Title: Dark Fires in the Sky: Model-Independent Dark Matter Detection via Kinetic Heating of Neutron Stars

Date: Jul 20, 2017 04:00 PM

URL: http://pirsa.org/17070012

Abstract:

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

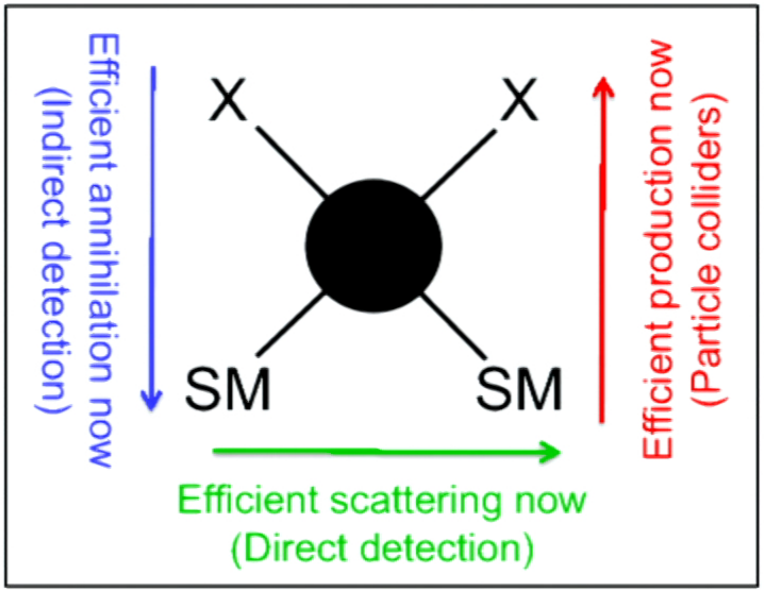
Nirmal Raj
Notre Dame

with
Masha Baryakhtar, Joe Bramante, Shirley Li, Tim Linden **1704.01577**
Flip Tanedo, Hai-Bo Yu **1707.xxxxx**

New Directions in Dark Matter & Neutrinos
20 Jul 2017, Perimeter Institute


(4)

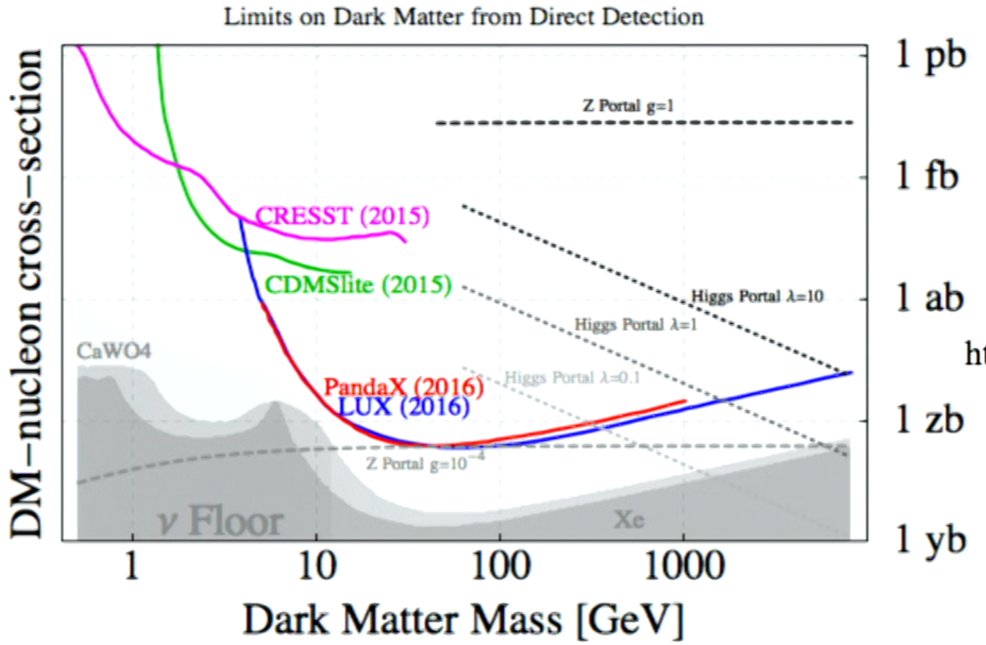
The hunt



Efficient annihilation now
(Indirect detection)
X
X
SM
SM
Efficient production now
(Particle colliders)
Efficient scattering now
(Direct detection)

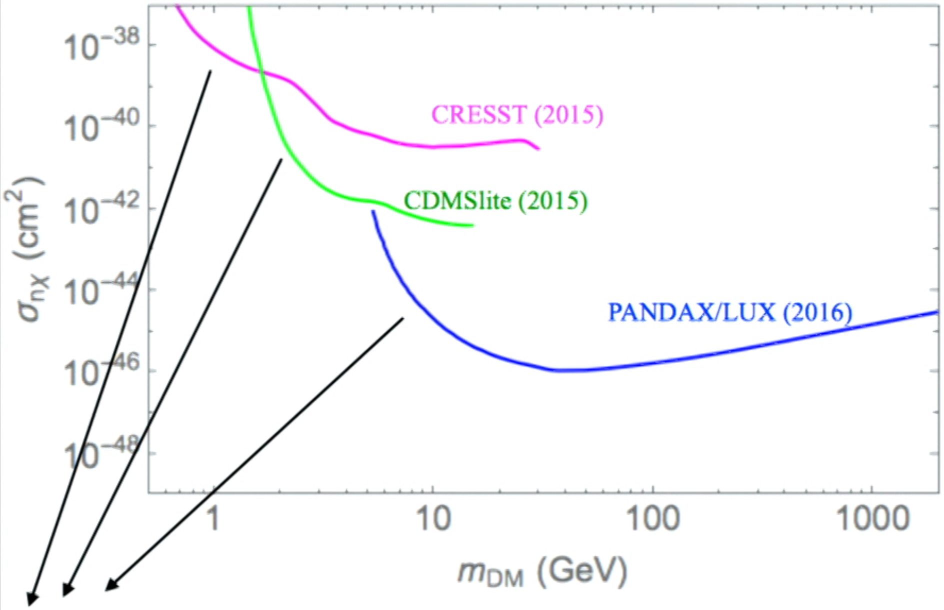
Direct searches: status

After 100 kg-year exposure:



http://resonaances.blogspot.com/

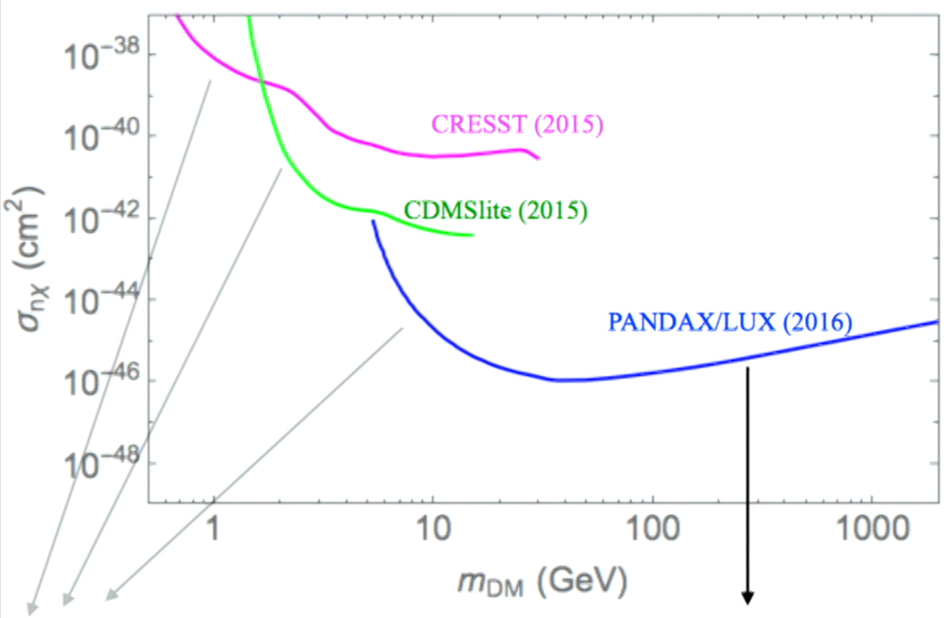
Direct searches: challenges



(1) Nuclear recoil below
detector thresholds at low mass

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

Direct searches: challenges

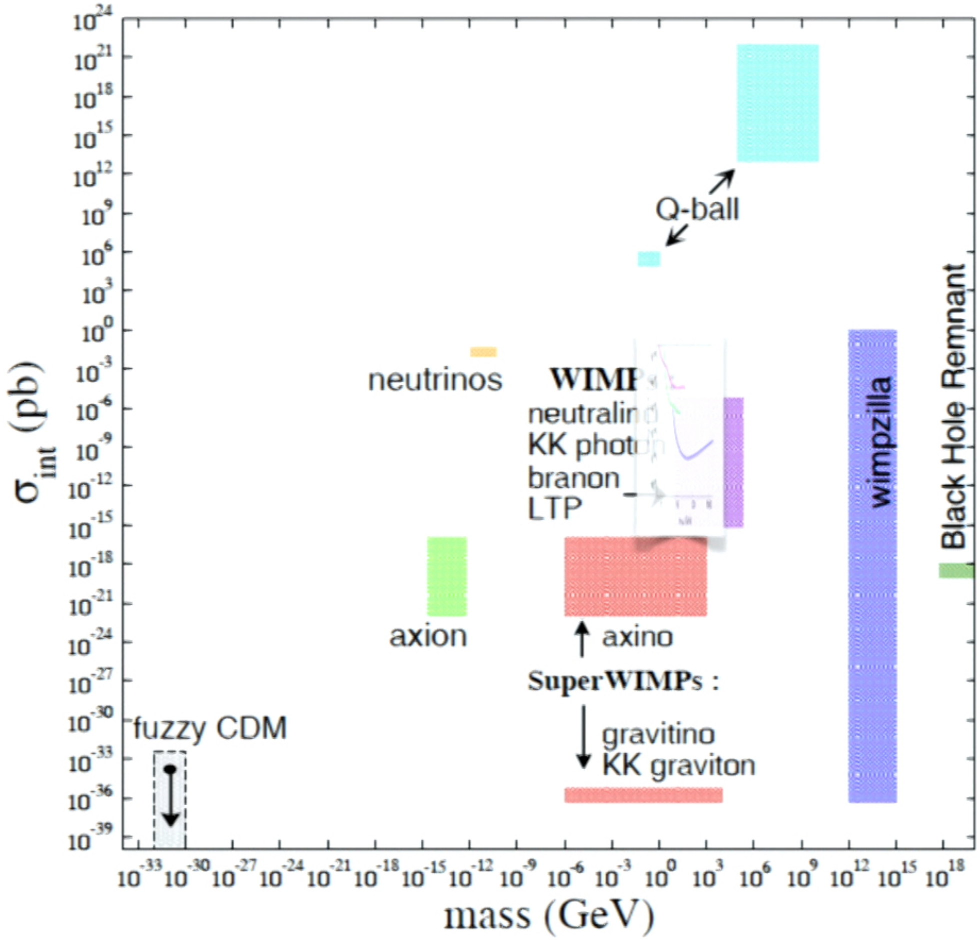


(1) Nuclear recoil below detector thresholds at low mass

(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), …

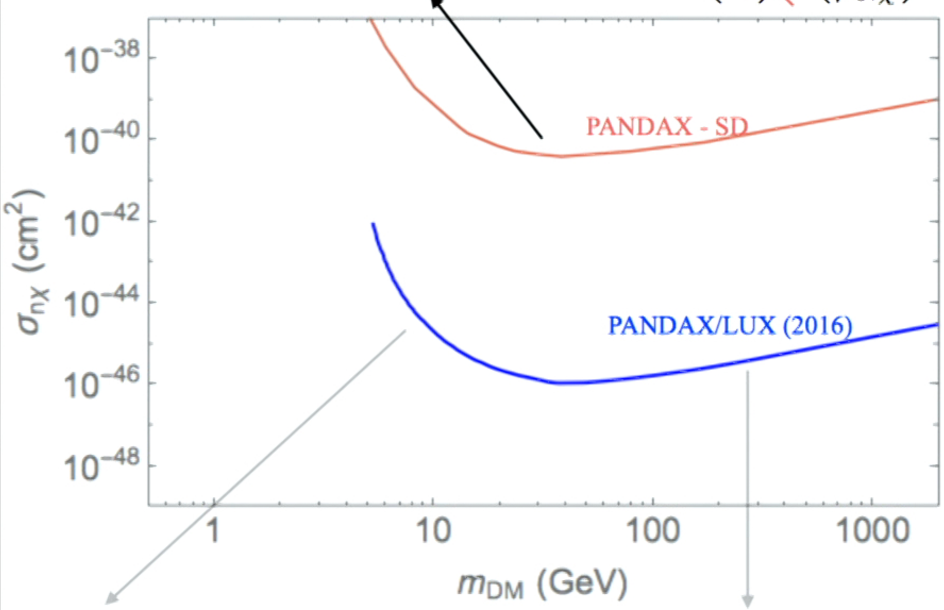
(Context)


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

Direct searches: challenges

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

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



(1) Nuclear recoil below detector thresholds at low mass

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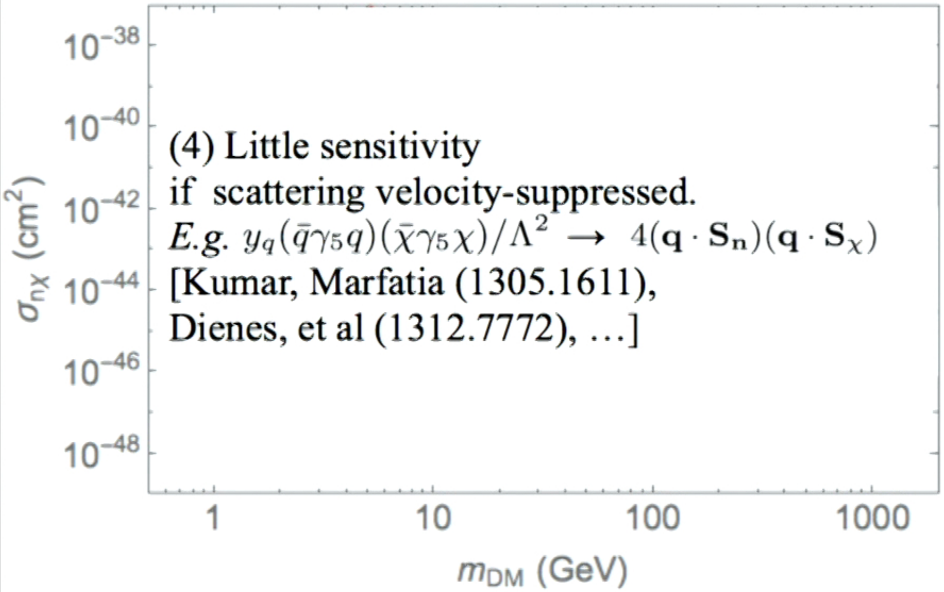
Direct searches: challenges

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



(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 low mass

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

Direct searches: challenges

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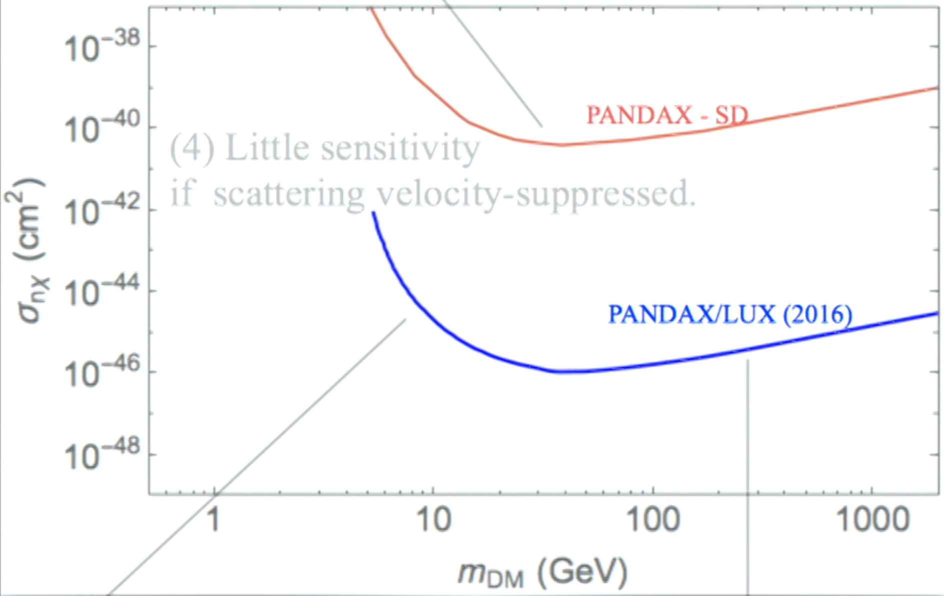
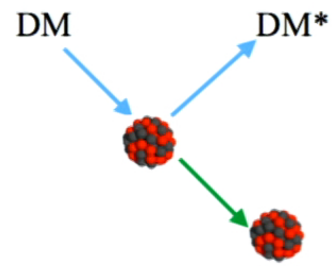
if scattering spin-dependent: $\sigma_{\rm nucleon} = \cancel{\left(\frac{1}{A}\right)^2} \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \sigma_{\rm Nucleus}$



(4) Little sensitivity
if scattering velocity-suppressed.

(Image: G. Kribs)



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

(5) 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

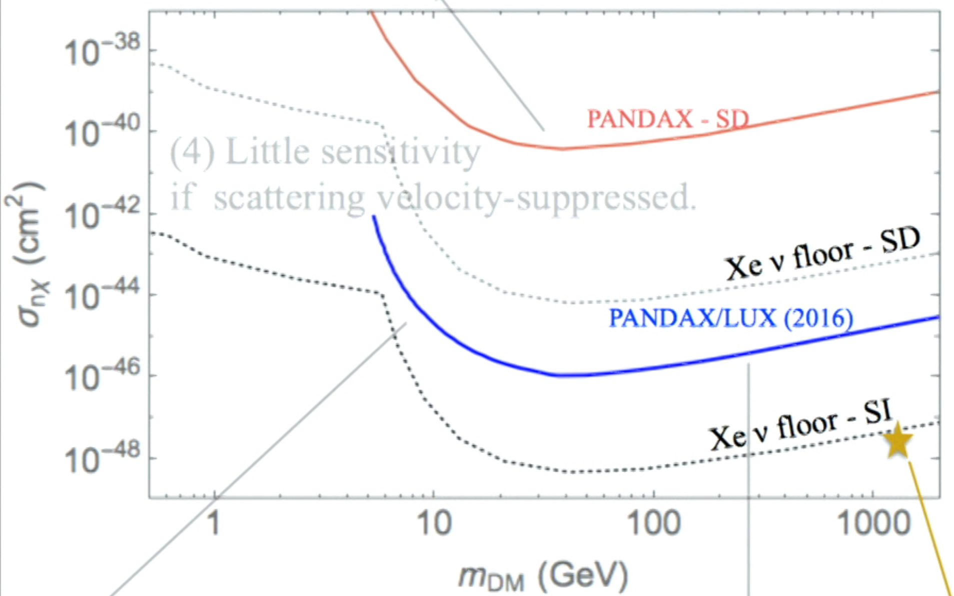
(1) Nuclear recoil below
detector thresholds at low mass

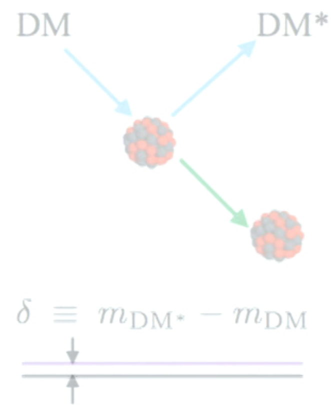
(2) DM flux $\propto \frac{1}{m_{\rm DM}}$
at high mass

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

Direct searches: challenges

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





(4) If scattering inelastic,
no recoil when

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

(1) Nuclear recoil below
detector thresholds at low mass

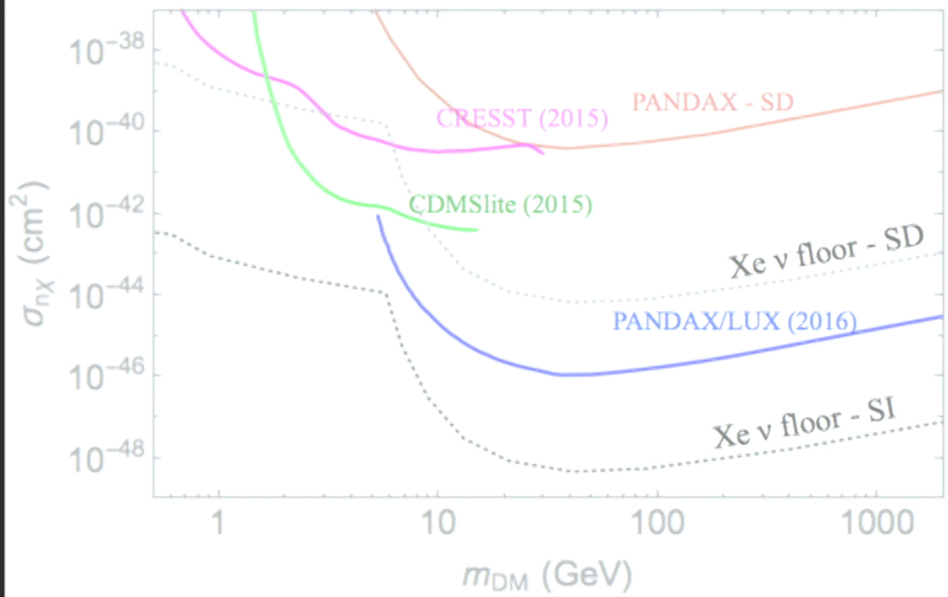
(2) DM flux $\propto \frac{1}{m_{\rm DM}}$
at high mass

(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.

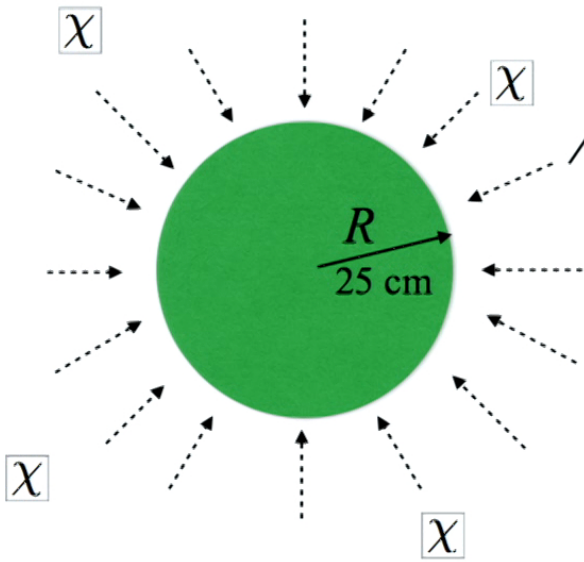
(Dark) Kinetic Heating

Soup getting cold

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

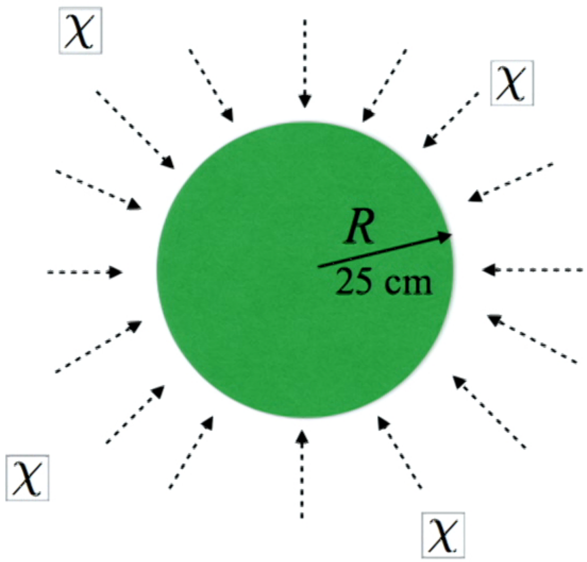
Keeping soup hot: dark fire

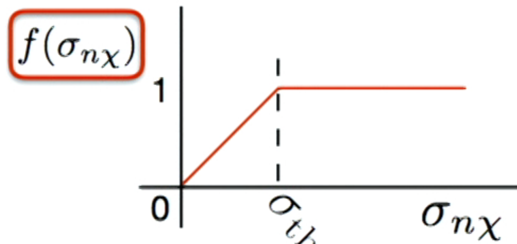
$$\cancelto{0}{CM\frac{dT}{dt}} = -\sigma_{\mathrm{SB}}(\mathrm{Area})T^4 + \dot{E}_{\mathrm{external}}$$



Keeping soup hot: dark fire

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



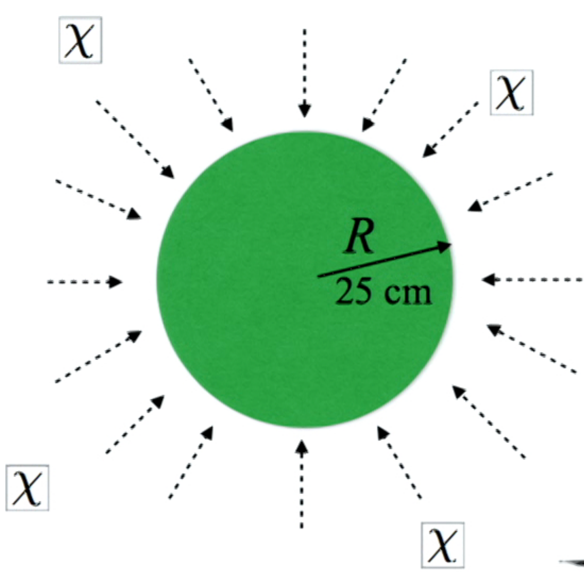


$$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold}R\right)$$

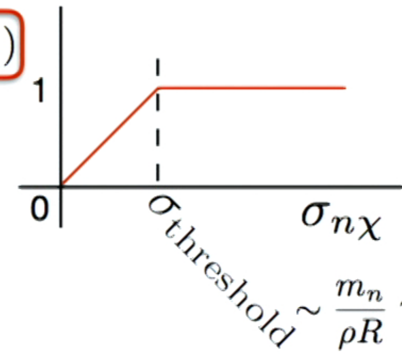
$$\sigma_{\rm threshold} \sim \frac{m_n}{\rho R} \sim 10^{-29}\text{cm}^2$$

Keeping soup hot: dark fire

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



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



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

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

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

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

T = 3 nanoKelvin

Detector improvements

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

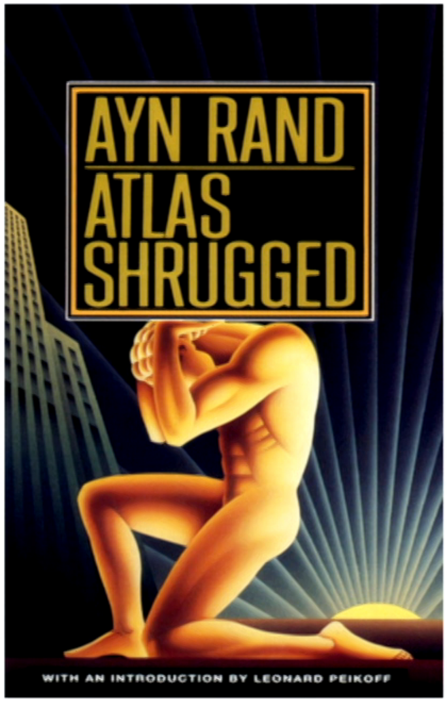
$$\sigma_{\mathrm{threshold}} \sim \frac{m_n}{\rho R} \sim 10^{-29}\mathrm{cm}^2$$

Bigger
and denser

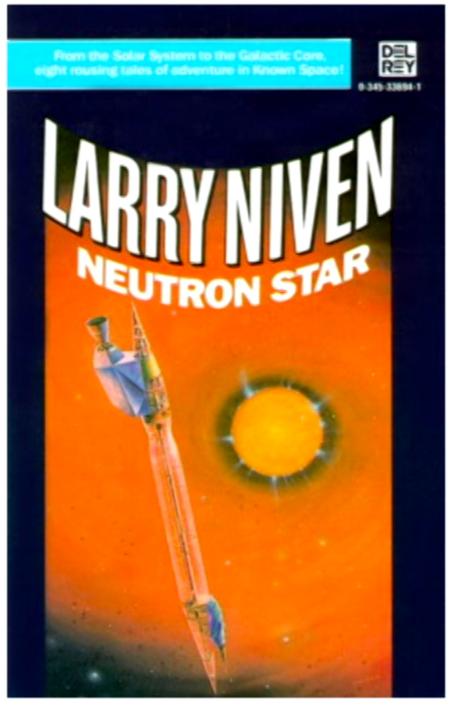
$\boxed{\mathrm{KE}}$ $\frac{1}{2}m_{\mathrm{DM}}v_{\mathrm{DM}}^2$

T = 3 nanoKelvin

What's big, dense, and cold?



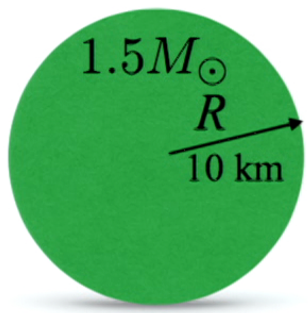
What's big, dense, and cold?



Page 23 of 54

big, dense

7×10^{17} kg/m^3

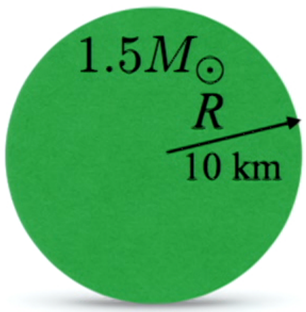


Lake Michigan (weighing 5×10^{12} kg) in a teaspoon

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

big, dense, and cold

7×10^{17} kg/m^3



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

$v_{esc} \simeq 0.7$

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

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

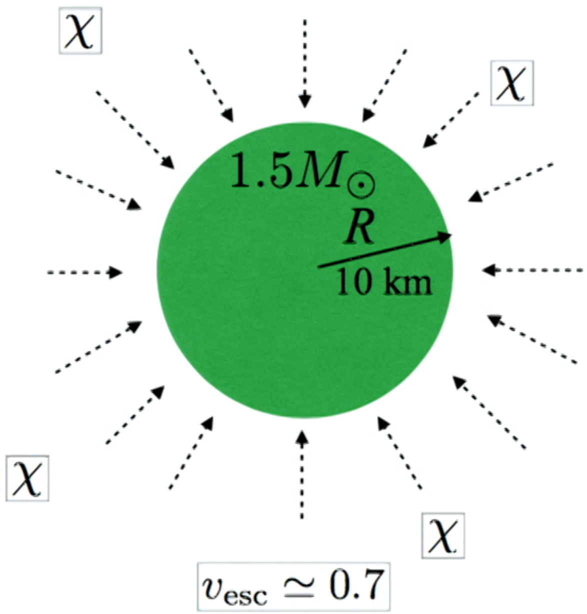
Page, Lattimer, Prakash, Steiner (2004)
Yakovlev, Pethick (2004)

Keeping N star hot: dark fire

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

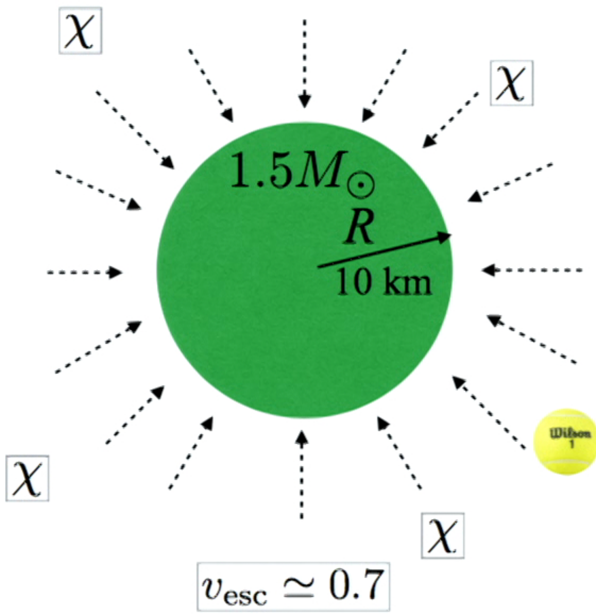
$$\boxed{f(\sigma_{n\chi})} \quad \sigma_{\rm threshold} \sim 10^{-45}\ \text{cm}^2$$

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



Keeping N star hot: dark fire

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



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

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

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

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

DM mass drops out of this calculation!

←60 grams of DM/ second

25 grams x c^2 of DM KE/ second

Keeping N star hot: dark fire

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

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

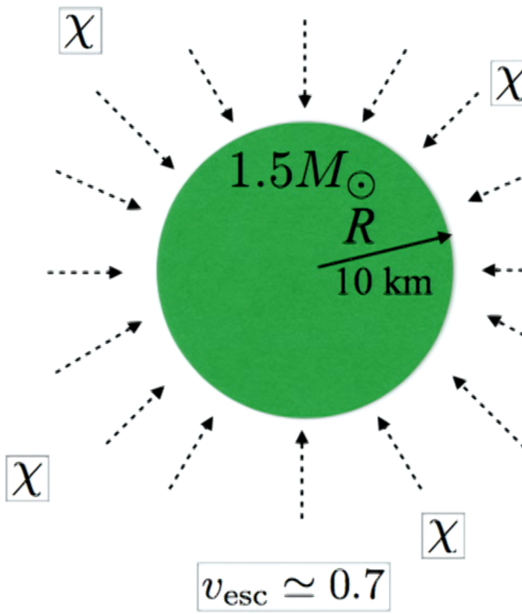
$\left(1 = \frac{R}{\text{mean free path}} = n\sigma_{\rm threshold}R\right)$

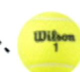
$R\left(\frac{v_{\rm esc}}{v_{\rm DM}}\right)$

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

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

DM mass drops out of this calculation!





← 60 grams of DM/ second

20 grams x c^2 of DM KE/ second

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

Keeping N star hot: dark fire

snowball

fresh lava

χ χ $\boxed{\mathrm{KE}}$

$v_{\rm esc} \simeq 0.7$

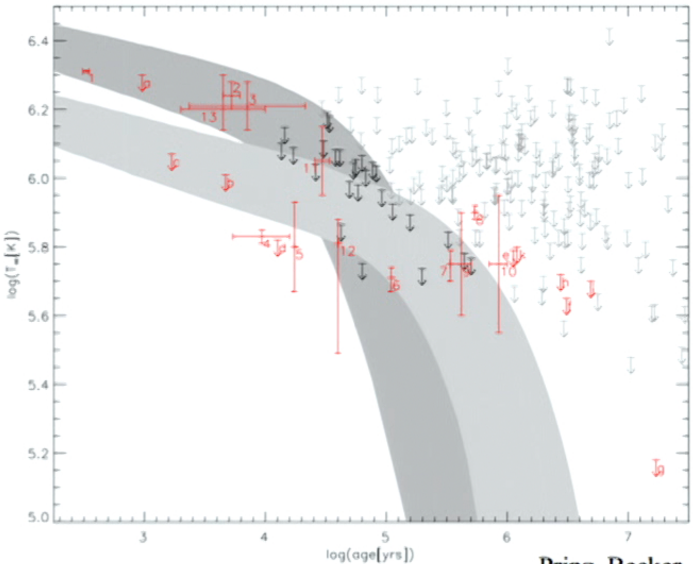
20 grams x c^2 of DM KE/ second

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

Detection?

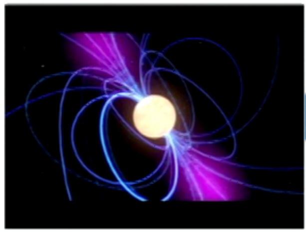
T = **1750 Kelvin** (infrared emission)

O(100) below current T bound



Prinz, Becker
astro-ph:1511.07713

Detection: radio pulsing

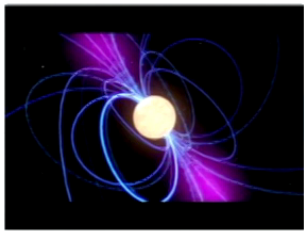


FAST
http://fast.bao.ac.cn/en/science_pulsar.html

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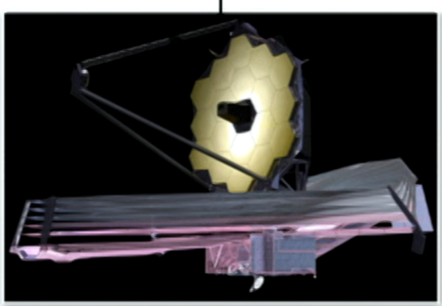
1 - 5 old, cold neutron stars must reside in the local 10 pc; 100 in the local 50 pc.

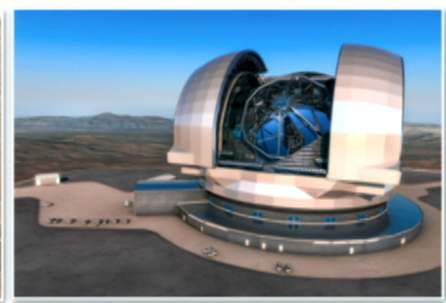
O. Blaes, P. Madau (1993)

coming online Oct 2018!



James Webb

Thirty Meter

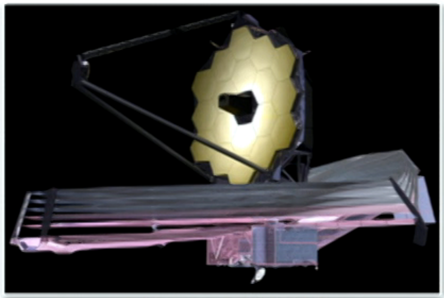


European Extremely Large

Detection: infrared telescopes

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

Peak wavelength: $1.65\ \mu$m

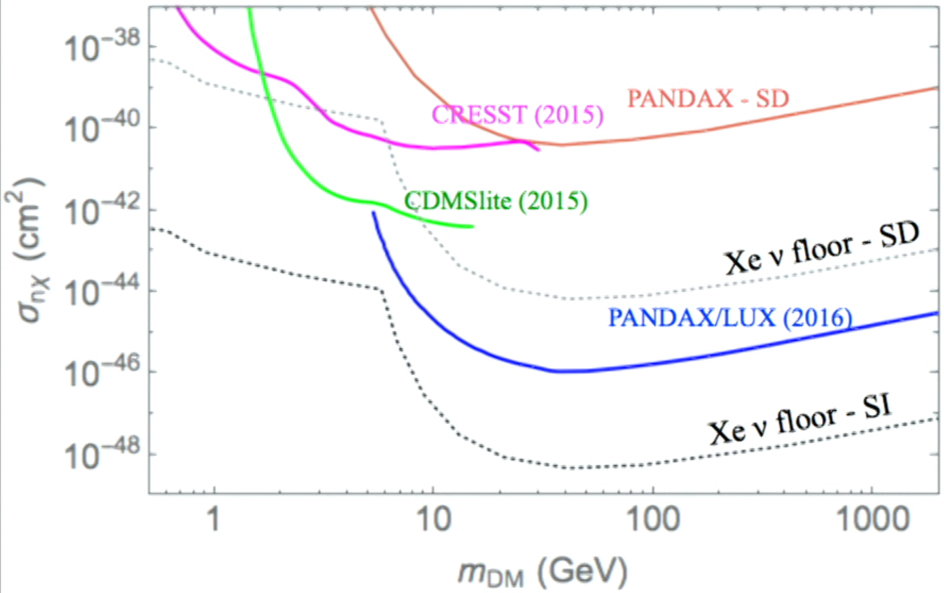


James Webb

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?

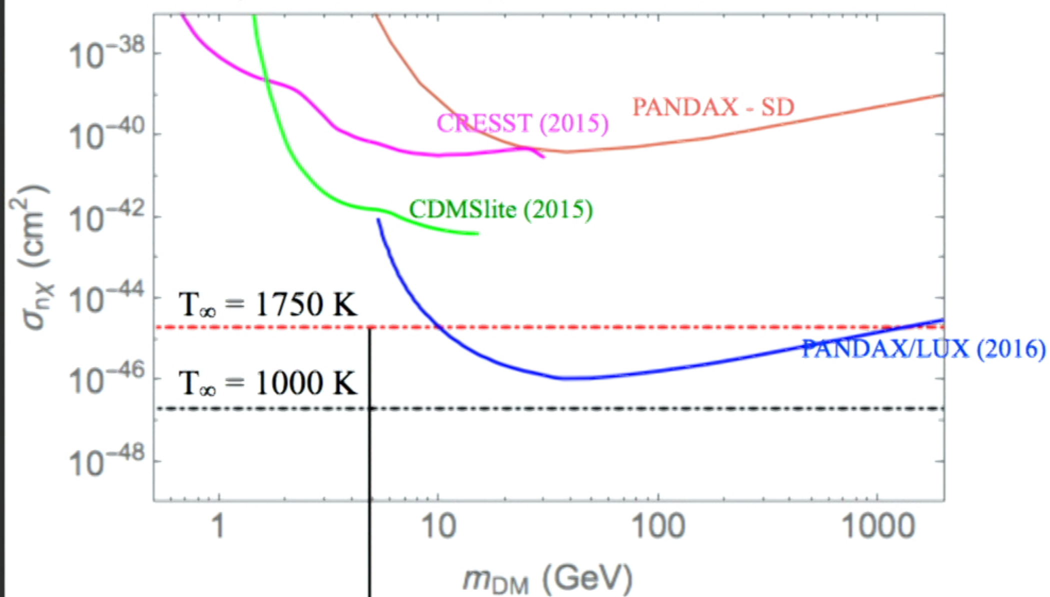


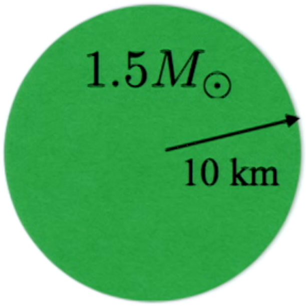
(1) Low mass
(2) High mass
(3) Spin-dependent
(4) v-suppressed
(5) Inelastic
(6) Neutrino floors

Dark kinetic heating help these frontiers?

Comparison

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

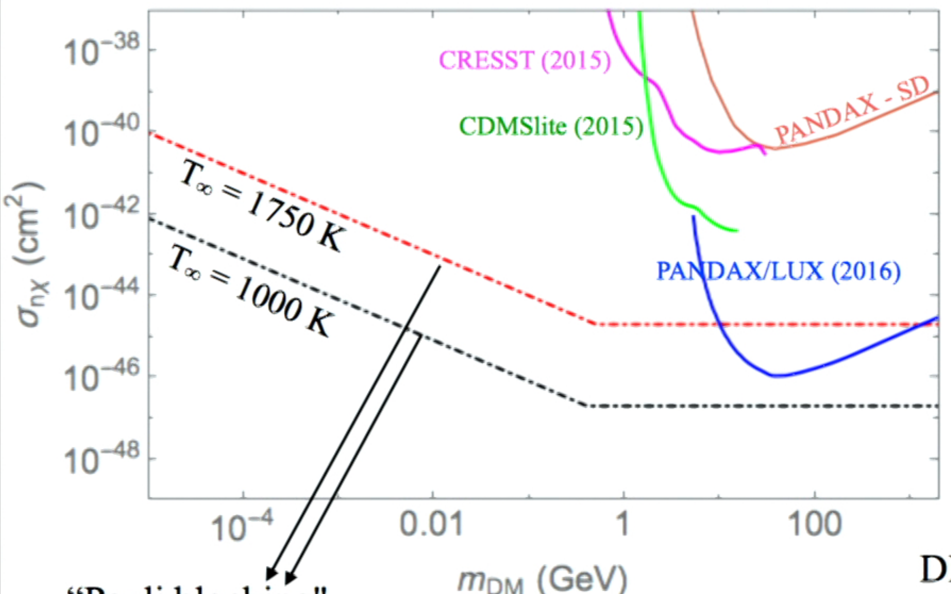




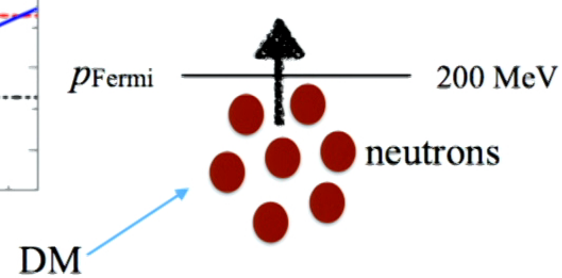
$$\sigma_{\text{threshold}} = \pi R^2 \left(\frac{m_n}{M_{\text{NS}}} \right)$$

Complementing

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



(1) Low mass ✅



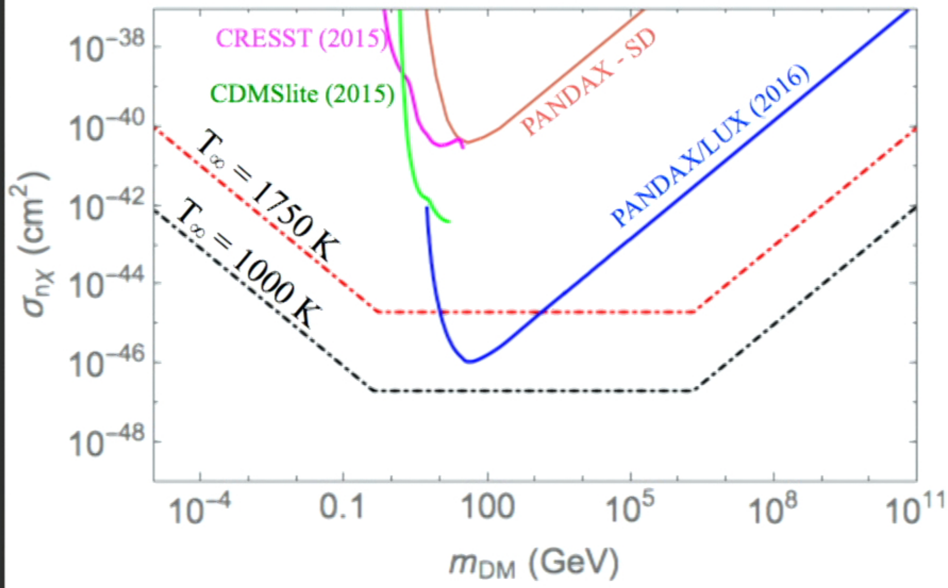
"Pauli blocking"

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

Page 37 of 54

Complementing

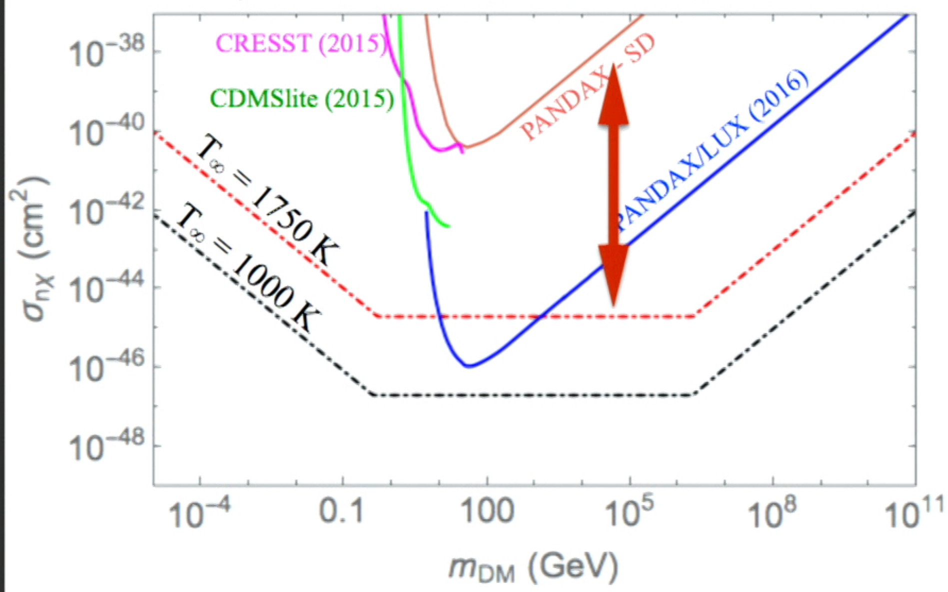
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



(1) Low mass ✅
(2) High mass ✅

Complementing

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

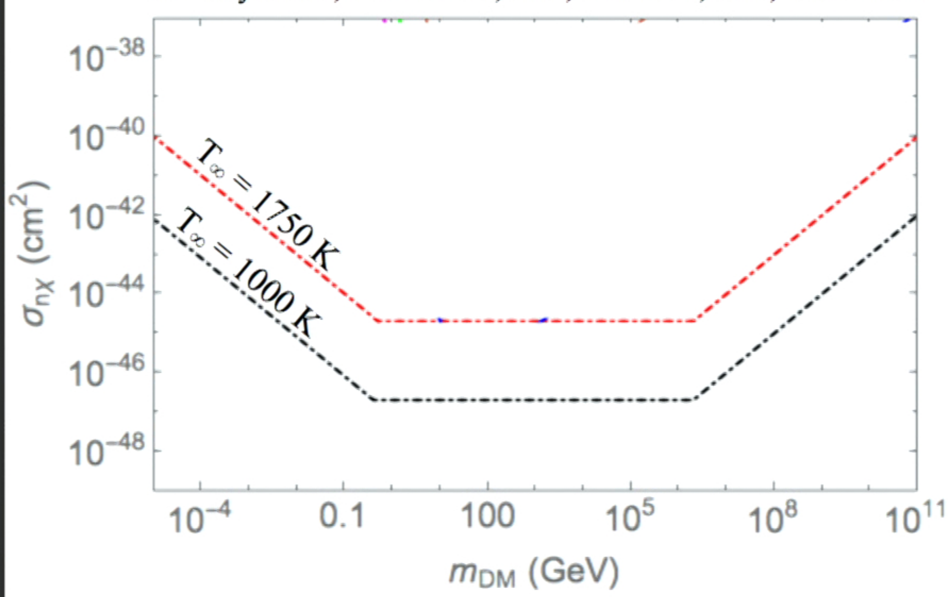


(1) Low mass ✅
(2) High mass ✅
(3) Spin-dependent ✅

Scattering with neutrons:
apathy to nuclear coherence

Complementing

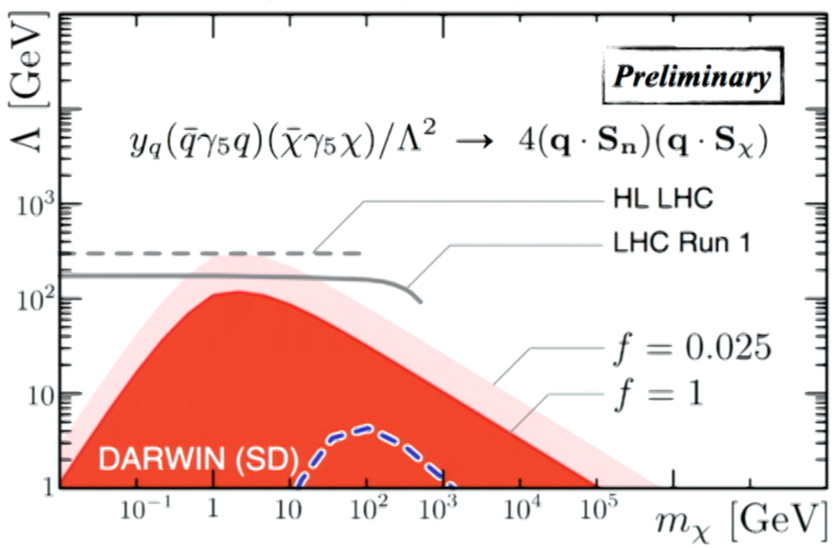
M Baryakhtar, J Bramante, S Li, T Linden, **N R**;1704.01577



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

Complementing

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

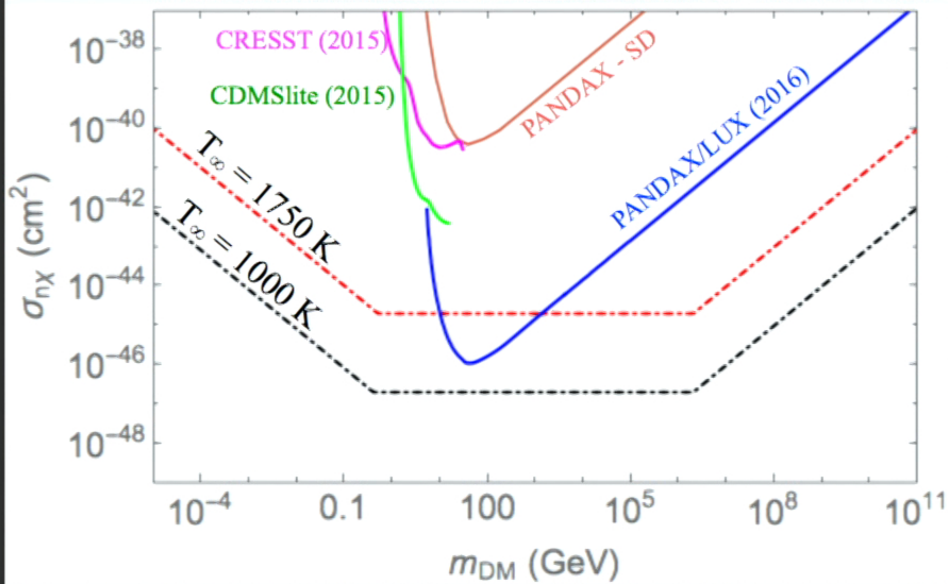


- (1) Low mass ✅
- (2) High mass ✅
- (3) Spin-dependent ✅
- (4) v-suppressed ✅

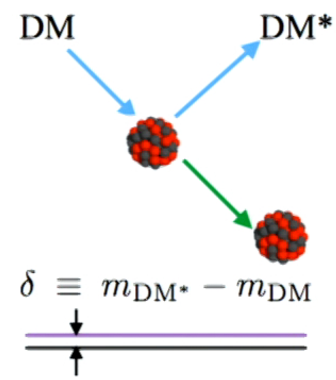
Page 42 of 54

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

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

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.

Kinetic vs annihilation heating

Difference in luminosity spreads