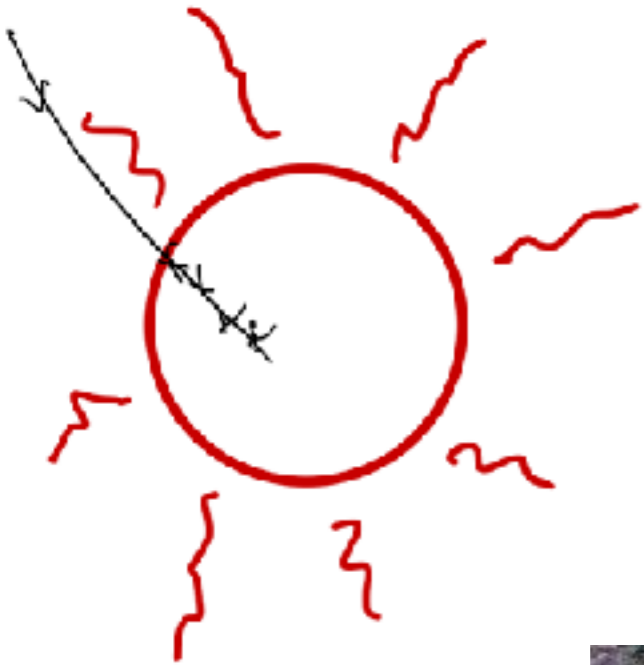


Dark Matter Heating Nearby Neutron Stars to BBQ Temperatures

GGI Collider Physics and the Cosmos 2017

Joseph Bramante

Queen's University
and CPARC and Perimeter



Masha
Baryakhtar



Nirmal
Raj



Shirley
Weishi Li



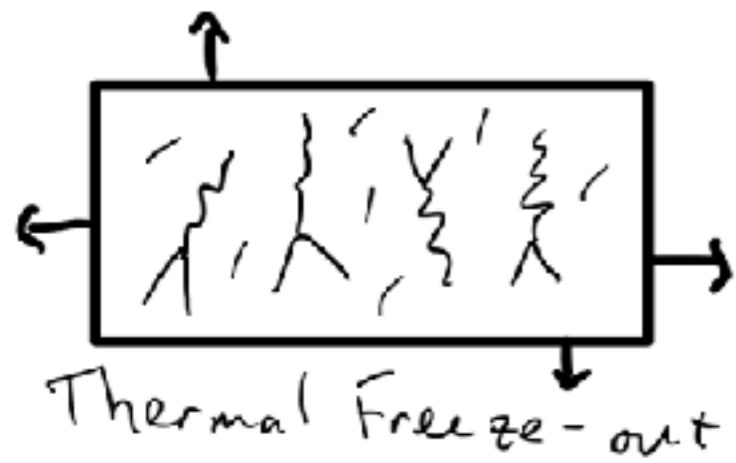
Tim
Linden

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

JB, Fox, Kribs, Martin 2016

JB, Delgado, Martin 2017

The WIMP Miracle



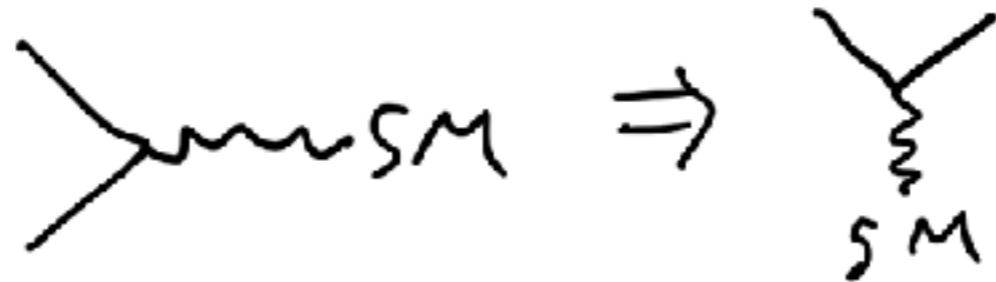
- As universe cools, DM falls out of thermal equilibrium, annihilates to SM particles

Final Abundance

$$\Omega_{DM} h^2 \propto \frac{X_{FO}}{\sigma_a} \quad \left| \quad X_{FO} [\ln(m_X)] \sim 10 \right.$$

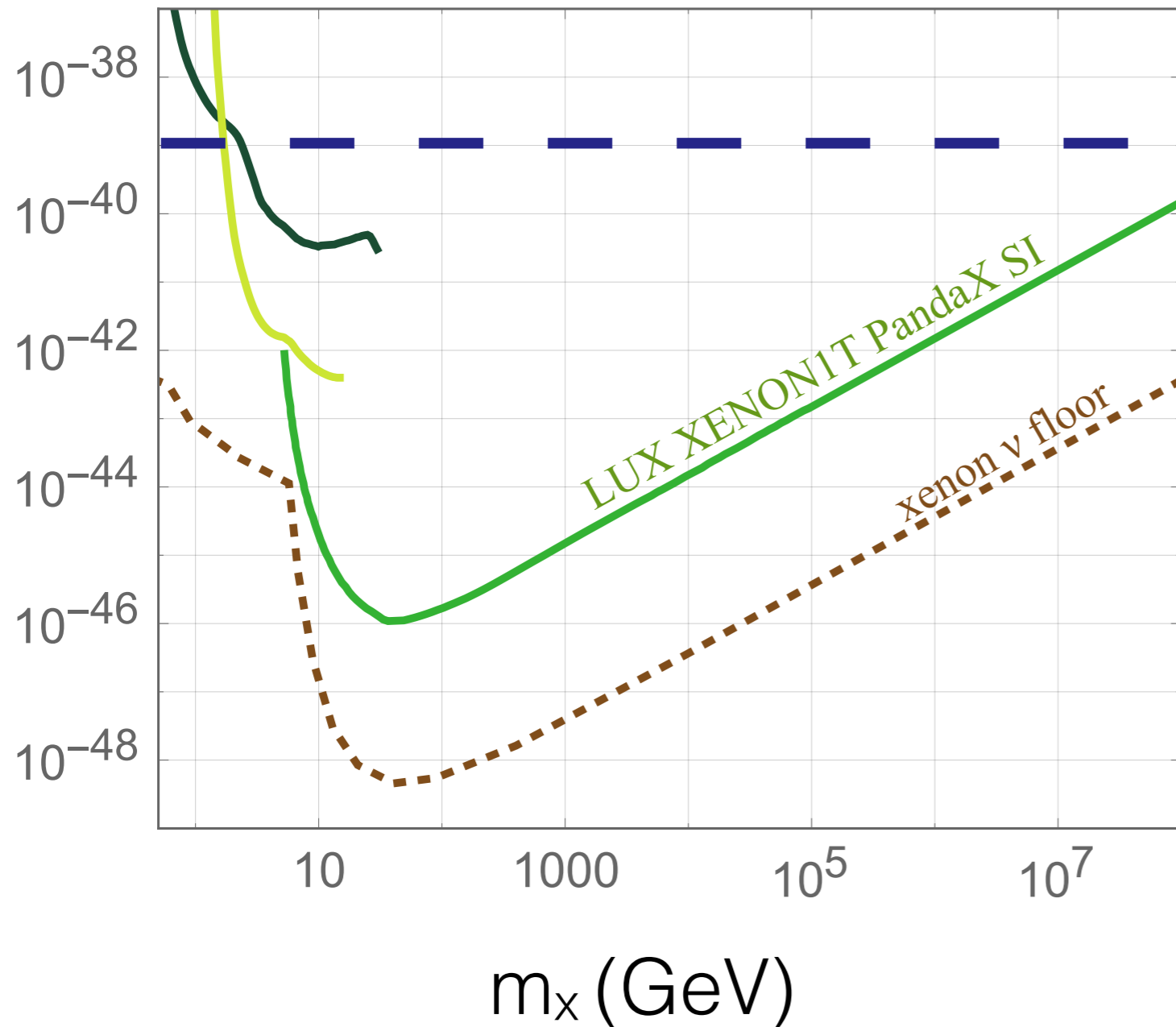
$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_\nu}{100 \text{ GeV}} \right)^2 \left(\frac{0.03}{\alpha_w} \right)^2$

This implies weak mass scale coupling to SM



So where is the WIMP dark matter?

σ_n (cm²)



Freeze-out WIMP

$$\sigma_n = \frac{\pi d^2 M_{Xn}^2}{m_Z^4} \sim 10^{-39} \text{ cm}^2$$

- Just hiding - 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

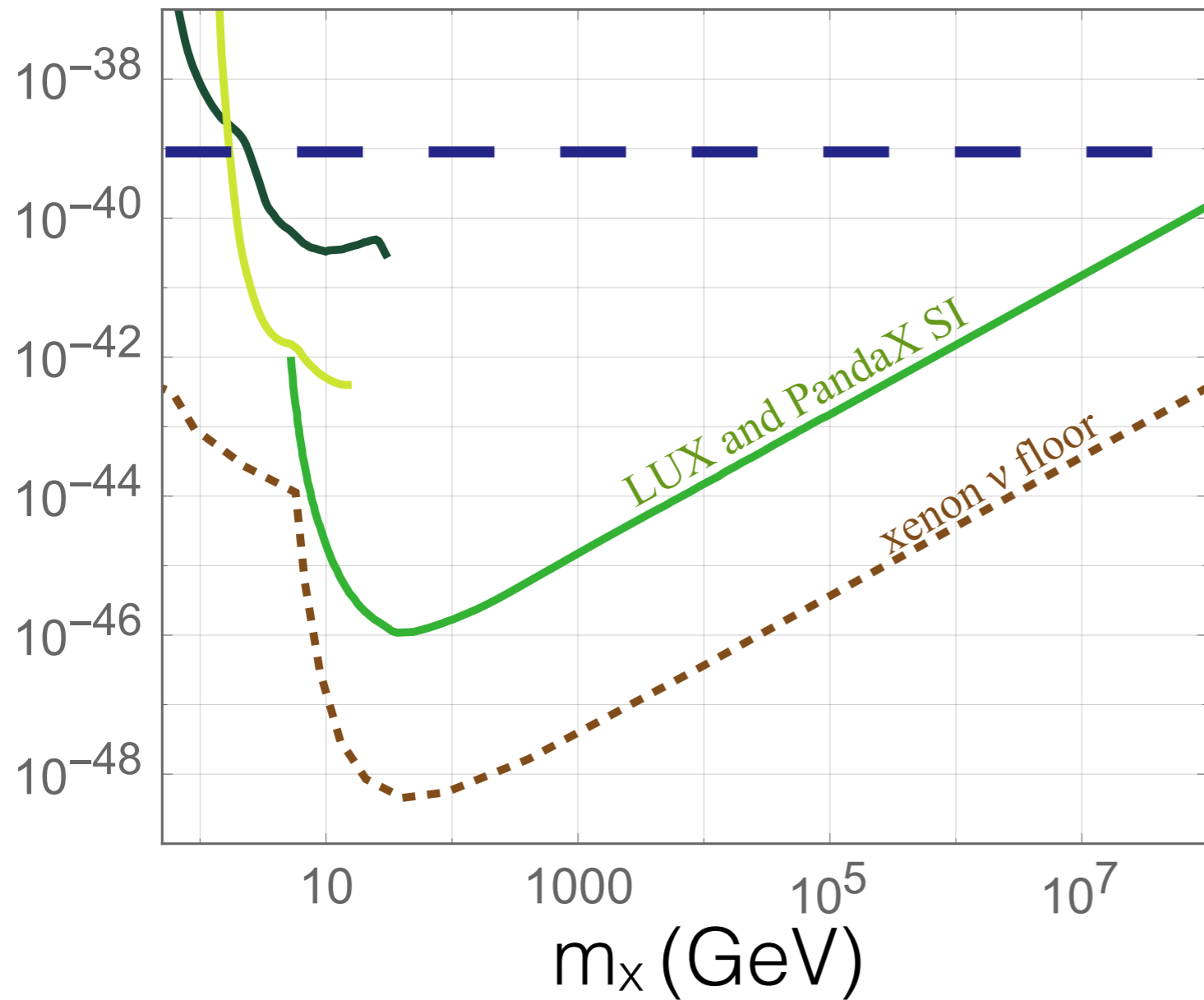
→ Probes Inelastic, SD

→ Direct detection complements dark kinetic heating

3. Bringing our astro friends to
the backyard DM BBQ

Spin-Independent WIMPs
 → Endangered Species

σ_n (cm²)



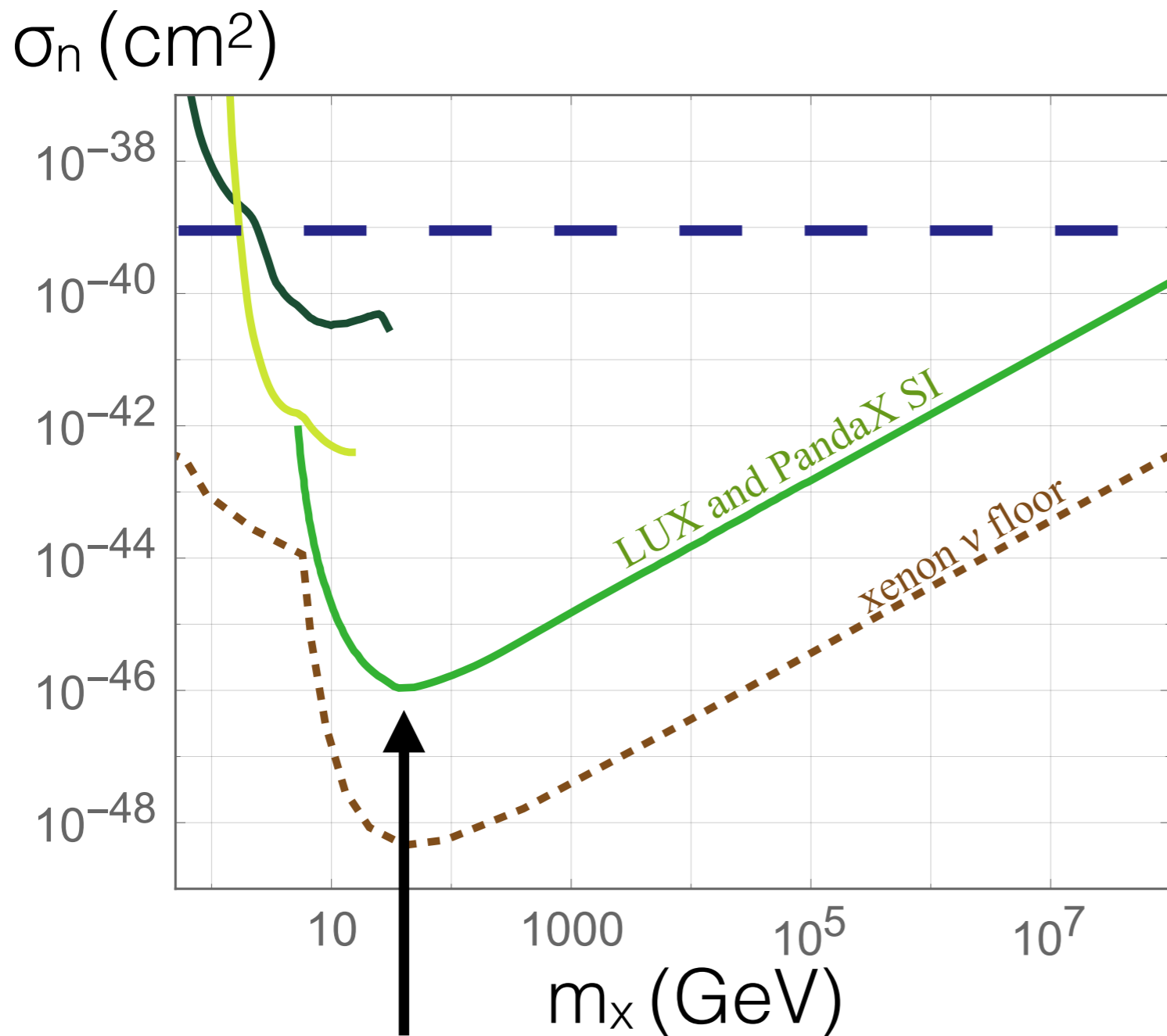
$$\sigma_z \sim \frac{M_{N\chi}^2 \alpha_w^2}{M_Z^4}$$

$$\sigma_n = \left(\frac{1}{A^2} \right) \frac{M_{N\chi}^2}{M_{HX}^2} \sigma_N$$

SI

smart scientists
 use heavy nuclei

Spin-Independent WIMPs
 → Endangered Species



accidentally weak-centric



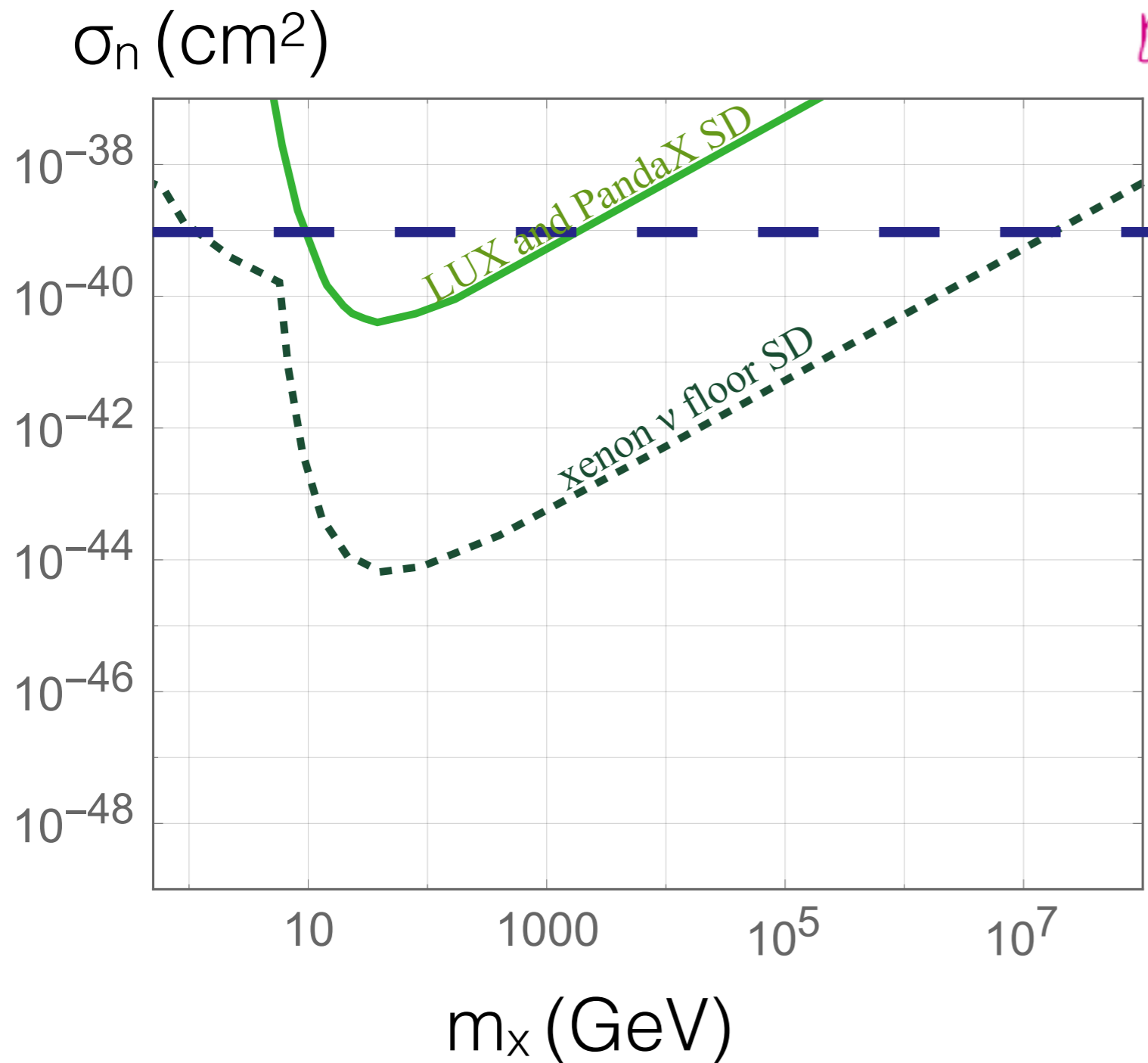
$$g_z \sim \frac{M_{N\chi}^2 \alpha_w^2}{M_Z^4}$$

$$\sigma_n = \underbrace{\left(\frac{1}{A^2}\right)}_{\text{SI}} \frac{M_{N\chi}^2}{M_{H\chi}^2} \sigma_N$$

smart scientists
 use heavy nuclei

Spin-Dependent WIMPs

→ Cleverly Incoherent



Ex: Majorana Fermion χ
Coupled through Z'

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

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

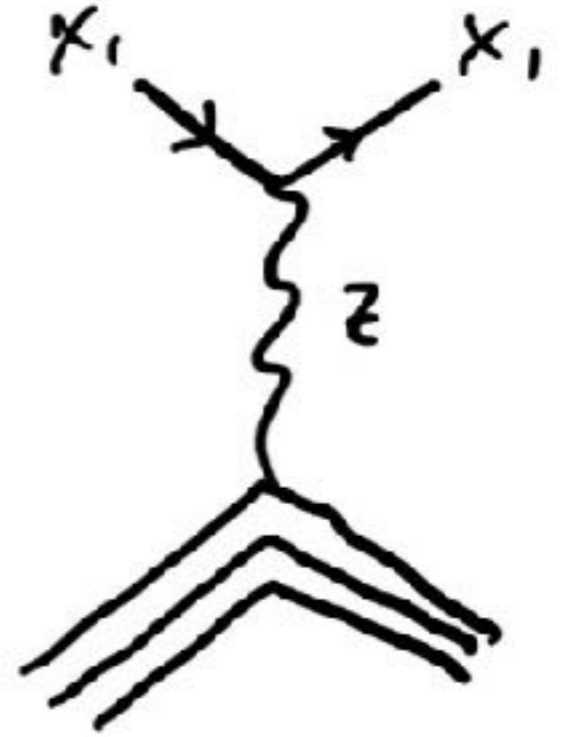
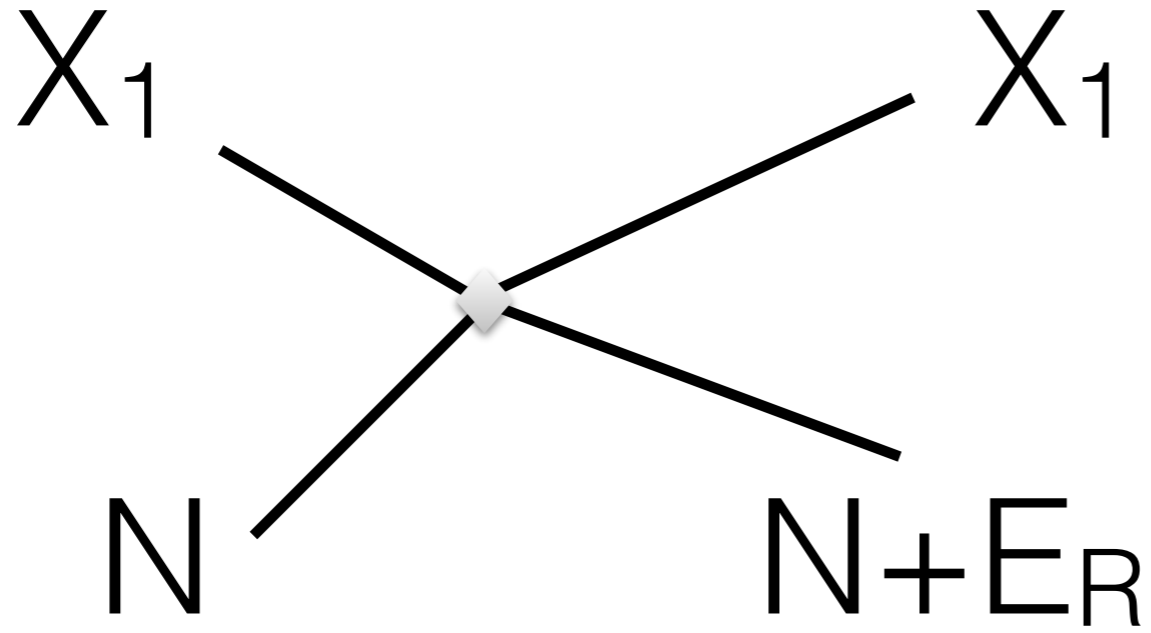


$$\sigma_n = \left(\frac{1}{A^2} \right) \frac{\mu_{n\chi}^2}{\mu_{H\chi}^2} \sigma_N$$

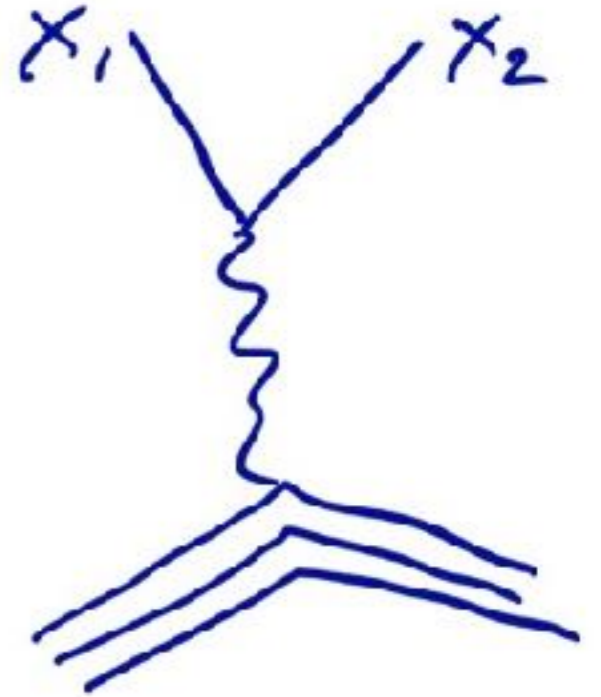
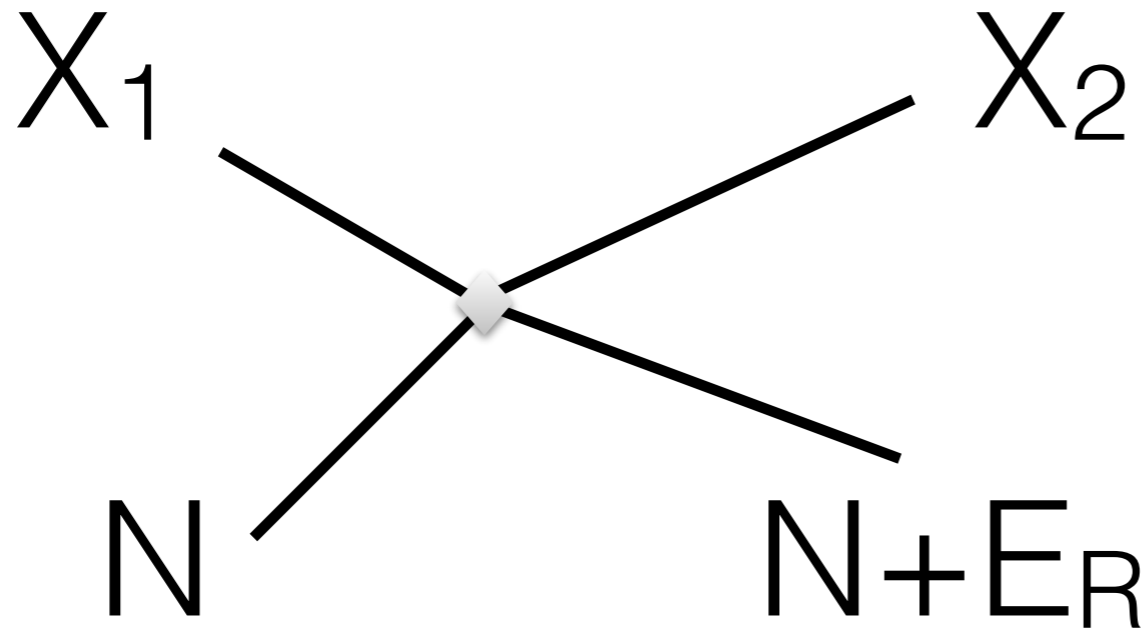
SD

(heavy nuclei don't work as well)

Elastic Dark Matter



Inelastic Dark Matter

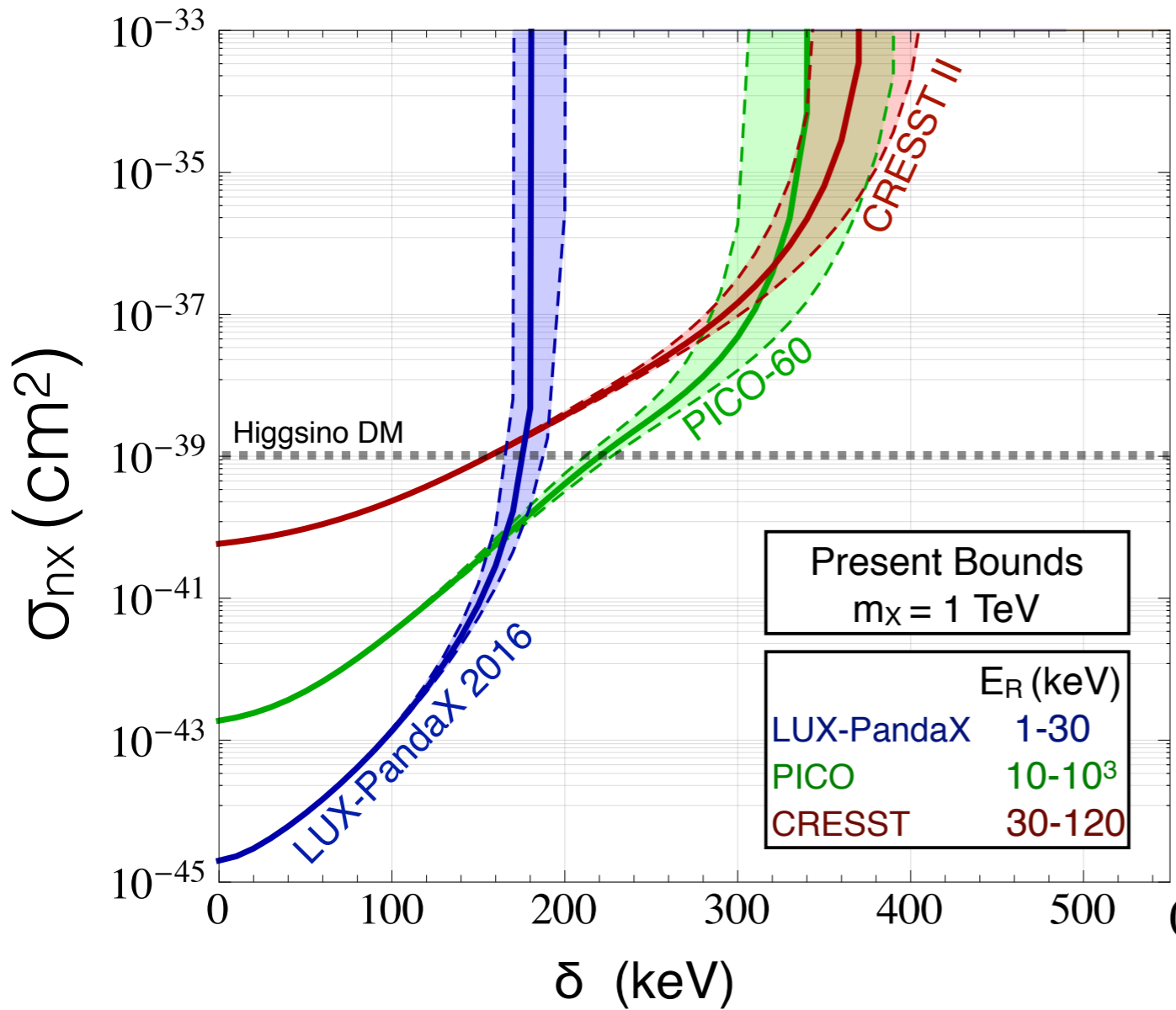


$$\begin{array}{c} X_2 \\ \text{---} \\ X_1 \end{array} \quad \delta \equiv m_{X_2} - m_{X_1}$$

Dark matter scattering forbidden (by broken symmetry) unless

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

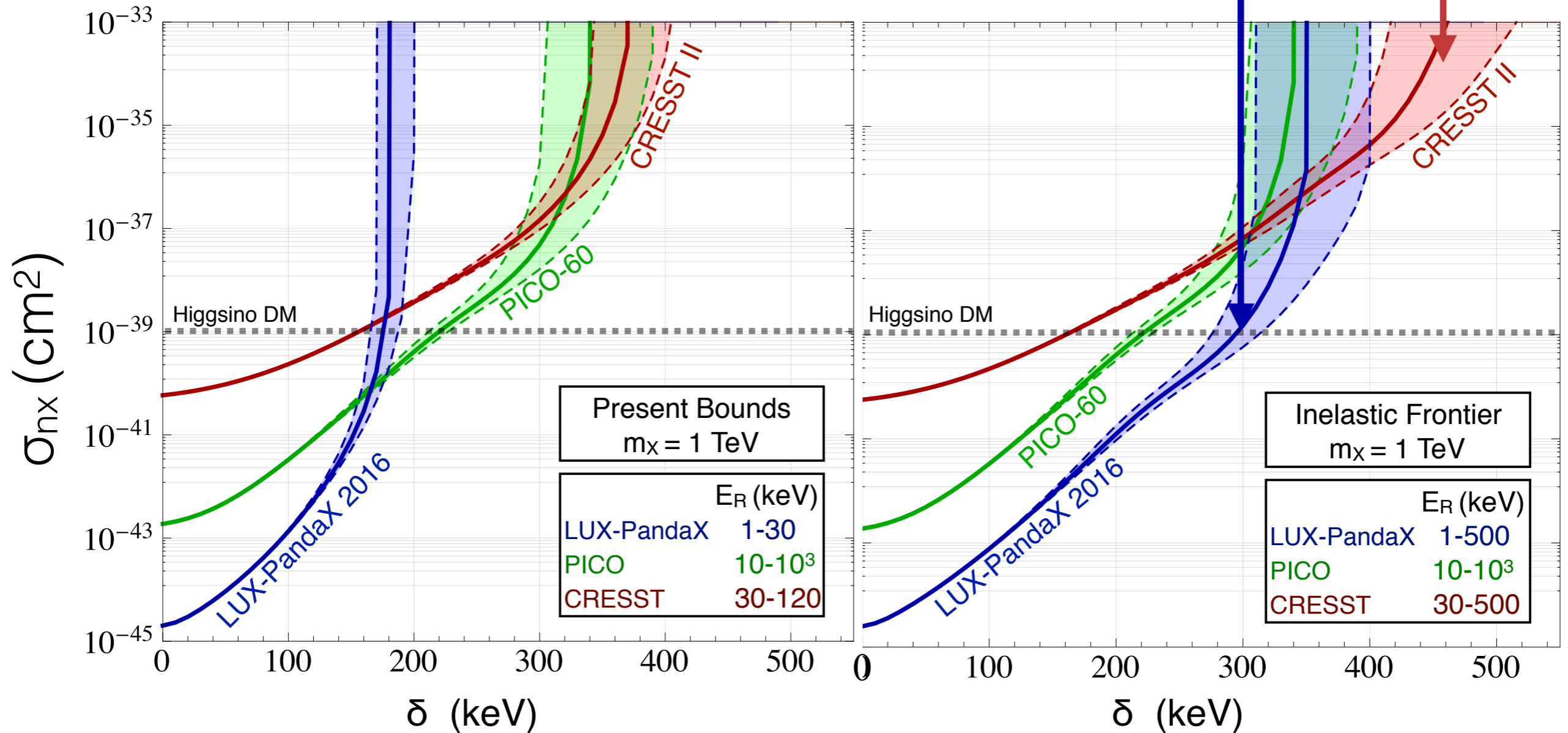
(energy exchange required to make X_2 from X_1)



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

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

Higher Recoil Searches



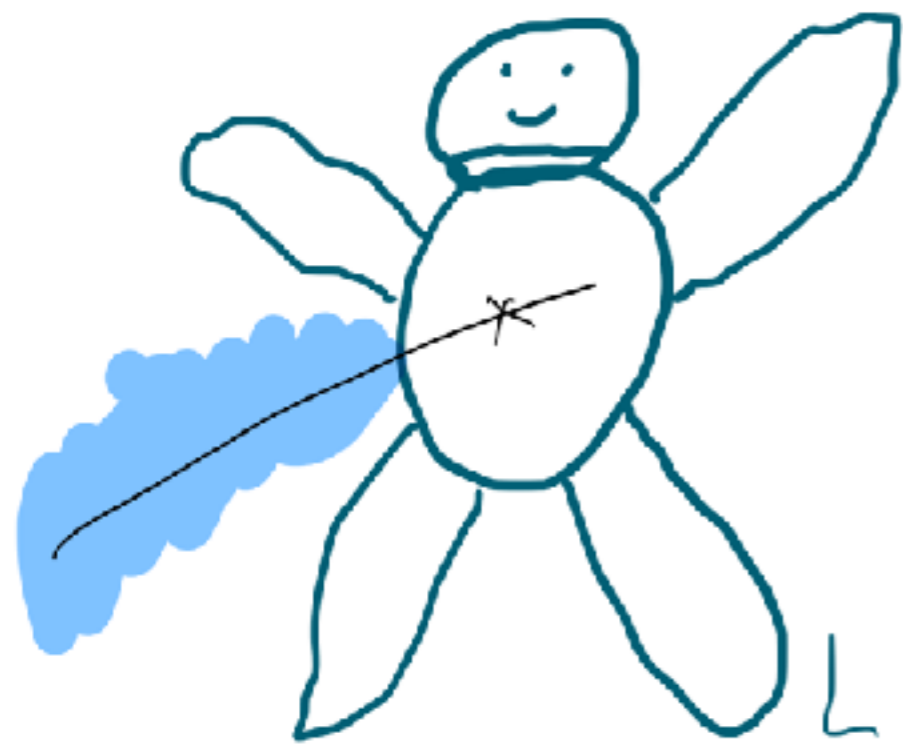
$\delta = 500 \text{ keV}$ is a much better sensitivity,
but for Higgsinos really want δ up to GeV...

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



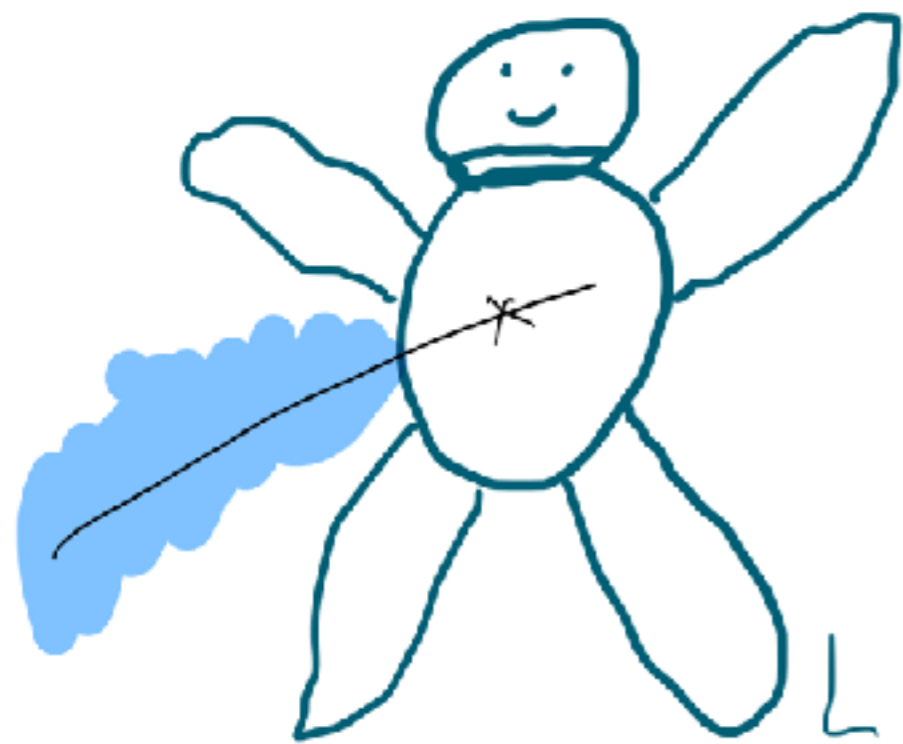
1 hit / yr - DD limit

Dark kinetic heating

$$L \sim \left(\frac{\text{event}}{\text{yr}} \right) \underbrace{m_{\text{carbon}} v_x^2}_{\text{energy}} = 4\pi R_{\text{ast}}^2 \sigma_3 T_{\text{ast}}^4$$

$$T_{\text{ast}} \sim 75 \mu\text{Kelvin}$$

DM heated astronaut



1 hit/yr - DD limit

Dark kinetic heating

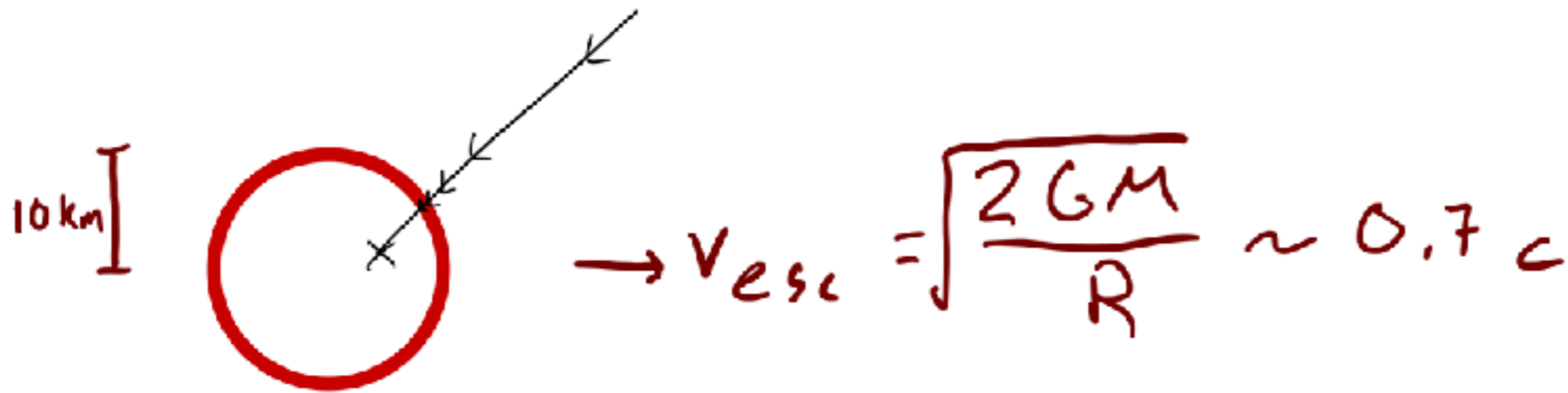
$$L \sim \left(\frac{\text{event}}{\text{yr}} \right) \underbrace{m_{\text{carbon}} v_x^2}_{T_{\text{ast}} \sim 75 \mu\text{Kelvin}} = 4\pi R_{\text{ast}}^2 \sigma_B T_{\text{ast}}^4$$


$T_{\text{ast}} \sim 75 \mu\text{Kelvin}$

$$\overline{v_x^2} \rightarrow v_x^2 + \frac{2GM_{\text{ast}}}{R_{\text{ast}}} \quad \left| \begin{array}{l} \text{Grav} \\ \text{Accelerated} \end{array} \right.$$

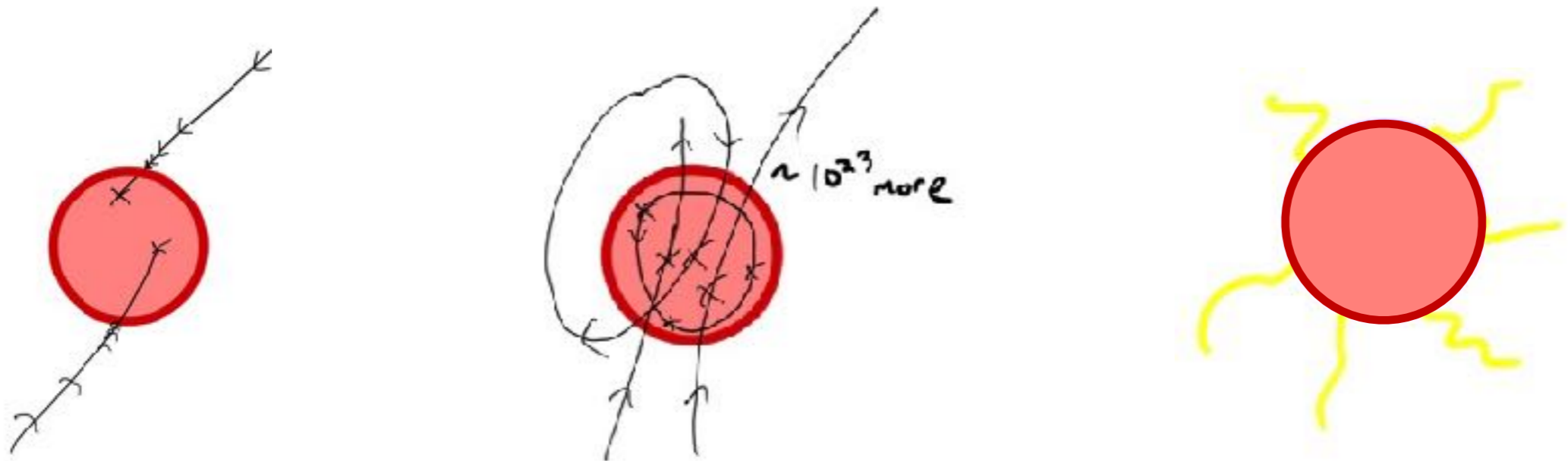
($v_g \sim 81 \mu\text{m/s}$)

Neutron Stars: Nature's Dark Matter Accelerators



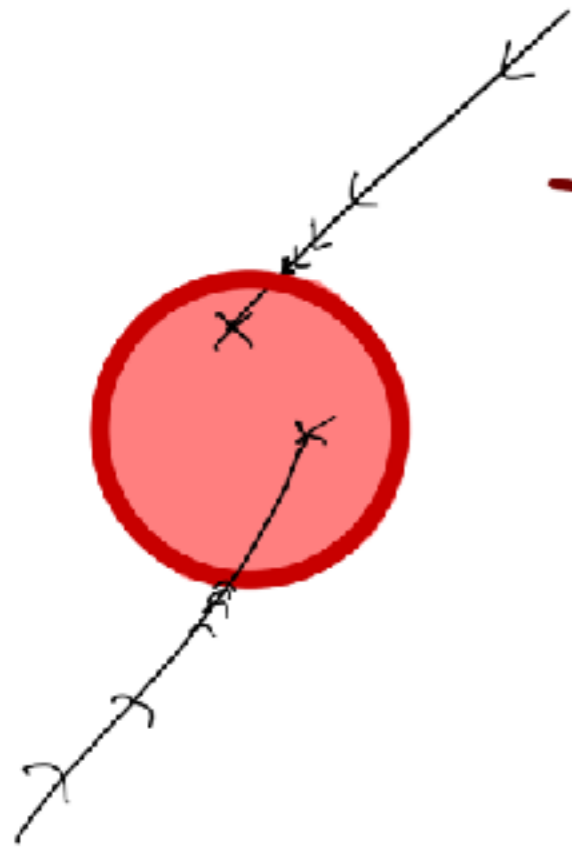
 { Interior \rightarrow fiducial mass 10^{57} beV
Neutrons: protons: electrons
 $\sim 10:1:1$

Dark Kinetic Heating



1. Dark matter gravitationally accelerated to $\sim 0.7 c$ 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

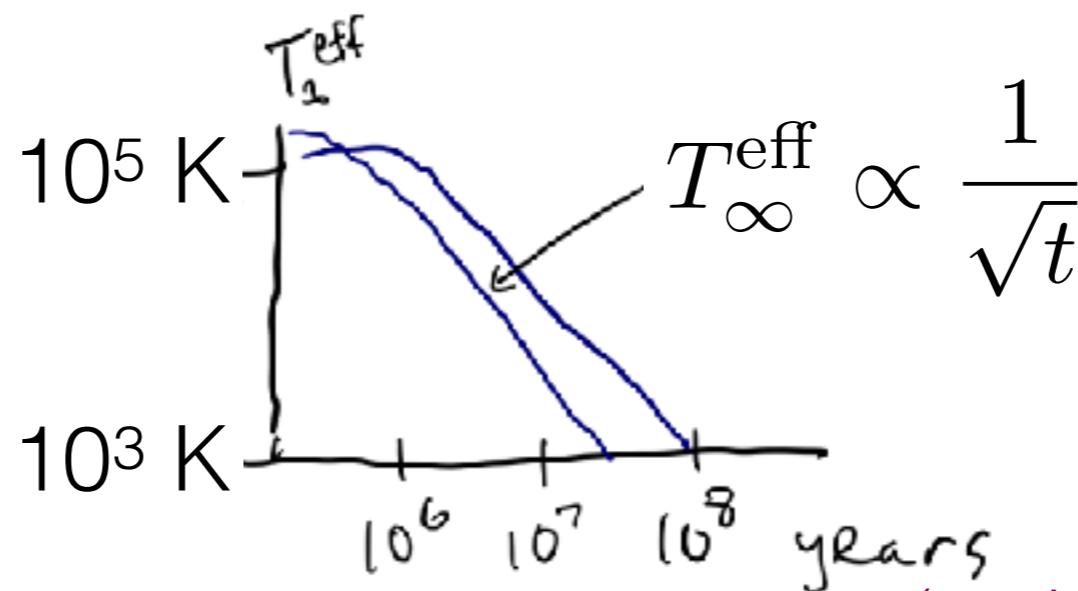
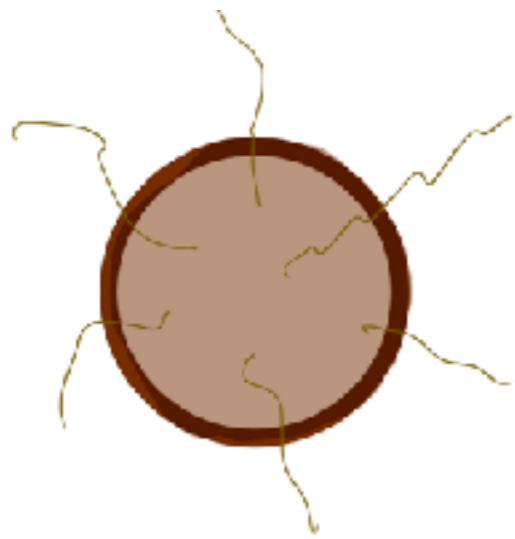
matter by earth ($0.4 \frac{\text{GeV}}{\text{cm}^3}$)



- Only requirement is scattering
with neutrons, protons, electrons

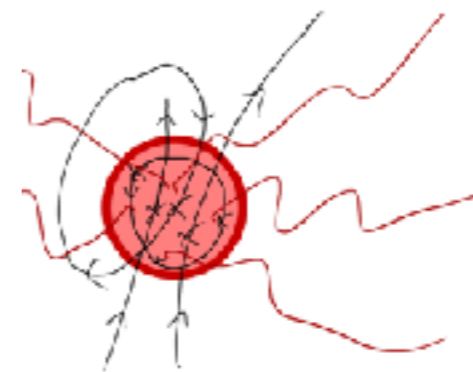
Dark Kinetic Heating

- After 10^8 years, neutron stars should emit as black bodies with $T^{\text{eff}} \ll 10000$ K.



(e.g. Yakovlev and Pethick 2004)

- Most neutron stars (all stars) are older than a billion years, by which time $T^{\text{eff}} \ll 10000$ K).
- Maximum dark kinetic heating results in $T^{\text{eff}} \sim \underline{\underline{17500}} \text{ K}$.

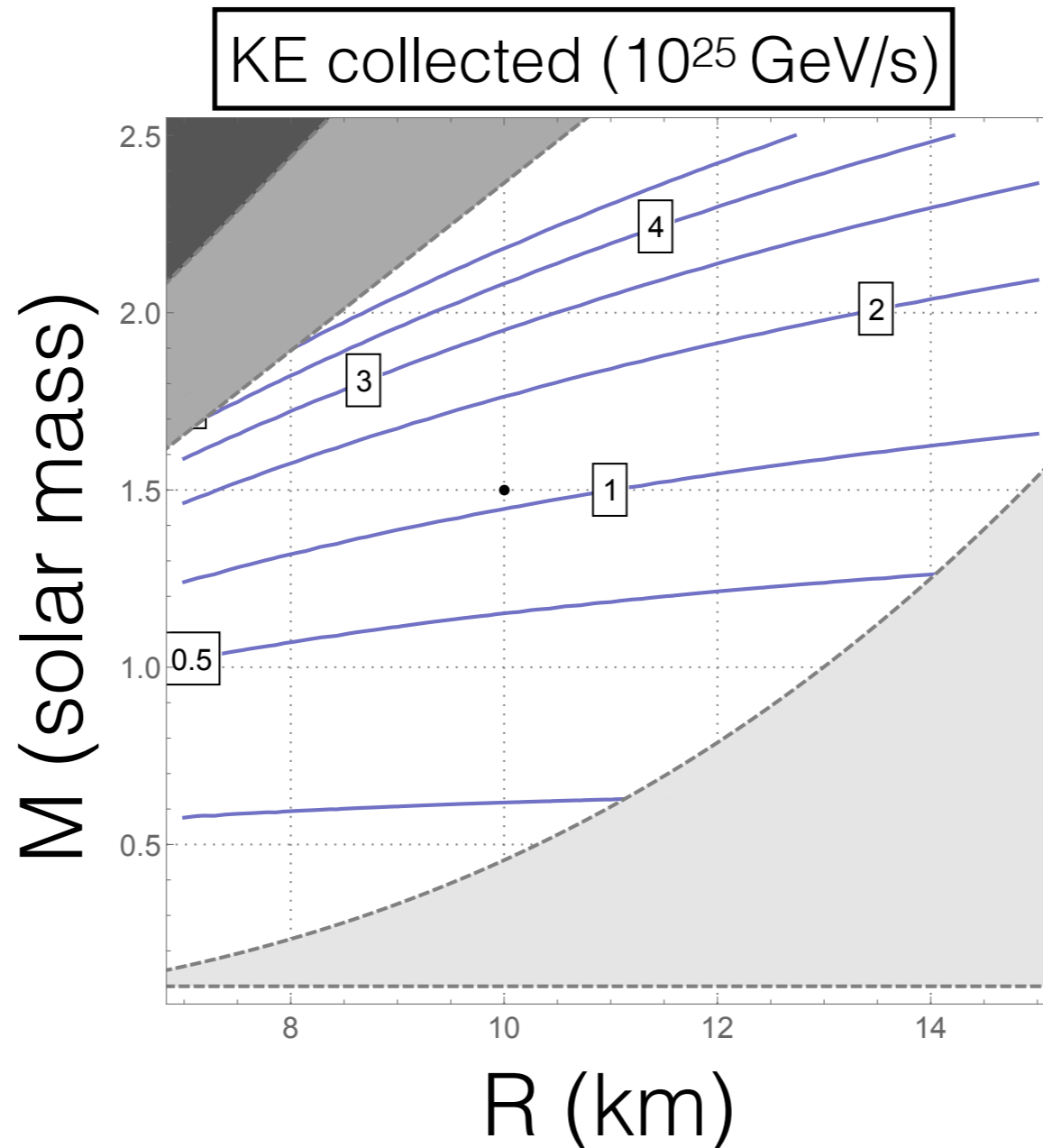


DM Flux Through the Neutron Star

$$\dot{m}_x = \pi \frac{2GM R}{v_x} \rho_x r^2$$



↳ Independent of DM Mass

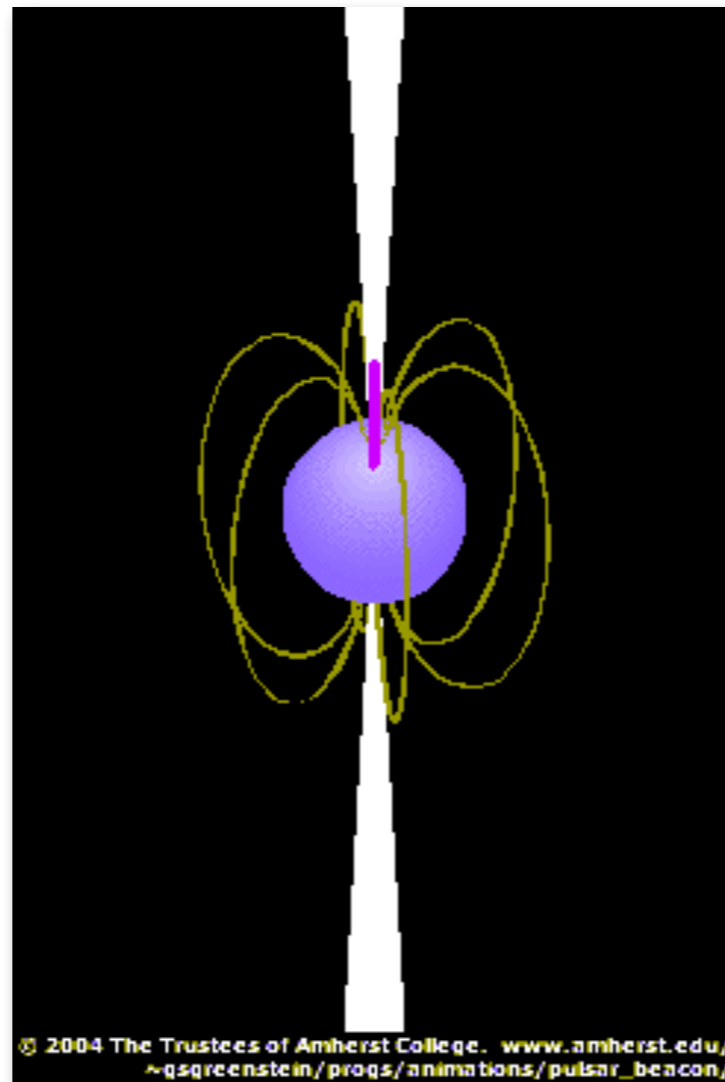


Pulsars

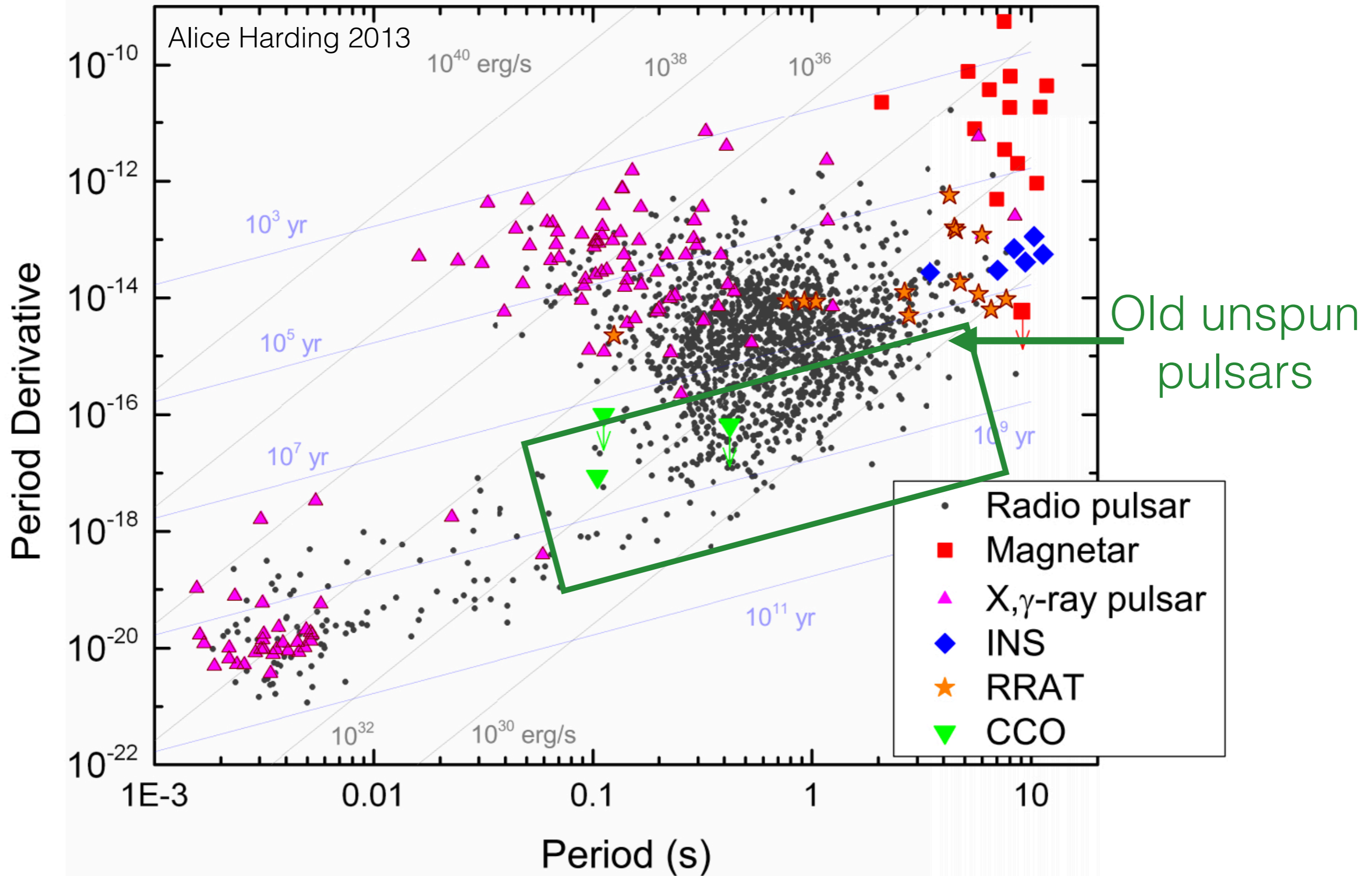
-Rotating, neutron stars with magnetic dipole

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

-Pulsed radio emission along the magnetic dipole axis

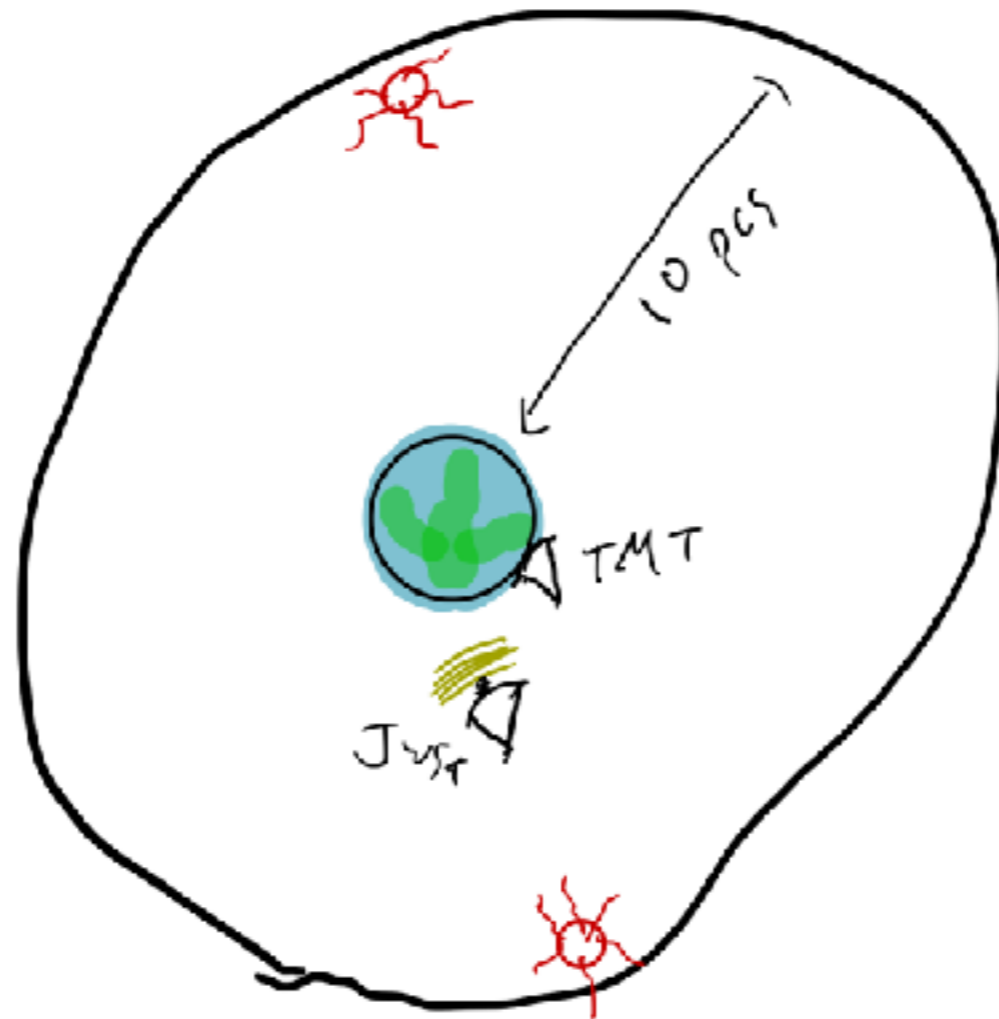


Known Pulsars



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.)

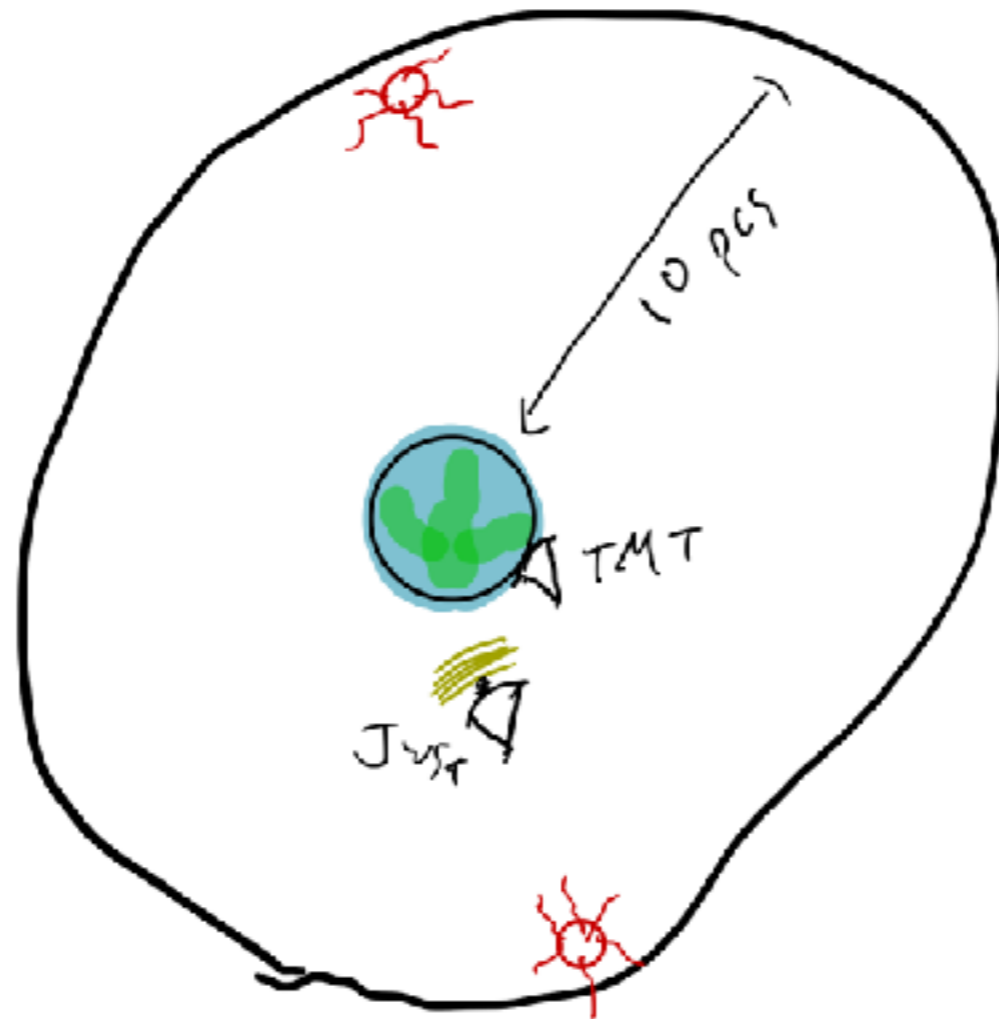
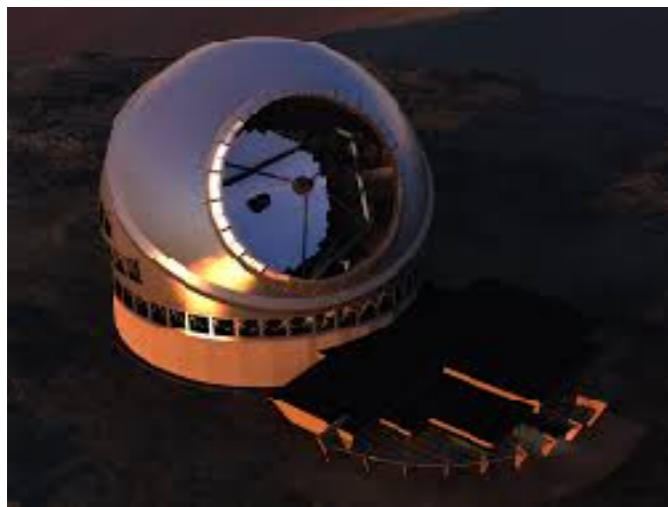


$\sim 1-3$ neutron stars
10 parsecs
from Earth

(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.)



$\sim 1-3$ 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)

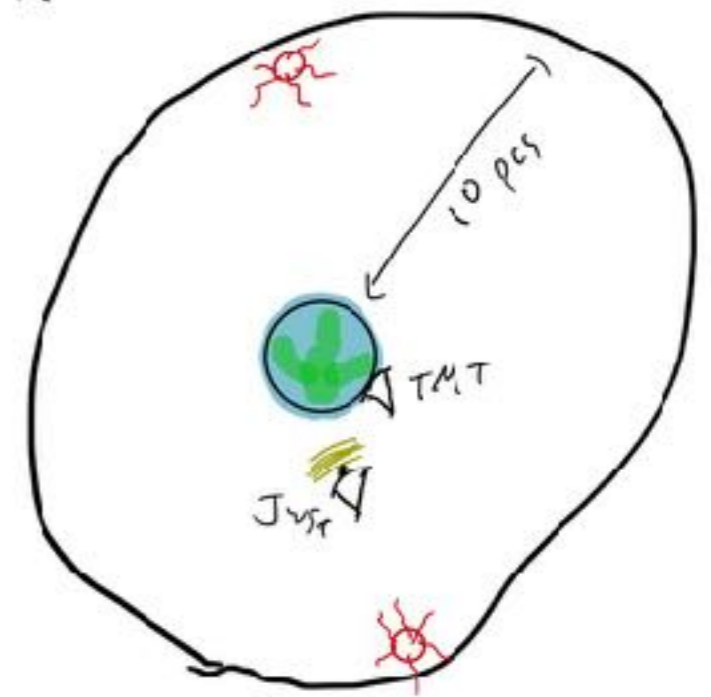
kinetic only 10^5 seconds $\left(\frac{d}{10 \text{ parsecs}}\right)^4$

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

Thirty Meter Telescope

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

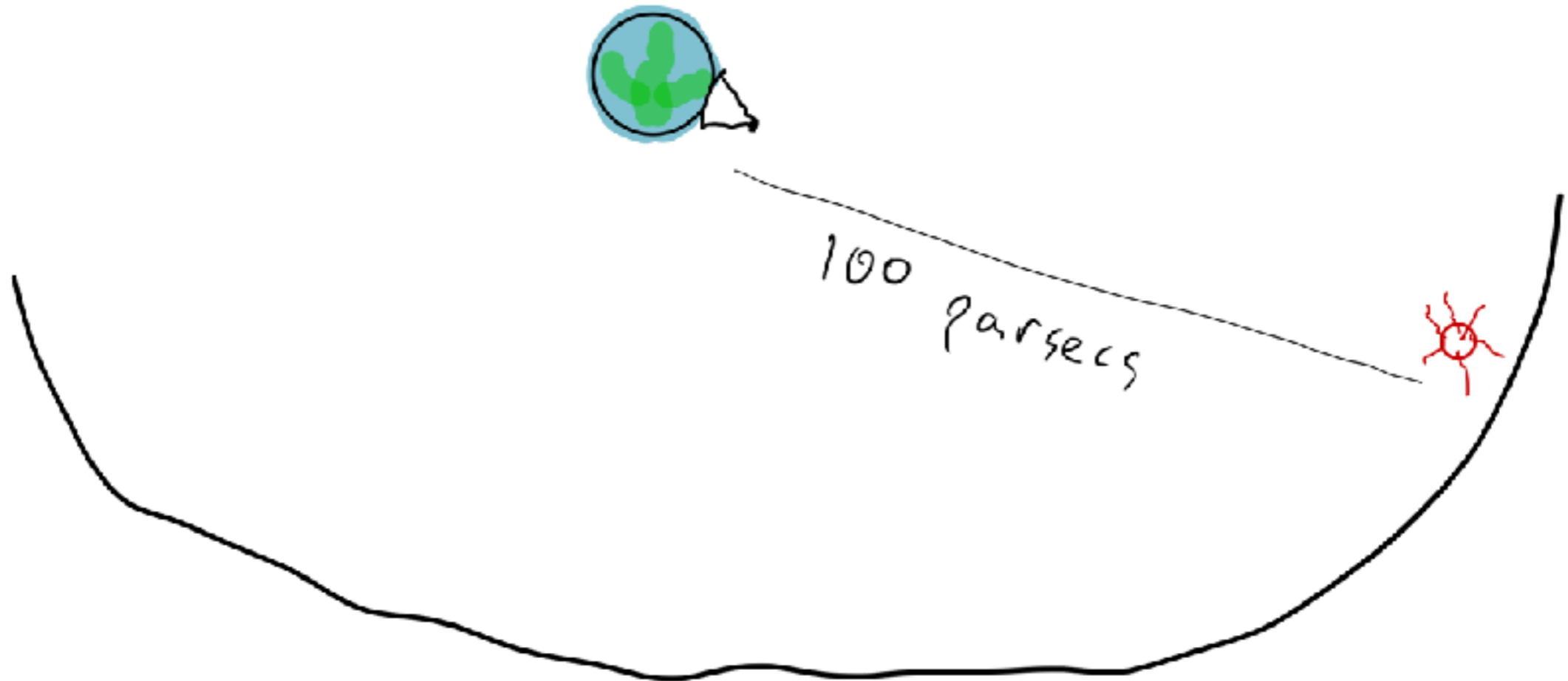
annihilation 2000 seconds $\left(\frac{d}{10 \text{ parsecs}}\right)^4$



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

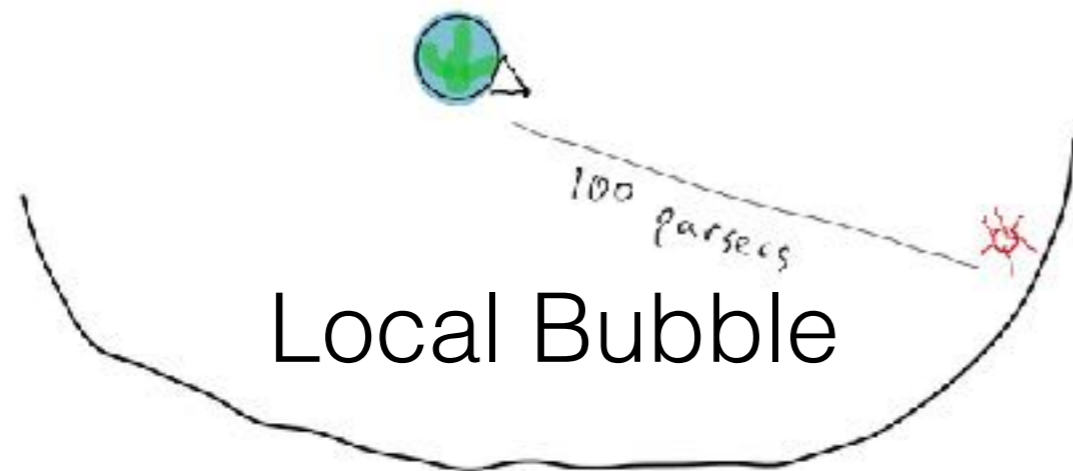
Long Term Braise

- 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 $<0.01 \text{ GeV/cm}^3$
- Portion of ISM deflected by NS magnetic field

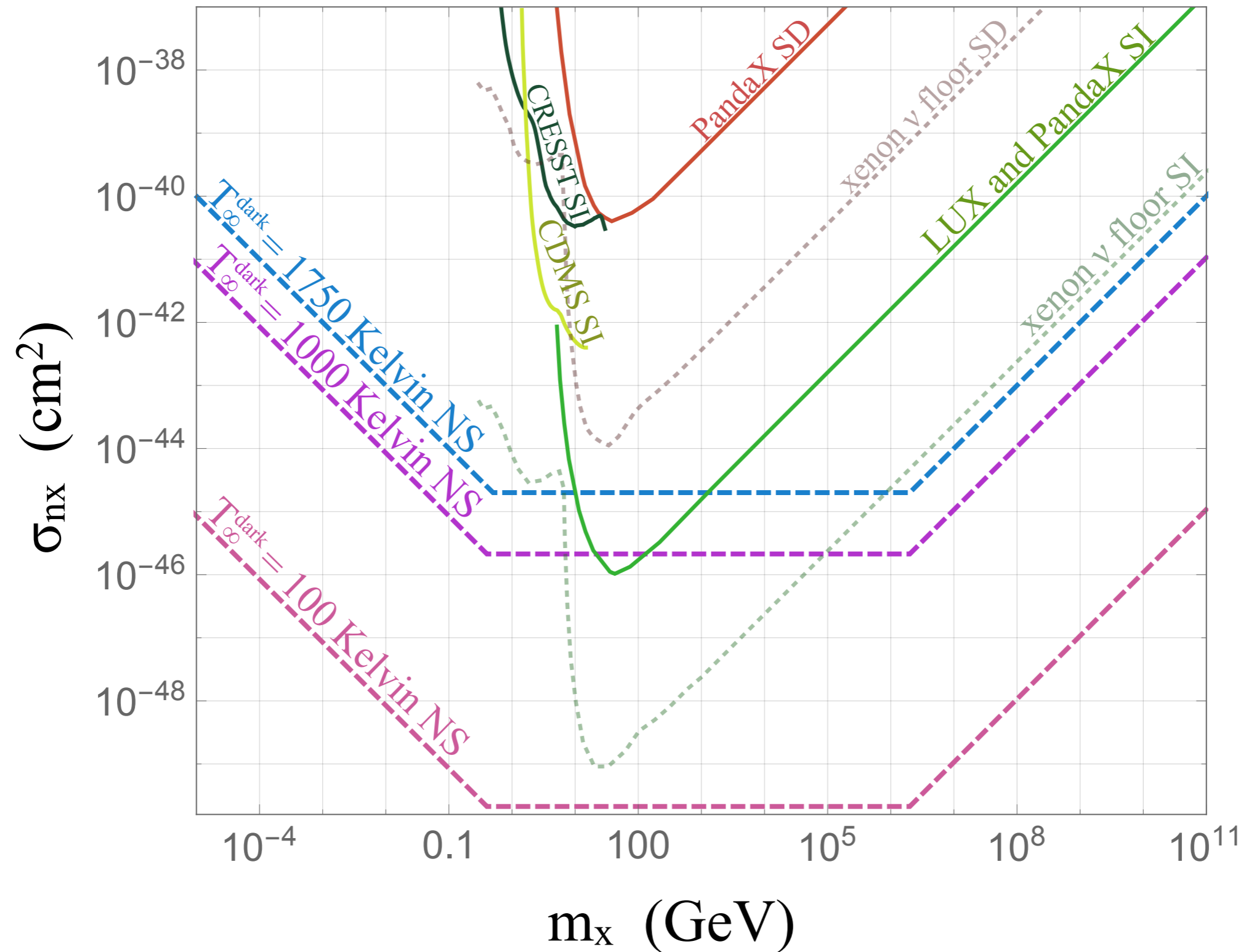
Magneto-Thermal Heating

- 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 \sim Gyr

Dark Kinetic Heating Sensitivity

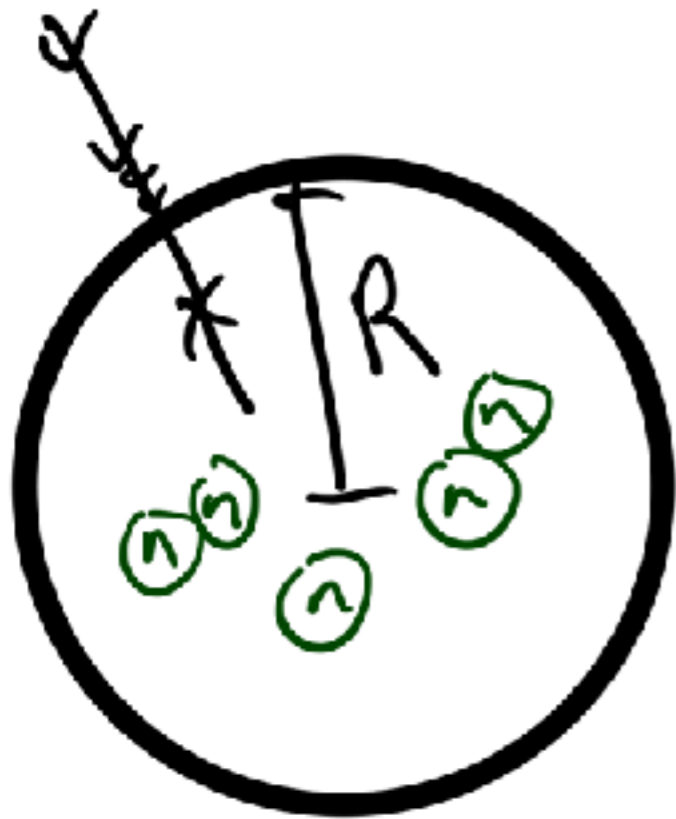


DM Capture

Fraction of DM captured:

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

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



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

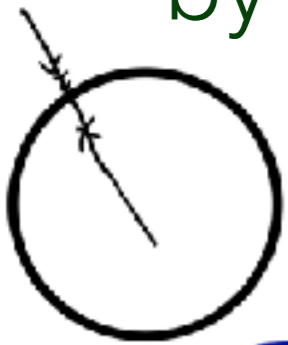
Star opaque to DM if

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

→ $2 \times 10^{-45} \text{ cm}^2$

DM Capture - By Mass

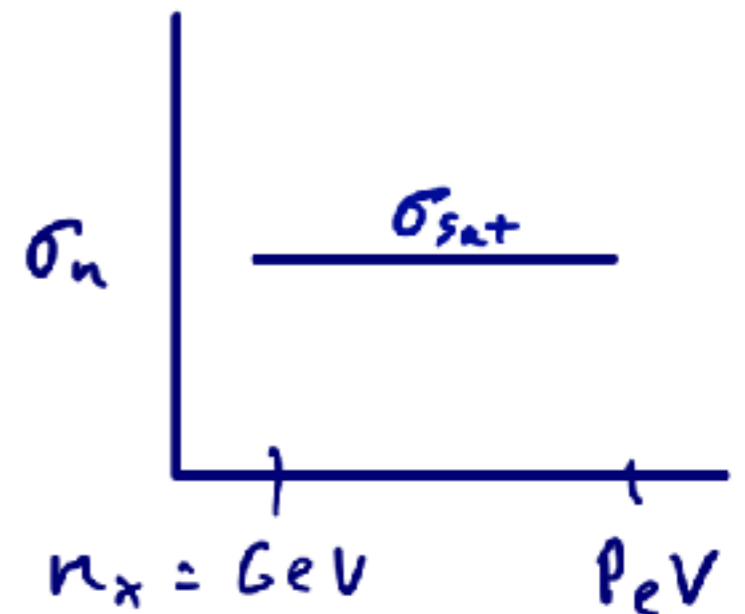
DM must lose its halo kinetic energy ($10^{-6} m_x$) by scattering with the neutron star to become captured.



$$m_x = \text{GeV} - \text{PeV}$$

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

$$E_R \sim \mu_{nx} v_s^2 \sim \text{GeV}$$



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

$M_x < \text{GeV}$ Pauli Blocking

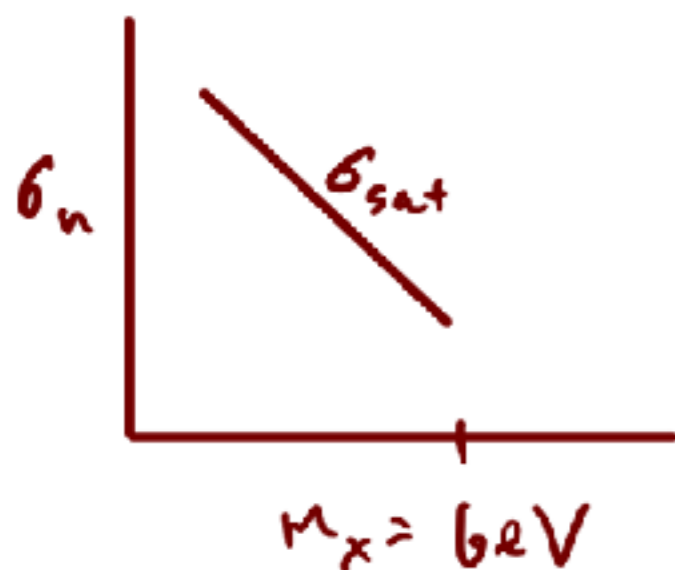


Only a fraction $\left(\frac{\Delta\rho}{\rho_F}\right)$ of neutrons can scatter above Fermi surface

$$\Delta\rho \sim \gamma m_x v_s \sim m_x$$

So scattering is suppressed

$$\text{by } \frac{m_x}{\rho_F}$$



$$\sigma_{sat} = \frac{\pi R^2 m_n}{M} \frac{\rho_F}{m_x} = 2 \cdot 10^{45} \text{ cm}^2 \left(\frac{\text{GeV}}{m_x}\right)$$

$m_x > \text{PeV}$

Multi-Scatter

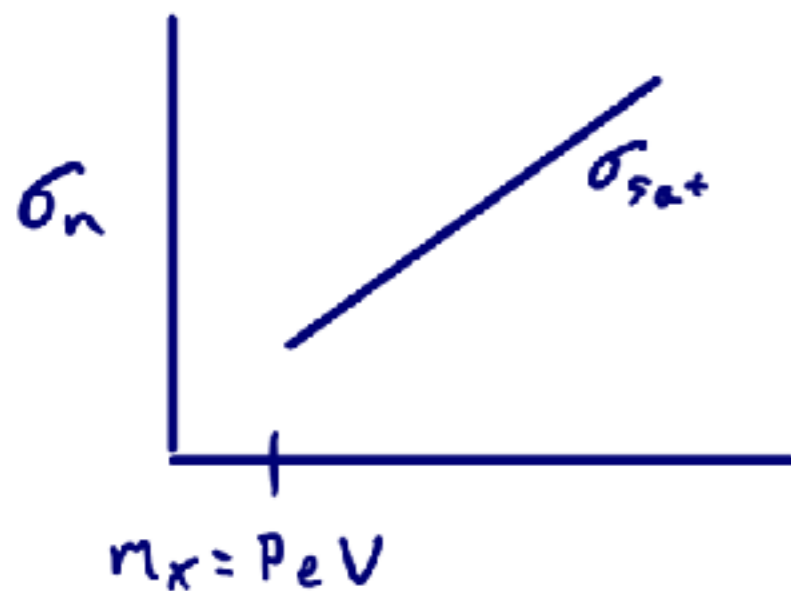
For dark matter masses $> \text{PeV}$, need to scatter multiple times (N) while crossing the star to capture



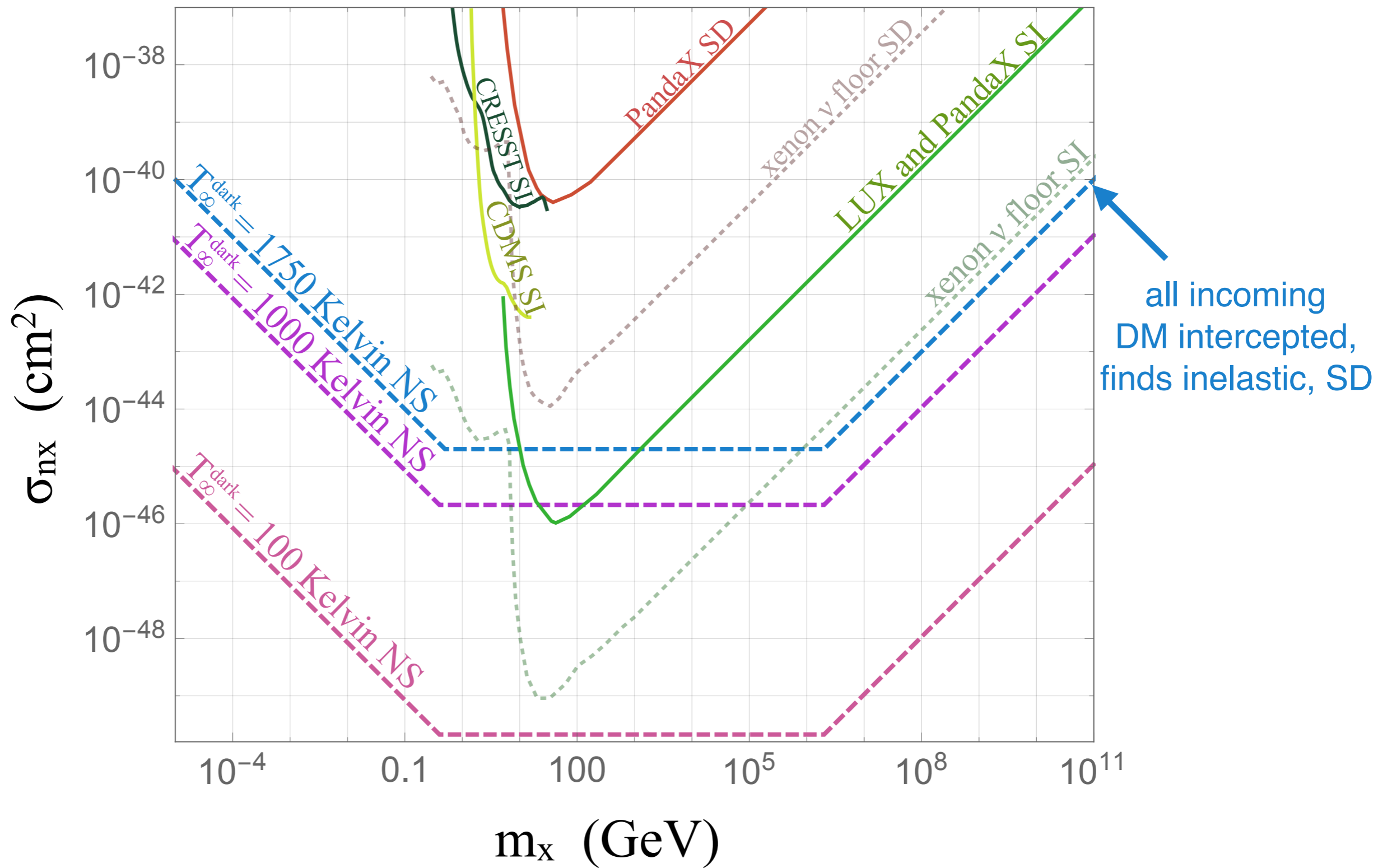
$$E_k = \frac{1}{2} m_x v_x^2 \lesssim (N) E_R$$

$$\frac{1}{2} m_x v_x^2 \sim N E_R \sim (n_n \sigma_n R) m_n$$

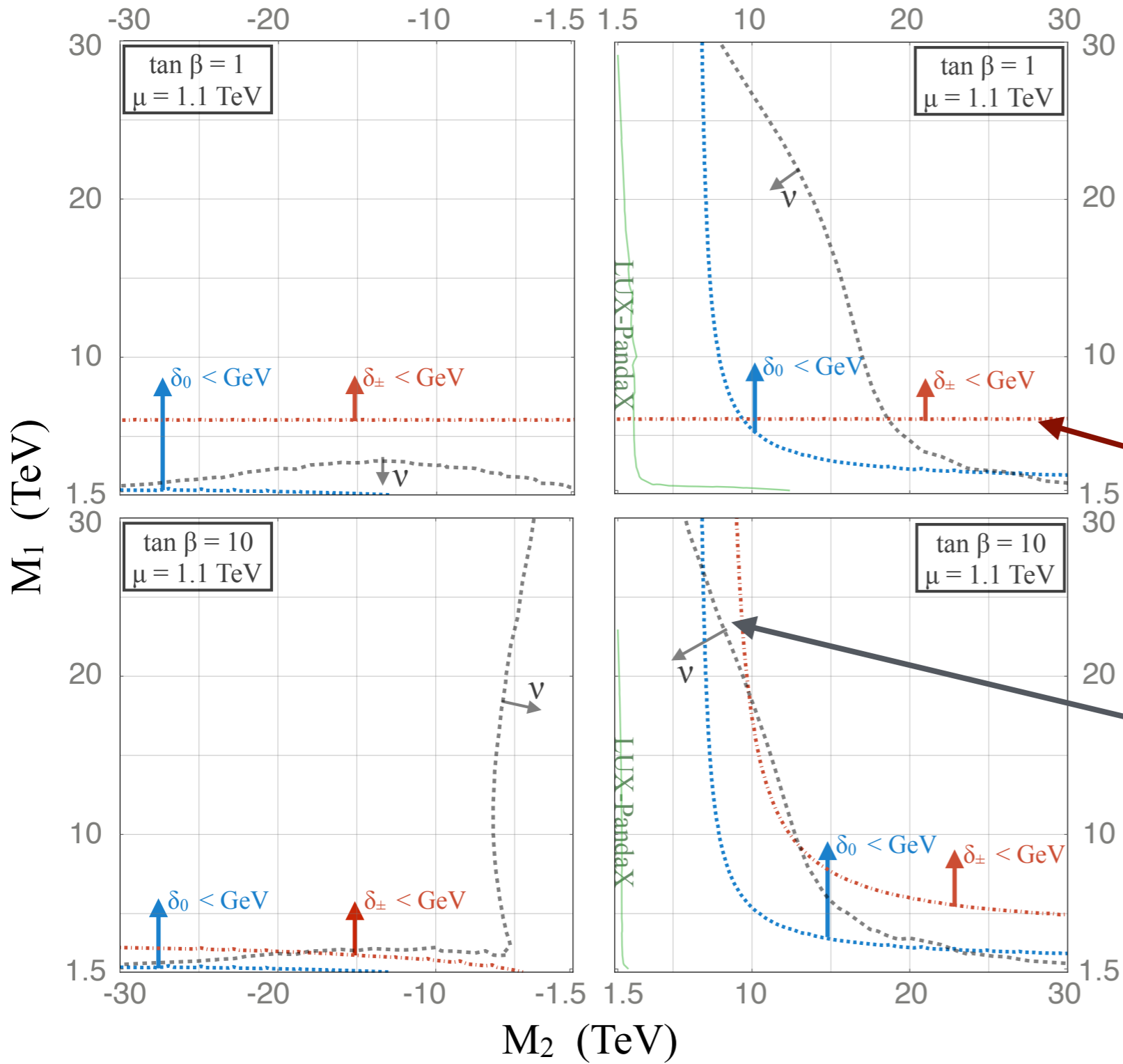
$$\rightarrow \boxed{\sigma_{\text{sat}} \propto m_x}$$



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



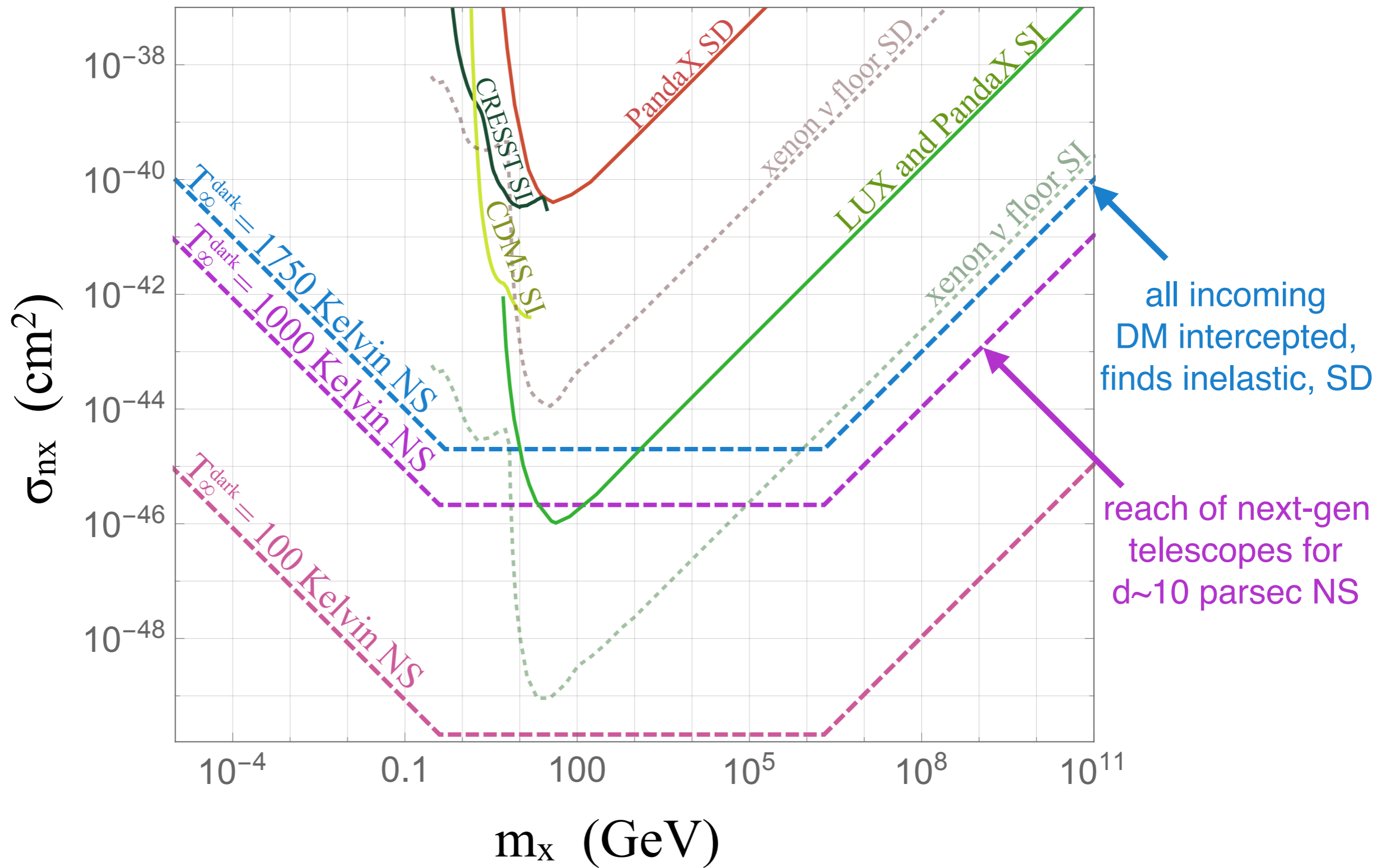
Higgsinos



Mass splittings include one loop EW corrections

Neutrino Floor (Future DD reach)

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



kinetic only

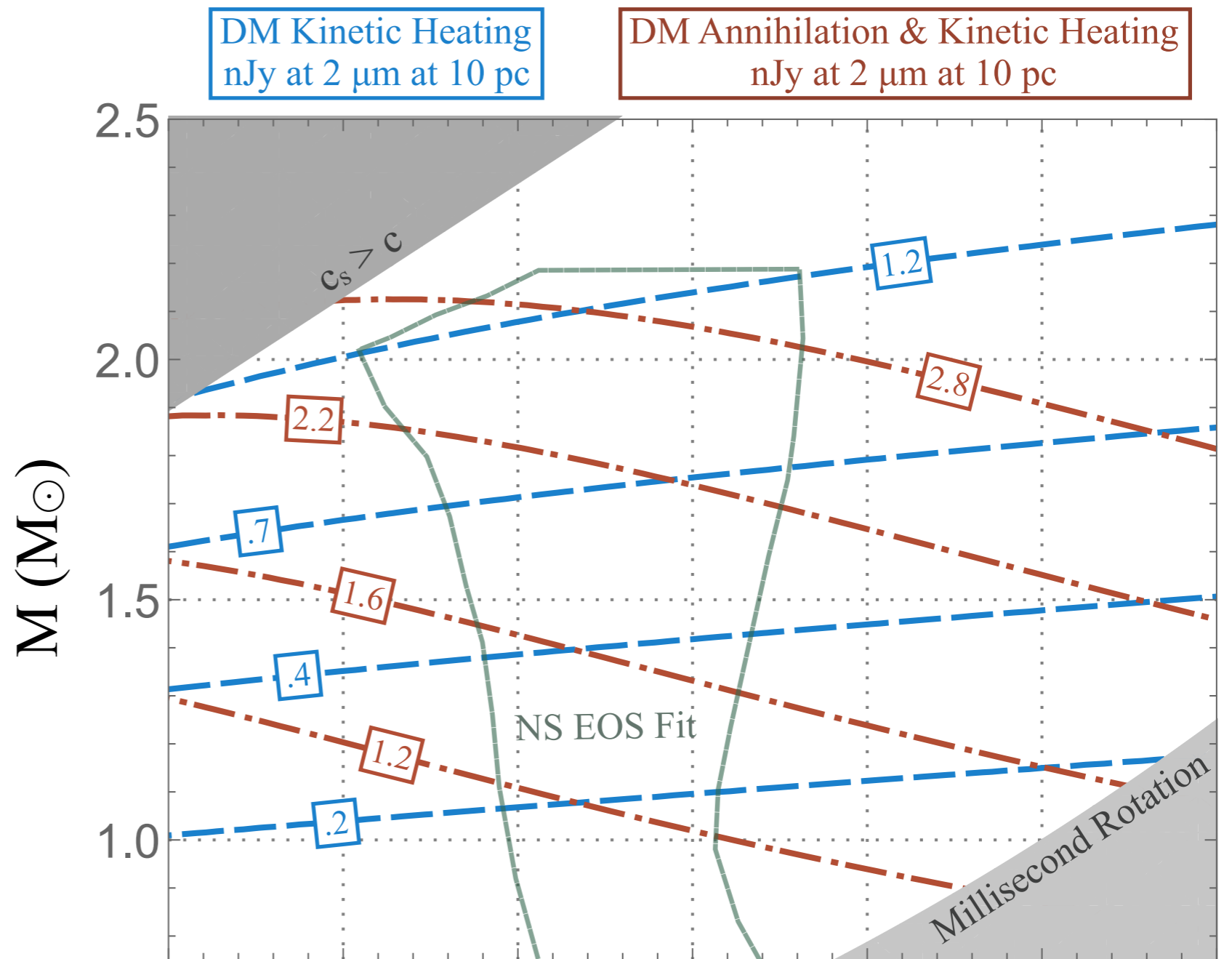
$$(\gamma - 1)\dot{m}_x$$

(very sensitive to escape velocity)

annihilation

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

(heating from captured mass, scales with NS mass)



nanoJansky $\sim 10^{-30}$ GeV / (cm² s Hz)

kinetic only

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

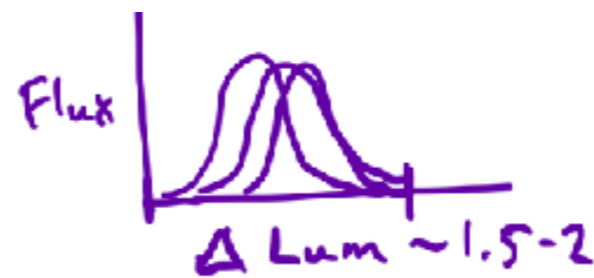
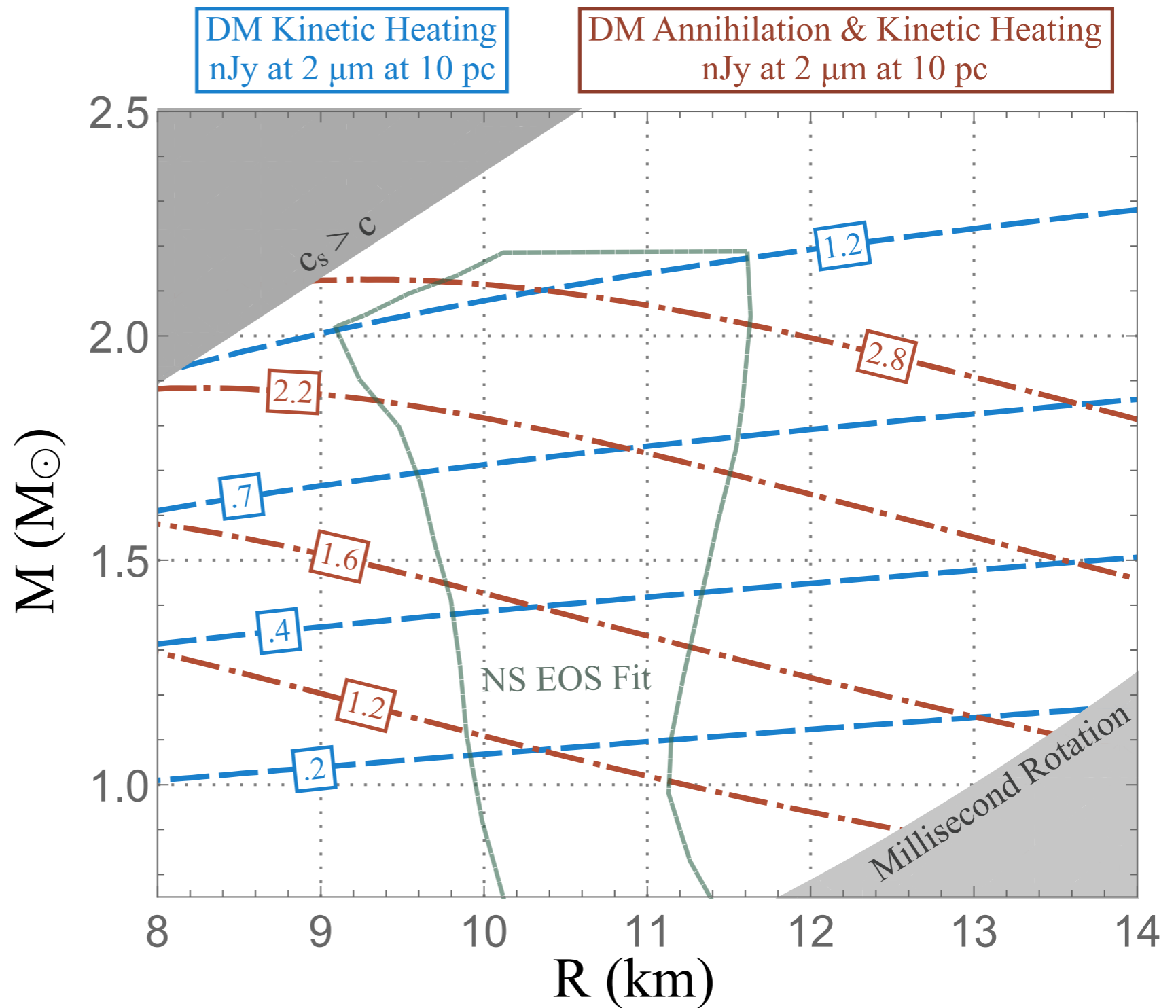
(very sensitive to escape velocity)

annihilation

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

(heating from captured mass, scales with NS mass)

kinetic heating

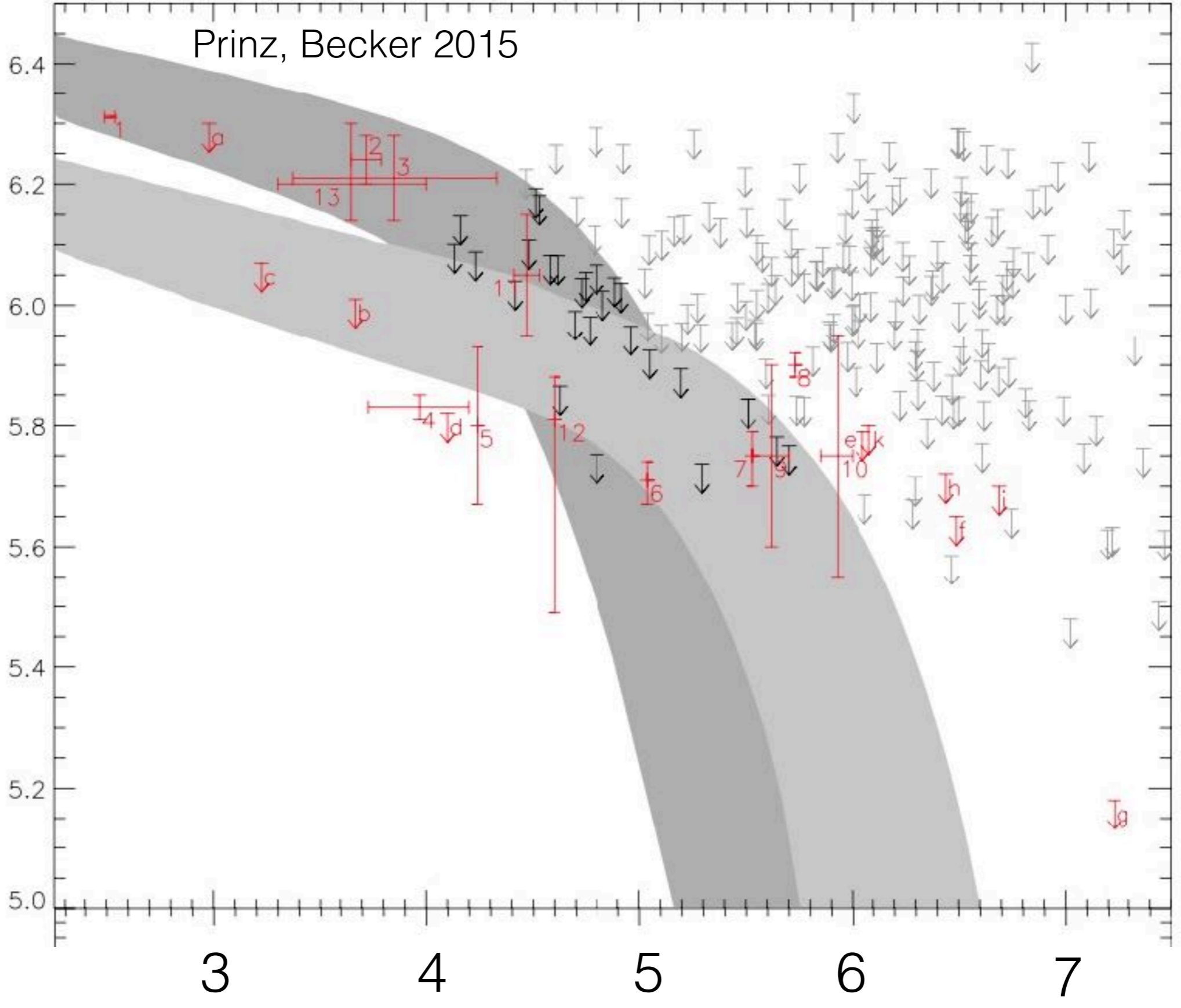


Broader variety of Neutron Star luminosities for only dark kinetic heating

- 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!

Log T in Kelvin

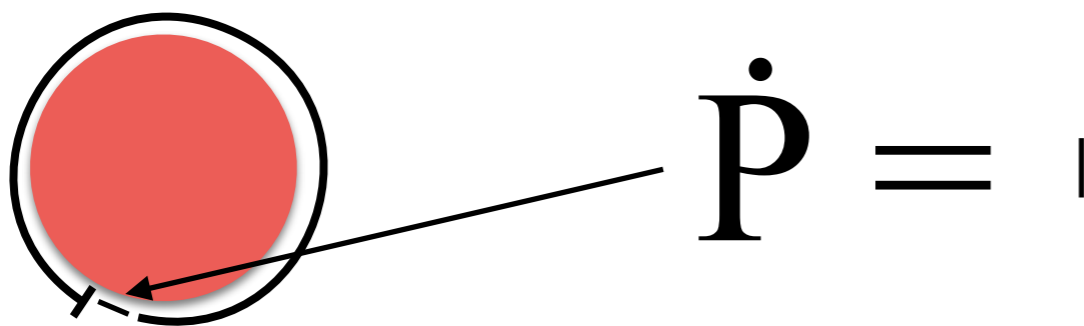
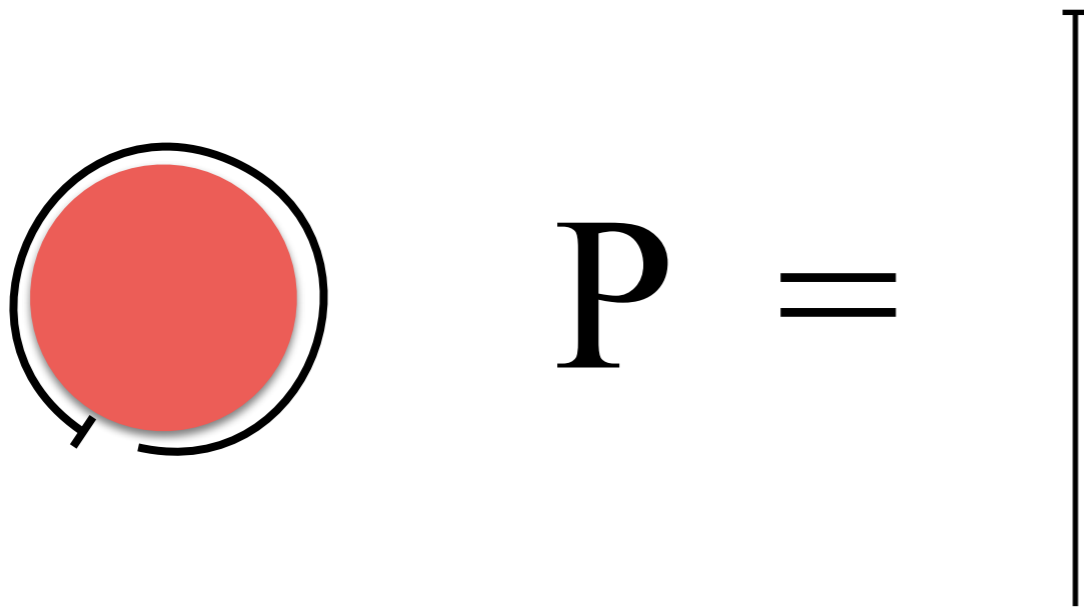
Prinz, Becker 2015



Log Age in Years

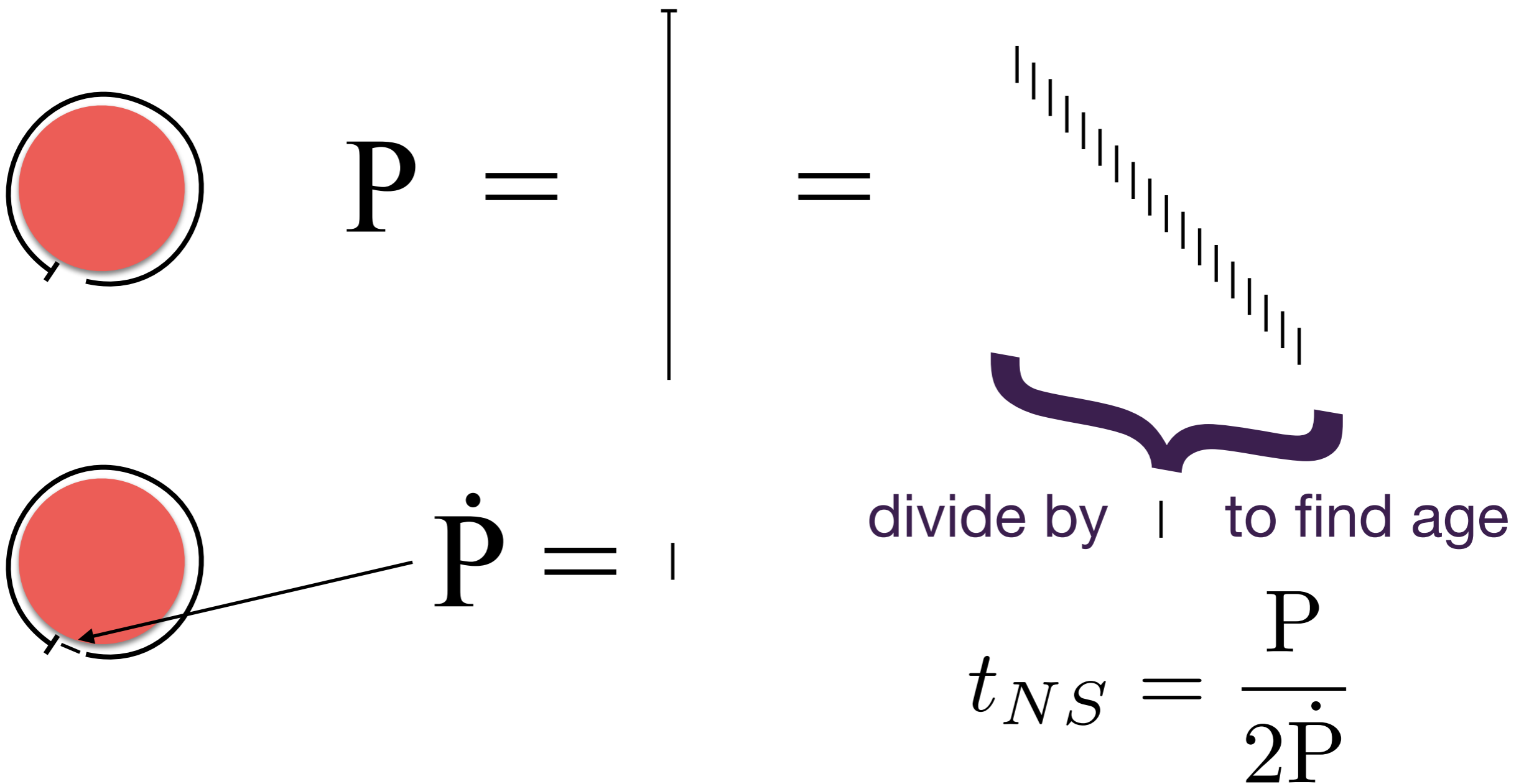
Pulsars

Estimate pulsar age measuring pulse period (P)
and slowdown per pulse (\dot{P})



Pulsars

Estimate pulsar age measuring pulse period (P)
and slowdown per pulse (\dot{P})



P =

\dot{P} =

divide by \dot{P} to find age

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