Detecting dark matter from Supernovae

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WIMP searches

*Figure taken from arxiv:1709.00688*
WIMP searches

FIG. 4. The projected sensitivity (dashed curves) on the spin-independent WIMP-nucleon cross-sections of a selected number of upcoming and planned direct detection experiments, including XENON1T and the post-LHC-Run1 minimal-SUSY allowed WIMP mass (GeV/c^2). The solid curves are primarily due to different crossings of the experimental sensitivities and the WIMP searches.

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

Low kinetic energy: \[ \nu \sim 10^{-3} \]
\[ K \sim 10^{-6} m_\chi < \text{keV} \]
Challenges for sub-GeV DM

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

Large background:

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


Goodman & Witten
Many strategies

- Search for electron scattering
- Accelerator searches
- New targets

...
Many strategies

- Search for electron scattering
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- New targets

Searching for boosted dark matter from Supernovae
Outline

- Model
- Source: Supernovae
- Computing fluxes and projected sensitivity
- Conclusion and future directions
Dark photon portal

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

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

\[ \mathcal{L} \supset \frac{g_d e e}{m^2_{A'}} \bar{\chi} \gamma_\mu \chi J^\mu_{\text{EM}} \]
Dark photon portal

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

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

\[ \sigma \sim \frac{\alpha y}{m_\chi^2} \frac{s}{m_\chi^2} \]
Dark photon portal

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- Invisibly Decaying Dark Photon \( A' \rightarrow \overline{\chi} \chi \)
- Missing Mass/Momentum Experiments (Kinetic Mixing, \( m_{A'} = 3m_\chi \))

* Figure from US Cosmic Visions Report
Dark photon portal

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

This chapter has reviewed the science case for an accelerator-based program and outlined prospects for visibly-decaying dark photon. The scenario in which DM directly annihilates to the SM defines a series of well-motivated and bounded targets. The accelerator-based approach has the attractive feature of robustly testing this scenario and is needed to uniquely probe all predictive models. A new generation of small-scale collider and fixed-target experiments can present results when \( g-2 \) and missing momentum approaches. The green band shows the values required to explain the muon mediator coupling and missing momentum.

Invisibly Decaying Dark Photon \( A' \to \bar{\chi} \chi \)

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

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

* Figure from US Cosmic Visions Report
Supernovae
Very massive stars, $M > 8 \, M_{\text{sun}}$, become unstable at the end of their life.

Once the iron core reaches the Chandrasekhar limit, $M \sim 1.5 \, M_{\text{sun}}$, electron degeneracy cannot support the core and it collapses.

Densities are so large neutrinos become trapped and the gravitational binding energy is transferred to a large lepton chemical potential.
Core-Collapse Supernova

Fig. 11.1. Schematic picture of the core collapse of a massive star ($M \sim >8M_\odot$), 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 ($R_{\text{shock}}$) 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 $Y_L \approx 0.35$.

Core-Collapse Supernova

- Inner region is hot and quasi-static from 1 to 10 seconds
- Dark matter flux will be mostly sensitive to what happens at radii < $10^3$ km

Core-Collapse Supernova

$T_{\text{core}} \sim 30 \text{ MeV}$

$R_{\text{core}} \sim 15 \text{ km}$

Is dark matter production efficient?

Core-Collapse Supernova

\[ \Delta R = 1 \text{ km} \]

\[ T_{\text{core}} \sim 30 \text{ MeV} \]

\[ R_{\text{core}} \sim 15 \text{ km} \]

Focus on production near edge of the core

\[ \frac{dN}{dt} \sim (4\pi R_{\text{core}}^2 \Delta R) n_{e^+} n_{e^-} \langle \sigma v \rangle \]

\[ \frac{dN}{dt} \sim (10^3 \text{ km}^3) (30 \text{ MeV})^6 \frac{4\pi \alpha y}{m_{\chi}^2} \]
Core-Collapse Supernova

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\[ \frac{dN}{dt} \sim \left( \frac{y}{10^{-11}} \right) 10^{66} / \text{s} \]
SN1987a

Detected neutrino signal!

\[ d \approx 55 \text{ kpc} \]

Dark matter flux
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 → signal is significantly spread in time
Velocity spread

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

\[ \langle E_\chi \rangle \sim 60 \text{ MeV} \]
\[ \langle v_\chi \rangle \sim 0.98 \]
Velocity spread

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

$\langle E_\chi \rangle \sim 60$ MeV
$\langle v_\chi \rangle \sim 0.98$

55 kpc $\sim 180000$ 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

- Dark matter from SN1987a: still some years to get here
- Signal spread: $10^{-13}$ dilution

- SN1987a not useful
- Sensitive to older SN (potentially much closer)
- Sensitive to diffuse background of older SN
Effects of large interactions?

- If interactions are large, dark matter can annihilate fast before getting out of Supernova.
- It takes time for dark matter to move out since it bounces around scattering with other particles.
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.
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Freeze-out in time

Rate \sim \frac{1}{\text{timescale}}

e.g.

\[ H \sim n\langle \sigma v \rangle \]

Freeze-out in space
Understanding Trapped Regime

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

**Freeze-out in time**

Rate $\sim 1$/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
- $R_E$: Energy sphere
- $R_T$: Transport sphere

\[

\chi\chi \rightarrow e^+ e^-
\]

\[

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

\[

\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 $\lambda_{\text{ann}}$
Radial freeze-out

Freeze-out requirement:

\[ \tau_x = \int_{r_x}^{\infty} \frac{dr}{\lambda_x} = \frac{2}{3} \]

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

\[ \lambda_T \ll \lambda_{\text{ann}} \]

Annihilations become effectively more efficient
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

$$\Phi|_{r_N} = \frac{1}{4\pi^2} \int_{m_\chi}^{\infty} dE \frac{(E^2 - m_\chi^2)}{eE/T(r_N) + 1}$$
Flux decreases due to scattering with protons
Currently we treat the effect of the energy sphere by assuming it doesn’t change the total flux but redistributes momenta according to the temperature in $r_E$. 

\[
\Phi(r \gg r_N) = \frac{\Phi(r_N)}{(1 + \frac{3}{4}s_*)} \left( \frac{r_N}{r} \right)^2
\]

\[
s_* = \sigma T \int_{r_N}^{\infty} dr \ n_p(r) \left( \frac{r_N}{r} \right)^2
\]
Computing the flux

Snapshot at 1.5 seconds post bounce
What is the flux on Earth?

- Single Supernova near Earth

- **Diffuse signal from past Supernovae in the galaxy**

- Diffuse signal from extra galactic Supernovae
Estimated galactic rate is around 2 Supernovae per century (maybe higher in the past)

Assuming constant rate across the galactic disk we can translate the diffuse flux in terms of an equivalent single event

\[
\Phi_{\text{diff}} = 0.038 \Phi_{1\text{-}sn}(R_{SN}) \left( \frac{R_{SN}}{\text{kpc}} \right)^2 \frac{\Delta t}{50 \text{years}}
\]
Detecting DM flux

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

- Electron targets:
  \[ \Delta k_e \approx m_e \nu_{\text{DM}} \]
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- Nuclear targets
  \[ \Delta k_n \approx 2p_\chi \]
  \[ \sigma_{\chi n} \propto Z^2 \]
Detecting DM flux

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

- **Nuclear targets**
  \[ \Delta k_n \approx 2p_{\chi} \]
  \[ \sigma_{\chi n} \propto Z^2 \]
  \[ E_r \approx \frac{2p_{\chi}^2}{m_n} \]
  \[ p_{\text{min}}^{Xe} \approx 17 \text{ MeV} \]
Cooling bounds

- We have observed the neutrinos from SN1987a with spectrum consistent with predictions.
- A conservative criteria for when new particles lead to such large deviations that the expected neutrino signal would be significantly changed is:

\[ L_\chi \gtrsim 3 \times 10^{52} \text{ergs/s} \]
Preliminary reach plot

Galactic diffuse Supernovae flux

- DARWIN (200 ton–yrs)
- LZ (15 ton–yr)
- BaBar
- E137
- LSND
- Relic Density
- Cooling
- thresh=5 keV
- Δt=log(10) s
- diffuse galactic bg
Preliminary reach plot

Galactic diffuse Supernovae flux

mass (MeV)

log(y)

thresh = 2.5 keV

Δt = log(10) s

diffuse galactic bg

BBN

E137

LSND

BaBar

Relic Density

DARWIN (200 ton-yr)

LZ (15 ton-yr)

1 ton-yr

Cooling
Conclusions

- Supernovae can be a source of boosted dark sector particles. Because of their large kinetic energy, they are more easily detected than the local dark matter population.
- Some regions of parameter space could be probed by Xenon1T and a large region will be tested in future Xe experiments.
- Fluxes could be larger depending on time-scales associated with the Supernova.
- 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.
extra material
It contains 534 kg of mass, and a low background, we consider 6 t of fiducial LXe mass for this physics channel.

In the high energy region relevant for the double beta decay search, the fiducial volume cut is less sensitive to the double beta decay channel as demonstrated by XENON100. A threshold of 1.5 keV would result in 38 events/(t y), would yield an integrated rate of 0.03 events/(t y), dominated by atmospheric neutrinos.

The recoil spectra induced by solar (8B), hep solar neutrinos, and the electron recoil spectrum from the use supernova background (DSNB), and the atmosphere (ATM). The coherent scattering effects predominantly the sensitivity to low-mass WIMPs. The recoil spectra predicted in the Standard Model. The largest impact comes from neutrino-nucleus elastic scattering has not been observed so far, but the cross section is well understood. The difference in recoil scale and a nuclear recoil acceptance of 50% is assumed.

The diagram shows two plots. On the left, it shows the differential nuclear recoil spectrum for WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 x 10^{-48} cm^2. (Left): Expected nuclear recoil spectrum from WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 x 10^{-48} cm^2.

The right plot compares the differential nuclear recoil spectrum for WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 x 10^{-48} cm^2. The figure shows the recoil spectra induced by solar (8B and hep) and the electron recoil spectrum from the use supernova background (DSNB), and the atmosphere (ATM). The coherent scattering effects predominantly the sensitivity to low-mass WIMPs. The recoil spectra predicted in the Standard Model. The largest impact comes from neutrino-nucleus elastic scattering has not been observed so far, but the cross section is well understood. The difference in recoil scale and a nuclear recoil acceptance of 50% is assumed.

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It contains 534 kg of mass, and a low background, we consider 6 t of fiducial LXe mass for this physics channel. As a compromise between a high gamma in liquid xenon. In the high energy region relevant for the double beta decay search, the fiducial volume cut shown in Figure is less event sensitive to the double beta decay channel as demonstrated by XENON10. A threshold of 1.5 keV however these neutrinos become relevant at WIMP-nucleon cross sections below 10^{-48} cm^2. The largest impact comes from neutrino-nucleus elastic scattering has not been observed so far, but the cross section is well predicted in the Standard Model. The largest impact comes from solar, diﬀerential energy spectrum for pp and Be neutrinos (red), and the electron recoil spectrum from the use supernova background (DSNB), and the atmosphere (ATM). The coherent scattering events of neutrinos (red) from various WIMP masses and cross sections (black) to coherent scattering events of neutrinos (red) from the Sun, diﬀerential nuclear recoil spectrum for WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 \times 10^{-47} cm^2. For both plots, the nuclear recoil signals are converted to an electronic rate will provide an irreducible background for low-mass WIMPs, limiting the cross section sensitivity to 4.1 \times 10^{-3} \text{ events/ton x year x keV}. A nuclear recoil energy threshold of 6.6 keV \text{ keV} will be needed to observe WIMPs of 6 GeV/c^2 with a half life of 2.1 \times 10^{28} y. Other assumptions are: 99.5% discrimination of electronic recoils, 50% maximum energy of atmospheric, and diﬀerential nuclear recoil acceptance. For WIMP 40 GeV/c^2 the recoil spectrum is more sensitive in reducing material backgrounds, compared with the low-energy region, as shown in Figure. (Left): Expected nuclear recoil spectrum from WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 \times 10^{-47} cm^2. (Right): Comparison of the diﬀerential nuclear recoil spectrum for WIMPs of 6 GeV/c^2 (solid black) and 2 \times 10^{-47} cm^2 (dashed red). For both plots, the nuclear recoil signals are converted to an electronic rate will provide an irreducible background for low-mass WIMPs, limiting the cross section sensitivity to 4.1 \times 10^{-3} \text{ events/ton x year x keV}. A nuclear recoil energy threshold of 6.6 keV \text{ keV} will be needed to observe WIMPs of 6 GeV/c^2 with a half life of 2.1 \times 10^{28} y. Other assumptions are: 99.5% discrimination of electronic recoils, 50% maximum energy of atmospheric, and diﬀerential nuclear recoil acceptance. For WIMP 40 GeV/c^2 the recoil spectrum is more sensitive in reducing material backgrounds, compared with the low-energy region, as shown in Figure. (Left): Expected nuclear recoil spectrum from WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 2 \times 10^{-47} cm^2. (Right): Comparison of the diﬀerential nuclear recoil spectrum for WIMPs of 6 GeV/c^2 (solid black) and 2 \times 10^{-47} cm^2 (dashed red). For both plots, the nuclear recoil signals are converted to an electronic rate will provide an irreducible background for low-mass WIMPs, limiting the cross section sensitivity to 4.1 \times 10^{-3} \text{ events/ton x year x keV}. A nuclear recoil energy threshold of 6.6 keV \text{ keV} will be needed to observe WIMPs of 6 GeV/c^2 with a half life of 2.1 \times 10^{28} y. Other assumptions are: 99.5% discrimination of electronic recoils, 50% maximum energy of atmospheric, and diﬀerential nuclear recoil acceptance.
Realistic Vela Jr

Cooling

$$\Delta t = 1 \text{ s}$$

thresh = 5 keV

d = 700 ly

Relic Density

mass (MeV)

log(y)

BaBar

E137

LSND

BBN

DARWIN (200 ton–yrs)