The MeV Window on Dark Matter

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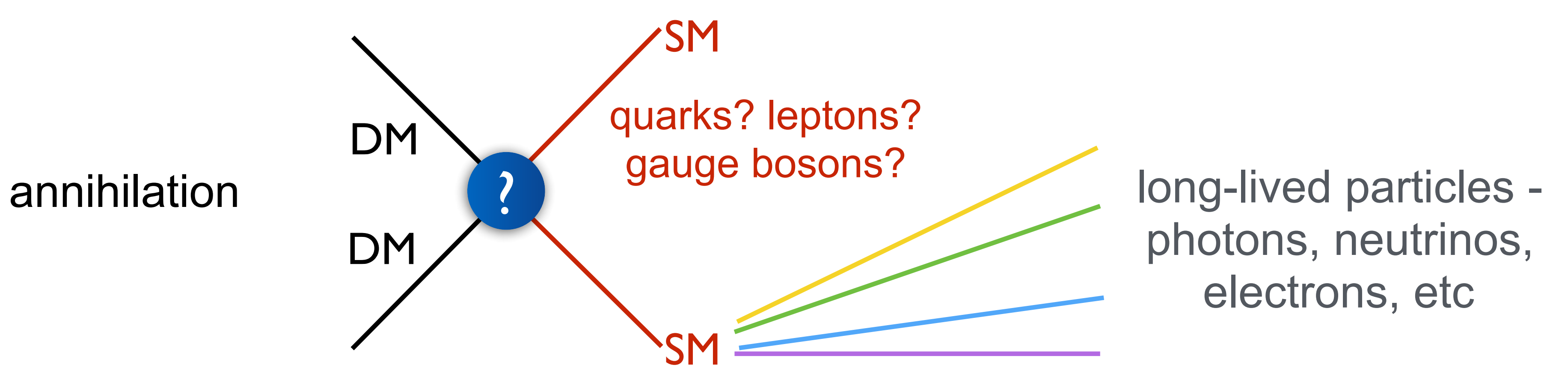
Dark matter (DM)

- More than 80% of the matter in the universe is dark - no electric charge, interacts at most very weakly with known particles - detected so far solely by gravitational effects. Could be a major clue to new physics beyond the Standard Model (SM).
- Long-standing experimental program to search for DM - lots of recent interest in DM lighter than ~1 GeV, which is less constrained by sensitive underground experiments.
- What can we learn about DM from new MeV-band telescopes?
- Enormous range of possibilities for DM, but in many scenarios, DM could annihilate or decay producing visible SM particles including photons.



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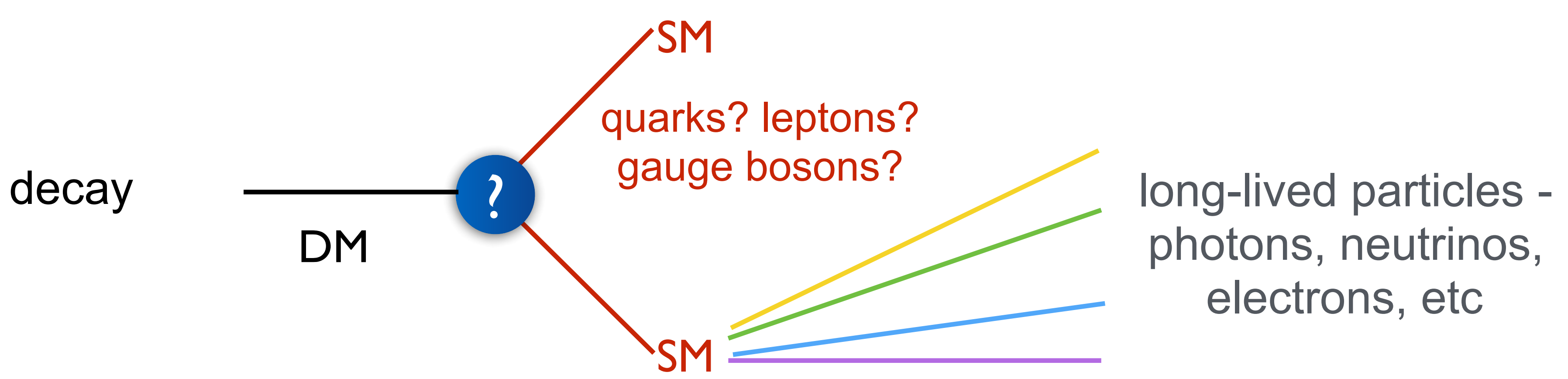


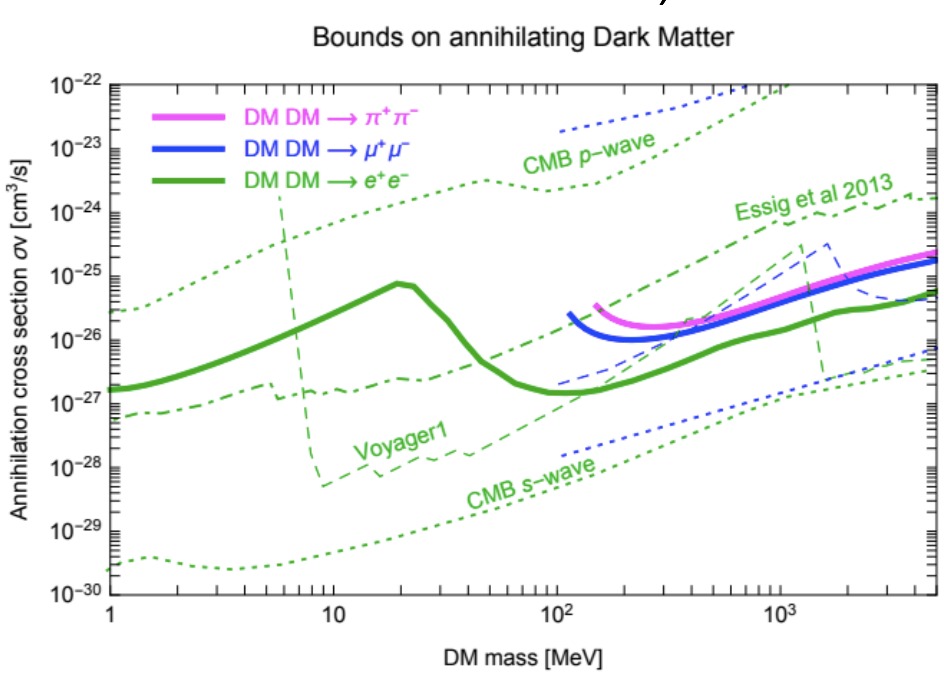
Indirect searches for MeV-GeV dark matter

- Most obvious channel: look for photons produced by annihilation/decay of MeV-GeV DM
- Q: how competitive are MeV-band photon searches with other probes of DM in this mass range?
- Sub-GeV dark matter can annihilate to:
    - charged particles (e.g. leptons, charged pions) - primarily decay to electrons/positrons/neutrinos, radiating photons in the process and from the subsequent interactions of the electrons/positrons.
    - neutral particles (e.g. photons, neutral pions, neutrinos) - produce copious photons unless the neutrino branching ratio is large.
- Competitor indirect-detection probes:
    - Observations of the cosmic microwave background (CMB) constrain annihilation/decay in the early universe when the density was much higher - powerful limits on annihilation to photons/electrons/positrons.
    - Observations of low-energy electrons/positrons from Voyager (now outside the heliopause) can set competitive bounds for decay to charged particles [Boudaud et al ’16, Boudaud et al ’18].

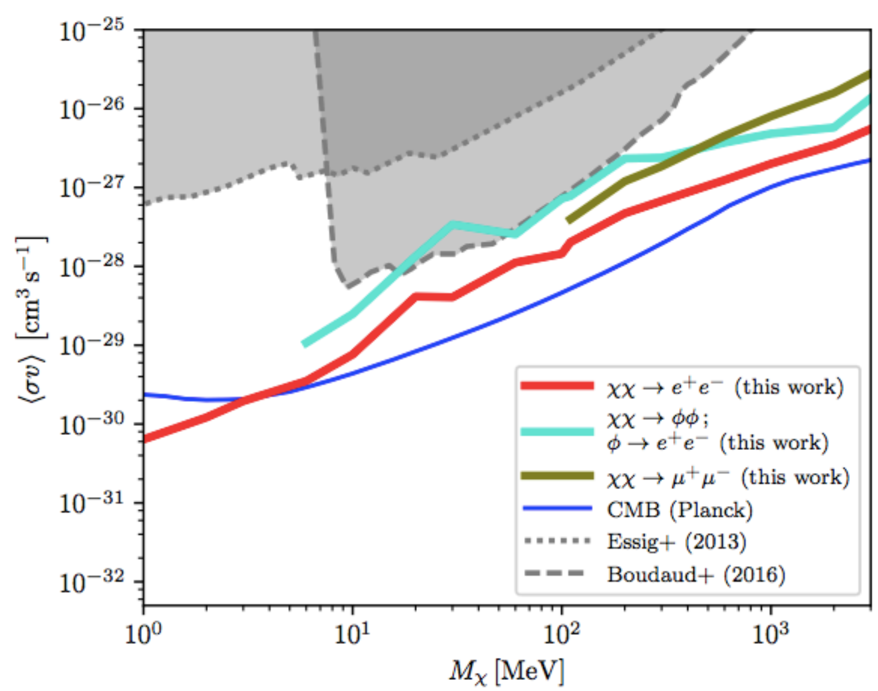
Indirect searches: annihilation

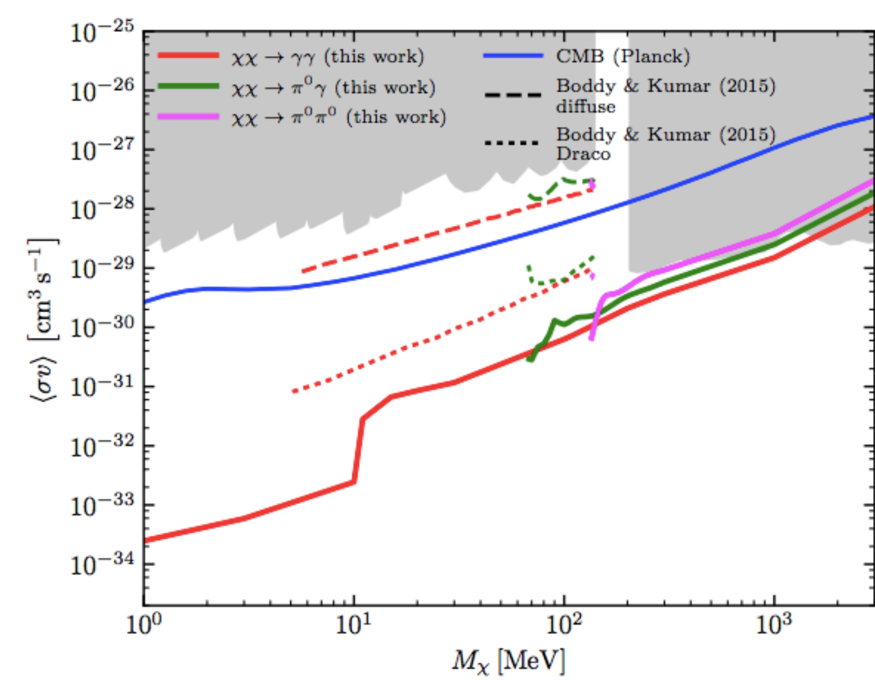
- Forecasts: Boddy & Kumar ’15, Bartels et al ’17, Gonzalez-Morales et al ’17, Dutra et al ’18.
- For annihilation (with no velocity dependence), CMB bounds currently win out for all channels for DM masses below ~ 200 MeV.
- Prospective MeV-band searches will beat the CMB sensitivity for annihilation producing monoenergetic photons / neutral pions, & can be competitive for DM annihilating into electrons/positrons with mass < 10 MeV.
- For annihilation that is suppressed at low velocities (e.g. p-wave annihilation), the CMB bounds become irrelevant and other limits take over.

Current example limits (Cirelli et al 2007.11493)



Forecast limits (1703.02546)

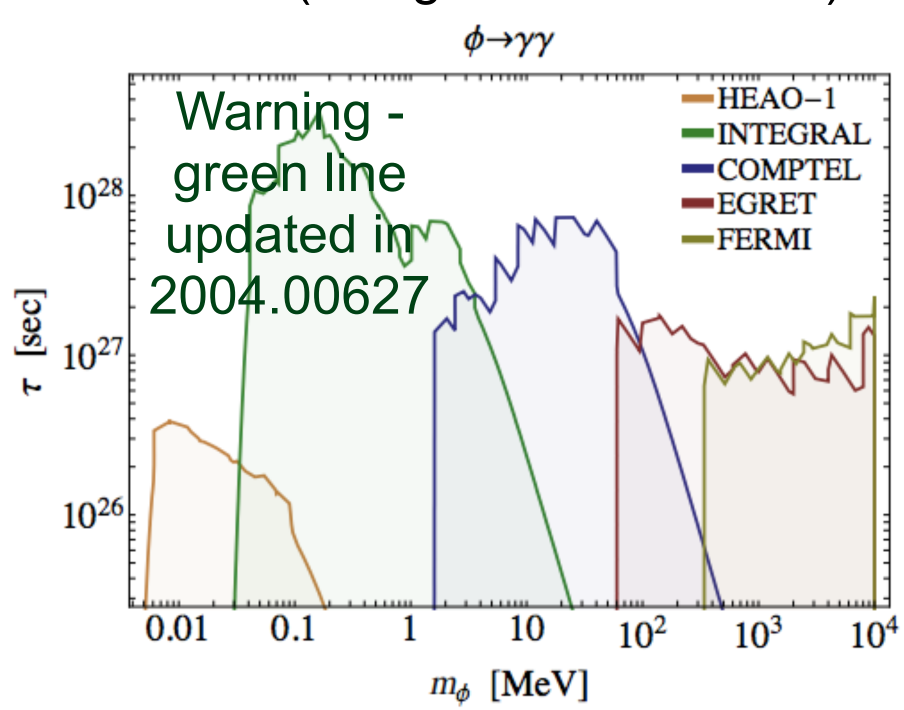




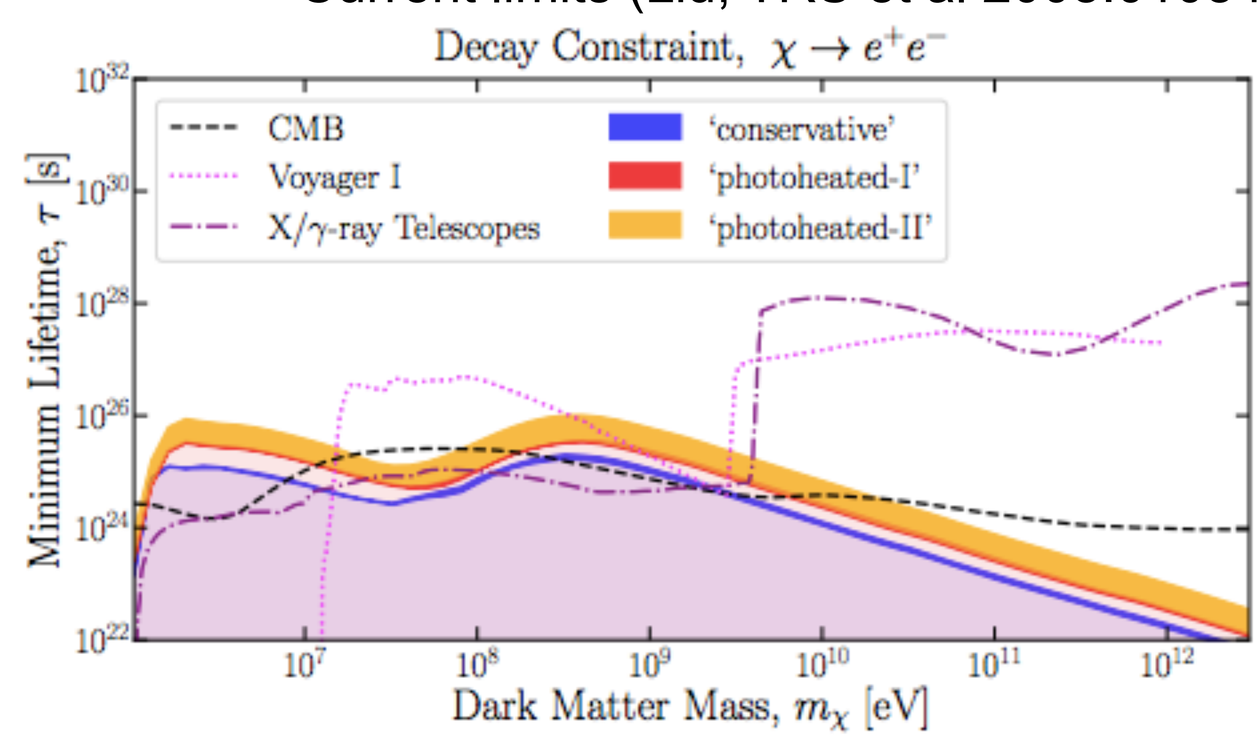
Indirect searches: decay

- For decaying DM, current MeV-band gamma-ray searches already provide the strongest constraints for decays producing copious photons.
- Current MeV-band searches, the CMB and other cosmological bounds, and Voyager (>10 MeV) are competitive for decays to leptons. New MeV-band missions should take the lead in sensitivity (although future 21cm observations may also be very powerful).

Current limits (Essig et al 1309.4091)



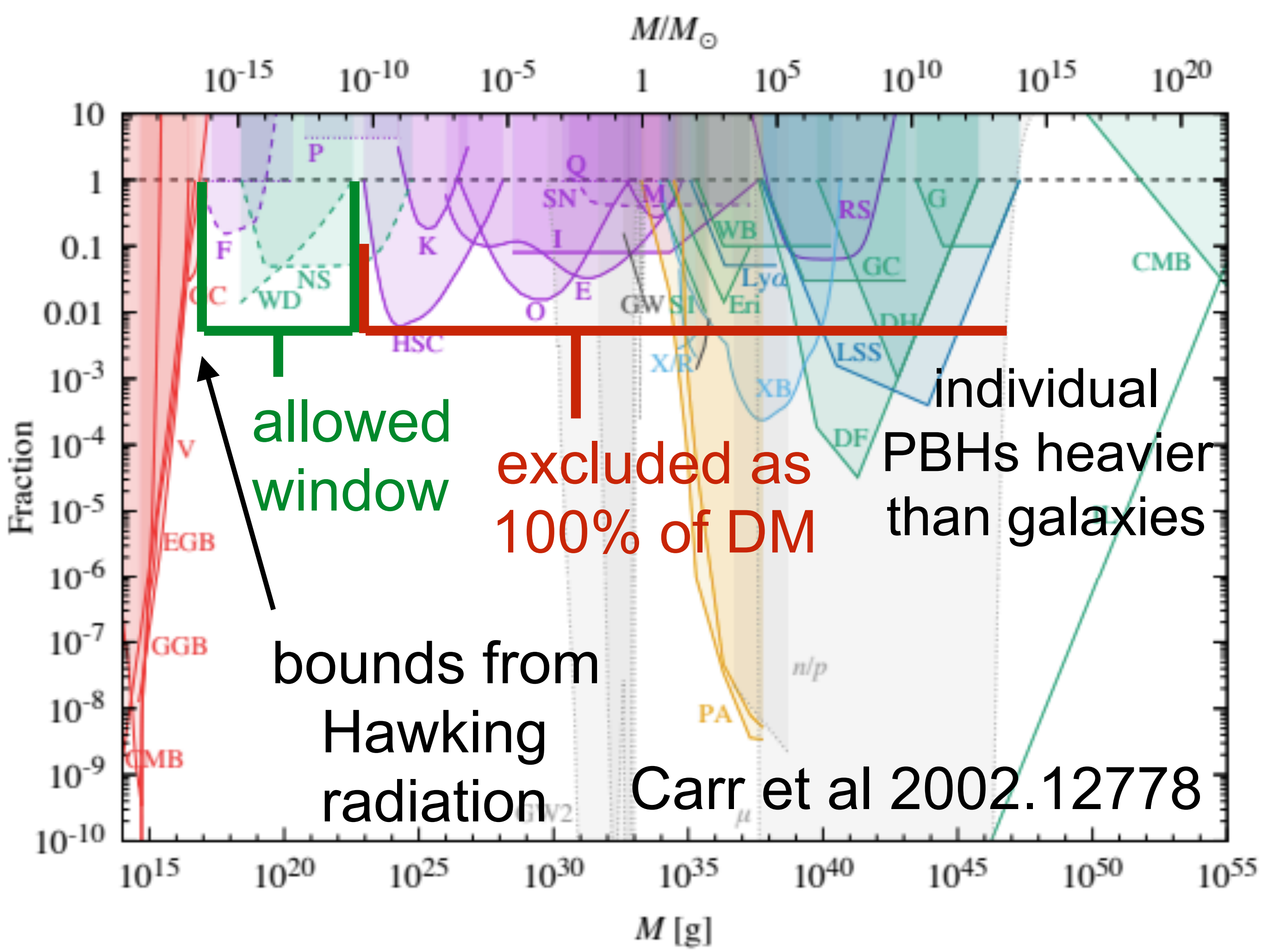
Current limits (Liu, TRS et al 2008.01084)

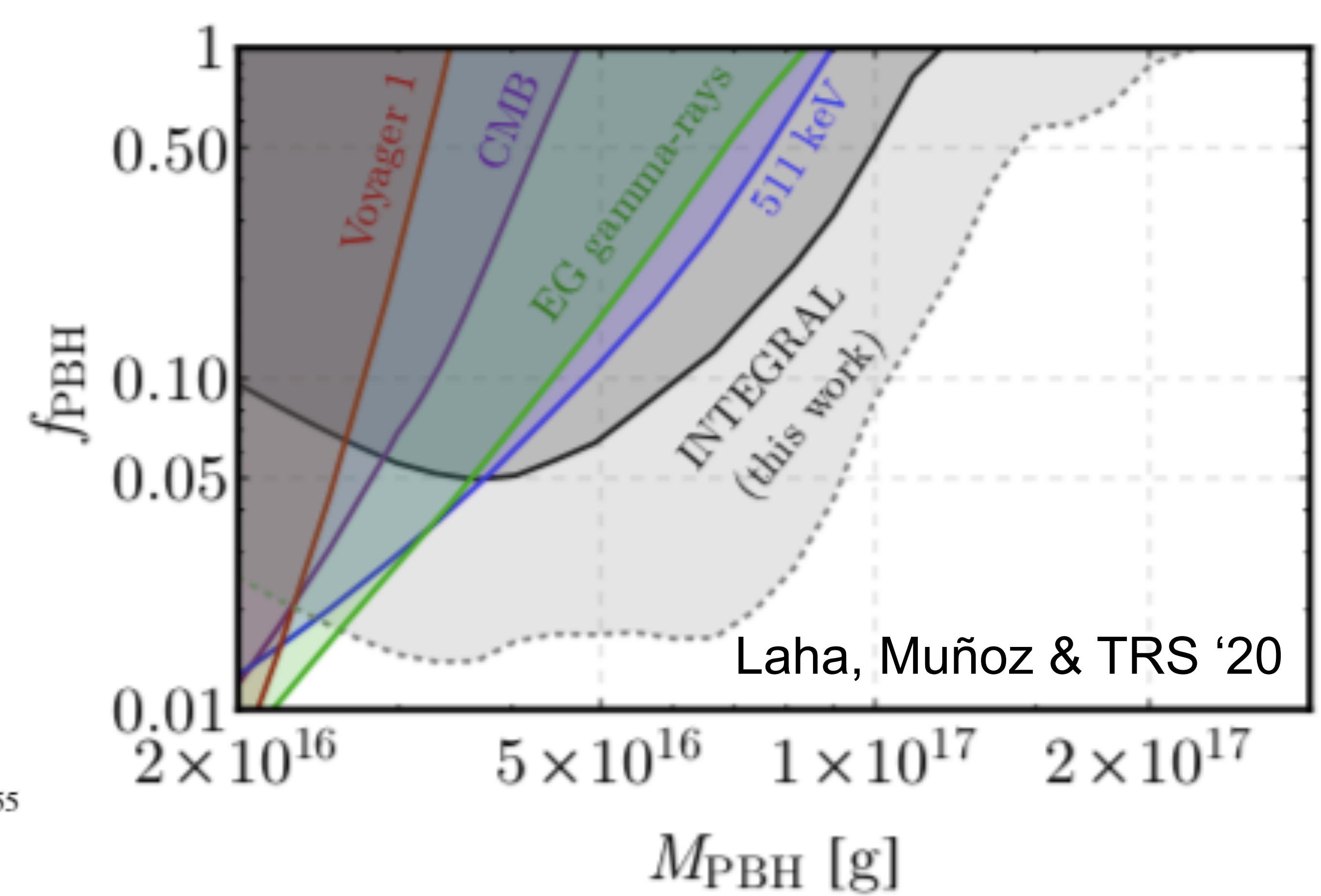


dominant branching ratio to:	photons / neutral pions	charged leptons
annihilation (s-wave)	CMB → MeV-band	CMB → CMB, MeV-band?
annihilation (p-wave)	MeV-band → MeV-band	Voyager, MeV-band → MeV-band
decay	MeV-band → MeV-band	Voyager, MeV-band, cosmology → MeV-band, future cosmology

Primordial black holes

- Primordial black holes (PBHs) can also serve as a DM candidate if they lie in the right mass range - 10^{17-23} g PBHs appear viable to constitute 100% of the DM.
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs around 10^{17} g would produce X-ray and soft gamma-ray radiation.
- The non-observation of this radiation sets the strongest current bounds on such PBHs - possibility to improve the limit with future MeV-band observations (see SNOWMASS21-CF3_CF7-TF9_TF0_Julian_Munoz-214).





The importance of backgrounds

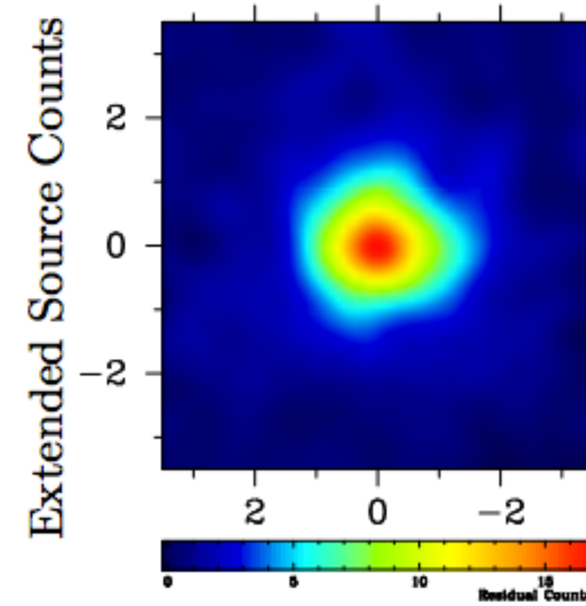
- Considering higher PBH masses pushes down the energy of the Hawking radiation, into the X-ray band, and also greatly reduces the strength of the signal; even the current bound relies mostly on few-hundred-keV photons rather than MeV+ photons.

- However, current bounds are very simple, with little to no modeling of backgrounds; a better understanding of the astrophysical background emission could allow for much stronger constraints.

- Improved MeV-band observations could inform the background modeling by measurements at higher energy; for example, the spectrum of gamma-rays from cosmic-ray interactions with the gas has a characteristic feature associated with the π^0 mass, allowing for better measurements of this component with AMEGO (Caputo et al '19).

- This idea is also relevant for constraints on higher-mass DM (GeV+), where the MeV band is the low-energy sideband.

The Galactic Center excess



- There is an excess of ~1-3 GeV gamma rays from the inner Galaxy (in *Fermi* data) that has attracted a great deal of attention over the last decade.
- Has several properties consistent with a DM annihilation signal (consistent with e.g. 50 GeV DM annihilating to quarks), but also with a previously-unknown population of pulsars.
- There have been many tests designed to distinguish these hypotheses, but systematic uncertainties in the astrophysical diffuse background modeling can have a large effect on the outcome and make it hard to draw robust conclusions.
- Future MeV-band telescopes have the potential to constrain the diffuse background and/or a potential pulsar population and help us disentangle the various contributions.

Summary

- The nature of dark matter is a major open problem of particle physics, cosmology, and astrophysics.
- Upcoming MeV-band gamma-ray observations have the potential to set the strongest constraints on a broad range of MeV-GeV dark matter models annihilating or decaying to SM particles.
- These stringent limits can also be applied to the decay of primordial black holes through Hawking radiation.
- As well as direct searches for photons from DM annihilation/decay, MeV-band observations can provide sideband measurements of the relevant backgrounds, and improve sensitivity by that route.
- This may be particularly relevant for working out the nature of the Galactic Center Excess, where we are currently limited by our understanding of the astrophysical diffuse emission and point-source populations in the inner Milky Way.
- There are also other searches I didn’t get to in 12 minutes, e.g. MeV-band supernova observations will let us test for axion-photon oscillations (ask me if you want to know more!)

BONUS SLIDES

WISP searches

- Ultralight DM particles, such as axions, can oscillate into photons in the presence of an external B-field
- During a core-collapse supernova, Weakly Interacting sub-eV Particles (WISPs) could be produced by conversion from thermal photons, escape the supernova, and then re-convert to photons in the B-field of the galaxy
- The expected signal would peak around 50 MeV and would be prompt - no backgrounds
- Non-observation of such a burst from SN1987A sets the current limit, future telescopes could search for both galactic and extragalactic SN