Dark Matter Indirect Detection With Sub-GeV Gamma Rays

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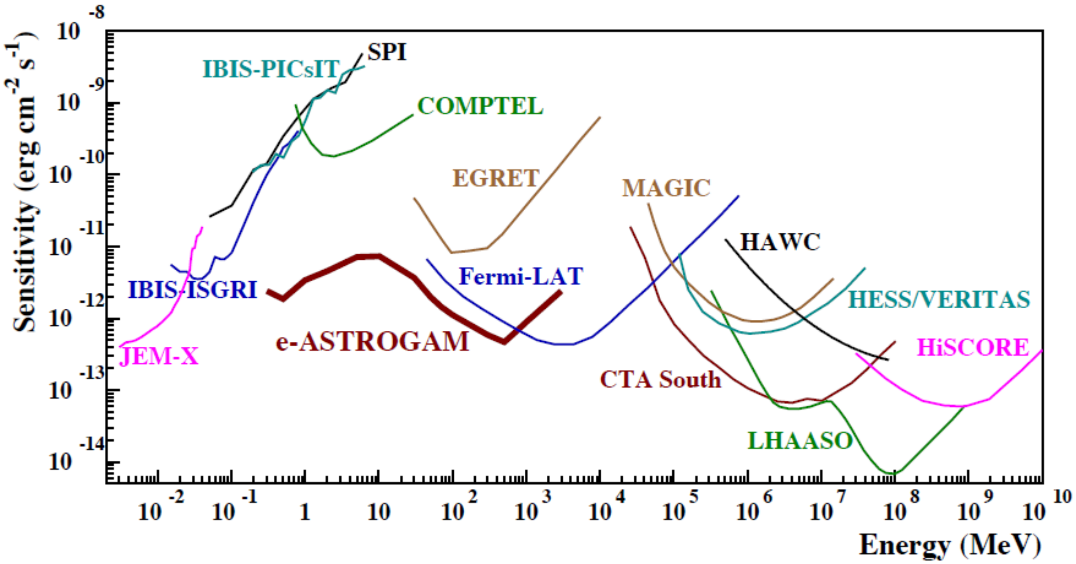
- PRD **92**, 023533 (2015), arXiv:1504.04024 – KB, JK
- PRD **94**, 095027 (2016), arXiv:1606.07440 – KB, KD, DK, JK, J-CP, BT
- PRD **95**, 055024 (2017), arXiv:1609.09104 – KB, KD, DK, JK, J-CP, BT
- PRD **98**, 116009 (2018), arXiv:1808.02579 – JK
- arXiv:190x.xxxxx – DB, JK, AR
- arXiv:19xx.xxxxx – JK, PS

Sub-GeV DM and photons

- good time to think about indirect detection of sub-GeV dark matter with sub-GeV gamma rays
  - theoretical interest in sub-GeV dark matter (SIMP, ELDER, etc.)
  - avoids tight direct detection limits
  - new observatories planned to improve sensitivity to MeV-GeV range photons (e-ASTROGAM, AMEGO)
- gamma ray signals from sub-GeV DM are especially useful
  - fewer final state particles are kinematically accessible
  - final states constrained by symmetry
  - primary and secondary photon spectra have striking features
- new instruments can make big improvements in sensitivity for annihilating and (especially) decaying dark matter

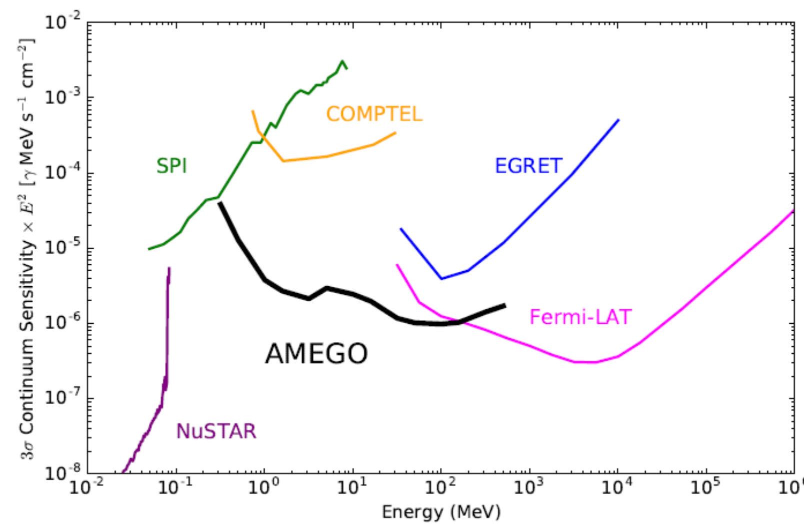
MeV-Gap

- for E ~ 1-100 MeV, relatively poor sensitivity currently
- aiming for larger effective area, better energy, angular resolution



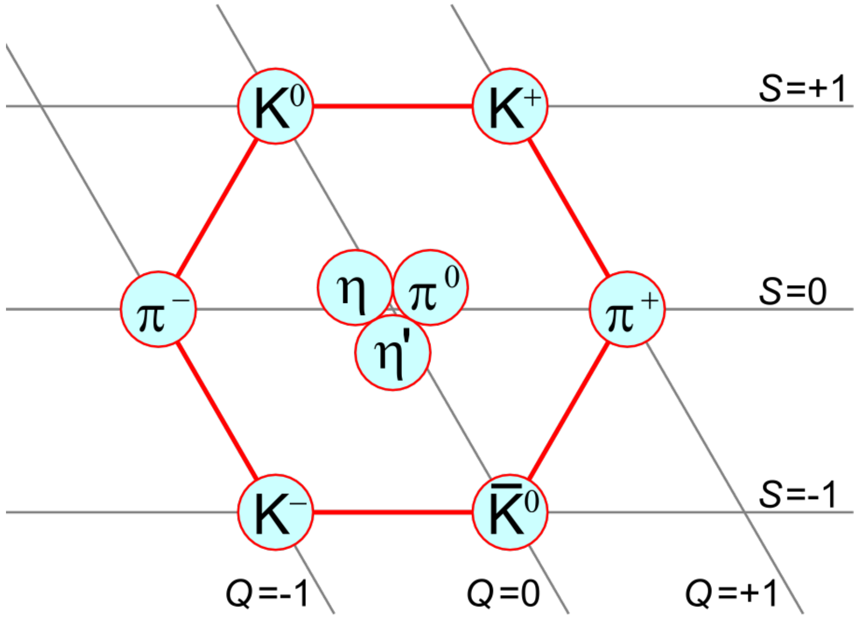
e-ASTROGAM TDR
1711.01265

AMEGO
ICRC 2017



Chiral Perturbation Theory

- if sub-GeV DM couples to quarks, end up with photons and light mesons
- dominant interaction is QCD
- weak interactions suppressed by $m_{Z,W}$
- final states constrained by symmetries of massless QCD
  - C, P, strangeness, isospin
- π^0, $\eta \rightarrow \gamma\gamma$ become the most important secondary photon production channels
- get striking signals … "lines and boxes"



Wikipedia

gameplan

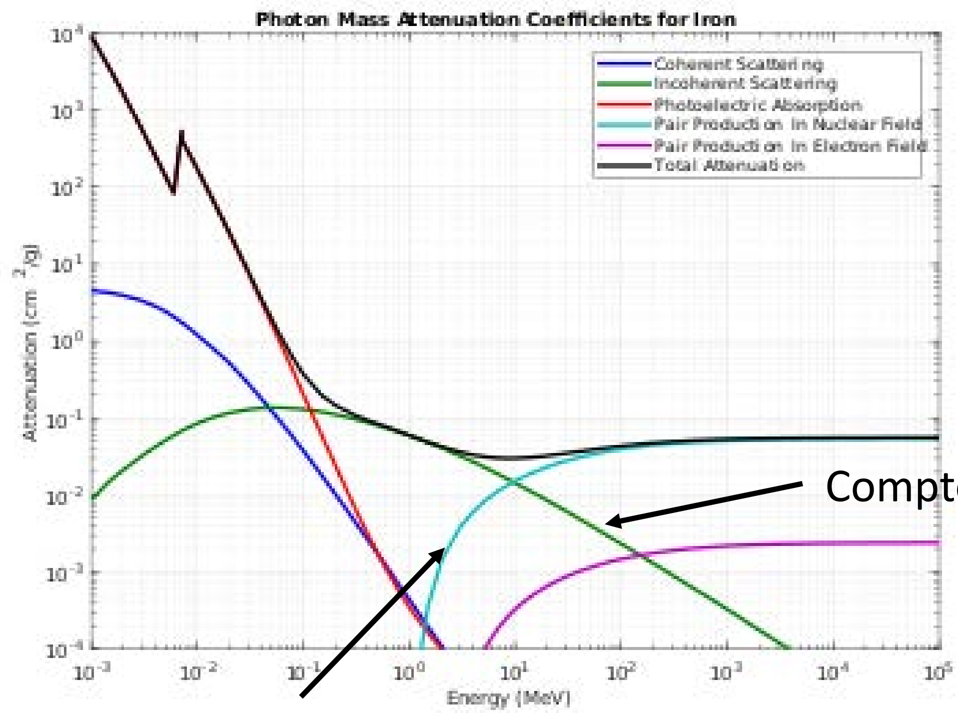
- look at diffuse and dSph searches for DM annihilation and decay, using future instruments
- find major improvements over current bounds
- competitive with Planck for annihilation, but much better for decay

- focus here on two simple scenarios
  - $E_{cm} < 2m_{\pi^\pm}$ → look for photon line and $\pi^0 \to \gamma\gamma$
  - $E_{cm} \lesssim$ GeV → look for $\eta \to \gamma\gamma$

- next step is a more comprehensive study of all channels for $E_{cm} \lesssim$ GeV
- going backwards from a photon spectrum to a dark matter model?

MeV-range detection strategies

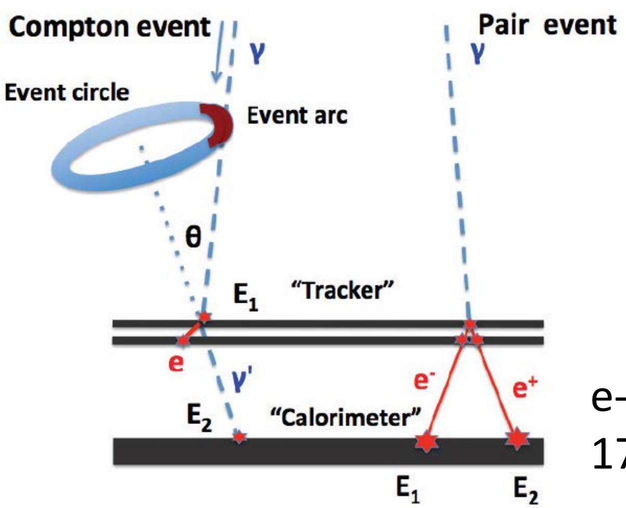
- two detection strategies
- choice set by energy range
- Compton scattering
  - dominant for E $\lesssim$ 30 MeV
- pair production
  - dominant for E $\gtrsim$ 30 MeV
  - energy resolution gets worse



Compton

pair production

NIST
Wikipedia

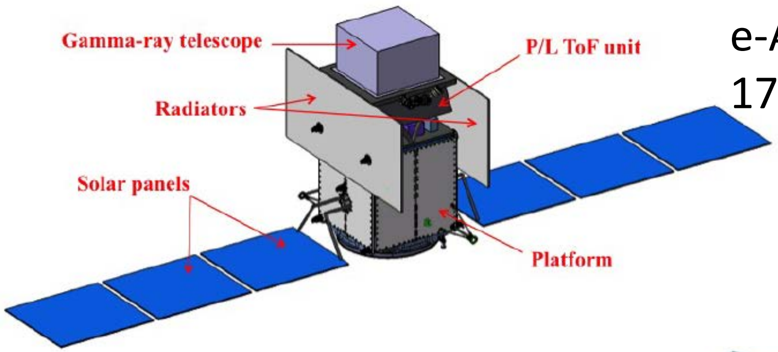


e-ASTROGAM
1711.01265

future instruments

- a few proposals, using both technologies
  - e-ASTROGAM
  - AMEGO
- we'll take the e-ASTROGAM specifications (pair production) as a benchmark

- $\varepsilon = 0.3$ (1σ energy res.)
- exposure = $3000\ \mathrm{cm}^2\ \mathrm{yr}$
- angular resolution $\sim$ 1°
- what can they do?



e-ASTROGAM
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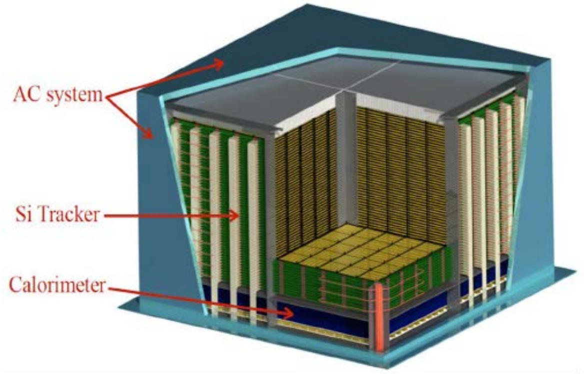
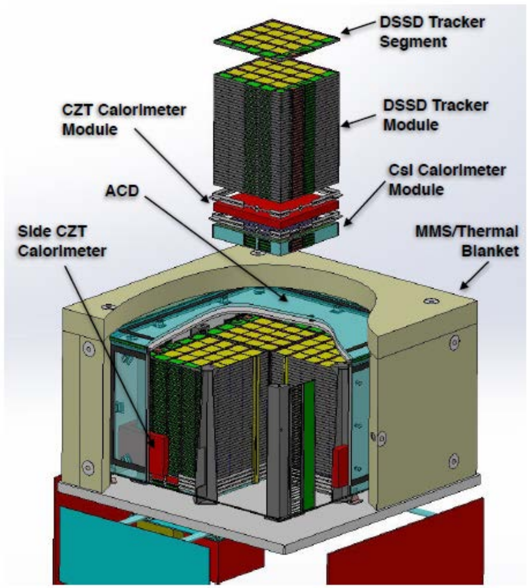




AMEGO
ICRC 2017

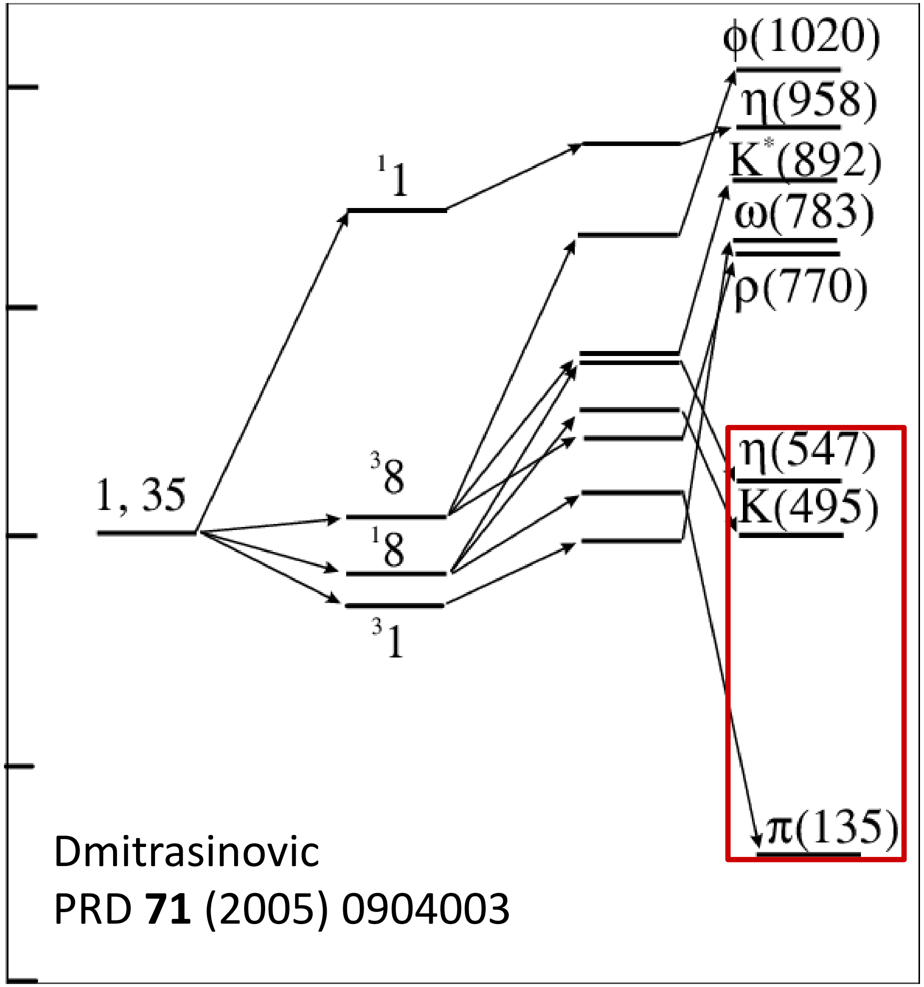
symmetry and kinematics

- assume dark matter couples to quarks
- basic assumptions about primary annihilation/decay process
  - QCD dominates
  - QED subleading, but may be dominant if purely QCD processes are kinematically forbidden, or forbidden by symmetry
  - weak interactions are negligible (suppressed $sG_F \ll \alpha$)
- so C, P, J, strangeness quantum numbers of initial and final state match (not violated by QED/QCD)

- isospin (I) also approximately a good symmetry, if QED negligible
  - transformation properties of quark current to which dark matter couples determine the transformation properties of final state

final state particles

- care about photons, light pseudoscalar meson octet
- leptons suppressed by extra powers of sG_F or α
- photon sources
  - primary – QED
  - secondary – $\pi^0 \rightarrow \gamma\gamma$ (~ 99%), $\eta \rightarrow \gamma\gamma$ (~ 39%)
  - tertiary – decays of heavier mesons to π^0
- focus on 2- and 3-body final states
- in all cases we consider, at least one of these is accessible



Dmitrasinovic
PRD **71** (2005) 0904003

$E_{cm} < 2m_{\pi^\pm}$

- focus on 2-body final states here
- $\gamma\gamma$ → C-even
- $\gamma\pi^0$ → C-odd
  - QED suppressed
- $\pi^0\pi^0$ → C-even
  - threshold at $2m_{\pi^0}$
  - P-even, J=I=even
  - dominates if accessible
- can classify final state by C, P, I properties of the quark bilinear to which DM couples
- we'll focus on cases where one of these states is unsuppressed

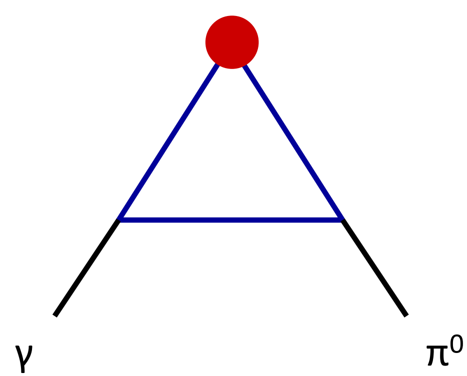
- $\phi\phi^*$ state
  - C: $(-1)^L$
  - P: $(-1)^L$
- $\pi\pi$ state
  - I = L mod 2 (symmetry of wavefunction)
  - I = isospin of $\pi\pi$ state
  - for $E > 2m_{\pi^\pm}$, get charged pion contributions to isospin multiplets
    - $\pi^\pm$ decays produce few photons, but affects branching fractions
    - can get C-odd states (L=I=1), but no $\pi^0\pi^0$ contribution

couplings and symmetries

- DM decay – $X\,(\bar{q}\,\Gamma_q\,q)$
- DM annihilation – $(X\,\Gamma_X\,X)\,(\bar{q}\,\Gamma_q\,q)$
- $\Gamma_q = 1,\ i\gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5$ (S,P,V,A,… not T)
- only the vector current is C-odd
  - can only get a $\gamma\pi^0$ final state if DM couples to a vector current
  - same form as a $\pi^0\gamma\gamma$ coupling, with DM replacing one photon

quark current	C	P
S	+	+
P	+	-
V (space)	-	-
A (time)	+	-
A (space)	+	+

replace $A^\mu \rightarrow$ DM, or DM current



$$O = \frac{1}{M^2}\left(\bar{X}\gamma^\mu X\right)\left(\bar{q}\gamma_\mu q\right)$$

$$O_{eff.} \sim \frac{e}{16\pi^2 f_\pi M^2}\left(\bar{X}\gamma^\mu X\right)F^{\nu\rho}\left(\partial^\sigma \pi^0\right)\varepsilon_{\mu\nu\rho\sigma}$$

photon spectra

- each channel gives a distinctive spectrum
- two-body final state
  - directly produced photons are monoenergetic
- π^0 decay produces two monoenergetic γs in CM frame
  - boosting gives a "box" spectrum
- since $s < (2m_{\pi\pm})^2$, pion not very boosted
  - box may not be very wide
  - $\Delta E < 107$ MeV ($\gamma\,\pi^0$)
  - $\Delta E < 36$ MeV ($\pi^0\,\pi^0$)

- $\gamma\,\gamma \rightarrow$ line

$$E_{line} = \sqrt{s}/2$$

- $\gamma\,\pi^0 \rightarrow$ line plus box

$$E_{line} = \left(\sqrt{s}/2\right)\left(1 - m_{\pi^0}^2/s\right)$$

$$E_{\pm} = \left(\sqrt{s}/4\right)\left[\left(1 + m_{\pi^0}^2/s\right) \pm \left(1 - m_{\pi^0}^2/s\right)\right]$$

- $\pi^0\,\pi^0 \rightarrow$ box

$$E_{\pm} = \left(\sqrt{s}/4\right)\left(1 \pm \sqrt{1 - 4m_{\pi^0}^2/s}\right)$$

$E_{cm} > 2m_{\pi^\pm}$

- 2- or 3-meson states typically accessible
- drop QED
- use SU(3) chiral Lagrangian, $\mathcal{O}(p^2)$
- introduce pseudoscalar meson octet (Φ)
- fields transform under $SU(3)_L \times SU(3)_R$ chiral symmetry
- DM-quark coupling introduced as a spurion whose vev breaks chiral symmetry (s, p, v, a)
- coefficient of coupling derived from data, using SM spurions ($B = m_\pi^2/(m_u+m_d)$)

$$\mathcal{L} = \frac{F^2}{4}\mathrm{Tr}\left[D_\mu U D^\mu U^\dagger + \chi U^\dagger + U\chi^\dagger\right]$$

$$\Phi \equiv \begin{bmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{bmatrix}$$

$$U \equiv \exp\left[i\sqrt{2}\Phi / F\right]$$

$$\chi \equiv 2B(s + ip)$$

$$D_\mu U = \partial_\mu U - i(v_\mu + a_\mu)U + iU(v_\mu - a_\mu)$$

$$F \approx 92\ \mathrm{MeV}$$

spurions

- spurion couples to quark current in fundamental Lagrangian
  - breaks flavor symmetries
- also appears in the chiral Lagrangian parameterizing flavor breaking
- coefficients relate symmetry breaking parameters in fundamental Lagrangian (like quark mass) to those in chiral Lagrangian (like meson mass)
- sets coefficients for s, p, v, a
- flavor structure of DM spurion determines final state

$$s = \begin{bmatrix} m_u + \alpha_u \frac{\bar{X}X}{\Lambda^2} & 0 & 0 \\ 0 & m_d + \alpha_d \frac{\bar{X}X}{\Lambda^2} & 0 \\ 0 & 0 & m_s + \alpha_s \frac{\bar{X}X}{\Lambda^2} \end{bmatrix}$$

or

$$s = \begin{bmatrix} m_u + \alpha_u \phi & 0 & 0 \\ 0 & m_d + \alpha_d \phi & 0 \\ 0 & 0 & m_s + \alpha_s \phi \end{bmatrix}$$

final states of interest

- focus on $E_{cm} \lesssim 1$ GeV
  - simplifies accessible states
- conservation of strangeness → kaons only come in pairs
  - not accessible
  - can mostly simplify to SU(2) chiral Lagrangian
- only get pions ($m_\pi \sim 140$ MeV) and at most one η ($m_\eta \sim 548$ MeV)
- only relevant final states are ππ, $\pi^0\eta$, ππη, and πππ
- $\pi^\pm$ decay doesn't contribute photons
- photons from $\pi^0 \to \gamma\gamma$ less energetic than from $\eta \to \gamma\gamma$
  - background drops rapidly with energy
- we'll focus on photons produced by $\eta \to \gamma\gamma$
- care about $\pi^0\eta$, ππη for now

connecting the quark current to the final state

- properties of chiral Lagrangian at $\mathcal{O}(p^2)$
  - s, v spurions couple to even number of mesons
  - p, a spurions couple to odd number of mesons
  - s, p spurions couple to terms with no derivatives acting on mesons
  - a, v couple to terms with one derivative acting on mesons
  - if I=0, can partially integrate the derivative
    - acts on spurion, not meson (L=0)

- symmetry of final states
- $\pi^0\eta \rightarrow$ C=even, s spurion
  - $I=1$, $I_3=0$
  - P: $(-1)^J$
  - $J^{PC} = 0^{++}$ (s)
- $\pi\pi\eta \rightarrow$ p or a spurion $\rightarrow$ C=even
  - $I=L_\pi \bmod 2$, $I_3=0$
  - C: $(-1)^{L\pi}$, P: $(-1)^{L\pi+L\eta+1}$
  - $| L_\pi - L_\eta | < J < L_\pi + L_\eta$
  - C=even $\rightarrow L_\pi$, I=0 $\rightarrow L_\eta = 0$
  - $J^{PC} = 0^{-+}$ (p,a^0)
  - matrix element independent of meson momenta

boosting the photons

- we basically have $\eta \rightarrow \gamma\gamma$, where the η is boosted
- in η rest frame, $E_\gamma = m_\eta/2$
- if we boost η by β, then we get a box again
- for $\pi^0\eta$, η is monoenergetic, so photon spectrum is a box of fixed width
- for $\pi\pi\eta$, η has some injection spectrum dN_η / dE_η
  - sum over boxes to get photon spectrum

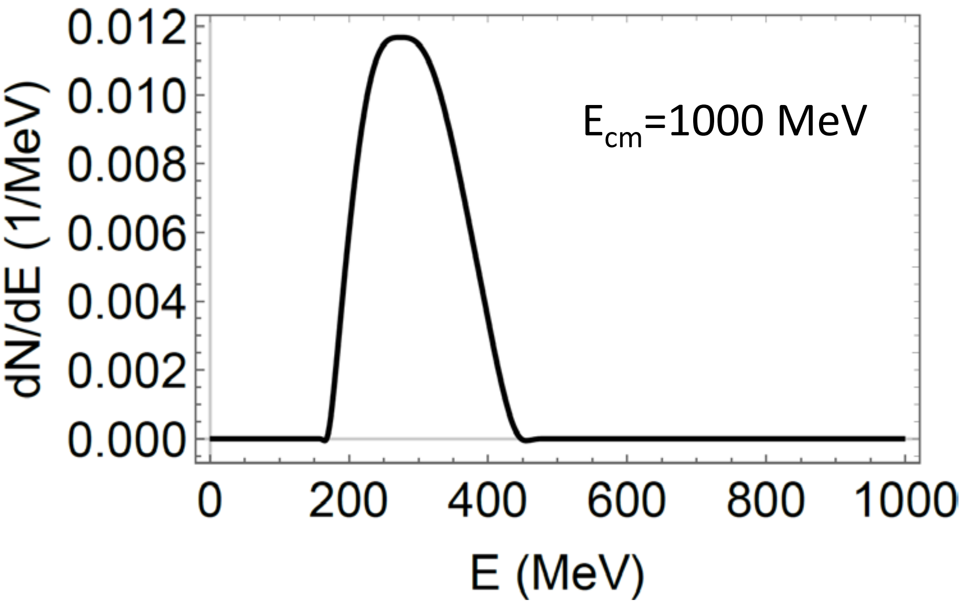
$$E_\gamma^{min} = \frac{m_\eta}{2}\sqrt{\frac{1-\beta}{1+\beta}}$$

$$E_\gamma^{max} = \frac{m_\eta}{2}\sqrt{\frac{1+\beta}{1-\beta}}$$

$$\frac{dN_\gamma}{dE_\gamma} = \int_{\frac{m_\eta}{2}\left(\frac{2E_\gamma}{m_\eta}+\frac{m_\eta}{2E_\gamma}\right)}^{\infty} dE_\eta \left[\frac{dN_\eta}{dE_\eta}\frac{2}{\sqrt{E_\eta^2 - m_\eta^2}}\right]$$

photon spectra

- $\pi^0\eta$ case straightforward
  - get a box
- $\pi\pi\eta$ case → integrate three-body phase space over pion momenta to get η injection spectrum
  - looks like a bump
  - vanishes at zero boost, and at maximum boost β_{max}
- plug in to get photon spectrum
  - also looks like a bump
  - peaked at $E_*=m_\eta/2 \sim$ 274 MeV
  - goes to zero at $(m_\eta/2)[\gamma_{max}(1\pm\beta_{max})]$



bump not very wide, compared to 30% energy resolution, even at upper end of E_{cm} range….

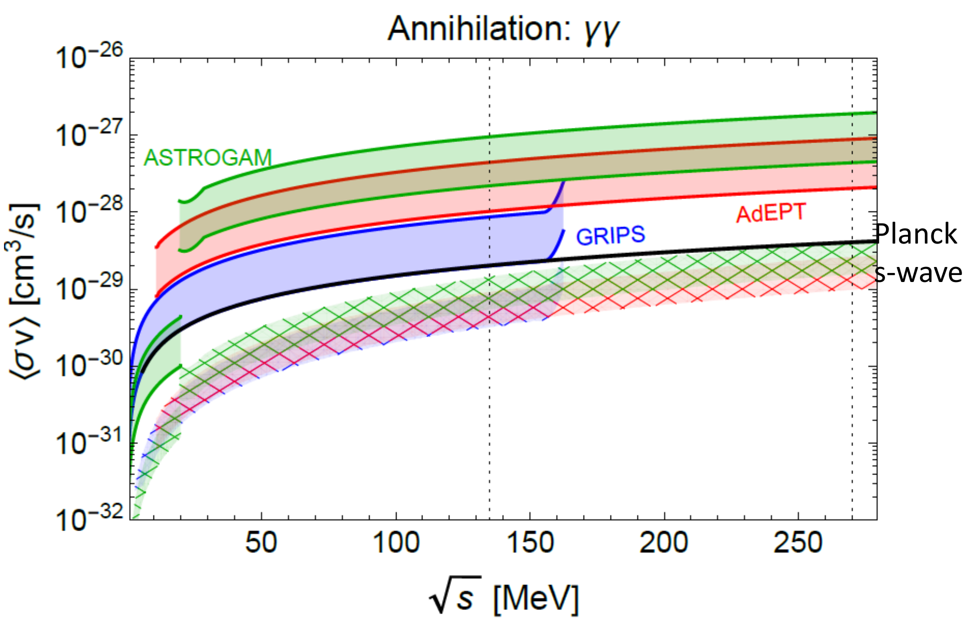
constraining models

- given Lorentz, flavor structure of quark current, we have a dominant final state
- from that, got photon spectra
- convolve with energy resolution
- now, estimate constraints from….
  - diffuse emission search
  - dwarf spheroidal search
- start with fit to observed spectrum in EGRET/COMPTEL data ($\sim 0.00274\ [E/\mathrm{MeV}]^{-2}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{MeV}^{-1}$)
- choose an energy bin near the peak of signal

- diffuse search
  - assume you don't know bgd.
  - can only constrain models which predict a signal larger than observed flux, up to fluctuations
  - limit depends only on ε if narrow peak
- dSph (Draco)
  - assume observed diffuse spec. is the bgd to emission from dSph
  - constrain models which predict a signal larger than the fluctuation of bgd.
  - depends on ε, exposure, PSF

sensitivity -- $E_{cm} < 2m_{\pi^\pm}$

- all at 2σ , branching fraction = 100%, exposure = 2500 cm^2 yr (5yrs)
  - conservative diffuse search → signal (- 2σ) = observed
  - optimistic diffuse search → signal (- 2σ) = 15% of observed
    - ends of solid region
  - dwarf search → signal = 2σ of bgd. (diffuse)
    - cross-hatched region, for Draco
    - width → uncertainty in J (1E19.05+0.22-0.21 GeV^{-2} cm^{-5}, for ann.)



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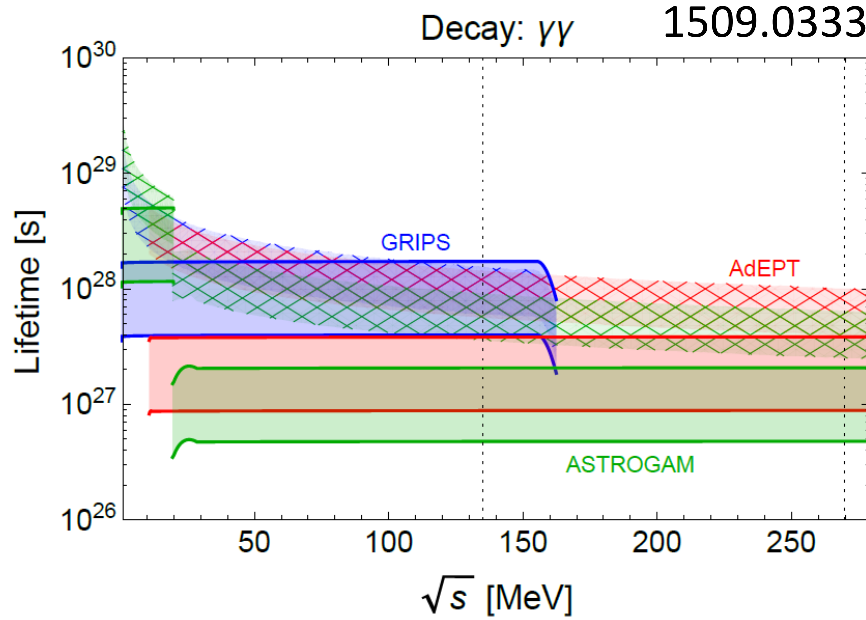
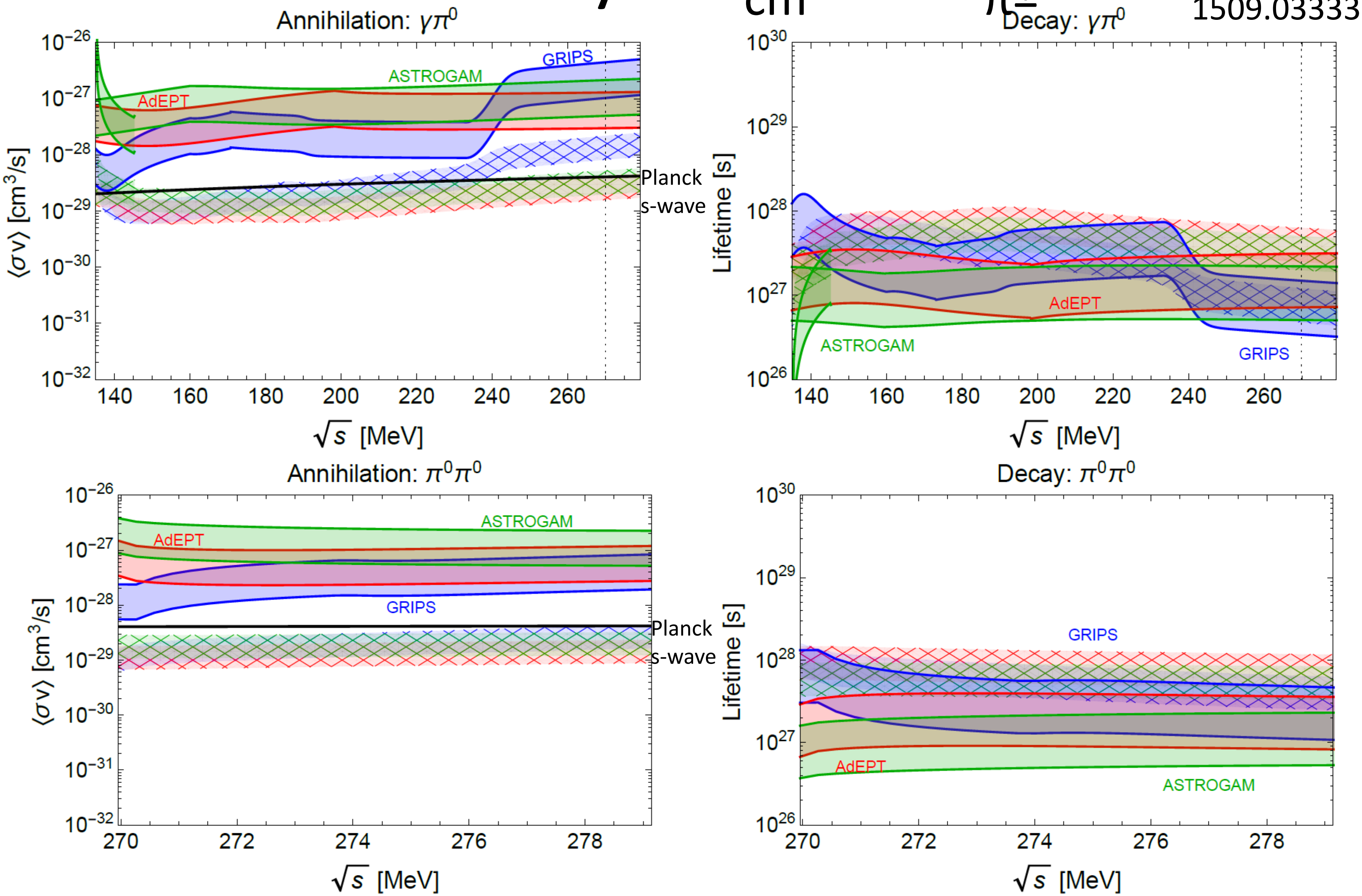


sensitivity -- $E_{cm} < 2m_{\pi^\pm}$

1509.03333

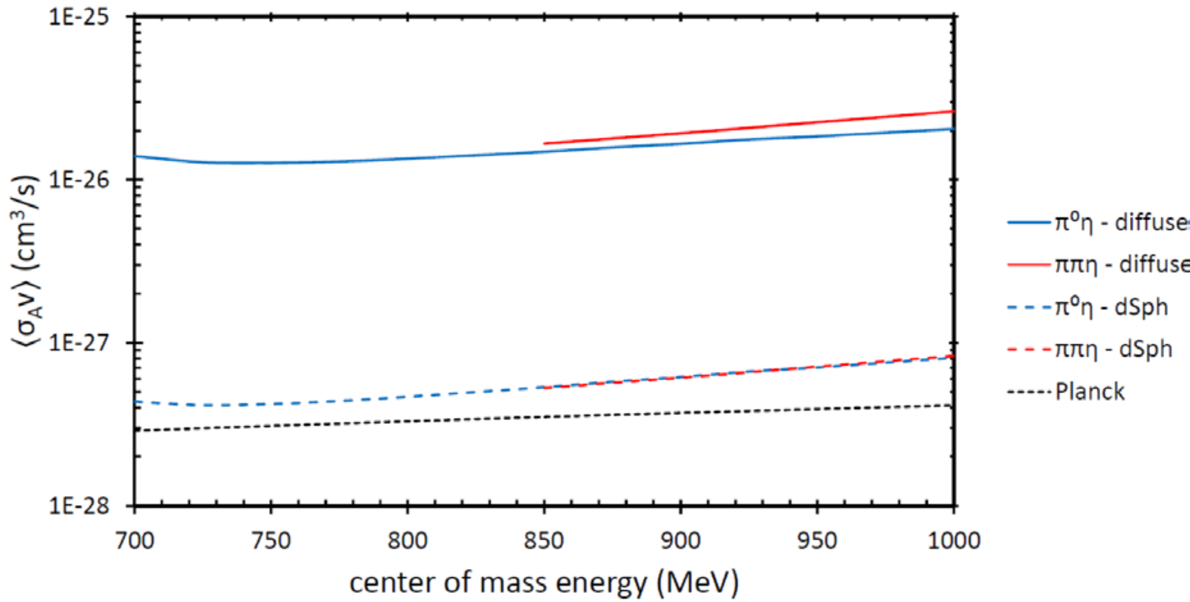


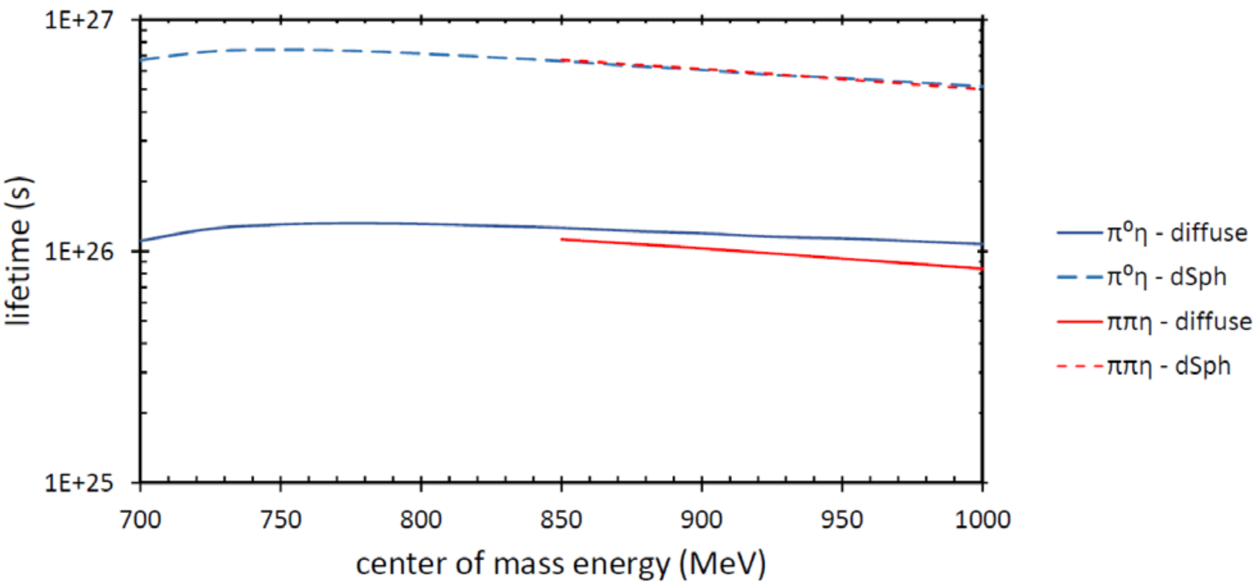
$E_{cm} > 2m_{\pi^\pm}$, $\eta \to \gamma\gamma$,

diffuse → signal = observed

dSph (Draco)→ signal =
2σ of bgd (diffuse)

These limit figures have been completed in an entirely different style
at great expense and at the last minute.





1808.02579

cross section bounds weaken as E_{cm} increases, since number density decreases

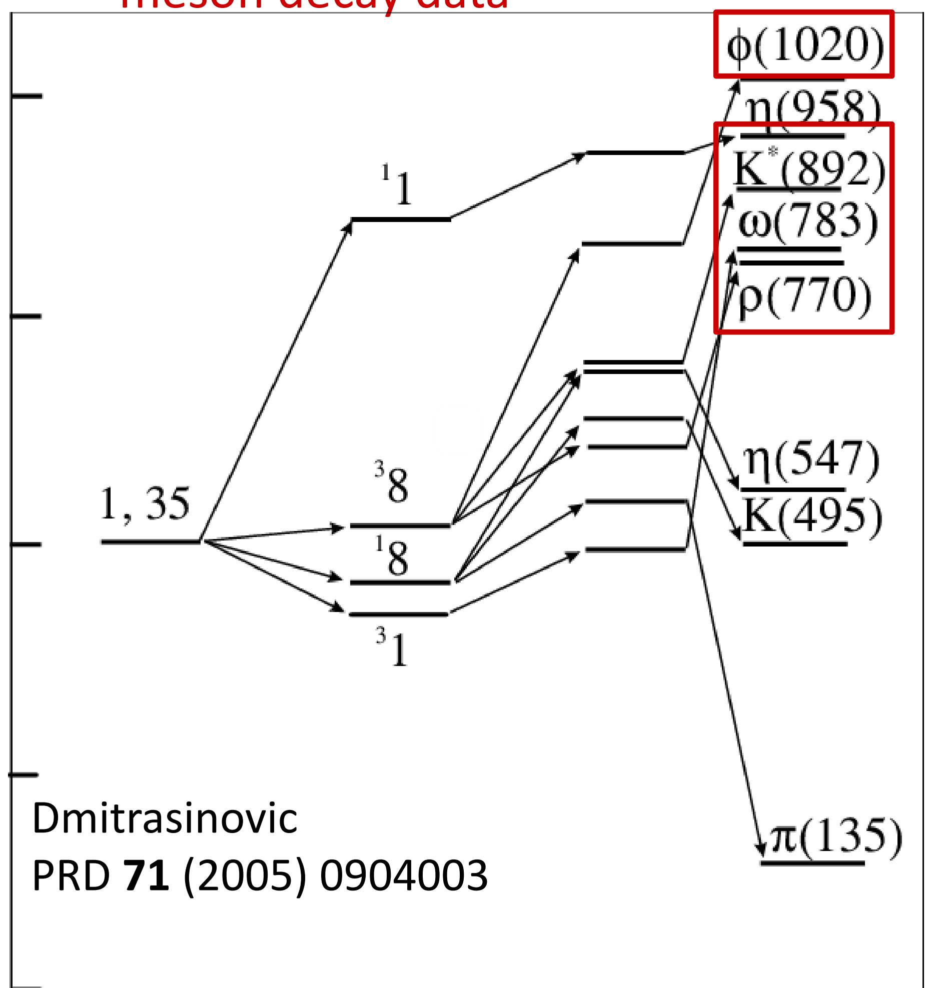
upshot

- bounds on annihilation compete with Planck, but bounds on decay are a couple of orders of magnitude stronger than Planck ($\sim 10^{24}$s)
  - early Universe = higher number density → favors annihilation
  - Planck bounds for s-wave only, but $\pi^0\eta$ comes from a p-wave process
- diffuse bounds compare signal flux (integrated over a bin) to observed flux
  - don't really benefit from statistics
  - once energy bin comparable to signal width, instrument doesn't matter, if diffuse flux fixed
  - but new instruments with better angular resolution and exposure may identify more point sources, and masking them would reduce the diffuse flux
  - not accounted for here
- dSph search beats diffuse, but especially for dark matter annihilation
  - not included stacking of dSphs

vector coupling

- say dark matter couples to a vector current, $E_{cm} \lesssim 1$ GeV
  - need a two-body final state with $J^{PC} = 1^{--}$
  - C-odd → $\pi^+\pi^-$ (L=I=1)
  - negligible photon production
- need to consider higher energy, $\mathcal{O}(p^4)$ in ChPT, or 4-body
- at higher energy, can produce kaon pairs, which decay to π^0
- also need to consider vector mesons (ρ, ω)
- new terms in chiral Lagrangian (Terschlusen, Leupold, Lutz- 1204,4125)

- again, new couplings fixed by meson decay data



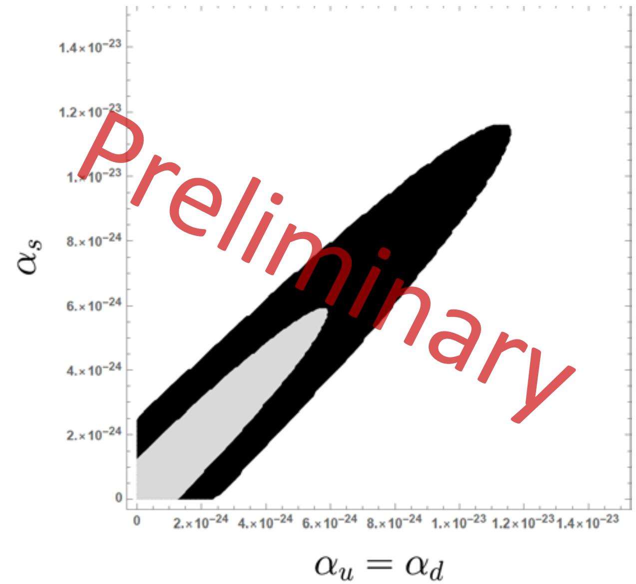
constraints

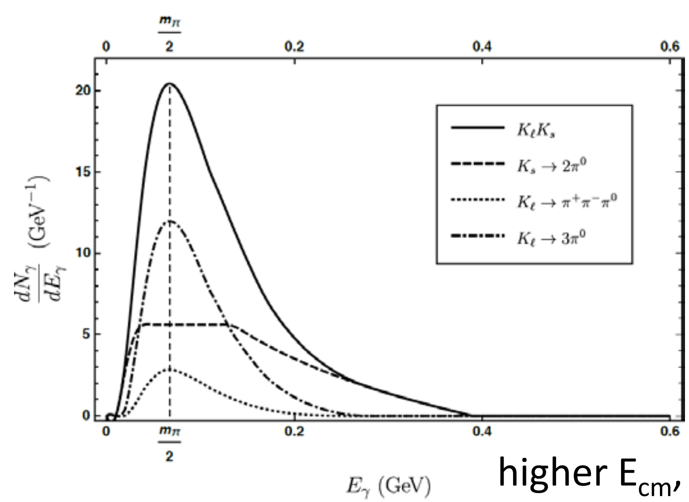
DB, JK, AR

- start above ρπ threshold (~910 MeV), up to roughly ~1.15 GeV
- accessible states allowed by symmetry → $\pi^+\pi^-$, K^+K^-, $K_L K_S$, ρπ, $\omega\pi^0$
  - all L=1 (C-odd)
  - constrained by isospin, U-, V-spin
- few primary or secondary photons
- tertiary photons come from decay of $K^\pm$, K_L, K_S, ω, $\rho^\pm$ to π^0
- can go to higher mass, but will start getting more mesons, glueballs

allowed regions
black=diffuse
grey=Draco

$\tau_{diff} \sim$ 2.3E25 s
$\tau_{Draco} \sim$ 9E25 s





E_{cm}=1.14 GeV

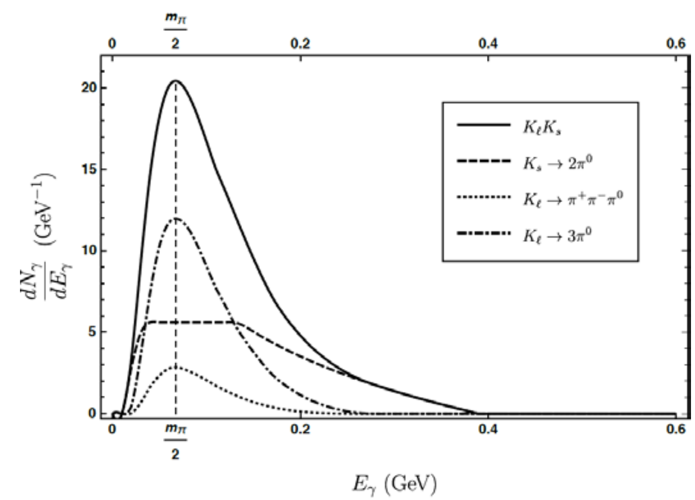
higher E_{cm}, but lower peak E_γ

spectrum to a model?

- interesting features of photon spectrum arising from decay of boosted $\phi \rightarrow \gamma\gamma$
  - log-symmetric about $E_\gamma = m_\phi/2$
  - global maximum at $E_\gamma = m_\phi/2$
  - decreases monotonically going away from maximum
- shape of peak at $E_\gamma = m_\phi/2$ set by the ϕ injection spectrum at peak
  - sharp peak → finite injection spectrum at zero boost
  - smooth peak → inj. spectrum goes to zero at zero boost
  - plateau → boost threshold

$$\frac{dN_\gamma}{dE_\gamma} = \int_{\frac{m_\phi}{2}\left(\frac{2E_\gamma}{m_\phi}+\frac{m_\phi}{2E_\gamma}\right)}^{\infty} dE_\phi \left[\frac{dN_\phi}{dE_\phi}\frac{2}{\sqrt{E_\phi^2-m_\phi^2}}\right]$$

$$\left(\frac{d^2N_\gamma}{dE_\gamma^2}\right)_{E_\gamma\to\frac{m_\phi}{2}} = \frac{4}{m_\phi}\,\mathrm{sgn}\left(\frac{m_\phi}{2}-E_\gamma\right)\left(\frac{dN_\phi}{dE_\phi}\right)_{E_\phi\to m_\phi}$$



scenarios

- two-body final state → plateau
- multi-body final state → smooth peak
- particle production near threshold → sharp peak
  - multi-component dark matter (for example, Dynamical Dark Matter, 1606.07440, 1609.09104)
  - many DM components, with non-trivial contribution from components just above threshold

- can we distinguish these scenarios from data?

- basically a question of exposure and energy resolution
- signal peaked near $m_{\pi^0}/2 \sim 70$ MeV, $m_\eta/2 \sim 275$ MeV

conclusion

- sub-GeV gamma rays a promising tool for dark matter indirect detection
- new interest in theoretical models in this mass range
- region of parameter space not well-constrained by other tools
- new gamma-ray instruments planned
- if DM couples to quarks, final states constrained by kinematics and symmetry

- get striking photon signatures
- can improve sensitivity by orders of magnitude

Mahalo!

Back-up slides

analysis details

- energy bin choice
  - if monoenergetic γ is present, bin is centered at that energy
  - if box generated by π^0 decay is present, upper edge of window is at upper edge of box
  - for η channels, just center box at $m_\eta/2$
- J-factors
  - diffuse (PPPC 4 DM ID)
    - J_{ann} = 3.5E21 $GeV^2\ cm^{-5}\ sr^{-1}$
    - J_{dec} = 1.5E22 $GeV\ cm^{-2}\ sr^{-1}$
  - Draco (Geringer-Sameth, Koushiappas, Walker 1408.0002) (1.3° cone)
    - J_{ann} = 6.94E21 $GeV^2\ cm^{-5}\ sr^{-1}$
    - J_{dec} = 5.77E22 $GeV\ cm^{-2}\ sr^{-1}$

direct detection constraints

- no constraints if quark current couples to single DM particle, as in case of dark matter decay
- if quark current couples, no bounds for m_X < 350 MeV or so (where CRESST kicks in → σ_N ~ 10-100 pb).
- for m_X > 350 MeV, no bounds for p or a spurion case, since cross section is SD (p and a) and velocity-suppressed (p)
- for scalar spurion, SI-scattering, p-wave suppressed annihilation
  - getting annihilation to Planck limit means ramping couplings, so $\sigma_{SI} \sim 10^7$ pb
  - but isospin-violating, so detection suppressed by 10^5 (1307.1758)
  - at Planck limit, near boundary of CRESST search… needs more study
- vector spurion case → need coupling to up and down quarks
  - still preliminary, but annihilation is s-wave, so at Planck limit, couplings smaller
  - but CRESST limits improve by 3 orders of magnitude, and coupling need not be IVDM… so some scenarios will be constrained
  - evade direct detection limits entirely if DM couples to strange quarks only….

LHC constraints

- can look at constraints from mono-jet searches
- again, no useful constraints for DM decay case (single DM particle couples to quark current)
  - very weak bounds on coupling
- for case where DM current couples to quark current, naïve LHC bounds in contact approximation will rule out models which saturate Planck
- but can scale α and Λ down while keeping operator coefficient fixed, and LHC sensitivity goes away