hypothesis: a new particle "χ"

its character:
- 0 : charge under all fundamental forces
- $1/2$: spin
- 1 : baryon number

James Chadwick

It's called a neutron.
N. E. U. T. R. O. N.,
neutron.

also $\Lambda^0, \Sigma^0, \Delta^0, \ldots$

neutron

"dark" neutron (hidden)

n $\quad\quad$ χ

m_n $\quad\quad$ m_χ

939.5654 MeV/c^2 $\quad\quad$?

Hamiltonian

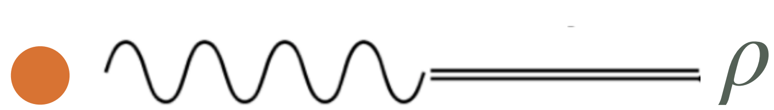
$$\begin{pmatrix} \bar{m}_n & \epsilon_{n\chi} \\ \epsilon_{n\chi} & \bar{m}_\chi \end{pmatrix}$$

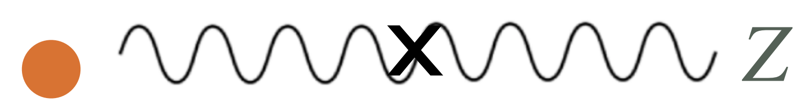
$\epsilon_{n\chi}$ nothing forbids it: compulsory!

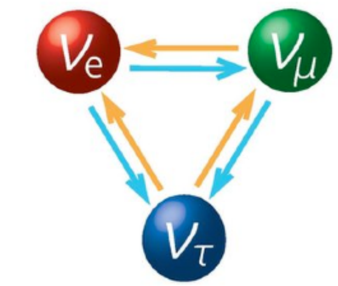
=>

quantum mixing

quantum mixing already seen in Nature:



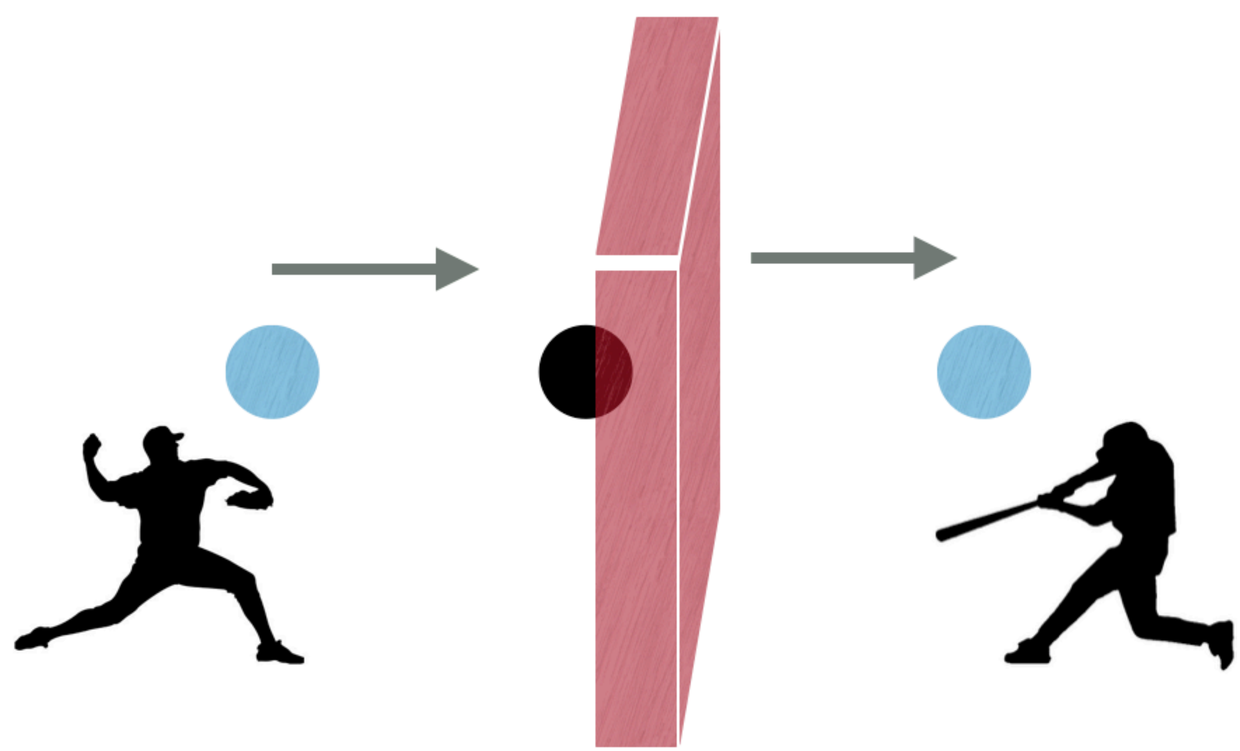




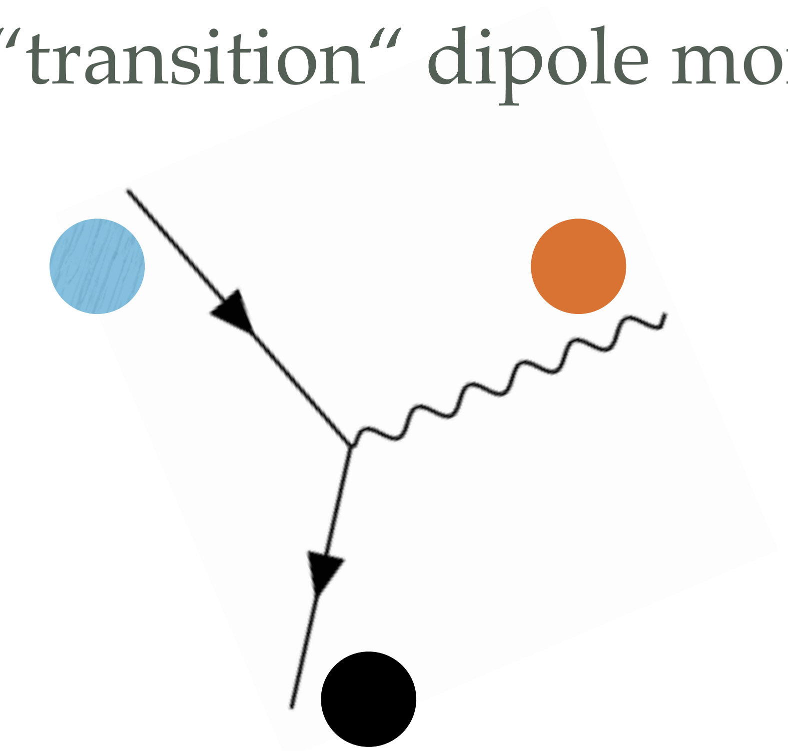
photon - rho meson | photon - Z boson | neutrino flavours

Consequences for neutrons

oscillations



magnetic “transition“ dipole moment



Constraining neutron conversions

heating rate

$$\int_{\mathrm{NS}} d^3r \, n_n(\mathbf{r}) \dot{E}_{n'}(\mathbf{r})$$

neutron number density

energy release rate

$$\leq$$

cooling rate
(blackbody emission)

$$4\pi R_{\mathrm{NS}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{NS}}^4$$

Conversions to dark neutrons

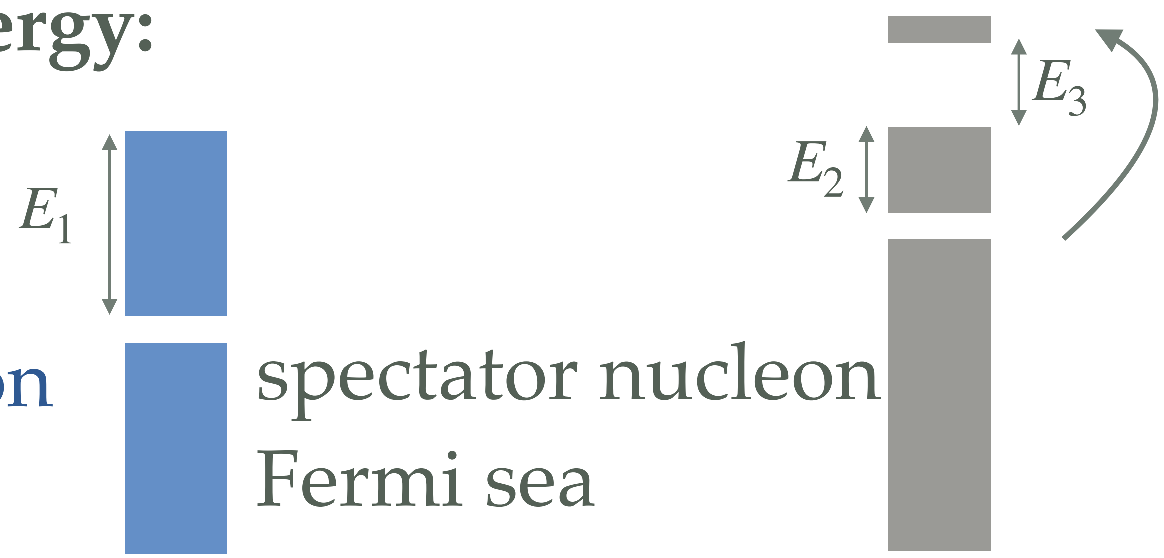
symmetry factor — neutron chemical potential*

$$\dot{E}_{n'} = \sum_{N=n,p} f_N n_N \left\langle \left(\tilde{\mu}_n - \frac{p_{n'}^2}{2m_{n'}}\right)\sigma_{n'N} v \right\rangle_{p_N > p_{F_N}}$$

energy release rate — number density* — Pauli blocking condition

3 sources of energy:

scattering neutron Fermi sea



Amusement

proton spectators
(~ 10% of NS nucleons
supply more heat!
less Pauli-blocked,
greater cross section

* determined from high-density equation of state + NS mass & radius,
in practice used Brussels-Montreal BSk24 with $M_{NS} = 1.5\ M_\odot$, $R_{NS} = 12.6$ km

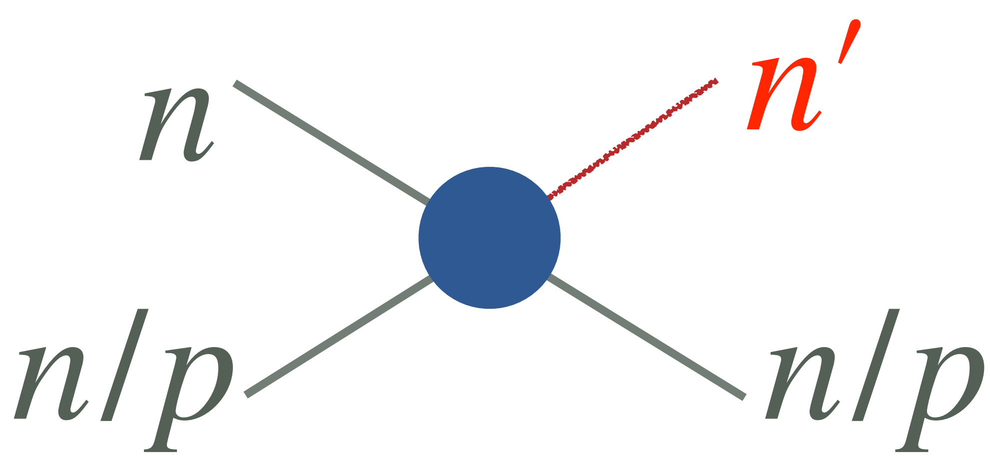
Conversions to dark neutrons

medium-dependent splitting

$$H = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_{n'} \end{pmatrix}$$

e.g. neutron star nuclear self-energies, 10—100 MeV

$$\sigma_{n'N} \simeq g_N \left(\frac{\epsilon_{nn'}}{\Delta E}\right)^2 \sigma_{nN\to nN}$$



$$\sigma_{nn\to nn} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} \sin^2\delta_S,$$

$$\sigma_{np\to np} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} \left(\sin^2\delta_S + 3\sin^2\delta_T\right)$$

energy-dependent phase shifts from nuclear potential models (https://nn-online.org/)