Stellar Basins of Gravitationally Bound Particles

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Based on: KVT, “Stellar Basins of Gravitationally Bound Particles”, arXiv:2006.12431
R. Lasenby, KVT, “Dark Photons in the Solar Basin”, arXiv:2008.08594

UC Davis, September 21, 2020
Stellar Emission

- Red Giant (RG)
- Horizontal Branch (HB)
- Neutron Star (NS)
- White Dwarf (WD)

Celestial objects and their associated representations.
Stellar Emission

- Red Giant (RG)
- Horizontal Branch (HB)
- Neutron Star (NS)
- White Dwarf (WD)

[Diagram showing stellar emission with various types of stars and their properties]
Stellar Emission

- Stellar type: O, B, A, F, G, K, M
- Surface temperature (K)
- Luminosity ($L_\odot$)
- Gaia G absolute magnitude
- Gaia BP-RP colour
- Main sequence
- Giant branch
- White dwarfs
- Neutron Stars
- Neutron Star (NS)
- Horizontal Branch (HB)
- Red Giant (RG)
- White Dwarf (WD)

- Photon
- Neutrino
Stellar Emission

**NS Cooling**

- Temperature [K]
  - Center
  - Surface

- Luminosity [erg/sec]
  - Neutrinos
  - Photons

Age [yr]

- $10^{-2}$
- $10^{-1}$
- $1$
- $10$
- $10^2$
- $10^3$
- $10^4$
- $10^5$

$T$ [keV]

- $10^1$
- $10^{-1}$
- $10^2$
- $10^3$
- $10^4$
- $10^5$

**Images**

- Horizontal Branch (HB)
- Red Giant (RG)
- Neutron Star (NS)
- White Dwarf (WD)

**Symbols**

- Photon
- Neutrino
Stellar Emission

- Red Giant (RG)
- Horizontal Branch (HB)
- Neutron Star (NS)
- White Dwarf (WD)

Neutron Stars

- photon
- neutrino

Gaia G absolute magnitude

- main sequence
- giant branch
- white dwarfs

Surface temperature (K)

Luminosity ($L_\odot$)

Gaia BP–RP colour

- bluer → redder
Stellar Emission

- Red Giant (RG)
- Horizontal Branch (HB)
- Neutron Star (NS)
- White Dwarf (WD)

Neutron Stars

- photon
- unbound axion
- neutrino

- Main sequence
- Giant branch
- White dwarfs

Gaia G absolute magnitude vs Gaia BP-RP colour

Luminosity vs Surface temperature (K)
Stellar Emission

- Red Giant (RG)
- Horizontal Branch (HB)
- Neutron Star (NS)
- White Dwarf (WD)

Neutron Stars
- photon
- unbound axion
- neutrino
- DM axion
## Bosonic Particles Produced in Stars

| Scalar          | Pseudoscalar | Vector                        |
|-----------------|--------------|-------------------------------|
| $\phi ee$       | $\phi \bar{q}q$ | $a\bar{e}i\gamma_5e$         |
| $\phi F^2$      | $\phi G^2$   | $a\bar{q}i\gamma_5q$         |
| $a\bar{F}\tilde{F}$ | $aG\tilde{G}$ | $\epsilon A'_\mu J^\mu_{EM}$ |
| $gA'_\mu J^\mu_{B-L}$ |             |                               |
Bosonic Particles Produced in Stars

Scalar
\[ \phi \bar{e}e \quad \phi \bar{q}q \]
\[ \phi F^2 \quad \phi G^2 \]

Pseudoscalar
\[ a \bar{e}i\gamma_5 e \]
\[ a \bar{q}i\gamma_5 q \]
\[ a F\tilde{F} \]
\[ a G\tilde{G} \]

Bremsstrahlung

Vector
\[ \epsilon A'_\mu J^\mu_{EM} \]
\[ g A'_\mu J^\mu_{B-L} \]

Compton
Bosonic Particles Produced in Stars

Scalar

- $\phi \bar{e} e$
- $\phi \bar{q} q$
- $\phi F^2$
- $\phi G^2$

Bremsstrahlung

Pseudoscalar

- $a \bar{e} i \gamma_5 e$
- $a \bar{q} i \gamma_5 q$
- $aF \tilde{F}$
- $aG \tilde{G}$

Compton

Vector

- $\epsilon A'_\mu J_{EM}^\mu$
- $gA'_\mu J_{B-L}^\mu$

Primakoff

Decay to Photons
Bosonic Particles Produced in Stars

Scalar
\[ \phi \bar{e}e \quad \phi \bar{q}q \quad \phi F^2 \quad \phi G^2 \]

Pseudoscalar
\[ a \bar{e}i\gamma_5 e \quad a \bar{q}i\gamma_5 q \quad aF\tilde{F} \quad aG\tilde{G} \]

Bremsstrahlung

Compton

Decay to Photons

Vector
\[ \epsilon A'_\mu J_{EM}^\mu \quad gA'_\mu J_{B-L}^\mu \]
Bosonic Particles Produced in Stars

Scalar

\( \phi \bar{e} e \)

\( \phi \bar{q} q \)

\( \phi F^2 \)

\( \phi G^2 \)

Bremsstrahlung

Pseudoscalar

\( a \bar{e} i \gamma_5 e \)

\( \bar{a} \bar{q} i \gamma_5 q \)

Compton

\( a F \bar{F} \)

\( a G \bar{G} \)

Vector

Decay to Photons

\( \epsilon A'_\mu J^\mu_{\text{EM}} \)

\( g A'_\mu J^\mu_{B-L} \)
Anomalous Stellar Emission

\[
\mathcal{L} = \frac{(\partial a)^2}{2} - \frac{m^2 a^2}{2} + \frac{g_{\text{ace}}}{2m_e} (\partial_\mu a) \bar{\psi}_e \gamma^\mu \gamma^5 \psi_e
\]

Solar Axion Spectrum

[1310.0823]
Bound Stellar Emission

Differential specific energy loss rate per energy

\[ \omega = m \left( 1 + \frac{v_{\text{esc}}^2}{2} \right) \]

\[ \omega = m \]

total energy loss rate \( Q \)

energy loss rate into bound orbits

Hannestadt, Raffelt, arXiv:hep-ph/0110067
DiLella, Zioutas, arXiv:astro-ph/0207073
KVT, arXiv:2006.12431
Bound Stellar Emission

Differential specific energy loss rate per energy

\[ \frac{dQ}{d\omega} \sim \int d^3k \ \tilde{Q} \ \frac{1}{m^3} \]

\[ Q \sim \int d^3k \ \frac{1}{m^3} \]

\[ \omega = m \left(1 + \frac{v^2_{\text{esc}}}{2}\right) \]

\[ \omega = m \]

total energy loss rate \( Q \)

energy loss rate into bound orbits

bound: \( (mv_{\text{esc}})^3 \)

unbound: \( T^3 \)

Hannestadt, Raffelt, arXiv:hep-ph/0110067
DiLella, Zioutas, arXiv:astro-ph/0207073
KVT, arXiv:2006.12431
Bound Stellar Emission

Differential specific energy loss rate per energy

\[
\frac{dQ}{d\omega} [\text{a.u.}] = 0.001, 0.010, 0.100
\]

- total energy loss rate \( Q \)
- energy loss rate into bound orbits

\[
\omega = m + \frac{v^2_{\text{esc}}}{2}
\]

- m=0 spectrum

\[
Q \sim \int d^3k \frac{\tilde{Q}}{m^3}
\]

bound: \((mv_{\text{esc}})^3\)

unbound: \(T^3\)

\[
\rho_b(R) = \frac{3}{16\pi} \frac{G_N M_*}{R^4} \int d^3R' \tilde{Q}(R') \sqrt{-\Phi(R')}
\]

\[
\rho_\infty(R) = \frac{1}{4\pi R^2} \int d^3R' Q(R')
\]

\[
\frac{\rho_b}{\rho_\infty} \sim \frac{\tau}{R} v_{\text{esc}}^2(R) v_{\text{esc}}(0) \min \left\{ \frac{m^4}{T^4}, 1 \right\} \sim \frac{\tau}{10^6 \text{yr}} \quad @ \quad R = 1 \text{ AU}
\]

Hannestadt, Raffelt, arXiv:hep-ph/0110067
DiLella, Zioutas, arXiv:astro-ph/0207073
KVT, arXiv:2006.12431
Bound Stellar Emission

Differential specific energy loss rate per energy

\[ \dot{\rho}_b(R) = \frac{3}{16\pi} \frac{G_N M_*}{R^4} \int d^3 R' \tilde{Q}(R') \sqrt{-\Phi(R')} \]

\[ \rho_\infty(R) = \frac{1}{4\pi R^2} \int d^3 R' Q(R') \]

\[ \frac{\rho_b}{\rho_\infty} \sim \frac{\tau}{R} v_{\text{esc}}^2(R) v_{\text{esc}}(0) \min \left\{ \frac{m^4}{T^4}, 1 \right\} \sim \frac{\tau}{10^6 \text{yr}} \quad @ \quad R = 1 \text{AU} \]

\[ Q \sim \int d^3 k \frac{\tilde{Q}}{m^3} \quad \text{bound: } (m v_{\text{esc}})^3 \quad \text{unbound: } T^3 \]

\( \omega = m + \frac{1}{2} v_{\text{esc}}^2 \)

\( \omega = m \)

\( \text{energy loss rate into bound orbits} \)

\( \text{total energy loss rate } Q \)

m=0 spectrum

Hannestadt, Raffelt, arXiv:hep-ph/0110067
DiLella, Zioutas, arXiv:astro-ph/0207073
KVT, arXiv:2006.12431
Bound Stellar Emission

Differential specific energy loss rate per energy

\[ \frac{dQ}{d\omega} [\text{a.u.}] \]

\[ \omega = m(1 + \frac{v_{\text{esc}}^2}{2}) \]

\[ \omega = m \]

total energy loss rate \( Q \)

energy loss rate into bound orbits

bound: \( (mv_{\text{esc}})^3 \)

unbound: \( T^3 \)

basin lifetime = orbital ejection time

- conservative: 2 Lyapunov times
  \[ \rightarrow \tau \sim 10^7 \text{ yr} \]

- fiducial: asteroid data + sims
  \[ \rightarrow \tau \sim 10^8 \text{ yr} \]

- optimistic: secular PT
  \[ \rightarrow \tau \sim 4.5 \times 10^9 \text{ yr} \]

\[ \rho_b(R) = \frac{3}{16\pi} \frac{G_N M_*}{R^4} \int d^3 R' \frac{\tilde{Q}(R')}{\sqrt{-\Phi(R')}} \]

\[ \rho_{\infty}(R) = \frac{1}{4\pi R^2} \int d^3 R' Q(R') \]

\[ \frac{\rho_b}{\rho_{\infty}} \sim \left( \frac{v_{\text{esc}}^2(R)}{v_{\text{esc}}(0)} \right) \min \left\{ \frac{m^4}{T^4}, 1 \right\} \sim \frac{\tau}{10^6 \text{ yr}} \quad @ \quad R = 1 \text{ AU} \]
Gravitational Ejection

[Anderson et al, “Direct detection signatures of a primordial Solar dark matter halo”, arXiv:2007:11016]

31% of non-Jupiter-crossing phase space survives 4.6 Gyr

(a)  
(b)
N-body simulations

100 particles, $t_{\text{int}} = 5.0 \times 10^5$ y suggests that $\tau \gg 10^7$ y

[C. Giovanetti, R. Lasenby, KVT, in progress]
Solar Axion Basin

axion coupling $g_{aee} = 3 \times 10^{-13}$

![Graph showing the solar axion basin with different lines representing optimistic, fiducial, and conservative cases.](image-url)

- Optimistic: $\tau = 4.6 \times 10^9$ y
- Fiducial: $\tau = 2.3 \times 10^9$ y
- Conservative: $\tau = 10^7$ y

Local axion energy density $\rho_{\text{DM}}$ [GeV/cm$^3$]

Axion mass $m$ [keV]
XENON1T: Results
XENON1T: Results
XENON1T: Results
XENON1T: Interpretations

(a) Tritium

(b) Solar axion

(d) Solar axion vs tritium background
XENON1T: Interpretations

(a) Tritium

(b) Solar axion

(d) Solar axion vs tritium background
XENON1T: Interpretations

(a) Tritium

(b) Solar axion

(d) Solar axion vs tritium background
XENON1T: Interpretations

(a) Tritium

(b) Solar axion

Events/(t·y·keV)

Energy [keV]

Events/(t·y·keV)

Energy [keV]

[2006.14598]
XENON1T: Dark Matter Interpretations

**Axion DM absorption**

- **Graph**
  - Axes: $m_a$ [keV/c²] vs. $g_{ae}$
  - Data points from various experiments:
    - SuperCDMS
    - CDEX-1B
    - PandaX-II
    - LUX
    - XENON100
    - XMASS
    - GERDA
    - XENON1T (S2-only)
    - XENON1T (this work)

**Dark Photon DM absorption**

- **Graph**
  - Axes: $m_V$ [keV/c²] vs. kinetic mixing $\kappa$
  - Data points from various experiments:
    - SuperCDMS
    - CDEX-1B
    - XENON100
    - XMASS
    - GERDA
    - XENON1T (S2-only)
    - XENON1T (this work)

- Additional graph showing:
  - Solar $\nu$
  - Experiments:
    - CDMS
    - CoGeNT
    - EDELWEISS
    - XENON100
    - MJD
    - LUX 2013 (this work)
XENON1T: Axion Basin Interpretation

Solar Axion Basin Limit

- Flux excess
- Fiducial
- Optimistic
- WD hint
- Basin excess
- RG
- WD

XENON1T S2 (DM)
LUX (DM)
PandaX–II (DM)
XENON1T S1+S2 (DM)

axion mass $m$ [keV]

axion coupling $g_{aee}$
XENON1T: Axion Basin Interpretation

Solar Axion Basin Limit

- Flux excess
- Conservative

- Fiducial
- Optimistic

- RG
- WD hint
- WD
- Basin excess
- PandaX–II (DM)
- LUX (DM)
- DM excess

- XENON1T S2 (DM)
- XENON1T S1+S2 (DM)

Axion coupling $g_{aee} = 3 \times 10^{-13}$

- Local axion energy density $\rho_{a}$
- $[GeV/cm^3]$

Axion mass $m [keV]$

- $10^{-10}$
- $10^{-11}$
- $10^{-12}$
- $10^{-13}$
- $10^{-14}$

- $10^{-4}$
- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
- $10^{0}$
- $10^{1}$
- $10^{2}$

Axion mass $m [keV]$
XENON1T: Axion Basin Interpretation

Solar Axion Basin Limit

Flux excess

Conservative

Optimistic

Fiducial

WD hint

XENON1T S2 (DM)

PandaX–II (DM)

DM excess

LUX (DM)

XENON1T S1+S2 (DM)

Axion mass $m$ [keV]

Local axion energy density $\rho$ [GeV/cm$^3$]

Axion coupling $g_{aee} = 3 \times 10^{-13}$

DM excess

$\rho_{\nu}$

$\rho_{\nu}$

$\rho_{\nu}$

$\rho_{\nu}$
XENON1T: Axion Basin Interpretation

- Flux excess
- Solar Axion Basin Limit
- Optimistic, Fiducial, Conservative

Axion mass $m$ [keV]
Local axion energy density $\rho_{\text{ax, VeV}}$ [GeV/cm$^3$]
Axion coupling $g_{\text{aee}} = 3 \times 10^{-13}$
DM hint
WD hint
PandaX–II (DM)
LUX (DM)
XENON1T S1+S2 (DM)
DM excess
XENON1T S2 (DM)
RG
WD

- 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} axion coupling $g_{\text{aee}}$
- 10^{-14} 10^{-11} 10^{-8} 10^{-5} 10^{-2} 10^{0} 10^{1} 10^{2} axion mass $m$ [keV]
XENON1T: Axion Basin Interpretation

Solar Axion Basin Limit

Flux excess

Conservative

Fiducial

Optimistic

WD hint

Basin excess

XENON1T S2 (DM)

DM excess

XENON1T S1+S2 (DM)

Local axion energy density $\rho_{\text{ax}}$ [$\text{GeV/cm}^3$]

Axion coupling $g_{aee} = 3 \times 10^{-13}$
Resonant Dark Photon Emission

R. Lasenby, KVT, “Dark Photons in the Solar Basin”, arXiv:2008:XXXXX.

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F_{\mu\nu} F''^{\mu\nu} + \frac{m^2}{2} A'_\mu A'^\mu + e A_\mu J^\mu_{\text{EM}} \]

**Graph:**
- Emission function \( \dot{Q} \) [erg s\(^{-1}\) cm\(^{-3}\)] vs. Solar interior radius \( R' [R_\odot] \)
- Curves for different masses:
  - \( m = 10^3 \text{ eV} \) (brown)
  - \( m = 10^2 \text{ eV} \) (blue)
  - \( m = 10 \text{ eV} \) (green)
  - \( m = 1 \text{ eV} \) (red)
- \( \epsilon = 10^{-15} \)

Graph title:
- Solar interior radius \( R' [R_\odot] \)
- Emission function \( \dot{Q} \) [erg s\(^{-1}\) cm\(^{-3}\)]
Resonant Dark Photon Emission

R. Lasenby, KVT, “Dark Photons in the Solar Basin”, arXiv:2008:XXXXX.

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{e}{2} F_{\mu\nu} F'^{\mu\nu} \]
\[ + \frac{m^2}{2} A'_\mu A'^\mu + e A_\mu J_{EM}^\mu \]

\[ \epsilon = 10^{-15} \]

emission function \( \dot{Q} [\text{erg s}^{-1} \text{ cm}^{-3}] \)

\[ m = 10^3 \text{ eV} \]
\[ m = 10^2 \text{ eV} \]
\[ m = 10 \text{ eV} \]
\[ m = 1 \text{ eV} \]

Solar interior radius \( R' [R_\odot] \)
Dark Photon Basin Density

$$\rho_{\text{DM}}$$

Energy density

$$\rho_{b,\odot}$$

Saturation:

$$\rho_{b,\odot}^{\text{sat}} = 10^{-16}$$

Current limit:

$$\epsilon = \text{current limit}$$

$$\epsilon = 10^{-16}$$

$$\rho_{\infty}$$

Dark photon mass $$m$$ [eV]

$$\tau = 4.6 \times 10^9 \text{y}$$

$$\tau = 2.3 \times 10^9 \text{y}$$

$$\tau = 10^7 \text{y}$$
Dark Photon Basin

Solar Dark Photon Basin Limit

XENON1T (Solar)

Solar cooling

RG cooling

HB cooling

kinetic mixing $\epsilon$

dark photon mass $m$ [eV]

basin excess ($\tau = 2.3 \times 10^9 y$)

$\tau = 10^7 y$

$\tau = 2.3 \times 10^9 y$

$\tau = 4.6 \times 10^9 y$

$\tau = 4.6 \times 10^9 y$, future

$\tau = 2.3 \times 10^9 y$
Dark Photon Dark Matter

- Dark photon mass $m$ [eV]
- Kinetic mixing $\epsilon$

Solar Dark Photon Basin Limit
Unbound Stellar Emission Limit

Current DM limit
Projected DM reach

Optical Phonons
SuperCDMS Ge
XENON10
XENON1T (S1+S2)
XENON1T (S2)
DM excess

Stacks
DAMIC
Future Directions

Indirect Detection
X-ray lines from decay/conversion of axion basin around Sun and compact remnants
[J. Huang, S. Wegsman Gueron, KVT, in progress]

Other Couplings and Particles
hidden photon, CP-even scalar, general axion, fermion production

Orbital Dynamics of Stellar Basin
gravitational ejection time, re-absorption, statistical/temporal characteristics

Dedicated Direct Detection Analyses
LZ, XENONnT, PandaX, XMASS, SuperCDMS, coherent absorption schemes
XENON1T: Interpretations

(a) Tritium

Energy [keV]

Events/(t·y·keV)
XENON1T: Interpretations

1. Above ground production
2. Underground decay
3. Condensation
4. Decay
5. Purification

Activation at sea level: $31.58 \text{ (kg d)}^{-1}$

C. Zhang et al. (2016)

$^{3}\text{H}\text{ Activity [}\mu\text{Bq/tonne]}$

$^{3}\text{H}/\text{Xe [}\text{mol/mol]}$
XENON1T: Interpretations

SR2 (24.4 days)

$H_0$: $B_{SR2}$

$H_1$: $B_{SR2} + ^3H$

SR2 data

Events/(t·y·keV)

Energy [keV]
XENON1T: Interpretations
XENON1T: Interpretations

### Solar Axion

- **H₀: B₀**
- **H₁: B₀ + axion**
- **₅⁷Fe axion**
- **Primakoff axion**

### Solar Axion vs Tritium Background

- **H₀: B₀ + ³H**
- **H₁: B₀ + ³H + axion**
- **₅⁷Fe axion**
- **Primakoff axion**
- **³H**
XENON1T: Interpretations

(b) Solar axion

(d) Solar axion vs tritium background
