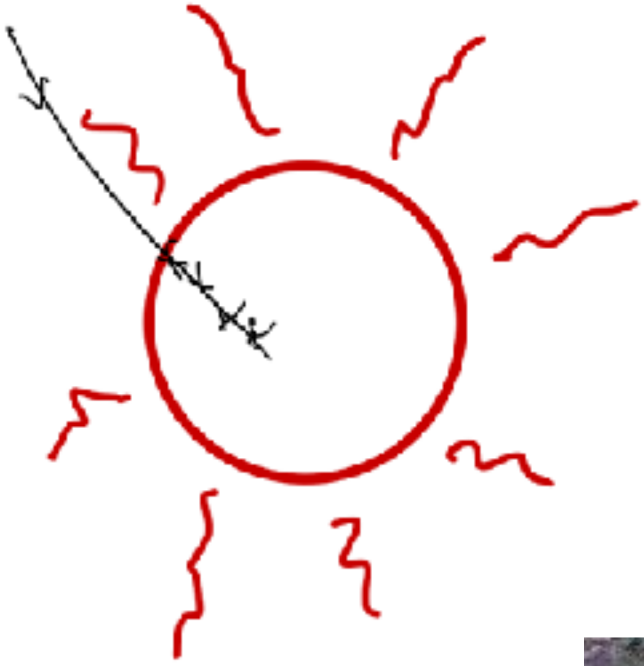
Dark Matter Heating Nearby Neutron Stars to BBQ Temperatures



Joseph Bramante

Perimeter Institute

TAUP 2017

Masha
Baryakhtar

Nirmal
Raj

Shirley
Weishi Li

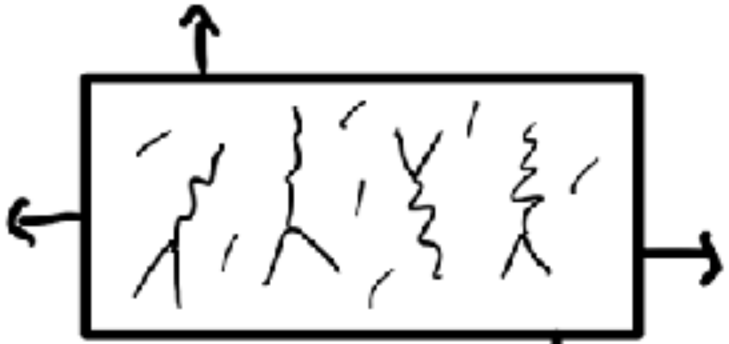
Tim
Linden

Based on Baryakhtar, JB, Li, Linden, Raj 2017

JB, Fox, Kribs, Martin 2016

JB, Delgado, Martin 2017

The WIMP Miracle


Thermal Freeze-out

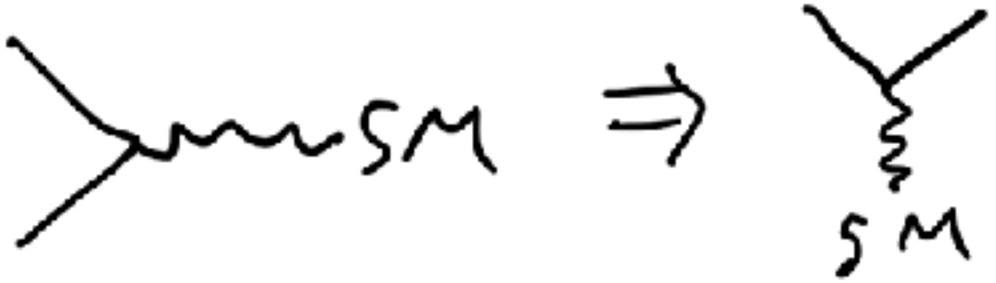
- As universe cools, DM falls out of thermal equilibrium, annihilates to SM particles

Final Abundance

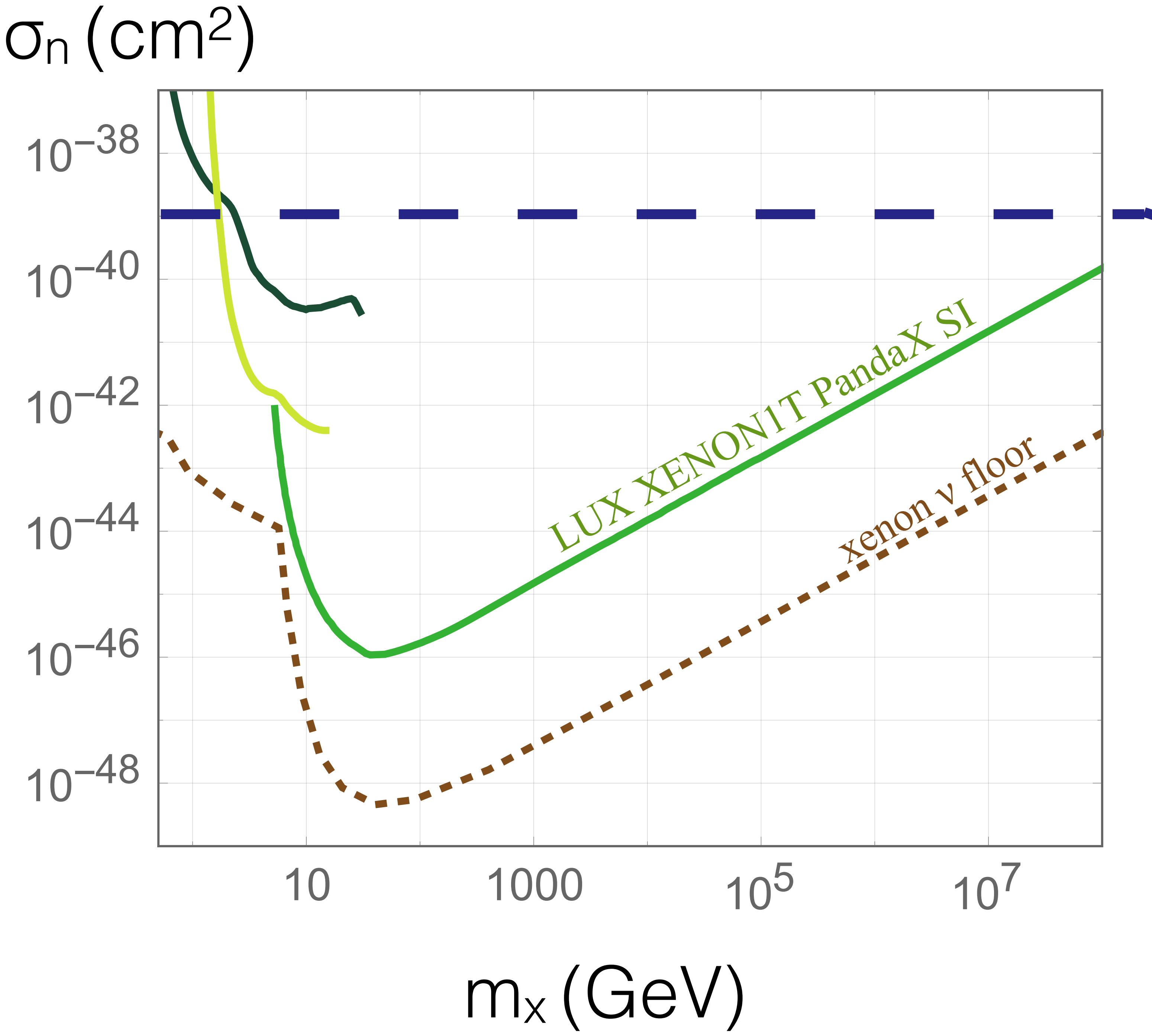
$$\Omega_{DM} h^2 \propto \frac{x_{FO}}{\sigma_a} \quad \Big| \quad x_{FO}\left[\ln(m_\chi)\right] \sim 10$$

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_v}{100\text{ GeV}}\right)^2 \left(\frac{0.03}{\alpha_w}\right)^2$$

This implies weak mass scale coupling to SM



So where is the WIMP dark matter?



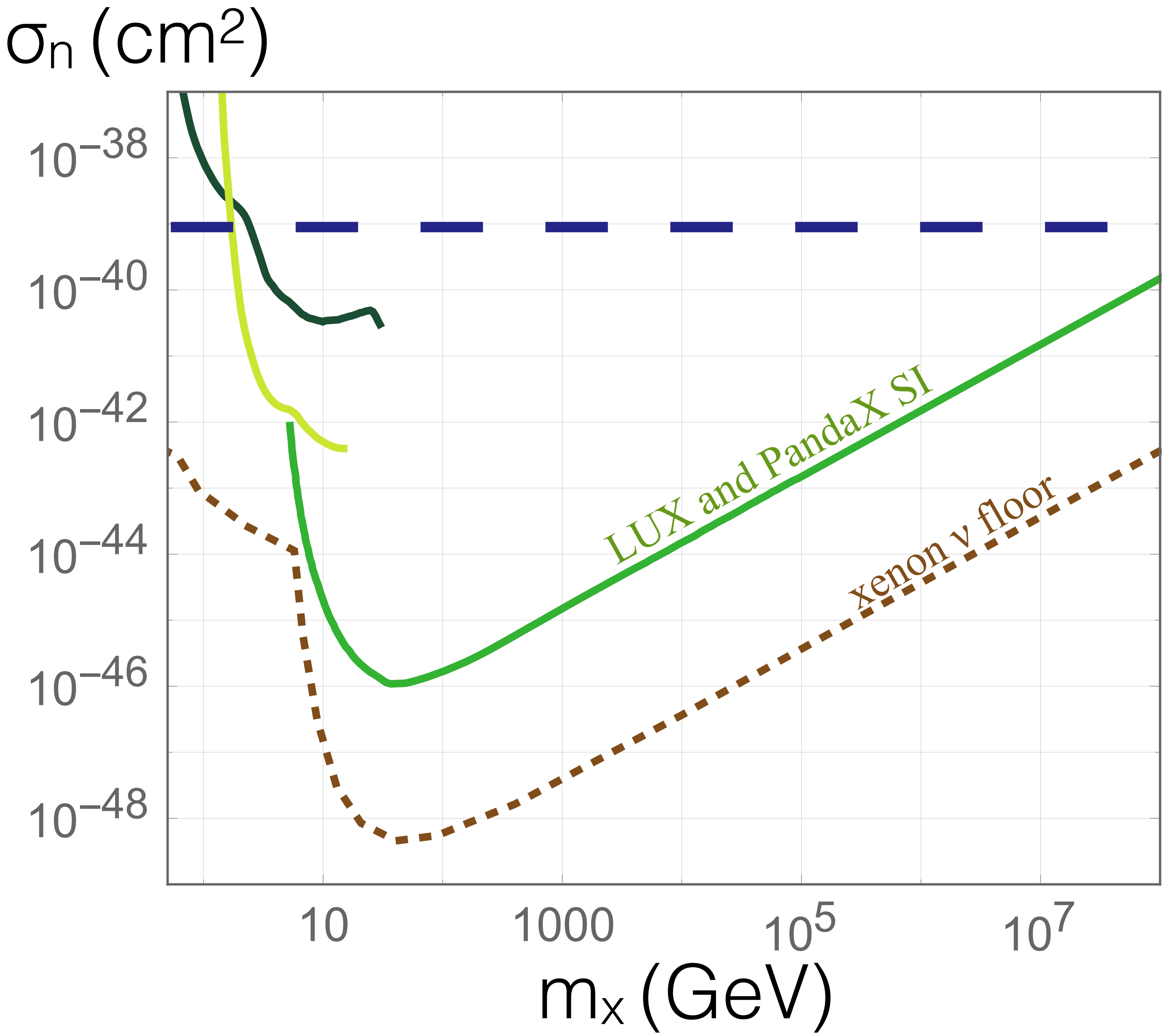
Freeze-out WIMP

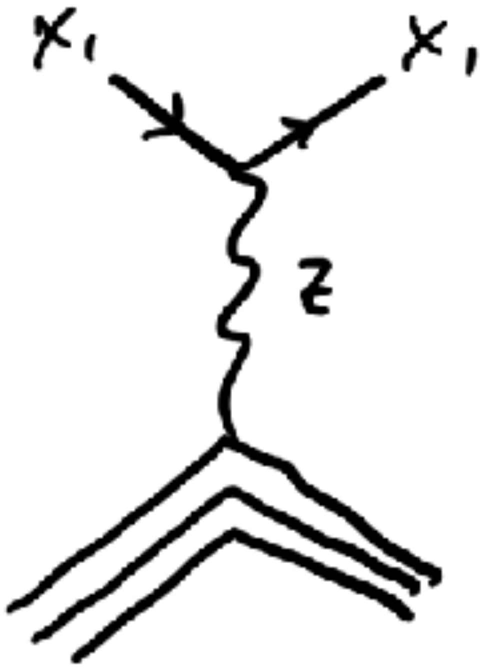
$$\sigma_n = \frac{\pi \alpha^2 \mu_{xn}^2}{m_Z^4} \sim 10^{-39}\,\text{cm}^2$$

- <u>Just hiding</u> - need new detector to find all WIMPs!

1. **On the importance of being semi-relativistic and abundant**
   - → Inelastic WIMPs hide by being slow
   - → Direct detection experiments rate-limited
2. **Neutron stars as nature's dark matter accelerators**
   - → Dark kinetic heating of nearby pulsars
   - → Probes Inelastic, SD
   - → Direct detection complements dark kinetic heating
3. **Bringing our astro friends to the backyard DM BBQ**

Spin-Independent WIMPs
→ Endangered Species



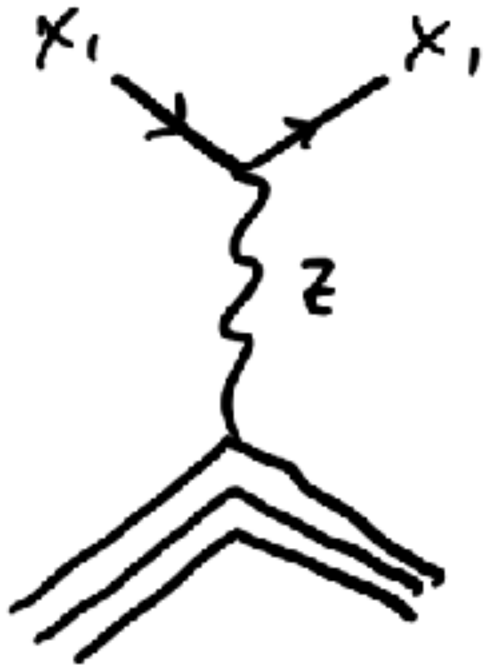


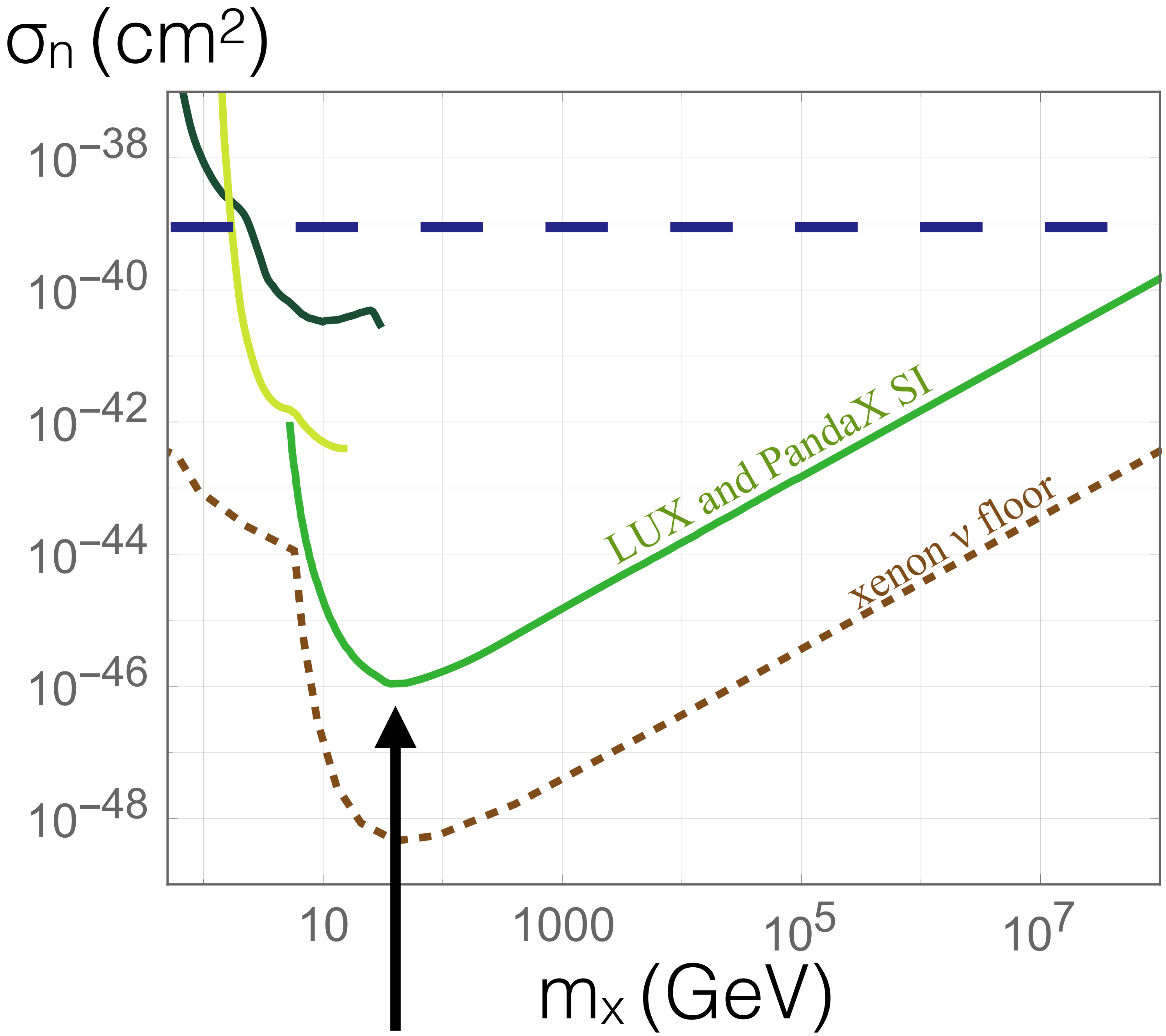
$$\sigma_N \sim \frac{\mu_{N\chi}^2 \, \alpha_w^2}{m_Z^4}$$

$$\sigma_n = \underbrace{\left(\frac{1}{A^2}\right)}_{\boxed{SI}} \frac{\mu_{n\chi}^2}{\mu_{N\chi}^2} \, \sigma_N$$

smart scientists
use heavy nuclei

Spin-Independent WIMPs → Endangered Species





accidentally weak-centric

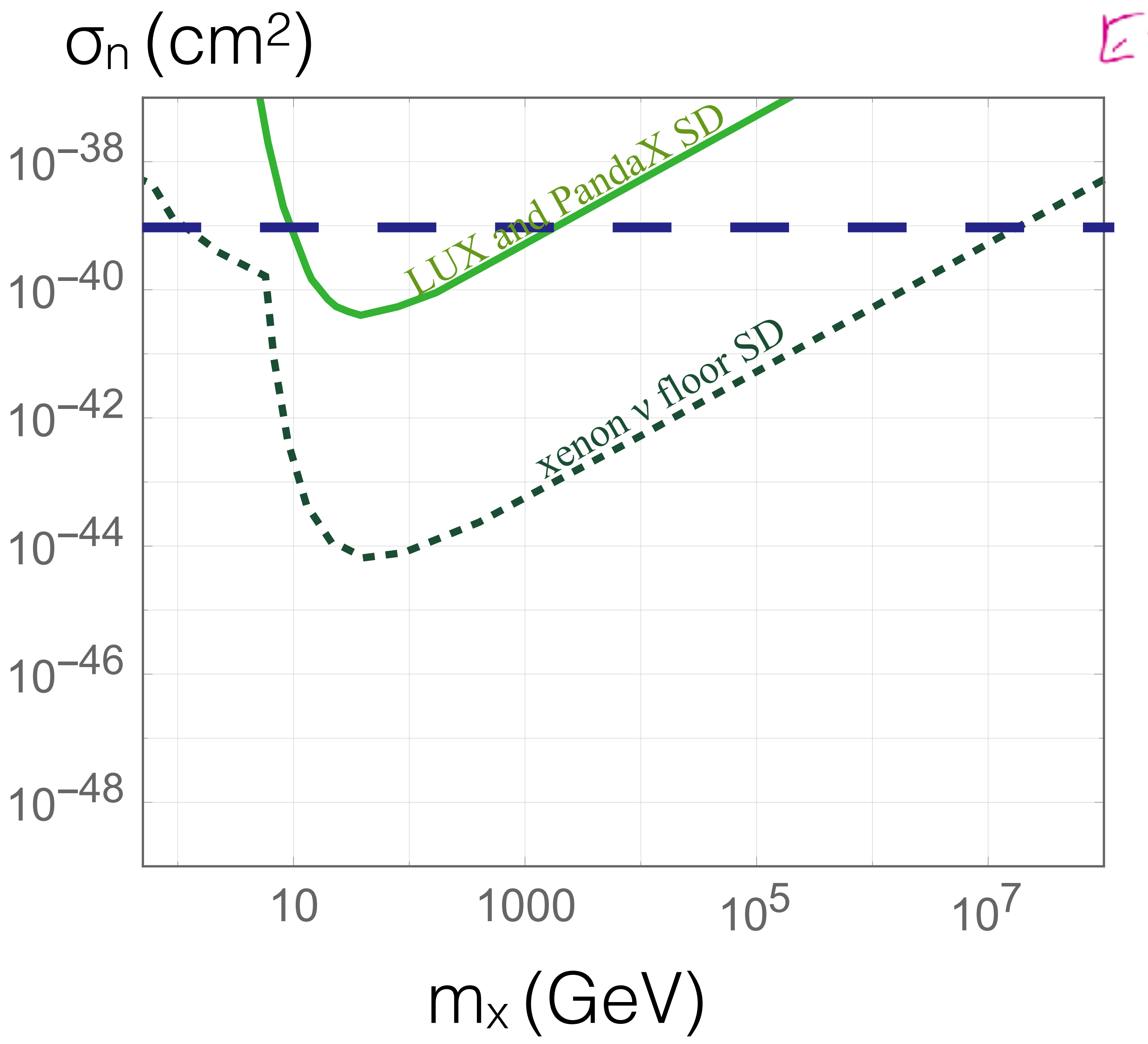
$$\sigma_N \sim \frac{\mu_{N\chi}^2\,\alpha_w^2}{m_Z^4}$$

$$\sigma_n = \underbrace{\left(\frac{1}{A^2}\right)}_{\boxed{SI}}\frac{\mu_{n\chi}^2}{\mu_{N\chi}^2}\,\sigma_N$$

smart scientists use heavy nuclei

Spin-Dependent WIMPs

→ Cleverly Incoherent



Ex: Majorana Fermion χ

Coupled through Z'

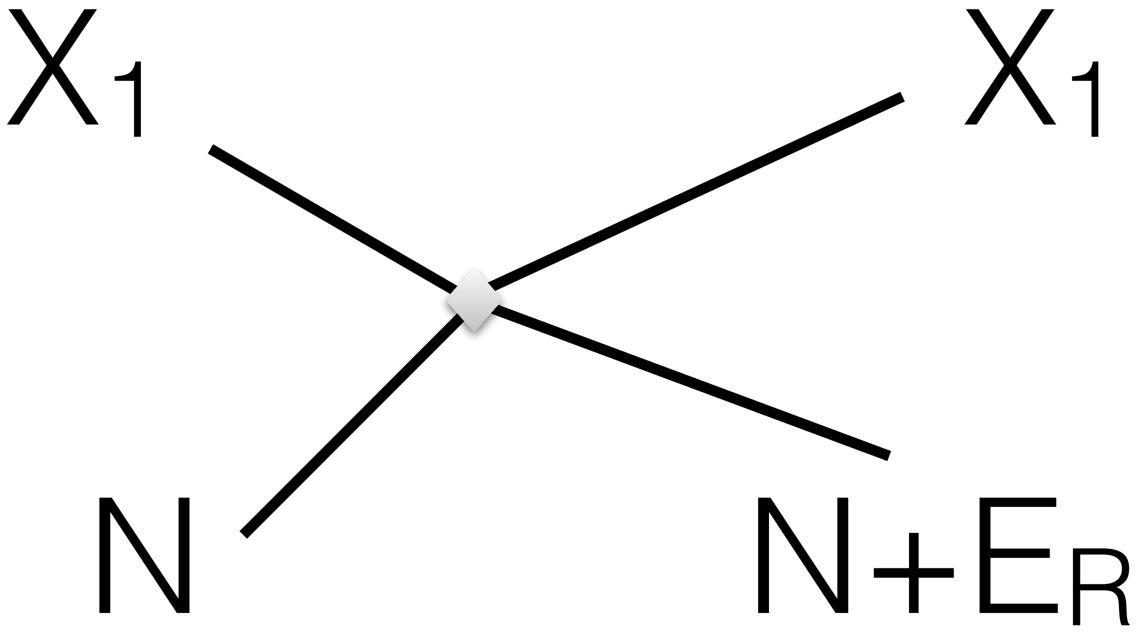
$$\chi\gamma_\mu\bar{\chi} = 0$$

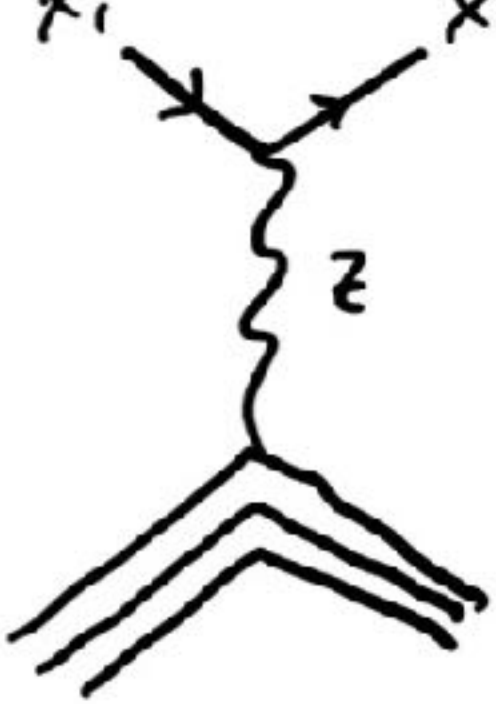
$$\chi\gamma_\mu\gamma_5\bar{\chi} \quad ✓$$

$$\sigma_n = \underbrace{\left(\cancel{\frac{1}{A^2}}\right)}_{\boxed{SD}} \frac{\mu_{n\chi}^2}{\mu_{N\chi}^2}\,\sigma_N$$

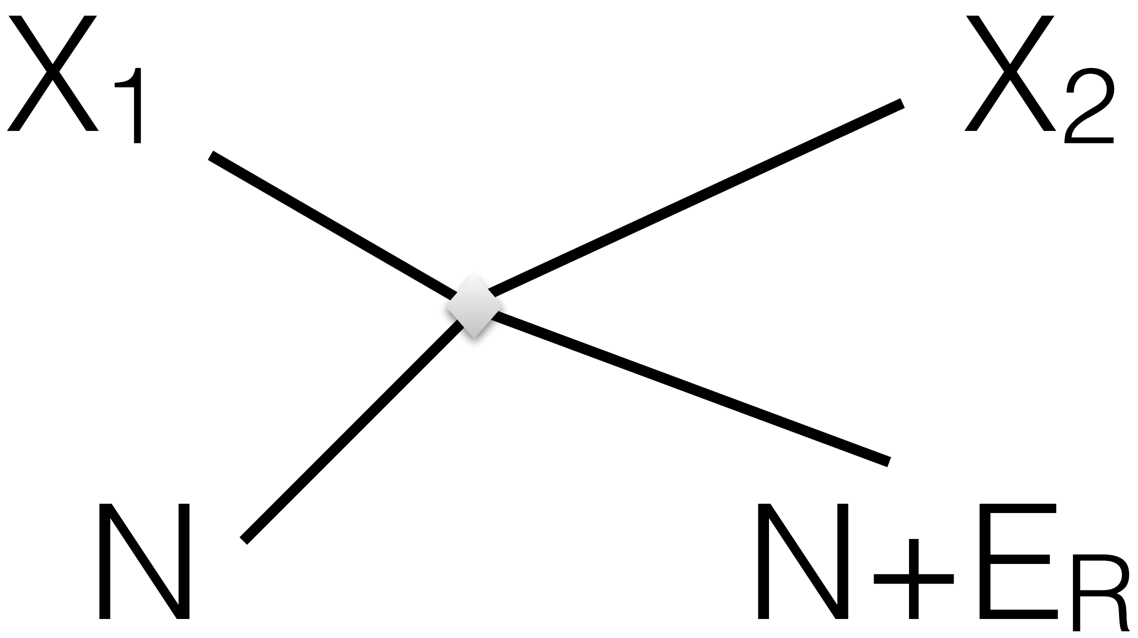
(heavy nuclei don't work as well)

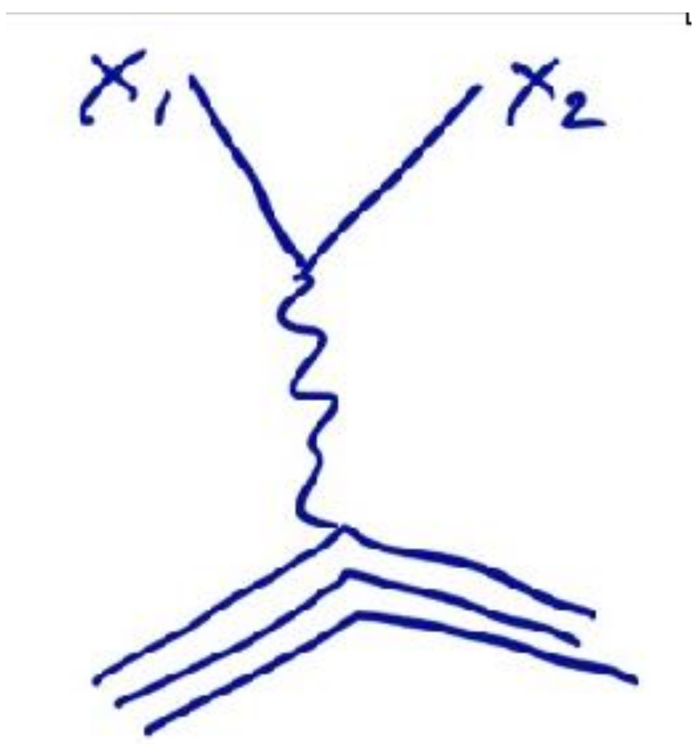
Elastic Dark Matter

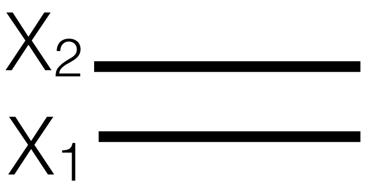




Inelastic Dark Matter





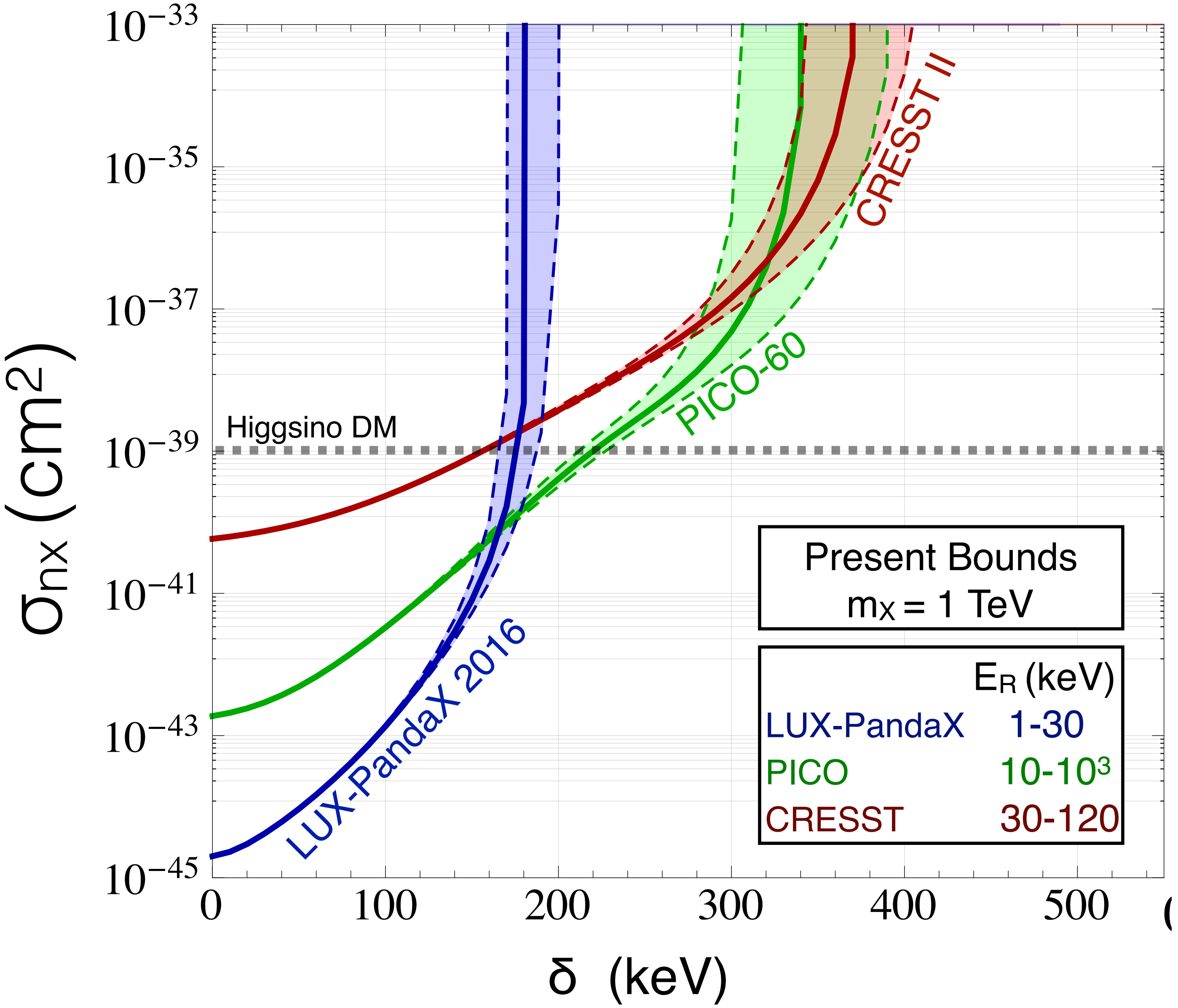


$$\delta \equiv m_{X_2} - m_{X_1}$$

Dark matter scattering forbidden (by broken symmetry) unless

$$E_R \approx m_N v_x^2 > \delta$$

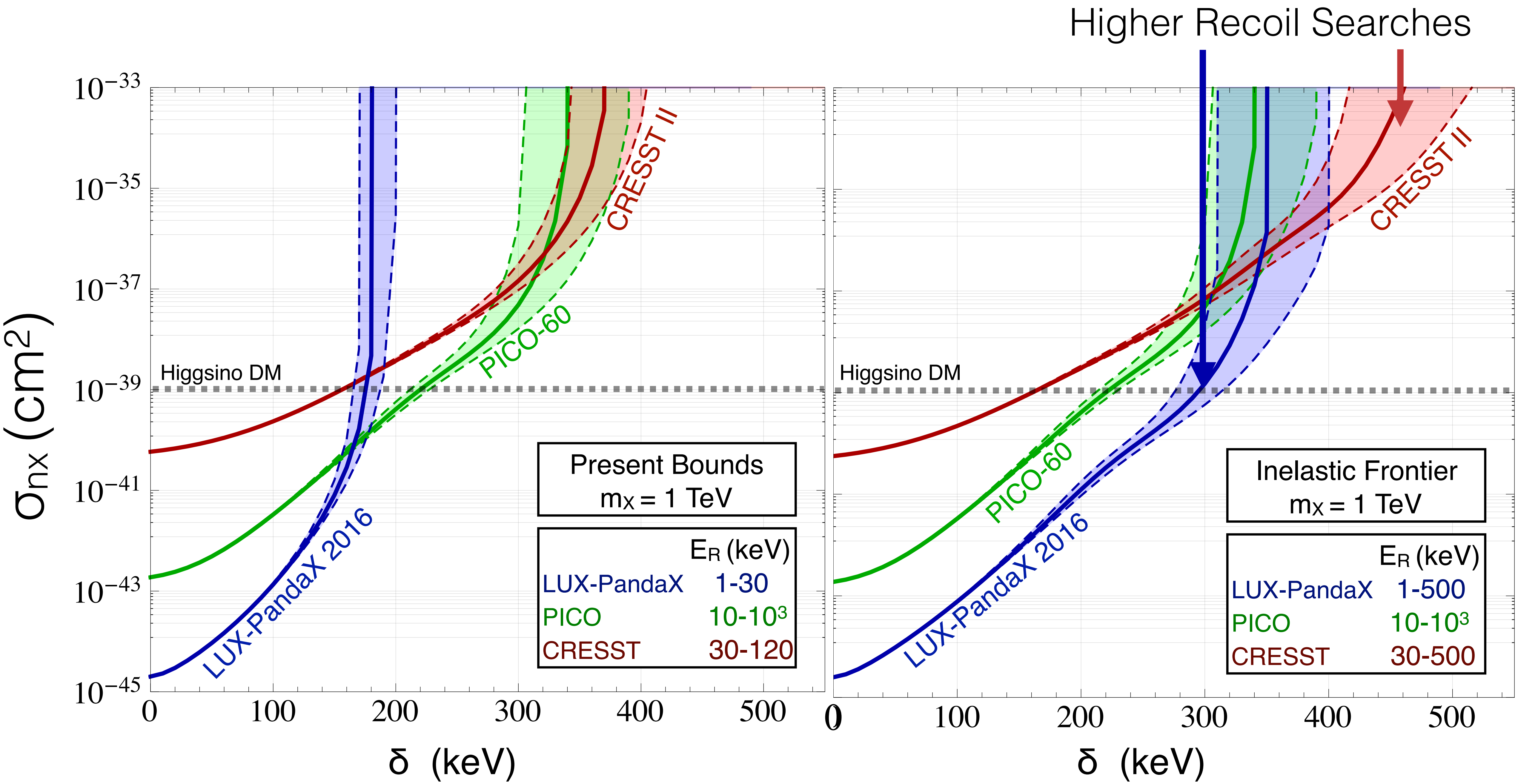
(energy exchange required to make X_2 from X_1)



These are the bounds from CRESST and Xenon without high recoil searches.

JB Fox Kribs Martin 2016

To find inelastic dark matter look at high recoil energy events!


Higher Recoil Searches

δ = 500 keV is a much better sensitivity, but for Higgsinos really want δ up to GeV…

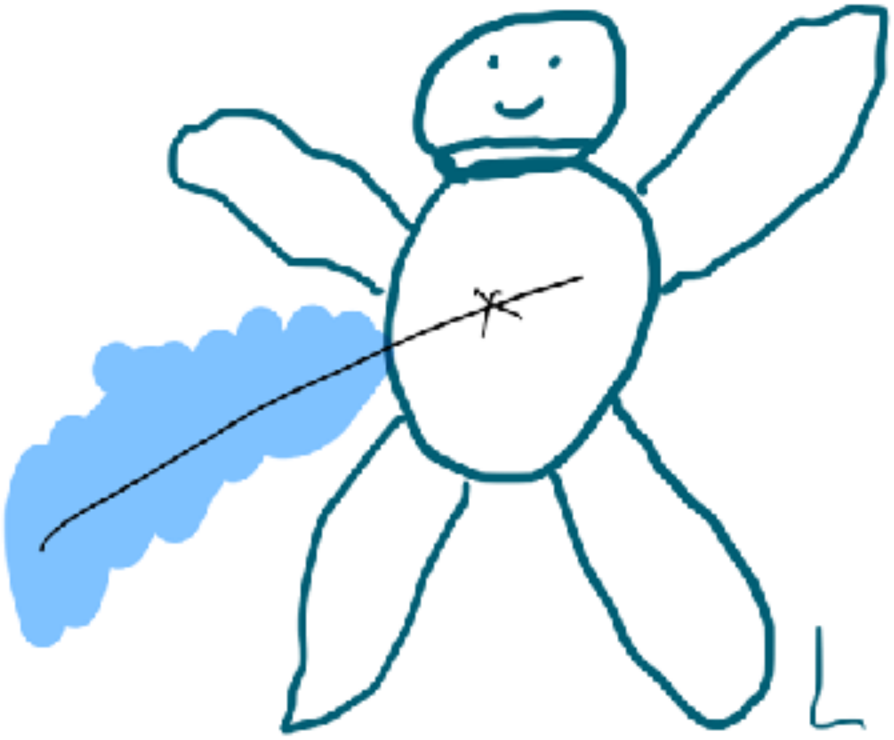
Ideal Direct Detector

-Probe mass scales evenly
(less weak-centric [~100 GeV nuclei])

-Sensitive without nuclear coherence
(spin-dependent dark matter)

-Accelerate dark matter to speed of light
(blast inelastic dark matter)

DM heated astronaut



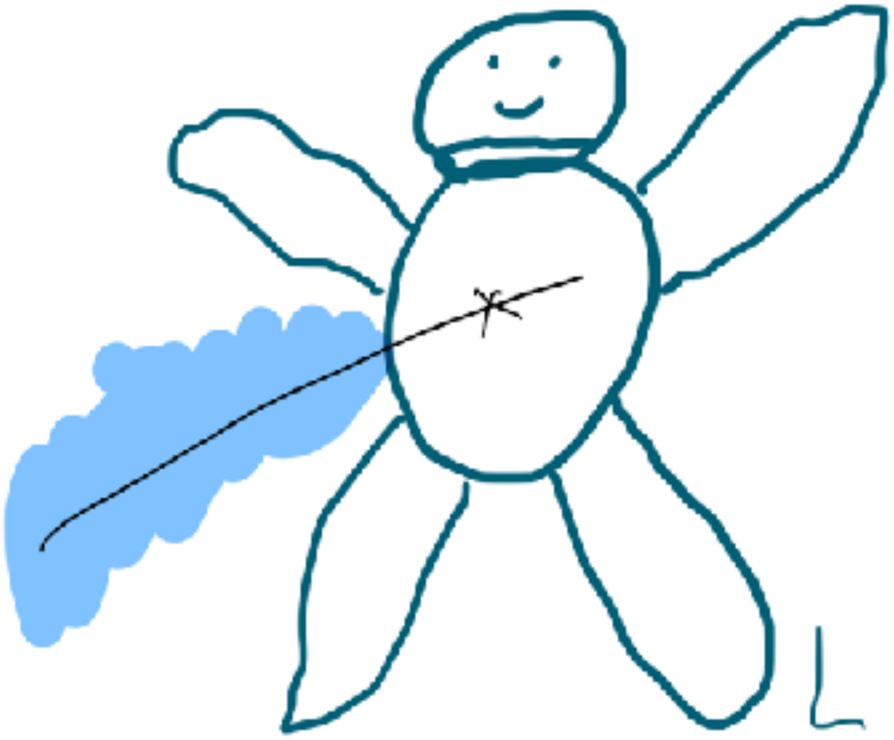
1 hit/yr - DD limit

Dark kinetic heating

$$L \sim \left(\frac{\text{event}}{\text{yr}}\right) \underbrace{m_{\text{carbon}} V_x^2} = 4\pi R_{ast}^2 \sigma_B T_{ast}^4$$

$T_{ast} \sim 75$ μKelvin

DM heated astronaut



1 hit / yr - DD limit

Dark kinetic heating

$$L \sim \left(\frac{\text{event}}{\text{yr}}\right) \underbrace{m_{carbon} v_x^2} = 4\pi R_{ast}^2 \sigma_B T_{ast}^4$$

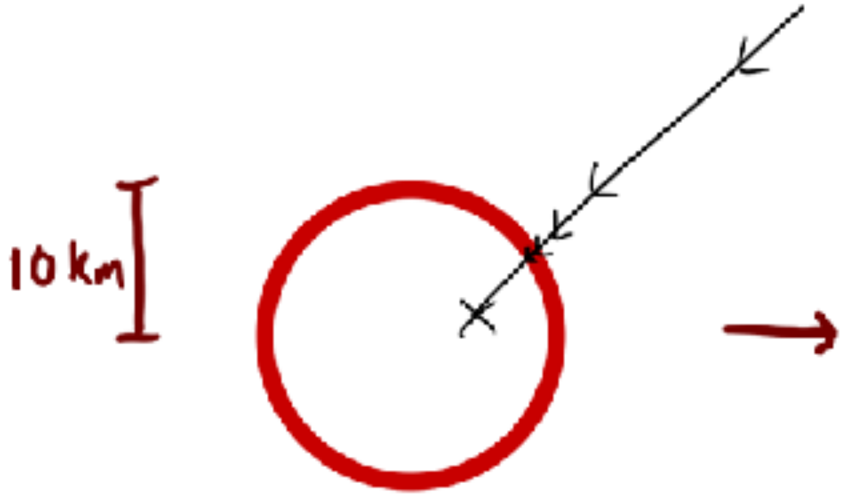
$T_{ast} \sim 75$ μKelvin

$$\bar{v}_x^2 \longrightarrow v_x^2 + \frac{2GM_{ast}}{R_{ast}}$$

Grav
Accelerated

$(v_g \sim 81$ microns/s$)$

Neutron Stars: Nature's Dark Matter Accelerators



$$\rightarrow v_{esc} = \sqrt{\frac{2GM}{R}} \sim 0.7\,c$$

Interior → fiducial mass 10^{57} GeV

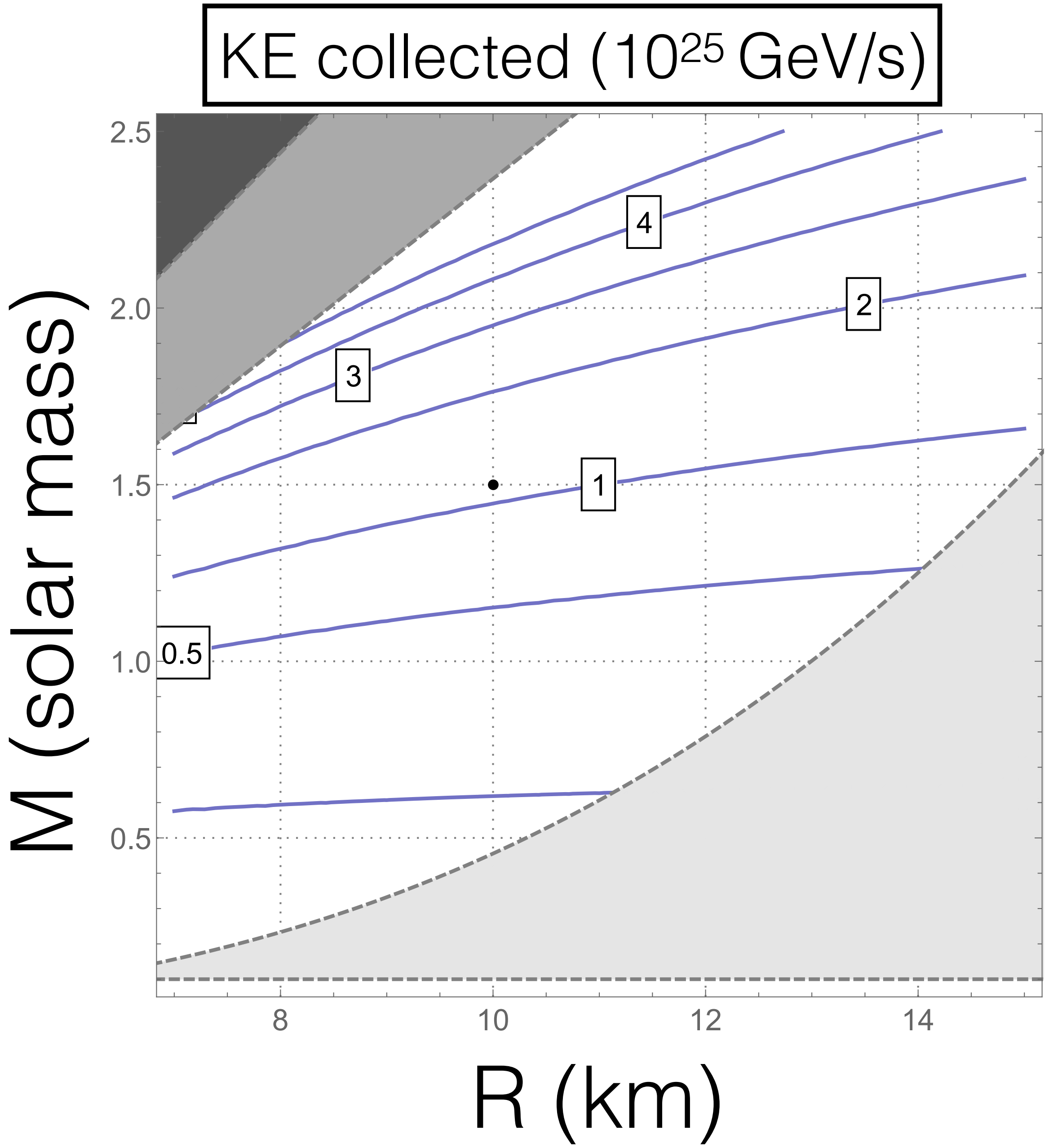
Neutrons : protons : electrons

$\sim 10:1:1$

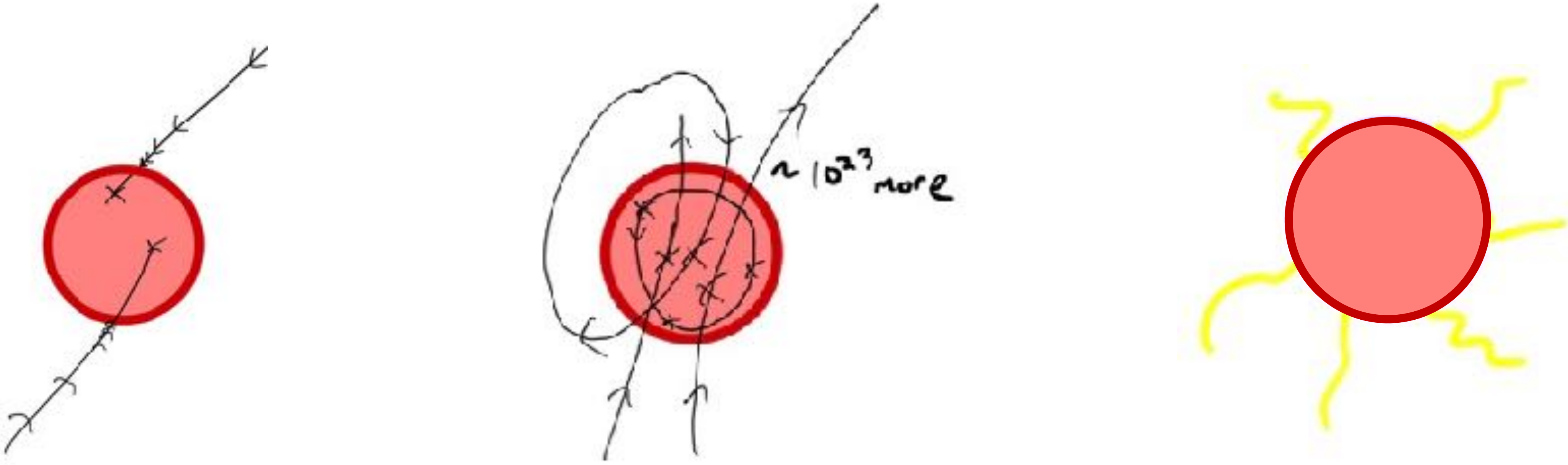
DM Flux Through the Neutron Star

$$\dot{m}_\chi = \pi \frac{2GMR}{v_\chi} r^2 \rho_\chi$$

$\hookrightarrow$ Independent of DM Mass

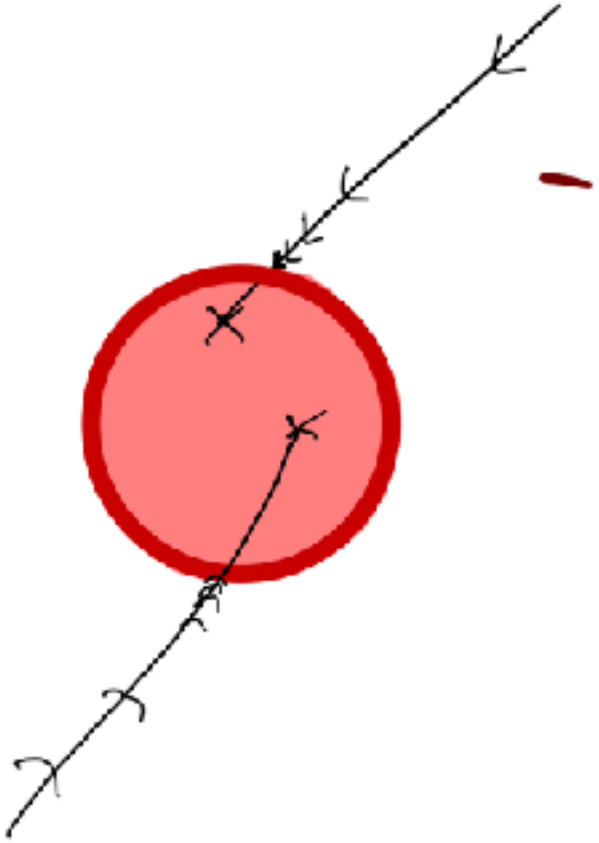


Dark Kinetic Heating



1. Dark matter gravitationally accelerated to ~0.7 c by neutron star
2. Scatters (re-scatters) against neutrons, electrons, or protons
3. Heats neutron star, resulting in blackbody emission

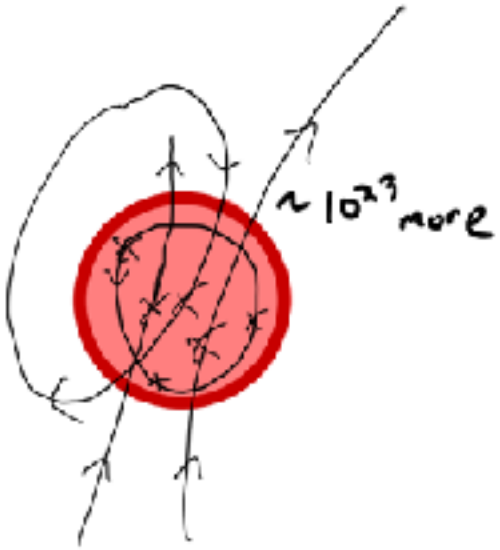
Dark Kinetic Heating



- Halo dark matter has

$$E_K = (\gamma - 1) m_\chi \sim \boxed{0.4\, m_\chi}$$

kinetic energy on impact.

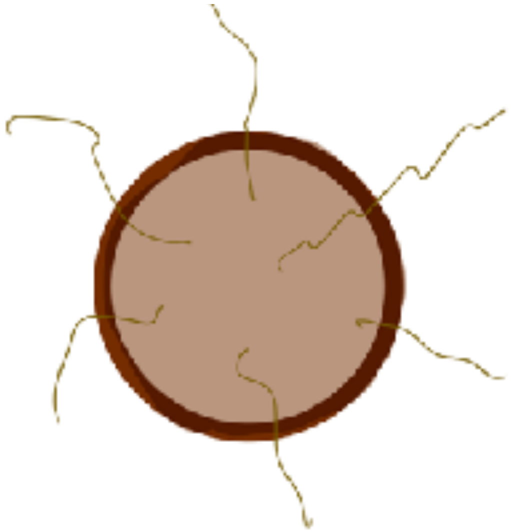


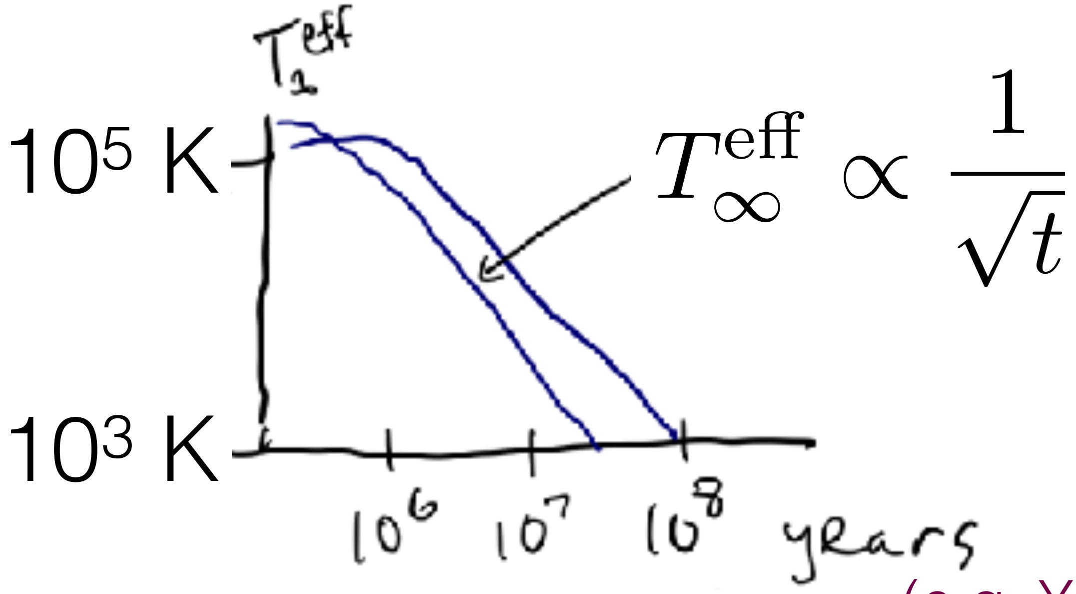
- Dark kinetic injection up to $\sim 10^{25}\,\frac{\text{GeV}}{\text{s}}$ for halo dark matter by earth $\left(0.4\,\frac{\text{GeV}}{\text{cm}^3}\right)$

- Only requirement is scattering with neutrons, protons, electrons

Dark Kinetic Heating

- After 10^8 years, neutron stars should emit as black bodies with $T^{\mathrm{eff}} << 1000$ K.

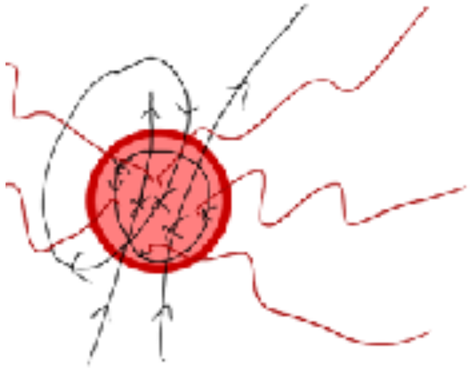




(e.g. Yakovlev and Pethick 2004)

- Most neutron stars (all stars) are older than a billion years, by which time $T^{\mathrm{eff}} << 100$ K).

- Maximum dark kinetic heating results in $T^{\mathrm{eff}} \sim \underline{1750 \text{ K}}$.

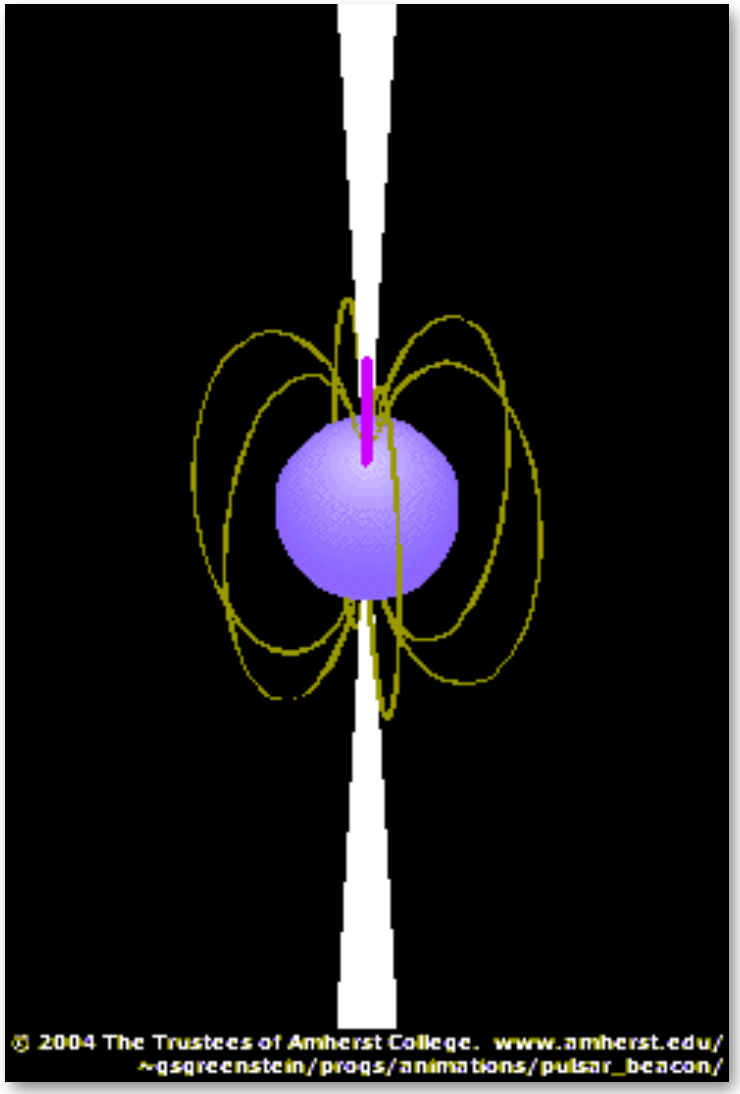


Pulsars

-Rotating, neutron stars with magnetic dipole

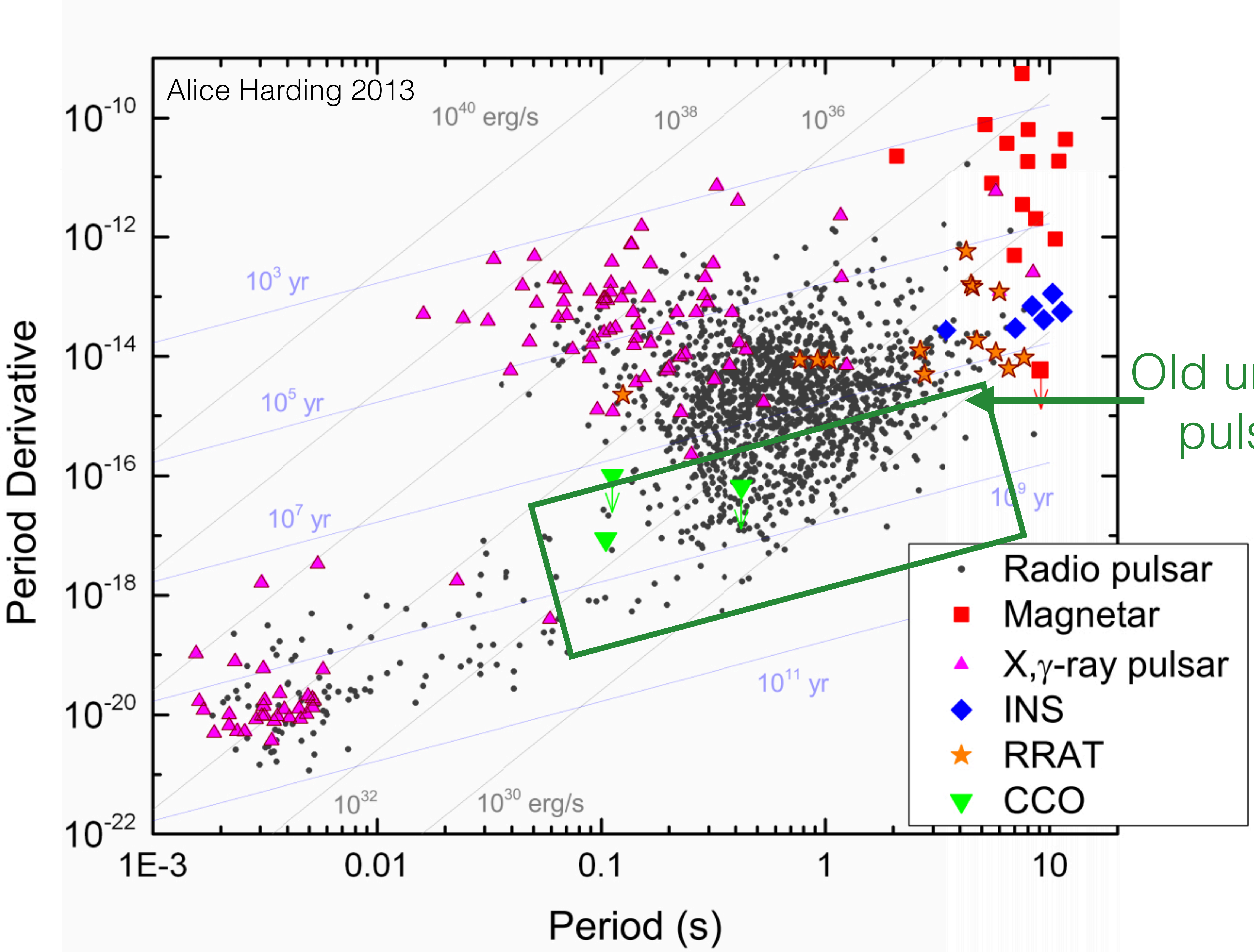
$$B \sim 10^8 - 10^{14}\ \mathrm{G}$$

-Pulsed radio emission along the magnetic dipole axis



© 2004 The Trustees of Amherst College. www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/

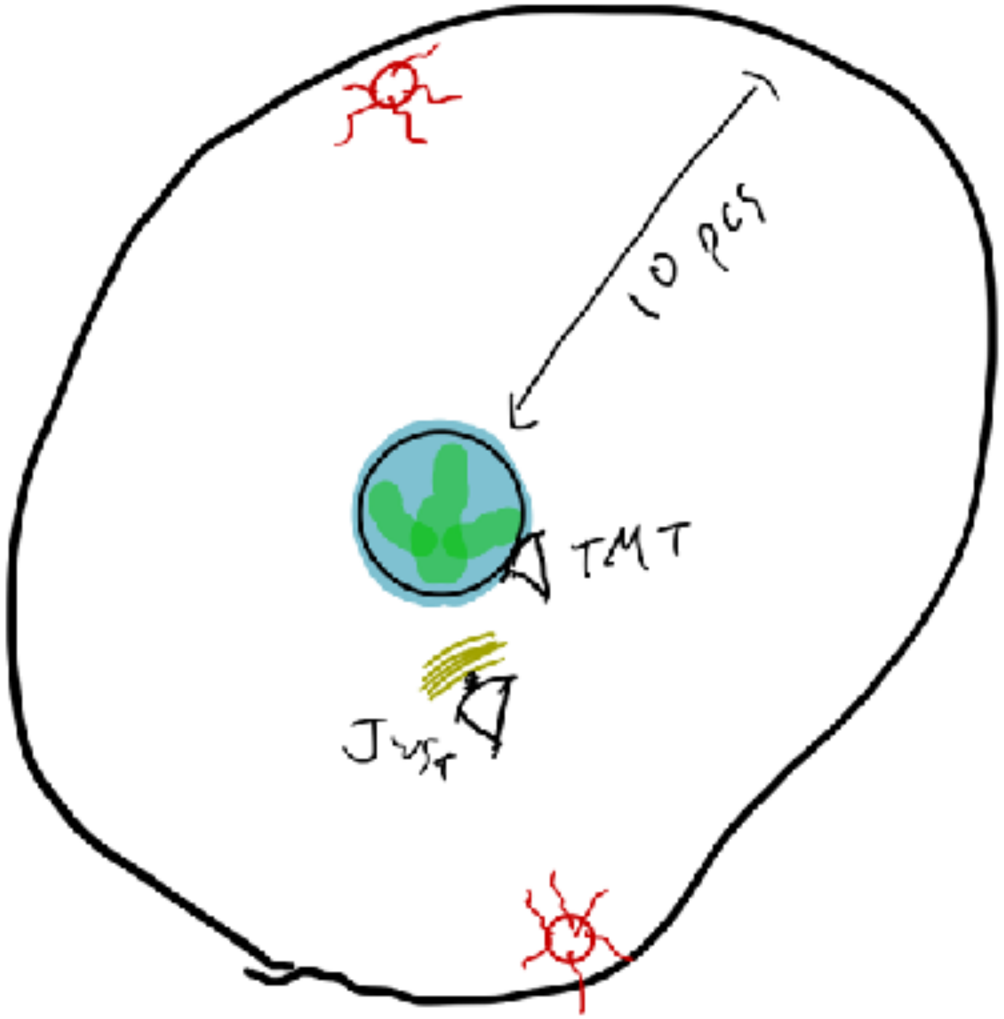
Known Pulsars



Old unspun pulsars

Backyard Neutron Star BBQ

1. Find a few pulsars in radio with FAST, SKA, CHIME up to ~50 parsecs from earth (radio emission separate from temp.)

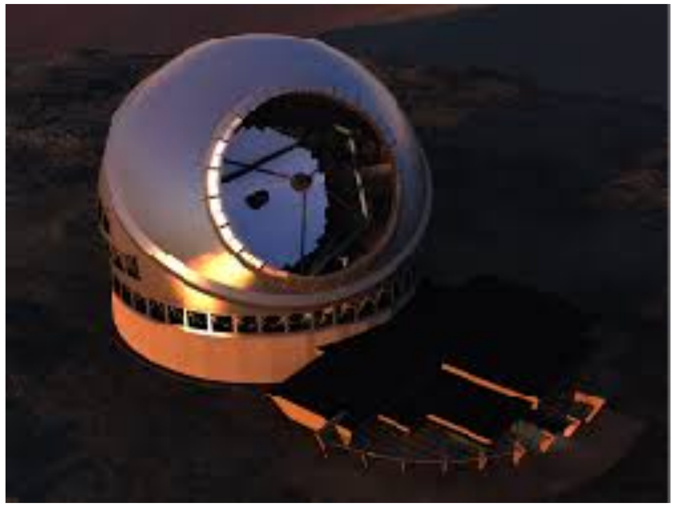


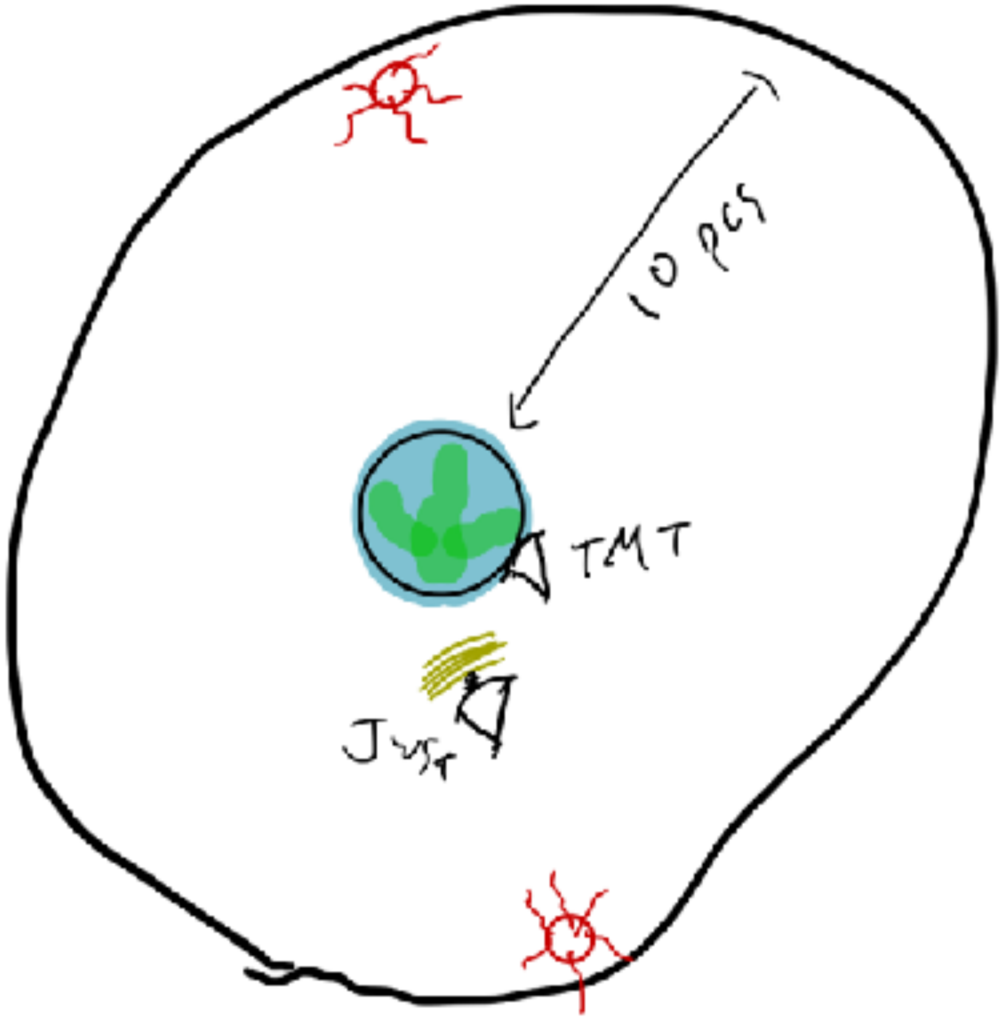
~1-3 neutron stars
10 parsecs
from Earth

(Blaes & Madau ’93)

Backyard Neutron Star BBQ

1. Find a few pulsars in radio with FAST, SKA, CHIME up to ~50 parsecs from earth (radio emission separate from temp.)





~1-3 neutron stars
10 parsecs
from Earth

(Blaes & Madau '93)

2. Use James Webb Space Telescope or Thirty Meter Telescope to observe or constrain dark kinetic heating

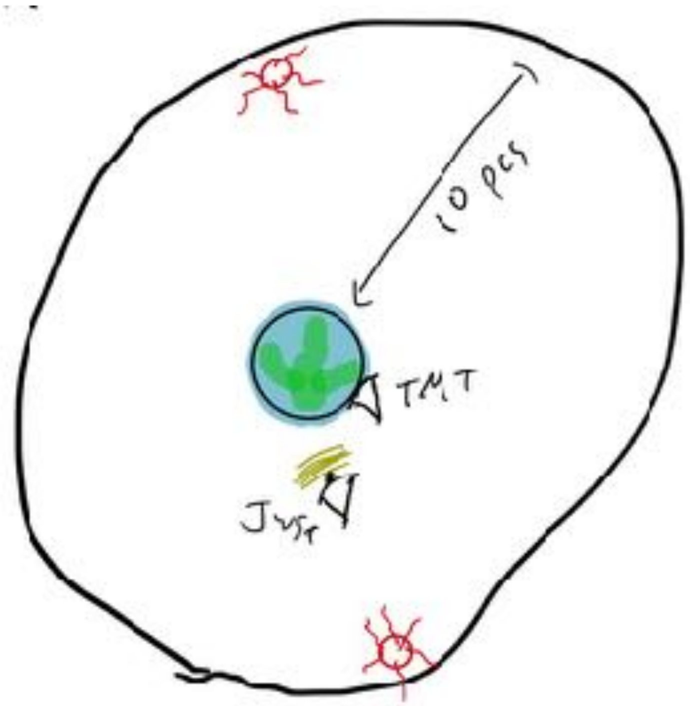
2 Sigma Integration Times

James Webb Space Telescope

(and its smorgasbord of filters)

kinetic only $$10^5 \text{ seconds} \left(\frac{d}{10 \text{ parsecs}}\right)^4$$

annihilation $$9000 \text{ seconds} \left(\frac{d}{10 \text{ parsecs}}\right)^4$$



Thirty Meter Telescope

kinetic only $$7 \times 10^4 \text{ seconds} \left(\frac{d}{10 \text{ parsecs}}\right)^4$$

annihilation $$2000 \text{ seconds} \left(\frac{d}{10 \text{ parsecs}}\right)^4$$

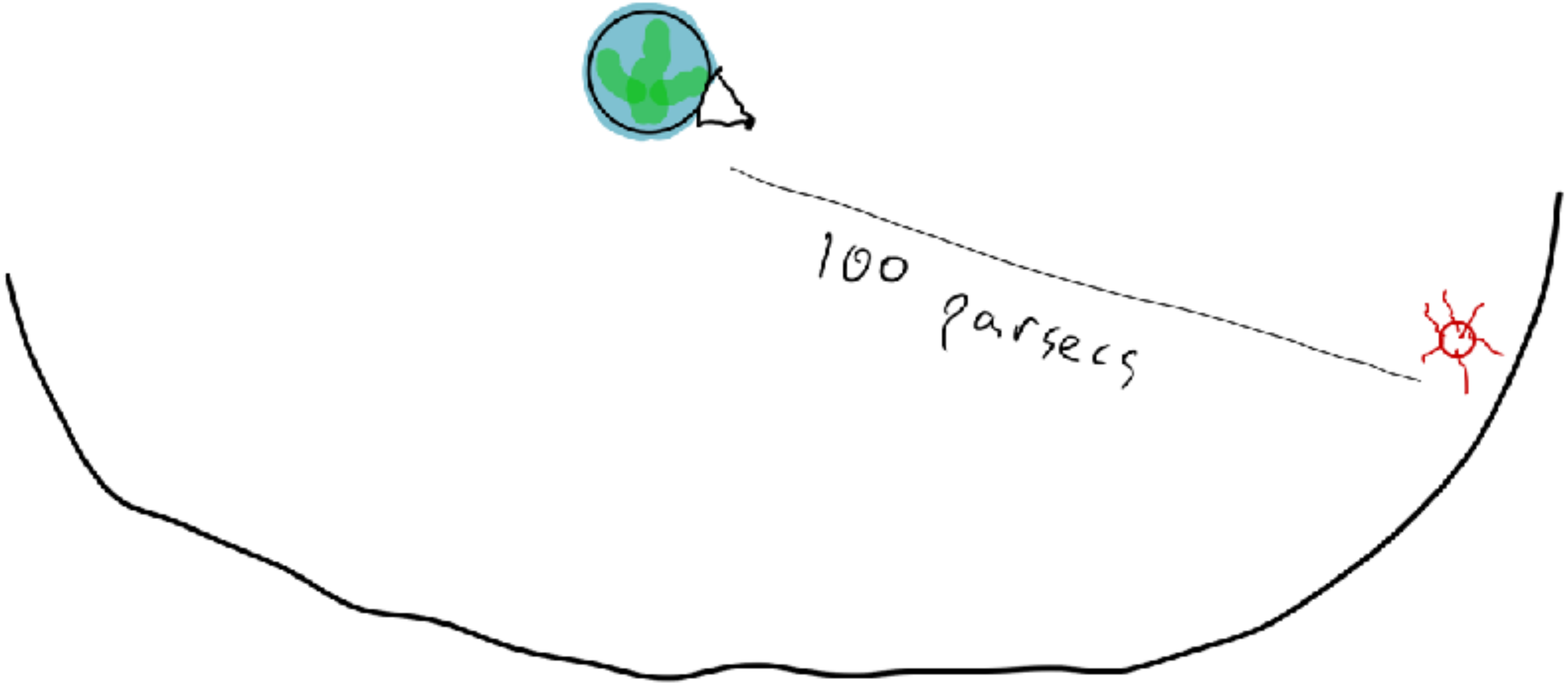
Can get out to ~50 parsecs with next-gen telescopes.

Long Term Braise

-100 meter telescope, an "OWL"

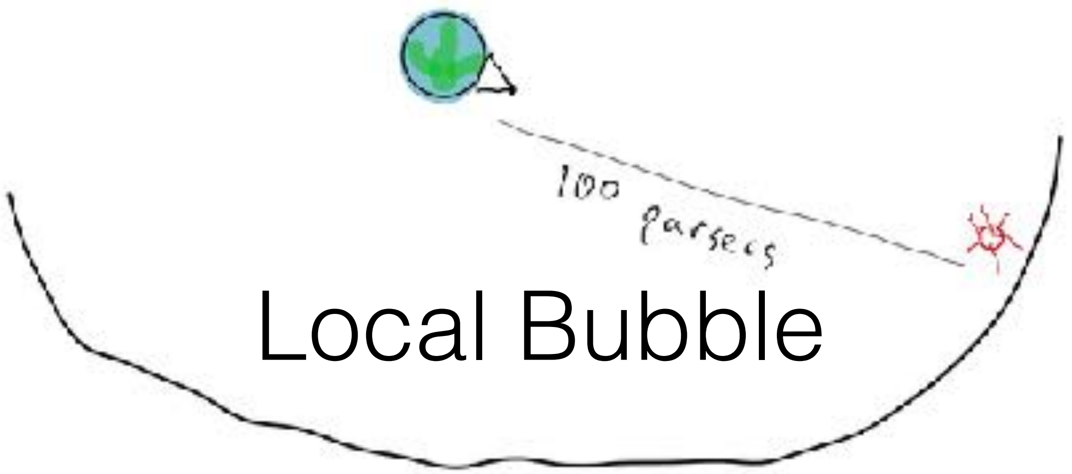
-2 sigma on known pulsars in ~100 hours

-Excellent task for exoplanet atmosphere telescopes



Possible backgrounds:

Interstellar medium accretion



-Local bubble around earth has ISM of <0.01 GeV/cm^3

-Portion of ISM deflected by NS magnetic field

Magneto-Thermal Heating

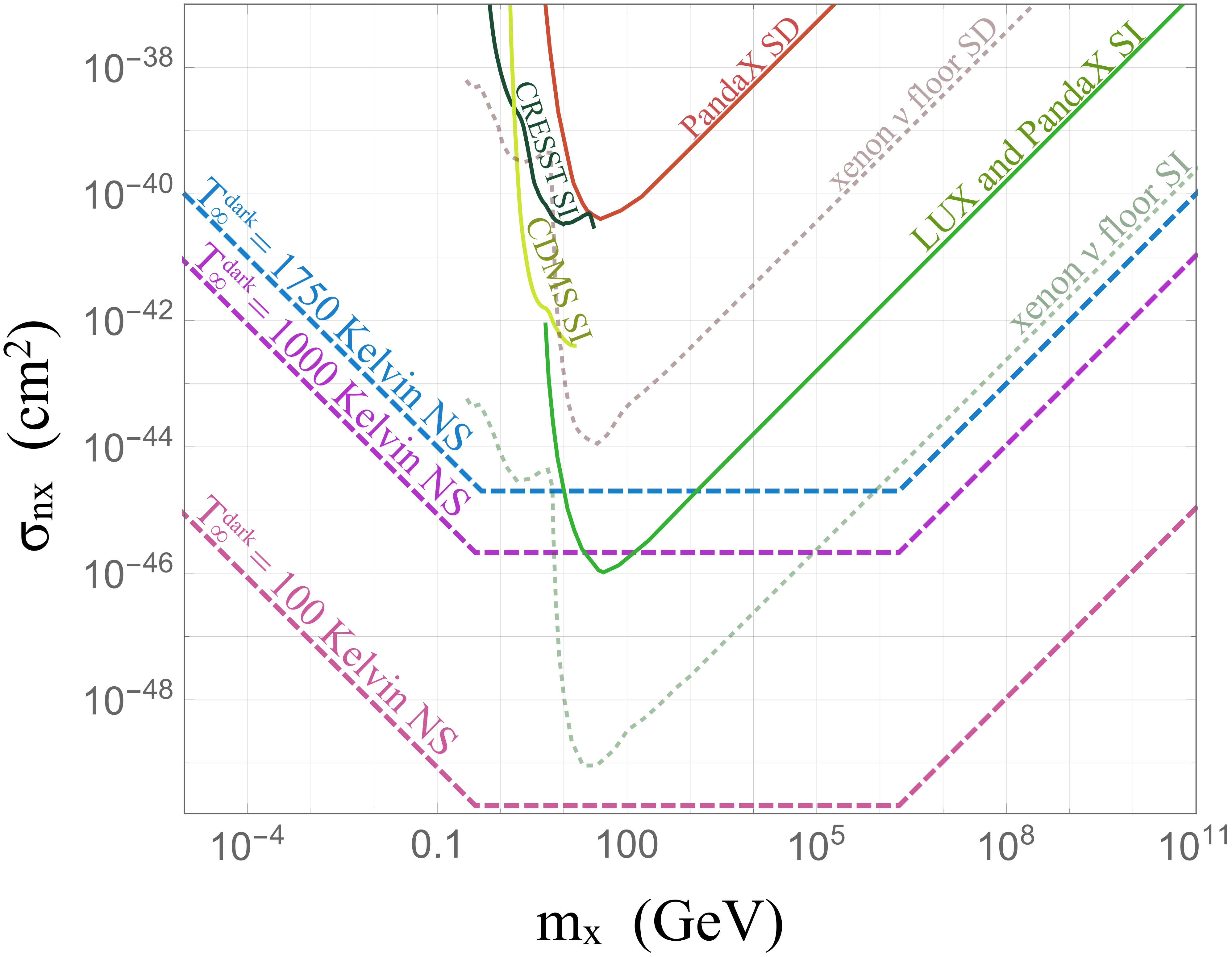
-Magneto-thermal heating can occur for B>10^{13} Gauss

-Damps out after a million years, Pons et al '08

Other

— Standard thermodynamics and NS cooling indicate 100 K after ~Gyr

Dark Kinetic Heating Sensitivity

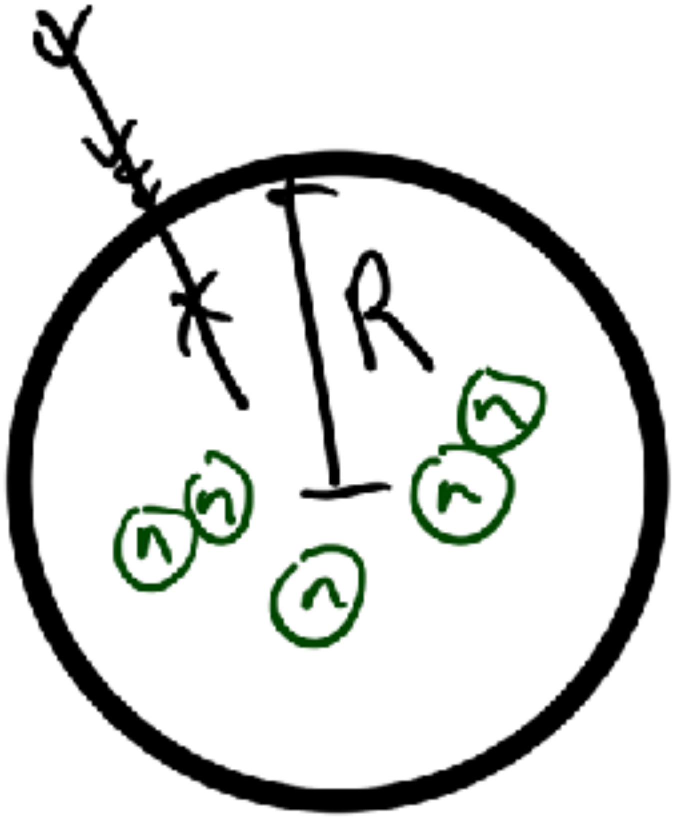


DM Capture

Fraction of DM captured:

$$f \equiv \mathrm{Min}\left[1, \frac{\sigma_{nx}}{\sigma_{sat}}\right]$$

- σ_{sat} is the cross-section for all NS transiting DM to be captured



Mean free path $\ell_1 = (n\sigma)^{-1}$

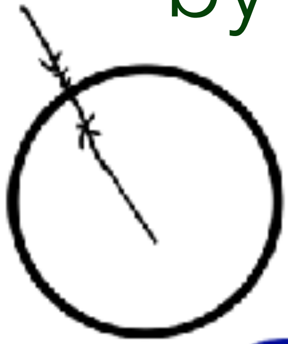
Star opaque to DM if

$$\frac{\pi R^2}{N_n} = \frac{\pi R^2 m_n}{M} < \sigma_{nx}$$

→ 2×10^{-45} cm^2

DM Capture - By Mass

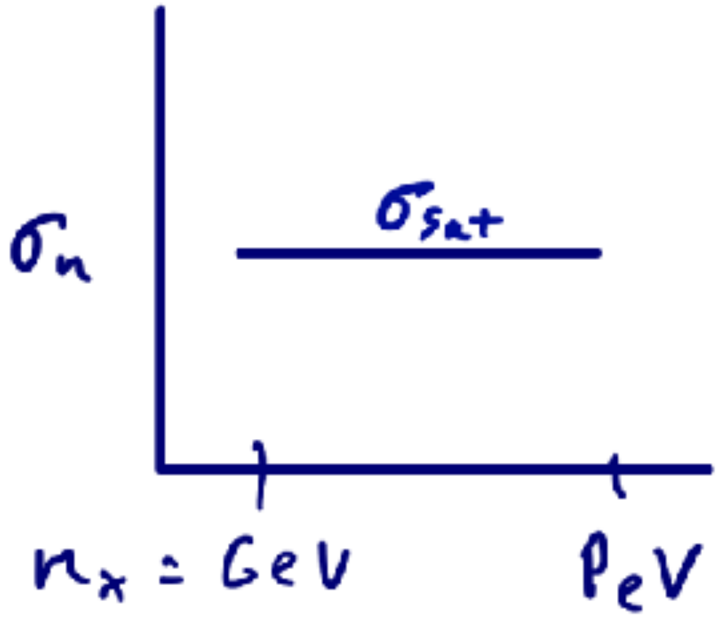
DM must lose its halo kinetic energy ($10^{-6}\ m_x$) by scattering with the neutron star to become captured.



$$\boxed{M_x = \text{GeV} - \text{PeV}}$$

Compare $\frac{1}{2} m_x V_x^2 \sim 10^{-6} m_x$ to energy lost scattering

$$E_R \sim \mu_{Nx} V_s^2 \sim \text{GeV}$$



$$\boxed{\sigma_{sat} = \pi R^2 m_n / M \sim 2 \cdot 10^{-45}\ \text{cm}^2}$$

$\boxed{m_\chi < \mathrm{GeV}}$ Pauli Blocking

Only a fraction $\left(\frac{\Delta p}{p_F}\right)$ of neutrons can scatter above Fermi surface

$$\boxed{\Delta p \sim \gamma m_\chi v_s \sim m_\chi}$$

So scattering is suppressed by $\frac{m_\chi}{p_F}$

$$\boxed{\sigma_{sat} = \frac{\pi R^2 m_n}{M}\,\frac{p_F}{m_\chi} = 2\cdot 10^{-45}\,\mathrm{cm}^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)}$$

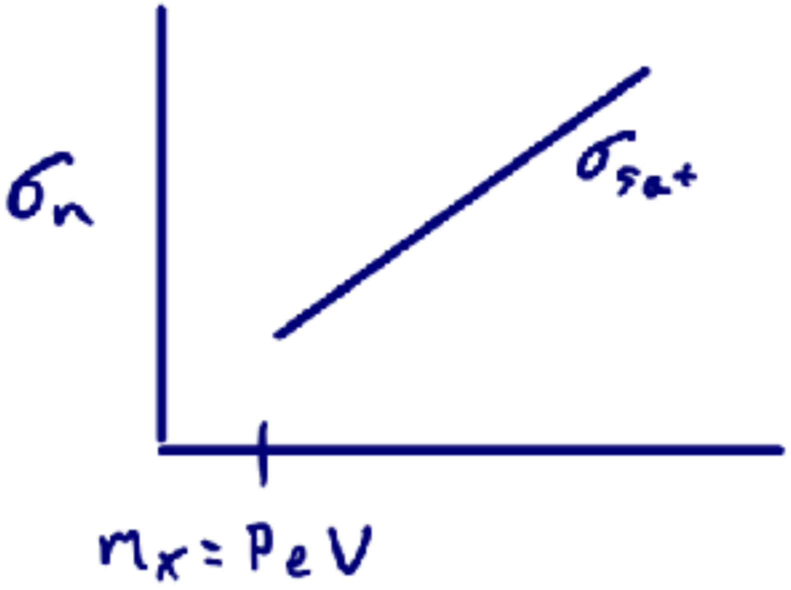
$\boxed{m_\chi > \text{PeV}}$ Multi-Scatter

For dark matter masses > PeV, need to scatter multiple times (N) while crossing the star to capture

$$E_k = \tfrac{1}{2} m_\chi v_\chi^2 \lesssim (N) E_R$$

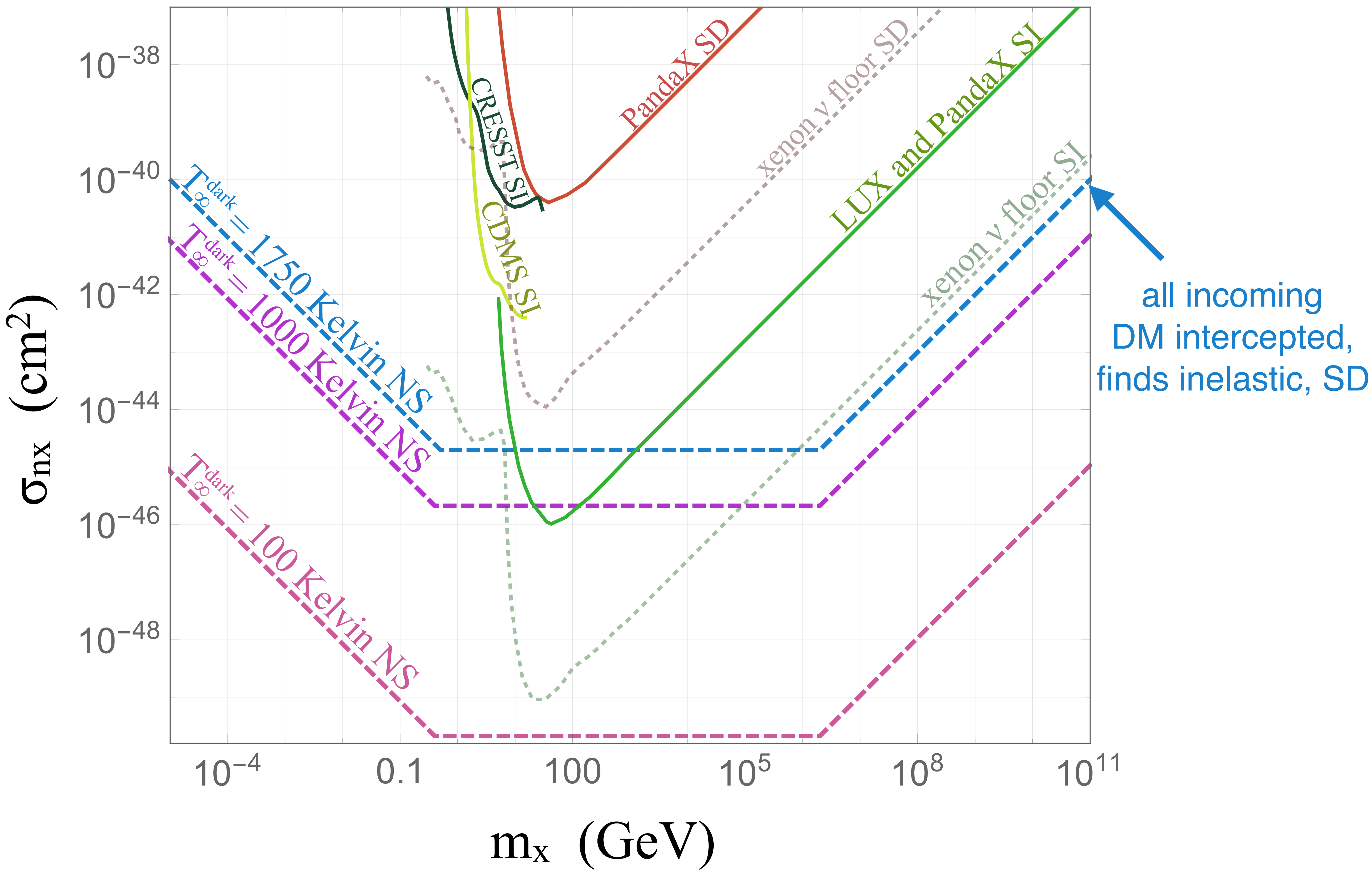
$$\tfrac{1}{2} m_\chi v_\chi^2 \sim N\, E_R \sim (n_n\, \sigma_n\, R)\, m_n$$

$$\longrightarrow \boxed{\sigma_{sat} \propto m_\chi}$$



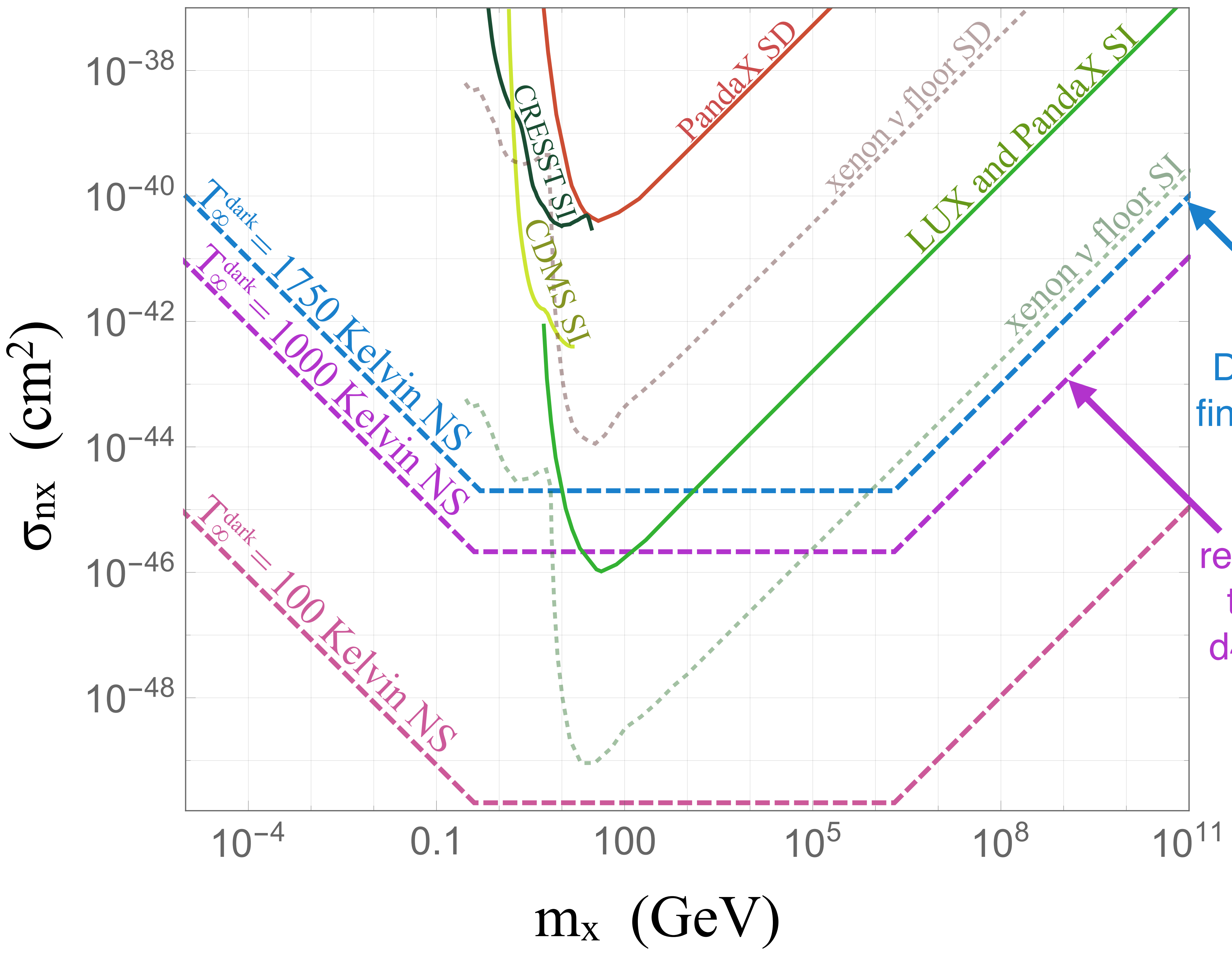
$$\boxed{\sigma_{sat} = 2 \cdot 10^{-45}\,\text{cm}^2 \left(\frac{m_\chi}{\text{PeV}}\right)}$$

JB, Delgado, Martin 2017



all incoming
DM intercepted,
finds inelastic, SD

Will Motivate Kiloton-Year+ Detectors!

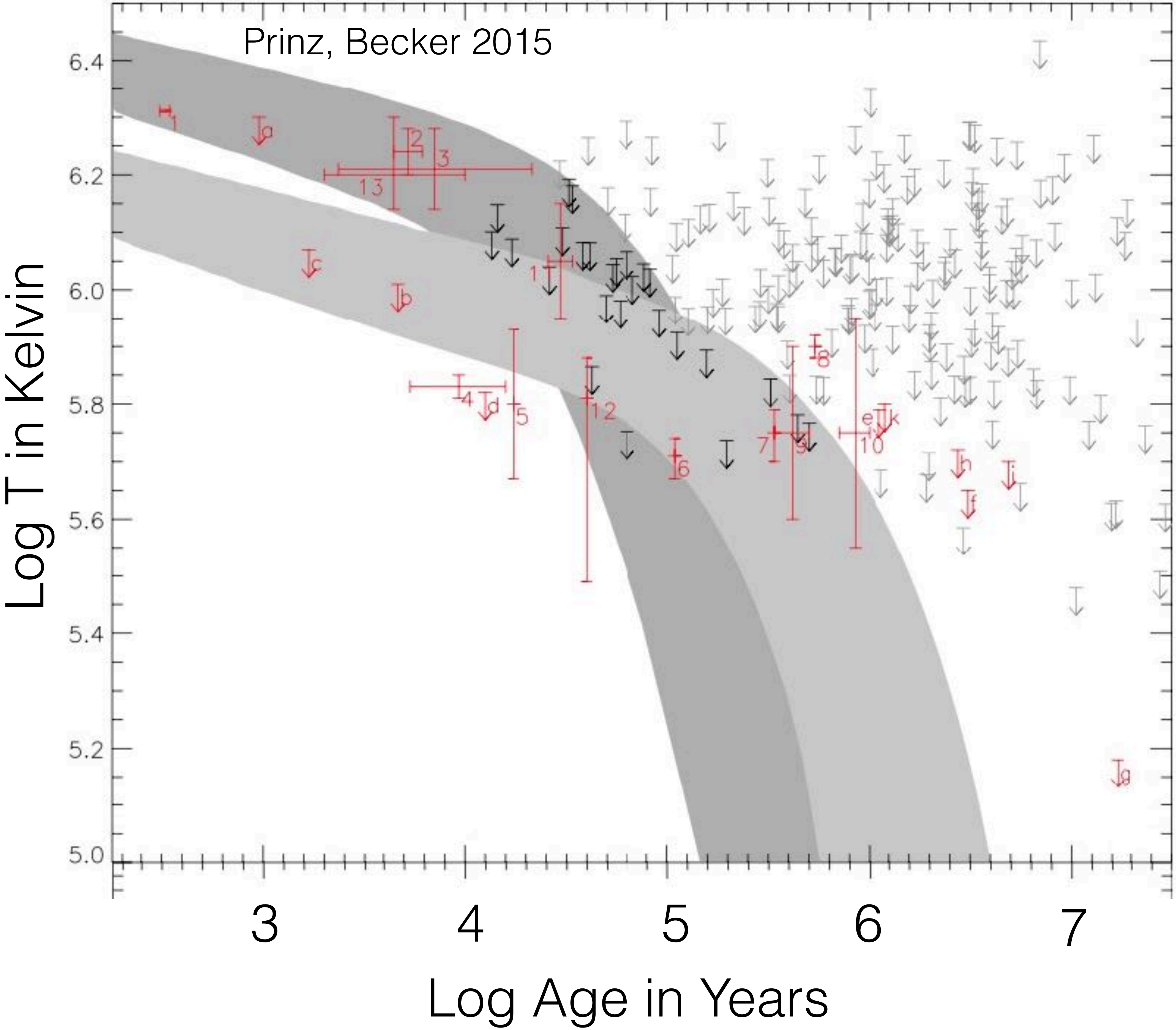


all incoming
DM intercepted,
finds inelastic, SD

reach of next-gen
telescopes for
d~10 parsec NS

- Dilute, Inelastic, Spin-Dependent WIMPs _all_ probed by dark kinetic heating
- The importance of being semi-relativistic: the natural WIMP state!
- Infrared Telescopes - exoplanets, OK...

But Also Dark Matter!


Prinz, Becker 2015
Log T in Kelvin
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
Log Age in Years
3
4
5
6
7
1
a
2
3
13
c
b
1
4
d
5
12
6
7
9
8
e
k
10
h
i
f
g

kinetic only

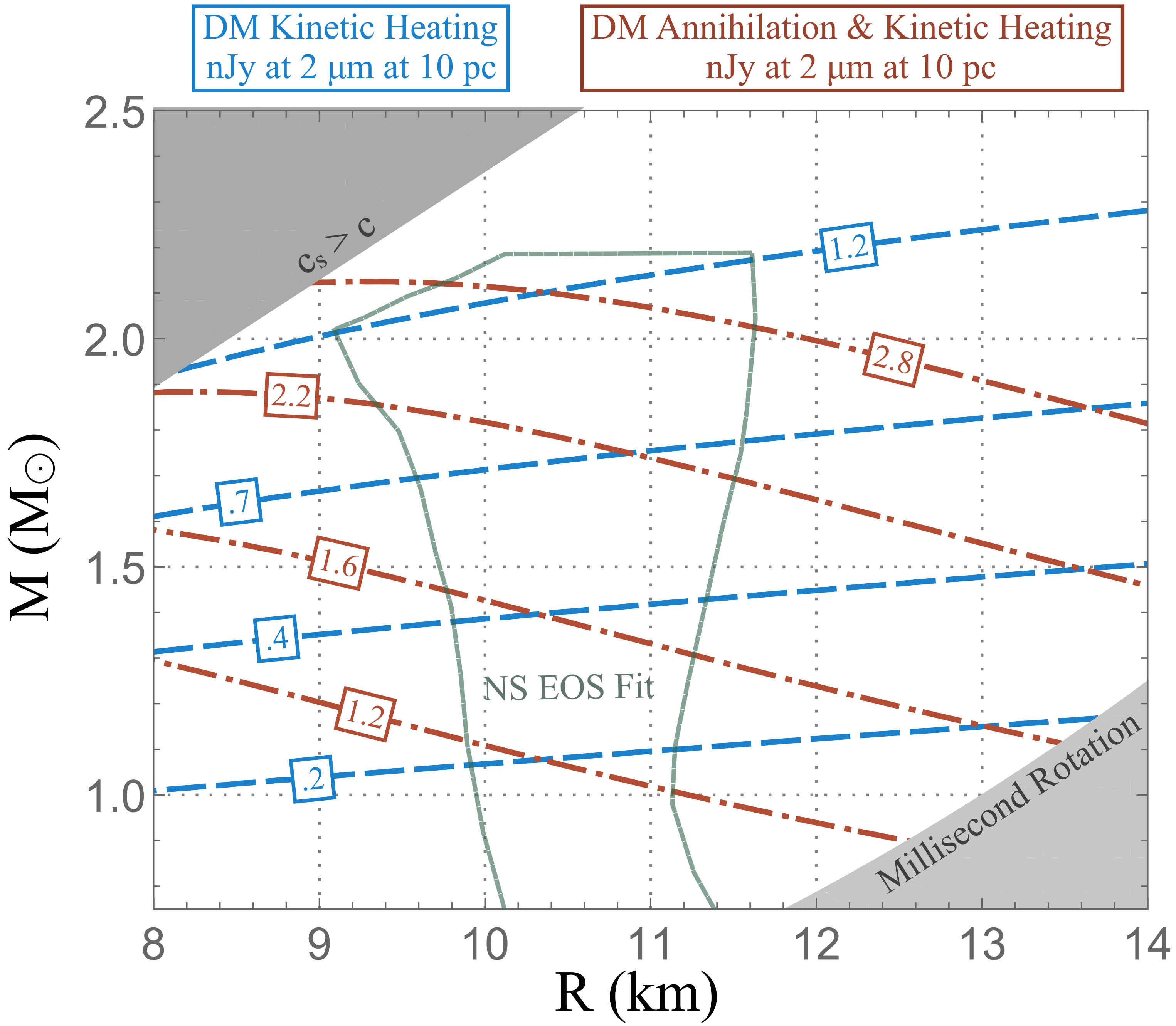
$$(\gamma - 1)\dot{m}_x$$

(very sensitive
to escape velocity)

annihilation

$$\gamma \dot{m}_x$$

(heating mostly from captured
mass, scales with NS mass)



nanoJansky ~ 10^{-30} GeV / (cm^2 s Hz)

kinetic only

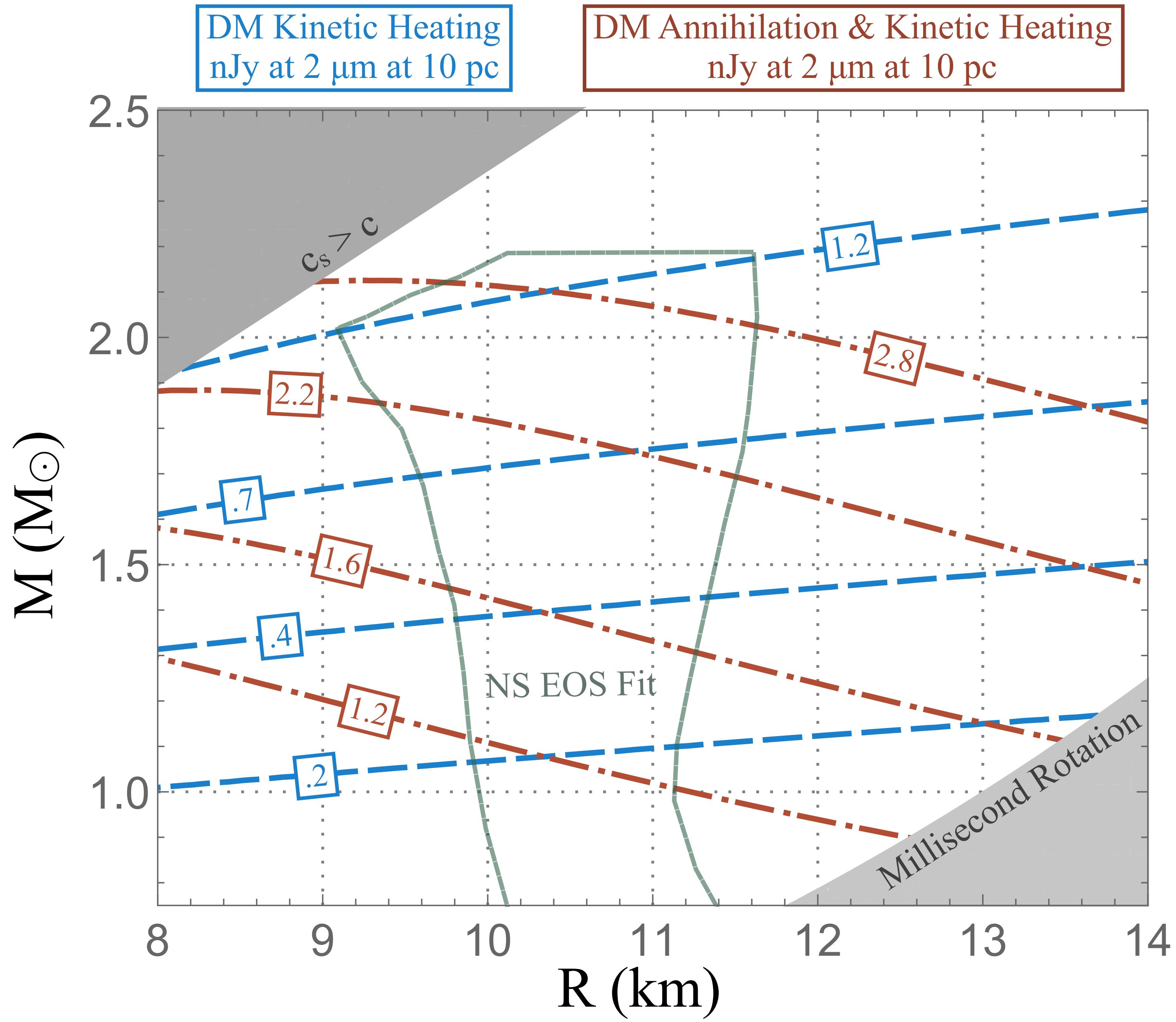
$$(\gamma - 1)\dot{m}_x$$

(very sensitive
to escape velocity)

annihilation

$$\gamma \dot{m}_x$$

(heating mostly from captured
mass, scales with NS mass)

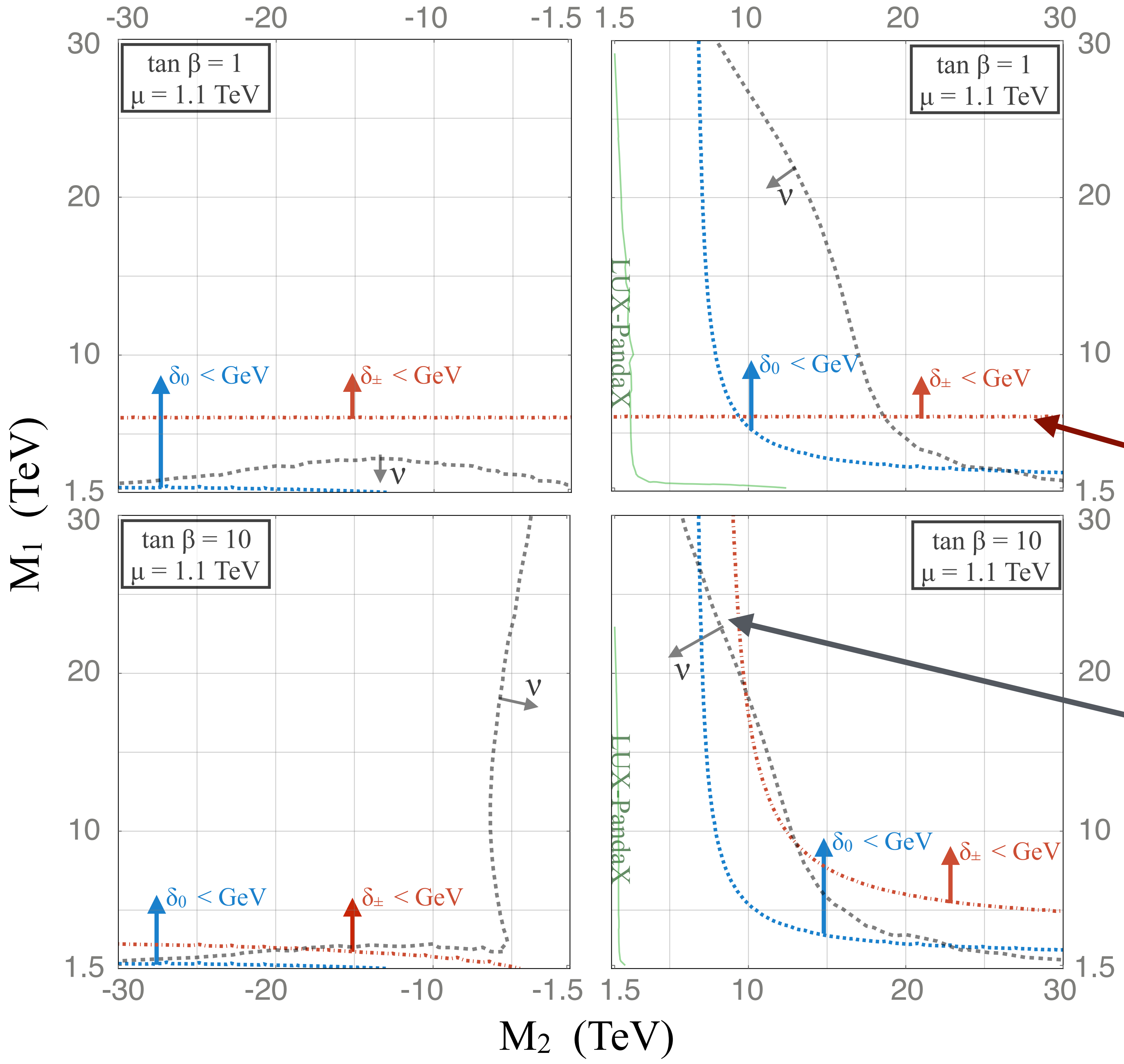


kinetic heating

annihilation heating

Broader variety of Neutron Star
luminosities for only dark kinetic heating

Higgsinos



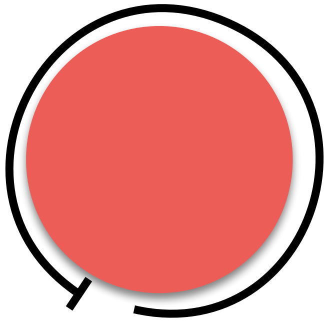
Mass splittings include one loop EW corrections

Neutrino Floor
(Future DD reach)

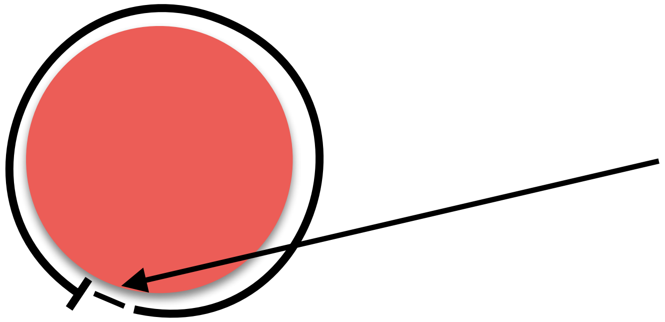
GeV recoil energies probe Higgsinos (compare to 500 keV at Xenon)

Pulsars

Estimate pulsar age measuring pulse period (P)
and slowdown per pulse (Ṗ)



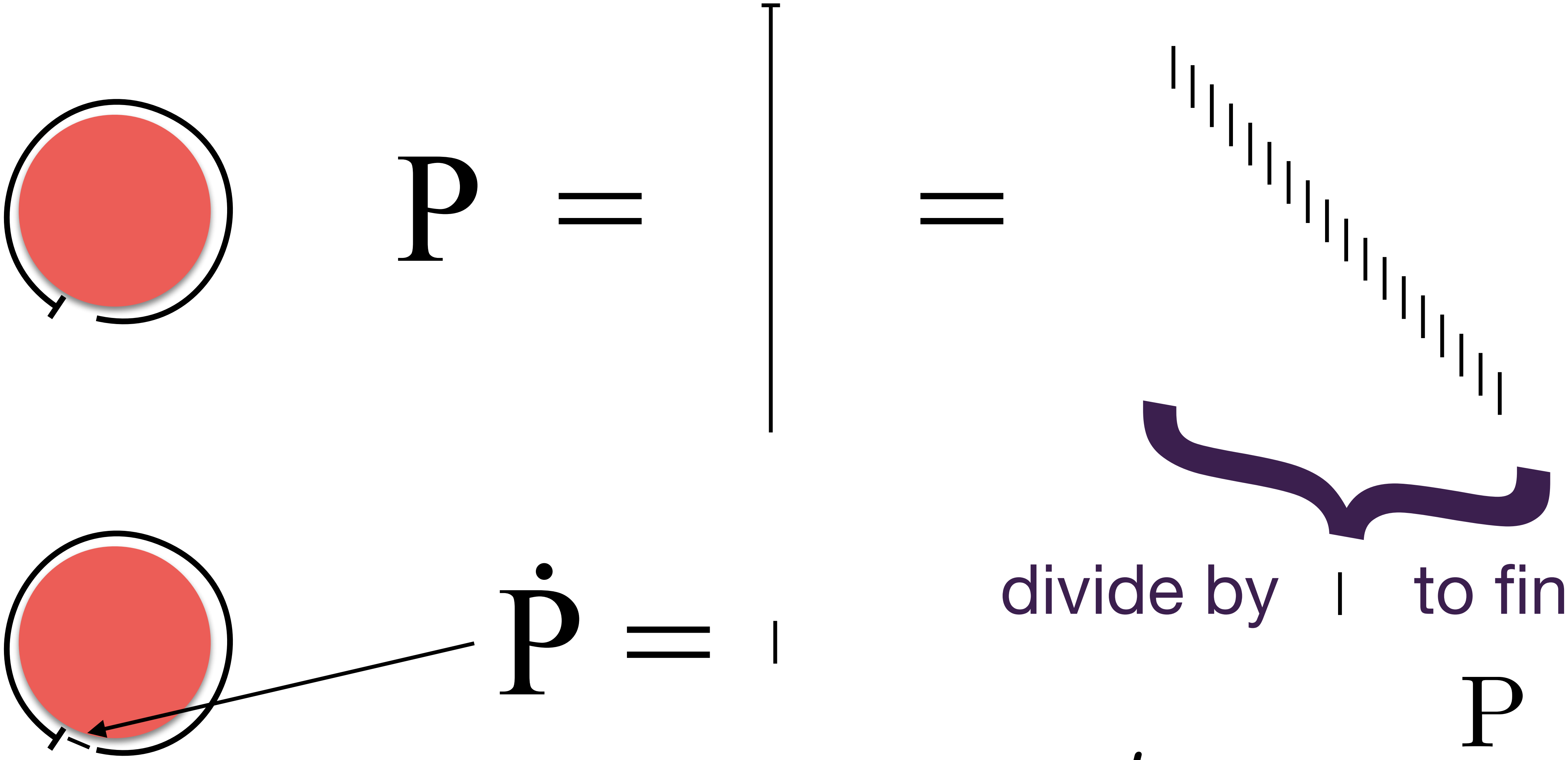
$$P =$$



$$\dot{P} =$$

Pulsars

Estimate pulsar age measuring pulse period (P)
and slowdown per pulse (Ṗ)



divide by | to find age

$$t_{NS} = \frac{\mathrm{P}}{2\dot{\mathrm{P}}}$$