Title: Revealing Dark Matter With Imploding Pulsars, White Dwarf Explosions, and Warm Neutron Stars

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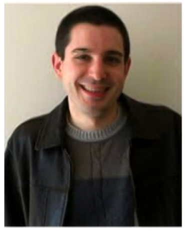
Abstract: <p>I will first show that a number of persistent astrophysical puzzles, including missing pulsars in the galactic center, fast radio bursts, the abundance of r-process elements, and the type Ia supernova progenitor problem, may all be an emerging signature of dark matter. I will address some theoretical implications and new astrophysical phenomena -- for example "quiet kilonovae" and "r-process donuts" -- associated with this dark matter. Then, I will describe a newly discovered effect, that dark matter crashing into neutron stars warms them to infrared temperatures detectable with the Thirty Meter, European Extremely Large, and James Webb Space telescopes.</p>

Revealing Dark Matter With Imploding Pulsars, White Dwarf Explosions, and Warm Neutron Stars

Joseph Bramante
Perimeter Institute
Perimeter Colloquium

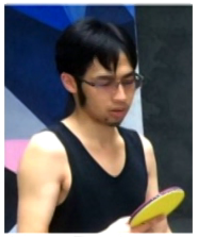

Tim
Linden


Fatemeh
Elahi


Nirmal
Raj


Masha
Baryakhtar


Shirley
Weishi Li


Yu-Dai
Tsai


Jason
Kumar

based on:

- JB Linden 2014, 2016
- JB Elahi 2015
- JB 2015
- JB Fox Kribs Martin 2016
- Baryakhtar JB Li Linden Raj 2017
- JB Linden Tsai 2017

Imploding Pulsars

e.g. Goldman, Nussinov, Bertone, Fairbairn, Kouvaris, Tinyakov, McDermott, Yu, Zurek, Baldes, Bell, Petraki, Bertoni, Nelson, Reddy, Fuller, Ott

White Dwarf Explosions

Graham, Rajendran, Varela

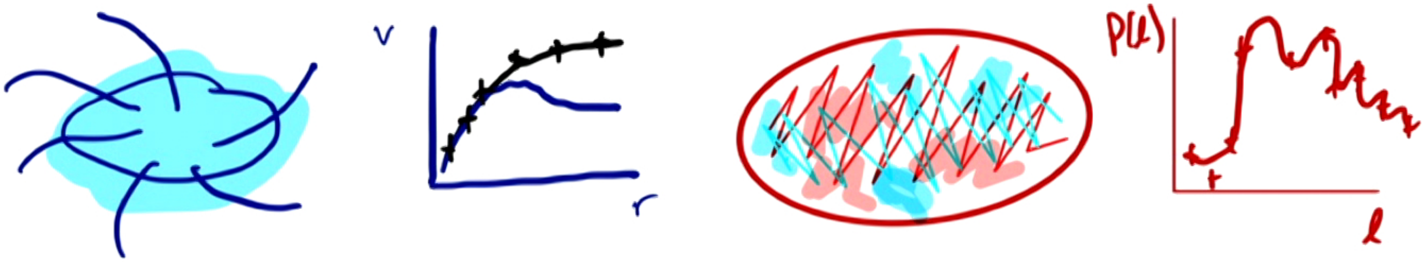
My work: Direct detection, **collider phenomenology**, connecting **inflation and low energy** particle physics.

Today:

1. Some emerging evidence that dark matter may implode pulsars, ignite Type Ia supernovae
2. New astrophysical signatures of an atomically productive dark sector
3. Detecting dark matter using dark kinetic heating of pulsars and telescopes

Unifying principle: search for dark sector connections to visible sector (σ_{nx})

For over 40 years, dark matter seen in gravitational interactions



Emerging evidence for dark matter interactions with neutron stars and white dwarfs

1. Missing pulsars in Milky Way's center
2. Fast radio bursts
3. Abundance of r-process elements
4. Ignition of Type Ia supernovae
5. *Quiet kilonovae and r-process donuts

Dark Matter Imploding Pulsars in the Galactic Center

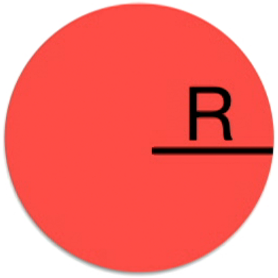
1. Asymmetric dark matter can implode pulsars.

2. Dark matter more abundant in the galactic center, collects in and implodes pulsars faster than by Earth.

JB, Linden 2014
JB, Elahi 2015

Neutron Stars

(or any ball stabilized against collapse by quantum pressure)



virial theorem | $\langle U \rangle \sim \langle T \rangle$

$$N = \frac{M_*}{m_n}$$

To find $\langle T \rangle$, we need to know momentum of fermions:

Pauli degenerate momentum

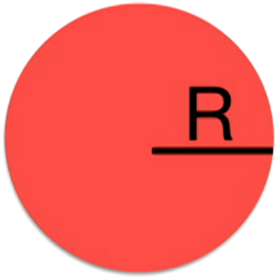
density of deg. fermions $\sim \frac{N}{R^3}$

$$p \sim \frac{1}{\Delta x} = \text{linear density} \sim \frac{N^{1/3}}{R}$$

Heisenberg uncertainty

Neutron Stars

(or any ball stabilized against collapse by quantum pressure)



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virial theorem $\Big| \; \langle U \rangle \sim \langle T \rangle$

Pauli degenerate momentum $\Big| \; \frac{GM_*^2}{R} \simeq N \frac{N^{2/3}}{2m_n R^2} \longrightarrow \boxed{p \sim \frac{1}{\Delta x} = \text{linear density} \sim \frac{N^{1/3}}{R}}$

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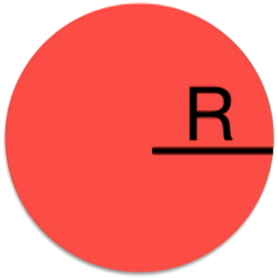

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degenerate
momentum $$\Big|\ \frac{GM_*^2}{R} \simeq N\frac{N^{2/3}}{2m_nR^2} \longrightarrow \boxed{p \sim \frac{1}{\Delta x} = \text{linear density} \sim \frac{N^{1/3}}{R}}$$

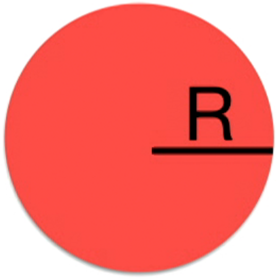
-Immediately find deep physical properties

$$R \propto \frac{1}{N^{1/3}}$$

More massive degenerate stars
are smaller, denser

Neutron Stars

(or any ball stabilized against collapse by quantum pressure)



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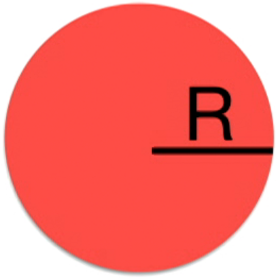
$$\boxed{p \sim \frac{1}{\Delta x} = \text{linear density} \sim \frac{N^{1/3}}{R}}$$

max degeneracy momentum is relativistic $\dfrac{GM_*^2}{R} \simeq N \dfrac{N^{1/3}}{R}$

How heavy can it be?
Relativistic momentum
implies $\langle T \rangle \sim Np$

Neutron Stars

(or any ball stabilized against collapse by quantum pressure)



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max degeneracy
momentum is
relativistic

$$\frac{GM_*^2}{\cancel{R}} \simeq N \frac{N^{1/3}}{\cancel{R}}$$

$$\boxed{M_* \lesssim \frac{M_{\rm pl}^3}{m_{\rm n}^2} \sim M_\odot}$$

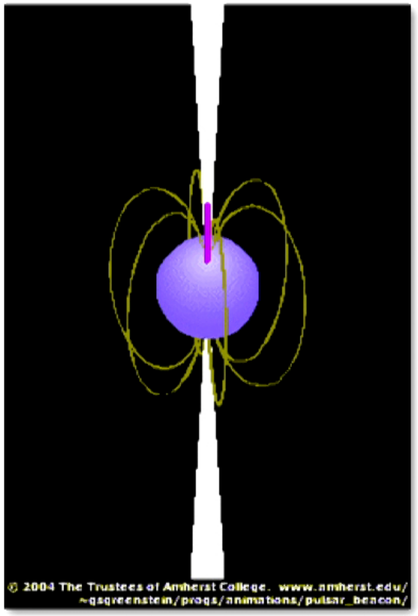
Find mass of neutron star!
(Solar mass —hmm, sun not
supported by degeneracy.)

Pulsars

-Rotating, neutron stars with magnetic dipole

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

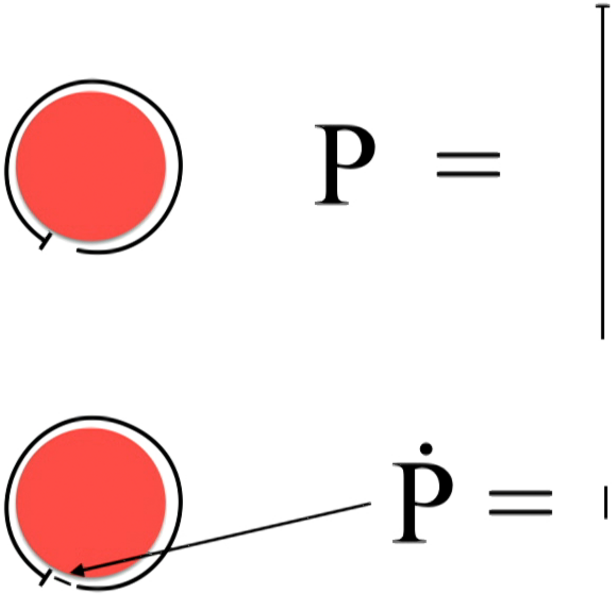
-Pulsed radio emission along the magnetic dipole axis



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

Pulsars

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

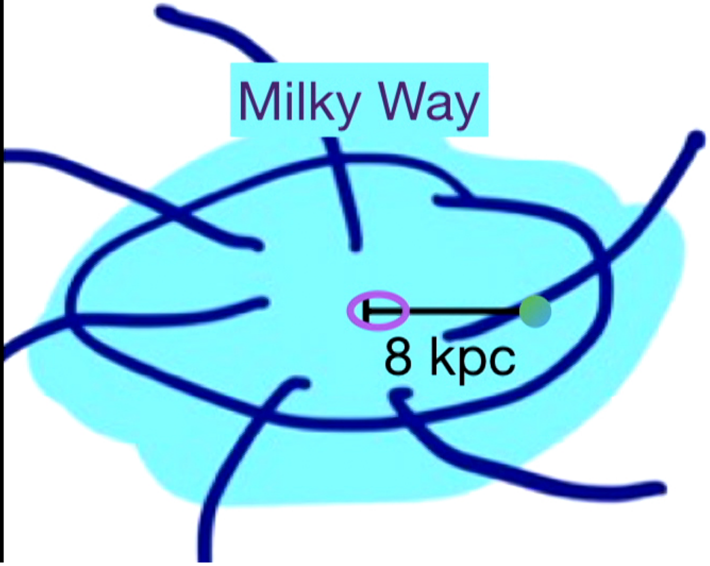


$P =$

$\dot{P} =$

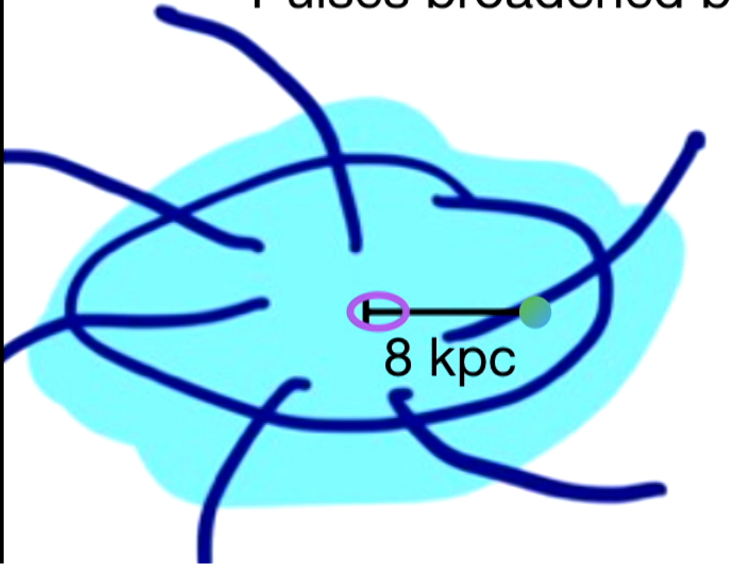
Missing Pulsars

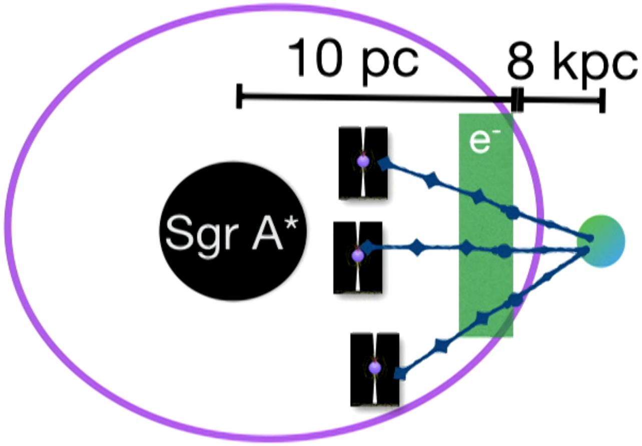
- Many pulsars expected at galactic center
- Up to 10^3 pulsars expected in central parsecs
- Only a few ~10^4 year old magnetars found so far



Missing Pulsars

- Many pulsars expected at galactic center
- Up to 10^3 pulsars expected in central parsecs
- Only a few ~10^4 year old magnetars found so far
- Pulses broadened by electron scattering?





Where are the galactic center pulsars?

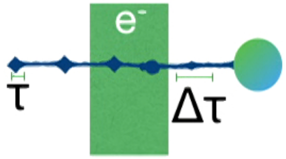
Dexter, O’Leary
1310.7022

Where are the galactic center pulsars?

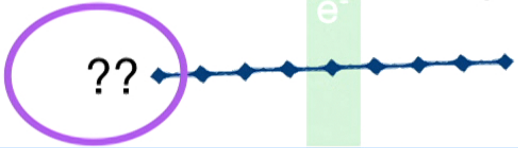
1. Temporal pulse broadening scales with the ~fourth power of observation frequency

$$\Delta\tau \sim 1\ \mathrm{s}\left(\frac{\mathrm{Ghz}}{\nu}\right)^{4}$$

2. Magnetars (B~10^{14} Gauss) found in the central parsec, allow for exact (multi-freq.) measurements of temporal pulse broadening from the galactic center

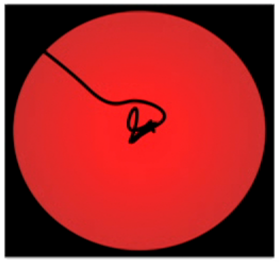


3. Based on these measurements, we should have already seen up to ~50 millisecond period and ~50 "standard" period pulsars



Dark Matter Imploding Pulsars

1. DM captured

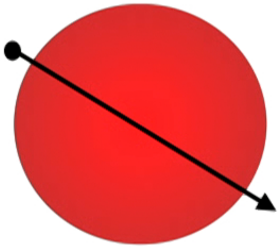


capture rate $C_X \propto \frac{\rho_x \sigma_{nx}}{v_x}$

$$= \frac{\text{DM density} \times \text{DM-nucleon cross section}}{\text{DM velocity}}$$

v_x velocity
ρ_x density
in MW halo

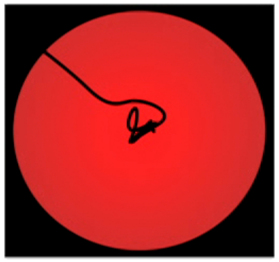
more pulled in
by neutron
star grav
potential
for small v_x



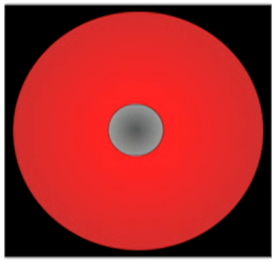
σ_{nx}
determines
whether DM
scatters,
gets trapped

Dark Matter Imploding Pulsars

1. DM captured



2. DM thermalizes



3. DM collapses

DM will collapse to a black hole if it

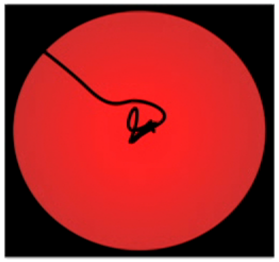
1. Self-gravitates $\rho_{DM} > \rho_{ns}$

2. Exceeds its own degeneracy pressure

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

Dark Matter Imploding Pulsars

1. DM captured



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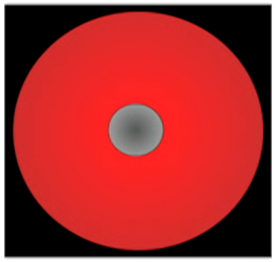
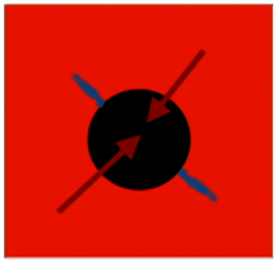


3. DM collapses

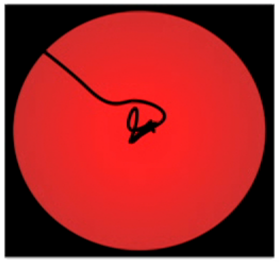
4. BH consumes neutron star



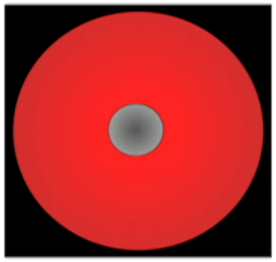
Bondi accretion
faster than
Hawking radiation

Dark Matter Imploding Pulsars

1. DM captured



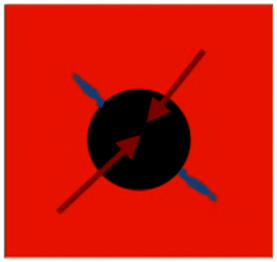
2. DM thermalizes



5. **Form solar mass BH**

3. DM collapses

4. BH consumes neutron star



Asymmetric Dark Matter Implodes Pulsars

-Suppose dark matter (like ordinary matter) composed of particles and not antiparticles of some symmetry.

$$\enclose{circle}{\phi}\,\phi^* \quad \text{or} \quad \enclose{circle}{\psi}\,\bar{\psi}$$

-Dark asymmetry can be linked to baryon/lepton asymmetry.

-Dark matter asymmetry allows efficient collection and collapse in stars without annihilating to lighter particles.

-Annihilation is forbidden by the conserved dark asymmetry.

Dark matter that implodes pulsars

X

~GeV mass, asymmetric dark fermions — degeneracy pressure stabilizes up to a solar mass of dark matter.

Dark matter that implodes pulsars

✗ ~GeV mass, asymmetric dark fermions — degeneracy pressure stabilizes up to a solar mass of dark matter.

m_X

✓ **KeV-PeV**

Bosonic dark matter without repulsive self interactions — requires very small effective quartic ($\lambda < 10^{-15}$).

Some of best bosonic DM Constraints
JB, Kumar, et al. 2013

Dark matter that implodes pulsars

✗

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m_x

KeV-PeV

✓

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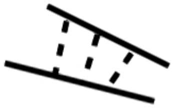
Some of best bosonic DM Constraints
JB, Kumar, et al. 2013

MeV-PeV

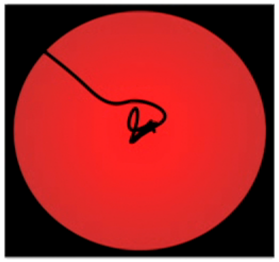
✓

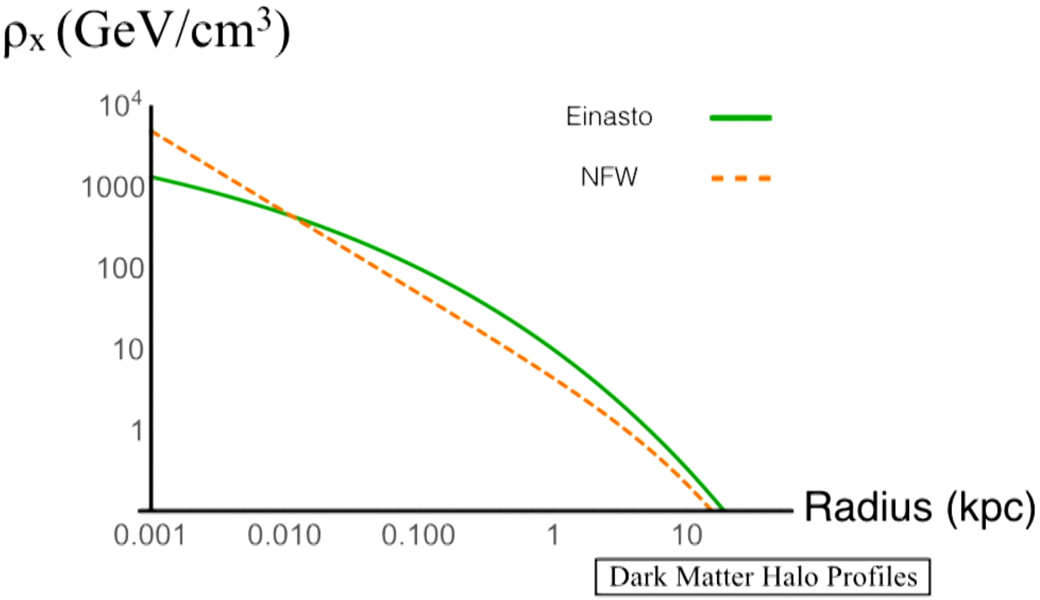
Higgs portal dark matter with ~MeV scalar portal mediator provides attractive Yukawa force that prompts collapse.



Some of best Higgs Portal Constraints
JB,Elahi 2015

Dark Matter Capture in MW



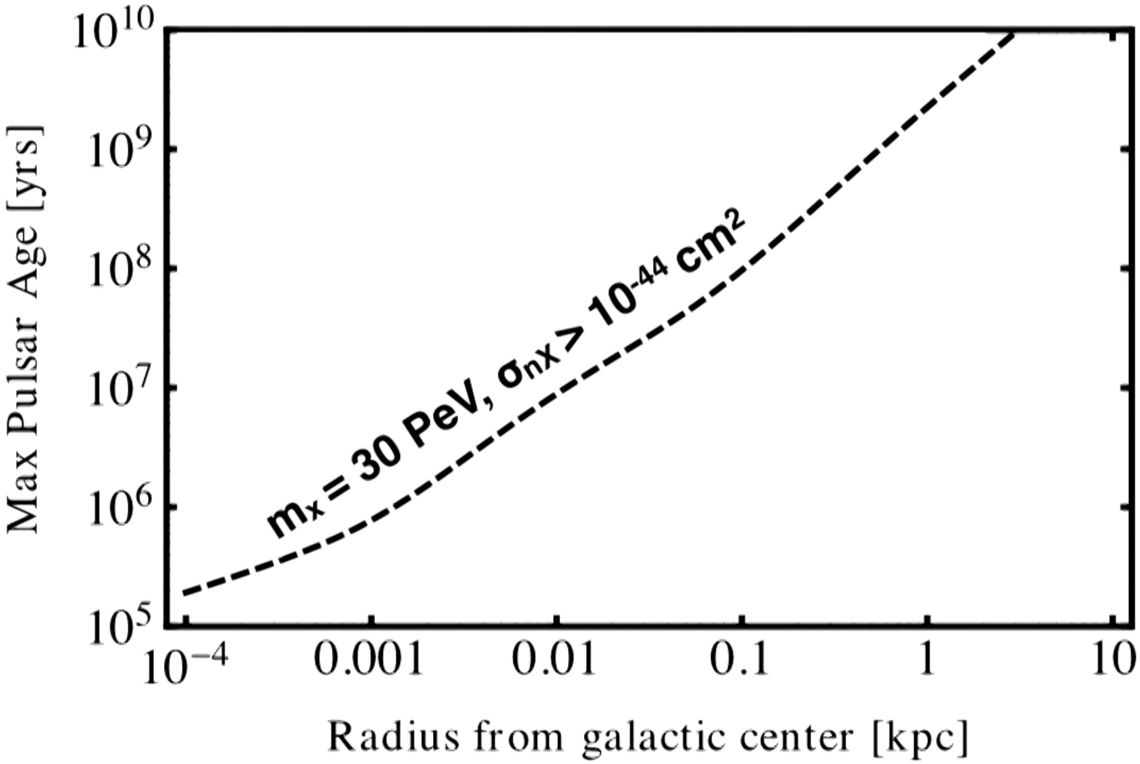


DM capture
in Milky Way:

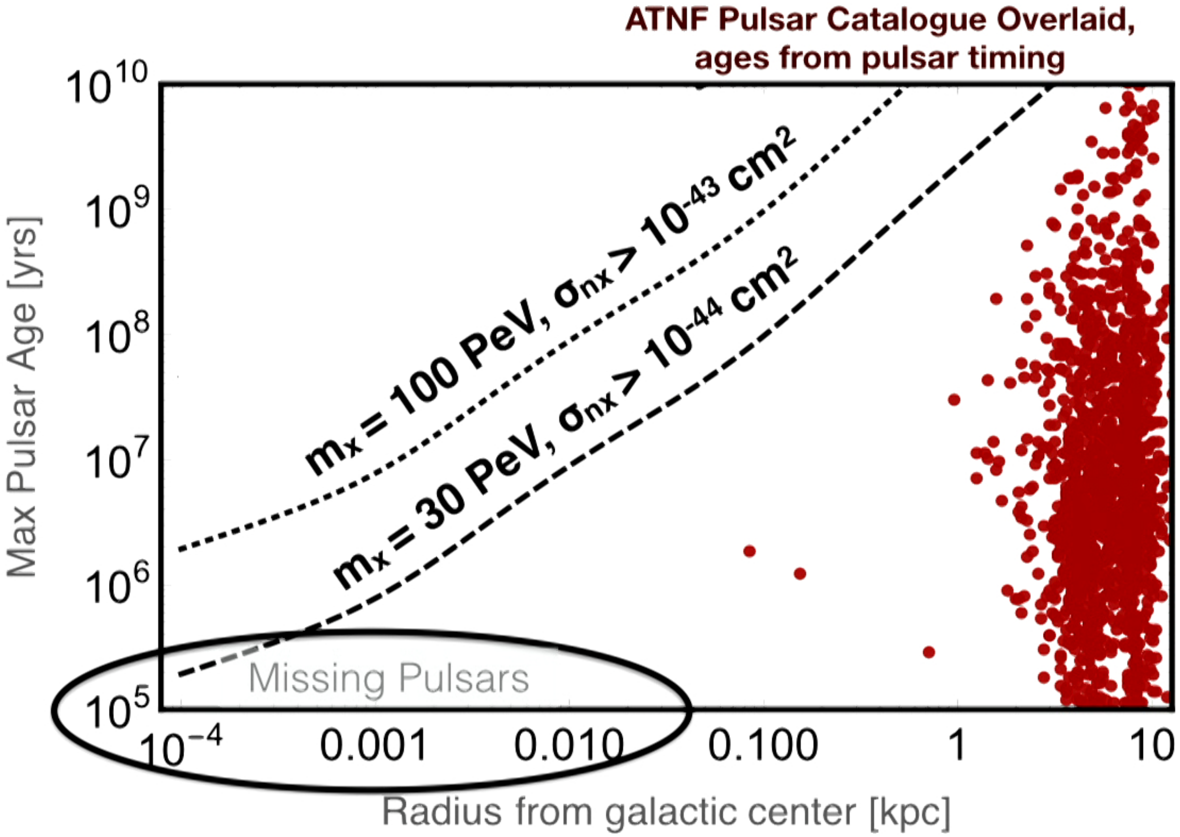
$$C_x \propto \frac{\boxed{\rho_x}}{v_x}$$

More dark matter captured in the center of galaxies
➜so pulsar implosions occur there more rapidly.

Dark Matter and Maximum Pulsar Age Curves



Dark Matter and Maximum Pulsar Age Curves



-Milky Way's 1-500 pc center surveyed in the next decade by FAST, SKA.

R-Process Elements from Pulsar Implosions

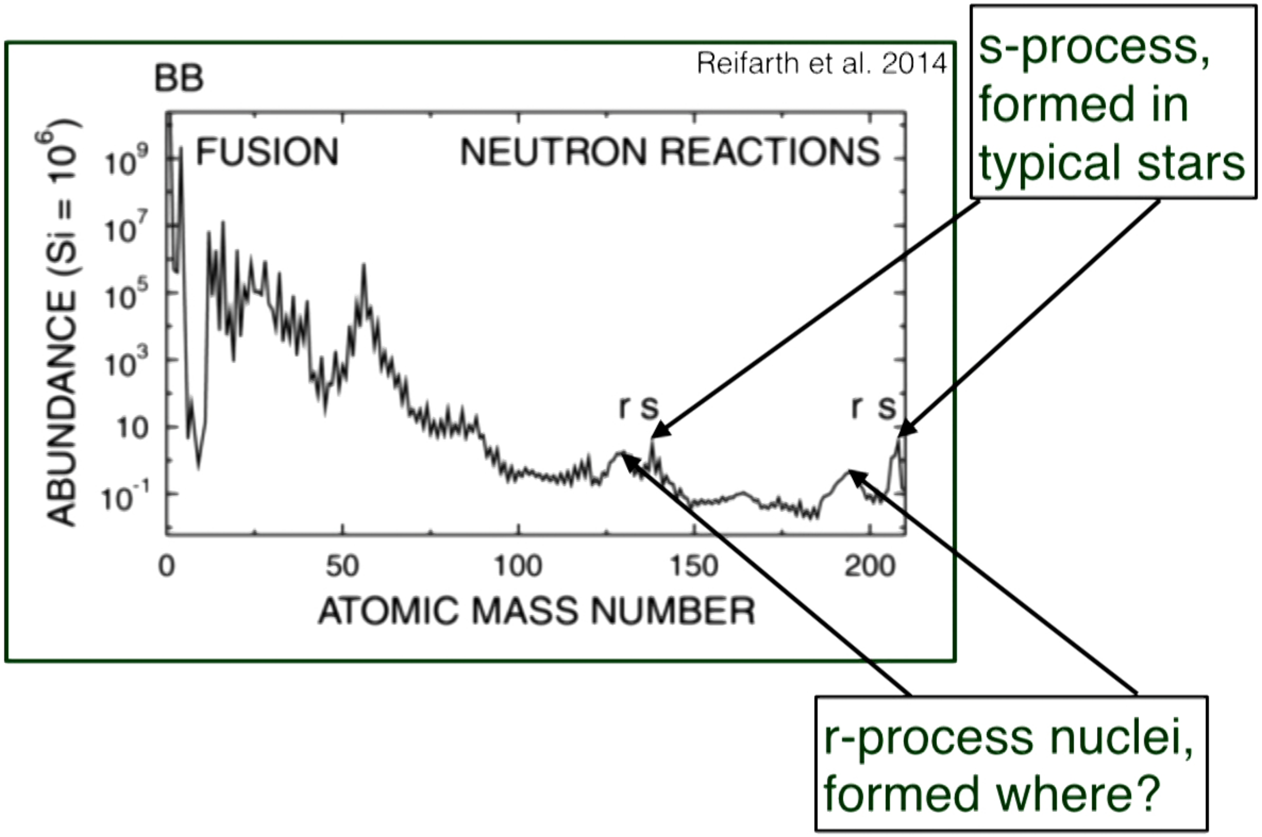
1. Imploding neutron stars eject neutron star fluid that forms heavy r-process elements.

2. DM-induced neutron star implosions can explain why r-process elements are in just one of ten dwarf galaxies.

JB Linden 2016

-R-process elements: heavy elements with atomic masses around ~80, ~130, ~195

-Formed in an as-yet-undetermined astrophysical sites rich in neutrons

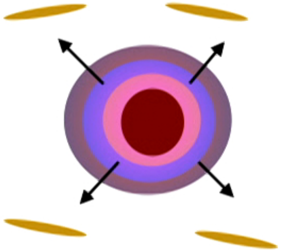


Reifarth et al. 2014

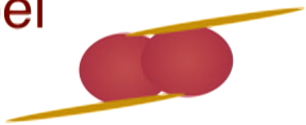
s-process, formed in typical stars

r-process nuclei, formed where?

Possible r-process sites — total 10^4 $M_\odot$ produced in Milky Way



-Neutrons ejected by neutrino wind during core collapse supernovae (frequent, ~1/100 years)



-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)

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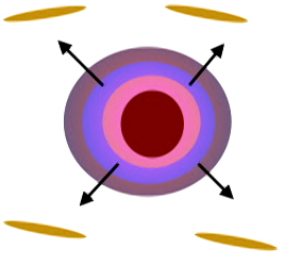

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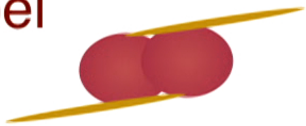

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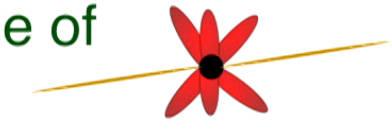
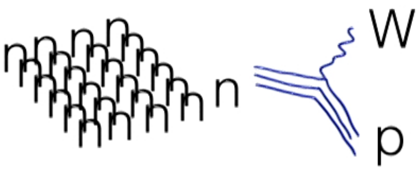


-Neutron star slurped into a black hole made of dark matter at its core.

implosion
tidally spurts
neutron fluid

In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.



… Gold, Uranium, Europium, Barium…

R-process in Ultra Faint Dwarf Galaxies

-Alexander Ji, grad student — "go look for r-process elements in ultra-faint dwarfs"

-Ultra faint dwarfs are star-poor dwarf galaxies formed in a billion year burst ~10 billion years ago

R-process in Ultra Faint Dwarf Galaxies

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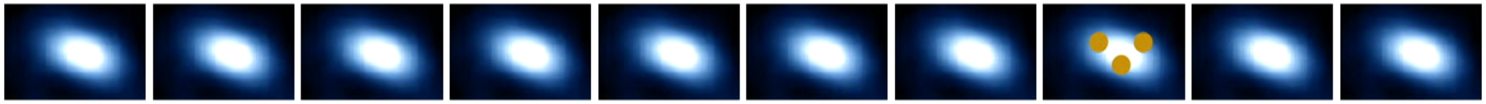
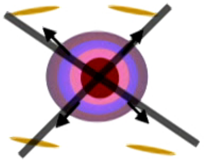
-Ultra faint dwarfs are star-poor dwarf galaxies formed in a billion year burst ~10 billion years ago

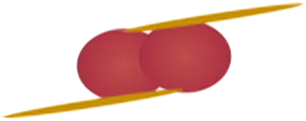
-Found just one with high r-process abundance — low r-process abundance expected in all ultra faint dwarfs



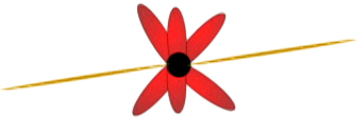
One UFD with r-process, and 9 without, implies rare r-process events.



many CCSN



few NS mergers

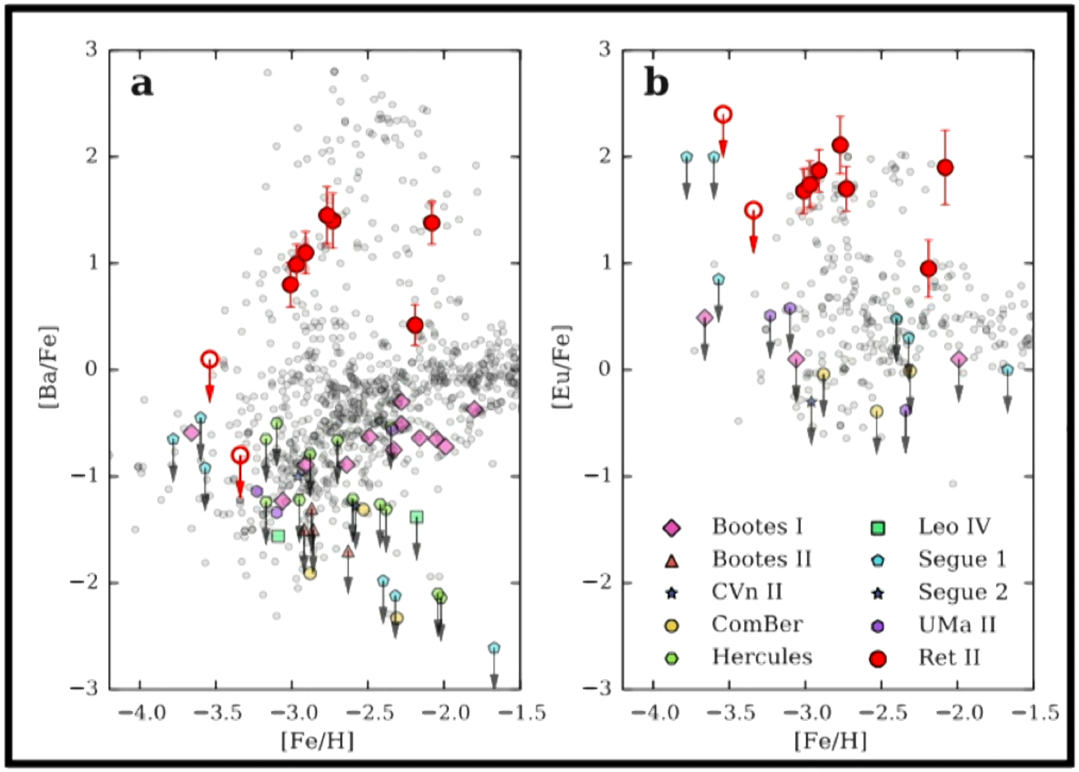


few implosions

Plot of r-process in dwarfs — grey points are MW stars

→ [X/Y] is log(X/Y) abundance.

→ Ba, Eu are r-process elements, [Fe/H] grows with age



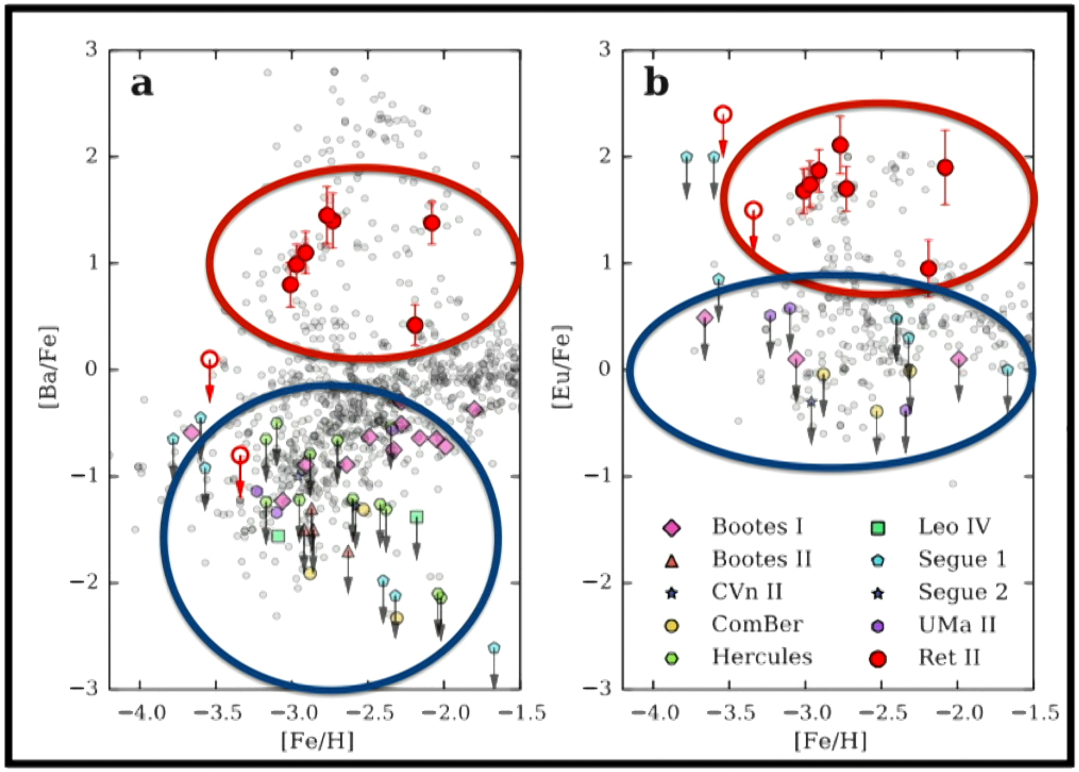
Plot of r-process in dwarfs — grey points are MW stars

→ [X/Y] is log(X/Y) abundance.

→ Ba, Eu are r-process elements, [Fe/H] grows with age

Reticulum II high r-process abundance

Other dwarfs, low r-process abundance



Unexpectedly high r-process abundance in Reticulum II
-indicates r-process from rare event

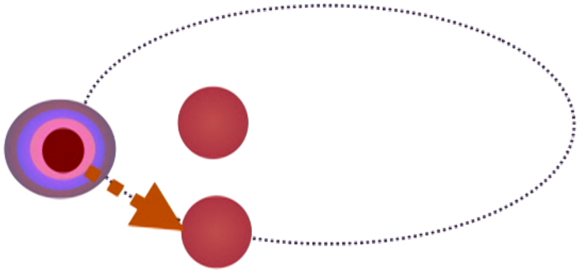
Reticulum II r-process from NS-NS merger?

**Neutron stars kicked at birth ~100 km/s.

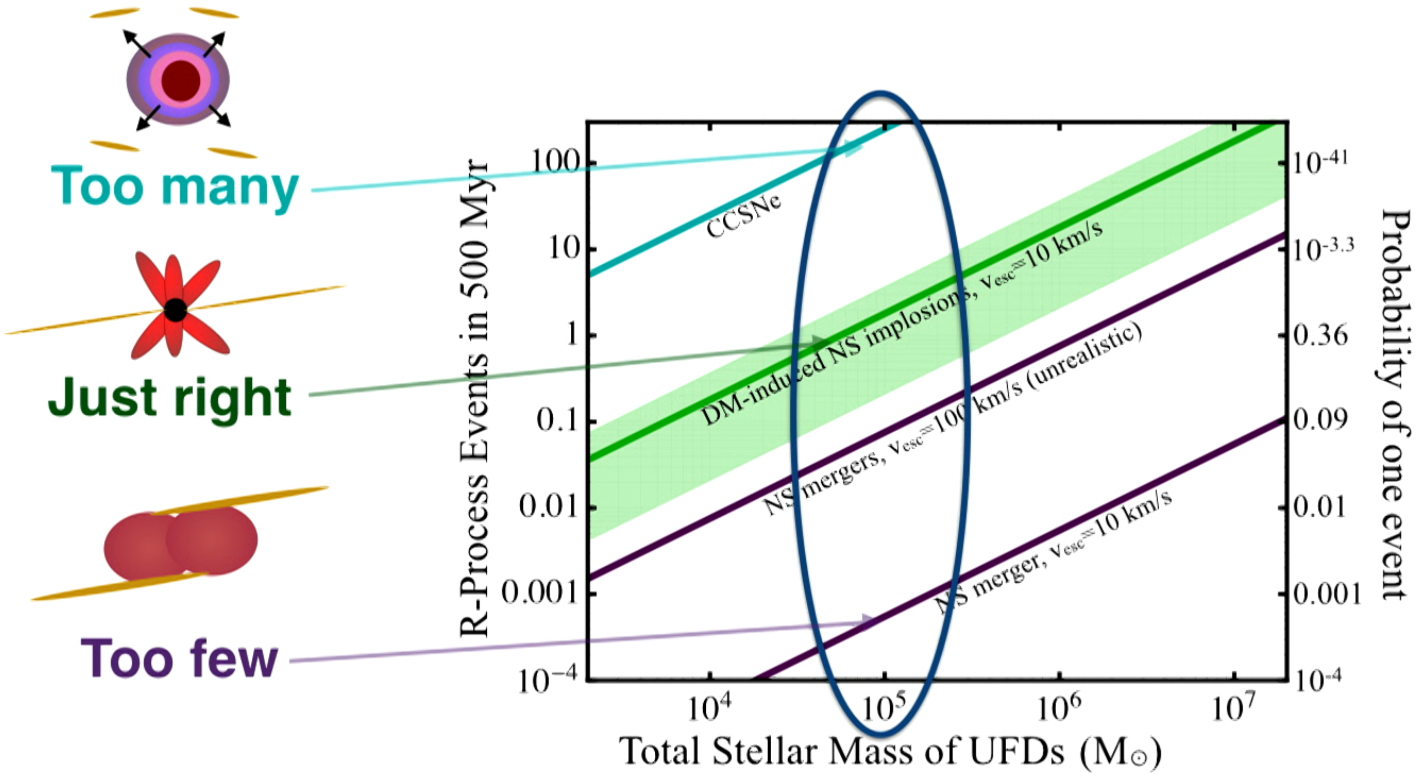
**This kicks NS binary system to ~50 km/s.

**Merging neutron stars are ejected from dwarf spheroidals

—Reticulum II escape velocity <10 km/s.



UFD r-process rates

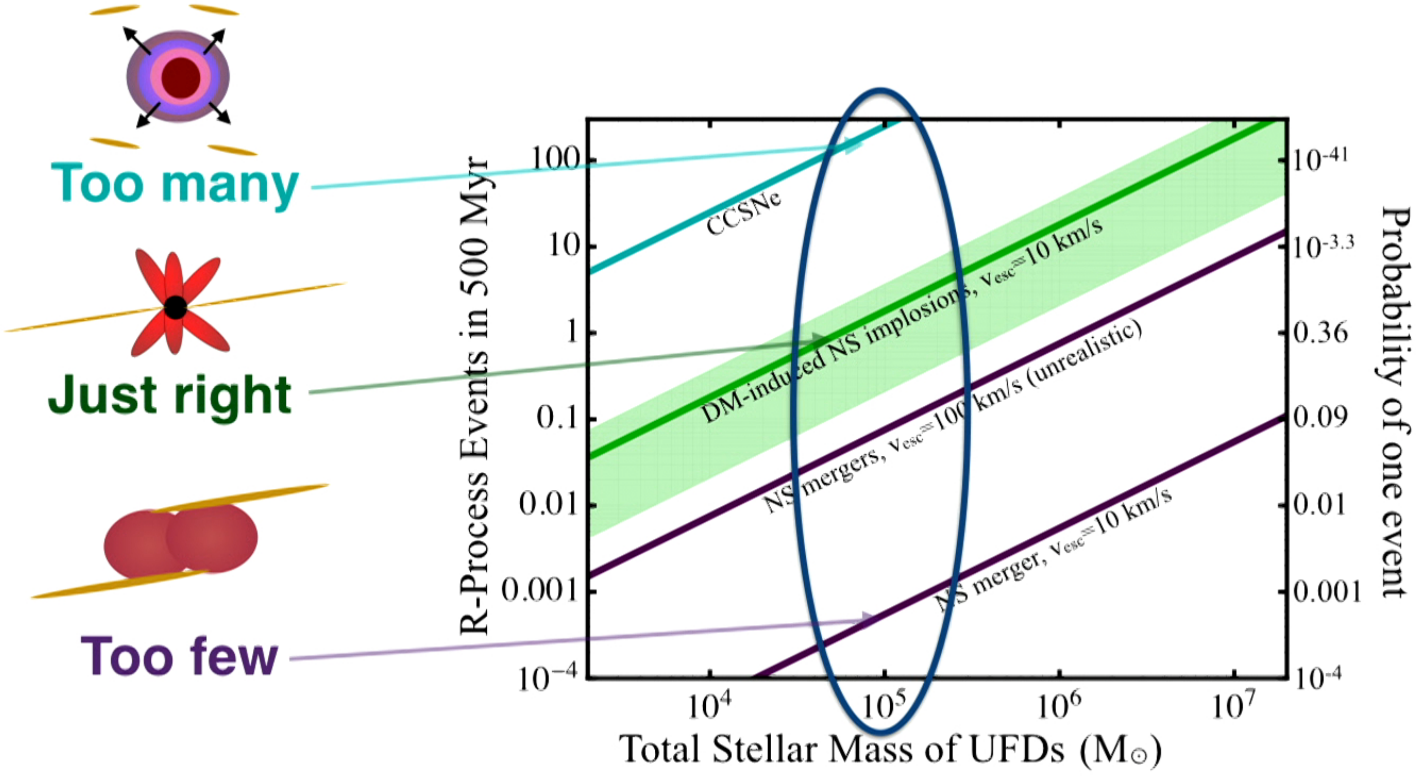


Too many

Just right

Too few

UFD r-process rates



Too many

Just right

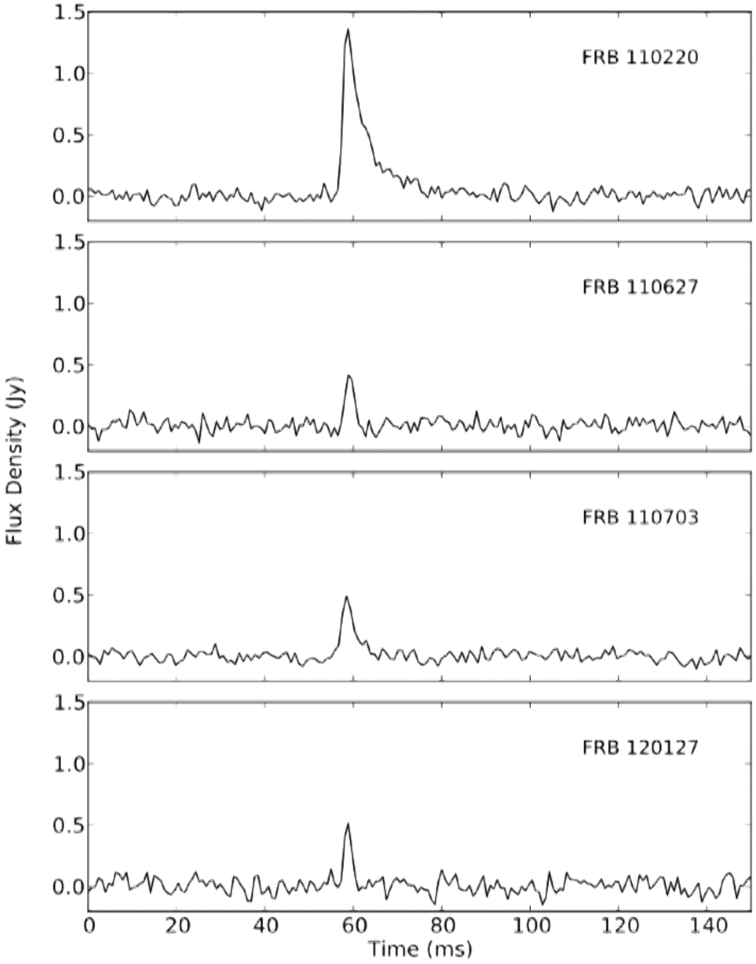
Too few

Fast Radio Bursts from Pulsar Implosions

1. A bunch (10^4/day) of unexplained millisecond-long radio pulses may be pulsar implosions.

2. The rate of fast radio bursts matches missing pulsars at the galactic center.

Fast Radio Bursts



-Unexplained ~ms long radio pulses

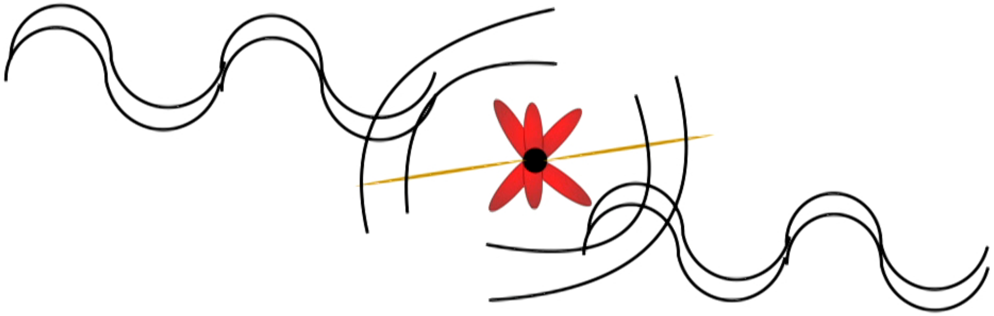
-High rate and power output

-Many applications, cosmology

$$\boxed{R_{\rm FRB} \sim 5 \times 10^{-5}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}}$$

Thornton et al. 2013

Imploding Neutron Stars Shed Magnetosphere



-Power emitted at Ghz frequencies estimated to match fast radio bursts

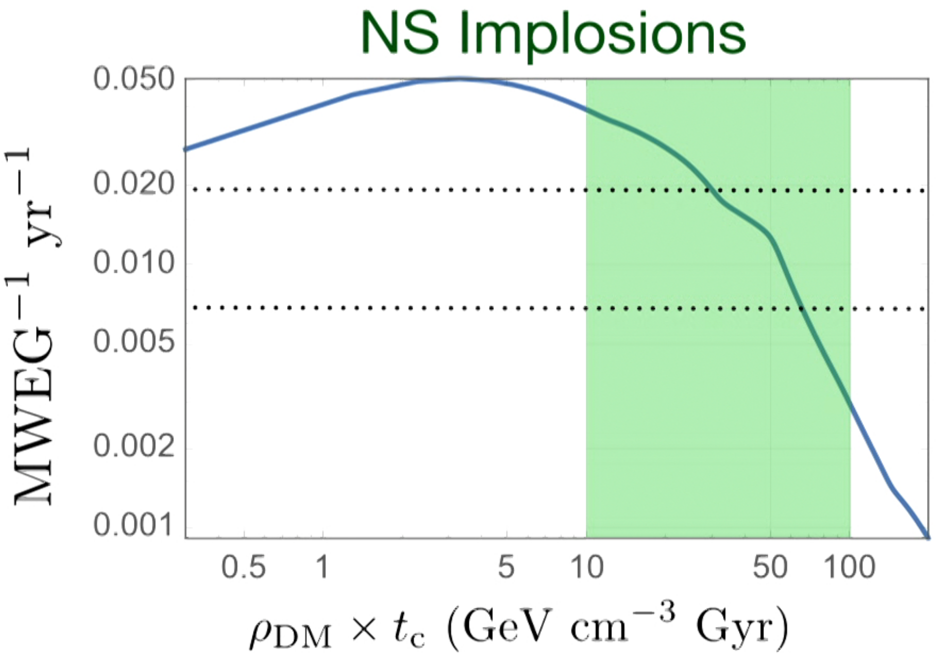
Fuller et al. 2014

-Corroborated by simulations of accretion-induced collapse

Falcke and Rezzolla 2014

NS Implosion Rate matches Fast Radio Bursts

$$\boxed{R_{frb} \sim 10^{-2}\ \mathrm{MWEG}^{-1}\ \mathrm{yr}^{-1} \left(\frac{D}{2\ \mathrm{Gpc}}\right)^{-3}}$$



-Incorporates NS dynamics, birthrates in Milky Way, capture rate for position in galaxy

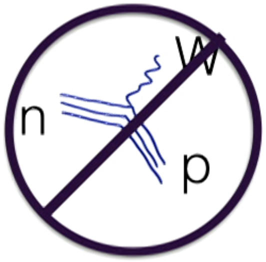
JB, Linden, Tsai 2017

Black Mergers, Quiet Kilonovae,

JB, Linden, Tsai 2017

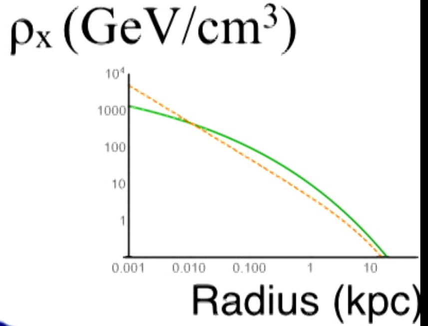
and r-process donuts

Black Mergers,

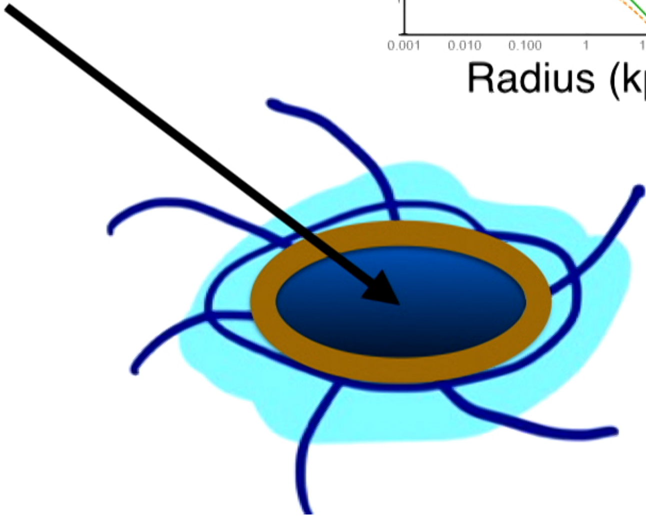


Gravity Waves
From NS mass
mergers

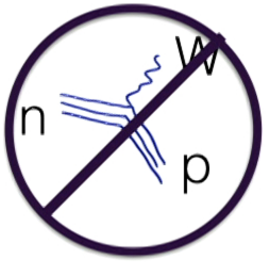
Kilonova: beta decay
of neutron fluid flung
from NS merger
creates a ~days-long
luminous outburst



Black merger: no kilonova accompanies
collapsed NS mergers in galactic interior

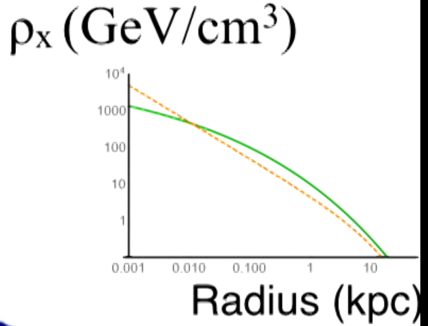


Black Mergers,



Gravity Waves From NS mass mergers

Kilonova: beta decay of neutron fluid flung from NS merger creates a ~days-long luminous outburst



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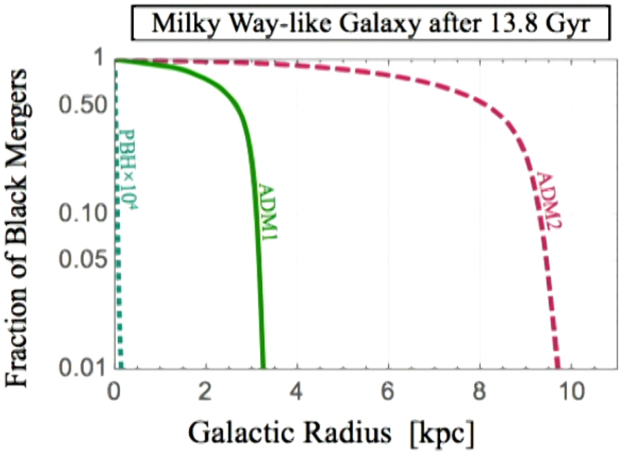
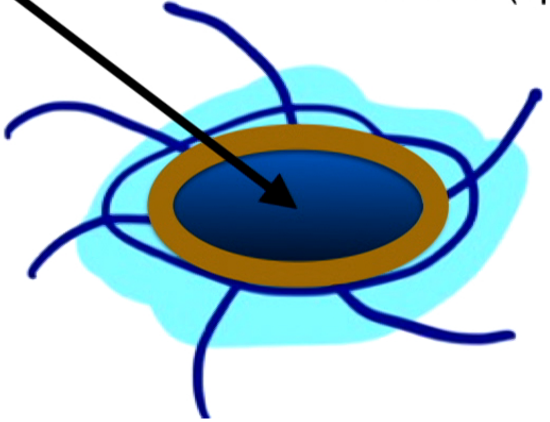
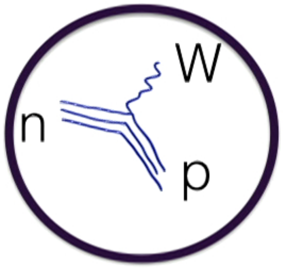


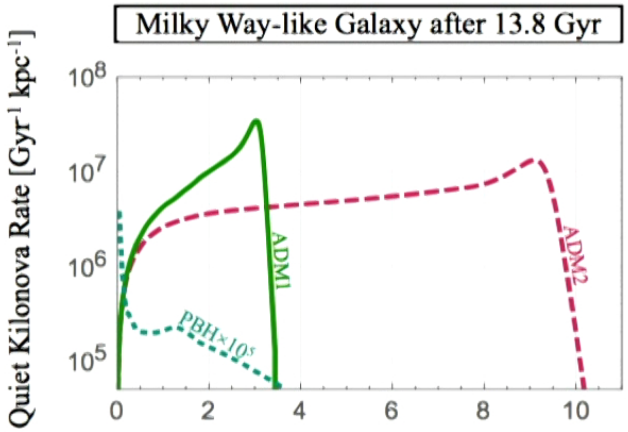


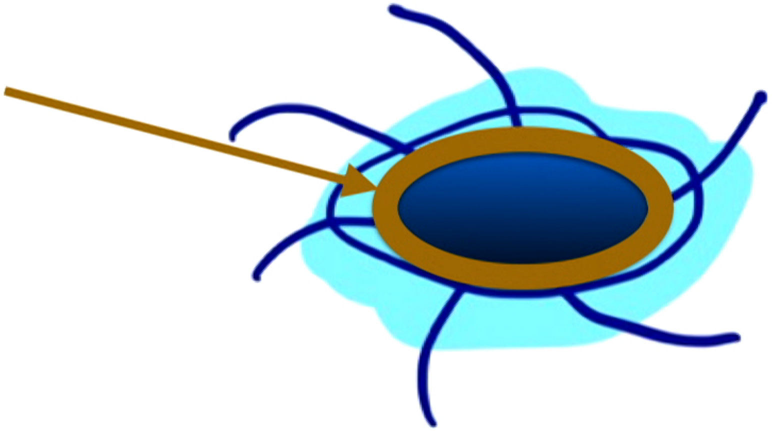
Black Mergers, Quiet Kilonovae,



~~Gravity Waves~~
~~From NS mass~~
~~mergers~~

Quiet Kilonovae: NS implosions create a (less luminous?) kilonova, with no gravity wave signal





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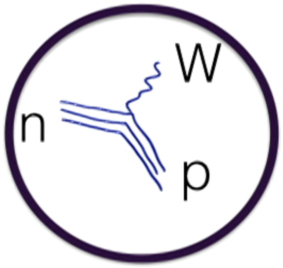


Gravity Waves
From NS mass
mergers

R-Process Donuts: Quiet kilonovae and standard NS merger kilonovae occur in donut shaped external regions of disc galaxies

and r-process donuts

Dark Matter Ignition of Type Ia Supernovae

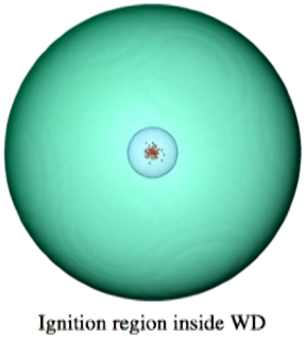
1. Dark matter that implodes pulsars also collapses inside and explodes white dwarfs.

2. This could be the origin of Type Ia Supernovae

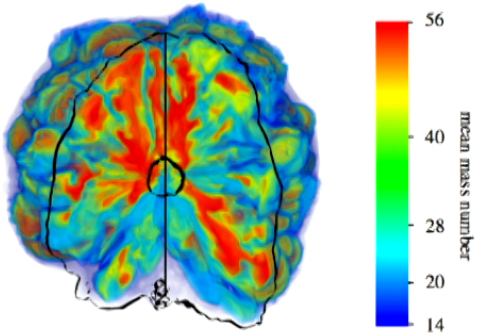
JB 2015

Type Ia supernovae

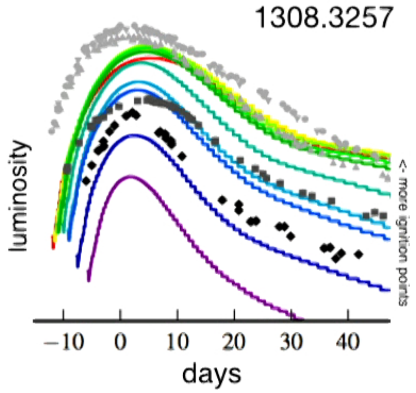
-Standard Story: Thermonuclear flame-front ignited in Chandrasekhar mass (1.4 $M_\odot$) white dwarf



ignition



nuclei fuse (^{56}Ni)



nuclei decay

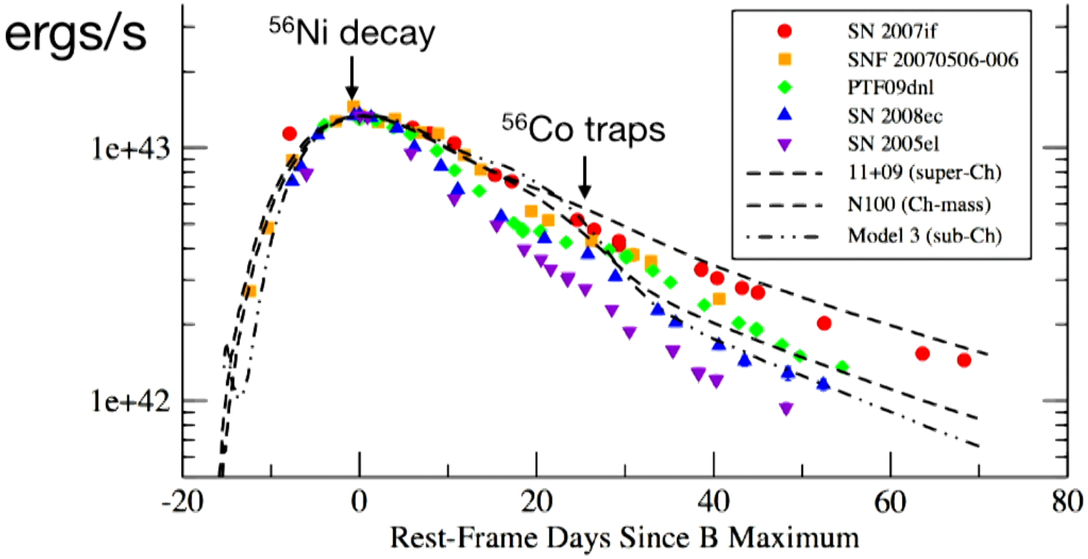
-Decaying nuclei emit light over ~100 days

-Phillips relation: fixed relation between width and height of curve

-Used for measuring Hubble constant, dark energy

Recently, sub-Chandrasekhar (< 1.4 $M_\odot$) type Ia supernovae discovered

-Type Ia progenitor masses found by measuring maximum luminosity (dominated by $^{56}Ni \rightarrow {}^{56}Co$ decay) and the luminosity tail (shaped by ^{56}Co decay and bulk optical trapping)



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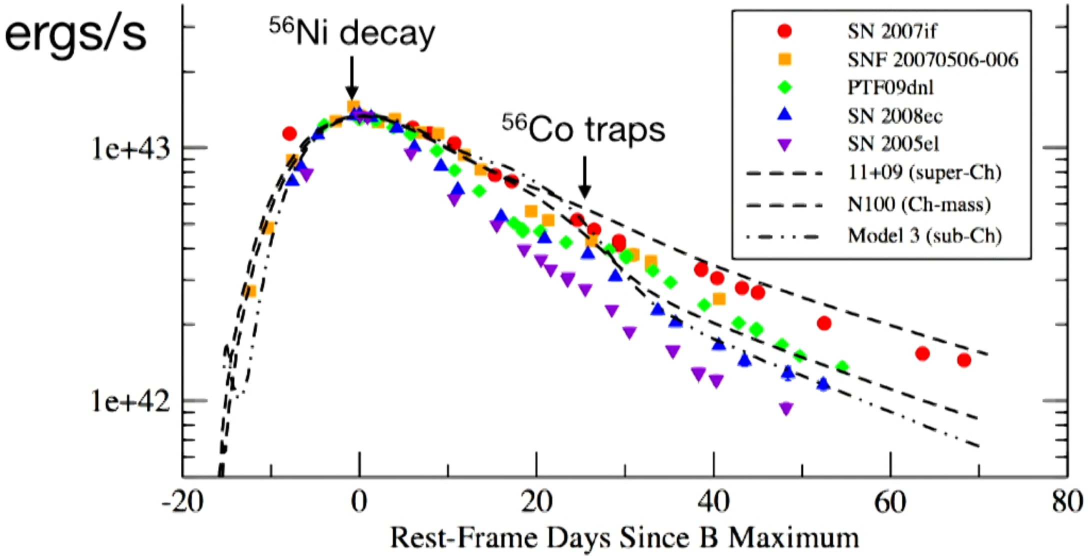


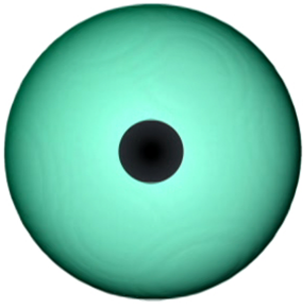
-Sub-Chand. dwarfs can't be ignited by reaching "critical" mass so some other ignition mechanism needed.

$$\boxed{\frac{M_{\rm ej}}{M_\odot} = (1.322 \pm 0.022) + (0.185 \pm 0.018)x_1, \quad x_1 = [-3, 2]}$$

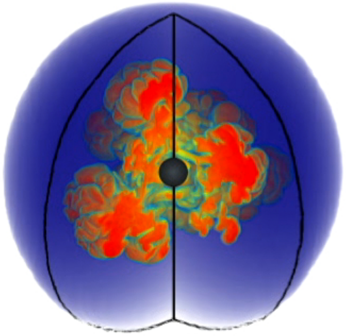
Strizinger et al. 2006, Scalzo et al. 1402.6842, Scalzo Ruiter Sim 1408.6601

Dark Matter Ignition of Type Ia Supernovae

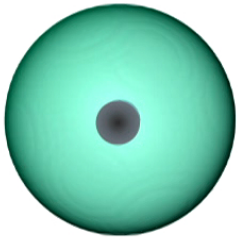
-**Heavy** dark matter thermalizes inside a *small* volume within the white dwarf, and collects to the point of self-gravitation within 10^8–10^9 years.



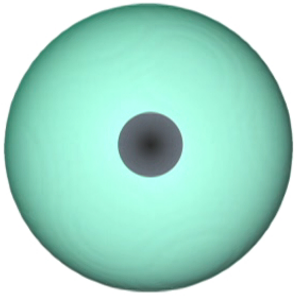
DM collects to the point of self-gravitation.



DM collapses, shedding gravitational potential energy, igniting a SNIa.



more massive WD,
DM collapses sooner



less massive WD,
DM collapses later

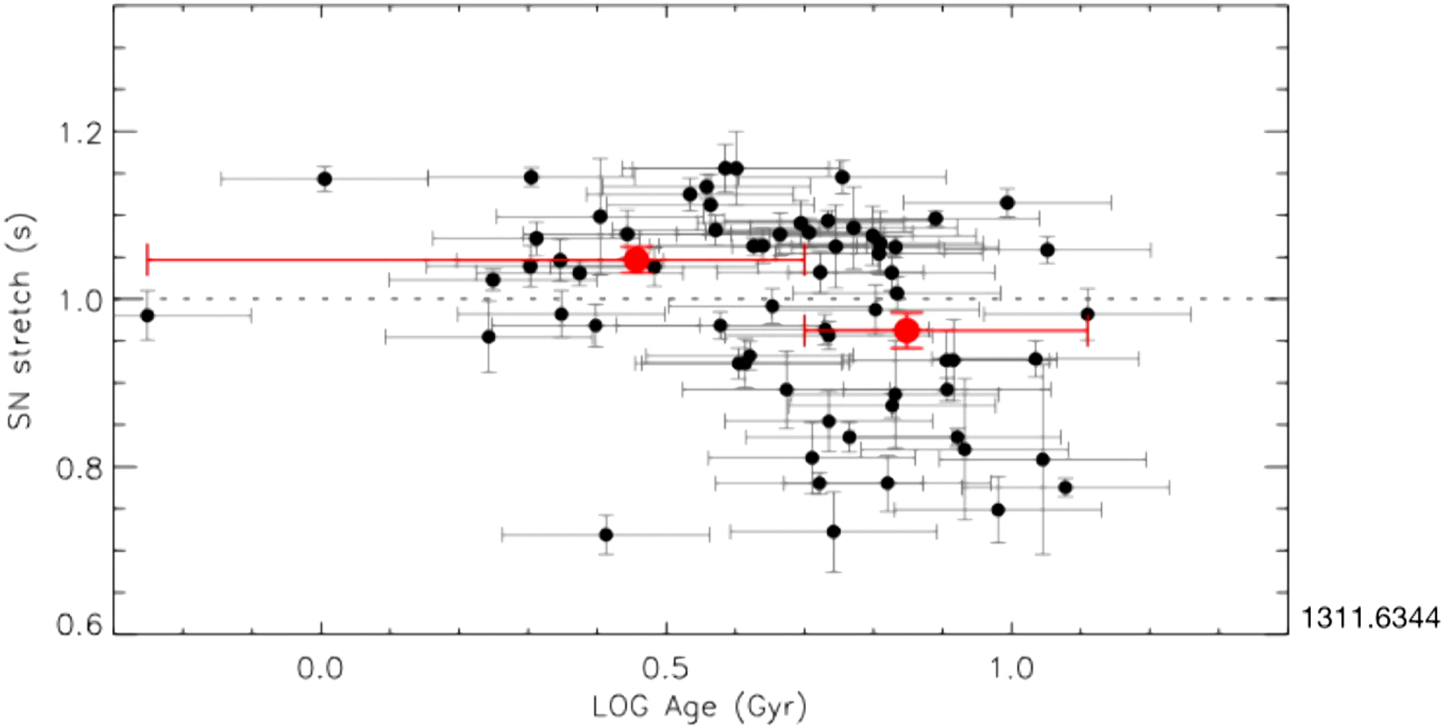
$$r_{th} \propto \frac{\sqrt{T_{wd}}}{\sqrt{\rho_{wd} m_x}}$$

-More massive white dwarf is denser, dark matter collects into a smaller denser ball, and collapses sooner.

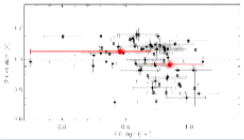
$$R \propto \frac{1}{N^{1/3}}$$

-Also, more massive white dwarfs collect dark matter faster.

-For both these reasons, shorter time for dark matter collapse and ignition in more massive white dwarfs.

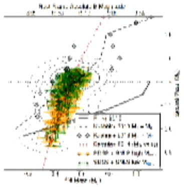


Unexplained correlation between the age of type Ia supernovae host galaxies, and the "stretch" of the type Ia lightcurve.



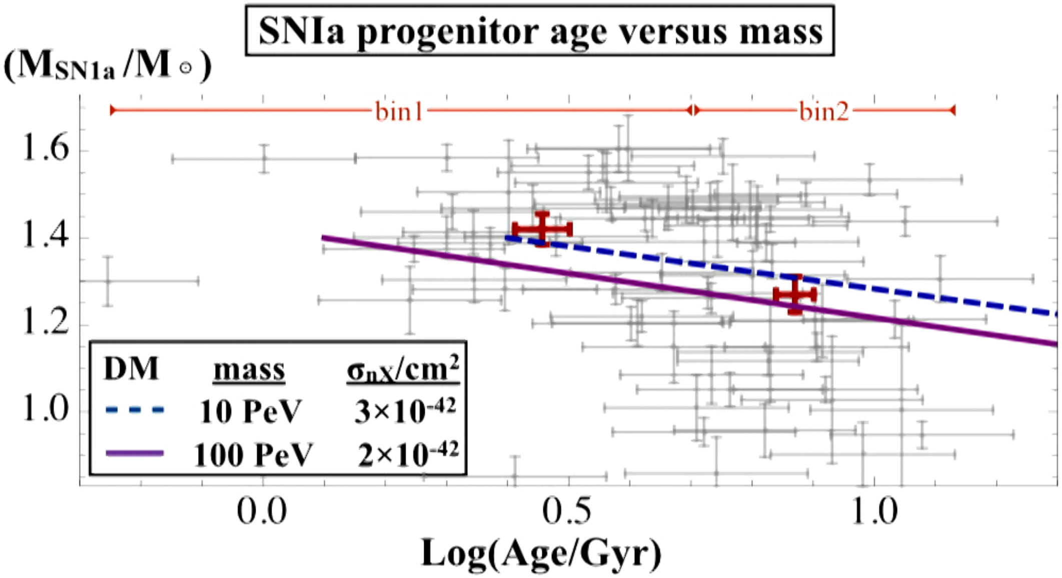
1311.6344

Data on the ages of stars adjacent to type Ia supernovae

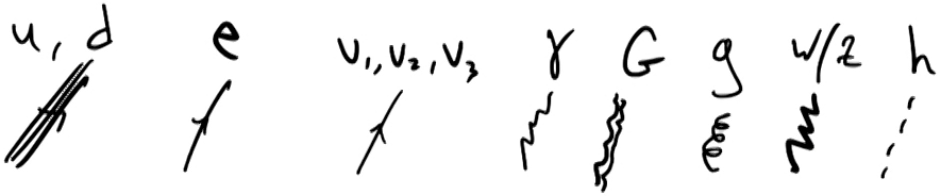


1408.6601

Data on the mass of type Ias inferred from luminosity



Cosmologically Stable Particles + Bosons



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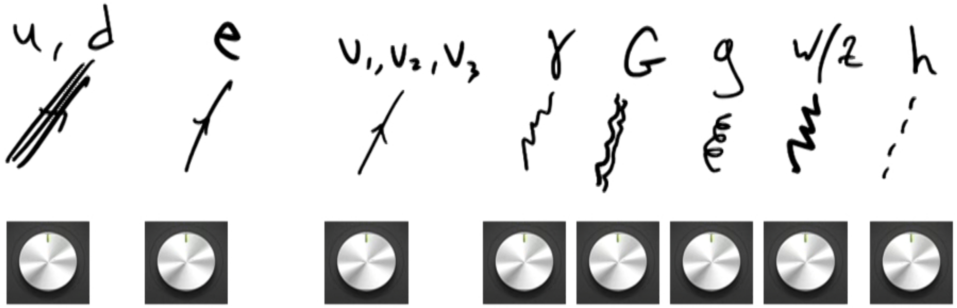
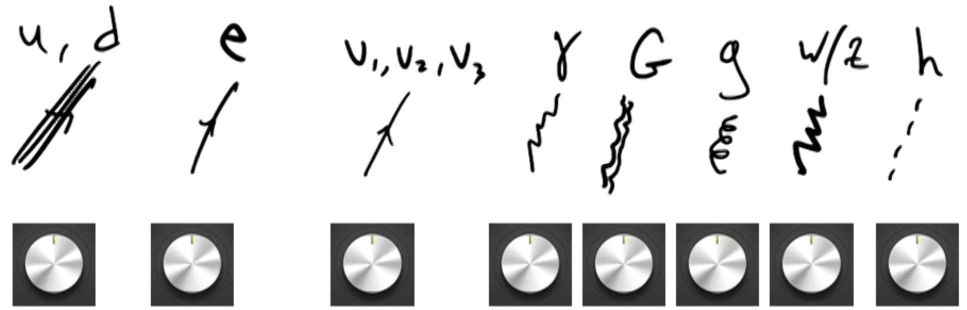


-Tuned towards atomic stability & production in supernovae

-Shift mass or couplings ⇒ supernovae disrupted

Cosmologically Stable Particles + Bosons



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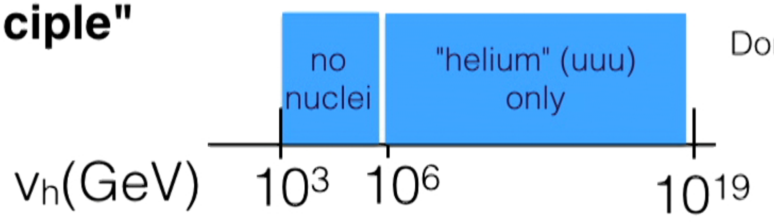
"The Atomic Principle"

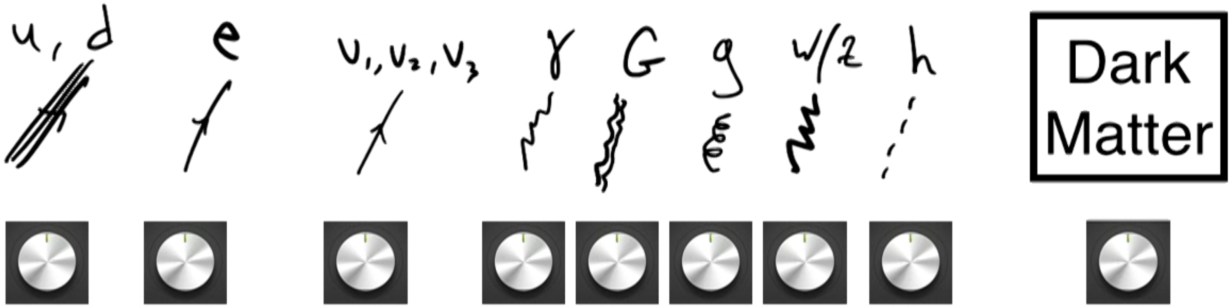


Donoghue et al. '96

If higgs vev heavier, no atoms because $|m_n - m_p| >$ MeV.

Related work by, e.g., Arvanitaki, Bousso Dimopoulos, Gorbenko, Harnik, Johnson, Kribs, Hall, Huang, March-Russell, Perez, Smolin, Susskind, van Tilburg

Cosmologically Stable Particles + Bosons



-Tuned towards atomic stability & production in supernovae

-Shift mass or couplings ⇒ supernovae disrupted

Variation on Atomic Principle

All cosmologically stable matter tuned
for heavy element production.

Technical Naturalness and the Weak Scale

TN: All terms in Lagrangian that preserve symmetries of theory should have O(1) coefficients.

$\delta m_h^2 = \Lambda^2/32\pi^2(6\lambda - y_t^2 + ...)$

(Need new states at Λ to preserve naturalness.)

-Does TN assume scanning? or aesthetics?

Technical Naturalness and the Weak Scale

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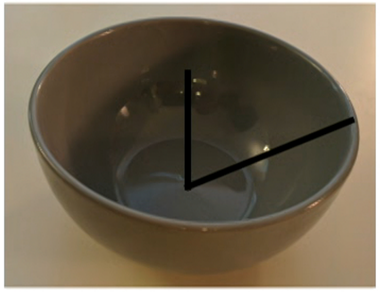
TN universe

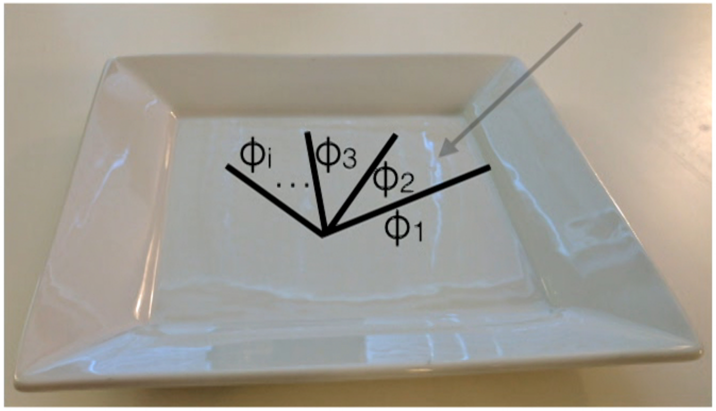


double well

tilted

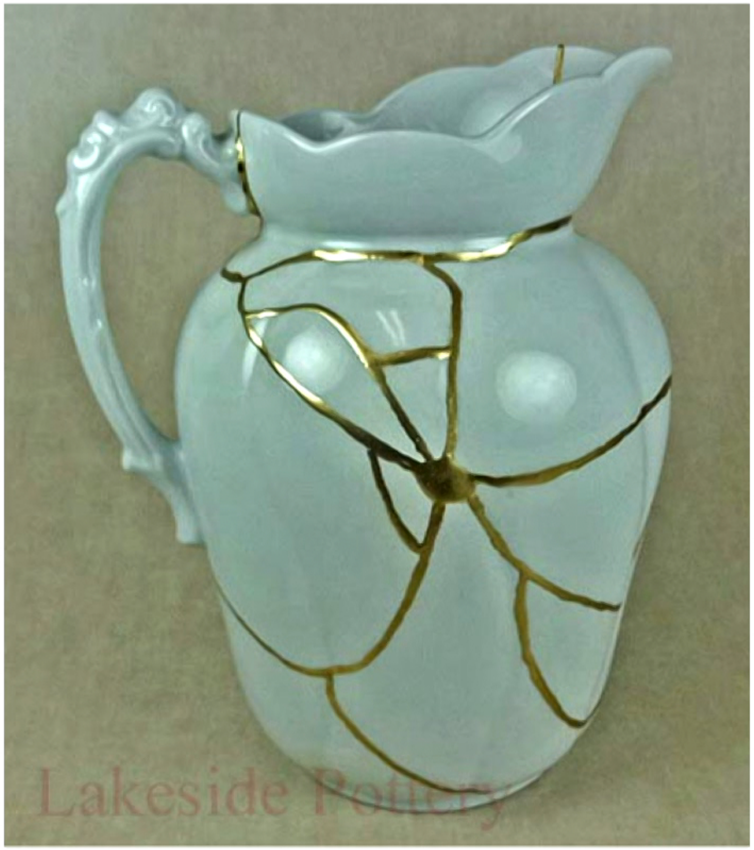
simple, a few broken symmetries
gauge mediation / spontaneous

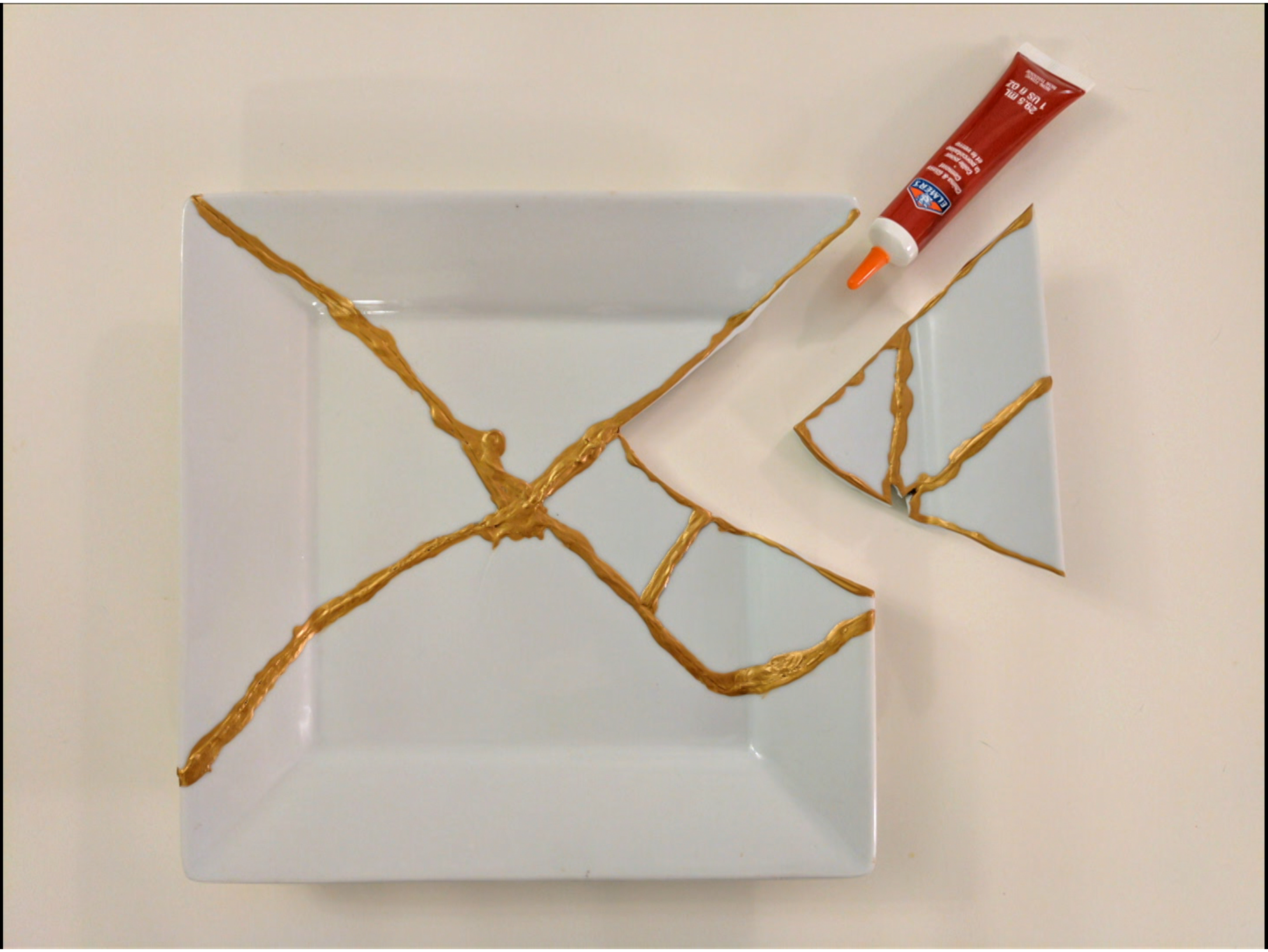
Other universe



messy, obscured minimum
in multidimensional moduli space

Kintsugi: "golden joinery"





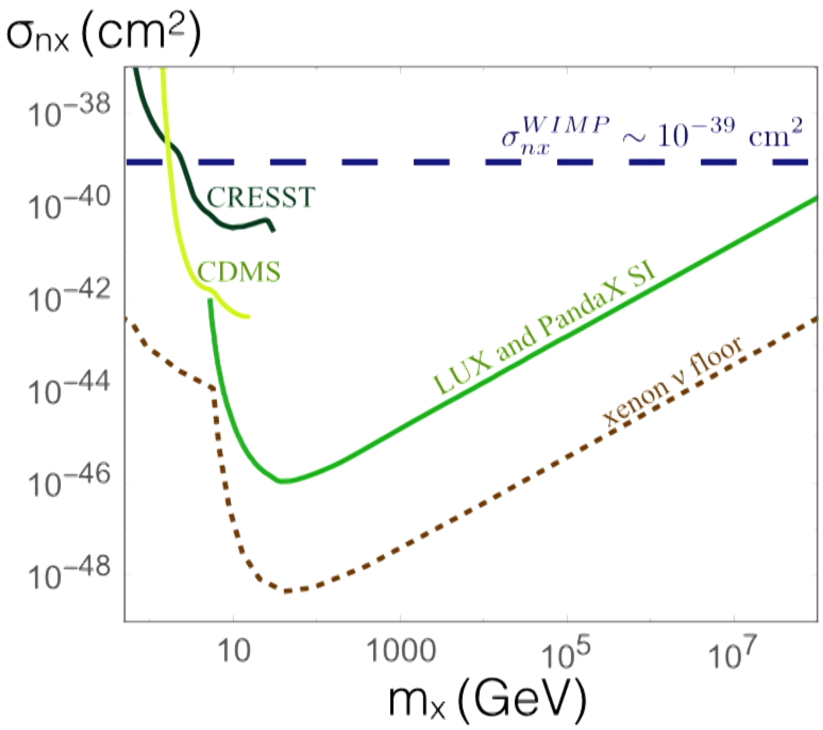
Dark Kinetic Heating of Neutron Stars

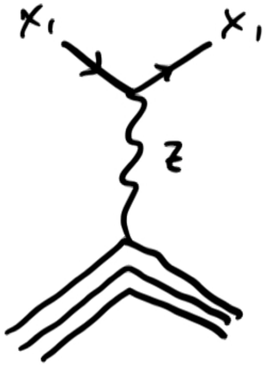
1. New way to search for dark matter!

JB, Baryakhtar, Li, Linden, Raj 2017

Spin-Independent WIMPs

→ Endangered Species



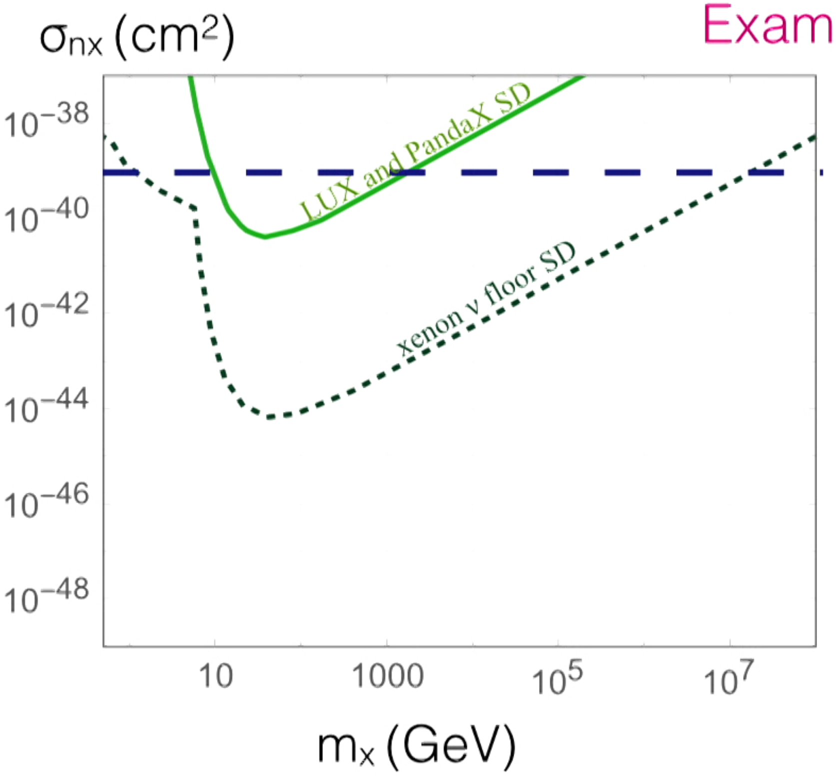


coherent enhancement

$$\sigma_{nx} = \underbrace{\left(\frac{1}{A^2}\right)}_{\boxed{SI}} \frac{\mu_{nx}^2}{\mu_{Nx}^2}\,\sigma_N$$

smart scientists use heavy nuclei

Spin-Dependent WIMPs
→ Cleverly Incoherent



Example: Majorana Fermion X Coupled through Z'

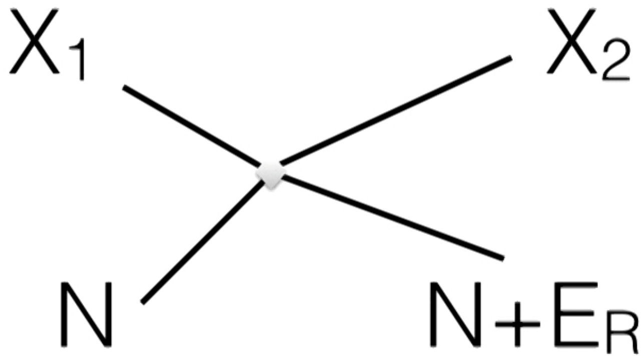
$X\gamma_\mu \bar{X} = 0$

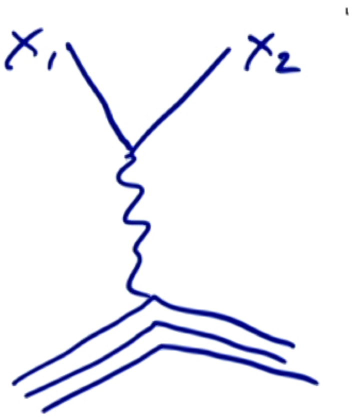
$X\gamma_\mu\gamma_5 \bar{X}$ ✓

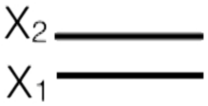
$$\sigma_{nx} = \underbrace{\cancel{\left(\frac{1}{A^2}\right)}}_{\boxed{SD}} \frac{\mu_{nX}^2}{\mu_{NX}^2}\,\sigma_N$$

(heavy nuclei don't work as well)

Inelastic Dark Matter







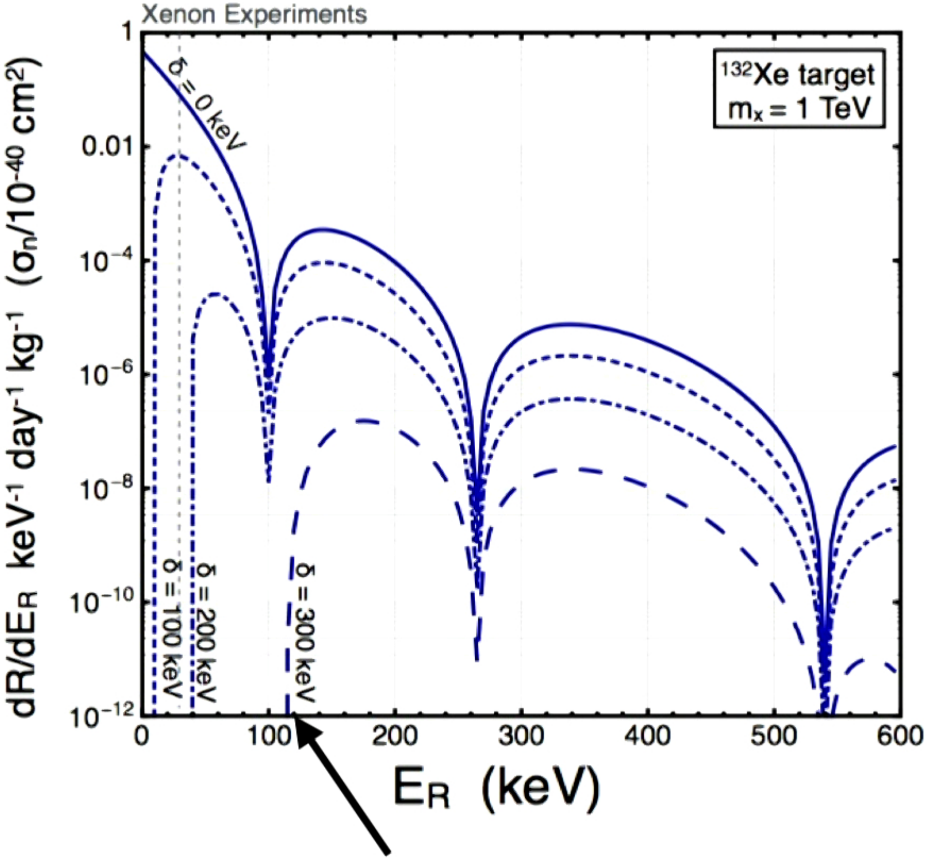
$$\delta \equiv m_{X_2} - m_{X_1}$$

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)

Inelastic Recoil Spectrum

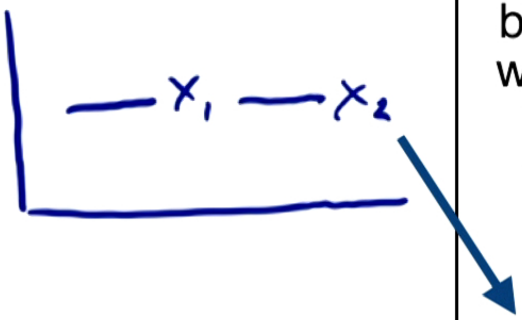


Y-axis is just the event rate for a typical WIMP per kg per day

-Most direct detection experiments analyze only up to E_R~30 keV

-Need to look at recoil energies of at least 120 keV to see δ=300 keV inelastic dark matter

Higgsinos — Broken Symmetry Makes Inelastic DM



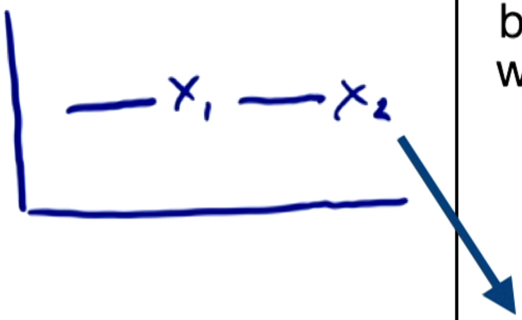
Elastic Allowed

$$\sigma_{nx} \sim 10^{-39}\ \mathrm{cm}^2$$

$$\begin{array}{c} \text{bino} \\ \text{wino} \\ H_1 \\ H_2 \end{array} \begin{pmatrix} M_1 & & \multicolumn{2}{c}{\text{[redacted]}} \\ & M_2 & & \\ \multicolumn{2}{c}{\text{[redacted]}} & & -\mu \\ & & -\mu & \end{pmatrix}$$

diagonalize
mass matrix
(like neutrinos)

Higgsinos — Broken Symmetry Makes Inelastic DM



$$\begin{array}{c} \text{bino} \\ \text{wino} \\ H_1 \\ H_2 \end{array} \begin{pmatrix} M_1 & & \blacksquare & \blacksquare \\ & M_2 & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & & -\mu \\ \blacksquare & \blacksquare & -\mu & \end{pmatrix}$$

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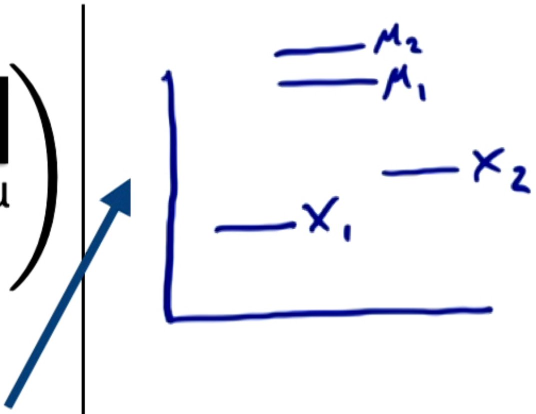

Elastic Allowed

$$\sigma_{nx} \sim 10^{-39}\ \text{cm}^2$$

■ = **electroweak symmetry breaking terms**

M_1,M_2, ■, result in mass splittings

$$\delta \sim \text{GeV}\left(\frac{\text{TeV}}{M_1}\right)$$

Higgsinos — Broken Symmetry Makes Inelastic DM

Elastic Allowed

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$$\begin{array}{c} \text{bino} \\ \text{wino} \\ H_1 \\ H_2 \end{array} \begin{pmatrix} M_1 & & \blacksquare & \\ & M_2 & & \\ \blacksquare & & & -\mu \\ & & -\mu & \end{pmatrix}$$

diagonalize mass matrix (like neutrinos)

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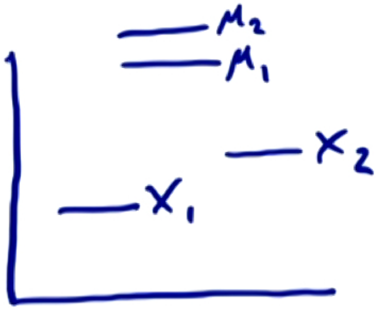
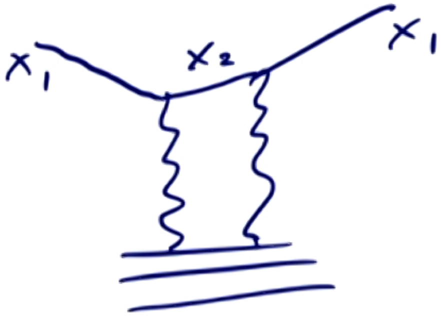
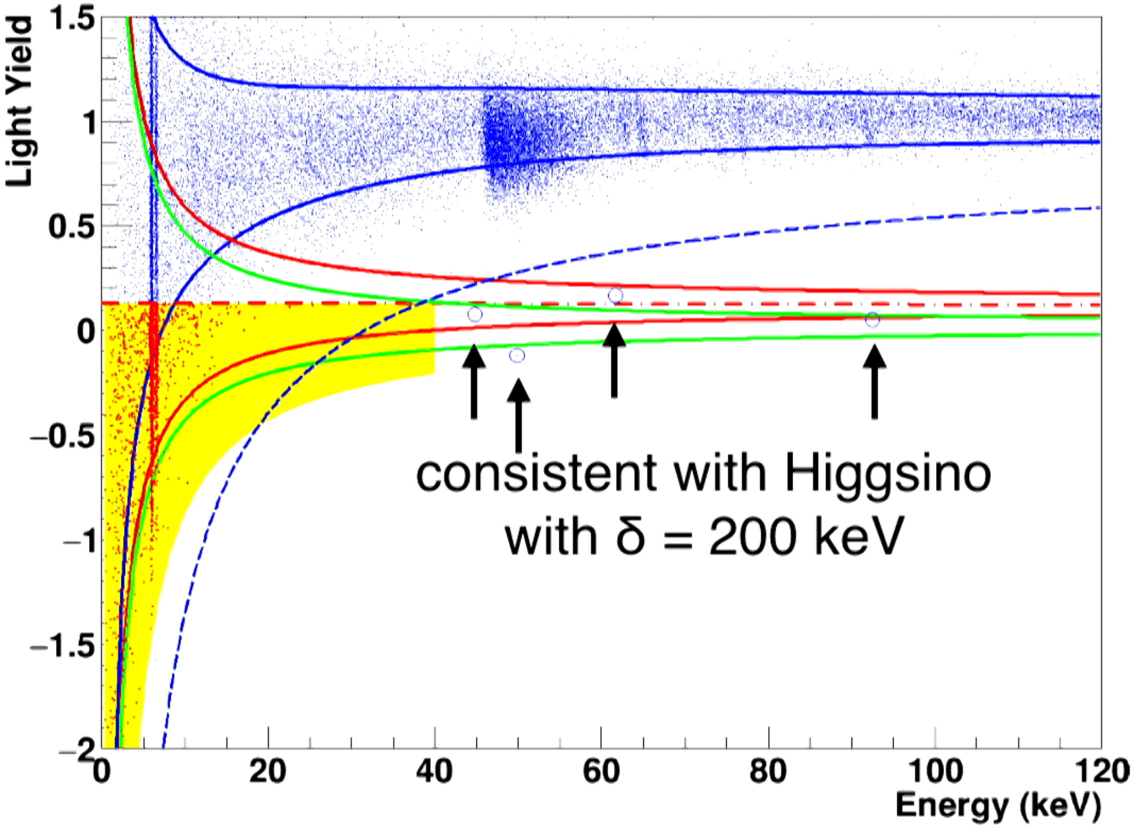


If Too Inelastic, Dominant Loop Cross-Section



$$\sigma_{nx} < 10^{-48}\ \text{cm}^2$$

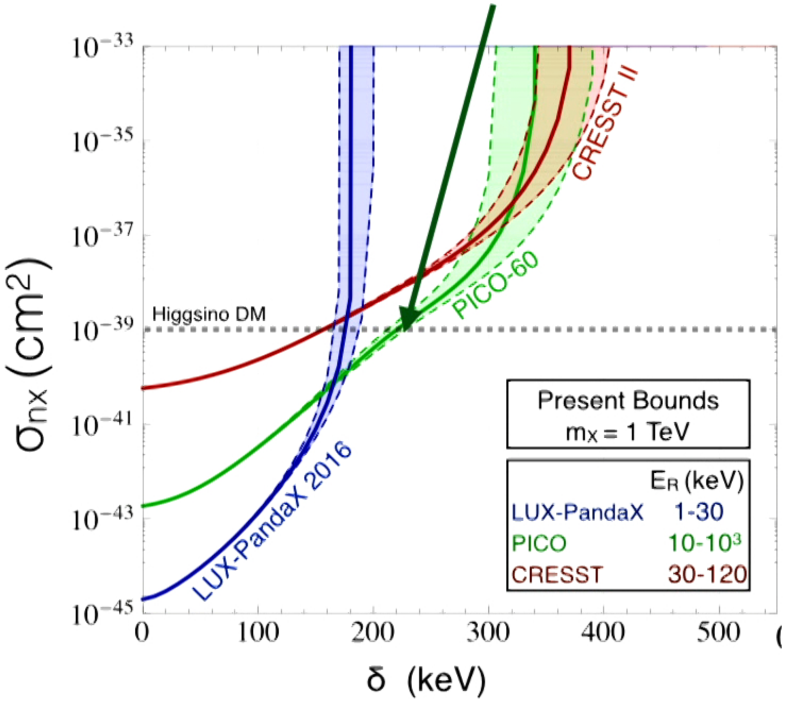
e.g. Hisano et. al., Hill and Solon



CRESST 1509.01515

At one point we "found" a Higgsino in
4 high recoil energy events at CRESST…

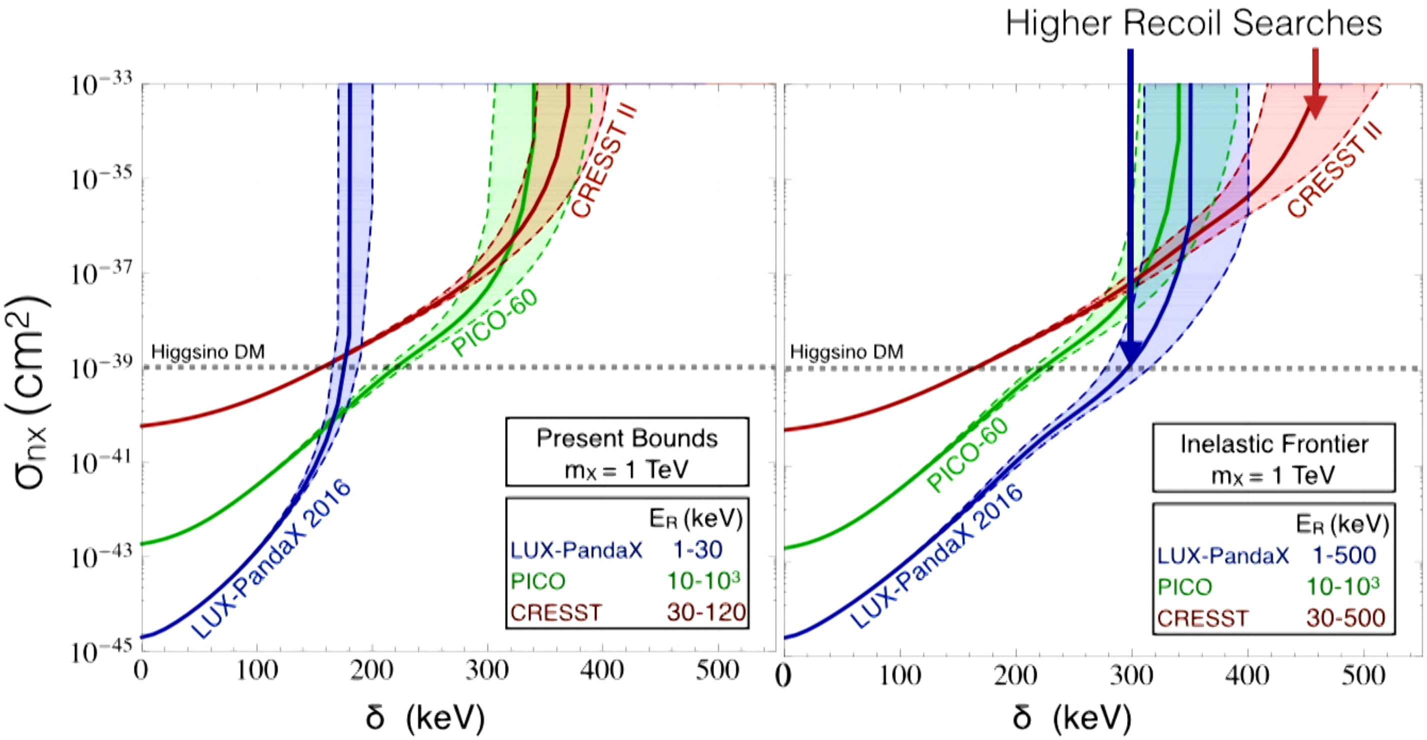
But PICO accepts up to 1000 keV recoil energies, and excludes the CRESST Higgsino



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!



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

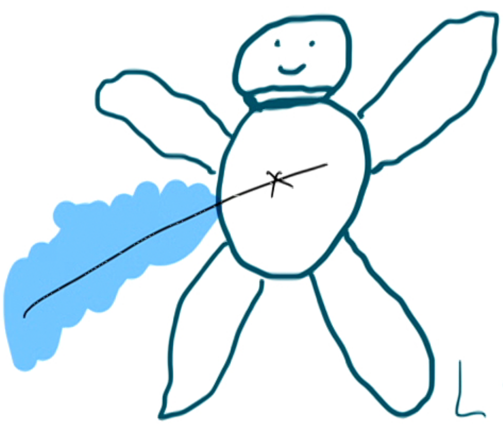
Ideal Direct Detector

-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



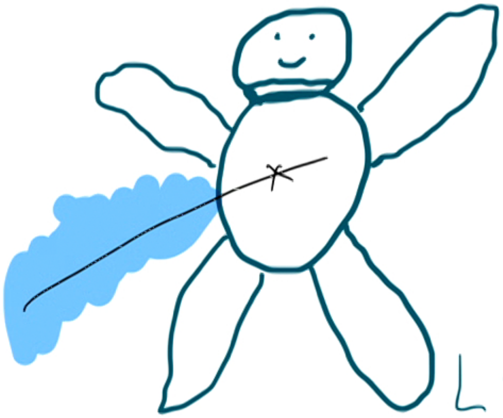
1 hit/yr - DD limit

Dark kinetic heating

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

$T_{\text{ast}} \sim 75$ μKelvin

DM heated astronaut



1 hit/yr - DD limit

Dark kinetic heating

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

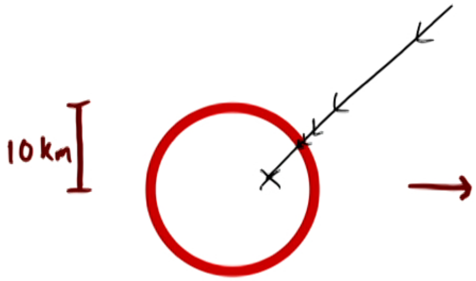
$T_{ast} \sim 75$ μKelvin

$$\bar{V}_x^2 \rightarrow V_x^2 + \frac{2GM_{ast}}{R_{ast}}$$

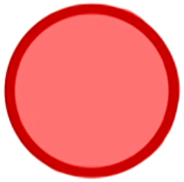
Grav Accelerated

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

Neutron Stars: Nature's Dark Matter Accelerators



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

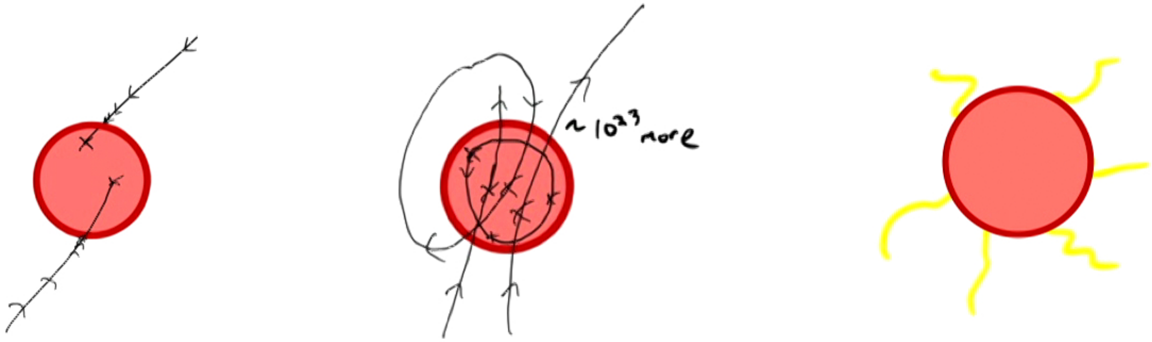


Interior → fiducial mass 10^{57} GeV

Neutrons : protons : electrons

$\sim 10:1:1$

Dark Kinetic Heating



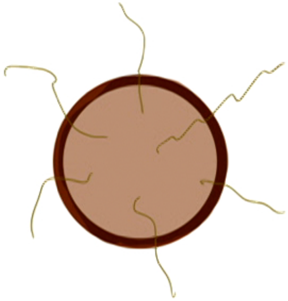
1. Dark matter gravitationally accelerated to ~0.7 c by neutron star

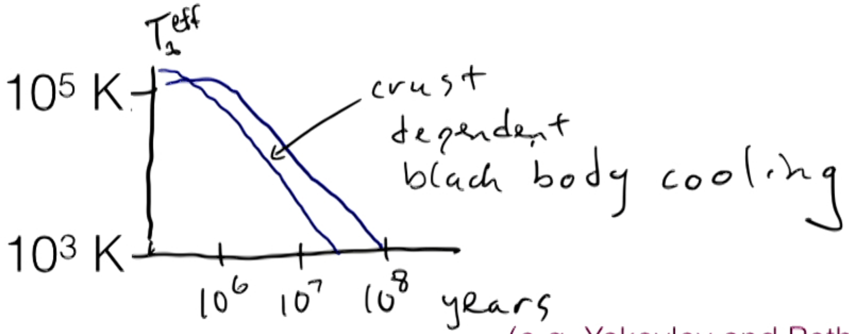
2. Scatters (re-scatters) against neutrons, electrons, or protons

3. Heats neutron star, resulting in blackbody emission

Dark Kinetic Heating

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

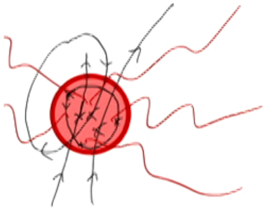




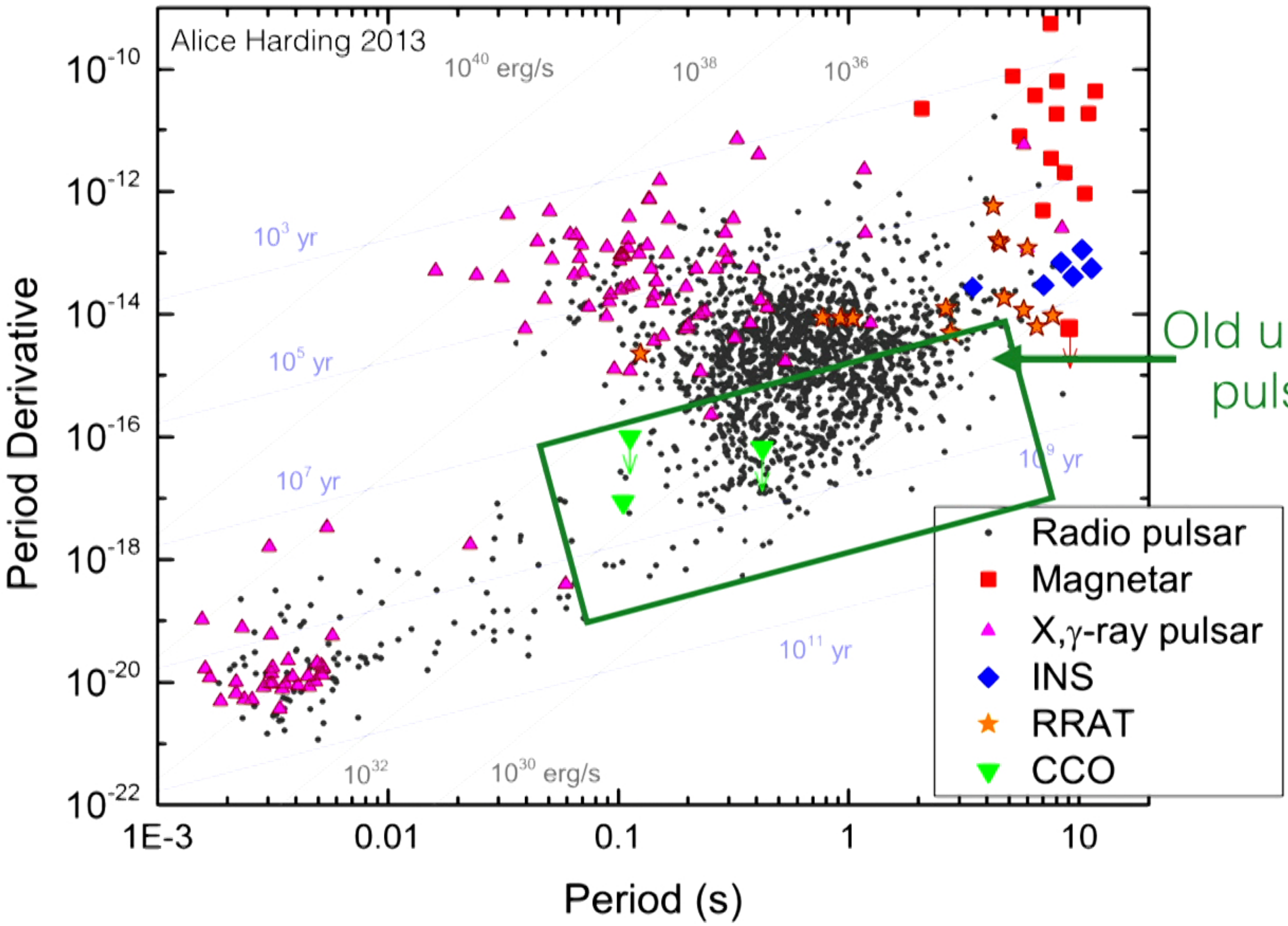
(e.g. Yakovlev and Pethick 2004)

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

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



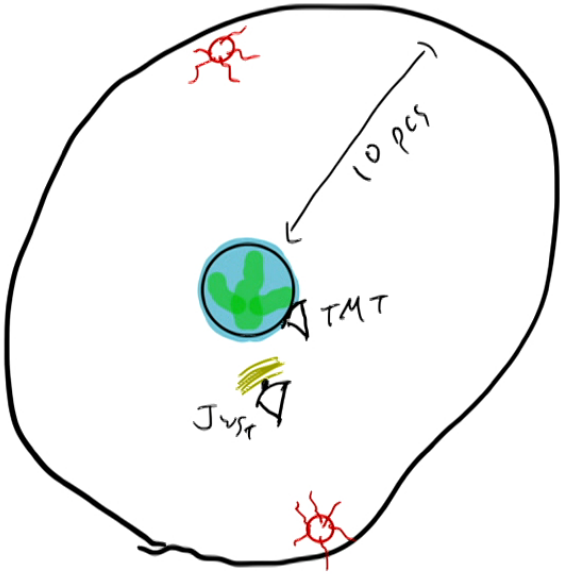
Known Pulsars



Old unspun pulsars

Backyard Neutron Star BBQ

- Find a few pulsars with FAST, SKA, CHIME up to ~50 parsecs from earth



~1-3 neutron stars
10 parsecs
from Earth

(Blaes & Madau '93)

- JWST or Thirty Meter Telescope

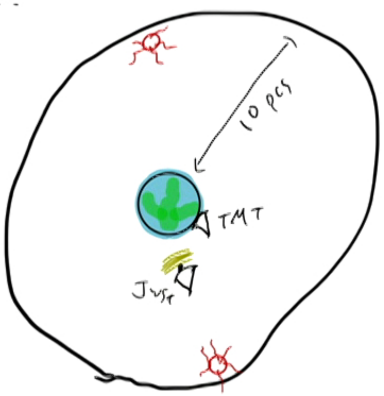
2 Sigma Integration Times

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

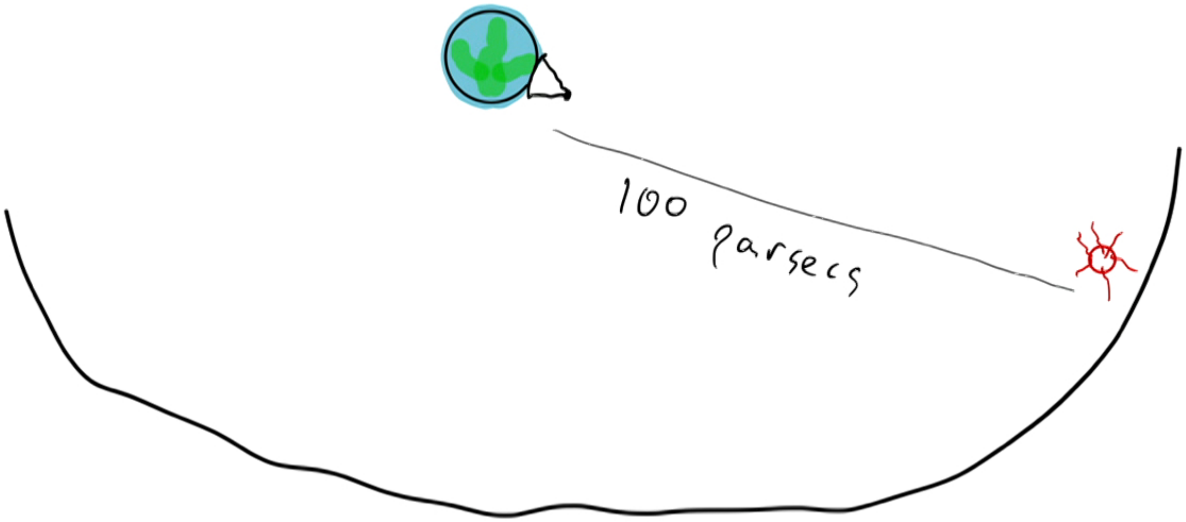
kinetic only 7×10^4 seconds $\left(\frac{d}{10 \text{ parsecs}}\right)^4$

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

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

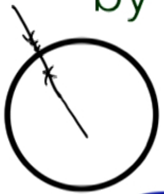
Long Term Braise

-100 meter telescope, an "OWL"
-2 sigma on known pulsars in ~100 hours
-Excellent task for exoplanet atmopshere telescopes



DM Capture - By Mass

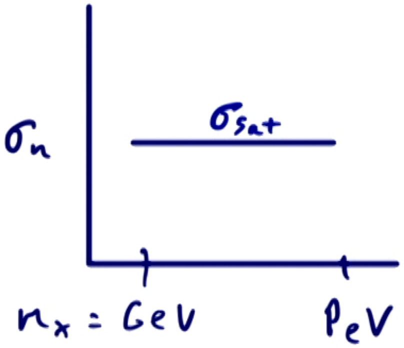
DM must lose its halo kinetic energy (10^{-6} m_x) by scattering with the neutron star to become captured.



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

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

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



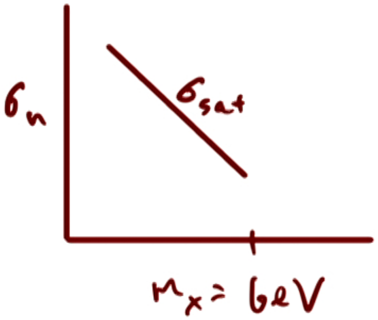
$$\boxed{\sigma_{sat} = \pi R^2 m_n / M \sim 2 \cdot 10^{-45}\,\text{cm}^2}$$

$\boxed{M_\chi < \text{GeV}}$ 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 $\frac{m_\chi}{p_F}$



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

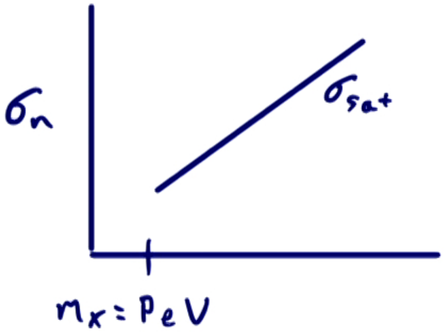
$\boxed{m_\chi > \text{PeV}}$ Multi-Scatter

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

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

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

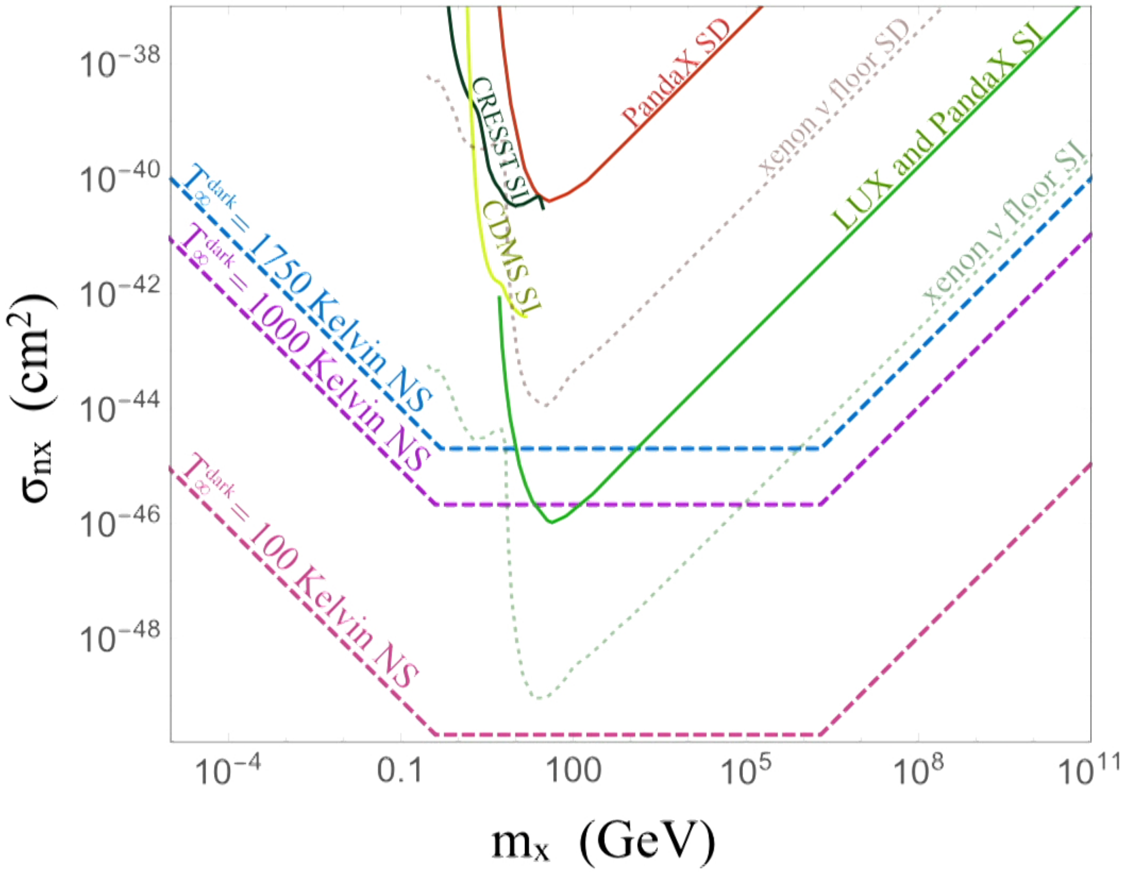
$$\rightarrow \boxed{\sigma_{sat} \propto m_\chi}$$

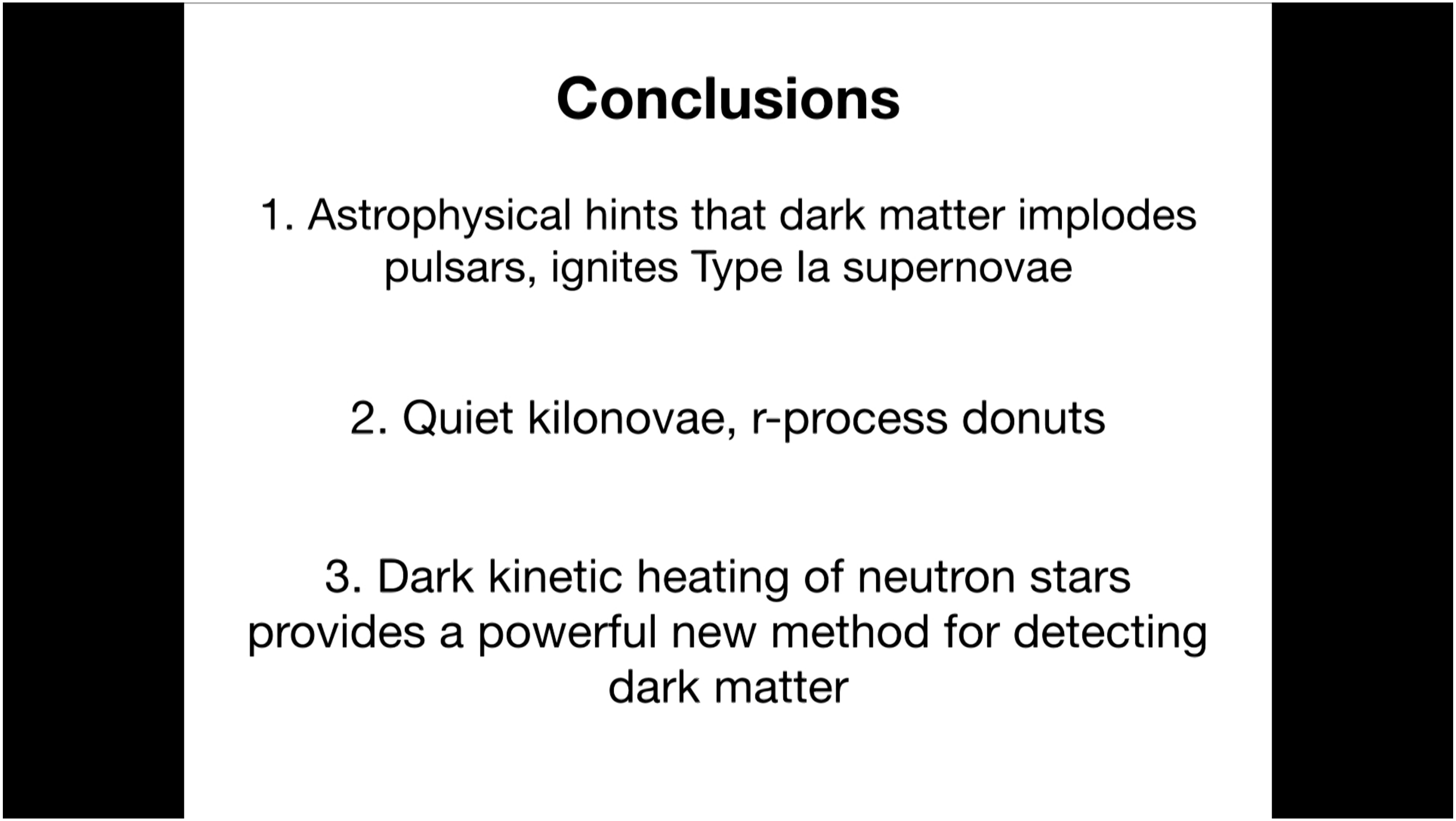


$$\boxed{\sigma_{sat} = 2\cdot 10^{-45}\,\text{cm}^2 \left(\frac{m_\chi}{\text{PeV}}\right)}$$

JB, Delgado, Martin 2017

Dark Kinetic Heating Complements Dark Matter Searches (also finds the "pure" Higgsinos)





Conclusions

1. Astrophysical hints that dark matter implodes pulsars, ignites Type Ia supernovae

2. Quiet kilonovae, r-process donuts

3. Dark kinetic heating of neutron stars provides a powerful new method for detecting dark matter

kinetic only

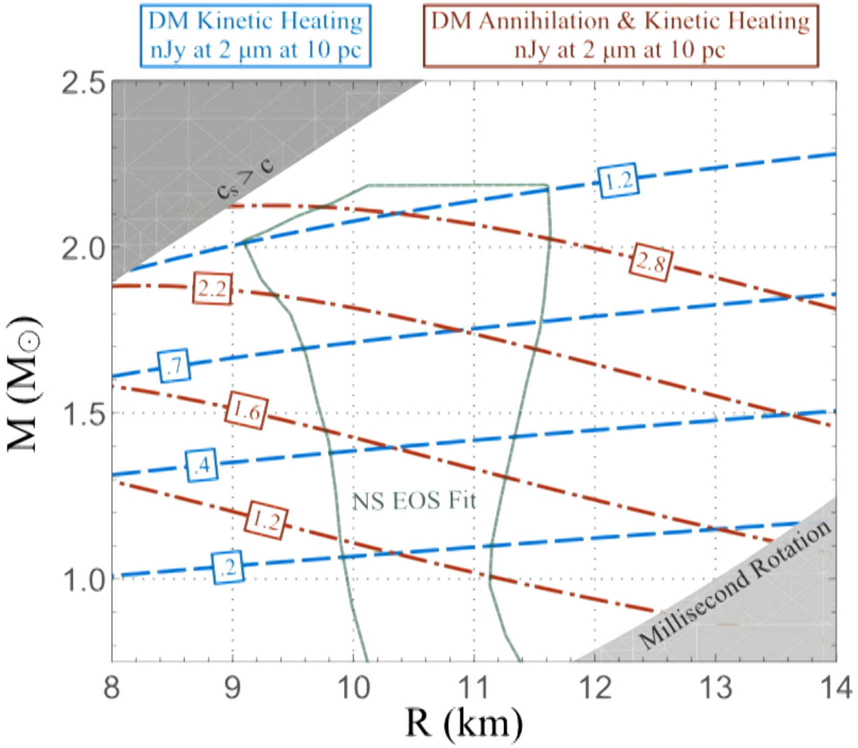
$$(\gamma - 1)\dot{m}_x$$

(very sensitive
to escape velocity)

annihilation

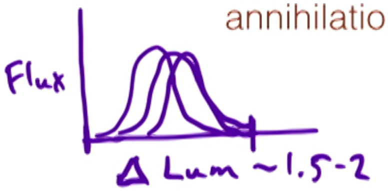
$$\gamma \dot{m}_x$$

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



kinetic heating

annihilation heating



Broader variety of Neutron Star
luminosities for only dark kinetic heating