Stellar Constraints on Dark Matter and Dark Sectors

Sam McDermott

1611.03864 & 1803.00993 (+ Rouven Essig & Jae Hyeok Chang) & ongoing…

August 5, 2019
Big Picture, ca. 2009

10 GeV 100 TeV

we knew the dark matter mass!
we knew the dark matter mass!

lower limit: Lee-Weinberg bound $\langle \sigma v \rangle_{\text{ann}} > \frac{m^2}{m_W^2}$

upper limit: unitarity $\Rightarrow \langle \sigma v \rangle_{\text{ann}} < \frac{4\pi}{m^2 v}$
Big Picture, ca. 2009

\[\mu\text{eV} \quad 10\text{ meV} \quad 10\text{ GeV} \quad 100\text{ TeV}\]

we knew the dark matter mass!

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[*well okay, maybe it’s the QCD axion*]
Big Picture, ca. 2009

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[*well okay, maybe it’s the QCD axion]
[**well okay, maybe it’s primordial black holes]
Big Picture, ca. 2019

The dark matter can be anything!

- QCD axion
- canonical WIMP
- composite states, non-ΛCDM cosmology
- PBHs

MeV, TeV, Planck mass, 10^{-16} M_{⊙}, 100 M_{⊙}

The dark matter can be anything!
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lower bound: does it fit in a galaxy?
upper bound: gravitational effects
Big Picture, ca. 2019

What changed?
the dark matter can be anything!
lower bound: does it fit in a galaxy?
upper bound: gravitational effects
Two Pheno Developments

1. Hidden Sectors
   - evade the Lee-Weinberg bound $\langle \sigma v \rangle_{\text{ann}} > m^2/m_W^2$ if there is a new force that allows annihilations with mass scale $m_{\text{NP}} \ll m_W$
     - Bjorken, Essig, Schuster, Toro 0906.0580 & PRD; Morrissey, Poland, Zurek 0904.2567 & JHEP; Cheung, Ruderman, Wang, Yavin 0902.3246 & PRD

2. Asymmetric Dark Matter
   - the dark matter abundance is not set by (symmetric) thermal freezeout
     - Kaplan, Luty, Zurek 0901.4117 (earlier work by Kitano et al, Nussinov…)
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2. Asymmetric Dark Matter
   - the dark matter abundance is not set by (symmetric) thermal freezeout
   *implication: DM doesn’t annihilate*
   - Kaplan, Luty, Zurek 0901.4117 (earlier work by Kitano et al, Nussinov...)
# How to look for DM in stars?

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**Part 2**
SN1987A: Zeroth Order Facts

Supernova 1987A:

~ 99% of the grav. binding energy of a collapsing blue supergiant radiated away in the form of neutrinos over the course of ~ 10s
Supernova at the Order of Magnitude Level

\[ \rho_c = m_N (110 \text{ MeV})^3, \ T_c = 30 \text{ MeV}, \ \omega_{p,c} \approx 13 \text{ MeV} \]

\[ \rho(r) = \rho_c \times \begin{cases} 
1 + k_\rho \left(1 - \frac{r}{R_c}\right) & r < R_c \\
\left(\frac{r}{R_c}\right)^{-\nu} & r \geq R_c 
\end{cases} \]

\[ T(r) = T_c \times \begin{cases} 
1 + k_T \left(1 - \frac{r}{R_c}\right) & r < R_c \\
\left(\frac{r}{R_c}\right)^{-\nu/3} & r \geq R_c 
\end{cases} \]

“fiducial model”
(Raffelt, 1995)
Numerical Models

“fiducial model” differs from sims by ~O(10):

value of $R_f$ (important for optical depth, $\tau(r) = \int_r^{R_f} \Gamma'(r') \, dr'$)

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This Talk: Dark Photons

vector boson of a new U(1) gauge group, kinetically mixed with Standard Model photon

Dark photons get produced / absorbed in EM interactions (~$\epsilon^2$ as often as photons)
This Talk: Dark Photons

vector boson of a new U(1) gauge group, kinetically mixed with Standard Model photon

Dark photons get produced / absorbed in EM interactions ($\sim \varepsilon^2$ as often as photons)
Efficiently Produced

No Trapping

Thermal Emission

Efficiently Trapped

Luminosity vs. mixing angle

$\rho_r (m')$

$\rho_t (m')$

$L_y$

mixing

$\rho'$
Luminosity vs. mixing angle

\[ \epsilon_{pr}(m') \epsilon_{tr}(m') \]

ruled out
Kinetic Mixing

gauge invariant product of field strengths

\[ \mathcal{L} \supset \epsilon F_{1\mu\nu} F_{2}^{\mu\nu} / 2 \leftrightarrow A_1 \times A_2 \]
Kinetic Mixing

gauge invariant product of field strengths*

\[ \mathcal{L} \supset \epsilon F_{1 \mu \nu} F_{2 \mu \nu} / 2 \iff \begin{array}{c}
A_1 \\
\times
\end{array} A_2 \]

*(“EFT tells me to write down”)*
Kinetic Mixing

gauge invariant product of field strengths*

\[ \mathcal{L} \supset \epsilon F_{1\mu\nu} F_{2\mu\nu} / 2 \iff \]

implicitly \( \sim q^2 \)

*(“EFT tells me to write down”)*
Coupling to Dark Photon in vacuum:

\[ e^- e^- \gamma e^- A' \bar{X} X \bar{X} f f \]
Coupling to Dark Photon in vacuum:

\[ \varepsilon q^2 \]

The diagram shows a process involving a dark photon (\( A' \)) and other particles, with the coupling given by \( \varepsilon q^2 \).
Coupling to Dark Photon

in vacuum:

\[ \varepsilon q^2 \]

\[ 1/q^2 \]
Coupling to Dark Photon in vacuum:

\[ \mathcal{L} \supset \epsilon J_{\mu}^{\text{SM}} A'^{\mu} \]

Diagram:

- $f \rightarrow \gamma \rightarrow A'$
- $1/q^2$
- $\epsilon q^2$
“Plasmas Give Photon a Mass”

High density of charge carriers modifies the SM photon dispersion relation:

\[ \omega^2 = k^2 + \text{Re} \Pi(k^2, \omega^2, n_e) \]

At low \( k \), \( \Pi \) equals the “plasma mass” \( \omega_p \)

\[
\lim_{k \to 0} \Pi = \omega_p^2(n_e) \approx \frac{4\pi\alpha n_e}{E_F}
\]

\[
\omega_p^2(n_e) = \int \frac{4\pi\alpha d^3p}{(2\pi)^32E} \left(1 - \frac{p^2}{3E^2}\right) [f_e^-(E) + f_e^+(E)]
\]
Coupling to Dark Photon

in vacuum:

\[ \mathcal{L} \supset \epsilon J_{\mu}^{SM} A'_{\mu} \]

\[ \epsilon q^2 \]

\[ 1/q^2 \]
Coupling to Dark Photon

in vacuum:

\[ \mathcal{L} \supset \epsilon J_{\mu}^{SM} A'^{\mu} \]

in plasma:

\[ \mathcal{L} \supset \frac{\epsilon q^2}{q^2 - \Pi} J_{\mu}^{SM} A'^{\mu} \]
Coupling to Dark Photon

in vacuum:

\[ \mathcal{L} \supset \epsilon J_{\mu}^{\text{SM}} A'^\mu \]

in plasma, on-shell:

\[ \mathcal{L} \supset \frac{\epsilon}{1 - \Pi/m'^2} J_{\mu}^{\text{SM}} A'^\mu \]

\[ \epsilon m'^2 \]

\[ 1/(m'^2 - \Pi) \]
Rates for A’s

dark photon rates $\propto$ SM photon rates:

$$\Gamma'_p = \left| \frac{\epsilon}{1 - \Pi/m'^2} \right|^2 \Gamma_p$$

$$= \frac{\epsilon^2 \Gamma_p}{(1 - \text{Re}\Pi/m'^2)^2 + (\text{Im}\Pi/m'^2)^2}$$
Rates for A's

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\Gamma'_p = \left| \epsilon \frac{\Pi}{1 - \Pi/m'^2} \right|^2 \Gamma_p
$$

$$
= \frac{\epsilon^2 \Gamma_p}{(1 - \text{Re}\Pi/m'^2)^2 + (\text{Im}\Pi/m'^2)^2}
$$

[*resonance if $m'^2 \gg \text{Im}\Pi$ and $\exists \omega_{\text{res}}$ with $\text{Re}\Pi(\omega_{\text{res}}) = m'^2$]*
Photon Self-Energy

\[
\text{Re}\Pi = \begin{cases} 
\frac{3\omega_p^2}{\nu^2} (1 - \nu^2) \left[ \frac{1}{2\nu} \ln \left( \frac{1+\nu}{1-\nu} \right) - 1 \right] & L \\
\frac{3\omega_p^2}{2\nu^2} \left[ 1 - \frac{1-\nu^2}{2\nu} \ln \left( \frac{1+\nu}{1-\nu} \right) \right] & T 
\end{cases}
\]

(v=|k|/\omega)

different dispersion relations for \( L \) and \( T \) modes
Photon Self-Energy

\[ \text{Re}\Pi = \begin{cases} 
\frac{3\omega_p^2}{v^2} (1 - v^2) \left[ \frac{1}{2v} \ln \left( \frac{1+v}{1-v} \right) - 1 \right] & L \\
\frac{3\omega_p^2}{2v^2} \left[ 1 - \frac{1-v^2}{2v} \ln \left( \frac{1+v}{1-v} \right) \right] & T \end{cases} \]

Different dispersion relations for \( L \) and \( T \) modes.

\[ \text{Im}\Pi \sim \text{rate at which photon thermalizes}: \]

\[ \text{Im}\Pi = \omega \left( \Gamma_{\text{prod}} - \Gamma_{\text{abs}} \right) \]
Particle Luminosity

\[ dL = e^{-\tau} \, dP \]
Particle Luminosity

energy lost in A’s per unit time

\[ dL = e^{-\tau} dP \]
Particle Luminosity

energy lost in A’s per unit time

erate at which A’s are produced

\[ dL = e^{-\tau} dP \]
Particle Luminosity

\[ dL = e^{-\tau} dP \]

energy lost in A's per unit time
rate at which A's are produced

odds of escaping
Power and Optical Depth

differential power is the integral of production rate:

\[
\frac{dP}{dV} = \int \frac{d^3 k}{(2\pi)^3} \omega \Gamma_{\text{prod}}
\]

not all power gets out because of a nonzero “optical” depth:

\[
\tau = \int_{r}^{R_{\text{far}}} \Gamma_{\text{abs}}(r') dr'
\]

by detailed balance, \( \Gamma_{\text{prod}} = e^{-\omega/T} \Gamma_{\text{abs}} \), so calculate \( \Gamma_{\text{abs}} \) only.
Differential Luminosity

\[
\frac{dL}{dV} = \int \frac{d\omega}{2\pi^2} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r)}{\Gamma_{\text{abs}}(\omega, r)} \left[ 1 - \frac{\text{Re}\Pi(\omega, r)}{m'^2} \right]^2 + \left[ \frac{\text{Im}\Pi(\omega, r)}{m'^2} \right]^2 \right] \frac{e^2}{\lambda^2 + \text{Im}\Pi(\omega, r)} \int d\omega \Gamma_{\text{abs}}(\omega, r)
\]
\[
\frac{dL}{dV} = \int \frac{d\omega}{2\pi^2} \frac{\epsilon^2 \omega^3 \nu e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r) e^{-\frac{\epsilon^2}{1 - \frac{\text{Re}\Pi(\omega, r)}{m^2}^2 + \left(\frac{\text{Im}\Pi(\omega, r)}{m^2}\right)^2}}}{\left[1 - \frac{\text{Re}\Pi(\omega, r)}{m^2}\right]^2 + \left(\frac{\text{Im}\Pi(\omega, r)}{m^2}\right)^2} \int dr \Gamma_{\text{abs}}(\omega, r) \]
Differential Luminosity

\[ \frac{dL}{dV} \approx \frac{\Delta \omega_{\text{res}}}{2\pi^2} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r)}{0 + [\text{Im}\Pi(\omega, r)/m'^2]^2} e^{-\epsilon^2 \cdots} \]

(for small \( \epsilon \))

(for \( \text{Im}\Pi_{\text{res}} << m'^2 \))
\[
\frac{dL}{dV} \approx \frac{\Delta \omega_{\text{res}}}{2\pi^2} \frac{\varepsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r)}{0 + [\text{Im} \Pi(\omega, r)/m'']^2} e^{-\Delta \omega_{\text{res}}/2} \quad \text{(for small } \varepsilon) \\
\]

rates cancel since \( \text{Im} \Pi \sim \Gamma, \Delta \omega_{\text{res}} \sim \Gamma \)
Differential Luminosity

\[ \frac{dL}{dV} \approx \Delta \omega_{\text{res}} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r)}{2\pi^2} 0 + [\text{Im}\Pi(\omega, r)/m'{}^2]^2 e^{-\epsilon} \ldots \]

rates cancel since \(\text{Im}\Pi \sim \Gamma, \Delta \omega_{\text{res}} \sim \Gamma\)

at low mixing, resonant luminosity is

\[ \frac{dL_{\text{res}}}{dV} \approx \frac{\epsilon^2 m'{}^2 \omega_{\text{res}}^3 v^3}{2\pi \left(e^{\omega/T} - 1\right)} \implies \frac{dL_{\text{res}}}{dV} \times \text{Vol} \sim L_v \left(\epsilon/5 \times 10^{-9}\right)^2 (m'/\text{MeV})^2 \]
Differential Luminosity

(for Im\(\Pi\)\(_{\text{res}}\)\(<\(<m^{'2}\))

\[
\frac{dL}{dV} \sim \frac{\Delta \omega_{\text{res}}}{2\pi^2} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\text{abs}}(\omega, r)}{0 + [\text{Im}\Pi(\omega, r)/m^{'2}]^2} e^{-\epsilon^2 \ldots}
\]

(for small \(\epsilon\))

rates cancel since Im\(\Pi\)\(\sim\)\(\Gamma\), \(\Delta \omega_{\text{res}}\)\(\sim\)\(\Gamma\)

at low mixing, resonant luminosity is

\[
\frac{dL_{\text{res}}}{dV} \sim \frac{\epsilon^2 m^{'2} \omega_{\text{res}}^3 v^3}{2\pi (e^{\omega/T} - 1)} \implies \frac{dL_{\text{res}}}{dV} \times \text{Vol} \sim L_v (\epsilon/5 \times 10^{-9})^2 (m^{'}/\text{MeV})^2
\]

bounds not flat in \(\epsilon\)-\(m^{'\prime}\) plane
Higher Mixing

at large mixing: $\tau$ is large, $dP_{res}$ is suppressed

differential luminosity $dL = e^{-\tau} dP \neq dP$
Higher Mixing

at large mixing: $\tau$ is large, $dP_{\text{res}}$ is suppressed

differential luminosity $dL = e^{-\tau} dP \neq dP$

need to know $\Gamma$ for all $r$ and $\omega$
use $np$ scattering data with soft emission:

$$
\Gamma'_{\text{br.}}|_{L,T} = \frac{32}{3\pi} \frac{\alpha_{\text{EM}} (\epsilon_m)^2_{L,T} n_n n_p}{\omega^3} \left( \frac{\pi T}{m_N} \right)^{3/2} \langle \sigma_{np}^{(2)} \rangle \left[ \frac{m'_{2}}{\omega^2} \right]_L
$$

Rrapaj & Reddy, 1511.09136
Soft Radiation Approximation

use \emph{np} scattering data with soft emission:

\[
\Gamma'_{\text{br.}|L,T} = \frac{32}{3\pi} \frac{\alpha_{\text{EM}} (\epsilon_m)^2 L_{n_T} n_n n_p}{\omega^3} \left( \frac{\pi T}{m_N} \right)^{3/2} \langle \sigma_{np}^{(2)} \rangle \left[ \frac{m'^2}{\omega^2} \right]_L
\]

\text{key point: falls sharply with } \omega
Soft Radiation Approximation

key point: falls sharply with $\omega$

($\Rightarrow$ lower optical depth at high $\omega$)

\[ \Gamma'_{\text{br.}|L,T} = \frac{32}{3\pi} \frac{\alpha_{\text{EM}} (\epsilon_m)^2}{L,T} \frac{n_n n_p}{\omega^3} \left( \frac{\pi T}{m_N} \right)^{3/2} \left\langle \sigma_{np}^{(2)} \right\rangle \left[ \frac{m'^2}{\omega^2} \right] L \]
$\frac{dL}{dV/d\omega/\varepsilon^2}$

$R=10\text{km}, m'=1\text{ MeV}$
\[ \frac{dL}{dV/d\omega/\epsilon^2} \]
\[ \frac{dL}{dV/d\omega/\varepsilon^2} \]

Graph: 
- \( R = 10 \text{km}, m' = 1 \text{ MeV} \)
- Legend:
  - \( \lim_{\varepsilon \to 0} \)
  - \( \varepsilon = 10^{-10} \)
  - \( \varepsilon = 10^{-9} \)

Axes:
- \( 4\pi r^2 \varepsilon^{-2} \frac{dL}{dV/d\omega} \) [\( L_c/\text{MeV} \cdot \text{km} \)]
- \( \omega \) [MeV]

Scale: 
- Logarithmic scale from \( 10^6 \) to \( 10^{18} \) for \( L_c/\text{MeV} \cdot \text{km} \)
- Logarithmic scale from \( 10^1 \) to \( 10^2 \) for \( \omega \) [MeV]
\[ \frac{dL}{dV/d\omega/\varepsilon^2} \]

**Graph**:

- **Title**: \( R=10\text{km, } m'=1 \text{ MeV} \)

- **Axes**:
  - Y-axis: \( 4\pi r^2 \varepsilon^{-2} \frac{dL}{dVd\omega} \) [\( L_c/\text{MeV\cdot km} \)]
  - X-axis: \( \omega \) [MeV]

- **Legend**:
  - \( \lim_{\varepsilon \to 0} \)
  - \( \varepsilon = 10^{-10} \)
  - \( \varepsilon = 10^{-9} \)
  - \( \varepsilon = 10^{-8} \)
\[ \frac{dL}{dV/\omega} \]
dL/dV/dω/ε^2
$$dL/dV/d\omega/\varepsilon^2$$
$\frac{dL}{dV/d\omega}$

$R=10\text{km}$, $m'=1\text{ MeV}$
\[ \frac{dL}{dV/d\omega} \]

\[ m' = 1 \text{ MeV} \]

\[ 4\pi r^2 \frac{dL}{dV d\omega} [L_v/\text{MeV} \cdot \text{km}] \]

\[ \omega \text{ [MeV]} \]

- \( \epsilon = 10^{-8} \)
- \( \epsilon = 10^{-5} \)
- \( R = 10 \text{ km} \)
- \( R = 30 \text{ km} \)

volume emission!
\[ \frac{dL}{dV/d\omega} \]

The diagram shows the distribution of neutrino emission as a function of energy \( \omega \) for different distances \( R \). The graph is labeled with the energy \( m' = 1 \) MeV. The curves represent surface emission and volume emission. The figure includes different emission rates denoted by \( \epsilon = 10^{-8} \) and \( \epsilon = 10^{-5} \). The axes are labeled as follows:

- Vertical axis: \( 4\pi r^2 \frac{dL}{dVd\omega} \) [\( L_v \)/MeV·km]
- Horizontal axis: \( \omega \) [MeV]

Key points:
- Surface emission
- Volume emission
- Emission rates
- Distance labels: R = 10 km, R = 30 km
- Thermal emission
$dL/dV/d\omega$

\[ m' = 1 \text{ MeV} \]

$\omega (\text{Wien peak}) \ll \omega (\text{real peak})$
\( \frac{dL}{dV/d\omega} \)

\[ m' = 1 \text{ MeV} \]

thermal spectrum underestimates total luminosity
\[ dL = e^{-\tau} dP \]
Results
Part II: Dark Pair Instability
Very small coupling

A’ production rate competes with SM photon or neutrino rate
Very small coupling

A' production rate competes with SM photon or neutrino rate

nonrelativistic A' produced at very low rates
Pair Instability SNe

FIG. 1: Stellar death regions with schematic stellar evolution tracks in the plane of central density ($\rho_c$) and central temperature ($T_c$). Colored death regions are labeled by the instability process causing the collapse of the stellar core, and the blue tracks are labeled by the corresponding rough birth-mass range of objects reaching the different stages of central burning (indicated by red dashed lines). Yellow diagonal lines mark the beginning of degeneracy (short-dashed) and strong degeneracy (long-dashed) of the electron plasma. Note that realistic stellar tracks exhibit wiggles and loops when the ignition of the next burning stage is reached and the stellar core adjusts to the new energy source (see Ref. [20]).

Stars beyond certain birth-mass limits can reach the “death zones” in the upper and right parts of Fig. 1, where the stellar core becomes gravitationally unstable. Contraction, and in the case of a runaway process, finally collapse, sets in when the effective adiabatic index drops below the critical value of $\frac{4}{3}$ for mechanical stability (the actual value is slightly decreased by rotation and increased by general relativistic gravity).

Three different processes can initiate the implosion of stellar cores in three areas of the $\rho_c$-$T_c$-plane indicated by different colors in Fig. 1, playing a role in different kinds of CC events.

Fermions approach the degeneracy when their Fermi energy begins to exceed the thermal energy $k_B T$, i.e., at $T_8 \sim \frac{\rho_{25}}{3}^{0.08}$ for nonrelativistic electrons and at $T_{10} \sim \frac{\rho_{18}}{3}^{0.08}$ for relativistic ones with $T_x \equiv \frac{T}{(10^x K)}$ and $\rho_y \equiv \frac{\rho}{(10^y \text{ gc m}^{-3})}$. [Janka, 1206.2503]
Pair Instability SNe

Appearance of non-relativistic e+e- pairs (catastrophically) causes adiabatic index to fall below 4/3 (n.b.: this has nontrivial $\rho$-dependence due to Pauli blocking at high $\rho$)
Pair Instability SNe

if $T_c$ much less than $m_e$, too few “missing photons” to matter
Pair Instability SNe

If $T_c$ greatly in excess of $m_e$, all electrons are relativistic and adiabatic index climbs again.
Tightly Coupled Dark States

Could a new particle (with or w/o pre-collapse abundance) have a similar effect?
Could a new particle (with or w/o pre-collapse abundance) have a similar effect?
Could a new particle (with or w/o pre-collapse abundance) have a similar effect?
Tightly Coupled Dark States

Could a new particle (with or w/o pre-collapse abundance) have a similar effect?

Order of magnitude estimate: 
\[ \Gamma \sim \varepsilon^2 m_{A'}^2 / 3T \]

Equilibration after \(10^7\) yr for \(m_{A'} \sim T \sim 100\) keV and \(\varepsilon \sim 10^{-16}\)
How to look for DM in stars?

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**Stellar Populations**

**Dense Objects (WDs, NSs, ...)**

**Supernova**
# How to look for DM in stars?

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**talks tomorrow by Giannotti and Raen**
**How to look for DM in stars?**

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**Exciting opportunities for crosstalk between theorists / experimentalists / observationalists / modelers / etc.!!**

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