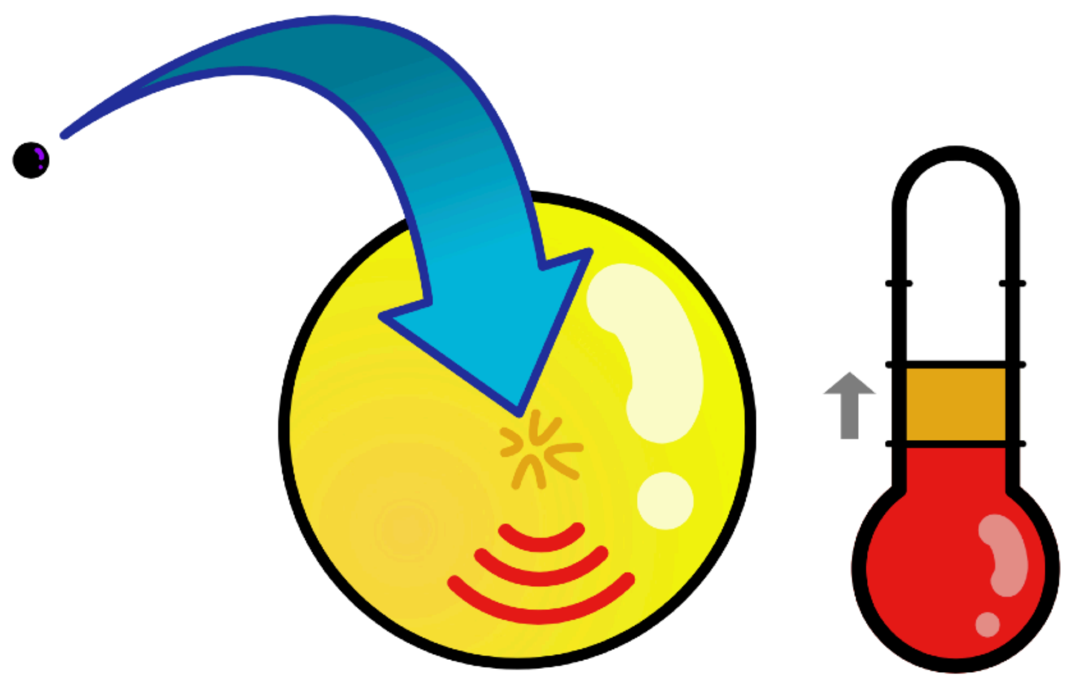
Nucleons, Electrons, and Pasta:
Discovering Dark Matter by Reheating the Neutron Star Soup



Nirmal Raj

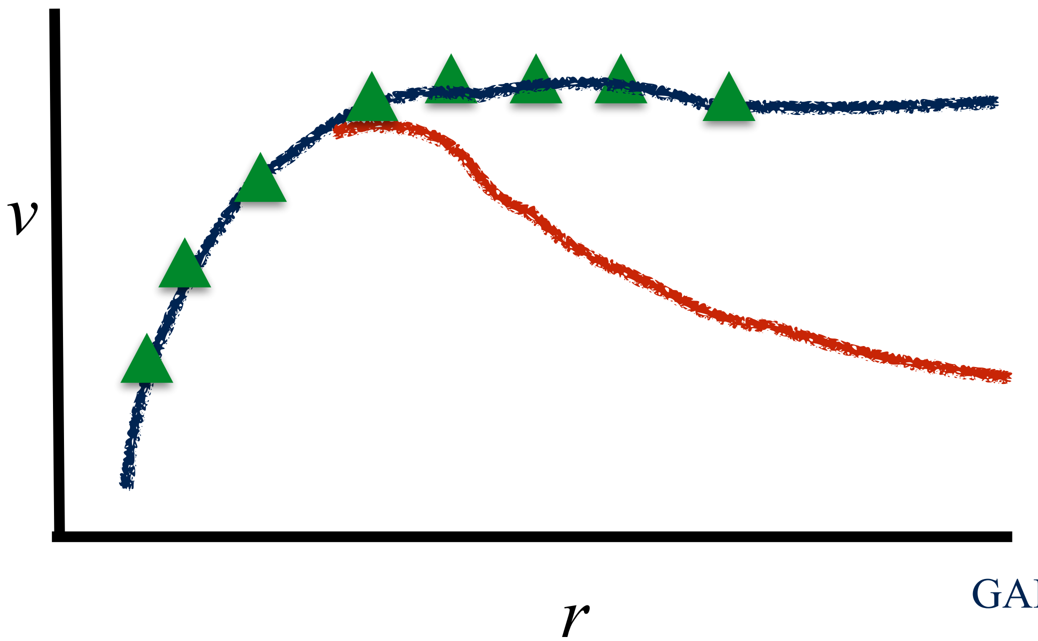
TRIUMF

with

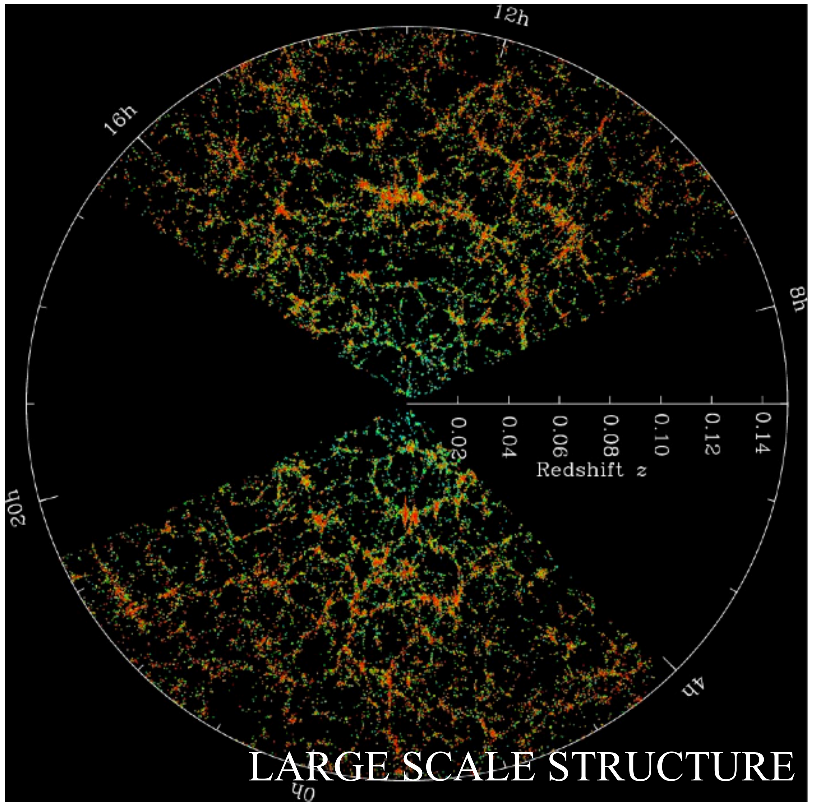
Javier Acevedo | Masha Baryakhtar | Joe Bramante | Aniket Joglekar
Rebecca Leane | Shirley Li | Tim Linden | Flip Tanedo | Hai-Bo Yu

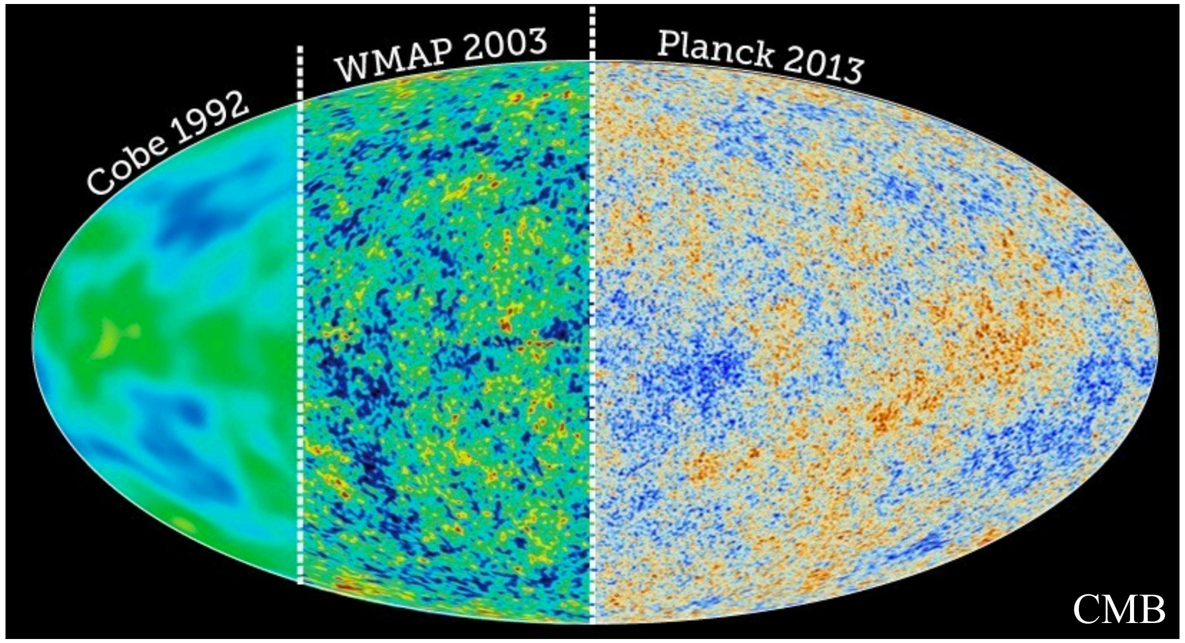
09/10 Jun 2020, Kavli IPMU

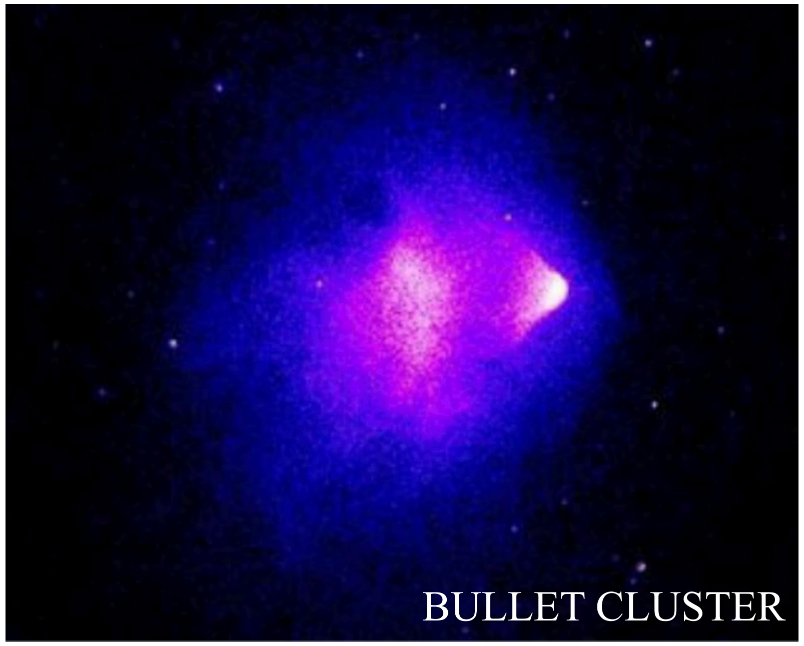
Dark reality



GALACTIC ROTATION

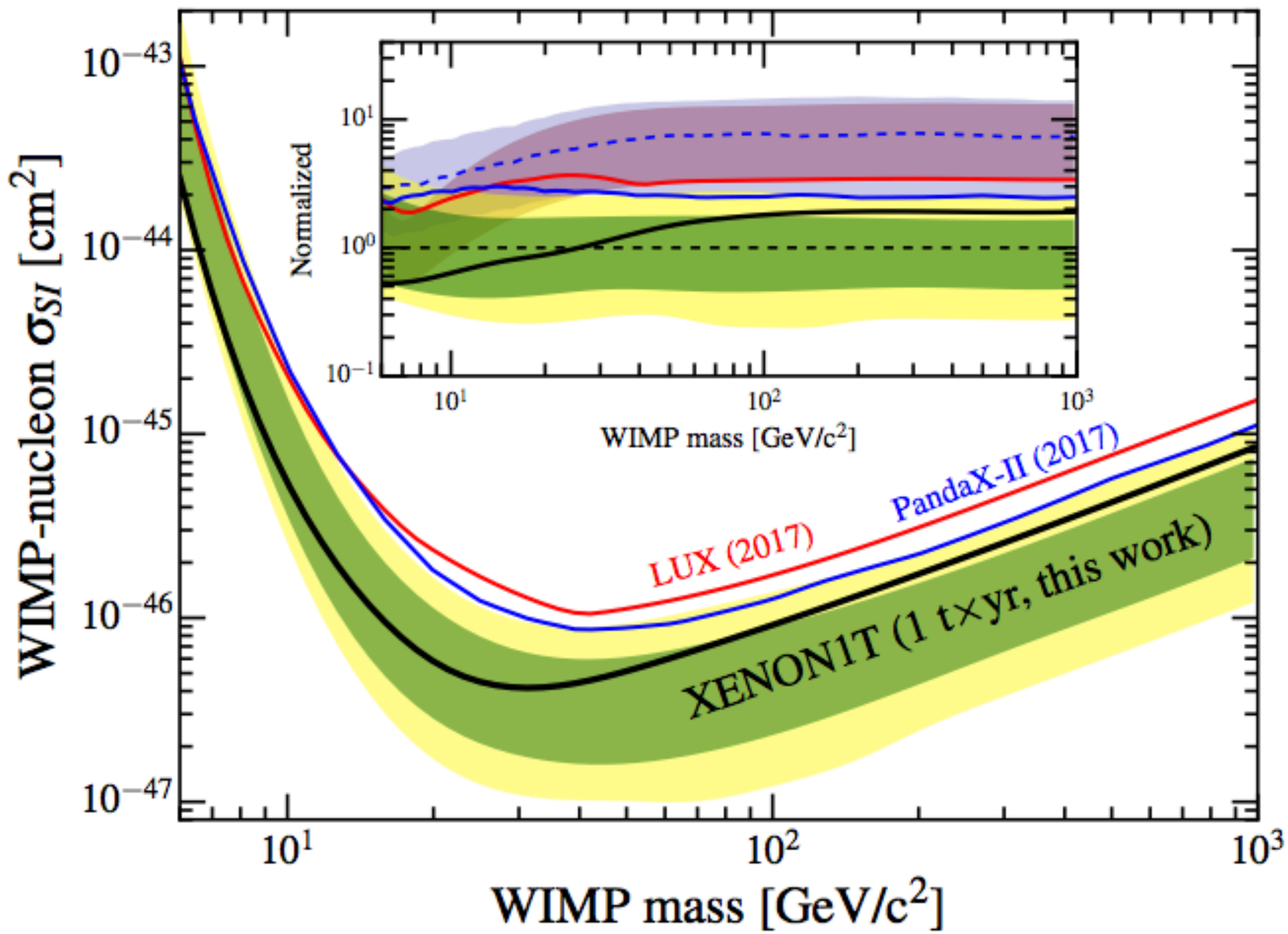




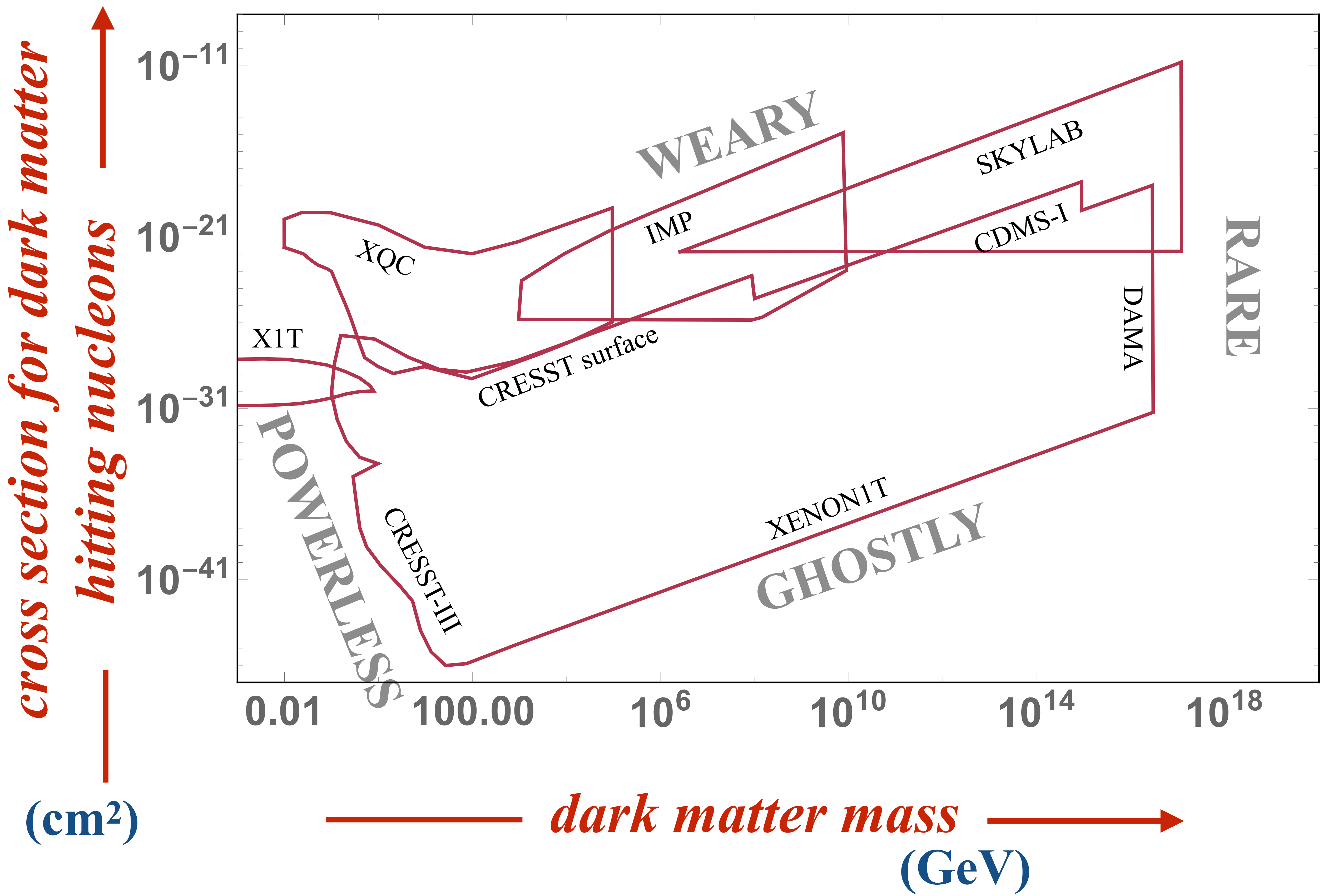


After 1000 kg-year exposure:

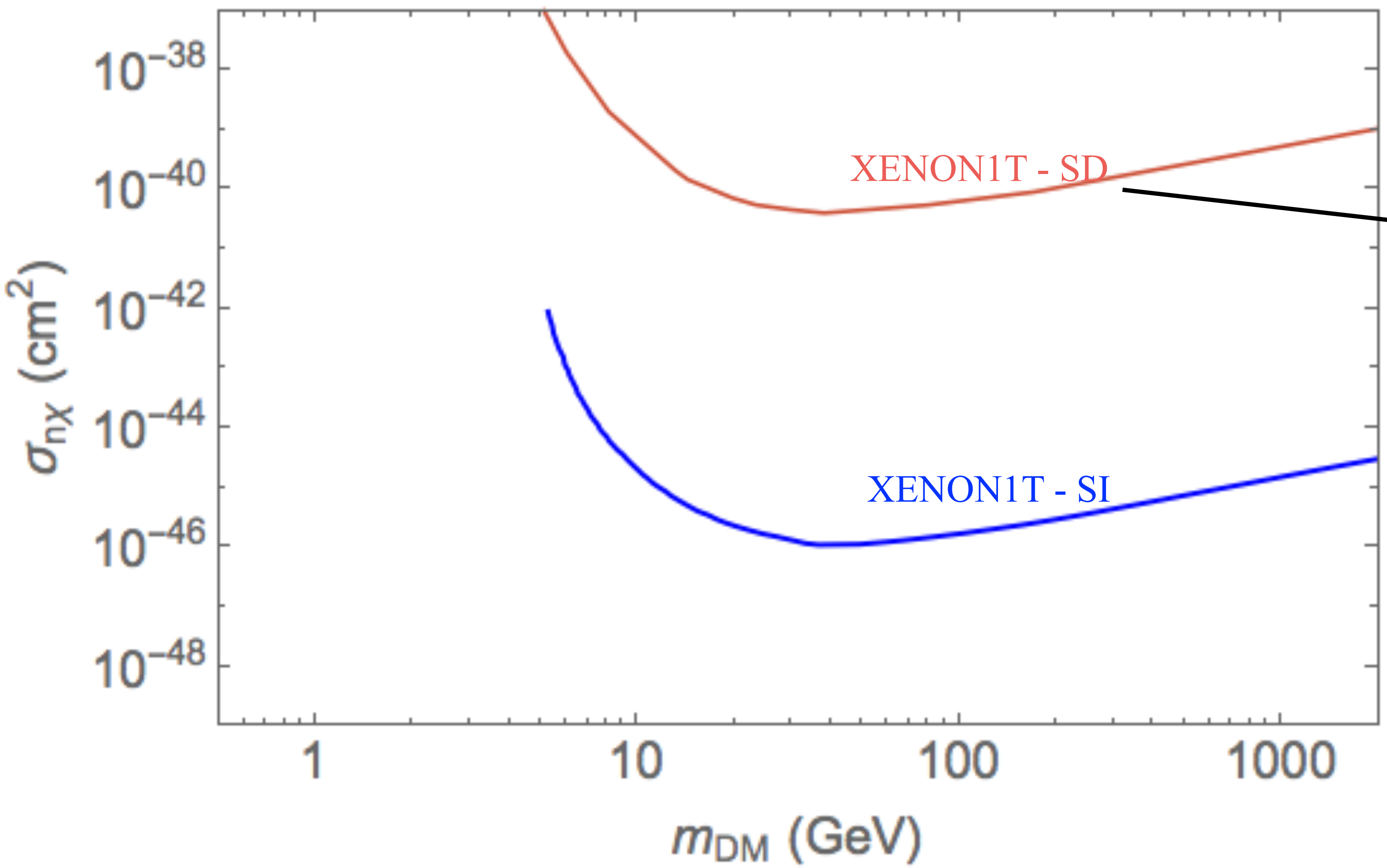
1805.12562



Challenges of direct searches



More challenges: spin dependence

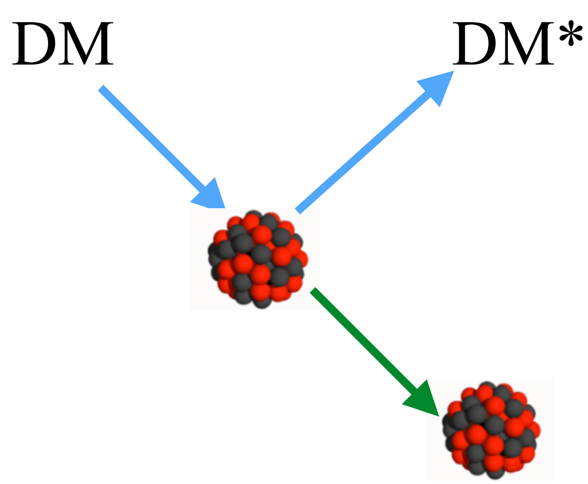


No nuclear coherence
if scattering spin-dependent:

$$\sigma_{\rm nucleon} = \left(\frac{1}{A}\right)^2 \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \sigma_{\rm Nucleus-DM}$$

E.g. (Majorana) DM coupling to axial quark current $\bar{q}\gamma_\mu\gamma_5 q$

More challenges: inelasticity



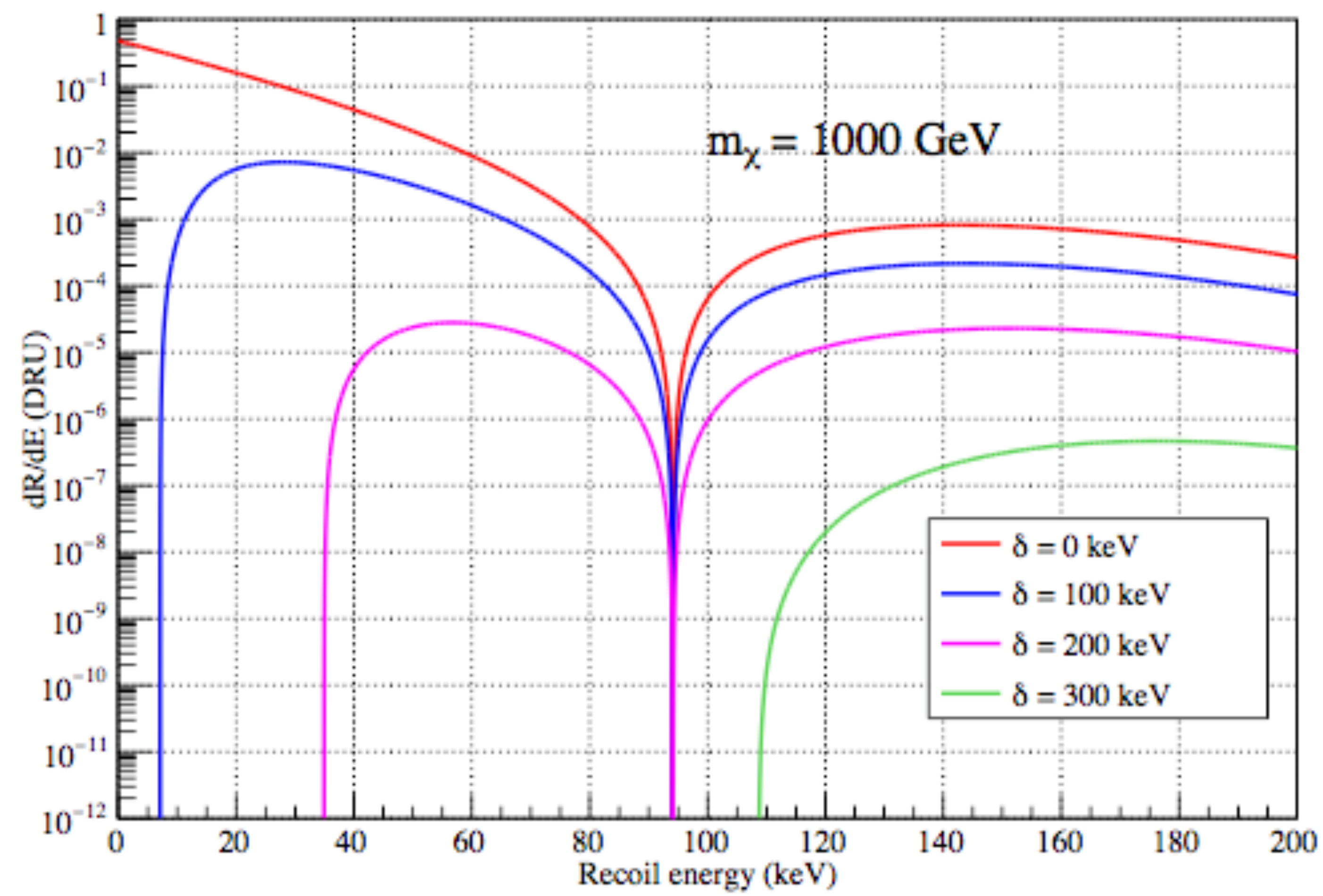
$$\delta \equiv m_{\mathrm{DM}^*} - m_{\mathrm{DM}}$$

(Image: G. Kribs)

If scattering <u>inelastic</u>,
no recoil when

$$\delta > 2\mu_{N\chi} v_{\mathrm{DM}}^2 = \mathcal{O}(100\mathrm{keV})$$

Tucker-Smith, Weiner 0101138, 0402065,
Barello, Chang, Newby 1409.0536



PandaX-II, 1708.05825

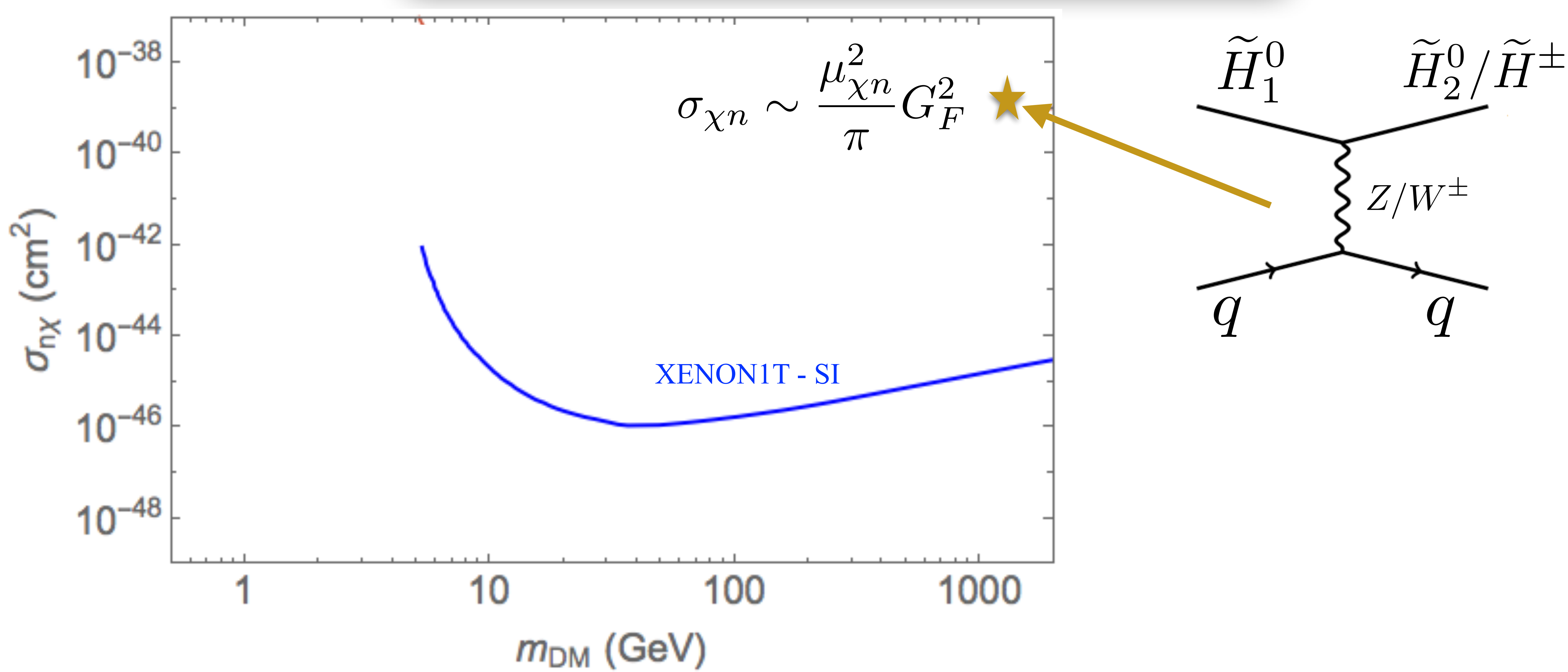
More challenges: inelasticity

Last Electroweak WIMP Standing

Pseudo-Dirac Higgsino Status and Compact Stars as Future Probes

Rebecca Krall and Matthew Reece
Department of Physics, Harvard University, Cambridge, MA, 02138

May 16, 2017



More challenges: inelasticity

Last Electroweak WIMP Standing

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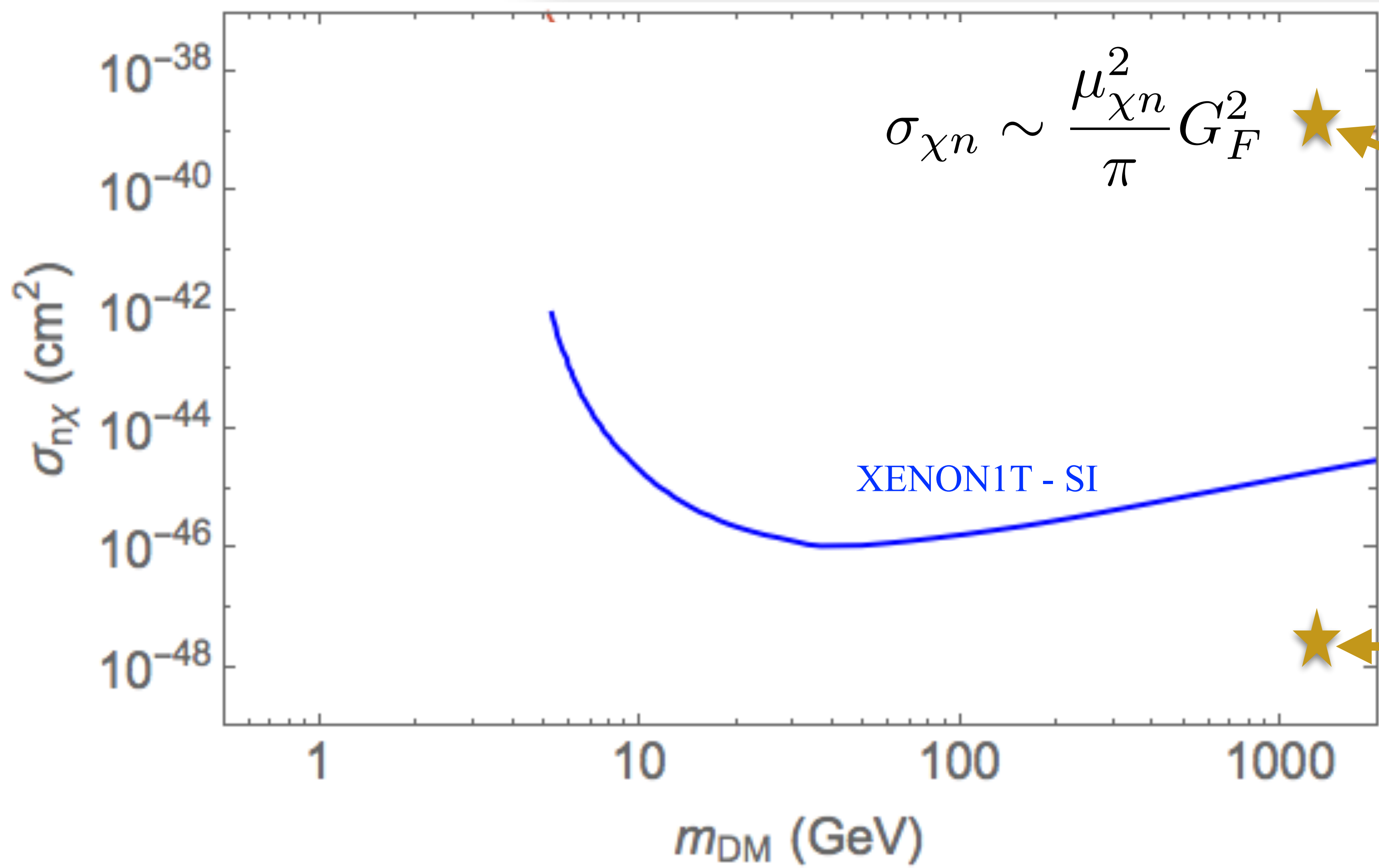
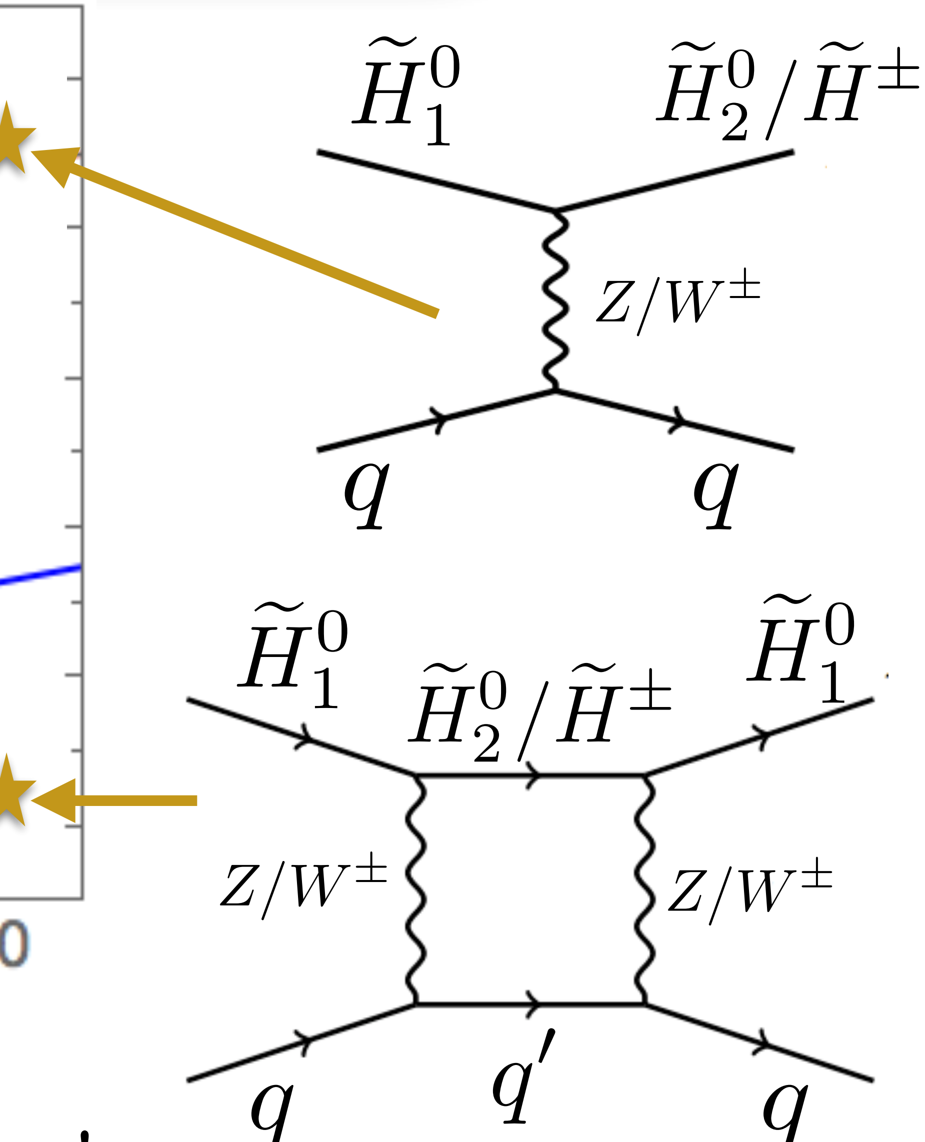
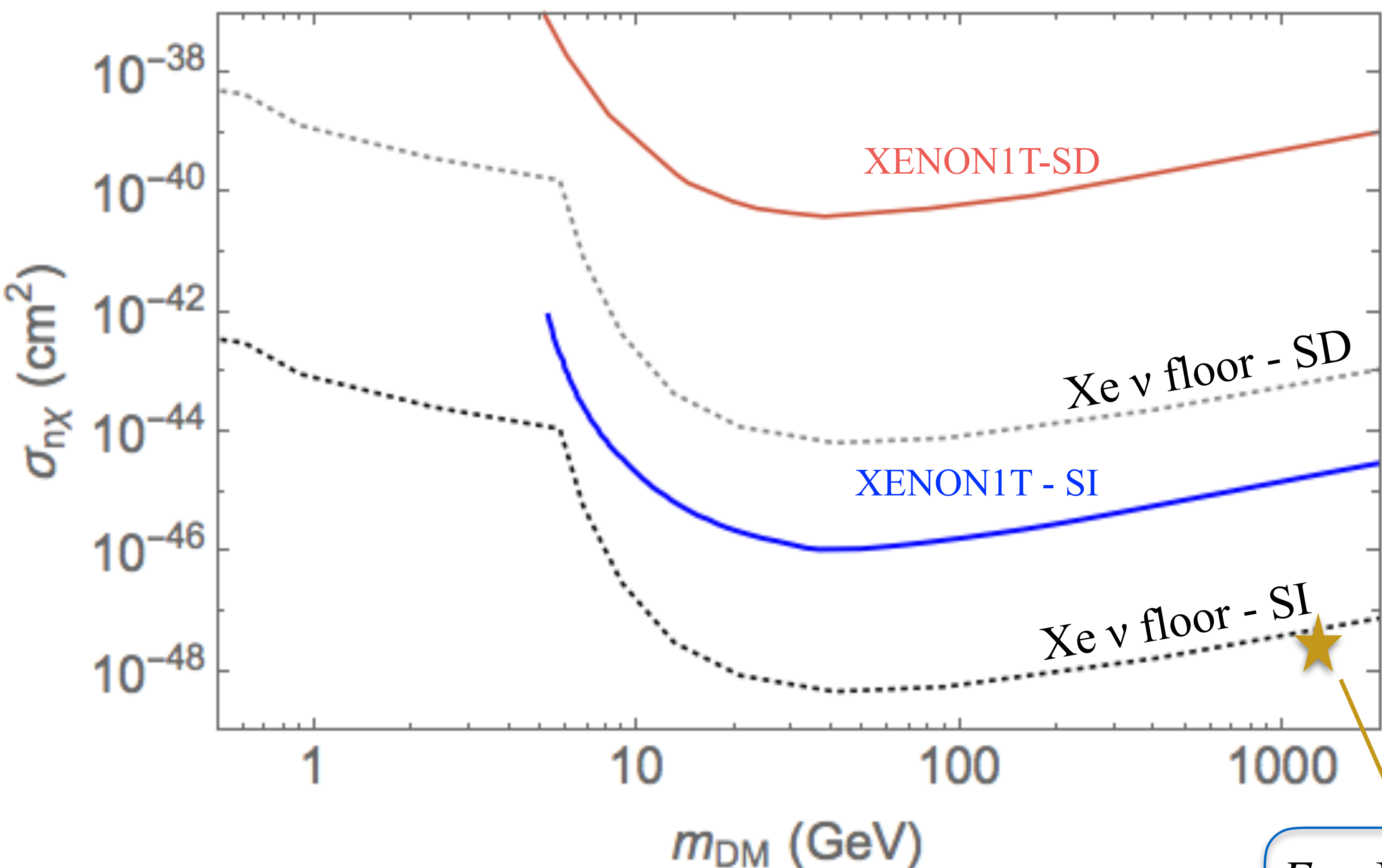




Thermal Higgsino — elusive!

Hill & Solon 1408.8290

More challenges: irreducible backgrounds



Atmospheric +
diffuse supernovae +
solar
<u>neutrino background</u>

E.g. Higgsino elastic scattering (loops)

Hill & Solon 1408.8290

Challenges: summary

(1) Low mass ✗
(2) High mass ✗
(3) Strongly interacting ✗
(4) Spin-dependent ✗
(5) Inelastic ✗
(6) Neutrino floors ✗

Crucial frontiers — beyond which dark matter could be.

(Dark) Kinetic Heating

heating rate = cooling rate

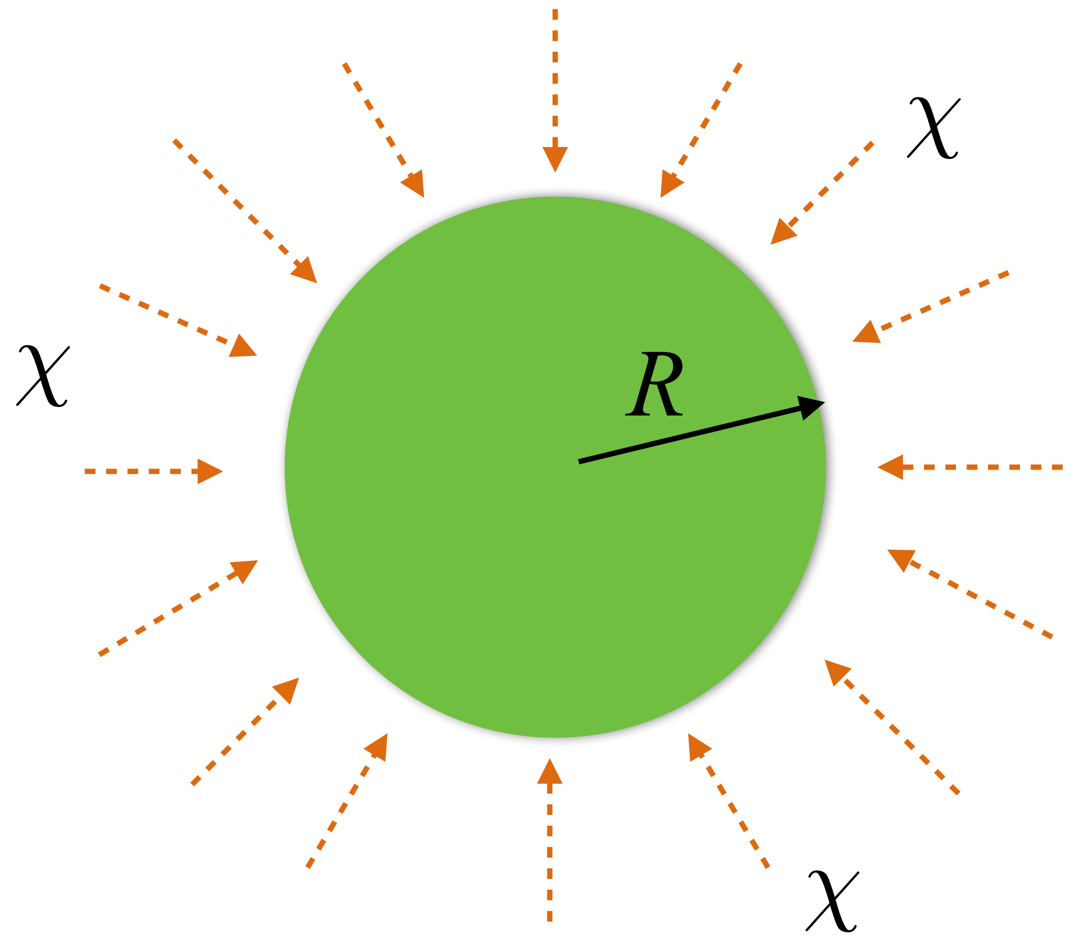
heating rate = cooling rate

$$\propto \mathrm{KE}$$

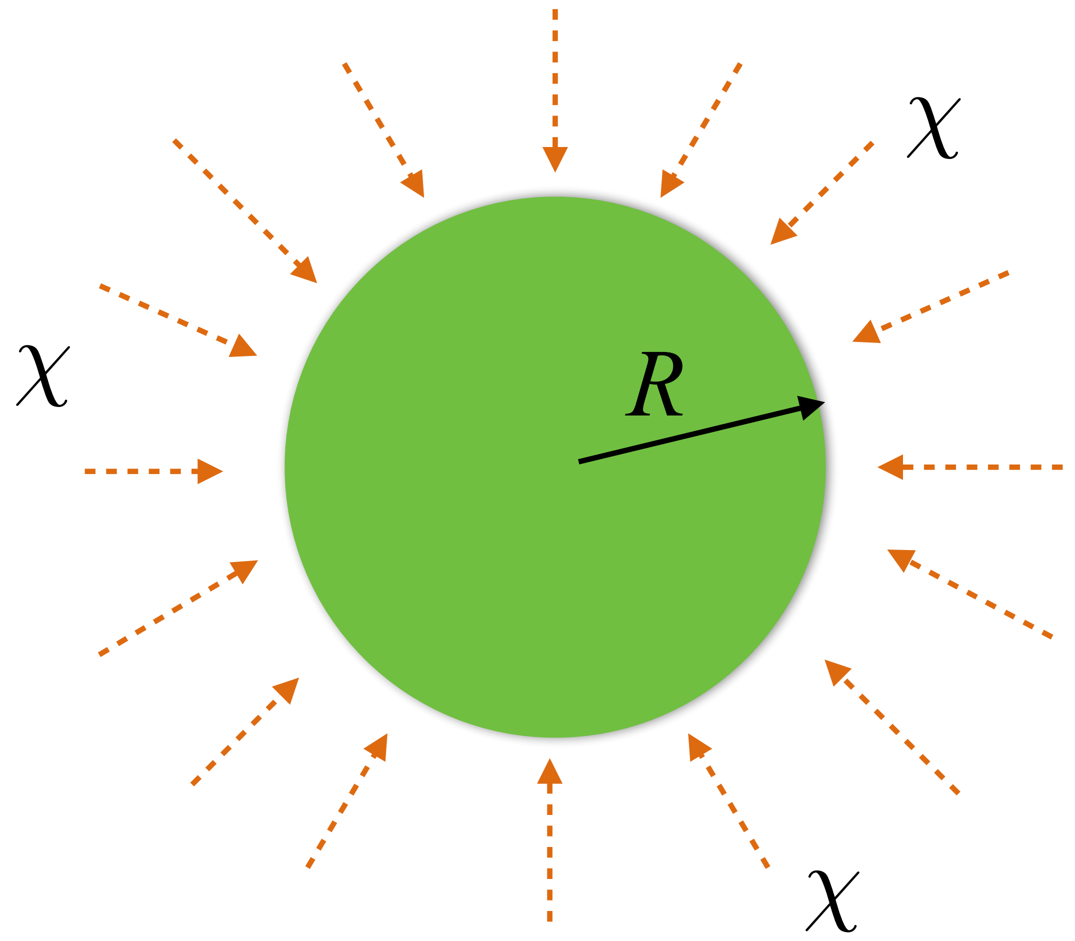
$$\propto \frac{dN}{dt}$$

$$\propto T^4$$

Dark fire



$$\text{heating rate} = \text{KE}_{\text{DM}} \times \frac{dN_{\text{DM}}}{dt}$$



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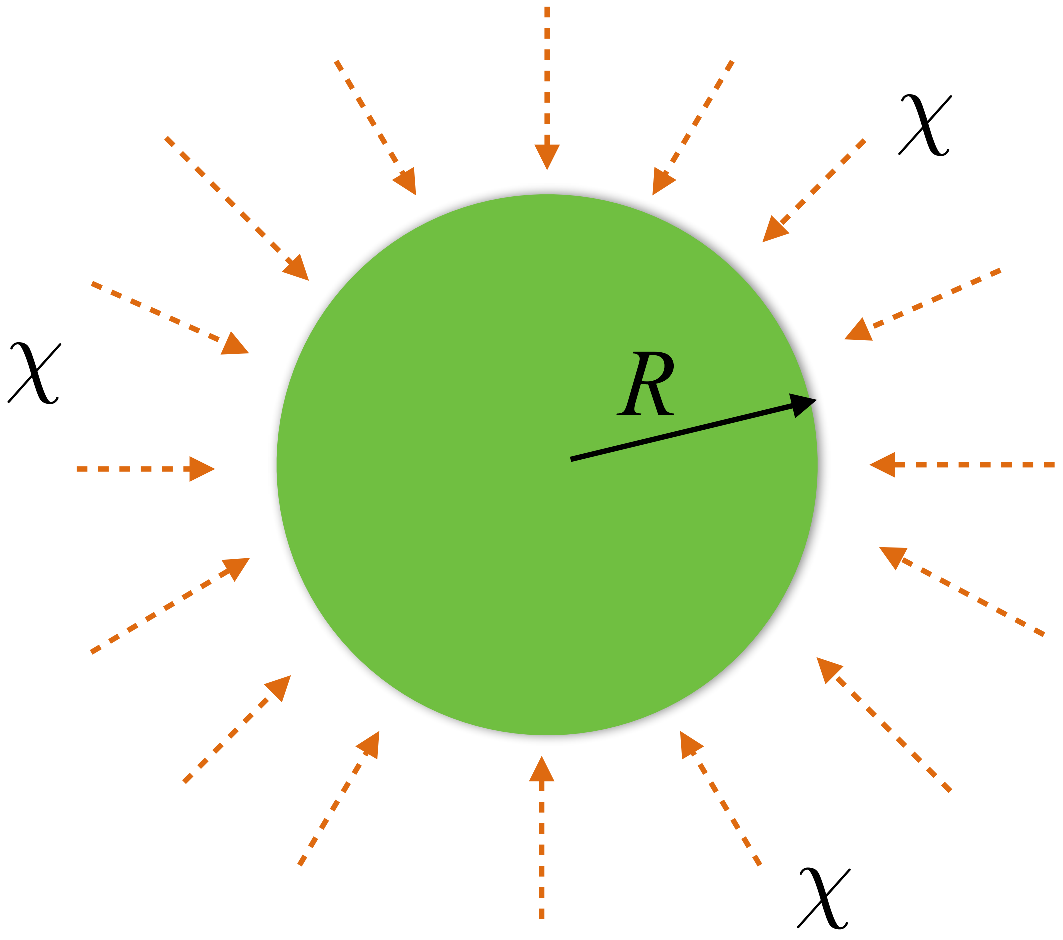


How hot can dark matter keep my soup?

$$\text{heating rate} = \text{KE}_{\text{DM}} \times \frac{dN_{\text{DM}}}{dt}$$

one hit per transit:

$$\frac{R}{\text{mean free path}} = \sigma n R = 1$$

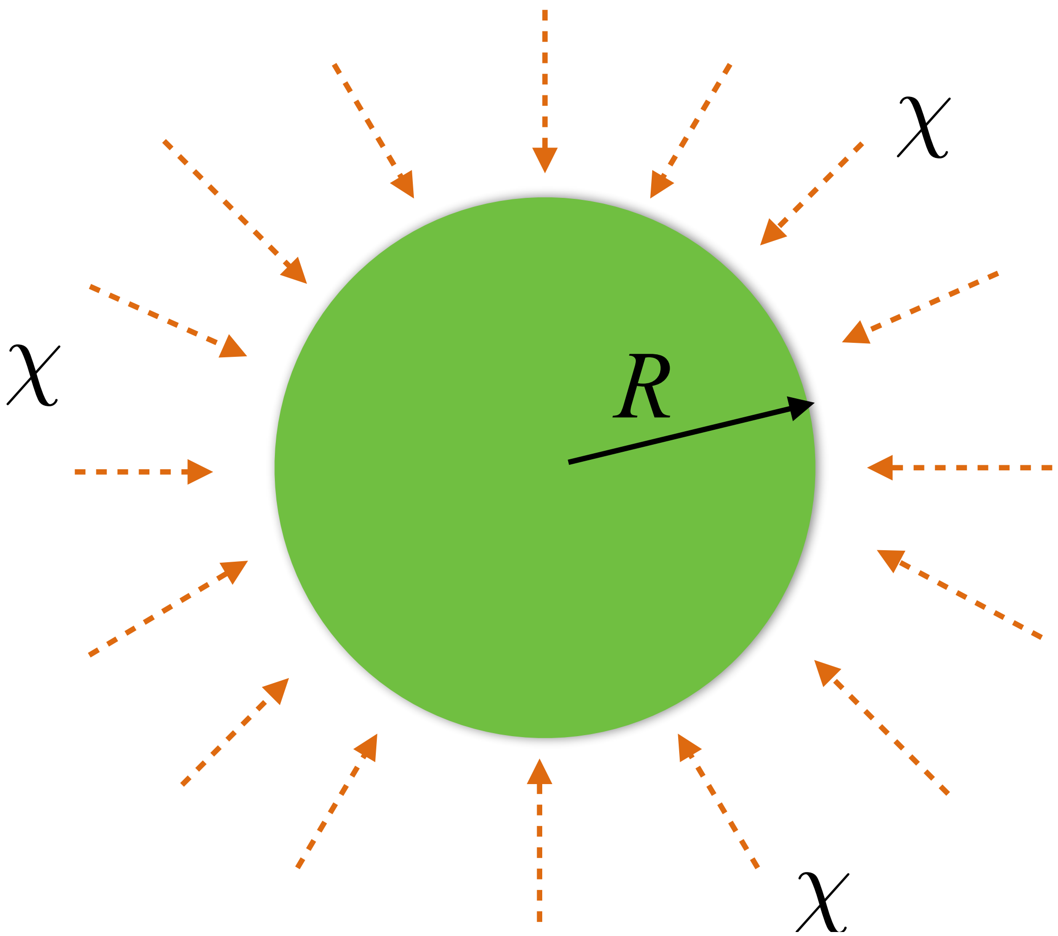
$$\sigma_{\text{threshold}} = \boxed{10^{-29}\ \text{cm}^2}$$

$$\text{heating rate} = \text{KE}_{\text{DM}} \times \frac{dN_{\text{DM}}}{dt}$$

mass drops out!

$$\frac{1}{2} m_{\text{DM}} (300\ \text{km/s})^2$$

$$\frac{0.3\ \text{GeV/cm}^3}{m_{\text{DM}}} \text{A}_{\text{soup}} (300\ \text{km/s})$$



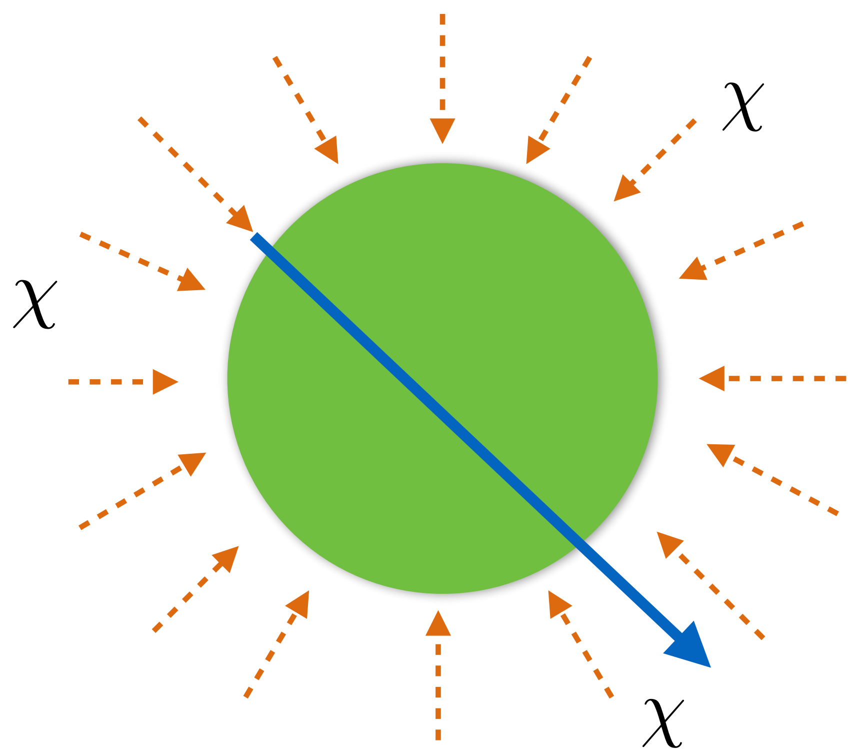
How hot can dark matter keep my soup?

$T = 0.003$ Kelvin

Need a better detector

better

$$\sigma_{\text{threshold}} = \frac{m_{\text{molec}}}{\rho_{\text{soup}} R_{\text{soup}}} = 10^{-29}\ \text{cm}^2$$

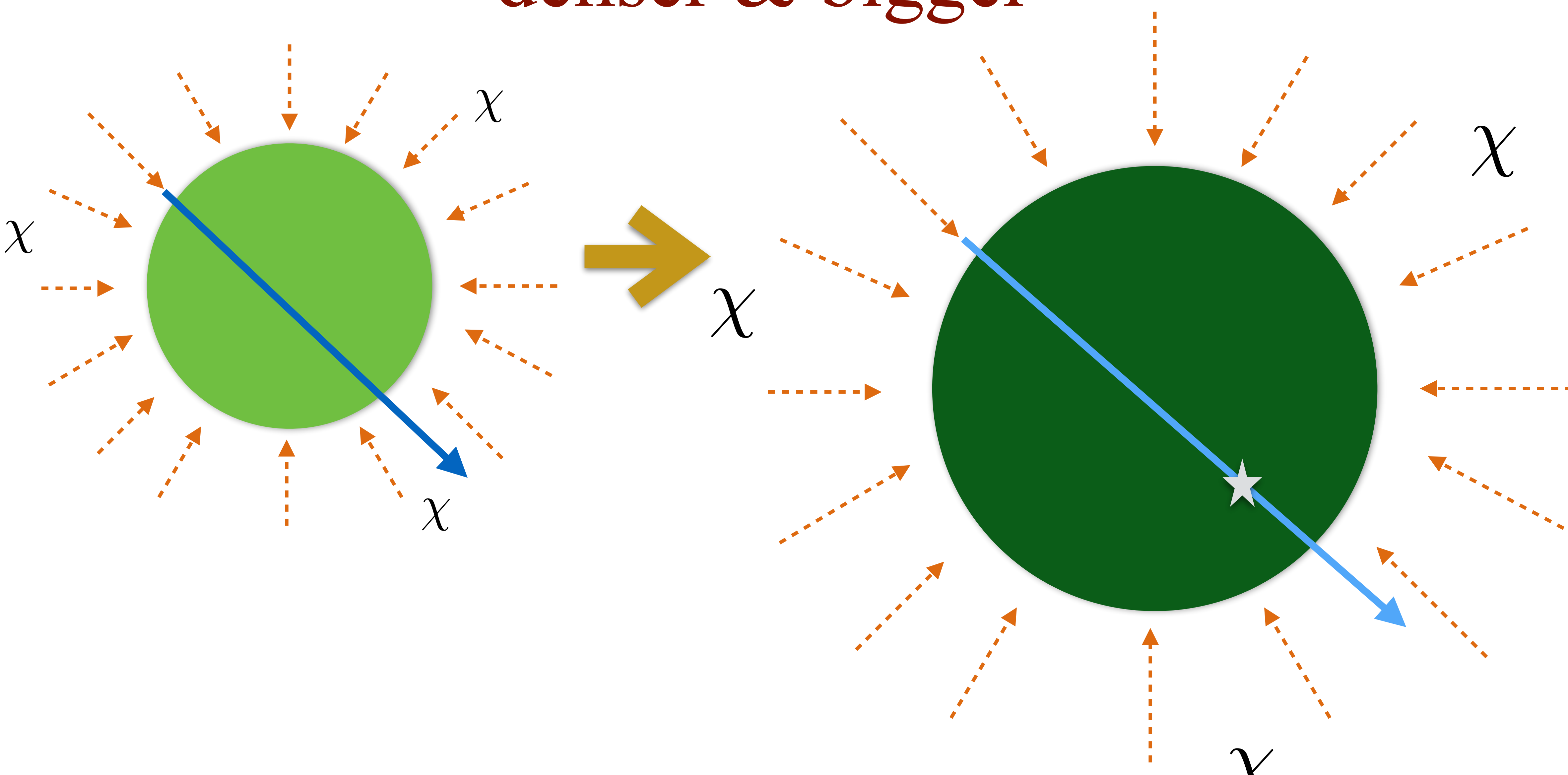


better

$$\sigma_{\text{threshold}} = \frac{m_{\text{molec}}}{\rho_{\text{soup}} R_{\text{soup}}}$$

$<<10^{-29}\ \text{cm}^2$

denser & bigger

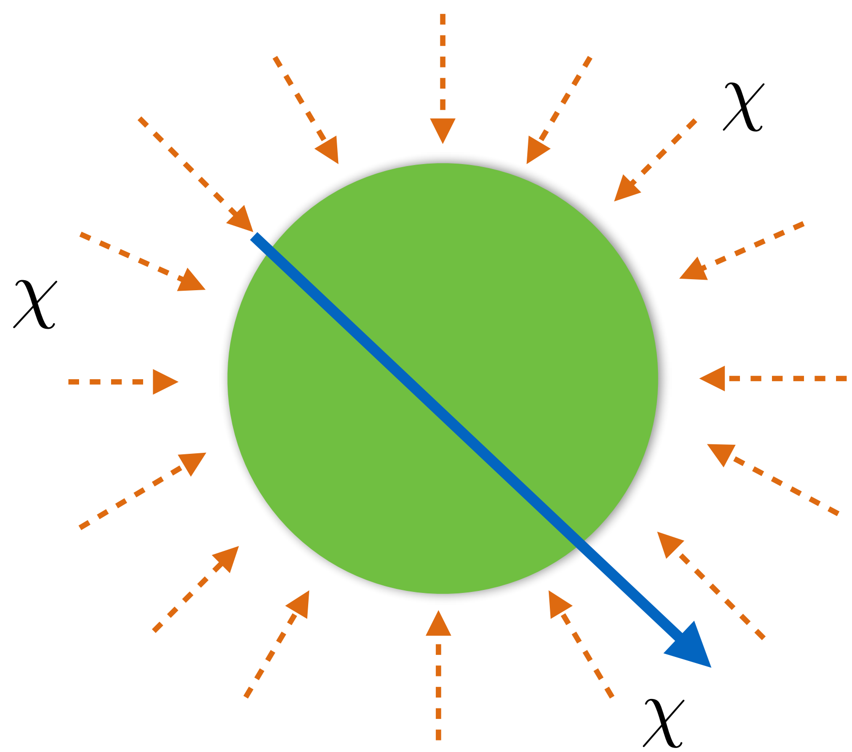


better

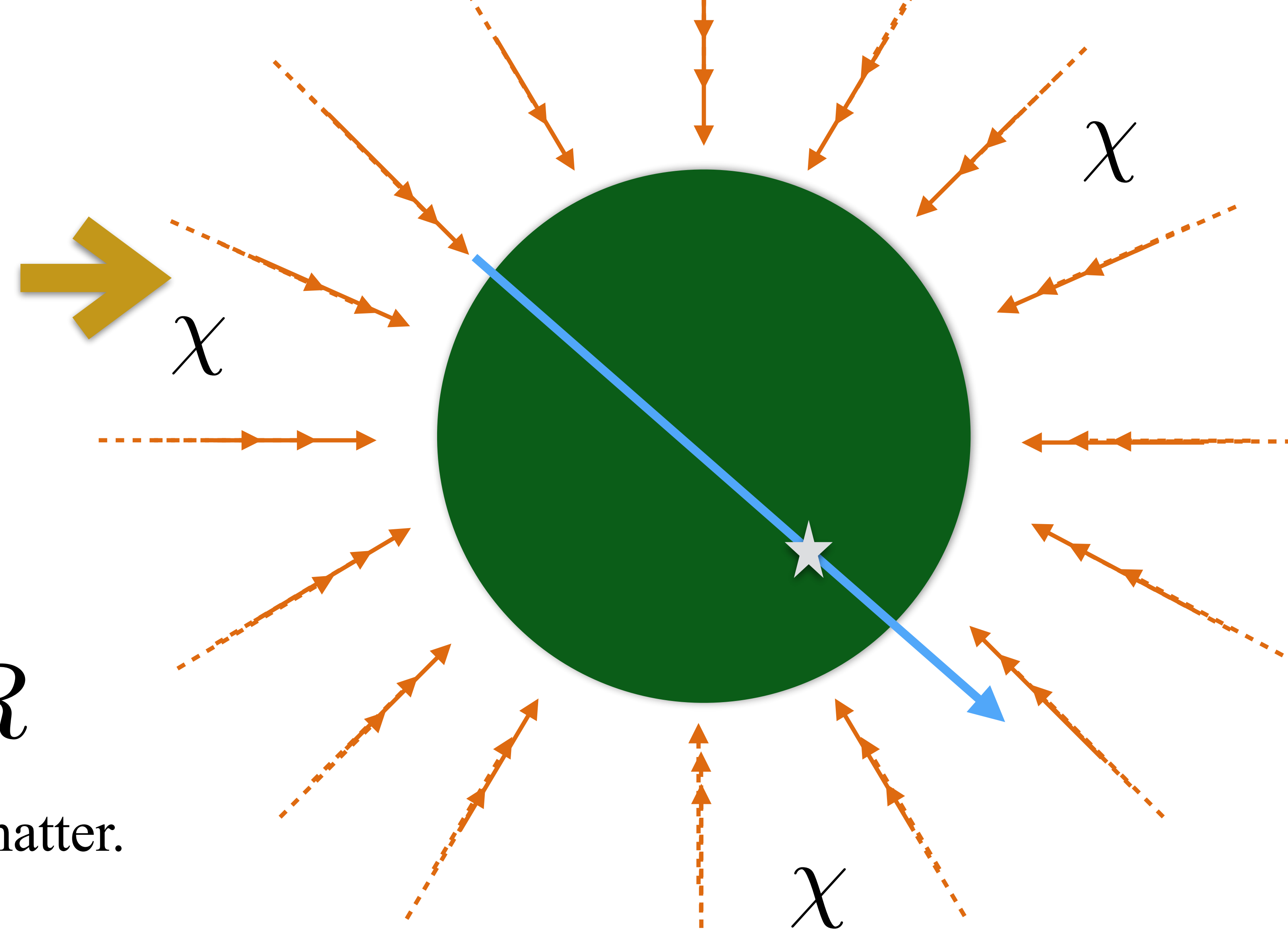
$$\sigma_{\mathrm{threshold}} = \frac{m_{\mathrm{molec}}}{\rho_{\mathrm{soup}} R_{\mathrm{soup}}}$$

<<10^{-29} cm^2

denser & bigger



$$v_{\mathrm{esc}} \propto \sqrt{\rho} R$$



Gravity bonus! Accelerate dark matter.

(higher KE, *dN/dt*)

better

left to itself	$T = 278$ Kelvin
dark fire-heated	$T = 0.003$ Kelvin

better

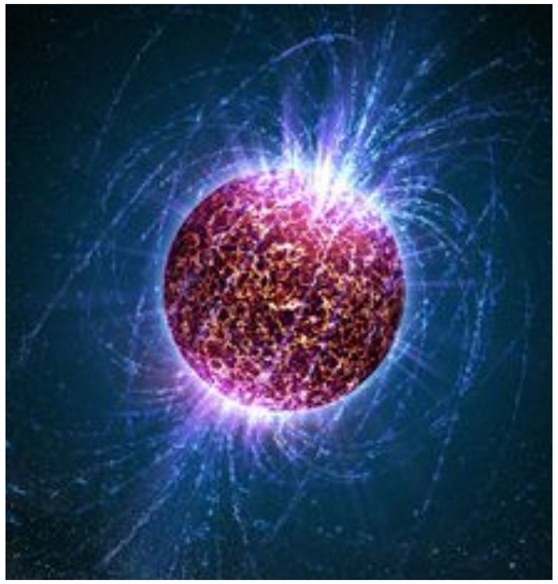
left to itself	$T = 278$ Kelvin
dark fire-heated	$T = 0.003$ Kelvin

be colder in natural state

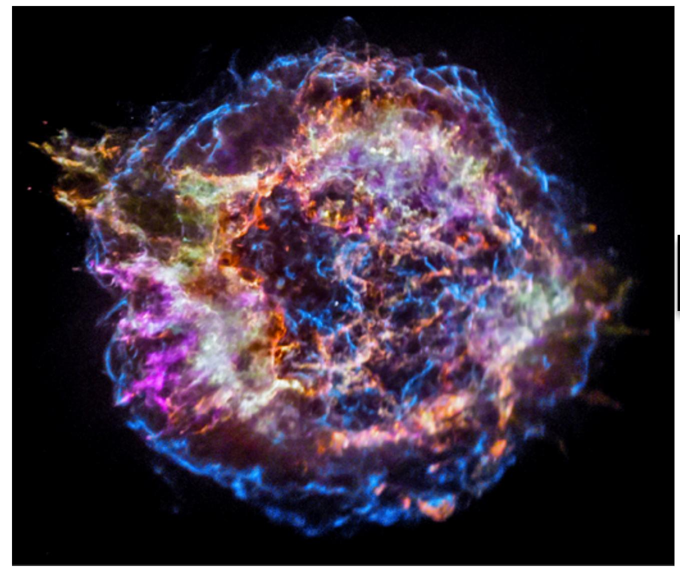
What’s dense, big, and cold?

What’s dense, big, and cold?

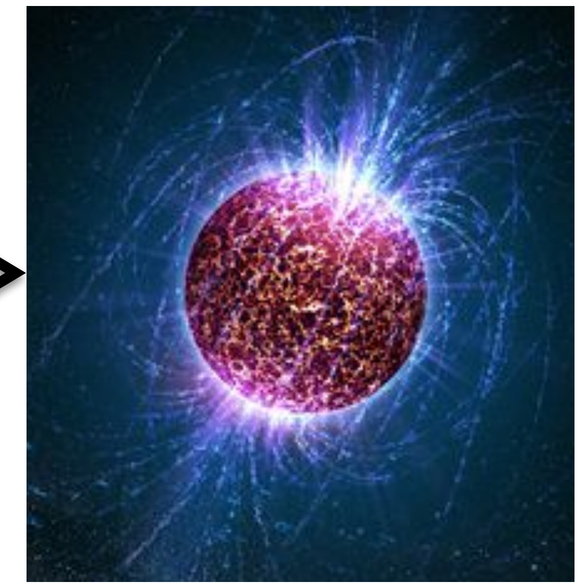
a neutron star!



1934



core-collapse supernova



neutron star

Zwicky again

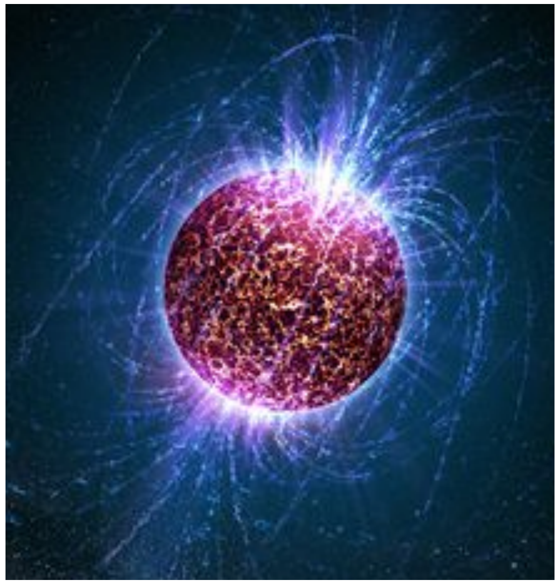
dense

density: 7 x 10^{14} g/cm^3

dense, big

density: 7 x 10^{14} g/cm^3

radius: 10 km



dense, big

density: 7×10^{14} g/cm^3

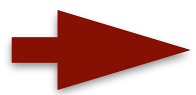
radius: 10 km

$$v_{\mathrm{esc}} \propto \sqrt{\rho} R$$
$$\simeq 0.7\,c$$

dense, big, and cold

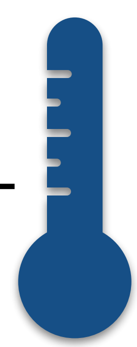
density: 7×10^{14} g/cm^3

radius: 10 km



$$v_{\rm esc} \propto \sqrt{\rho} R$$
$$\simeq 0.7\, c$$

$$\frac{20 \times 10^6 \text{ years}}{1 \;\; \times 10^9 \text{ years}}$$



$$\frac{T_{\rm effective} \lesssim 1000 \text{ K}}{T_{\rm effective} \sim 100 \text{ K}}$$

(compare with snowball)

Page, Lattimer, Prakash, Steiner (2004)
Yakovlev, Pethick (2004)

Detector properties

density: 7×10^{14} g/cm^3

radius: 10 km

$T_{\text{effective}} \sim 100$ K

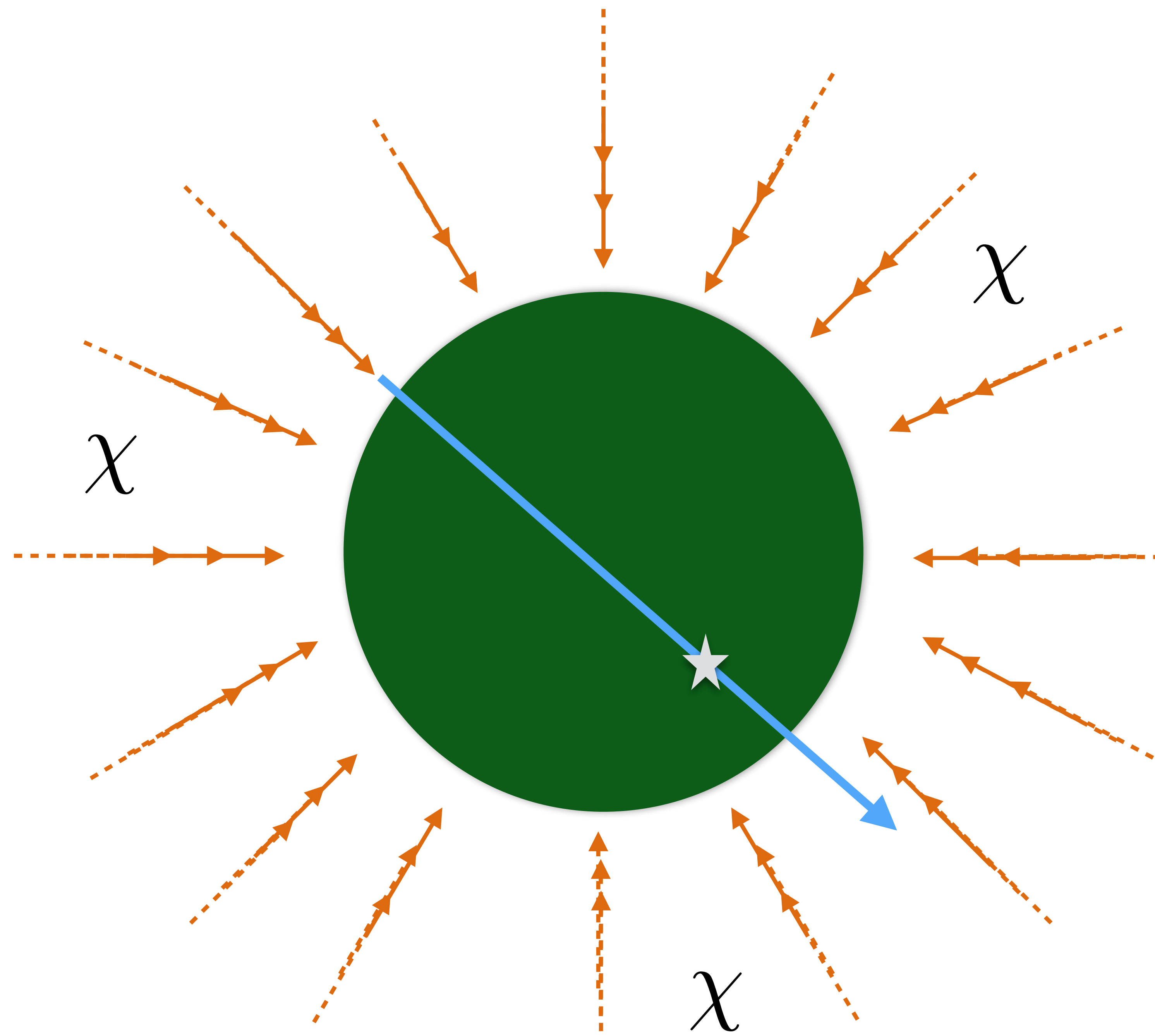
Dark fires in the sky

$$\mathrm{KE}_{\mathrm{DM}} \times \frac{dN_{\mathrm{DM}}}{dt}$$

density: 7×10^{14} g/cm^3

radius: 10 km

$T_{\mathrm{effective}} \sim 100$ K



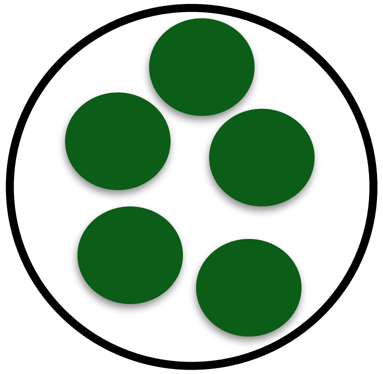
How hot can dark matter keep my neutron star?

M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *119, 131801 (2017)*
N. Raj, *P Tanedo, H-B Yu*
Phys.Rev.D. *97, 043006 (2017)*

Zwicky misses the party

FROM LOCAL MEASUREMENTS

300 km/s



0.3 GeV/cm³

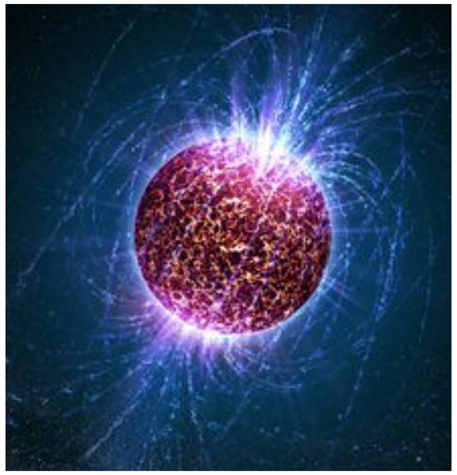
unknown to Zwicky

dark matter

1933

$$\mathrm{KE}_{\mathrm{DM}} \times \frac{dN_{\mathrm{DM}}}{dt}$$

neutron star



1934

density: 7×10^{14} g/cm^3

radius: 10 km

$T_{\text{effective}} \sim 100$ K

estimable by Zwicky

How hot can dark matter keep my neutron star?

Dark fire: neutron star temperature

$$\text{heating rate} = \mathrm{KE}_{\mathrm{DM}} \times \frac{dN_{\mathrm{DM}}}{dt}$$

$$\sigma_{\mathrm{threshold}} = \frac{m_{\mathrm{neutron}}}{\rho_{\mathrm{NS}} R_{\mathrm{NS}}}$$

$10^{-45}\ \mathrm{cm}^2 \ll 10^{-29}\ \mathrm{cm}^2$

M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *119, 131801 (2017)*
N. Raj*, P Tanedo, H-B Yu*
Phys.Rev.D. *97, 043006 (2017)*

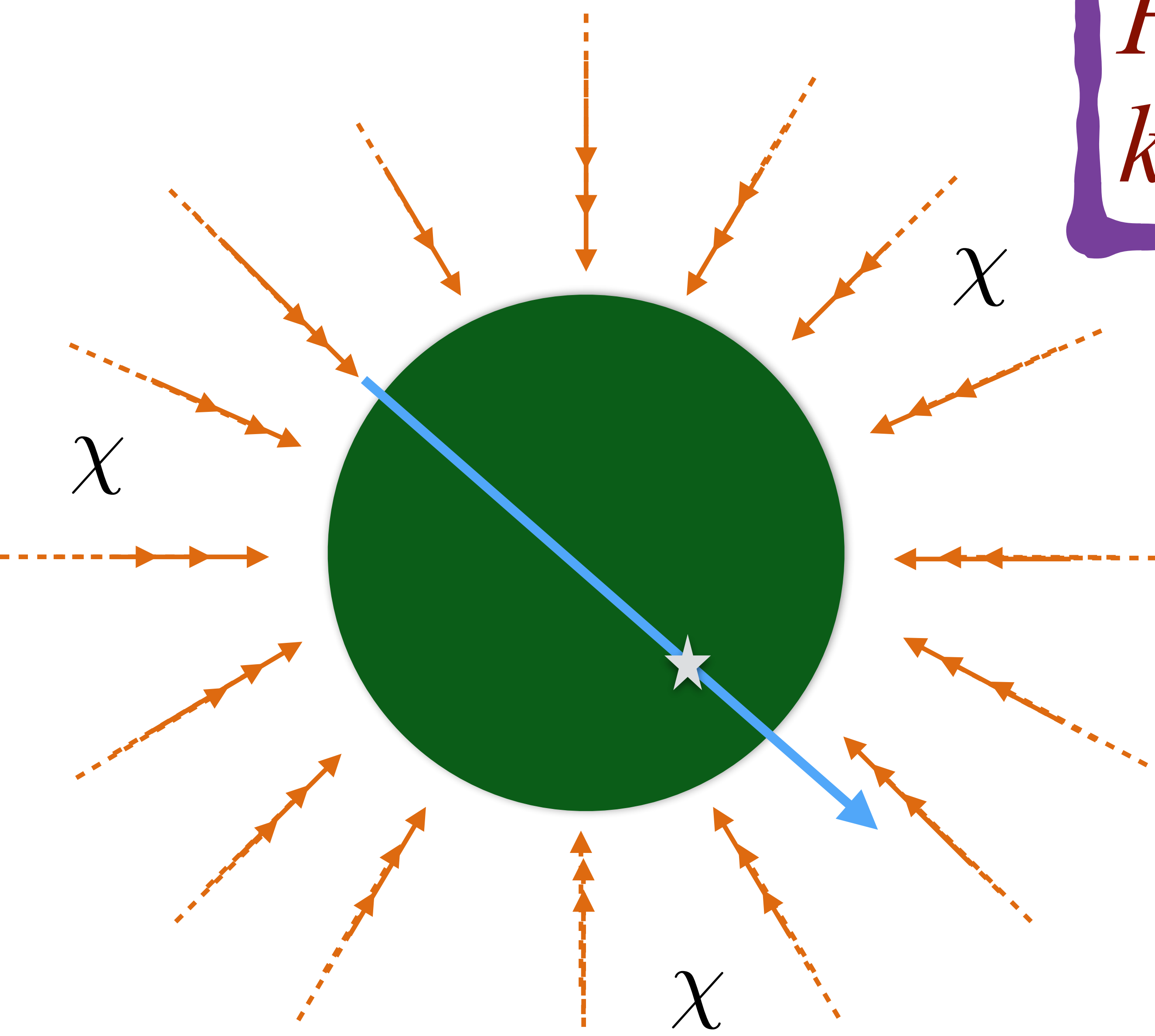
$$\text{heating rate} = \mathrm{KE}_{\mathrm{DM}} \times \frac{dN_{\mathrm{DM}}}{dt}$$

mass drops out!

$$0.35\ m_{\mathrm{DM}}$$

$$\frac{0.3\ \mathrm{GeV/cm^3}}{m_{\mathrm{DM}}} \pi R_{\mathrm{NS}}^2 \left(\frac{v_{\mathrm{esc}}}{300\ \mathrm{km/s}}\right)^2 (300\ \mathrm{km/s})$$

Dark fire: neutron star temperature



How hot can dark matter keep my neutron star?

$T = 1750$ Kelvin

(infrared)

$T = 1750$ Kelvin

snowball star

lava star

Coldest neutron star temperatures we were <u>able to measure</u>:

$T = 10^5$ Kelvin

How to find dark fire-heated, lava-cold neutron stars?

Observation prospects

Radio telescopes
(design: pulsar discovery)

CHIME

FAST

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

O. Blaes, P. Madau (1993)

Observation prospects

Radio telescopes
(design: pulsar discovery)

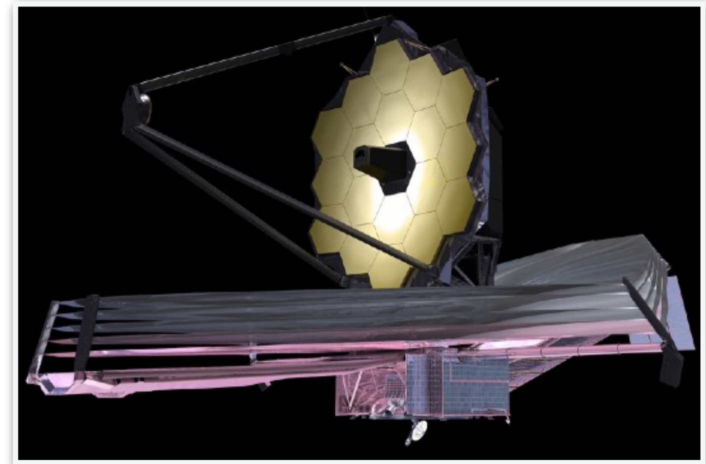
CHIME

FAST

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

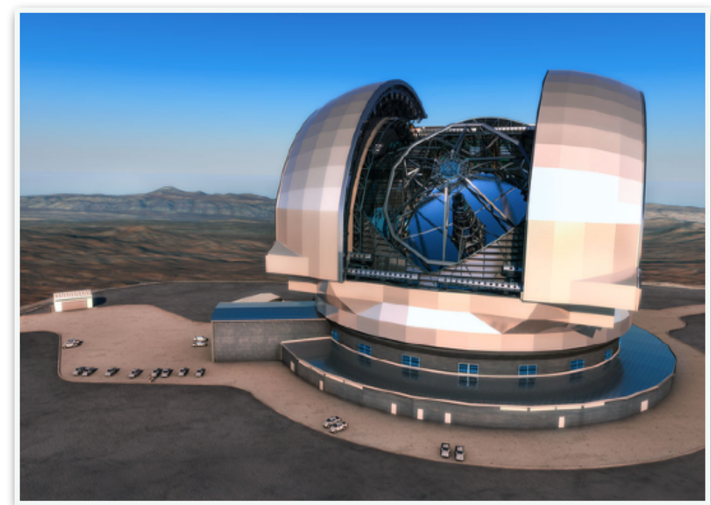
O. Blaes, P. Madau (1993)

Infrared telescopes
(design: exoplanet atmosphere study)



James Webb

2021



European Extremely Large

2025

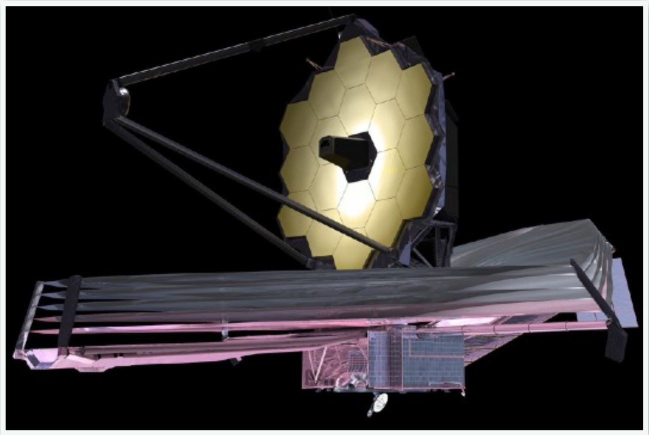
Thirty Meter

2027

Observation times

kinetic heating

(1.5 solar mass, 10 km star) 1750 K



James Webb

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

Thirty Meter

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

for 2σ sensitivity

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

kinetic heating

Minimum signature

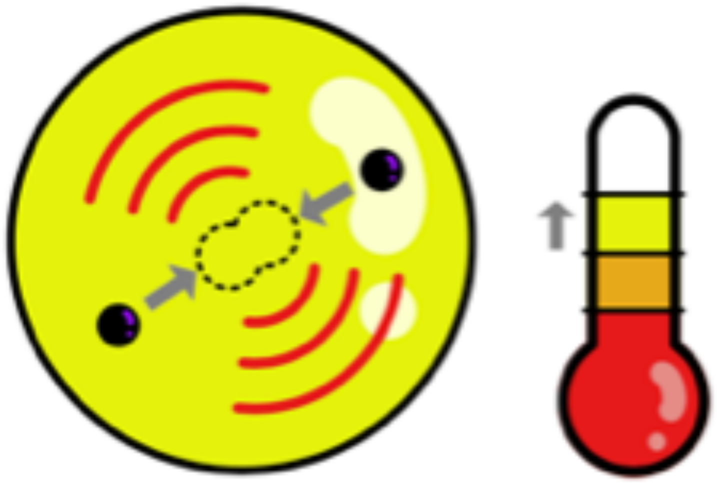
$$L \propto \boxed{\boxed{(\gamma - 1) m_{\mathrm{DM}}} + m_{\mathrm{DM}}}$$

kinetic heating

+ annihilation

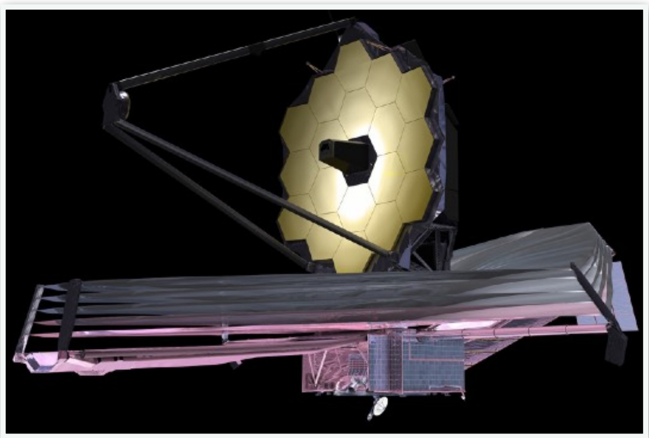
Minimum signature

Possible bonus



Observation times

(1.5 solar mass, 10 km star)	kinetic heating	+ annihilation
	1750 K	2480 K
James Webb	$10^5 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$	$9 \times 10^3 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$
Thirty Meter	$7 \times 10^4 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$	$2 \times 10^3 \text{ sec} \left(\frac{d}{10\text{pc}}\right)^4$



James Webb

Thirty Meter

for 2σ sensitivity

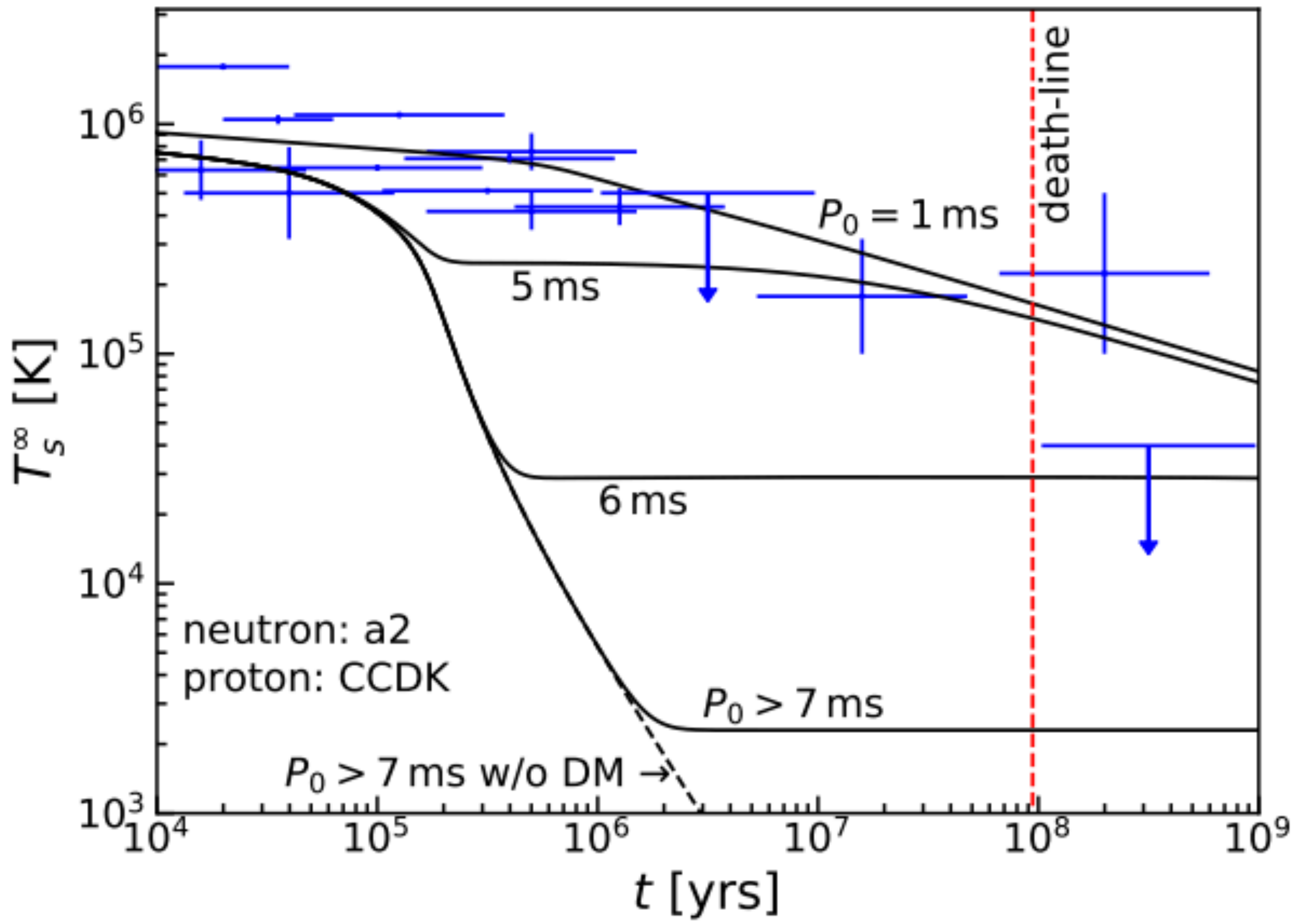
Annihilation saves observation time (= $$)
by a factor of >10!

Difficulties

- Old, nearby neutron stars must turn up
- Age determination not fully reliable
- Internal backgrounds may be present

Claim of dark matter discovery will be premature/exaggerated! (As opposed to exclusion = clean.)

e.g. rotochemical heating



Hamaguchi, Nagata, Yanagi 2019

Rewards?

- Old, nearby neutron stars must turn up
- Age determination not fully reliable
- Internal backgrounds may be present

} Claim of dark matter discovery will be premature/exaggerated! (As opposed to exclusion = clean.)

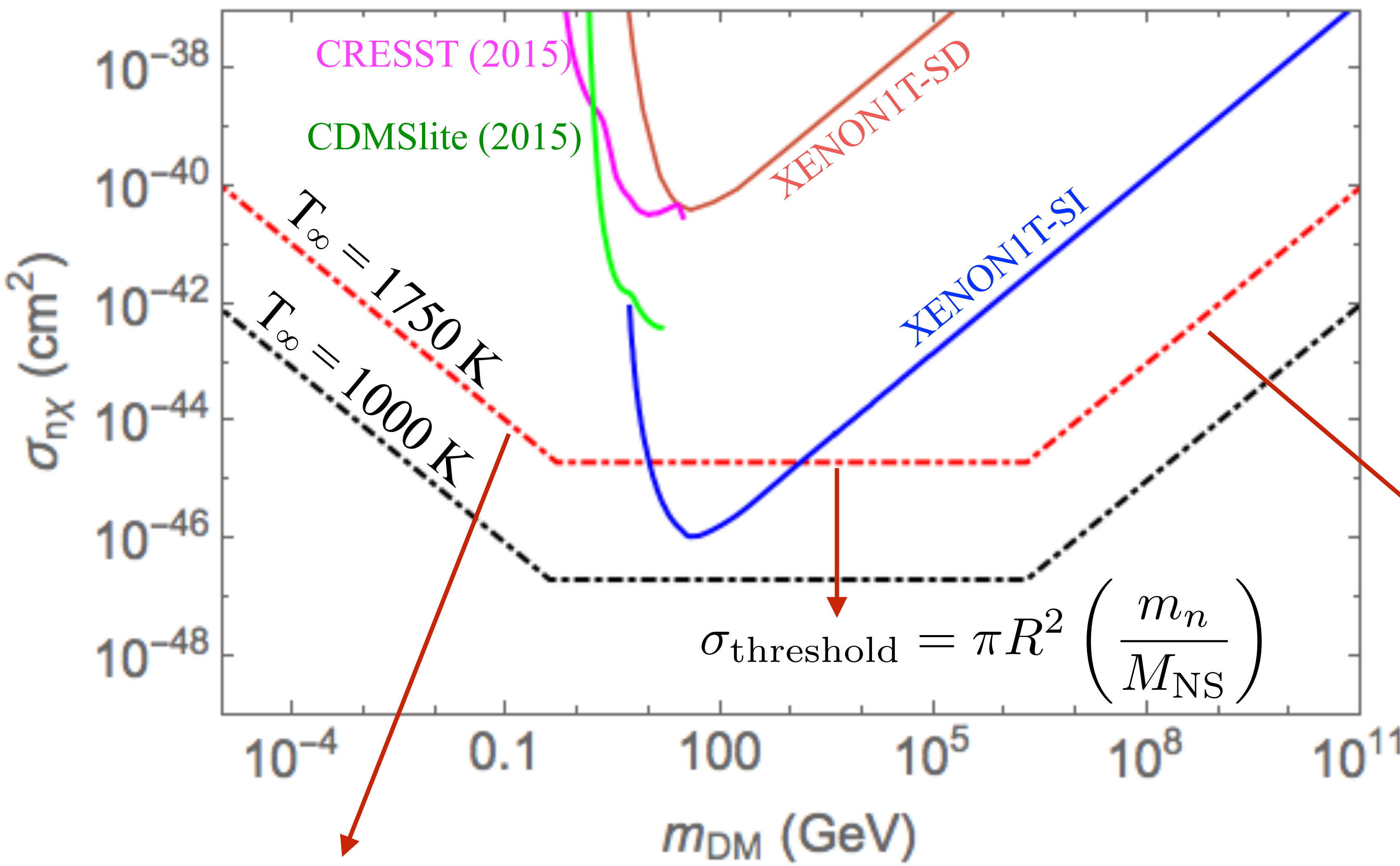
So what do you buy?

→ Does dark kinetic heating expand our direct detection frontiers?

→ (1) Low mass ✕
(2) High mass ✕
(3) Strongly interacting ✕
(4) Spin-dependent ✕
(5) v-suppressed ✕
(6) Inelastic ✕
(7) Neutrino floors ✕

Complementing terrestrial searches

M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



$$\sigma_{\text{threshold}} = \pi R^2 \left(\frac{m_n}{M_{\text{NS}}}\right)$$

(1) Low mass ✅

(2) High mass ✅

$\sigma_{\text{threshold}} \propto$ number of scatters

$$= E_{\text{DM}}/E_{\text{recoil}}$$

$$E_{\text{recoil}} \sim 2 m_n v_{\text{esc}}^2$$

versus

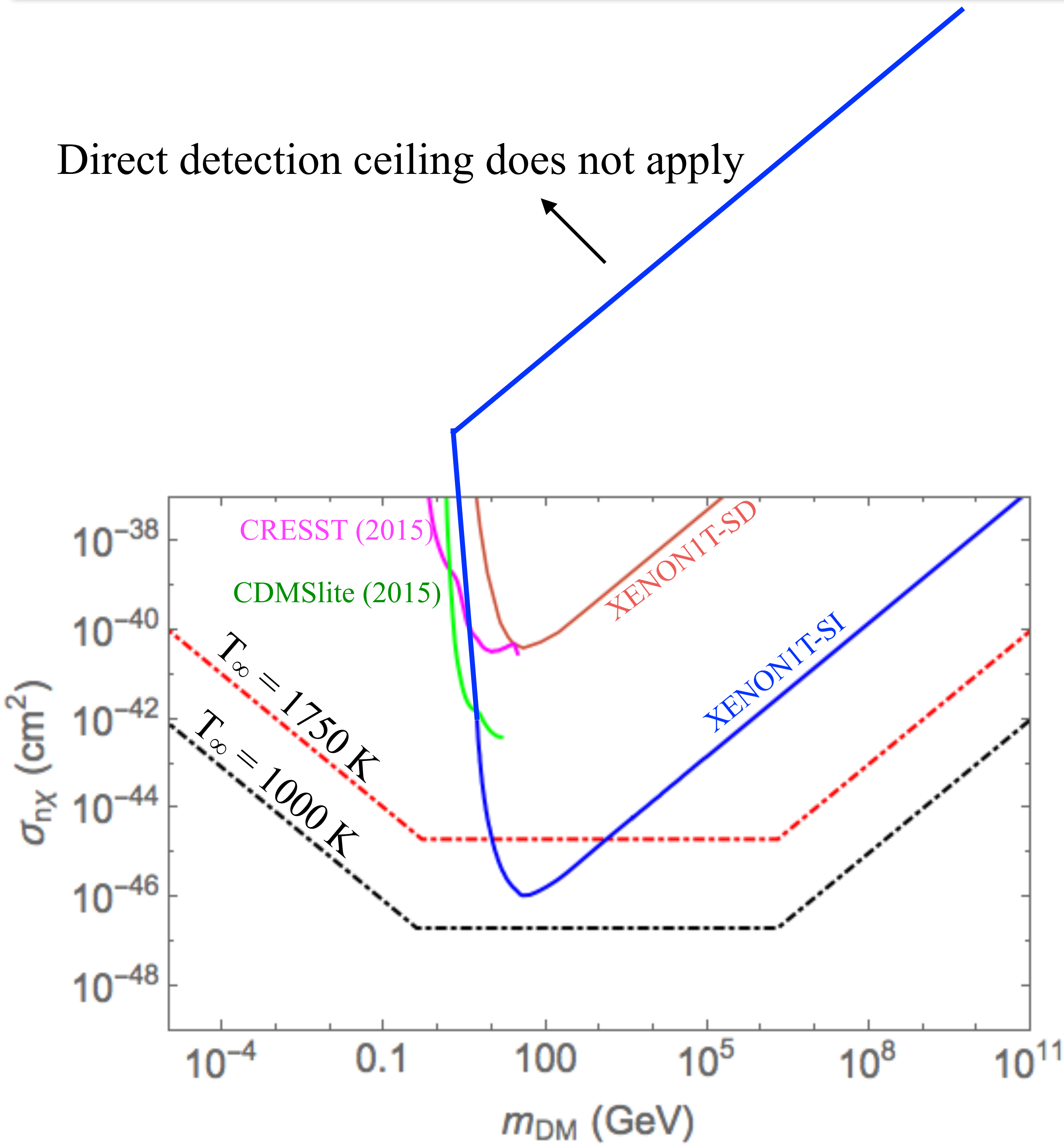
$$E_{\text{DM}} \sim \frac{1}{2} m_{DM} v_{\text{DM}}^2$$

"Pauli blocking"

$\sigma_{\text{threshold}}^{-1} \propto$ fraction of nucleons excitable to > Fermi momentum $\quad \dfrac{\gamma m_{\text{DM}} v_{\text{esc}}}{p_{\text{Fermi}}}$

Complementing terrestrial searches

Direct detection ceiling does not apply



(1) Low mass ✅
(2) High mass ✅
(3) Strong ✅

Complementing terrestrial searches

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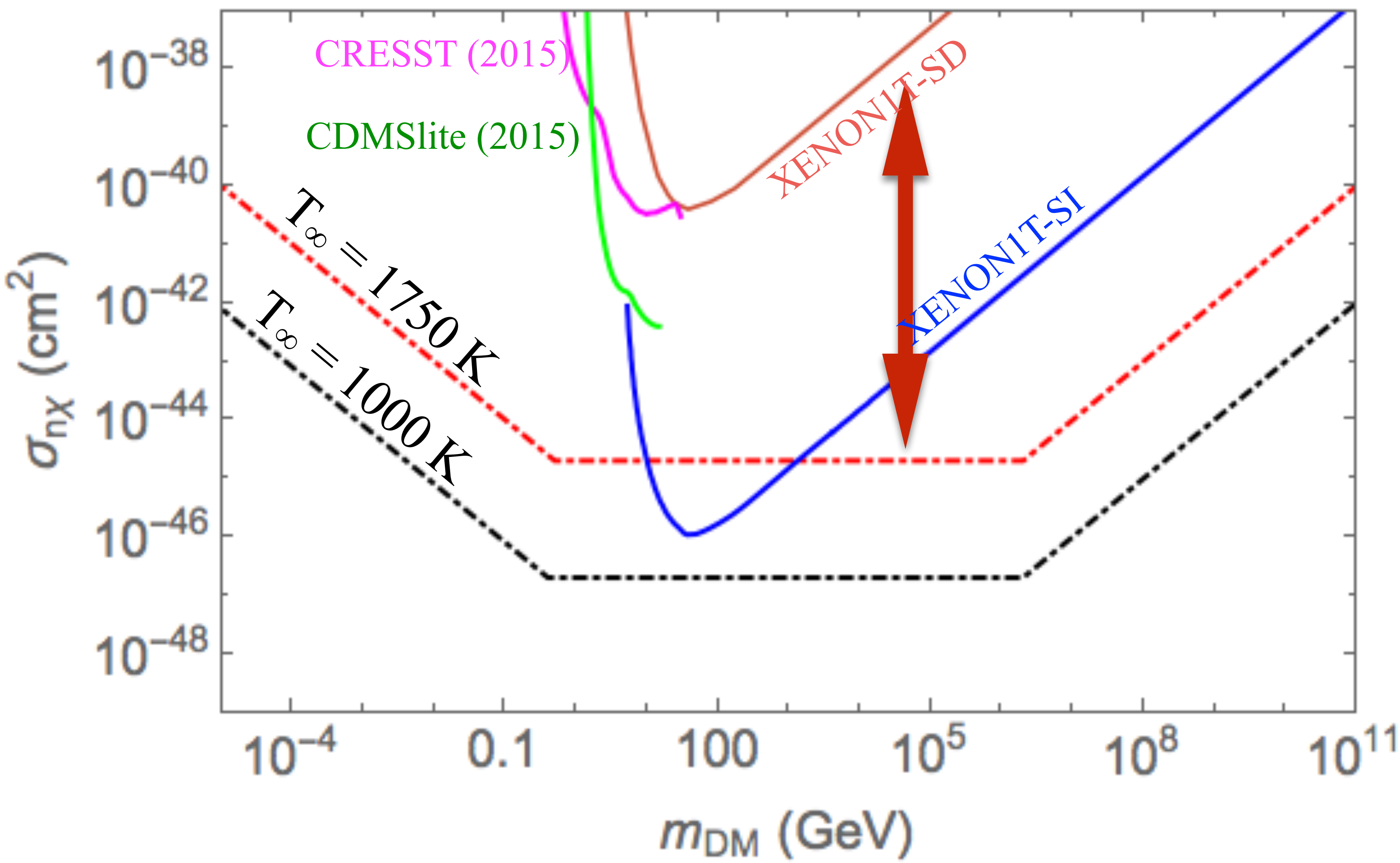
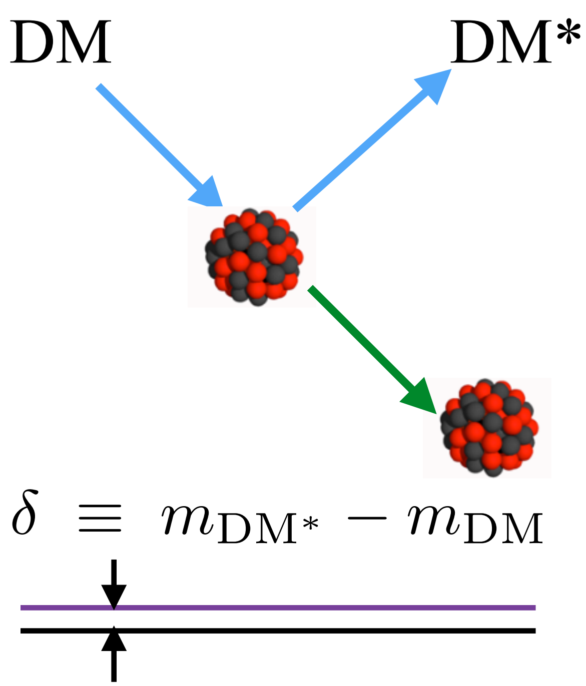


(1) Low mass ✅
(2) High mass ✅
(3) Strong ✅
(4) Spin-dependent ✅

Scattering with neutrons:
apathy to nuclear coherence

Complementing terrestrial searches



Scattering proceeds so long as mass splitting is below

$$\delta_{\max} = \frac{\mu_{n\chi} v^2}{2}$$

$$= 200 \text{ MeV}$$

(Direct detection $\delta_{\max}$: $O(100 \text{ keV})$)

(1) Low mass
(2) High mass
(3) Strong
(4) Spin-dependent
(5) Inelastic

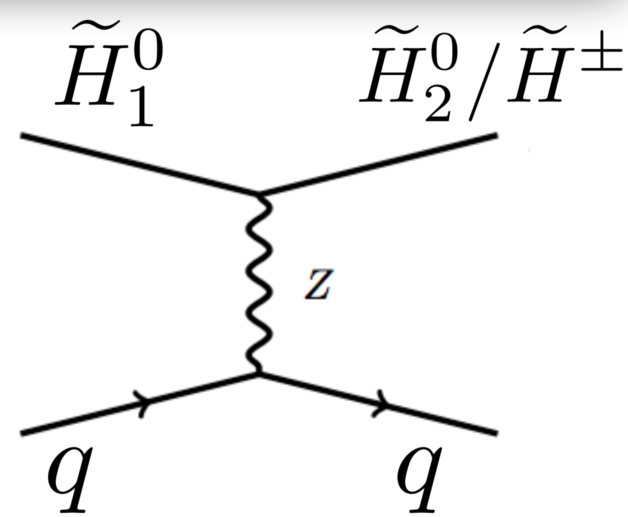
Heating up neutron stars with inelastic dark matter

Nicole F. Bell, Giorgio Busoni and Sandra Robles

ARC Centre of Excellence for Particle Physics at the Terascale
School of Physics, The University of Melbourne,
Victoria 3010, Australia

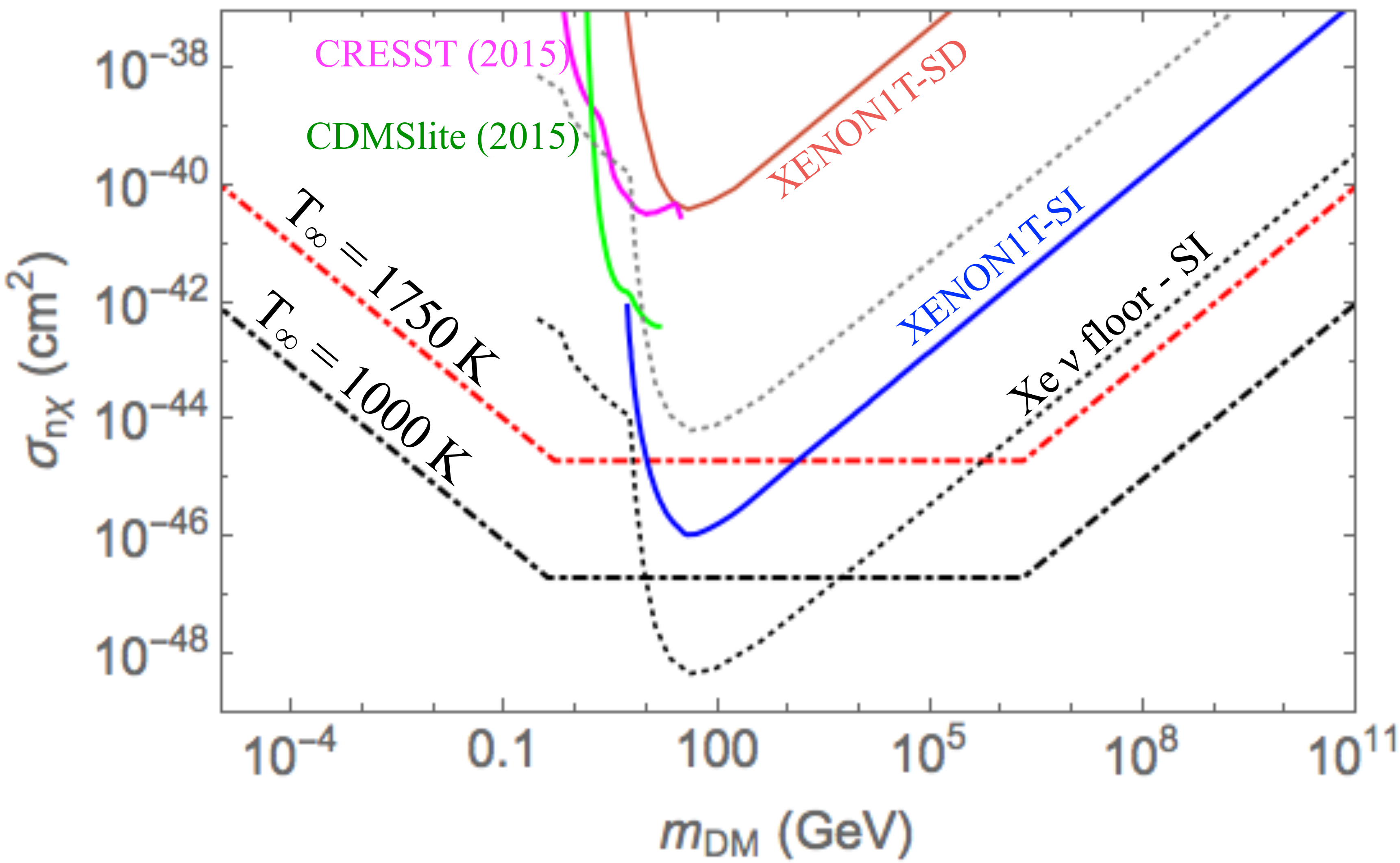
1807.02840

Great news for Higgsino lovers!



Complementing terrestrial searches

M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577

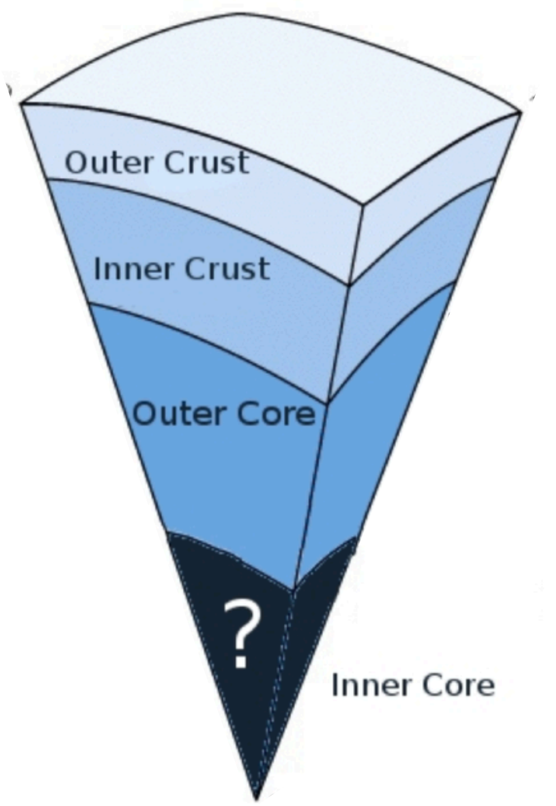


(1) Low mass ✅
(2) High mass ✅
(3) Strong ✅
(4) Spin-dependent ✅
(5) Inelastic ✅
(6) Neutrino floors ✅

Important variations on a theme

Are we barking down the wrong target particle?

A Joglekar, **N R**, P Tanedo, H-B. Yu; 1911.13293, 2004.09539



Are we barking down the wrong stellar region?

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

Zippy electrons in the core

products of β equilibrium (e, μ, p)

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

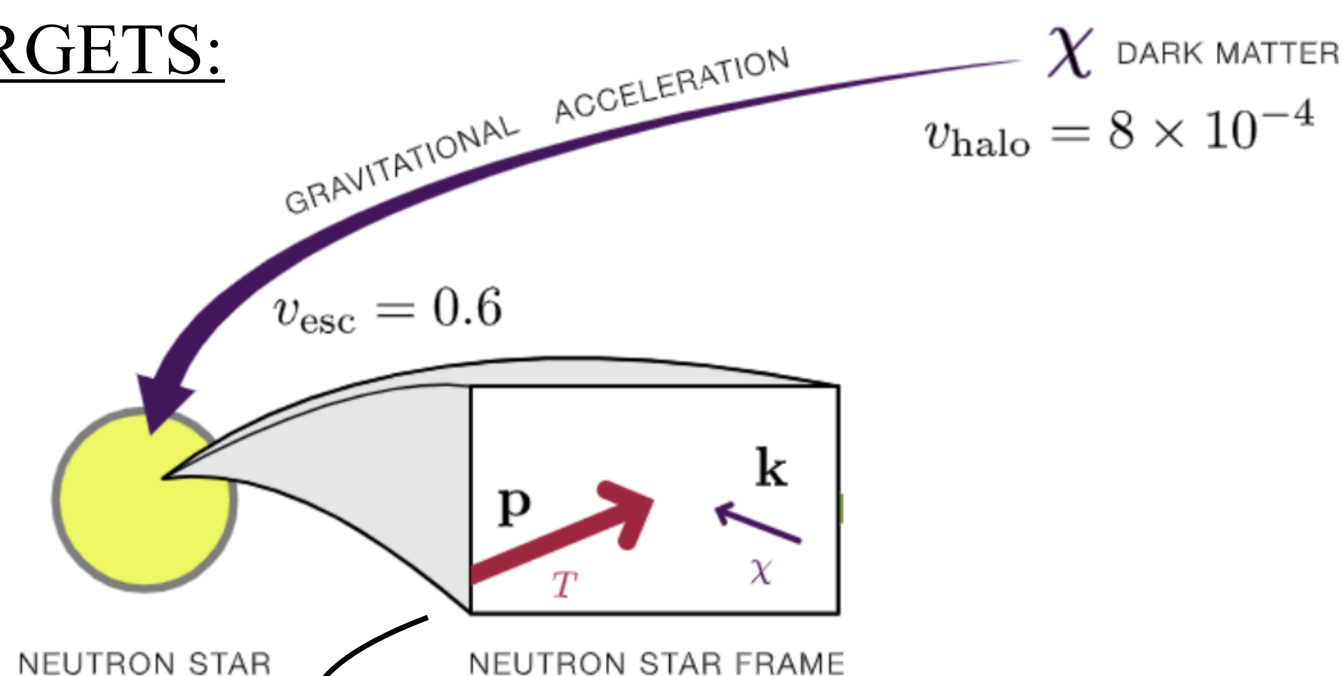
e: speed $\sim c$, random directions

μ, p, n: frozen in the star

NON-RELATIVISTIC TARGETS:

$$\text{capture probability } f = \frac{\text{scattering cross section}}{\text{geometric cross section}} = \sigma n_T R_\star$$

ELECTRON TARGETS:



notion of "geometric cross section" breaks down!

A Joglekar, **N R**, P Tanedo, H-B. Yu; 1911.13293, 2004.09539

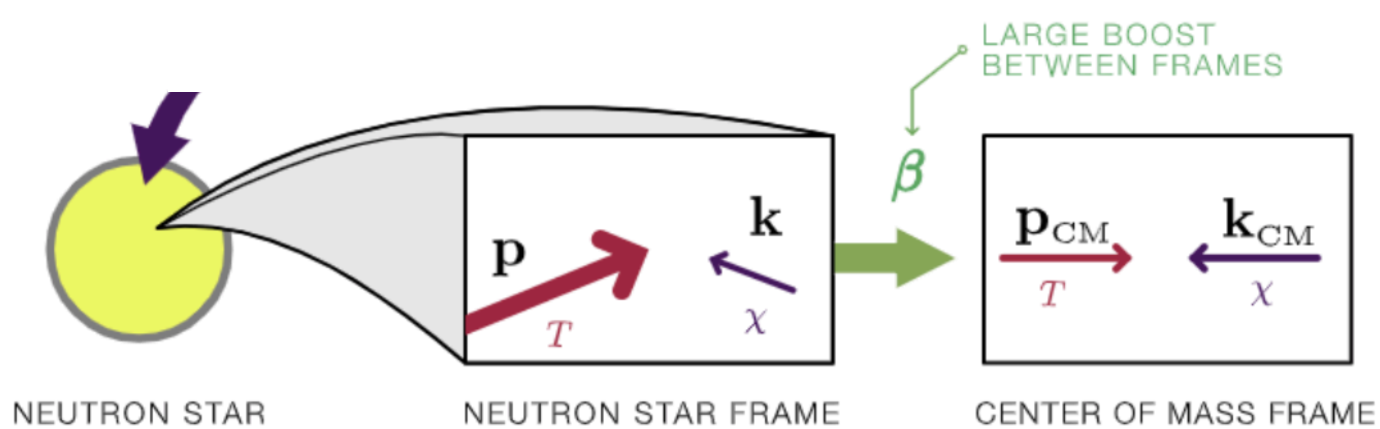
Frame dependence

capture probability f must be Lorentz-invariant

But scattering ingredients aren't

Fermi-Dirac distribution best known (to me) here

cross sections most conveniently expressed here



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Putting frames together Lorentz-invariantly

DM's stellar transit time — Møller velocity — energy transfer to electron — electron Fermi momentum

$$f = \sum_{N_{\rm hit}\in\mathbb{Z}} \frac{\langle n_{\rm T}\rangle\,\Delta t}{N_{\rm hit}} \int d\Omega_{\rm NS} \int_0^{p_{\rm F}} d|\bar{p}|\, \frac{|\bar{p}|^2}{V_{\rm F}} v_{\rm M\o l} \int d\Omega_{\rm CM} \left(\frac{d\sigma}{d\Omega}\right)_{\rm CM} \Theta\left(\Delta E + E_p - E_{\rm F}\right) \Theta\left(\frac{E_{\rm halo}}{N_{\rm hit}-1} - \Delta E\right) \Theta\left(\Delta E - \frac{E_{\rm halo}}{N_{\rm hit}}\right)$$

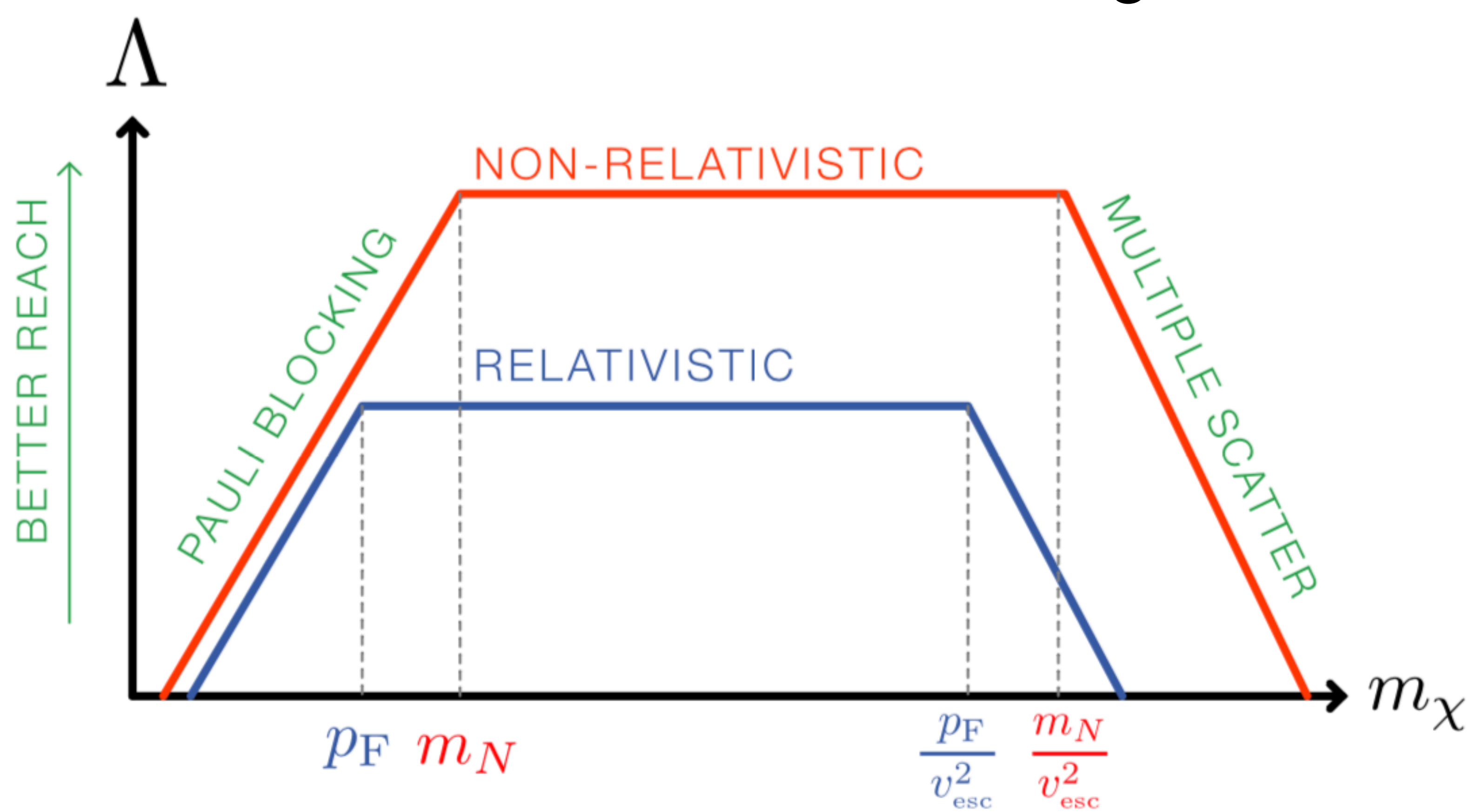
electron orientation with respect to star — Fermi sphere volume — Pauli blocking — possible multiscatter capture

In limit of non-relativistic target (& $N_{\rm hit} \to 1$):

$$f = \langle n_{\rm T}\rangle \Delta t \;\times\; 1 \;\times v_{\rm DM} \;\times\; \sigma \;=\; \sigma n_{\rm T} R_\star = \frac{\text{scattering cross section}}{\text{geometric cross section}}$$

For short-distance interactions:

$$\frac{(\bar{\chi}\Gamma_\chi \chi)(\bar{f}\Gamma_f f)}{\Lambda^2}$$



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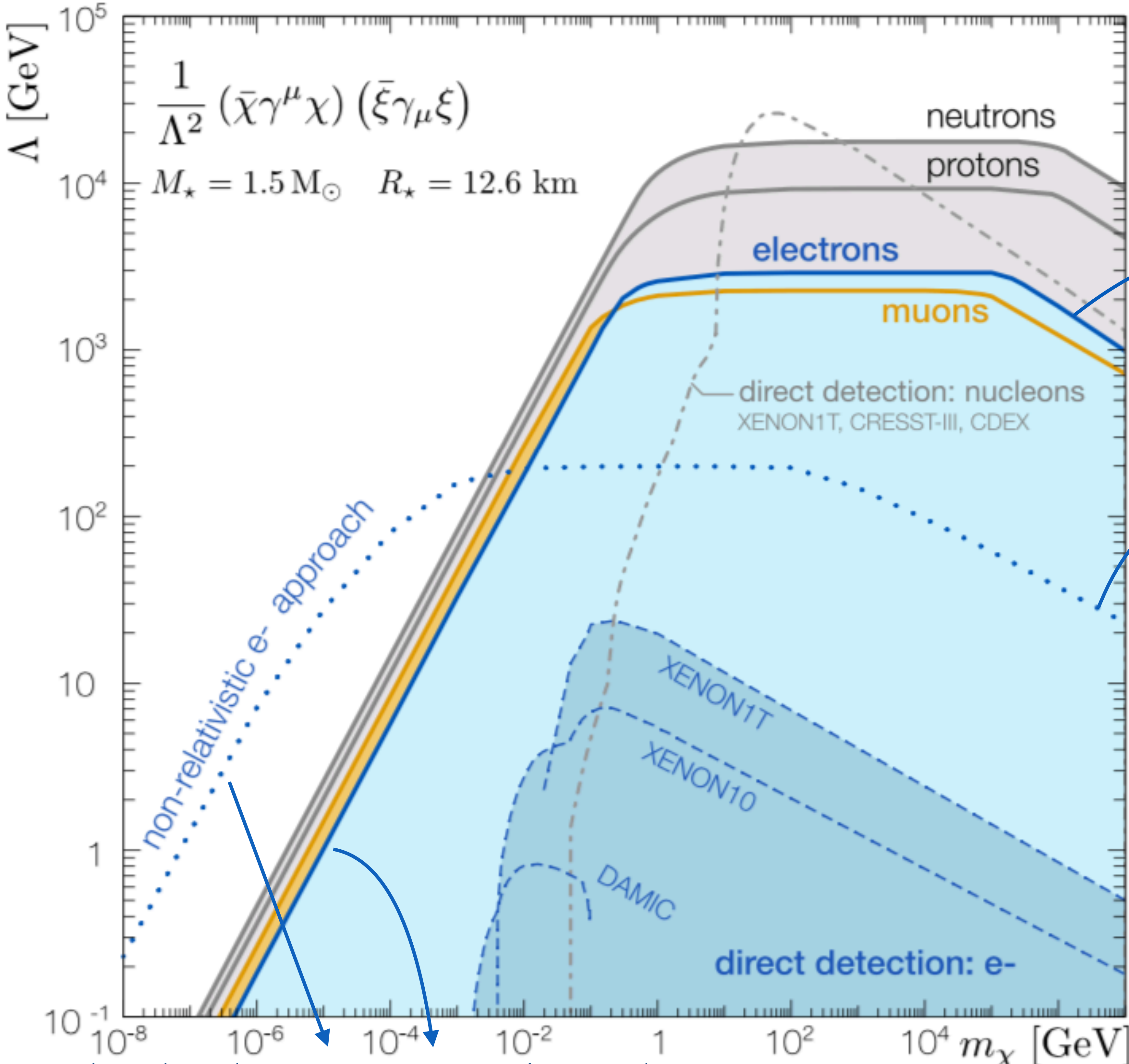
“Electron star” dark matter detection



cross section ∝ Fermi energy^2 [(150 MeV)^2]

cross section ∝ electron mass^2 [(0.5 MeV)^2]

hard to lose energy to zippy electrons

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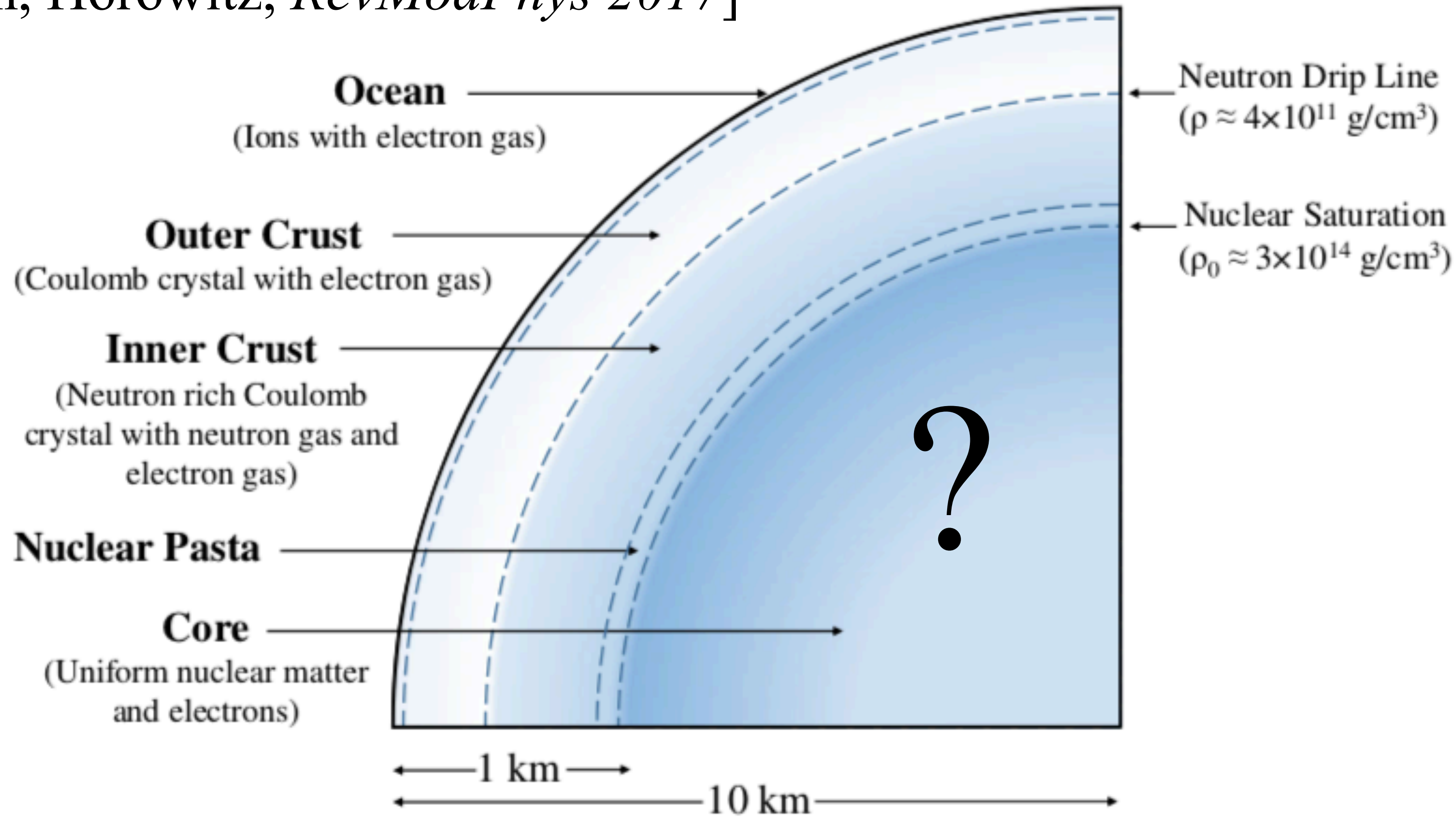
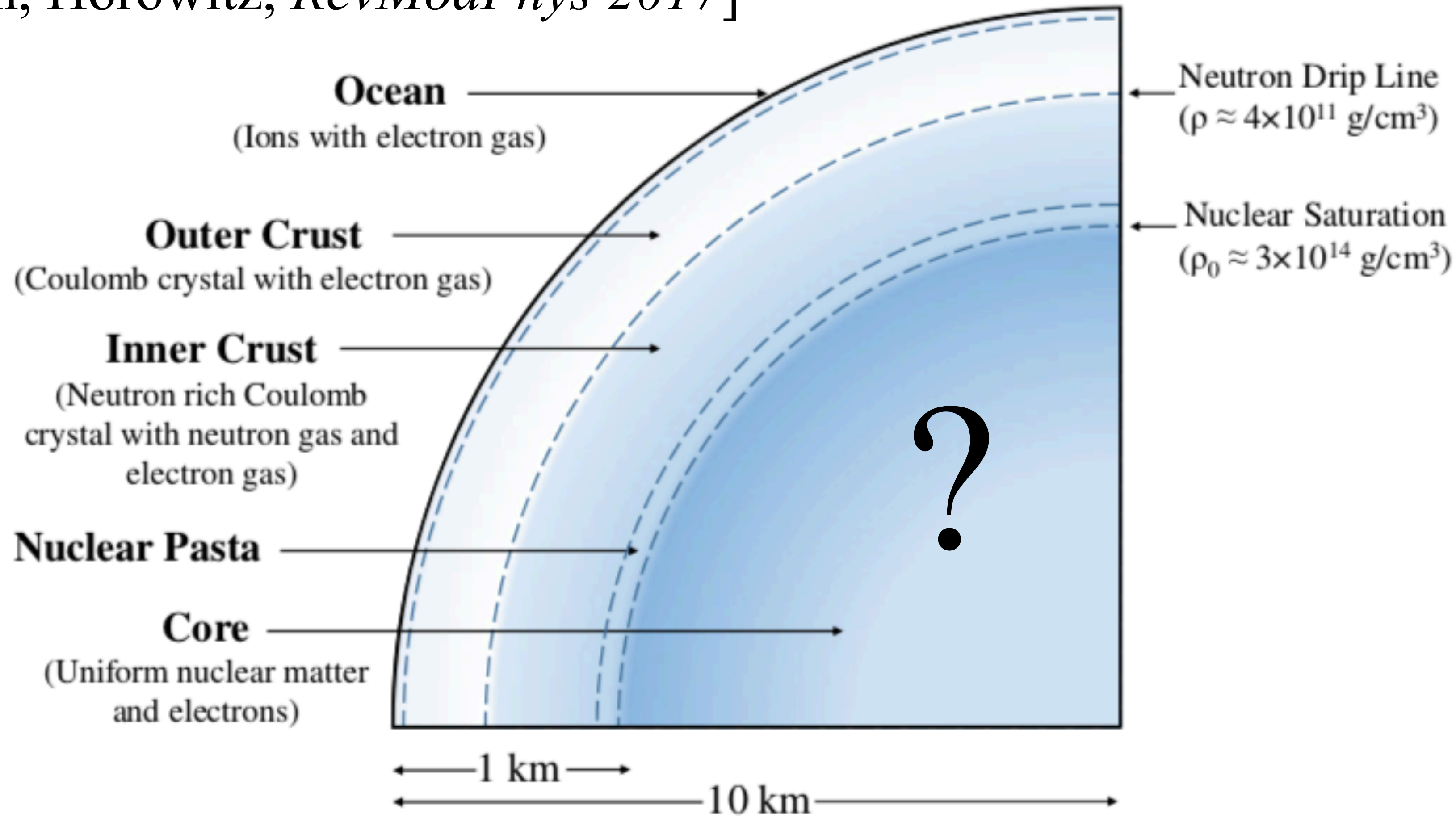
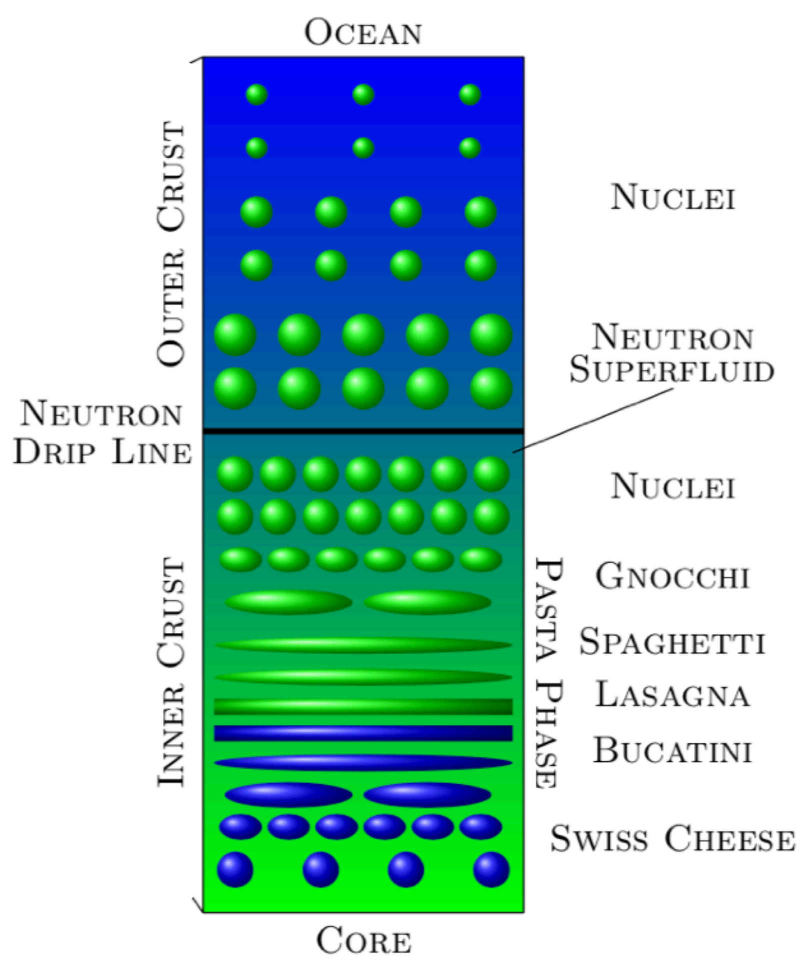
[Caplan, Horowitz, *RevModPhys 2017*]



Are we barking down the wrong region?

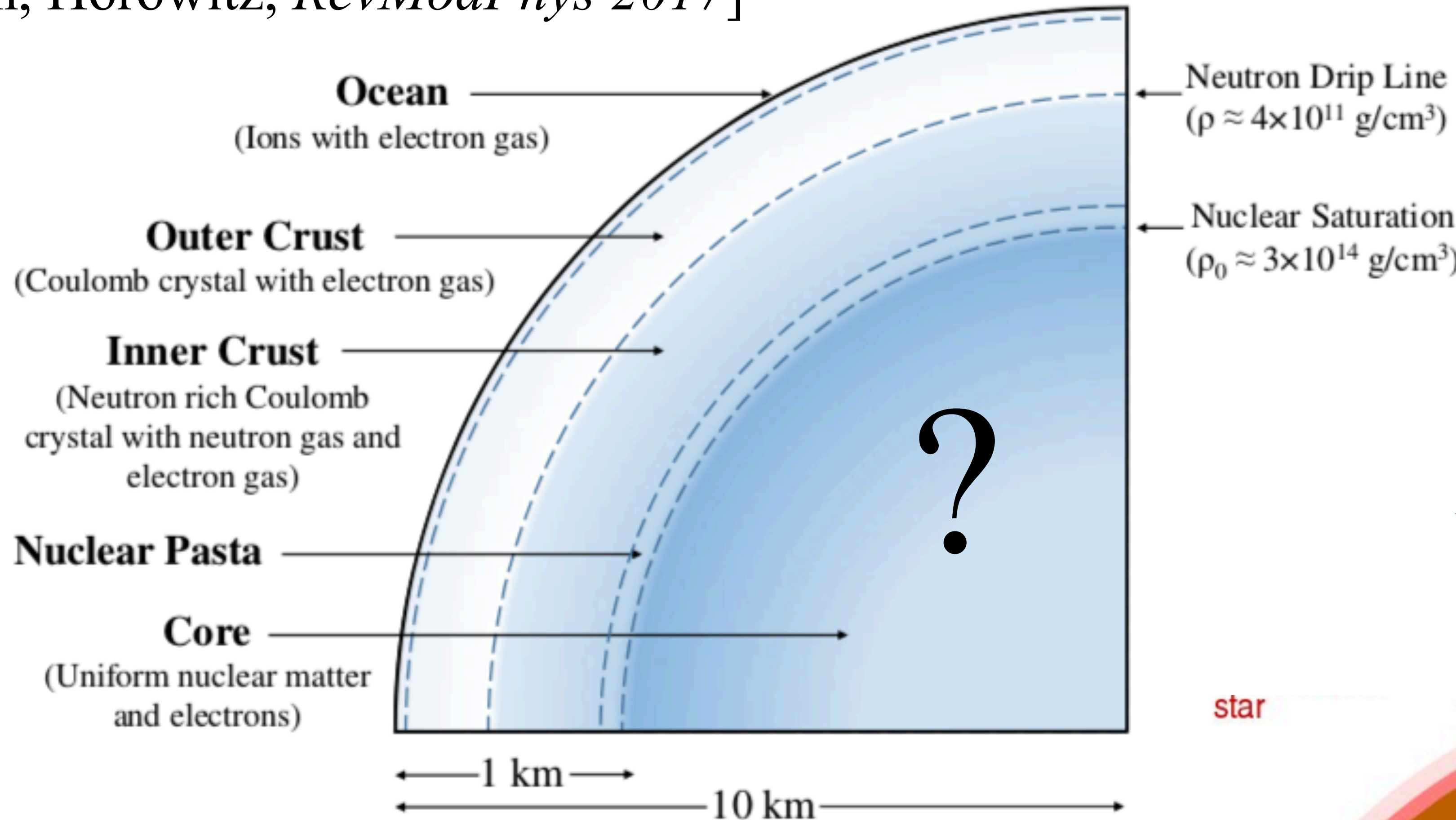
[Caplan, Horowitz, *RevModPhys 2017*]



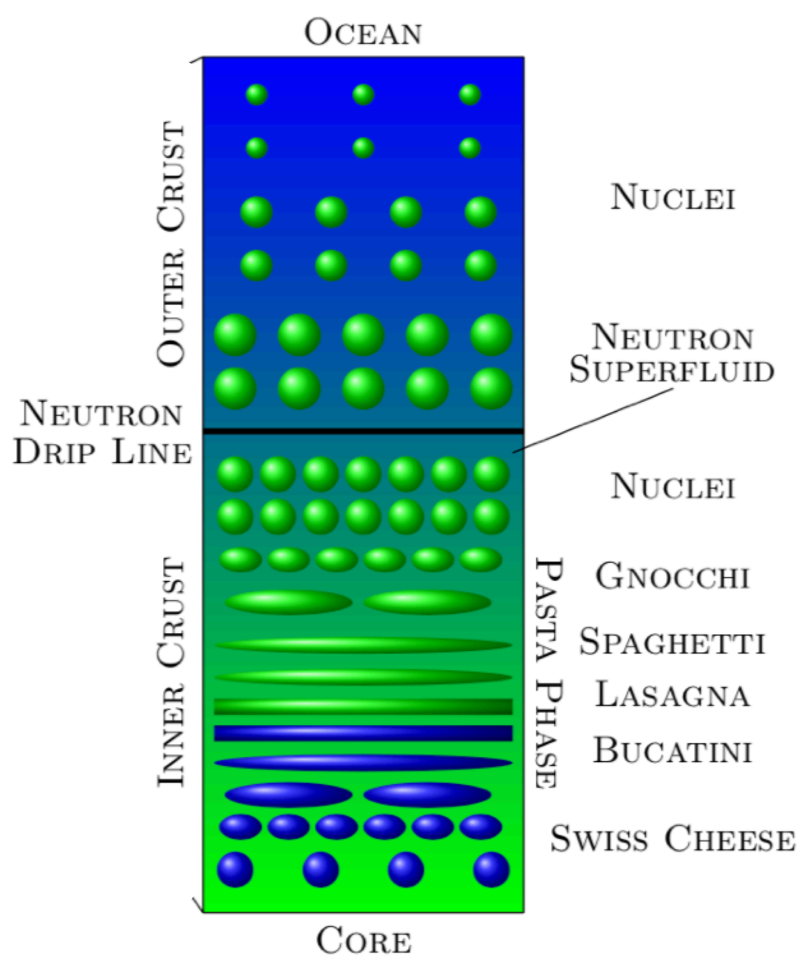


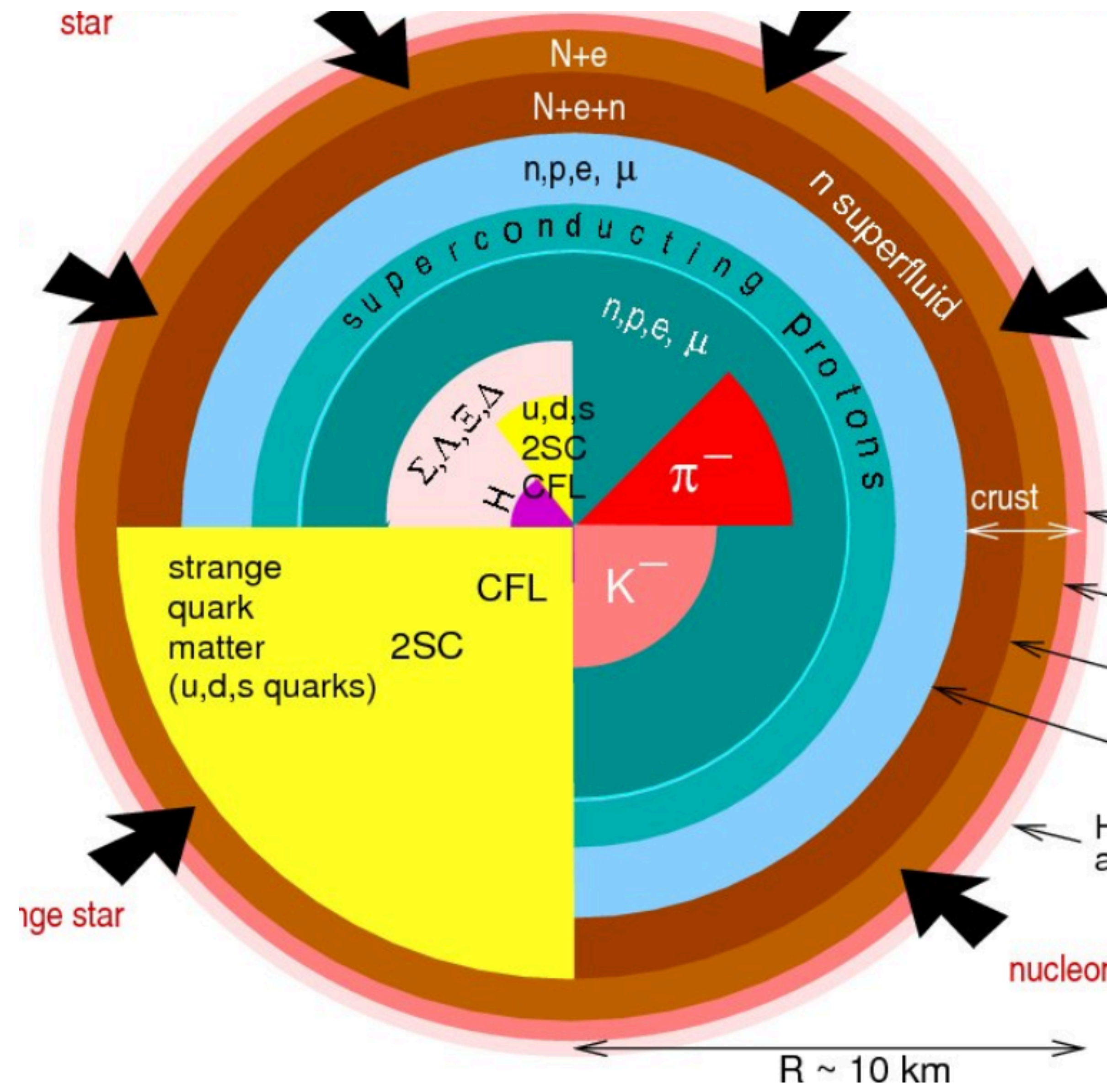
structure of the crust,
better understood than core

[Caplan, Horowitz, *RevModPhys 2017*]



deeper =>
knowledge of structure
more uncertain

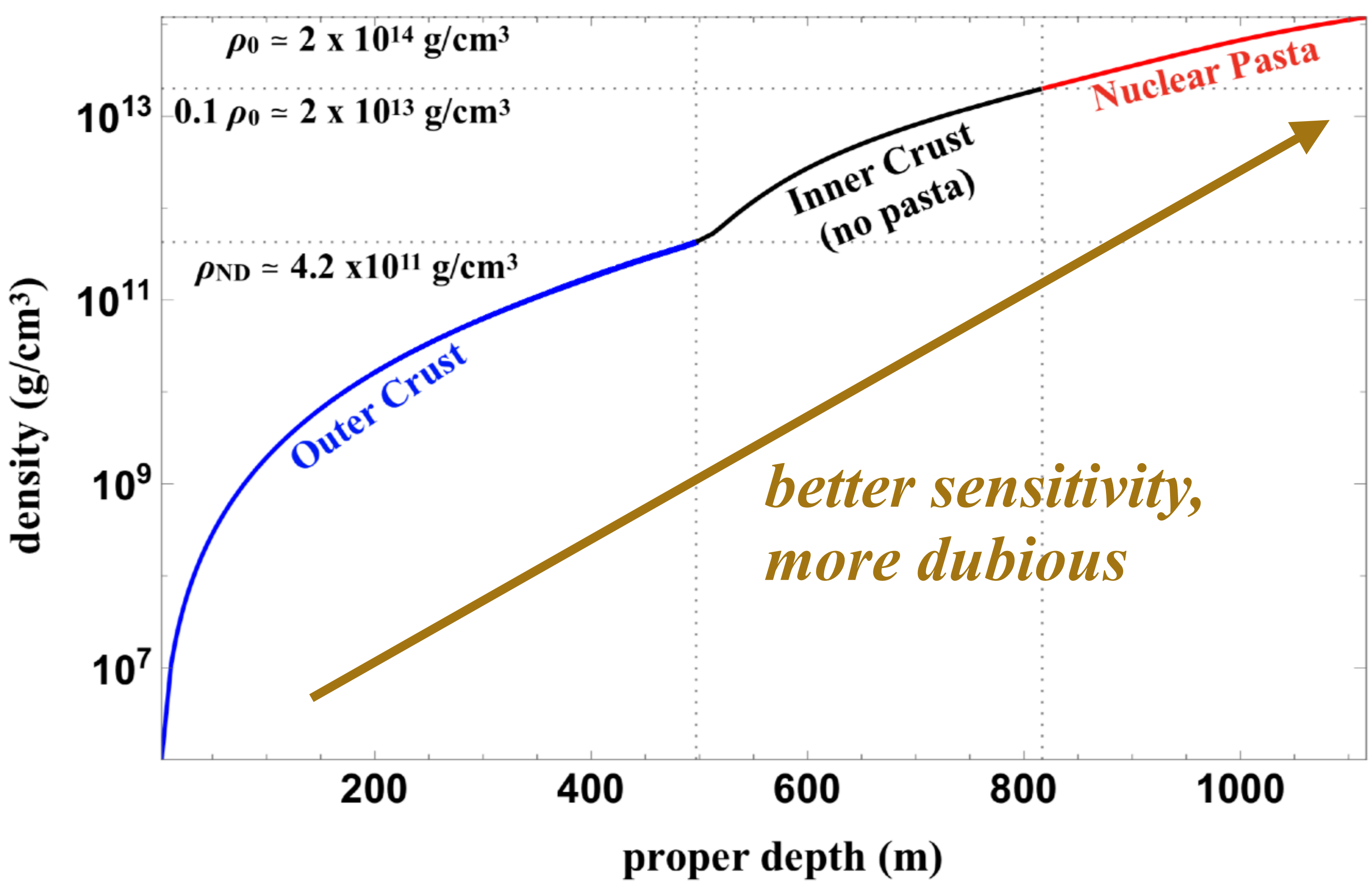




Climbing down the layers

deeper =>
knowledge of structure
more uncertain

worthwhile to investigate capability of every layer to capture dark matter



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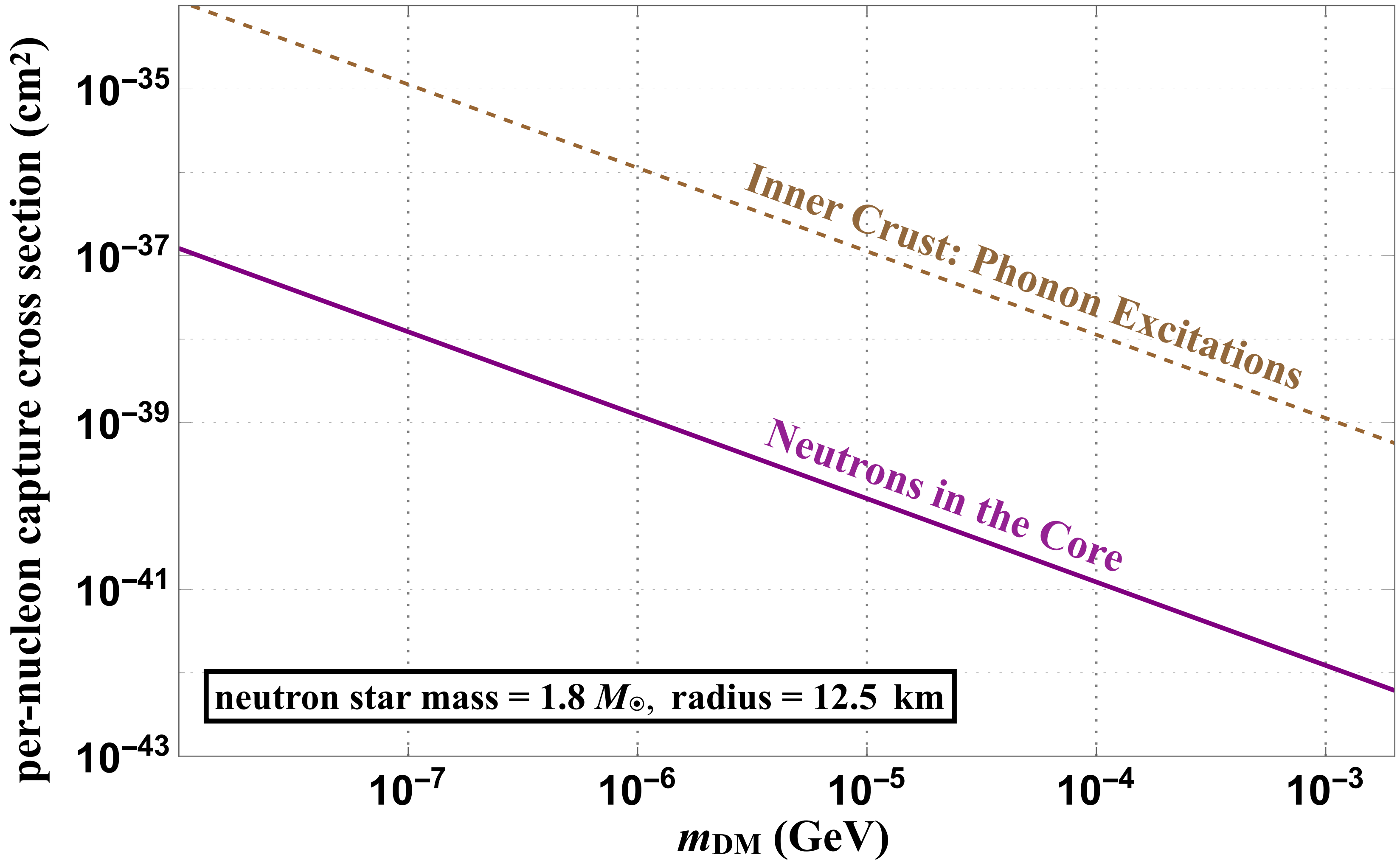
JCAP, 1911.06334

Crust vs low mass dark matter



capture by exciting single superfluid phonon:

energy deposited > halo KE

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

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

↓

q/ (2$m_{\rm n}$ x phonon speed)

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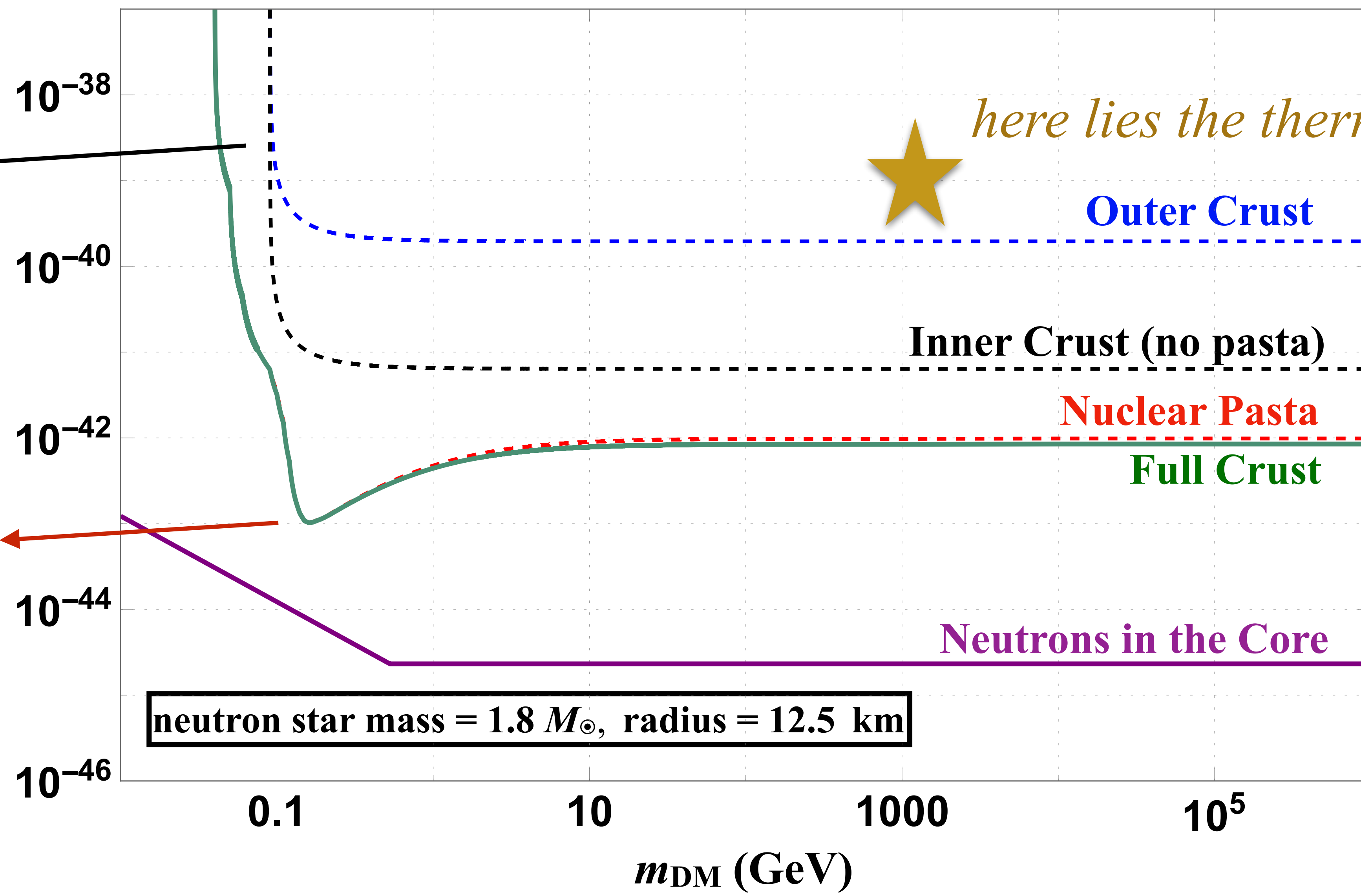
Crust vs WIMPs & heavier dark matter

capture by (quasi-)elastic scattering on *nucleons*

energy transfer < nucleon binding energy ~ 10 MeV

response peak



capture by pasta:

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

response function describing correlations among *nucleons* in pasta

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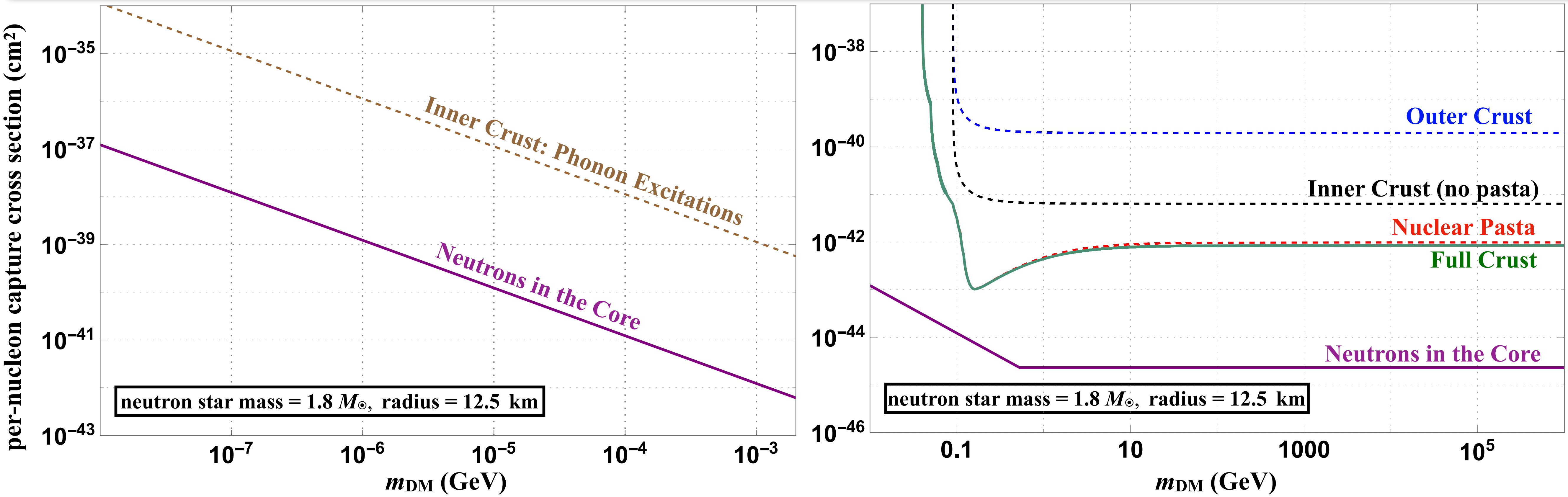
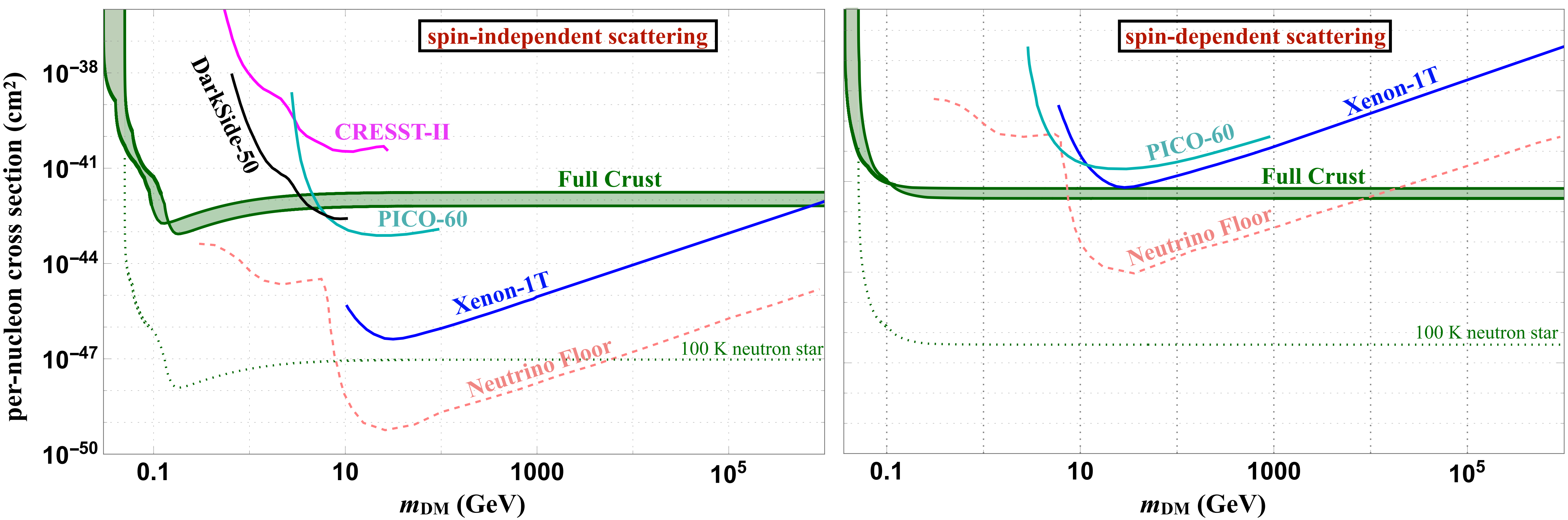
Neutron star crust vs Earth crust



versus direct detection:



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 the direct detection frontiers of

  low mass (sub-GeV) ,
  high mass ($>$ 100 GeV) ,
  spin-dependence ($\sigma_{SD} > 10^{-45}$ cm^2) ,
  velocity-dependence ,
  inelasticity ($<$ GeV splittings) , and
  sub-neutrino floors .

- Exoplanet observers like James Webb and Thirty Meter Telescope can unmask it with a day's worth of exposure.

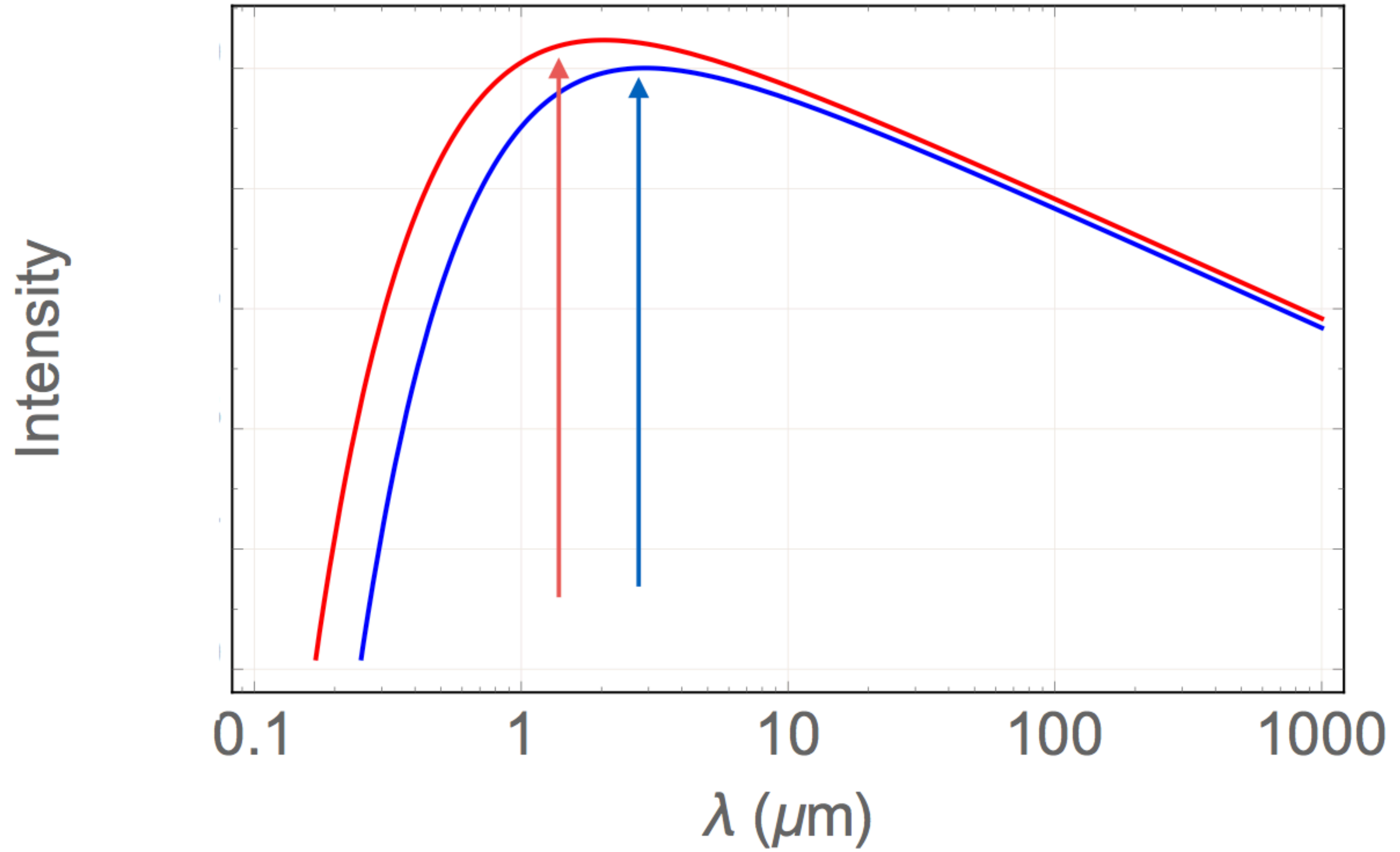
Backup

Brightness diagnosis

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

kinetic heating

+ annihilation



Affects choice of filter, observation time.

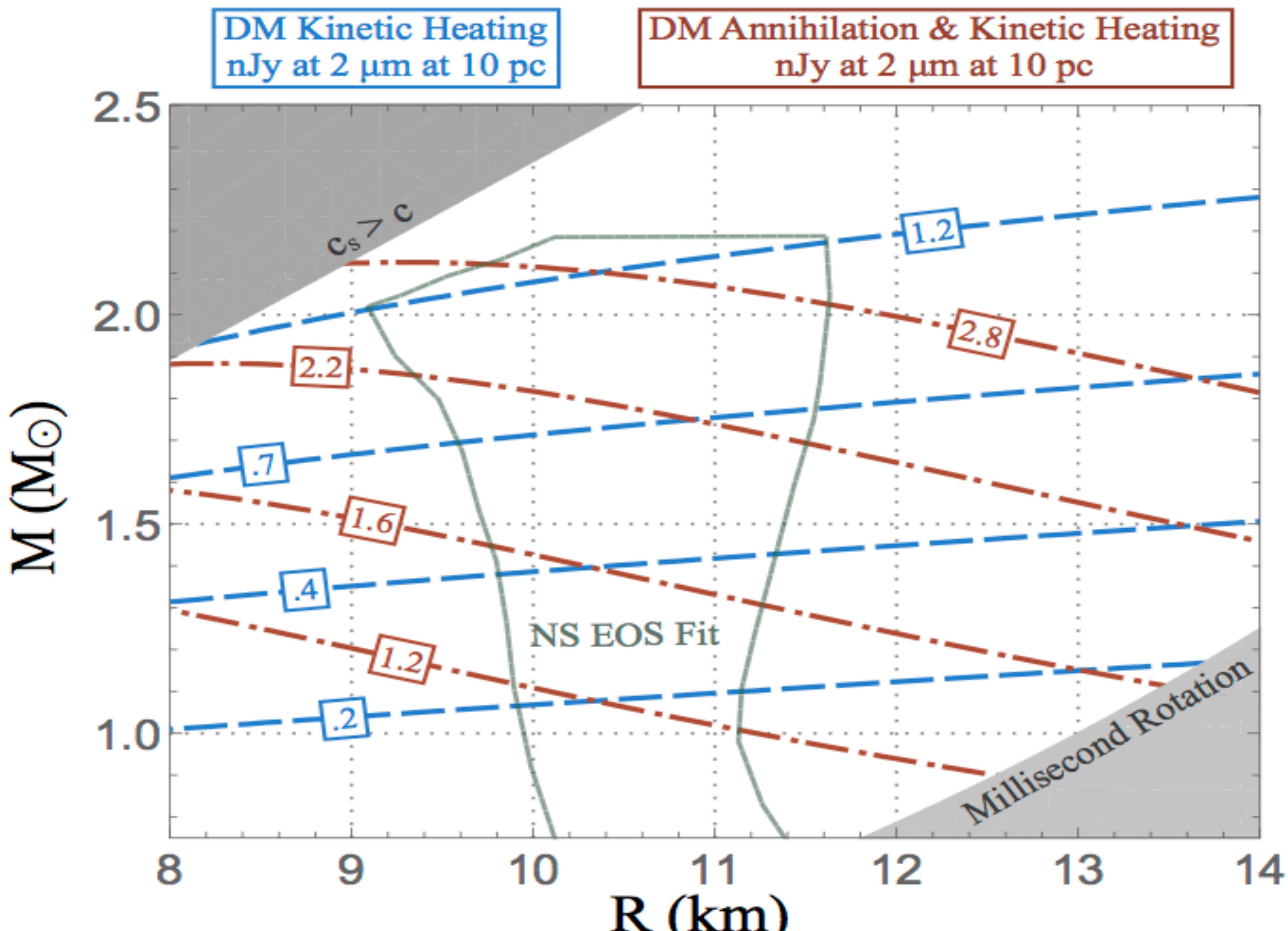
Brightness diagnosis

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

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

kinetic heating

+ annihilation



The importance of being

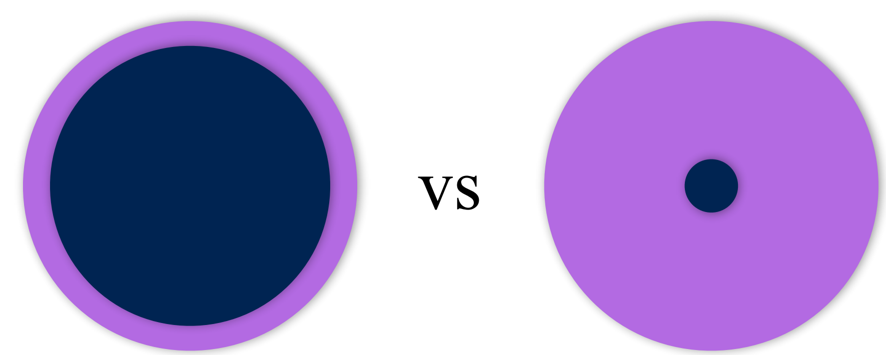
Annihilation saves observation time (= $$)
by a factor of >10!

But how much annihilation is guaranteed?

Asymmetric (with Z_2-given stability) — none
p-wave — very suppressed

Does DM even thermalize with the star?

Affects DM spatial distribution,
hence annihilation rate:



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Dark matter thermalization in neutron stars

Bridget Bertoni,[1,2,*] Ann E. Nelson,[1,†] and Sanjay Reddy[2,‡]

→ Spin-0 DM, vector interaction with quarks

What happens for other spins & interactions?
What if scattering is velocity-suppressed?
inelastic?

Investigation ongoing…

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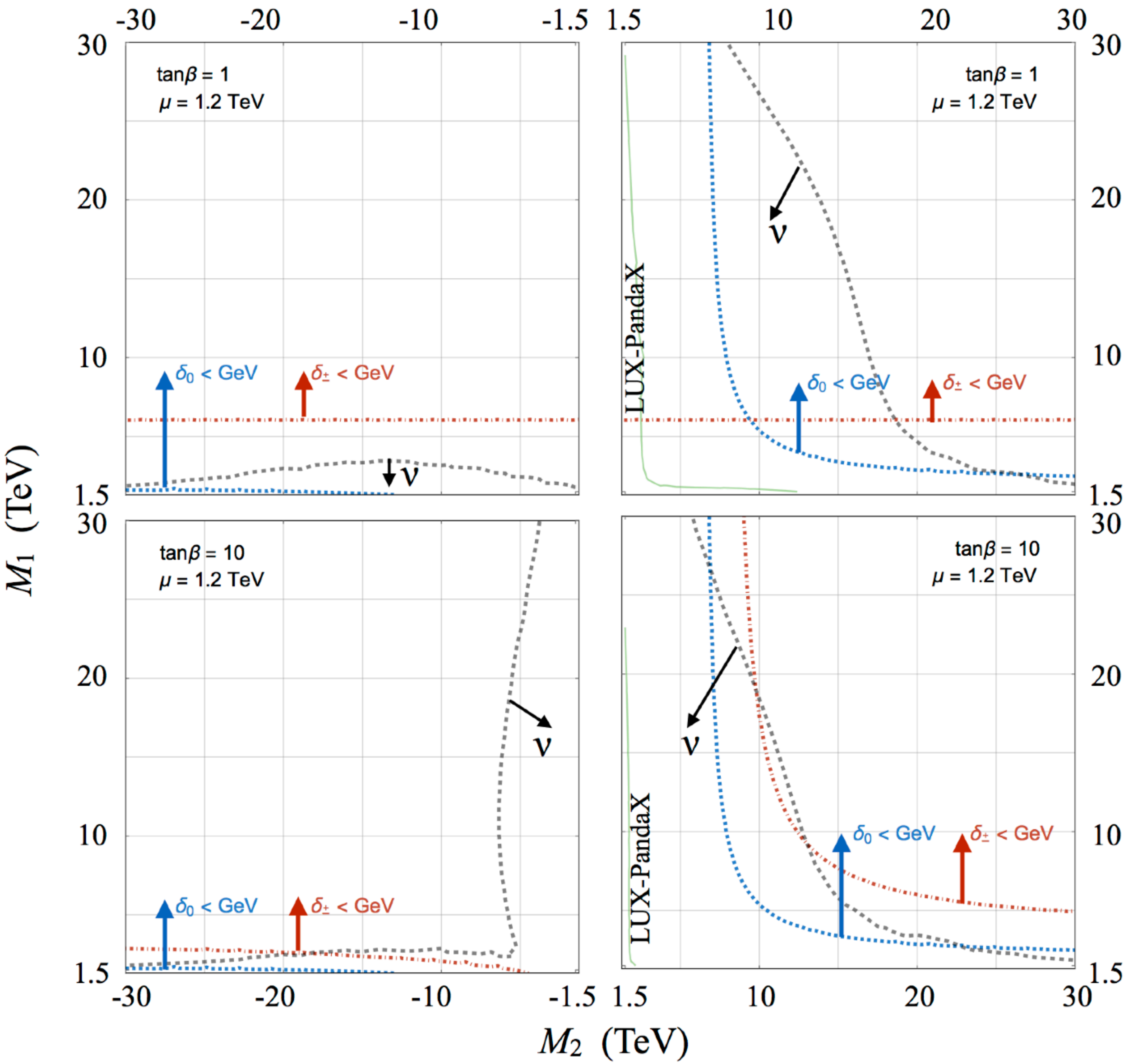


(1) Low mass ✅
(2) High mass ✅
(3) Strong ✅
(4) Spin-dependent ✅
(5) Inelastic ✅

$$\delta_0 \simeq \frac{v^2}{4}\left(\frac{g_1^2}{M_1}+\frac{g_2^2}{M_2}\right),$$

$$\delta_\pm^{\text{tree}} \simeq \frac{v^2}{4}\left(\frac{g_1^2}{M_1}(1+\sin 2\beta)+\frac{g_2^2}{M_2}(1-\sin 2\beta)\right),$$

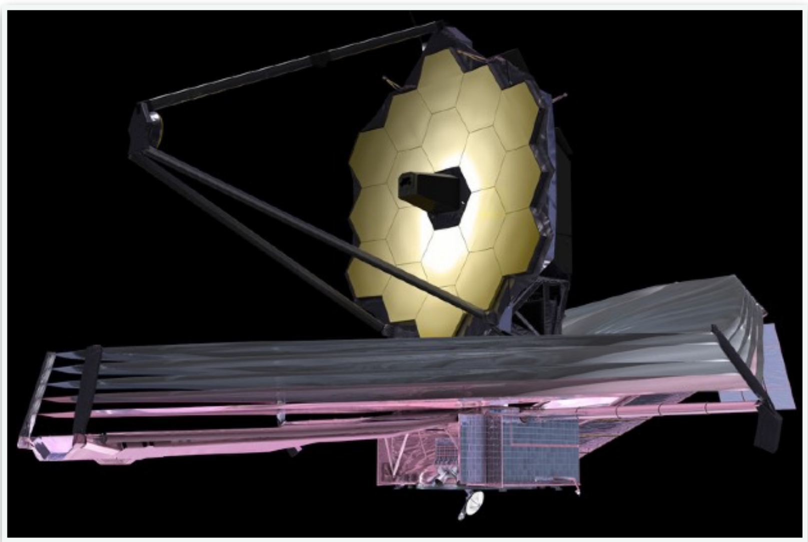
$$\delta_\pm^{\text{loop}} \simeq \left(\frac{g_2}{4\pi}\right)^2 \mu \sin^2\theta_W\, f\left(\frac{m_Z}{\mu}\right),$$

Detection: infrared telescopes

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

backup

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



James Webb

Thirty Meter

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