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Gamma rays from dark matter annihilating to mesons

T. Bringmann, A. Hryczuk, A. Raklev, I. Strümke, and JVdA, in arXiv:1711.01265
[e-ASTROGAM White Book]
A. Raklev, I. Strümke, and JVdA, in preparation

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Dark matter and gamma rays

Essentially, gamma rays ($E_\gamma \gtrsim 100$ keV) point to their source and can feature distinctive spectral signatures

- Possibly smoking gun for dark matter identification against large astrophysical backgrounds

Rapid advances in gamma-ray astronomy over the last 20 years

- Spectrometer on INTEGRAL, Fermi Large Area Telescope, COMPTEL, EGRET, ...

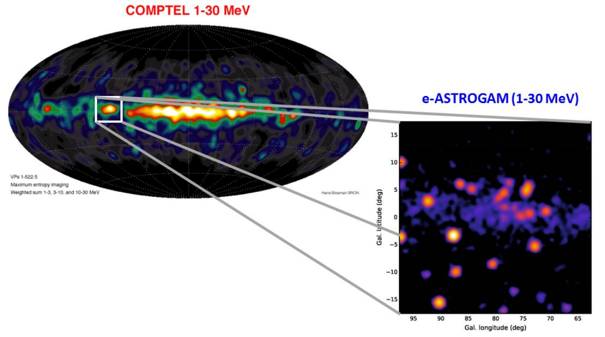
MeV gap: lack of experimental sensitivity between 0.1 – 100 MeV

- Proposed missions (e-ASTROGAM, AMEGO) address this range!

Dark matter and gamma rays

MeV gap: lack of experimental sensitivity between 0.1 – 100 MeV

- e-ASTROGAM promises significant increases in angular resolution and sensitivity in this energy range
- The diffuse gamma-ray background is the emission left after subtracting resolved sources and diffuse Galactic foregrounds



Observation of 1-30 MeV sky by COMPTEL vs. simulation for e-ASTROGAM.
[e-ASTROGAM Collaboration, 1711.01265]

Dark matter and gamma rays

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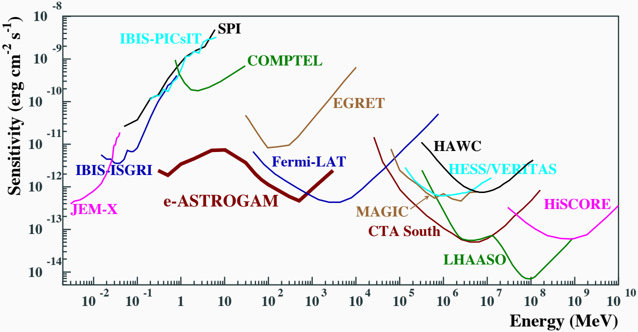


Point source continuum differential sensitivity for various experiments.
[e-ASTROGAM Collaboration, 1711.01265]

Spectral features

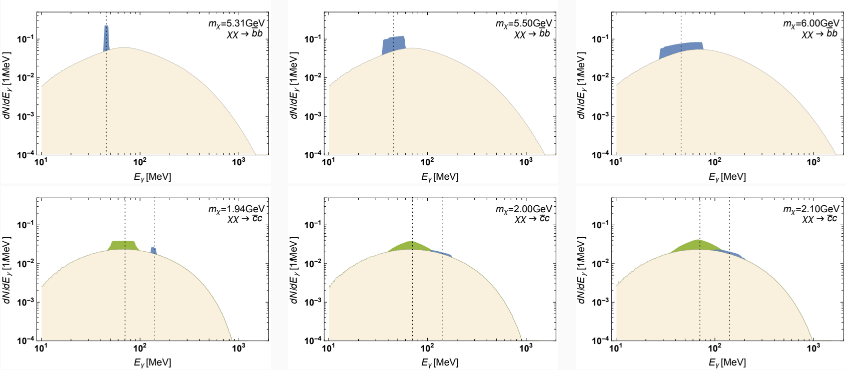
- For dark matter coupled to quarks, hadronic showers following annihilation typically lead to secondary photons
- The final gamma-ray spectrum dN_γ/dE_γ can be simulated in `Pythia`
- Large number of boosted $\pi^0 \to \gamma\gamma$ leads to featureless spectrum

  Monochromatic photon pairs ($E_\gamma = m_\pi/2$) in diverse π^0 rest frames

  $\Rightarrow$ Broad universal bump up to limit $E_\gamma = m_\chi$ after boosts to DM frame
- But if decay/fragmentation cascade creates excited heavy mesons...
  - Typical de-excitation by emitting monochromatic photon or pion
  - Box-shaped spectral feature around energy

$$\Delta m = m_{M*} - m_M \sim \text{MeV!}$$ [Bringmann et al., 1610.04613]

Spectral features: boxes from light (few-GeV) DM



Gamma-ray spectra from $\chi\chi \to \bar{b}b$ (top)/$\bar{c}c$ (bottom) for increasing m_χ. Continuum contribution mainly from π^0. Near threshold, box features from de-excitation ($B^* \to B\gamma$, $D^* \to D\gamma$ or $D\pi^0$) are pronounced.
[T. Bringmann, A. Hryczuk *et al.*, 1610.04613]

Current project

- Together with Are Raklev (Oslo) and Inga Strümke (Bergen)
- Exploring indirect detection possibilities for light DM in MeV gap
- Focus on DM dominantly annihilating to different heavy-meson final states through specific EFT annihilation operators

$\Rightarrow$ Trying to estimate relative branching ratios of possible final states for different operators, to assess possibility of discovery

Effective field theory for DM annihilation

Not restricted by specific model, but considering possible EFT coupling structures between dark matter and Standard Model quarks

- Require quarks coupled by vector structure to connect to e^+e^- collider experiments
- For example: $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ and $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$

Constraints on light DM coupled to heavy quarks

- From CMB power spectrum (Planck), meson decays, mono-jet searches, Fermi-LAT line search

Relevant annihilation channels

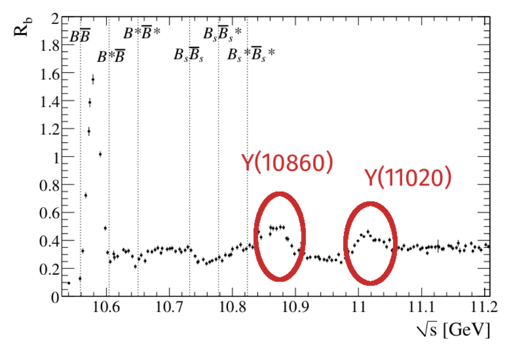
- $\chi\chi \to M_1 M_2$: two mesons, with radiative decays
  - $*$ Special case $\chi\chi \to (\bar{Q}Q) \to M_1 M_2$ through quarkonium resonance
- $\chi\chi \to (\bar{Q}Q)\gamma$: both potential signal and constraint [Srednicki+/Rudaz+ (1986)]

$\Rightarrow$ Hard to evaluate gamma-ray spectra for $\chi\chi \to \bar{b}b$ close to B-meson thresholds: many accessible states and quarkonium resonances

$\Rightarrow$ However, potential for greatly enhanced gamma-ray signal!

$$R_b(s) = \frac{\sigma_{e^+e^- \to \bar{b}b}(s)}{\sigma^0_{e^+e^- \to \mu^+\mu^-}(s)}$$

[BaBar Collaboration, 0809.4120]



Annihilation with quarkonia

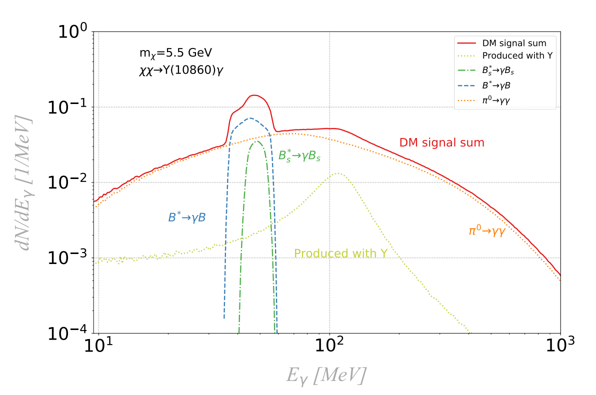
Annihilation producing quarkonium state and prompt photon

- Example: $\chi\chi \to \Upsilon(10860)\gamma$ with

$$\Upsilon(10860) \to B^*_{(s)}\bar{B}^*_{(s)} \text{ and } B^*_{(s)} \to B_{(s)}\gamma$$

Annihilation through quarkonium resonance

- If allowed, expected to dominate



Outlook and conclusion

- Computing the DM annihilation cross-sections into mesons

  Continuum contribution: amplitude factorises in vacuum saturation approximation. Hadronic form factors estimated from collider results.
  Resonance contribution: Breit-Wigner cross-section involving amplitude for non-relativistic bound state formation.

  $\Rightarrow$ Work in progress!

$*$ Spectral features boost experimental sensitivity to these DM annihilation channels. Resonances make shapes even more pronounced

$*$ The sensitivity gap in MeV gamma rays, to be explored by e-ASTROGAM (hopefully), could offer many opportunities

  $\rightarrow$ Confirming the DM particle nature, determining its mass, its branching ratios to quark final states, its interaction structure, ...

Thank you!

Backup slides

Computing annihilation cross-sections

Amplitude for DM annihilation into hadronic state $\mathcal{H}$ (e.g. $B^* \bar{B}^*$) through operator $\mathcal{O} = \bar{\chi}\gamma^\mu\chi\, \bar{b}\gamma_\mu b$:

$$\begin{aligned}\langle\mathcal{H}|\mathcal{O}|\chi\chi\rangle &= \langle\mathcal{H}|\bar{b}\gamma_\mu b\,\bar{\chi}\gamma^\mu\chi|\chi\chi\rangle = \sum_n \langle\mathcal{H}|\bar{b}\gamma_\mu b|n\rangle\langle n|\bar{\chi}\gamma^\mu\chi|\chi\chi\rangle \\ &\simeq \langle\mathcal{H}|\bar{b}\gamma_\mu b|0\rangle\langle 0|\bar{\chi}\gamma^\mu\chi|\chi\chi\rangle \equiv \mathcal{M}_{b\mu}\mathcal{M}_\chi^\mu\end{aligned}$$

Quark part same as for B-meson production in e^+e^- collisions!

$$\langle\mathcal{H}|\mathcal{O}|e^+e^-\rangle \simeq \langle\mathcal{H}|\bar{b}\gamma_\mu b|0\rangle\langle 0|\bar{\psi}_e\gamma^\mu\psi_e|e^+e^-\rangle \equiv \mathcal{M}_{b\mu}\mathcal{M}_e^\mu$$

Work in progress: use the factorisation, common matrix element and symmetries to find cross-section for DM annihilation