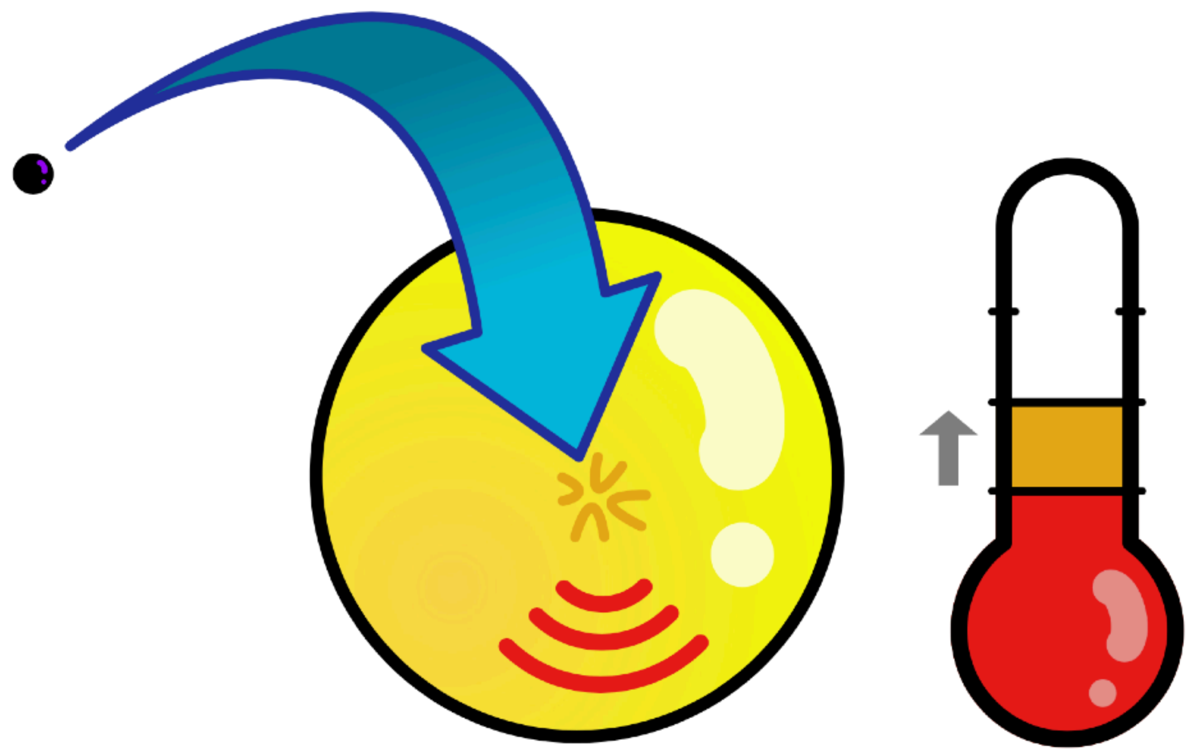
Model-Independent Dark Matter Detection via Kinetic Heating of Neutron Stars

Nirmal Raj
Notre Dame



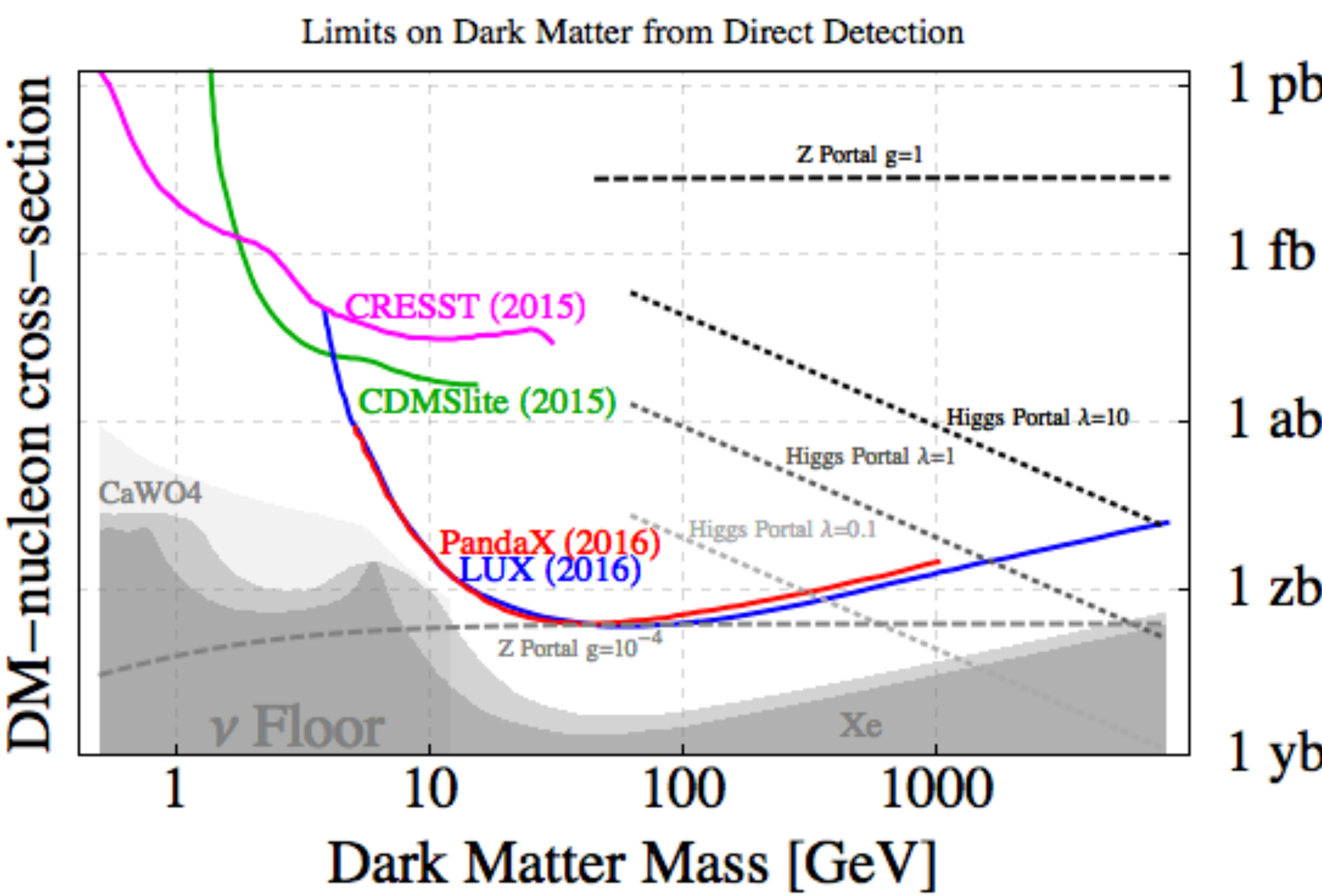
with
Masha Baryakhtar, Joe Bramante, Shirley Li, Tim Linden **1704.01577**
Flip Tanedo, Hai-Bo Yu **1707.09442**

[*Submitted to PRL*]

TeVPA 2017
08 Aug, Ohio State University

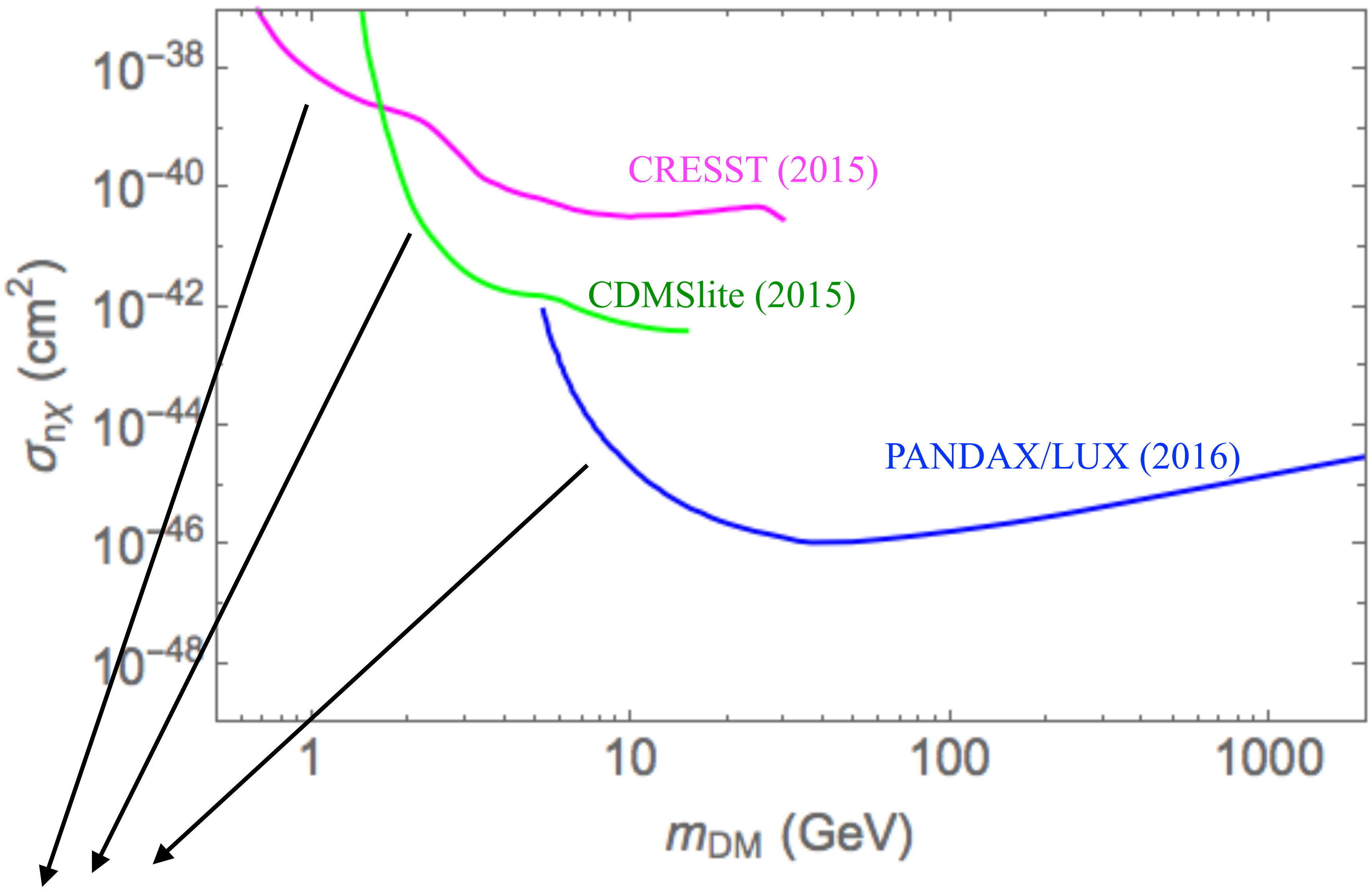
Direct searches: status

After 100 kg-year exposure:



http://resonaances.blogspot.com/

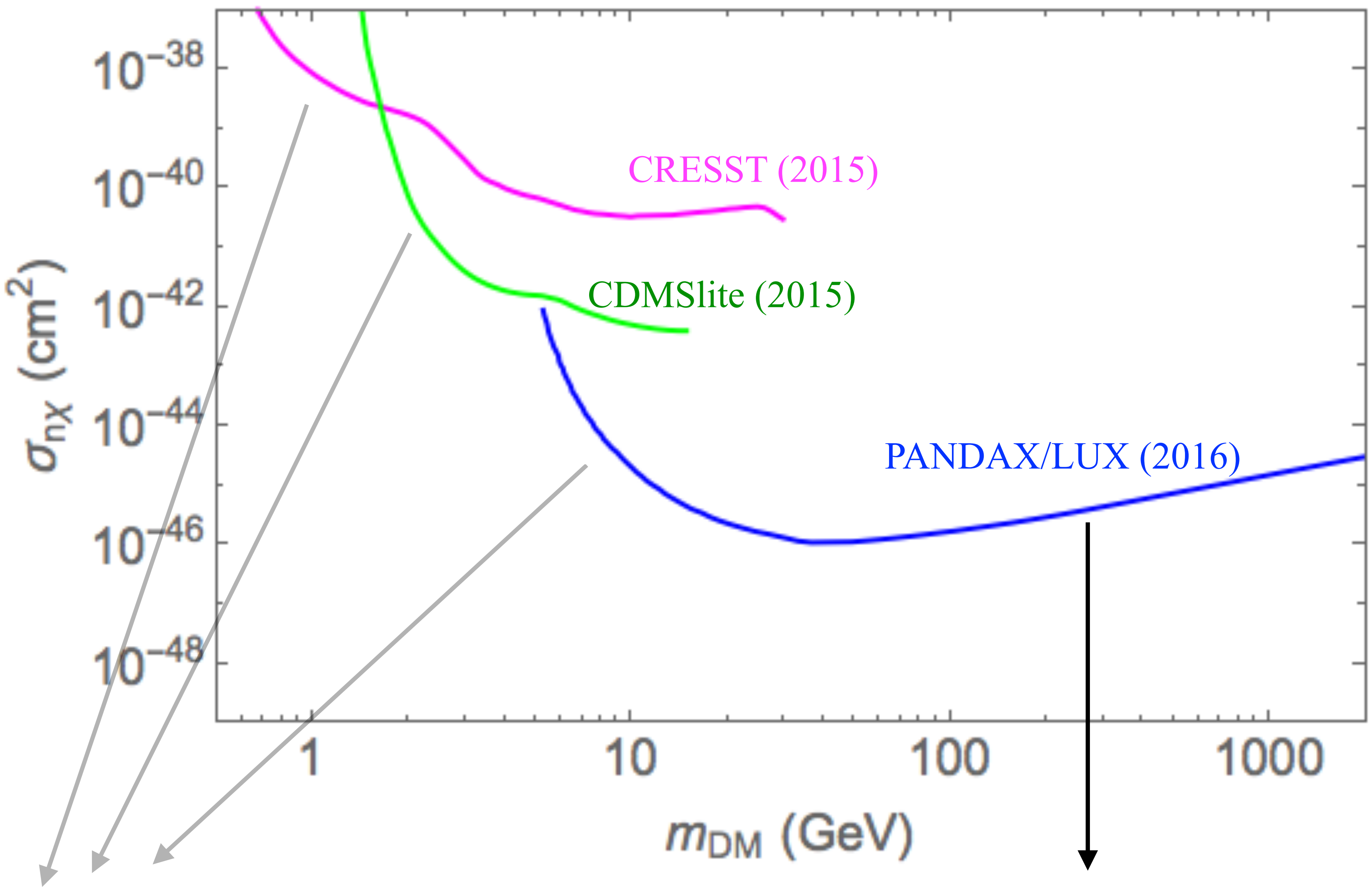
Direct searches: challenges



(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

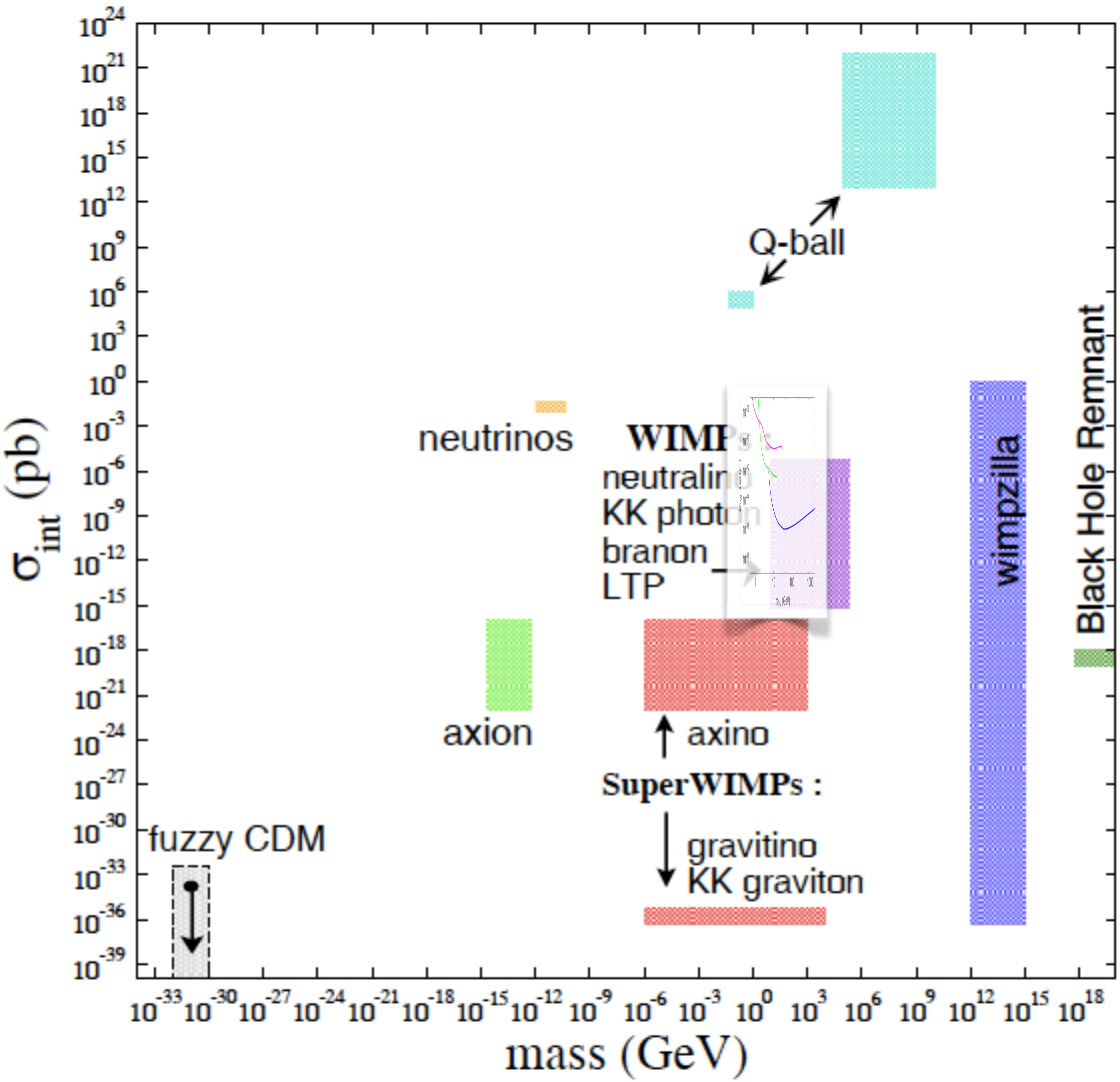


(1) Nuclear recoil below detector thresholds at low mass

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

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

(Context)

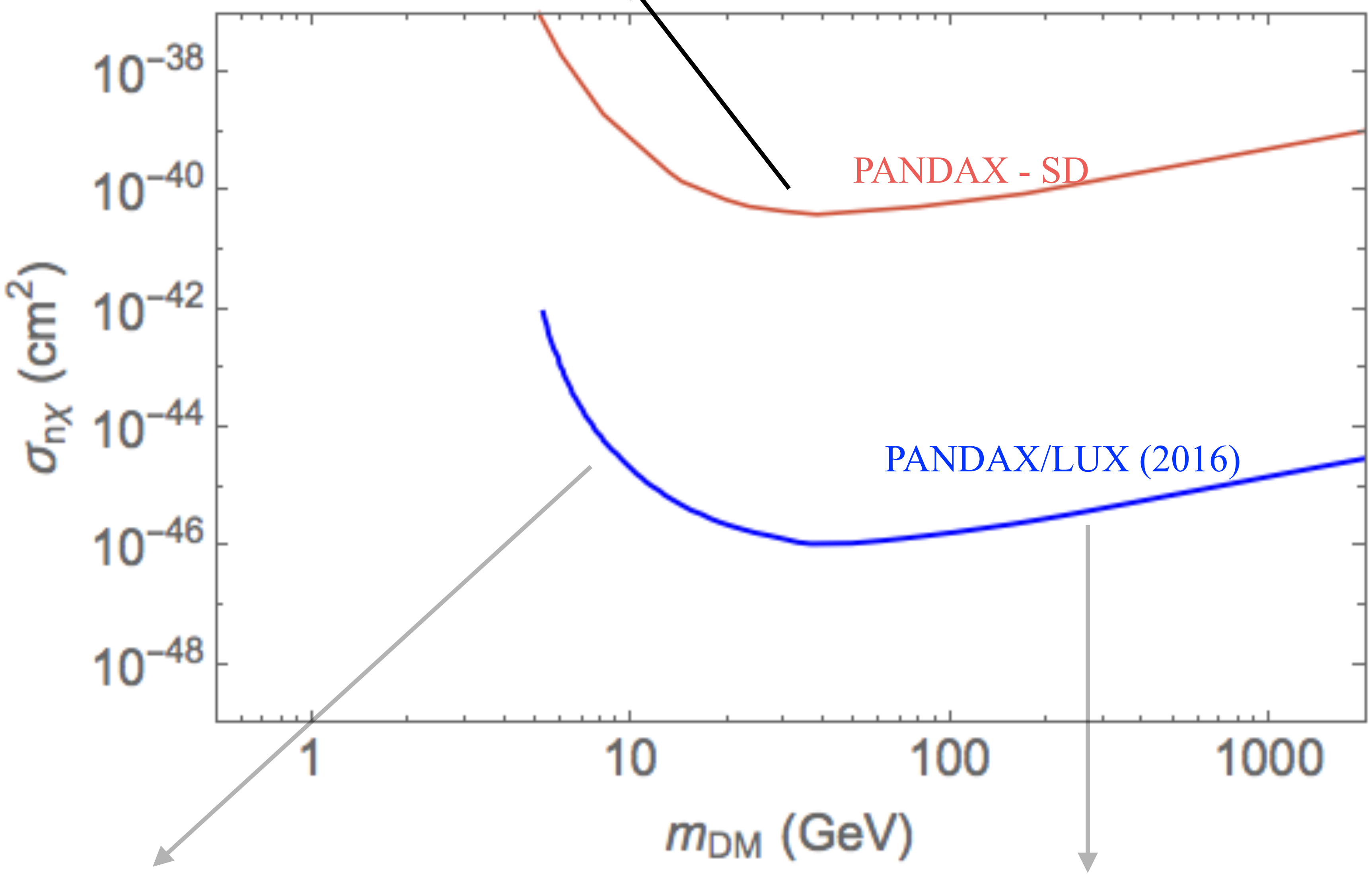


Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
wimpzilla
Black Hole Remnant
σ_{int} (pb)
mass (GeV)

Direct searches: challenges

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

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



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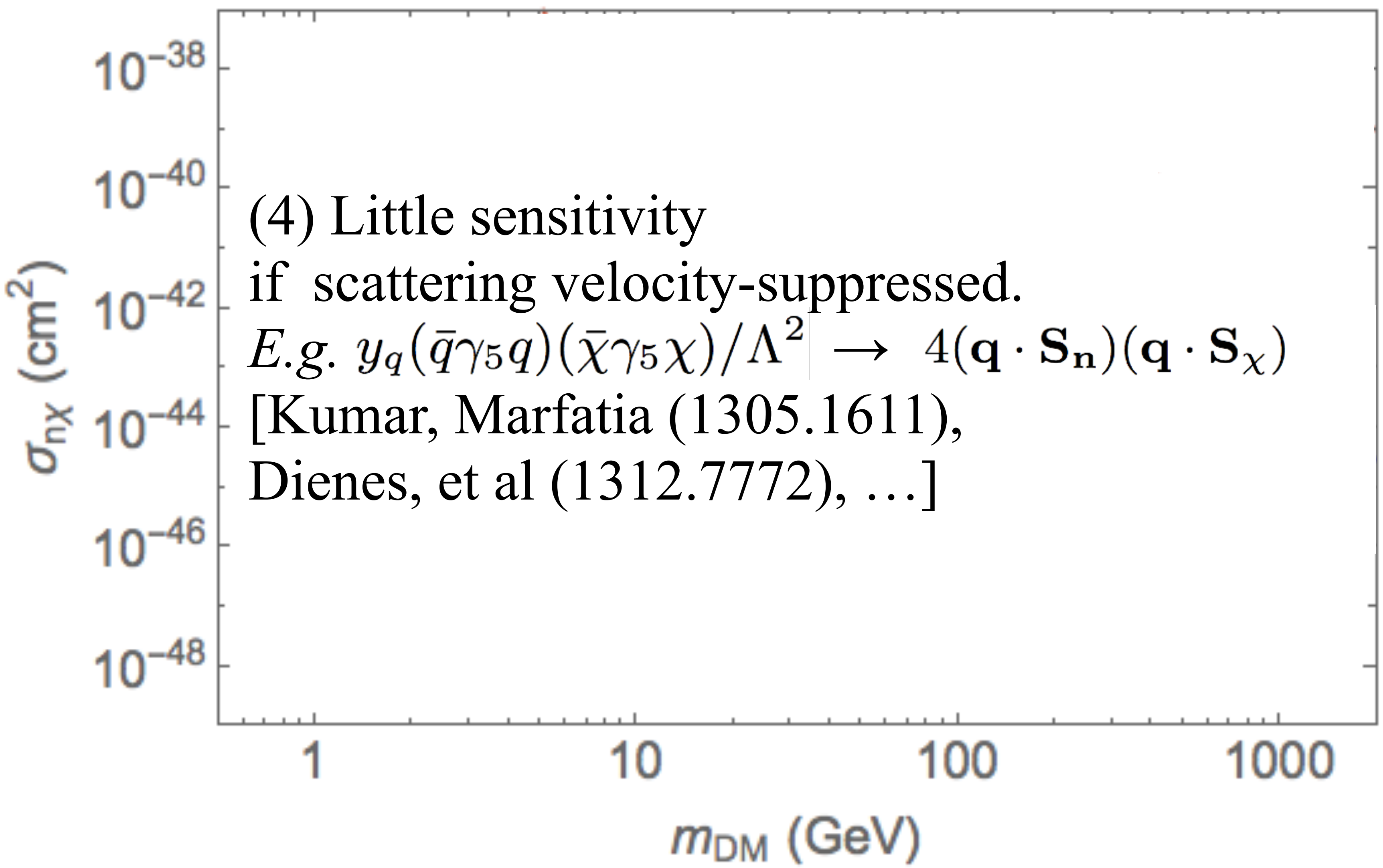

(4) Little sensitivity
if scattering velocity-suppressed.
E.g. $y_q(\bar{q}\gamma_5 q)(\bar{\chi}\gamma_5\chi)/\Lambda^2 \;\rightarrow\; 4(\mathbf{q}\cdot\mathbf{S_n})(\mathbf{q}\cdot\mathbf{S}_\chi)$
[Kumar, Marfatia (1305.1611),
Dienes, et al (1312.7772), …]

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

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Direct searches: challenges

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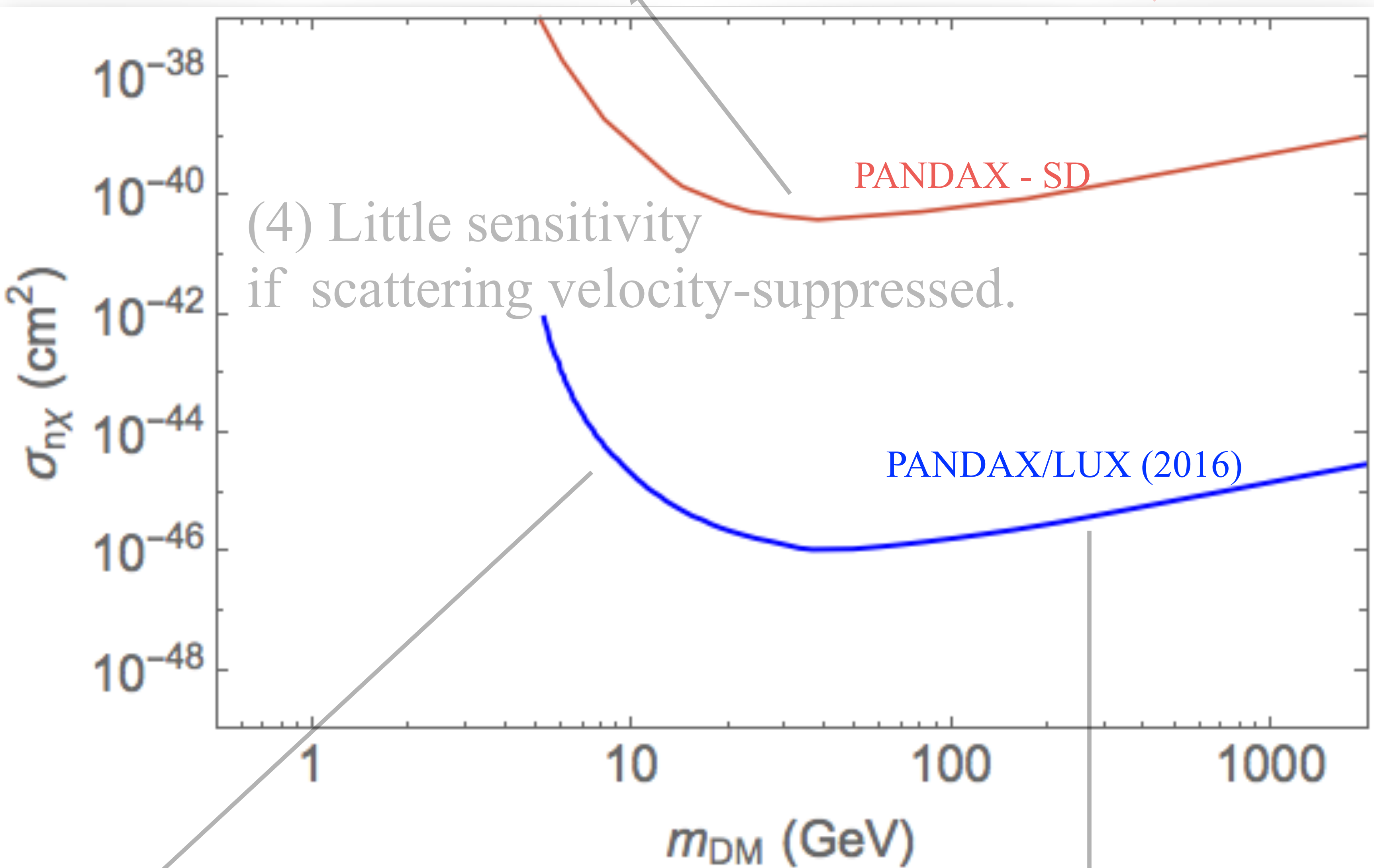

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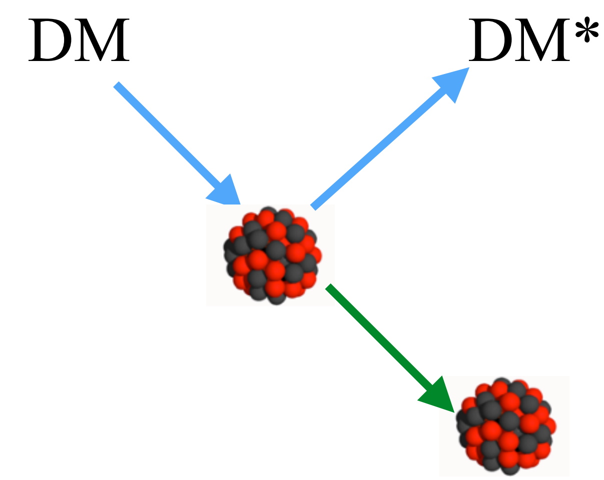
(Image: G. Kribs)



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

(5) If scattering <u>inelastic</u>,
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

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

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

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

Direct searches: challenges

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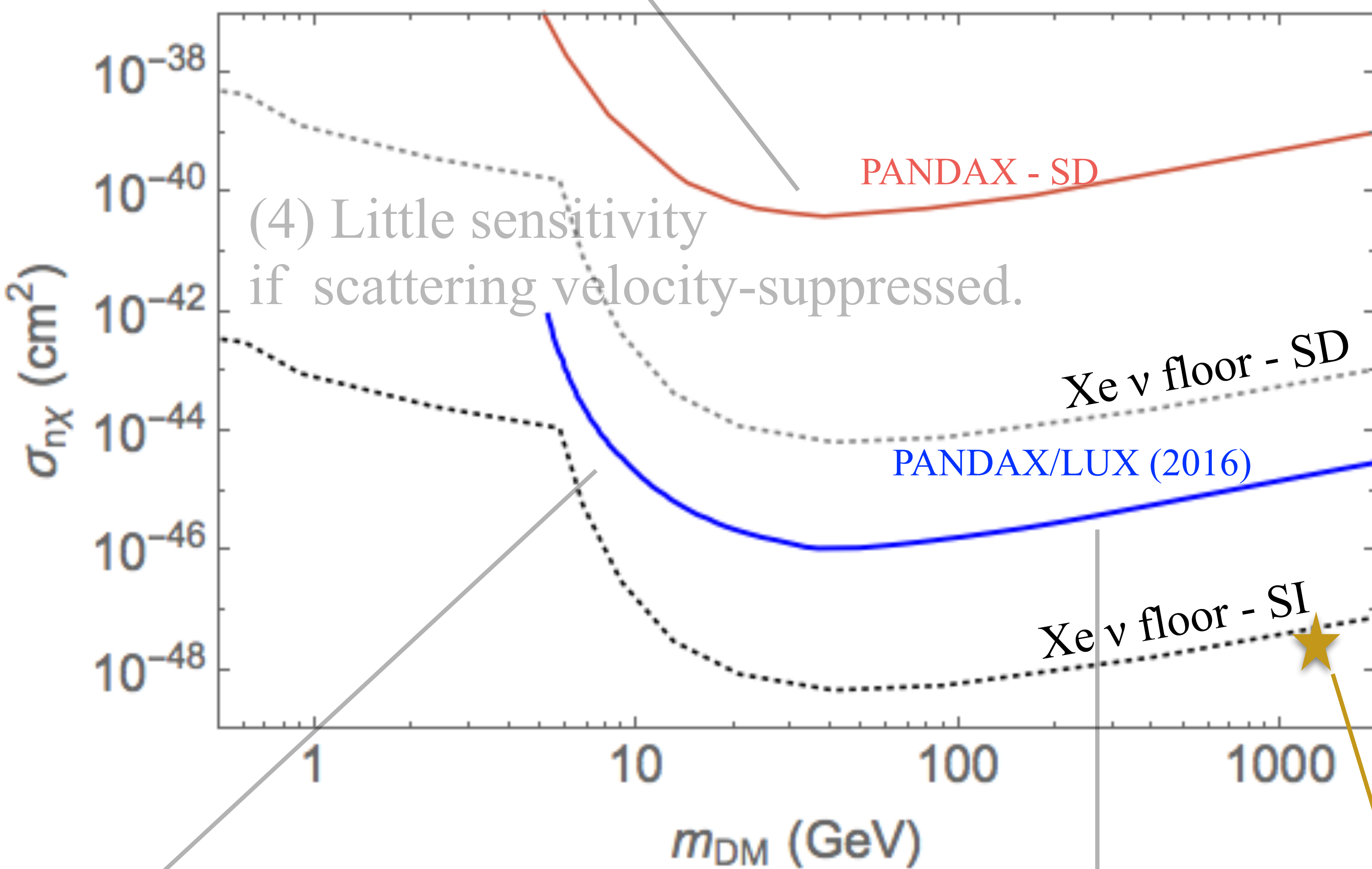
if scattering spin-dependent: $\sigma_{\rm nucleon} = \left(\frac{1}{A}\right)^2 \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \sigma_{\rm Nucleus}$



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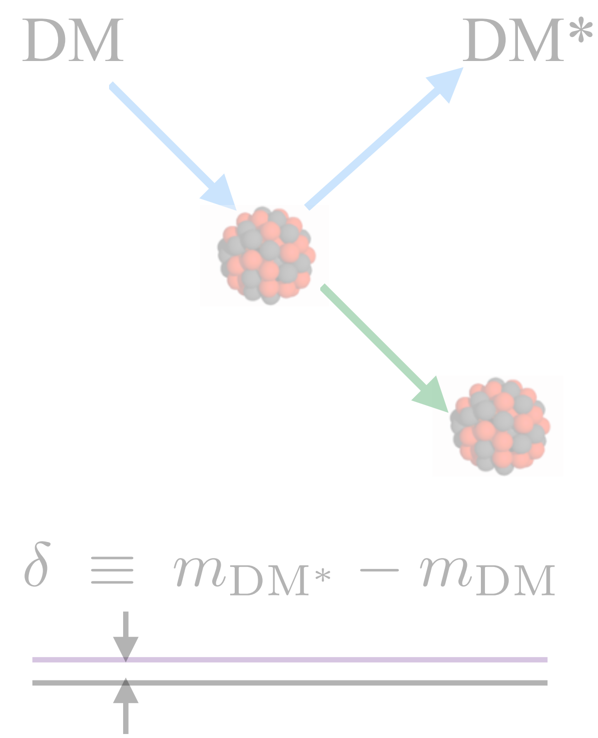

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(1) Nuclear recoil below
detector thresholds at low mass

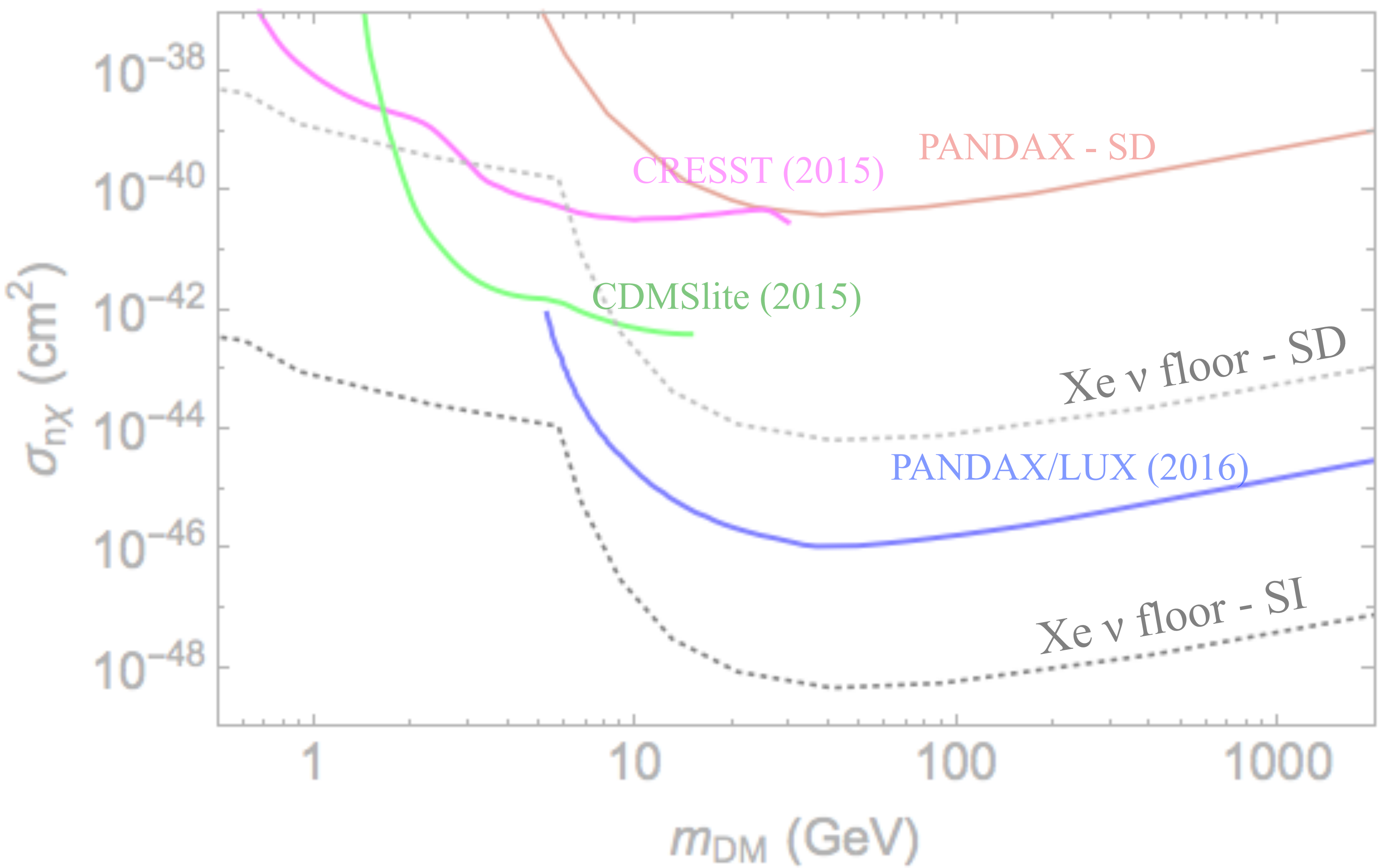
(2) DM flux $\propto \frac{1}{m_{\rm DM}}$
at high mass

(6) 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) v-suppressed ✕
(5) Inelastic ✕
(6) Neutrino floors ✕

Crucial frontiers — beyond which dark matter could be.

(Dark) Kinetic Heating

Soup getting cold

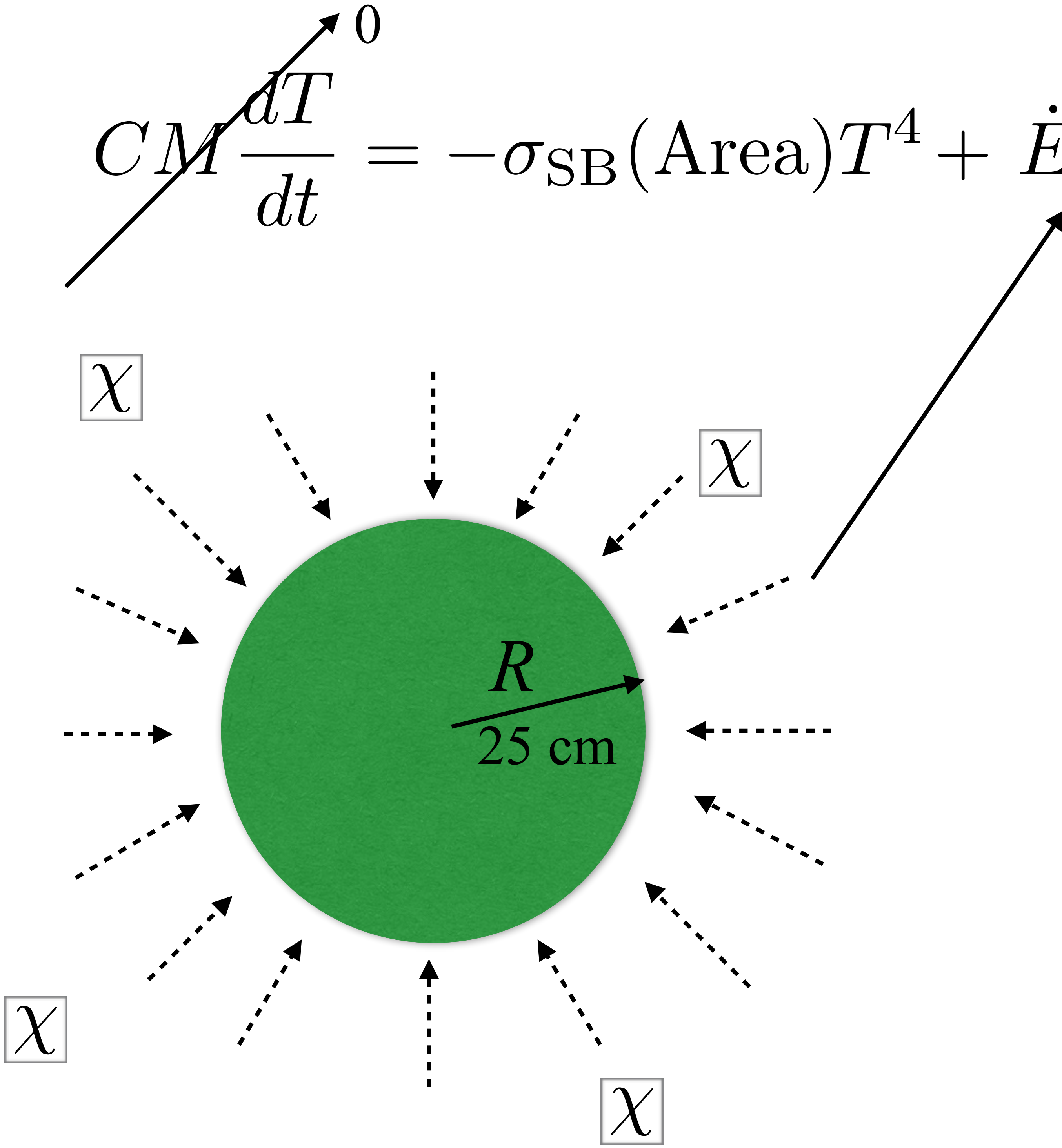
$$CM\frac{dT}{dt} = -\sigma_{\text{SB}}(\text{Area})(T^4 - T^4_{\text{ambient}})$$

Keeping soup hot: fire

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

Keeping soup hot: dark fire

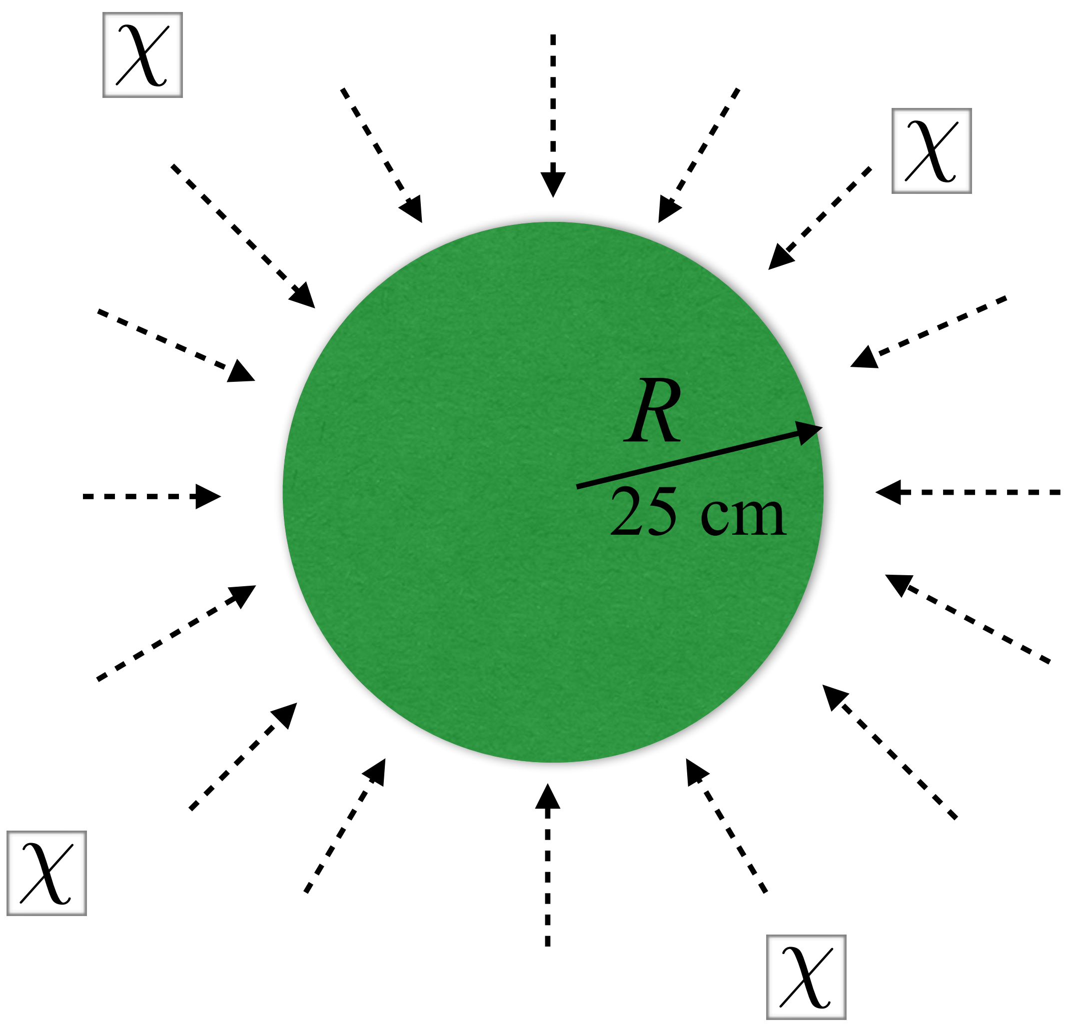
$$\cancel{CM\frac{dT}{dt}} = -\sigma_{\mathrm{SB}}(\mathrm{Area})T^4 + \dot{E}_{\mathrm{external}}$$

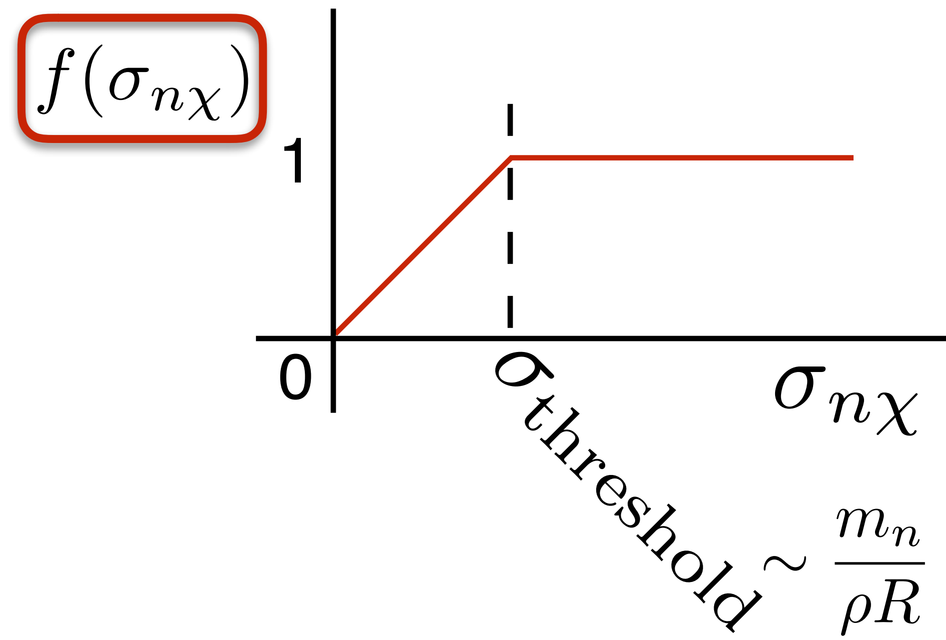


Keeping soup hot: dark fire

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

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



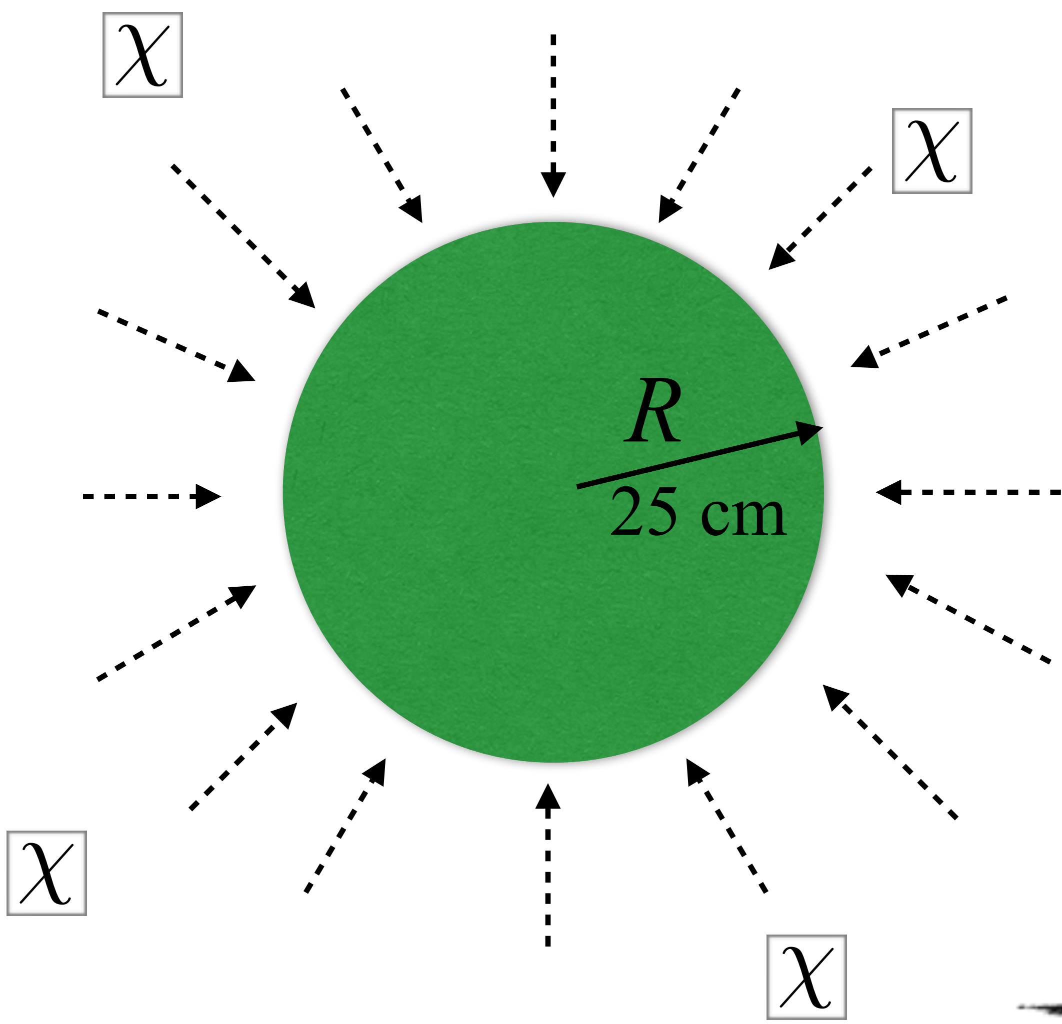


$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold}R\right)$$

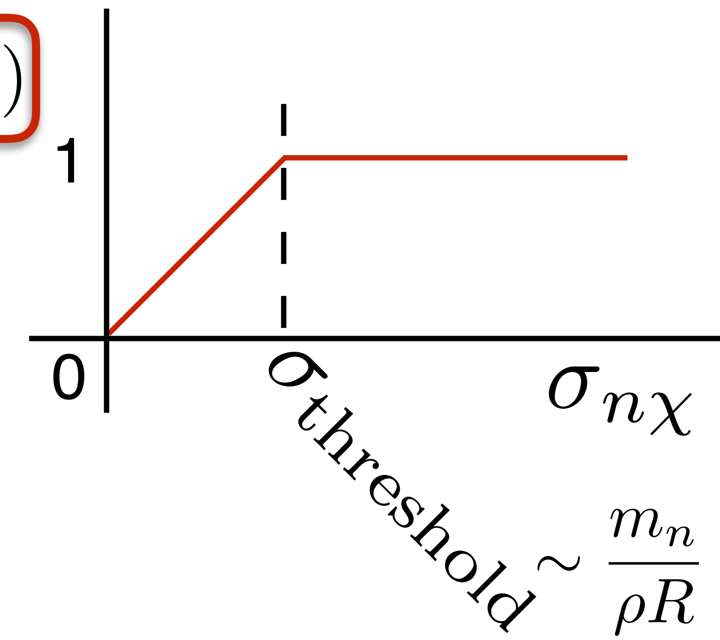
$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}\text{cm}^2$$

Keeping soup hot: dark fire

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



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



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

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

$\frac{dN}{dt}$ 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

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

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

Bigger
and denser

$$\boxed{\mathrm{KE}} \quad \frac{1}{2} m_{\mathrm{DM}} v_{\mathrm{DM}}^2$$

$T = 3$ nanoKelvin

Detector improvements

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Bigger
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Get a gravitational boost!
$v_{\text{esc}} \propto \sqrt{\rho R}$

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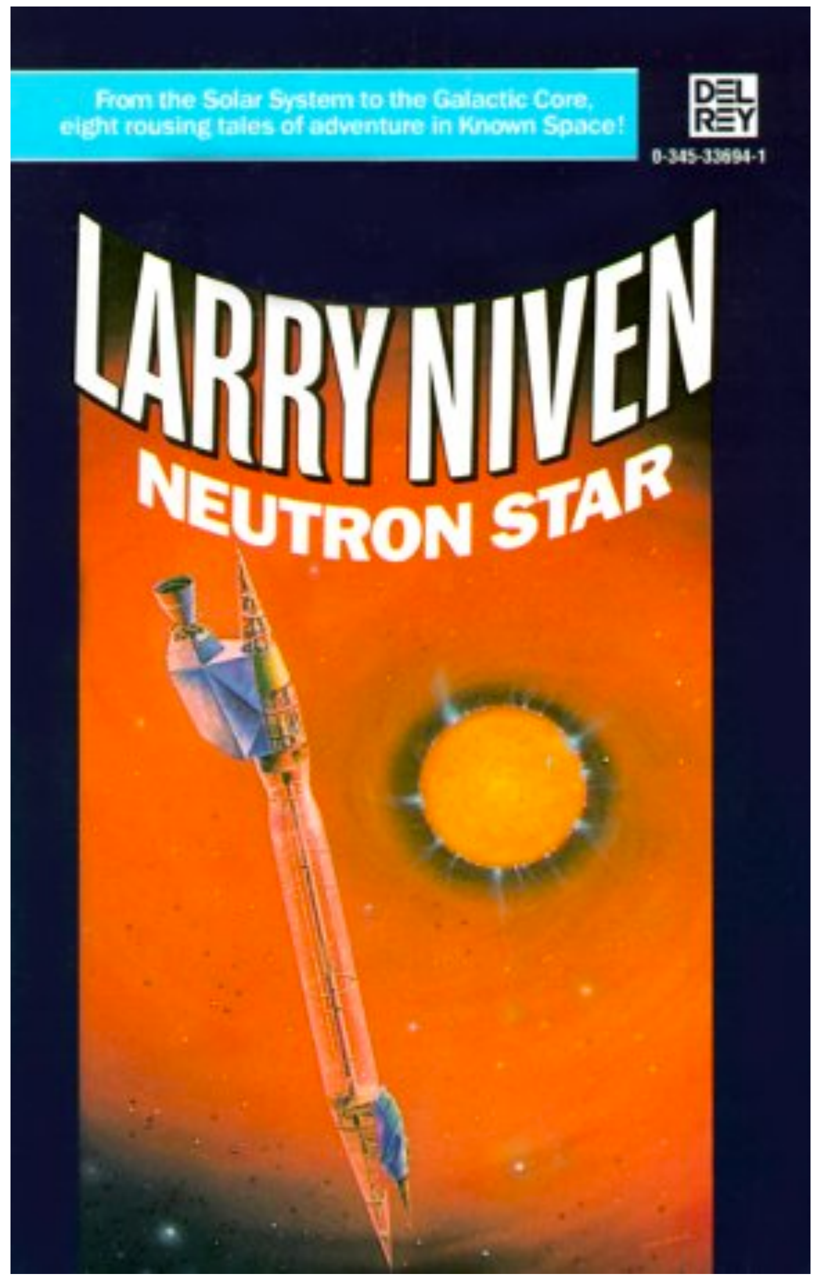
KE $\frac{1}{2} m_{\rm DM} v_{\rm DM}^2$

Be colder than
dark-kinetically-heated
temperature

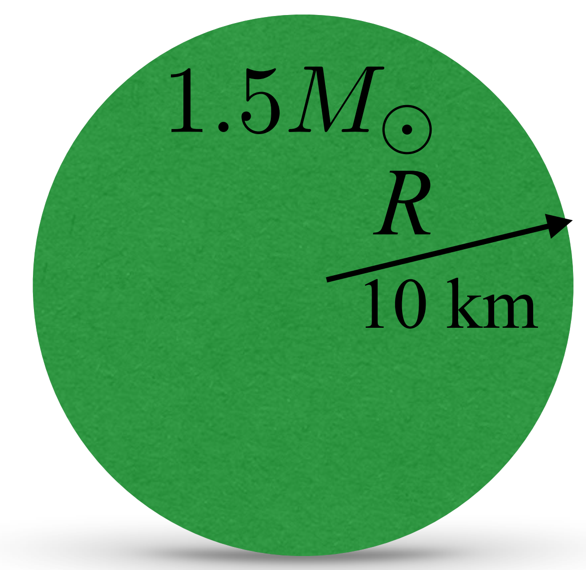
$T = 3$ nanoKelvin

What’s big, dense, and cold?



big, dense

7×10^{17} kg/m^3

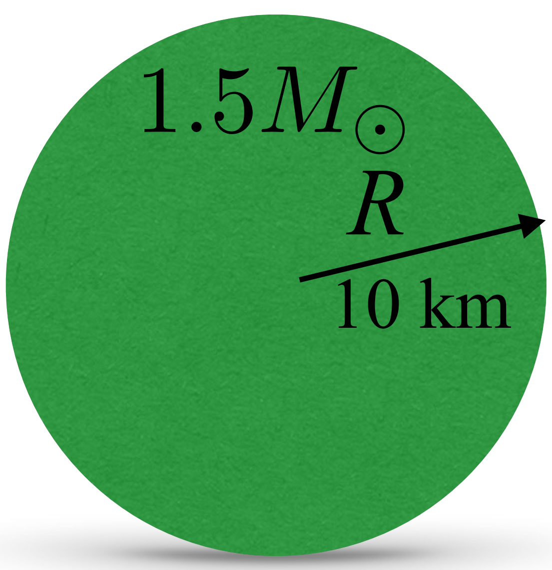


Lake Michigan (weighing 5×10^{12} kg) in a teaspoon

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

big, dense, and cold

7×10^{17} kg/m^3



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

$v_{\rm esc} \simeq 0.7$

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

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

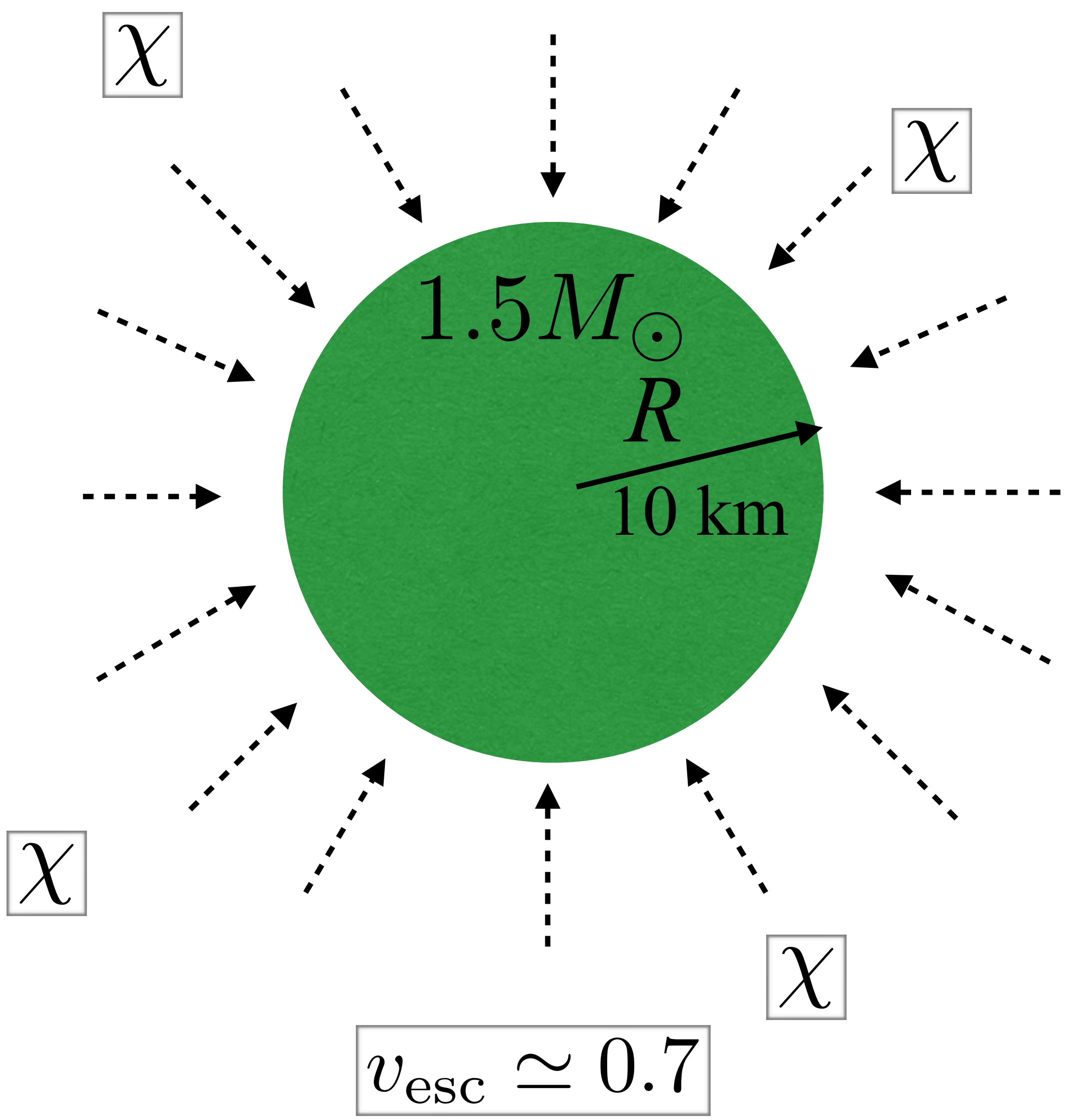
Page, Lattimer, Prakash, Steiner (2004)
Yakovlev, Pethick (2004)

Keeping N star hot: dark fire

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

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

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



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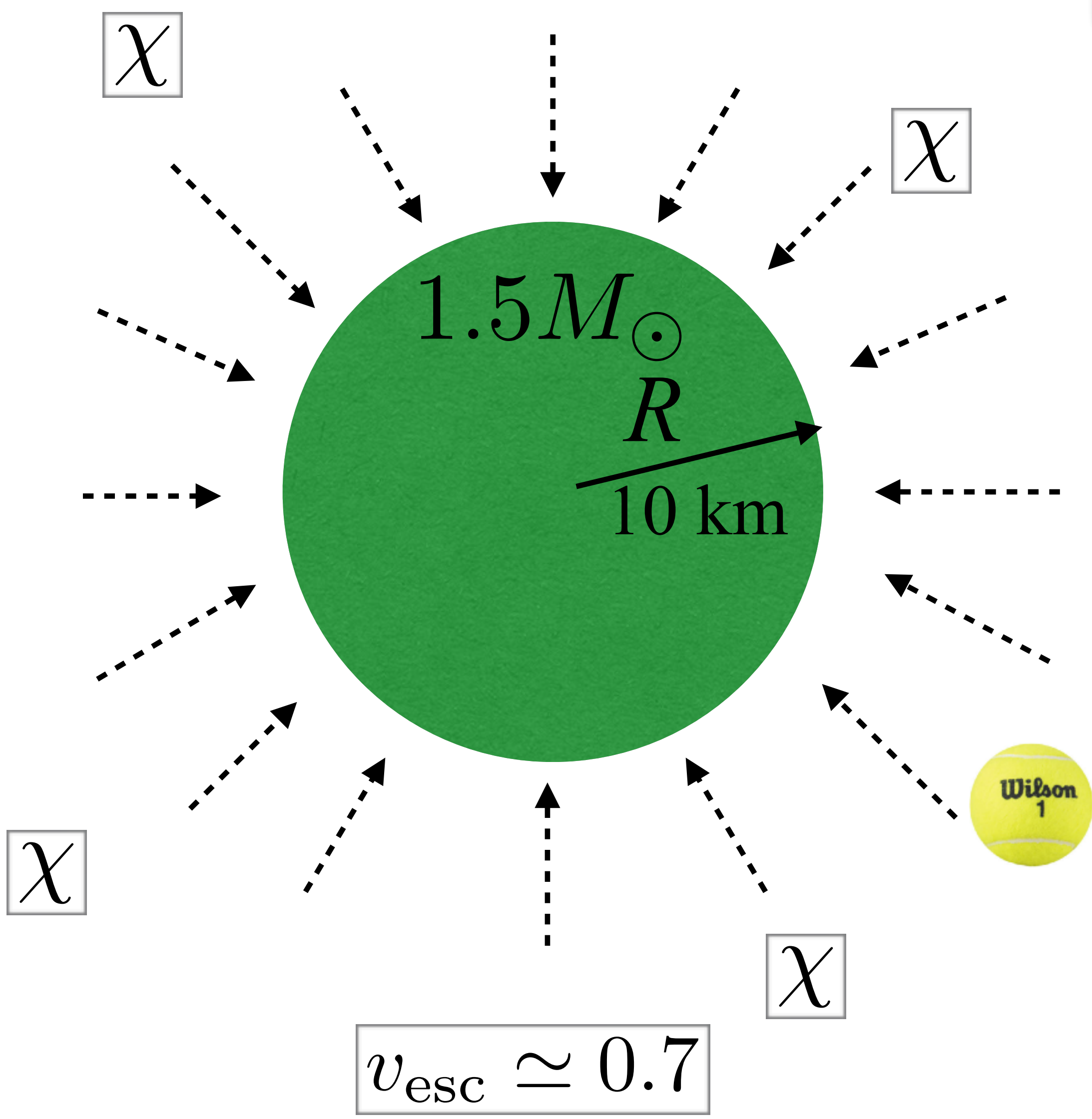
$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold} R\right)$$

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

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

DM mass drops out of this calculation!

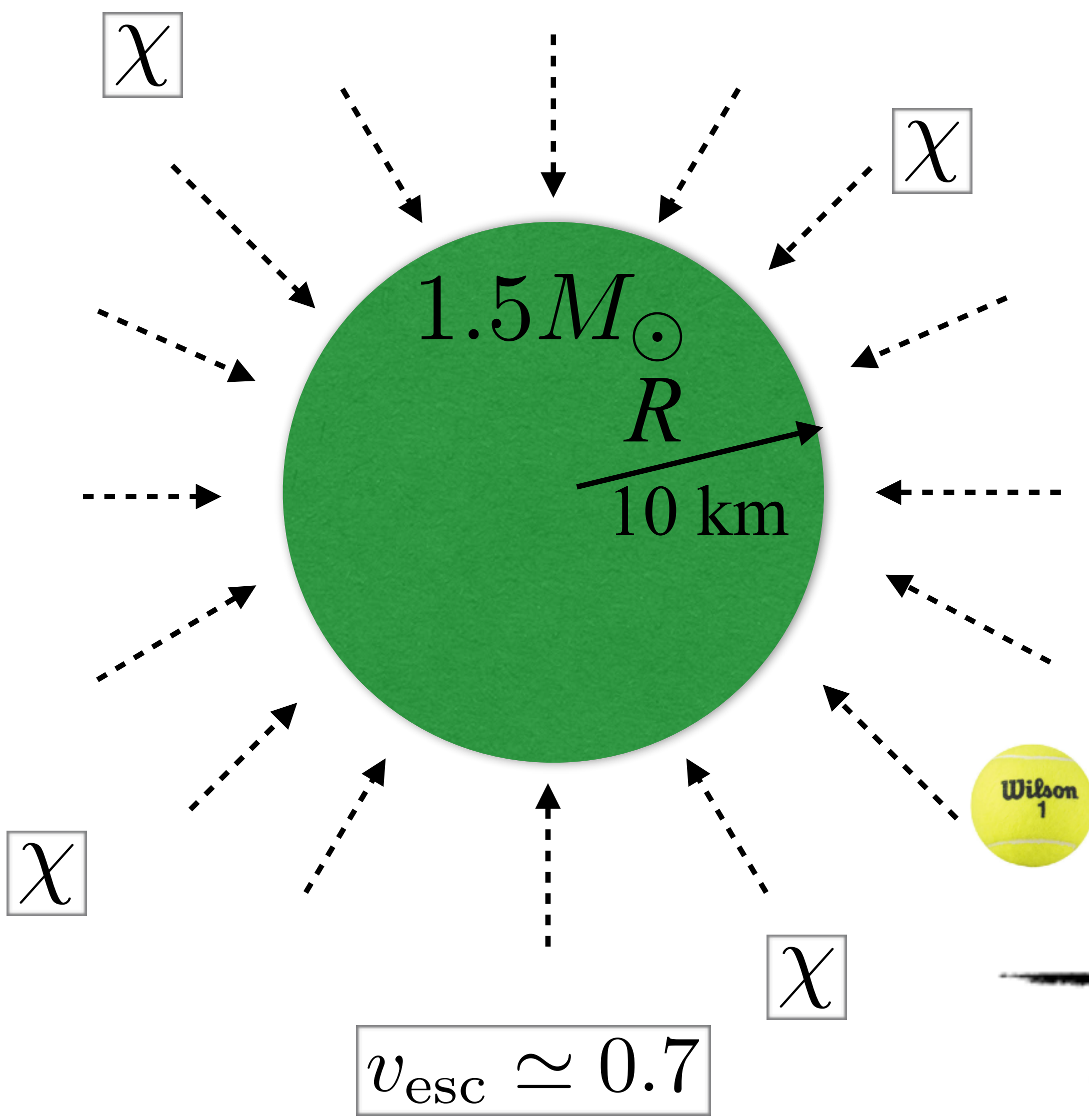


← 60 grams of DM/ second

25 grams x c^2 of DM KE/ second

Keeping N star hot: dark fire

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



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$\frac{dN}{dt}$ $\quad \pi b_{\max}^2 v_{\mathrm{DM}}\left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)$, with $b_{\max} \to R\left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{DM}}}\right)$

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DM mass drops out of this calculation!

← 60 grams of DM/ second

20 grams x c^2 of DM KE/ second

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

Keeping N star hot: dark fire

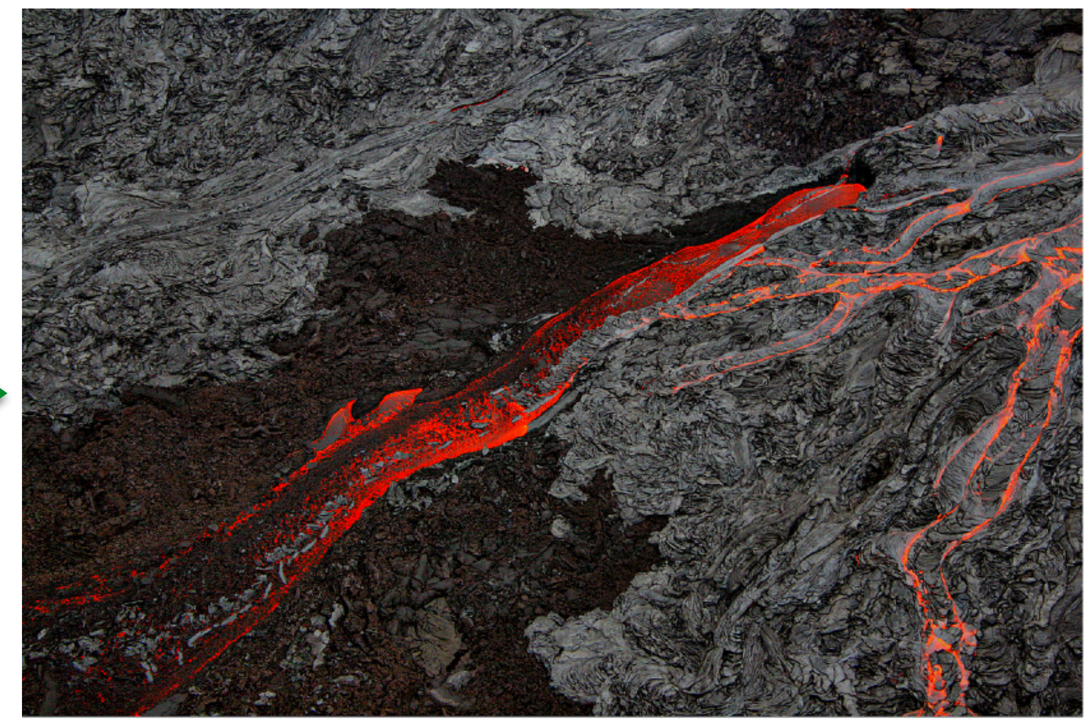
$\nearrow 0$

KE

$n\sigma_{\text{threshold}}R)$

snowball

fresh lava



χ

20 grams x c^2 of DM KE/ second

χ

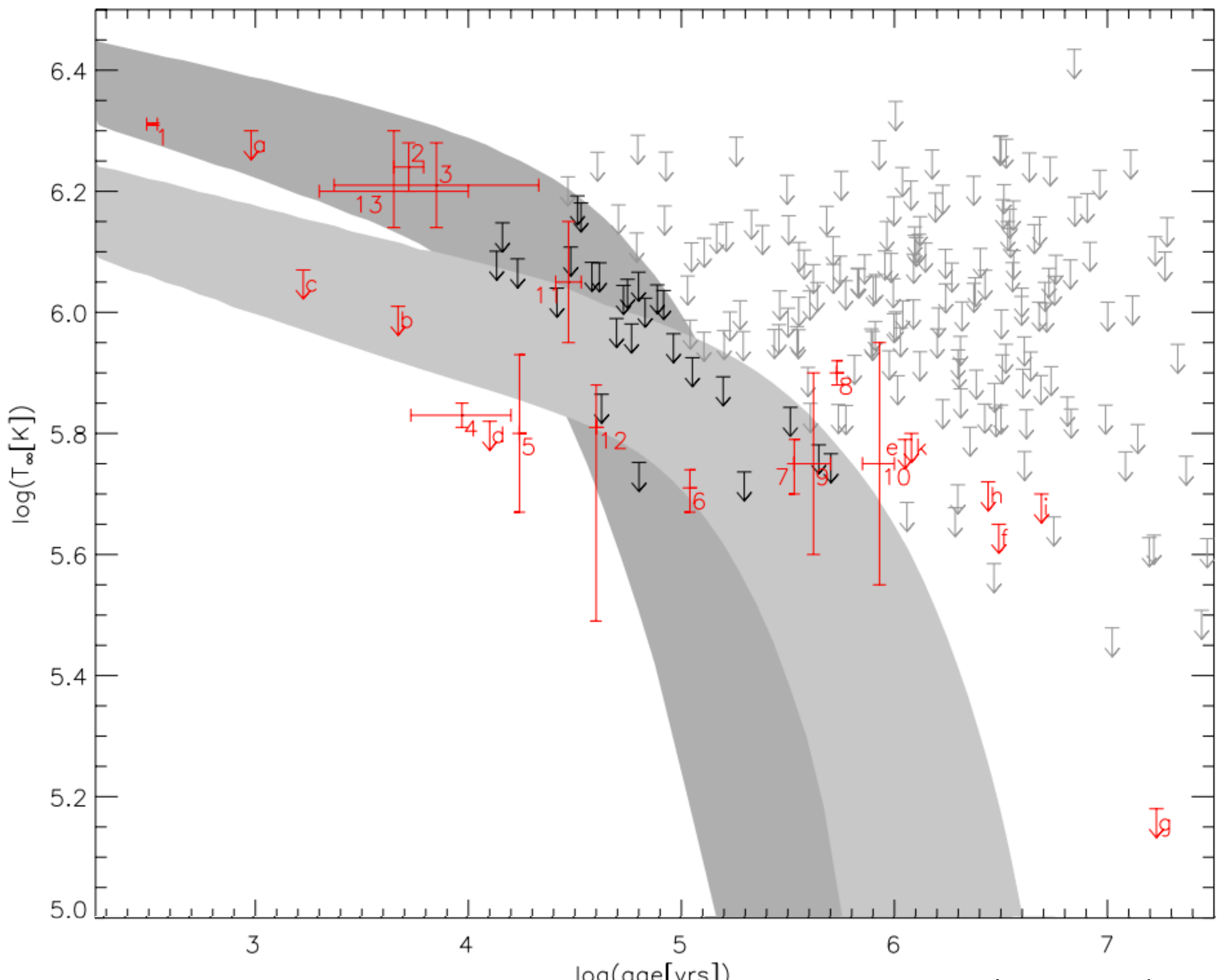
$v_{\text{esc}} \simeq 0.7$

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

Detection?

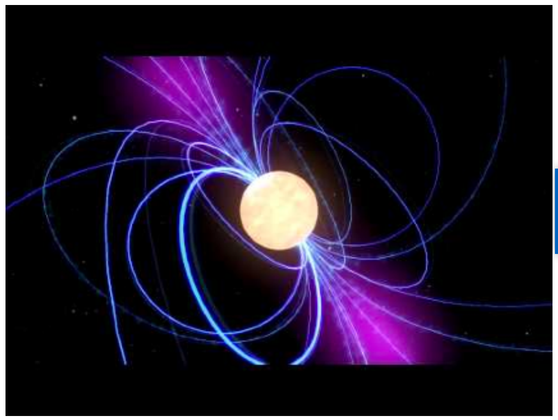
T = **1750 Kelvin** (infrared emission)

O(100) below current T bound



Prinz, Becker
astro-ph:1511.07713

Detection: radio pulsing



FAST

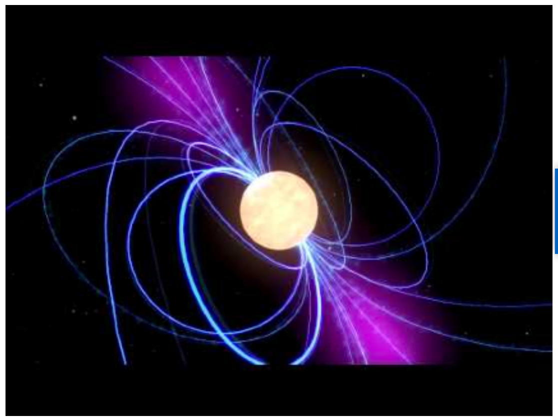
http://fast.bao.ac.cn/en/science_pulsar.html

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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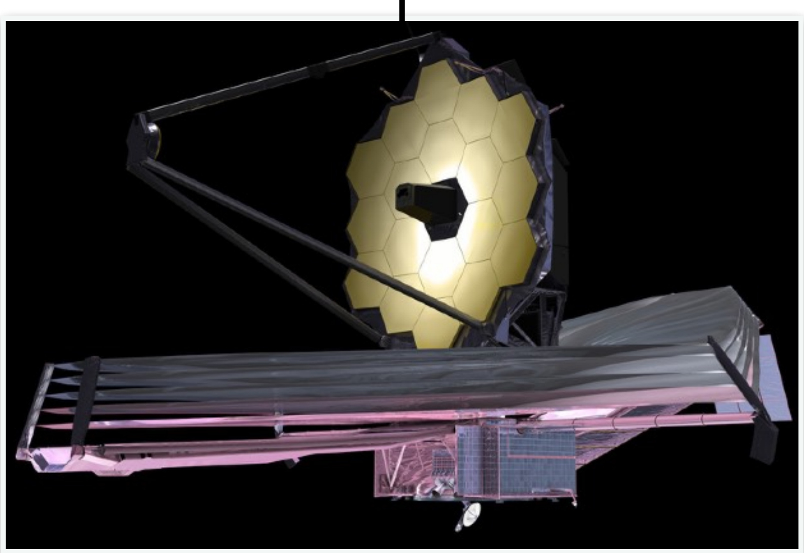
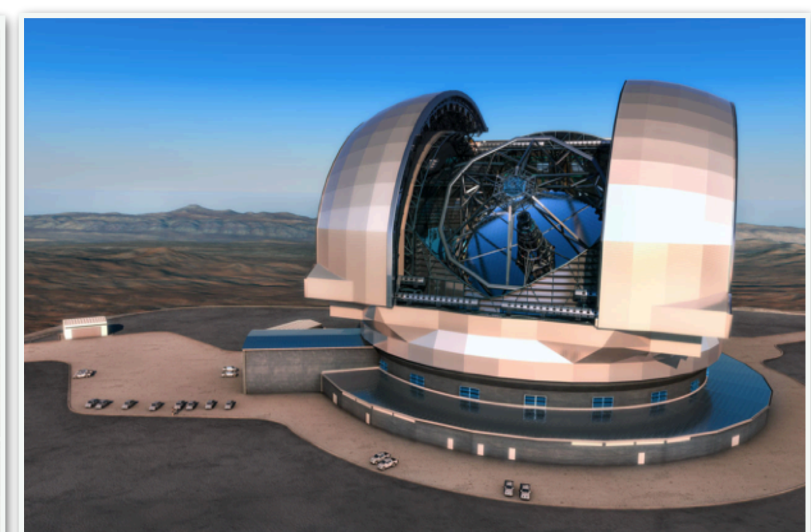
coming online Oct 2018!



James Webb

Thirty Meter

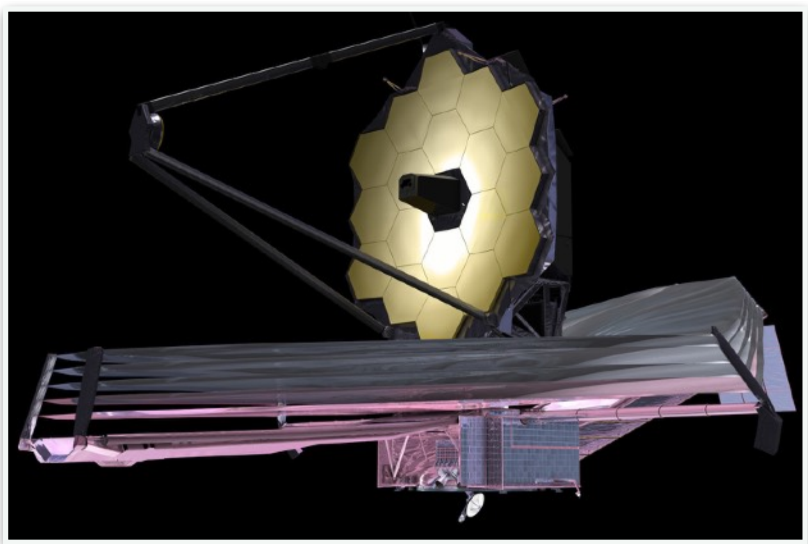


European Extremely Large

Detection: infrared telescopes

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

Peak wavelength: $1.65\ \mu m$

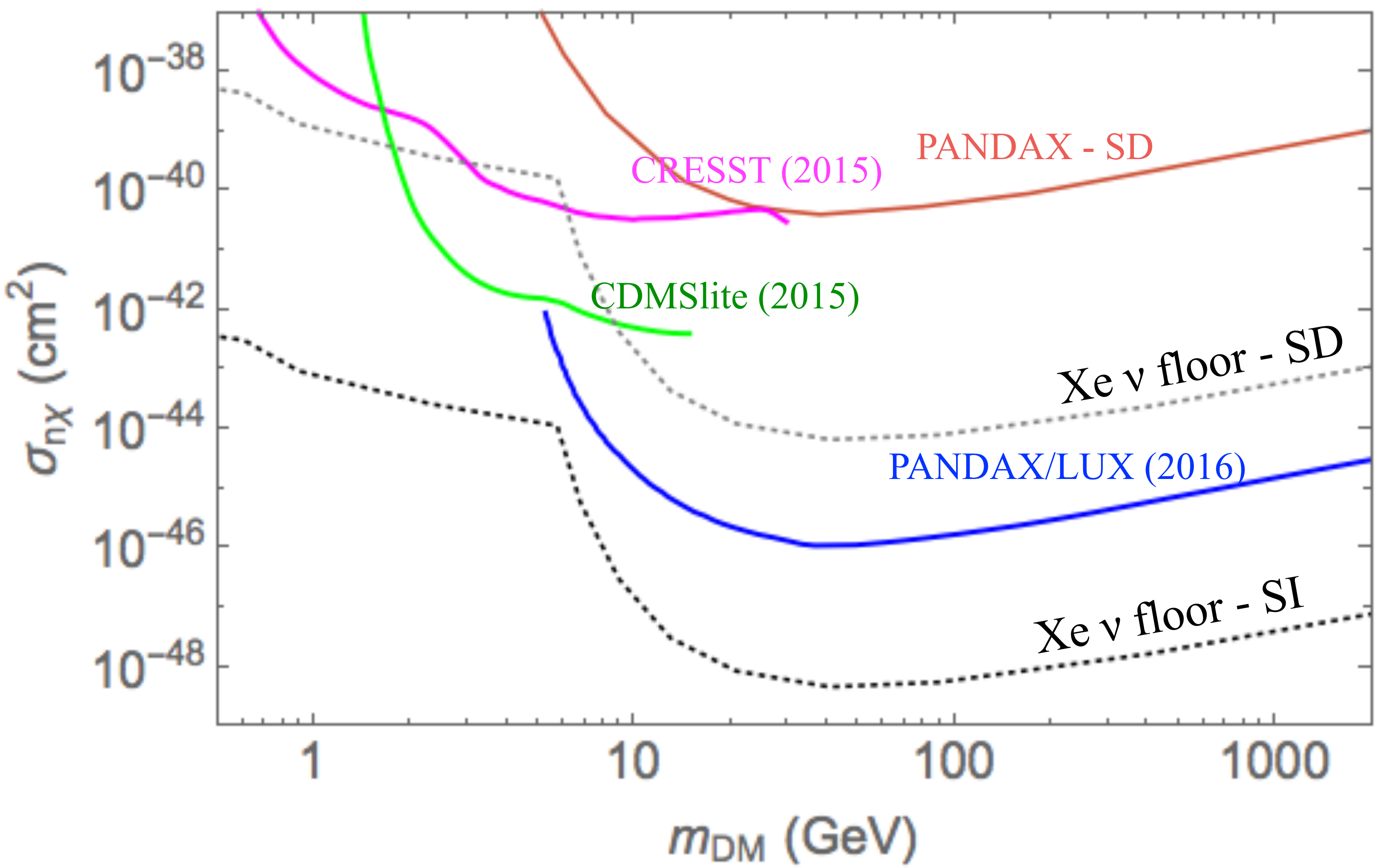


James Webb

Thirty Meter

	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	$10^5\ \text{sec} \left(\frac{d}{10\text{pc}}\right)^4$	$7 \times 10^4\ \text{sec} \left(\frac{d}{10\text{pc}}\right)^4$

Reward?

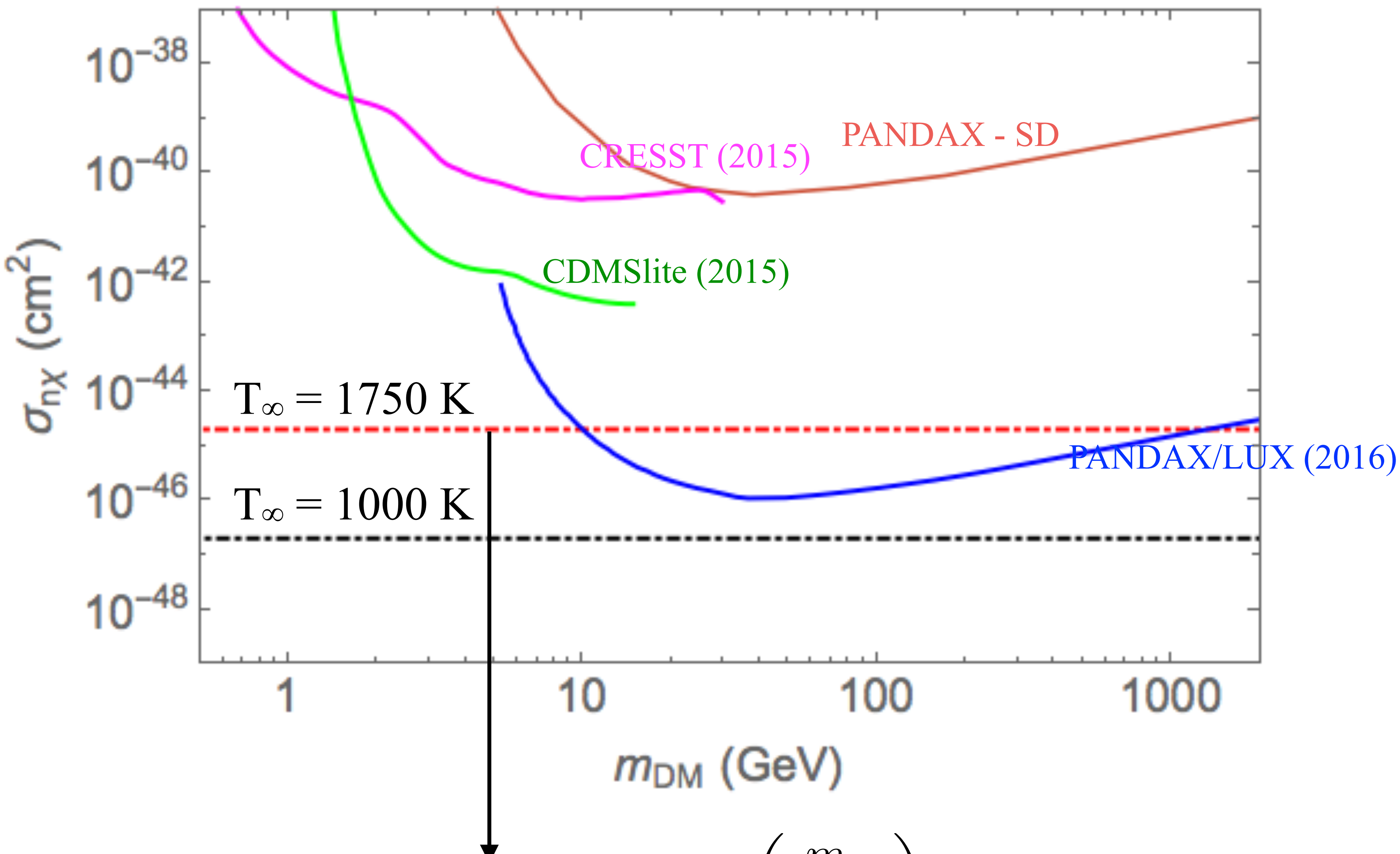


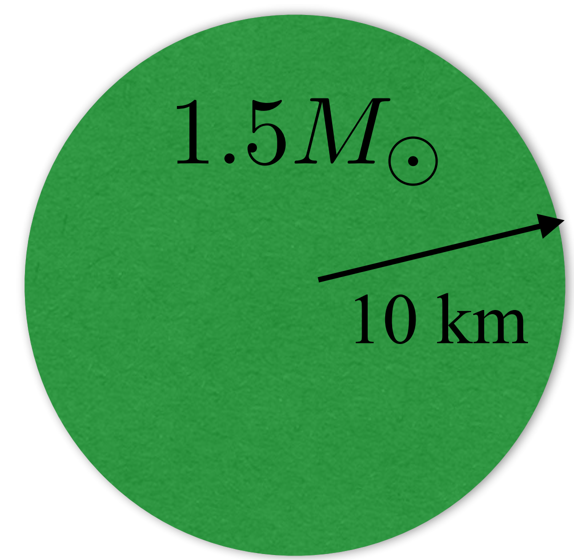
(1) Low mass
(2) High mass
(3) Spin-dependent
(4) v-suppressed
(5) Inelastic
(6) Neutrino floors

Dark kinetic heating help these frontiers?

Comparison

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

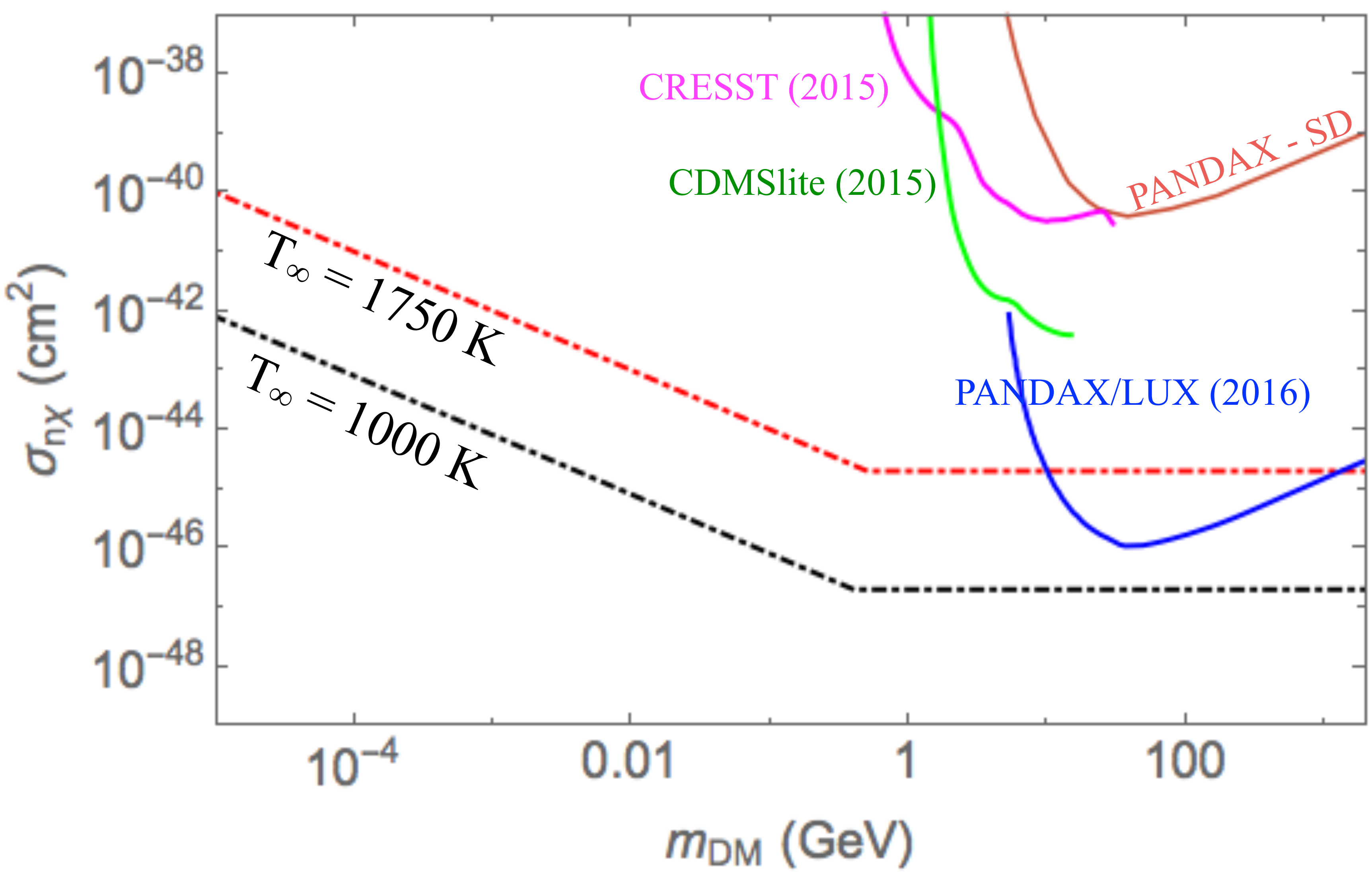




$$\sigma_{\text{threshold}} = \pi R^2 \left(\frac{m_n}{M_{\text{NS}}} \right)$$

Complementing

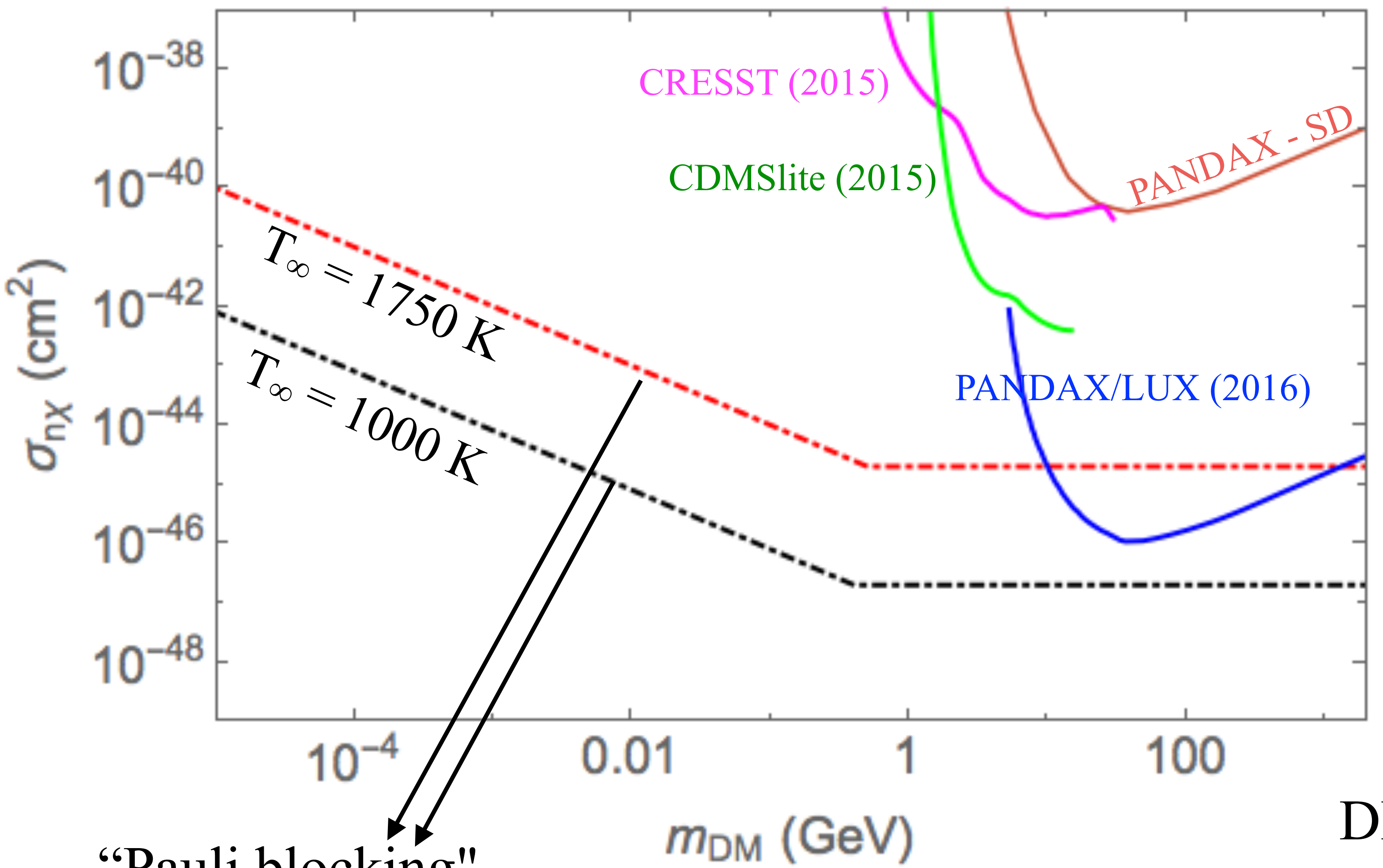
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



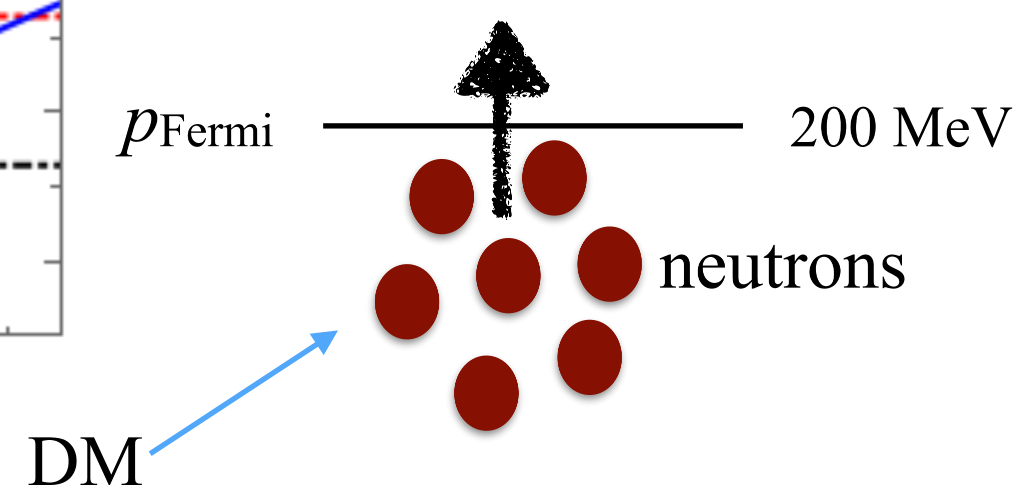
(1) Low mass ✅

Complementing

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



(1) Low mass ✅

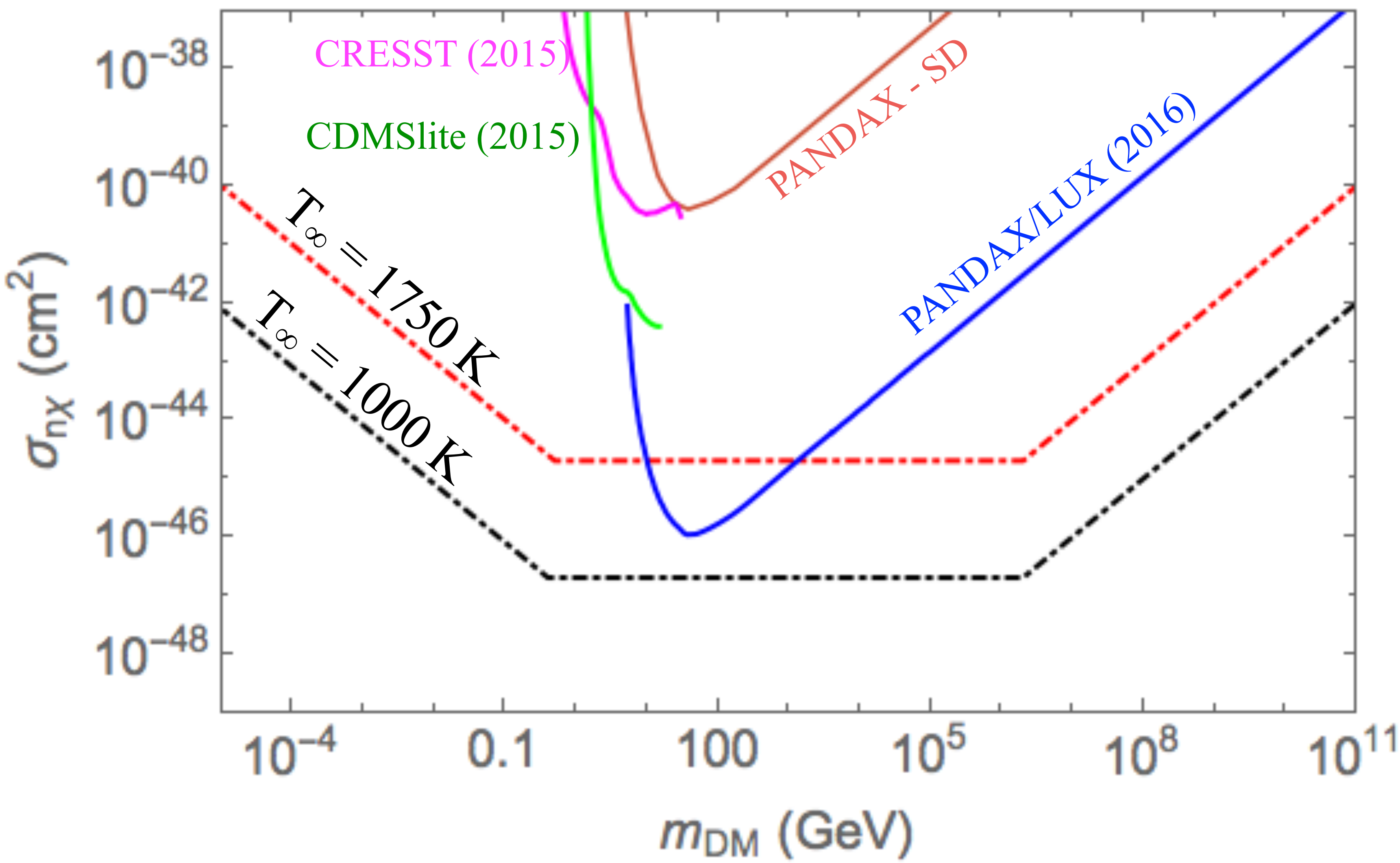


“Pauli blocking"

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

Complementing

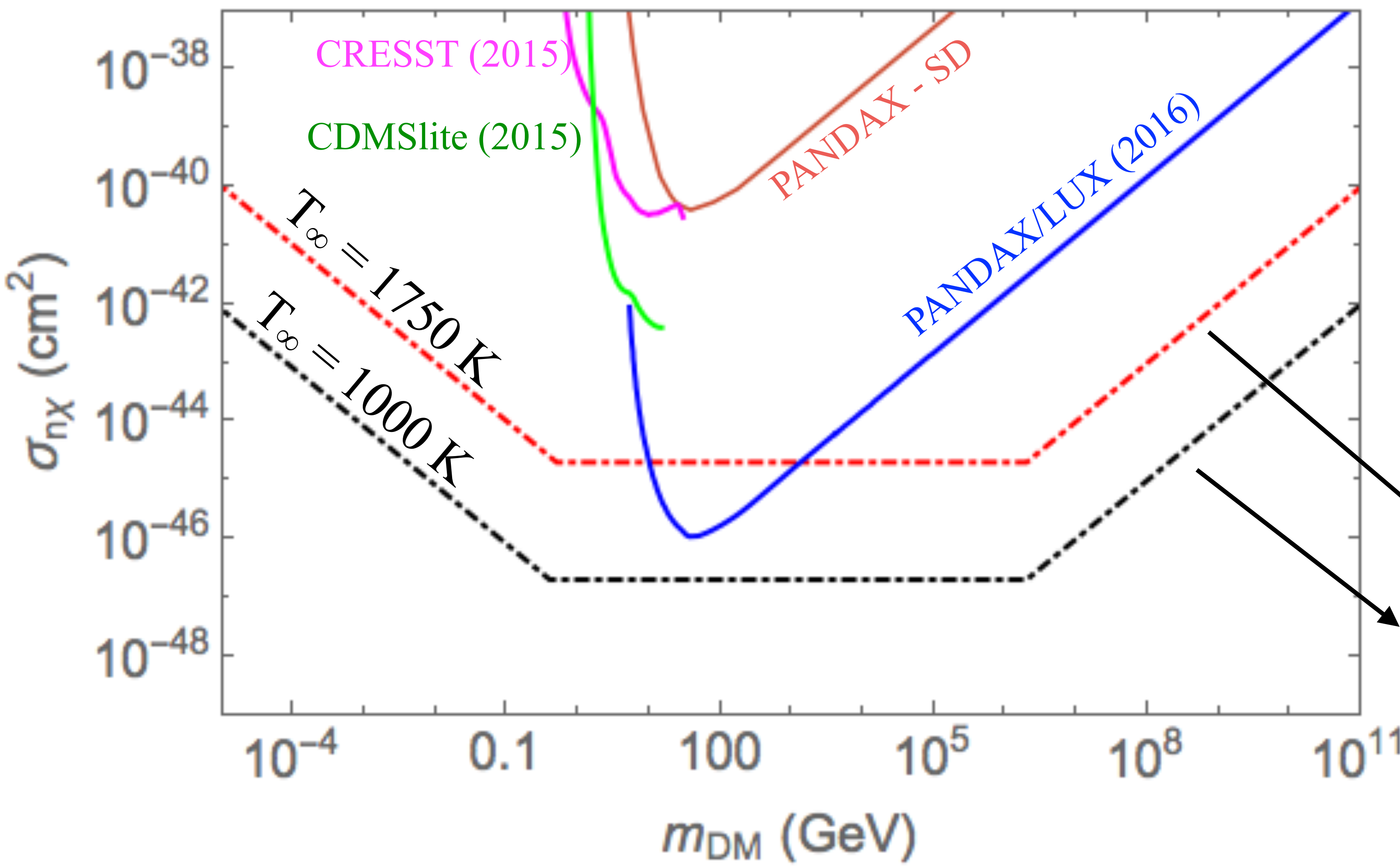
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



(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 ✅

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

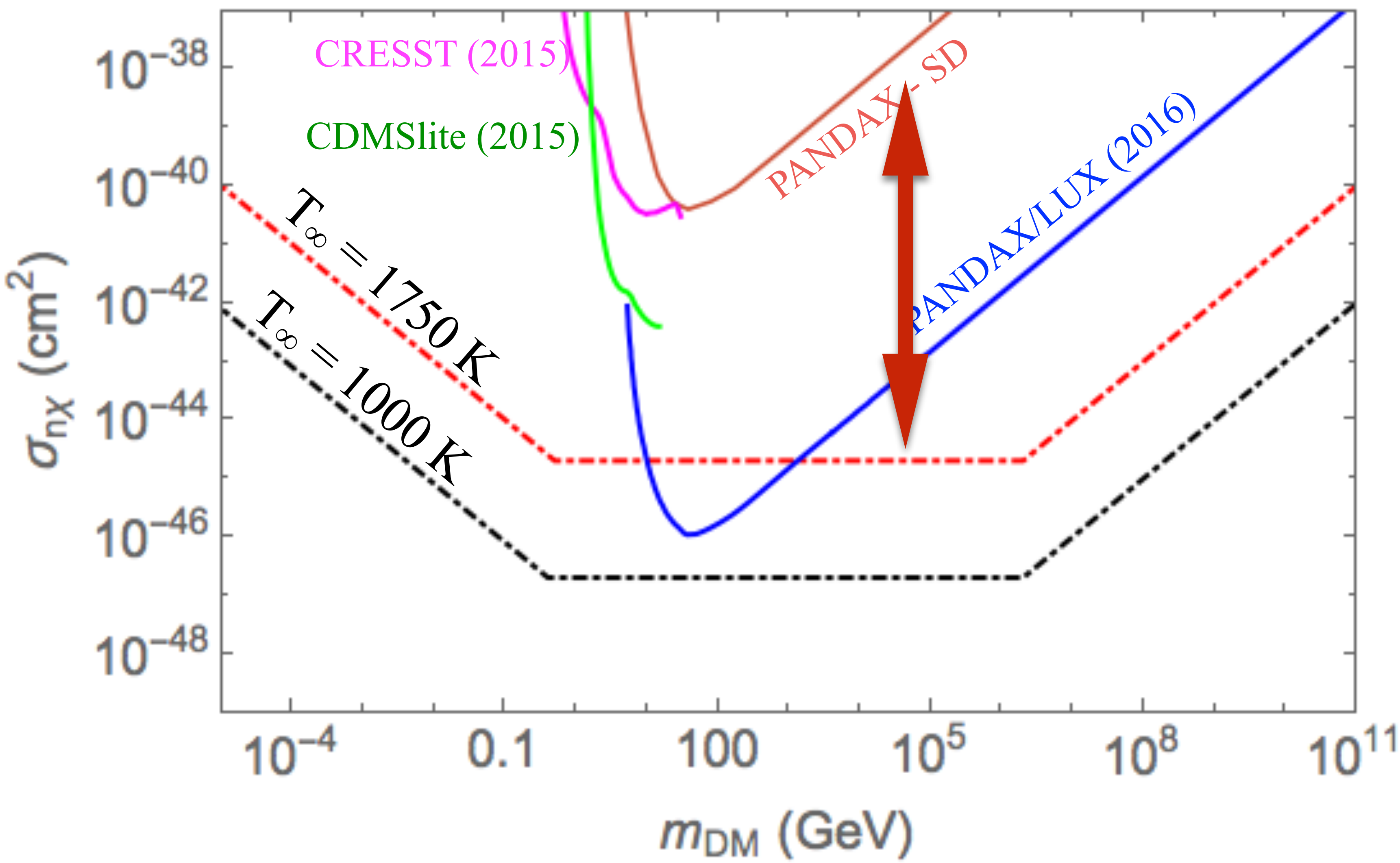
versus

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

$$\sigma_{\rm threshold} \propto \text{ number of scatters}$$
$$= E_{\rm DM}/E_{\rm recoil}$$

Complementing

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

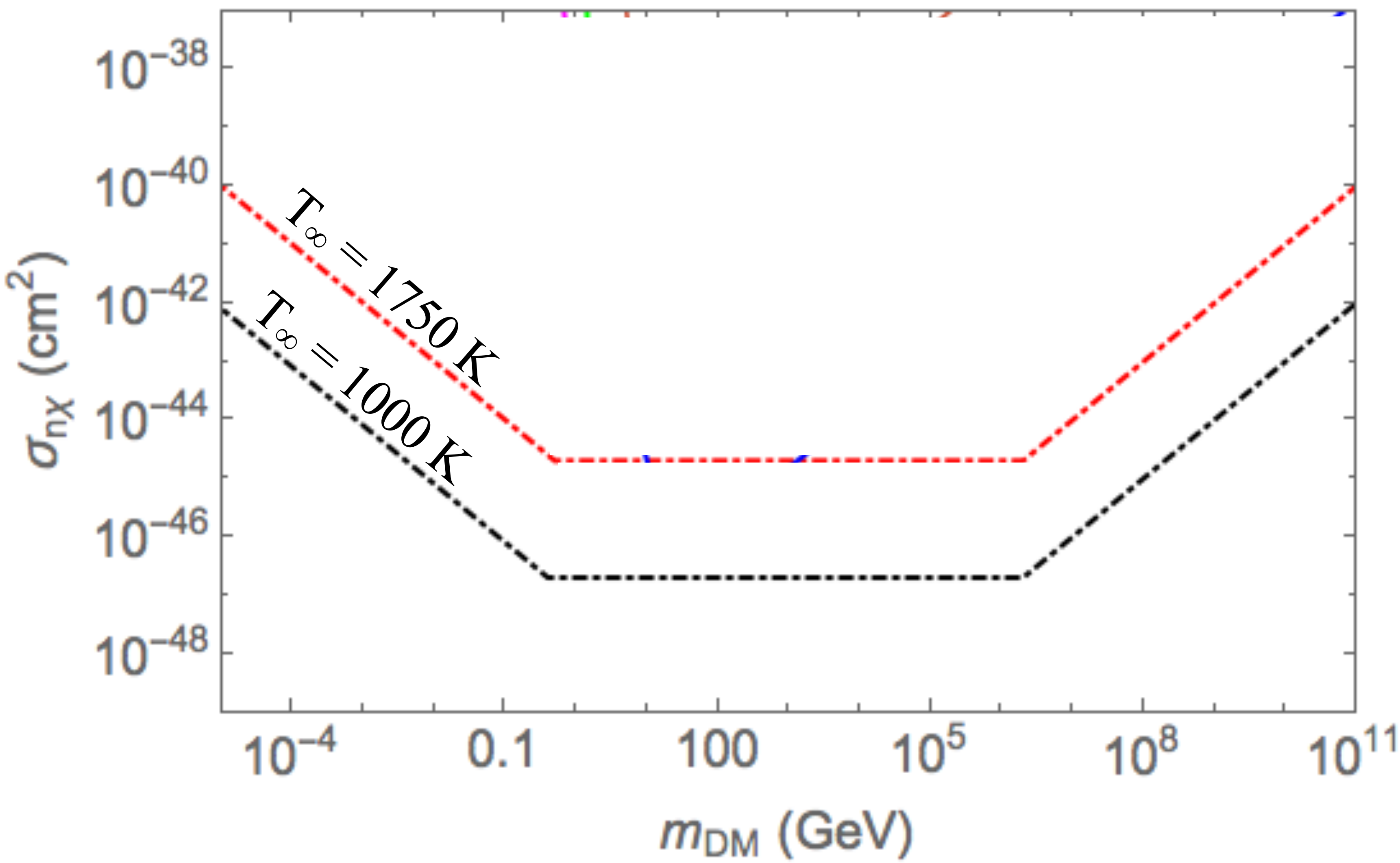


(1) Low mass ✅
(2) High mass ✅
(3) Spin-dependent ✅

Scattering with neutrons:
apathy to nuclear coherence

Complementing

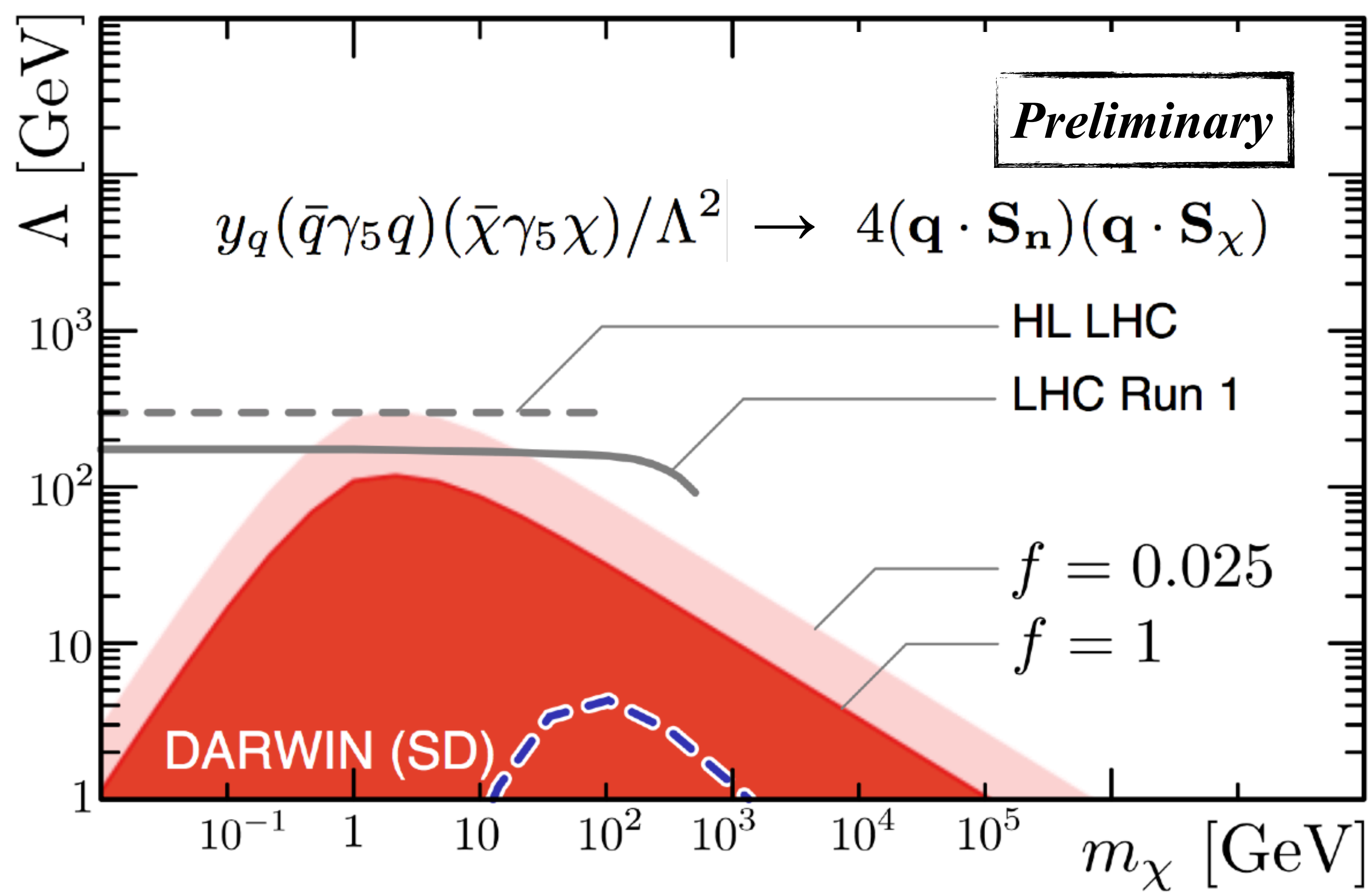
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



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

Complementing

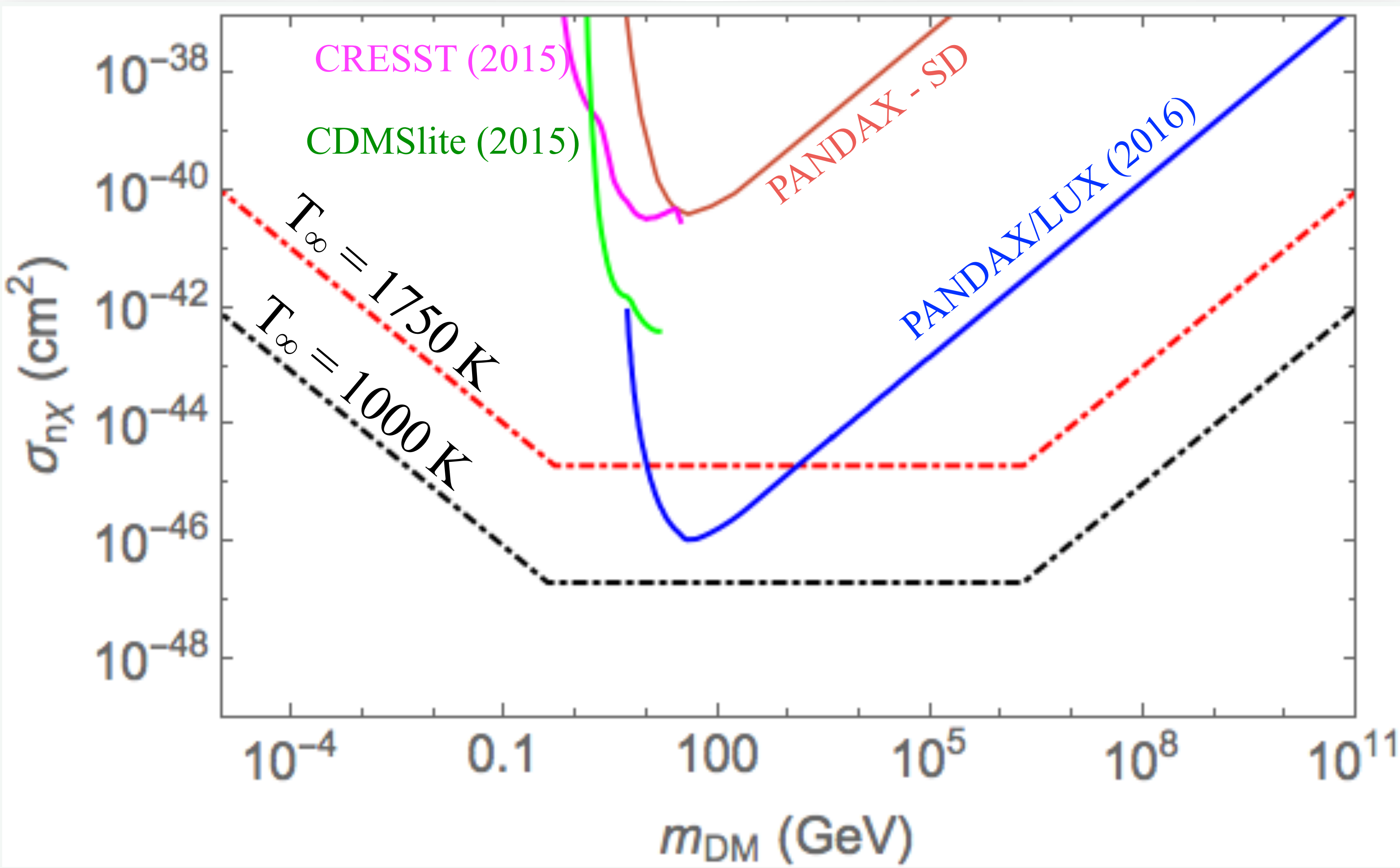
N R, P Tanedo, H-B Yu;1707.xxxxx



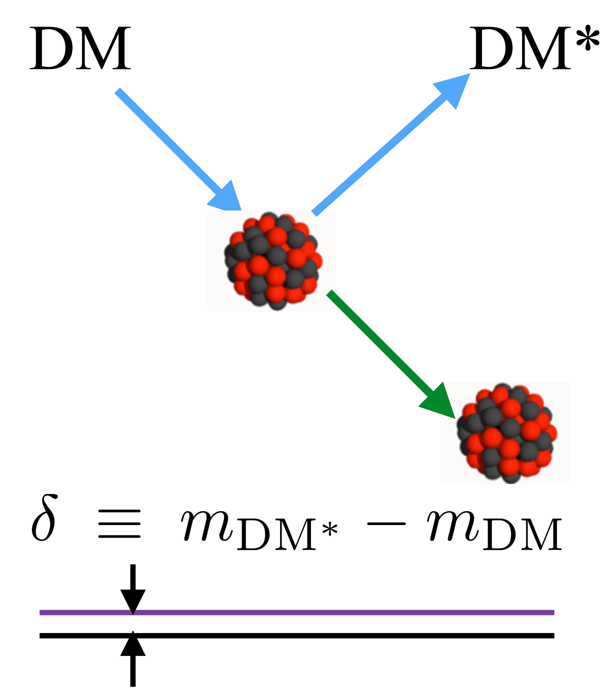
(1) Low mass ✅
(2) High mass ✅
(3) Spin-dependent ✅
(4) v-suppressed ✅

Complementing

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



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

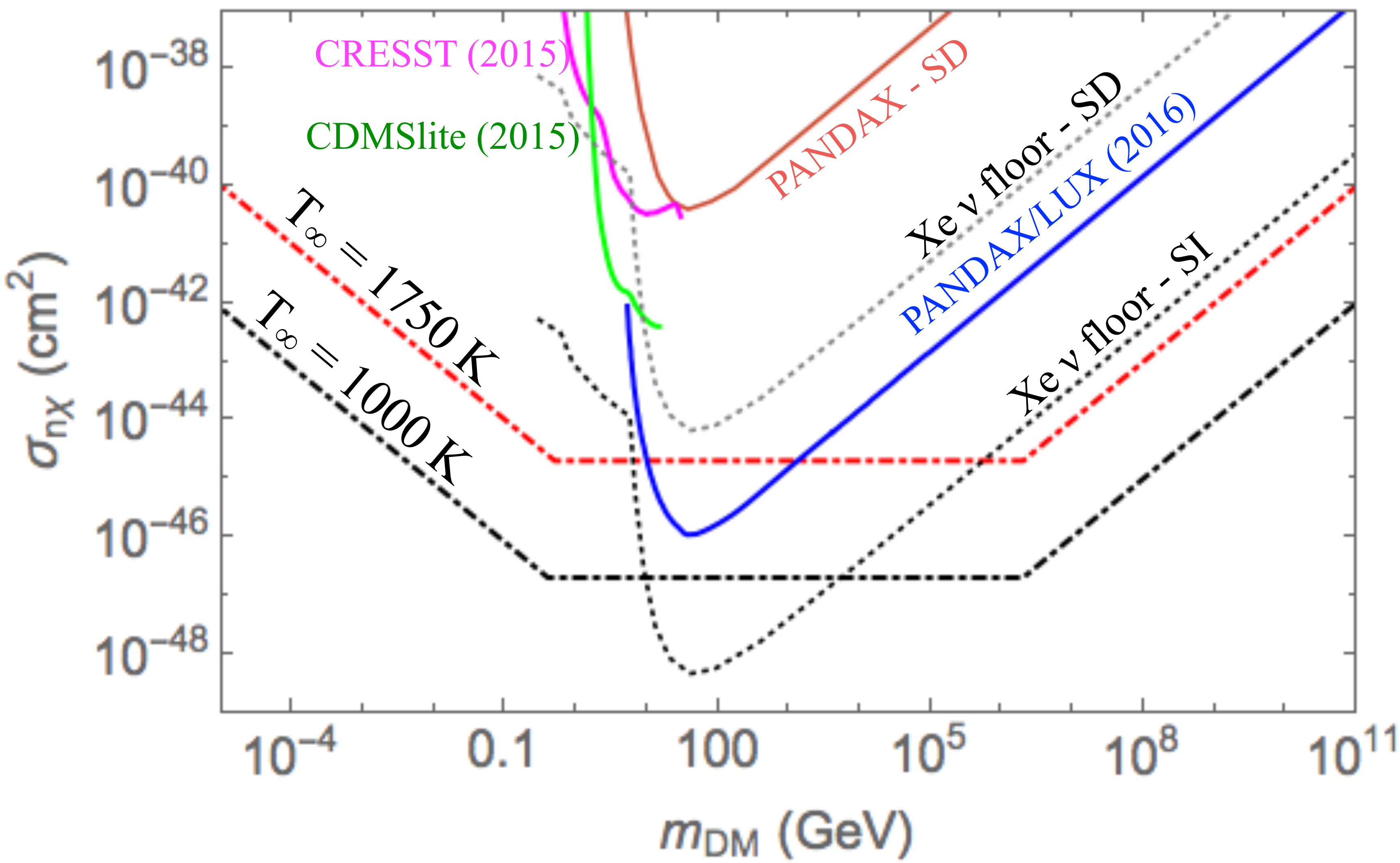


Scattering proceeds as long as

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

Complementing

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



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

Takeaways

- Dark kinetic heating of neutron stars

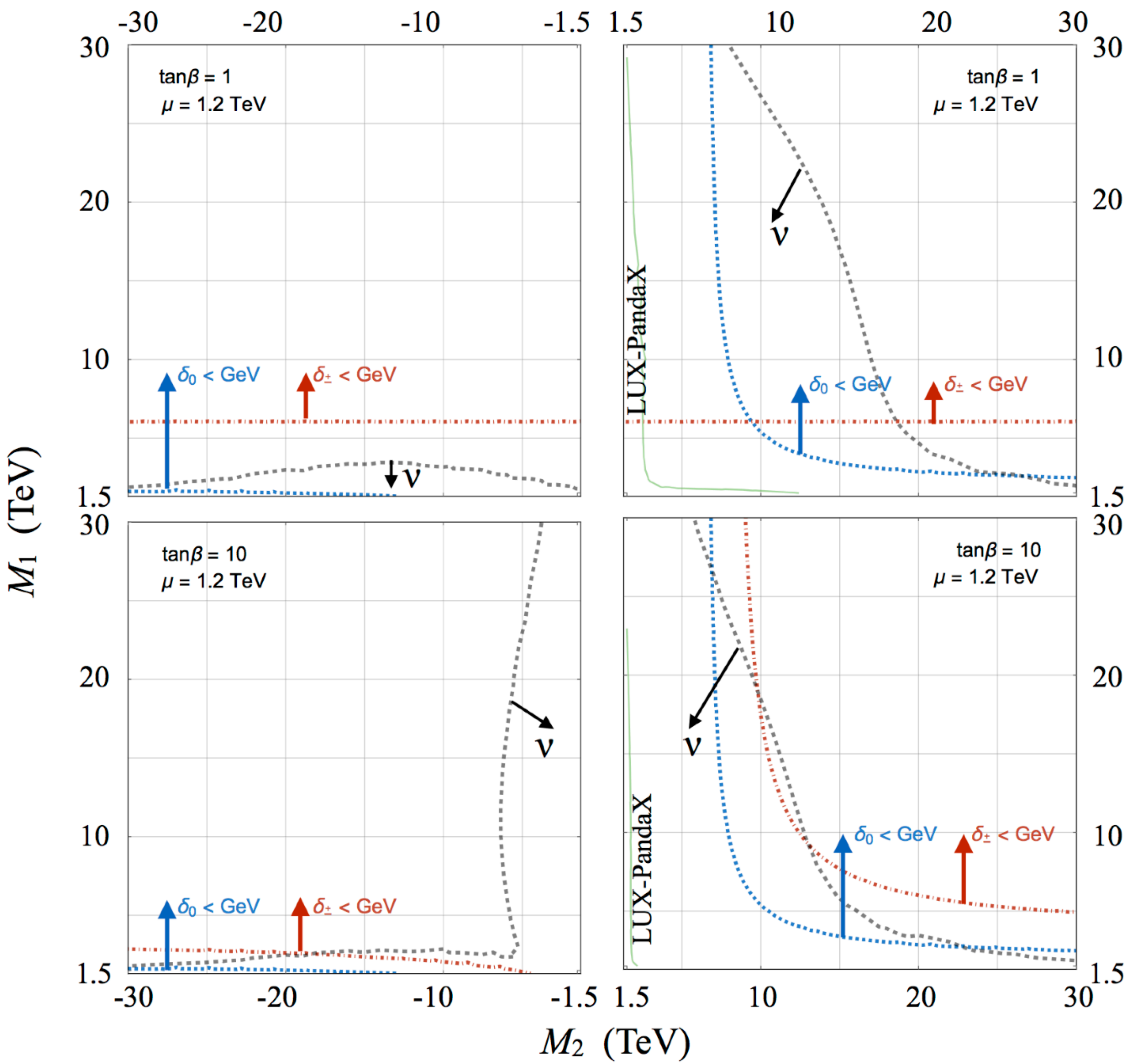
  - casts a vast net in the hunt for dark matter - nucleon interactions,

  - seriously advances the direct detection frontiers of
    low mass (sub-GeV) ,
    high mass ($>$ 100 GeV) ,
    spin-dependence ($\sigma_{SD} > 10^{-45}$ cm^2) ,
    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.

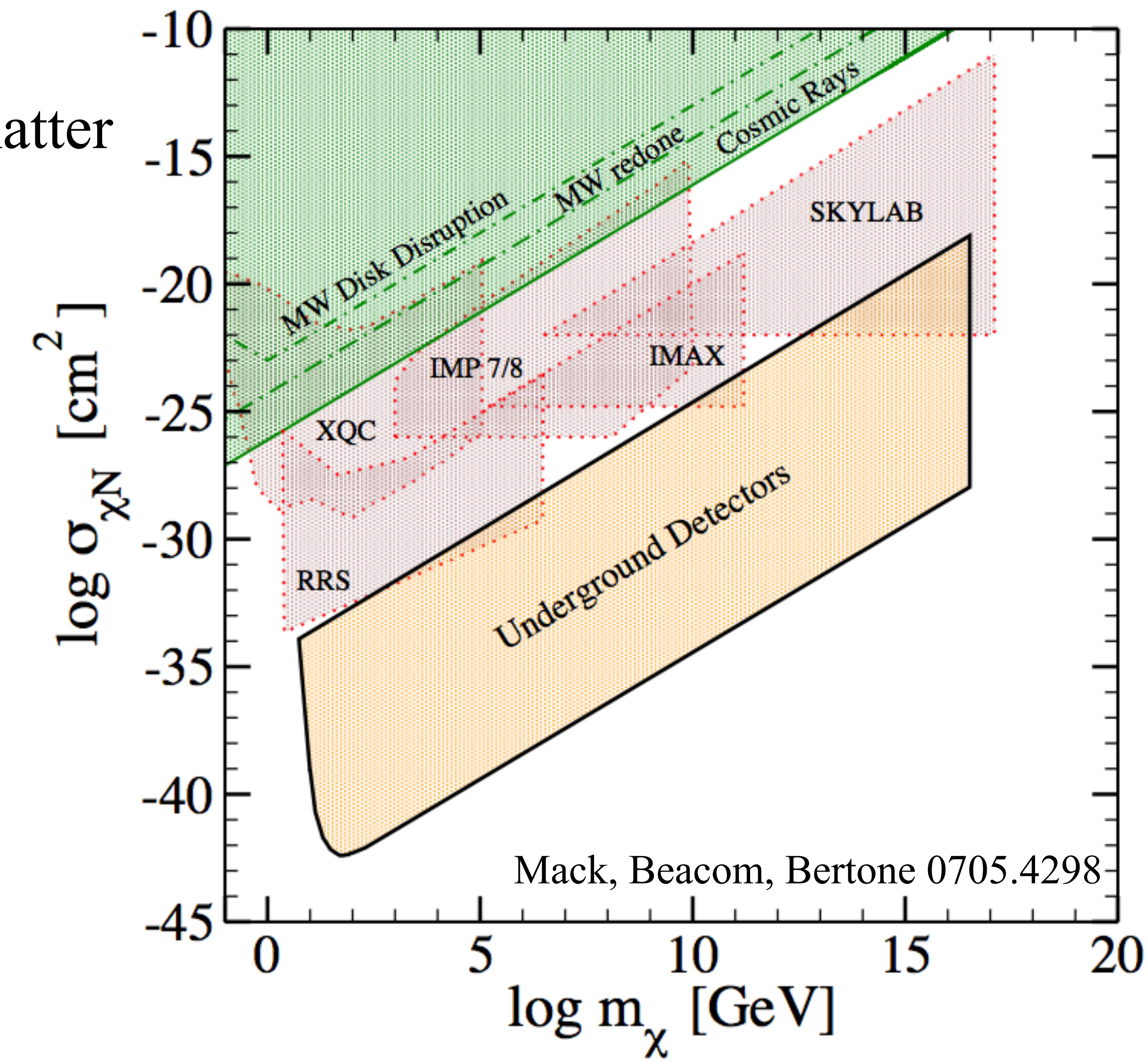
Backup

Uncovering thermal Higgsinos



Uncovering "side-stream" DM models

Strongly interacting dark matter



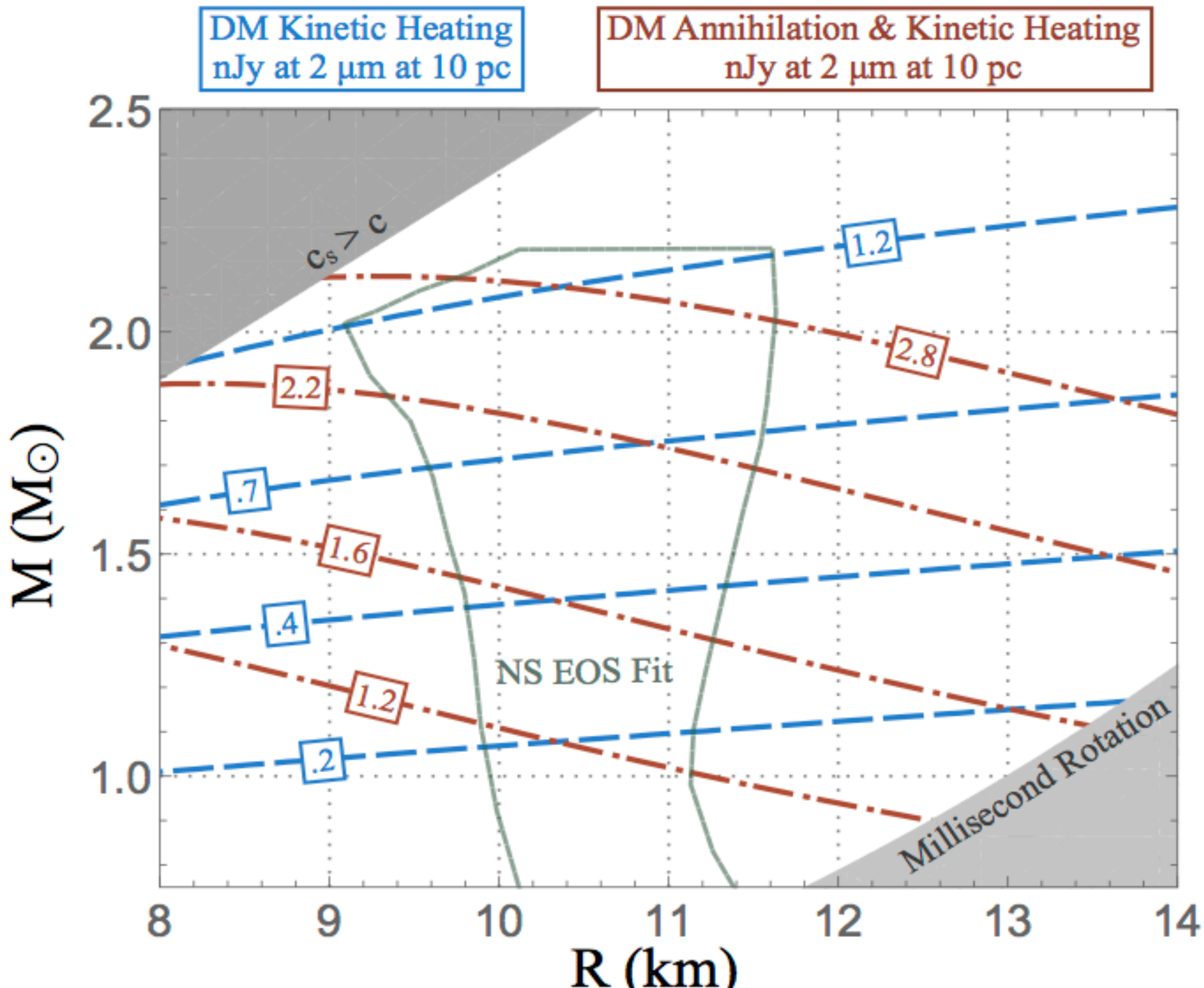
Primordial black holes

Macro objects

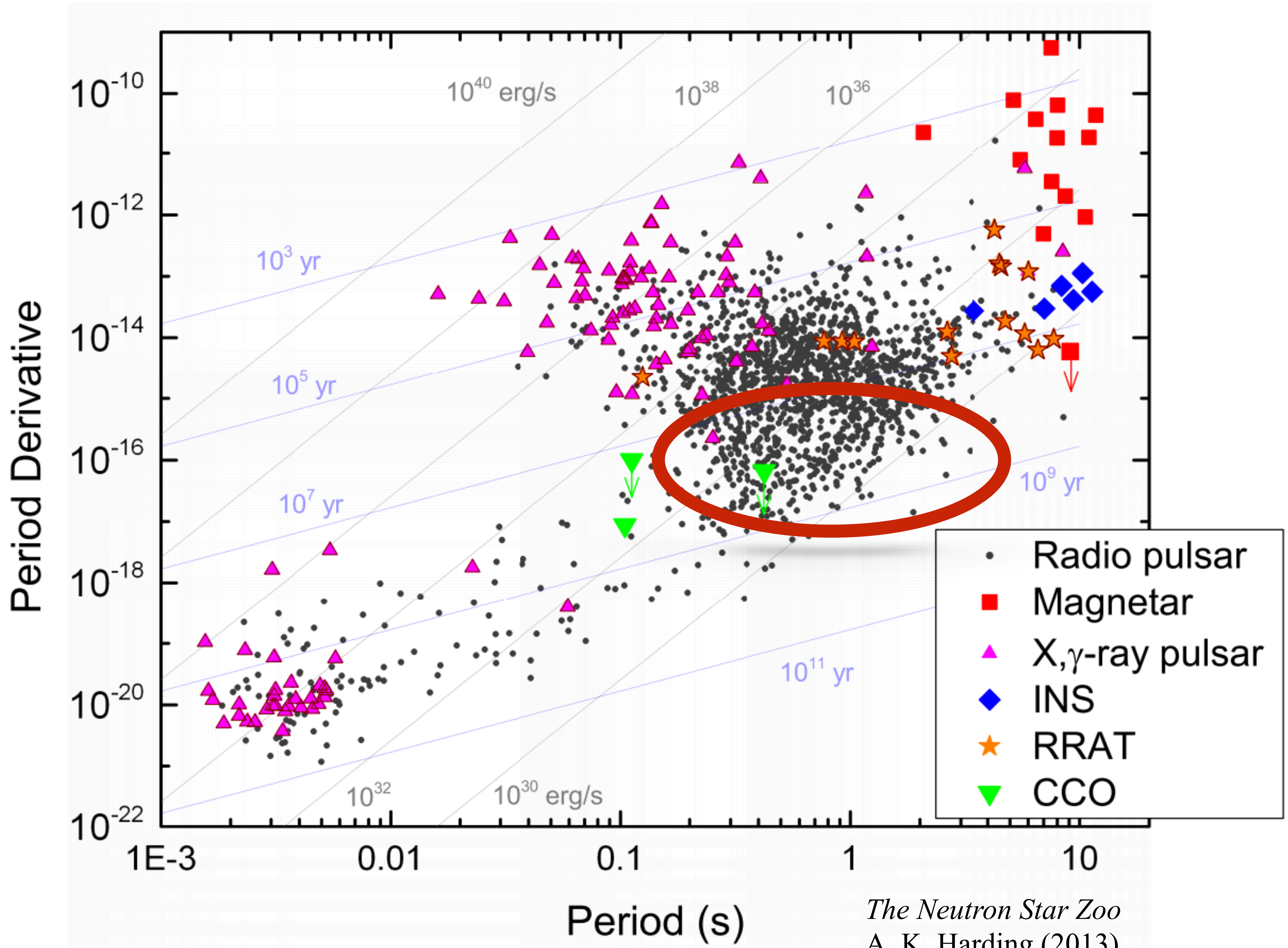
…

Kinetic vs annihilation heating

Difference in luminosity spreads

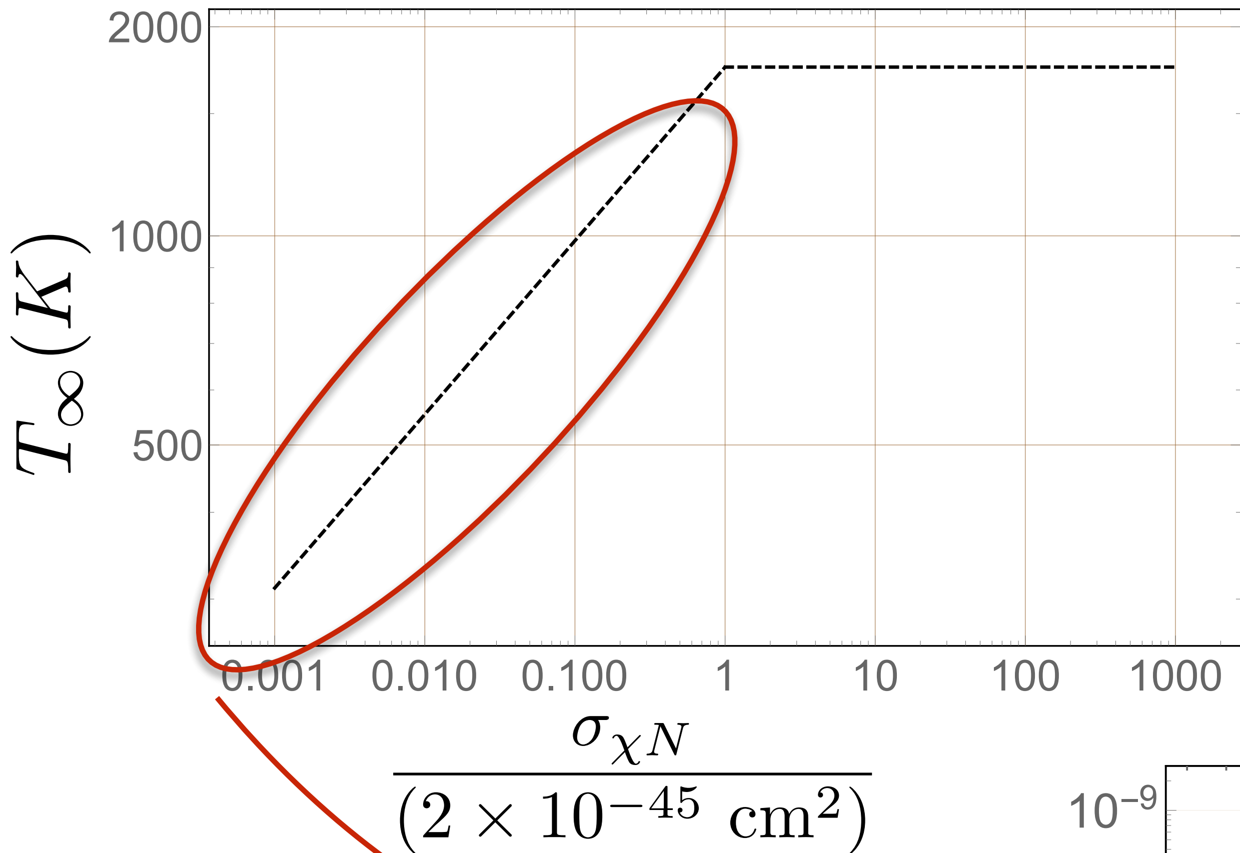


Detection: radio pulsing

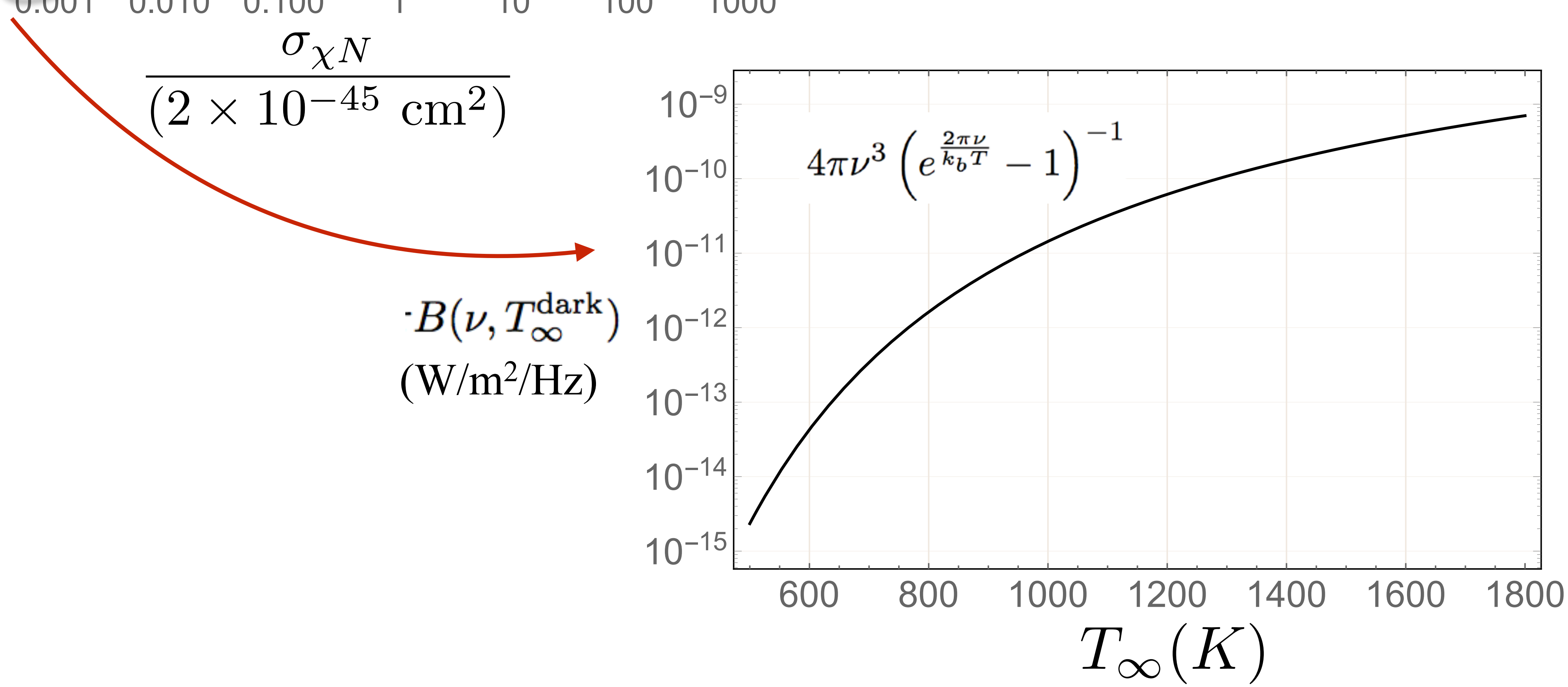


The Neutron Star Zoo
A. K. Harding (2013)

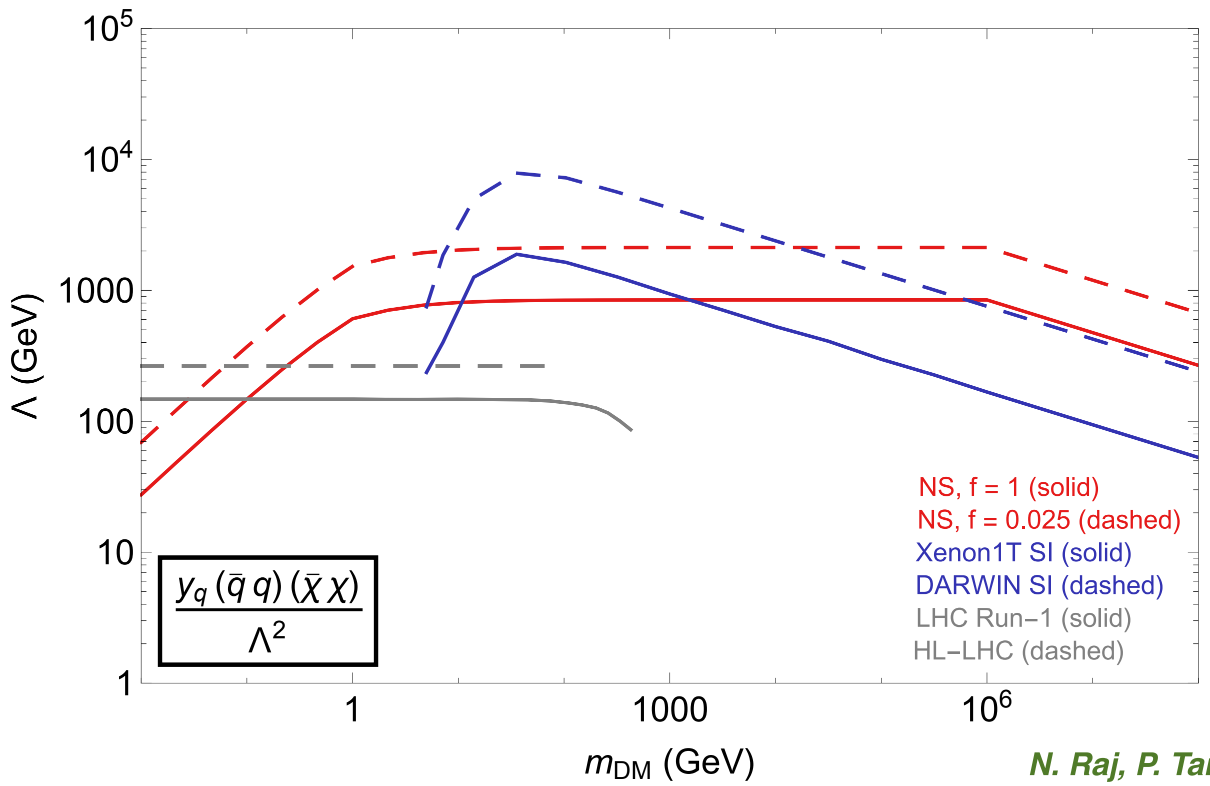
Detection: infrared telescopes

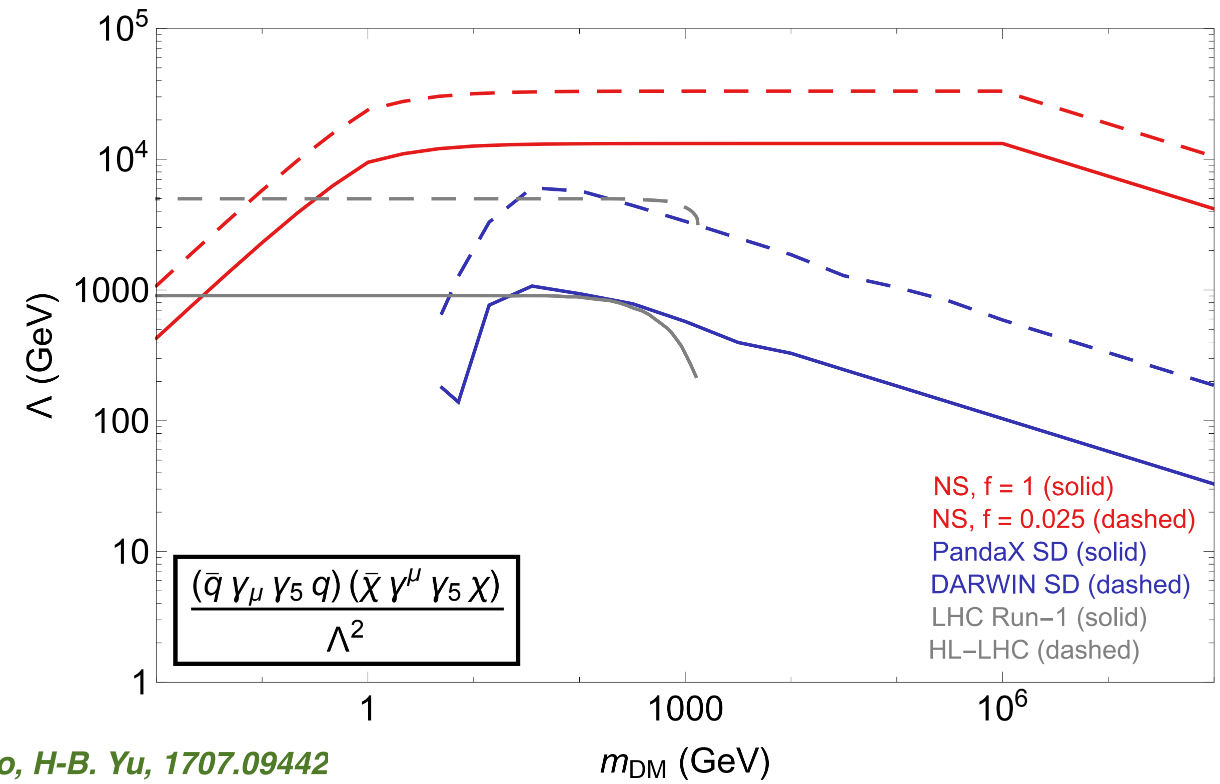


Smaller cross-sections,
dimmer stars,
longer exposures.



Operator bounds





N. Raj, P. Tanedo, H-B. Yu, 1707.09442