Dark matter velocity spectroscopy

Ranjan Laha

Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Stanford University
SLAC National Accelerator Laboratory

Thanks to my collaborators: Tom Abel, John F Beacom, Kenny C Y Ng, Devon Powell, Eric G Speckhard

Signal and background in indirect detection
Signals: continuum, box, lines, etc.

Various types of signal:

- Continuum
- Box
- Virtual internal bremsstrahlung
- Line

**Continuum:** $\chi\chi \rightarrow q\bar{q}, Z\bar{Z}, W^+ W^- \rightarrow$ hadronisation/decay $\rightarrow \gamma, e^+, \bar{p}, \nu$

**Box:** $\chi\chi \rightarrow \phi\phi; \phi \rightarrow \gamma\gamma$

**Virtual internal bremsstrahlung:** $\chi\chi \rightarrow \ell^+ \ell^- \gamma$

**Line:** $\chi\chi \rightarrow \gamma\gamma$

$\nu_s \rightarrow \nu\gamma$

Distinct kinematic signatures important to distinguish from backgrounds.
Due to the faint signal strength, astrophysical backgrounds can easily mimic the dark matter signal.

Ongoing controversy about the origin of the 3.5 keV line: dark matter or astrophysical
Confusion between signal and background

• Confusion between signal and background is prevalent in dark matter indirect detection

• Kinematic signatures are frequently used to distinguish between signal and background

• Is there a more distinct signature that we can identify?

• Yes, use high energy resolution instruments to see the dark matter signal in motion
Dark matter velocity spectroscopy

arXiv 1507.04744

Dark matter velocity spectroscopy

- Dark matter halo has little angular momentum
  Bett, Eke, et al., "The angular momentum of cold dark matter haloes with and without baryons"; Kimm et al., "The angular momentum of baryons and dark matter revisited"

- Sun moves at ~220 km/s

- Distinct longitudinal dependence of signal

- Doppler effect

\[
\mathbf{v}_{\text{LOS}} = (\mathbf{v}_\chi - \mathbf{v}_\odot) \cdot \hat{r}_{\text{LOS}} < 0
\]

\[
\mathbf{v}_{\text{LOS}} = (\mathbf{v}_{\text{gas}} - \mathbf{v}_\odot) \cdot \hat{r}_{\text{LOS}} > 0
\]
Order of magnitude estimates

\[ \nu_{\text{LOS}} \equiv (\langle \vec{v}_\chi \rangle - \vec{v}_\odot) \cdot \hat{r}_{\text{LOS}} \]

\( \langle \vec{v}_\chi \rangle \) is negligible in our approximation

\[ \nu_\odot \approx 220 \text{ km s}^{-1} \]

For \( \nu_{\text{LOS}} \ll c \), \( \delta E_{\text{MW}} / E = -\nu_{\text{LOS}} / c \)

\[
\frac{\delta E_{\text{MW}}(l, b)}{E} = +(\nu_\odot / c) (\sin l) (\cos b)
\]

\[ \frac{\delta E_{\text{MW}}}{E} \approx 10^{-3} \]

\( \text{sign}(\delta E_{\text{MW}}) \propto \sin l, \text{ for } l \in [-\pi, \pi] \)
Instruments with $\sim O(0.1\%)$ energy resolution

**Past**

**Hitomi/ Astro-H**

$\frac{\sigma_E}{E} \approx \frac{1.7 \text{ eV}}{3.5 \text{ keV}}$

**INTEGRAL/ SPI**

2.2 keV (FWHM) at 1.33 MeV

http://www.cosmos.esa.int/web/integral/instruments-spi

**Future**

**Micro-X**

FWHM of 3 eV at 3.5 keV

Figueroa-Feliciano et al. 2015

**ATHENA**

ATHENA X-IFU

1608.08105

includes noise contribution from simulations

Energy resolution for electrons and gamma will be < 1% at 200 GeV

Wang & Xu Progress of the HERD detector
Application to 3.5 keV line
Solutions to the 3.5 keV line controversy?

See talk by E Bulbul in TeVPA 2017

• Micro-X
  Wide field of view
  Rocket
  $\sim 10^{-3}$ energy resolution near 3.5 keV
  Figueroa-Feliciano et al. 2015

• SXS - Hitomi (Astro-H)
  Narrow field of view
  Satellite
  $\sim 10^{-3}$ energy resolution at $\sim 3.5$ keV
  Lost due to technical failure 😞
Looking at clusters

Dark matter line **broader** than plasma emission line

Plasma emission lines are broadened by the turbulence in the X-ray emitting gas
Shift and broadening of spectrum

\[ E_0 = 3.5 \text{ keV} \]

2 Ms 1800 cm\(^2\) arcmin\(^2\) observation 5\(\sigma\) detection

Broadening of line due to finite velocity dispersion

Shift of the centroid of line due to Doppler effect

Shift of the center of dark matter line is opposite to that of the shift of the center of baryonic line

\[
\frac{d\mathcal{J}}{dE} = \frac{1}{R_\odot \rho_\odot} \int ds \rho_X(r[s, \chi]) \frac{d\tilde{N}(E - \delta E_{MW}, r[s, \psi])}{dE}
\]


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Dark matter and baryonic emission line separation

Shift in centroid of dark matter and baryonic line

G1: distribution of free electrons

G2: hot gas distribution of MW

G3: observed distributions of $^{26}$Al gamma-rays

Follows the trend explained earlier

|b| = 5°
Micro-X observations

(1) \( \ell = 162^\circ, b = 7^\circ \)

(2) G.C.

(3) \( \ell = 0^\circ, b = -32^\circ \)

Field of view: 20° radius

Time of observation: 300 sec

Multiple observations in multiple flights

Very promising reach
Velocity spectroscopy using Micro-X

A wide field of view instrument like Micro-X can also perform dark matter velocity spectroscopy

Powell, Laha, Ng, and Abel 1611.02714 (Phys. Rev. D95 (2017) 063012)
Triaxiality can make the line shift asymmetric

The significance decreases in the presence of triaxiality, but the main effect is still present

The technique can be used to probe triaxiality

Powell, Laha, Ng, and Abel 1611.02714 (Phys. Rev. D95 (2017) 063012)
Conclusion

• Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection

• We see smoking gun in motion

• Immediate application to the 3.5 keV line

• Future improvements in the energy resolution of telescopes at various energies will result in this technique being widely adopted

Questions and comments: rlaha@stanford.edu
Introduction to Dark matter
The present Universe as a pie-chart

Most of the Universe is unknown

Finding this missing ~ 95% is the major goal of Physics

We concentrate on dark matter
Gravitational detection of dark matter

Astromony Picture of the Day

NGC 6503

Begeman, et al.
MNRAS 249 (1991) 523

Dwarf galaxies

A Riess website

WMAP website

http://www.dailygalaxy.com/my_weblog/2015/08/
dark-energy-observatory-discovers-eight-celestial-
objects-hovering-near-the-milky-way.html

Real observation from Hubble

eXtreme Deep Field Observations: left side

Mock observation from Illustris: right side

Illustris website
Gravitational evidence of dark matter at all scales

Dark matter is the most economical solution to the problem of the need of extra gravitational potential at all astrophysical scales.

Many different experiments probing vastly different scales of the Universe confirm the presence of dark matter.

Modifications of gravity at both non-relativistic and relativistic scales are required to solve this missing gravitational potential problem --- very hard --- no single unified theory exists.

Credit: Carsten Rott, Basudeb Dasgupta
What do we know?

• Structure formation tells us that the particle must be non-relativistic.

• Experiences “weak” interactions with other Standard Model particles.

• The lifetime of the particle must be longer than the age of the Universe.
What do we want to know?

• **Mass** of the particle

• **Lifetime** of the particle

• **Interaction strength** of the particle with itself and other Standard Model particles
Indirect detection of dark matter

- Search for *excess* of Standard Model particles over the expected astrophysical background

\[ \gamma \quad \nu \quad e^+ \quad \bar{p} \]

- **Spectral** features help --- astrophysical backgrounds are relatively smooth --- nuclear and atomic lines problematic

- **Targets:** Sun, Milky Way (Center & Halo), Dwarf galaxy, Galaxy clusters

See talk by Slatyer
Example with dark matter decay

\[
\frac{dI(\psi, E)}{dE} = \frac{\Gamma}{4\pi m_\chi} \frac{dN(E)}{dE} \int ds \rho_\chi(r[s, \psi])
\]

\[\Gamma = \text{Dark matter decay rate}\]
\[dN(E)/dE \text{ is independent of dark matter profile}\]

\[
\frac{d\tilde{N}(E, r[s, \psi])}{dE} = \int dE' \frac{dN(E')}{dE'} G(E - E'; \sigma_{E'})
\]

\[\sigma_E = \left(\frac{E}{c}\right) \sigma_{v_{LOS}} \]

\[\sigma^2_{v, r}(r) = \frac{G}{\rho_\chi(r)} \int_r^{R_{\text{vir}}} dr' \rho_\chi(r') \frac{M_{\text{tot}}(r')}{r'^2} \]

\[
\frac{dJ}{dE} = \frac{1}{R_\odot \rho_\odot} \int ds \rho_\chi(r[s, \chi]) \frac{d\tilde{N}(E - \delta E_{\text{MW}}, r[s, \psi])}{dE} \]

replaces \[
\frac{dN(E)}{dE} \frac{1}{R_\odot \rho_\odot} \int ds \rho_\chi(r[s, \chi][s, \chi])
\]

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Sterile neutrino

\[ \nu_s \rightarrow \nu_a + \gamma \]

\[ E_\gamma = \frac{m_s}{2} \]

\[ \Gamma_\gamma \approx 7 \times 10^{-33} \text{s}^{-1} \frac{\sin^22\theta}{10^{-10}} \left( \frac{m_s}{\text{keV}} \right)^5 \]

An excellent dark matter candidate --- right handed component of the active neutrino

Production scenarios:

Dodelson - Widrow mechanism (similar to vacuum oscillations of neutrinos)

Shi - Fuller mechanism (similar to MSW transitions of neutrinos)
3.5 keV

\[ \nu_s \rightarrow \nu_a + \gamma \]

Sterile neutrinos?
Baryonic astrophysics?

Stacking of 73 galaxy clusters
Redshift \( z = 0.01 \) to \( 0.35 \)
4 to 5σ detection with XMM-Newton and
2σ in Perseus with Chandra

2.3σ in Perseus with XMM-Newton
3σ in M31 with XMM-Newton
Combined detection ~ 4σ

Conflicting results in many different studies

See talk by Bulbul

Bulbul et al., 1402.2301

Bulbul et al., 1402.2301
3.5 keV controversy

Riemer-Sorensen 2014 Milky Way via Chandra ✗

Jeltema and Profumo 2014 Milky Way via XMM-Newton ✗ (Contested by Bulbul et al., 2014 and Boyarsky et al., 2014)

Boyarsky et al. 2014 Milky Way via XMM-Newton ✓

Anderson et al., 2014 Local group galaxies via Chandra and XMM-Newton ✗

Malyshev et al., 2014 satellite dwarf galaxies via XMM-Newton ✗

Tamura et al., 2014 Perseus via Suzaku ✗

Urban et al., 2014 Perseus via Suzaku ✓

Urabn et al., 2014 Coma, Virgo, and Ophiuchus via Suzaku ✗

Carlson et al., 2014 morphological studies ✗

Philips et al., 2015 super-solar abundance ✗

Iakubovskyi et al., 2015 individual clusters ✓

Jeltema and Profumo 2015 Draco dwarf ✗

Bulbul et al., 2015 Draco dwarf ✓

Franse et al., 2016 Perseus cluster ✓

Bulbul et al., 2016 stacked cluster ✓

Hofman et al., 2016 33 clusters ✗

HITOMI 2016 Perseus cluster ✗

Shah et al., 2016 Laboratory ✗

Conlon et al., 2016 Perseus ✓

Gewering-Peine et al., 2016 Diffuse ✓

Cappelluti et al., 2017 Diffuse ✓

Slide idea: Shunsaku Horiuchi and Kenny C Y Ng
Rotation of baryonic matter

Radial velocity of gas as measured by $^{26}$Al $1808.65$ keV line

Measurement by INTEGRAL/ SPI

Follows the trend explained earlier