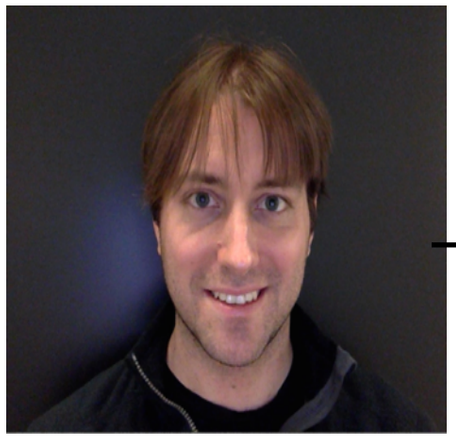
Detecting Dark Matter via Kinetic Heating of Neutron Stars

1704.01577

Nirmal Raj

Notre Dame

Joe Bramante



—*Perimeter*—

Masha Baryakhtar

Shirley Li

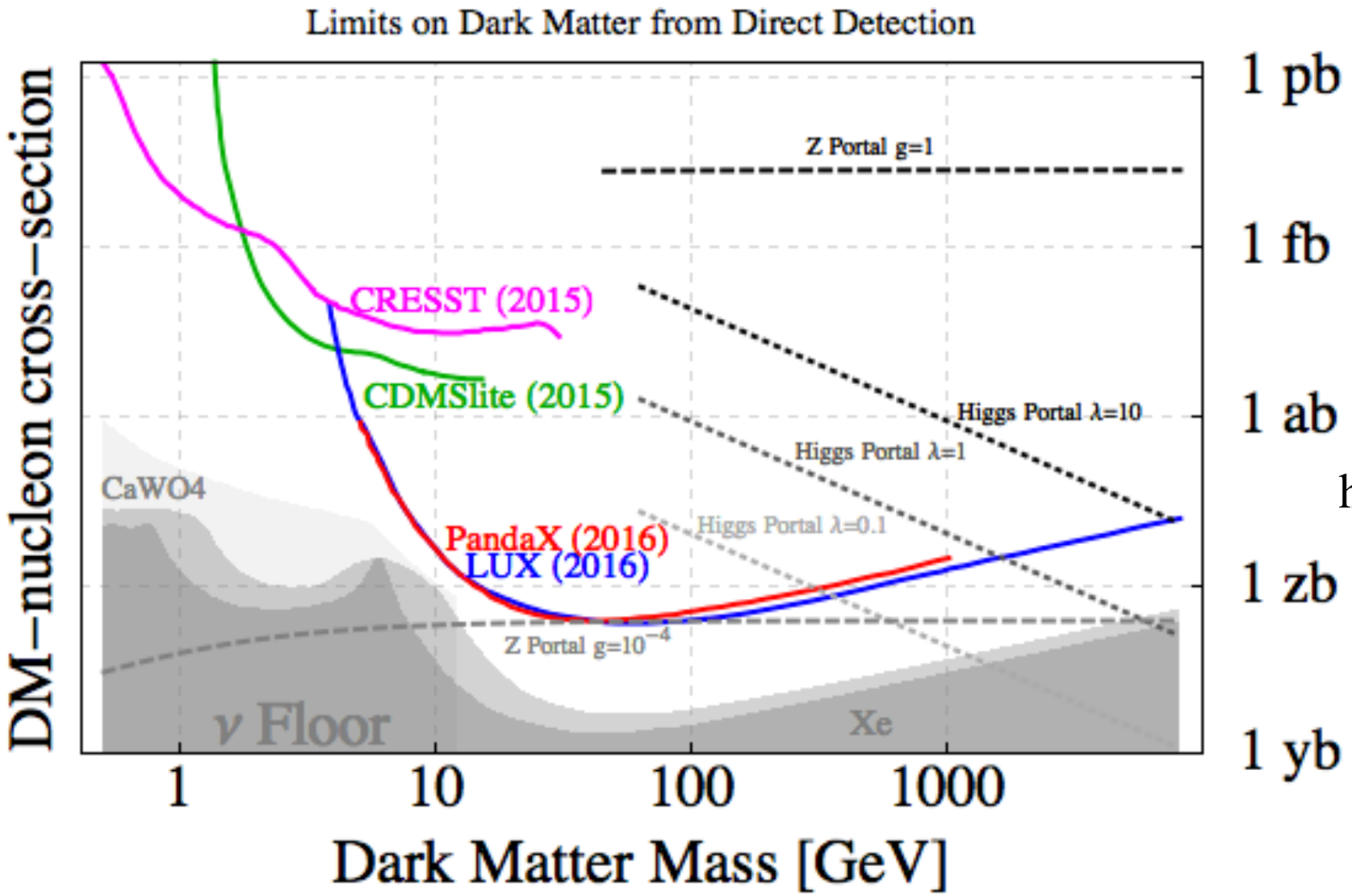
—*OSU*—

Tim Linden

Pheno @ U Pitt
09 May 2017

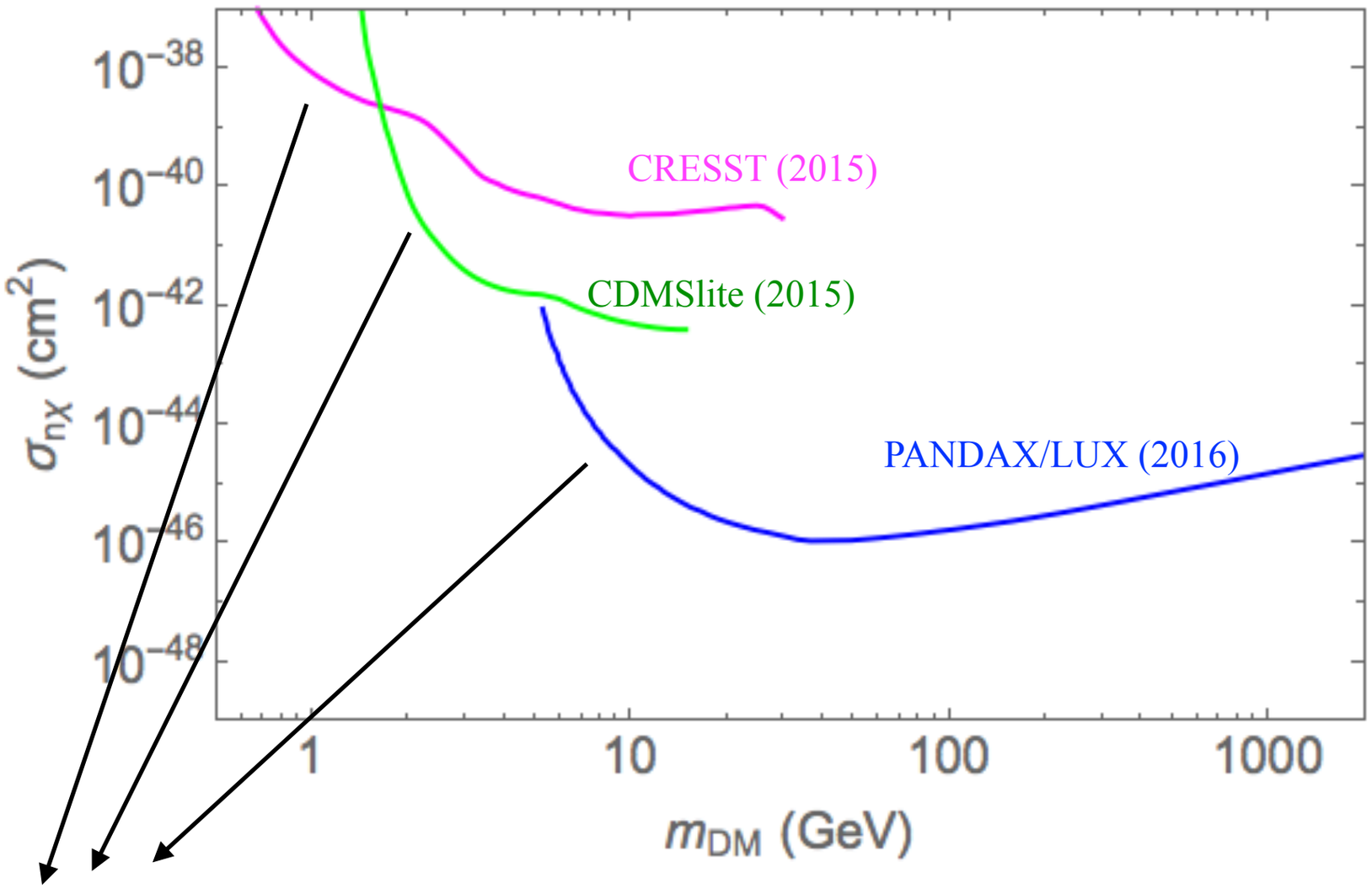
Direct searches: status

After 100 kg-year exposure:



http://resonaances.blogspot.com/

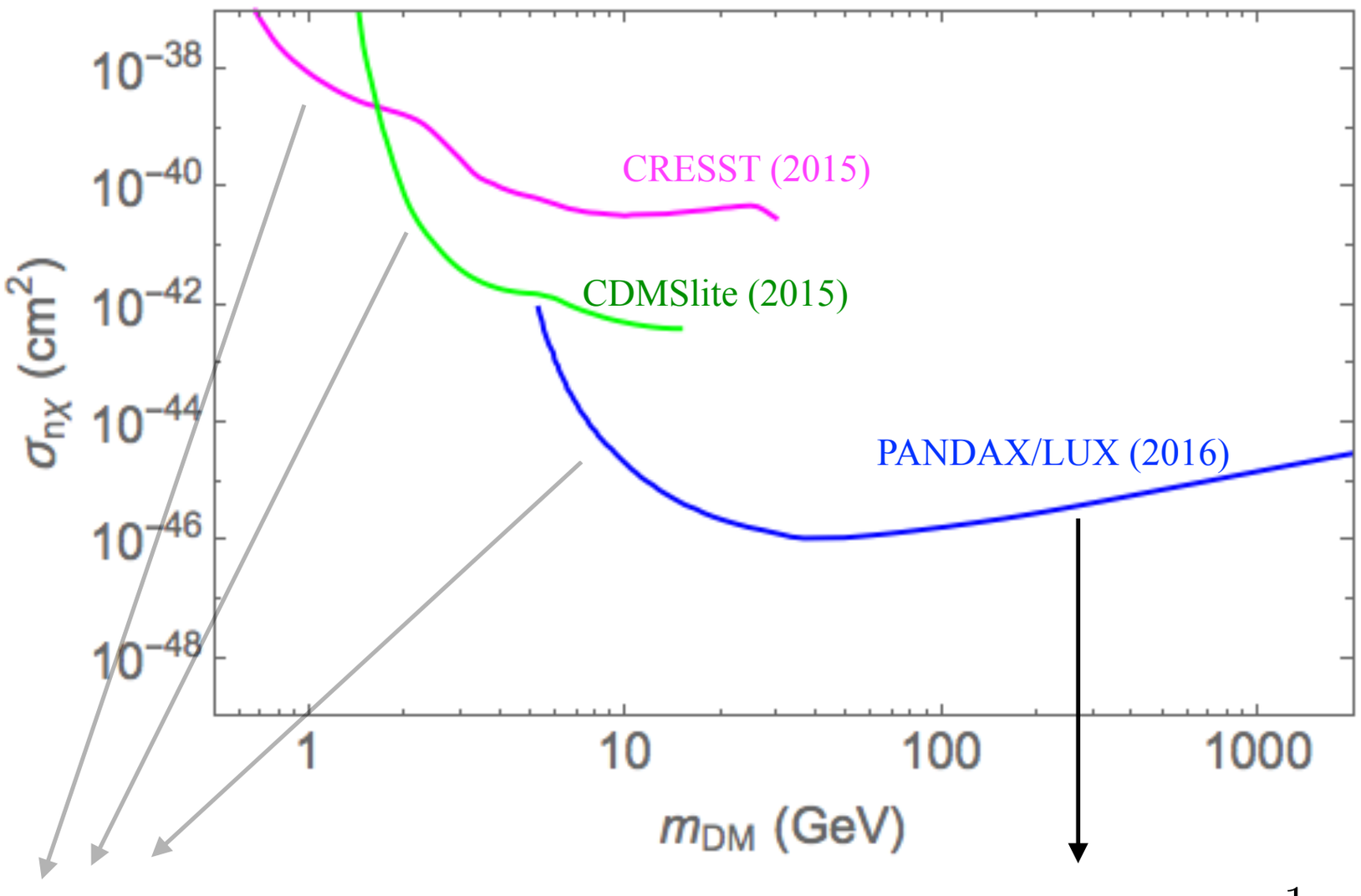
Direct searches: challenges



(1) Nuclear recoil below
detector thresholds at <u>low mass</u>

E.g. light DM + dark photon (1505.00011, 1505.07107), SIMP miracle (1402.5143),
WIMPless miracle (0803.4196), …

Direct searches: challenges

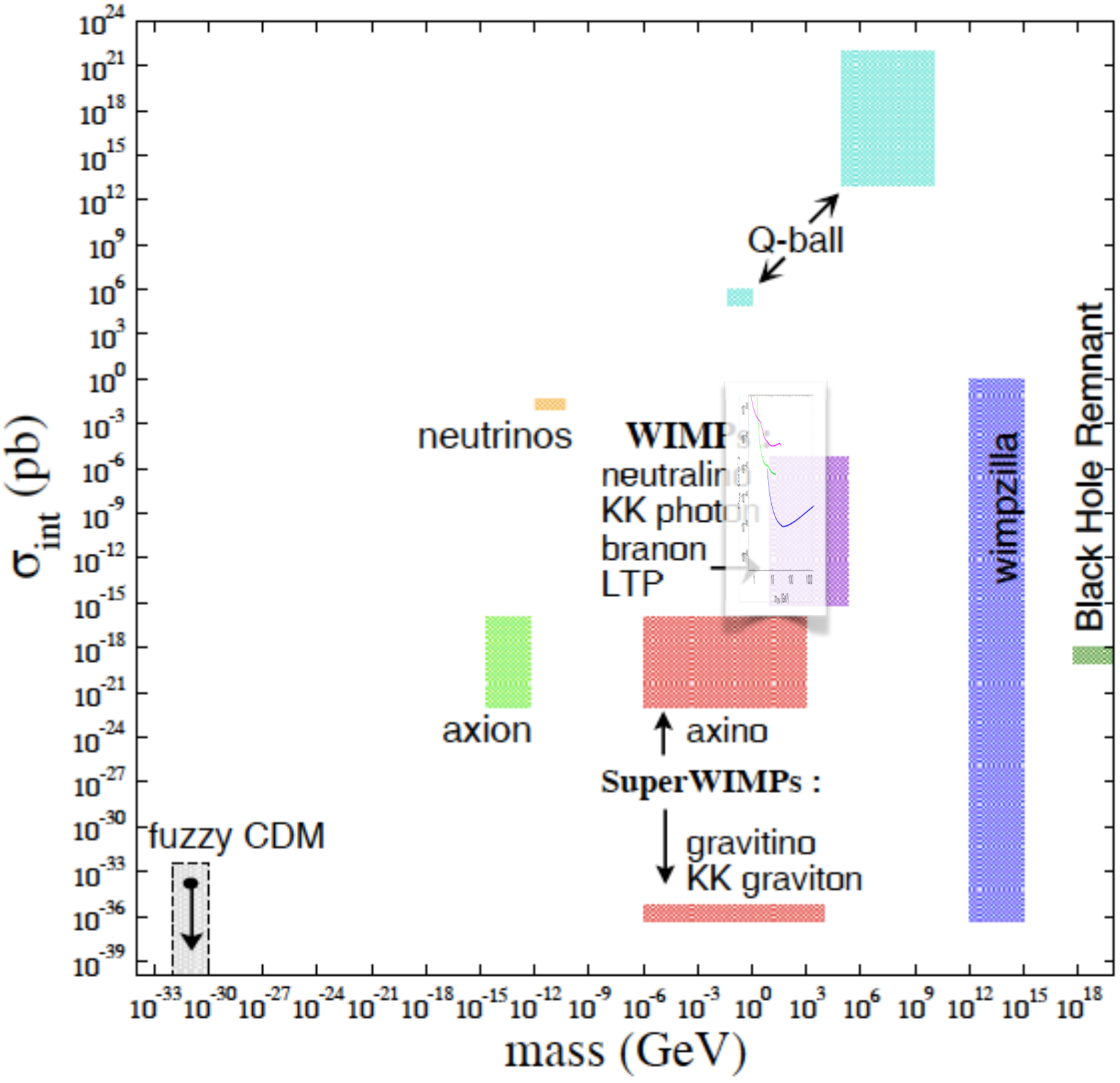


(1) Nuclear recoil below detector thresholds at low mass

(2) DM flux $\propto \frac{1}{m_{\rm DM}}$ at high mass

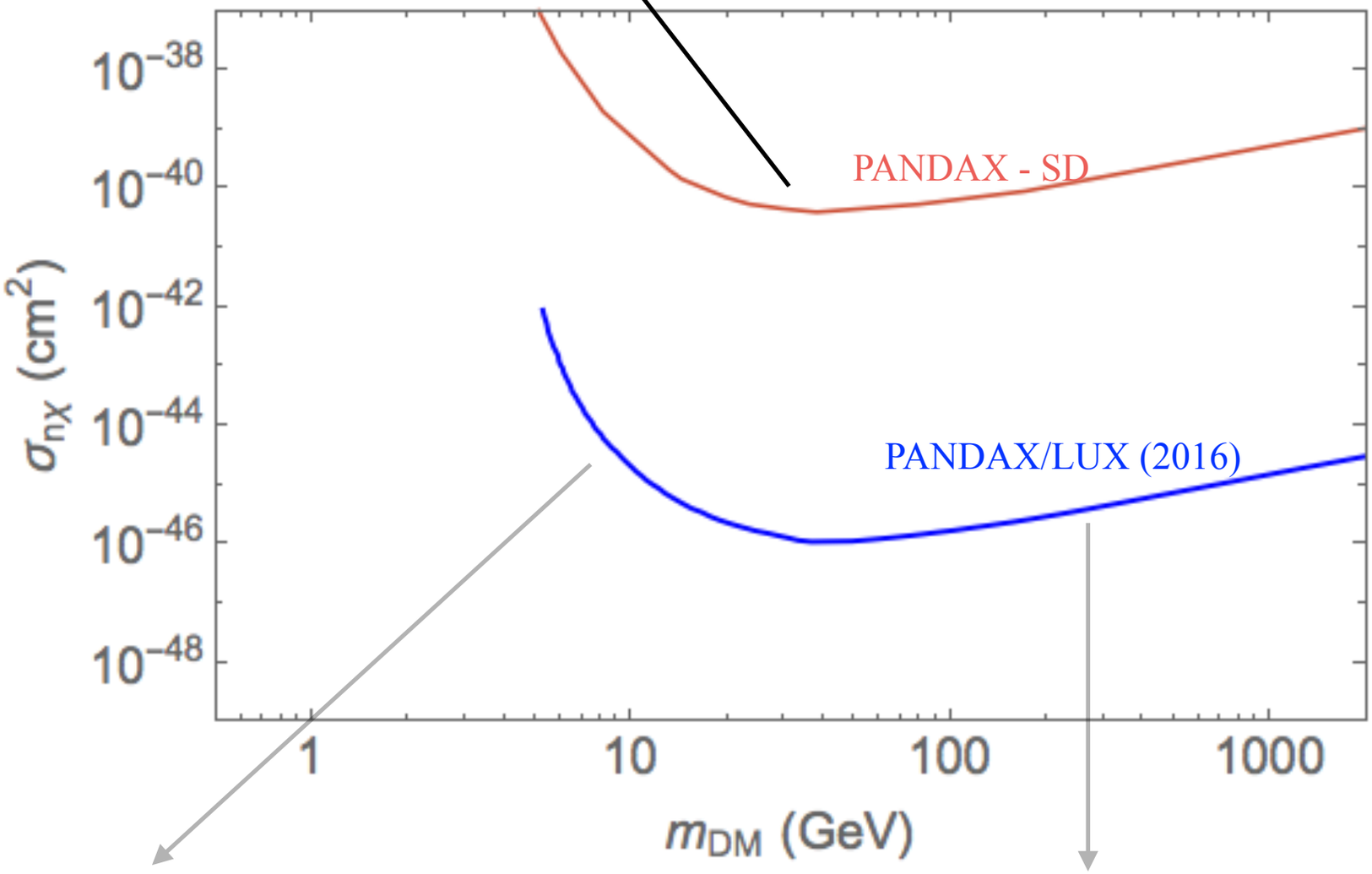
E.g., PeV-scale DM + late-time dilution (1609.02555, 1705.05859), WIMPless miracle (0803.4196), …

(Context)


Q-ball
neutrinos
WIMPs
neutralino
KK photon
branon
LTP
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
wimpzilla
Black Hole Remnant
σint (pb)
mass (GeV)

Direct searches: challenges

(3) No nuclear coherence
if scattering <u>spin-dependent</u>: $\sigma_{\rm nucleon} = \left(\frac{1}{A}\right)^2 \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \sigma_{\rm Nucleus}$



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

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(2) DM flux $\propto \frac{1}{m_{\rm DM}}$ at <u>high mass</u>

Direct searches: challenges

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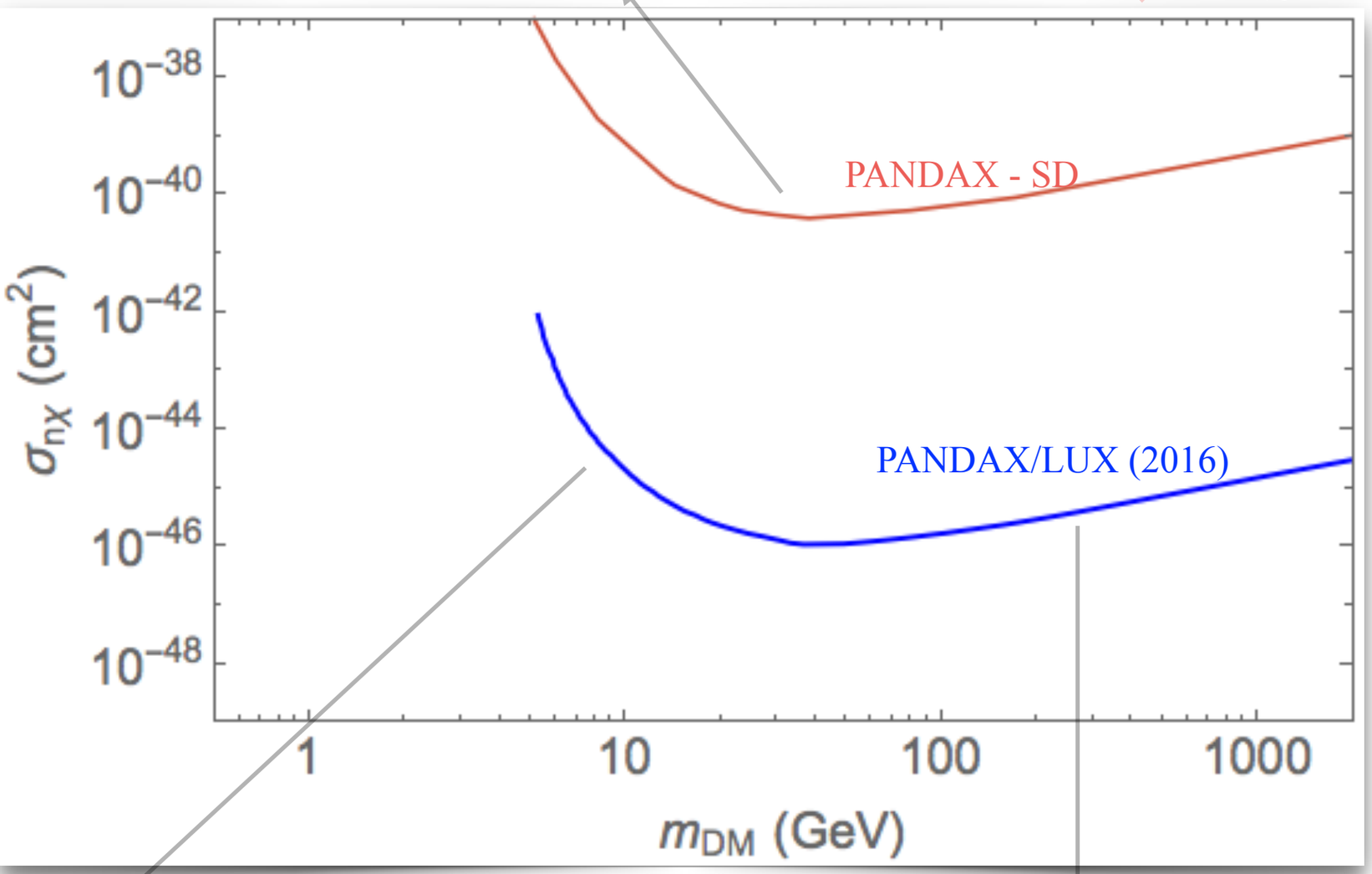
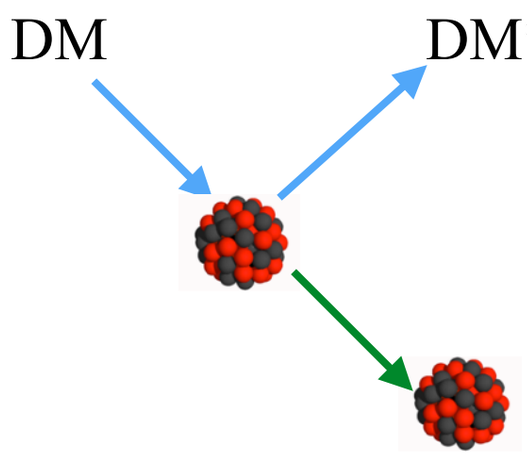


(1) Nuclear recoil below detector thresholds at low mass

(2) DM flux $\propto \frac{1}{m_{\rm DM}}$ at high mass

(Image: G. Kribs)



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

(4) If scattering inelastic, no recoil when

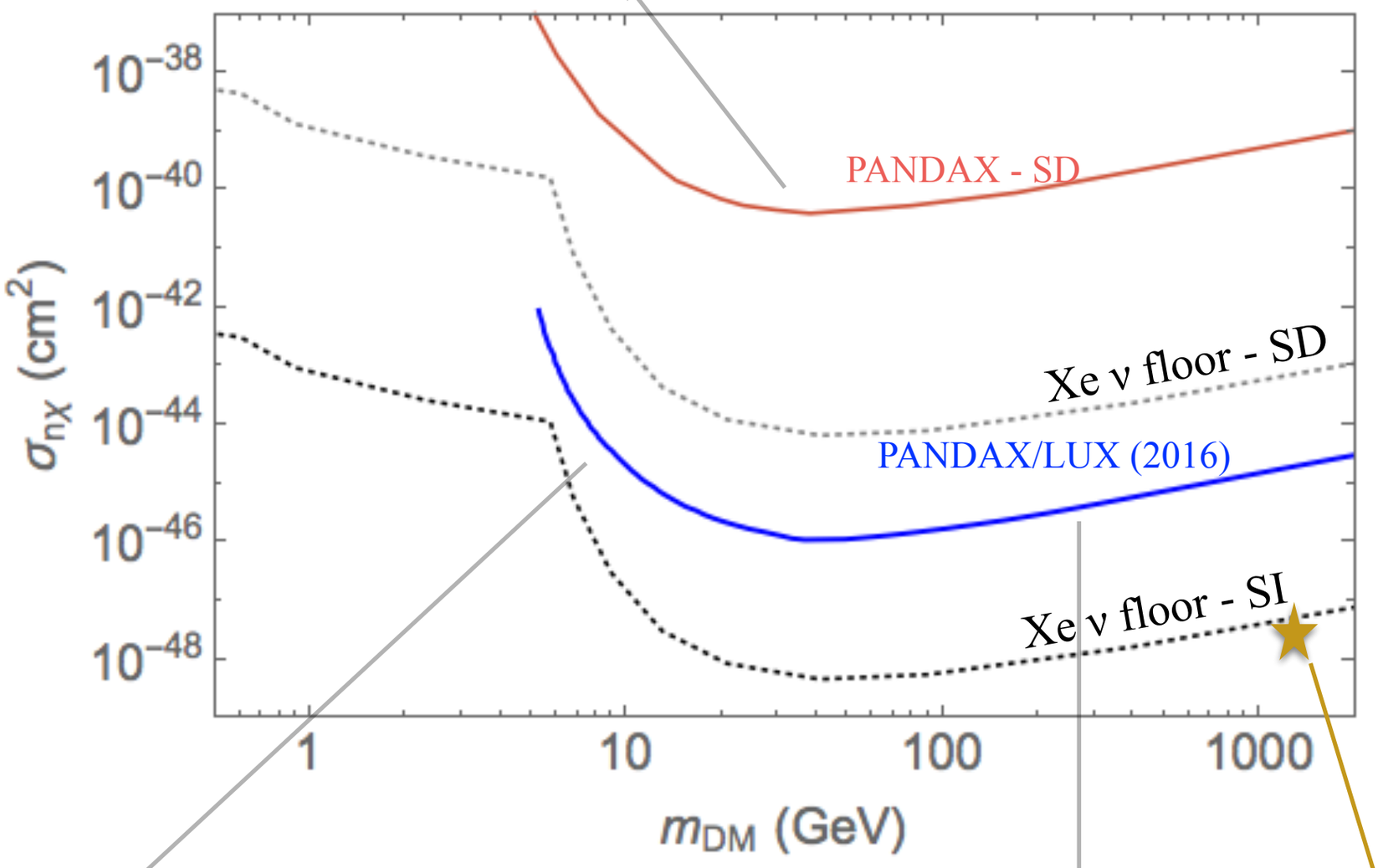
$\delta > 2\mu_{N\chi} v_{\rm DM}^2 = \mathcal{O}(100{\rm keV})$

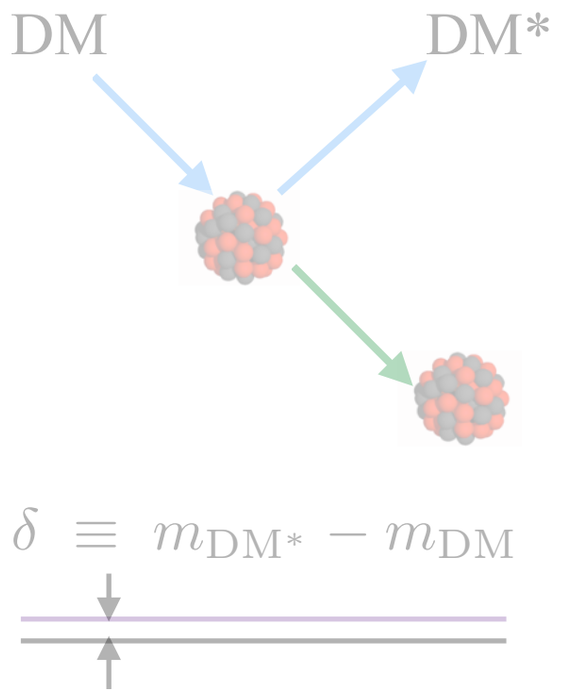
Tucker-Smith, Weiner 0101138, 0402065,
Barello, Chang, Newby 1409.0536

E.g. Higgsino tree-level *Z/W* exchange, pseudo-Dirac DM + dark photon, …

Direct searches: challenges

(3) No nuclear coherence
if scattering spin-dependent: $\sigma_{\rm nucleon} = \left(\frac{1}{A}\right)^2 \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \sigma_{\rm Nucleus}$





(1) Nuclear recoil below detector thresholds at low mass

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(4) If scattering inelastic, no recoil when

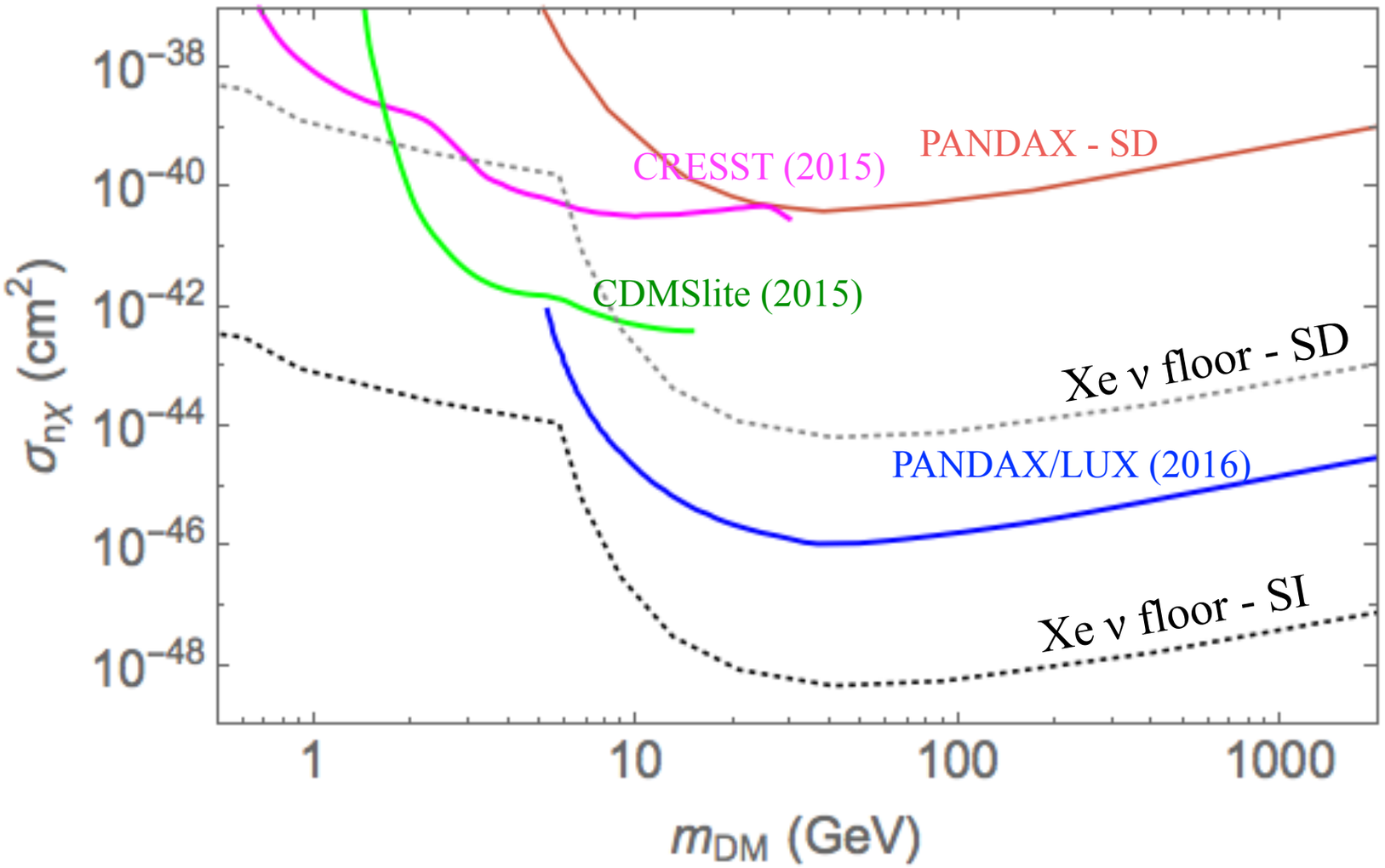
$\delta > 2\mu_{N\chi} v_{\rm DM}^2 = \mathcal{O}(100{\rm keV})$

(5) Atmospheric + solar neutrino background

E.g. Higgsino elastic scattering (loops)

Hill & Solon 1408.8290

Direct searches: challenges



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

Crucial frontiers — beyond which dark matter could be.

(Dark) Kinetic Heating

Soup getting cold

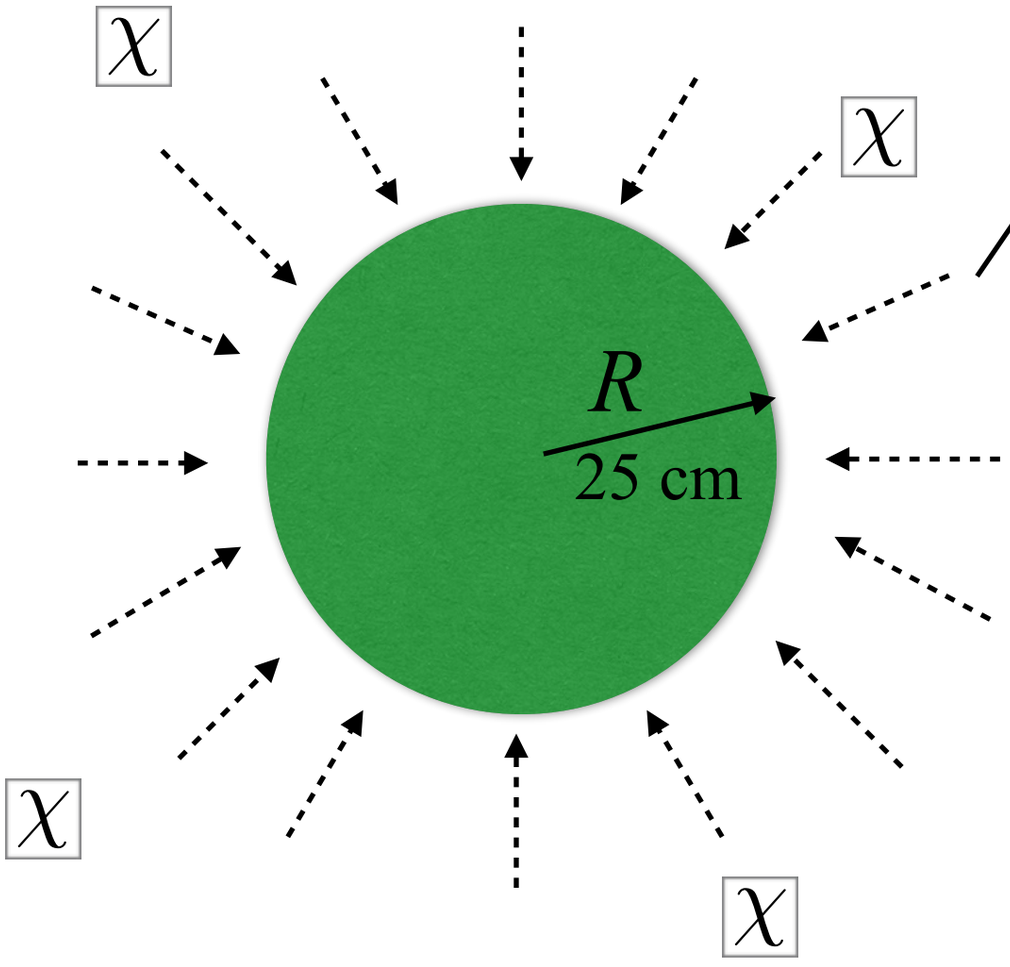
$$CM\frac{dT}{dt} = -\sigma_{\mathrm{SB}}(\mathrm{Area})(T^4 - T^4_{\mathrm{ambient}})$$

Keeping soup hot: fire

$$CM\cancel{\frac{dT}{dt}}^{0} = -\sigma_{\mathrm{SB}}(\mathrm{Area})(T^4 - T_{\mathrm{ambient}}^4) + \dot{E}_{\mathrm{external}}$$

Keeping soup hot: dark fire

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

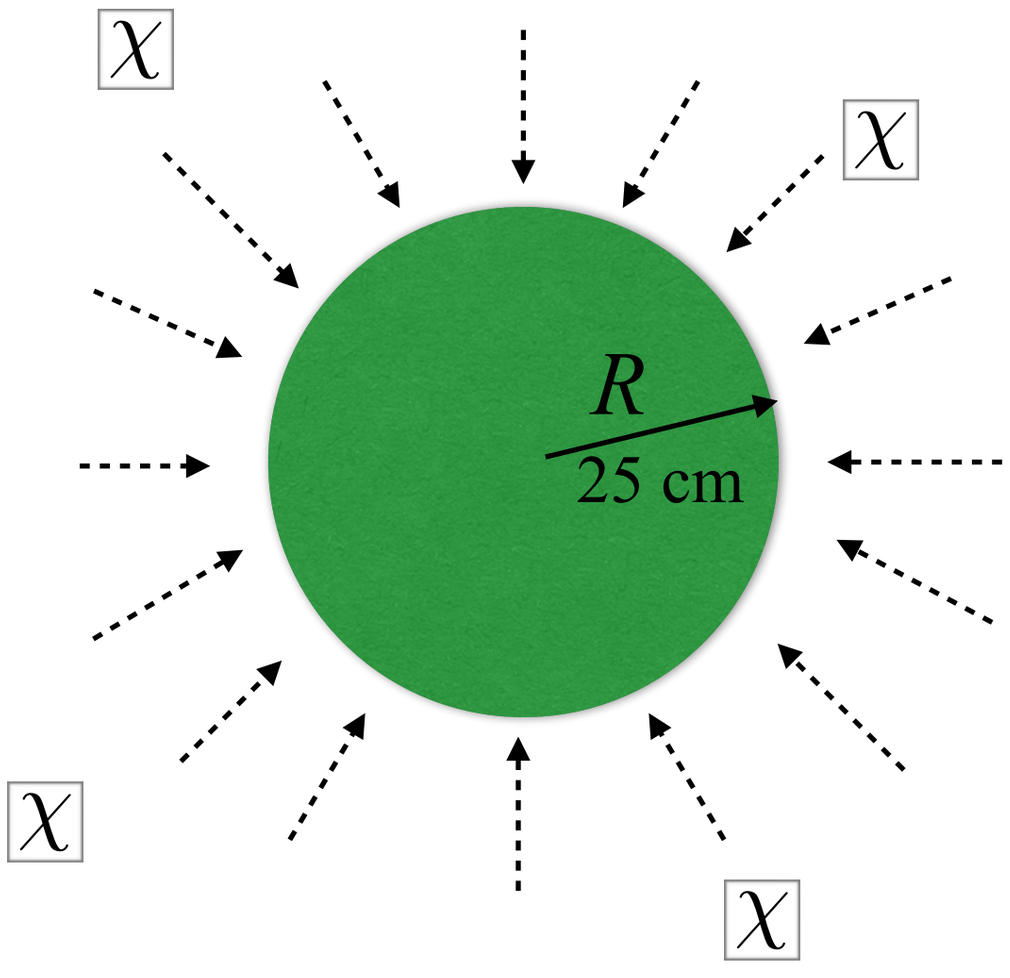


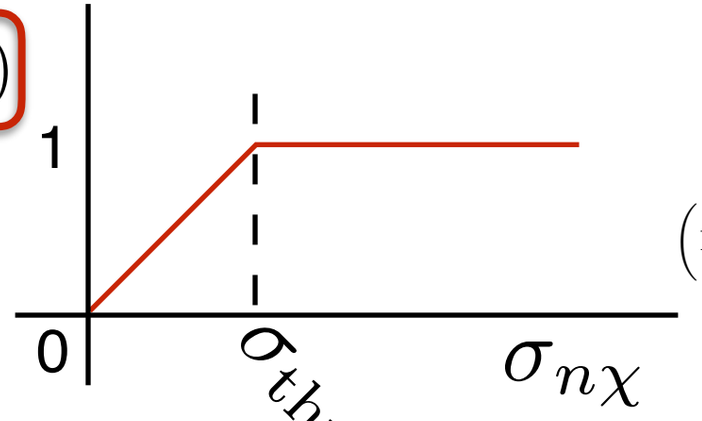
Keeping soup hot: dark fire

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

($CM\frac{dT}{dt}$ → 0)

$$\dot{E}_{\rm external} \to f(\sigma_{n\chi}) \times \frac{dN}{dt} \times \text{KE}$$



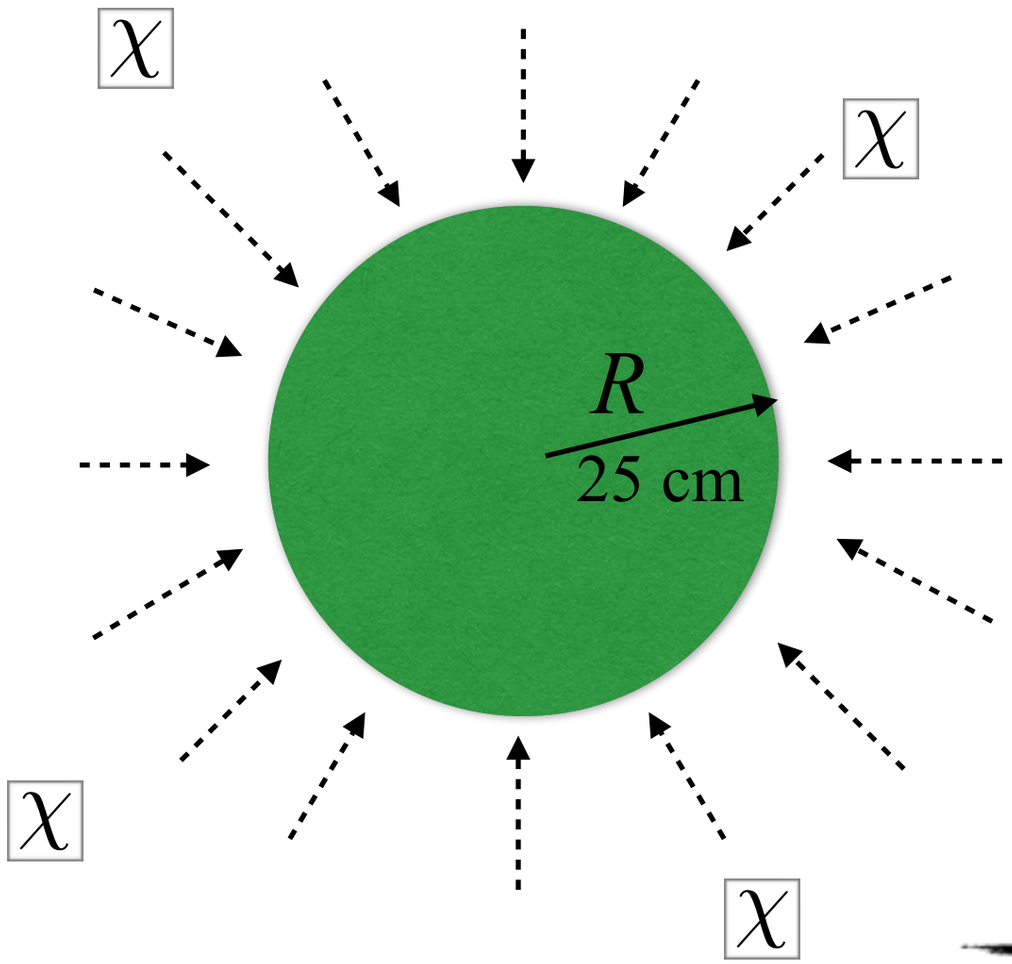


$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold}R\right)$$

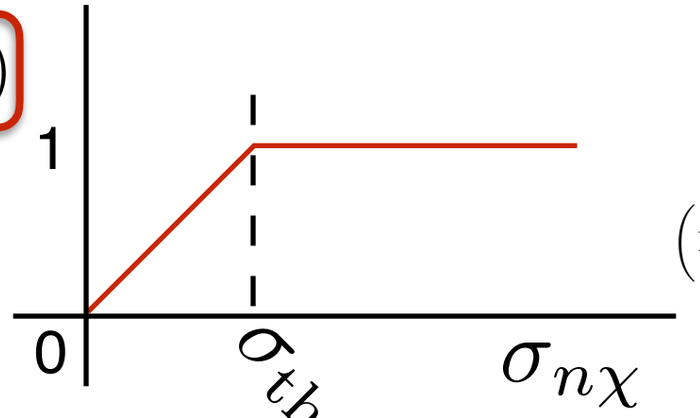
$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}\text{cm}^2$$

Keeping soup hot: dark fire

$$\cancel{CM\frac{dT}{dt}}^{\,0} = -\sigma_{\rm SB}(\text{Area})T^4 + \dot{E}_{\rm external} \rightarrow \boxed{f(\sigma_{n\chi})} \times \boxed{\frac{dN}{dt}} \times \boxed{\text{KE}}$$



$f(\sigma_{n\chi})$



$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold}R\right)$$

$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}\text{cm}^2$$

$\frac{dN}{dt}$ Current limit:
1 scatter/ 400 years

KE $\frac{1}{2}m_{\rm DM}v_{\rm DM}^2 = \frac{1}{2}m_{\rm Nitrogen}(.001)^2$

$T = 3$ nanoKelvin

Detector improvements

$$CM\frac{dT}{dt} = -\sigma_{\rm SB}({\rm Area})T^4 + \dot{E}_{\rm external} \to f(\sigma_{n\chi}) \times \frac{dN}{dt} \times \boxed{\rm KE}$$

0

$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}{\rm cm}^2$$

Bigger
and denser

KE $\frac{1}{2} m_{\rm DM} v_{\rm DM}^2$

T = 3 nanoKelvin

Detector improvements

$$\cancelto{0}{CM\frac{dT}{dt}} = -\sigma_{\rm SB}(\text{Area})T^4 + \dot{E}_{\rm external} \rightarrow \boxed{f(\sigma_{n\chi}) \times \frac{dN}{dt} \times \boxed{\text{KE}}}$$

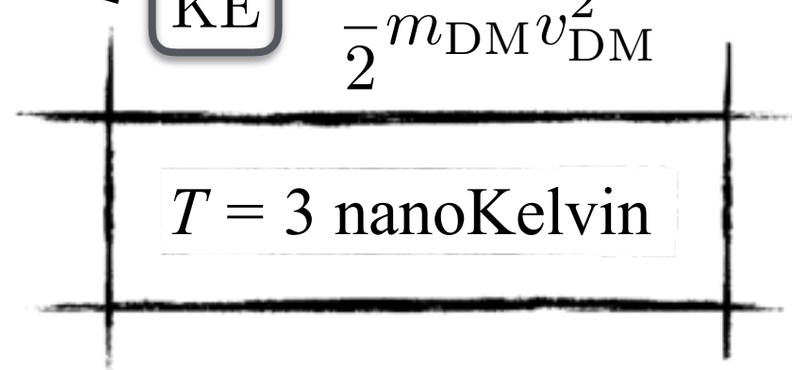
$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}\text{cm}^2$$

Bigger
and denser

Get a gravitational boost!

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

$\boxed{\text{KE}}$ $\frac{1}{2}m_{\rm DM}v_{\rm DM}^2$



Detector improvements

$$CM\frac{dT}{dt} = -\sigma_{\rm SB}({\rm Area})T^4 + \dot{E}_{\rm external} \to f(\sigma_{n\chi}) \times \frac{dN}{dt} \times \boxed{\rm KE}$$

0

$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}{\rm cm}^2$$

Bigger
and denser

Get a gravitational boost!

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

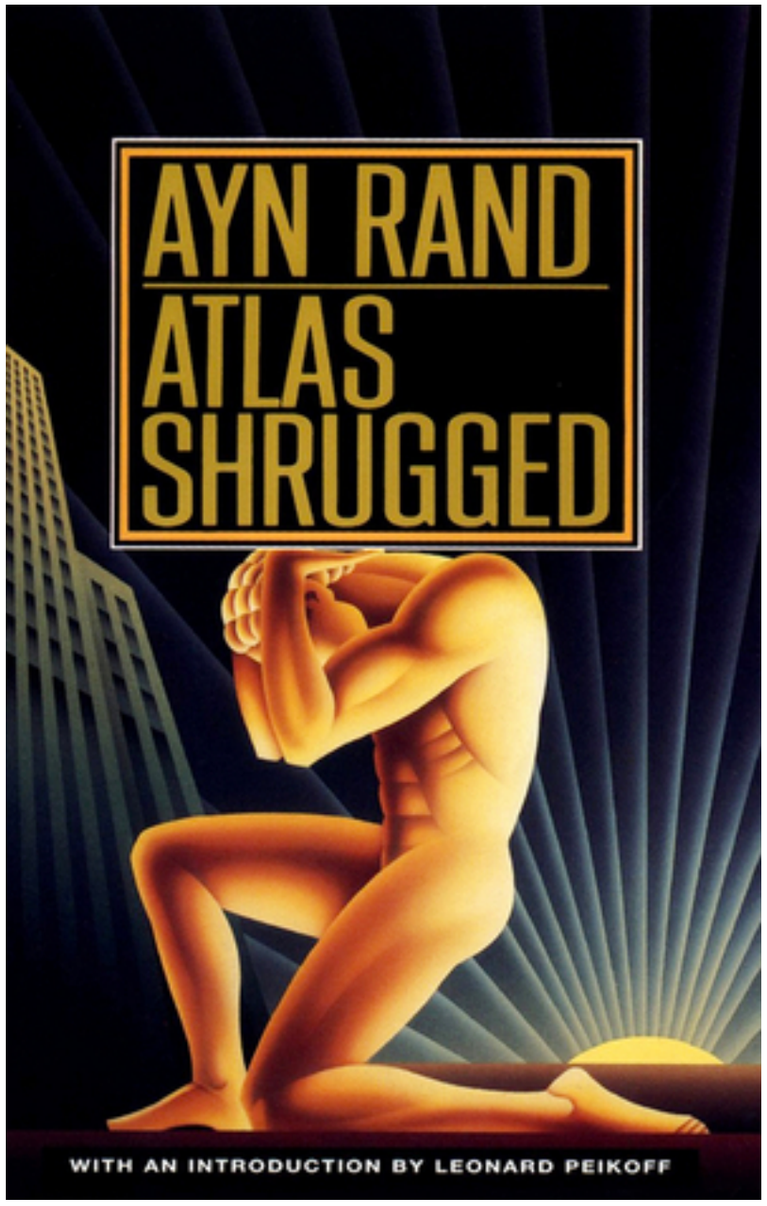
Be colder than
dark-kinetically-heated
temperature

KE $\frac{1}{2} m_{\rm DM} v_{\rm DM}^2$

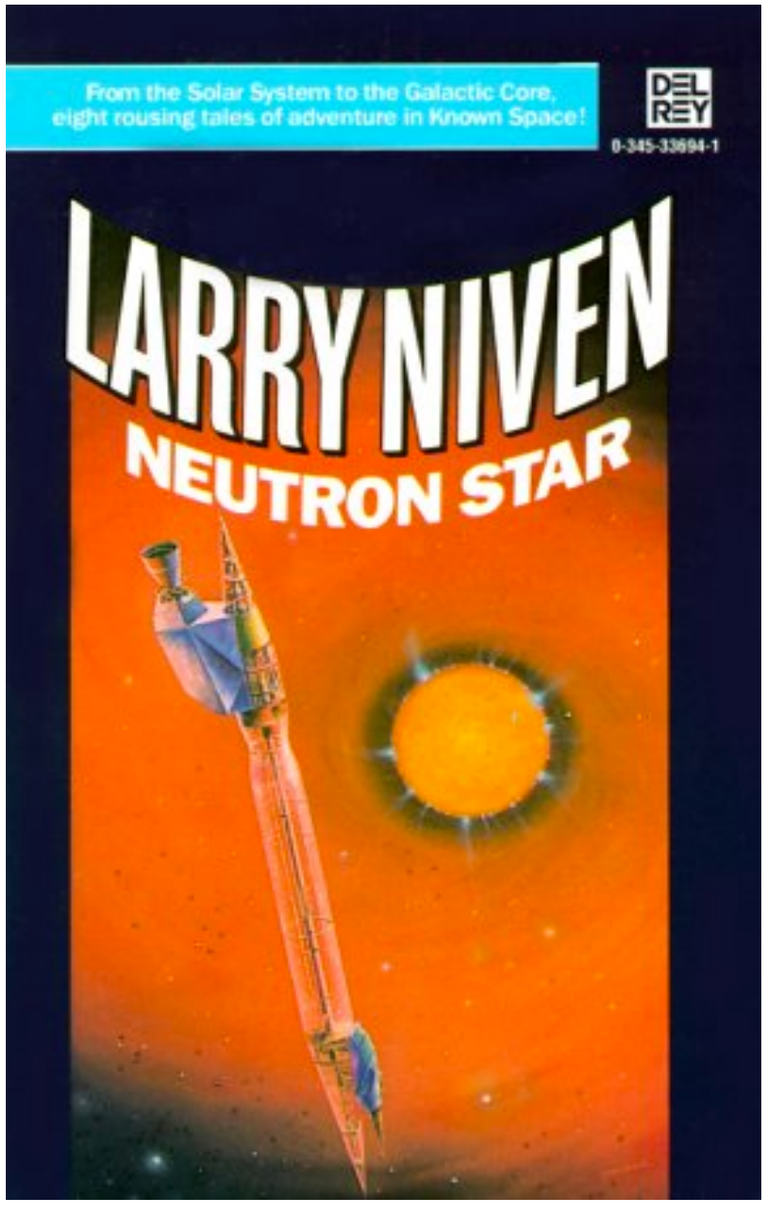
$T = 3$ nanoKelvin

What’s big, dense, and cold?

What's big, dense, and cold?

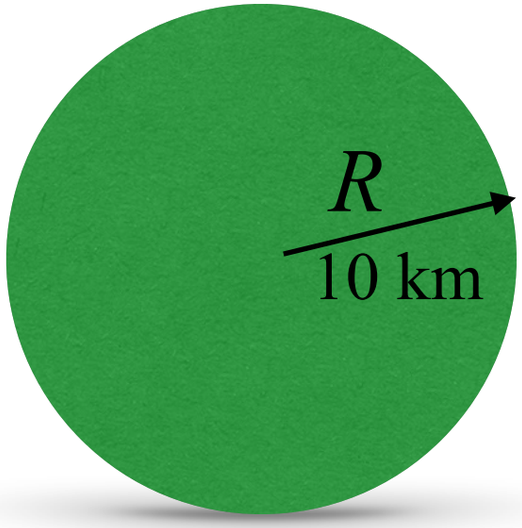


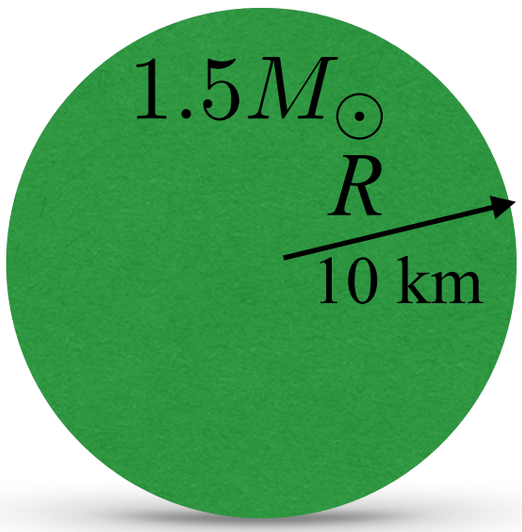
What's big, dense, and cold?



CHICAGO
HALF MARATHON/5K
20 YEARS
SUNDAY, SEPTEMBER 25, 2016
HALF MARATHON - 7:00 AM 5K - 7:45 AM
Race Start
Race Finish
Course Route
Mile Markers
Medical Aid
Fluid Station
Food
Finish Festival
Restrooms
Volunteer Check-in
Gear Check
Skratch Labs Hydration
GU Energy Gels
Shuttle Drop Off/Pick Up
Metra Station

big


R
10 km



$$v_{\rm esc} \simeq 0.7$$

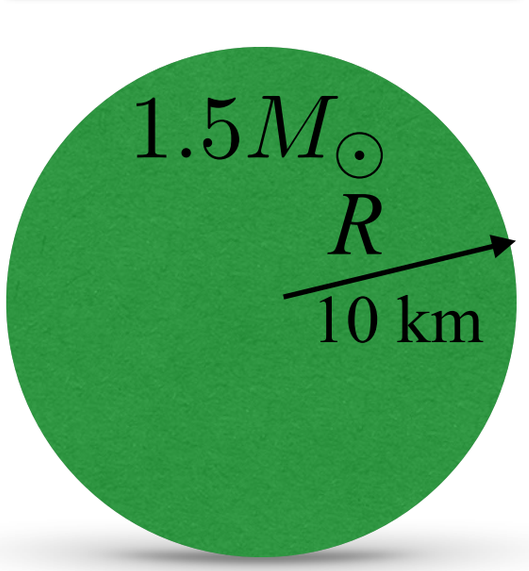
big, dense

7×10^{17} kg/m^3

Lake Michigan (weighing 5×10^{12} kg) in a teaspoon

big, dense, and cold

7×10^{17} kg/m^3



$v_{\rm esc} \simeq 0.7$

Lake Michigan (weighing 5×10^{12} kg) in a teaspoon

20 My old: $T_{\rm eff} \lesssim 1000$ K

1 By old: $T_{\rm eff} \sim 100$ K cf. snowball

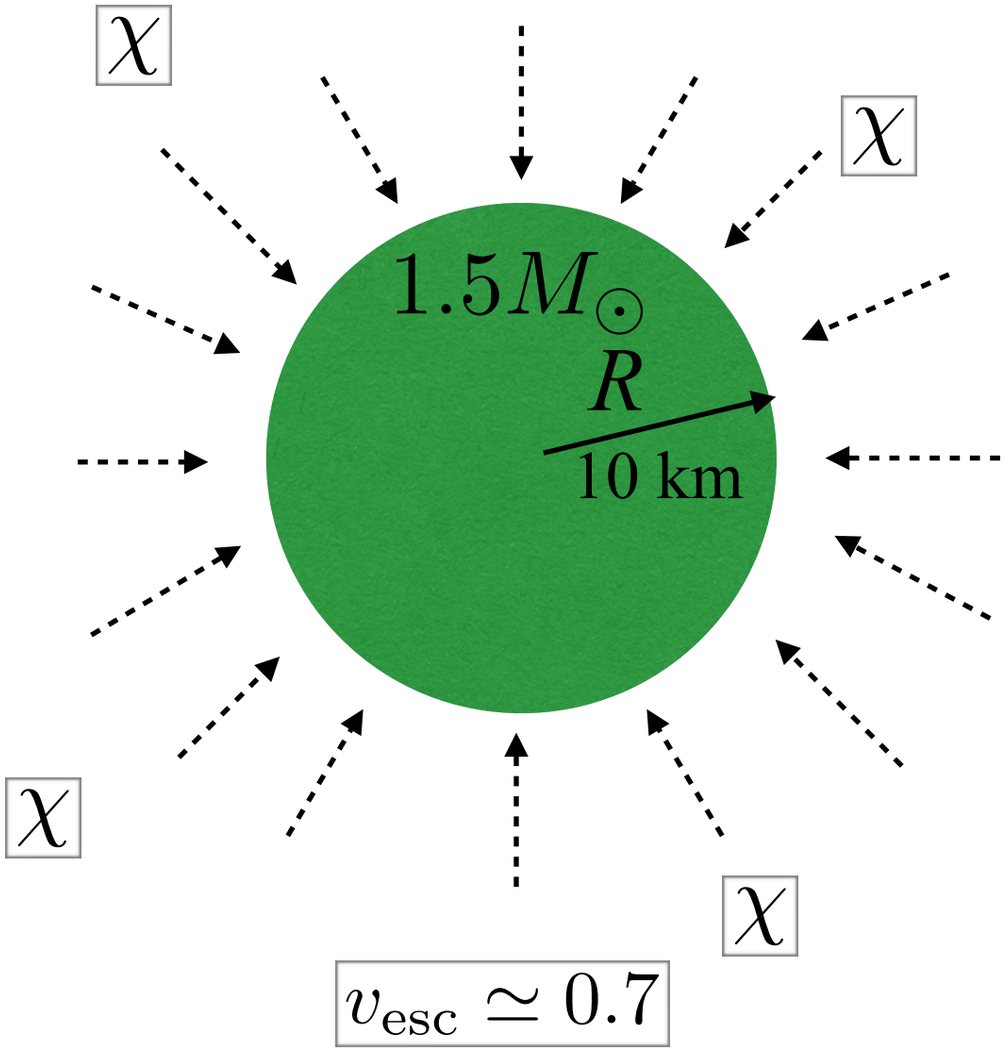
Page, Lattimer, Prakash, Steiner (2004)
Yakovlev, Pethick (2004)

Keeping N star hot: dark fire

$$\cancel{CM\frac{dT}{dt}}^{\,0} = -\sigma_{\rm SB}(\text{Area})T^4 + \dot{E}_{\rm external} \to \boxed{f(\sigma_{n\chi})} \times \boxed{\frac{dN}{dt}} \times \boxed{\text{KE}}$$

$\boxed{f(\sigma_{n\chi})}$ $\sigma_{\rm threshold} \sim 10^{-45}\ {\rm cm}^2$

$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold} R\right)$$



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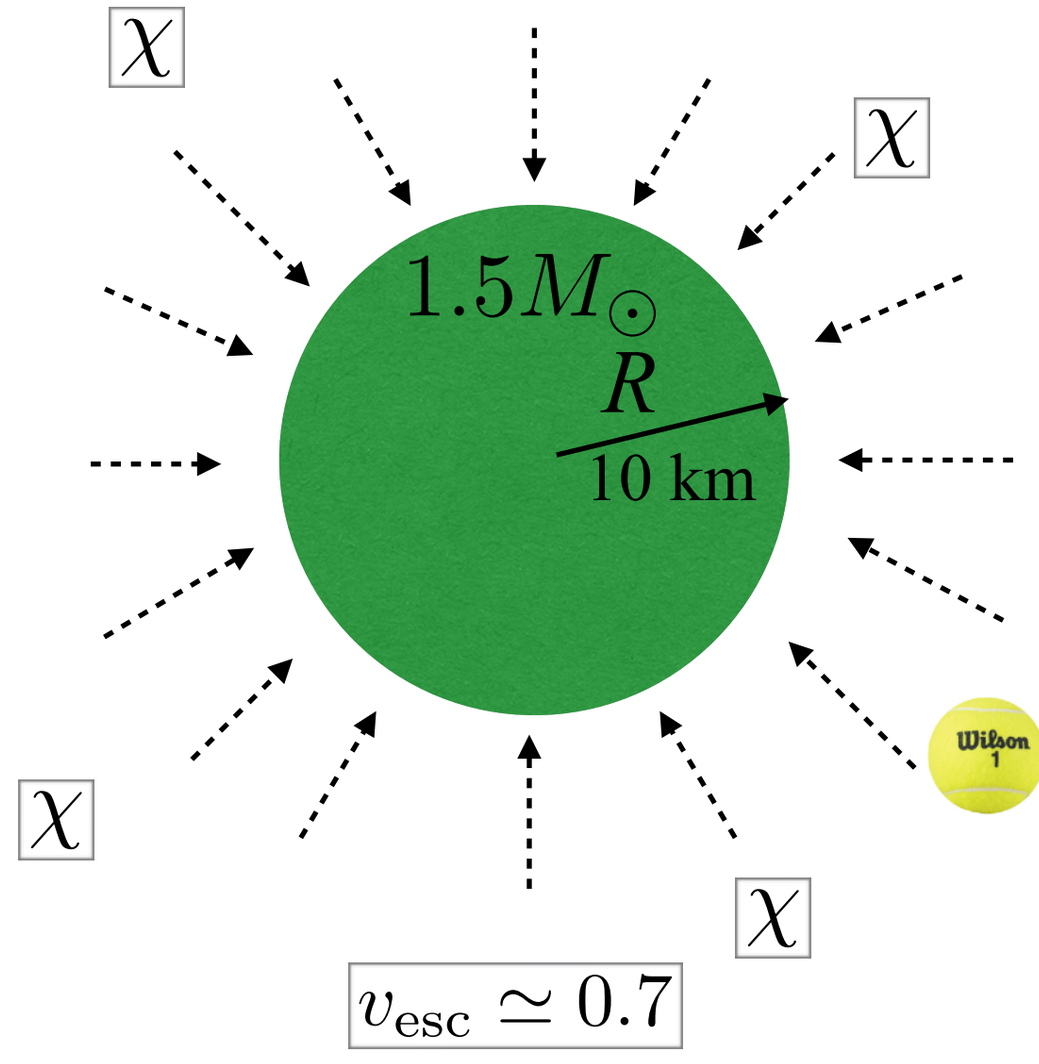

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$\boxed{\frac{dN}{dt}}$ $R\left(\frac{v_{\rm esc}}{v_{\rm DM}}\right)$ $\pi b_{\rm max}^2 v_{\rm DM}\left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)$

$\boxed{\text{KE}}$ $m_{\rm DM}(\gamma - 1) = 0.35 m_{\rm DM}$

DM mass drops out of this calculation!

← 60 grams of DM/ second
20 grams x c^2 of DM KE/ second

Keeping N star hot: dark fire

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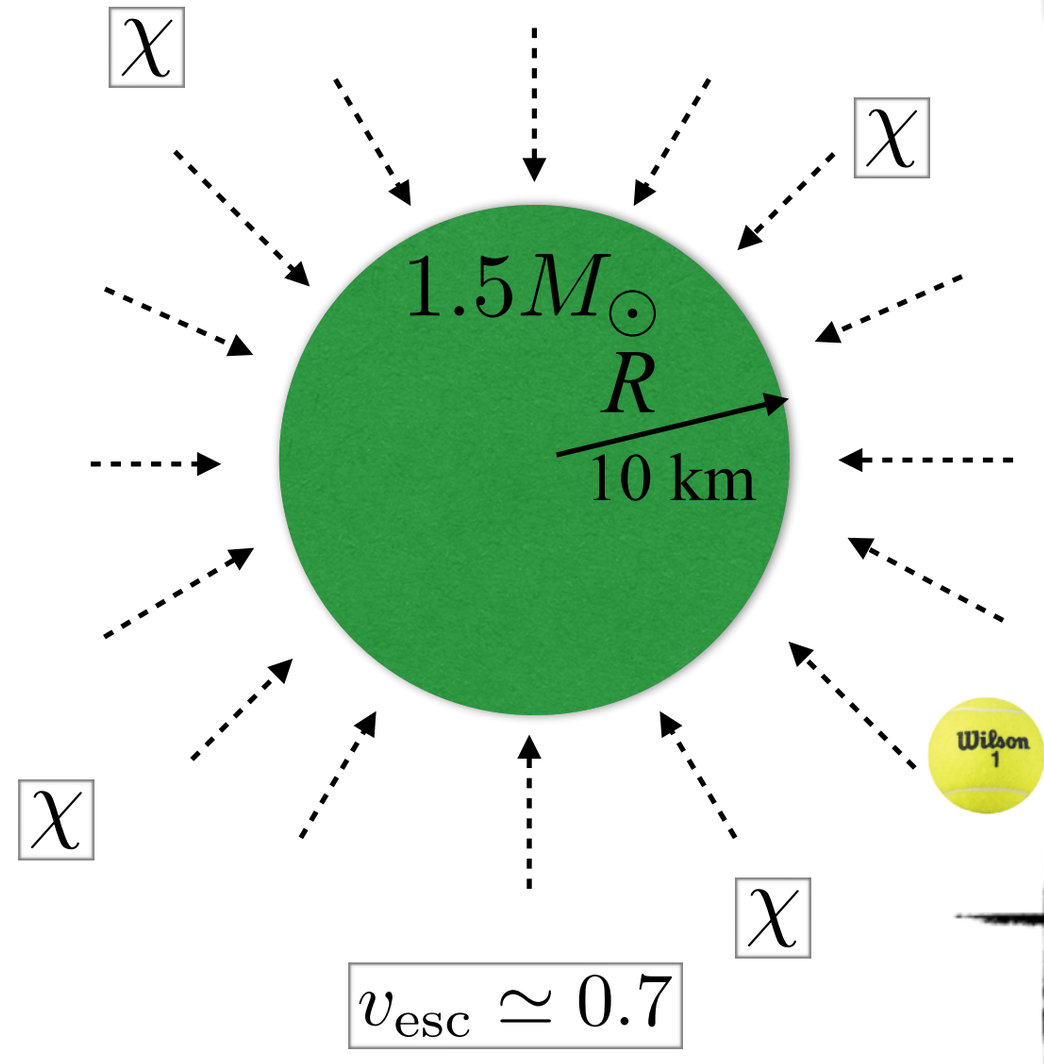

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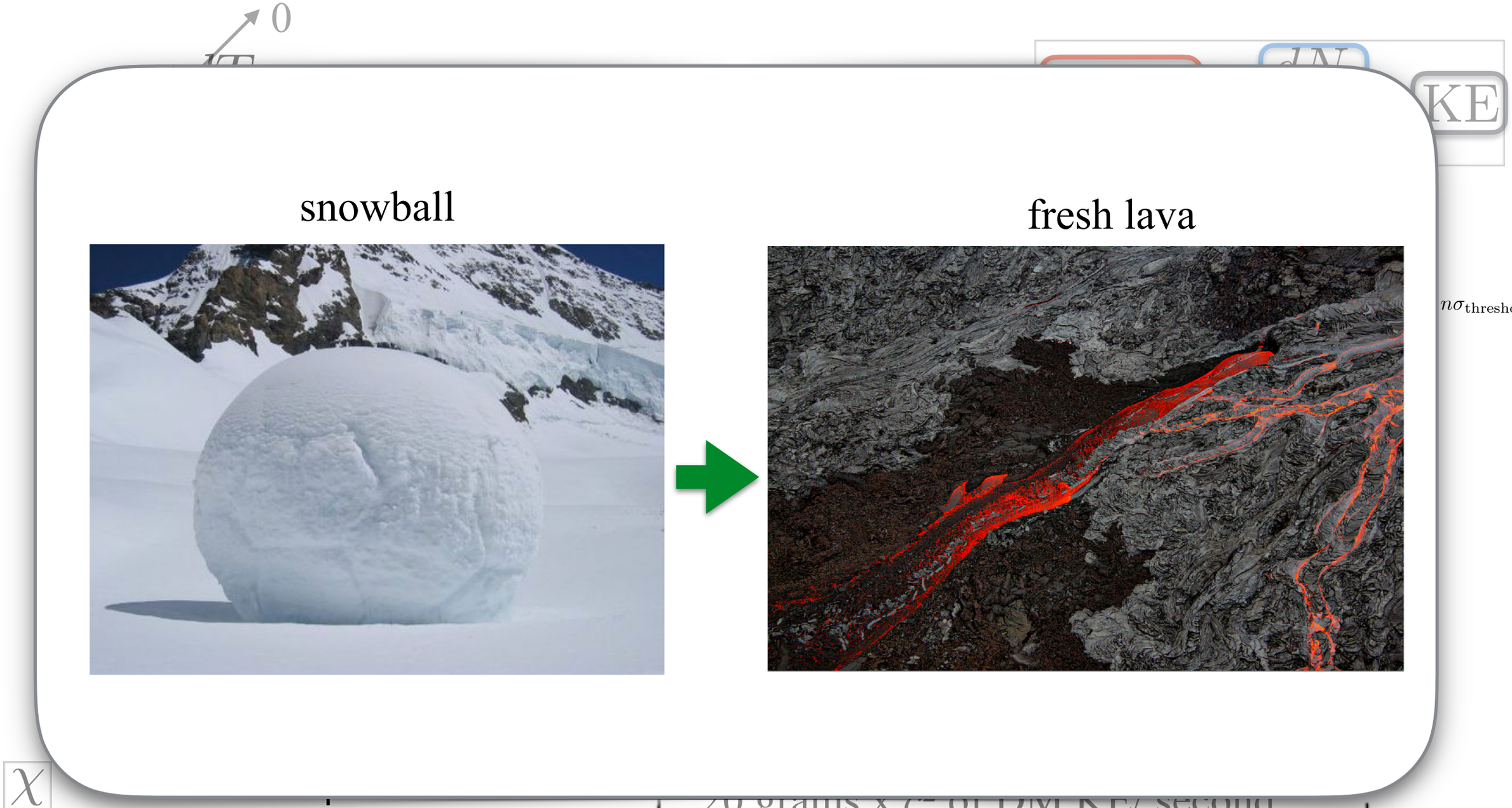
T = **1750 Kelvin** (infrared emission)

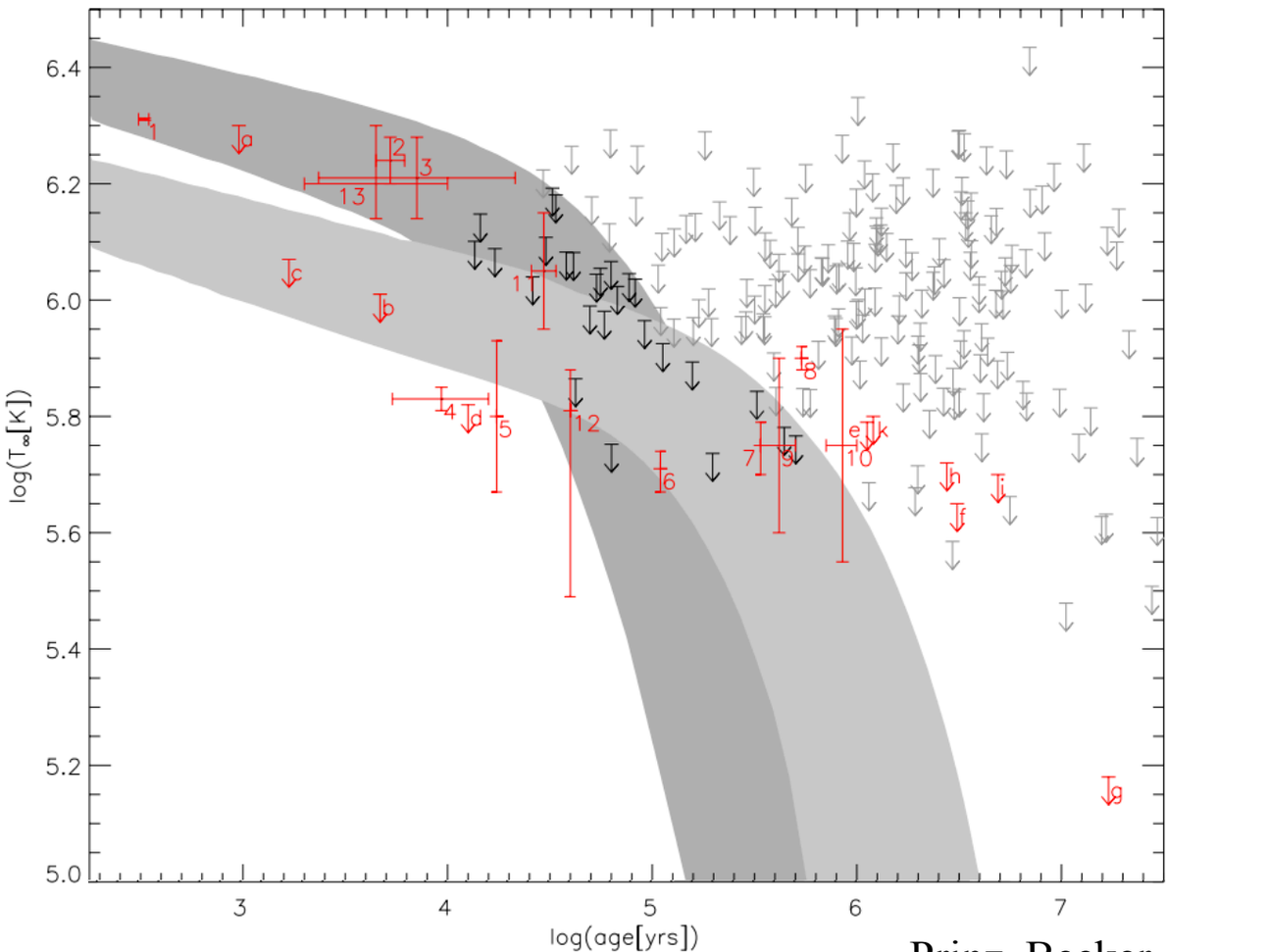
Keeping N star hot: dark fire



Detection?

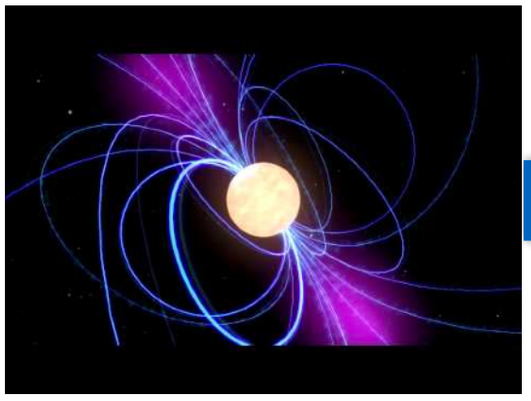
T = **1750 Kelvin** (infrared emission)

O(100) below current T bound



Prinz, Becker
astro-ph:1511.07713

Detection: radio pulsing



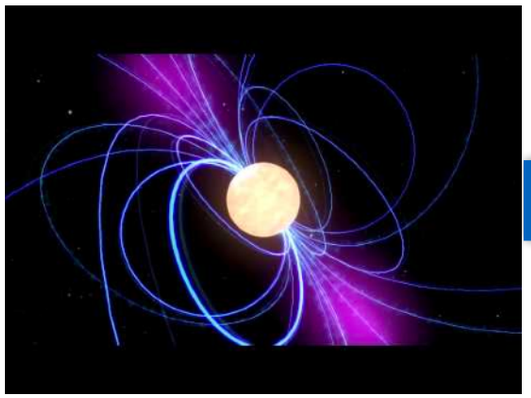
FAST
http://fast.bao.ac.cn/en/science_pulsar.html

1 - 5 old, cold neutron stars must reside in the local 10 pc; 100 in the local 50 pc.

O. Blaes, P. Madau (1993)

Detection: infrared telescopes

(exoplanet atmosphere)



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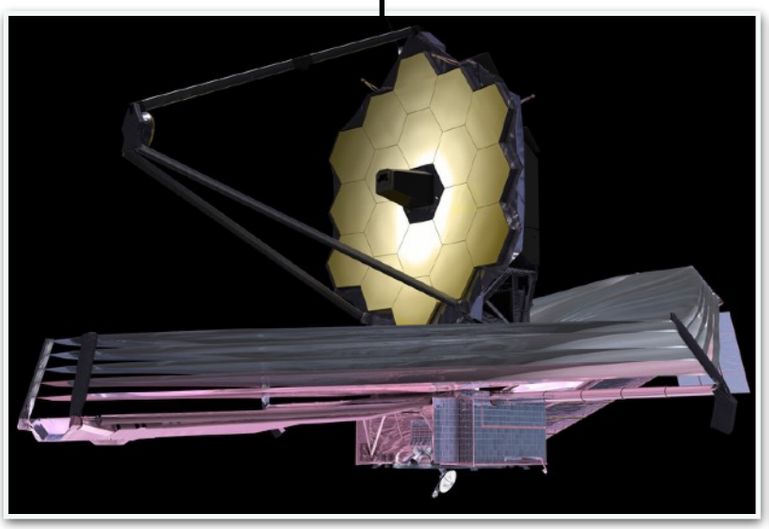
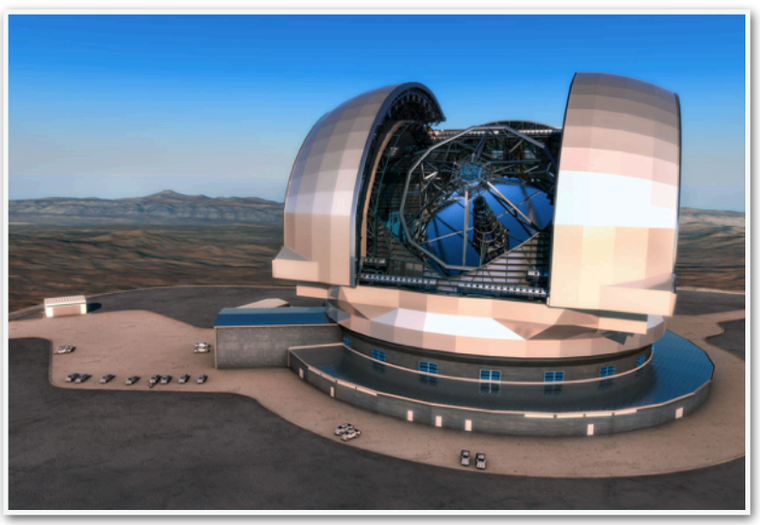
coming online Oct 2018!



James Webb

Thirty Meter

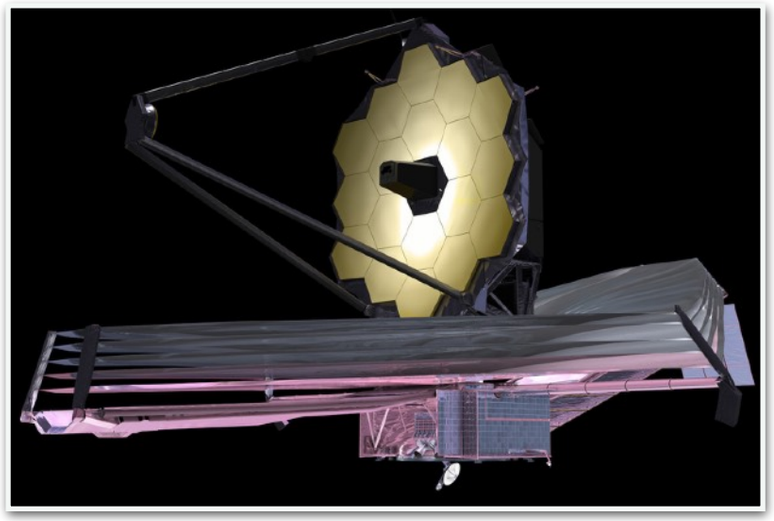


European Extremely Large

Detection: infrared telescopes

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

Peak wavelength: $1.65\ \mu$m

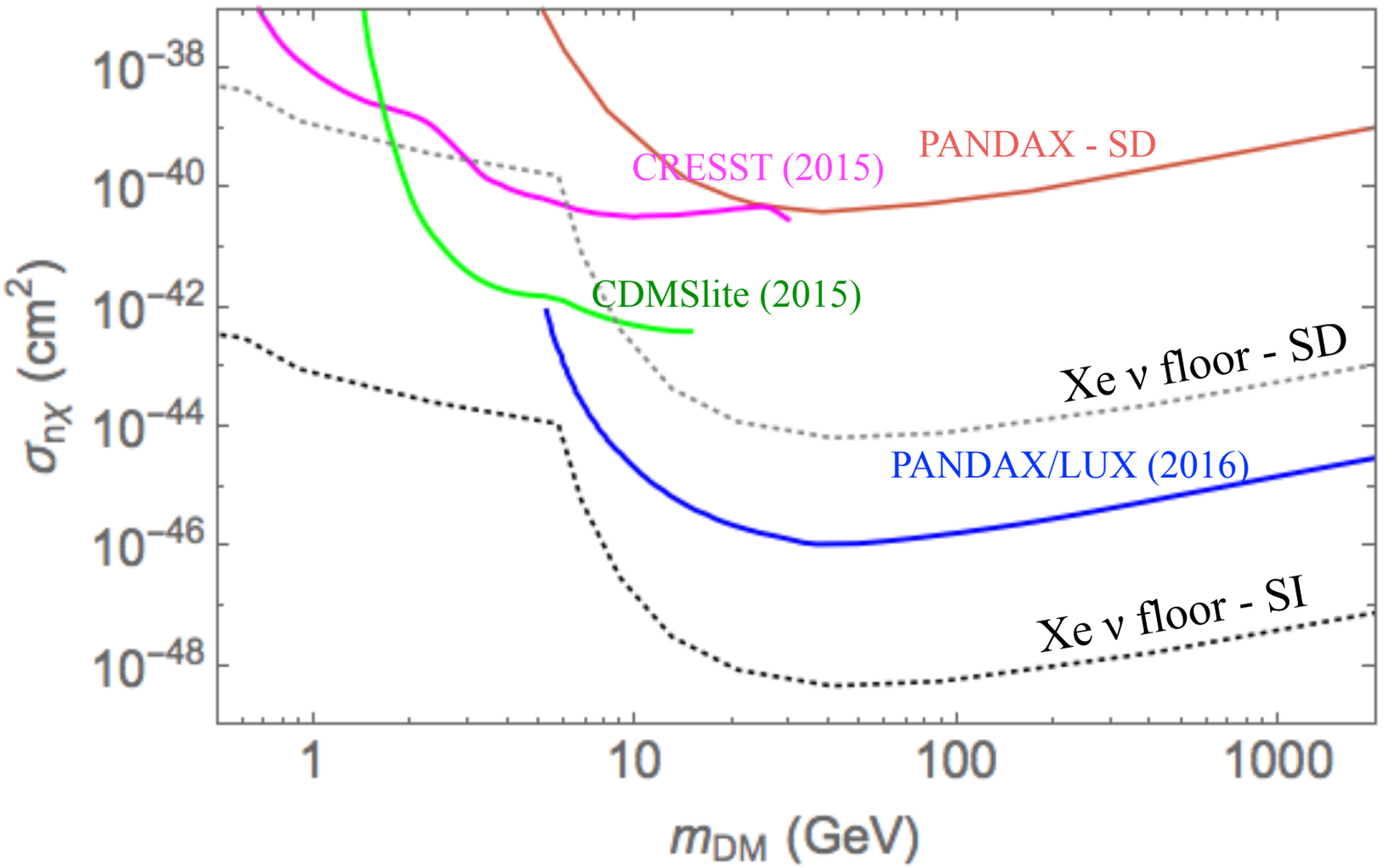


James Webb

Thirty Meter

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

Reward?

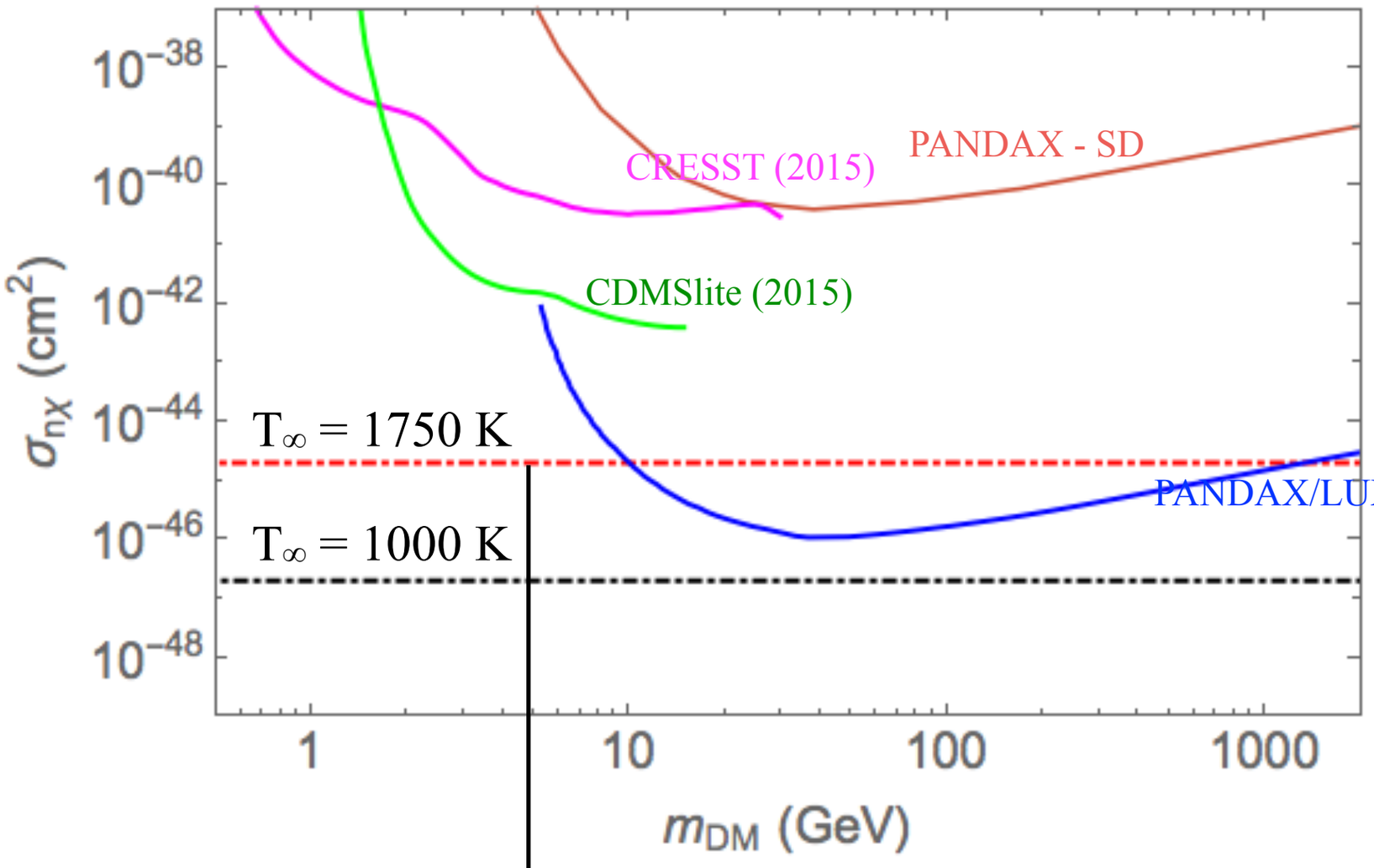


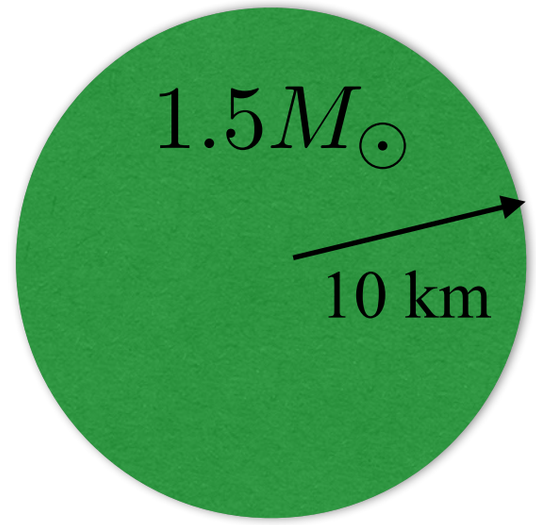
(1) Low mass
(2) High mass
(3) Spin-dependent
(4) Inelastic
(5) Neutrino floors

Dark kinetic heating help these frontiers?

Comparison

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

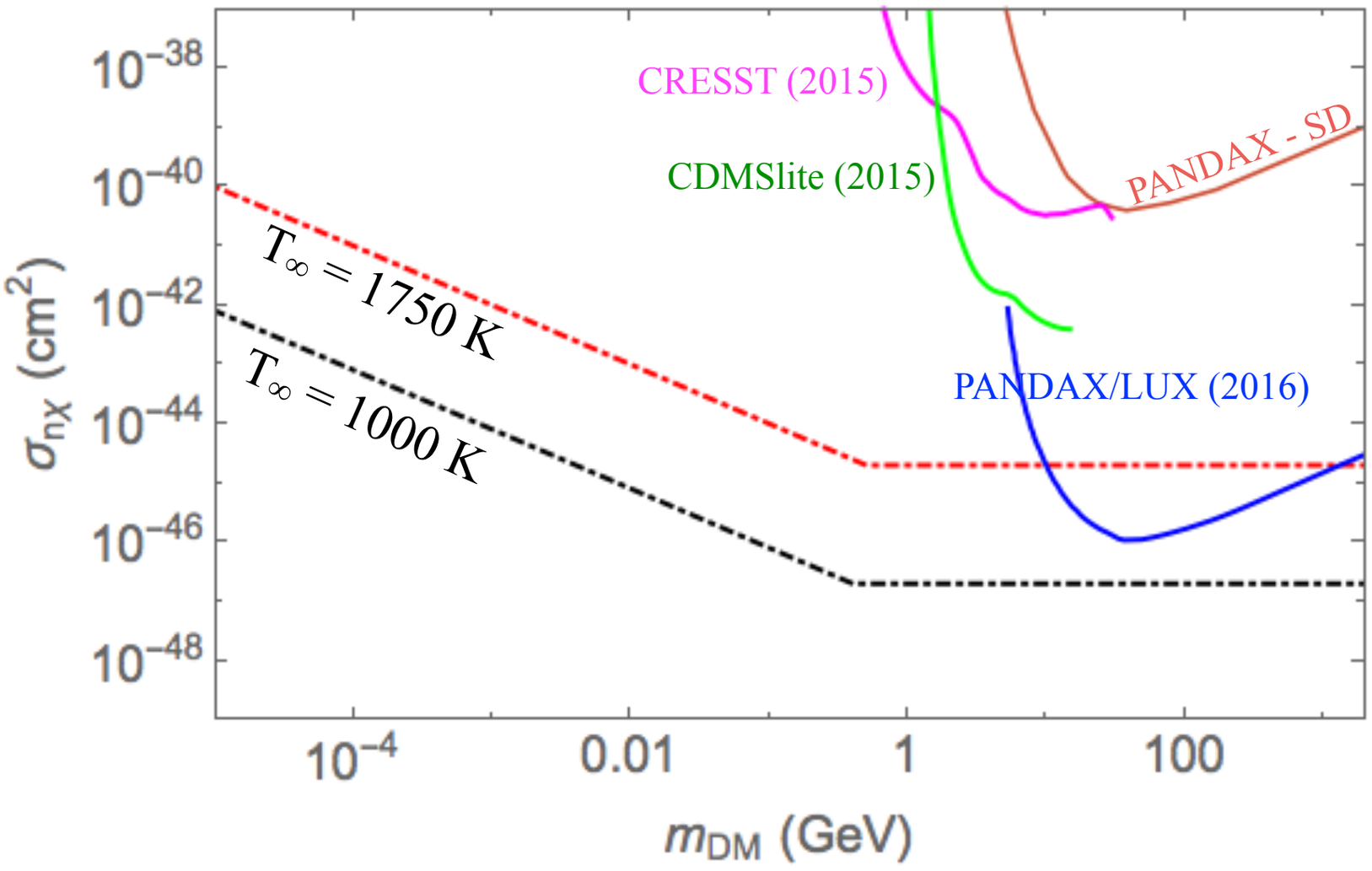




$$\sigma_{\rm threshold} = \pi R^2 \left(\frac{m_n}{M_{\rm NS}}\right)$$

Complementing

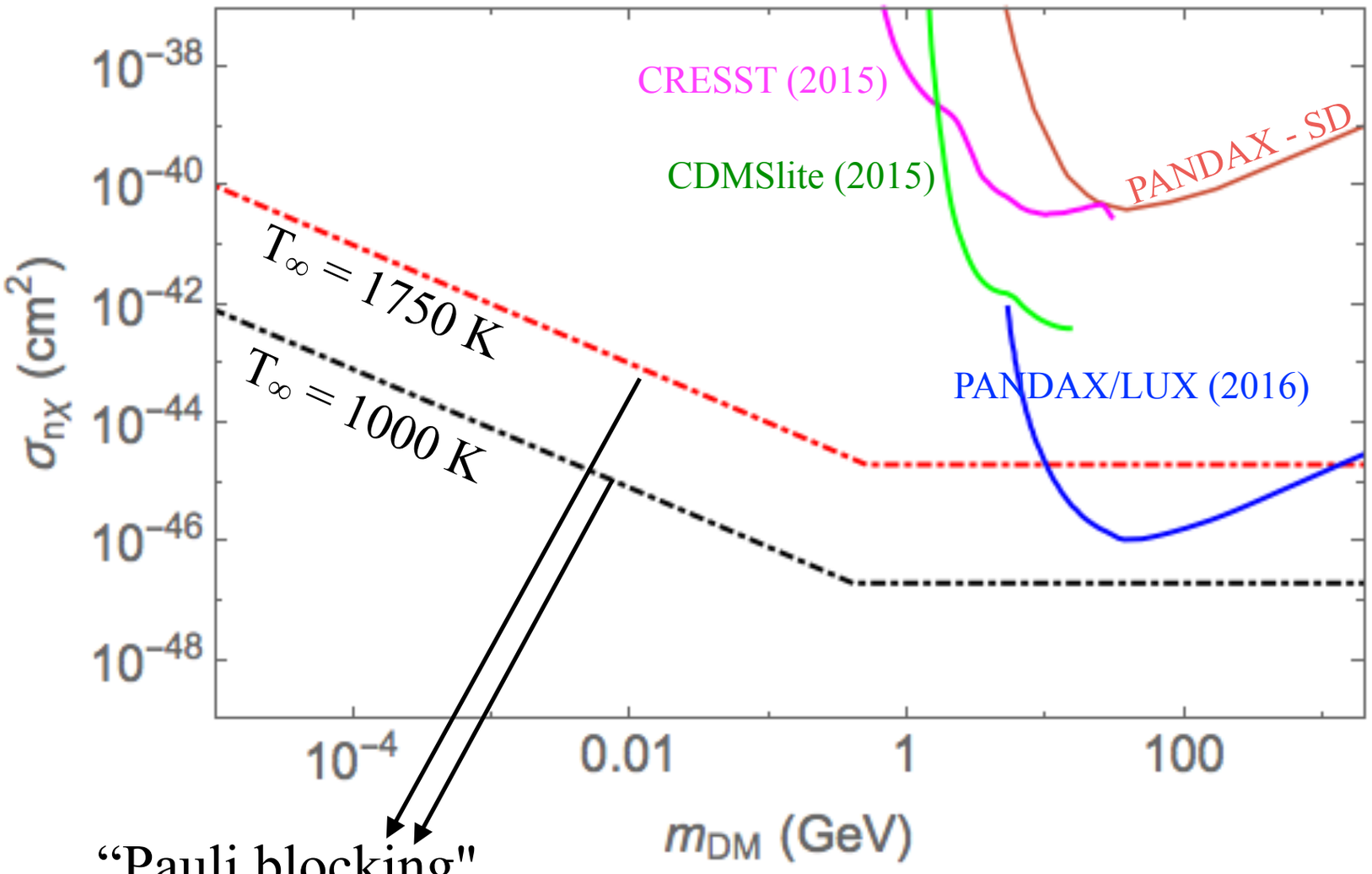
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



(1) Low mass ✅

Complementing

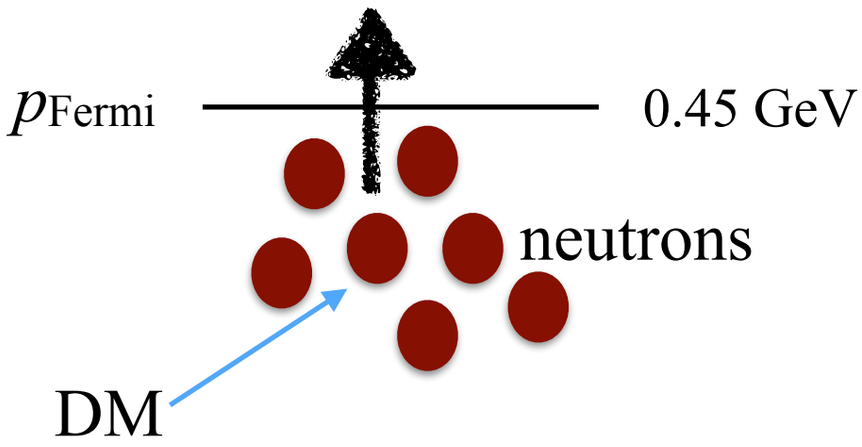
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



"Pauli blocking"

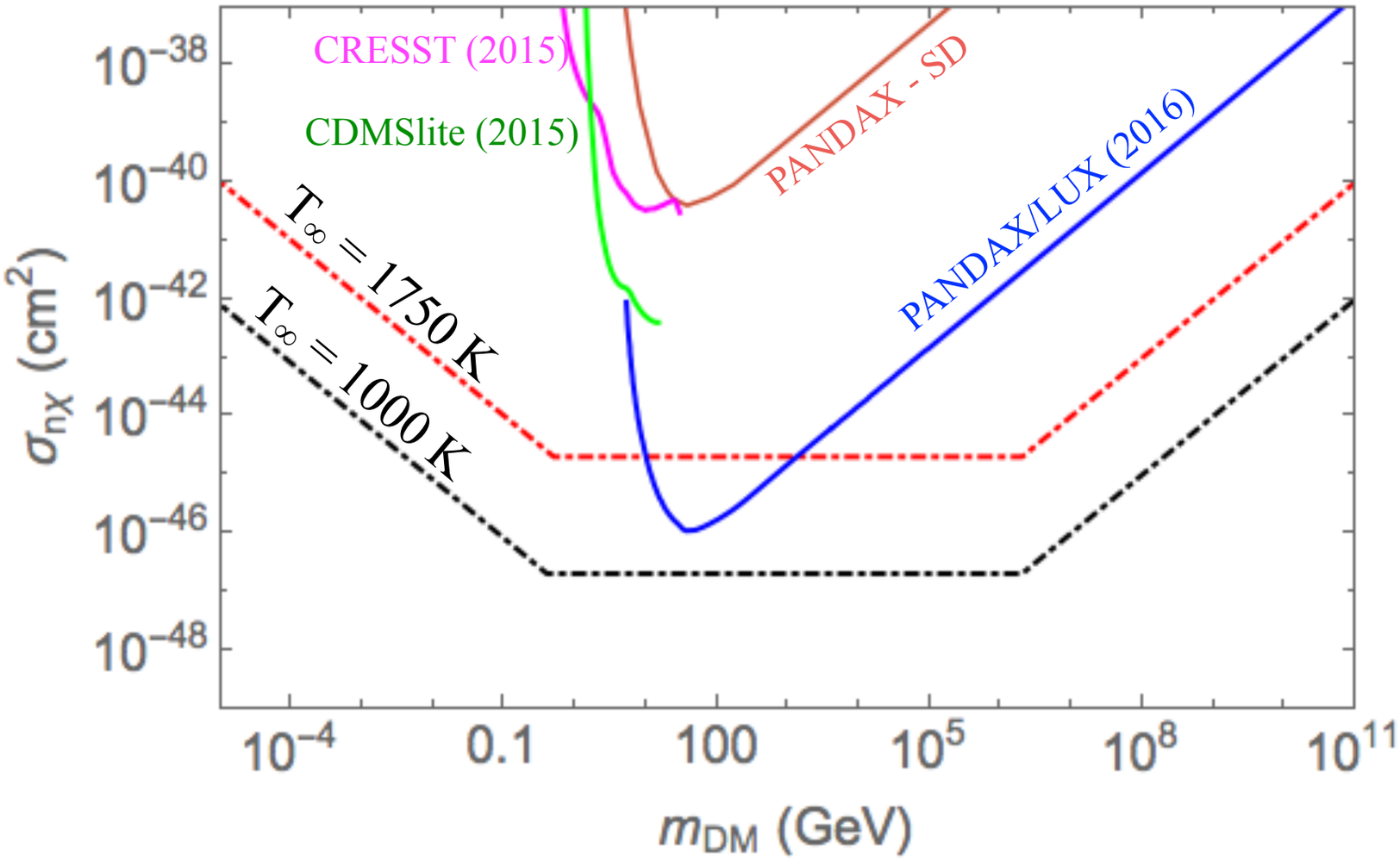
$\sigma^{-1}_{\text{threshold}} \propto$ fraction of nucleons excitable to > Fermi momentum $= \dfrac{\gamma m_{\text{DM}} v_{\text{esc}}}{p_{\text{Fermi}}}$

(1) Low mass ✅



Complementing

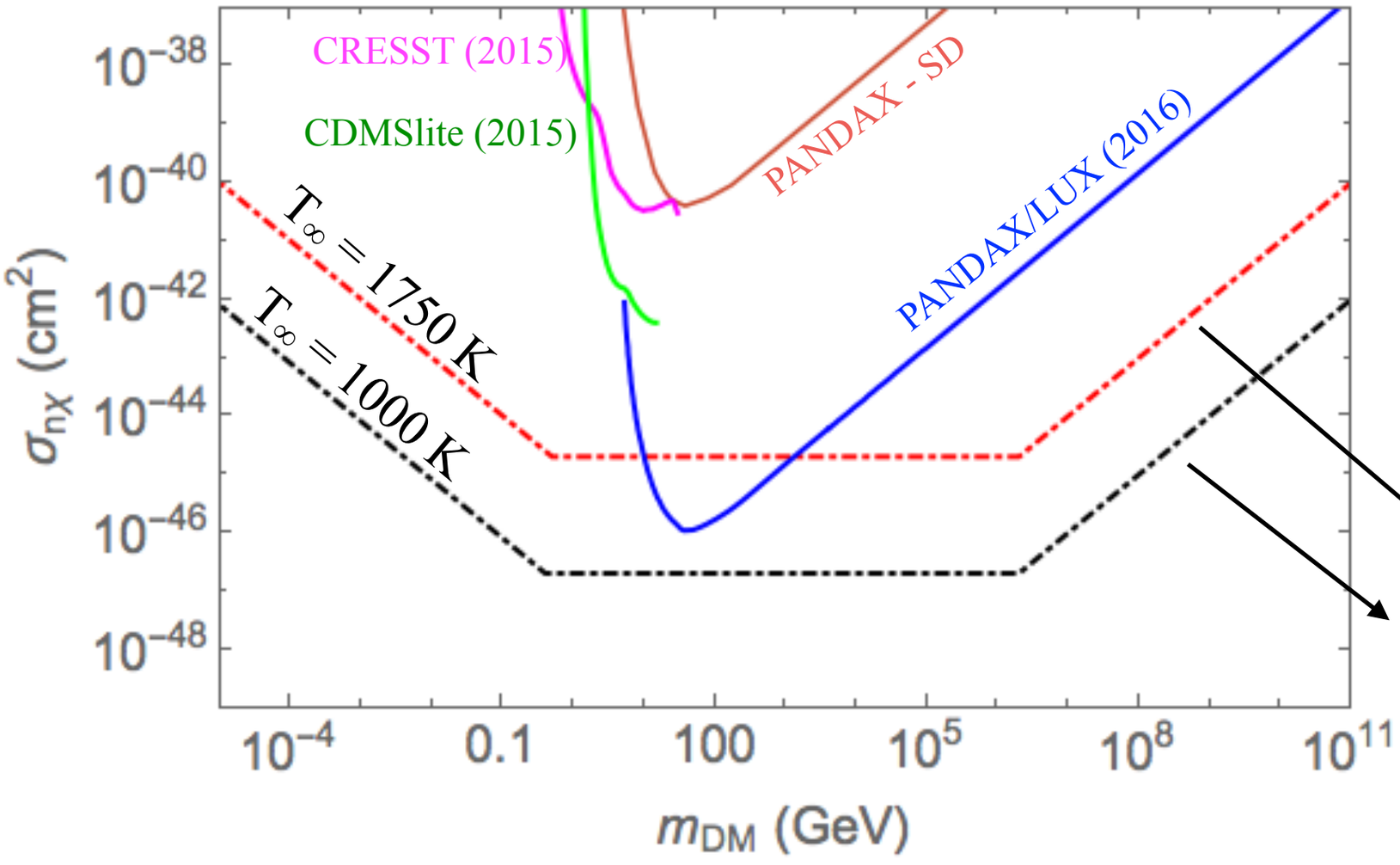
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



(1) Low mass ✅
(2) High mass ✅

Complementing

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



(1) Low mass ✅
(2) High mass ✅

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

versus

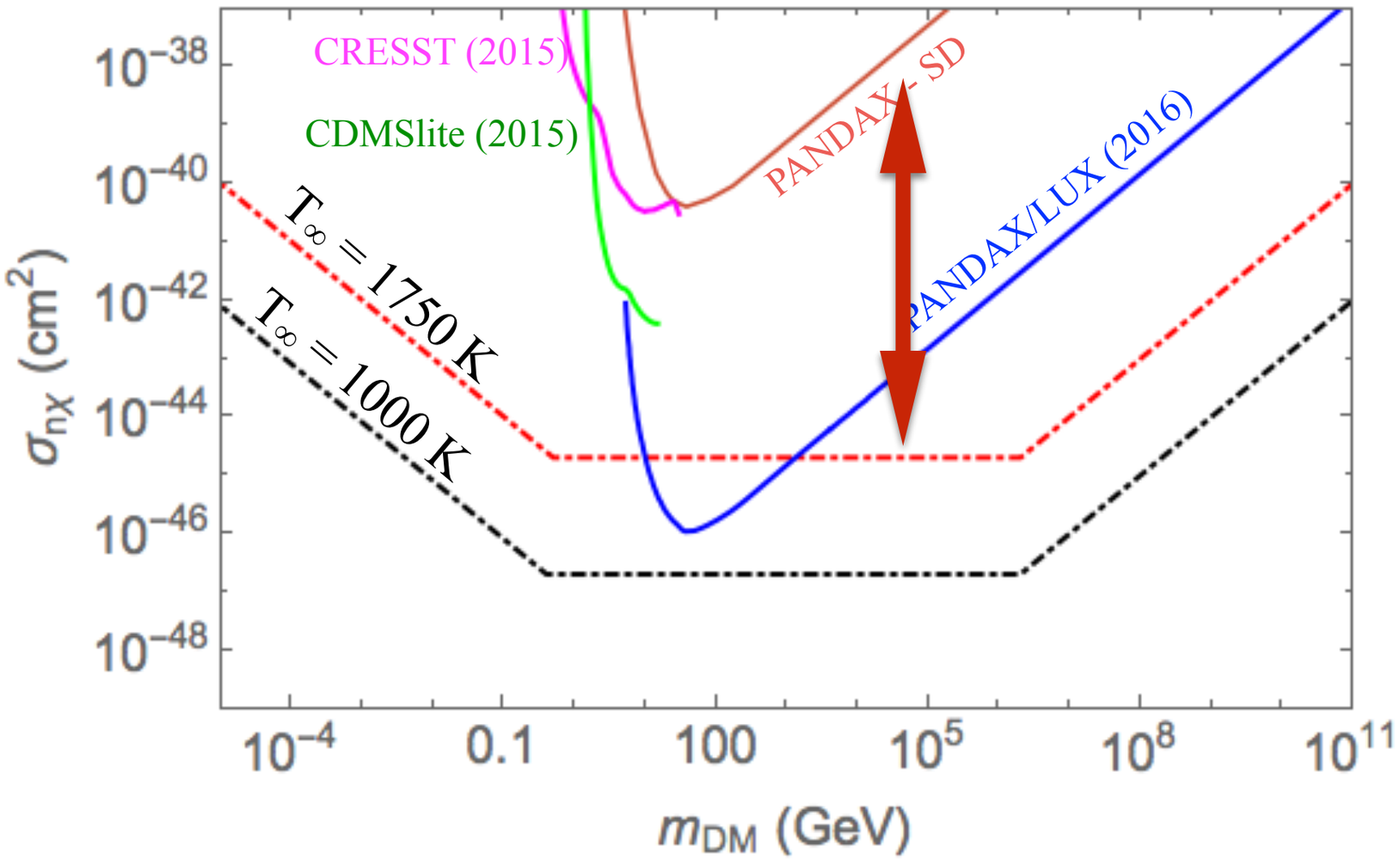
$$E_{\rm DM} \sim \frac{1}{2} m_{DM} v_{\rm DM}^2$$

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

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

Complementing

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

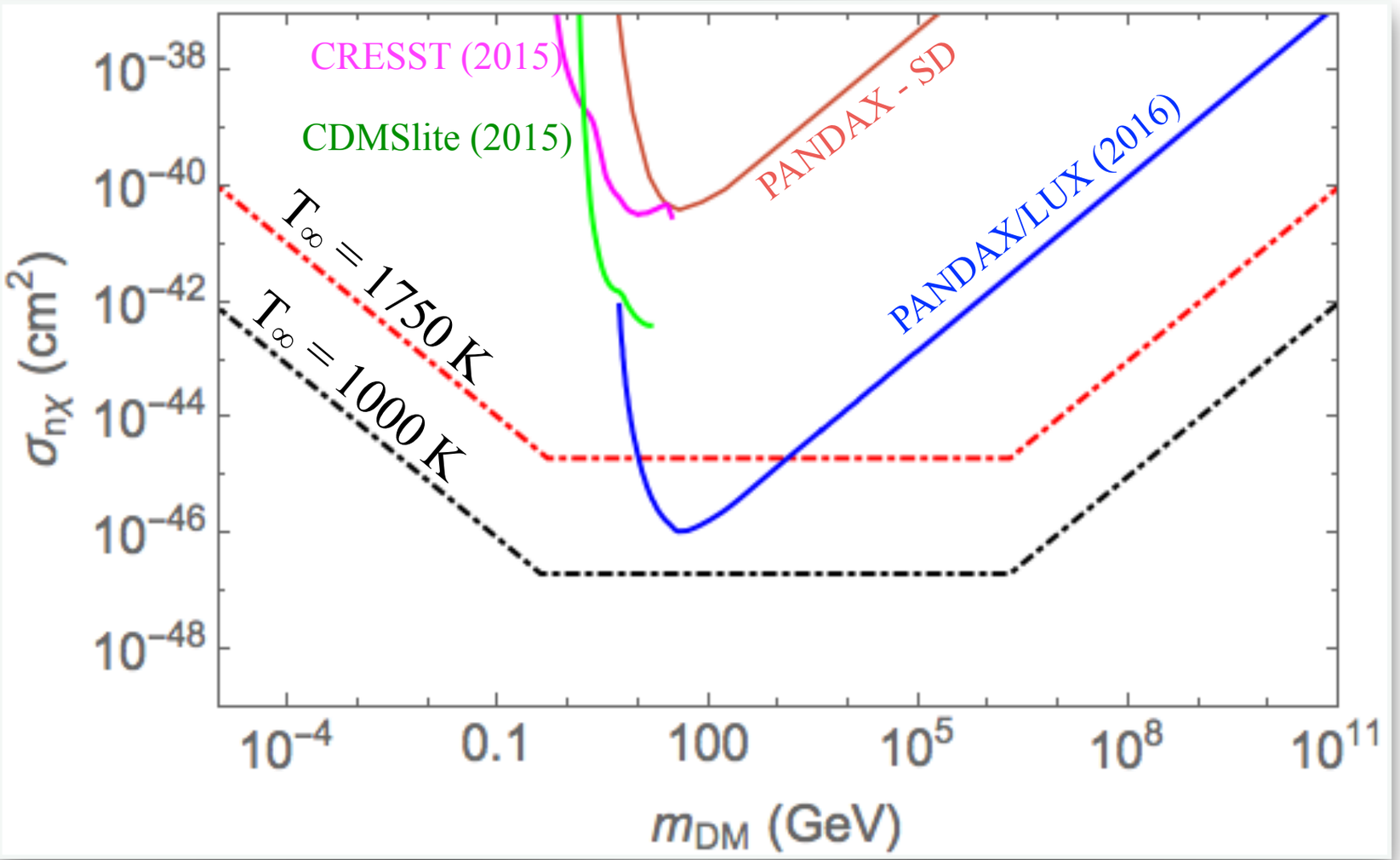


(1) Low mass ✅
(2) High mass ✅
(3) Spin-dependent ✅

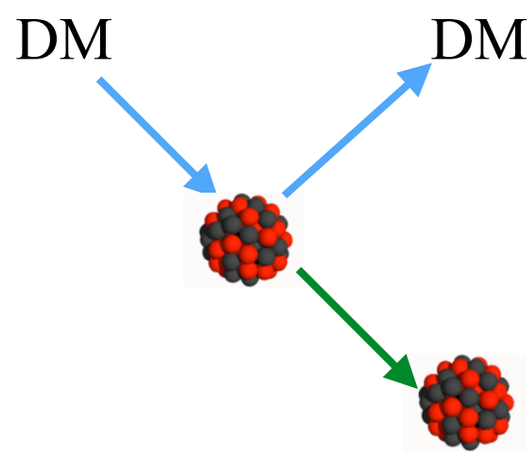
Scattering with neutrons: apathy to nuclear coherence

Complementing

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



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



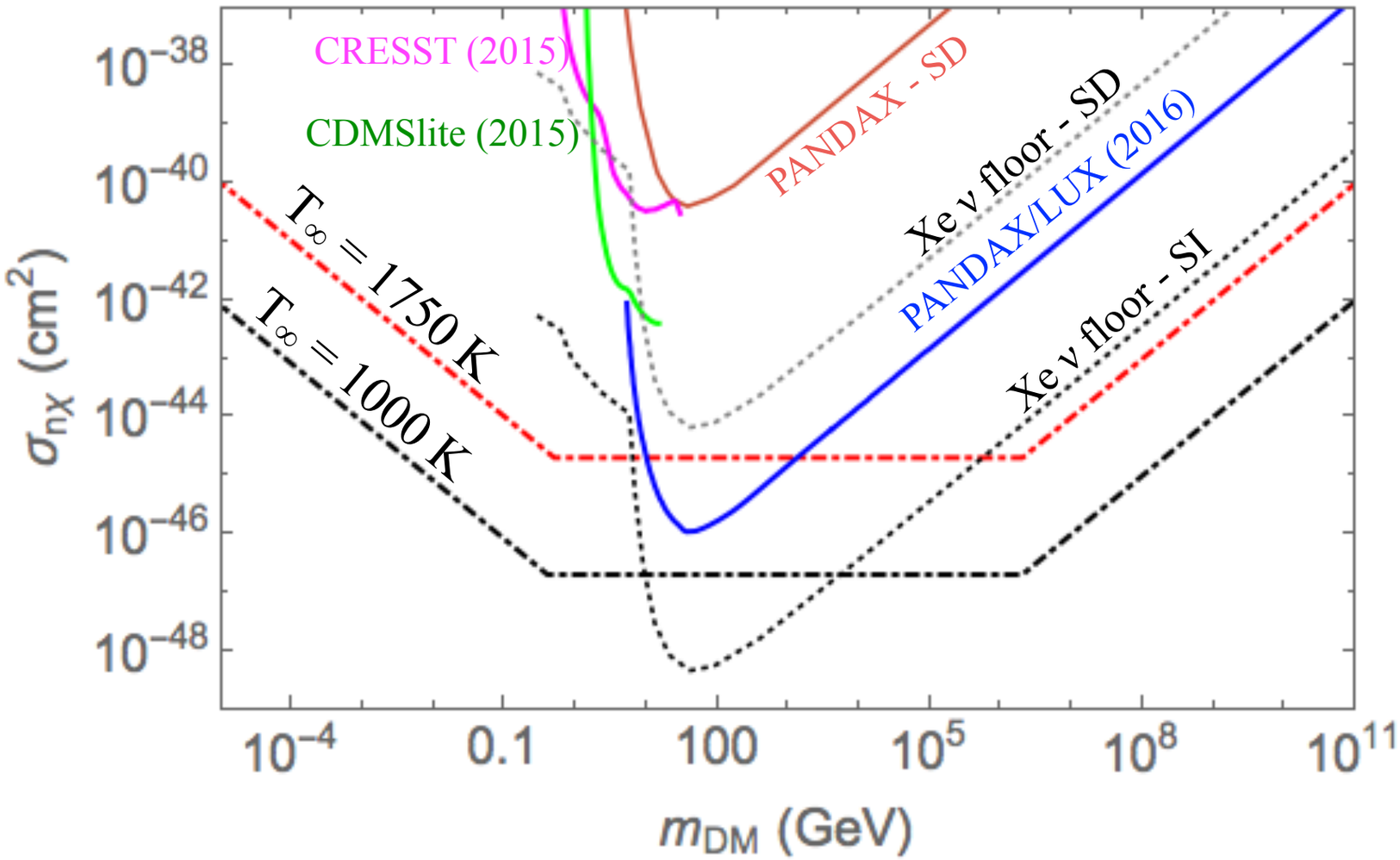
$$\delta \equiv m_{\rm DM^*} - m_{\rm DM}$$

Scattering proceeds as long as

$$\delta < 2\mu_{N\chi} v_{\rm esc}^2 \simeq 1 \text{ GeV}$$

Complementing

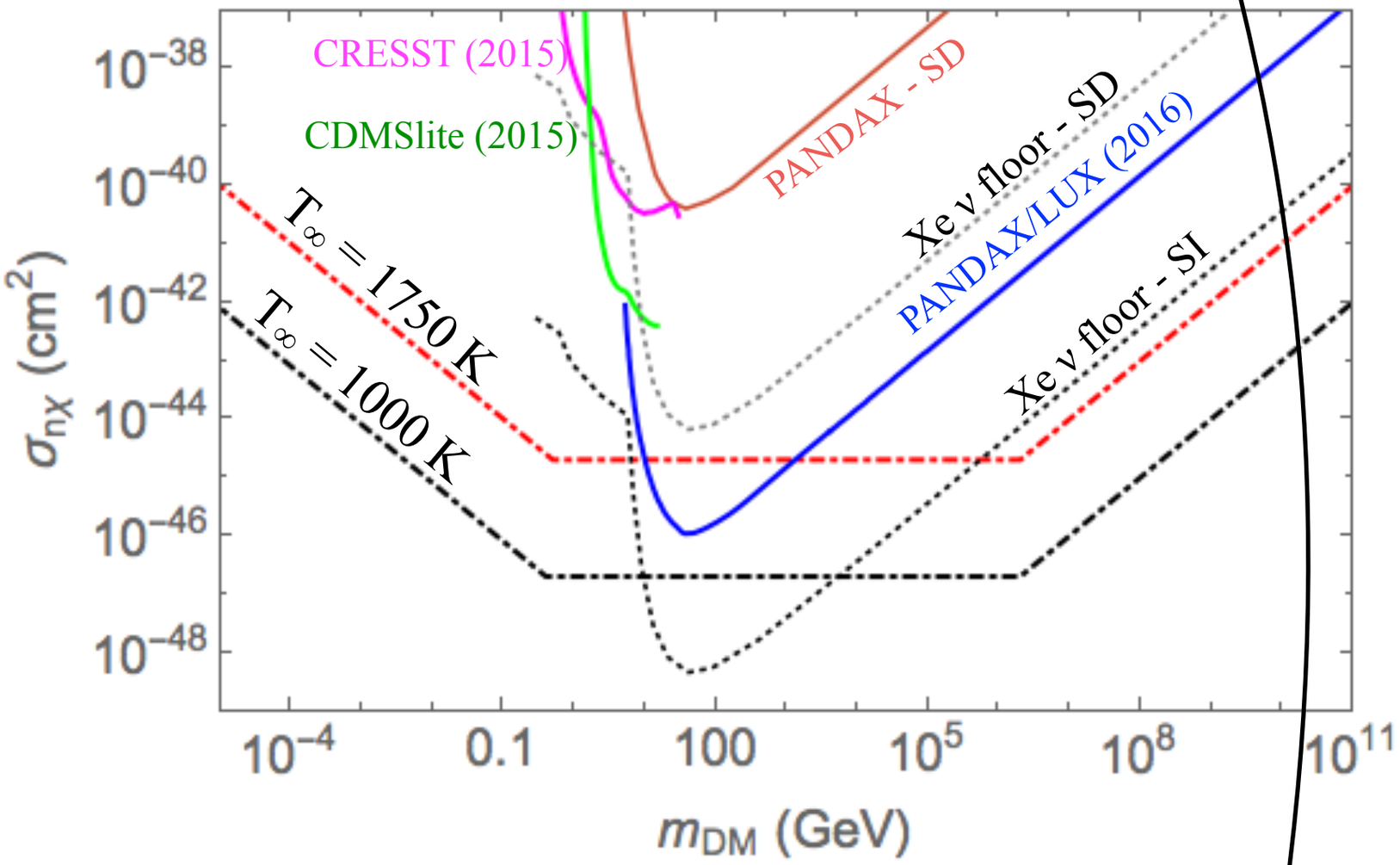
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



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

Complementing

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



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

Underground searches would terrifically complement us.

Takeaways

- Dark kinetic heating of neutron stars

  - casts a vast net in the hunt for dark matter - nucleon interactions,

  - seriously advances the direct detection frontiers of

    low mass (sub-GeV) ,

    high mass (> 100 GeV) ,

    spin-dependence ($\sigma_{SD} > 10^{-45}$ cm^2) ,

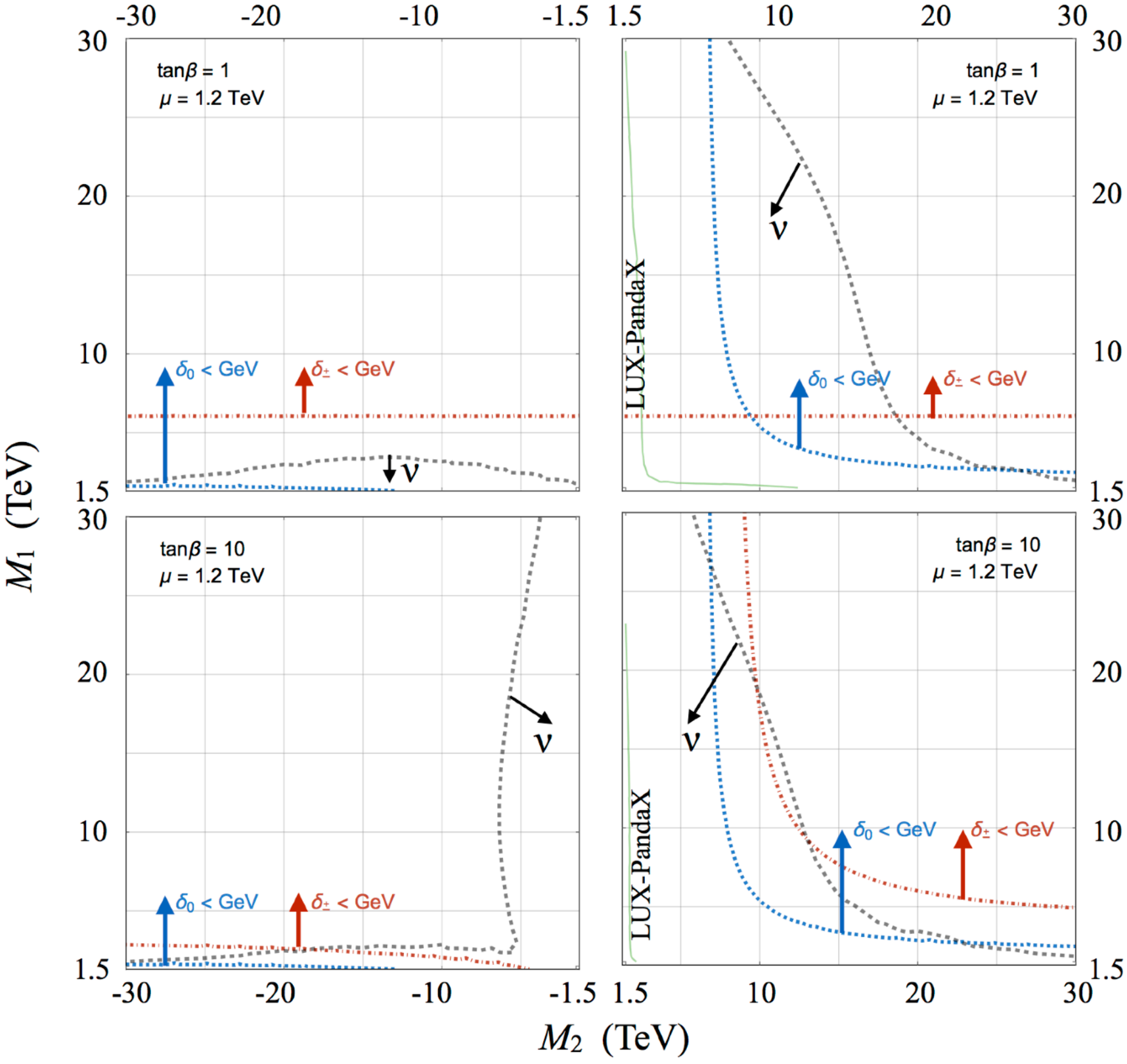
    inelasticity (< GeV splittings) , and

    sub-neutrino floors .

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

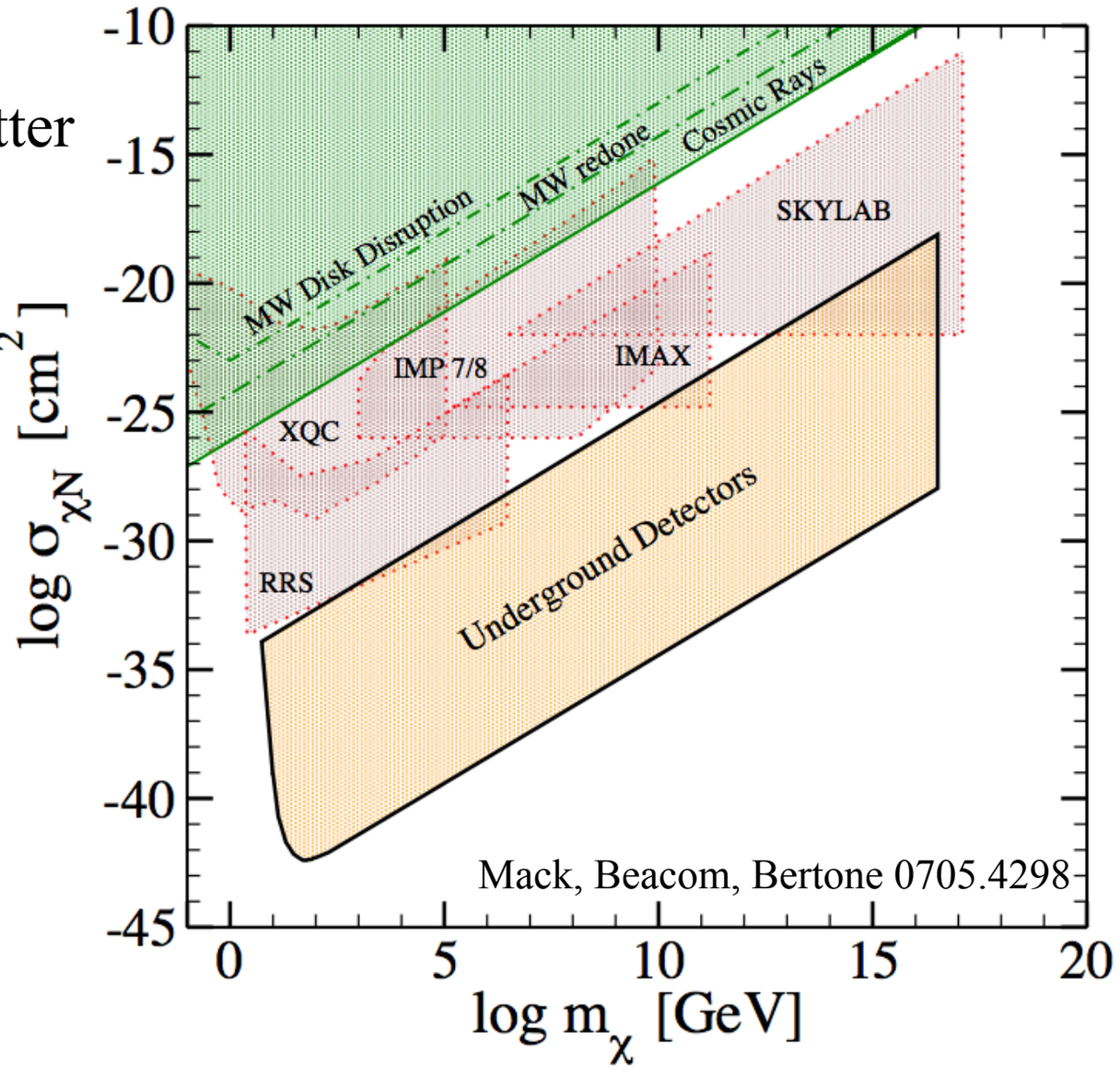
Backup

Uncovering thermal Higgsinos



Uncovering “side-stream” DM models

Strongly interacting dark matter



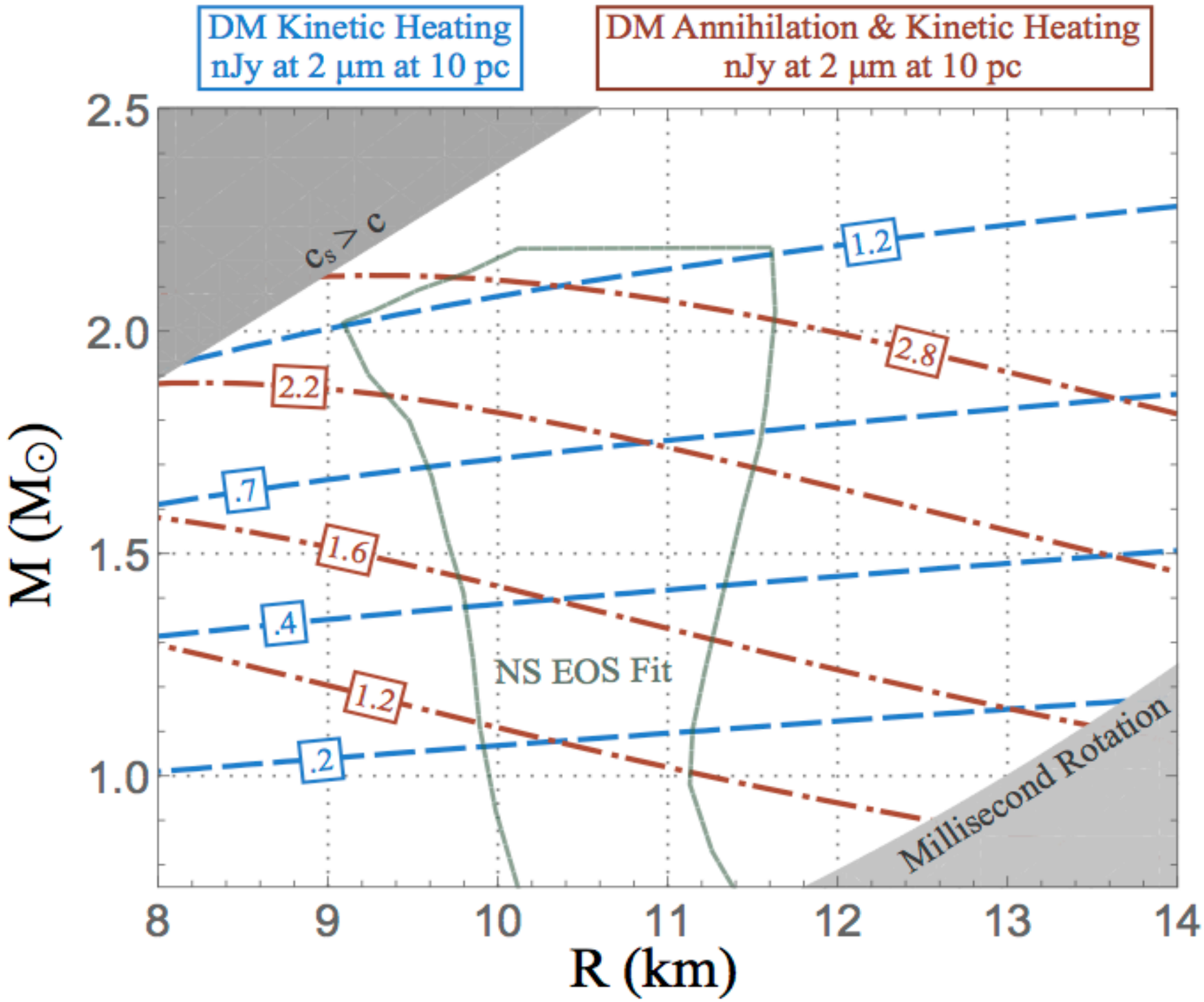
Primordial black holes

Macro objects

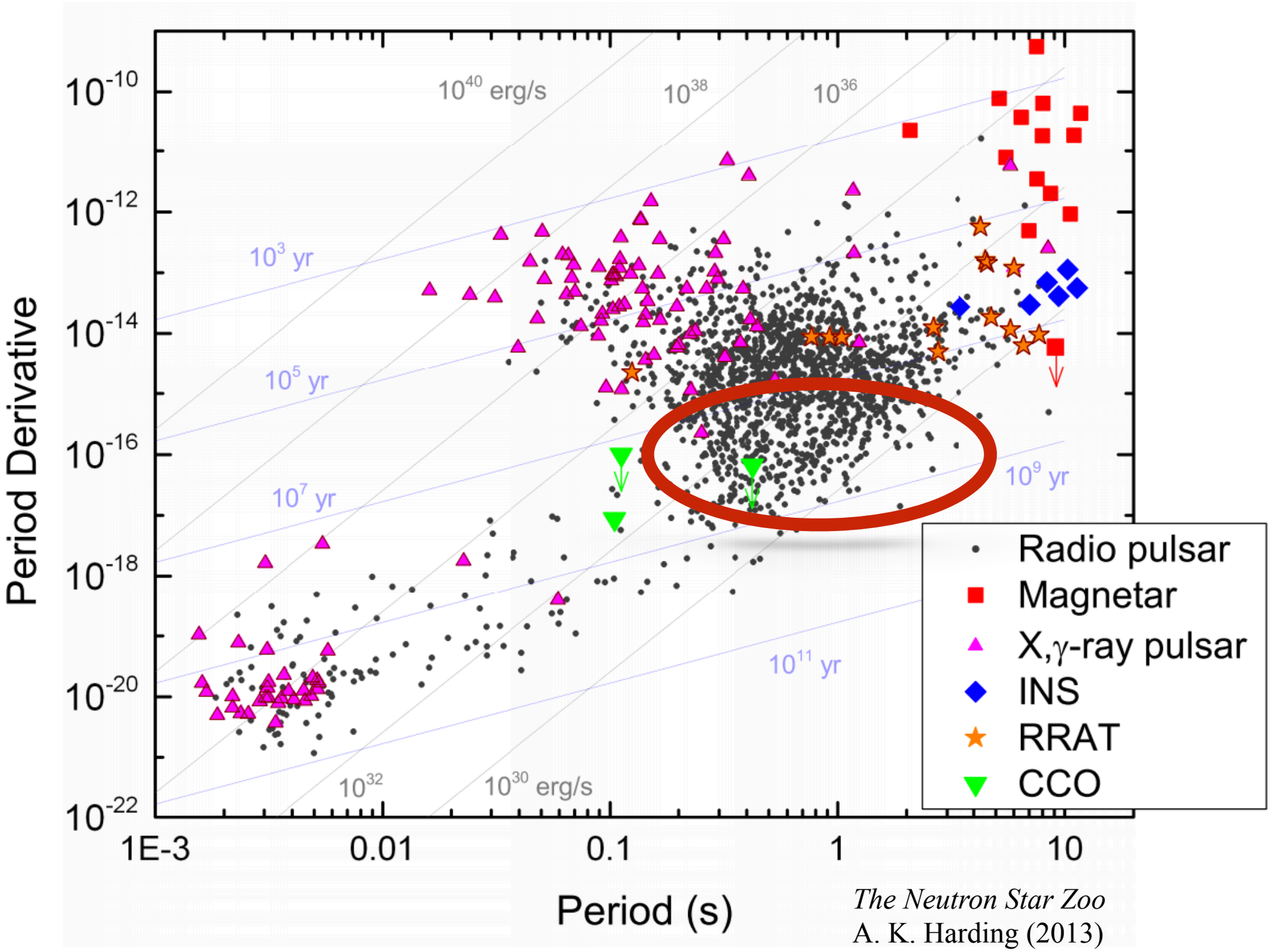
…

Kinetic vs annihilation heating

Difference in luminosity spreads

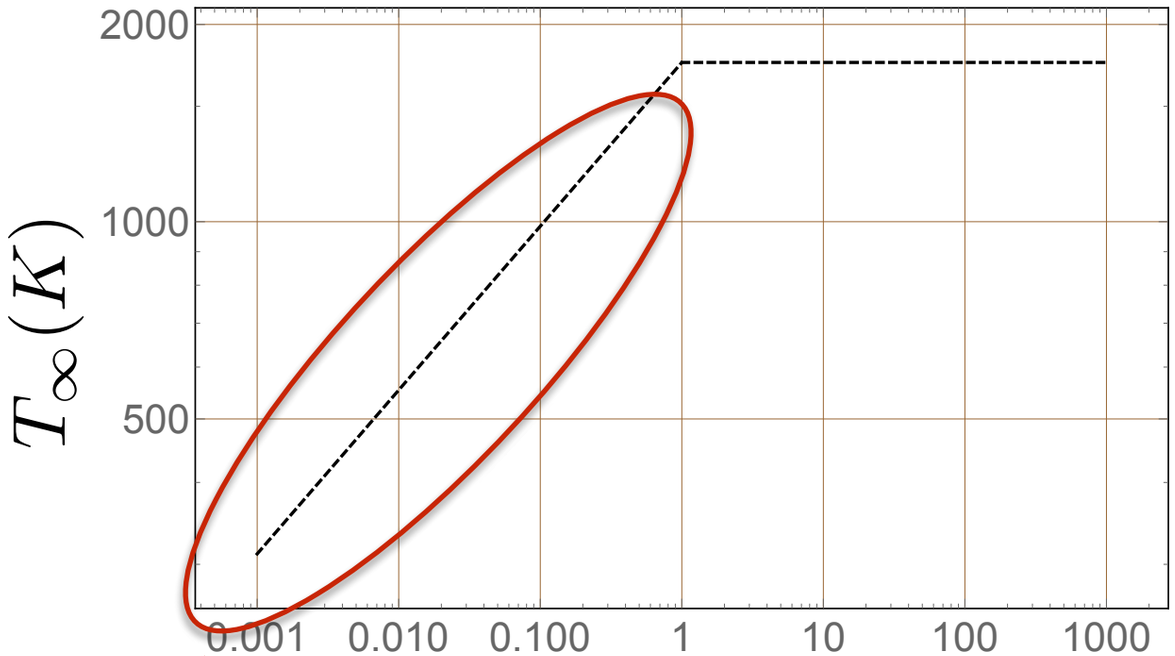


Detection: radio pulsing



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

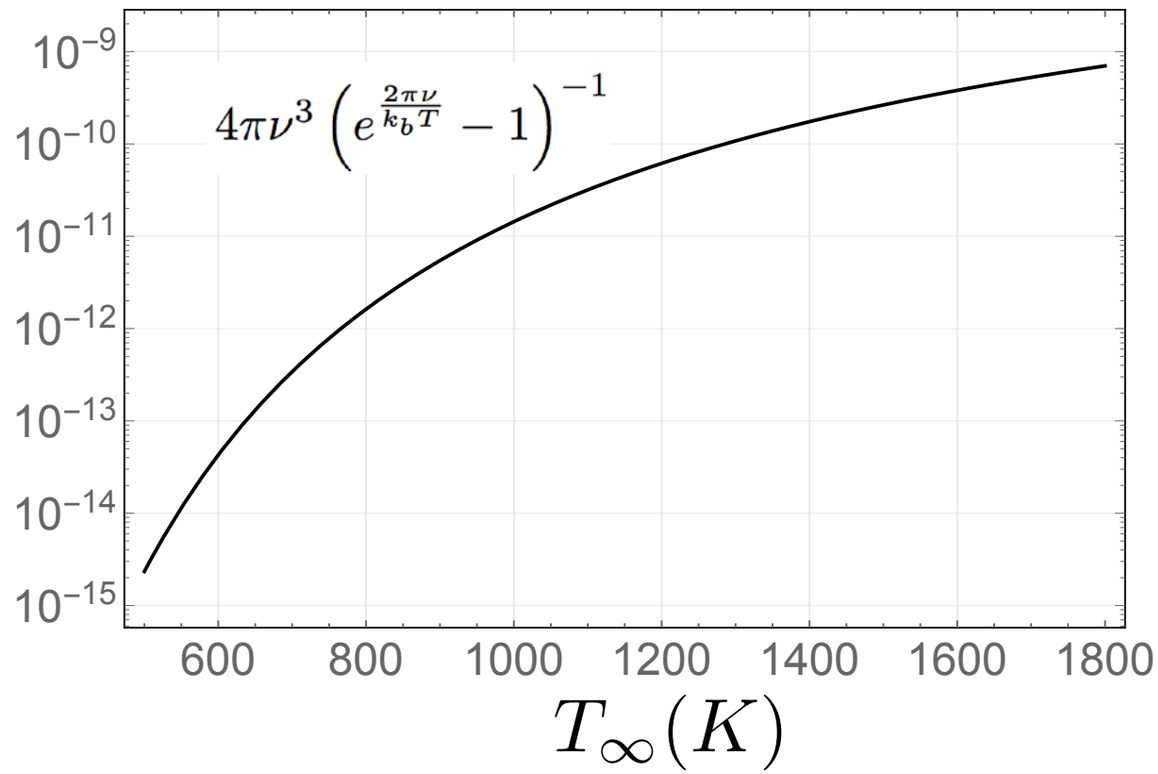
Detection: infrared telescopes



$$\frac{\sigma_{\chi N}}{(2\times 10^{-45}\ \mathrm{cm}^2)}$$

$$\cdot B(\nu, T_\infty^{\mathrm{dark}})$$

(W/m²/Hz)



Smaller cross-sections,
dimmer stars,
longer exposures.

Sixth author?

Let there be dark matter!
(1933)

Let there be neutron stars*!
(1934)

*spherical bastards I can stand

Cassius, in ‘Julius Caesar’

The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings.

Cassius, in ‘Julius Caesar’

The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings.

ground?