Deciphering the Universe's Dark History

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University of Toronto
Physics Colloquium
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PRD '18, 1803.09739 (Hongwan Liu, TRS)
PRD '18, 1803.09734 (TRS, Chih-Liang Wu)
arXiv:1904.09296 (Liu, Greg Ridgway, TRS)
arXiv:1904.10539 (Kahlhoefer, Kaplinghat, TRS & Wu)

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Outline

- The puzzle of dark matter
  - what we know, and what we don't
  - why astrophysical/cosmological data holds promise for testing currently-unknown properties of dark matter
- Testing possible effects of dark matter physics on the early universe
  - Confronting light dark matter with the cosmic microwave background (CMB)
  - Taking the universe's temperature with 21cm observations
- Could the history of the Milky Way's satellite galaxies be changed by dark matter self-interactions?


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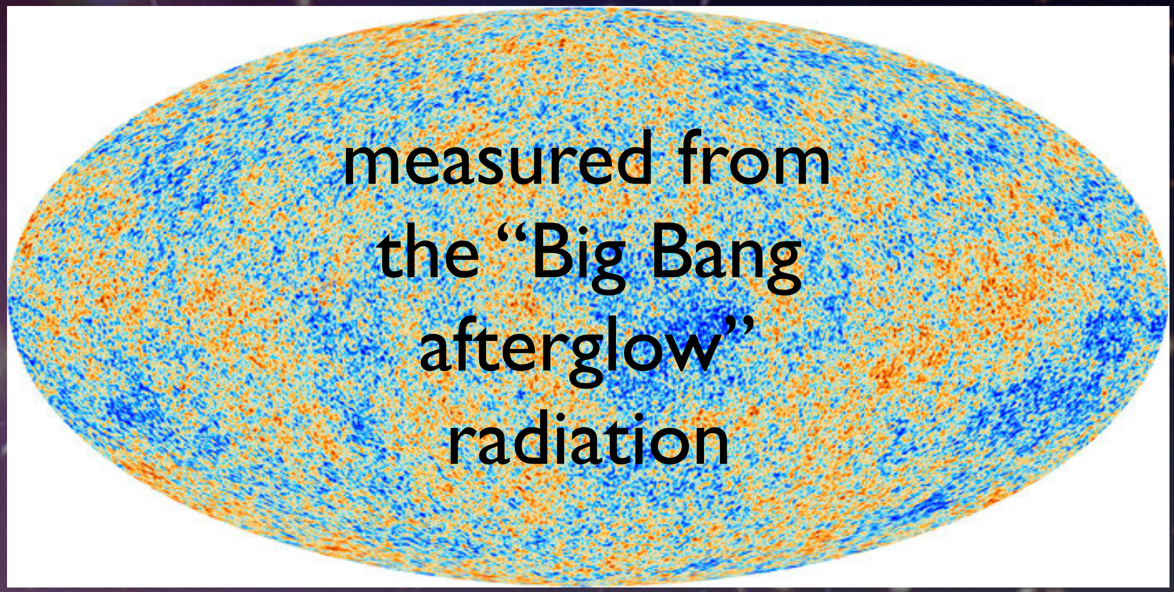

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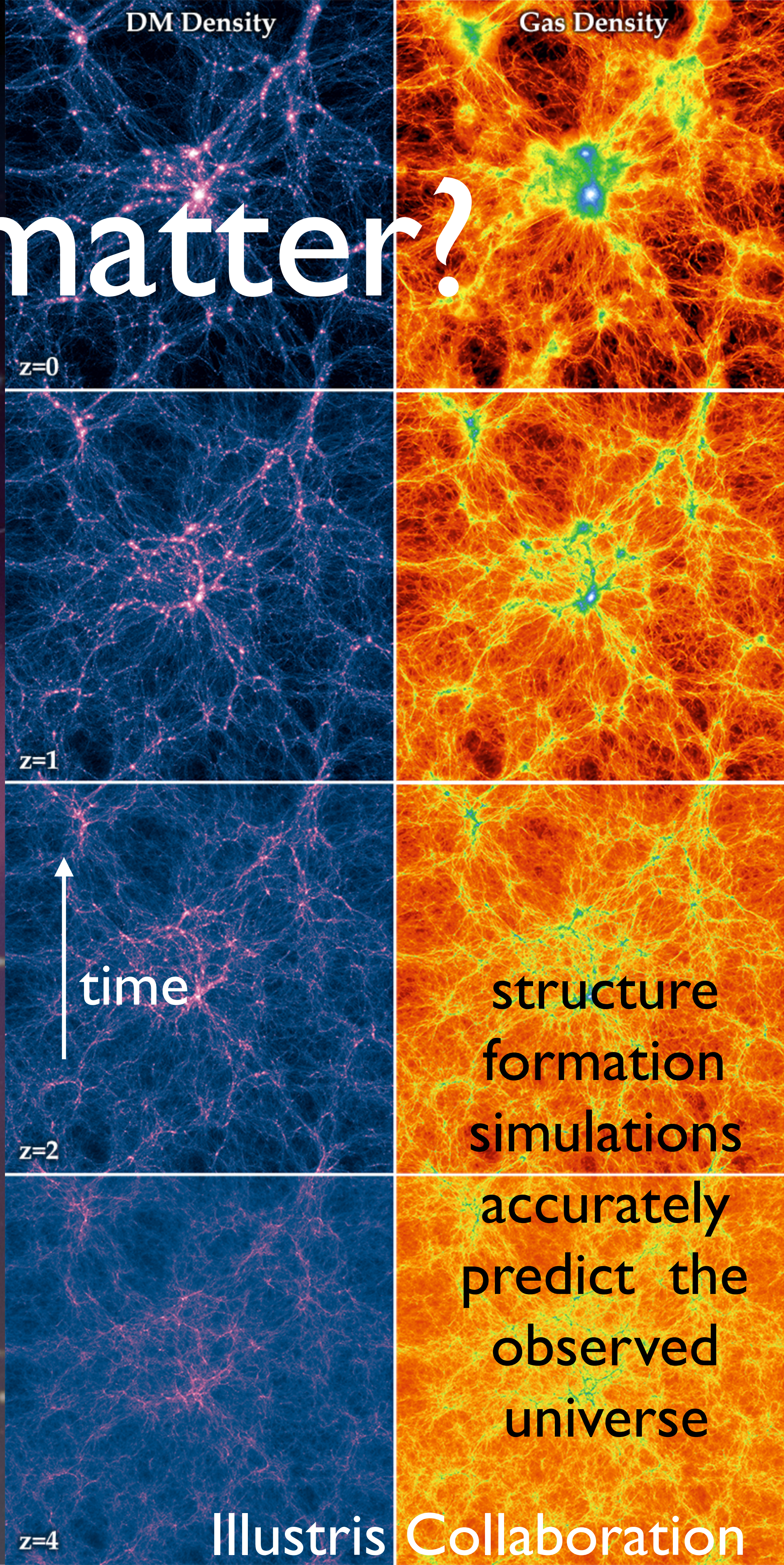

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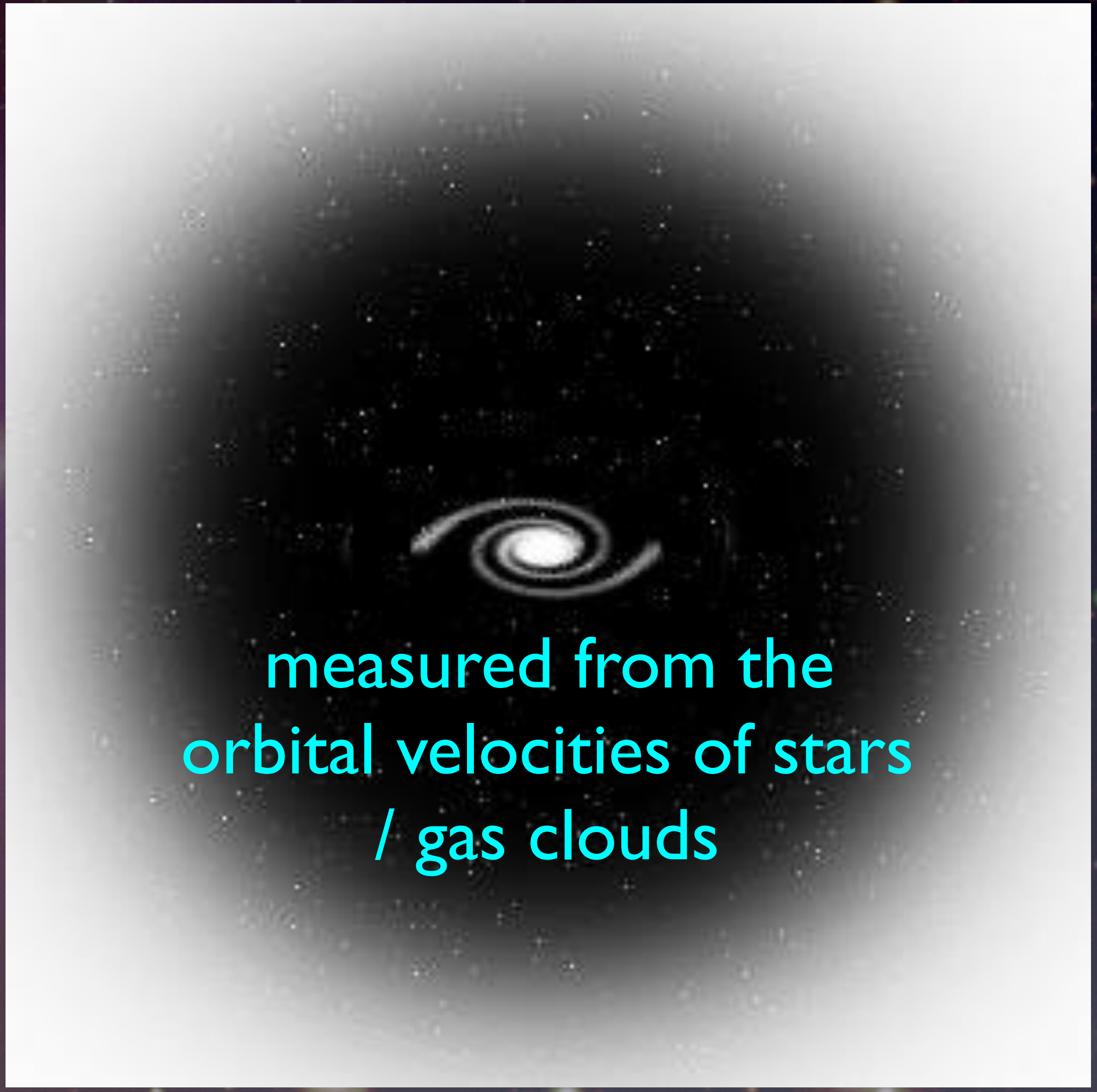

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- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

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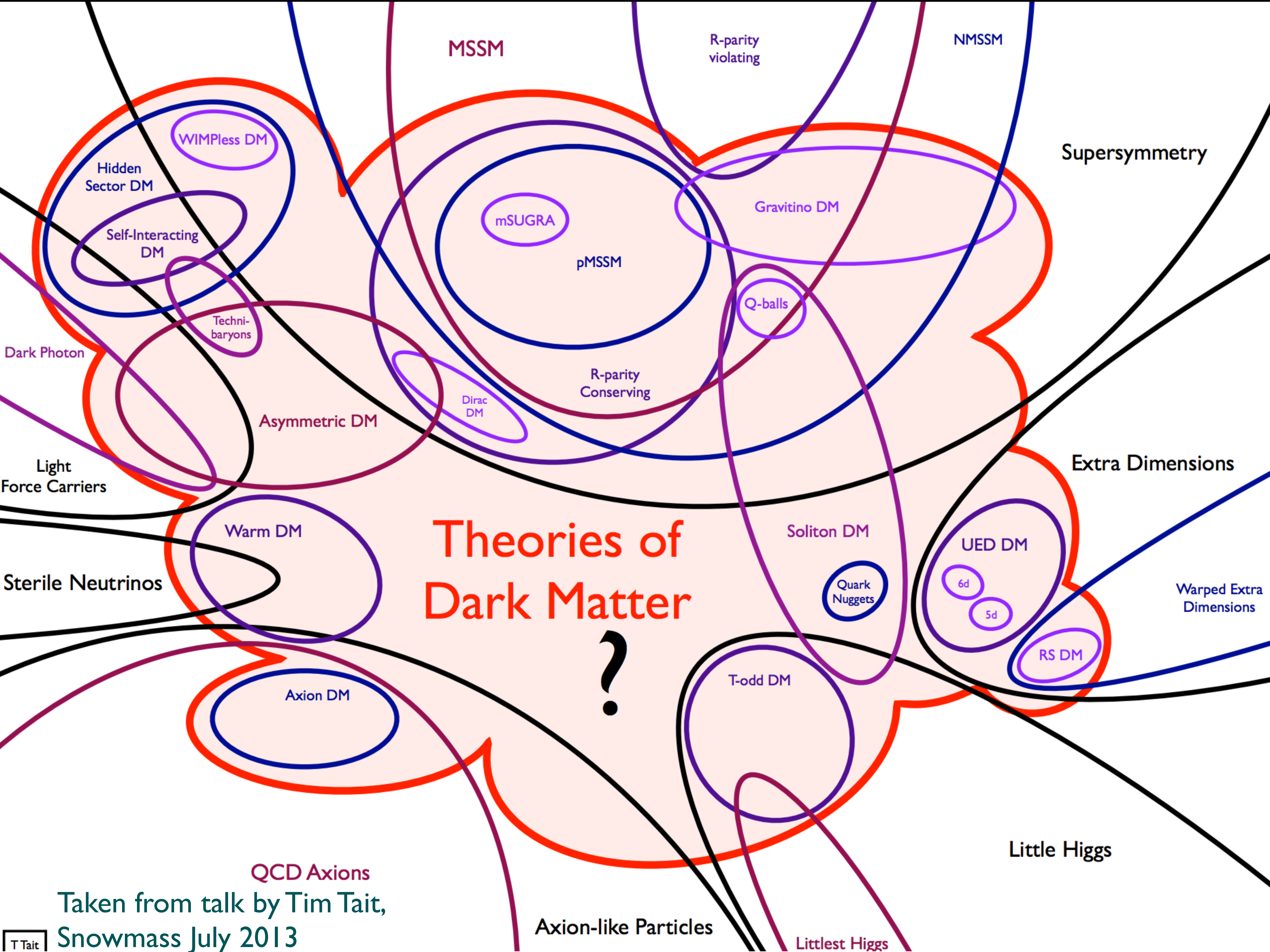
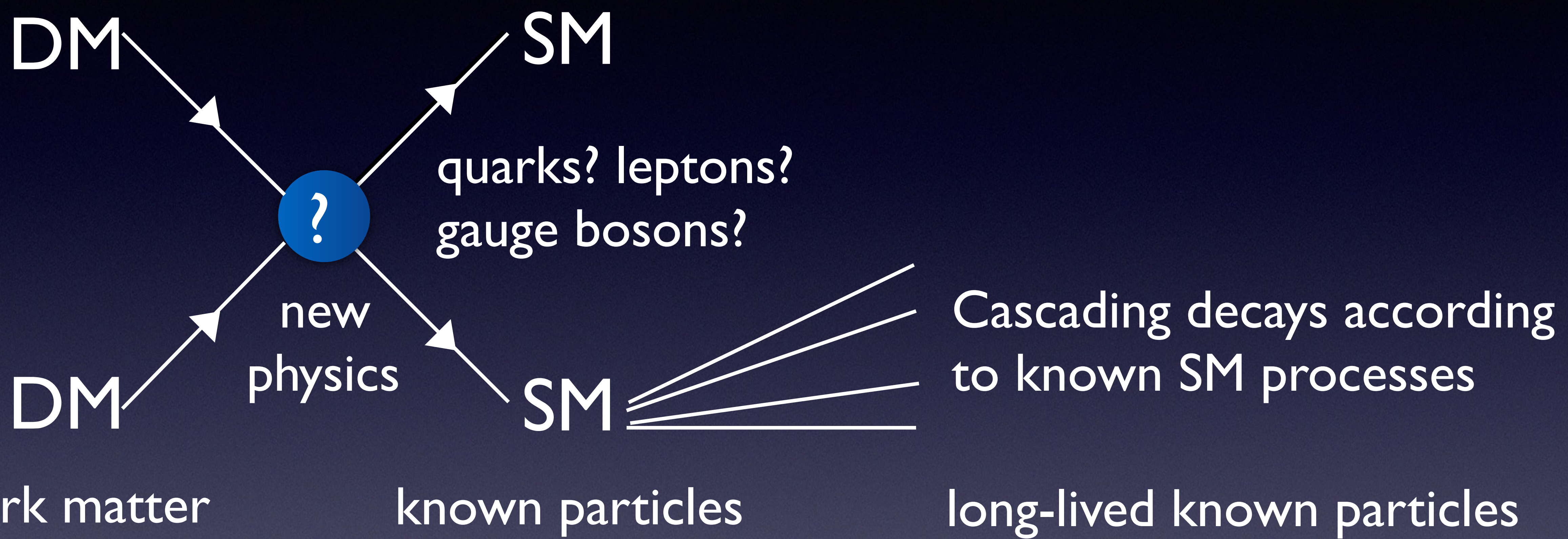
- and many more…



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?
- what are some generic ways dark matter might interact with the Standard Model, and itself?

Annihilation

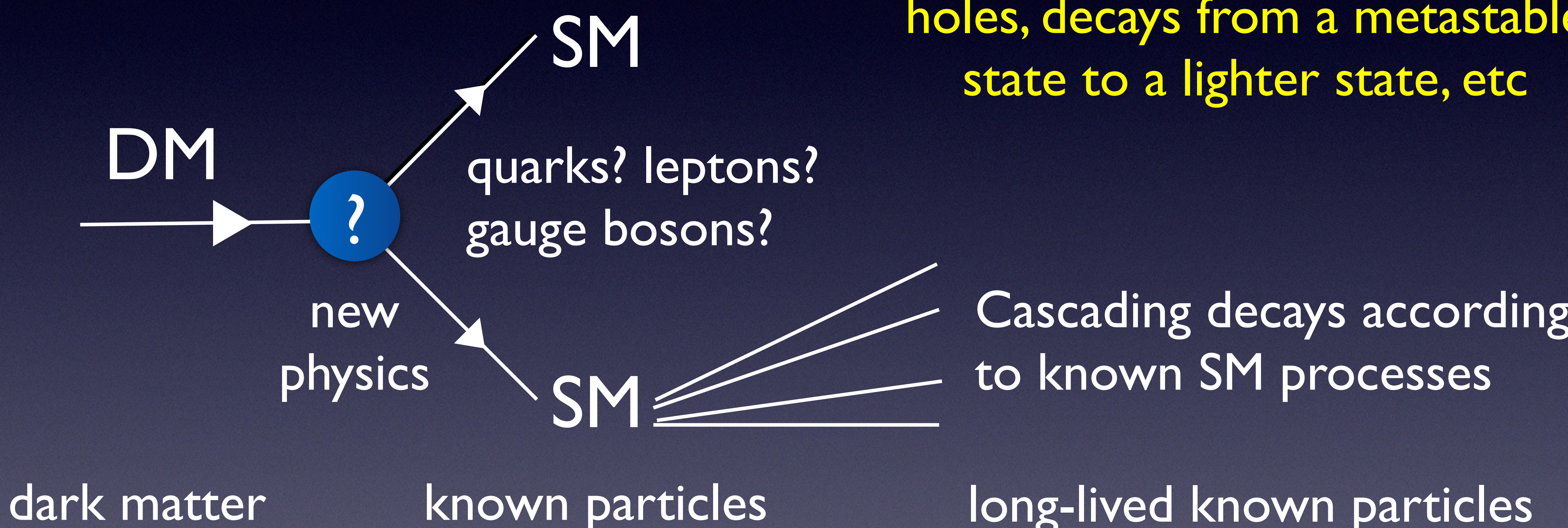


- Tightly linked to DM abundance in scenarios where the DM was initially much more abundant, and these annihilation processes depleted it ("thermal relic" scenario).
- Such scenarios favor a benchmark annihilation rate, called the "thermal relic cross section".

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

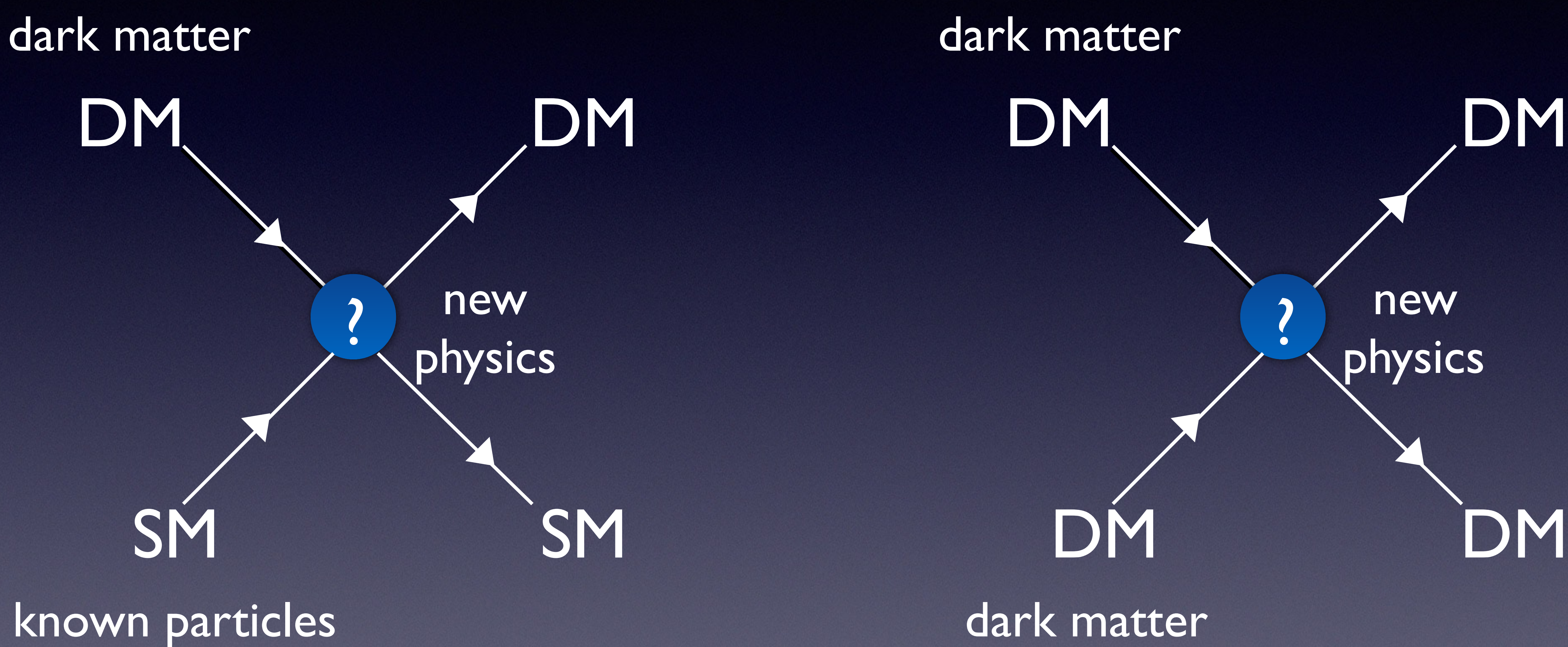
Decay

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



- 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

Scattering



- If the dark matter is colder than the visible matter, scattering could lead to an energy flow in the other direction, cooling the visible universe
- Scatterings between dark matter particles can lead to heat flow within dark matter clouds - change how the dark matter is distributed

A broad set of questions

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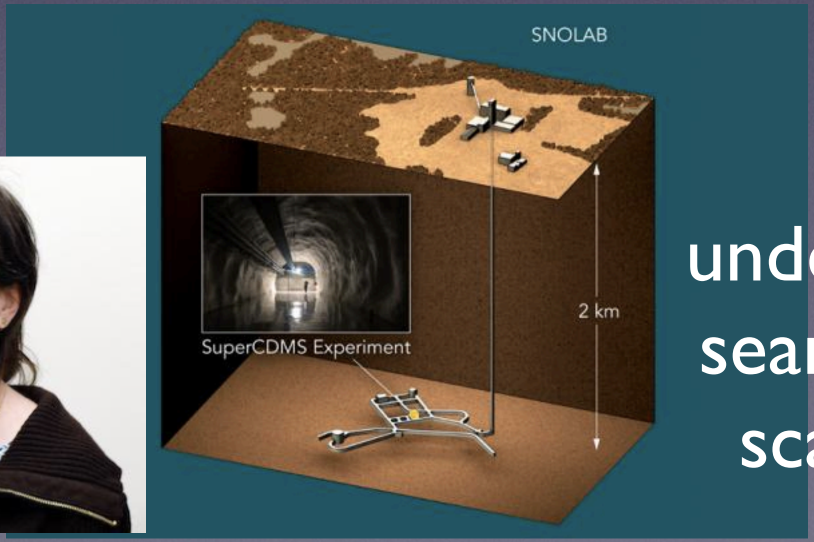

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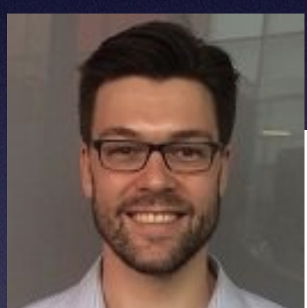
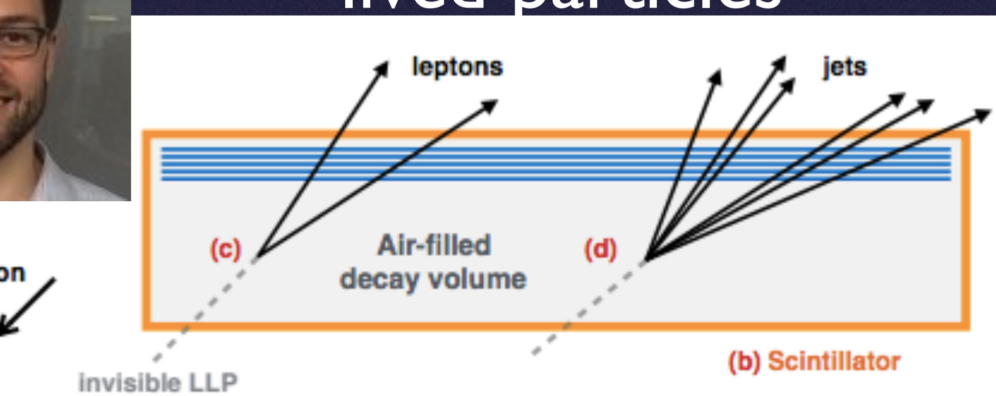
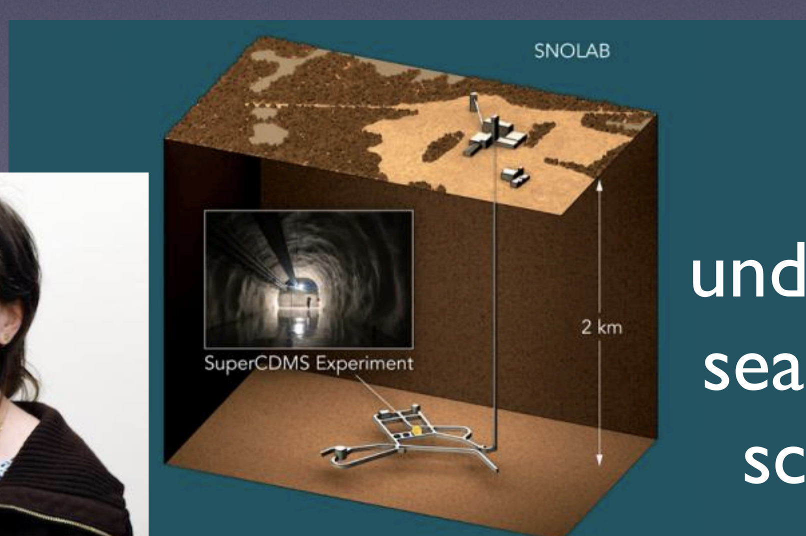


searches for exotic long-lived particles





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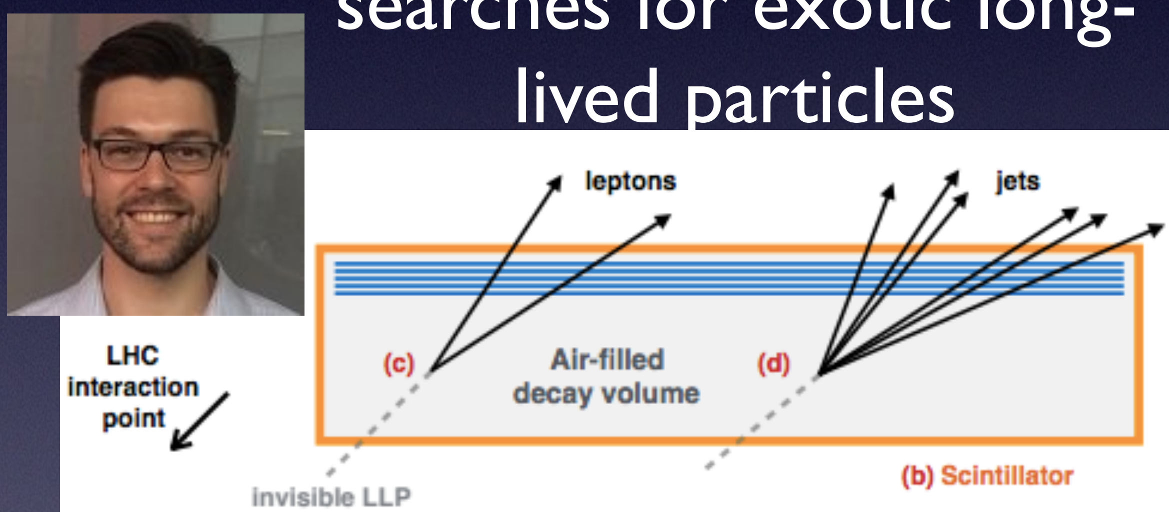

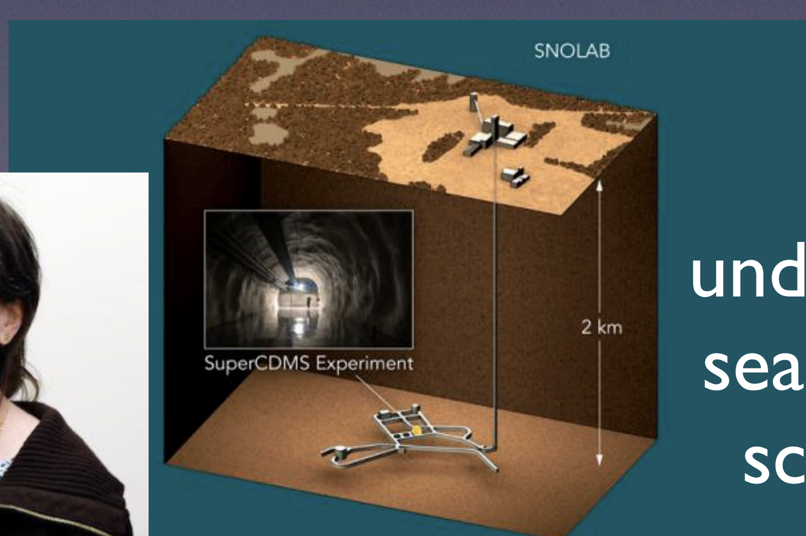

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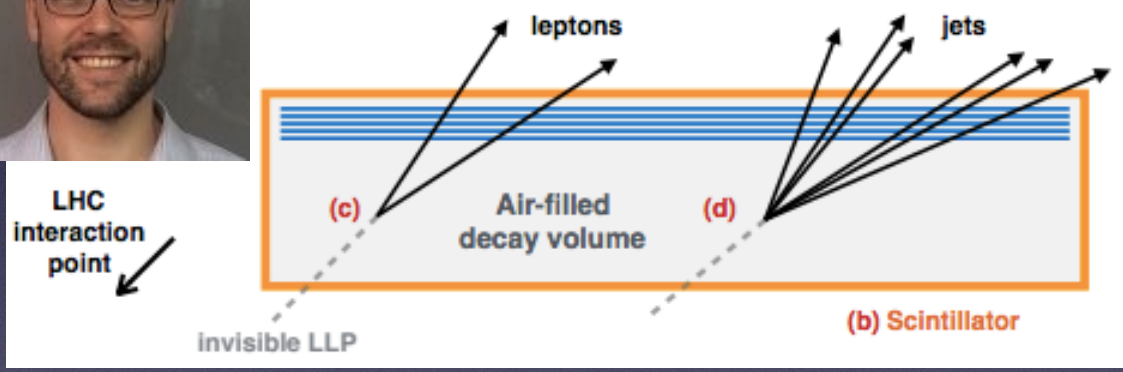

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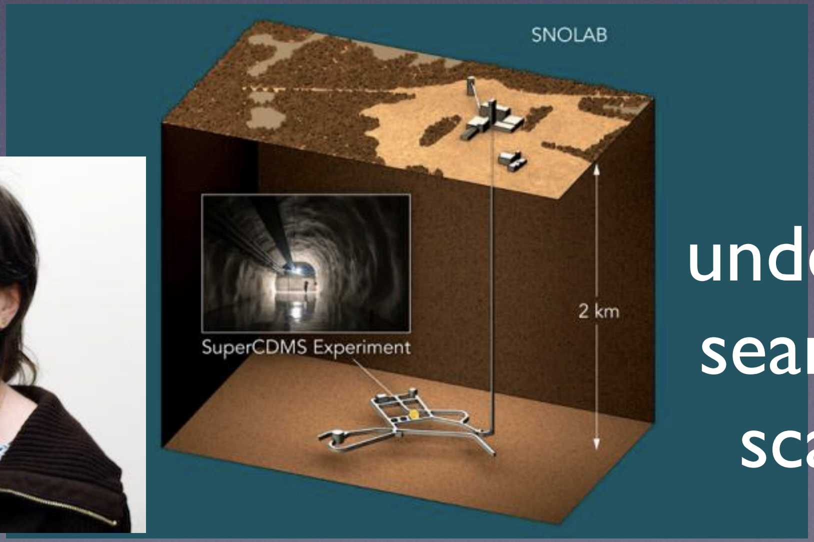

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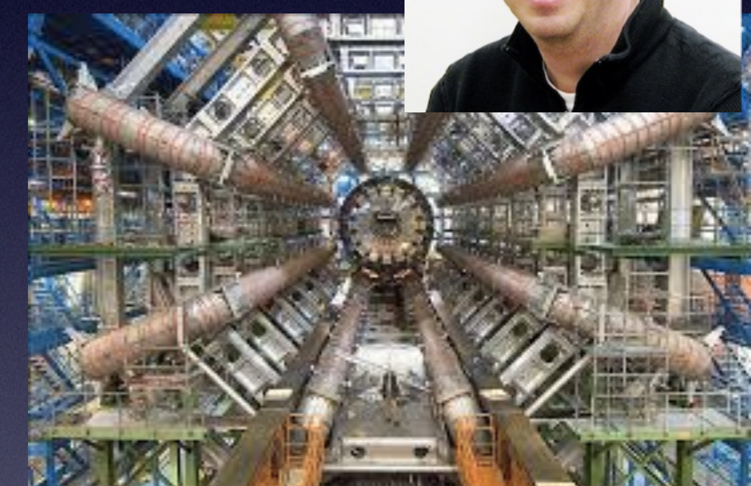

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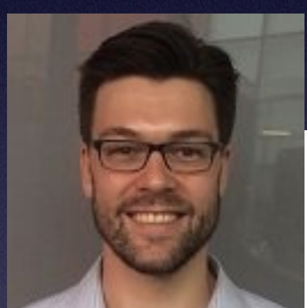
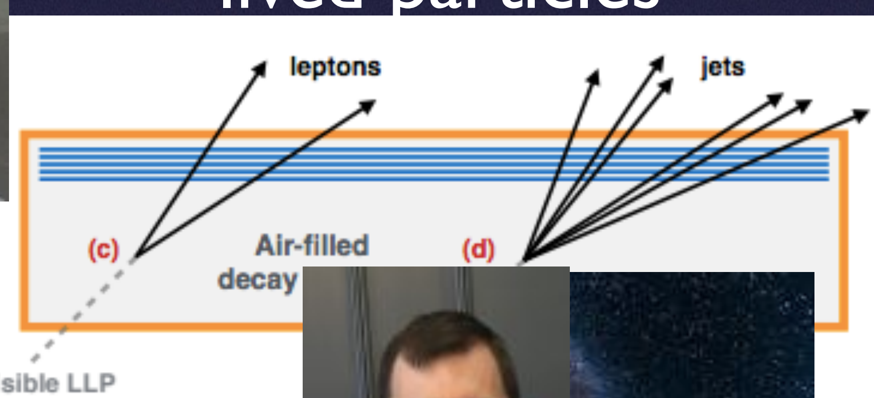
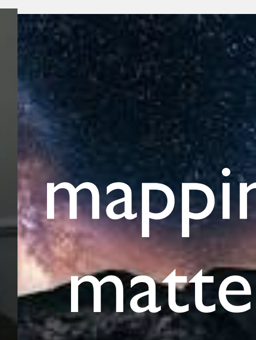
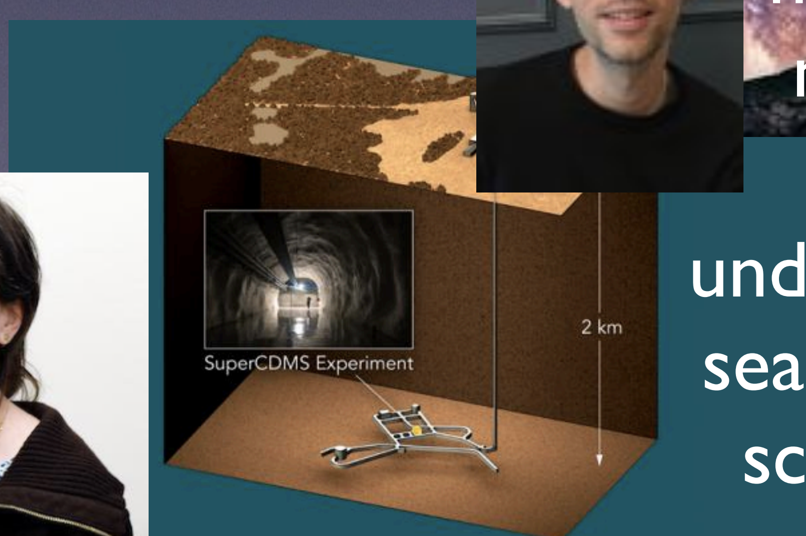






mapping dark matter with stars



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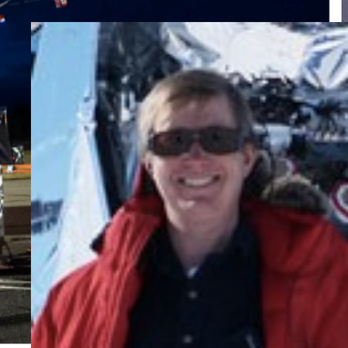

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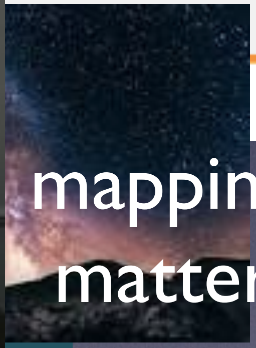

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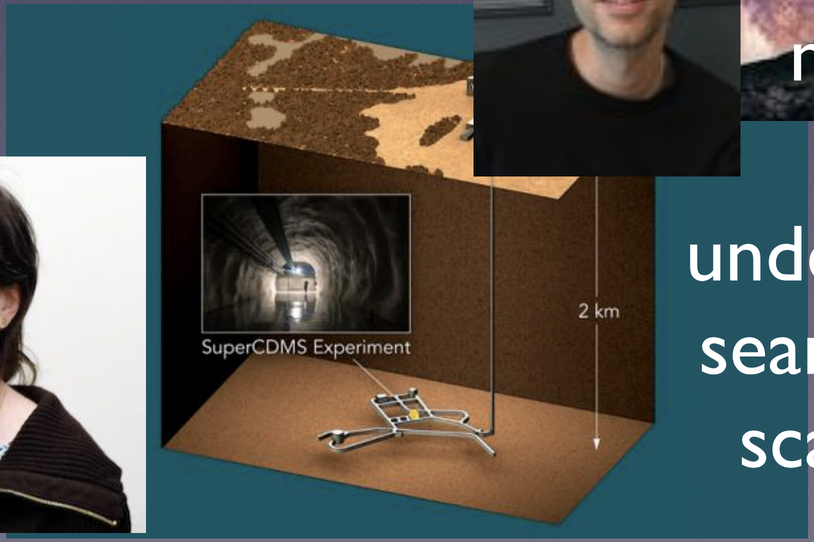

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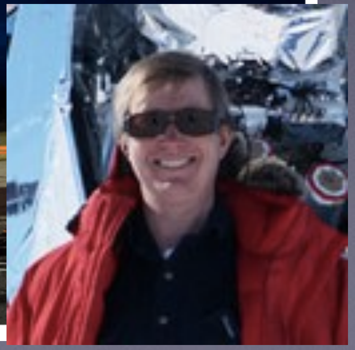


The cosmic microwave background

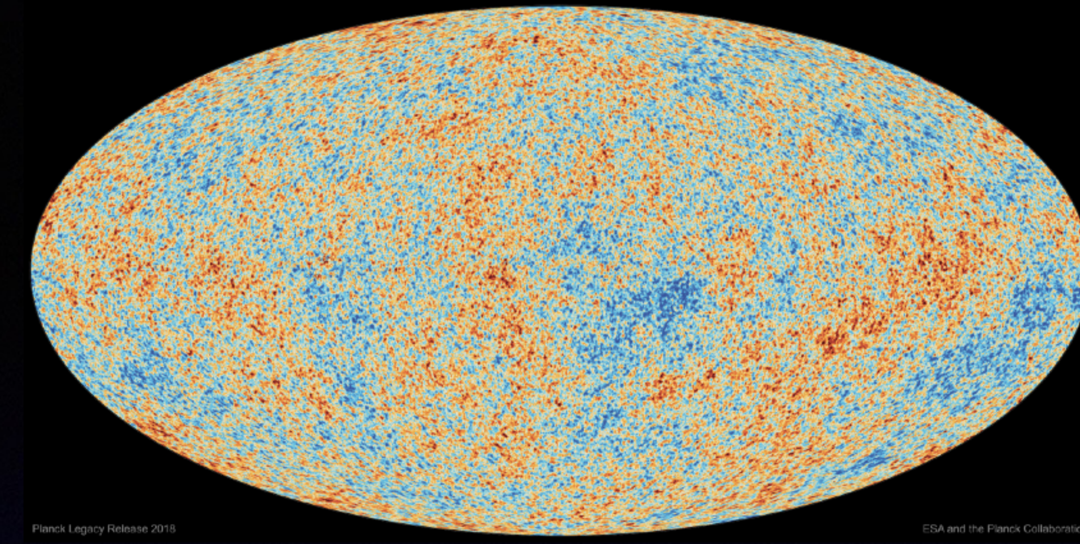
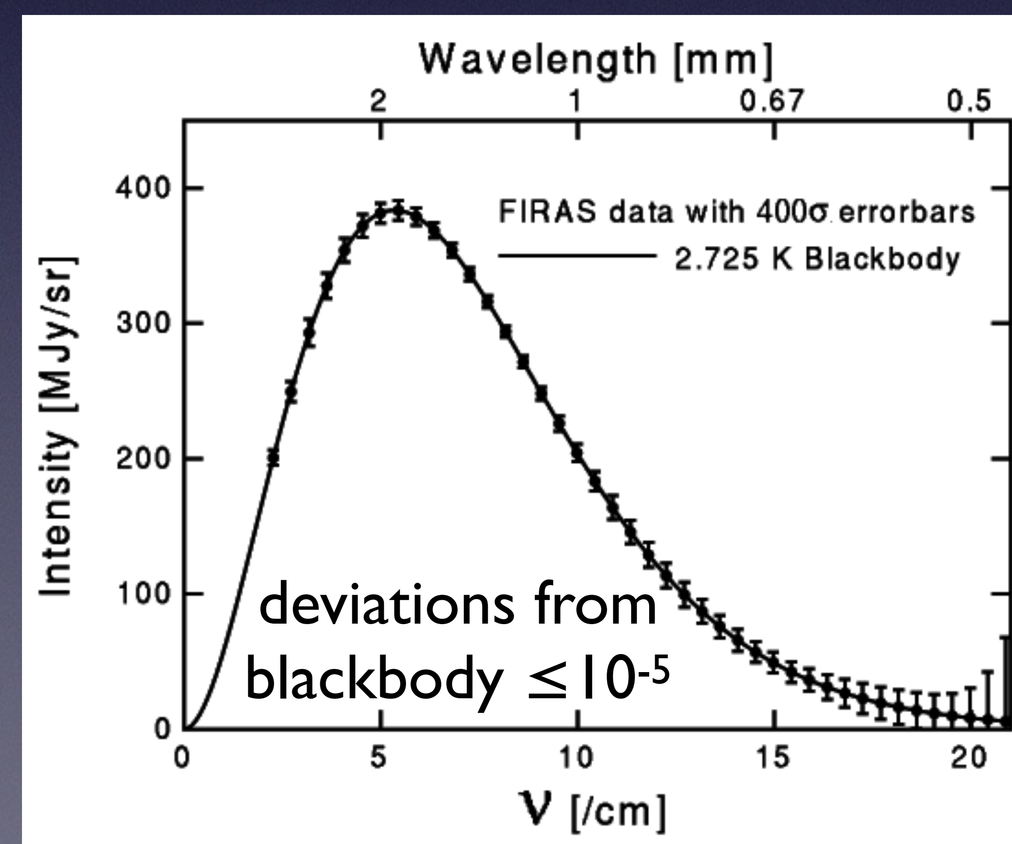


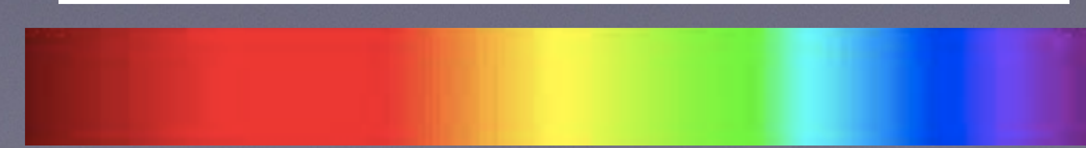
Image credit: European Space Agency / Planck Collaboration

- 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

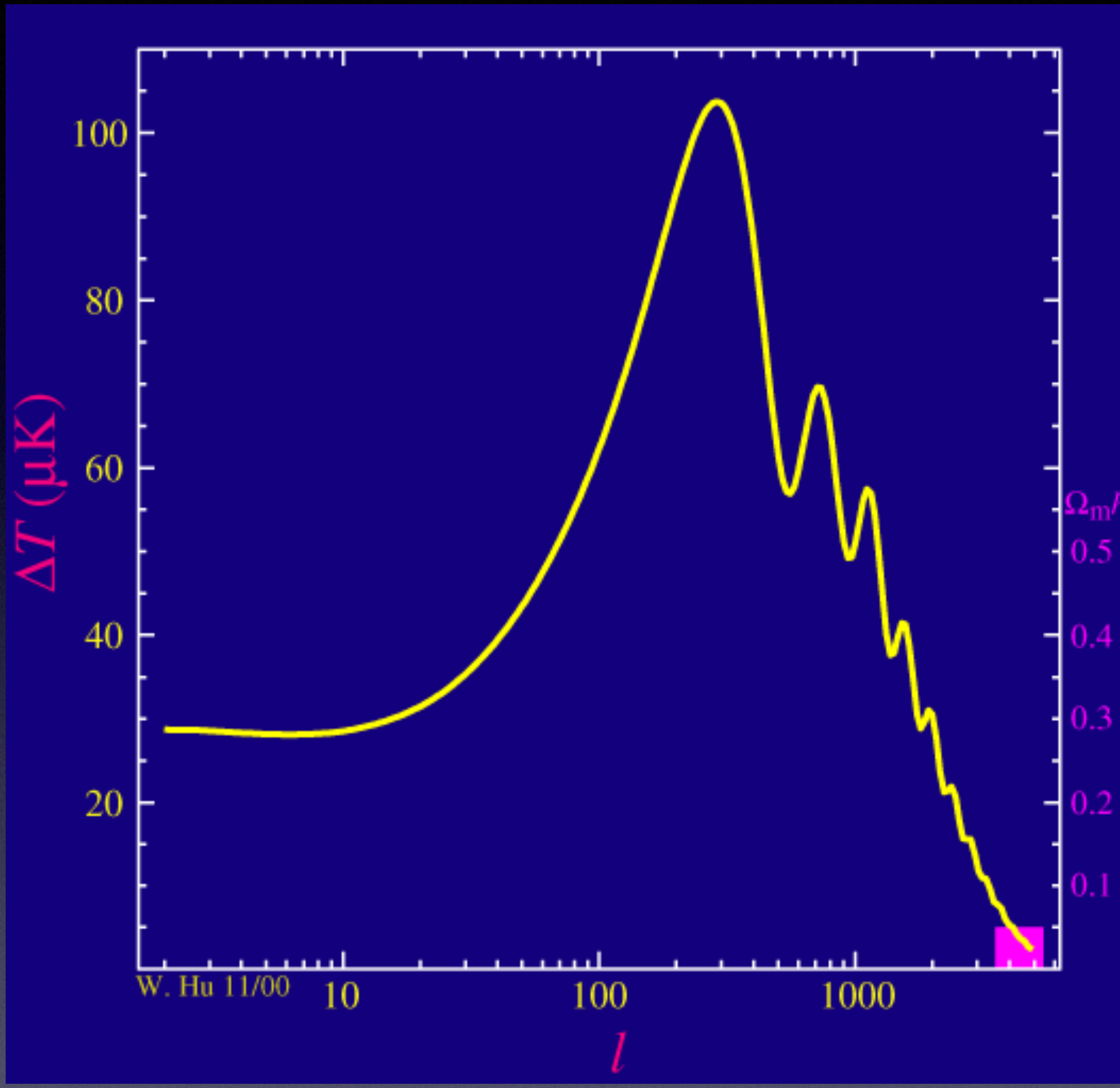
spectral information: near-perfect blackbody





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
- 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 slightly couple DM and baryons, and likewise modify the oscillation pattern.



Wayne Hu, http://background.uchicago.edu/~whu/

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- Changes energy spectrum of CMB.

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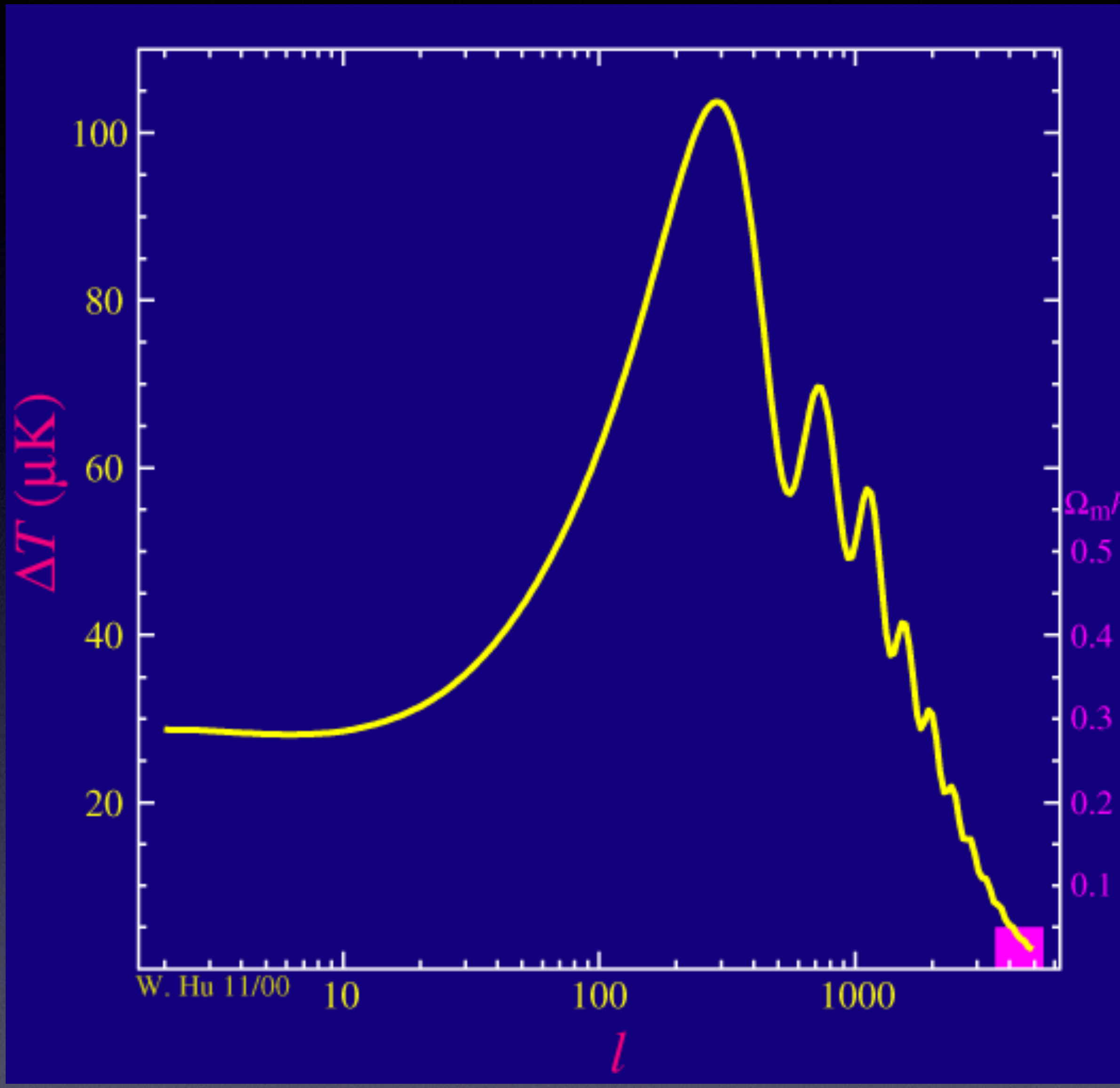

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- Second case (modification after emission): "cosmic dark ages" span redshift z ~ 30-1000, ionization level expected to be very low.
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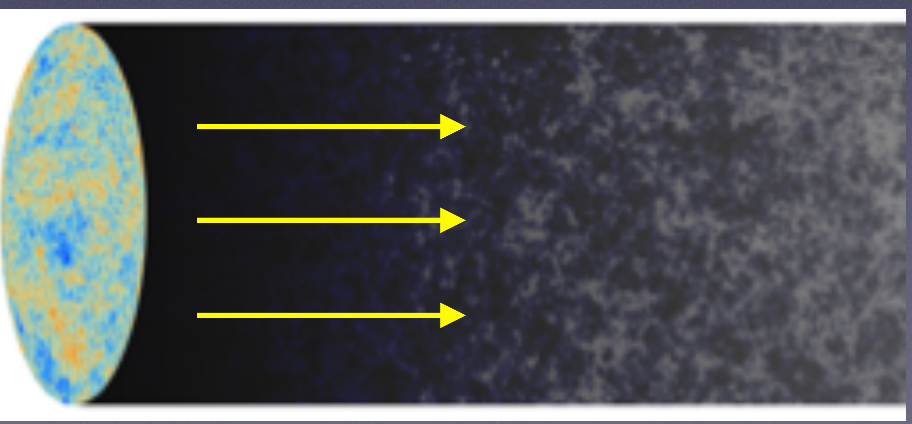
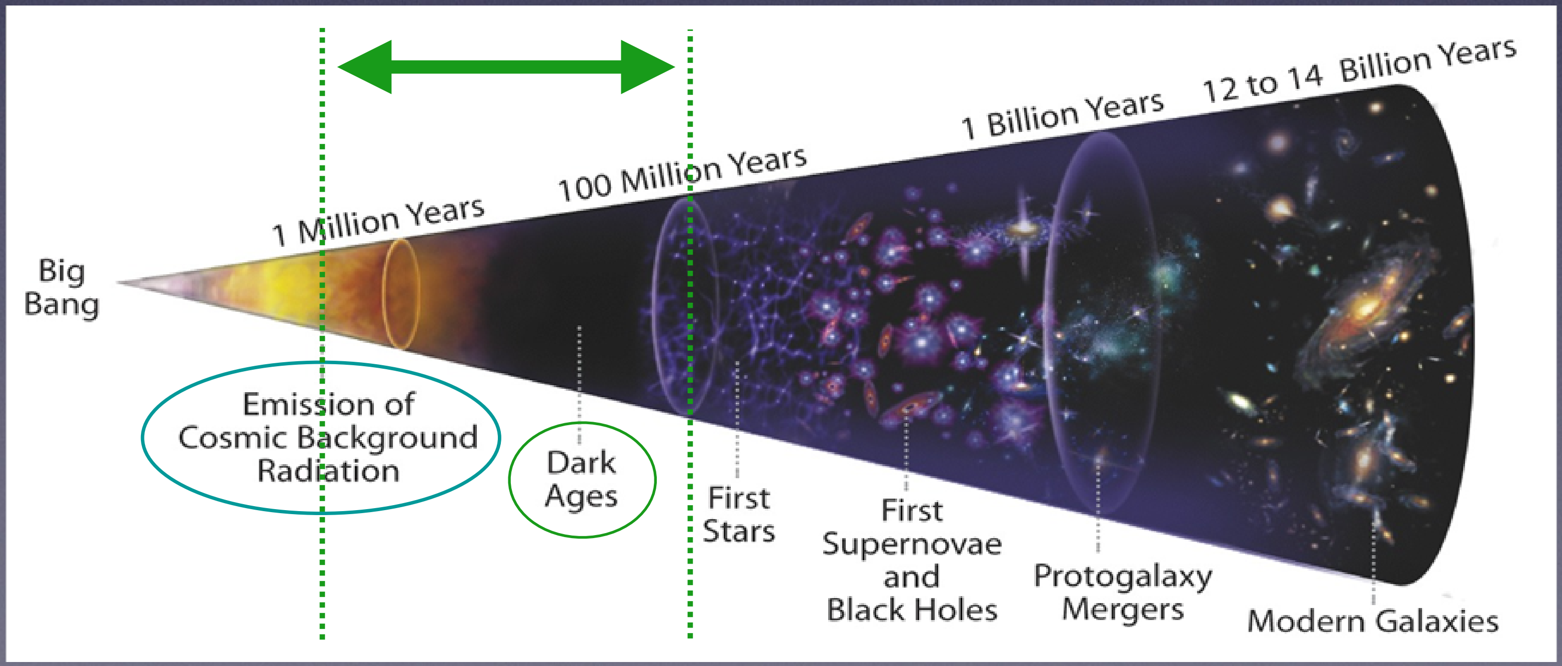
- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.





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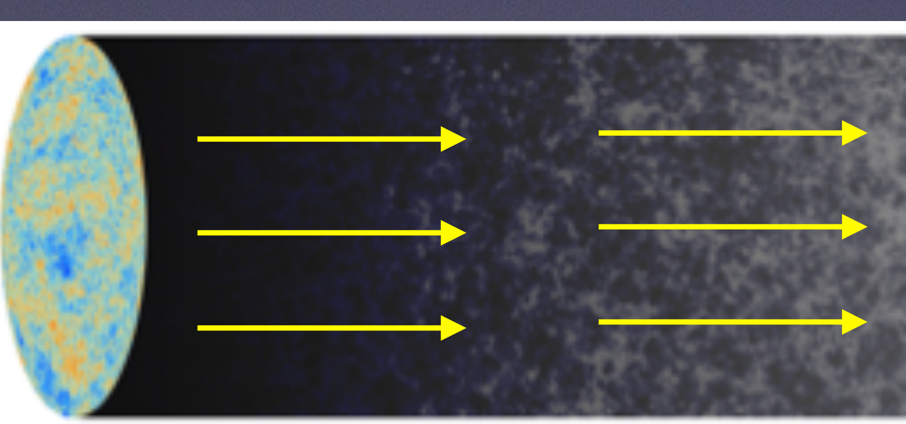
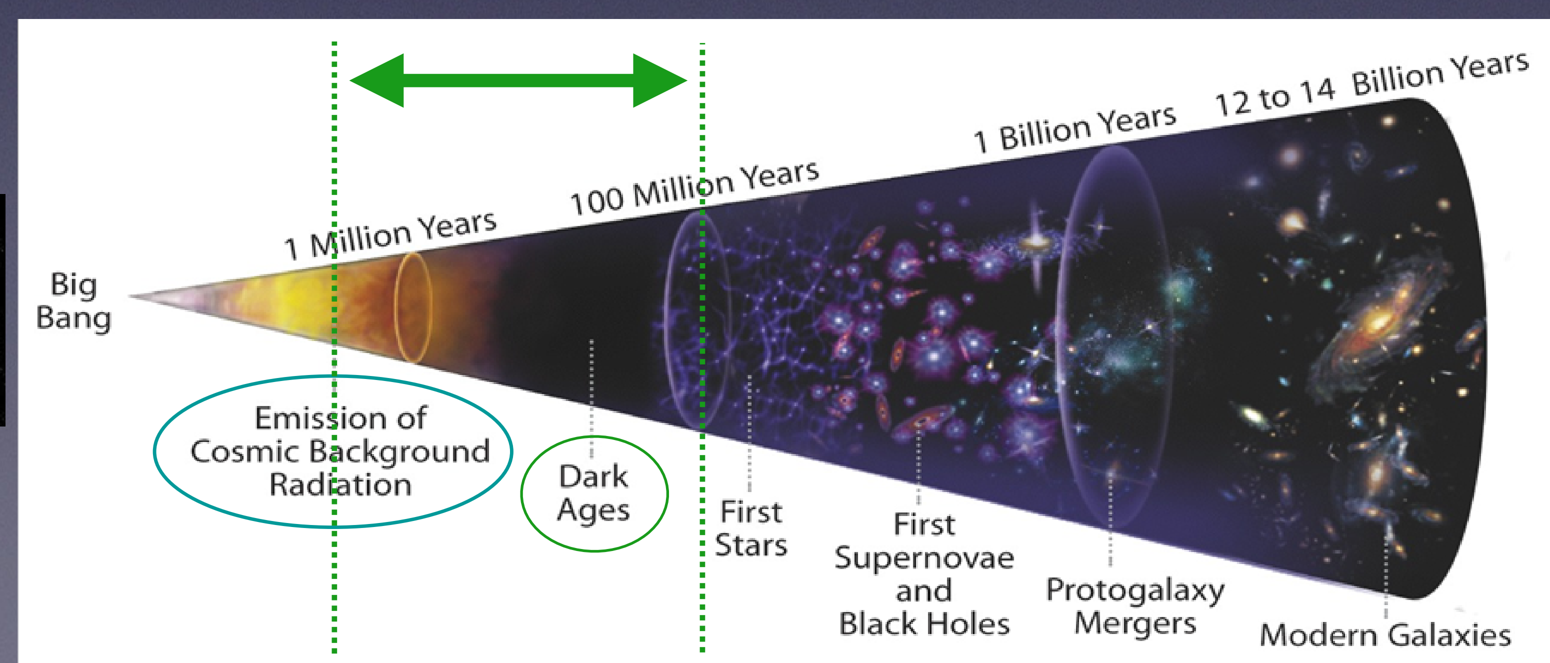


Planck



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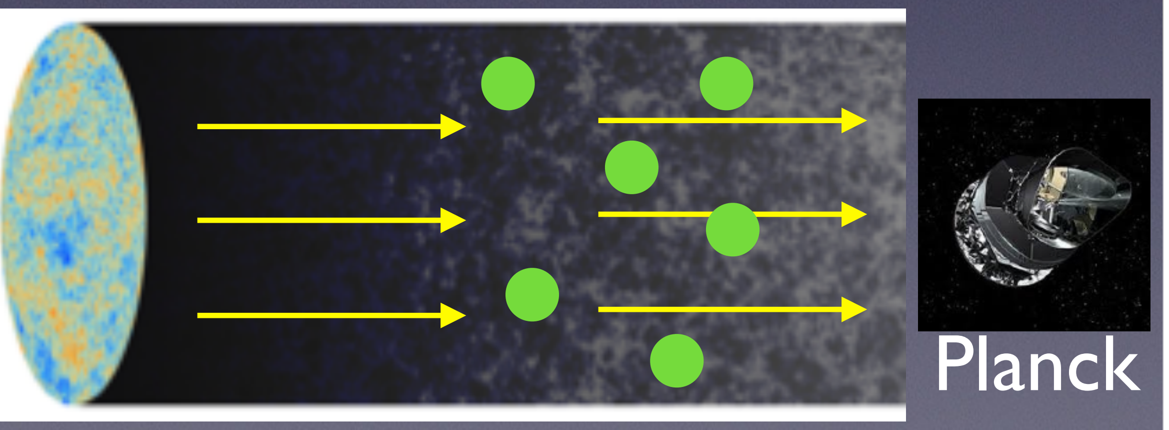

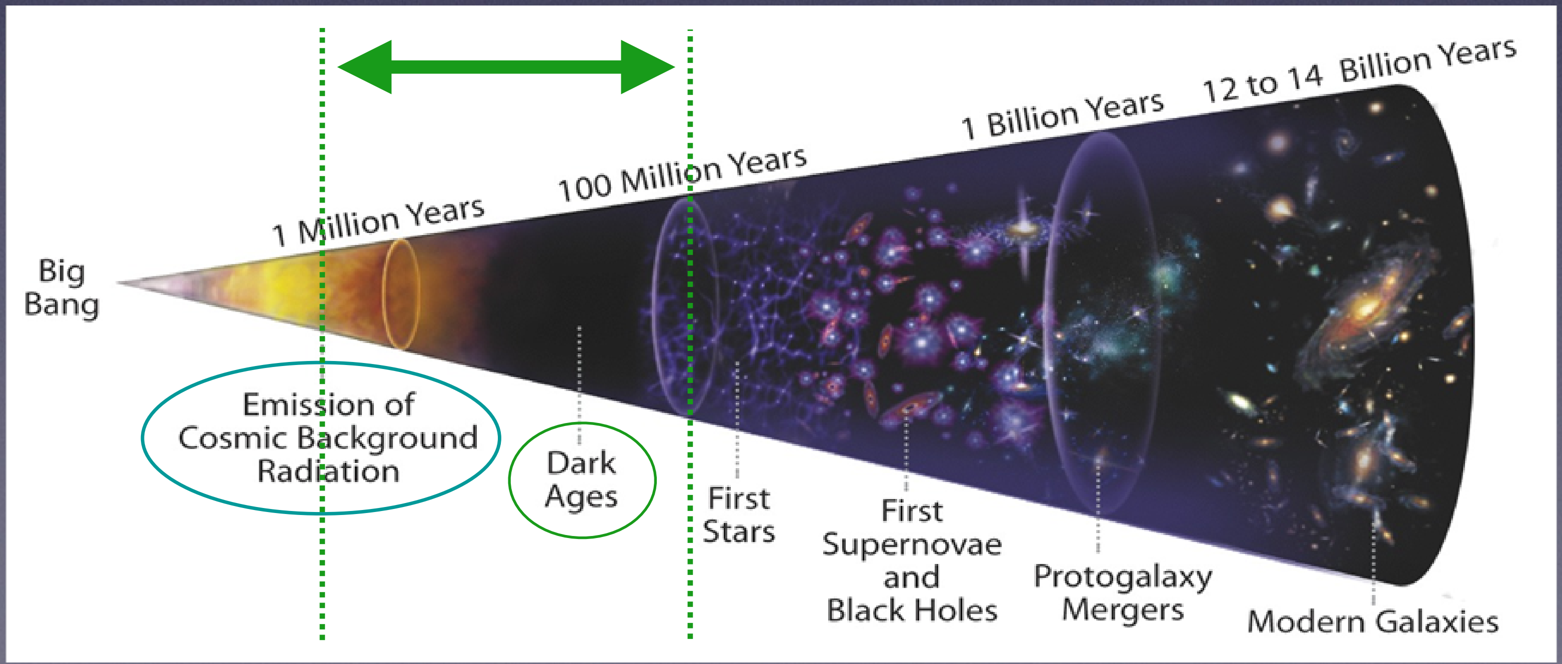

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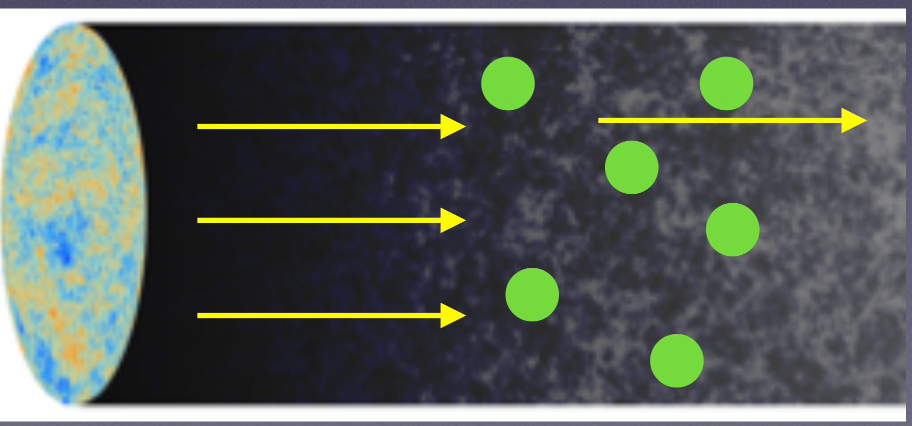

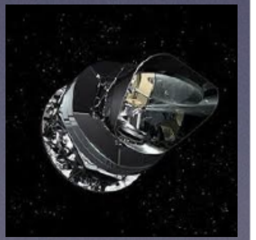

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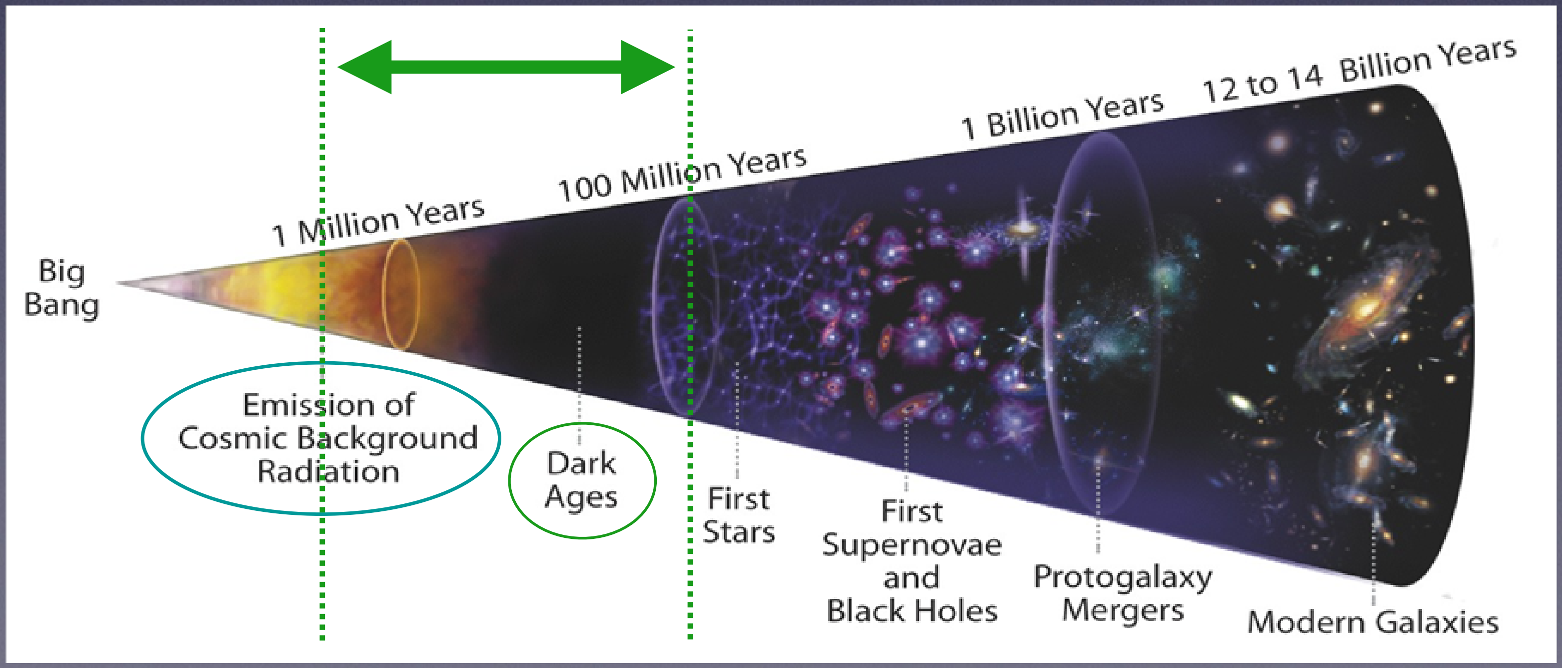
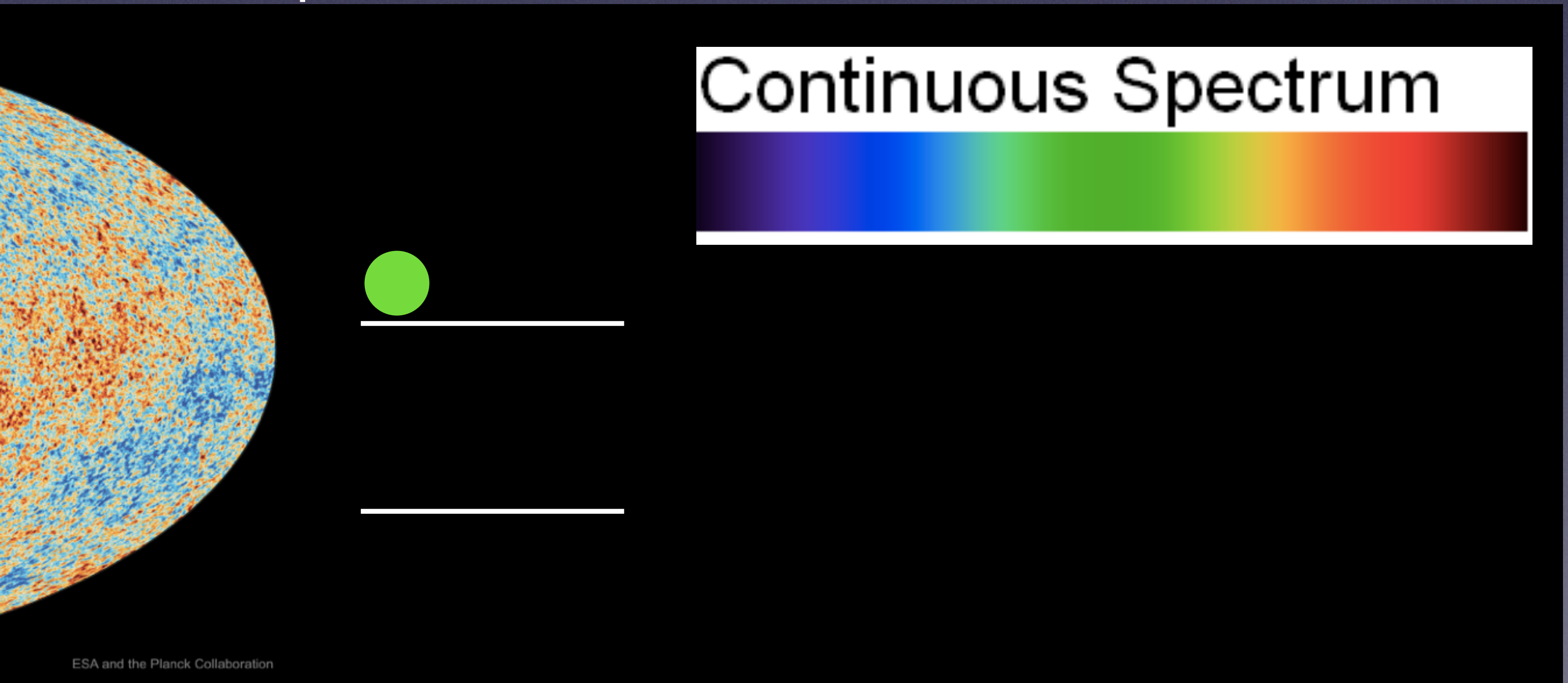


Taking the universe's temperature with 21cm

- 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.
- As the universe expands, the energy of these photons decreases - lines get smeared out into a broad structure.
- "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.



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

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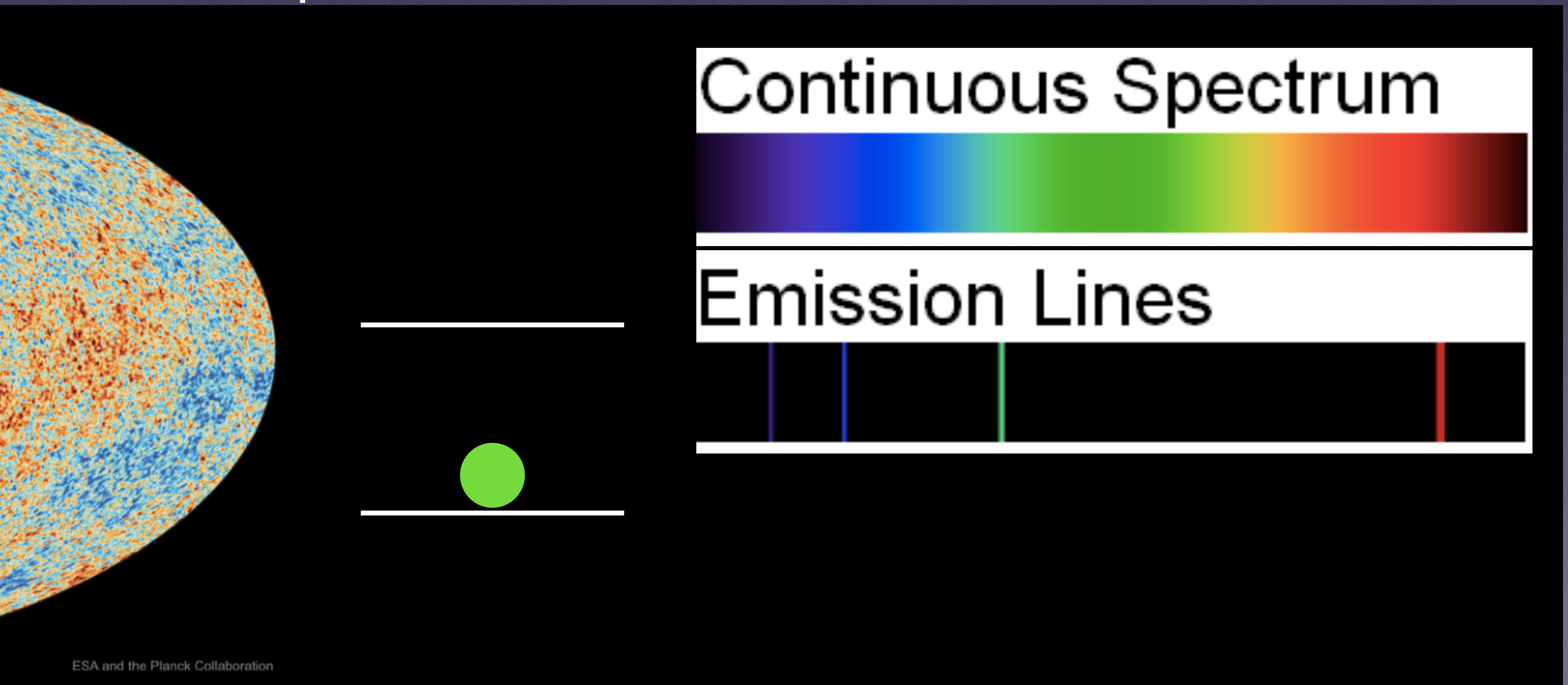

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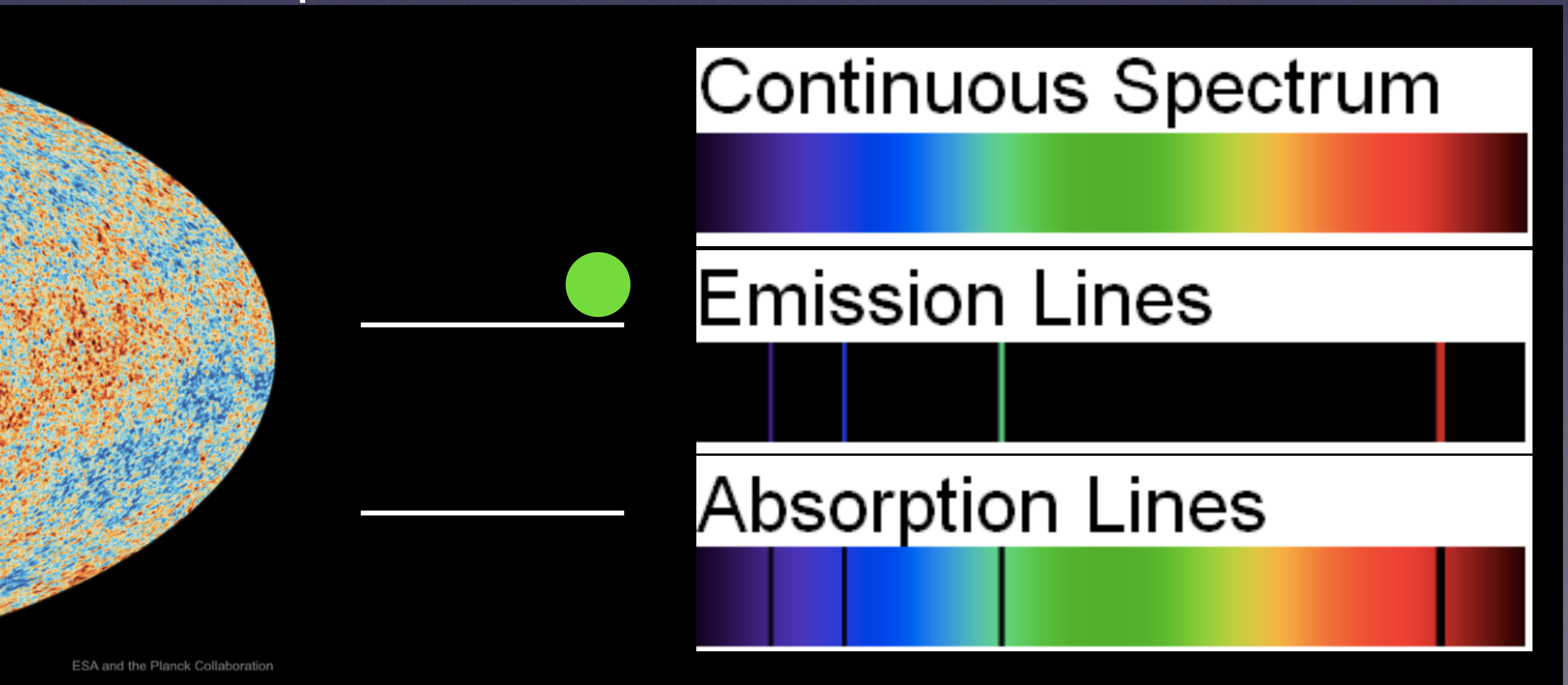

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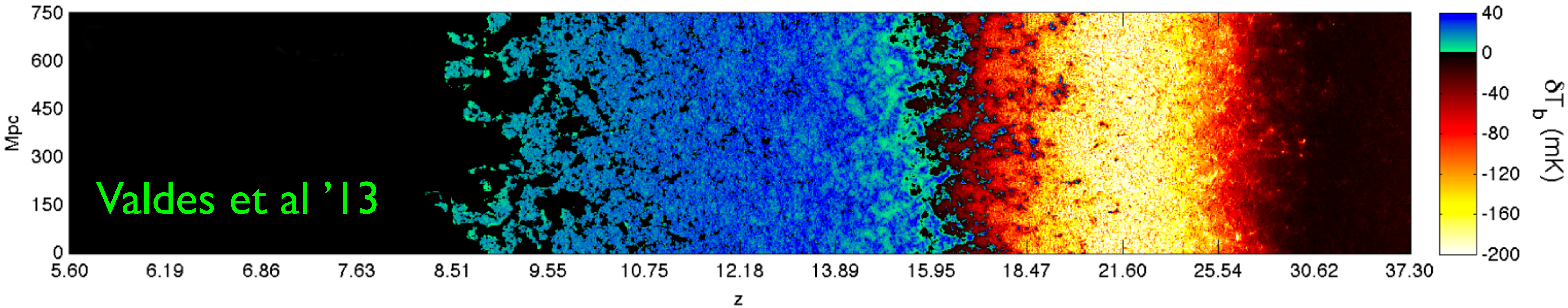
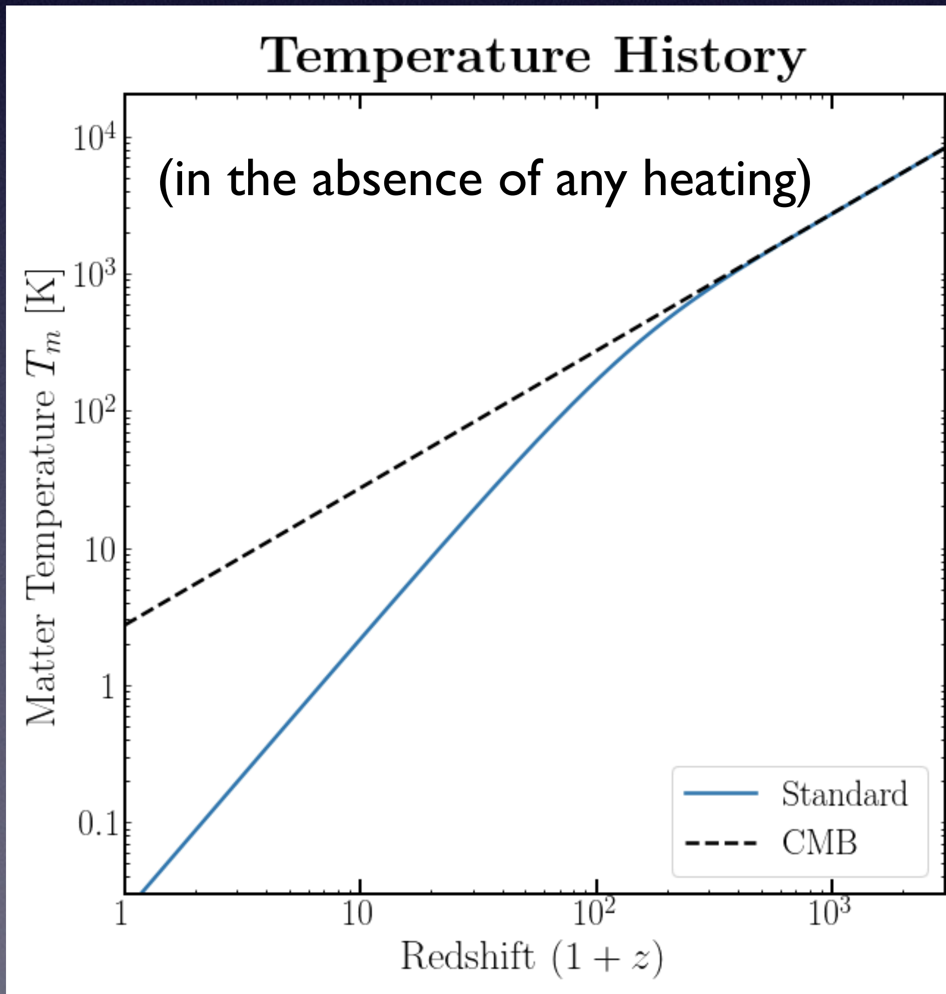
Expectations for a 21cm signal



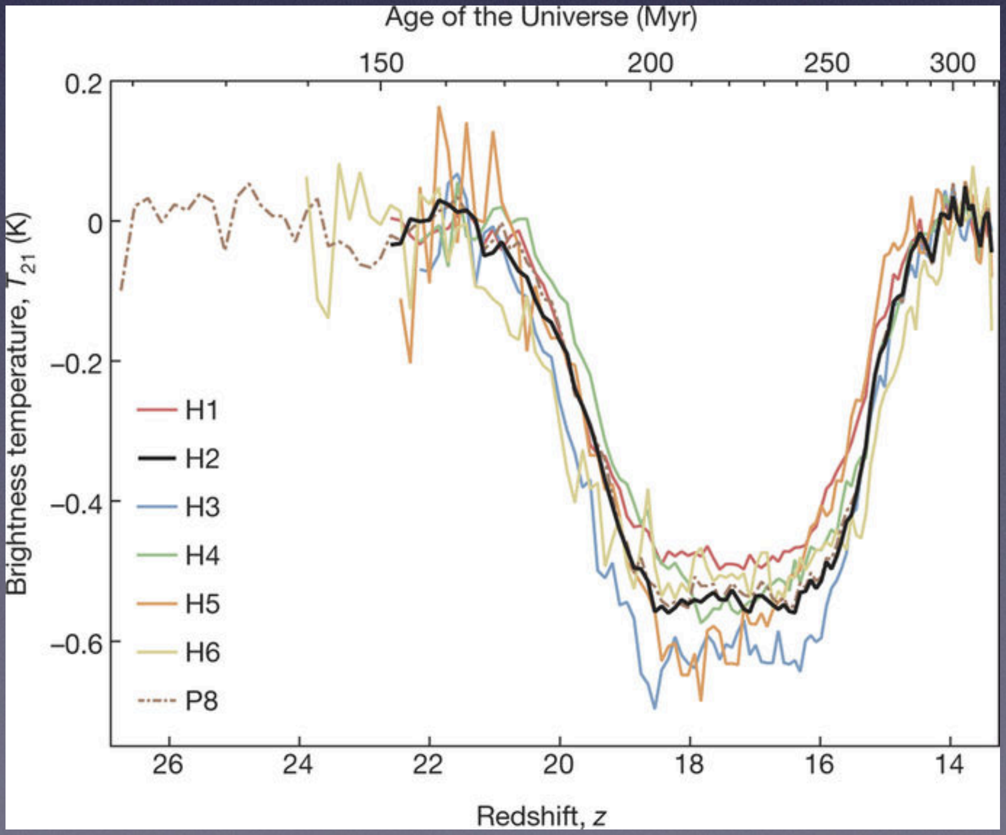
- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature.
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- Heating of the gas from DM decays could potentially lead to early emission at z~20-25 [e.g. Poulin et al '17].
- There are a number of current (e.g. EDGES, HERA, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.



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].

Ionization vs heating vs spectral distortions

Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation - 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…

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  - 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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probe of physics at z > 1000, or non-ionizing processes (e.g. scattering)

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

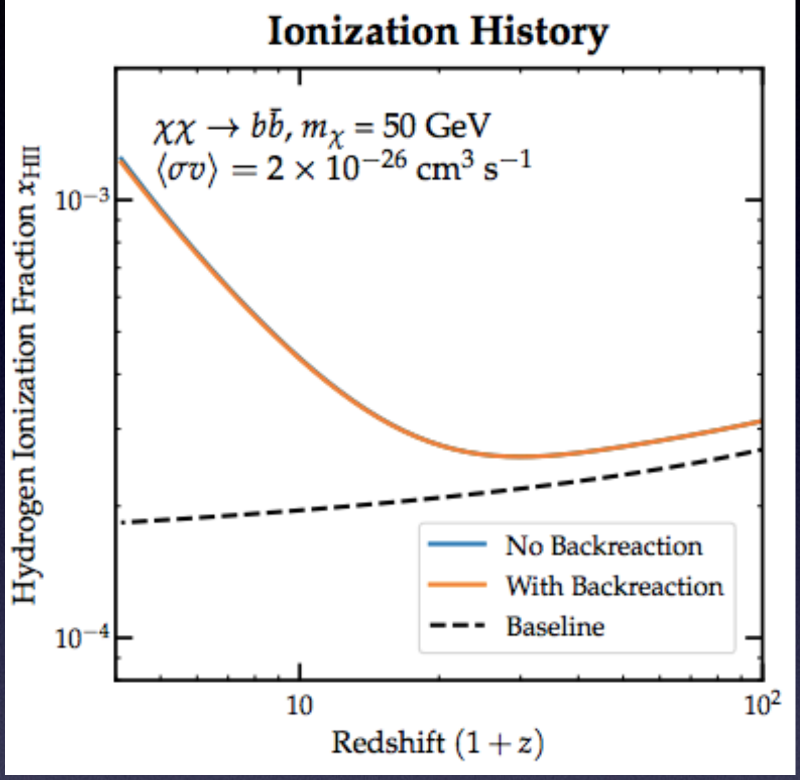
computing modified ionization/thermal histories

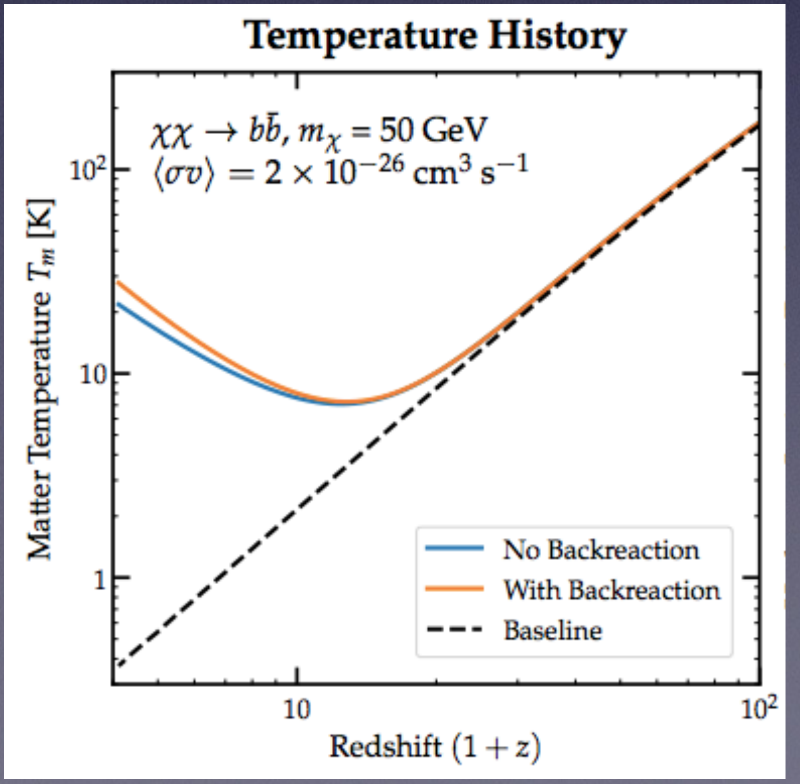
- To study any of these effects, we need to know how particles injected by annihilation/decay transfer their energy into heating, ionization, and/or photons.
- My collaborators (Hongwan Liu, Greg Ridgway) and I have written a Python package to:
  - model energy-loss processes and production of secondary 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

Running DarkHistory

```
bbbar_noBR = main.evolve(
    DM_process='swave', mDM=50e9,
    sigmav=2e-26,
    primary='b', start_rs=3000.,
    coarsen_factor=32, backreaction=False,
    struct_boost=phys.struct_boost_func()
)
```

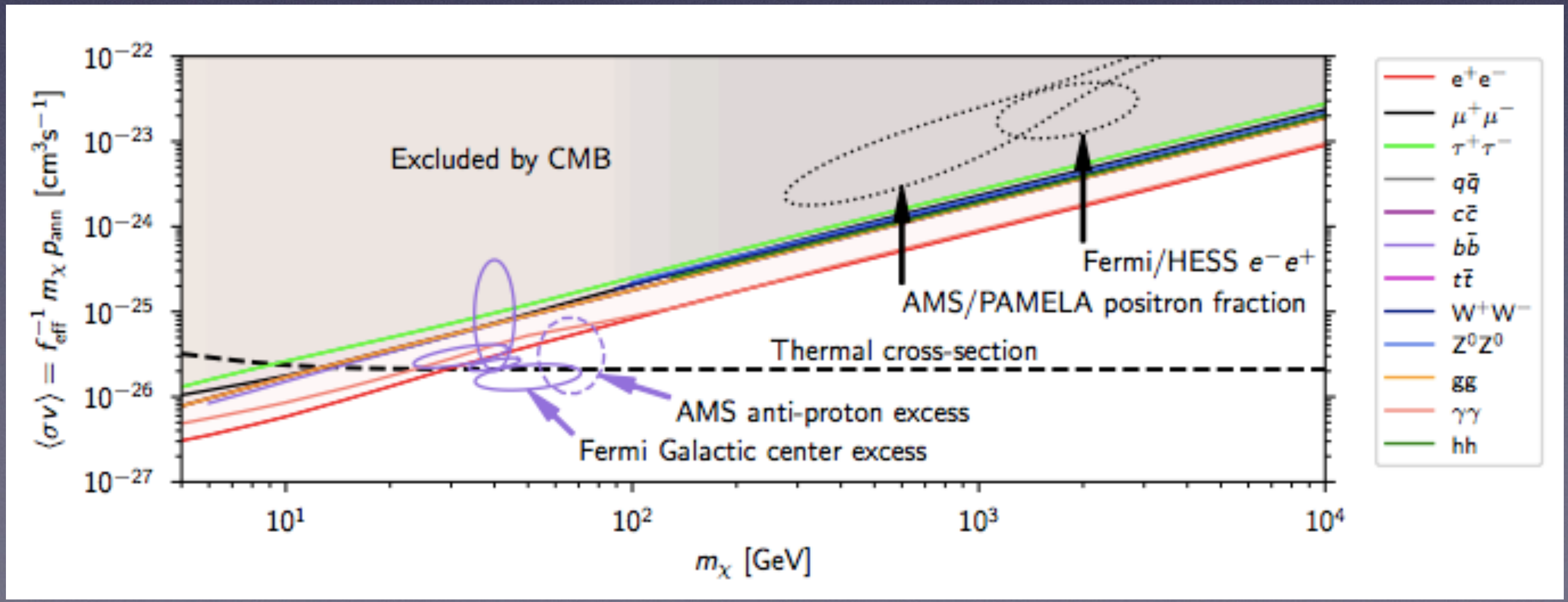
- DarkHistory is provided with extensive example notebooks.
- It contains built-in functions for:
  - redshift dependence corresponding to DM decay or s-wave annihilation
  - injection spectra of electrons/positrons/photons corresponding to all SM final states
- It can include backreaction effects, which can be important at low redshifts - turning this option on or off is a matter of a single keyword.
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks, with and without backreaction.





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.

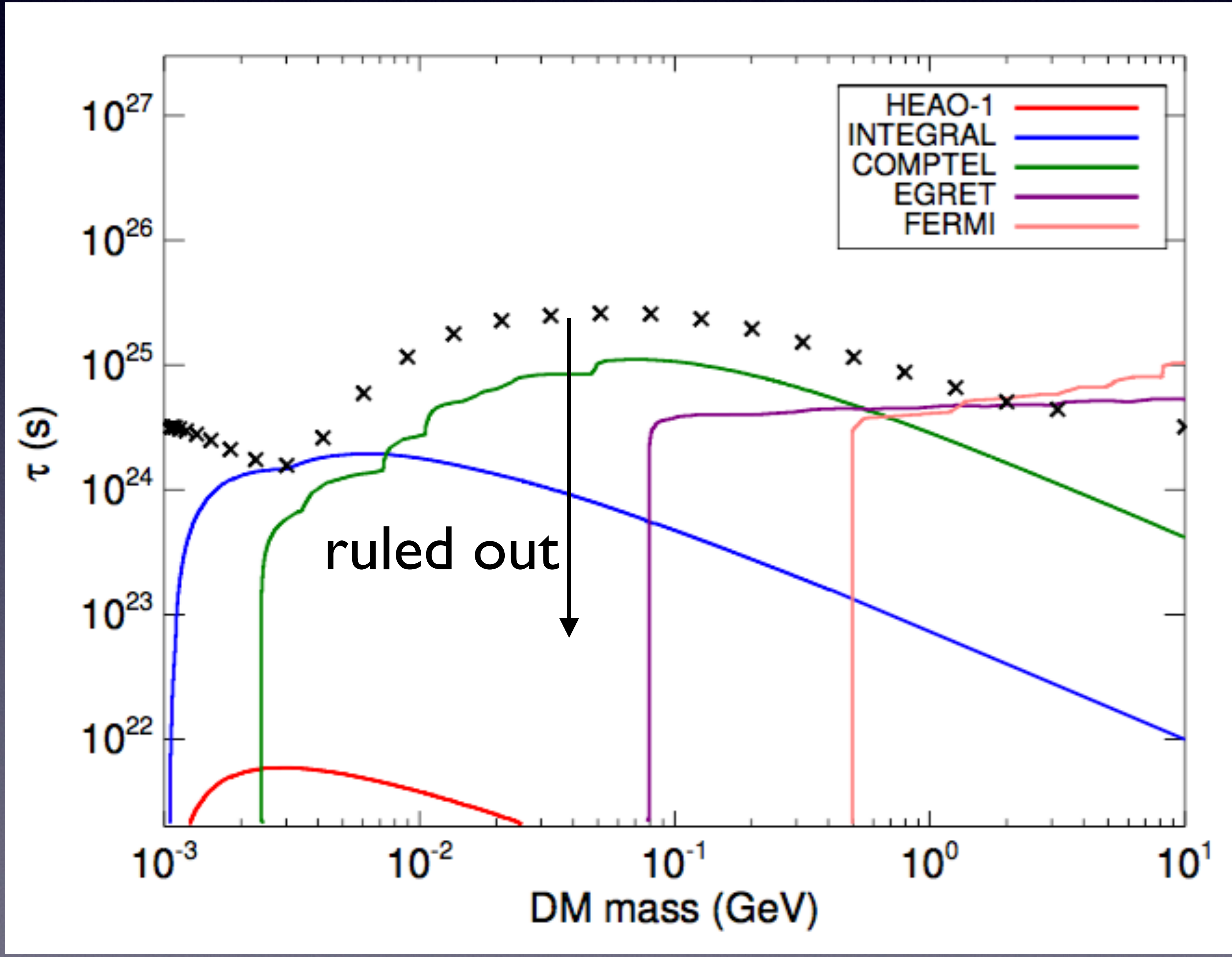


Planck Collaboration '18 1807.06209 based on results of TRS PRD '16

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 $\sim 10^{14}$ s)

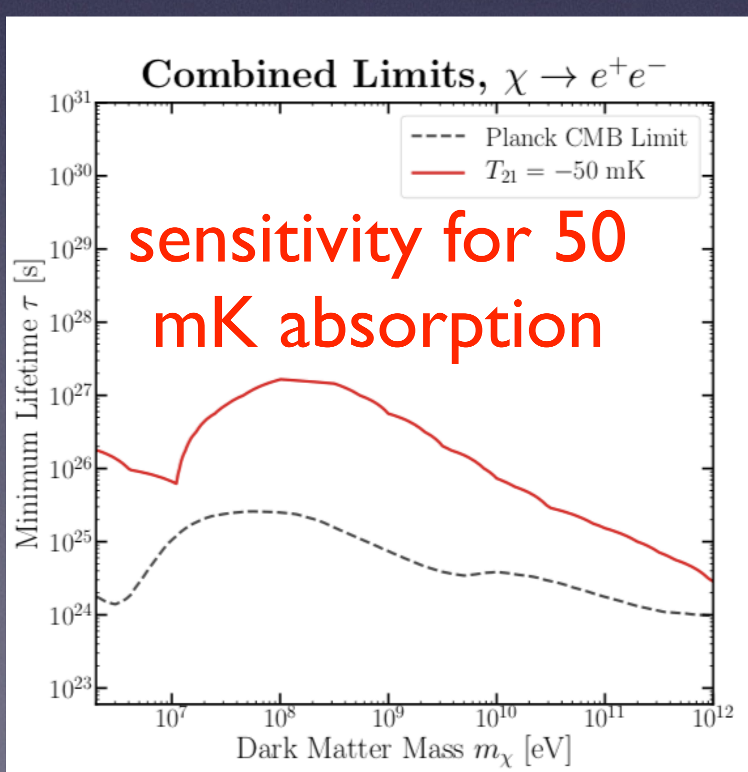
TRS & Wu, PRD '17

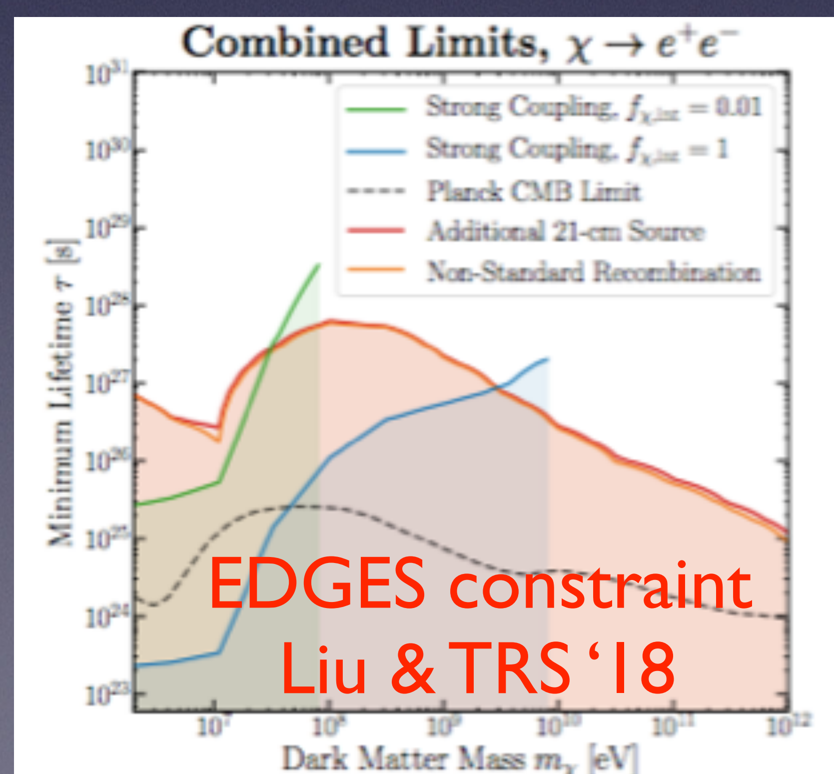


Other constraints (colored lines) from Essig et al '13

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

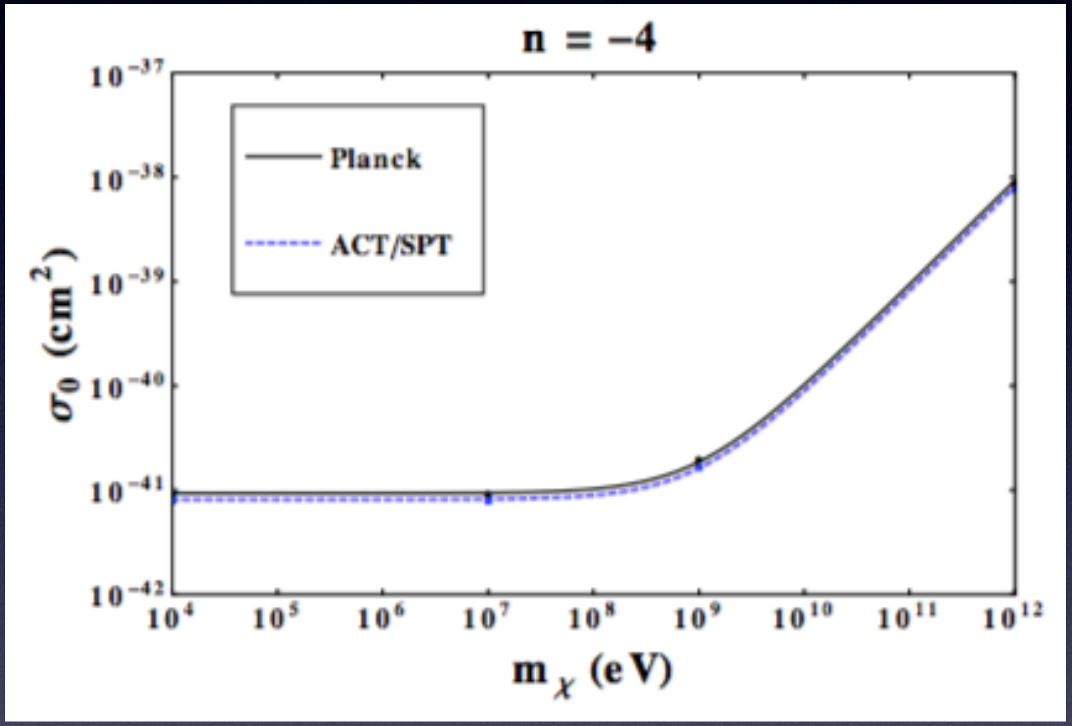
Can DM-baryon scattering explain EDGES?

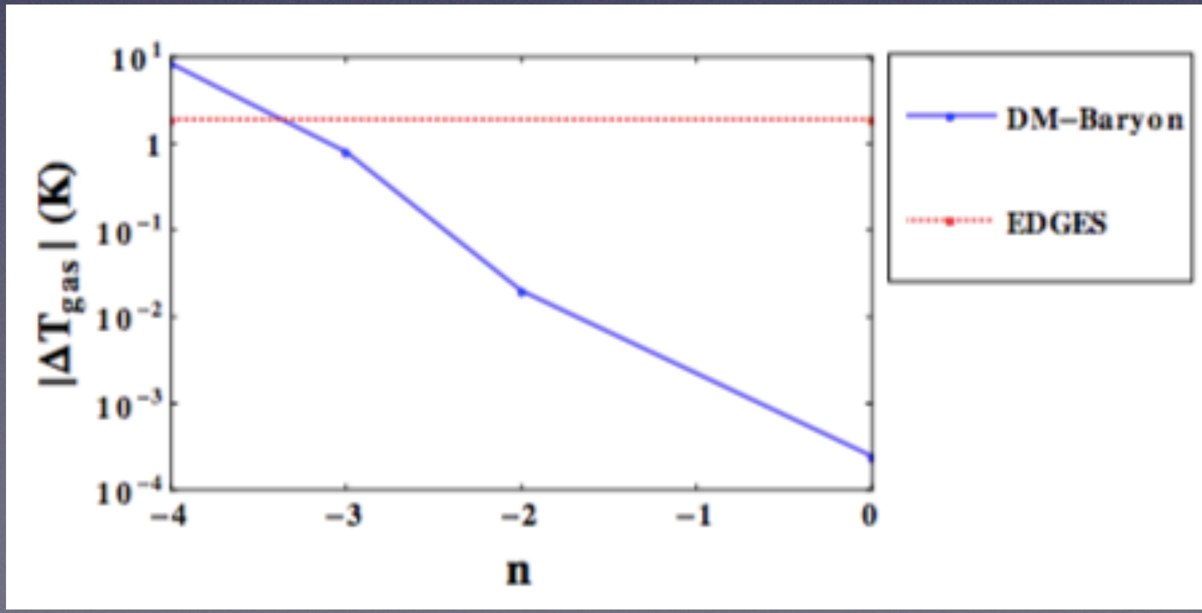
- DM-baryon scattering can cool down the ordinary matter [e.g. Munoz et al '15], leading to stronger 21cm absorption.
- But strong DM-baryon interactions would also modify both the CMB anisotropies and CMB blackbody spectrum [Dvorkin et al '13, Gluscevic et al '17, Boddy et al '18, Xu et al '18].
- There are also limits on DM-baryon interactions from powerful direct-detection experiments on Earth - tend to be much stronger than cosmological bounds at DM masses >> 1 GeV.
- Best-case scenario for a strong 21cm signal comes from models of low-mass DM where scattering is enhanced at low velocities - consider models where cross section scales as strongly as v^{-4} (Rutherford scattering).

DM-baryon scattering in the early universe

TRS & Wu, PRD '18

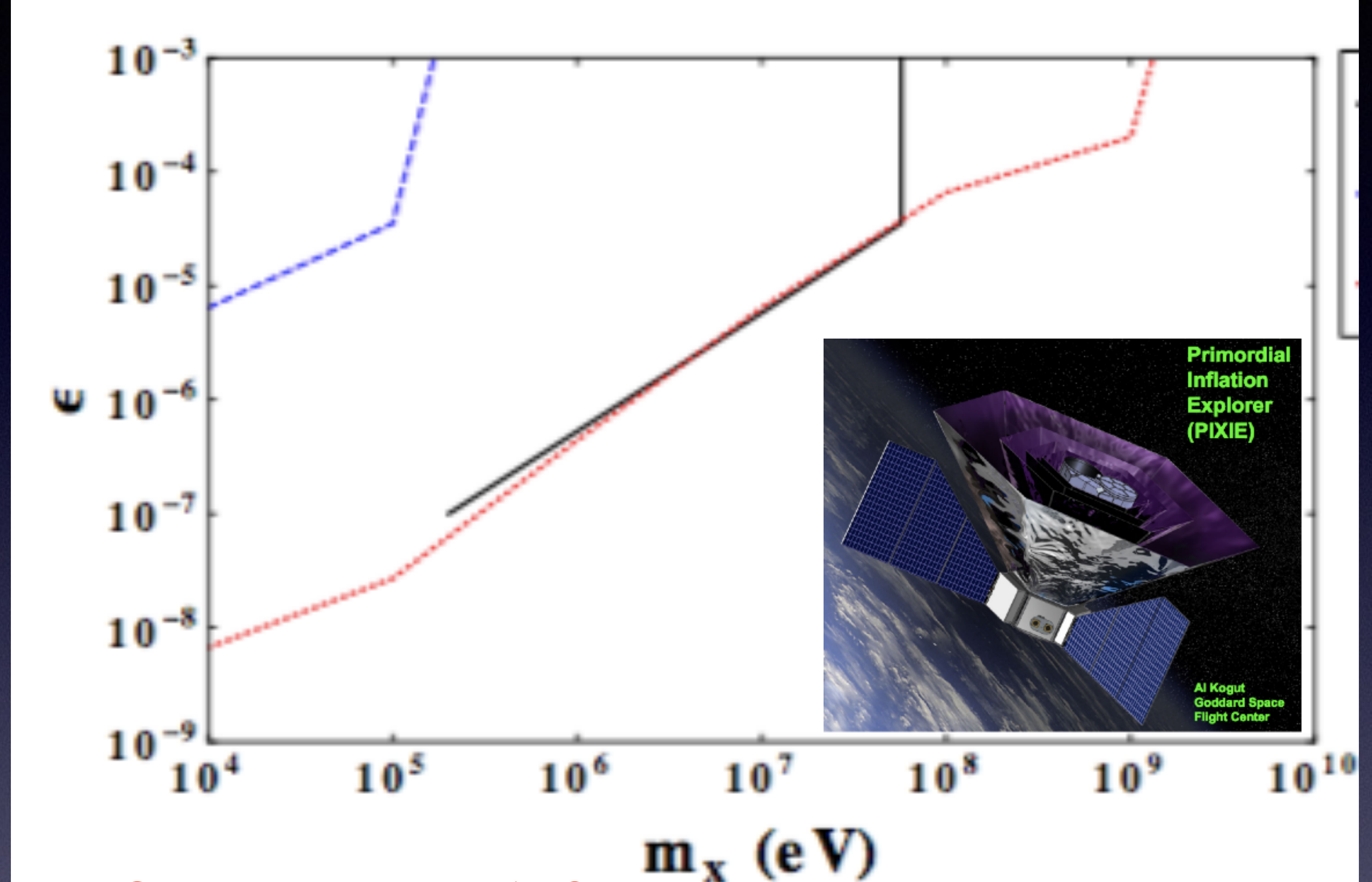
- We used the existing public CLASS code, modifying both perturbation-evolution and temperature-evolution equations.
- We calculated the upper bound on scattering rate from the CMB anisotropies, for different models.
- We determined the maximum change to temperature at z~17 (relevant for EDGES).
- Result: need $\sigma \sim v^{-4}$ scaling to explain EDGES, if all DM scatters. (Requires a very light mediator; highly constrained.)
- Note: this calculation neglects the automatic heating due to the Lyman-alpha photons that couple T_S to T_{gas} - in reality probably need even more cooling [Venumadhav et al 1804.02406].





A small interacting fraction

- Several authors [e.g. Munoz et al '18, Berlin et al '18, Barkana et al '18] have suggested that if <1% of (10-100 MeV) DM carries a tiny electric charge, this could explain the signal.
- Evade CMB-anisotropy constraints because bulk of DM is not interacting; millicharged fraction needs to be 0.01-0.4% of DM, in mass range 0.5-35 MeV [Boddy et al '18, Kovetz et al '18].

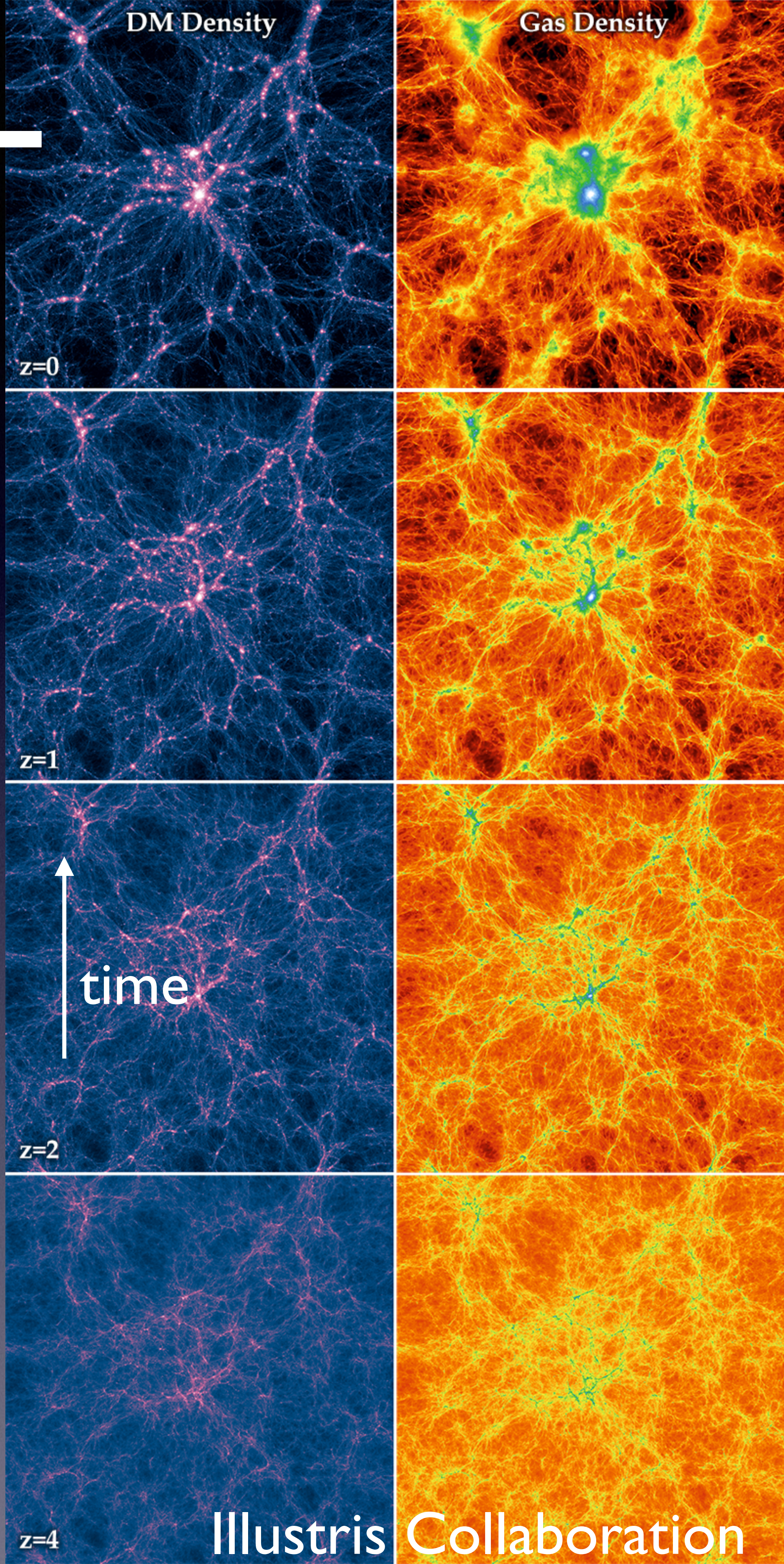


TRS & Wu PRD '18

- But early DM-baryon interactions (cooling the gas) could distort CMB blackbody spectrum [Ali-Haimoud et al '2015, Choi et al '17] - depends on energy flow from baryons to DM, like the 21cm temperature measurement.
- Extending these limits to fractional abundance with millicharge, proposed spectral-distortion experiment PIXIE could probe this parameter space.

The dark side: DM-only interactions

- All of the probes I have discussed so far rely on an energy transfer to/from visible particles.
- But even if DM only interacts with itself, the interactions can modify its distribution.
- In particular, such DM self-interactions can change the inner cores of DM halos around galaxies.



Estimating self-interaction effects

- Self-interactions allow heat conduction between different regions of the halo - when interaction rate is large, can model as a thermally conducting gravitating fluid
- Interaction rate required to modify the distribution: average particle scatters in a dynamical timescale τ:

$$1 \sim \sigma v n \tau = (\sigma / m_{\mathrm{DM}}) v \rho_{\mathrm{DM}} \tau$$

particle physics astrophysics

$$\frac{\sigma}{m_{\mathrm{DM}}} \sim \frac{1}{v \rho_{\mathrm{DM}} \tau} \sim \frac{1}{10^{-4} c \times 1 \mathrm{GeV/cm}^3 \times 10^9 \mathrm{yr}} \sim 1 \mathrm{cm}^2/\mathrm{g}$$

- Standard history for SIDM haloes:
  - First, original density peak evolves into a flat-density core, central density drops.
  - Outward heat transfer results in a gravothermal core collapse, core becomes smaller and denser with time.
- Timescale for core collapse in isolated haloes ~ 100 t_0 where $t_0^{-1} \sim (\sigma/m_{\mathrm{DM}}) v \rho_{\mathrm{DM}}$

What happens in satellite galaxies?

- The Milky Way contains many smaller satellite galaxies - clumps of dark matter + stars
- Prior to this year, most studies of self-interacting DM focused on isolated halos
- In satellite galaxies, there is an interplay between:
  - Self-interaction within the satellites
  - Gravitational interactions between satellite and main halo, i.e. tidal forces
  - Self-interaction between satellite and main halo

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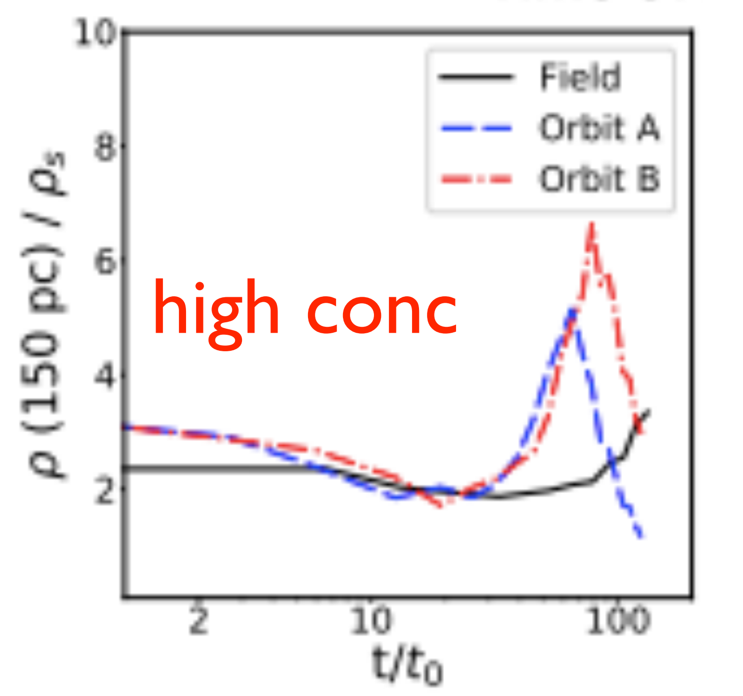
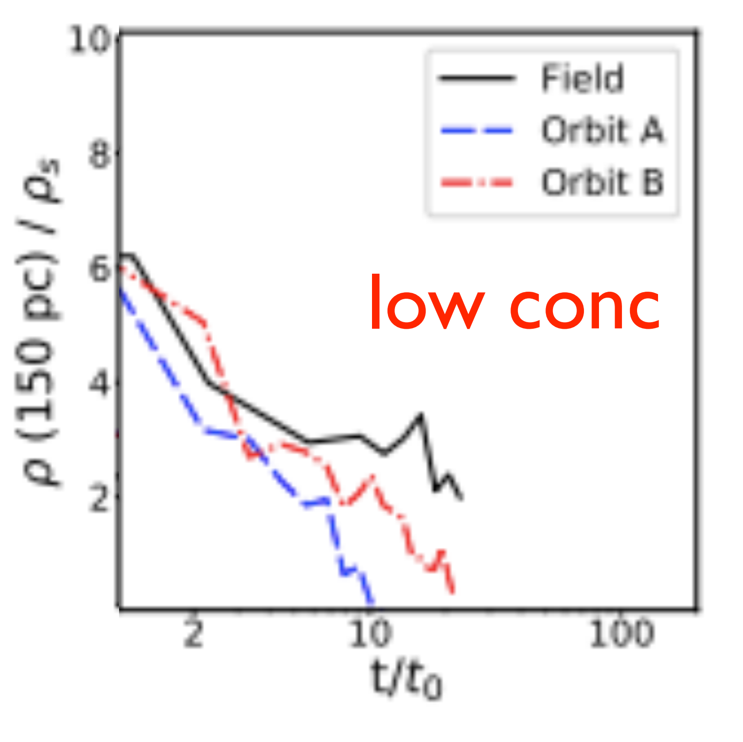
Ignore for now to separate out effects (could be naturally small if interaction is velocity-dependent)

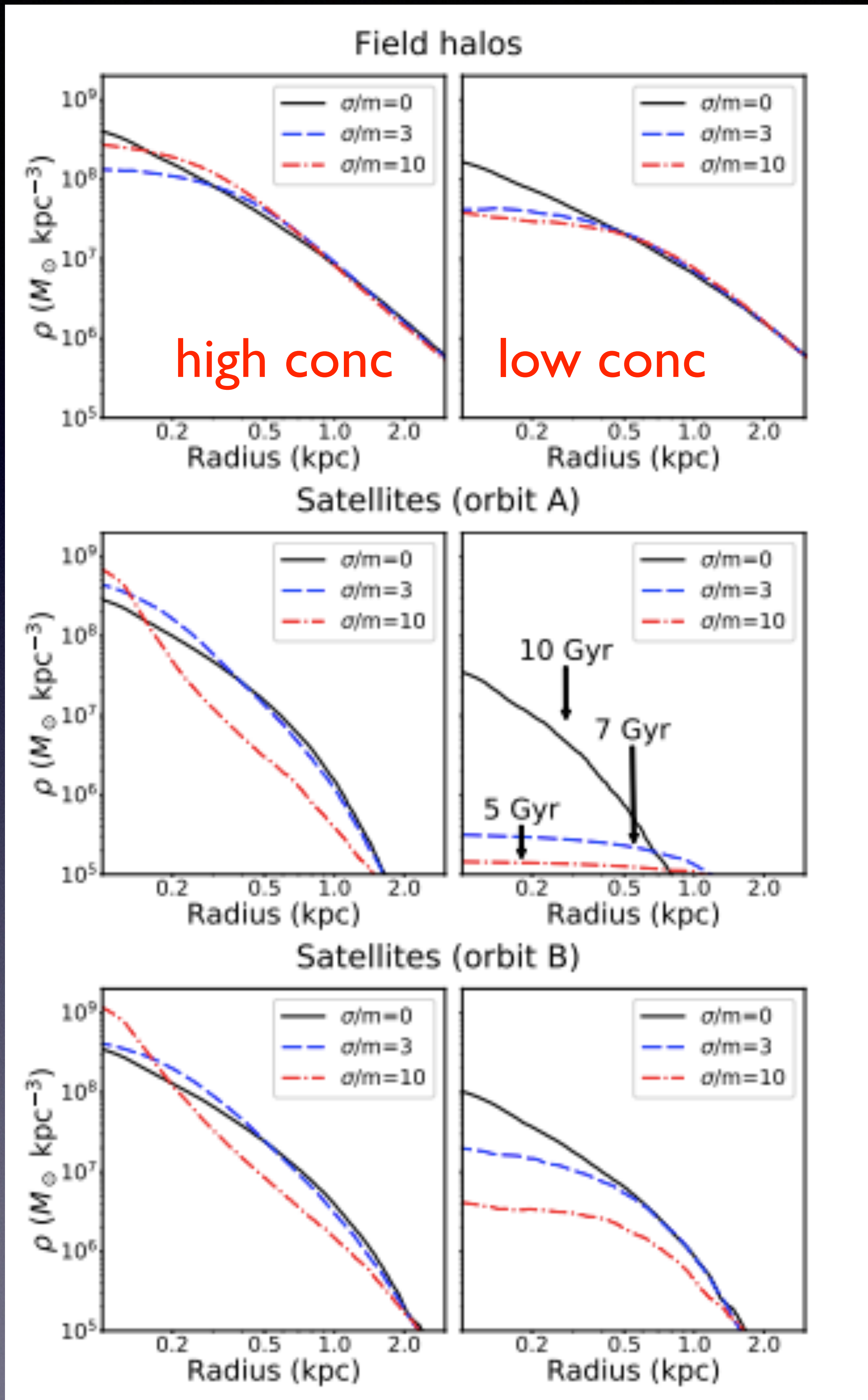
Self-interactions + tidal stripping → diverse histories

Kahlhoefer, Kaplinghat, TRS & Wu

- Tidal stripping from main halo acts as a positive feedback effect on halo density/concentration
  - halos with compact dense cores lose their outer parts to tidal stripping → further increases the rate of core-collapse [Nishikawa et al 1901.00499], increasing central density
  - low-density halos with cored profiles are severely disrupted → produces larger cores, even lower density, or complete destruction







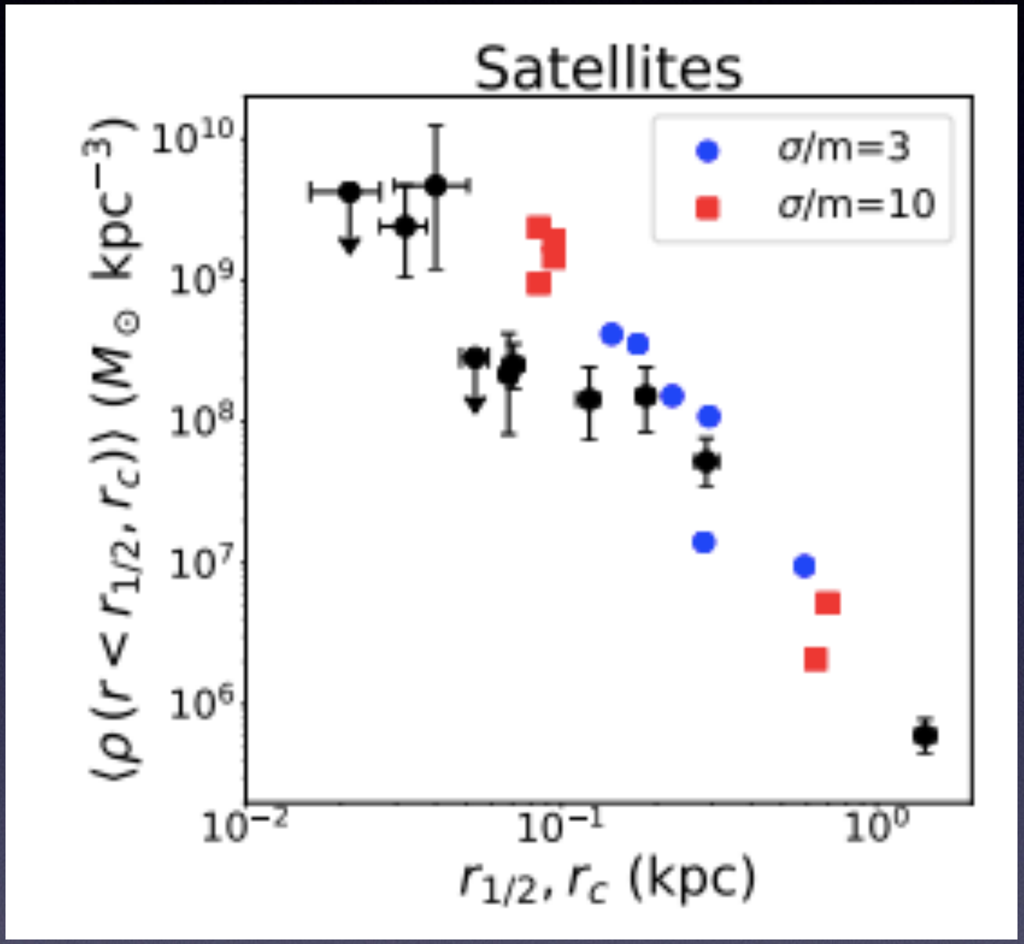
The density slope

- In field halos, SIDM halos (for these cross-sections) develop flat-density cores
- In satellites:
  - enhanced core-collapse of high-concentration halos yields steep density profiles (steeper than CDM)
  - low-concentration cored profiles undergo enhanced disruption, and develop large shallow cores

Implications to explore

Kahlhoefer, Kaplinghat, TRS & Wu

- There is observationally a wide scatter in properties of the dark matter halos of Milky Way dwarf satellites [Oman et al '15].
- In SIDM, expect low-DM-density satellite halos to possess large expanded cores, and high-density halos to have small collapsed cores.
- If stars respond adiabatically to changes in the DM density profile, then we would expect a wide range of half-light radii, correlated with the core sizes of the DM haloes (& halo densities).



- Especially for low-density haloes with large cores, tidal stripping effects are important and depend on the orbit (period, pericenter/apocenter, orientation to disk) - expect correlations between these parameters and halo density in SIDM.

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.
- The cosmic microwave background provides stringent limits on DM interactions with the Standard Model.
- Scenarios that are not yet ruled out could have large effects on the matter temperature at the end of the cosmic dark ages. Equivalently, 21cm measurements could set powerful new constraints on DM-SM interactions.
- 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.
- DM self-interactions could manifest themselves in the properties of satellite galaxies of the Milky Way; the interplay between self-interactions and tidal stripping effects increases the expected variability of satellite dark matter haloes.