Detecting dark matter from Supernovae

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Dark matter
WIMP searches

*Figure taken from arxiv:1709.00688*
Challenges for sub-GeV DM

Low kinetic energy: \( v \sim 10^{-3} \)
\( K \sim 10^{-6} m_\chi < keV \)

Large background:

Ideas do exist how to go beyond this "floor" (directional, annual modulation, etc), but the pragmatic issue is still how to get there.

Challenges for sub-GeV DM

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Neutrino "floor"

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Goodman & Witten

If dark matter is light it can be produced inside Supernovae with $v \sim c$
Dark photon portal

\[ \mathcal{L} \supset A'_\mu \bar{\chi} \gamma^\mu \chi + \epsilon F'_{\mu \nu} F^{\mu \nu} \]

\[ m_{A'} \gtrsim 200 \text{ MeV} > m_\chi \]

\[ \mathcal{L} \supset \frac{g_d e \epsilon}{m_{A'}^2} \bar{\chi} \gamma \mu \chi J_{\text{EM}}^\mu \]

\[ y = \alpha_d \epsilon^2 \left( \frac{m_\chi}{m_{A'}} \right)^4 \]
Dark photon portal

\[ \mathcal{L} \supset \frac{g_d e e}{m_{A'}^2} \bar{X} \gamma_\mu X J^\mu_{\text{EM}} \]

\[ y = \alpha_d \epsilon^2 \left( \frac{m_\chi}{m_{A'}} \right)^4 \]

In invisibly decaying dark photon, \( A' \to \bar{\chi} \chi \)

Missing Mass/Momentum Experiments (Kinetic Mixing, \( m_{A'} = 3m_\chi \))

\* Figure from US Cosmic Visions Report
Core-Collapse Supernova

Fig. 11.1. Schematic picture of the core collapse of a massive star ($M \sim > 8 M_\odot$), of the formation of a neutron-star remnant, and the beginning of a SN explosion. There are four main phases numbered 1−4 above the plot:

1. Collapse. 2. Prompt-shock propagation and break-out, release of prompt $\nu_e$ burst. 3. Matter accretion and mantle cooling. 4. Kelvin-Helmholtz cooling of "protoneutron star." The curves mark the time evolution of several characteristic radii: The stellar iron core ($R_{Fe}$). The "neutrino sphere" ($R_{\nu}$) with diffusive transport inside, free streaming outside. The "inner core" ($R_{ic}$) which for $t \sim < 0.1$ s is the region of subsonic collapse, later it is the settled, compact inner region of the nascent neutron star. The SN shock wave ($R_{shock}$) is formed at core bounce, stagnates for several 100 ms, and is revived by neutrino heating—it then propagates outward and ejects the stellar mantle. The shaded area is where most of the neutrino emission comes from; between this area and $R_{\nu}$ neutrinos still diffuse, but are no longer efficiently produced. (Adapted from Janka 1993.)

Neutrino trapping has the effect that the lepton number fraction $Y_L$ is nearly conserved at the value $Y_e$ which obtains at the time of trapping. However, electrons and electron neutrinos still interconvert ($\beta$ equilibrium), causing a degenerate $\nu_e$ sea to build up. The core of a collapsing star is the only known astrophysical site apart from the early universe where neutrinos are in thermal equilibrium. It is the only site where neutrinos occur in a degenerate Fermi sea as the early universe is thought to be essentially CP symmetric with equal numbers of neutrinos and antineutrinos to within one part in $10^{9}$. When neutrino trapping becomes effective, the lepton fraction per baryon is $Y_L \approx 0.35$.

* Figure from: G. Raffelt, “Stars as Laboratories for Fundamental Physics”, 1996
Important effects

Must take into account

- Interactions are large, so dark matter is trapped inside Supernova out to larger radii:
  - Emits as a black-body (surface vs volume)
  - Lower temperature

- Significant velocity spread $\rightarrow$ signal is significantly spread in time
Velocity spread

\[ m_\chi = 10 \text{ MeV} \]
\[ T_{\text{core}} = 30 \text{ MeV} \]

\[ \langle E_\chi \rangle \sim 60 \text{ MeV} \]
\[ \langle v_\chi \rangle \sim 0.98 \]
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55 kpc \sim 180000 \text{ light years}

- Dark matter from SN1987a: still some years to get here
- Signal spread:

\[ \frac{\delta v}{v} \sim 1 \quad \rightarrow \quad \frac{\delta t}{180000 \text{yr}} \quad \text{dilution} \]
Semi-relativistic DM

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- Signal spread: $10^{-13}$ dilution
- SN1987a not useful
- Sensitive to older SN (potentially much closer)
- Sensitive to diffuse background of older SN
Semi-relativistic DM

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Focus on galactic diffuse background
Understanding Trapped Regime

Useful analogy with neutrino case

Interactions that change neutrino number and/or energy

Interactions that change direction without significant change in energy

Figure taken from: G. Raffelt astro-ph/0105250
Understanding Trapped Regime

- Ultimately described by a Boltzmann equation
- Reasonable results can be obtained using a “freeze-out” calculation.

### Freeze-out in time

Rate $\sim 1/\text{timescale}$

e.g.

$$H \sim n\langle \sigma v \rangle$$

### Freeze-out in space

Mean free path $\sim$ typical distance

e.g.

$$\frac{1}{n(r)\langle \sigma \rangle} \sim r$$
Freeze-out Picture

- $R_N$: Number sphere

\[ \bar{\chi} \chi \rightarrow e^+ e^- \]

- $R_E$: Energy sphere

\[ \chi e^\pm \rightarrow \chi e^\pm \]

- $R_T$: Transport sphere

\[ \chi p \rightarrow \chi p \]
Radial freeze-out

Freeze-out requirement:

No other interactions

Diffusion

It takes \( \left( \frac{\lambda_{\text{ann}}}{\lambda_T} \right) \) longer to cover \( \lambda_{\text{ann}} \)
Freeze-out calculation

Annihilation Sphere:

$$\tau_{\text{ann}} = \int_{r_N}^{\infty} \frac{dr}{\sqrt{\lambda_{\text{ann}} \lambda_T}} = \frac{2}{3}$$

Treat as a perfect black-body

$$\Phi|_{r_N} = \frac{1}{4\pi^2} \int_{m_\chi}^\infty dE \frac{(E^2 - m_\chi^2)}{e^{E/T(r_N)} + 1} \sim (MT)^{3/2} e^{-M/T}$$
Freeze-out calculation

**Annihilation Sphere:**

\[ \tau_{\text{ann}} = \int_{r_N}^{\infty} \frac{dr}{\sqrt{\lambda_{\text{ann}} \lambda_T}} = \frac{2}{3} \]

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\[ \sim (MT)^{3/2} e^{-M/T} \]

Include the effect of the energy sphere by assuming it doesn’t change the total flux but redistributes momenta according to the temperature in \( r_E \).
Computing the flux

Snapshot at 1.5 seconds post bounce
Detecting DM flux

- Electron targets:
  \[ \Delta k_e \approx m_e \nu_{DM} \]
  \[ \sigma_{\chi e} \propto \frac{m_e}{E_\chi} \]

- Nuclear targets
  \[ \Delta k_n \approx 2p_\chi \]
  \[ \sigma_{\chi n} \propto Z^2 \]

- Energy release
  \[ E_r \approx \frac{2p_\chi^2}{m_n} \]

- Minimum energy
  \[ p_{\text{min}}^{Xe} \approx 17 \text{ MeV} \]
Preliminary sensitivity

Galactic diffuse Supernovae flux

Relic Density

SENSEI

BBN

$10^{1}$

$10^{2}$

mass (MeV)

log$(y)$

$10^{-6}$

$10^{-8}$

$10^{-10}$

$10^{-12}$

$10^{-14}$

$10^{-16}$

$10^{-18}$

DARWIN (200 ton–yrs)

LZ (15 ton–yr)

Cooling

thresh = 5 keV

$\Delta t = \log(10)$ s

diffuse galactic bg

1 ton–yr

$10^{1}$

$10^{2}$

mass (MeV)

log$(y)$

$10^{-6}$

$10^{-8}$

$10^{-10}$

$10^{-12}$

$10^{-14}$

$10^{-16}$

$10^{-18}$

SENSEI

BBN

DARWIN (200 ton–yrs)

LZ (15 ton–yr)

Cooling

thresh = 2.5 keV

$\Delta t = \log(10)$ s

diffuse galactic bg
Conclusions

‣ Supernovae can be a source of boosted dark sector particles. Because of their large velocity, they are more easily detected than the local dark matter population.
‣ Some regions of parameter space might be probed by Xenon1T and a large region will be tested in future Xe experiments.
‣ Need to explore profile dependence.
‣ We explored a minimal heavy dark photon portal scenario. This analysis can be extended to a number of other dark sector scenarios.