Current Indirect Detection Searches

Tracy Slatyer

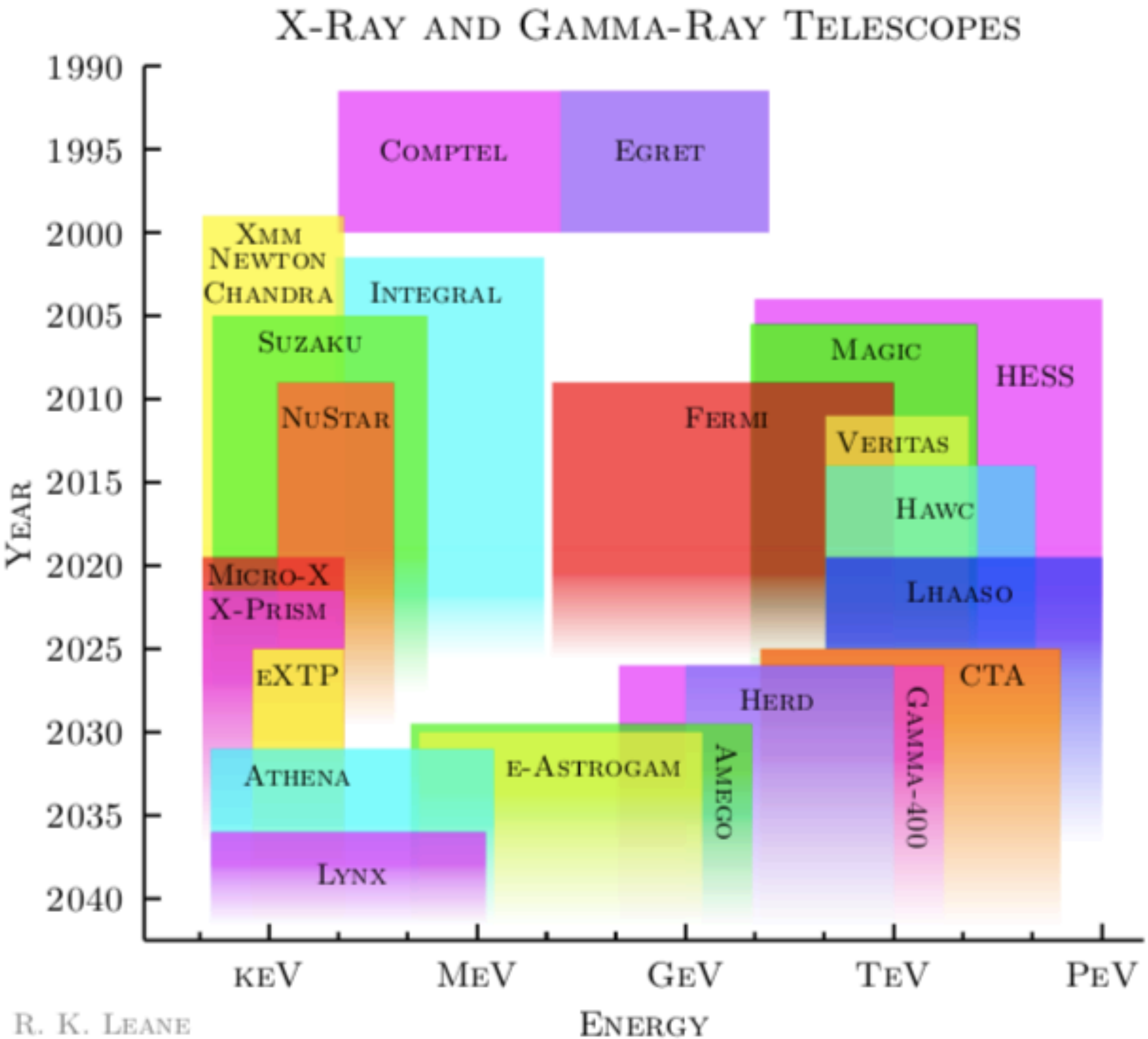
MIT

Les Houches Summer School on Dark Matter
Lecture 4

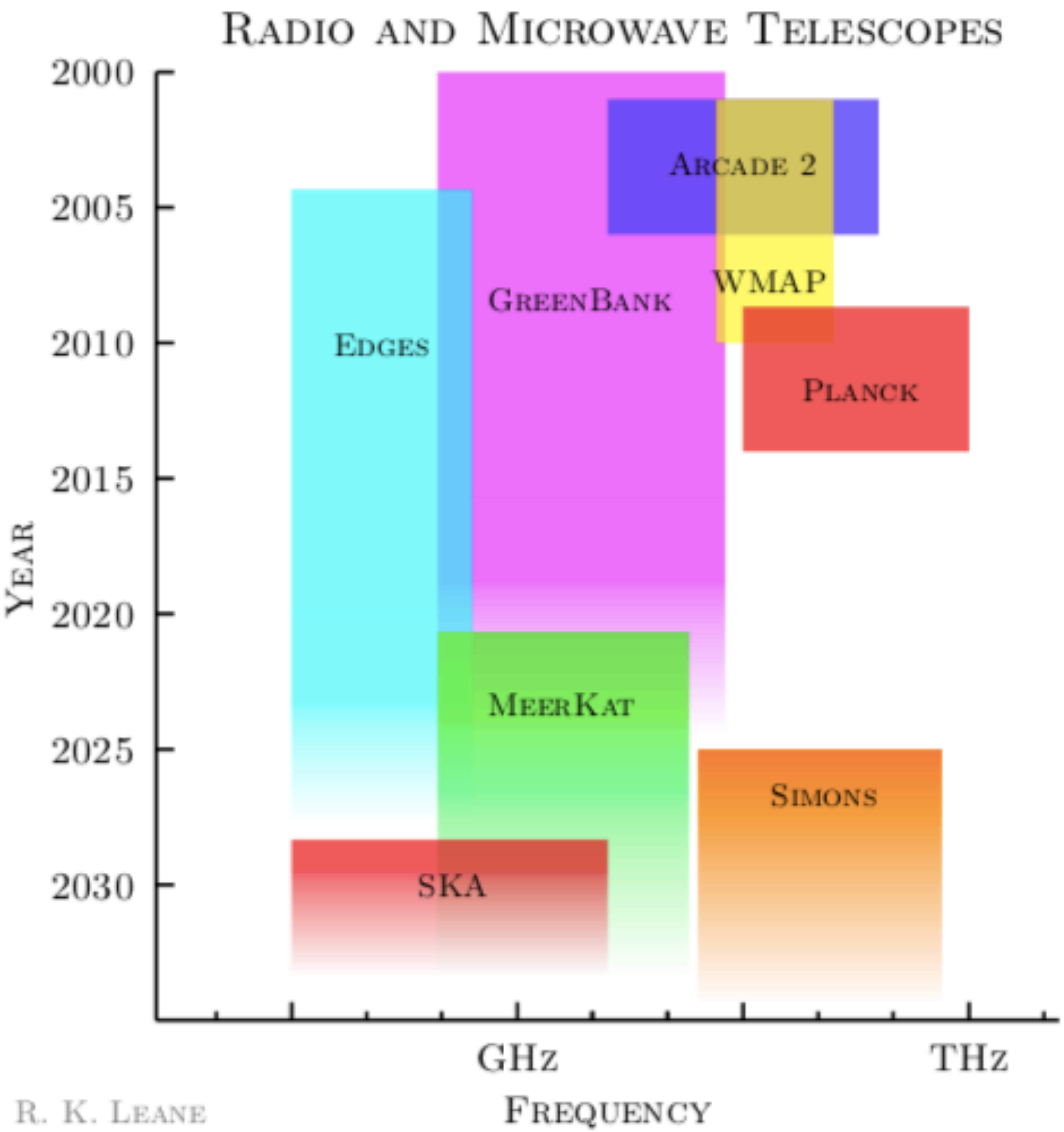
U.S. DEPARTMENT OF ENERGY | Office of Science

Goals for this section

- Know the general landscape of upcoming telescopes relevant for indirect detection (and where to look for more information)
- Discuss the strengths and weaknesses of different targets and channels for indirect detection
- Summarize leading indirect-detection constraints for both annihilation and decay, across a broad range of DM masses and final states

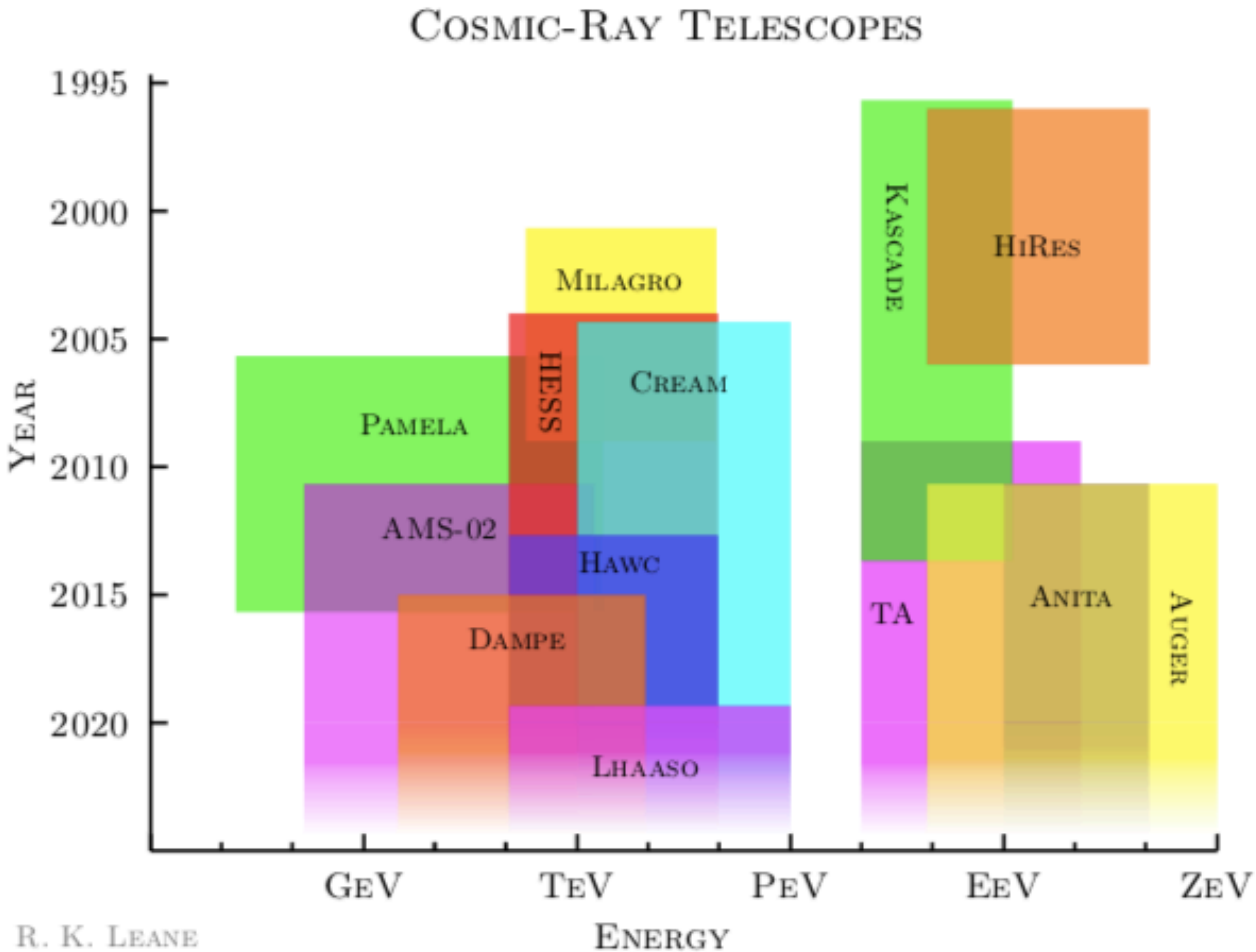


- At present, the Fermi Gamma-Ray Space Telescope has the highest sensitivity for O(0.1-100) GeV gamma rays
- At higher energies, ground-based telescopes such as HESS, VERITAS, HAWC, MAGIC take over due to larger area
- At lower energies, there are a number of sensitive X-ray experiments



- At even lower energies, radio and microwave telescopes measure the CMB
- These telescopes are also sensitive to:
  - synchrotron signals from electrons/ positrons
  - primordial 21cm radiation
  - pulsars, which serve as major backgrounds for many DM signals

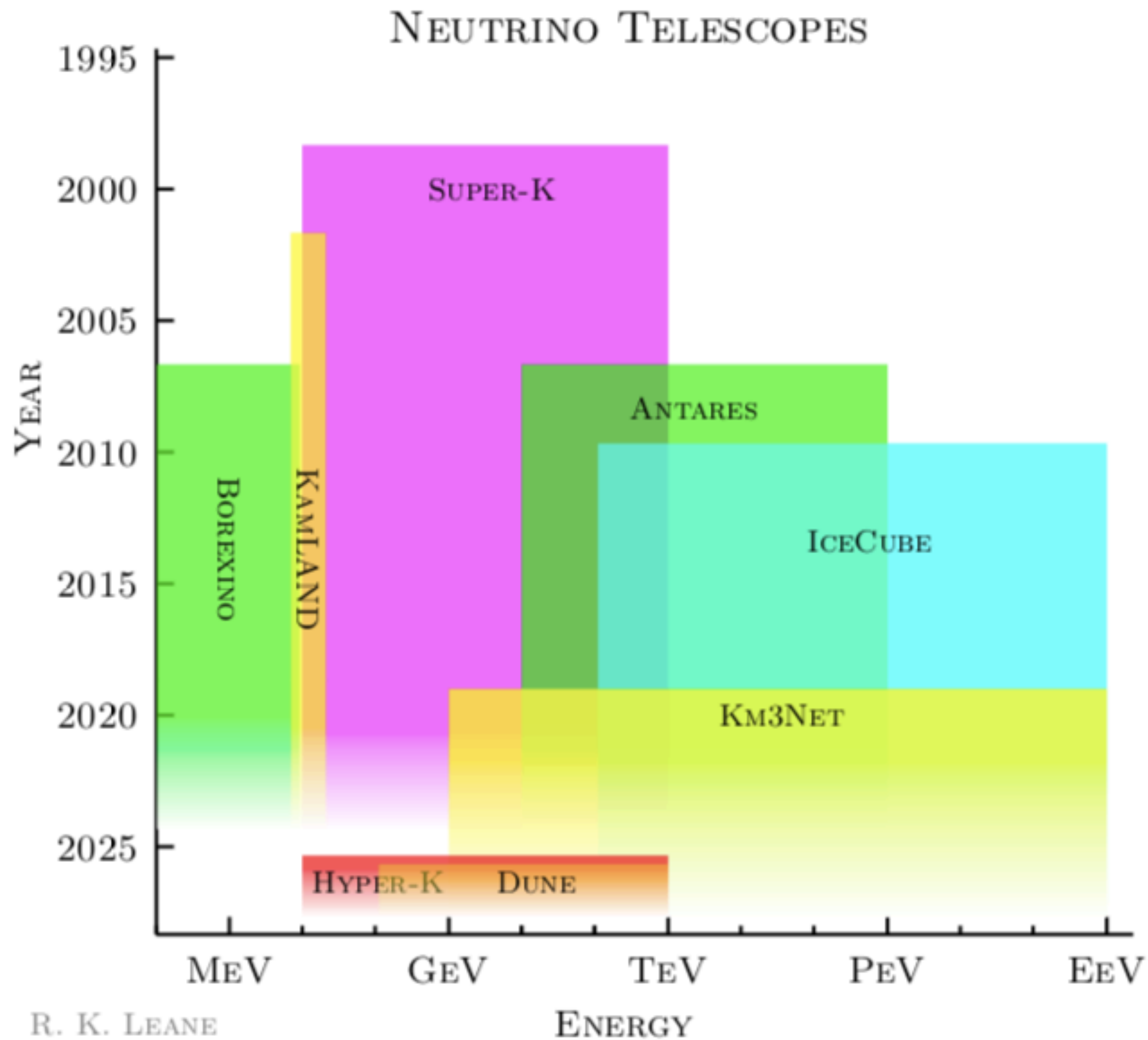
- AMS-02 reaches relatively low energies + has a magnet, allowing for charge discrimination
- AMS-02 typically sets most sensitive limits for classic WIMP DM
- Not on this plot: Voyager! Sensitive to even lower-energy cosmic rays - relevant for sub-GeV DM



- At very high energies, non-detection of CRs sets limits on ultraheavy decaying DM

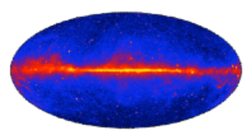
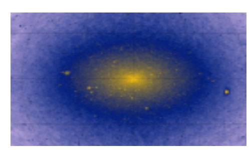
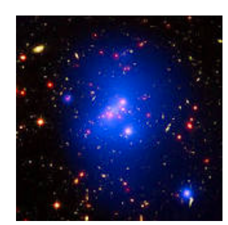
- IceCube (instrumented ice - South Pole) and ANTARES (instrumented water - Mediterranean) currently lead limits for decay/annihilation to neutrinos

- Become competitive with gamma-ray searches for hadronic channels + sufficiently heavy DM

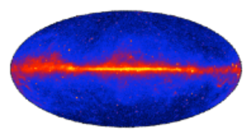
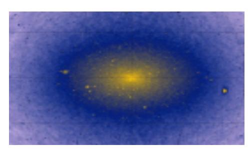
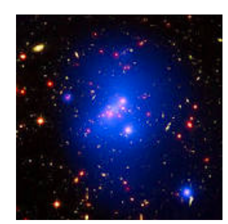
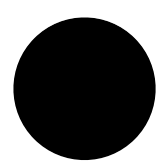


- Telescopes searching for lower-energy neutrinos can have sensitivity to DM capture in the Sun, "boosted DM" models where dark particles are produced relativistically

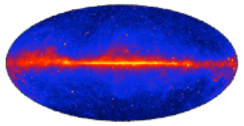
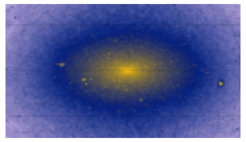
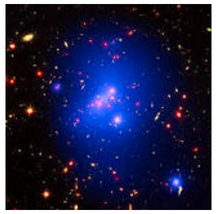
Where to look?

- Dwarf galaxies 
- Galactic center 
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos
- Extragalactic background radiation

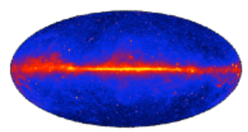
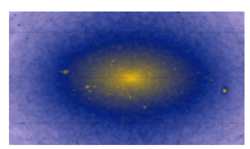
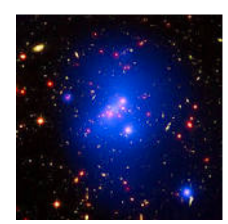
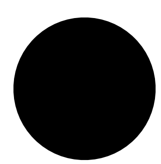
Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center 
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos 
- Extragalactic background radiation

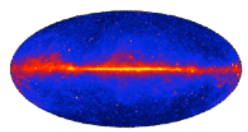
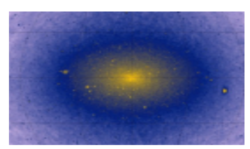
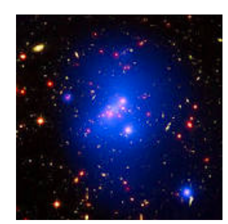
Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos
- Extragalactic background radiation

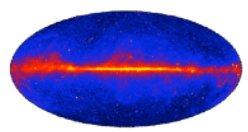
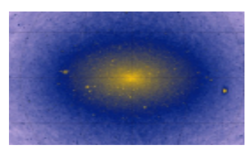
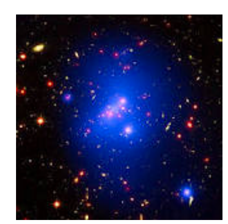
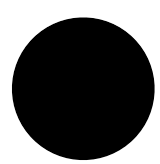
Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters 
- Dark matter subhalos 
- Extragalactic background radiation

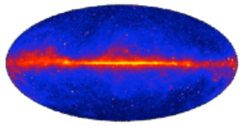
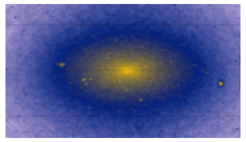
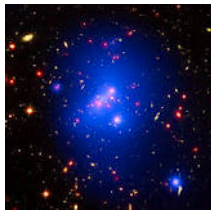
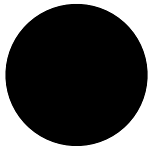
Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos
- Extragalactic background radiation

Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos  potentially numerous, probe small-scale structure
- Extragalactic background radiation

Where to look?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos  potentially numerous, probe small-scale structure
- Extragalactic background radiation holds redshift information, probes halos at all scales

Return to cosmological limits

- We can work out the detailed version of the cosmological energy-injection bounds described in Lecture 1 (e.g. from CMB, Lyman-alpha)
- As for other signals, this requires us to work out:
  - the spectrum of stable SM particles produced by annihilation/decay
  - how that injected spectrum translates into an observable
- The first part is done as for other indirect searches
- The second part requires modeling how high-energy particles cool and deposit their energy in the early universe

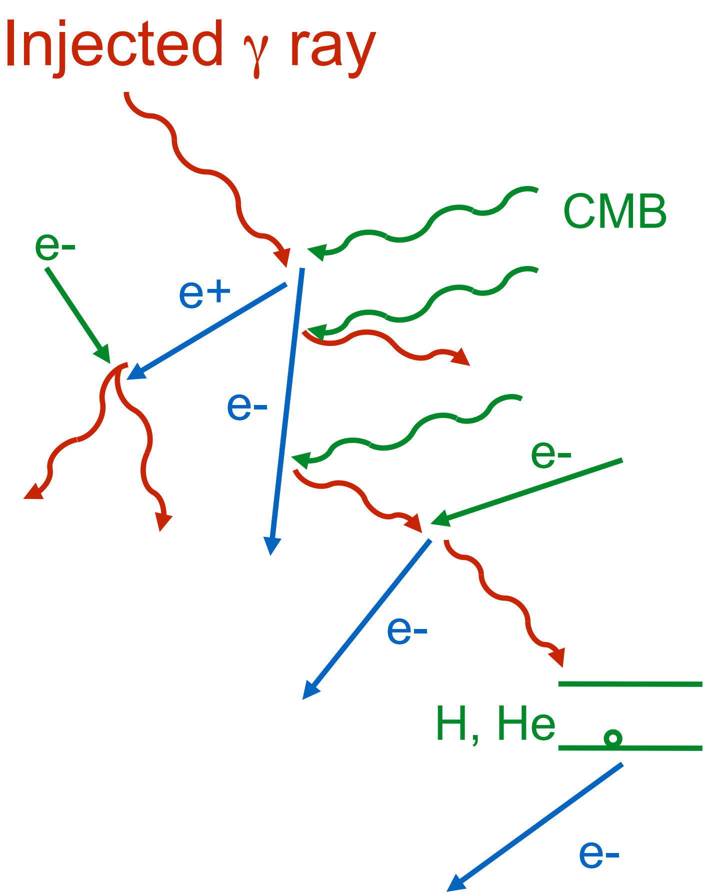
The energy deposition calculation (prelude)

- Simplifying approximations:
  - consider only electrons, positrons, photons (neutrinos are ~non-interacting, (anti)protons tend to give only a small contribution to energy deposition)
  - assume linearity: injected particles are rare enough they will not interact with each <u>other</u>, only with the background (although over time the extra heating/ionization may modify the background)
  - these two assumptions reduce the problem to considering the behavior of individual electrons/positrons/photons injected at some energy+redshift
- <u>Note</u>: this is purely SM physics - all the DM physics goes into setting the spectrum and redshift-dependence of the particle injection

The energy deposition calculation

ELECTRONS

- Inverse Compton scattering on the CMB.
- Excitation, ionization, heating of electron/H/He gas.
- Positronium capture and annihilation.
- All processes fast relative to Hubble time: bulk of energy goes into photons via ICS.



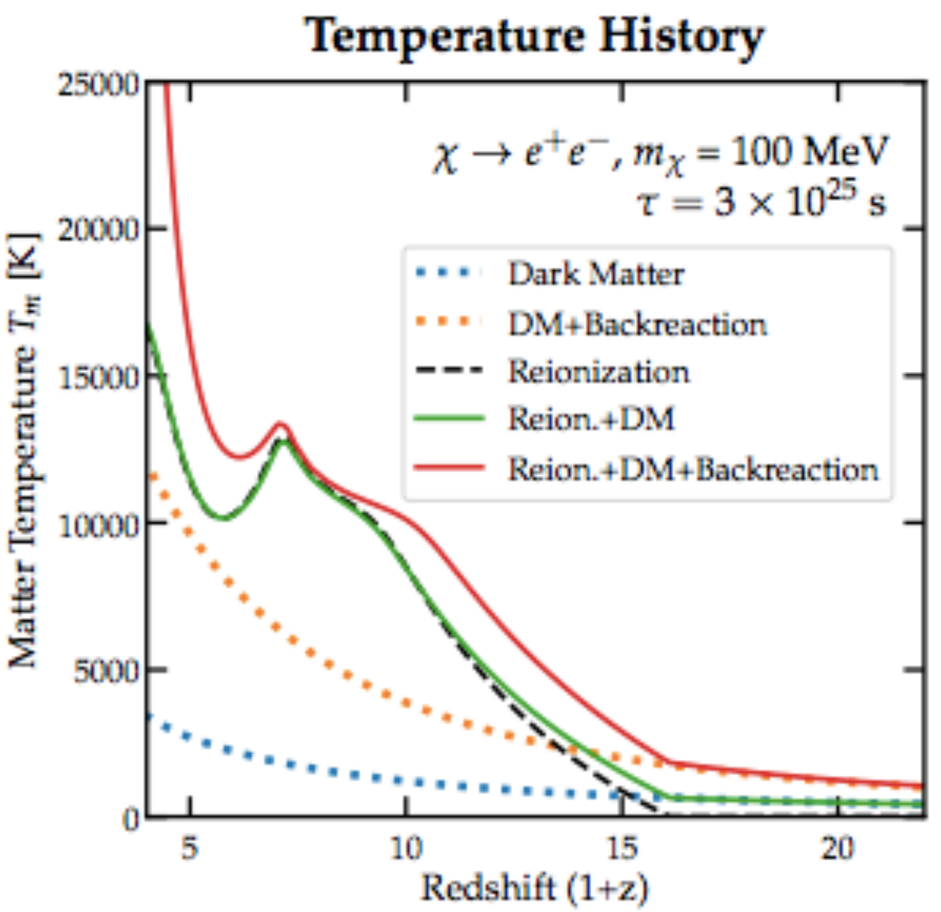
Schematic of a typical cascade:
initial γ-ray
-> pair production
-> ICS producing a new γ
-> inelastic Compton scattering
-> photoionization

blue/red = e+e-/photons carrying injected energy,
green=background

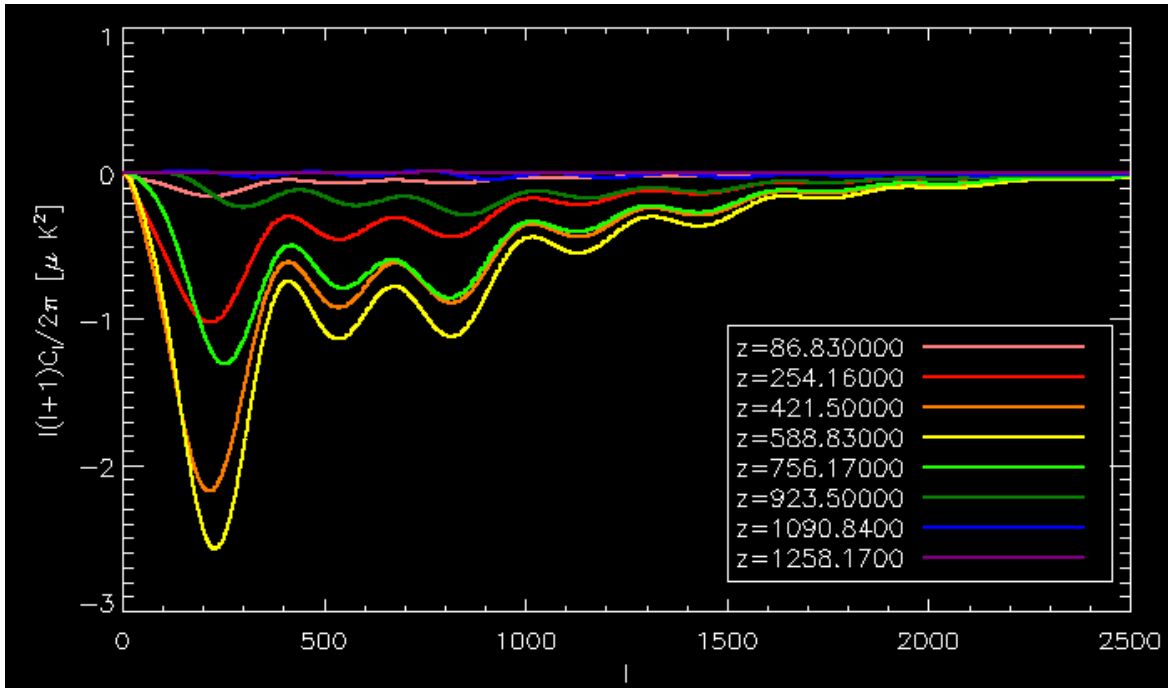
PHOTONS

- Pair production on the CMB.
- Photon-photon scattering.
- Pair production on the H/He gas.
- Compton scattering.
- Photoionization.
- Redshifting is important, energy can be deposited long after it was injected.

From energy deposition to a signal



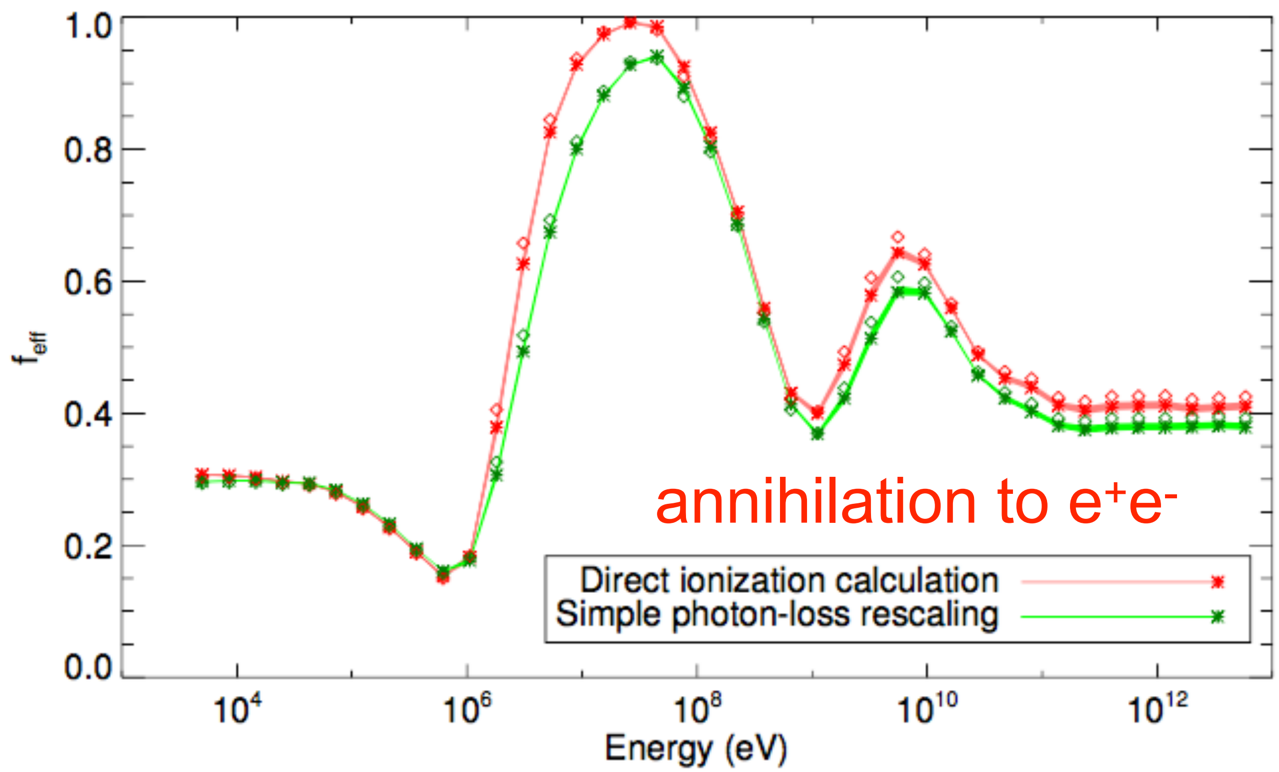
- Modeling this cascade tells us the power going into ionization, excitation, heating, distortions to CMB energy spectrum
- Results are tabulated (assuming standard background) in TRS 1506.03812; DarkHistory package [Liu, TRS et al '19] allows for variable ionization history + backreaction effects
- Feed these inputs into evolution equations for ionization/temperature (in public recombination codes RECFAST, HyREC, CosmoRec, DarkHistory)
- Compare temperature forecast to measurements, project CMB perturbations due to modified ionization history (via public codes CAMB, CLASS / ExoCLASS)

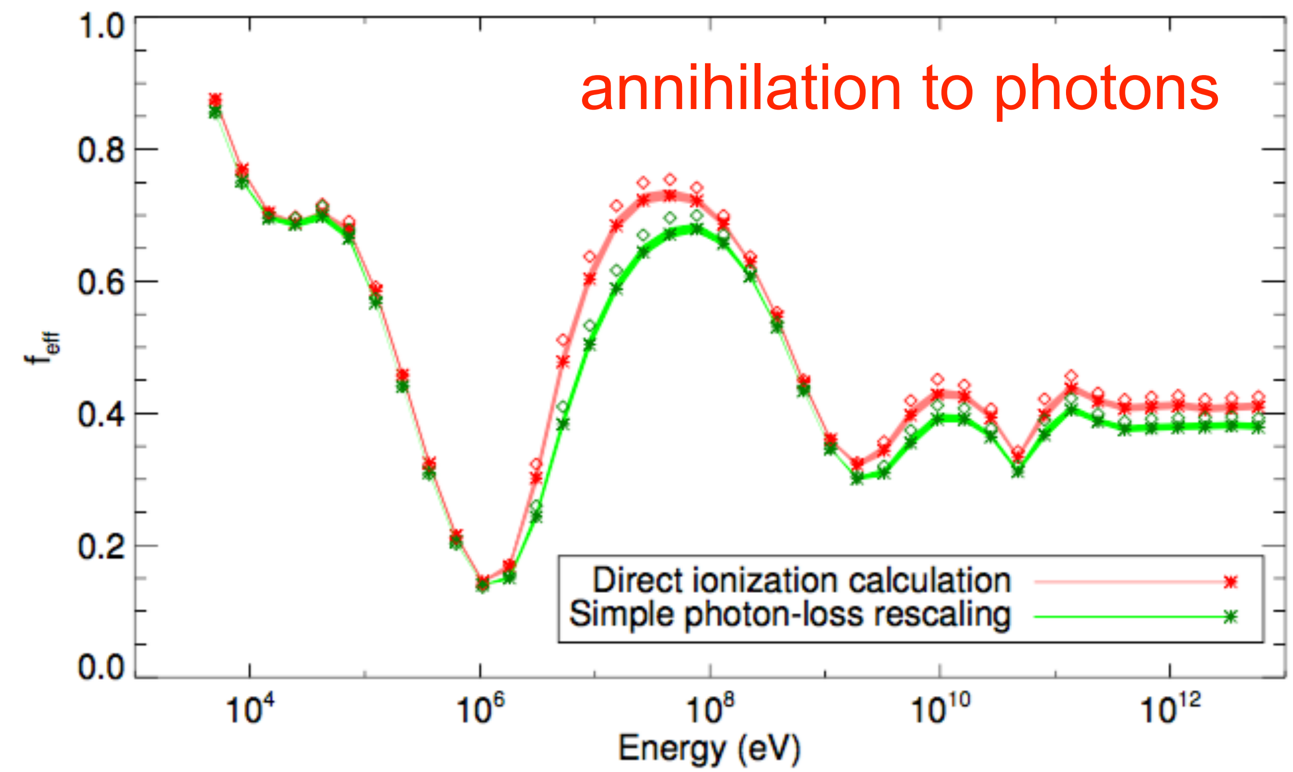


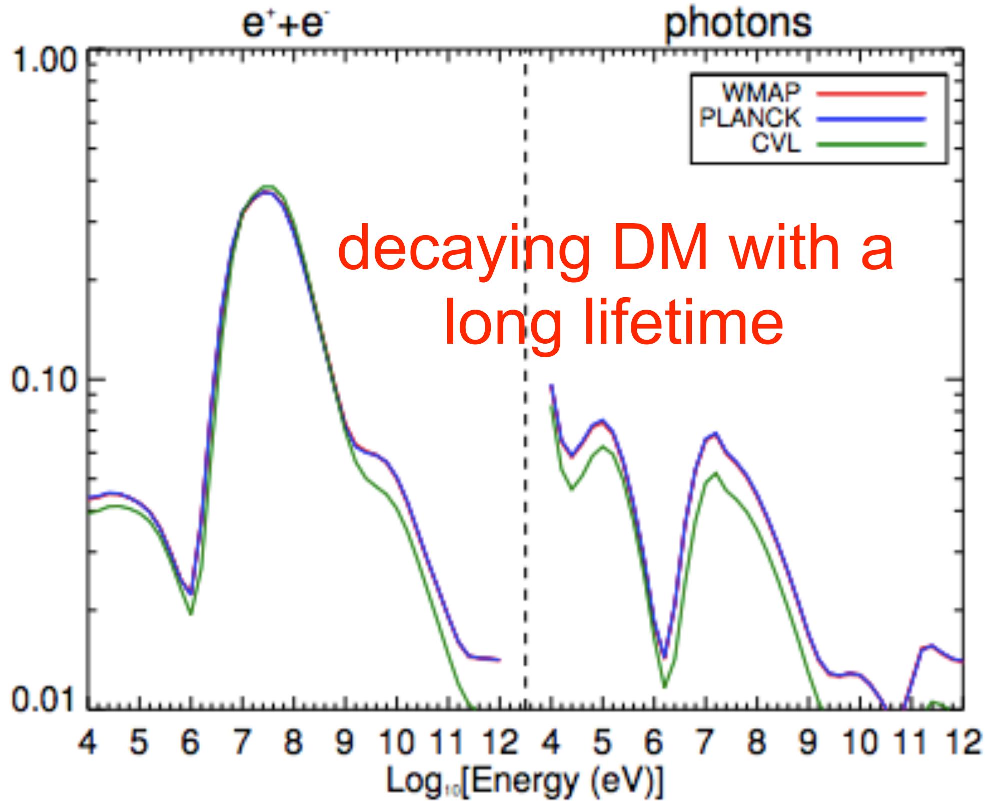
Signals of annihilation/ decay in the CMB

- We can take linear combinations of results for single photons/e^+/e^- to work out the CMB perturbation for a given particle spectrum
- When we do this, we find that different annihilating DM models (with different spectra) give ~identical perturbations to the CMB anisotropy spectrum, up to a rescaling factor (f_{eff} = effective deposition efficiency)
- Decaying models are also very similar to each other
- Intuition: shape of CMB perturbation is mostly fixed by redshift-dependence of energy deposition - mostly controlled by $(1+z)^6$ or $(1+z)^3$ density-based scaling
- From projected perturbation to CMB, read off the $f_{eff}(E)$ for photons/electrons/ positrons produced by DM
- CMB experimentalists can check for the distinctive imprint of an energy injection with rate scaling as $(1+z)^6$ or $(1+z)^3$ in the CMB, constrain its coefficient experimentally

Effective deposition efficiencies

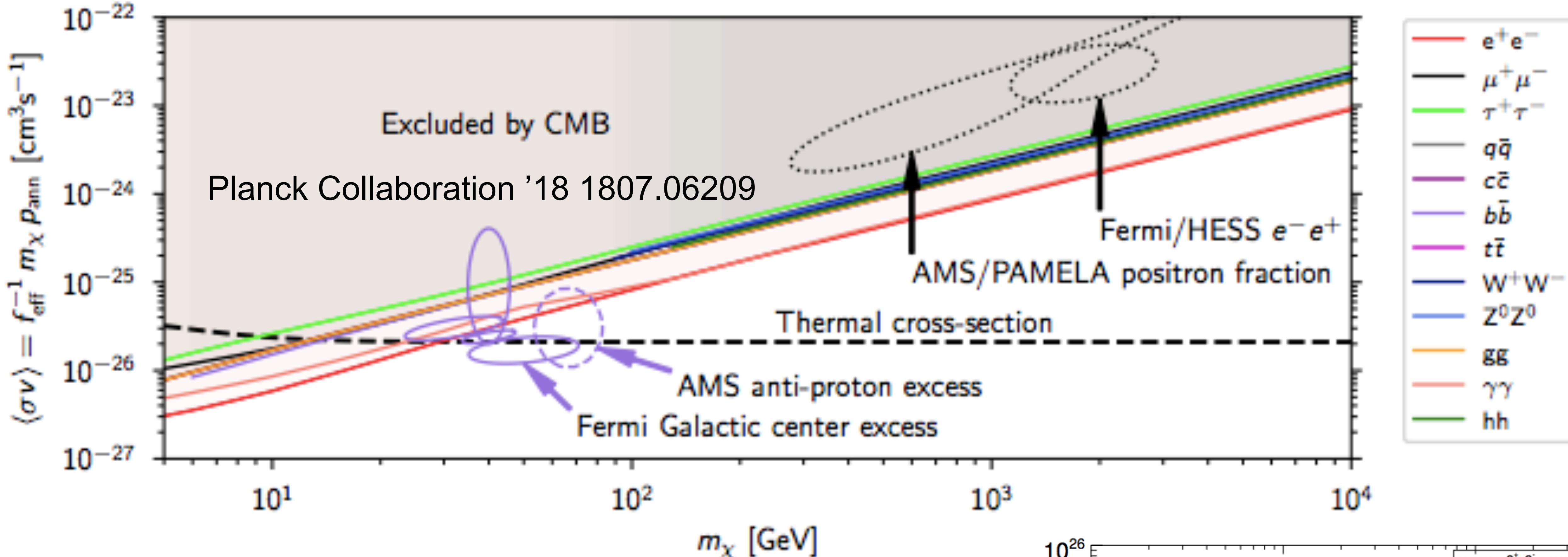






- We can get f_{eff} for a specific DM model by weighting these curves by the photon/e^+e^- spectra
- Planck '18 sets an upper bound for annihilation of $f_{\rm eff}\langle\sigma v\rangle/m_{\rm DM} < 3.2\times10^{-28}$cm³/s/GeV
- In 1610.06933 we set a limit using 2015 Planck data of $\tau \gtrsim \frac{f_{\rm eff}}{f_{\rm eff}(30{\rm MeV}e^+e^-)}\times 2.6\times10^{25}s$

Limits on annihilation and decay



- At lower masses the available final states become limited, but down to keV masses:
  - the limit on xsec continues to scale as ~m_{DM} for annihilation,
  - the limit on lifetime stays ~constant for decay
- Temperature limits from Lyman-alpha are comparable to the CMB bounds for decay - weaker for annihilation