Dark Matter Indirect Detection

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Dark Interactions: Perspectives from Theory and Experiment
Brookhaven National Laboratory
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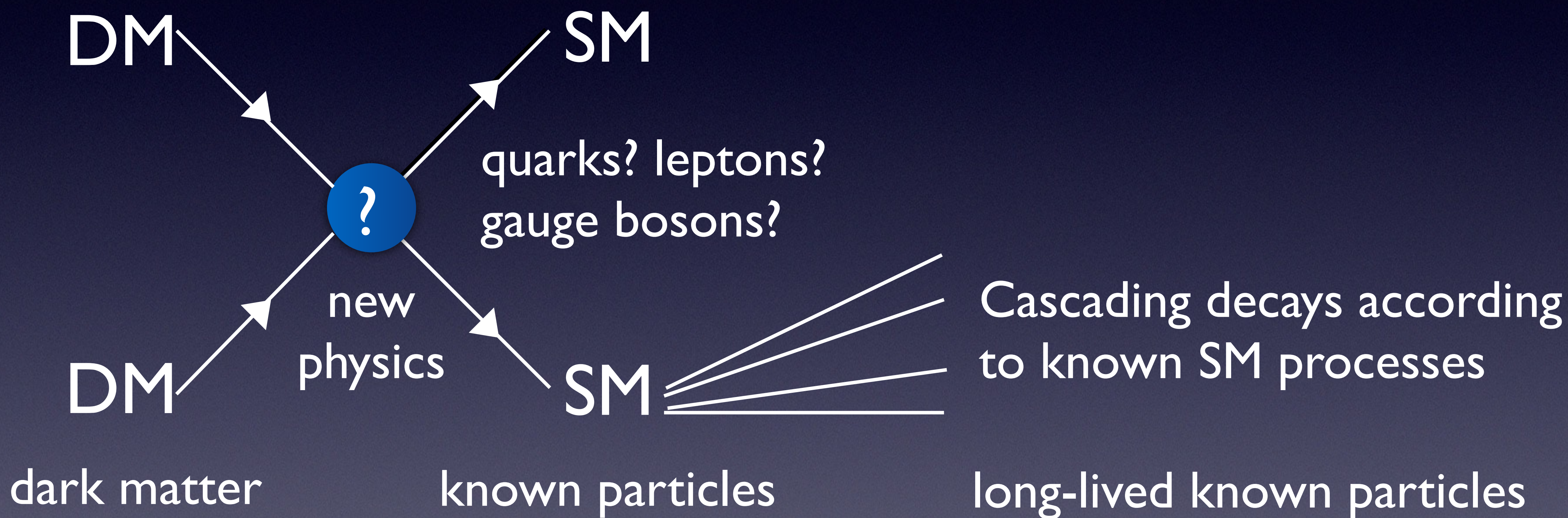
U.S. DEPARTMENT OF ENERGY | Office of Science

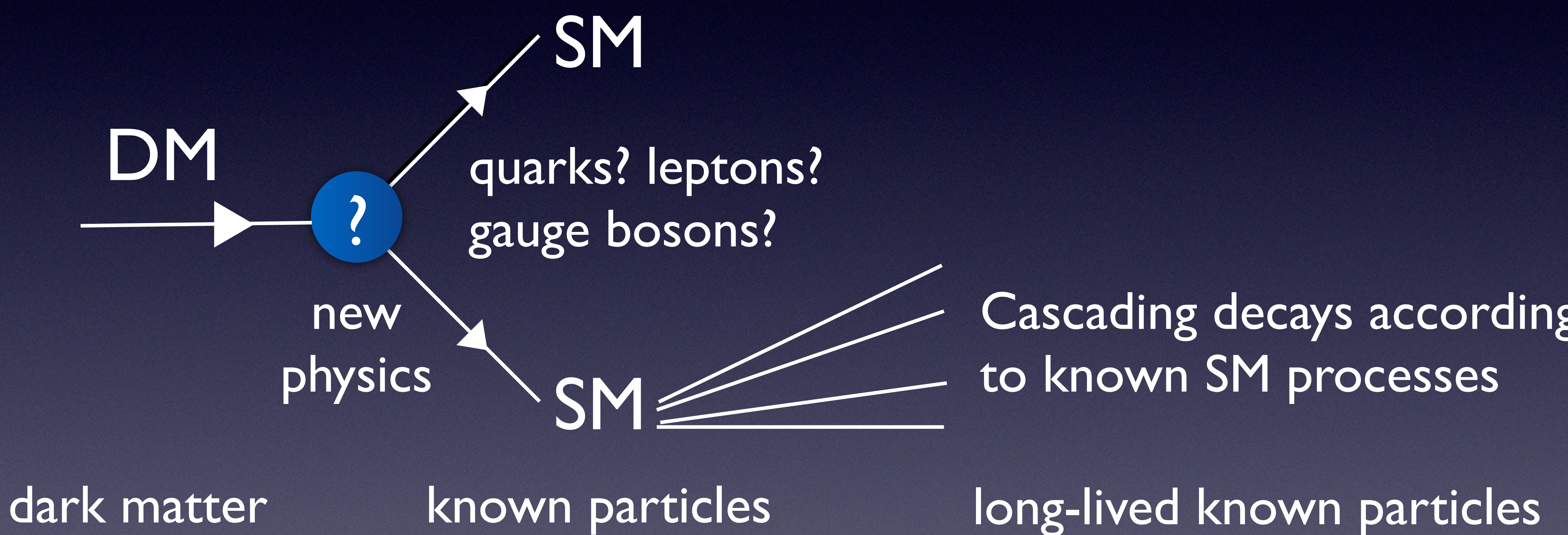
Annihilation



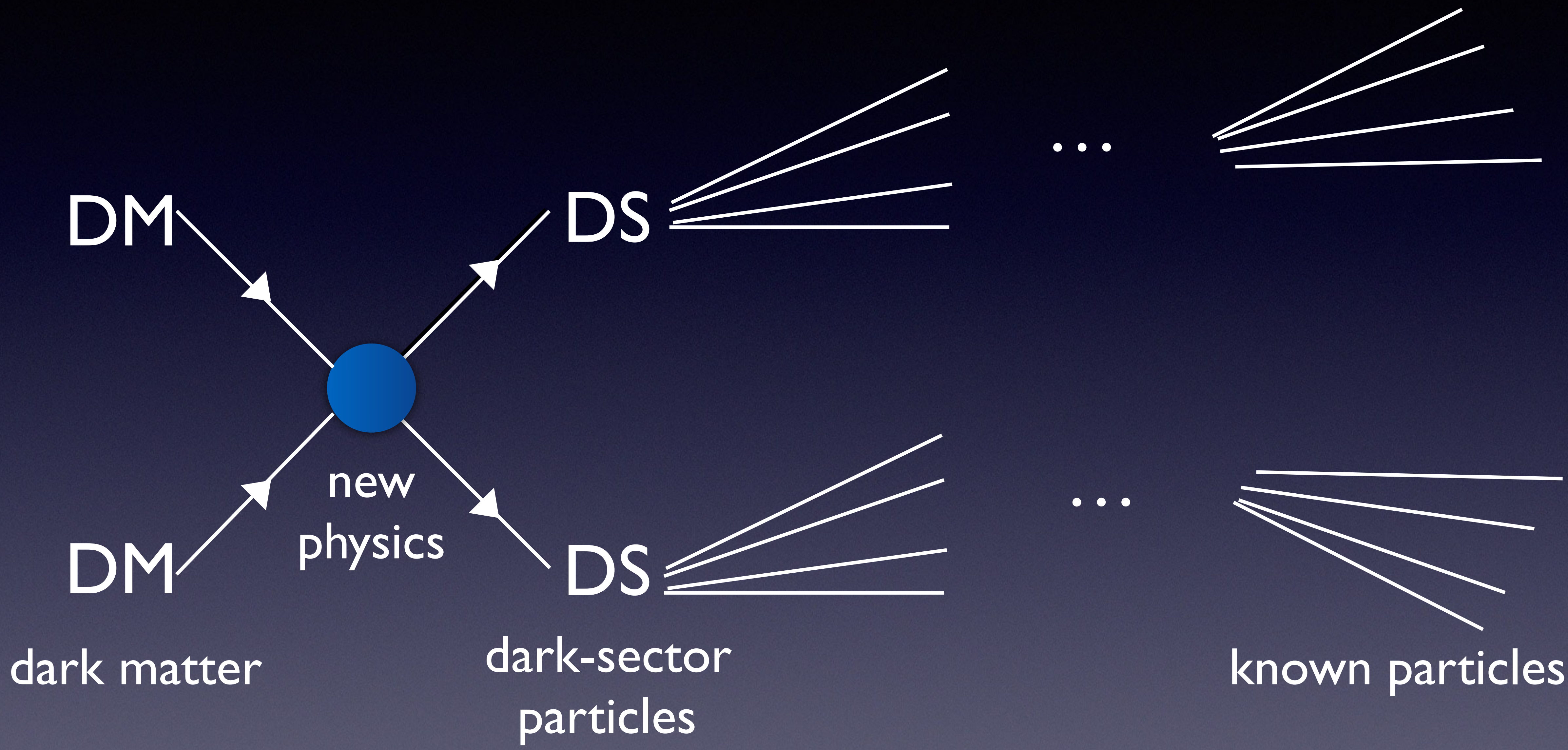
Characteristic "thermal relic" cross section naturally generates observed abundance, often used as a benchmark:

$$\langle \sigma v \rangle \sim 2 - 3 \times 10^{-26} \mathrm{cm}^3/s \sim \pi \alpha^2/(100\mathrm{GeV})^2$$

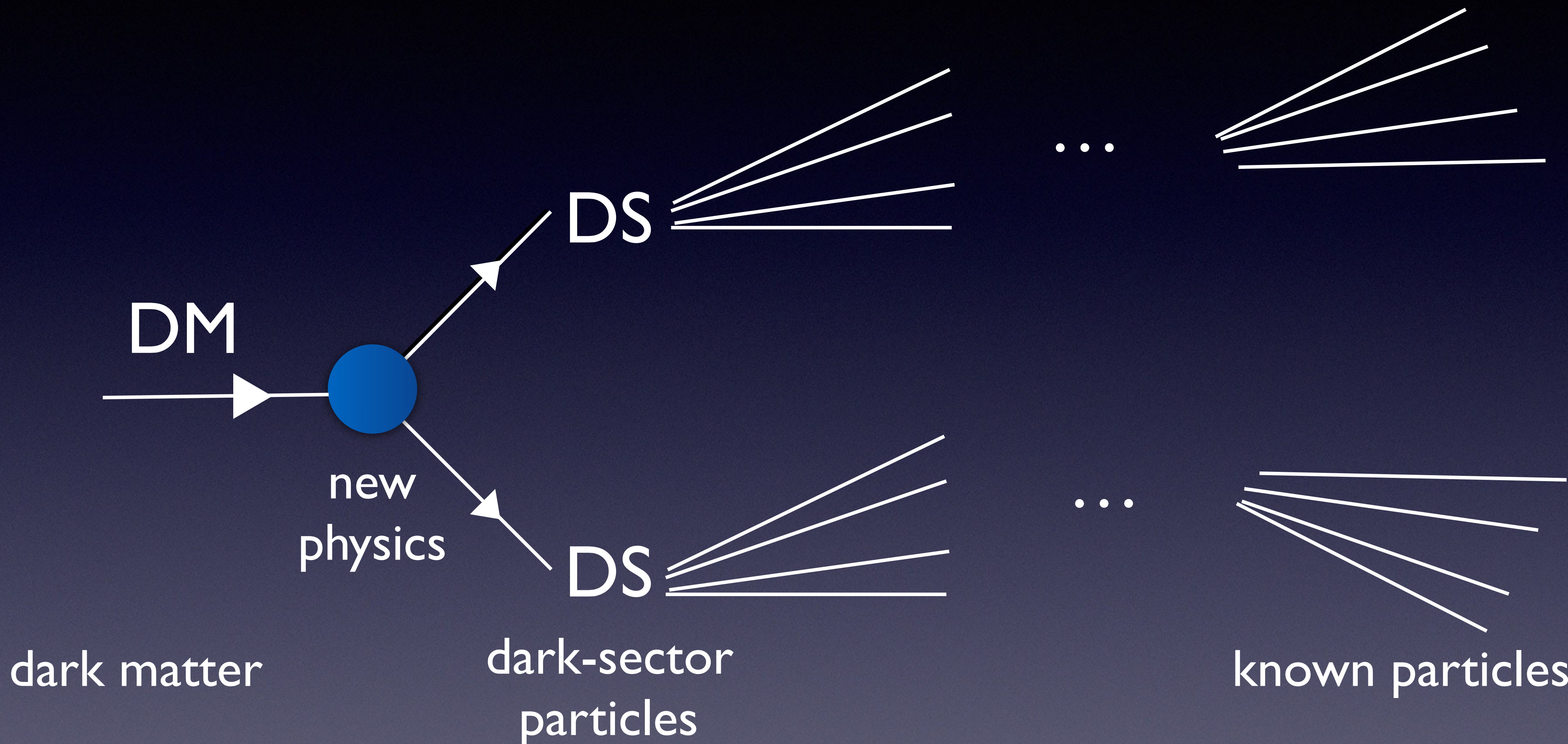
Decay


SM
DM
quarks? leptons?
gauge bosons?
?
new
physics
SM
Cascading decays according
to known SM processes
dark matter
known particles
long-lived known particles

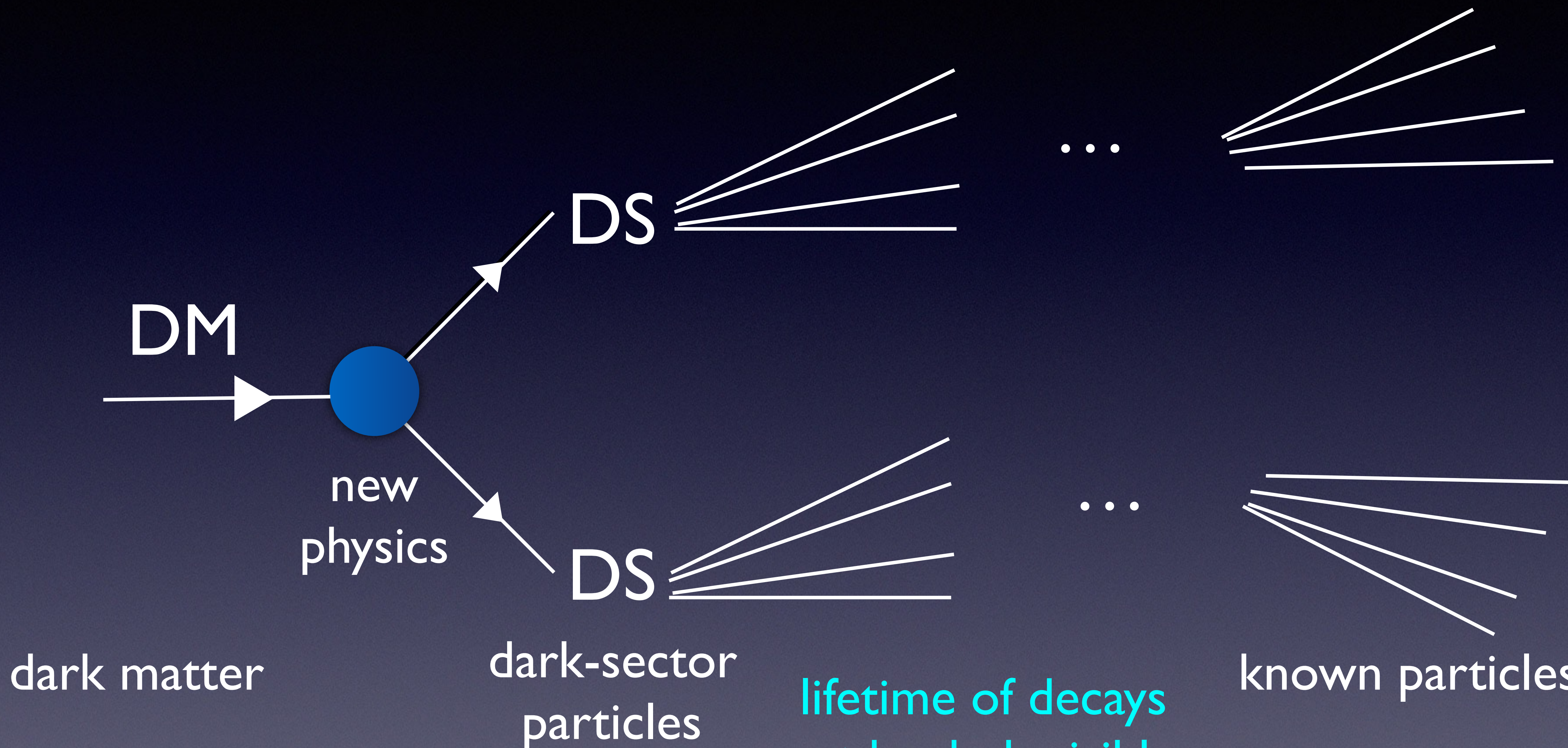
Dark sectors



Dark sectors



Dark sectors



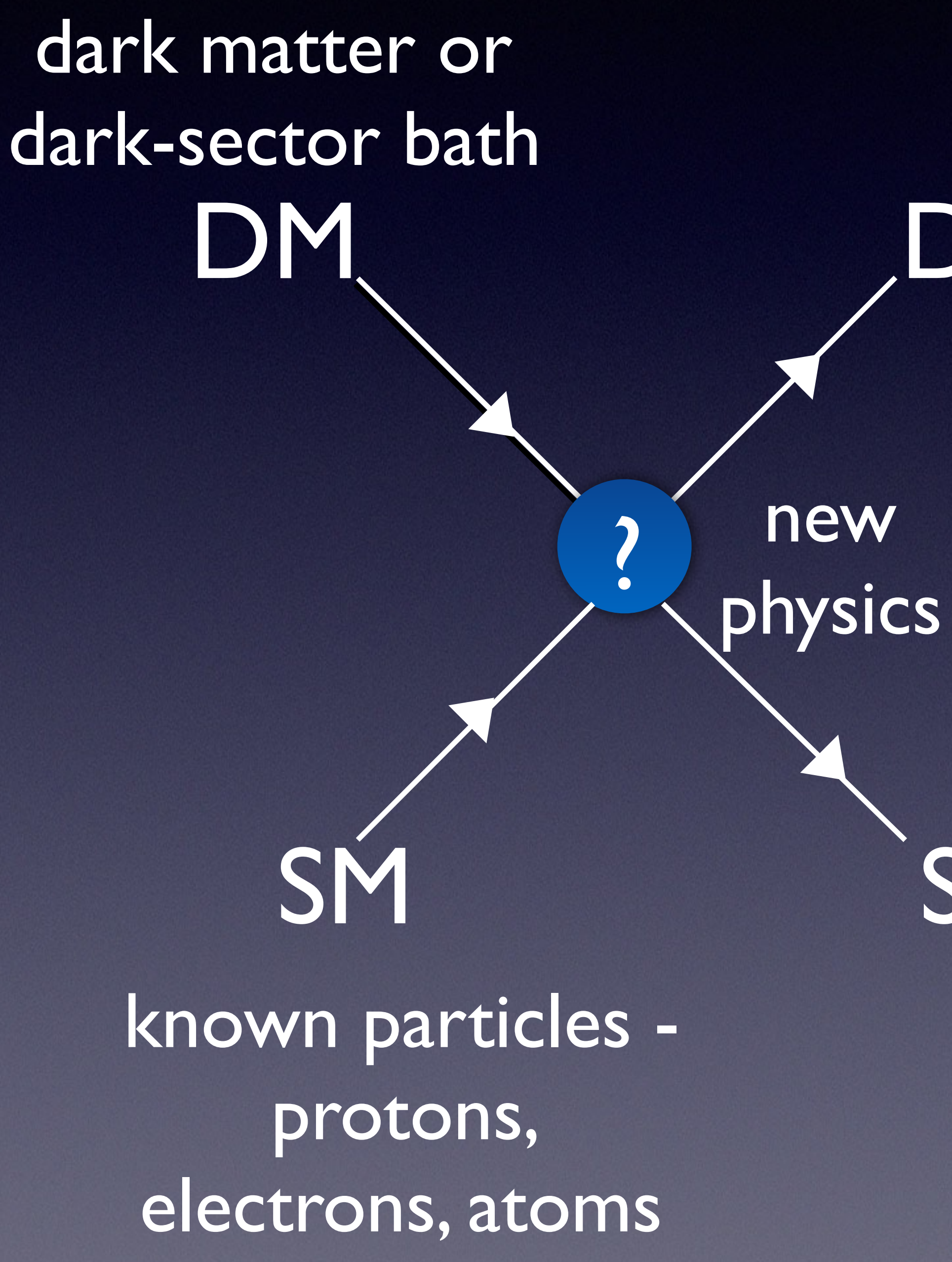
annihilation/decay determined purely by dark-sector physics

lifetime of decays set by dark-visible sector mixing

can still be “short” cosmologically for very small mixings!

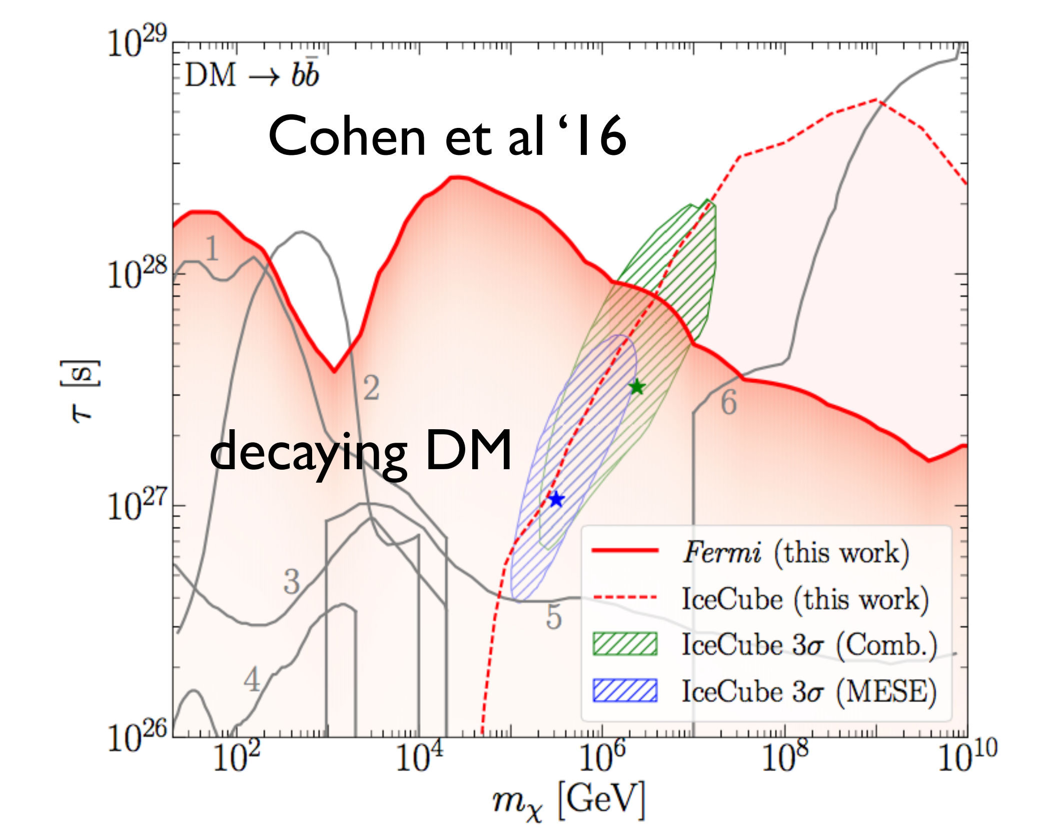
spectrum modified relative to direct annihilation/decay

Scattering

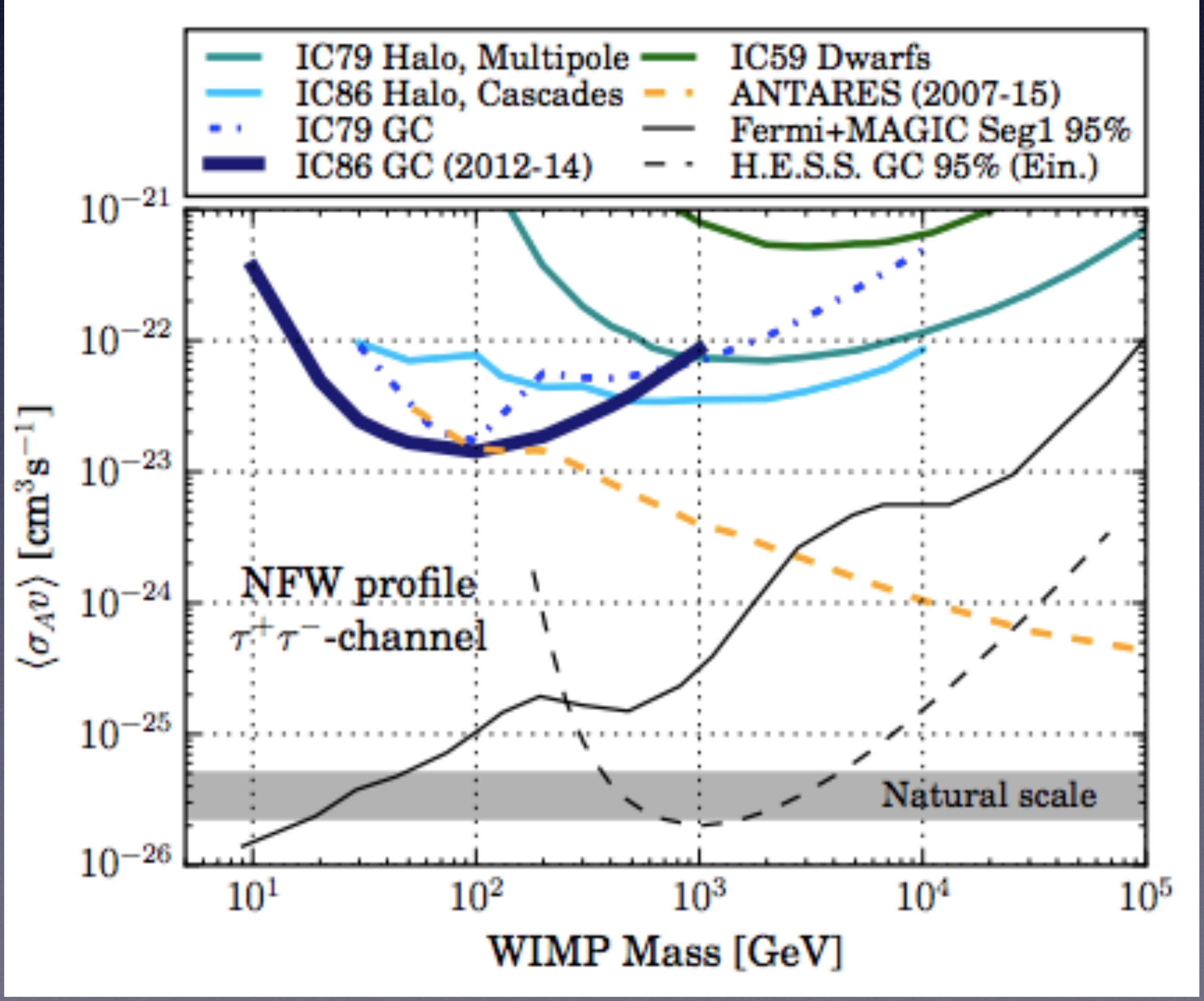


Look for effects of energy transfer to/from DM on visible matter

Indirect limits on annihilation and decay



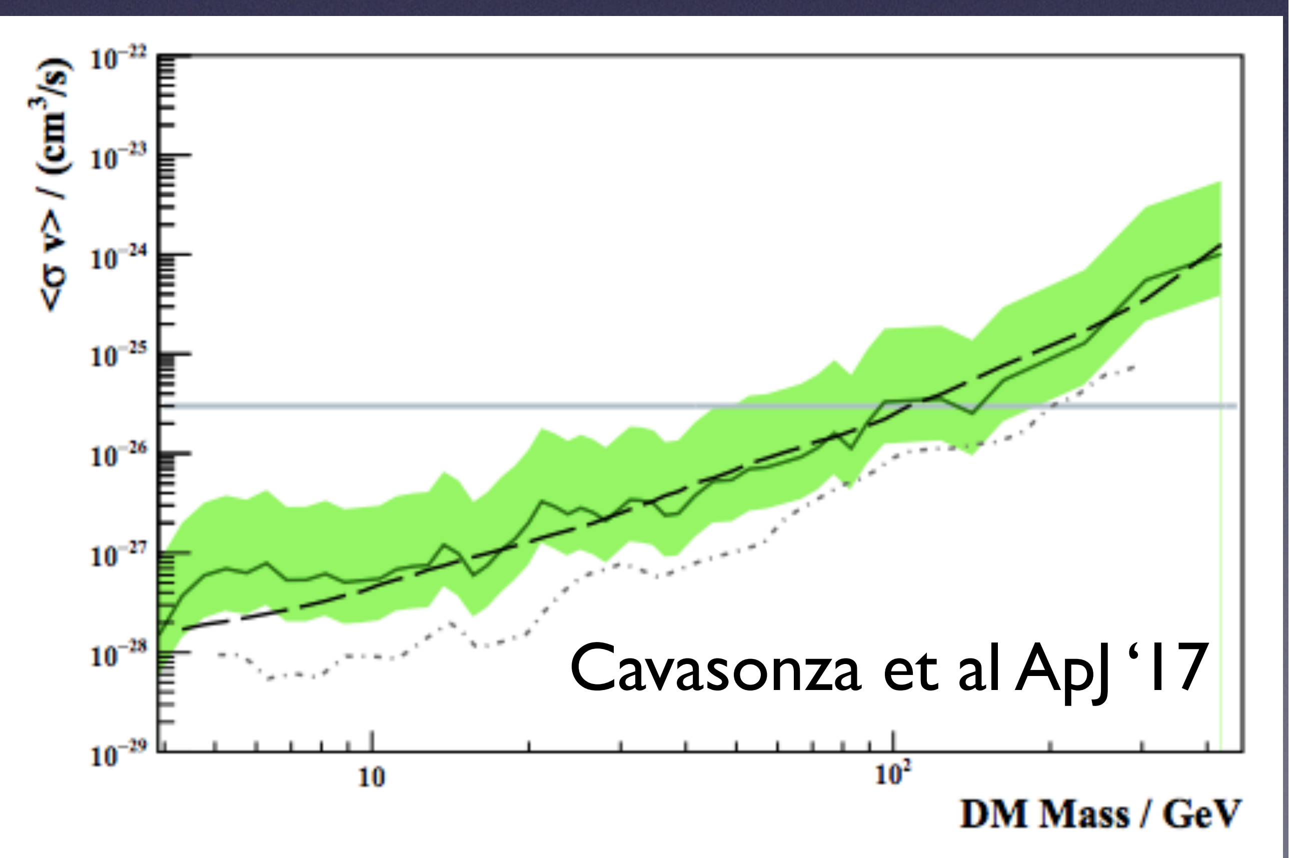
- GeV+ decaying or annihilating DM is constrained by observations of dwarf galaxies, galaxy clusters, extragalactic gamma-ray background, and the Milky Way halo.
- For hadronic channels, gamma-ray limits from dwarf spheroidal galaxies exclude the thermal benchmark cross-section for masses below a few 10s to 100 GeV.
- Lifetime lower limits ~$10^{27\text{-}28}$ s, for DM masses in the $10\text{-}10^{10}$ GeV range, for representative hadronic decay channels.
- Leptonic channels are less constrained by photon searches.

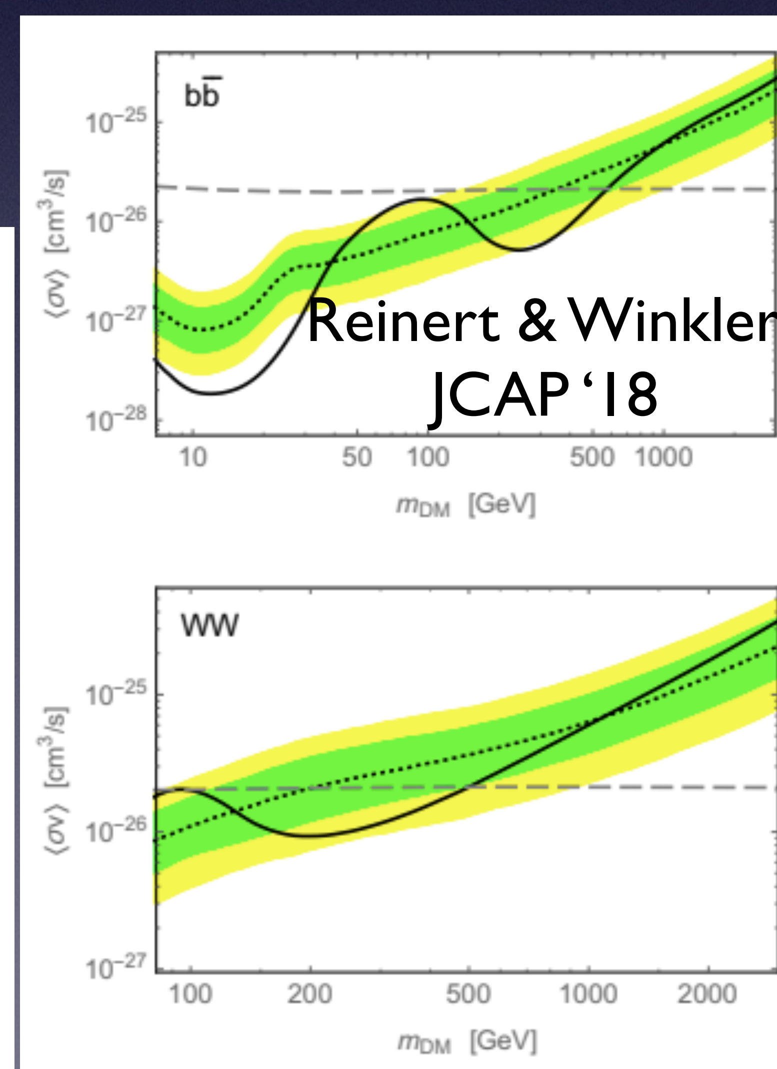


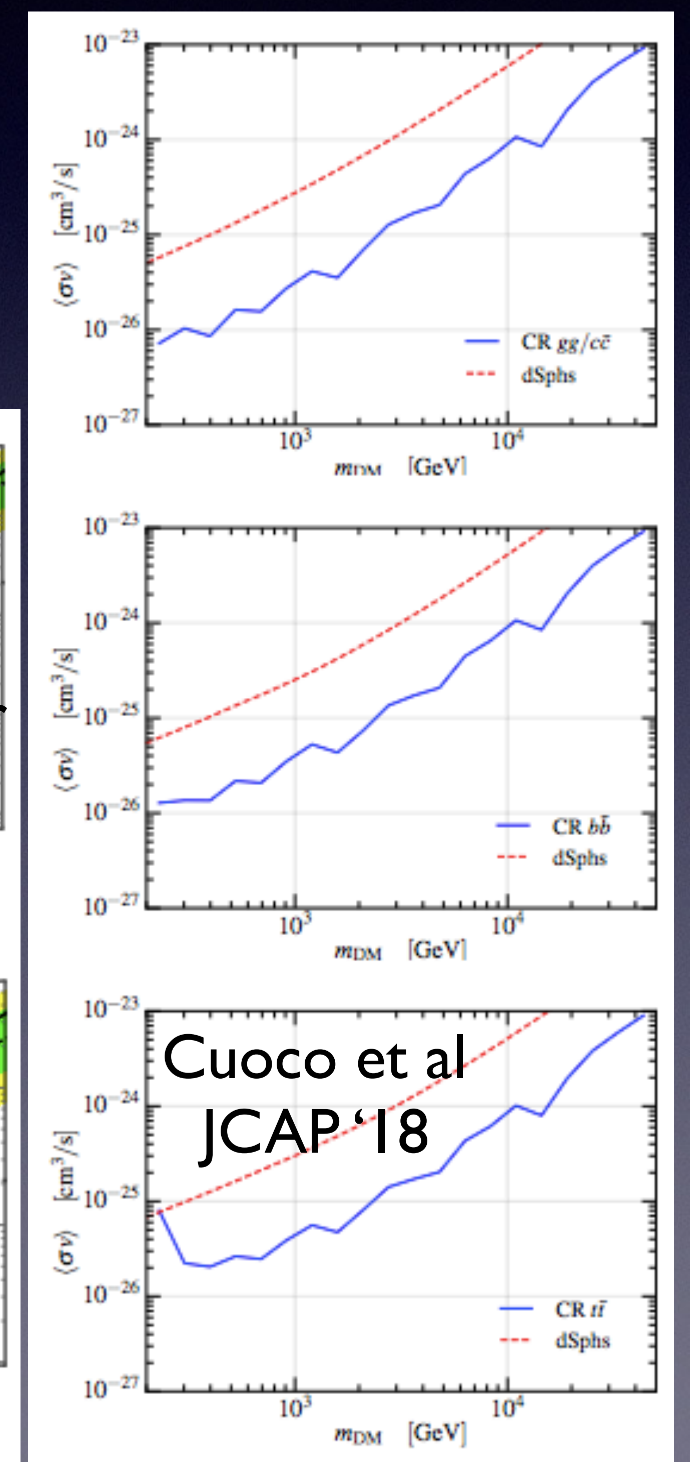
IceCube Collaboration '17 (1705.08103)

Indirect limits from cosmic rays

- Antiproton measurements by AMS-02 can probe canonical thermal cross section up to DM masses of ~500 GeV in specific channels
- Main uncertainties are due to cosmic-ray propagation (can be tested somewhat by other AMS-02 measurements), local DM density
- Positron measurements by AMS-02 can provide sensitive constraints on leptonic channels.

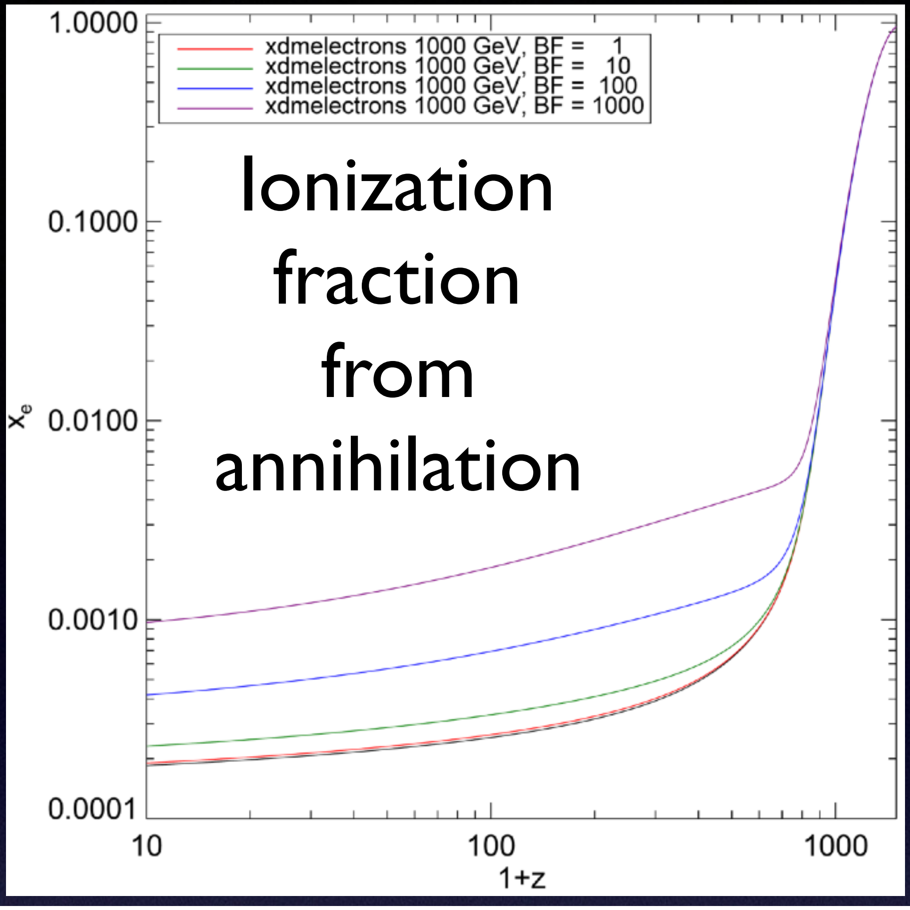




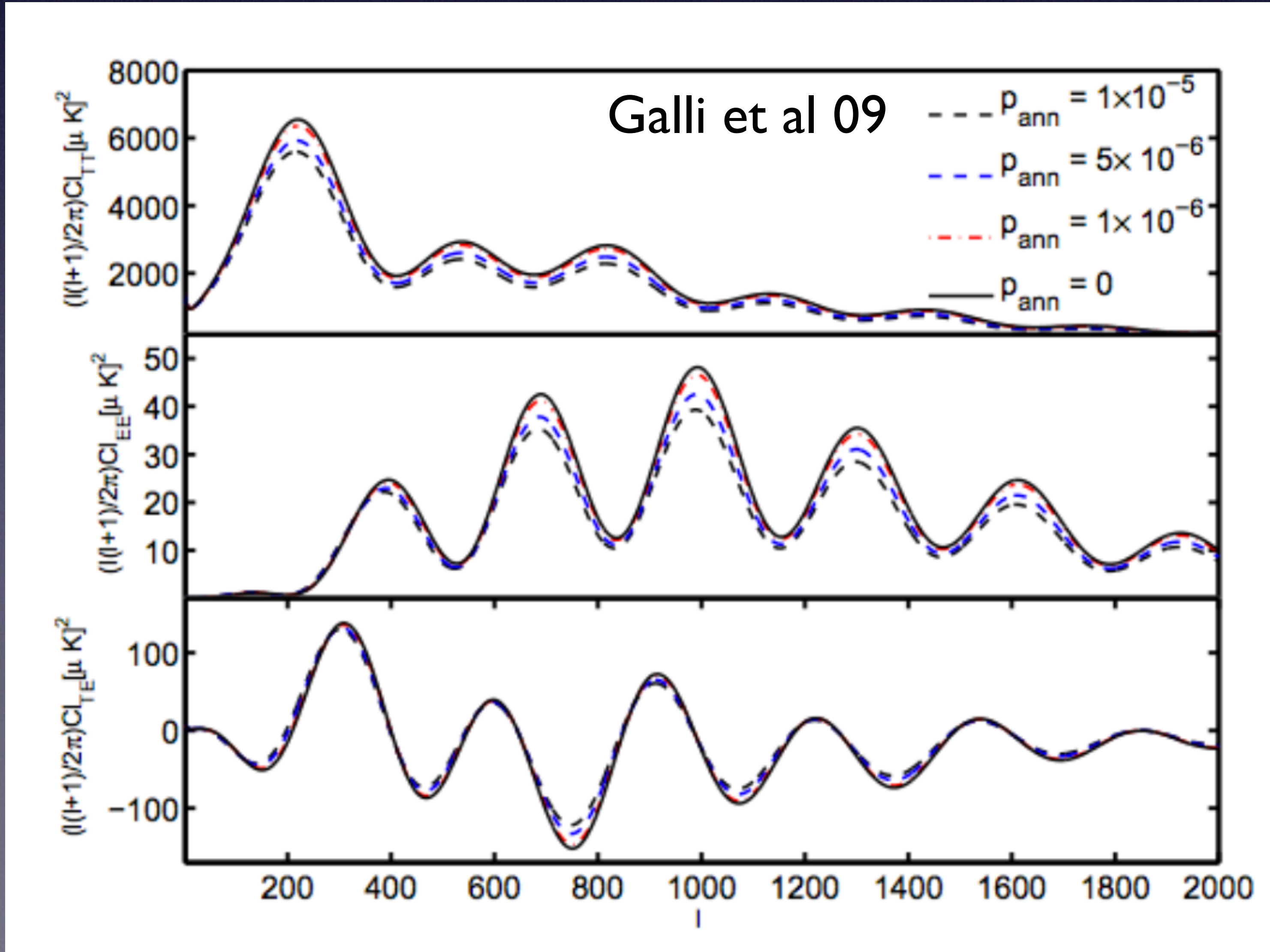


Indirect limits from the CMB

- CMB emitted at z~1000. "Cosmic dark ages" span redshift z ~ 30-1000, ionization level expected to be very low.
- Increasing ionization during the dark ages would provide a screen between CMB photons and our telescopes - can be sensitively measured.
- DM annihilation/decay can provide a source of ionizing photons/electrons.

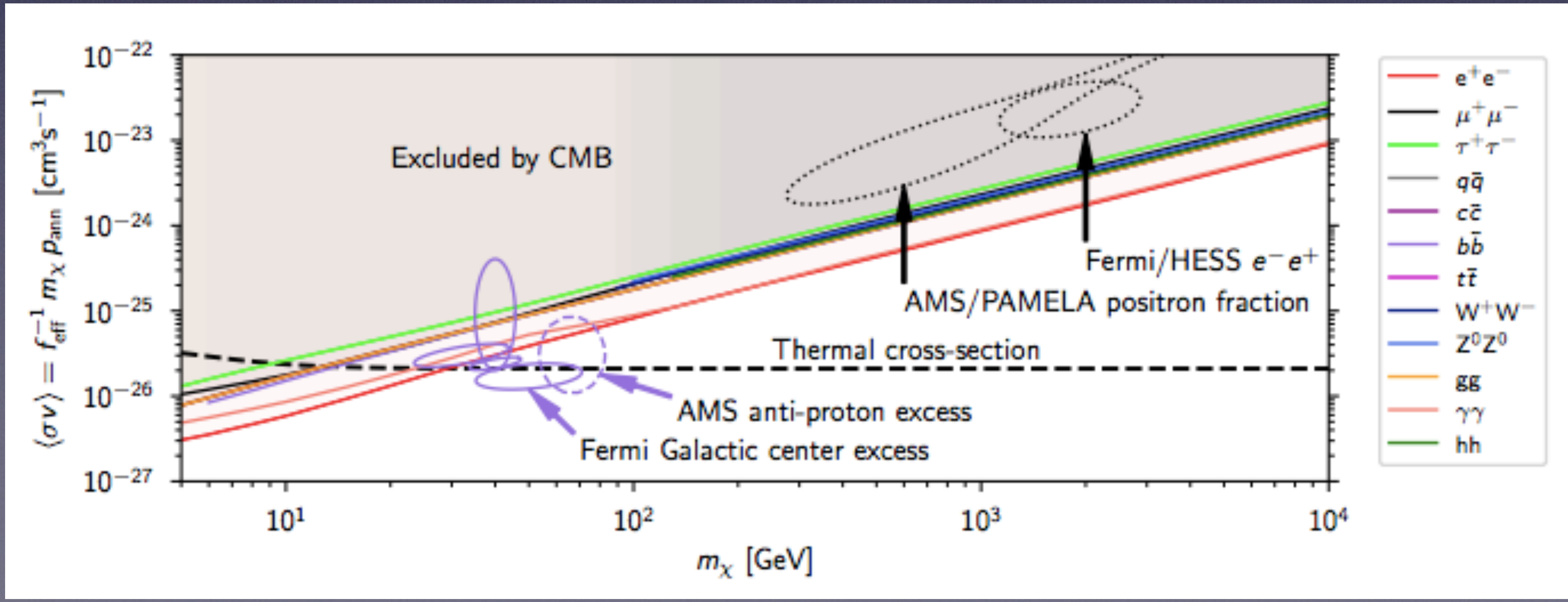


CMB signal from annihilation



Annihilation bounds at low masses

- The effect of DM annihilation on the CMB is universal in the keV-TeV+ range (TRS '16): for every model where DM annihilates with ~constant cross section during dark ages, effect on CMB can be captured by a universal shape with a model-dependent normalization factor.
- For any given annihilation final state, this factor can be calculated immediately from spectrum of photons/electrons/positrons produced per annihilation (using results of TRS '16).
- Can easily be extended to cases where DM annihilates to intermediate particles, which eventually (possibly after a long cascade) decay to SM - powerful test of dark sectors.
- One analysis simultaneously tests all annihilation channels, over a huge mass range. Thermal cross section excluded for all visible final states if mass is below ~10 GeV.

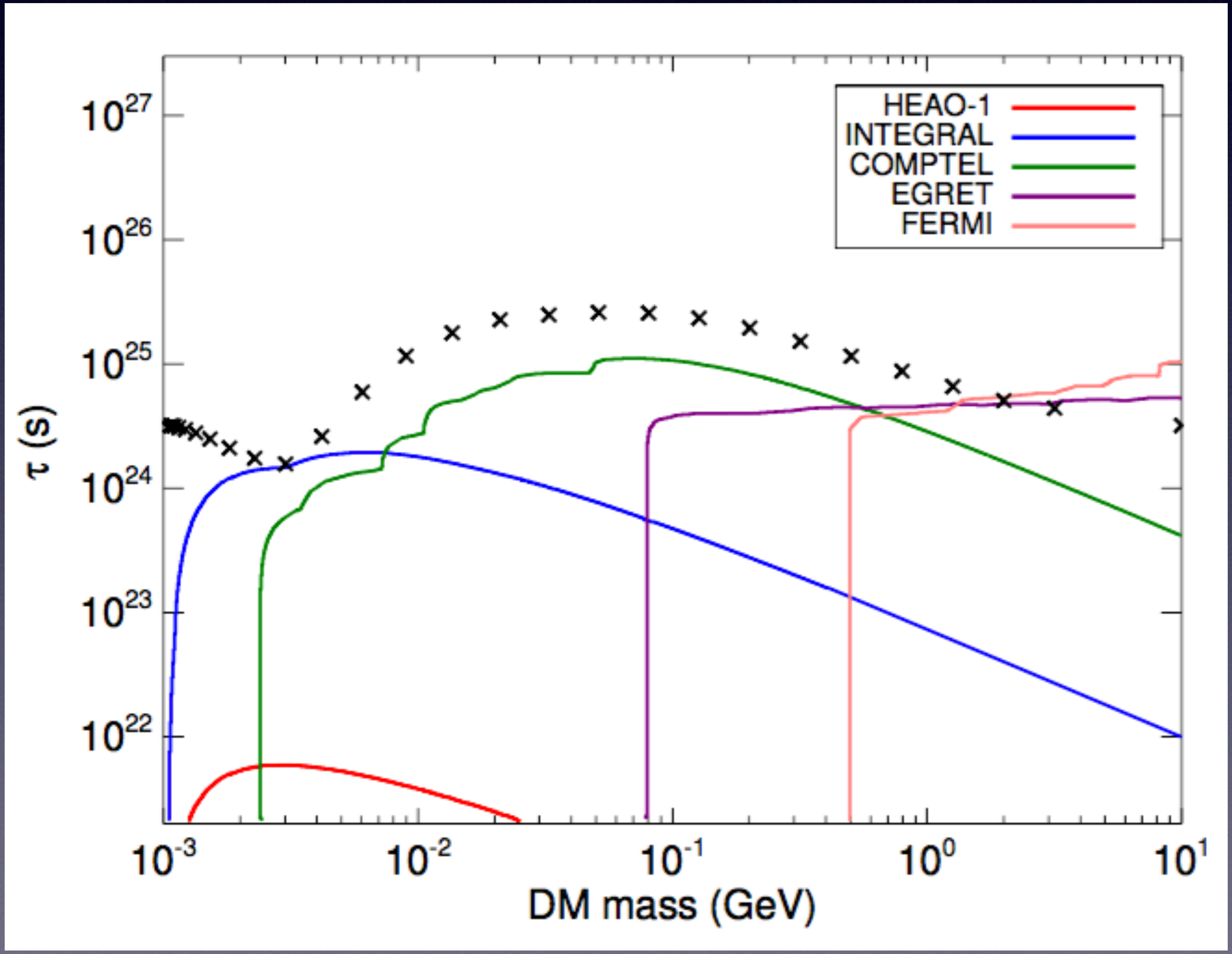


Planck Collaboration '18 1807.06209 based on results of TRS PRD '16

Constraints on decay from the CMB

- For decaying dark matter, can use same approach.
- Sets some of the strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even 10^{-11} of the DM decaying! (for lifetimes $\sim 10^{14}$ s)

TRS & Wu, PRD '17



Other constraints (colored lines) from Essig et al '13

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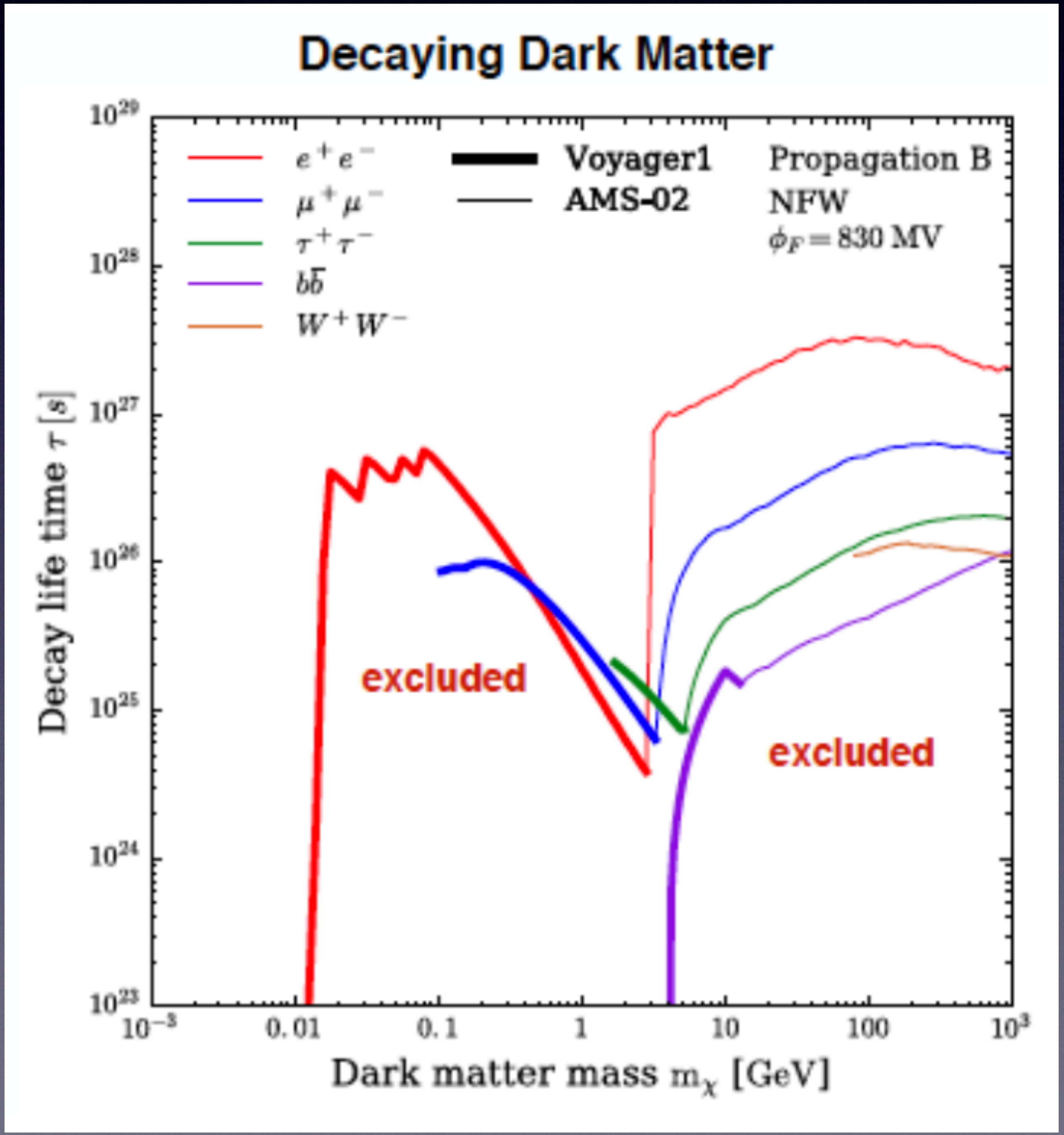
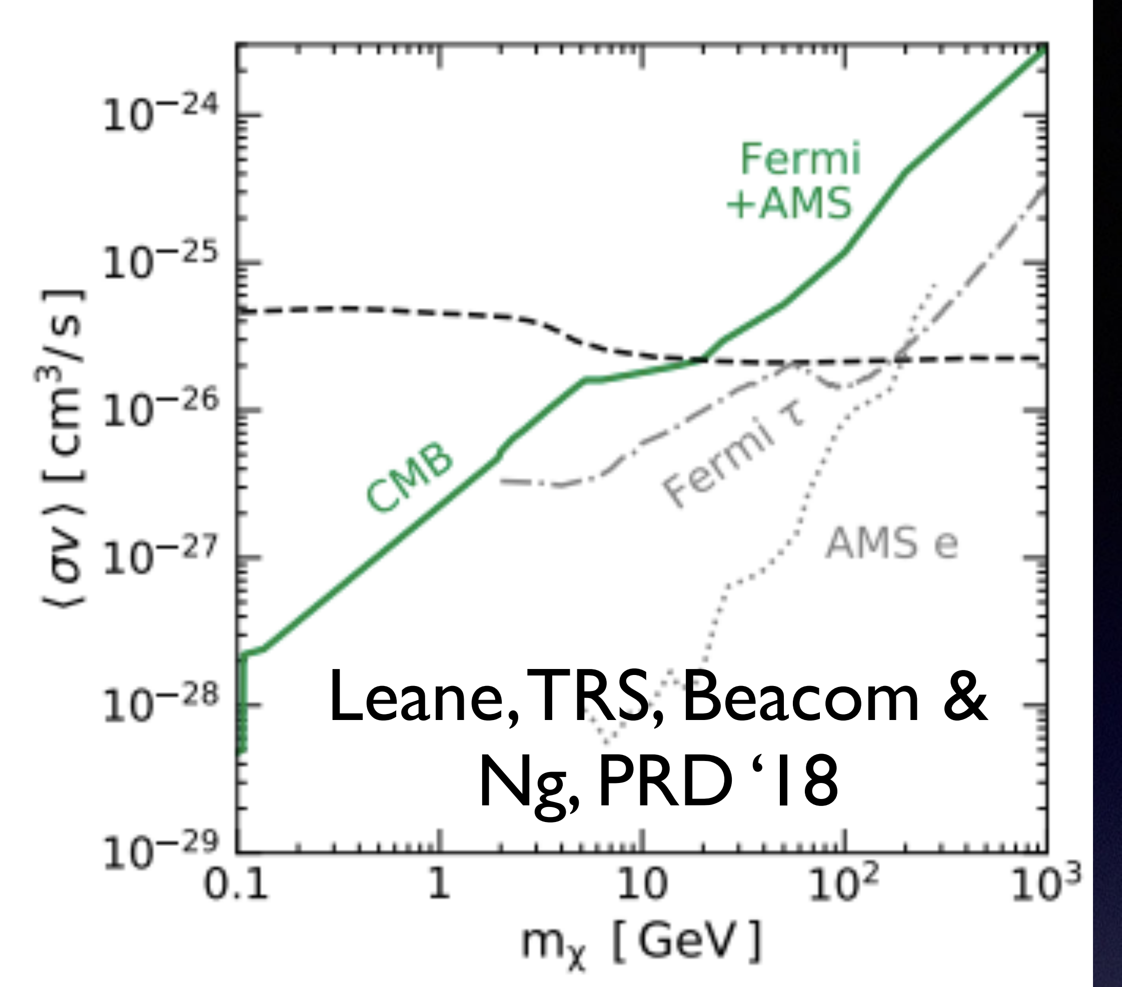
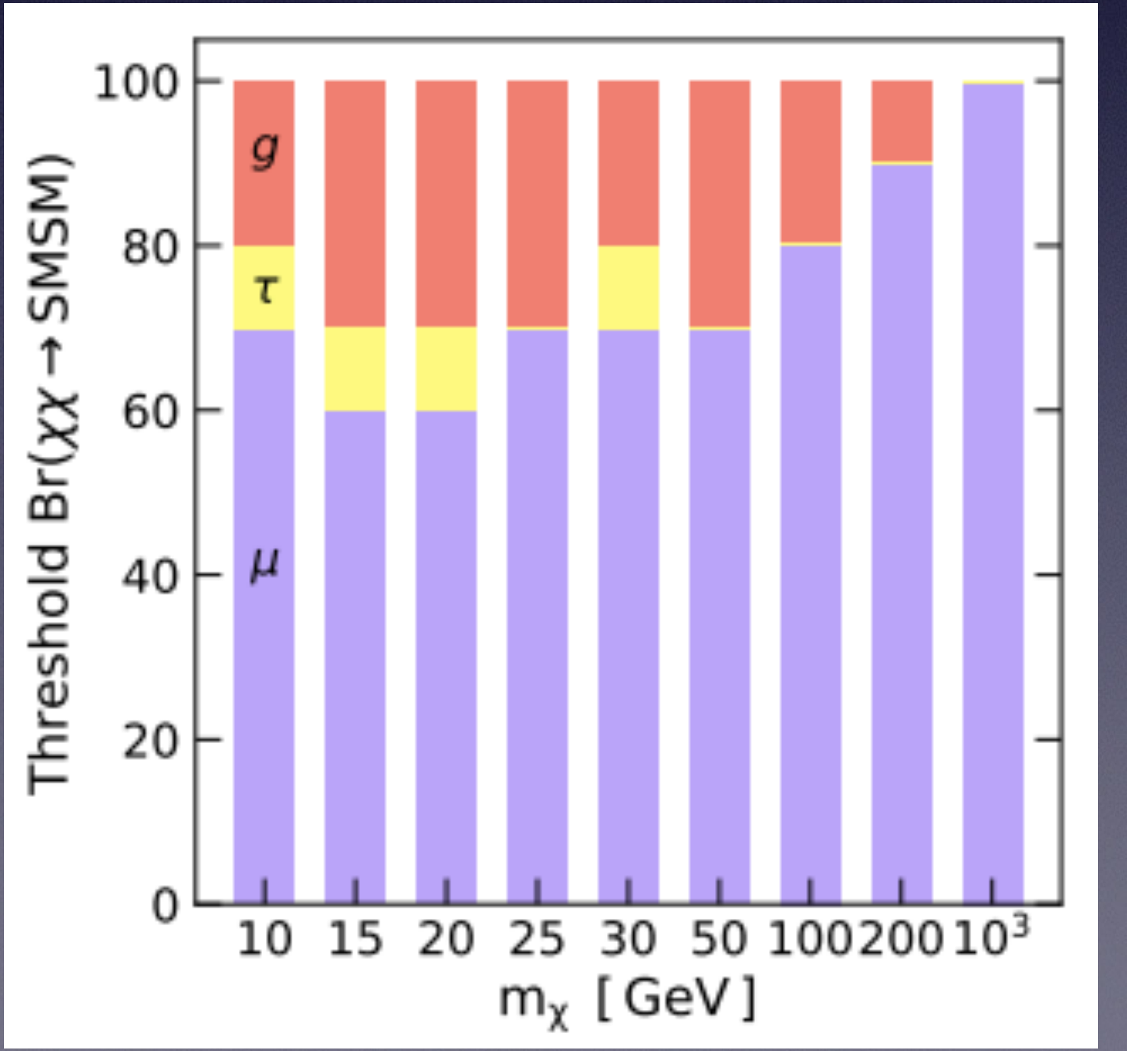


Boudaud et al '16

A combined analysis for annihilation of thermal DM

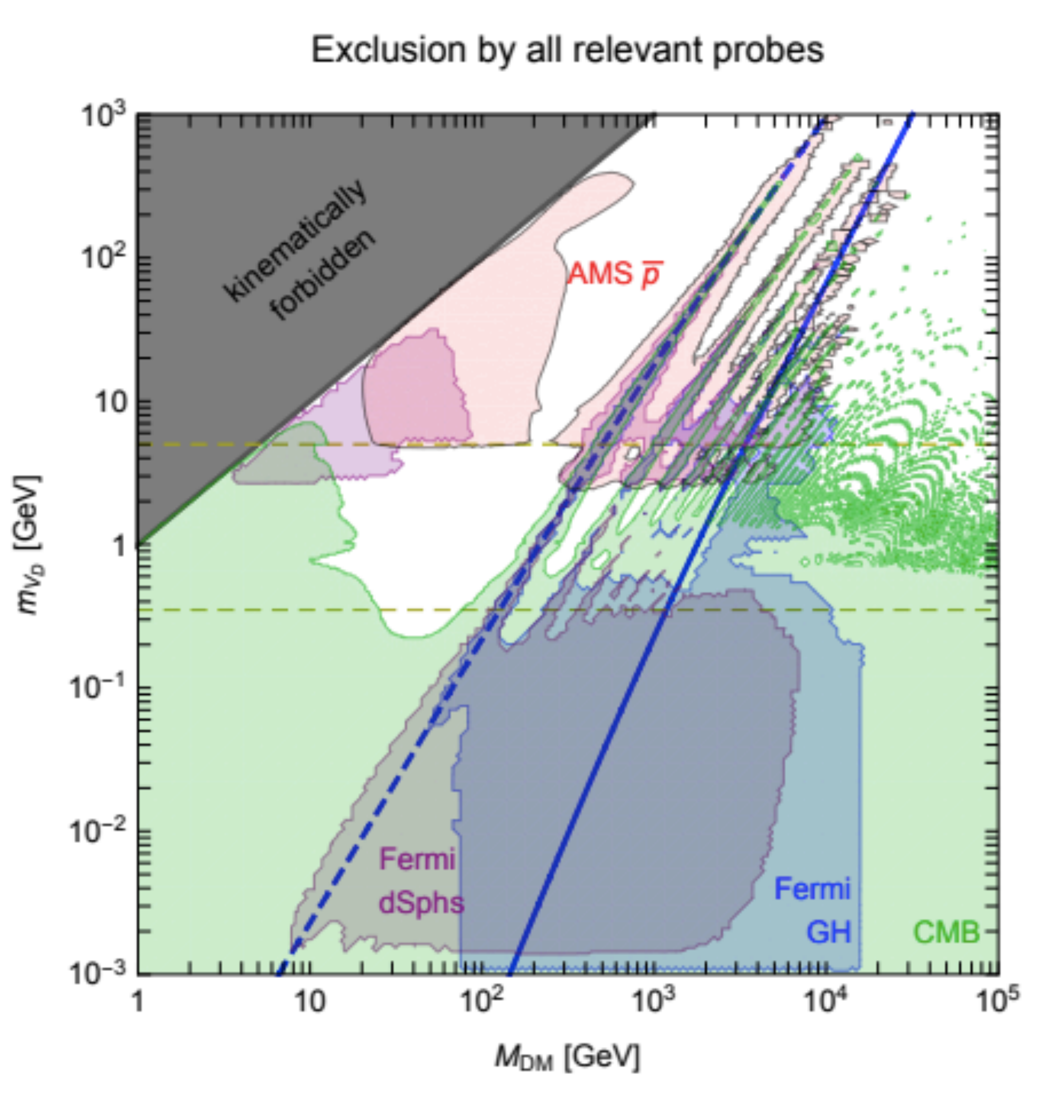
- Above the GeV scale, hadronic scenarios are constrained by photons (and antiprotons), leptonic scenarios by positrons
- At lower masses, the CMB probes all visible channels
- One can compute the maximum allowed cross-section / minimum allowed mass, scanning over all possible combinations of visible channels
- The least-constrained possibilities contain a large fraction of muons - in such cases the thermal relic xsec is tested for masses below ~20 GeV





Implications for light dark sectors

Dark photon model



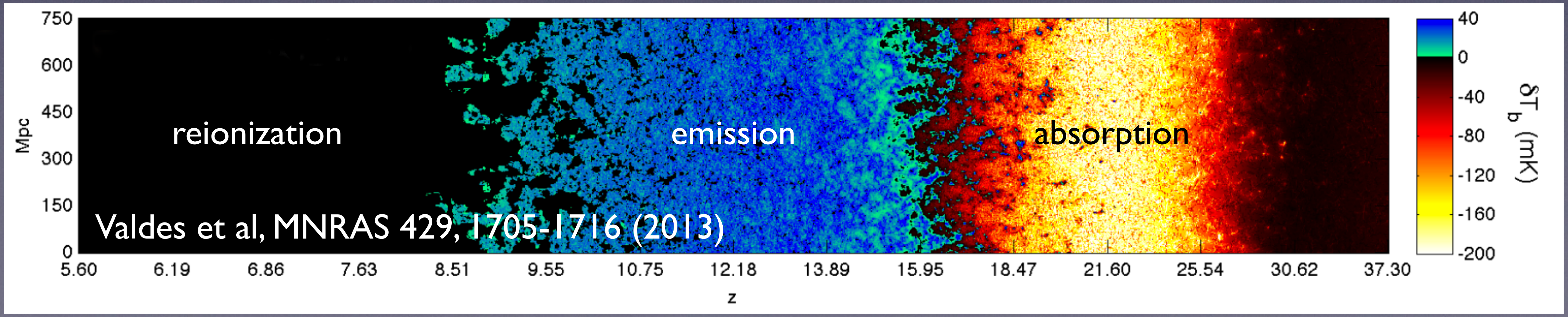
Cirelli et al JCAP '17

- For sub-GeV DM that underwent thermal freezeout, cross section should be suppressed today compared with freezeout (or annihilation should have large invisible branching ratio). Some examples:
  - asymmetric dark matter [see Baldes & Petraki JCAP '17 for a recent indirect-detection study]
  - coannihilation partner present in the early universe, absent today
  - 3-body annihilation
  - velocity-suppressed annihilation (e.g. p-wave, phase space suppression)
- Dark sectors containing long-range forces can be particularly constrained, e.g.:
  - attractive interactions enhance low-velocity annihilation rate (Sommerfeld enhancement)
  - bound state formation [see Asadi et al '17, Mitridate et al '17, Harz et al '18 for some recent calculations] can provide a "guaranteed" s-channel annihilation process, even if direct annihilation is p-wave [An et al PLB '17]

Beyond the CMB: 21cm

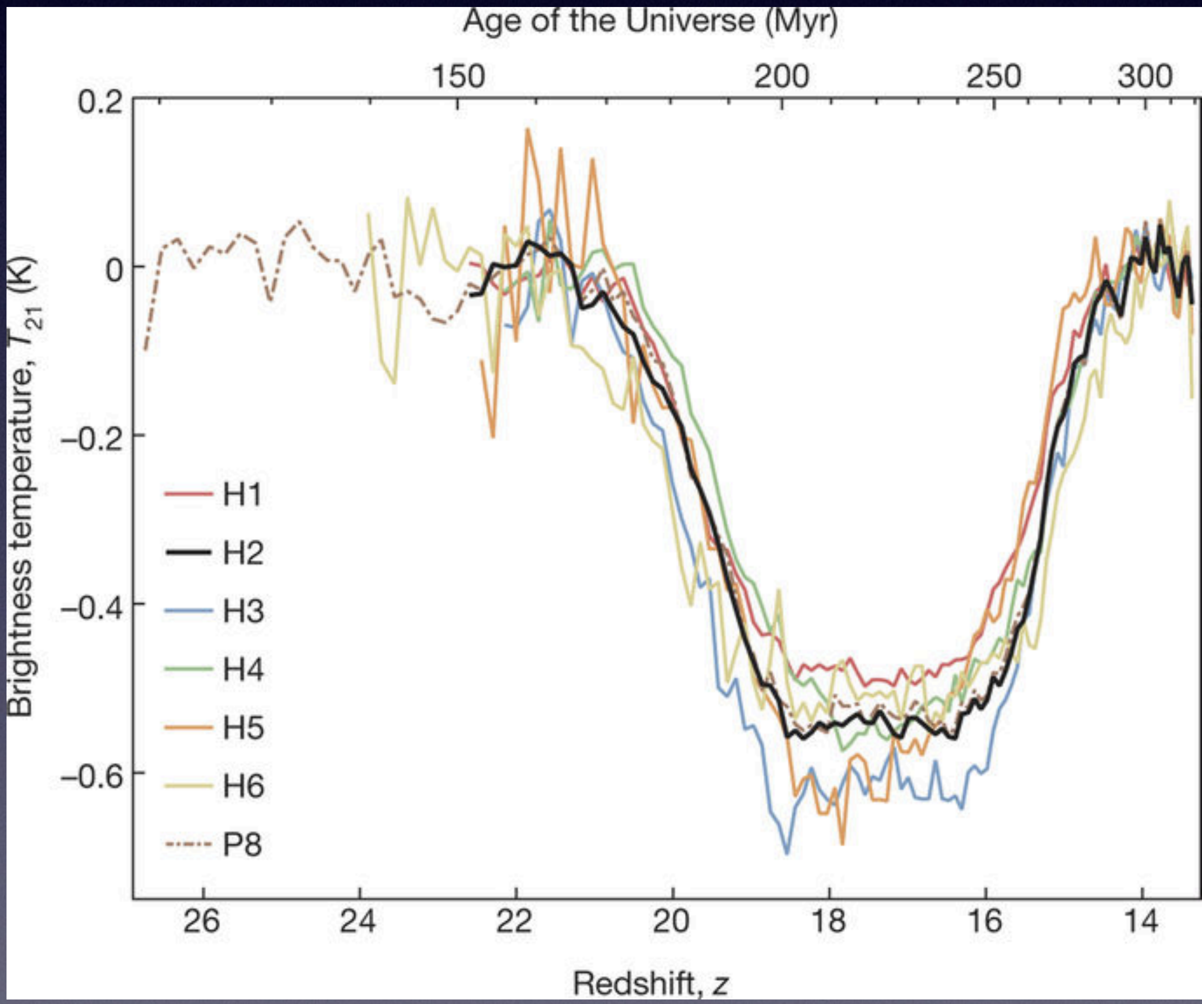
$$T_{21}(z) \approx x_{\rm HI}(z)\left(\frac{0.15}{\Omega_m}\right)^{1/2}\left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2}\left[1-\frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

- Spin-flip transition of neutral hydrogen can be used to probe temperature and distribution of the neutral gas in the early universe prior to reionization ($z > 7$ or so).
- 21cm absorption/emission signal strength depends on "spin temperature" T_S, measure of #H in ground vs excited state - expected to lie between gas temperature T_{gas} and CMB temperature T_{CMB}.
- Absorption signal when $T_S < T_R$ (radiation temperature), emission signal if $T_S > T_R$.
- T_R here describes # photons at 21cm wavelength - not necessarily thermally distributed.
- Expected behavior: T_{gas} decouples from T_{CMB} around redshift $z\sim150$, subsequently satisfies $T_{gas} \sim T_{CMB}\,(1+z)/(1+z)_{dec}$. Gas is later heated by the stars, and eventually T_{gas} increases above T_{CMB}. Thus expect early absorption, later emission.



A measurement of 21cm absorption in the dark ages?

- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18]
- Claim is a deep absorption trough corresponding to z~15-20 - implies spin temperature < CMB temperature.
- Measurement of $T_{gas}/T_R(z=17.2) < T_S/T_R < 0.105$ (99% confidence).

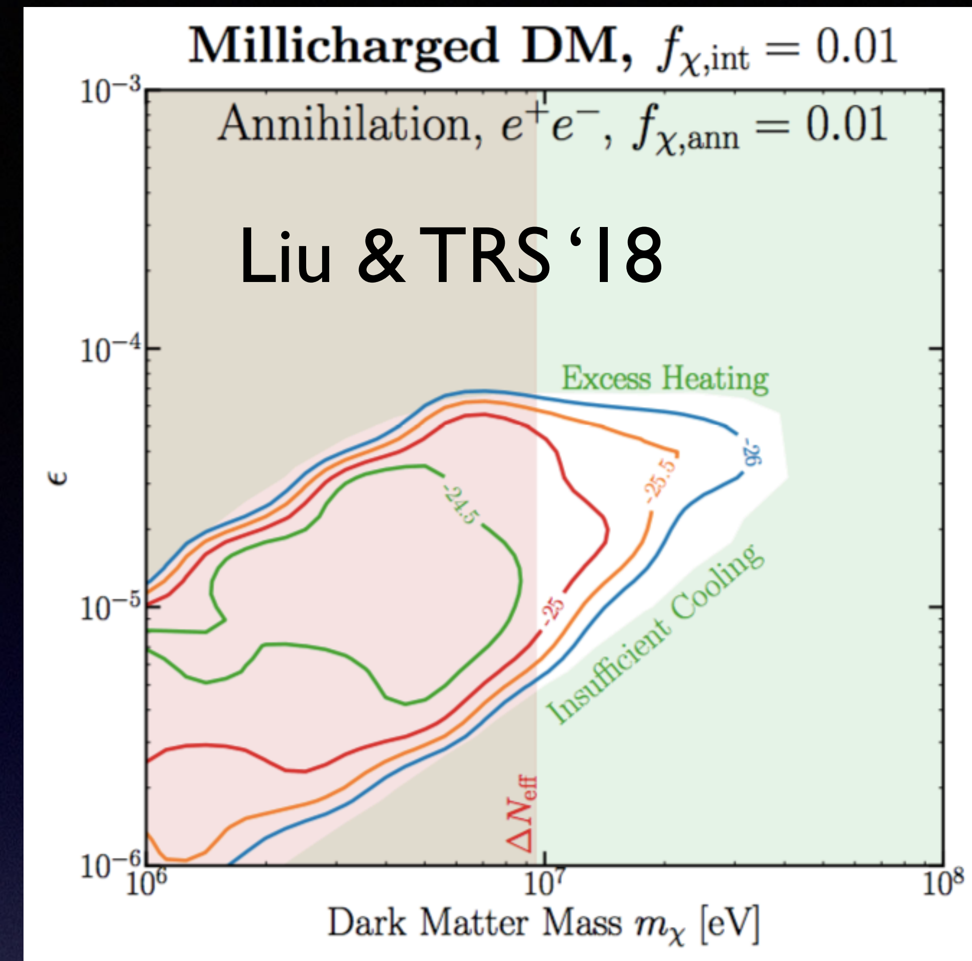


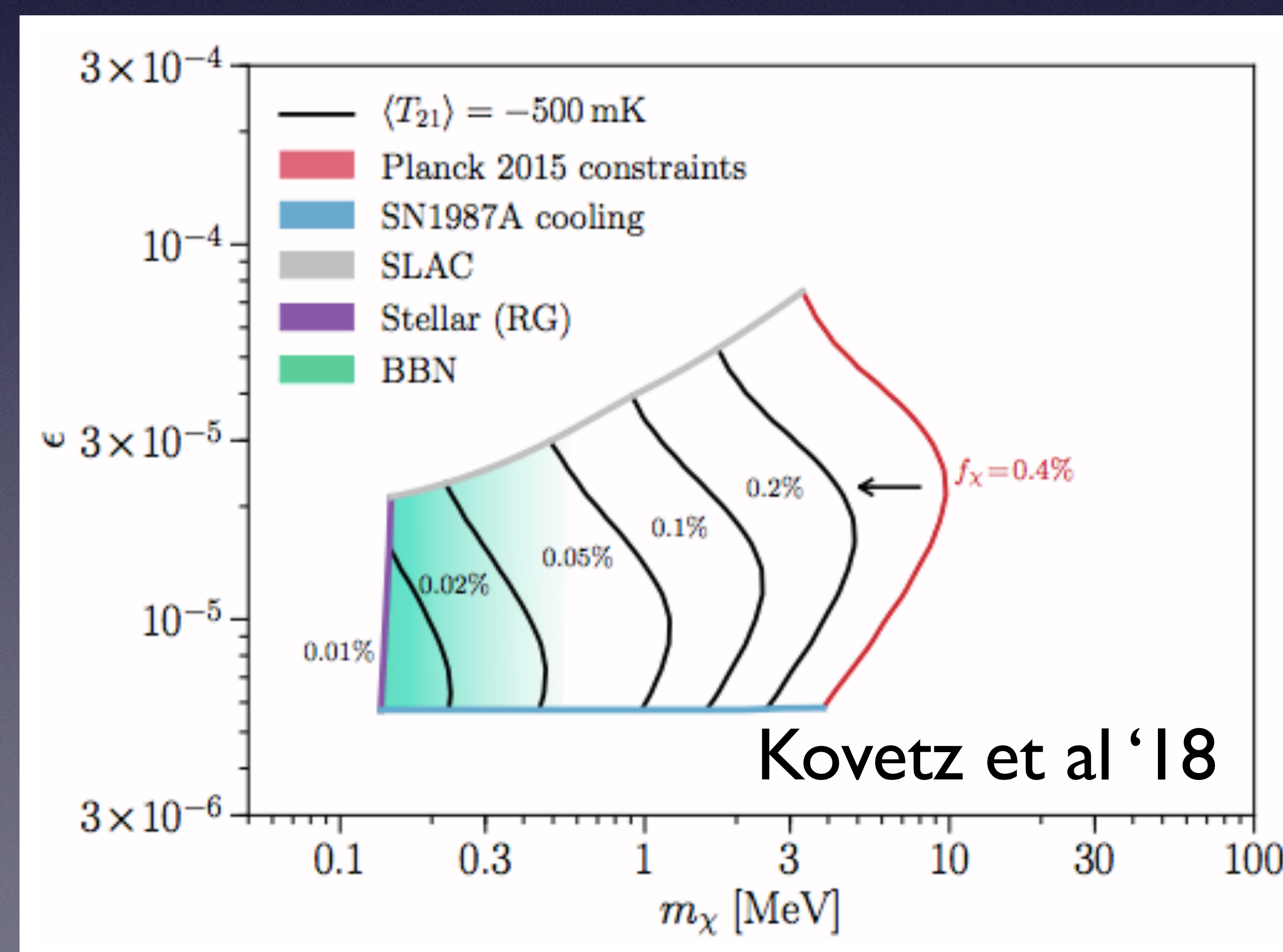
Interpreting EDGES

- If T_R is taken to be the CMB temperature, this gives $T_{gas} < 5.2$ K.
- But assuming standard decoupling and no stellar heating, we can calculate $T_{gas} \sim 7$ K.
- It is quite possible this result is spurious - e.g. due to instrumental effects and/or foregrounds [e.g. Hills et al 1805.01421].
- But if it is confirmed, suggests either $T_R > T_{CMB}$ (new radiation backgrounds) [Feng & Holder 1802.07432], or some modification to the standard scenario that lowers T_{gas}.
- New radiation backgrounds could arise from either novel astrophysics, i.e. radio emission from early black holes [Ewall-Wice et al 1803.01815] or more exotic (DM-related?) sources [e.g. Fraser et al 1803.03245, Pospelov et al 1803.07048].
- Additional cooling of the gas could be due to modified recombination history (earlier decoupling from CMB) [e.g. Falkowski & Petraki 1803.10096], or thermal contact of the gas with a colder bath, e.g. (some fraction of) the dark matter [e.g. Barkana, Nature, March '18; Munoz & Loeb 1802.10094; Berlin et al 1803.02804; Barkana et al 1803.03091], or gravitational interactions with an axion condensate [Houston et al 1805.04426; Sikivie 1805.05577].

The millicharged DM interpretation

- Mechanism: a small fraction of DM carries a tiny electric charge, scattering of this component with baryons cools the gas.
- Scattering is Rutherford, σ ∝ v^{-4}, enhanced in late dark ages.
- In order to evade constraints from the CMB [Dvorkin et al ’13, Gluscevic et al ’17, Boddy et al ’18, Xu et al ’18, TRS & Wu ’18], DM needs to be 0.01-0.4% of DM, in mass range 0.5-35 MeV [Kovetz et al ’18].
- Non-trivial interplay between cooling from scattering & heating from annihilation.
- Could potentially heat gas clouds in the inner Galaxy [Bhoonah et al 1806.06857].

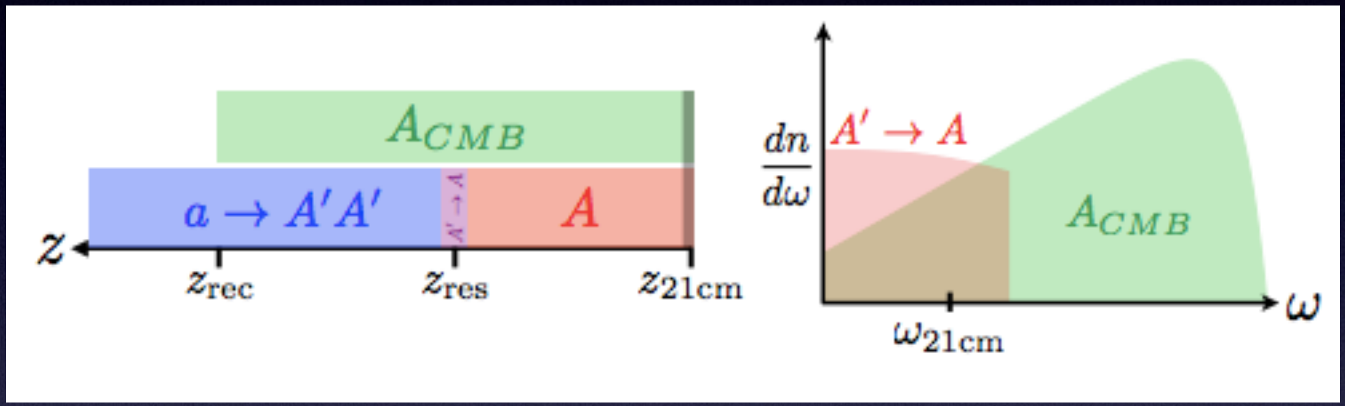


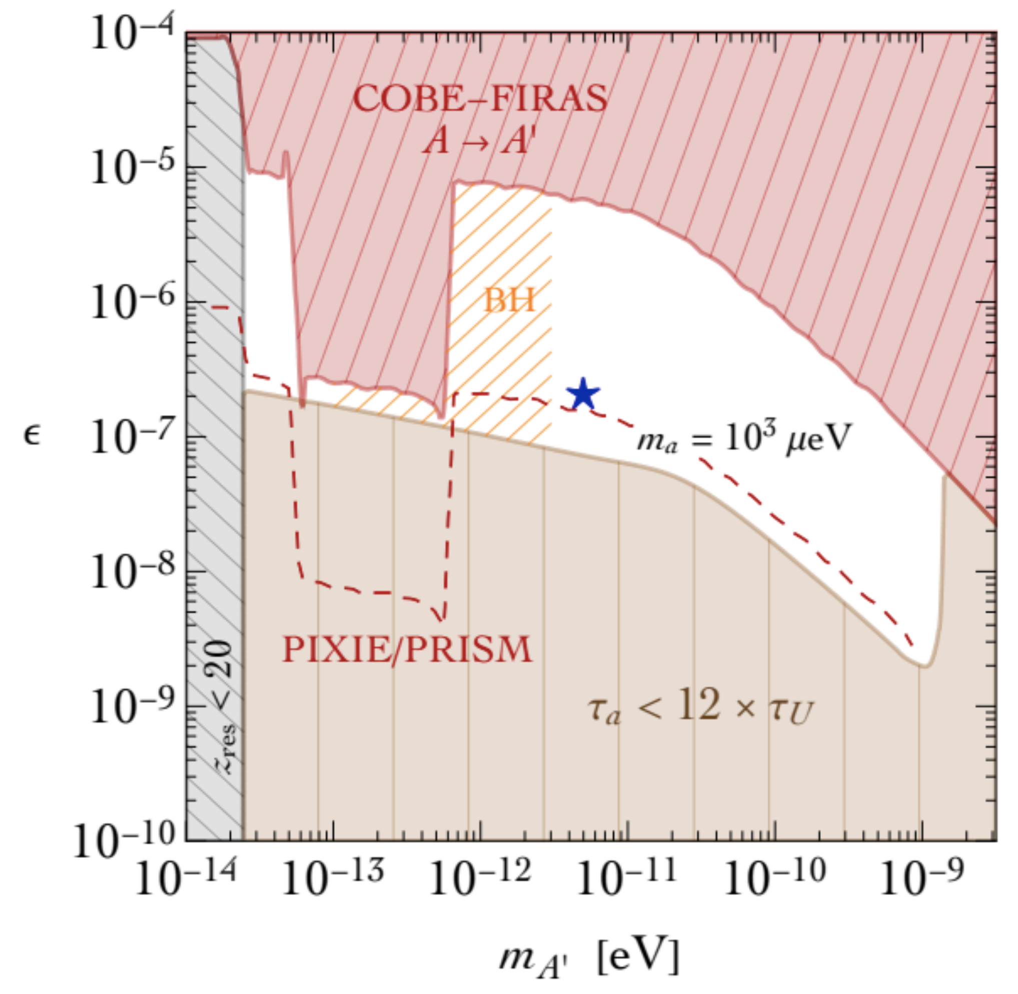


The “dark oscillations” interpretation

Pospelov et al 1803.07048

- Mechanism: DM decays to light dark photons (10^{-14}-10^{-9} eV), which subsequently resonantly convert into visible photons when the plasma frequency passes through the DM mass.
- The result is extra radiation at low frequencies - enhances the 21cm absorption trough.
- One key takeaway: not many constraints on new signals appearing in the very low-energy tail of the CMB - strong limits on spectral distortion are at higher wavelengths.

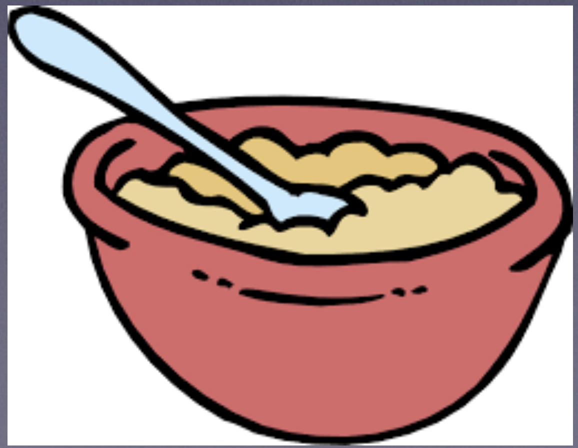




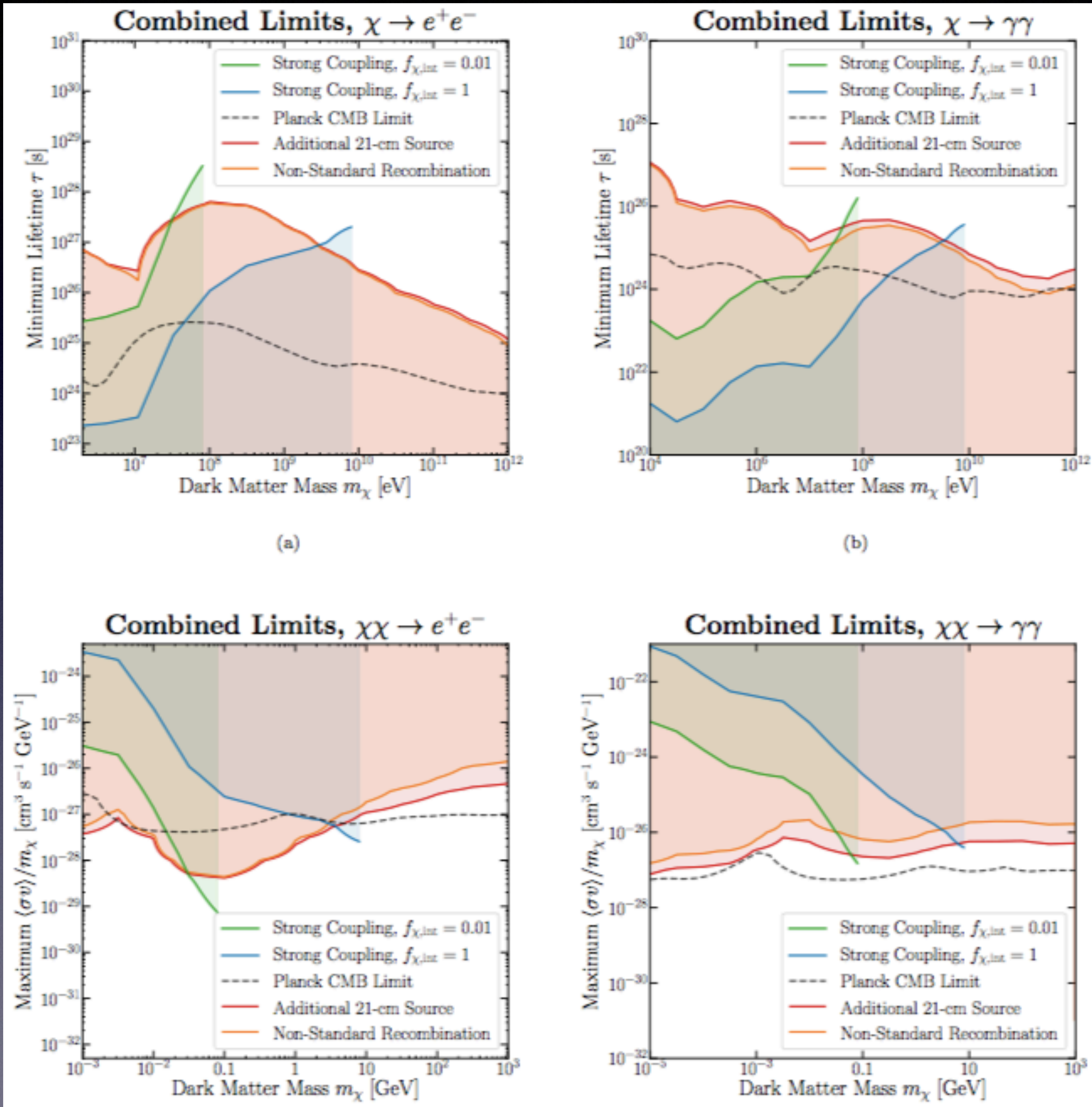
Implications for DM annihilation and decay

Liu & TRS 1803.09739

- Need to account for whatever process is causing the deep absorption trough (else limits can be unrealistically strong).
- Simplest case: extra radiation backgrounds, limit on gas temperature increases, but otherwise keep standard scenario.
- More complex cases: new gas-cooling processes (need to account for these when computing heating from decay/annihilation).
- We study the heating from annihilation and decay in the presence of:
  - DM-baryon scattering (all DM or sub-component)
  - Early baryon-photon decoupling
  - Extra radiation backgrounds



- Summary of limits assuming EDGES is correct
- Orange/red lines = limits in presence of early recombination (orange) or extra radiation up to same strength as CMB (red)
- Blue/green regions = allowed regions with 100%/1% of DM scattering, strong-coupling limit
- Dashed black lines = standard CMB bound
- Heating bounds are stronger than standard CMB limits for light DM in most cases (especially decay to e+e-)



Summary

- Indirect detection places stringent constraints on thermal DM and decaying DM.
- In particular, sub-GeV thermal DM annihilating into visible channels generically needs to have a velocity-suppressed cross section at late times, to evade CMB limits (by including non-CMB data this bound can be extended up to ~20 GeV).
- Long-range dark-sector forces (from light mediators) can mediate low-velocity enhancements to annihilation, and bound state formation, enhancing indirect signals.
- 21cm observations promise to place stringent constraints on light DM (especially light decaying DM).
- Claim of a first detection by EDGES could have striking implications for cosmology if confirmed - ingredients beyond standard cosmology are required, which could include dark-sector interactions. Parameter space for simple models is already quite constrained.