ASTROPHYSICAL SIGNATURES OF DARK MATTER ACCUMULATION IN NEUTRON STARS

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Kings College Seminar

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DARK MATTER DIRECT DETECTION

Thermal freeze-out (early Univ.)
Indirect detection (now)

Direct detection

Production at colliders

Dark Matter search strategies

Direct Method

Indirect Method

Production at the Large Hadron Collider

How to detect dark matter (credit: HAP / A. Chantelauze)
NEUTRON STARS AS DIRECT DETECTION LABORATORIES

- **Xenon1T**
  - 1000 kg
  - 730 day
  - $7.3 \times 10^5$ kg day

- **Neutron Star**
  - $2.8 \times 10^{30}$ kg
  - $1.8 \times 10^{10}$ day
  - $5.0 \times 10^{40}$ kg day
Neutron stars are sensitive to very small interaction cross-sections:

\[ \sigma_{\text{single}}^{\text{sat}} \approx \pi R^2 m_n / M \approx 2 \times 10^{-45} \text{ cm}^2 \left( \frac{1.5 \, M_{\odot}}{M} \right) \left( \frac{R}{10 \, \text{km}} \right)^2 \]

This saturates the sensitivity of neutron stars as dark matter detectors. Do not get additional sensitivity to higher cross-sections (in general).
DARK MATTER ACCUMULATION IN NEUTRON STARS

Three Stages of Dark Matter Accumulation:

- Dark Matter Capture
  - DM hits neutron and elastically scatters

- Dark Matter Thermalization
  - Trapped dark matter interacts with nucleon fluid and achieves temperature equilibrium.

- Dark Matter Collapse
  - Dark matter degeneracy pressure not capable of preventing collapse.
Two enhancements:

- NS gravitational potential well
- Regions with high dark matter density

Potential well moves slowly moving dark matter particles into collisional orbit.

Interaction rate scales as \( v_x^{-1} \).
Two enhancements:

- NS gravitational potential well
- Regions with high dark matter density
Two enhancements:

- Interactions are relativistic (p-wave)
- Spin-Dependent Interactions

Neutron Stars are a dark matter collider:

\[ v_{esc} = \sqrt{\frac{2GM}{r}} \sim 0.7c \]

Dark Matter interacts with a neutron star relativistically.

Can probe p-wave suppressed or mass-split (e.g. Higgsino) DM.
Two enhancements:

- Interactions are relativistic (p-wave)
- Spin-Dependent Interactions

Models of Neutron Star equations of state indicate that the majority of the NS mass is composed of individual neutrons.

No difference between spin-independent and spin-dependent interactions.
Two impediments to dark matter interactions:

- Pauli Blocking (low-mass dark matter)
- Dark Matter Capture (high-mass dark matter)

Dark Matter scattering imparts a momentum:

\[ \delta p \sim \gamma m_x v_{esc}, \]

Typical NS proton momentum is:

\[ p_{F,n} \approx 0.45 \text{ GeV} \left( \rho_{NS} / (4 \times 10^{38} \text{ GeV cm}^{-3}) \right) \]

This suppresses the interaction cross-section for low mass DM:

\[ \sigma_{\text{Pauli}} \approx \pi R^2 m_n p_f / (M \gamma m_x v_{esc}) \approx 2 \times 10^{-45} \text{ cm}^2 \left( \frac{\text{GeV}}{m_x} \right) \left( \frac{1.5 M_{\odot}}{M} \right) \left( \frac{R}{10 \text{ km}} \right)^2. \]
Two impediments to dark matter interactions:

- Pauli Blocking (low-mass dark matter)
- Dark Matter Capture (high-mass dark matter)

Dark Matter energy lost in a scatter with a GeV proton is approximately:

\[ E_{\text{loss}} = \frac{2m_p}{m_\chi} (m_\chi v_\chi^2) \]

If this is smaller than the DM kinetic energy at infinity the dark matter will not remain bound after a single interaction:
Dark Matter thermalization is always suppressed by Pauli blocking.

Analytical and numerical models have very different predictions.

However, if DM is trapped within the NS, interactions are still inevitable, and dark matter thermalizes on a significantly smaller timescale than DM capture:

\[
\tau \approx 3750 \text{ yrs} \frac{\gamma}{(1 + \gamma)^2} \left( \frac{2 \times 10^{-45} \text{ cm}^2}{\sigma} \right) \left( \frac{10^5 \text{ K}}{T} \right)^2,
\]
Two paths are now possible:

- If dark matter can annihilate, the large densities make annihilation inevitable.

- If dark matter cannot annihilate, dark matter builds mass until it exceeds its own degeneracy pressure. For Fermionic dark matter this is:

\[ M_{\text{crit}}^{\text{ferm}} \approx \frac{M_{\text{pl}}^3}{m_X^2} \]

- It then collapses on a timescale:

\[ \tau_{\text{co}} \approx \frac{1}{n \sigma_{nx} v_x} \left( \frac{p_F}{\Delta p} \right) \left( \frac{m_X}{2m_n} \right) \approx 4 \times 10^5 \text{ yrs} \left( \frac{10^{-45} \text{ cm}^2}{\sigma_{nx}} \right) \left( \frac{r_x}{r_0} \right), \]
Asymmetric Dark Matter is well-motivated
- e.g. Baryon/Lepton Asymmetry through dark baryogenesis

Some models do not work, e.g. GeV Fermions require \( \sim 1 \, M_\odot \) of dark matter to be accreted

Many models do work:
- PeV Fermionic DM (\( \sim 10^{-10} \, M_\odot \))
- Bosonic DM (MeV - PeV) with small quartic
- MeV-PeV DM with attractive potential (e.g. Scalar Higgs Portal)
PROBLEM: WE SEE OLD NEUTRON STARS

- Pulsars = Quickly rotating NS with strong B-fields
- Rotation slows due to dipole radiation
- Can approximate age if period and period-derivative are known:

\[ \tau \approx \frac{P}{2\dot{P}} \]
PROBLEM: WE SEE OLD NEUTRON STARS

- We observe ~5 Gyr old neutron stars.
- Thus dark matter must not collapse neutron stars too effectively.
- Sets strong constraints on dark matter that collapses neutron stars.
POSSIBLE SIGNATURES OF DARK MATTER INTERACTIONS

- Neutron star heating
- Neutron star collapse
  - Missing neutron stars
  - Electromagnetic signatures
    - Fast Radio Bursts
    - Kilonovae
    - r-process enrichment
- Gravitational wave signatures
In addition to pulsations, a handful of pulsars have been detected via blackbody radiation.

Primarily at temperatures $\sim 10^6$ K.
Older neutron stars are expected to cool effectively.

20 Myr neutron stars are believed to have temperatures < 1000 K.
A dark matter particle impacts a neutron star surface with significant kinetic energy:

\[ \dot{m} = \pi b_{\text{max}}^2 v_x \rho_x, \]

\[ E_s \approx m_x (\gamma - 1) \]

This sets a minimum energy input to the neutron star:

\[ \dot{E}_k = \frac{E_s \dot{m}}{m_x} f \approx 1.4 \times 10^{25} \text{ GeV s}^{-1} \left( \frac{f}{1} \right), \]

de Lavallez & Fairbairn (1004.0629)

The dark matter particle does not need to annihilate, but if it does, more energy is injected (\( E_s = \gamma m_x \)).
Dark matter then thermalizes with the NS.

Energy transferred into nucleon kinetic energy.

Neutron star emits as a blackbody with luminosity:

$$L_{\infty}^{\text{dark}} = \dot{E}_k \left(1 - \frac{2GM}{R}\right) = 4\pi\sigma_B R^2 T_s^4 \left(1 - \frac{2GM}{R}\right)$$

This corresponds to a temperature \(~1750\) K for dark matter saturating the direct detection cross-section.

Exceeds the sensitivity of standard direct detection.
Seeing this signal requires extremely sensitive infrared observations.

Fortunately, such telescopes are coming online:

- James Webb
- Thirty Meter Telescope

Nominal JWST sensitivity is \(~10\) nJy at \(10^4\) s.

TMT can reach 0.5 nJy in \(~10^5\) s, if backgrounds can be controlled.
Neutron star needs to be a pulsar, so it can be located in radio observations.

- Closest pulsar ~90 pc, but models indicate a pulsar with distance ~10-20 pc should exist.

Alternative heating mechanisms:

- Baryonic Heating on interstellar medium?
- Heating powered by magnetic turbulence?
Lots of star-formation in the Galactic center

Should produce lots of pulsars, but we haven’t seen them.
THE MISSING PULSAR PROBLEM

Large pulse dispersion was reasonable culprit

Magnetar found in X-Ray observations in 2013.

No pulse dispersion in X-Rays

Magnetar subsequently found in radio

Pulse dispersion is small!

Why aren’t any other pulsars observed !?
- High Dark Matter density near the GC.

- GC NS collapse in $\sim 10^5$ yr while nearby NS remain.

- GC NS collapse in $\sim 10^4 - 10^5$ yr while nearby NS remain.

Bosonic DM $\lambda |\phi|^4 = 10^{-15}$. 

Constraint Detection
Potential Observation: A correlation between maximum NS age and GC radius.

Can be confirmed or ruled out with one old pulsar observation near the GC.

Upcoming radio instruments (e.g. MeerKat, SKA) will definitively test the missing pulsar problem.
The Origin of the Solar System Elements

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Graphic created by Jennifer Johnson
Astronomical Image Credits: ESA/NASA/AASNova
Producing elements with large neutron over density requires extremely neutron-dense environment to avoid $\beta$-decay.
Differentiating supernovae and neutron star binary mergers

Supernovae are common: $0.02 \text{ SN yr}^{-1}$ in Milky Way

Neutron Star Mergers Rare: $10^{-4} \text{ yr}^{-1}$ in Milky Way

But r-process yields for each unknown - degenerate with rate!
Differentiating supernovae and neutron star binary mergers

- Supernovae are common: 0.02 SN yr\(^{-1}\) in Milky Way
- Neutron Star Mergers Rare: 10\(^{-4}\) yr\(^{-1}\) in Milky Way

Observe systems with small star-formation rates -> Poisson fluctuations in abundances!
Differentiating supernovae and neutron star binary mergers

- Supernovae are common: $0.02 \text{SN yr}^{-1}$ in Milky Way
- Neutron Star Mergers Rare: $10^{-4} \text{yr}^{-1}$ in Milky Way

Can also cross-correlate with metallicity, which should track supernovae rate.
Reticulum II dSph

- Discovered by DES in 2015
- Spectroscopic follow-up determined r-process abundances.
- Large r-process abundance, but low metallicity!

- Points to a rare formation channel (NS mergers)
Neutron stars receive large natal kicks due to asymmetries in the supernovae explosion.

\[ v_{\text{kick}} \approx 400 \text{ km s}^{-1}. \]

Escape velocity of dSph \( \approx 10 \text{ km s}^{-1}. \)

Low kick neutron star populations are possible (e.g. globular clusters)
Mergers require kicks to move binary from widely separated supergiant system to tightly bound NS-NS binary.

\[ \tau_m(m_1, m_2, w, b) = \frac{3}{85} \frac{a_0^4}{m_{\text{tot}}^3} (1 - e_0^2)^{7/2} \]

[Graph showing distribution of Kick Velocities for PSR J0737-3039 and PSR 1534+12]
The escape velocity from a dwarf spheroidal galaxy is small:

\[ v_{esc} = 10.9 \left( \frac{M}{10^7 M_{\odot}} \right)^{1/3} \left[ \frac{1+z}{9.5} \right]^{1/2} \text{ km/s} \]

- Natal kicks remove >99% of all binaries from the dwarf spheroidal galaxy.
The dispersion velocity in dwarfs is also small.

- Reticulum II: 3.3 +/- 0.7 km s\(^{-1}\) (Simon et al. 2015)

Dark matter accumulation rate scales inversely with velocity:

\[
\dot{m}_x = \pi \rho_x \frac{2GM R}{v_x} \left(1 - \frac{2GM}{R}\right)^{-1}
\approx 10^{26} \text{ GeV} \left(\frac{\rho_x}{\text{GeV/cm}^3}\right) \left(\frac{200 \text{ km/s}}{v_x}\right)
\]

Dwarf Spheroidal Galaxies are an optimal laboratory for asymmetric dark matter detection.
- We expect ~1 r-process event over all ultra-faint dwarf galaxies (total $10^5$ M$_\odot$).
- Supernovae produce ~100 events.
- Mergers produce ~0.0005 events.
- DM induced collapse produces ~0.1-3 events.
How much r-process enrichment per dark matter induced collapse?

Currently abundance

Yields between $5 \times 10^{-5} \, M_\odot$ and $10^{-3} \, M_\odot$ can explain Milky Way r-process abundance.

Significant uncertainties in r-process element transport throughout the Milky Way.
Can roughly estimate the maximal r-process production rate via energetics:

\[ E_i \approx 3G M_{NS}^2 \left( R_{Sch.}^{-1} - R_{NS}^{-1} \right)/5 = 3 \times 10^{57} \left( M_{NS}/1.5M_\odot \right) \text{ GeV,} \]

This energy can propel neutrons from the NS surface at \( v = 0.7c \). The maximum mass that can be lost is:

\[ M_{ej} \leq m_n \frac{E_i}{E_a} \lesssim 0.2 \left( \frac{M_{NS}}{1.5M_\odot} \right) \left( \frac{1.4}{\gamma(v_{ej})} \right) M_\odot. \]

The actual r-process enrichment depends on the quantity and density of neutrons which escape in the implosion. Computational models are needed.
Prediction: Globular Clusters should not be similarly r-process enriched.

In fact, no globular cluster has been observed to have an r-process overabundance exceeding 1.2 dex.

6 of 9 stars in Reticulum II have r-process enrichment exceeding 1.68 dex.
FAST RADIO BURSTS

- Short (~ms) radio bursts first discovered in 2007
- High dispersion measure indicates extragalactic origin.
- One repeating fast radio bursts, but others appear not to repeat.
- Origin unknown.
- Millisecond timescale indicates size < 300 km.
- Radio pulsar magnetic fields have energetics and cooling timescales needed to produce emission.
- Models of neutron star mergers and accretion induced collapse have been proposed.
- Accretion induced collapse acts similarly to DM induced collapse.
FAST RADIO BURSTS FROM PULSARS

- FRB rates may be as high as $10^5 \text{ day}^{-1}$.

- Consistent with a galactic FRB rate of $10^{-2} \text{ yr}^{-1}$ and with the SN rate.

- Consistent with the cross-sections needed to explain the missing pulsar problem.
FRB rates may be as high as $10^5 \text{ day}^{-1}$.

Consistent with a galactic FRB rate of $10^{-2} \text{ yr}^{-1}$ and with the SN rate.

Consistent with the cross-sections needed to explain the missing pulsar problem.
Dark Matter induced implosions can affect the signals expected from LIGO.
THREE POTENTIAL SIGNALS:

- Gravitational Waves from DM induced collapse
- Anomalies in the tidal strain of binary neutron star mergers.
- Disassociation of electromagnetic and gravitational wave signatures
Gravitational Waves from DM induced collapse

\[ h_c \sim 5 \times 10^{-22} \left( \frac{M}{M_{\odot}} \right) \left( \frac{10 \text{ kpc}}{D} \right) @ 531 \text{ Hz}, \]

Baiotti et al. (gr-qc/0701043)

- Single NS collapse models have been considered (primarily from accretion induced collapse).
- DM induced NS collapse observable throughout the Milky Way (0.01 yr\(^{-1}\)?)
GRAVITATIONAL WAVE SIGNATURES OF DM INDUCED COLLAPSE

- Anomalies in the tidal strain of binary neutron star mergers.
- DM induced NS collapse produces a population of 1.4 $M_\odot$ black holes.
- Can potentially see differences in merger and ring-down, but not presently feasible.
Disassociation of electromagnetic and gravitational wave signatures

Kilonovae - Days long afterglows of NS-NS mergers formed primarily by beta-decay of r-process materials.

Likely associated with sGRBs - but better localization.
Disassociation of electromagnetic and gravitational wave signatures

- No DM Induced Collapse
- DM Induced Collapse
- **Merger Kilonovae** - Bright r-process afterglows of NS-NS binary mergers.

- **Quiet Kilonovae** - Possible r-process afterglows of DM induced neutron star collapse

- **Dark Mergers** - Interactions that look like NS-NS binaries to LIGO, but both NS have already collapsed, and thus no electromagnetic counterpart is found.
A reasonable fraction of all NS-NS mergers should actually be LM-LM mergers.

LM-NS mergers occur in primordial black hole models.

Difficult to argue that you have found dark matter by not seeing something that you should....

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This scenario does not happen equivalently through the galaxy.

Bright kilo novae associated with NS-NS mergers should be detected, but only in the outskirts of galaxies.
These models reasonably re-produce the observed r-process abundance with “quiet kilonovae” that do not have a gravitational wave counterpart.
By localizing either merger kilonovae or fast-radio bursts, can differentiate models where DM collapses NS.

FRB instruments such as CHIME expected to detect ~1000 FRBs in the next few years.
TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are open
- Pre-meeting mini-workshops on Sunday, August 7
Asymmetric dark matter models naturally produce neutron star collapse in regions with high dark matter density and low velocity dispersion.

There are a number of astrophysical signals (and hints!) of such interactions.

Future observations are likely to definitively prove, or rule out, this class of models.