Nucleons, Electrons, and Pasta: Discovering Dark Matter by Reheating the Neutron Star Soup

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TRIUMF

with
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28 Jan 2020, U Toronto
Dark reality

- Galactic Rotation
- Large Scale Structure
- Bullet Cluster
- Cosmic Microwave Background
After 1000 kg-year exposure:

1805.12562
Challenges of direct searches

dark matter mass

(cm²)

RARE

SKYLAB

CDMS-I

DAMA

XENON1T

CRESST surface

CDMS-I

CRESST-III

X1T

XQC

IMP

WEARY

POWELLSS

POWERLESS

GHOSTLY

RARE

10^{-11}

10^{-21}

10^{-31}

10^{-41}

10^{-41}

0.01

100.00

10^6

10^{10}

10^{14}

10^{18}

dark matter mass

(GeV)

cross section for dark matter hitting nucleons
More challenges: spin dependence

No nuclear coherence if scattering spin-dependent:

\[ \sigma_{\text{nucleon}} = \left( \frac{1}{A} \right)^2 \left( \frac{\mu_{nX}}{\mu_{N X}} \right)^2 \sigma_{\text{Nucleus-DM}} \]

E.g. (Majorana) DM coupling to axial quark current \( \bar{q} \gamma_\mu \gamma_5 q \)
If scattering inelastic, no recoil when

\[ \delta \equiv m_{DM^*} - m_{DM} \]

\[ \delta > 2\mu_{N\chi}v_{DM}^2 = \mathcal{O}(100\text{keV}) \]

PandaX-II, 1708.05825

Tucker-Smith, Weiner 0101138, 0402065, Barello, Chang, Newby 1409.0536

More challenges: inelasticity
More challenges: inelasticity

Last Electroweak WIMP Standing
Pseudo-Dirac Higgsino Status and Compact Stars as Future Probes

Rebecca Krall and Matthew Reece
Department of Physics, Harvard University, Cambridge, MA, 02138
May 16, 2017

\[ \sigma_{\chi n} \sim \frac{\mu_{\chi n}^2}{\pi} G_F^2 \]

\[ \tilde{H}_1^0 \hspace{1cm} \tilde{H}_2^0/\tilde{H}^\pm \]

\[ Z/W^\pm \]

\[ q \hspace{1cm} q \]

\[ m_{DM} (GeV) \]

\[ \sigma_{nx} \text{ (cm}^2\text{)} \]

XENON1T - SI
More challenges: inelasticity

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\[ \sigma_{\chi n} \sim \frac{\mu_{\chi n}^2}{\pi} G_F^2 \]

XENON1T - SI

Thermal Higgsino — elusive!

Hill & Solon 1408.8290
More challenges: irreducible backgrounds

Atmospheric + diffuse supernovae + solar neutrino background

E.g. Higgsino elastic scattering (loops)

Hill & Solon 1408.8290
Challenges: summary

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

Crucial frontiers — beyond which dark matter could be.
(Dark) Kinetic Heating
heating rate = cooling rate
heating rate = cooling rate

\[ \propto KE \]

\[ \propto \frac{dN}{dt} \]

\[ \propto T^4 \]
Dark fire
heating rate = $\mathbf{KE}_{\text{DM}} \times \frac{dN_{\text{DM}}}{dt}$
Dark fire

heating rate = $K \mathbf{E}_{DM} \times \frac{dN_{DM}}{dt}$

How hot can dark matter keep my soup?
heating rate = $K E_{DM} \times \frac{dN_{DM}}{dt}$

one hit per transit:

$$\frac{R}{\text{mean free path}} = \sigma n R = 1$$

$\sigma_{\text{threshold}} = 10^{-29} \text{ cm}^2$
Dark fire: soup temperature

heating rate = \( KE_{DM} \times \frac{dN_{DM}}{dt} \)

mass drops out!

\[ \frac{1}{2} m_{DM} (300 \text{ km/s})^2 \]

\[ \frac{0.3 \text{ GeV/cm}^3}{m_{DM}} A_{soup} (300 \text{ km/s}) \]
Dark fire: soup temperature

How hot can dark matter keep my soup?

$T = 0.003$ Kelvin
Need a better detector
\[ \sigma_{\text{threshold}} = \frac{m_{\text{molec}}}{\rho_{\text{soup}} R_{\text{soup}}} = 10^{-29} \text{ cm}^2 \]
\( \sigma_{\text{threshold}} = \frac{m_{\text{molec}}}{\rho_{\text{soup}} R_{\text{soup}}} \ll 10^{-29} \text{ cm}^2 \)
\[ \sigma_{\text{threshold}} = \frac{m_{\text{molec}}}{\rho_{\text{soup}} R_{\text{soup}}} \]

<<10^{-29} \text{ cm}^2

**better**

denser & bigger

\[ \nu_{\text{esc}} \propto \sqrt{\rho R} \]

**Gravity bonus!** Accelerate dark matter.

( higher KE, \( dN/dt \) )
left to itself
\[ T = 278 \text{ Kelvin} \]
dark fire-heated
\[ T = 0.003 \text{ Kelvin} \]
better

left to itself

$T = 278$ Kelvin

dark fire-heated

$T = 0.003$ Kelvin

be colder in natural state
What’s dense, big, and cold?
What’s dense, big, and cold?
What’s dense, big, and cold?

a neutron star!
neutron star

core-collapse supernova

neutron star

1934

Zwicky again
dense

density: $7 \times 10^{14} \text{ g/cm}^3$
What's dense, big, and cold?

density: $7 \times 10^{14}$ g/cm$^3$

radius: 10 km
dense, big

density: \(7 \times 10^{14} \text{ g/cm}^3\)  

radius: 10 km

\[ v_{\text{esc}} \propto \sqrt{\rho R} \]

\[ \approx 0.7 \, c \]
dense, big, and cold

density: \( 7 \times 10^{14} \text{ g/cm}^3 \)  
radius: 10 km

\[ v_{\text{esc}} \propto \sqrt{\rho R} \approx 0.7 \, c \]

20 x 10^6 years \hspace{1cm} T_{\text{effective}} \approx 1000 \text{ K}
1 x 10^9 years \hspace{1cm} T_{\text{effective}} \sim 100 \text{ K}

(compare with snowball)

Yakovlev, Pethick (2004)
Detector properties

density: $7 \times 10^{14} \text{ g/cm}^3$

radius: 10 km

$T_{\text{effective}} \sim 100 \text{ K}$
Dark fires in the sky

How hot can dark matter keep my neutron star?

KE_{DM} \times \frac{dN_{DM}}{dt}

density: 7 \times 10^{14} \text{ g/cm}^3
radius: 10 \text{ km}
T_{\text{effective}} \sim 100 \text{ K}

M Baryakhtar, J Bramante, S Li, T Linden, N. Raj
N. Raj, P Tanedo, H-B Yu
Zwicky misses the party

FROM LOCAL MEASUREMENTS

300 km/s 0.3 GeV/cm$^3$

\[ KE_{DM} \times \frac{dN_{DM}}{dt} \]

density: $7 \times 10^{14}$ g/cm$^3$
radius: 10 km
$T_{\text{effective}} \sim 100$ K

1933
dark matter

1934
neutron star

How hot can dark matter keep my neutron star?
Dark fire: neutron star temperature

heating rate = $K E_{DM} \times \frac{dN_{DM}}{dt}$

$\sigma_{\text{threshold}} = \frac{m_{\text{neutron}}}{\rho_{NS} R_{NS}}$

$10^{-45} \text{ cm}^2 << 10^{-29} \text{ cm}^2$

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N. Raj, P Tanedo, H-B Yu
Dark fire: neutron star temperature

heating rate = \( KE_{DM} \times \frac{dN_{DM}}{dt} \)

mass drops out!

\[ 0.35 \ m_{DM} \]

\[ \frac{0.3 \ \text{GeV/cm}^3}{m_{DM}} \pi R_{NS}^2 \left( \frac{v_{esc}}{300 \ \text{km/s}} \right)^2 (300 \ \text{km/s}) \]
Dark fire: neutron star temperature

How hot can dark matter keep my neutron star?

$T = 1750$ Kelvin (infrared)
Coldest neutron star temperatures we were able to measure:

$T = 1750 \text{ Kelvin}$

How to find dark fire-heated, lava-cold neutron stars?

$T = 10^5 \text{ Kelvin}$
Observation prospects

Radio telescopes
(design: pulsar discovery)

CHIME

FAST

100 old, cold neutron stars in the local 50 pc.

O. Blaes, P. Madau (1993)
Observation prospects

Radio telescopes
(design: pulsar discovery)

Infrared telescopes
(design: exoplanet atmosphere study)

100 old, cold neutron stars in the local 50 pc.

O. Blaes, P. Madau (1993)
Observation times

(1.5 solar mass, 10 km star) 1750 K

kinetic heating

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

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

for 2\(\sigma\) sensitivity
$L \propto (\gamma - 1)m_{DM}$

kinetic heating

Minimum signature
$L \propto (\gamma - 1) m_{DM} + m_{DM}$

Minimum signature

Possible bonus

kinetic heating + annihilation
Brightness diagnosis

\[ L \propto (\gamma - 1)m_{DM} + m_{DM} \]

kinetic heating + annihilation

Affects choice of filter, observation time.
\[
L \propto (\gamma - 1)m_{\text{DM}} + m_{\text{DM}}
\]

\[
\gamma = \frac{1}{\sqrt{1 - 2GM/R}}
\]

Brightness diagnosis

kinetic heating
+ annihilation

DM Kinetic Heating
nJy at 2 \( \mu \)m at 10 pc

DM Annihilation & Kinetic Heating
nJy at 2 \( \mu \)m at 10 pc

\( M (M_\odot) \) vs \( R \) (km)

NS EOS Fit

Millisecound Rotation
**Observation times**

(1.5 solar mass, 10 km star)

**kinetic heating** 1750 K

**+ annihilation** 2480 K

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

\[
9 \times 10^3 \text{ sec} \left( \frac{d}{10\text{pc}} \right)^4
\]

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

\[
2 \times 10^3 \text{ sec} \left( \frac{d}{10\text{pc}} \right)^4
\]

for 2\(\sigma\) sensitivity

Annihilation saves observation time (= $$) by a factor of >10!
- Old, nearby neutron stars must turn up
- Internal backgrounds not fully understood
- Age determination not fully reliable

So what do you buy?

{Claim of dark matter discovery will be premature/exaggerated! (As opposed to exclusion = clean.)}
- Old, nearby neutron stars must turn up
- Internal backgrounds not fully understood
- Age determination not fully reliable

So what do you buy?

Does dark kinetic heating expand our direct detection frontiers?

Claim of dark matter discovery will be premature/exaggerated!
(As opposed to exclusion = clean.)

Rewards?

(1) Low mass
(2) High mass
(3) Strongly interacting
(4) Spin-dependent
(5) \( v \)-suppressed
(6) Inelastic
(7) Neutrino floors
Complementing terrestrial searches

\[ T_\infty = 1750 \, \text{K} \]
\[ T_\infty = 1000 \, \text{K} \]

CRESST (2015)
CDMSlite (2015)

XENON1T-SI
XENON1T-SD

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

(1) Low mass ✓
(2) High mass ✓

\[ \sigma_{\text{threshold}} = \pi R^2 \left( \frac{m_n}{M_{\text{NS}}} \right) \]

\[ \sigma_{\text{threshold}} \propto \text{number of scatters} = \frac{E_{\text{DM}}}{E_{\text{recoil}}} \]

\[ E_{\text{recoil}} \sim 2m_n v_{\text{esc}}^2 \]

versus

\[ E_{\text{DM}} \sim \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 \]

“Pauli blocking"

\[ \sigma_{\text{threshold}}^{-1} \propto \text{fraction of nucleons excitable to > Fermi momentum} \]

\[ \frac{\gamma m_{\text{DM}} v_{\text{esc}}}{p_{\text{Fermi}}} \]
Complementing terrestrial searches

Direct detection ceiling does not apply

(1) Low mass ✅
(2) High mass ✅
(3) Strong ✅

$T_\infty = 1750$ K
$T_\infty = 1000$ K

$\sigma_{nx} (\text{cm}^2)$ vs $m_{DM}$ (GeV)

CRESST (2015)
CDMSlite (2015)
XENON1T-SD
XENON1T-SI
Complementing terrestrial searches

$T_{\infty} = 1750\, \text{K}$

$T_{\infty} = 1000\, \text{K}$

Scattering with neutrons:
apathy to nuclear coherence

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

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

CRESST (2015)
CDMSlite (2015)
XENON1T-SI
XENON1T-SD
Complementing terrestrial searches

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

Scattering proceeds so long as mass splitting is below

$$\tilde{\delta}_{\text{max}} = \frac{\mu_{nX} v^2}{2} = 200 \text{ MeV}$$

(Direct detection $\delta_{\text{max}}$: $O(100 \text{ keV})$)

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

Great news for Higgsino lovers!

Heating up neutron stars with inelastic dark matter

Nicole F. Bell, Giorgio Busoni and Sandra Robles
ARC Centre of Excellence for Particle Physics at the Terascale School of Physics, The University of Melbourne, Victoria 3010, Australia
1807.02840

$\tilde{H}_1^0$, $\tilde{H}_2^0/\tilde{H}^\pm$
Complementing terrestrial searches

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

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

$T_\infty = 1750 \text{ K}$
$T_\infty = 1000 \text{ K}$
Important variations on a theme

Are we barking down the wrong target particle?

A Joglekar, N R, P Tanedo, H-B. Yu; 1911.13293

Are we barking down the wrong stellar region?

J Acevedo, J Bramante, R Leane, N R; 1911.06334
Zippy electrons in the core

<table>
<thead>
<tr>
<th>species</th>
<th>$\langle Y_T \rangle$</th>
<th>mass (MeV)</th>
<th>$\langle p_F \rangle$ (MeV)</th>
</tr>
</thead>
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<tr>
<td>$e$</td>
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- speed $\sim c$, random directions
- frozen in the star

products of $\beta$ equilibrium

A Joglekar, N R, P Tanedo, H-B. Yu; 1911.13293
Trouble with zippy electrons

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- speed $\sim c$, random directions
- frozen in the star

products of $\beta$ equilibrium

NON-RELATIVISTIC TARGETS:

$$f = \frac{\text{scattering cross section}}{\text{geometric cross section}} = \sigma n_T R_*$$

ELECTRON TARGETS:

$\nu_{esc} = 0.6$

$\nu_{halo} = 8 \times 10^{-4}$

notion of “geometric cross section” breaks down!

A Joglekar, N R, P Tanedo, H-B. Yu; 1911.13293
More trouble with zippy electrons

capture probability $f$ must be Lorentz-invariant

But scattering ingredients aren’t

Fermi-Dirac distribution best known (to me) here
cross sections most conveniently expressed here
Putting frames together Lorentz-invariantly

\[ f = \sum_{N_{\text{hit}} \in \mathbb{Z}} \frac{\langle n_T \rangle \Delta t}{N_{\text{hit}}} \int d\Omega_{NS} \int_{d|\vec{p}|}^{p_F} \frac{|\vec{p}|^2}{V_F} v_{M\Omega} \int d\Omega_{\text{CM}} \left( \frac{d\sigma}{d\Omega} \right)_{\text{CM}} \Theta (\Delta E + E_p - E_F) \Theta \left( \frac{E_{\text{halo}}}{N_{\text{hit}} - 1} - \Delta E \right) \Theta \left( \Delta E - \frac{E_{\text{halo}}}{N_{\text{hit}}} \right) \]

DM’s stellar transit time
Møller velocity
energy transfer to electron
electron Fermi momentum

electron orientation with respect to star
Fermi sphere volume
Pauli blocking
possible multiscatter capture

In limit of non-relativistic target (& \( N_{\text{hit}} \to 1 \)):

\[ f = \langle n_T \rangle \Delta t \times 1 \times v_{\text{DM}} \times \sigma = \sigma n_T R_* = \frac{\text{scattering cross section}}{\text{geometric cross section}} \]
Putting frames together Lorentz-invariantly

\[ f = \sum_{N_{\text{hit}} \in \mathbb{Z}} \frac{\langle n_T \rangle \Delta t}{N_{\text{hit}}} \int d\Omega_N \int_0^{p_F} \frac{|\bar{p}|^2}{V_F} v_{\text{Møller}} \int d\Omega_{\text{CM}} \left( \frac{d\sigma}{d\Omega} \right)_{\text{CM}} \Theta (\Delta E + E_p - E_F) \Theta \left( \frac{E_{\text{halo}}}{N_{\text{hit}} - 1} - \Delta E \right) \Theta \left( \Delta E - \frac{E_{\text{halo}}}{N_{\text{hit}}} \right) \]

- DM’s stellar transit time
- Møller velocity
- energy transfer to electron
- electron Fermi momentum
- electron orientation with respect to star
- Fermi sphere volume
- Pauli blocking
- possible multiscatter capture

In limit of non-relativistic target (& \( N_{\text{hit}} \to 1 \)):

\[ f = \langle n_T \rangle \Delta t \times 1 \times v_{\text{DM}} \times \sigma = \sigma n_T R_\star = \frac{\text{scattering cross section}}{\text{geometric cross section}} \]

For short-distance interactions:

\[ (\bar{\chi} \Gamma \chi \chi) (\bar{f} \Gamma f f) / \Lambda^2 \]

A Joglekar, N R, P Tanedo, H-B. Yu; 1911.13293
“Electron star” dark matter detection

\[ \frac{1}{\Lambda^2} \langle \bar{\chi} \gamma^\mu \chi \rangle \langle \bar{\xi} \gamma_\mu \xi \rangle \]

\[ M_\star = 1.5 M_\odot \quad R_\star = 12.6 \text{ km} \]

Cross section \( \propto \) Fermi energy\(^2\) \( [(150 \text{ MeV})^2]\)

Cross section \( \propto \) electron mass\(^2\) \( [(0.5 \text{ MeV})^2]\)

Hard to lose energy to zippy electrons

A Joglekar, N R, P Tanedo, H-B. Yu; 1911.13293
Are we barking down the wrong region?
structure of the crust, better understood than core
deeper => knowledge of structure more uncertain
Climbing down the layers

deeper =>
knowledge of structure
more uncertain
worthwhile to investigate capability of every layer to capture dark matter

better sensitivity, more dubious
capture by exciting single superfluid phonon:

energy deposited > halo KE

\[ q \times \text{phonon speed} \quad [m_{\text{DM}} (10^{-3} \, c)^2] \]

\sim m_{\text{DM}} v_{\text{esc}} \times 0.04 \, c \]

\[ \sigma_{\text{phonon}}(q) = S_{\text{phonon}}(q) \sigma_{n\chi} \]

\[ q/ (2m_{\text{n}} \times \text{phonon speed}) \]

J Acevedo, J Bramante, R Leane, N R; 1911.06334
Crust vs WIMPs & heavier dark matter

energy transfer < nucleon binding energy $\sim 10$ MeV

response peak

capture by pasta:
\[
\sigma_{\text{pasta}}(q) = S_{\text{pasta}}(q) \sigma_{n\chi}
\]

response function describing correlations among nucleons in pasta

J Acevedo, J Bramante, R Leane, N R; 1911.06334
Neutron star crust vs Earth crust

versus direct detection:
Dark kinetic heating of neutron stars via scattering on non-relativistic nucleonic or ultra-relativistic electronic targets, in the less-understood core or fail-safe crust, seriously advances the direct detection frontiers of

- low mass (sub-GeV),
- high mass (> 100 GeV),
- spin-dependence ($\sigma_{SD} > 10^{-45} \text{ cm}^2$),
- velocity-dependence,
- 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.
Backup
The importance of being

Annihilation saves observation time (= $$) by a factor of >10!

But how much annihilation is guaranteed?

Asymmetric (with $Z_2$-given stability) — none
p-wave — very suppressed

Does DM even thermalize with the star?

Affects DM spatial distribution, hence annihilation rate:

Spin-0 DM, vector interaction with quarks

What happens for other spins & interactions?

What if scattering is velocity-suppressed? inelastic?

Investigation ongoing…
Complementing terrestrial searches

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

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

\[
\delta_0 \approx \frac{v^2}{4} \left( \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2} \right),
\]

\[
\delta_{\text{tree}} \approx \frac{v^2}{4} \left( \frac{g_1^2}{M_1} (1 + \sin 2\beta) + \frac{g_2^2}{M_2} (1 - \sin 2\beta) \right),
\]

\[
\delta_{\text{loop}} \approx \left( \frac{g_2}{4\pi} \right)^2 \mu \sin^2 \theta_W f \left( \frac{m_Z}{\mu} \right),
\]
TARGET ASSUMED TO BE AT REST

SPHERICAL SYMMETRY IN MOMENTUM SPACE.

NON-RELATIVISTIC

FERMI SURFACE

ALLOWED SCATTERING

PAULI BLOCKED (NO SCATTERING)

DARK MATTER MOMENTUM

TARGET MOVING AWAY FROM DARK MATTER

TARGET MOVING TOWARD DARK MATTER

RELATIVISTIC

MOMENTUM SPACE
Detection: infrared telescopes

$T = 1750$ Kelvin (infrared emission)

Imager:
- NIRCam
- IRIS

Filter:
- F200W: $1.75 - 2.2 \, \mu m$
- K-band: $2.0 - 2.4 \, \mu m$

Observation time for $2\sigma$ sensitivity:
- NIRCam: $10^5 \, \text{sec} \left( \frac{d}{10 \, \text{pc}} \right)^4$
- IRIS: $7 \times 10^4 \, \text{sec} \left( \frac{d}{10 \, \text{pc}} \right)^4$
Detection: radio pulsing

The Neutron Star Zoo
A. K. Harding (2013)
Complementing

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

Underground searches would terrifically complement us.

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