Dark Matter Signals through Cosmic History

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DESY Colloquium
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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- The puzzle of dark matter
- Windows on cosmic history: the cosmic microwave background (CMB), Lyman-alpha forest, primordial 21cm radiation
- Probing imprints of decaying and annihilating dark matter
- Primordial black holes & signals from Hawking radiation, in cosmic history and the present day

What is dark matter?

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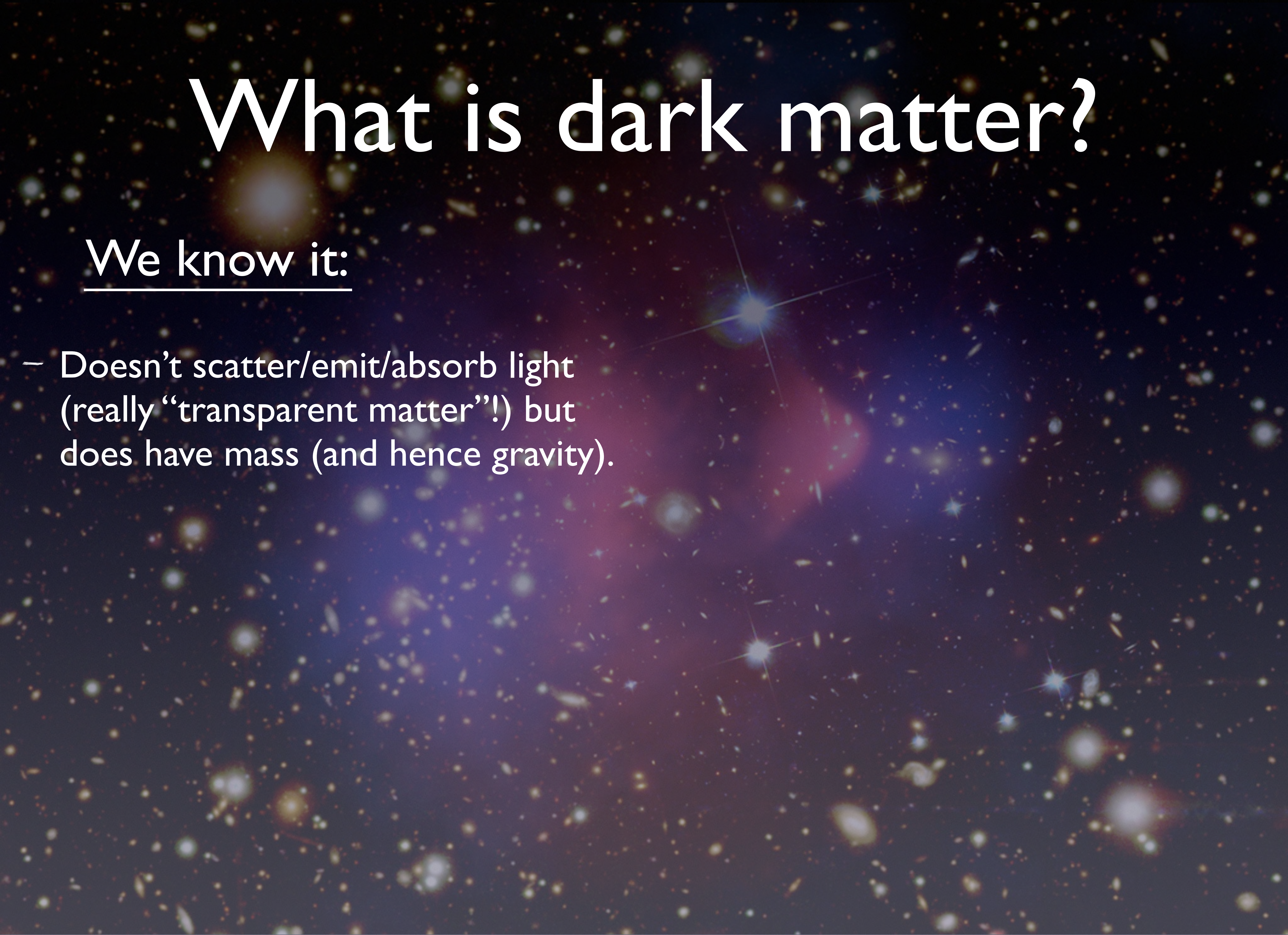

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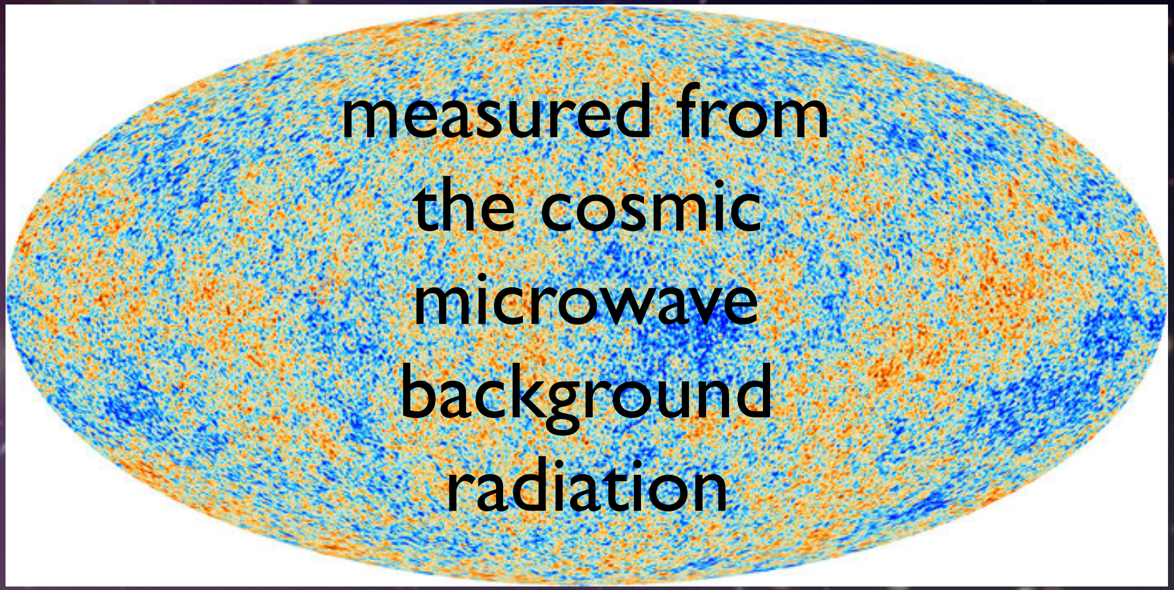

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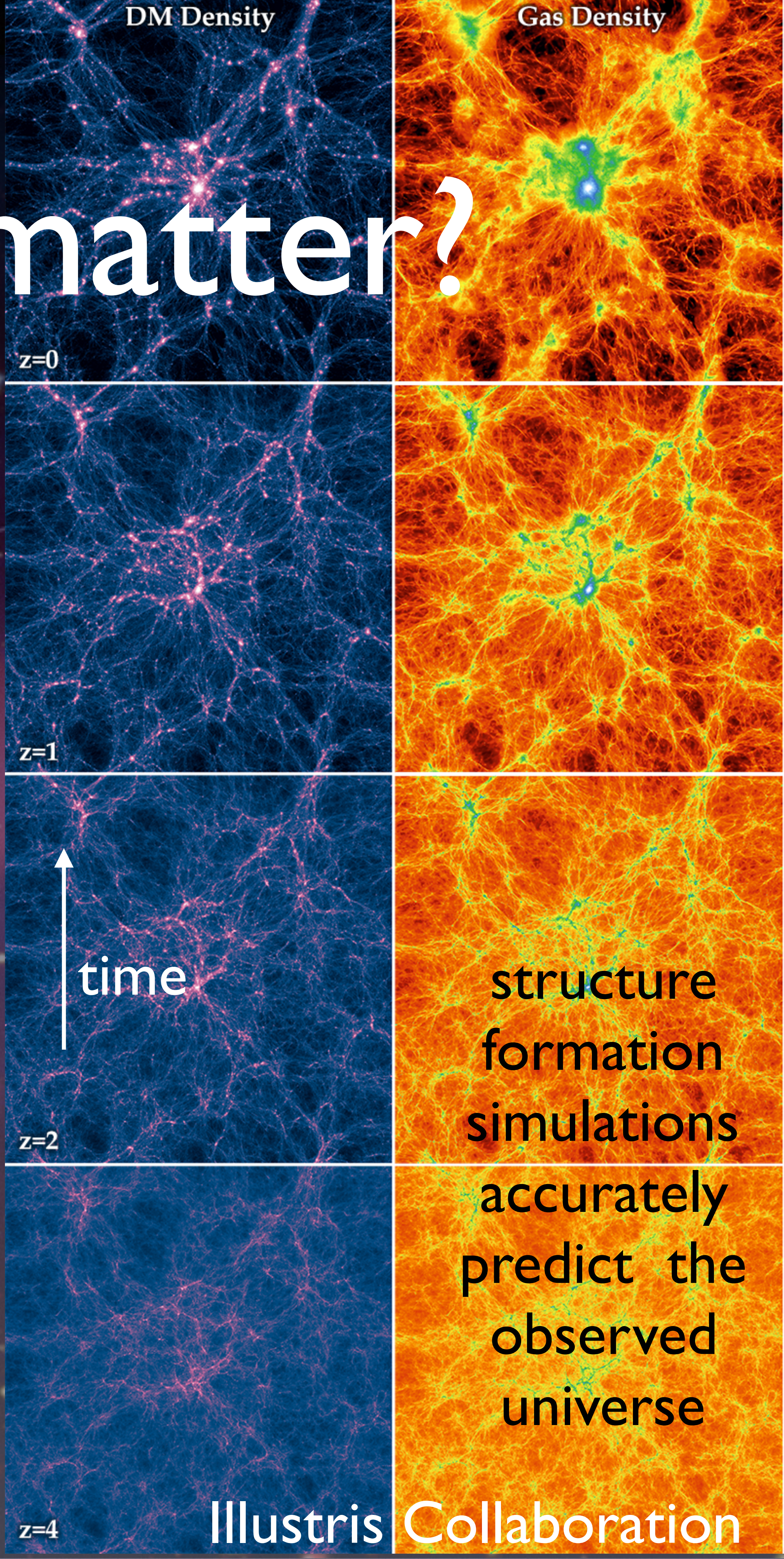

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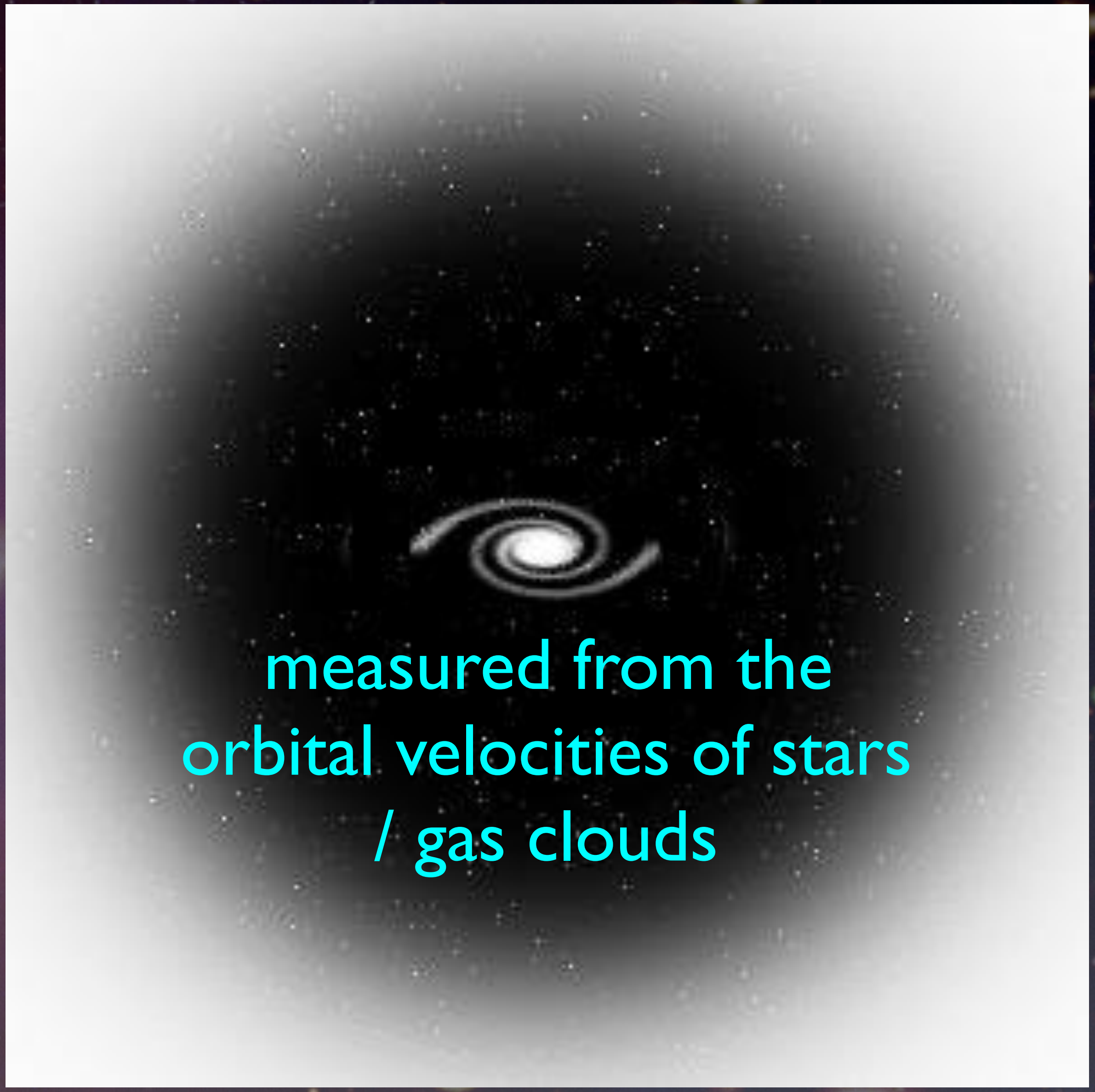

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- Forms the primordial "scaffolding" for the visible universe.
- Forms large clouds or "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

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We know it:

- Consequently, cannot be explained by any known particles

Open questions:

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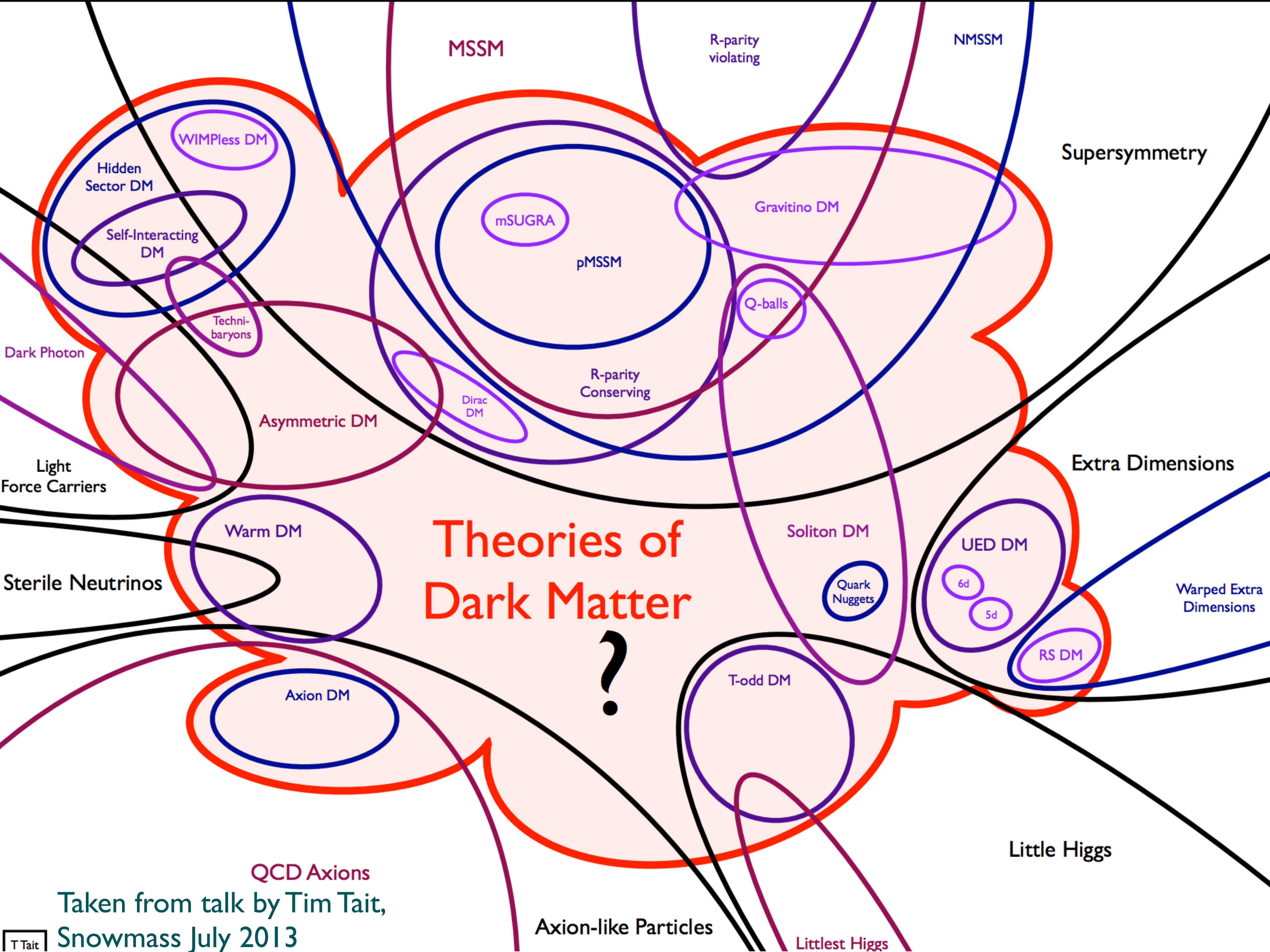
- Where did it come from?
- Does it interact with ordinary particles? If so how?
- and many more…

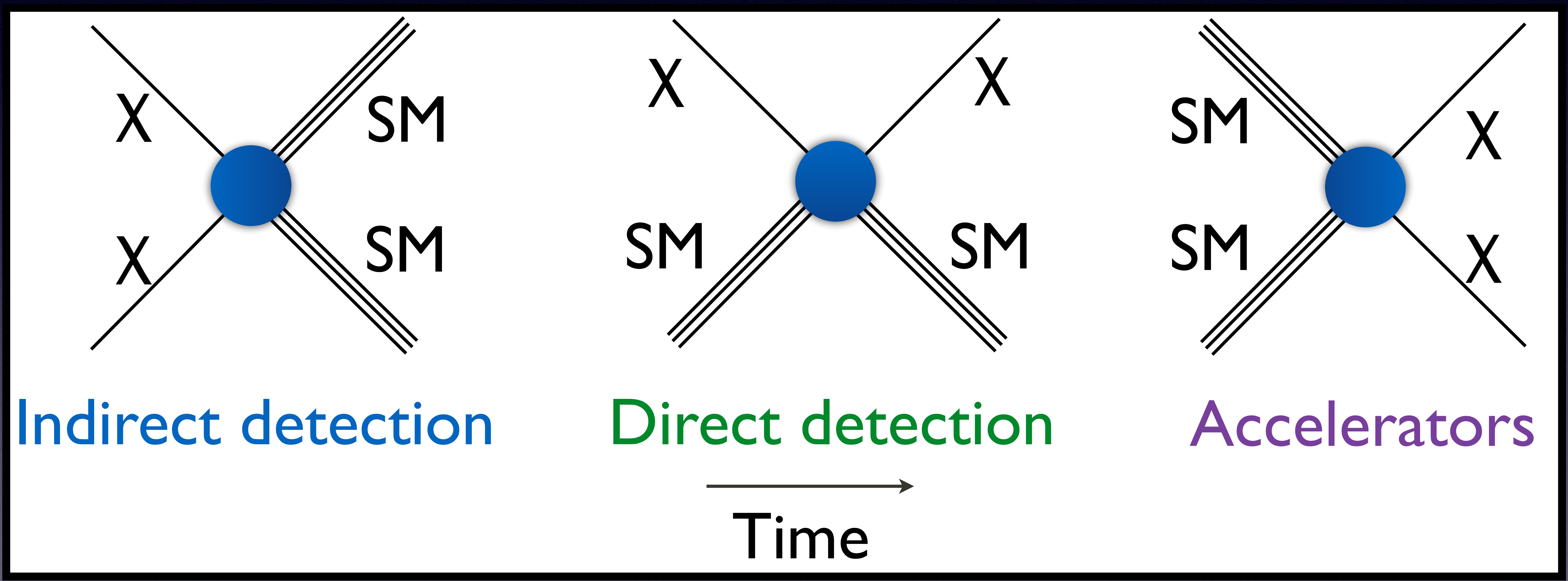


Taken from talk by Tim Tait, Snowmass July 2013

- we have already learned a great deal about dark matter from astrophysical + cosmological observations
- useful information from many datasets - ranging from studies of galaxies, to light emitted when the universe was a tiny fraction of its present age
- these data are extremely rich and getting better all the time - how can we use them to test different ideas for the nature and origin of dark matter?

Searches for DM interactions

- There is a large multi-faceted search program for signatures of dark matter, beyond the signals I will talk about today
- One "standard" classification:



- Not an exhaustive list - in recent years also lots of attention to oscillation (e.g. photon-axion conversion), absorption (in direct detection experiments for light particles), etc
- Many of these possible interaction structures can be tested with cosmological/astrophysical observables

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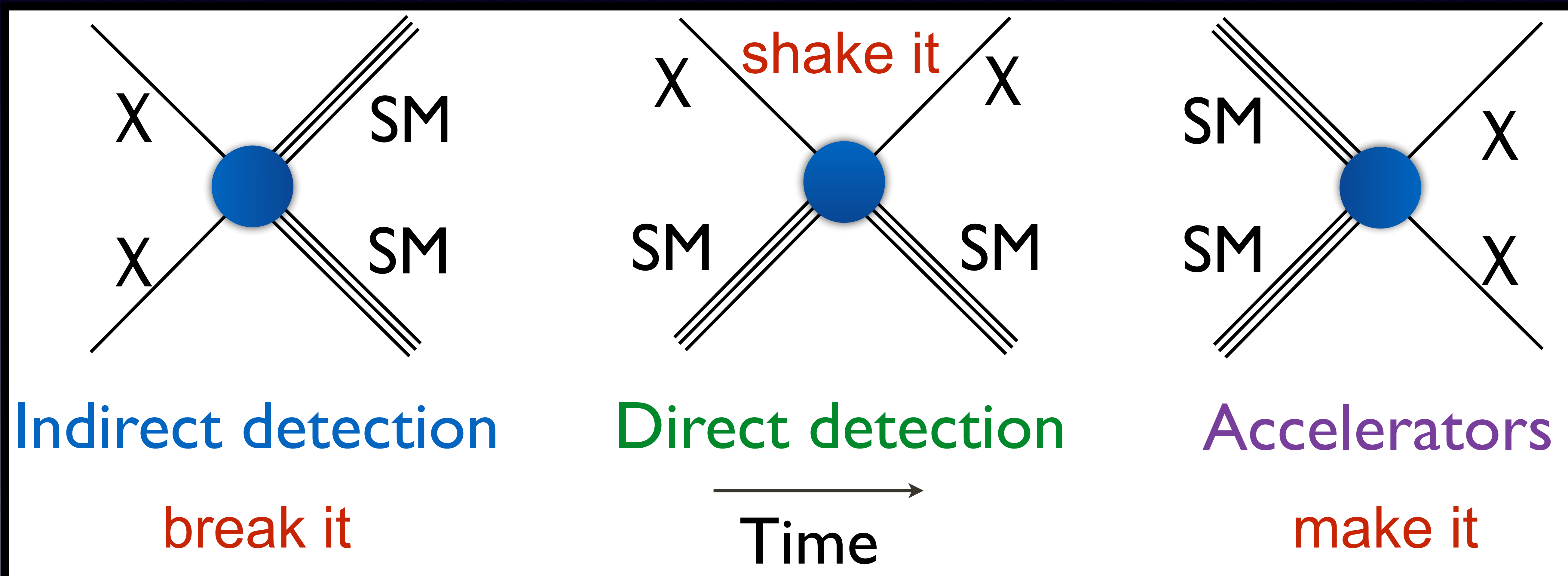

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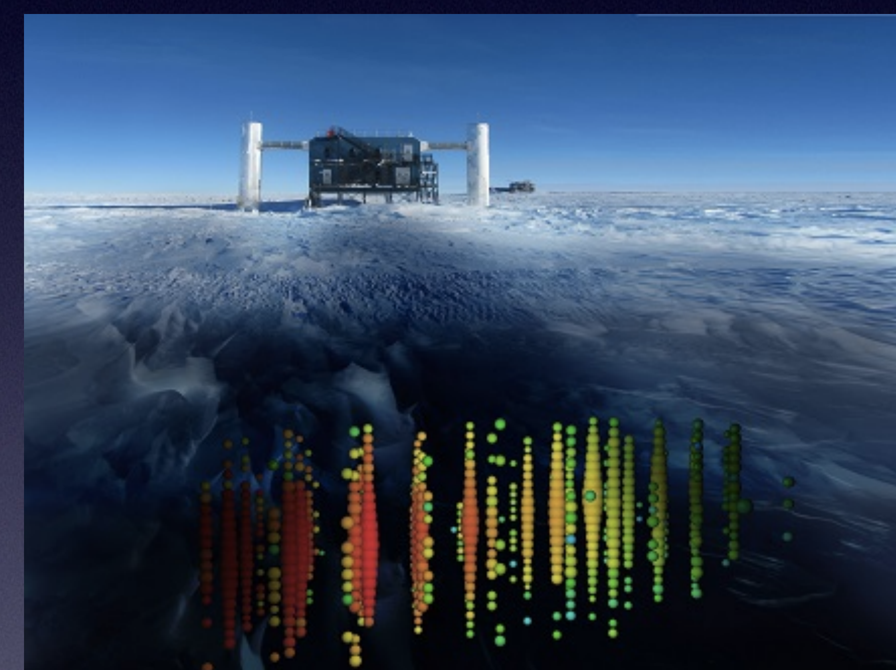
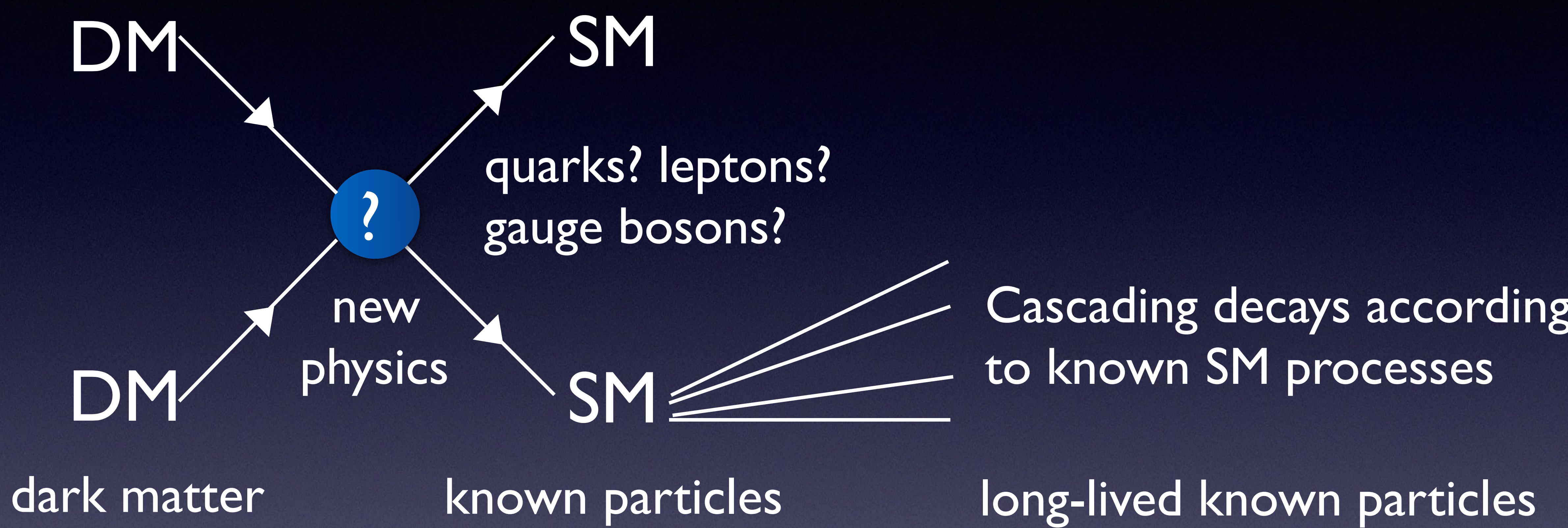
DM searches at DESY



Focus of this talk: indirect detection with early-universe probes, consider generic interactions and final states, explore space of possible signatures

Annihilation

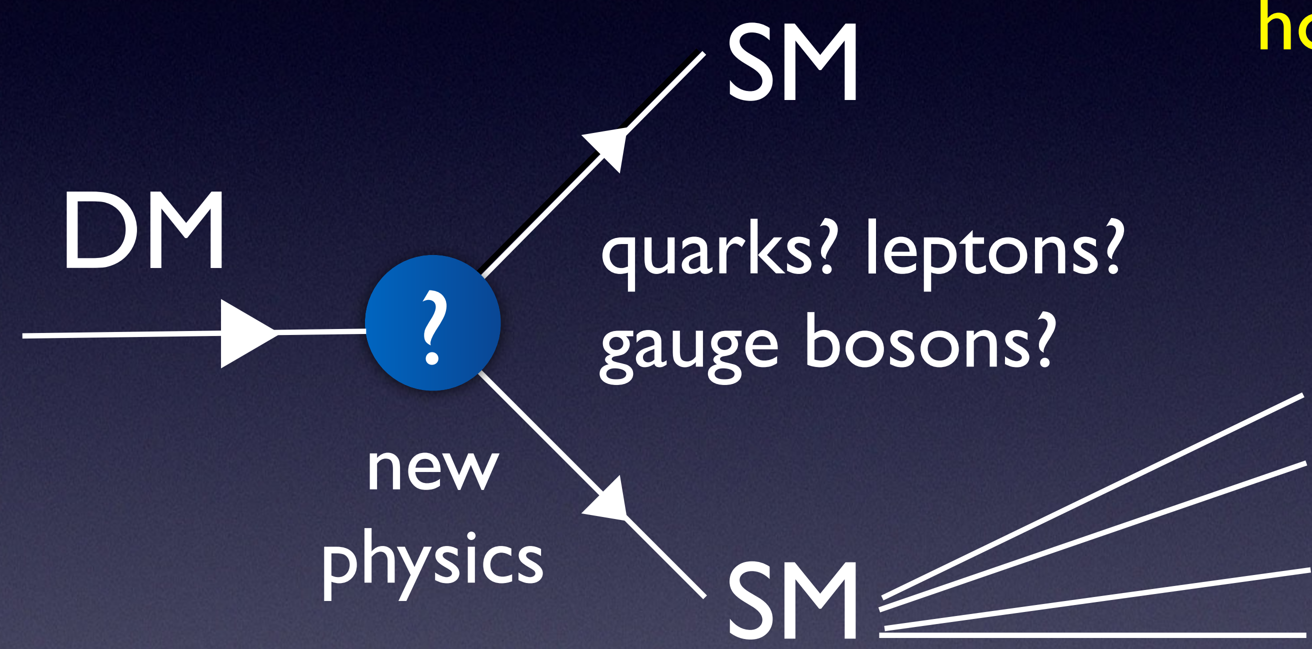


- Tightly linked to DM abundance in scenarios where the DM was initially much more abundant, and these annihilation processes depleted it (“thermal relic” scenario).
- Such scenarios favor a benchmark annihilation rate, called the “thermal relic cross section”.

$$\langle \sigma v \rangle \sim \frac{1}{m_{\mathrm{Planck}} T_{\mathrm{eq}}} \sim \frac{1}{(100\mathrm{TeV})^2} \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

Decay

also applicable to Hawking radiation from primordial black holes, decays from a metastable state to a lighter state, etc



Cascading decays according to known SM processes

dark matter

known particles

long-lived known particles

- Either annihilation or decay would lead to a slow trickle of energy into the visible sector over time
- We will explore the effects of this energy transfer on the history of the universe

The cosmic microwave background

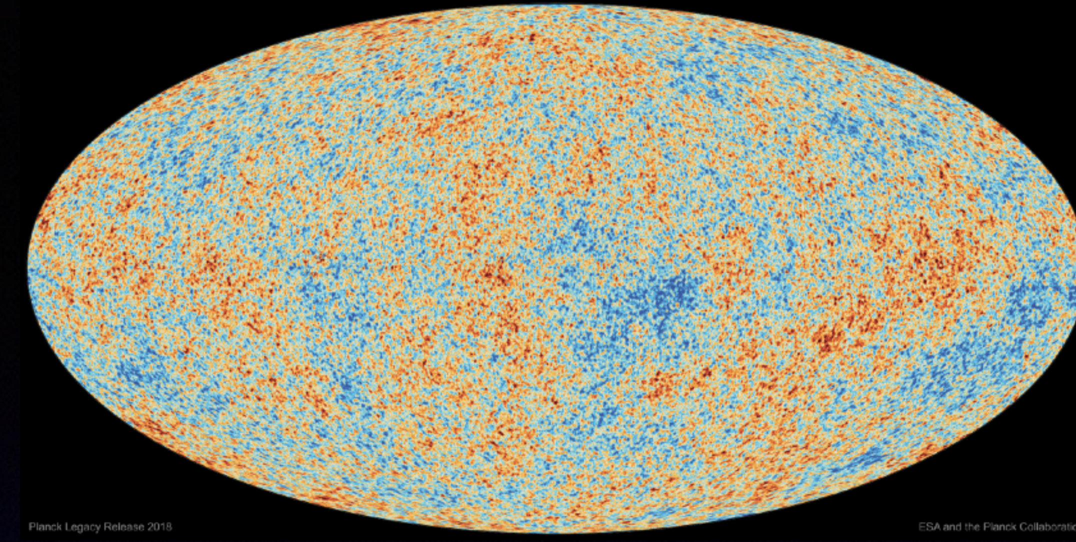
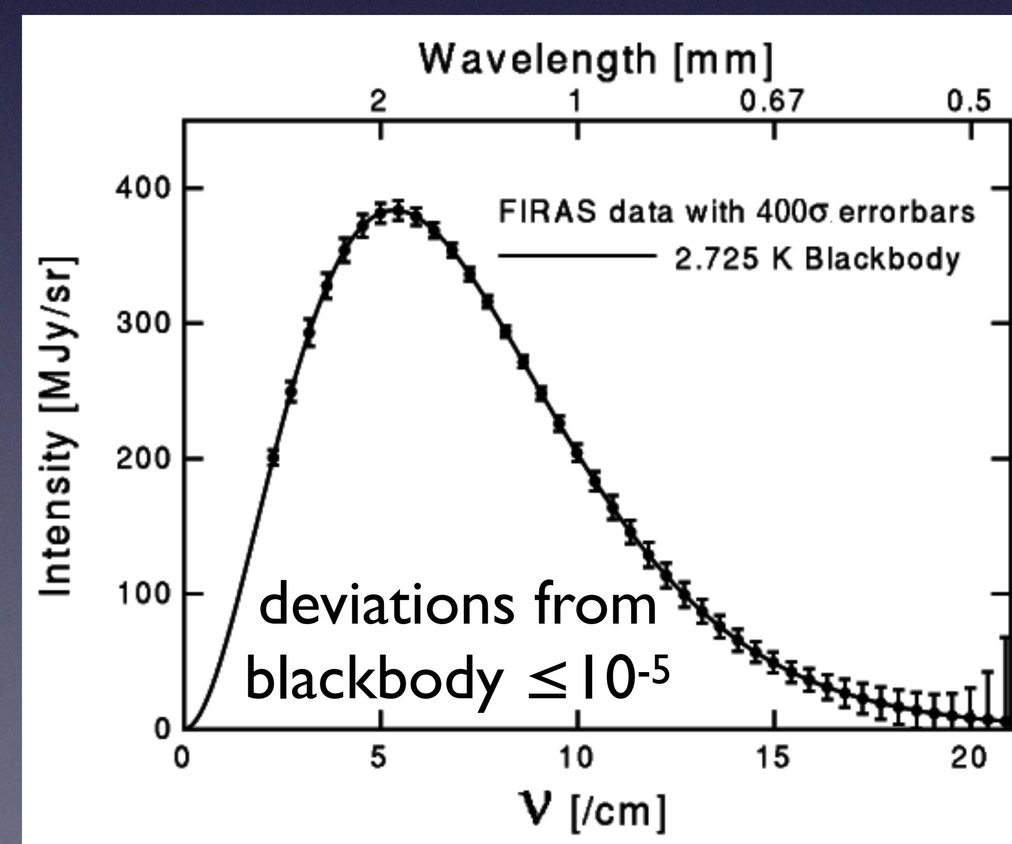


Image credit: European Space Agency / Planck Collaboration

- Convenient to measure epochs by redshift, denoted z; 1+z gives the factor by which the universe has expanded since that time (today: z=0)
- Redshift z > 1000 - universe is filled with a tightly-coupled plasma of electrons, protons and photons, + dark matter and neutrinos. Almost 100% ionized.
- Redshift z ~ 1000 - ionization level drops abruptly, cosmic microwave background (CMB) photons begin to stream free of the electrons/ protons.
- The cosmic microwave background provides a snapshot of the z~1000 universe - oldest light we measure, earliest direct observations of our cosmos.

spatial information: describes pattern of oscillations in density and temperature

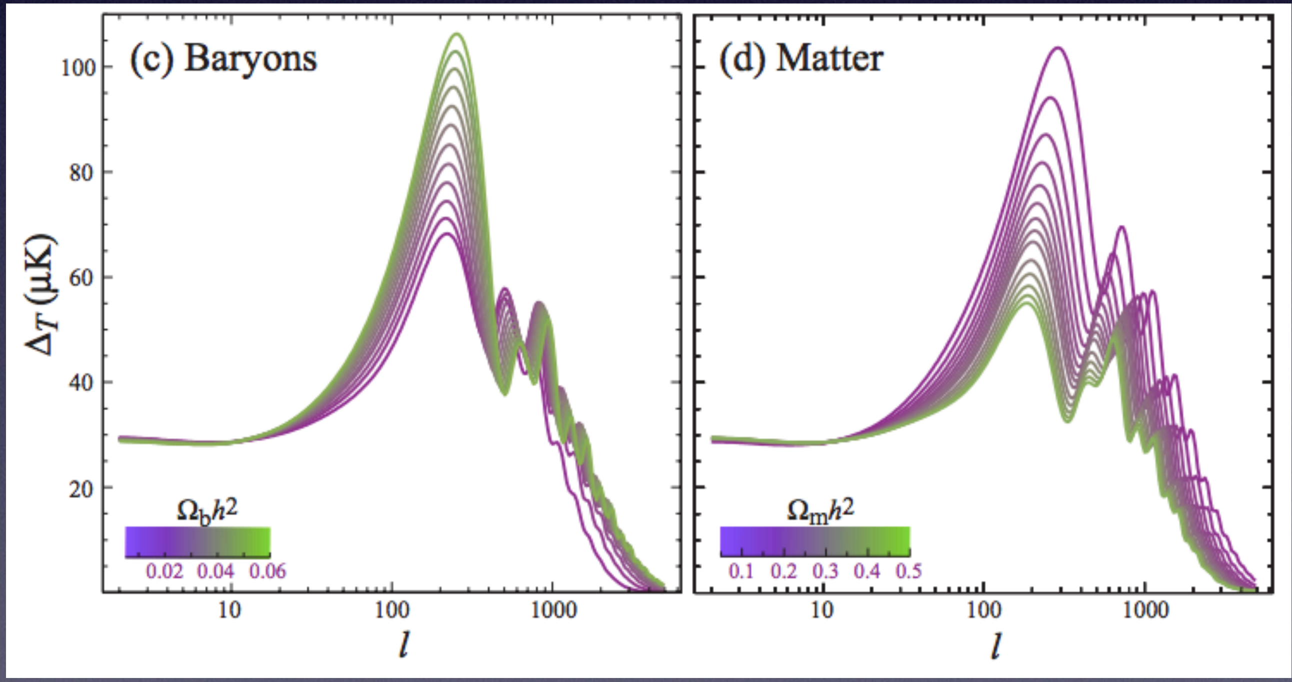
spectral information: near-perfect blackbody



Signatures in the CMB (I)

- We can change the observed CMB either by:
  - z > 1000: Modifying the target of the "snapshot" - change the plasma to which the photons couple before emission
  - z < 1000: Changing the photons on their way to us - modifying the "picture" after it is taken

Hu & Dodelson '02



- Classic example of first case: temperature/density oscillations in plasma are driven by competition between gravity and radiation pressure.

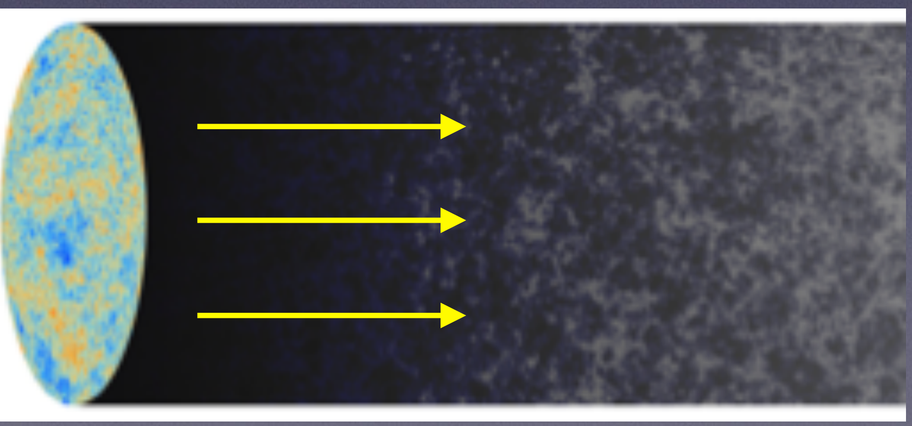
- Presence of matter that feels gravity but not radiation ("dark") changes properties of oscillations - used to measure DM abundance.

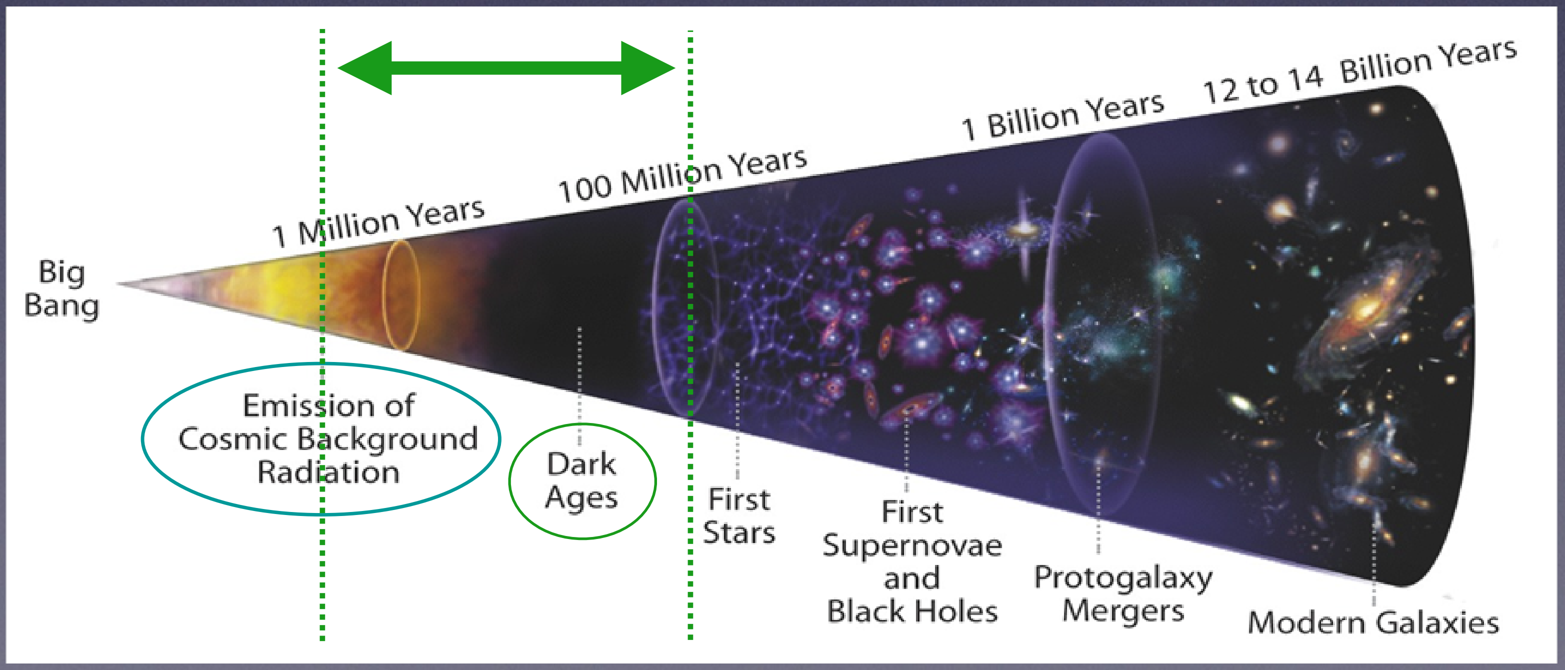
- Scattering between DM and ordinary matter would make DM not-quite-dark, and likewise modify the oscillation pattern

- Heating of the ordinary matter by DM annihilation/decay can also modify the photon/baryon plasma, changing the energy spectrum of the CMB.

Signatures in the CMB (II)

- Second case (modification after emission): "cosmic dark ages" span redshift z ~ 30-1000, ionization level expected to be very low.
- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.
- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.
- Oscillation between axion-like particles and CMB photons can also distort the energy spectrum.





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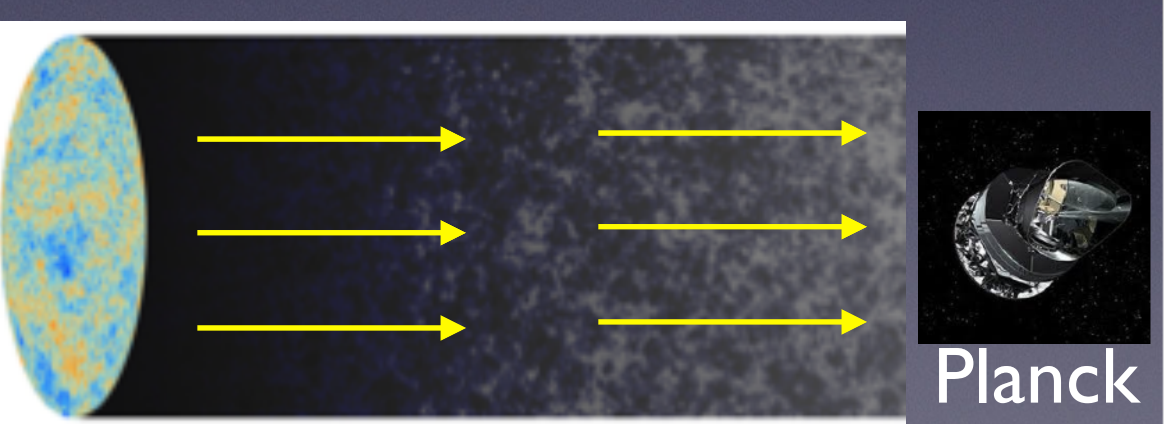

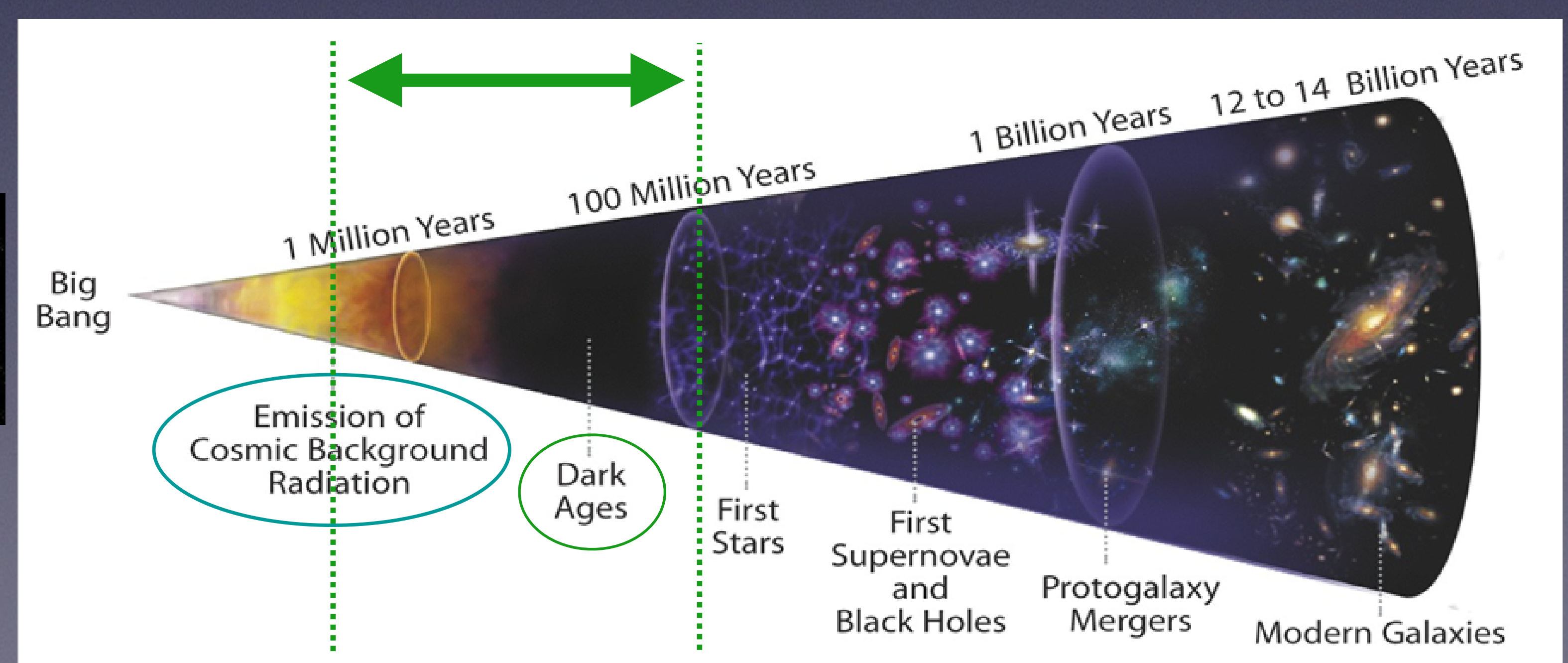

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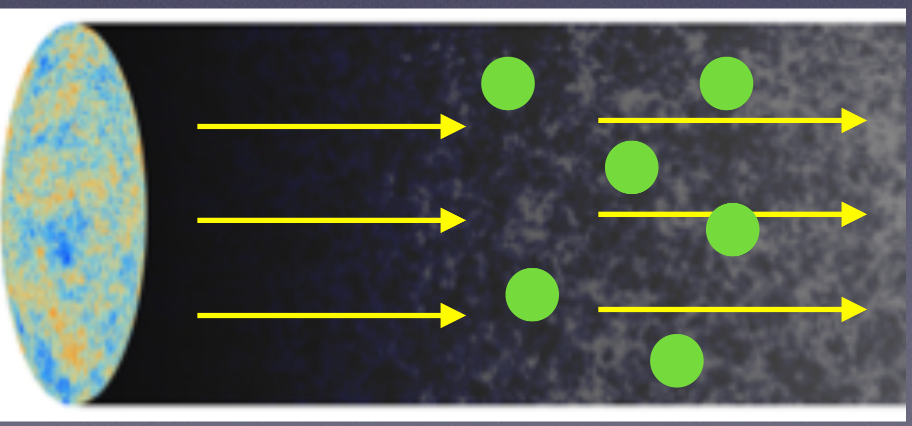

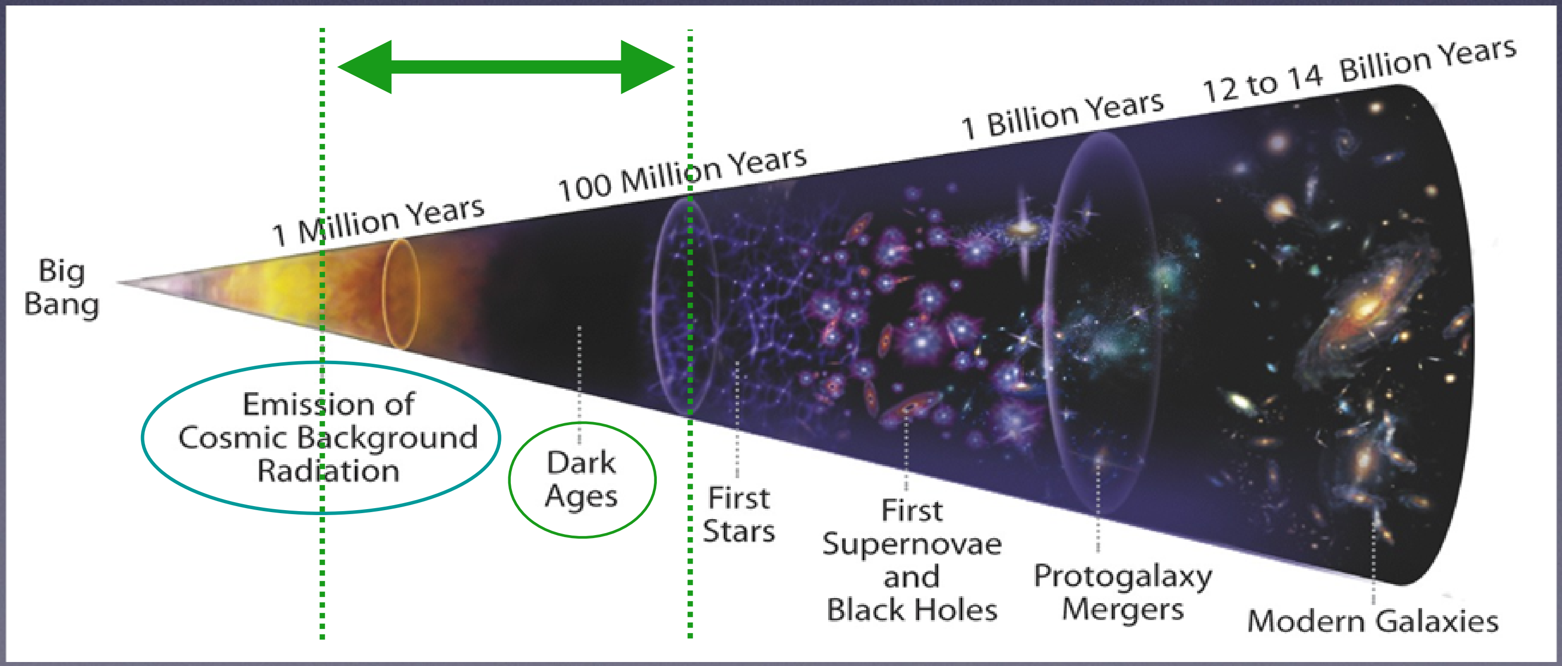

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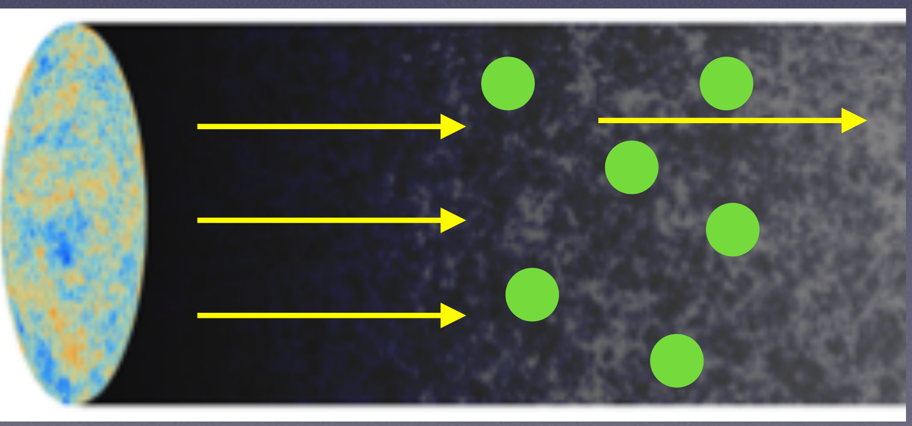
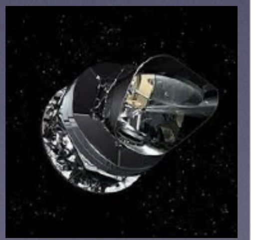
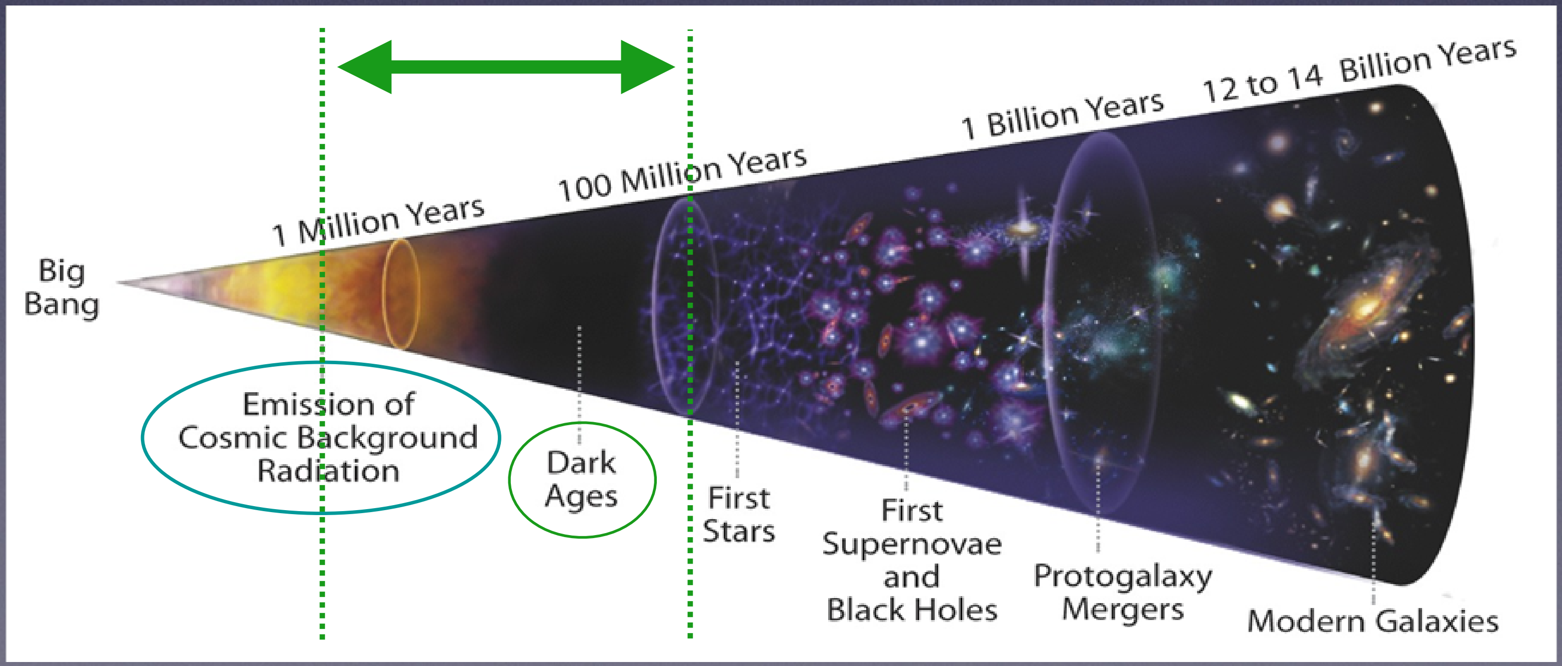


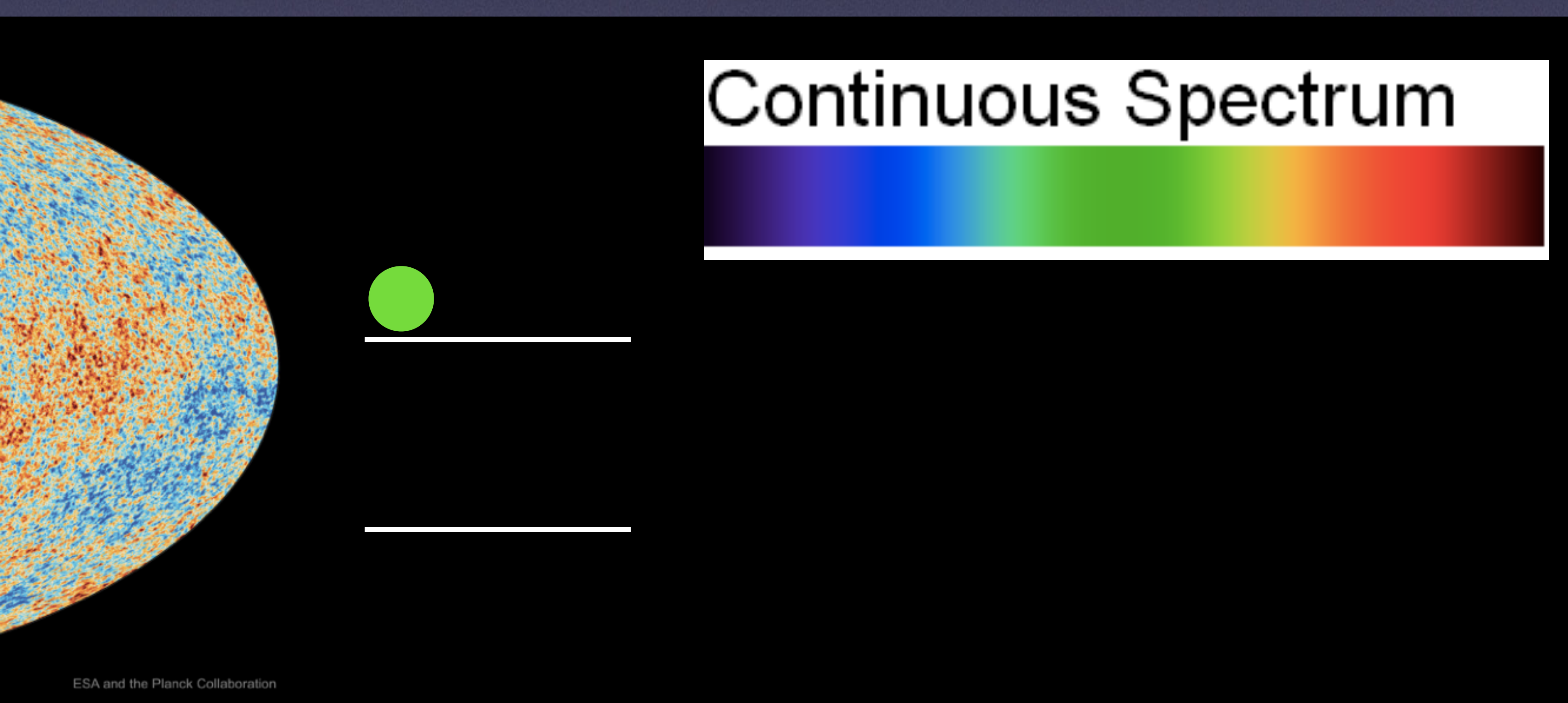


Planck



21cm and the cosmic thermal history

- Annihilation/decay could also heat the universe, liberating energy stored as DM mass; DM-baryon scattering, conversely, could cool the gas via energy transfer to the (colder) dark matter.
- To measure the gas temperature at late times, we can search for atomic transition lines, in particular the 21cm spin-flip transition of neutral hydrogen.
- "Spin temperature" T_S characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - T_S gives the temperature at which the equilibrium abundances would match the observed ratio.
- If T_S exceeds the ambient radiation temperature T_R, there is net emission; otherwise, net absorption.



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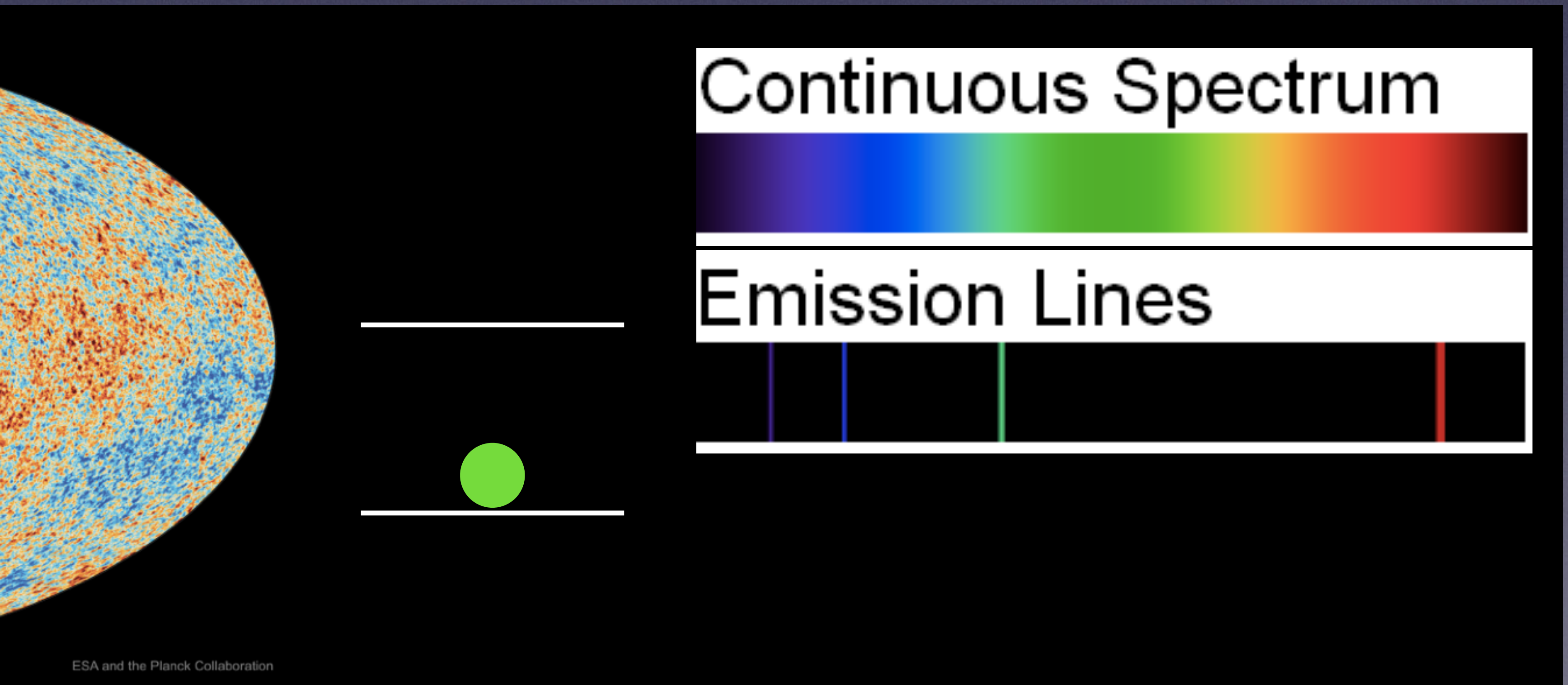

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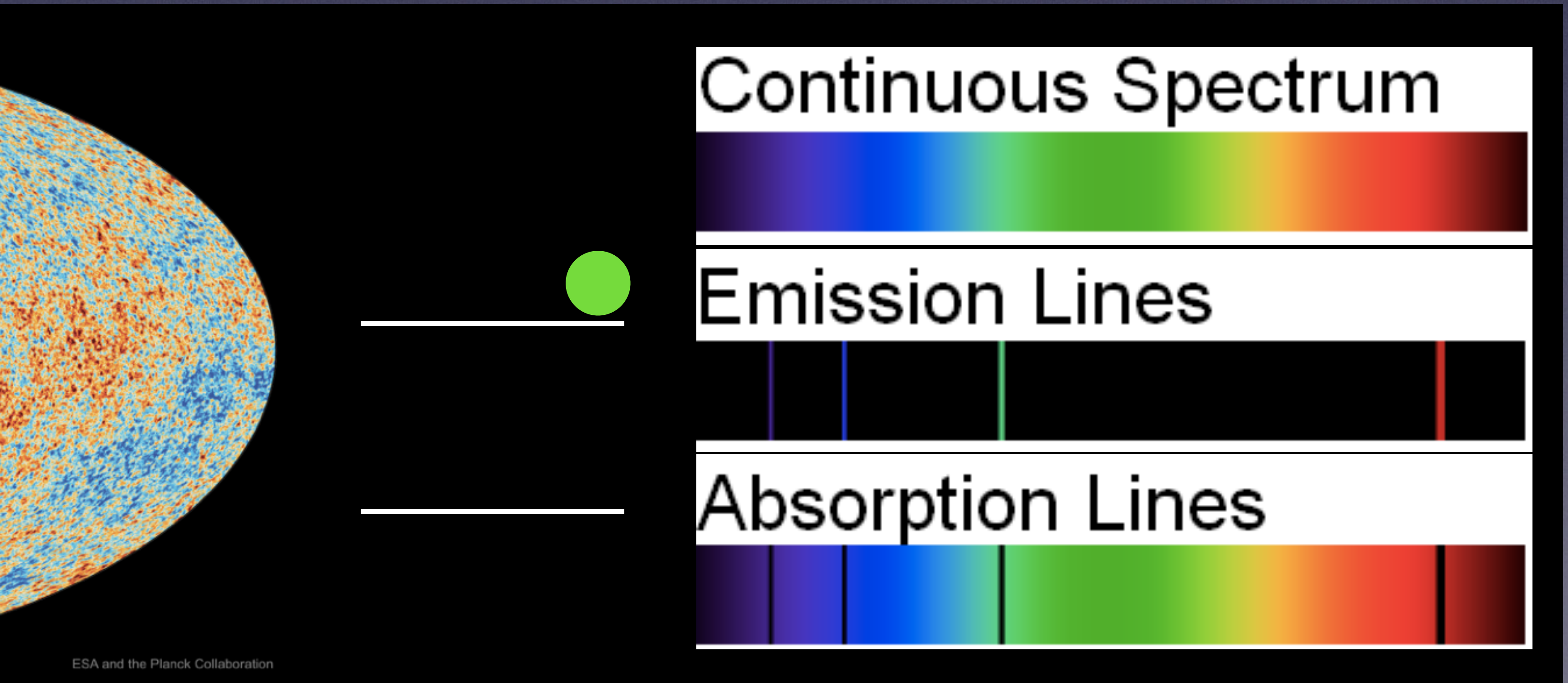

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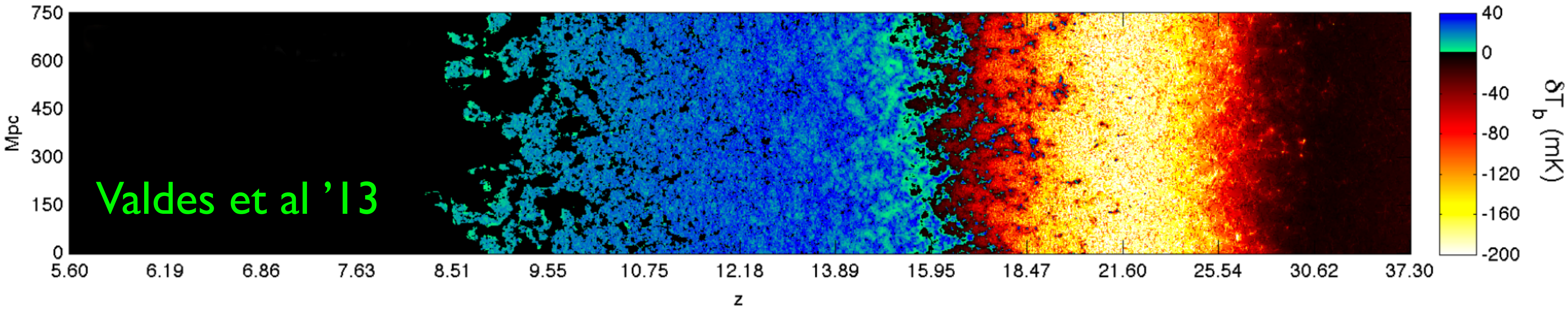
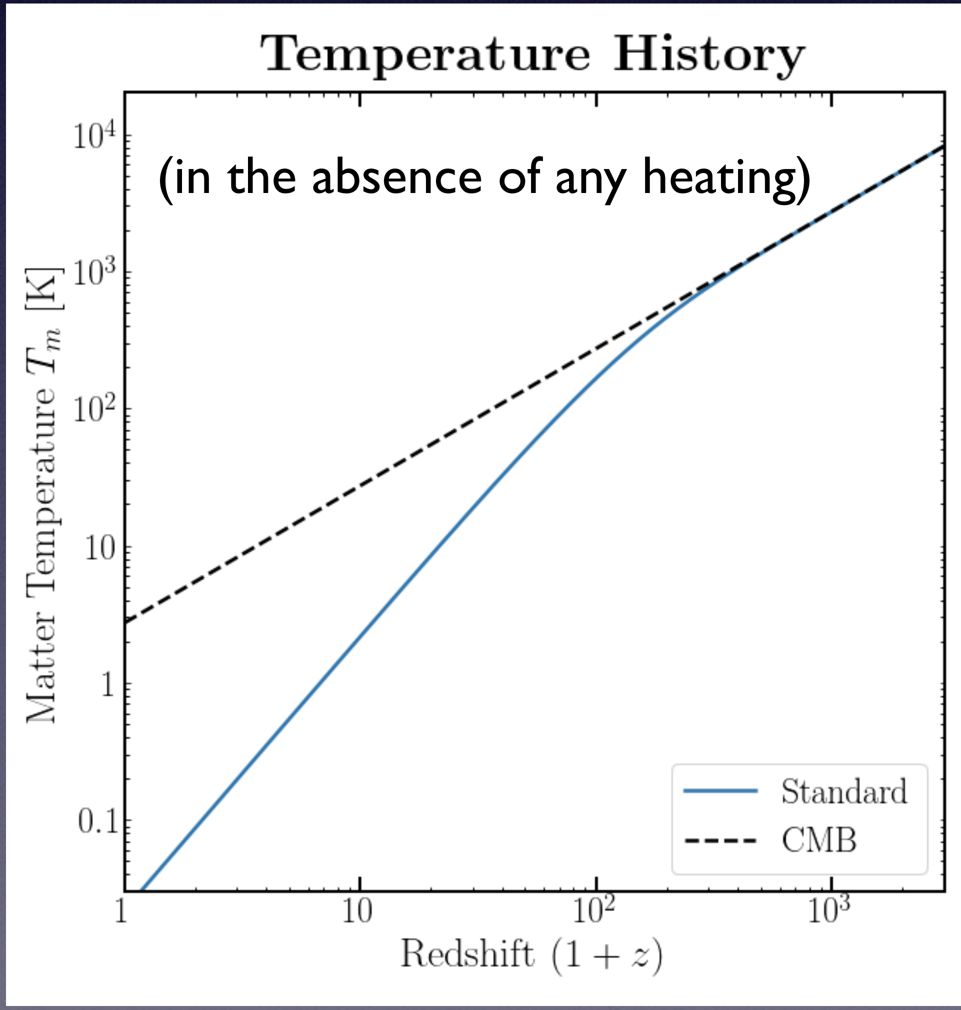
Expectations for a 21cm signal



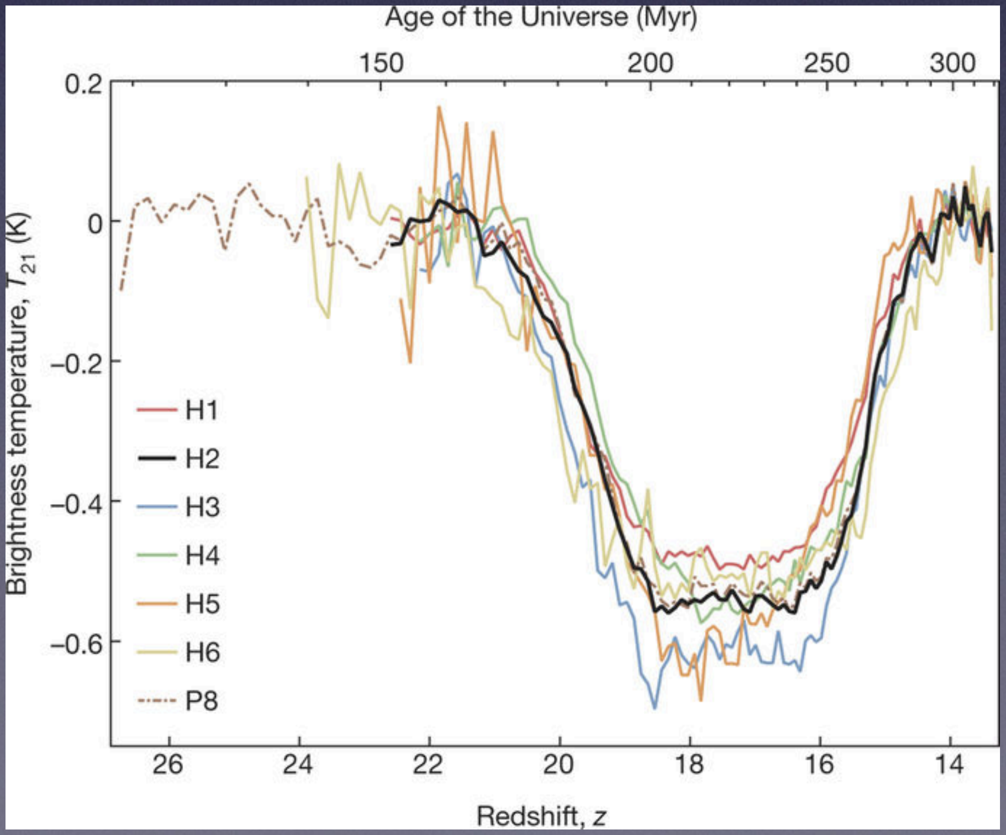
- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature.
- Exotic heating could lead to an early emission signal [e.g. Poulin et al '17].
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- There are a number of current (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, HERA, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Any measurement of global T_{21} will set a bound on T_{gas}.



Side note: have we already seen a signal?

- 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 very deep absorption trough corresponding to z~15-20 - implies spin temperature < CMB temperature, $T_{gas}/T_R(z=17.2) < T_S/T_R < 0.105$ (99% confidence).

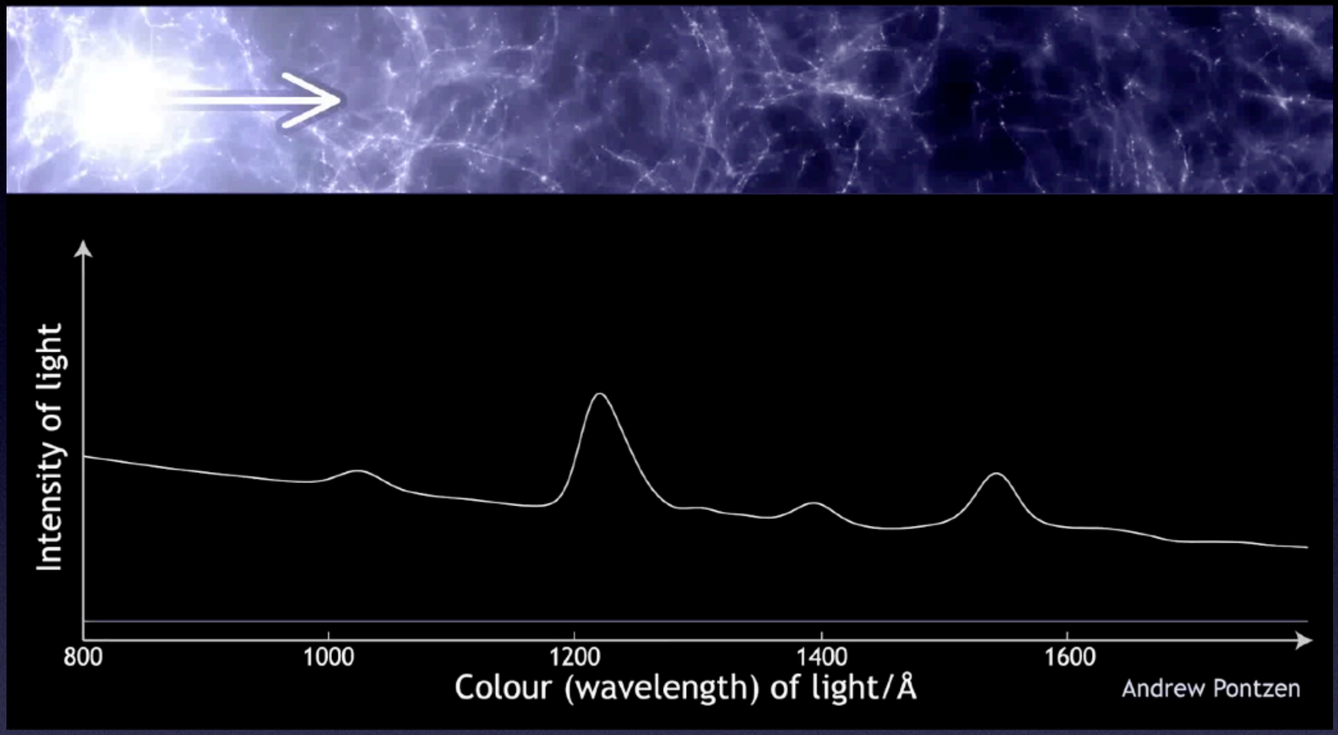
EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

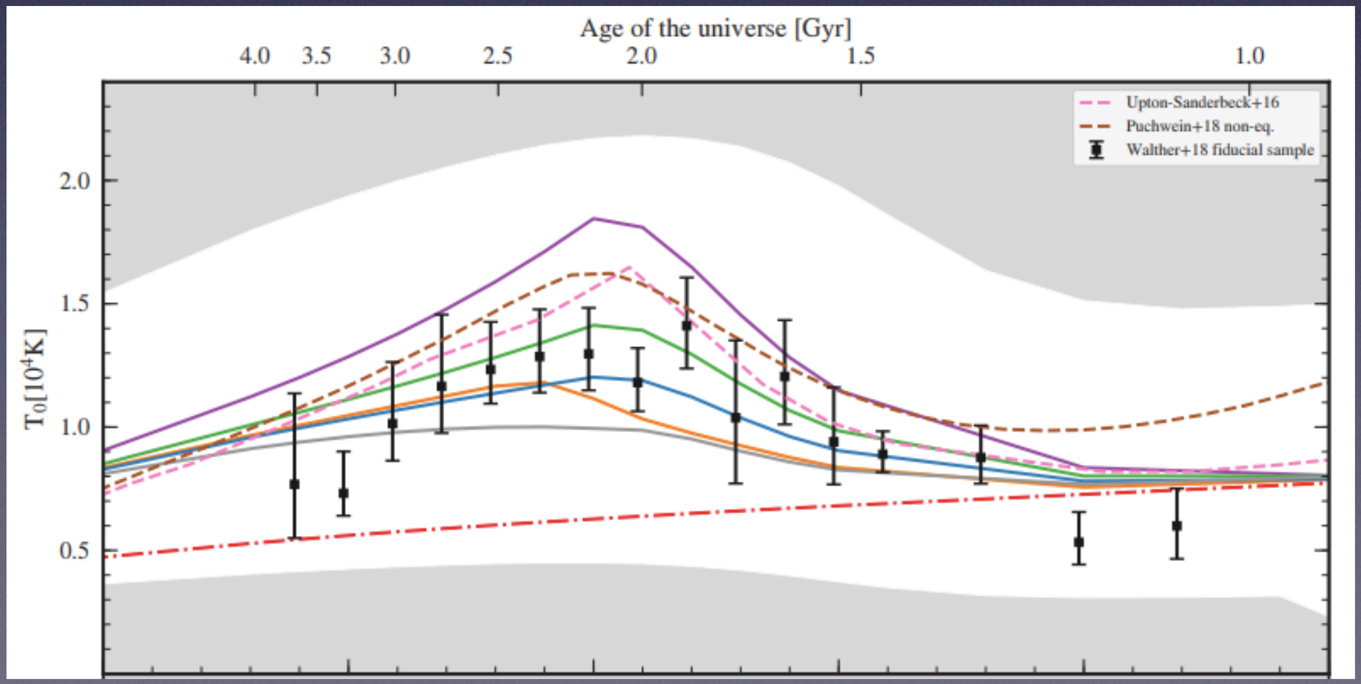


- Very surprising result - trough is much <u>deeper</u> than expected.
- Suggests either new physics of some form, or a systematic error [e.g. Hills et al '18, Bradley et al '19].

The Lyman-alpha forest

- After the universe mostly reionizes, there are still clouds of neutral hydrogen in the universe - light passing through these clouds produces the "Lyman-alpha forest" of absorption features in the spectrum.
- T_{gas} affects the width of the absorption features via Doppler broadening.
- Temperature also affects the distribution of the hydrogen gas - smoothed out by the gas pressure on small scales.
- Several recent studies [Walther et al '18, Gaikwad et al '20] have compared measurements of the Ly-α forest with simulations, to extract the gas temperature for z~2-6.





Gaikwad et al '20

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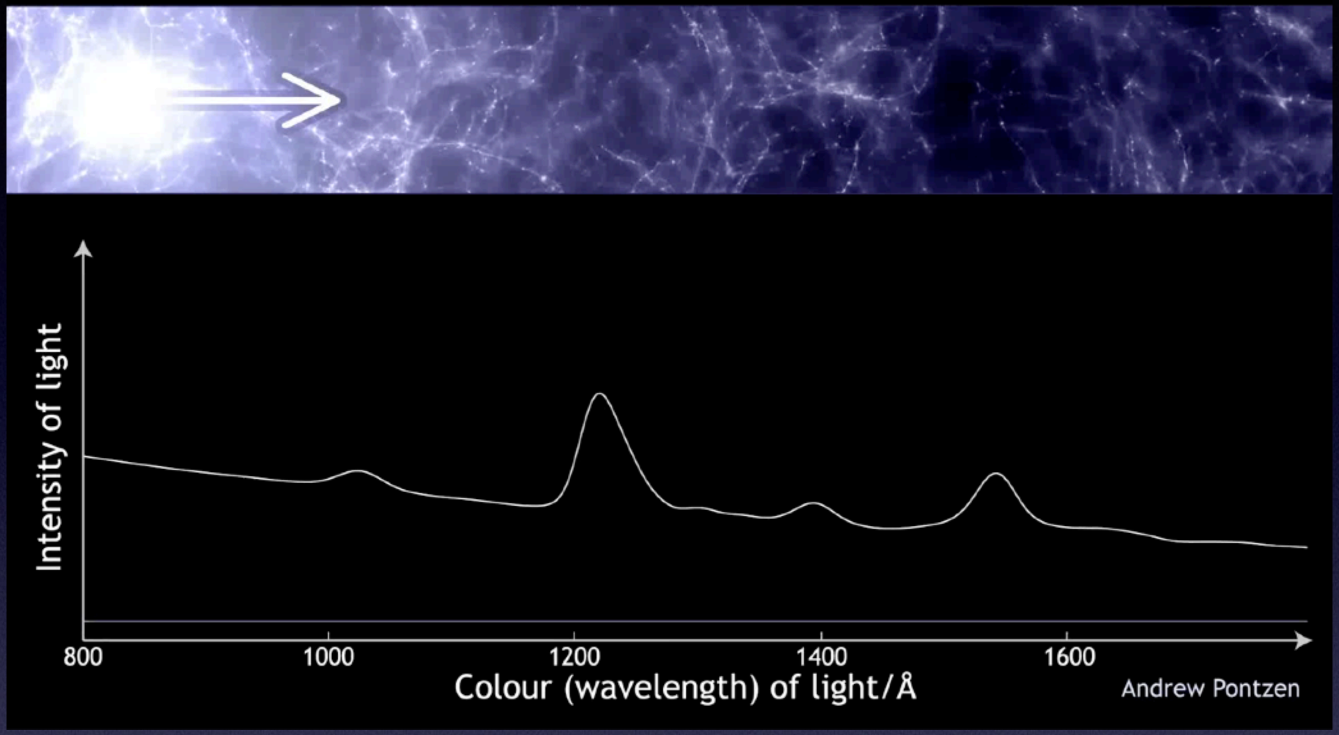

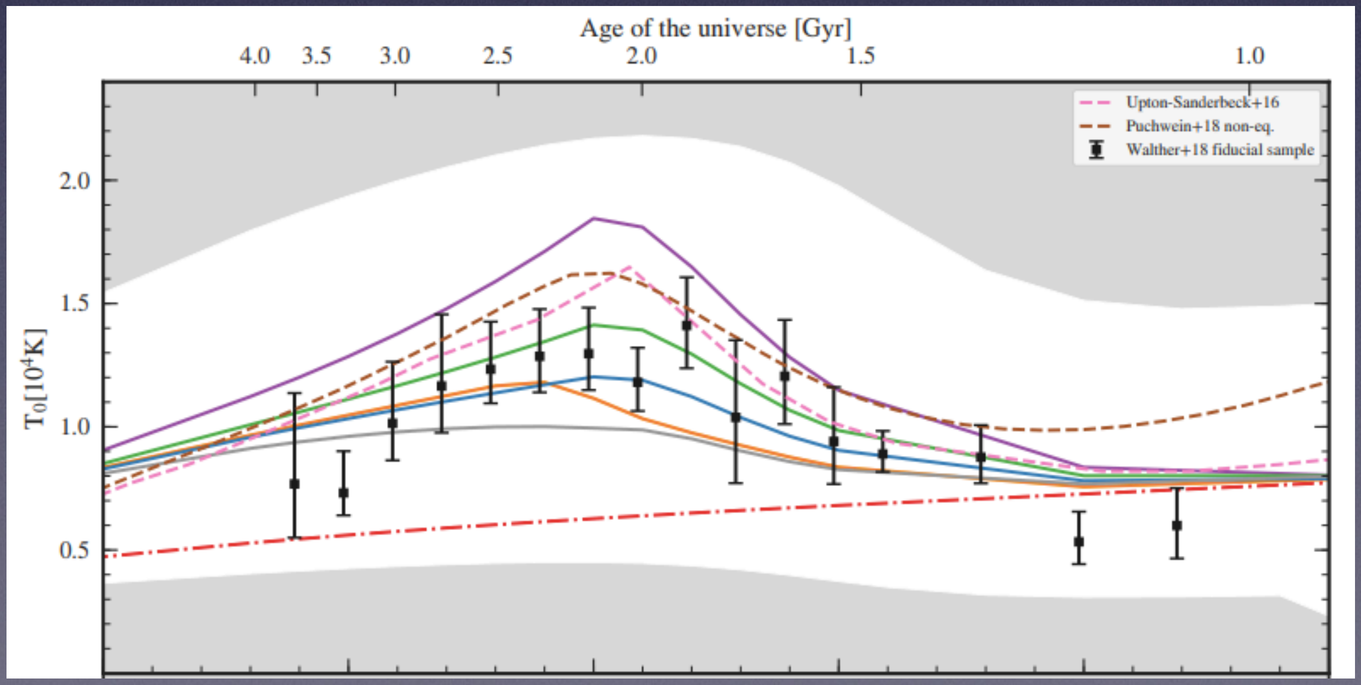

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Back-of-the-envelope signal estimates

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- Consider the power from DM decay - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe…
  - Planck CMB measurements can do a few orders of magnitude better than this - expect to constrain decay lifetimes ~10^{11-12} x the age of the universe during the cosmic dark ages ~ 10^{24-25} s.

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- How much spectral distortion to the CMB?
  - Radiation and matter energy densities were equal at z~3000, ratio scales as (1+z)
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in 10^6 or less. Much less sensitive than ionization for z < 1000.

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- How much change to the gas temperature?
  - Down to z~200, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is ~9 orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated => increase baryon temperature by ~5 eV per particle ~ 50,000 K - two orders of magnitude higher than baseline temperature at decoupling.
  - If we can test 10^{-11} of DM decaying at cosmic dawn, expect to test lifetimes of $10^{26\text{-}27}$ s.

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  - Down to z~200, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is ~9 orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated => increase baryon temperature by ~5 eV per particle ~ 50,000 K - two orders of magnitude higher than baseline temperature at decoupling.
  - If we can test 10^{-11} of DM decaying at cosmic dawn, expect to test lifetimes of 10^{26-27} s.

Back-of-the-envelope signal estimates

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  - If 10^{-8} of baryonic matt… …nize entire universe. There is ~5x as much DM mass as b…
  - If one in a billion DM… …half the hydrogen in the universe…
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probe of physics at z > 1000, or non-ionizing processes (e.g. scattering, oscillation)

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not probed by CMB, but potentially a large effect for z < 200 - can we see it in 21cm?

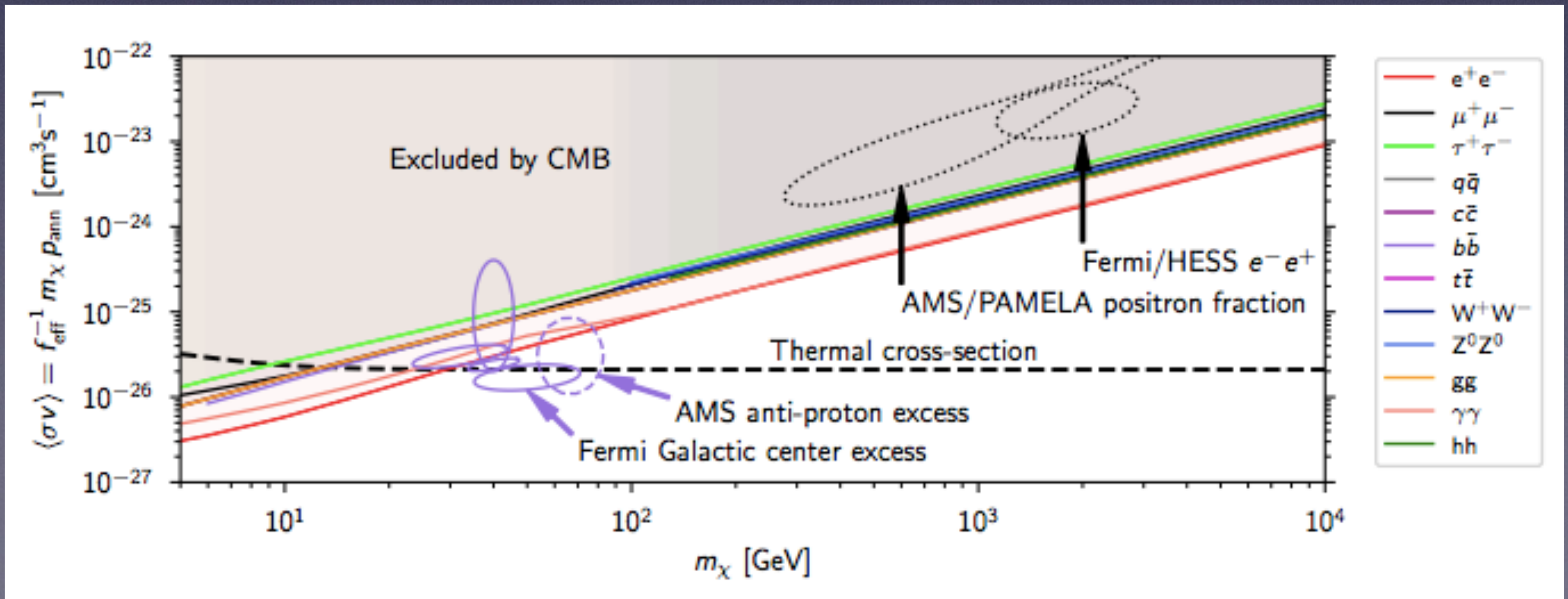
DarkHistory

computing modified ionization/thermal histories

- To study any of these effects, we need to know how particles injected by annihilation/decay transfer their energy into heating, ionization, and/or photons.
- My collaborators (Hongwan Liu, Greg Ridgway) and I have written a Python package to:
  - model energy-loss processes and production of secondary particles,
  - accounting for cosmic expansion / redshifting,
  - with self-consistent treatment of exotic and conventional sources of energy injection.
- Publicly available at https://github.com/hongwanliu/DarkHistory
- Calculates the modified cosmic temperature and ionization histories for arbitrary injection histories, reionization models.

Annihilation limits from ionization + the CMB

- 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 (which can be computed using DarkHistory or TRS '16).
- One analysis simultaneously tests all annihilation channels, huge mass range.
- Thermal relics with unsuppressed annihilation to non-neutrino SM final states (or intermediate states that decay to SM particles) can be ruled out for masses below ~10 GeV. Light DM needs a different origin mechanism, or suppressed annihilation.

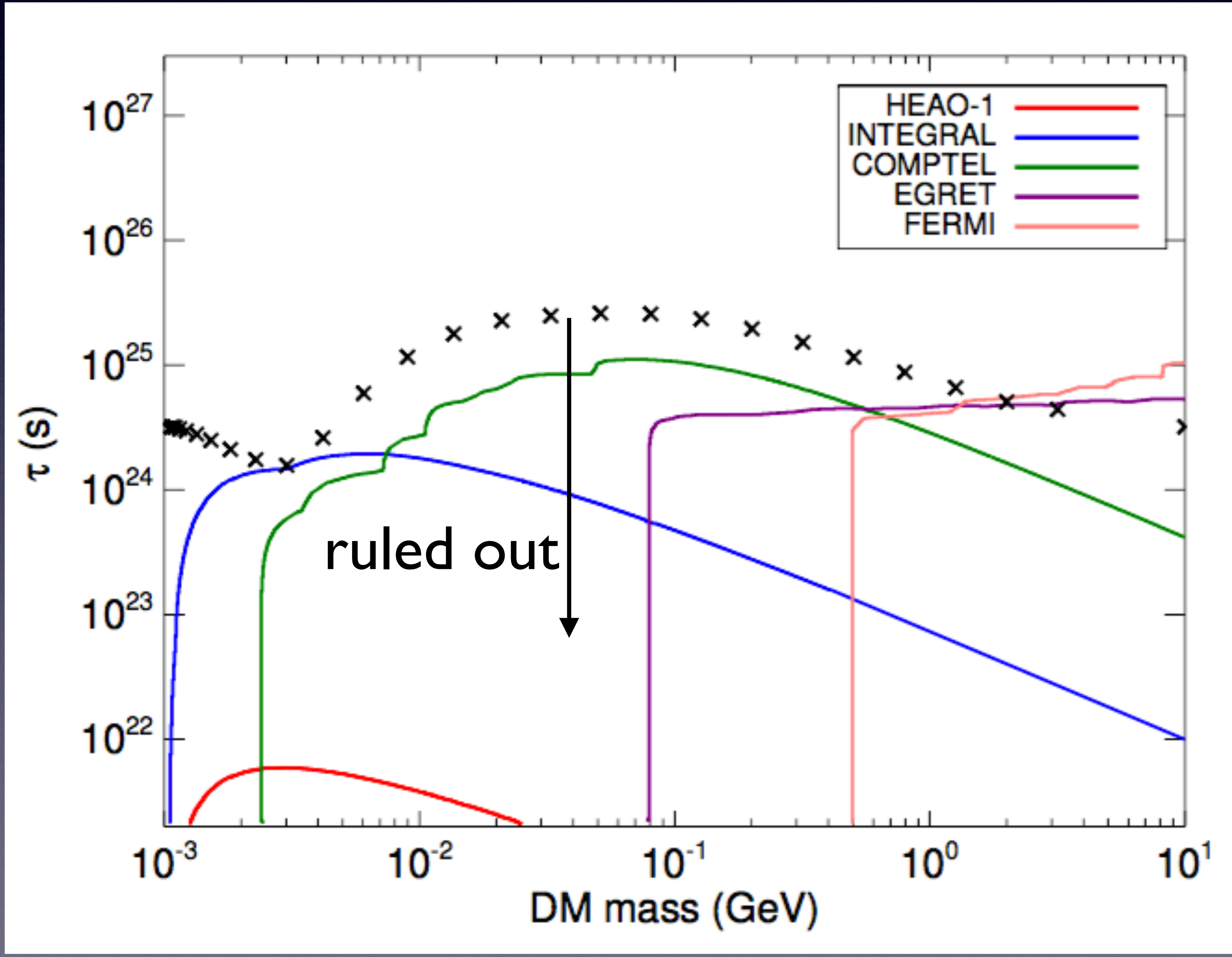


Planck Collaboration '18 1807.06209 based on results of TRS PRD '16

Decay limits from ionization + 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 ~10^{14} s)

TRS & Wu, PRD ‘17



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

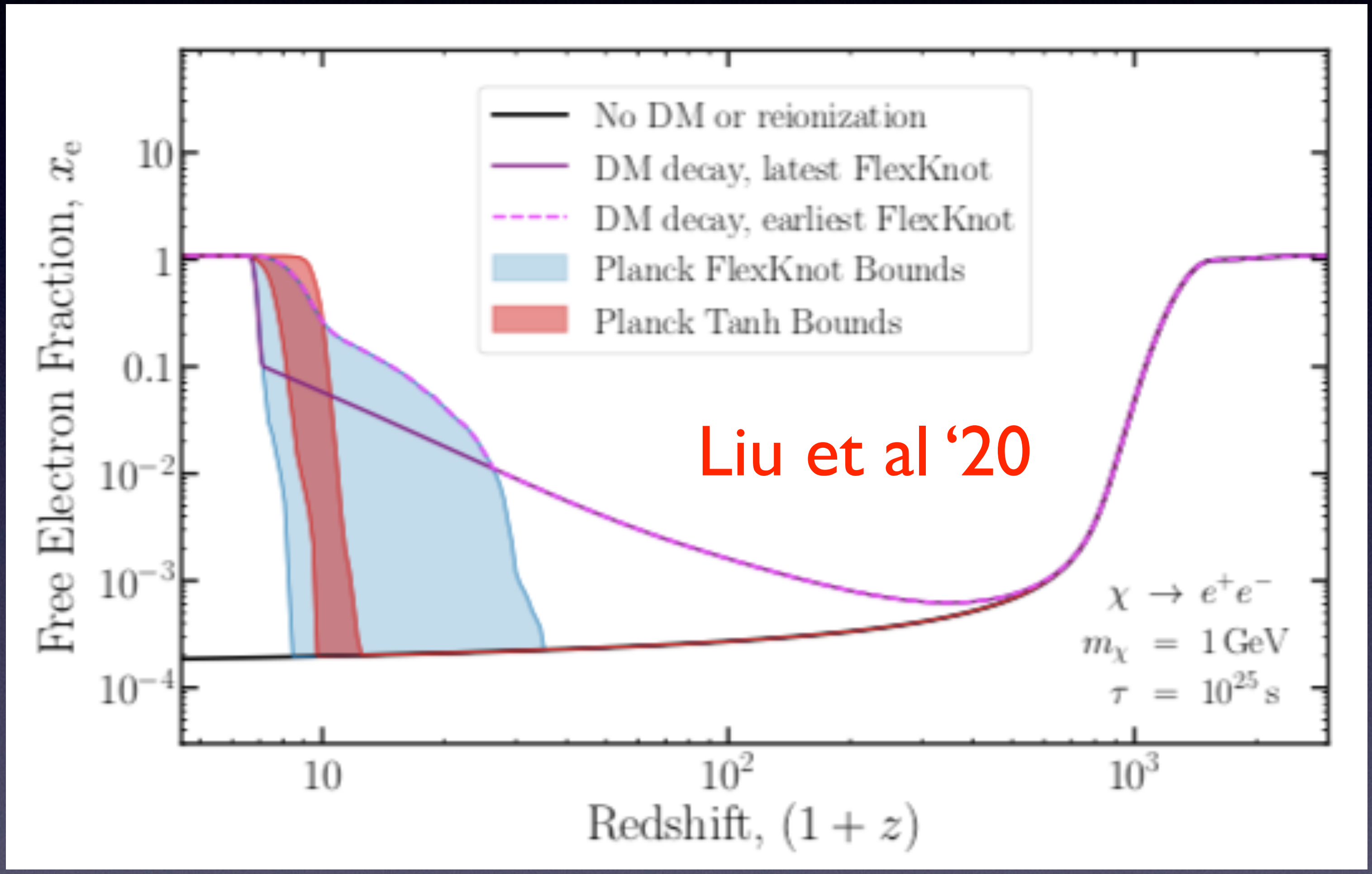
Testing DM with Ly-α

Liu, Qin, Ridgway & TRS '20

- We can compare the temperature history with a given DM model, computed by DARKHISTORY, to the temperature measurements extracted from the Ly-α forest
- Subtlety: these measurements apply to the epoch after reionization - what astrophysical reionization model should we assume?
- Need to account for interplay of ionization/heating:
  - when background ionization level is higher, injections of high-energy particles heat the gas more efficiently
  - radiation from stars/galaxies capable of reionizing the universe will also inevitably heat it

A self-consistent treatment of reionization

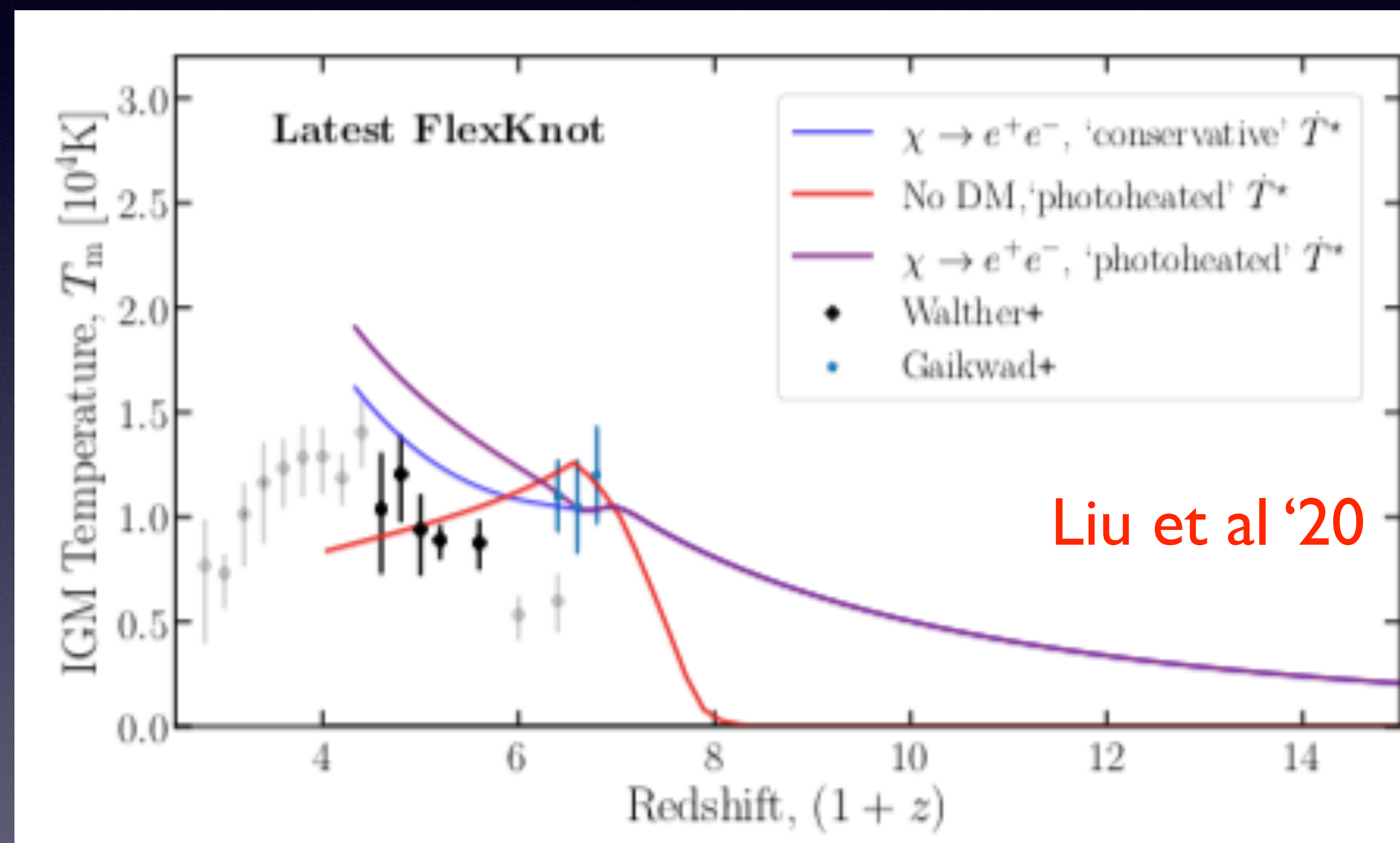
- Planck can now set fairly stringent constraints on the ionization history during reionization.
- Scan over the envelope of such allowed histories.
- Given a DM model and a reionization history, assume DM is the only source of ionization at early times. Fixed reionization history takes over when it exceeds DM-induced ionization.



- Effectively we assume that the fixed reionization history has a DM component and an astrophysical component - astro component is only constrained to be non-negative.
- Accommodates the largest possible DM signals.

Reionization-epoch heating from DM

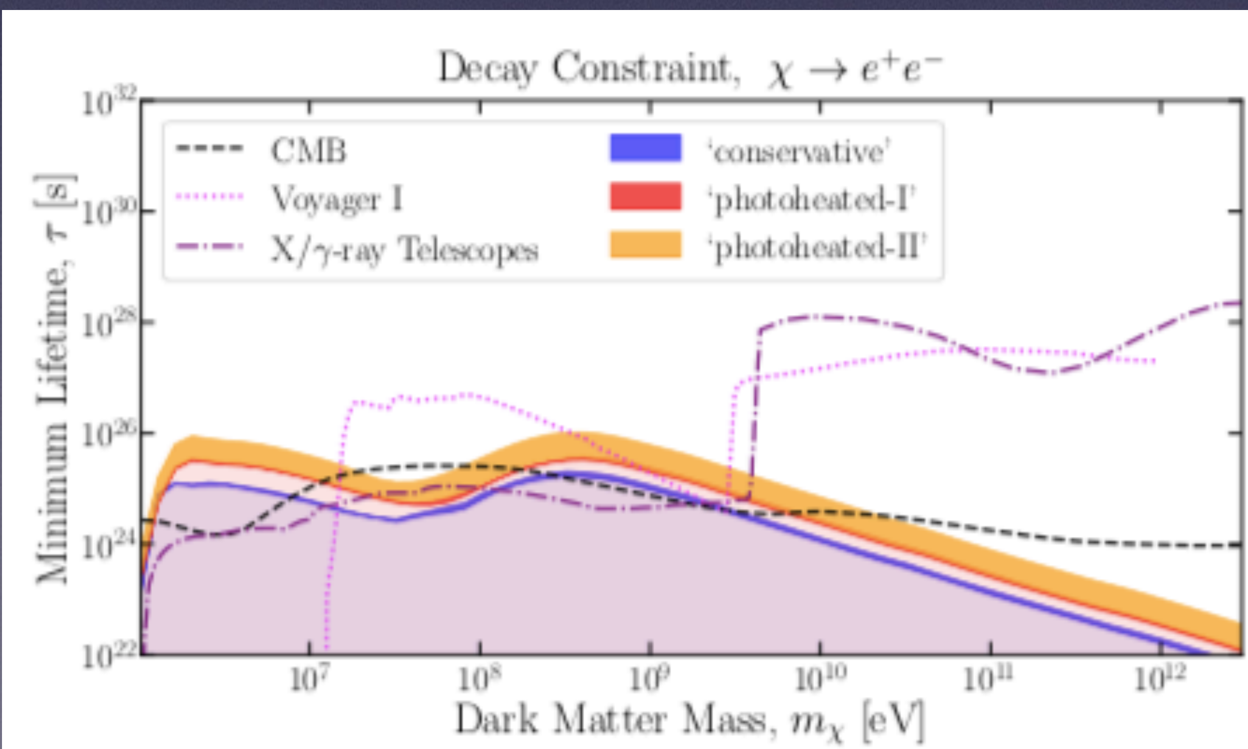
- Using DARKHISTORY + this approach, we can scan over a set of DM models + reionization histories allowed by Planck
- Two methods for characterizing heating:
  - "Conservative" - include no photoheating from astrophysics, only heating from DM
  - "Photoheated" - include a model for the photoheating associated with the photoionization needed to match the reionization history



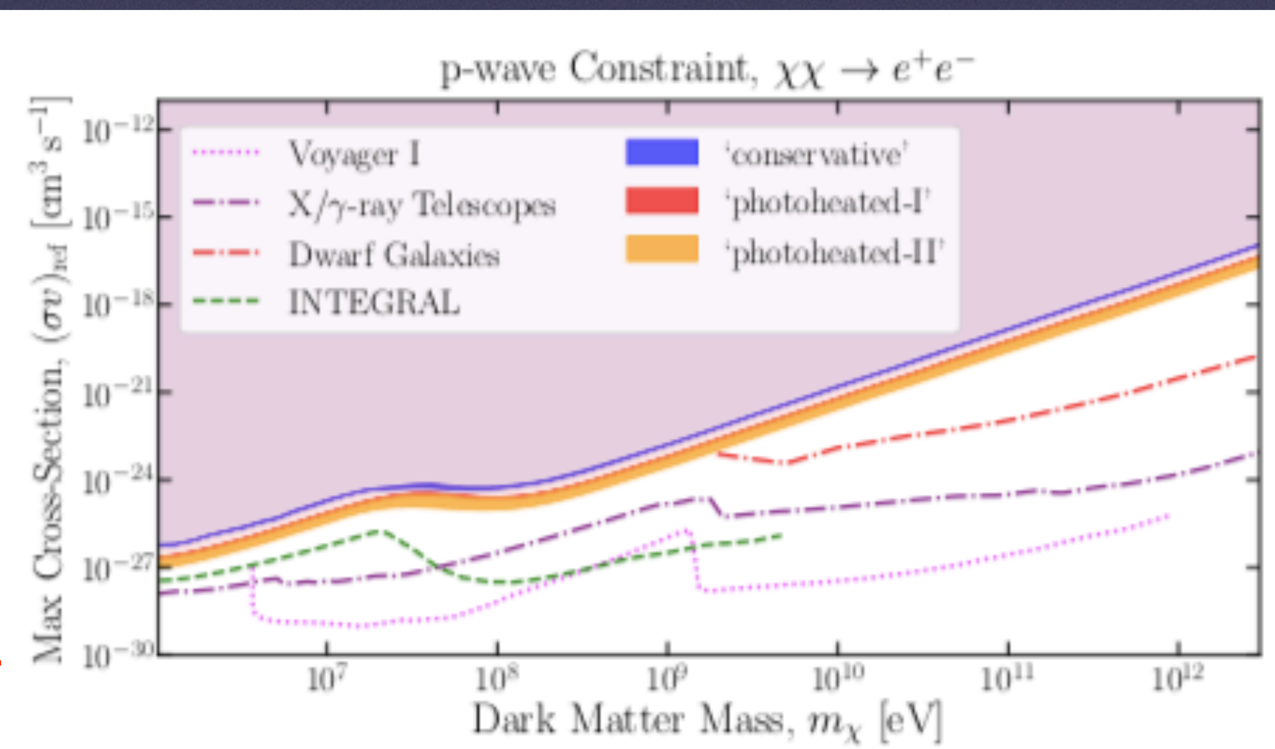
- Blue and purple lines correspond to the same DM model, on the edge of being excluded in "conservative" approach, clearly excluded for "photoheated" approach

Constraints on DM decay/annihilation

- Example limits on DM decaying or annihilating to electrons and positrons.
- Width of bands denotes uncertainty in reionization history. Conservative vs photoheated limits differ by a factor of a few, up to 1 order of magnitude.
- Limits are broadly competitive with other constraints for light DM that decays or annihilates through p-wave processes (suppressed at low velocities). For s-wave annihilation CMB bounds are stronger.

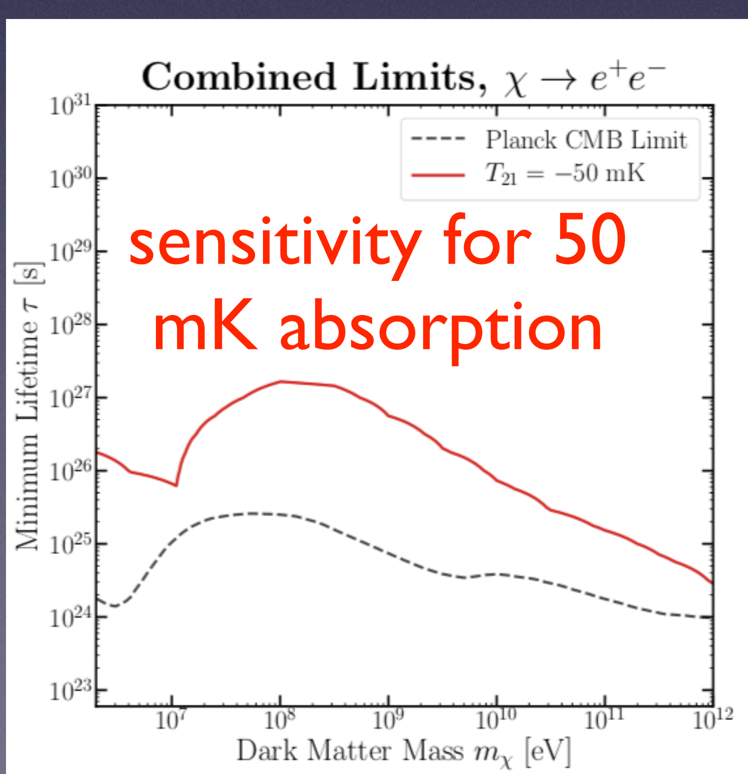


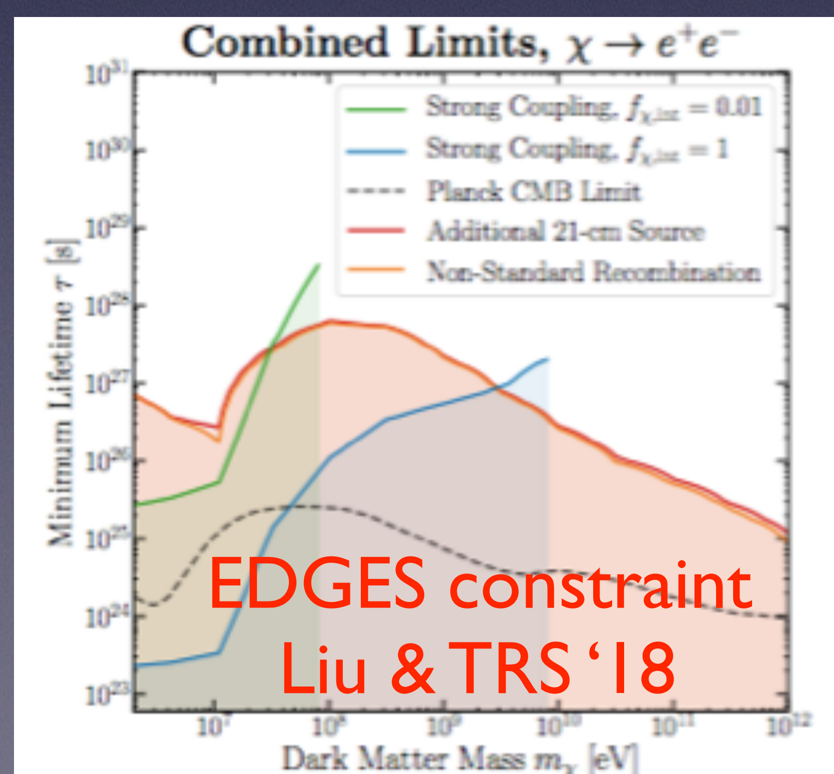
Liu et al '20



Decay sensitivity from heating + 21cm

- Consider a hypothetical 21cm measurement of T_{21} < -50 mK at z~17. If T_R=T_{CMB}, this corresponds to an upper limit on the gas temperature of T_m~20 K.
- With DarkHistory, it is easy to compute the resulting limits.
- Limits on light DM decaying leptonically (for example) could improve by two orders of magnitude - or optimistically, we could see a strong heating signal.
- Similar limits if EDGES signal is confirmed [Liu & TRS '18] - in this case you need other new physics to explain the deep absorption trough, but various options we tested all lead to strong constraints.



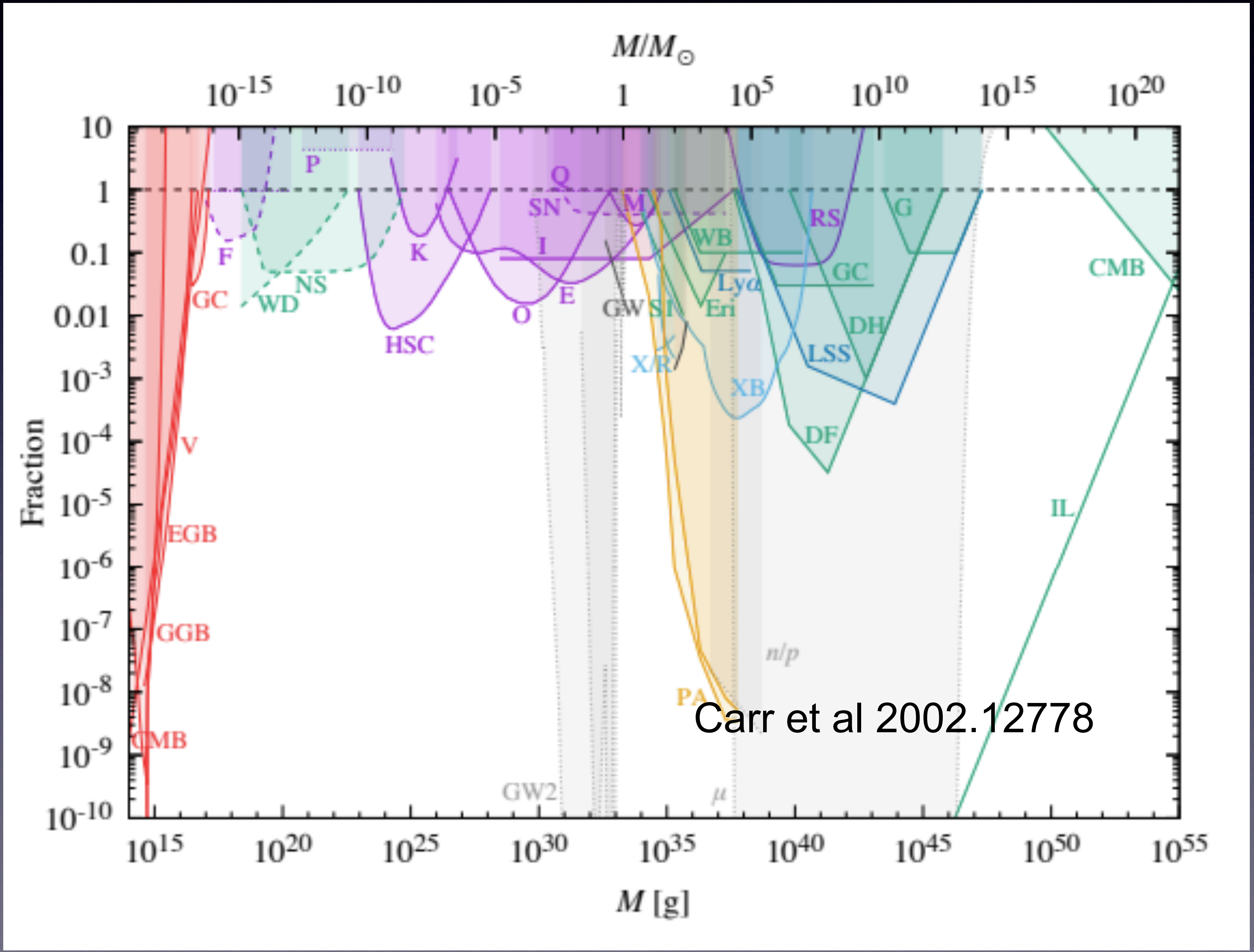


- Orange, blue, green regions correspond to excluded lifetime region under different assumptions about physics giving deep EDGES absorption trough
- Blue/green regions require DM mass below a certain cutoff to explain EDGES

Beyond particle dark matter: primordial black holes?

- General idea: black holes can be formed from inhomogeneities in the high-density early universe [see Carr et al 2002.12778 for a recent review containing more comprehensive references].
- Black holes are electrically neutral (or quickly become so) and interact primarily via gravity.
- Sufficiently heavy black holes have a lifetime >> age of the universe.
- Black holes would be heavy, non-relativistic "particles", and would play the cosmological role of DM provided they are formed well before matter-radiation equality.
- Perhaps the most plausible DM scenario that does not require DM to be comprised of new particles beyond the Standard Model.
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass).
- We have argued the early universe gives powerful limits on decaying particle DM - what about PBHs?

Constraints on PBHs as DM



- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from $M \sim 10^{17}$-10^{23}g
- The lower edge of the window is set by non-observation of Hawking radiation

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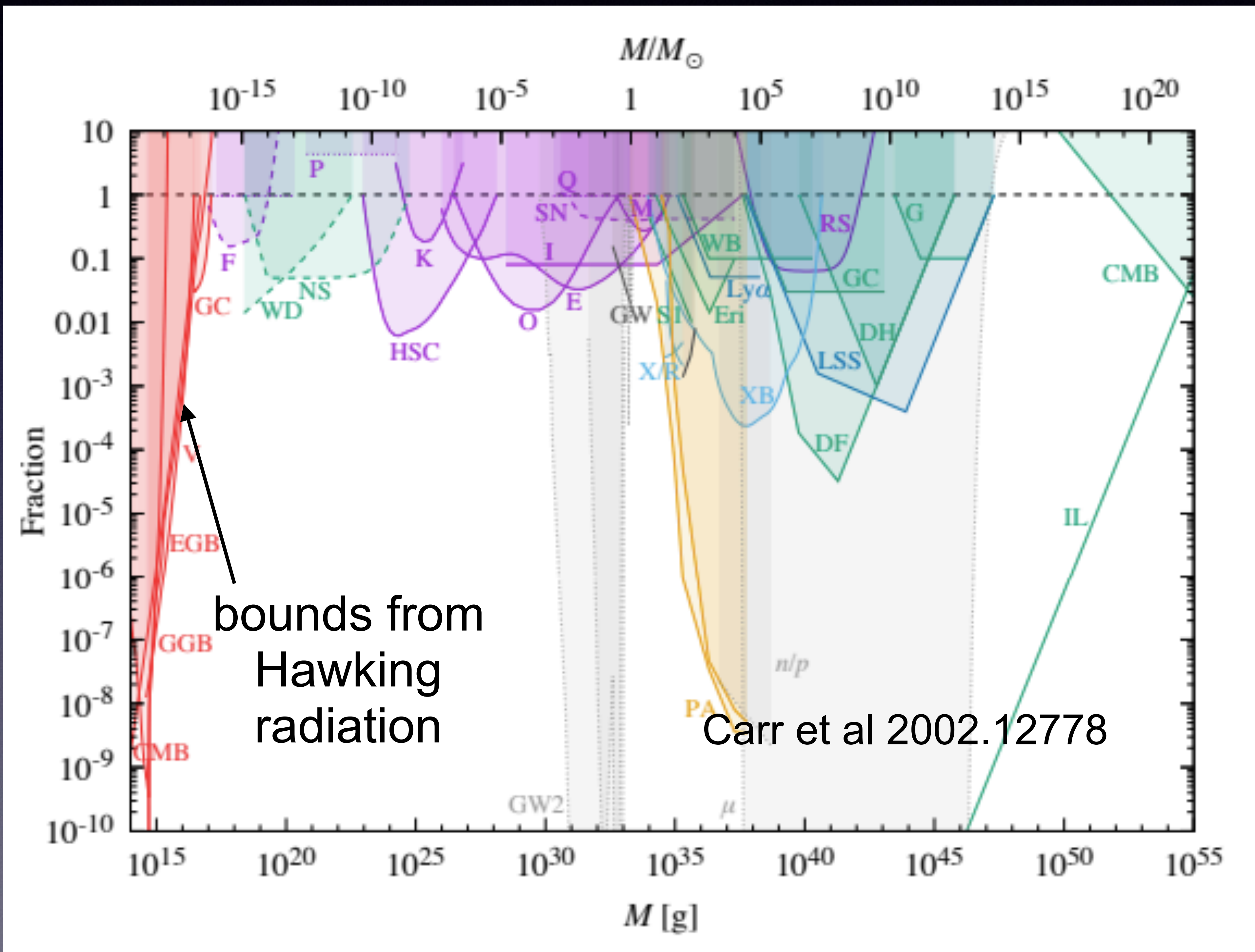

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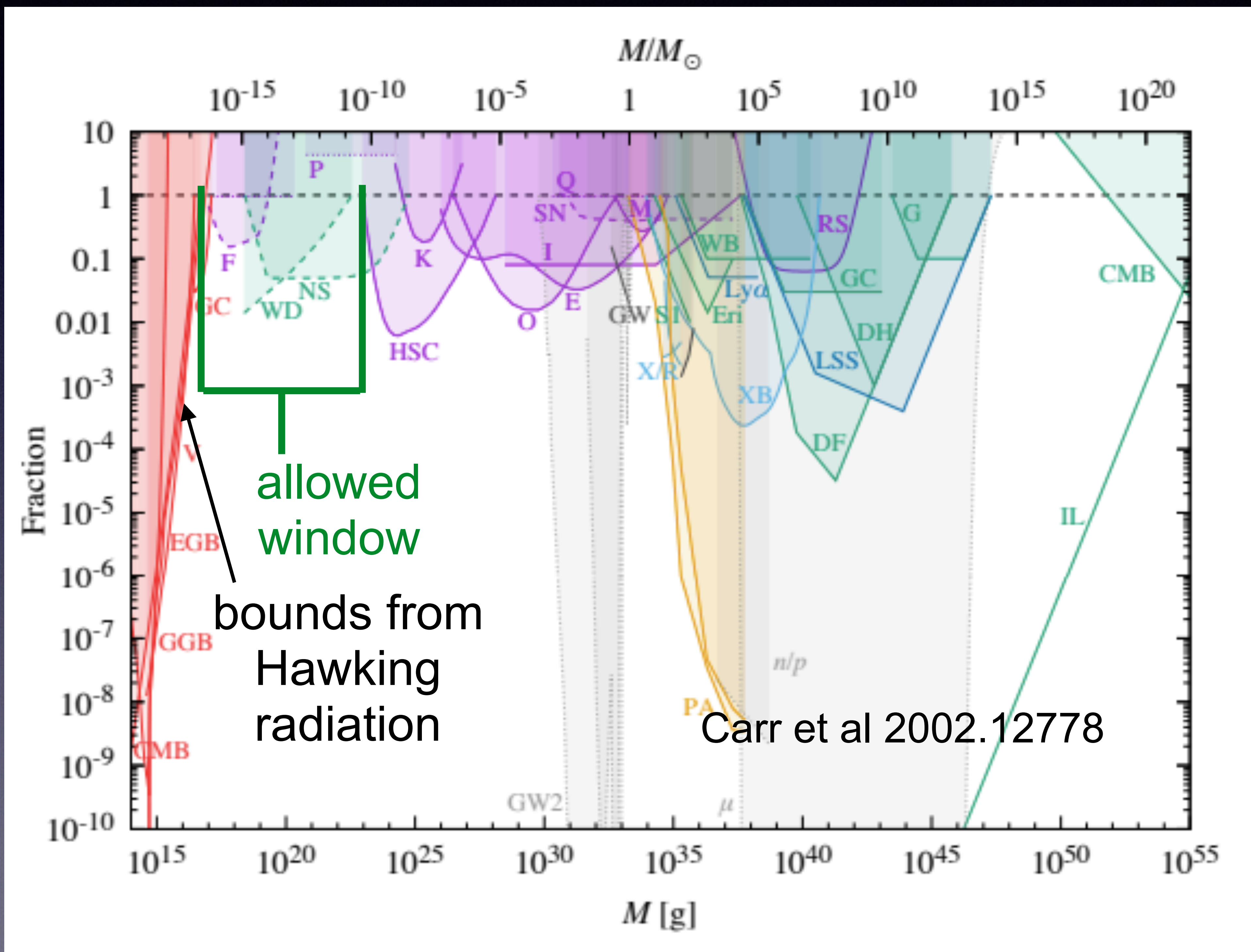

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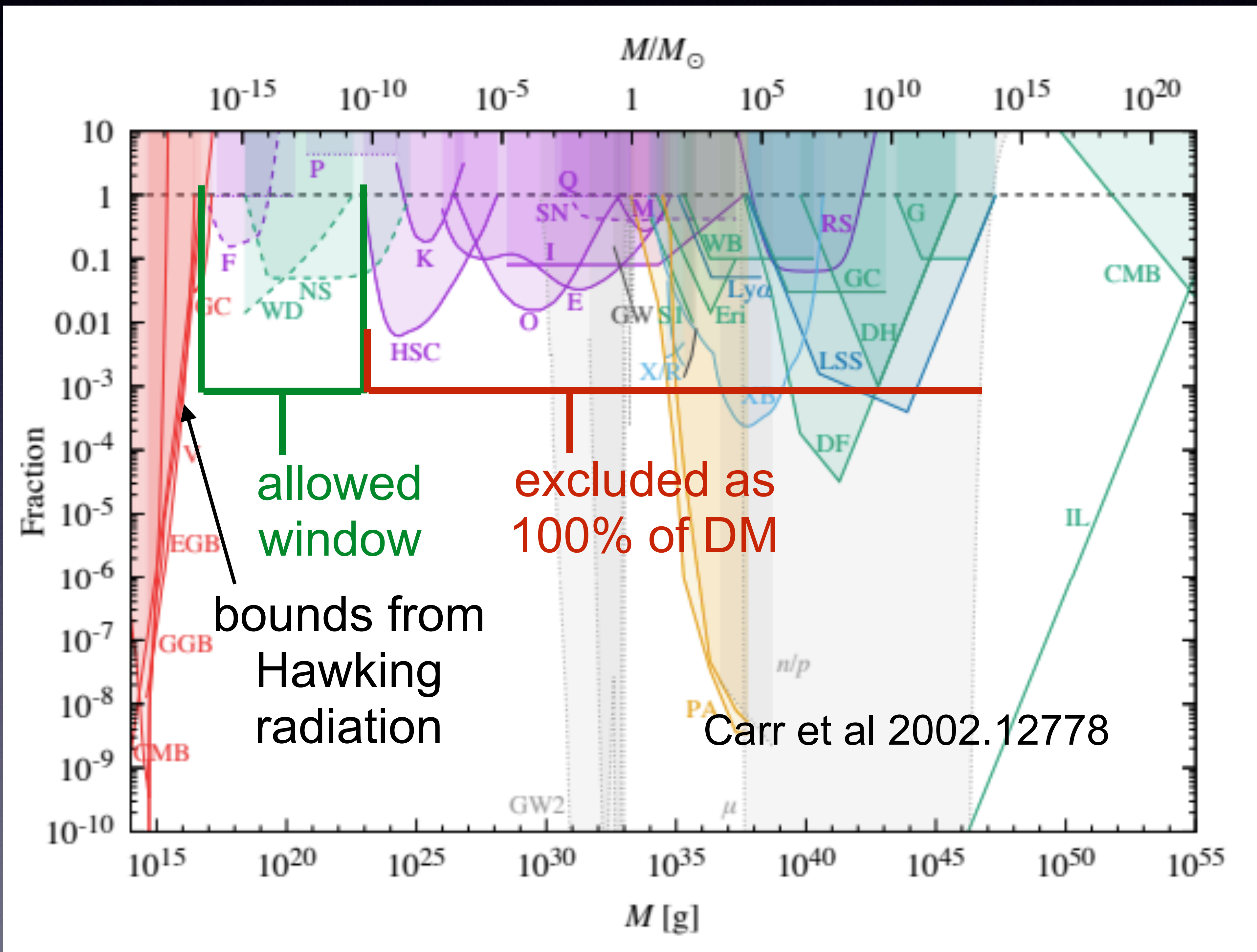

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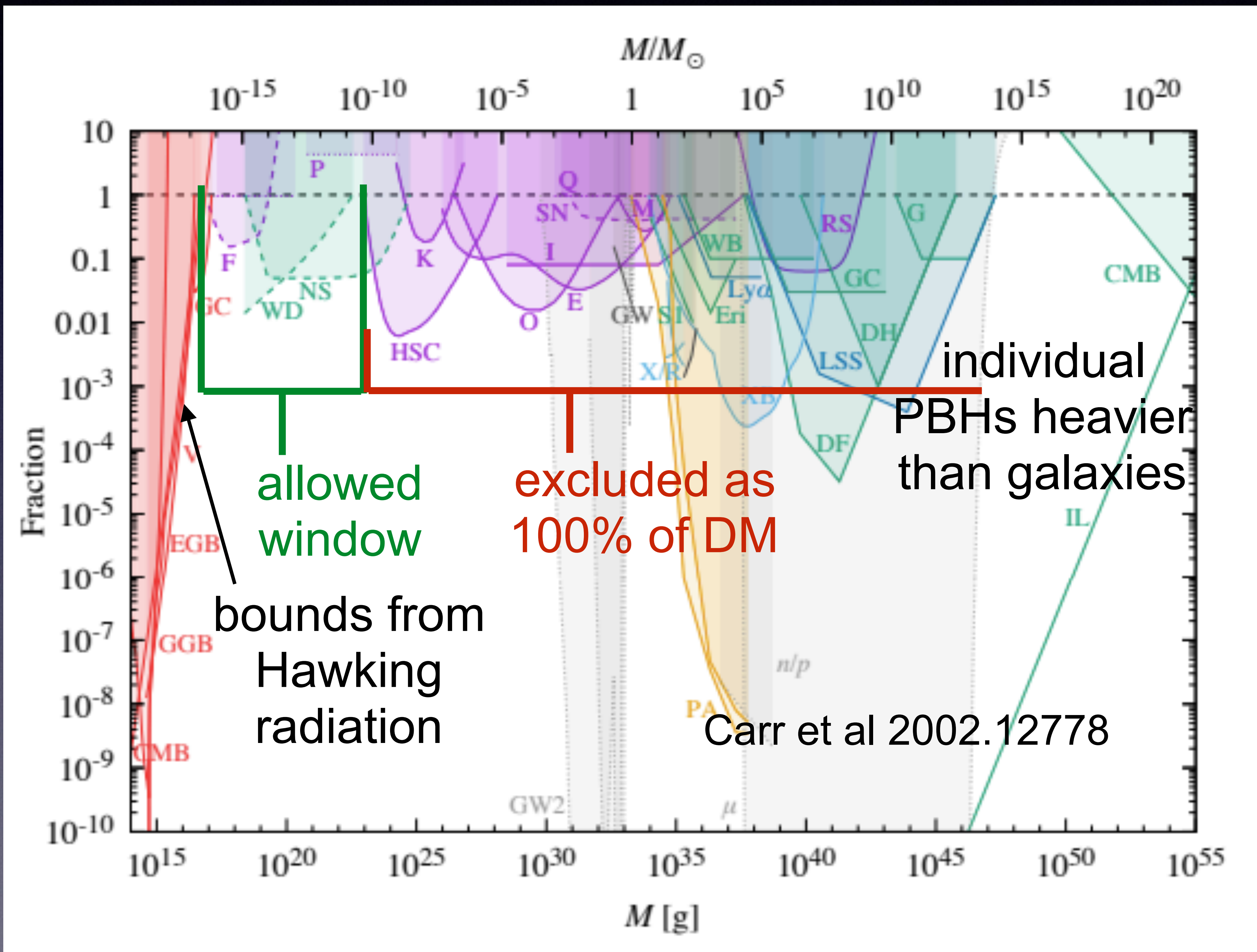

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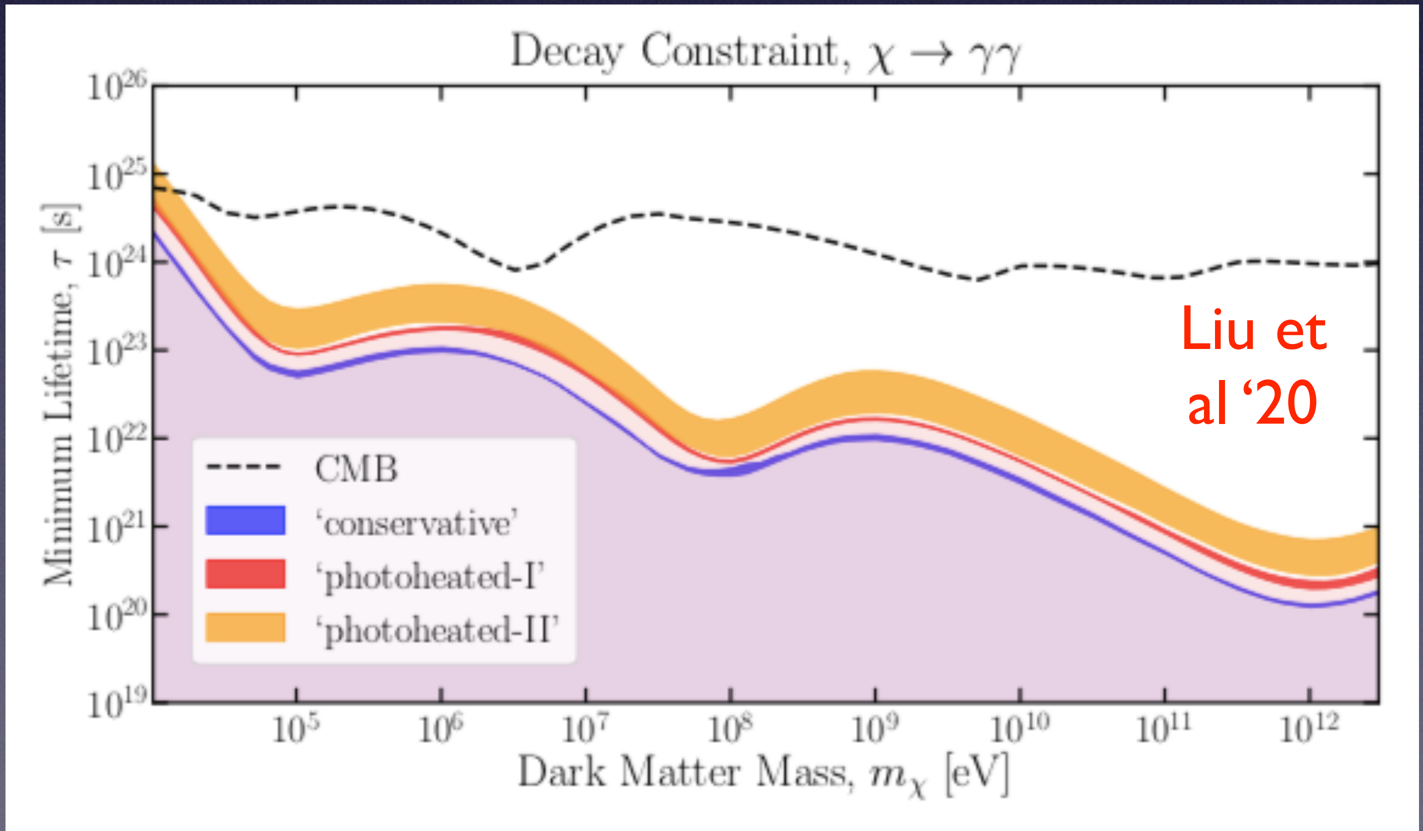
Hawking radiation from asteroid-mass PBHs

- For PBHs the lifetime and peak energy of radiated particles are not independent, both are controlled by DM mass:

$$E \approx 5.77 T_{\rm BH} \approx \left(\frac{10^{17}\text{g}}{M_{\rm BH}}\right) 0.4\text{MeV} \qquad \tau \approx 8\times 10^{25}\text{s} \left(\frac{M_{\rm BH}}{10^{17}\text{g}}\right)^3$$

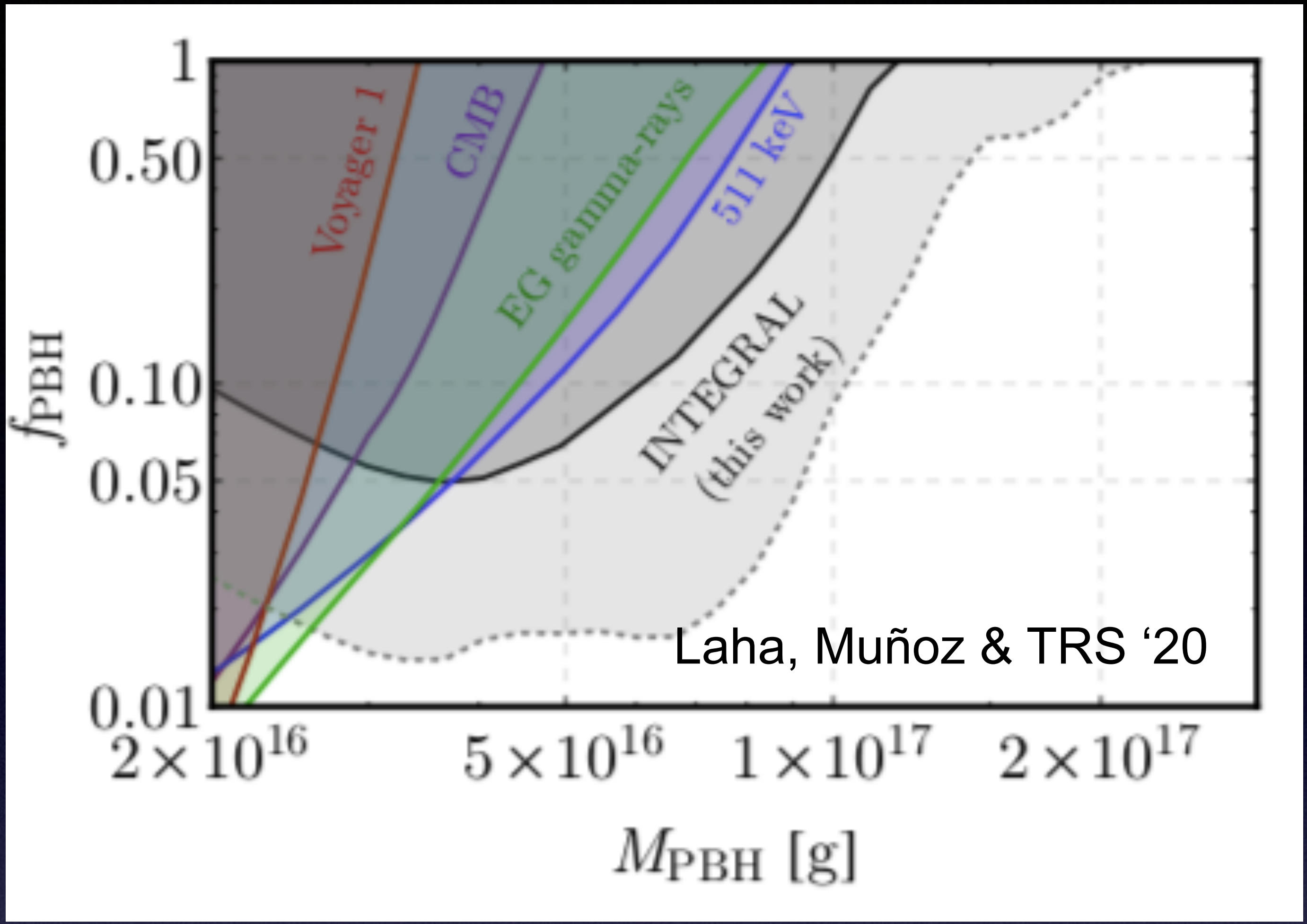
- Decay lifetime limits from CMB are around $10^{24\text{-}25}$ s - expect to constrain BH masses around 5×10^{16} g if they make up 100% of DM.
- Self-consistency check: signal at these masses peaks around 1 MeV; comparable to signal from O(MeV) particle DM.



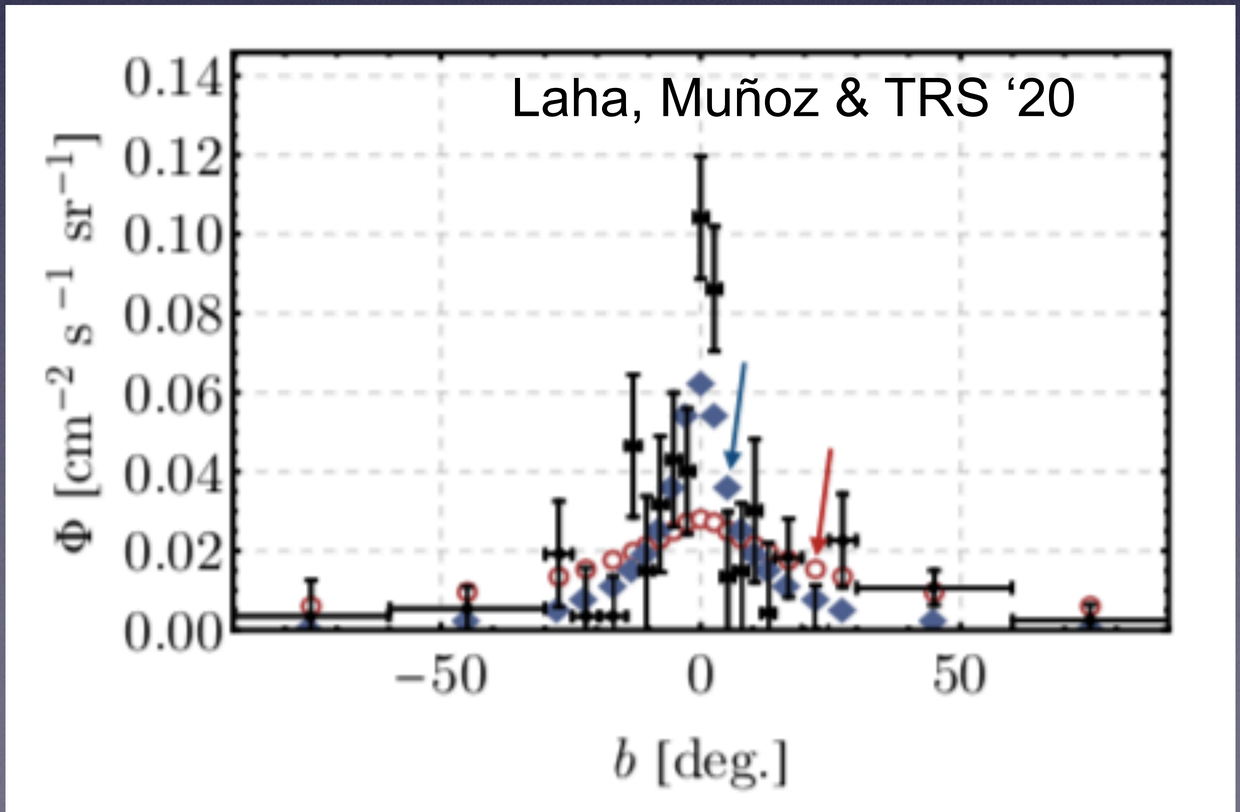
CMB/heating limits for decay to photons (and photon-rich final states)

The Galactic halo

- For emission of photons, especially with a pronounced spectral feature, direct searches for photons can beat these cosmological bounds
- Best current limit comes from re-analysis of data from INTEGRAL (launched 2002) - not a new instrument!
- Very simple analysis, no background subtraction, results averaged over wide bins in photon energy/direction
- Potential for considerable improvement!



200-600 keV, |l|<23.1°



Summary

- Astrophysical and cosmological datasets are enormously rich and can provide powerful probes of the non-gravitational properties of dark matter (as well as its gravitational effects), over a huge range of possible scenarios.
- We have developed a new public numerical toolbox, DarkHistory, to self-consistently compute the effects of exotic energy injections on the cosmic thermal and ionization histories.
- The cosmic microwave background provides stringent limits on DM interactions with the Standard Model, across a very broad range of models.
- Existing temperature measurements from the Lyman-α forest can provide even stronger limits on light DM decaying or annihilating to electrons.
- In the future, 21cm measurements could set powerful new constraints on DM-SM interactions, especially for light leptonically-decaying DM.
- Similar limits apply to Hawking radiation from primordial black holes - although in the near future, observations of the Milky Way DM halo may be a more promising channel.