

# Detecting Dark Matter via Kinetic Heating of Neutron Stars

1704.01577

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Pheno @ U Pitt  
09 May 2017

Thanks a lot for being here.

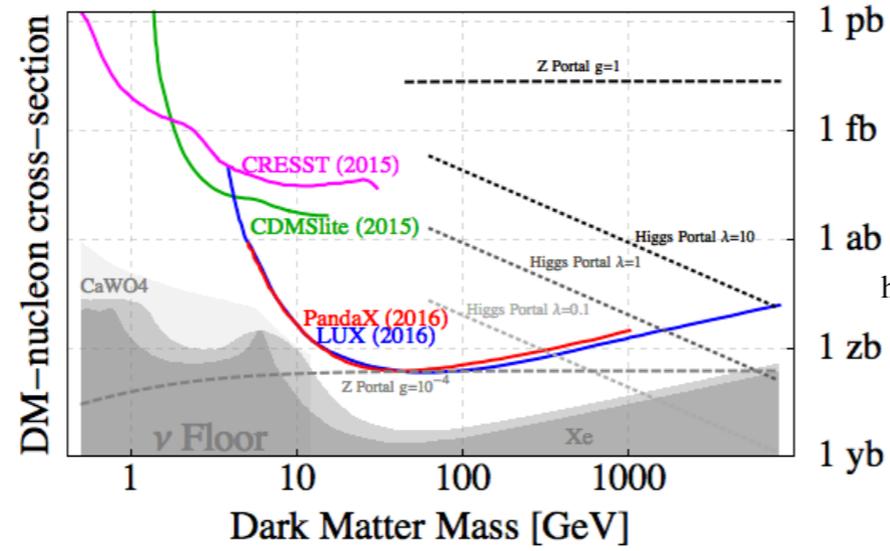
I'm excited to share with you guys super-fun stuff I wrapped up last month with Joe, Masha, Shirley, and Tim.

And I'm happy to chat about it any time.

# Direct searches: status

After 100 kg-year exposure:

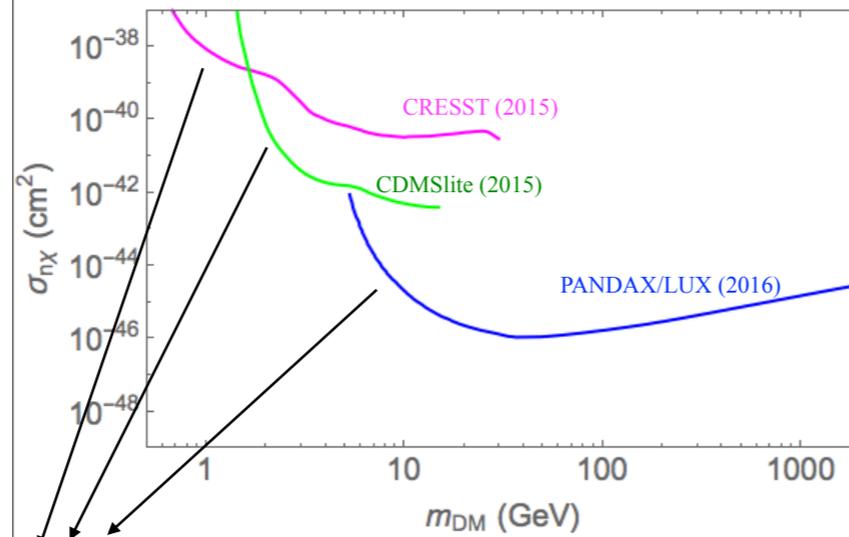
Limits on Dark Matter from Direct Detection



<http://resonaances.blogspot.com/>

Here's where we are in terms of direct searches for dark matter, after 100 kilogram years of exposure. Interpreting this with a broad brush, Z-mediation is dead, and Higgs-mediation is just around the corner. That's significant progress, but there's still significant challenges.

# Direct searches: challenges

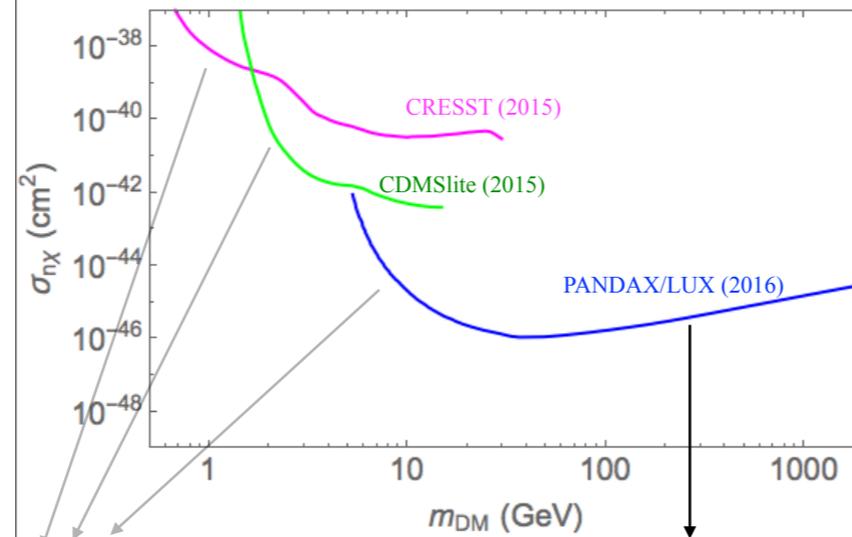


(1) Nuclear recoil below  
detector thresholds at low mass

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

For instance, if dark matter is much lighter than nuclear masses, there's no recoil above detector thresholds.

# Direct searches: challenges



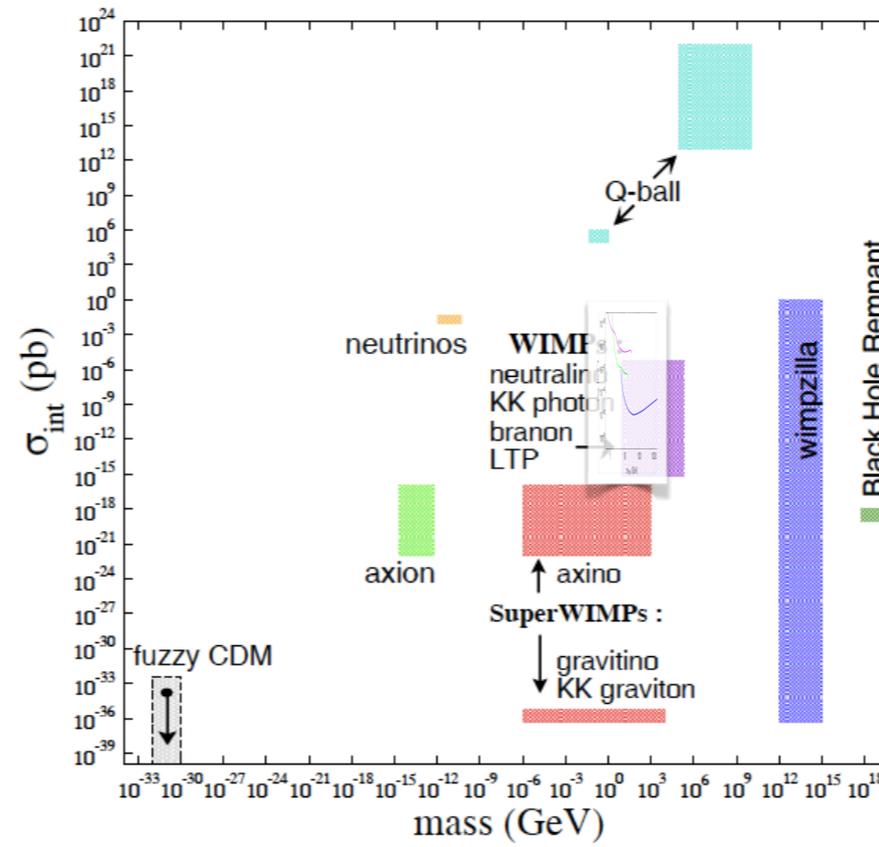
(1) Nuclear recoil below  
detector thresholds at low mass

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

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

And if dark matter is heavy, it is dilute in the halo, and you don't get enough dark matter particles sweeping through the detector, limiting your search.

# (Context)

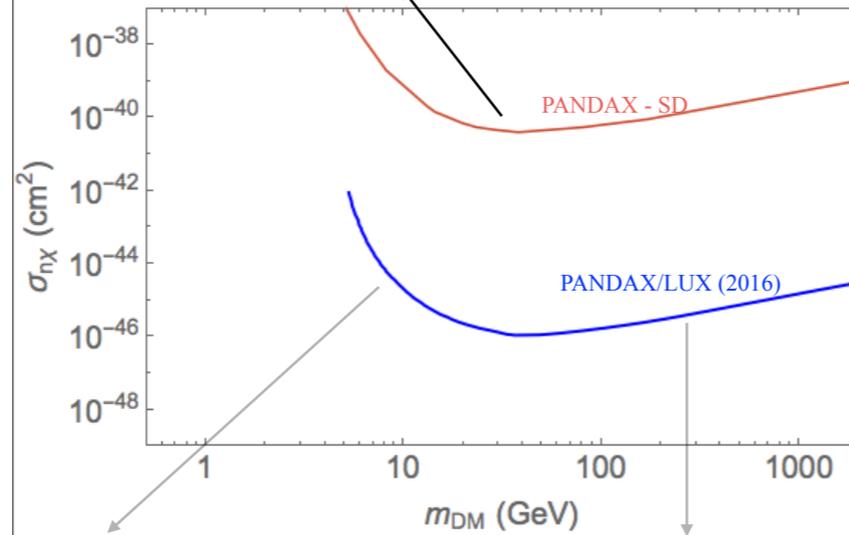


To put these two challenges in context, here's the region probed by direct detection in the cross-section—mass space of theoretical models.

# Direct searches: challenges

(3) No nuclear coherence

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



*E.g. DM coupling to axial current  $\bar{q}\gamma_\mu\gamma_5q$*

(1) Nuclear recoil below detector thresholds at low mass

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

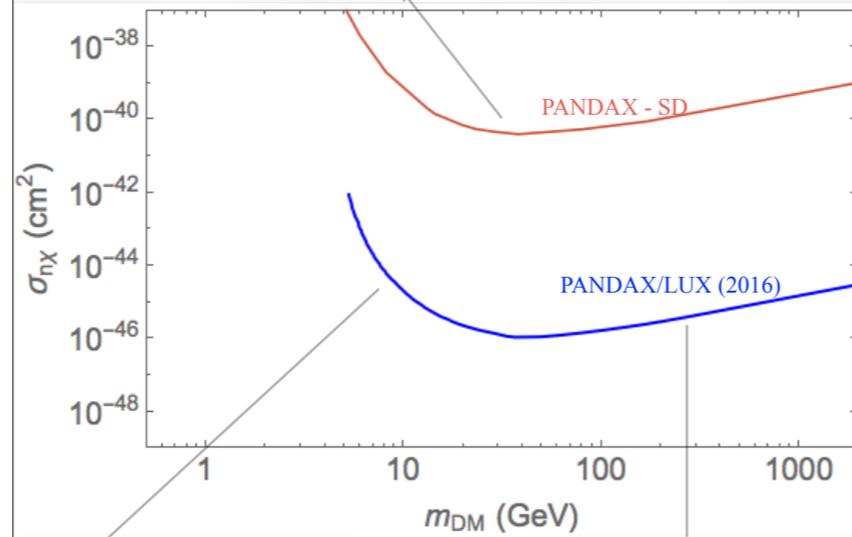
And if dark matter couples to the spin of nucleons, it doesn't scatter coherently over the nucleus, so you lose the  $(1/A^2)$  factor and you aren't sensitive to nucleonic cross-sections much below nuclear cross-sections.

This limits the search for Majorana dark matter that can only couple with axial currents, for example.

# Direct searches: challenges

(3) No nuclear coherence

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

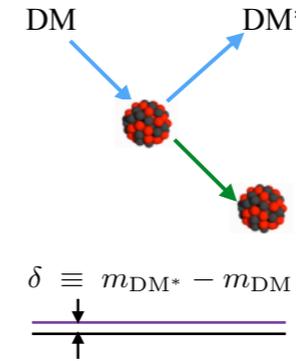


(1) Nuclear recoil below detector thresholds at low mass

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

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

(Image: G. Kribs)

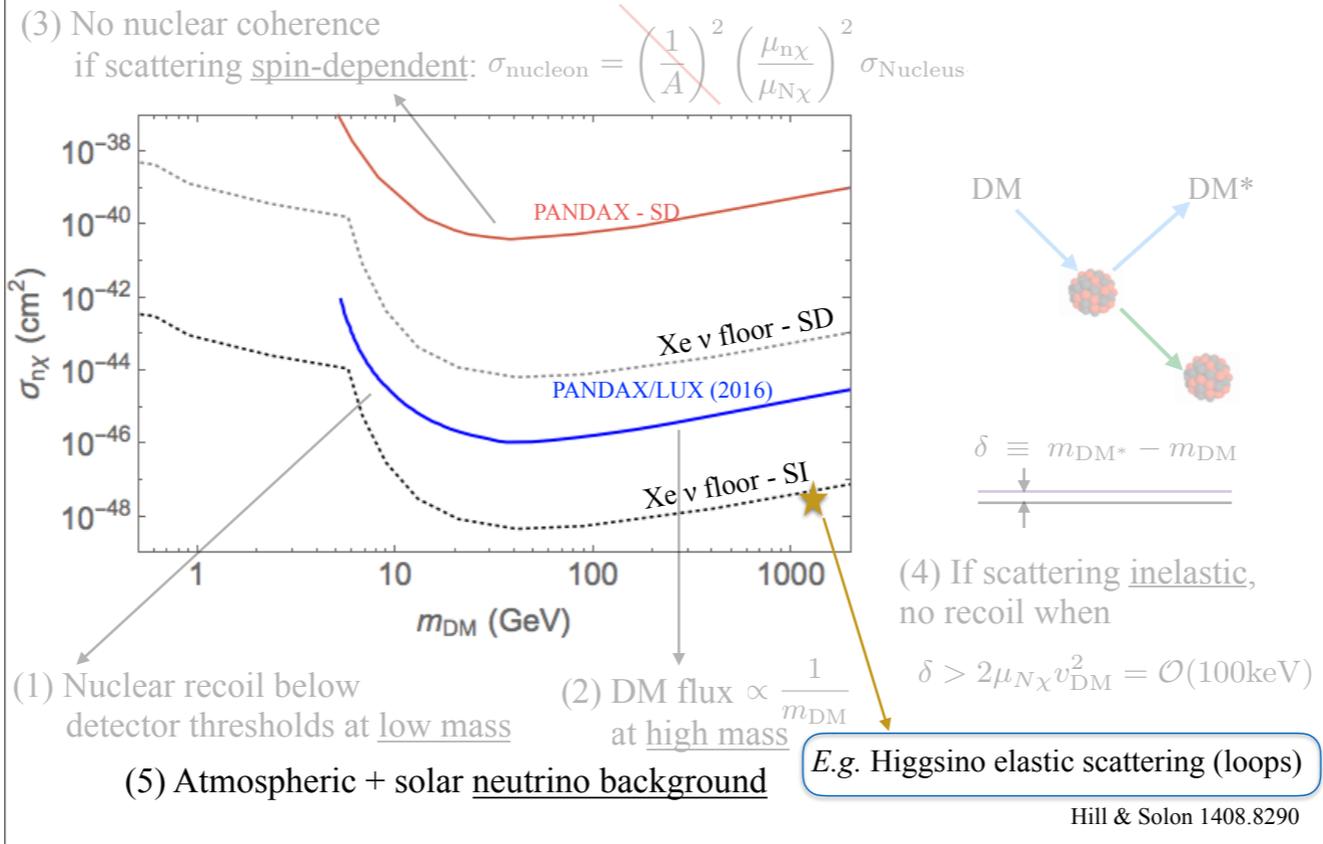


(4) If scattering inelastic, no recoil when

$\delta > 2\mu_{N\chi}v_{\text{DM}}^2 = \mathcal{O}(100\text{keV})$   
Tucker-Smith, Weiner 0101138, 0402065,  
Barello, Chang, Newby 1409.0536

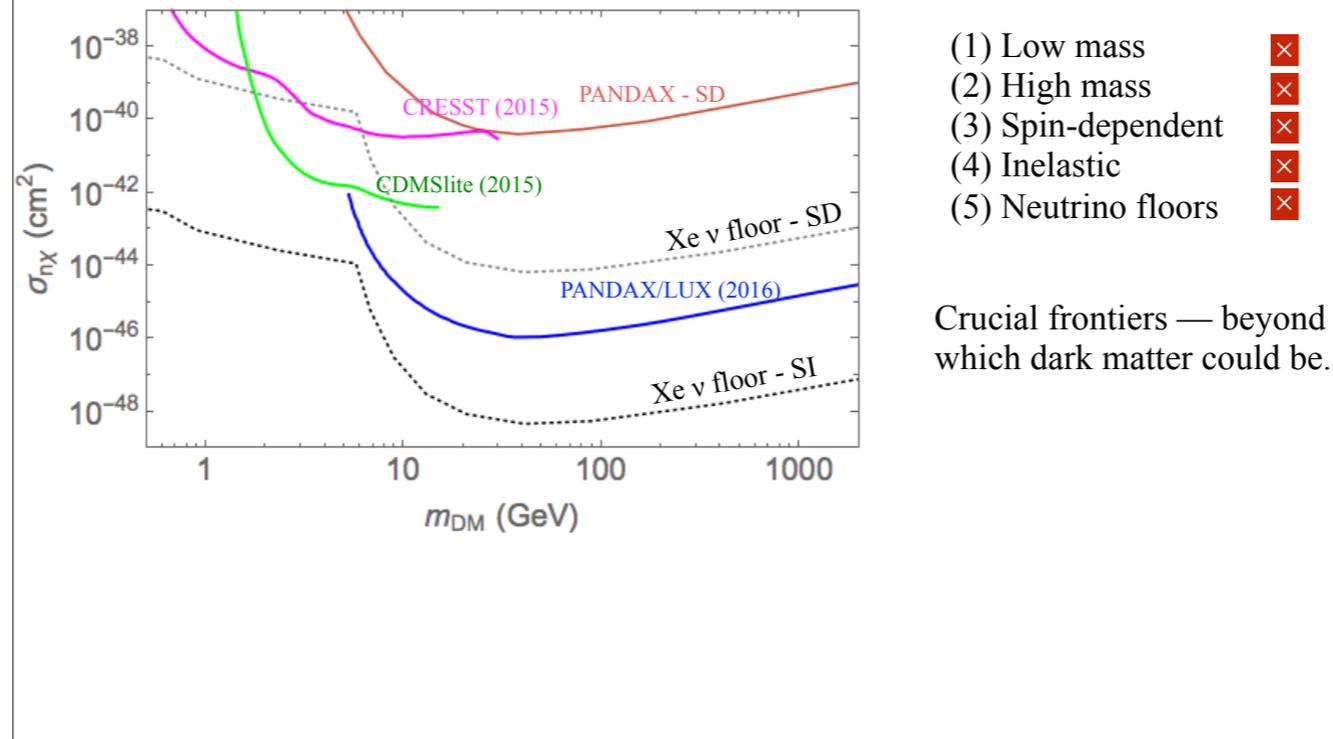
If dark matter can only scatter by transitioning to an excited state, the mass splitting between the states cannot be bigger than the nuclear recoil energy. That's only about a 100 keV for a detector on Earth, because dark matter only moves here at a thousandth the speed of light. This limits the search for, for example, Higgsino dark matter scattering through  $Z$  or  $W$  exchange, or pseudo-Dirac dark matter mediated by a dark photon.

# Direct searches: challenges



And then there's the impending "neutrino floor", the irreducible background from atmospheric and solar neutrinos. This would limit the search for, for example, elastic scattering of Higgsinos through loops.

# Direct searches: challenges



So these are some of the most crucial challenges that must *absolutely* be addressed by any probe posing to be the next serious upgrade to direct detection — direct detection 2.0 if you will. These are the burning frontiers of dark matter direct detection.

# (Dark) Kinetic Heating

So what's the idea here?

# Soup getting cold

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



If you make a bowl of hot soup, it is gonna get cold.

And if you model it as a blackbody, the rate at which it cools must go as the fourth power of the temperature.

# Keeping soup hot: fire

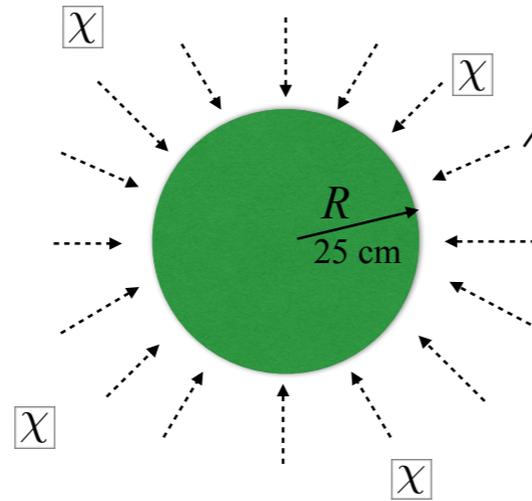
$$CM \frac{dT}{dt} = -\sigma_{\text{SB}}(\text{Area})(T^4 - T_{\text{ambient}}^4) + \dot{E}_{\text{external}}$$



But you can stop it from cooling by turning on an external power source, like a fire.  
And the power will determine the temperature you can maintain.

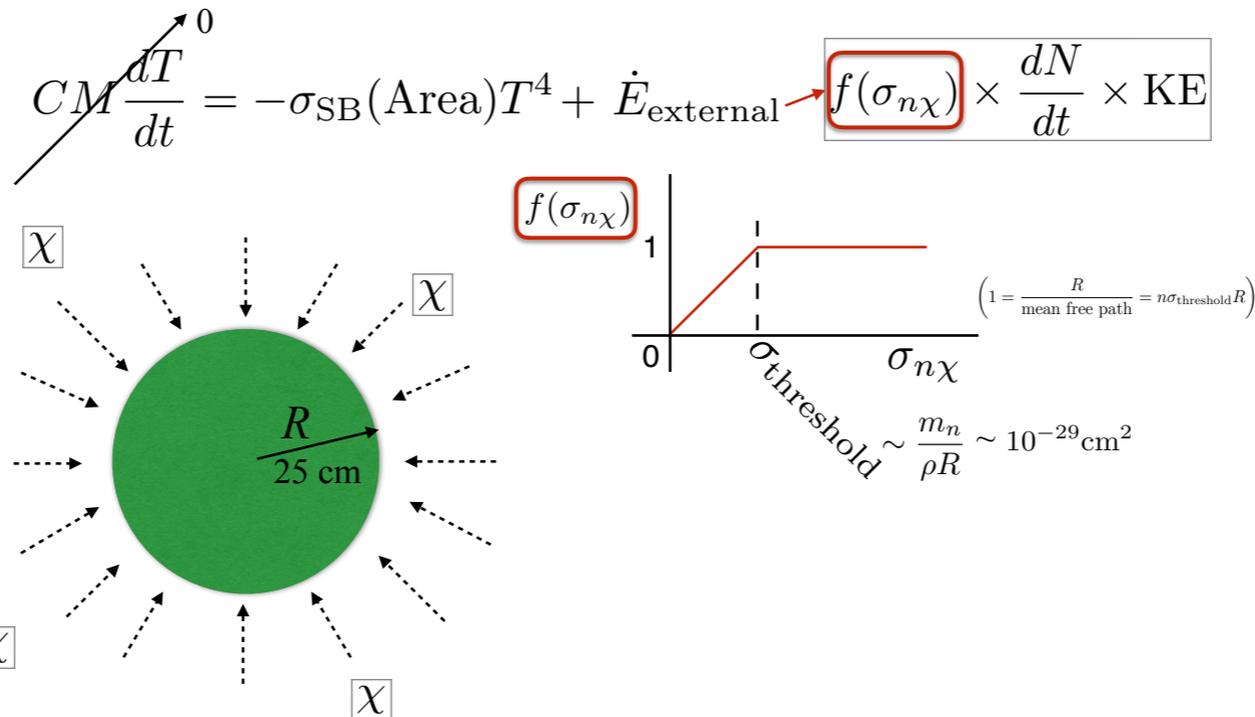
# Keeping soup hot: dark fire

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



Now if you take your soup to a region where there's very little Standard Model particles, can you still keep it hot?  
Yes, if dark matter has interactions with nucleons — then you can have a dark fire!

# Keeping soup hot: dark fire



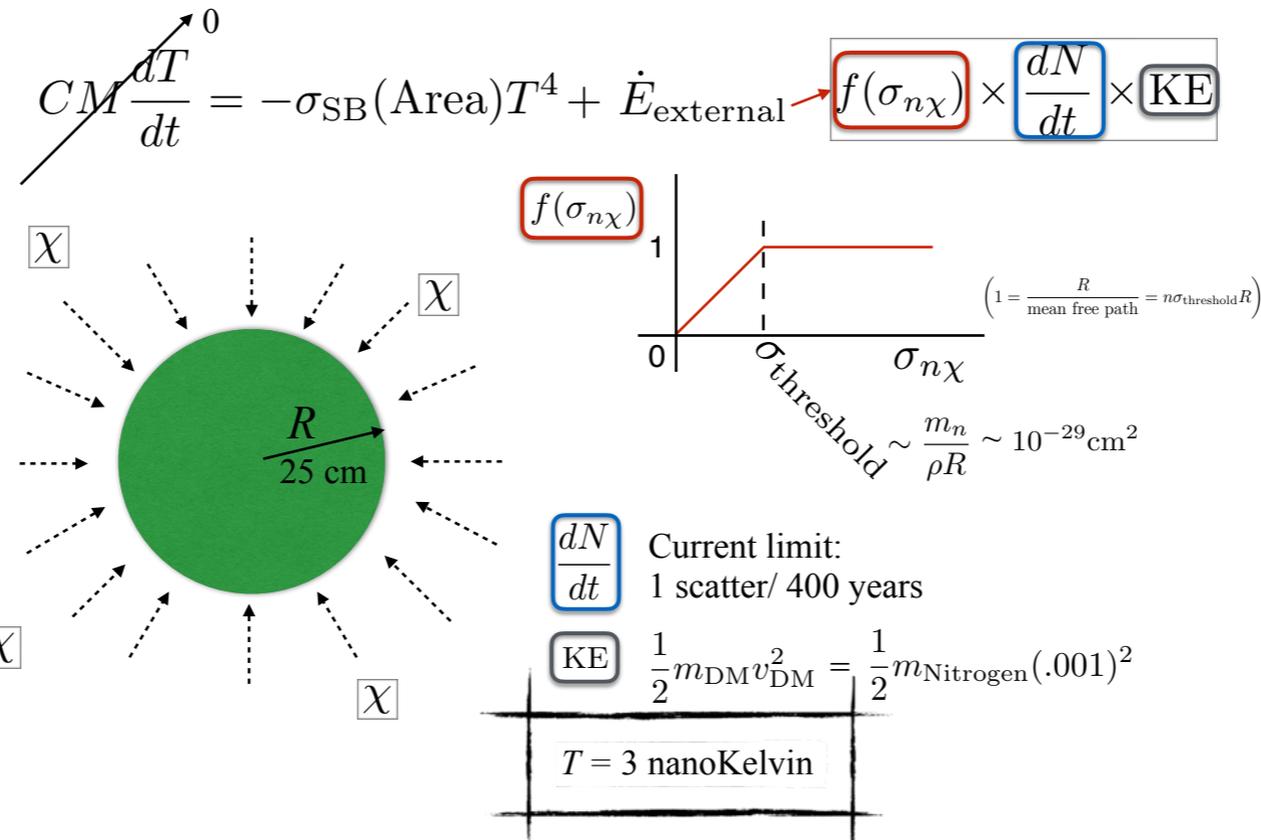
Your external power is now the rate at which dark matter deposits its kinetic energy into the soup.

Of course, this should depend on the dimensions of the soup and what your soup is made of.

Assuming that dark matter is lighter than soup molecules, for a given size and density of soup, there's a threshold cross-section above which dark matter would deposit all its kinetic energy into the soup.

For a ball of soup *this* big, that cross-section is  $10^{-29} \text{ cm}^2$ .

# Keeping soup hot: dark fire



How hot can the soup get?

If you plug in the current limit on the scattering rate — which for a soup-ball of this size is one hit every 400 years — and the kinetic energy for dark matter weighing as much as a nitrogen molecule, dark matter can keep your soup at the scalding temperature of 3 nanoKelvin.

# Detector improvements

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

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

Bigger  
and denser

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


---


$$T = 3 \text{ nanoKelvin}$$

Obviously you want a better detector.

By increasing the size and density of your detector, you can reduce the threshold cross-section.

That's another way of saying if you make the detector bigger and denser, it's easier to trap dark matter.

# Detector improvements

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

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

Bigger and denser

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

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

$$T = 3 \text{ nanoKelvin}$$

If you make it sufficiently big and dense, you would also turn it into a strong gravitational attractor, which would make dark matter come to it with greater kinetic energy!

# Detector improvements

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

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

Bigger  
and denser

Get a gravitational boost!

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

Be colder than  
dark-kinetically-heated  
temperature

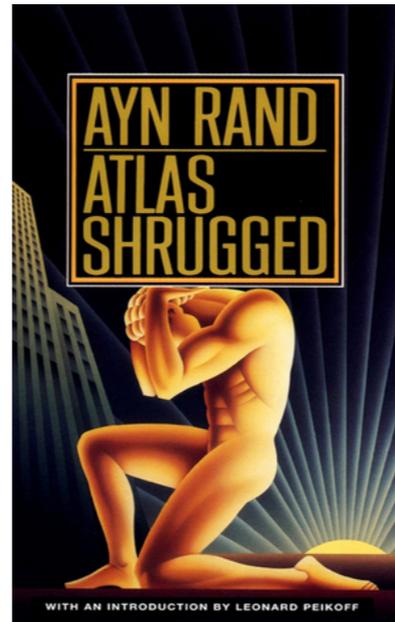
$$\text{KE} \quad \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2$$

$$T = 3 \text{ nanoKelvin}$$

And of course, you want the detector in its natural state to be colder than the temperature maintained by dark fire.

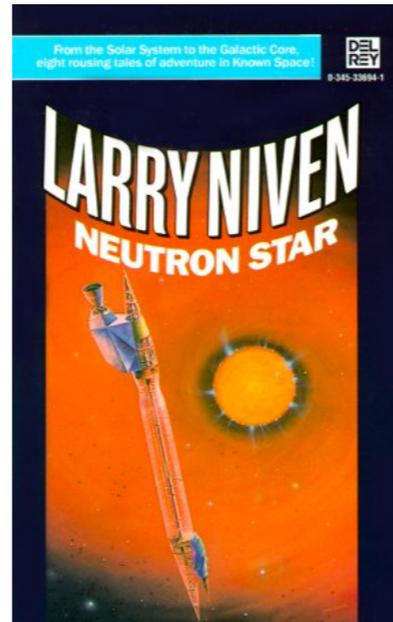
What's big, dense, and cold?

What's big, dense, and cold?



Besides an Ayn Rand novel...

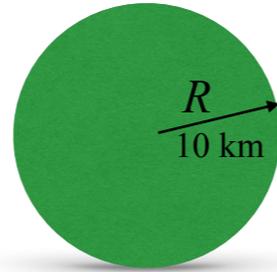
What's big, dense, and cold?



Well, a neutron star!



big

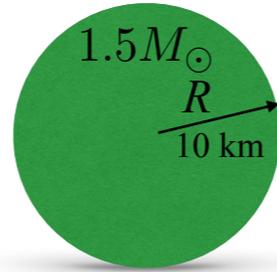


A neutron star has the size of a half-marathon, ...



big, dense

$$7 \times 10^{17} \text{ kg/m}^3$$



Lake Michigan (weighing  $5 \times 10^{12}$  kg) in a teaspoon

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

... and a density equal to cramming Lake Michigan into a teaspoon.  
The net effect is that ambient dark matter would come to its surface at more than half the speed of light!

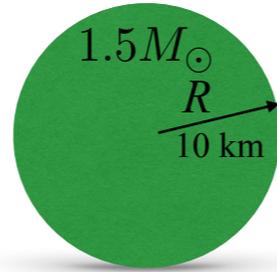


big, dense, and cold

$$7 \times 10^{17} \text{ kg/m}^3$$



Lake Michigan (weighing  $5 \times 10^{12}$  kg) in a teaspoon



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

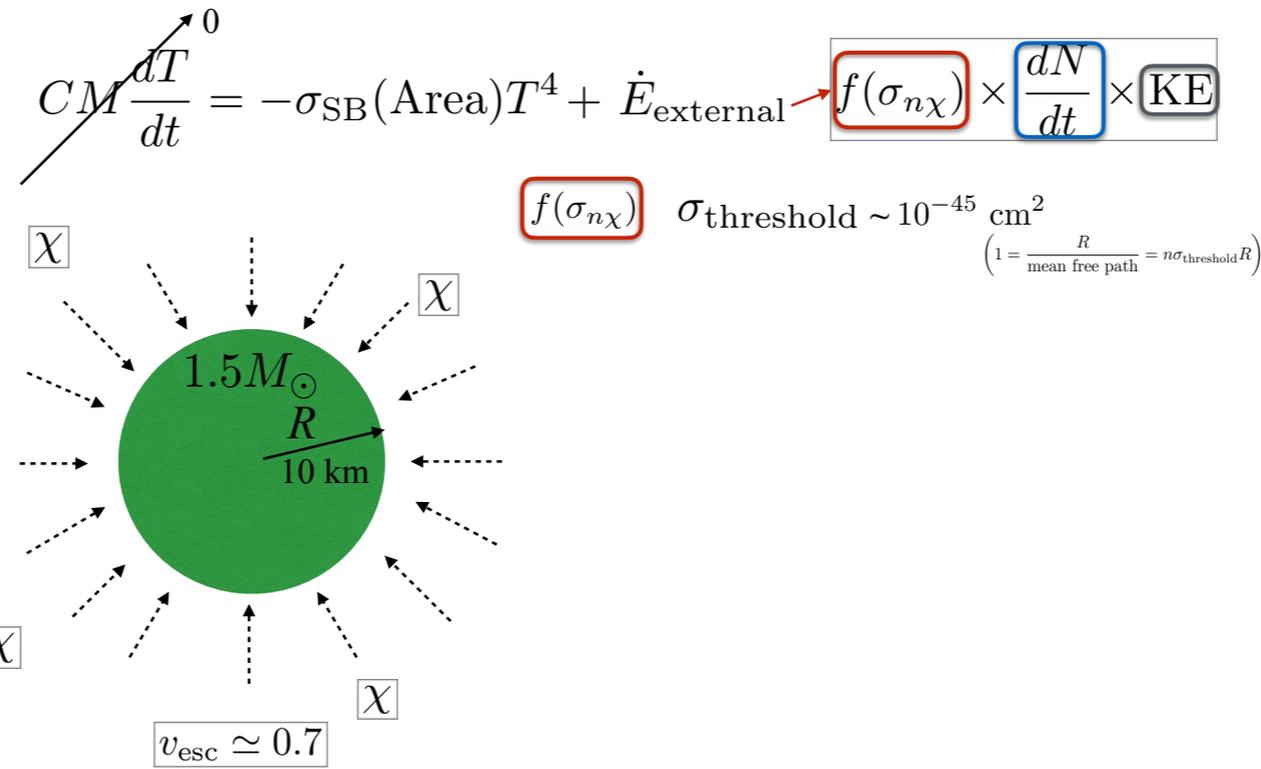
20 My old:  $T_{\text{eff}} \approx 1000 \text{ K}$

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

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

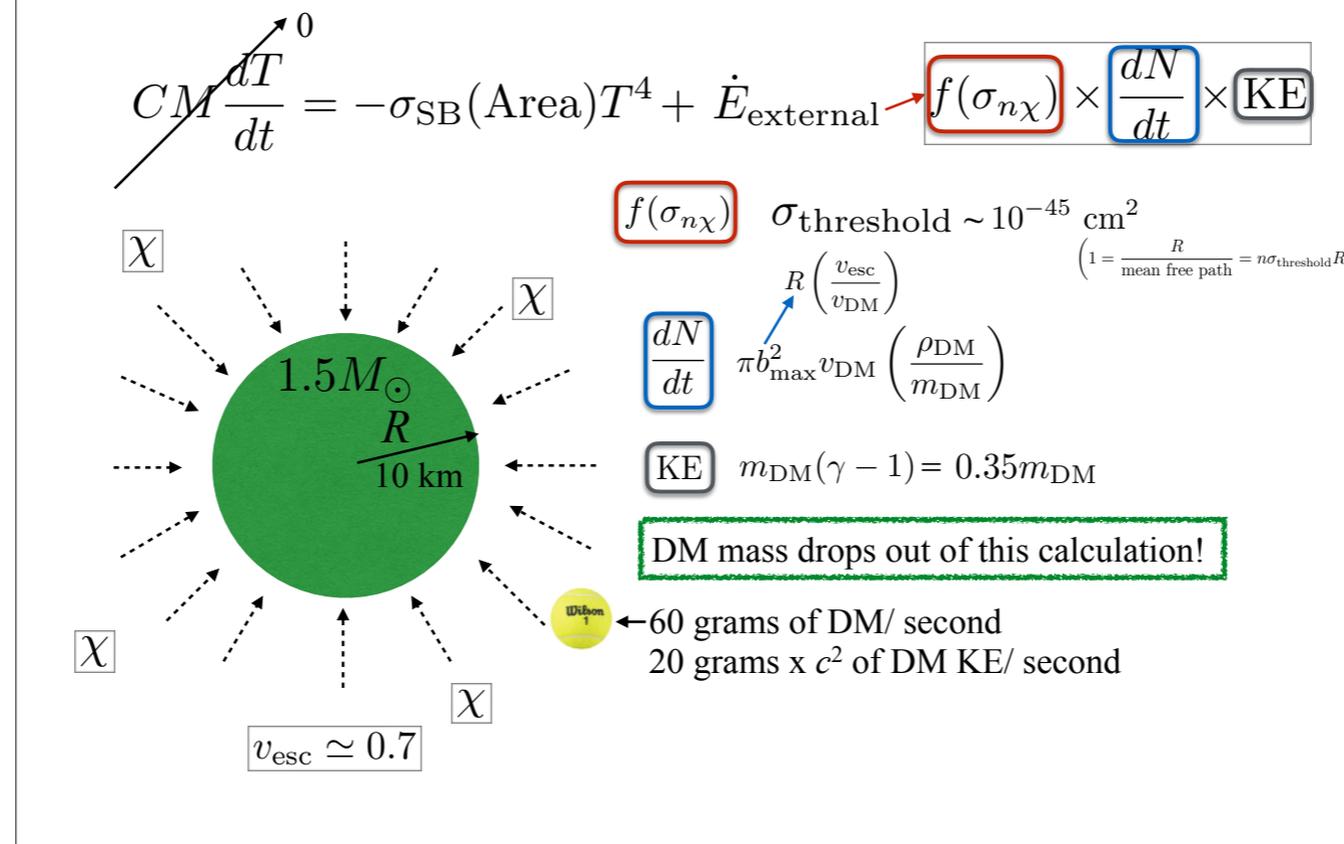
And a billion-year-old neutron star would have cooled down to the temperature of a snowball.

# Keeping N star hot: dark fire



So if you turn the crank again for a neutron star, you find that the threshold cross-section is  $10^{-45} \text{ cm}^2$ , which is already comparable to limits set by LUX and PandaX.

# Keeping N star hot: dark fire

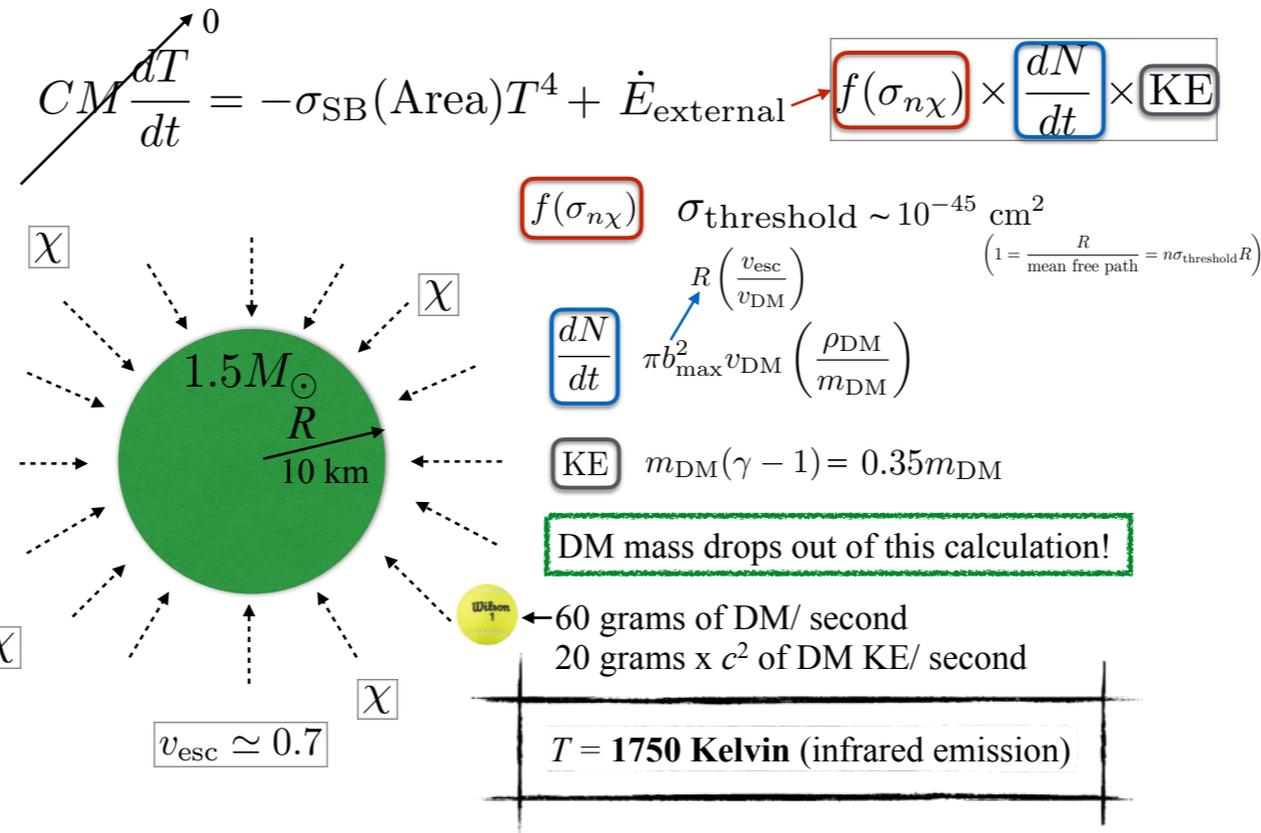


And the remarkable thing is that the mass of dark matter drops out of the total external power from kinetic energy deposition.

Basically the heavier the dark matter is, the fewer dark matter particles are attracted to the neutron star surface.

So you find that about 60 grams of dark matter — the mass of a tennis ball — pass through the neutron star every second carrying a kinetic energy about a third of its mass energy.

# Keeping N star hot: dark fire



And if this kinetic energy gets deposited, the neutron star glows at 1750 Kelvin, which is infrared emission!

# Keeping N star hot: dark fire

0

KE

snowball



fresh lava



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

$\chi$

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

$\chi$

20 grains x c of DM KE/ second

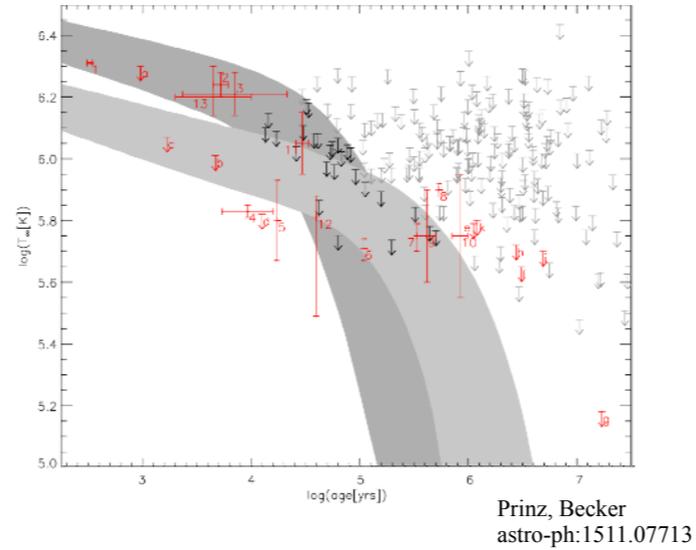
$T = 1750 \text{ Kelvin (infrared emission)}$

That's the temperature of fresh molten lava, as opposed to a snowball.

# Detection?

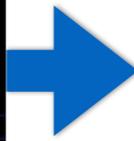
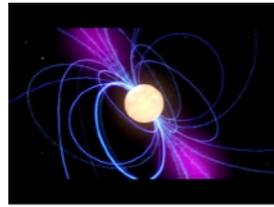
$T = 1750$  Kelvin (infrared emission)

O(100) below current  $T$  bound



But that's still a hundred times colder than the coldest neutron star we've seen.  
So how do we detect it?

# Detection: radio pulsing



FAST

[http://fast.bao.ac.cn/en/science\\_pulsar.html](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.

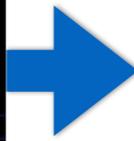
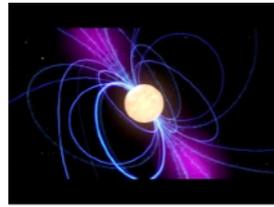
O. Blaes, P. Madau (1993)

Well, we have observed old neutron stars pulsing in radio frequencies.

And radio telescopes, like FAST in China that's already online, are poised to discover thousands of pulsars in one year, of which about a hundred must lie within the local 50 parsecs.

# Detection: infrared telescopes

(exoplanet atmosphere)



FAST

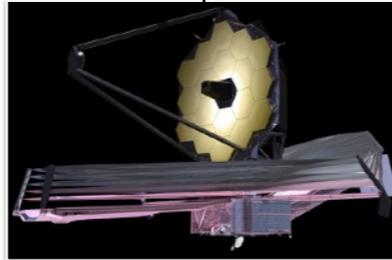
[http://fast.bao.ac.cn/en/science\\_pulsar.html](http://fast.bao.ac.cn/en/science_pulsar.html)

1 - 5 old, cold neutron stars  
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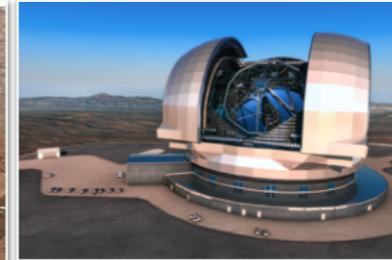
coming online Oct 2018!



James Webb



Thirty Meter



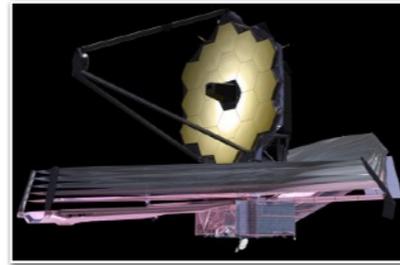
European Extremely Large

Once discovered, we can stare at these pulsars with upcoming infrared telescopes meant for staring at exoplanet atmospheres.  
The exciting news is James Webb is coming online next October and should be taking data two Phenos from now!

# Detection: infrared telescopes

$T = 1750 \text{ Kelvin}$  (infrared emission)

Peak wavelength:  $1.65 \mu\text{m}$



James Webb



Thirty Meter

Imager

NIRCam

IRIS

Filter

F200W

K-band

$1.75 - 2.2 \mu\text{m}$

$2.0 - 2.4 \mu\text{m}$

Observ. time  
for  $2\sigma$  sensitivity

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

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

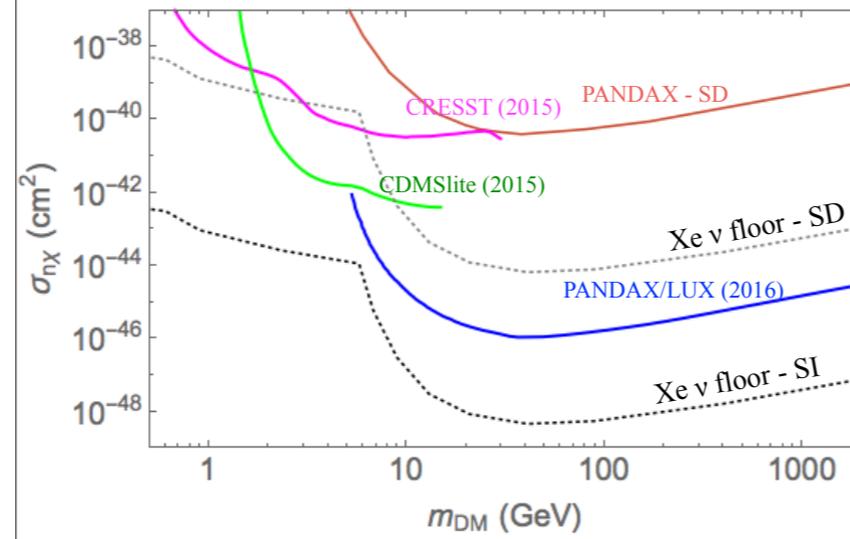
How long does it take to measure the thermal emission of these pulsars?

For a 1750 Kelvin pulsar 10 parsecs away, you get 2 sigma sensitivity with  $10^5$  seconds.

That's about a day's time.

And of course, if the dark matter-nucleon scattering cross-section is smaller than the threshold cross-section, dark matter is not going to heat up the star as much and you'd need longer exposures.

# Reward?

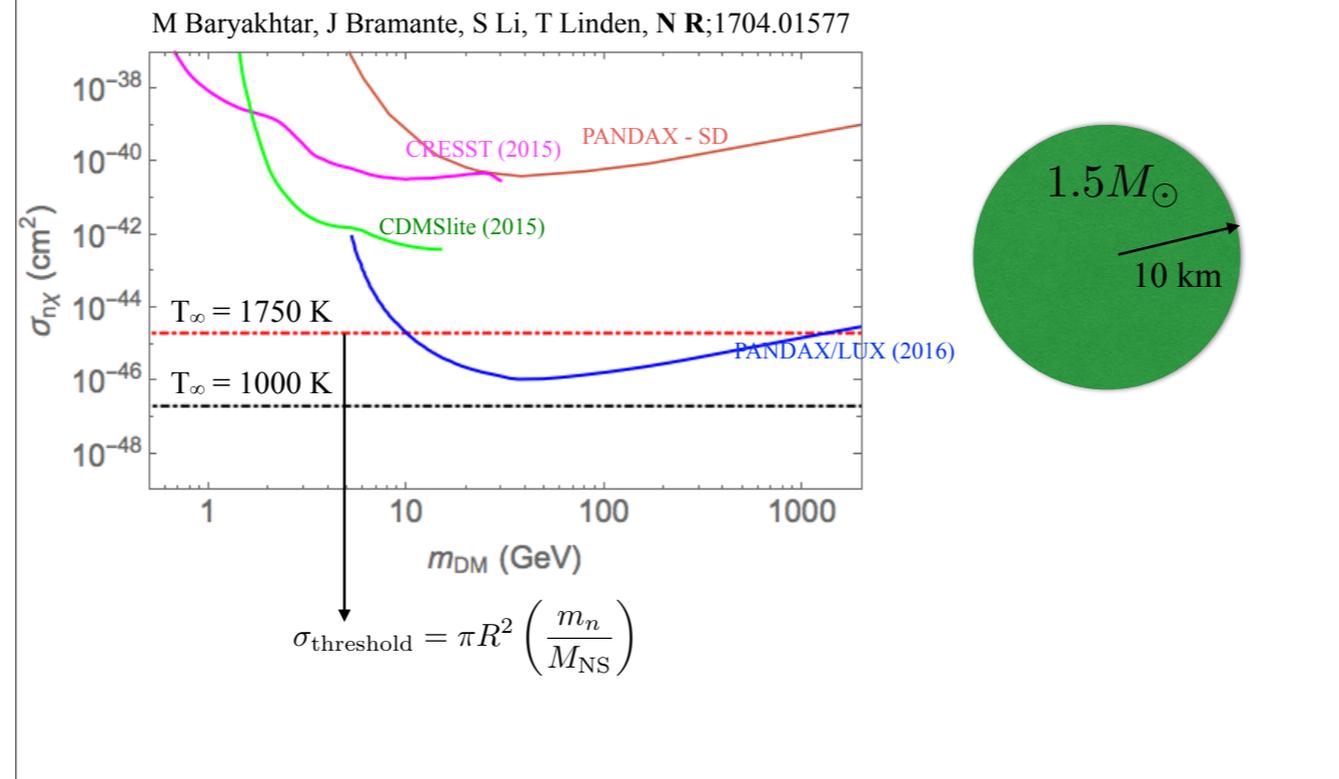


- (1) Low mass
- (2) High mass
- (3) Spin-dependent
- (4) Inelastic
- (5) Neutrino floors

Dark kinetic heating  
help these frontiers?

Now what does all this have to do with the burning frontiers of direct detection?

# Comparison



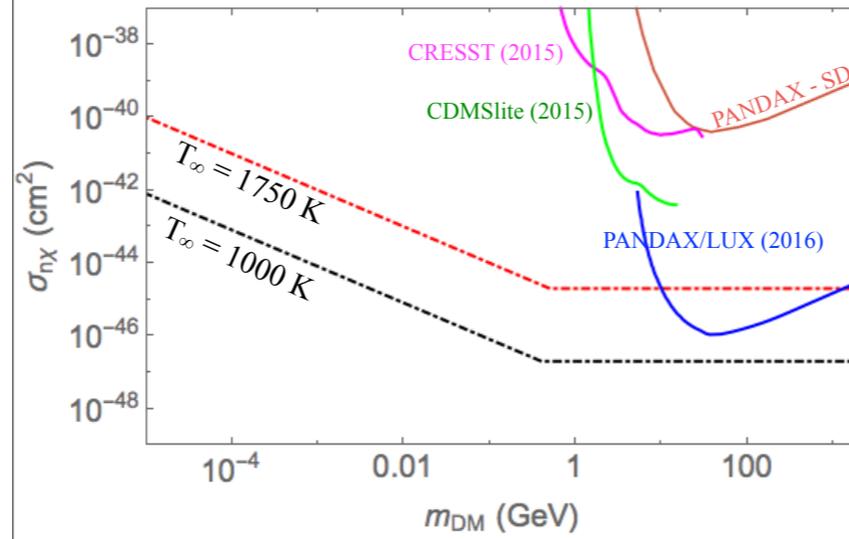
OK, here's how we compare in the direct detection window.

Smaller cross-sections, colder temperatures.

Like I said before, our cross-section sensitivity is independent of dark matter mass, so we already complement direct detection.

# Complementing

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



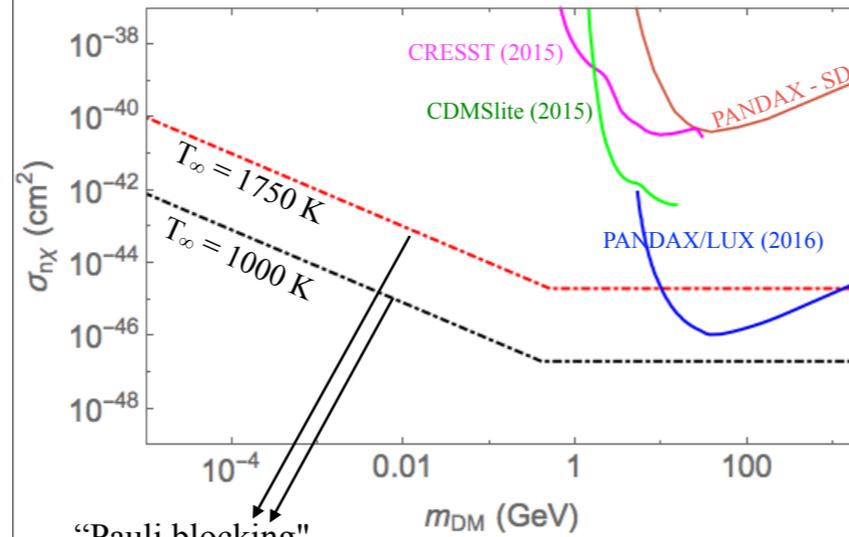
(1) Low mass



Now at the *low mass frontier*, we go several orders of magnitude lower.

# Complementing

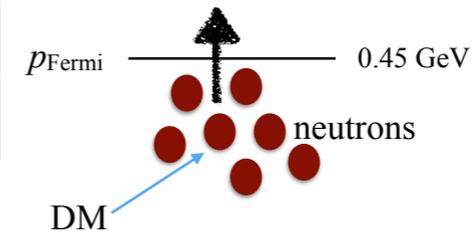
M Baryakhtar, J Bramante, S Li, T Linden, *N R*;1704.01577



“Pauli blocking”

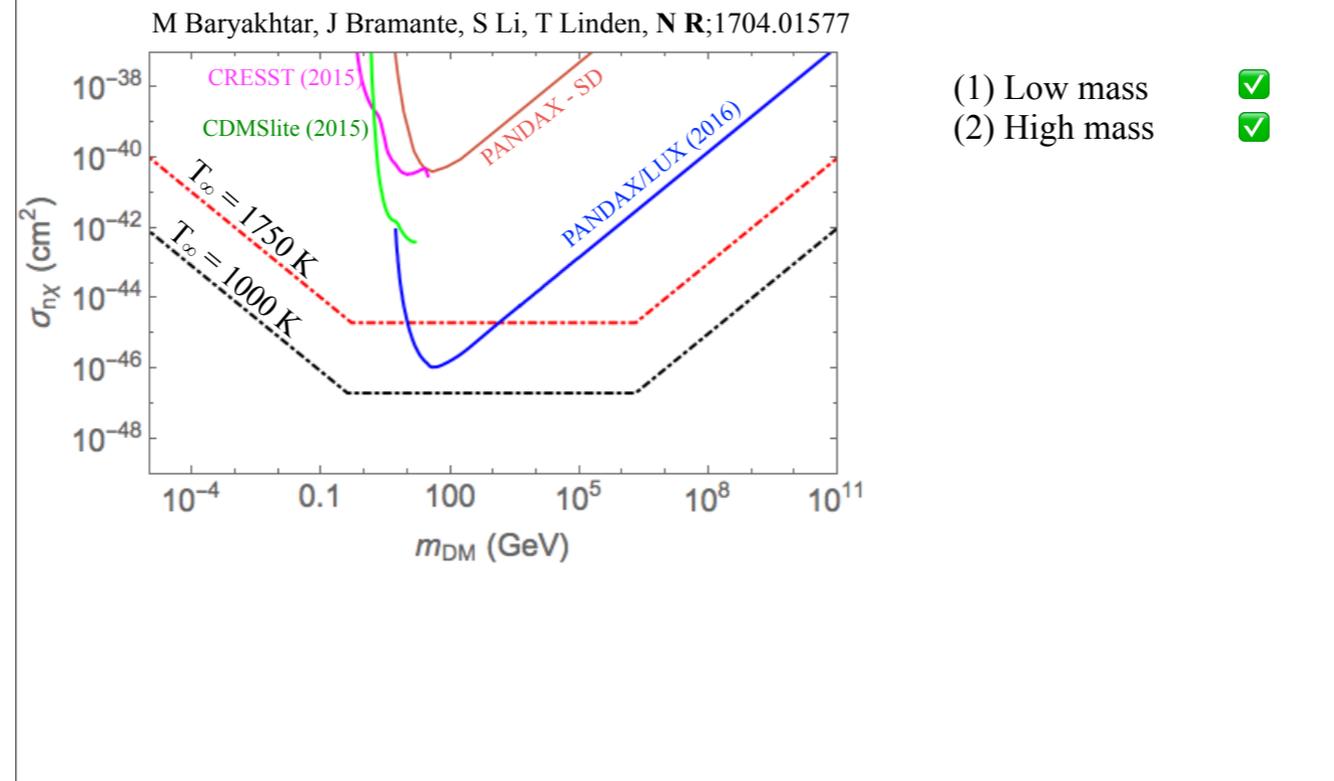
$$\sigma_{\text{threshold}}^{-1} \propto \text{fraction of nucleons excitable to } > \text{Fermi momentum} = \frac{\gamma m_{\text{DM}} v_{\text{esc}}}{p_{\text{Fermi}}}$$

(1) Low mass



The reason we start losing sensitivity below a GeV is that with sub-GeV momentum transfers it's harder to kick degenerate neutrons above the Fermi surface.

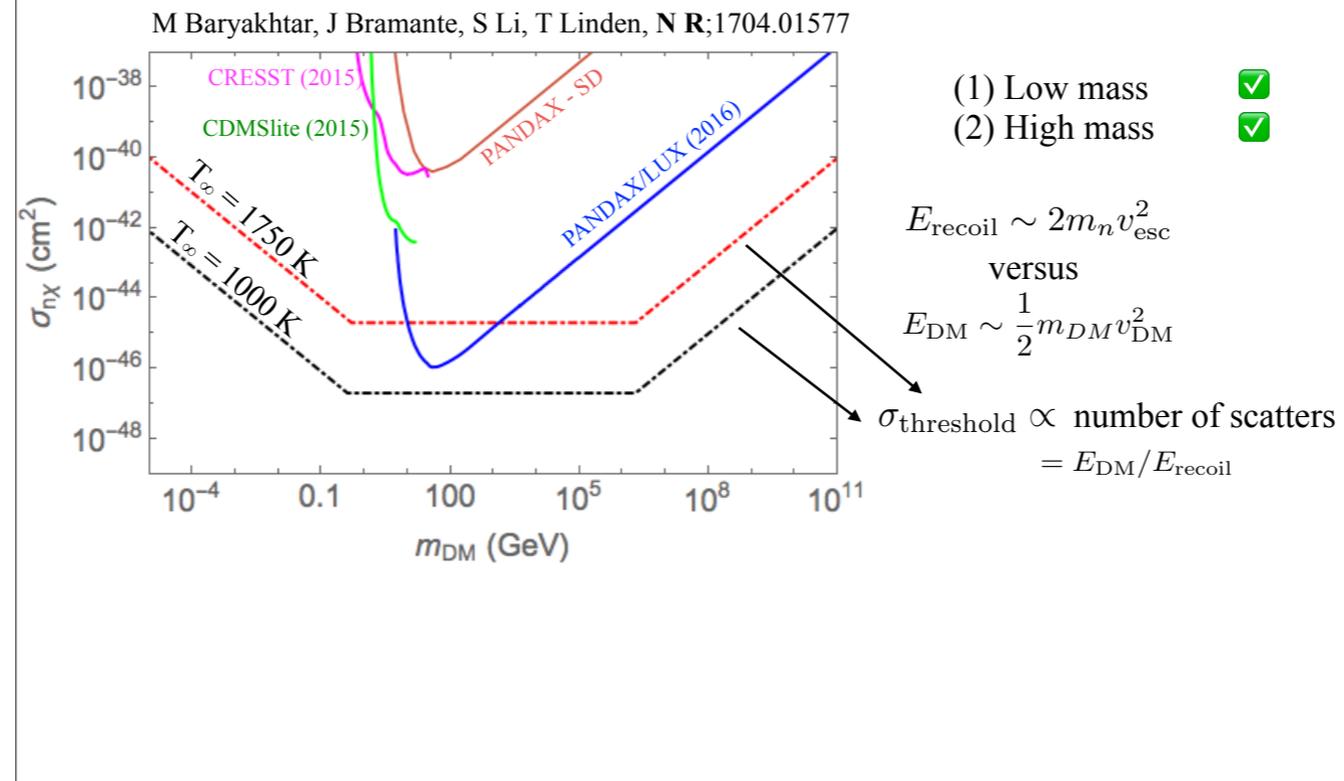
# Complementing



At the *high mass frontier*, we go several orders of magnitude higher.

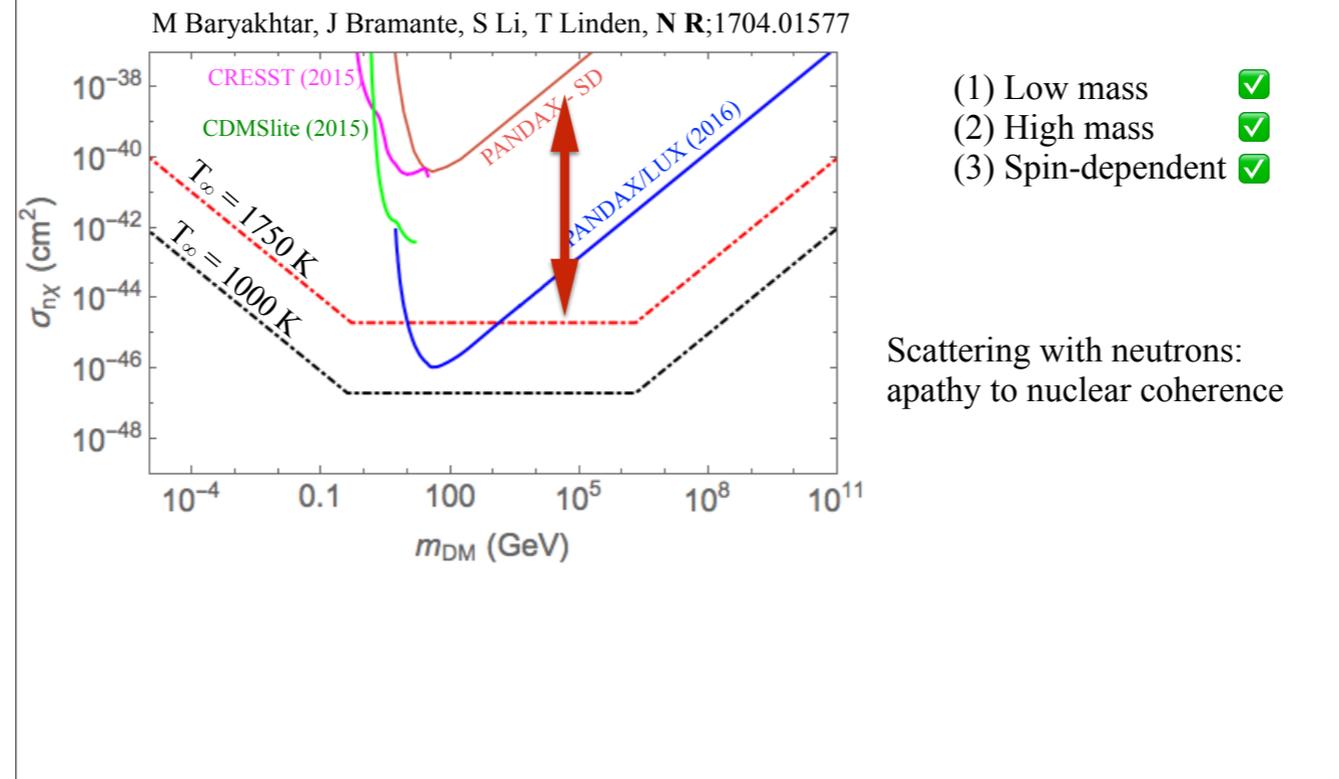
We can unmask cross-sections above  $2 \times 10^{-45} \text{ cm}^2$  up to dark matter mass of  $10^6 \text{ GeV}$ .

# Complementing



Above that mass we start losing sensitivity because dark matter starts out with so much kinetic energy that it takes multiple scatters to deposit all its kinetic energy into the star.

# Complementing



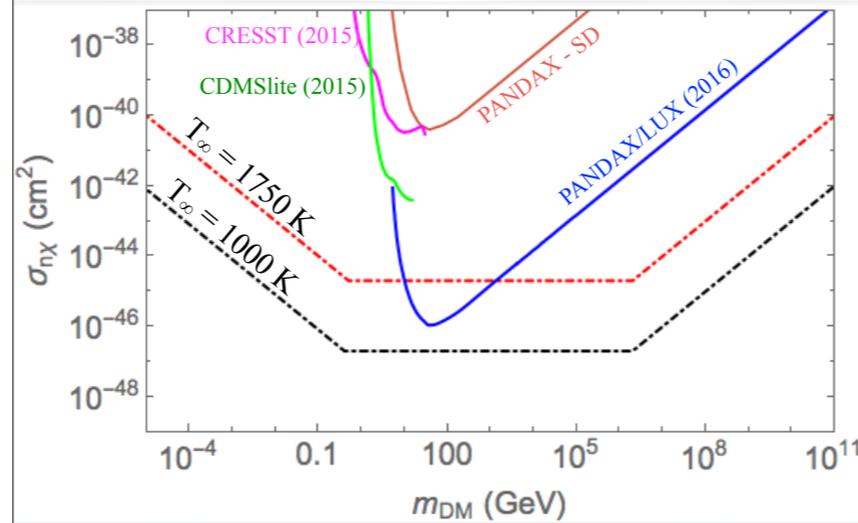
At the *spin-dependent frontier*, we can beat the latest limits by at least four orders of magnitude.

This is because dark matter here scatters with neutrons, and so you don't care about nuclear coherence.

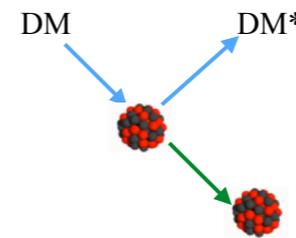
What you see is what you get.

# Complementing

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



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



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



Scattering proceeds as long as

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

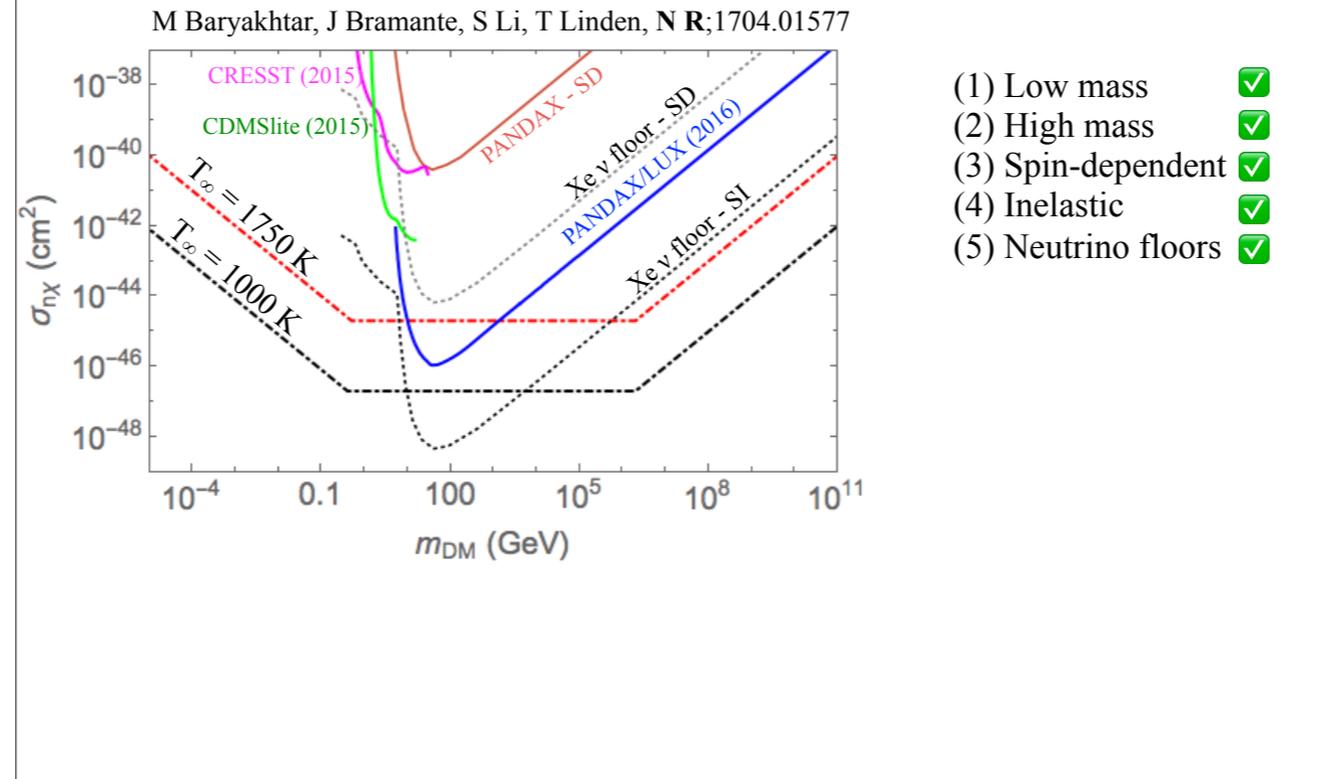
At the *inelastic frontier*, we could probe mass splittings of up to a GeV, which is four orders of magnitude higher than direct detection searches.

That's because dark matter is now scattering at close to the speed of light.

Amazingly, there's almost no MSSM parameter space where the inelastic splitting of Higgsino dark matter is above a GeV.

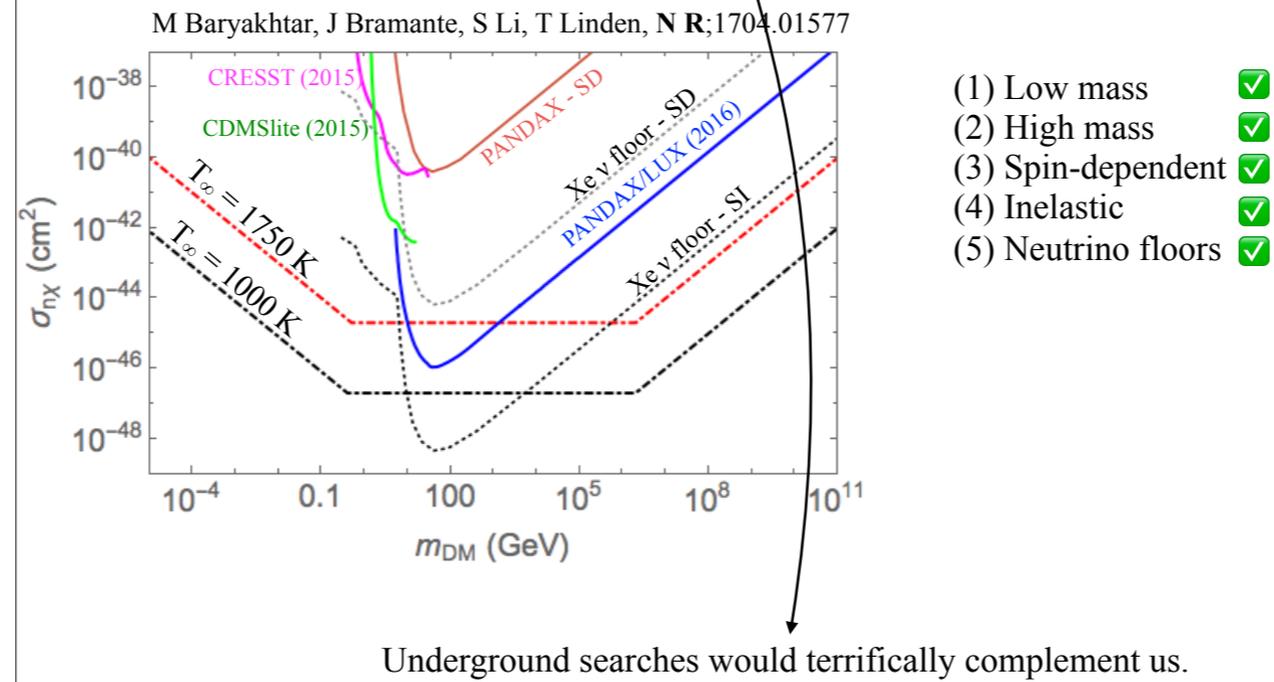
That means Higgsino dark matter is no longer elusive, and can totally be revealed by dark kinetic heating.

# Complementing



Finally, at the *neutrino floor frontier*, we operate around the spin-independent neutrino floor in most regions and we *start* below the spin-dependent neutrino floor.

# Complementing



So yeah, we are confident that underground direct detection searches would be an *excellent* complement to dark kinetic heating of neutron stars.

# Takeaways

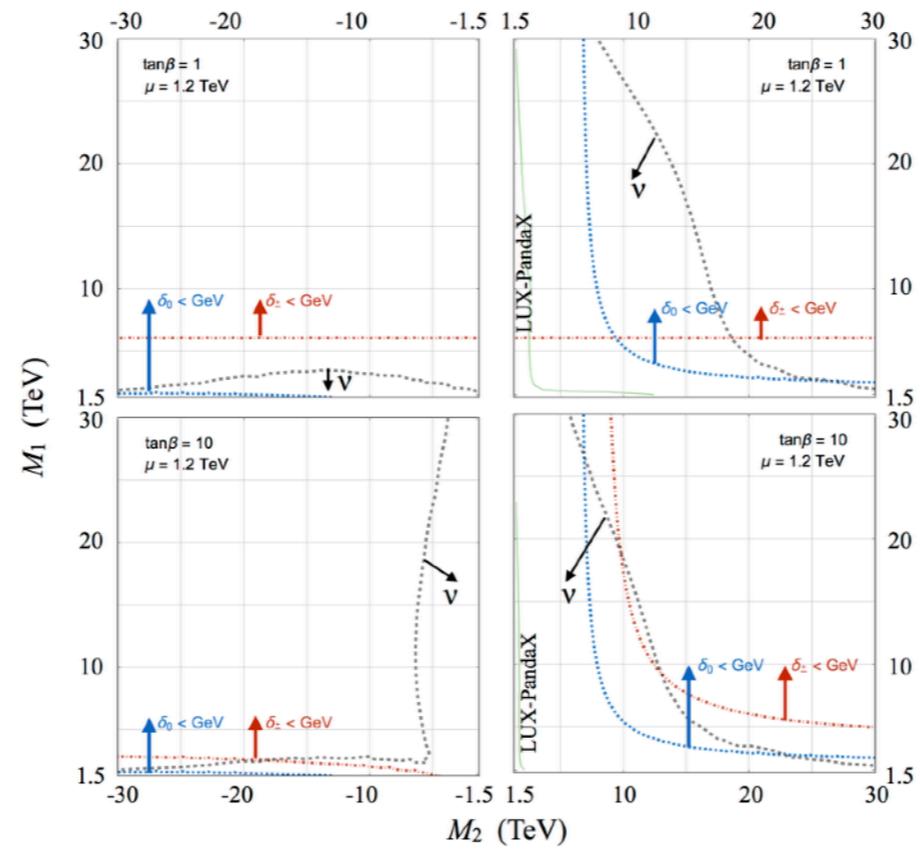
- Dark kinetic heating of neutron stars
  - casts a vast net in the hunt for dark matter - nucleon interactions,
  - seriously advances the direct detection frontiers of
    - low mass* (sub-GeV) ,
    - high mass* (> 100 GeV) ,
    - spin-dependence* ( $\sigma_{SD} > 10^{-45} \text{ cm}^2$ ) ,
    - 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.

In summary, dark kinetic heating should cast a very wide net in dark matter searches and should advance the frontiers of direct detection by orders of magnitude. And we should be able to do it if we in the particle physics community can get our hands on James Webb for a day.

Thank you!

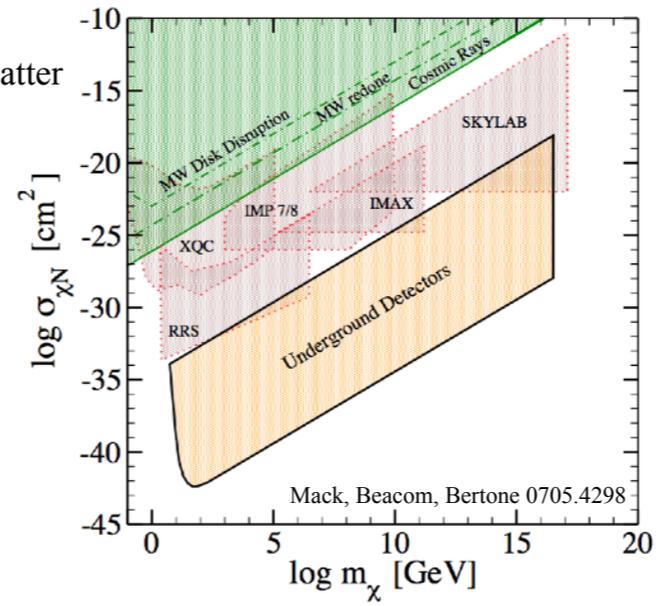
Backup

# Uncovering thermal Higgsinos



# Uncovering “side-stream” DM models

Strongly interacting dark matter



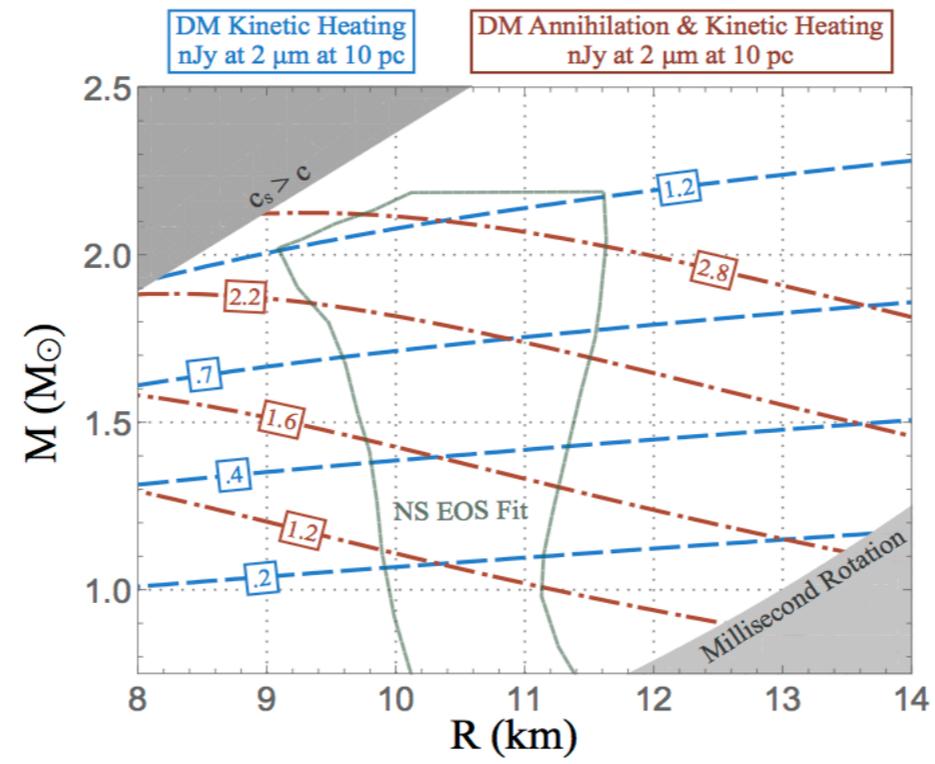
Primordial black holes

Macro objects

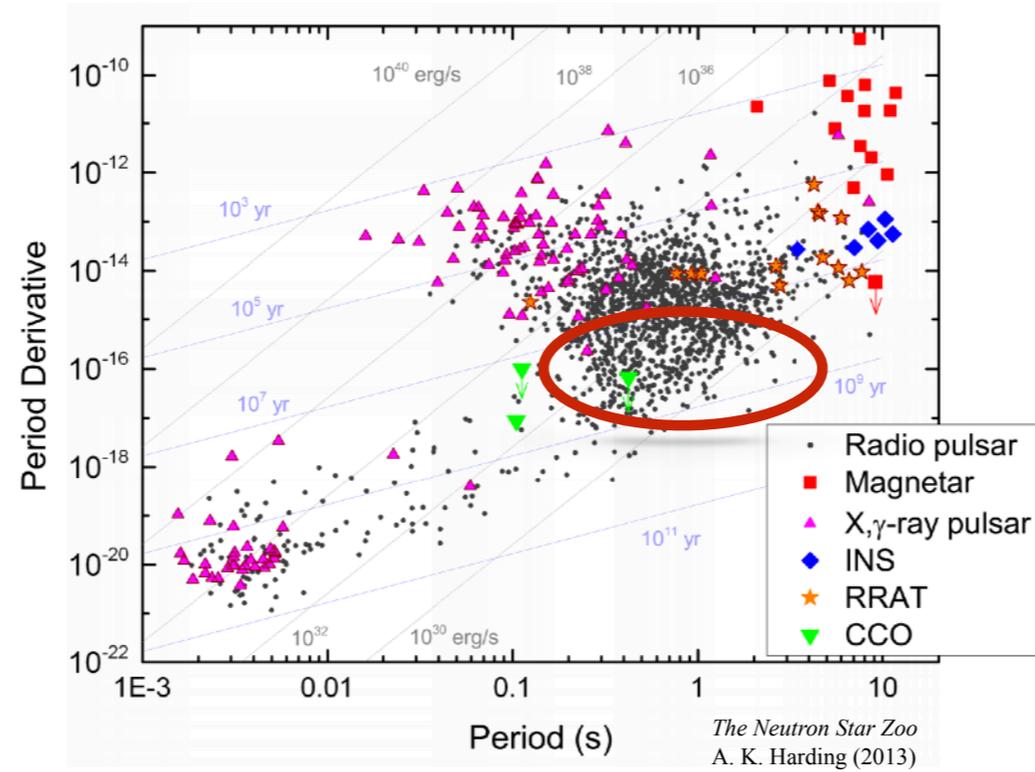
...

# Kinetic vs annihilation heating

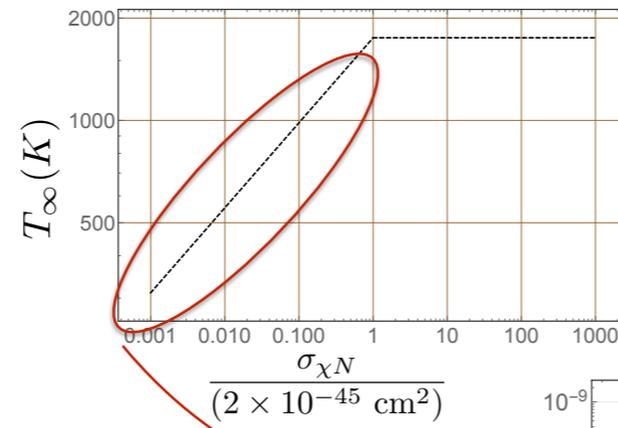
Difference in luminosity spreads



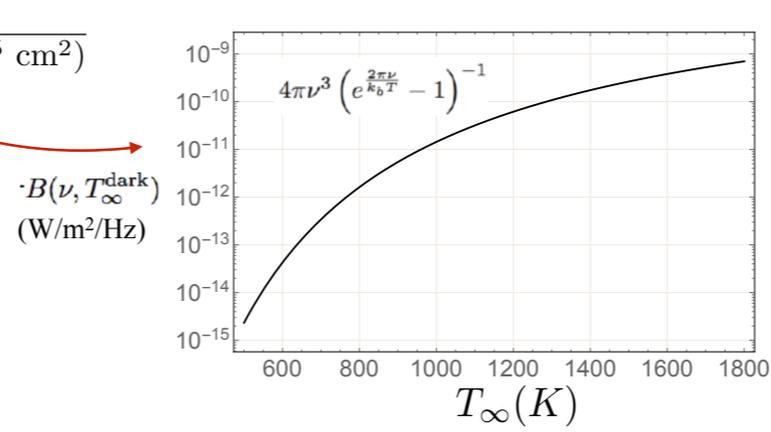
# Detection: radio pulsing



# Detection: infrared telescopes



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.*

I'd like to end my talk with one of my favourite quotes from Shakespeare.

I like this quote more now because Cassius is talking about stars.

Cassius, in 'Julius Caesar'

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

But now I also wonder if he misspoke.