Testing dark matter interactions through cosmic history

Tracy Slatyer

Theoretical Physics Colloquium
7 September 2022

Based on work with
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Greg Ridgway, and Yitian Sun

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
- How energy injection originating from (non-gravitational) dark matter interactions could change the early universe
- Some recent/upcoming developments:
  - Using neural networks as efficient function approximators to improve the signal calculation
  - Treating low-energy photons/electrons in detail
  - Full prediction of the space of post-recombination CMB spectral distortions from exotic energy injections

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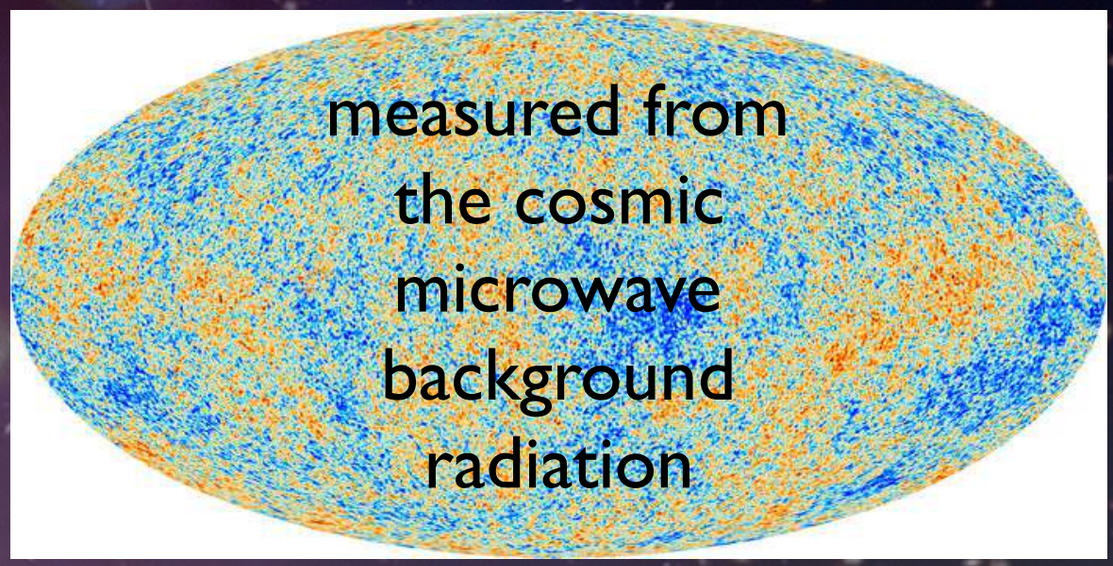

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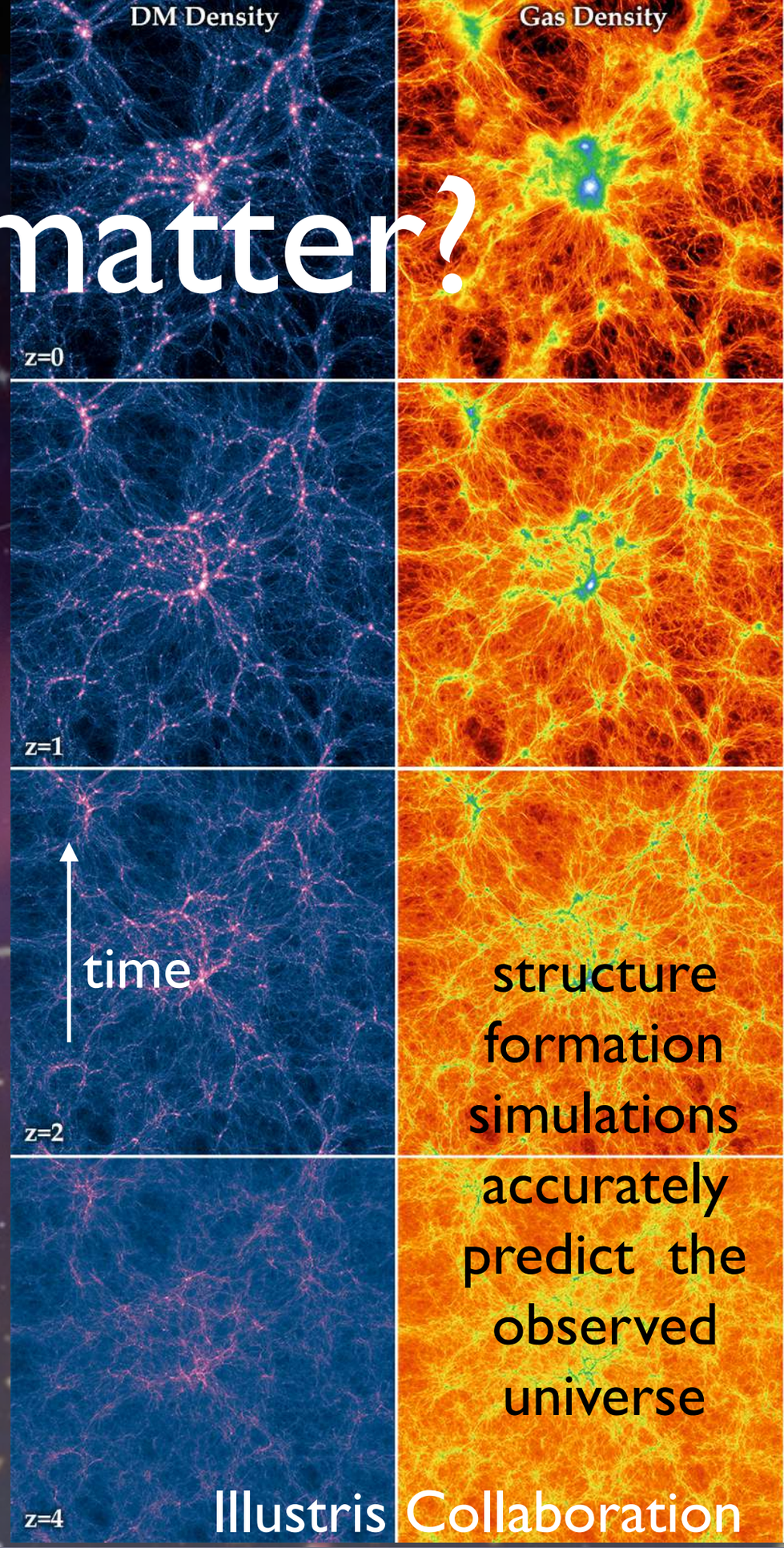

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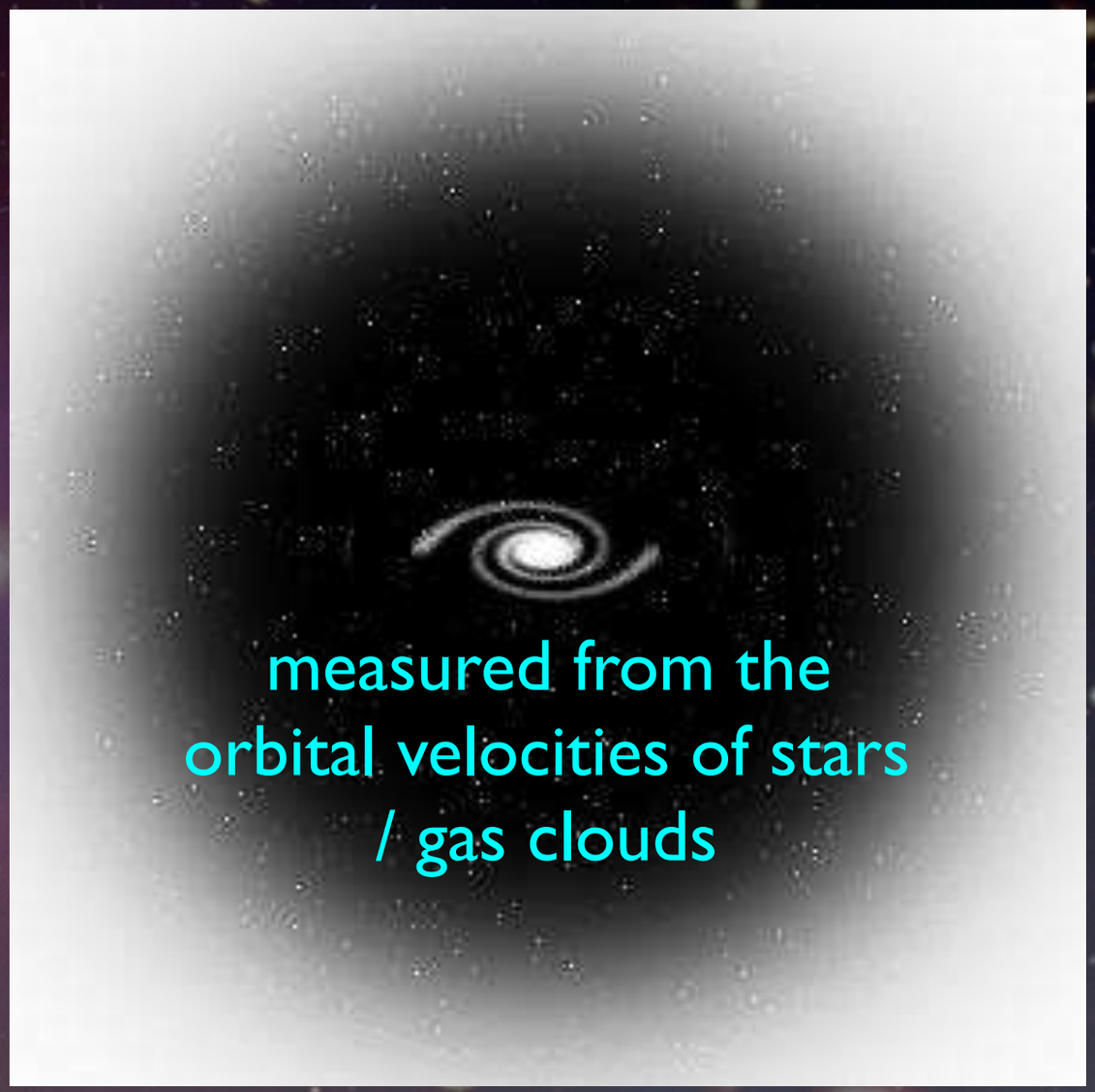

measured from the orbital velocities of stars / gas clouds

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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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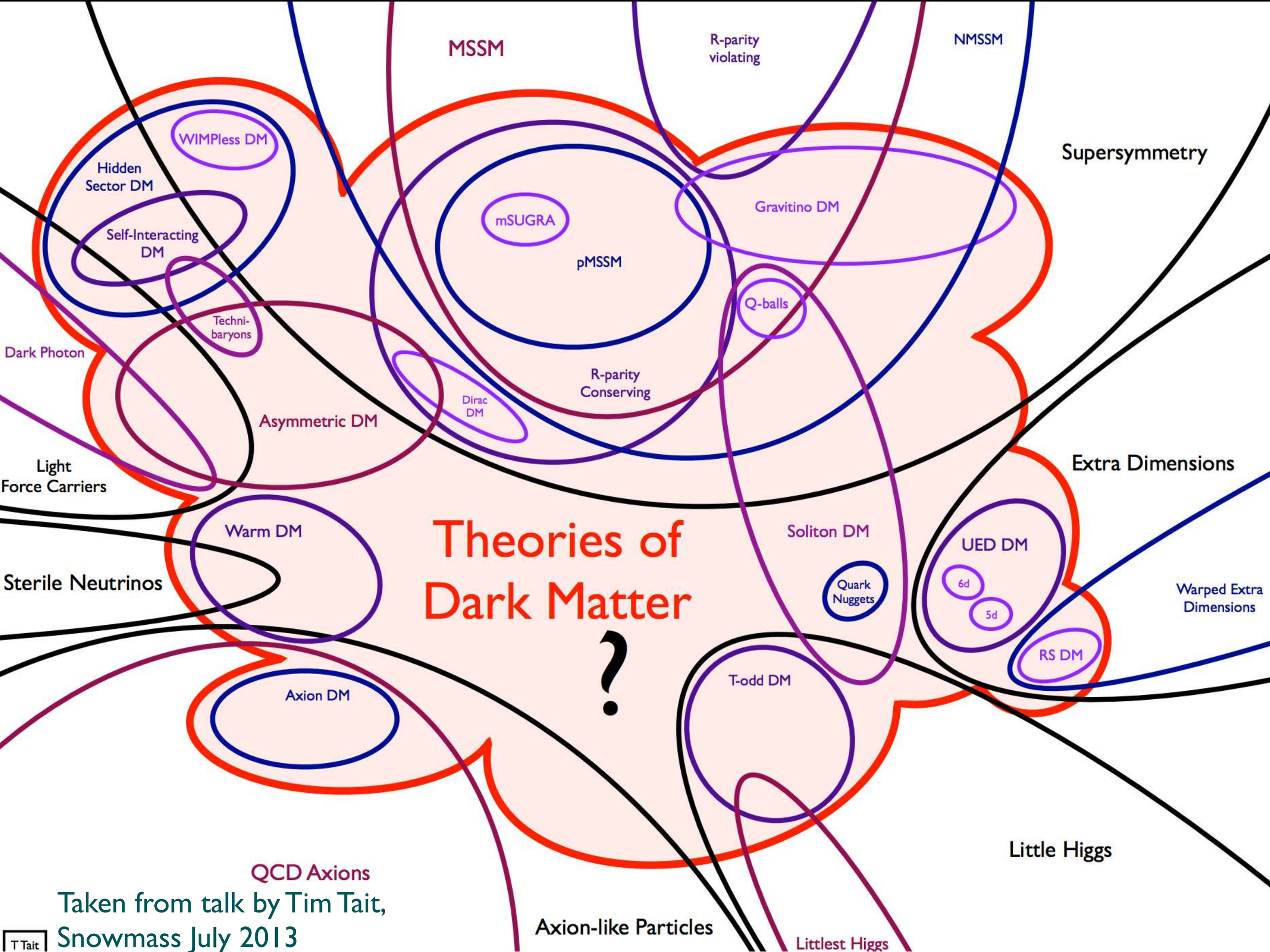
- and many more…



Taken from talk by Tim Tait, Snowmass July 2013

Searches for DM interactions

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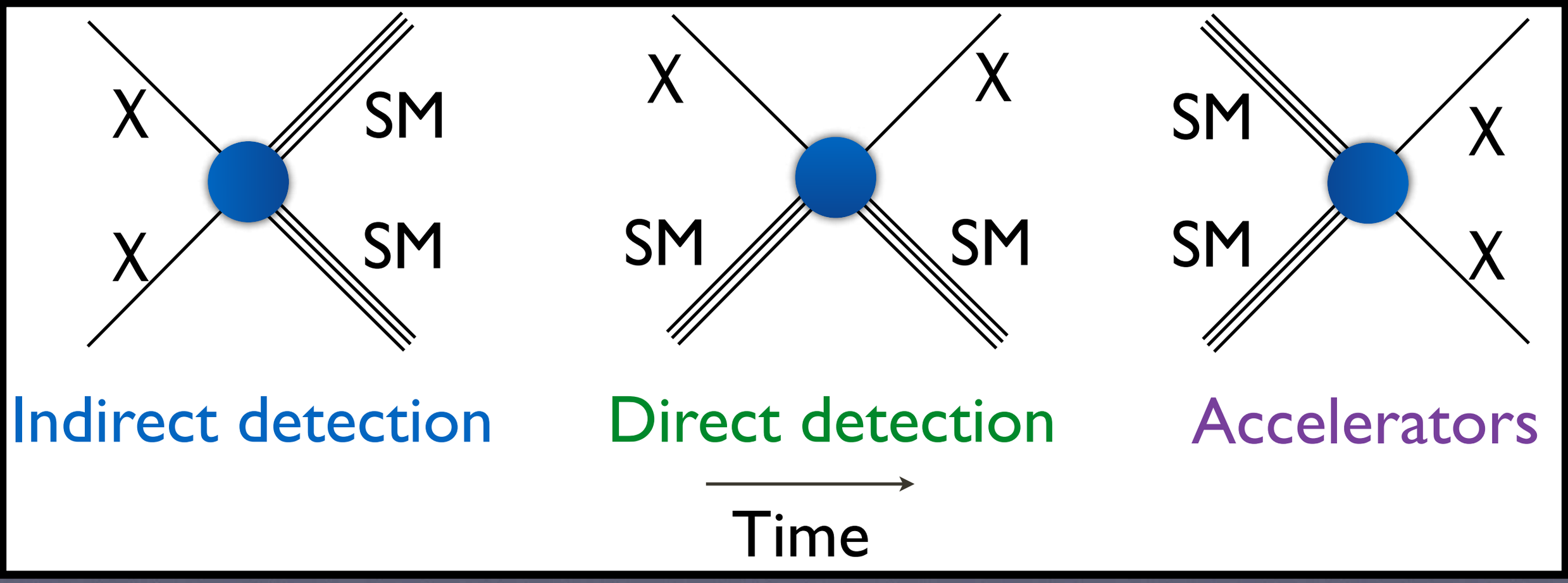

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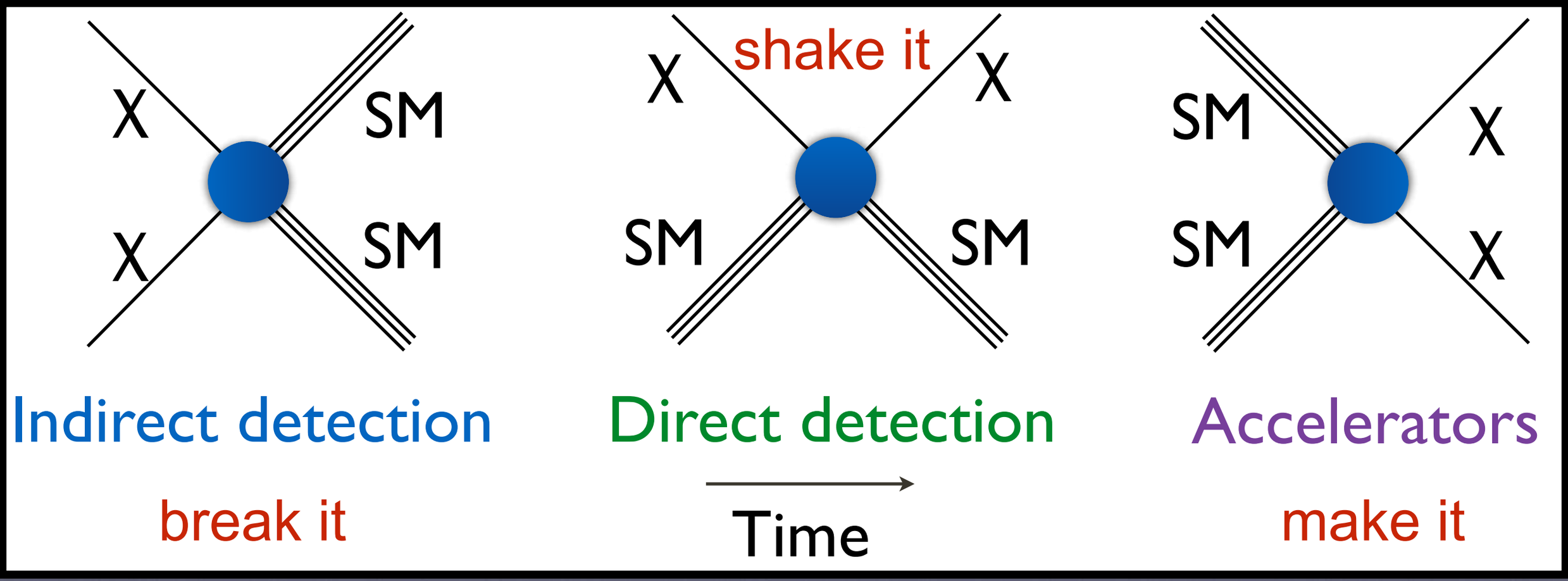

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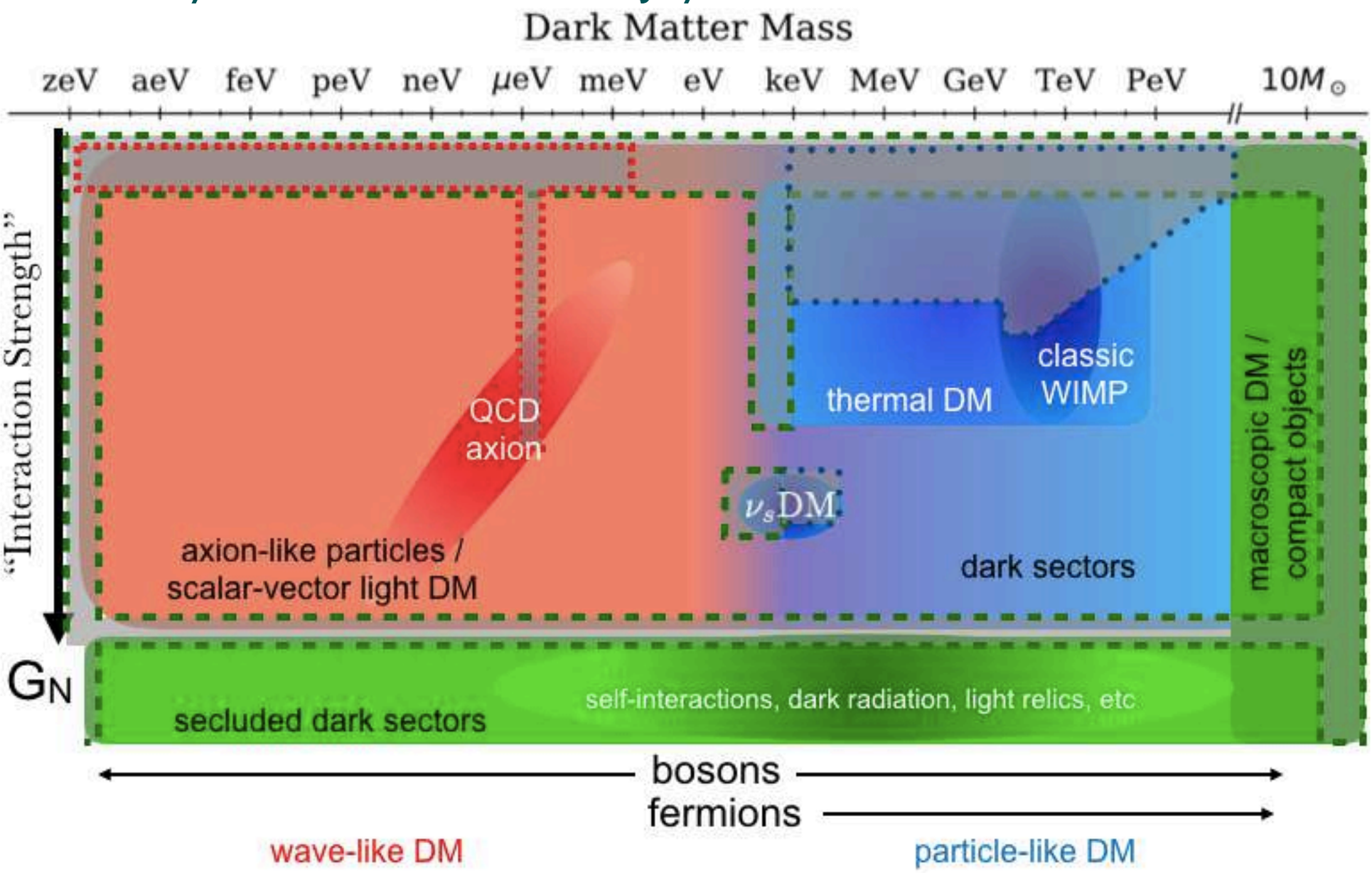
The Cosmic Frontier in the next 10 years

Taken from talk by Aaron Chou, Snowmass July 2022



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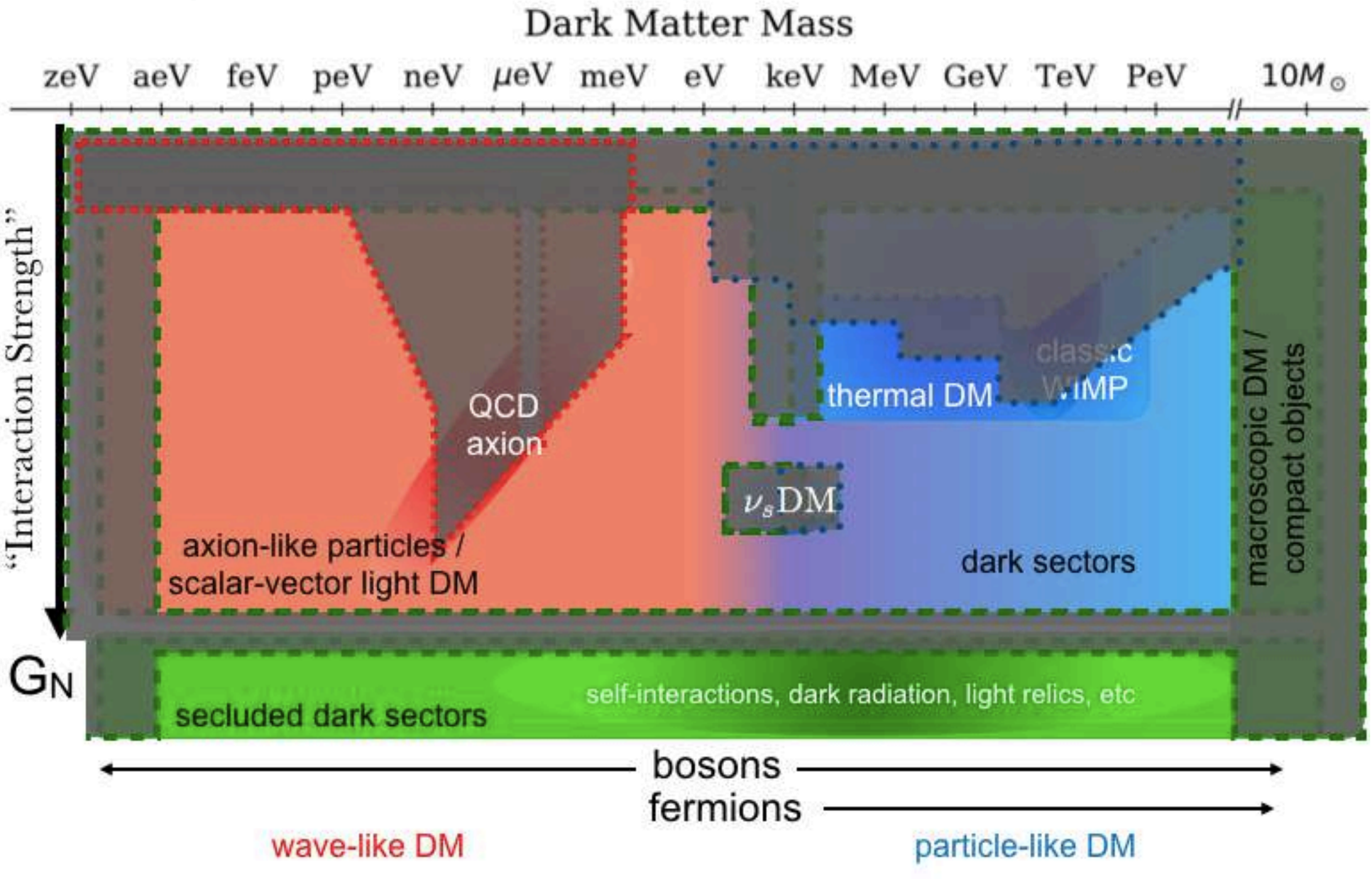
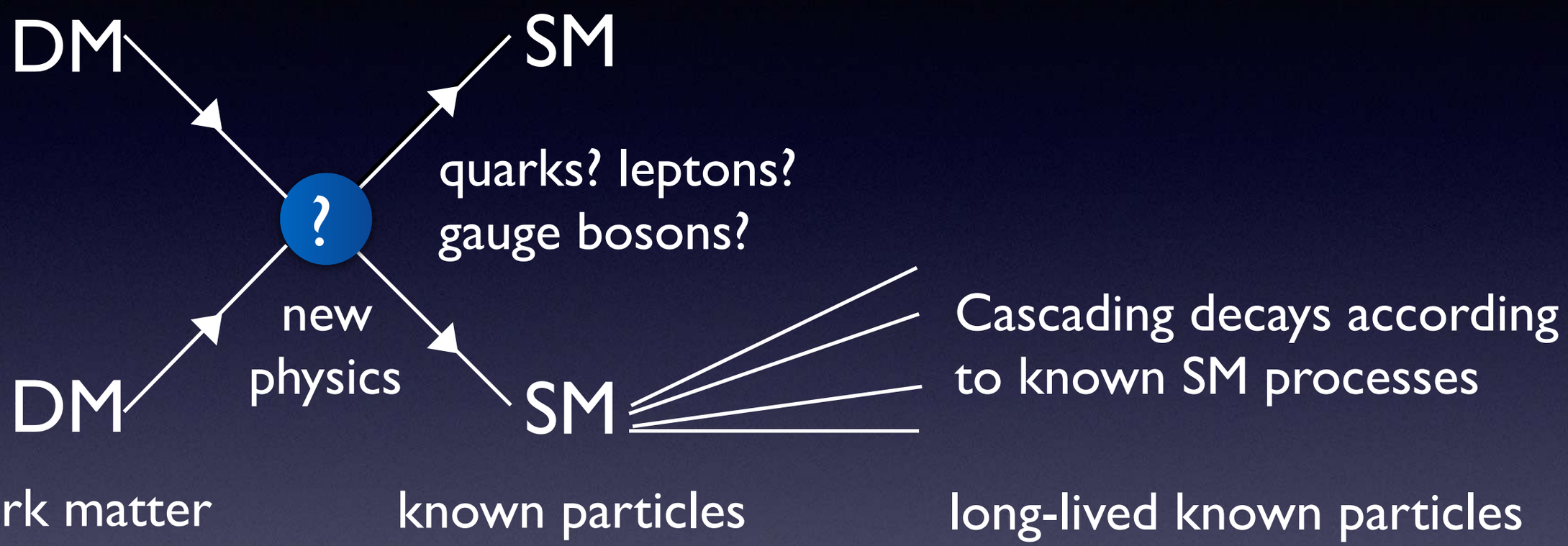


Identifying dark matter

- There is an enormous range of possible DM scenarios, spanning tens of orders of magnitude in mass.
- Many of these scenarios are ~equivalent from the perspective of gravitational effects
  - exceptions: DM is very light (fuzzy DM, ~10^{-21} eV), very heavy (PBHs), warm/fast-moving, or strongly self-interacting (cross section/mass > 0.1 cm^2/g)
- Non-gravitational interactions in principle provide much greater discriminating power (if they exist)
- Large ongoing experimental program to search for such interactions in accelerators, direct-detection searches, precision experiments, astrophysical observations
- Can regard such interactions as providing an energy transfer channel between dark and visible sectors - could have observable effects on cosmology
- Interactions can be either elastic (competes with Earth-based direct-detection experiments) or inelastic (focus of this talk)

Annihilation

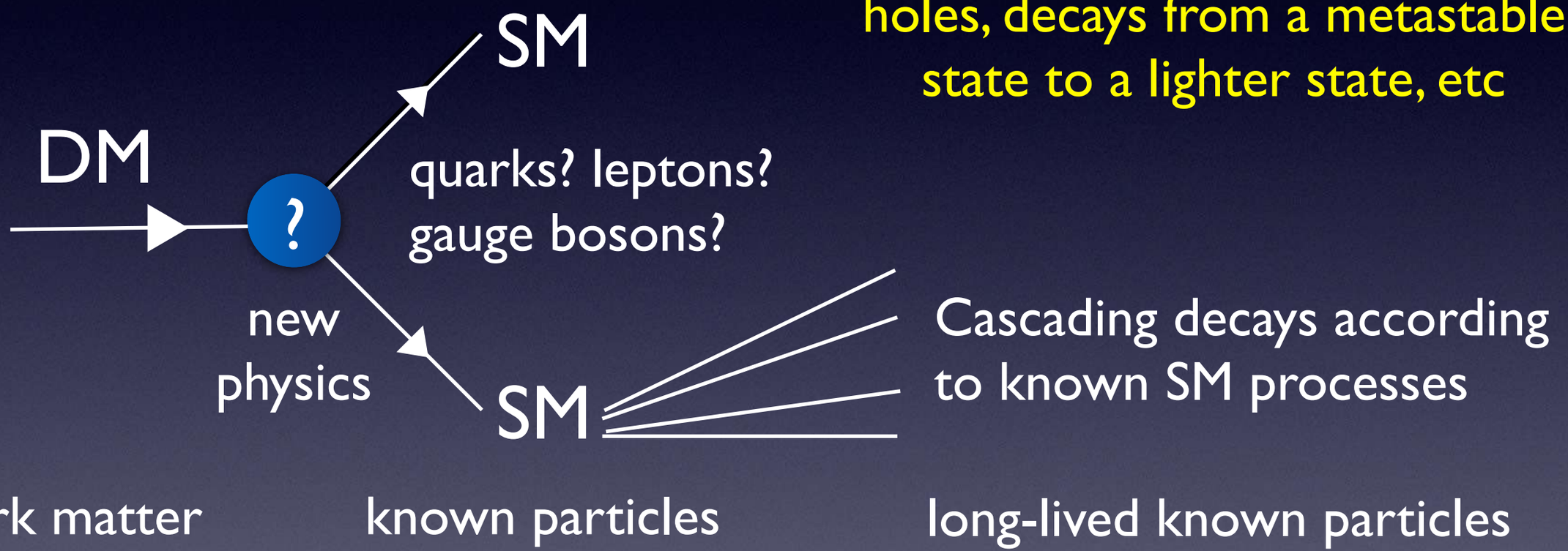


- Tightly linked to DM abundance in scenarios where (1) DM was in thermal equilibrium with SM in early universe, (2) annihilation depleted the initial abundance.
- Such scenarios favor a benchmark "thermal relic" cross section:

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

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 can explore the effects of this energy transfer on the history of the universe.

The cosmic microwave background radiation

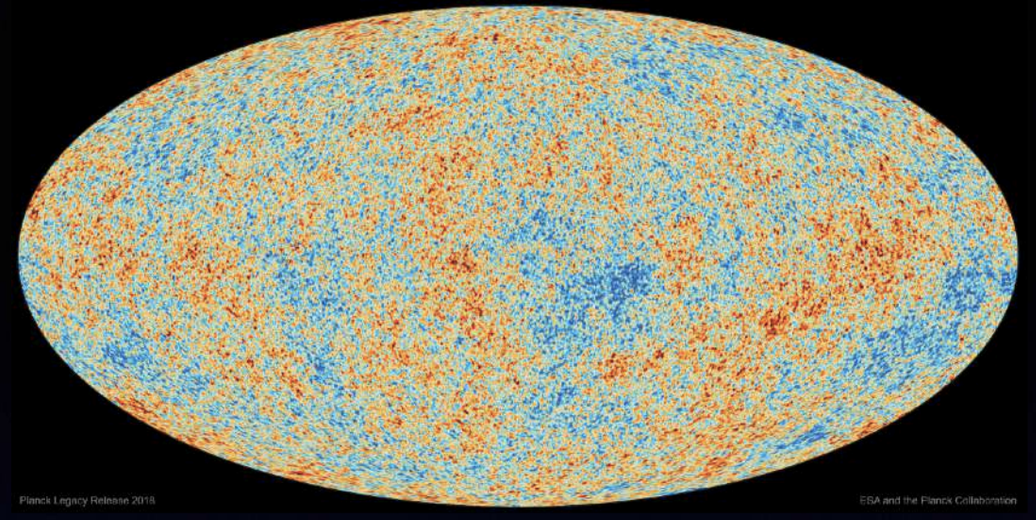
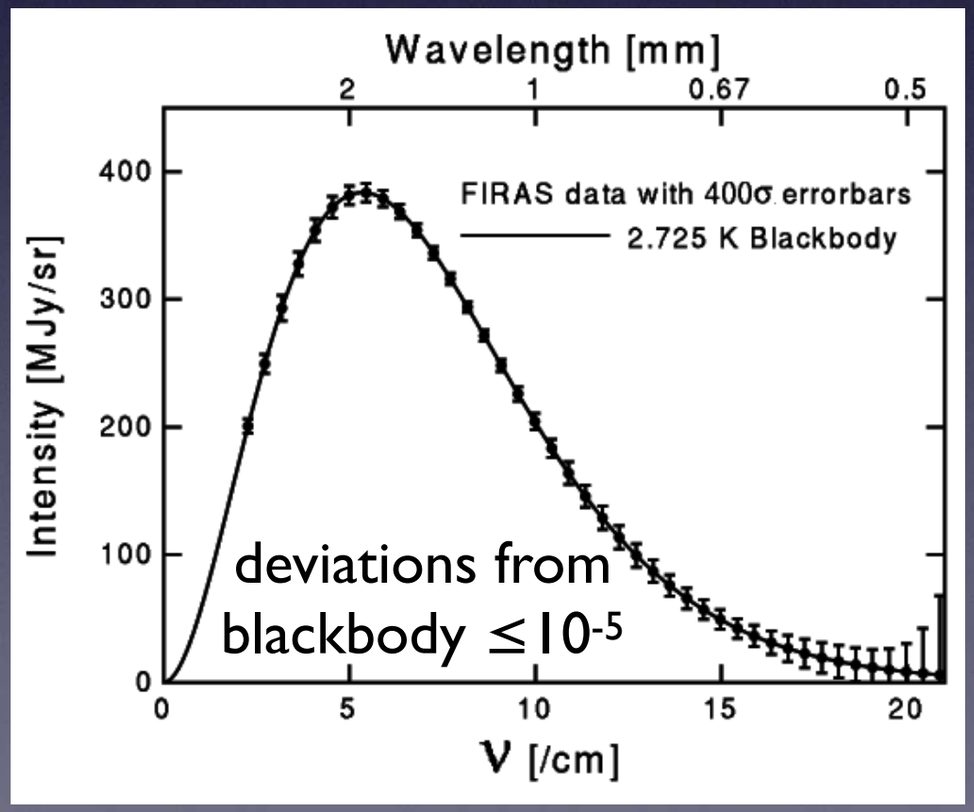


Image credit: European Space Agency / Planck Collaboration

- 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

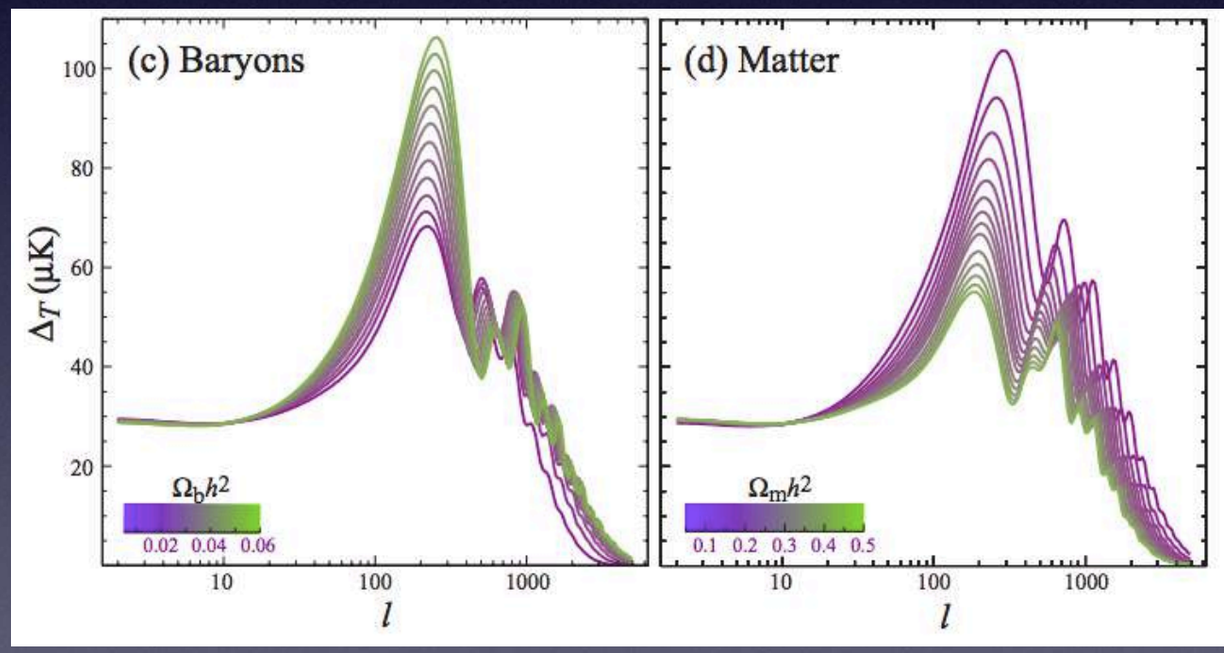
spectral information: near-perfect blackbody



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

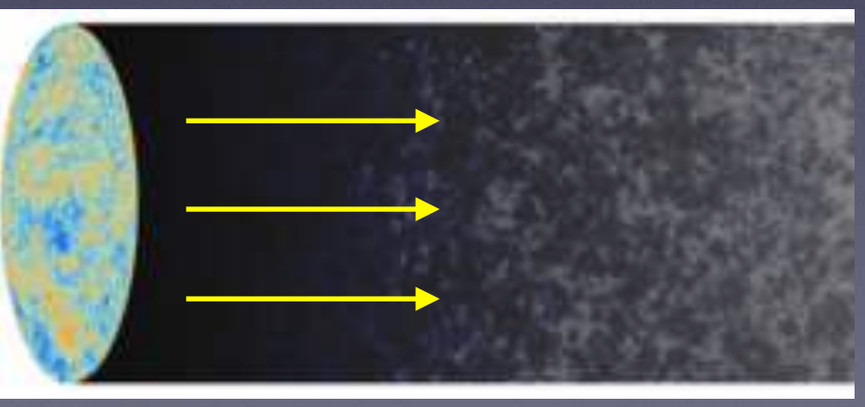
Hu & Dodelson '02

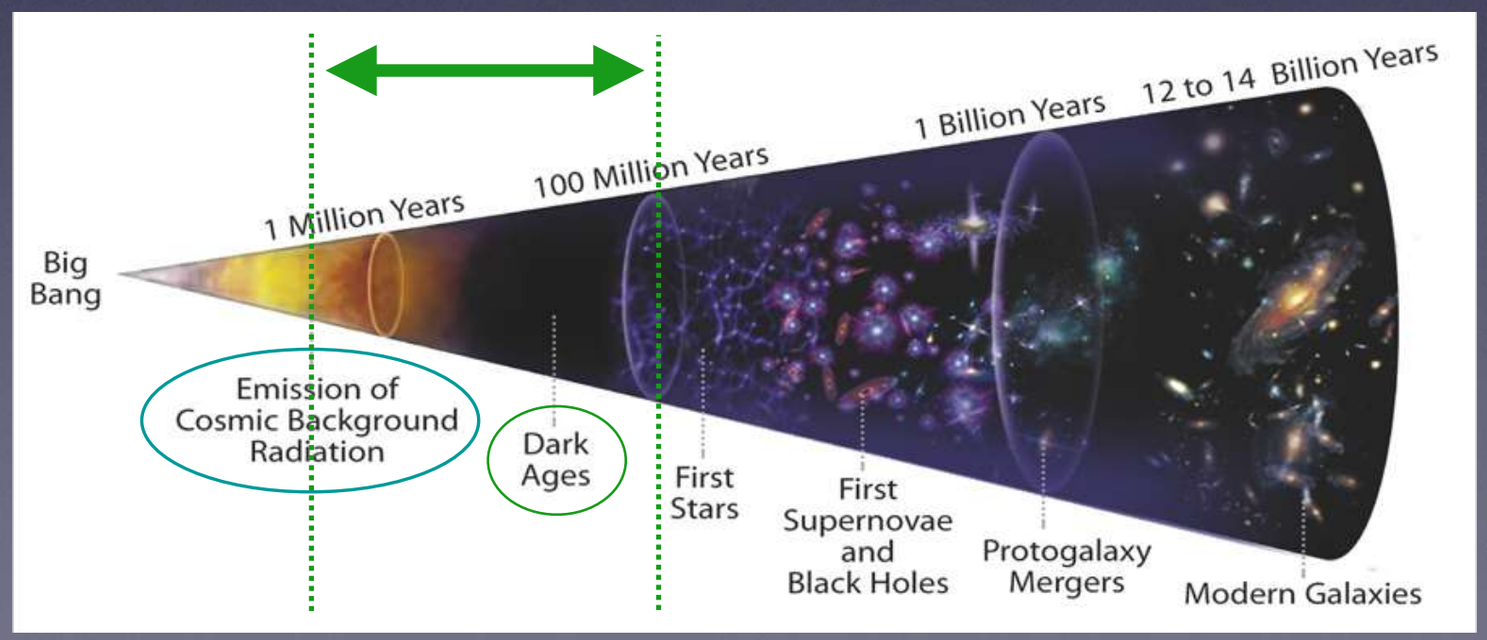


- Classic example of first case: temperature/ density oscillations in plasma are driven by competition between gravity and radiation pressure.
- Presence of matter that feels gravity but not radiation ("dark") changes properties of oscillations - used to measure DM abundance.
- Scattering between DM 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.





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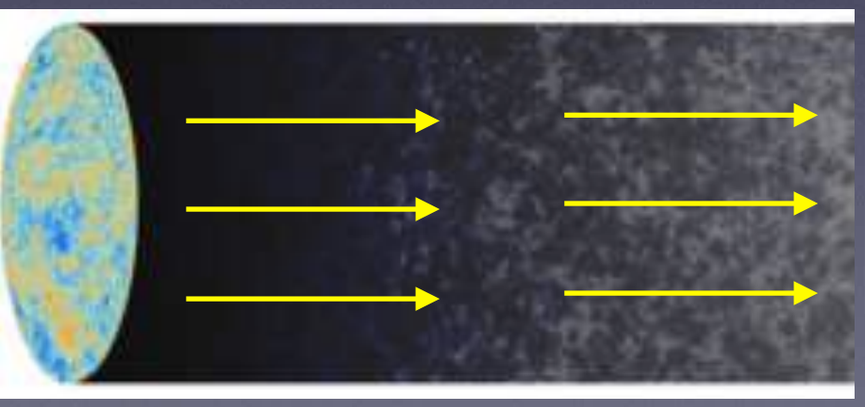
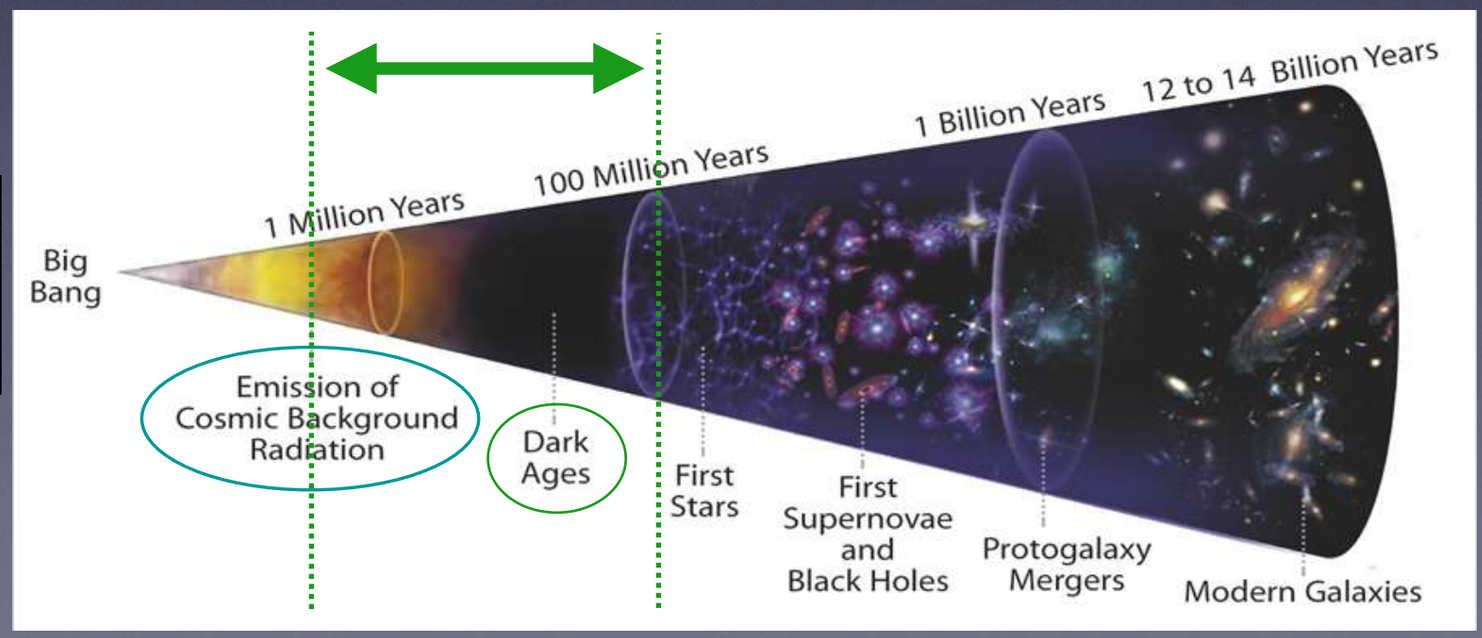


Planck



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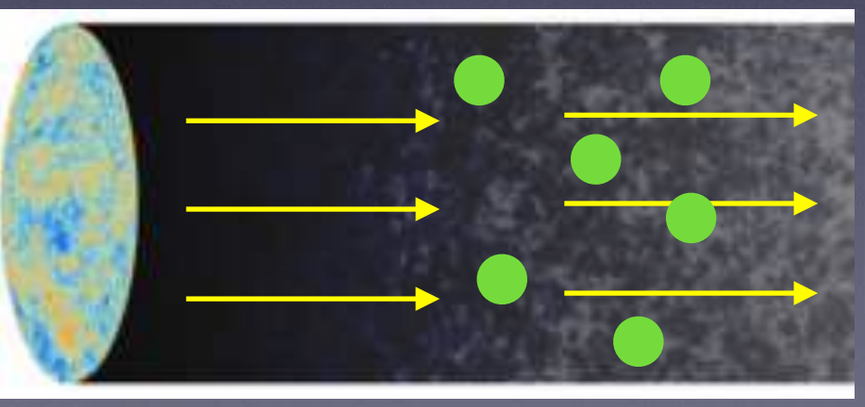

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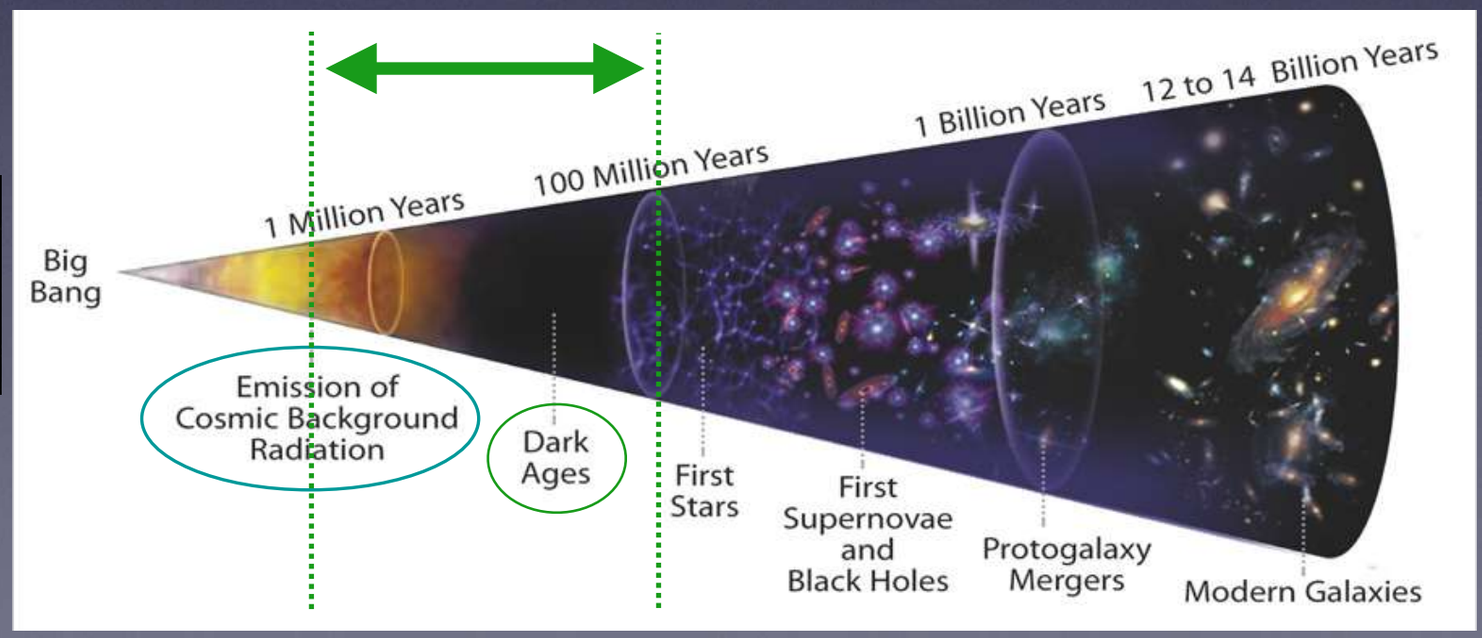

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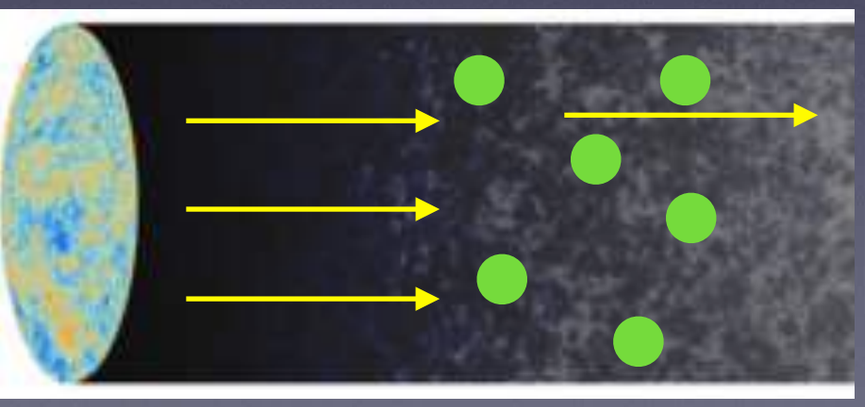

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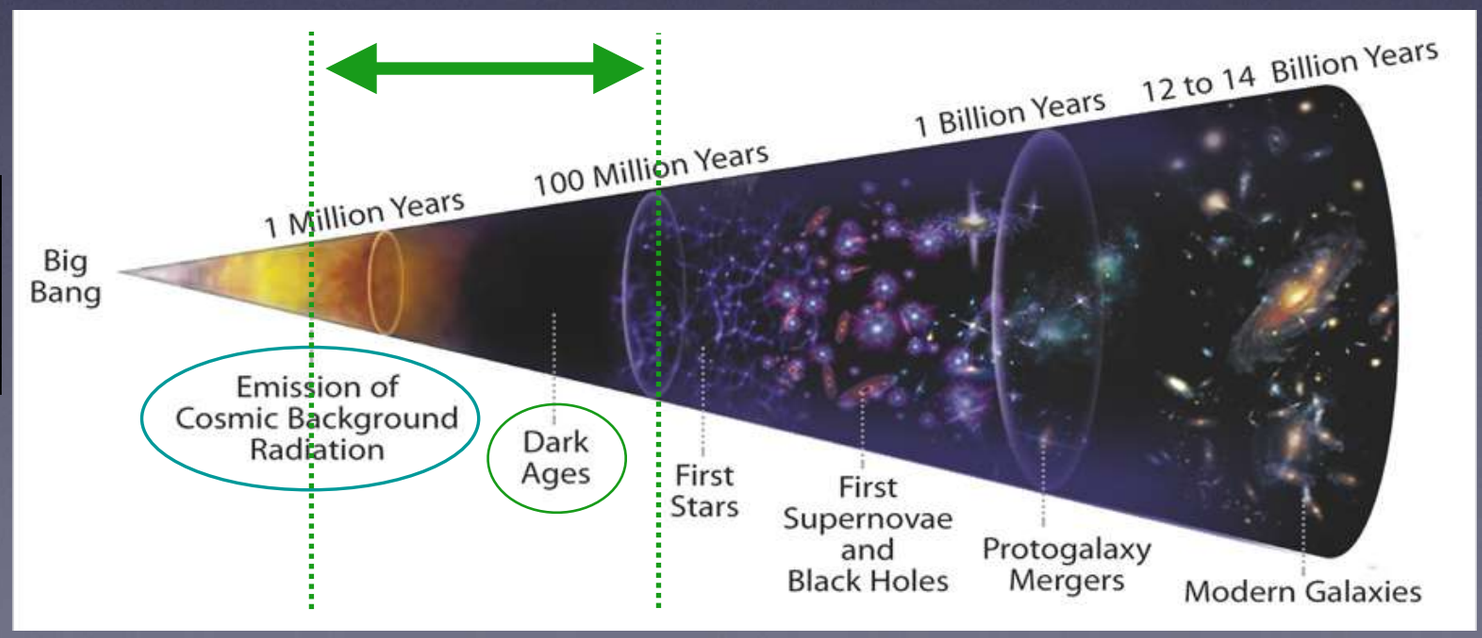
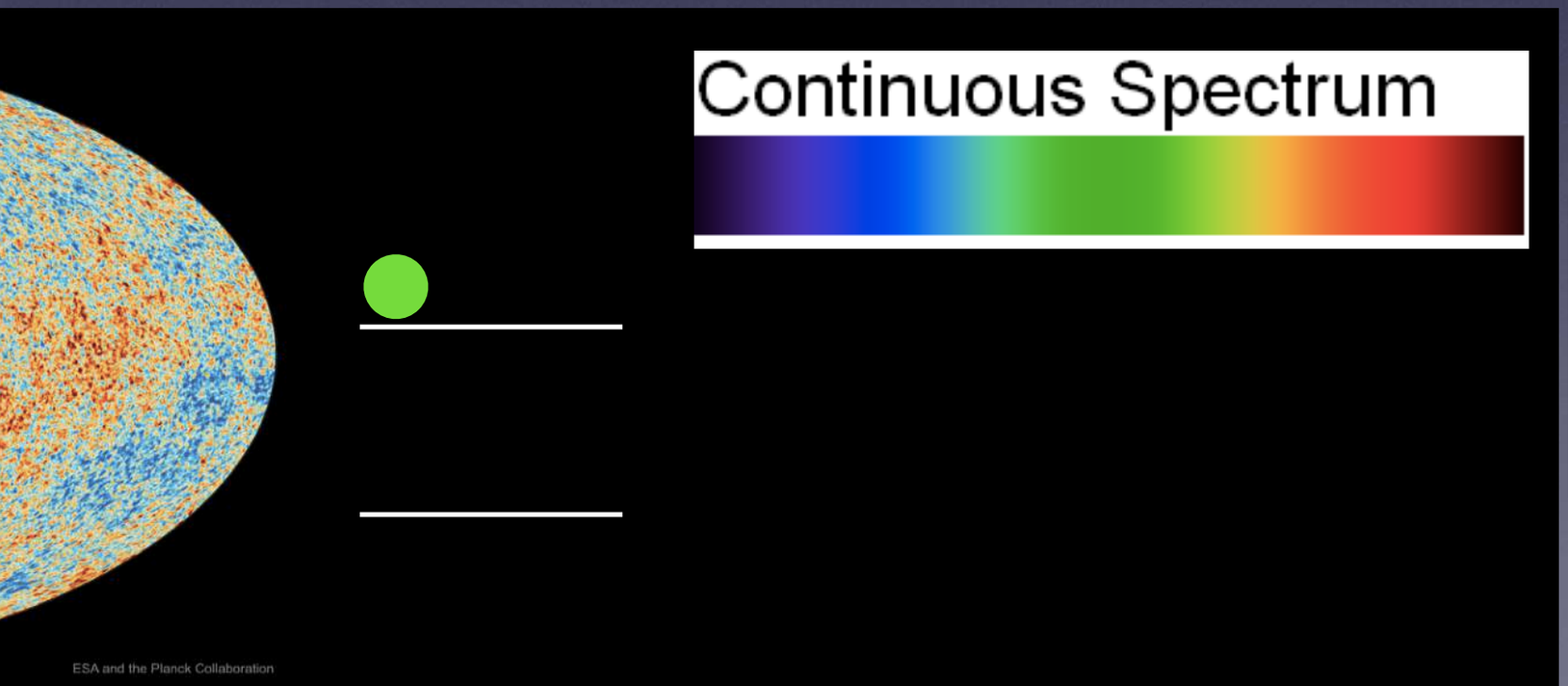


21cm and the cosmic thermal history

- 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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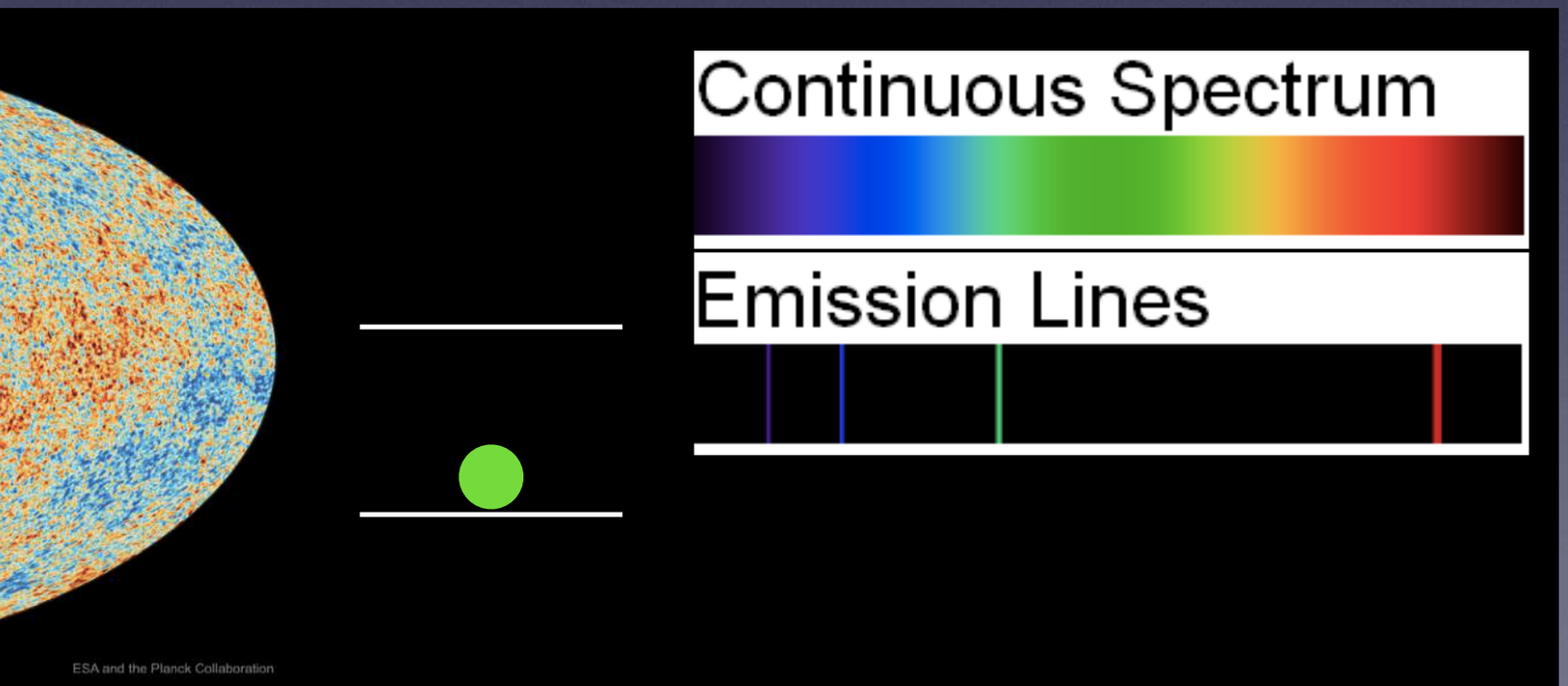

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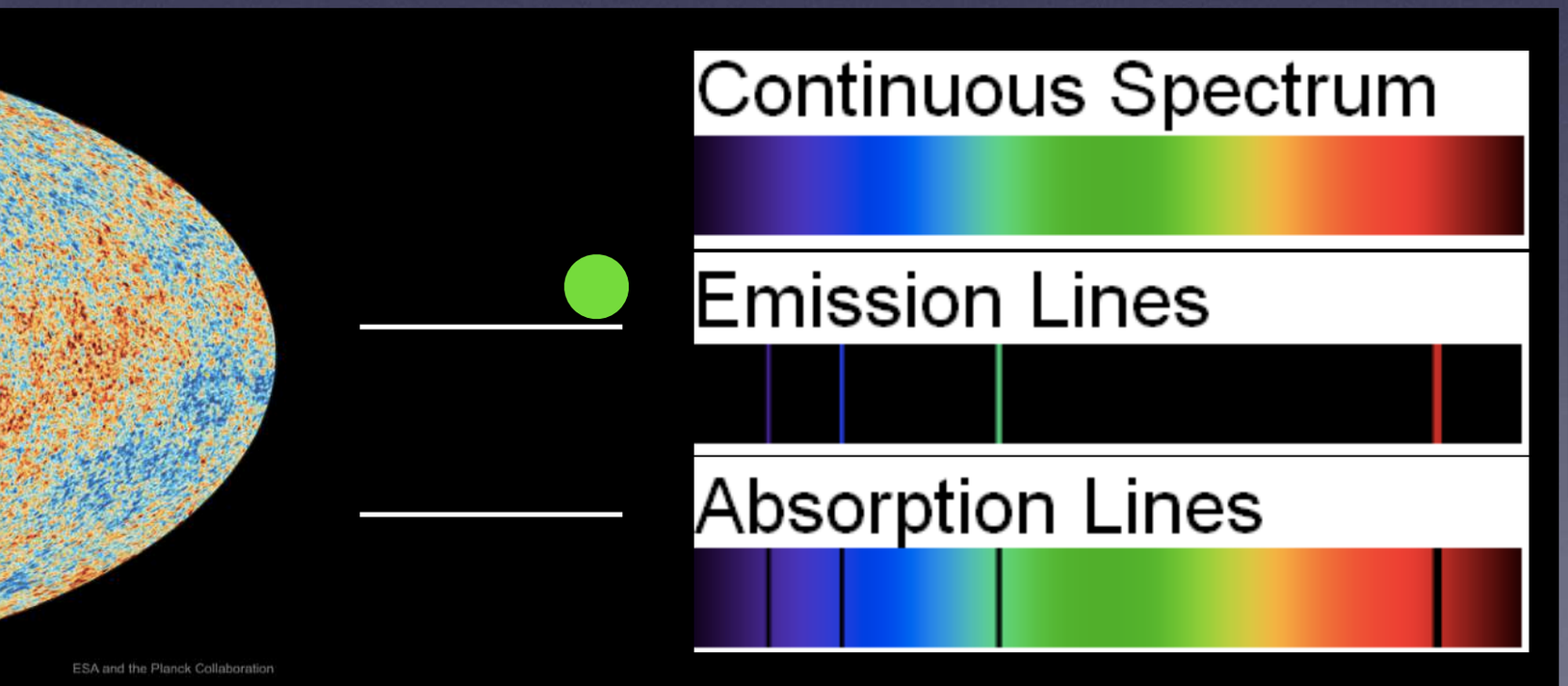

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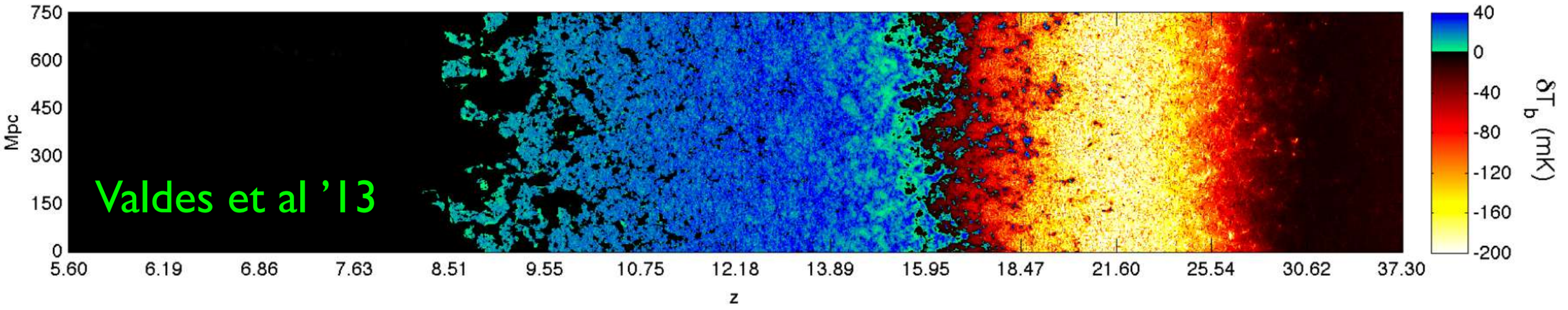
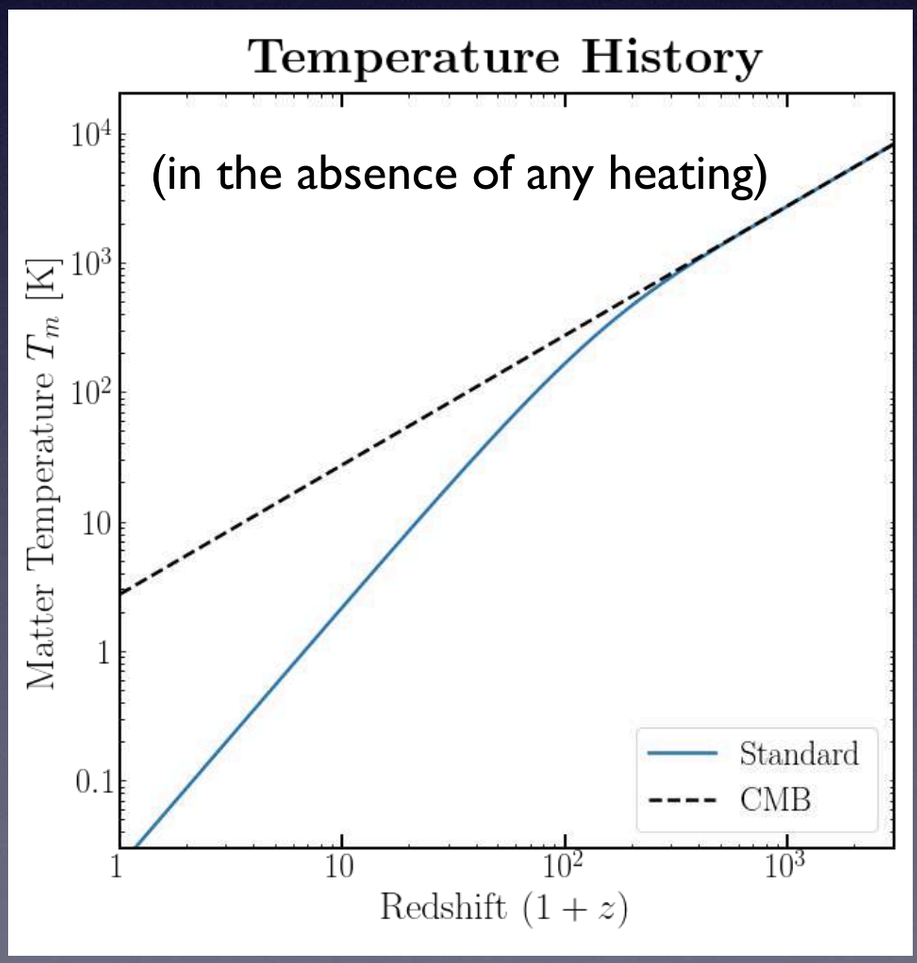
Expectations for a 21cm signal

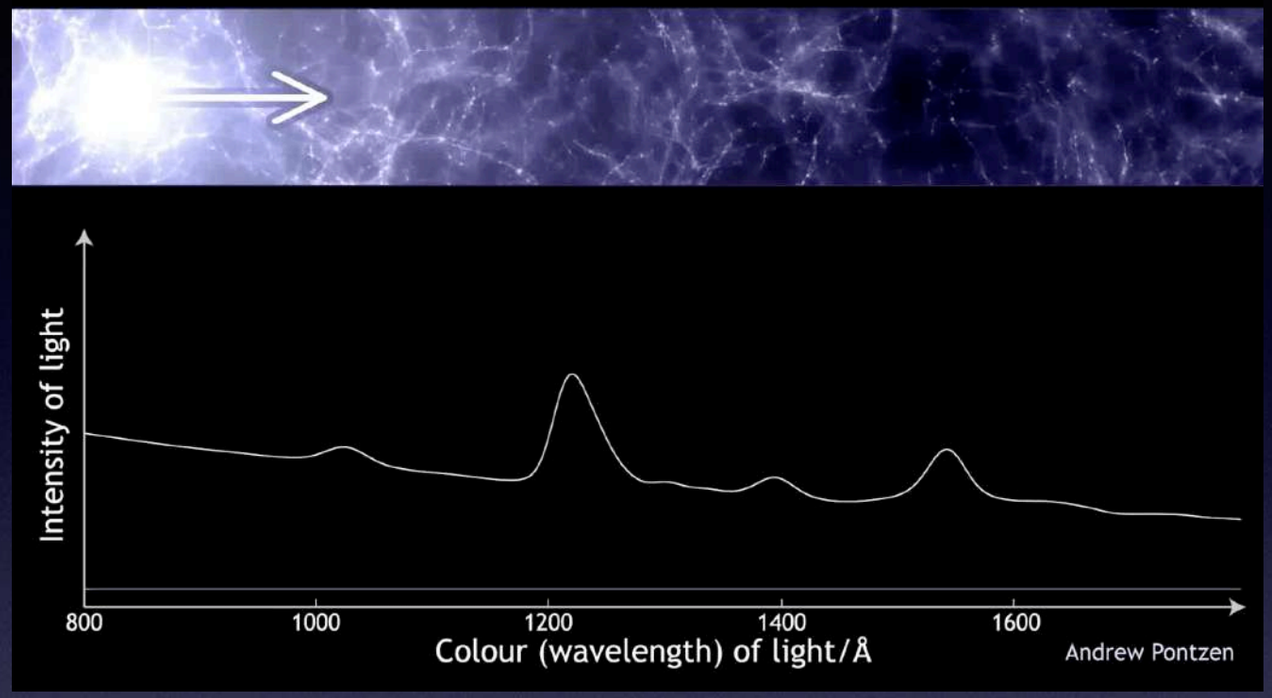


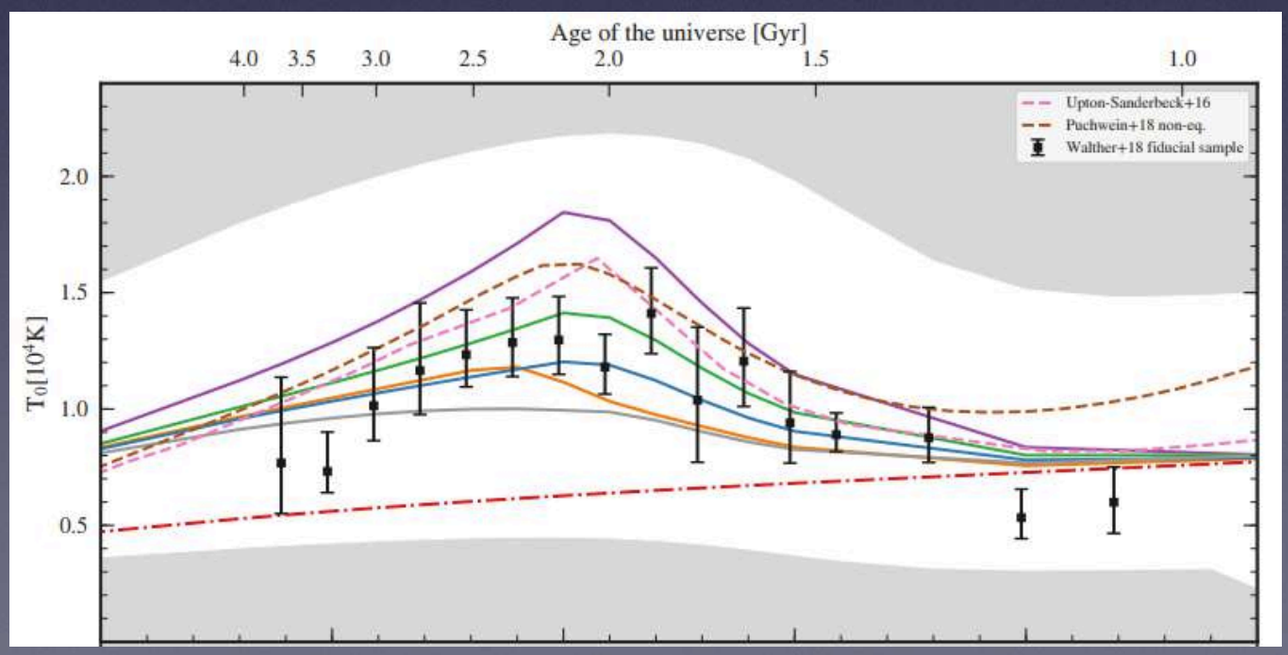
- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature.
- Exotic heating could lead to an early emission signal [e.g. Poulin 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}.



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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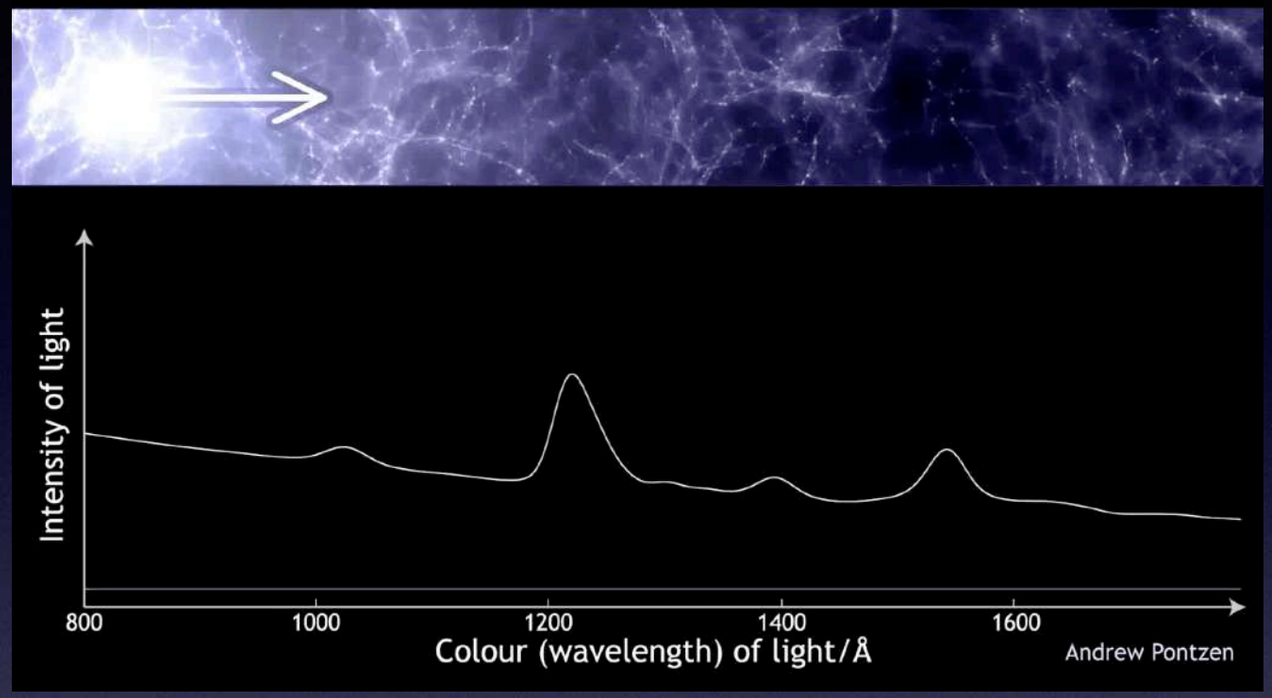

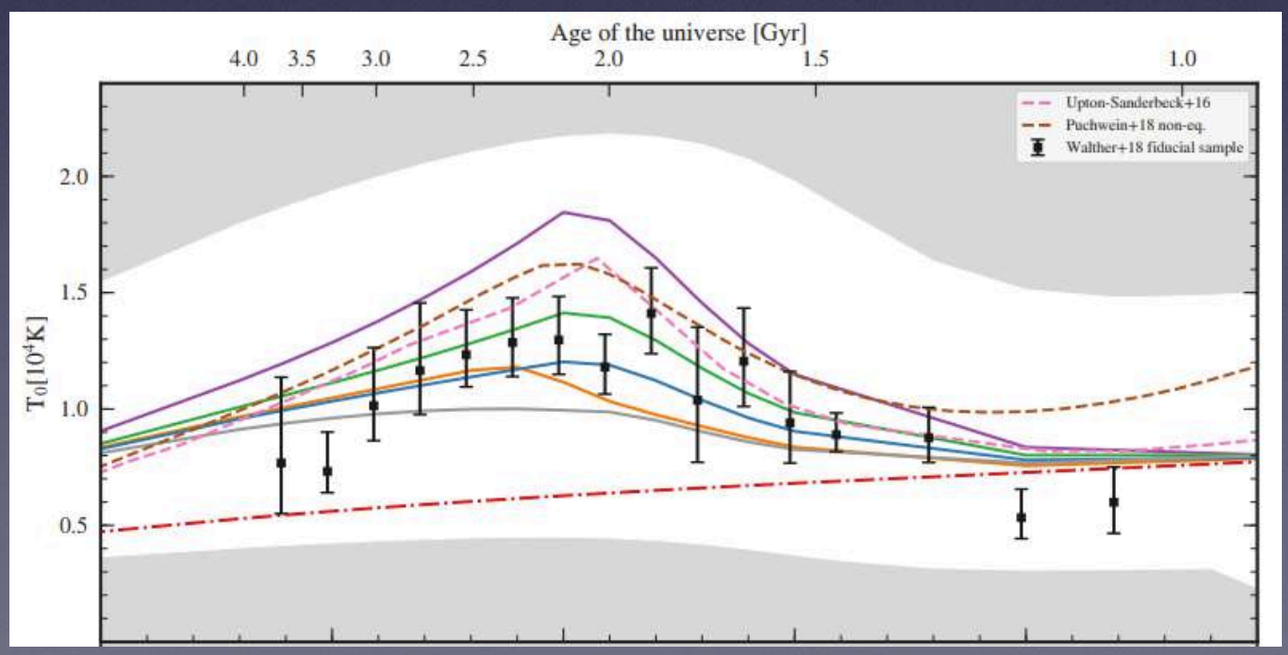

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Ionization vs heating vs spectral distortions

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  - 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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potentially a large effect for z < 200 - could be visible in 21cm

Example: estimating limits on decaying DM

- Fraction of DM decaying per e-fold in a given epoch ~ lifetime of cosmos / lifetime of DM
- Thus constraining a 10^{-9} fraction of DM decaying when the universe was 10% of its present age (O(100 million years) leads to limits on lifetimes of 10^{8} x age of the universe ~ few x 10^{25} s
- Similar constraints for 10^{-11} decaying fraction when the universe was O(10^{6} years) old, i.e. the CMB epoch
- Can also probe <u>tiny</u> metastable components decaying with lifetimes > 10^{6} years but < 10^{10} years

DarkHistory

computing modified ionization/thermal histories

- To study any of these effects in detail, 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

Predicting a signal

Annihilation/decay/etc injects high-energy particles

If unstable, decay with Pythia or similar program

↓

Time-dependent injection of high-energy photons + e^+e^- (others largely escape or are subdominant; neglect)

↓

Cooling processes

Absorbed energy (ionization+excitation+heating)

↓

Modify evolution equations, e.g. with public recombination calculator (RECFAST, CosmoRec, HyRec)

Cosmic ionization and thermal histories

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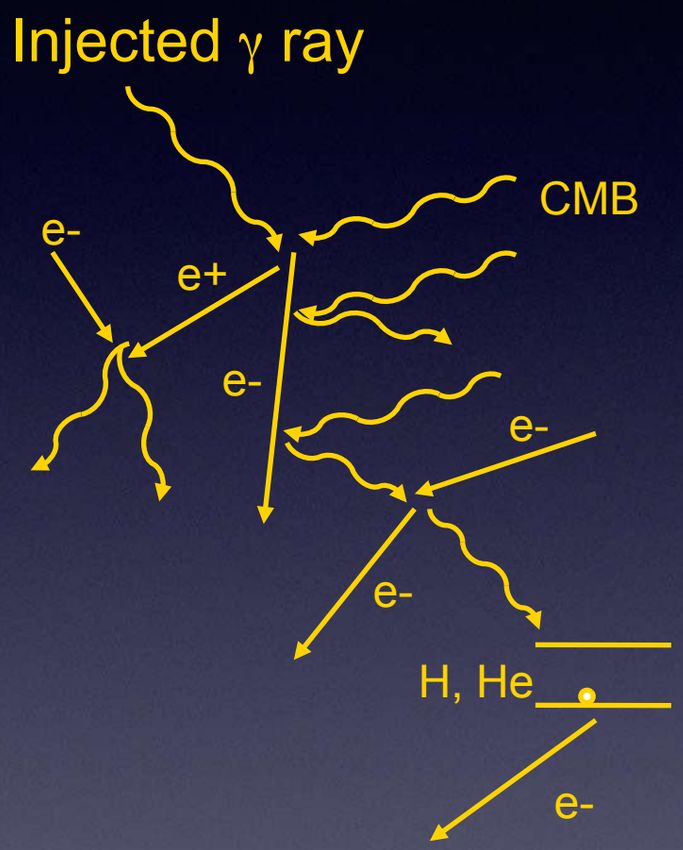
Cosmic ionization and thermal histories

The photon-electron cascade

Based on code developed in TRS, Padmanabhan & Finkbeiner 2009; TRS 2016

ELECTRONS

- Inverse Compton scattering (ICS) 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

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.

Note: rates depend on gas ionization level

From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history
- Energy deposition to ionization/heating provides extra source terms in these equations
- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code
- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen

$$\dot{T}_m = \dot{T}_m^{(0)} + \dot{T}_m^{\rm inj} + \dot{T}_m^{\rm re}\,,$$
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baseline exotic reionization/astro

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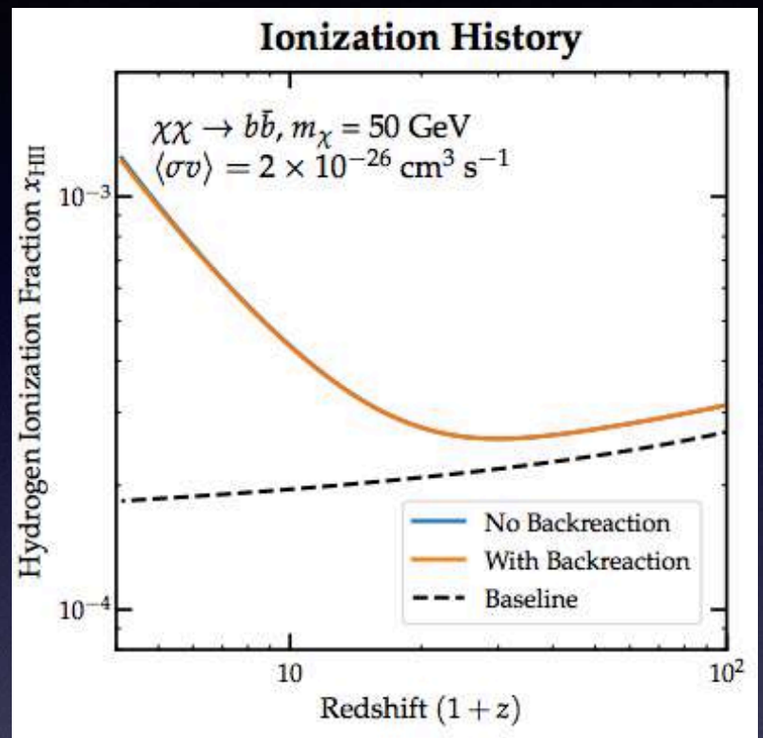
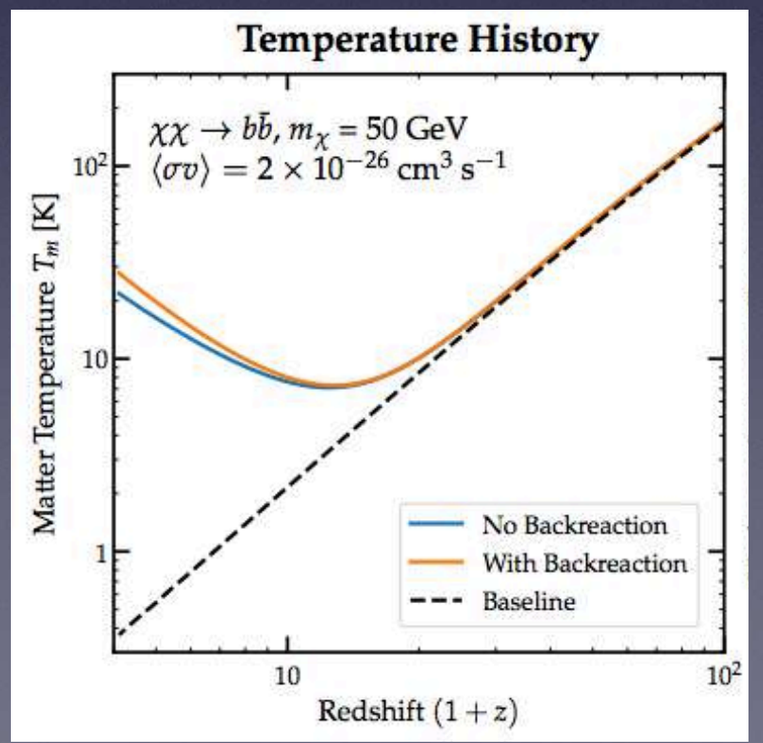
Running DarkHistory

- 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
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks.
- Easy to turn on/off "backreaction" effects (changes to ionization level from earlier energy injection modifies particle production cascade).

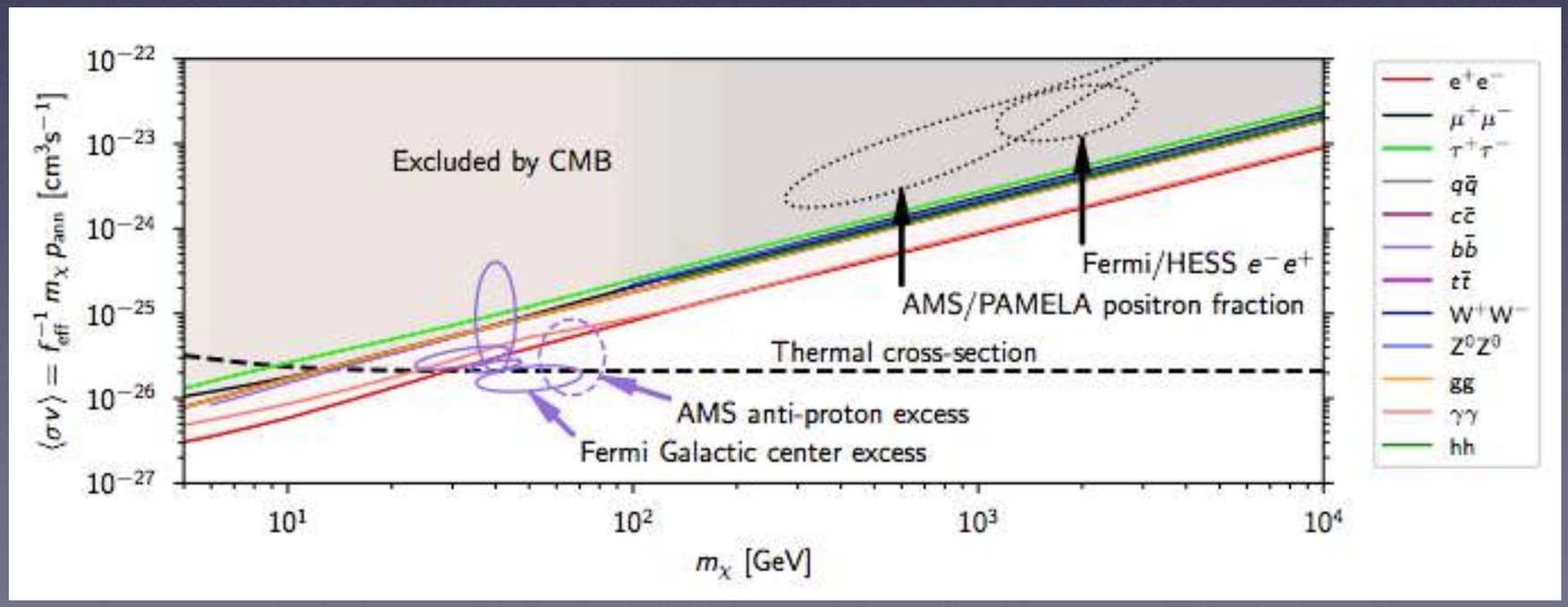
```
bbbar_noBR = main.evolve(
    DM_process='swave', mDM=50e9,
    sigmav=2e-26,
    primary='b', start_rs=3000.,
    coarsen_factor=32, backreaction=False,
    struct_boost=phys.struct_boost_func()
)
```





Annihilation limits from ionization + the CMB

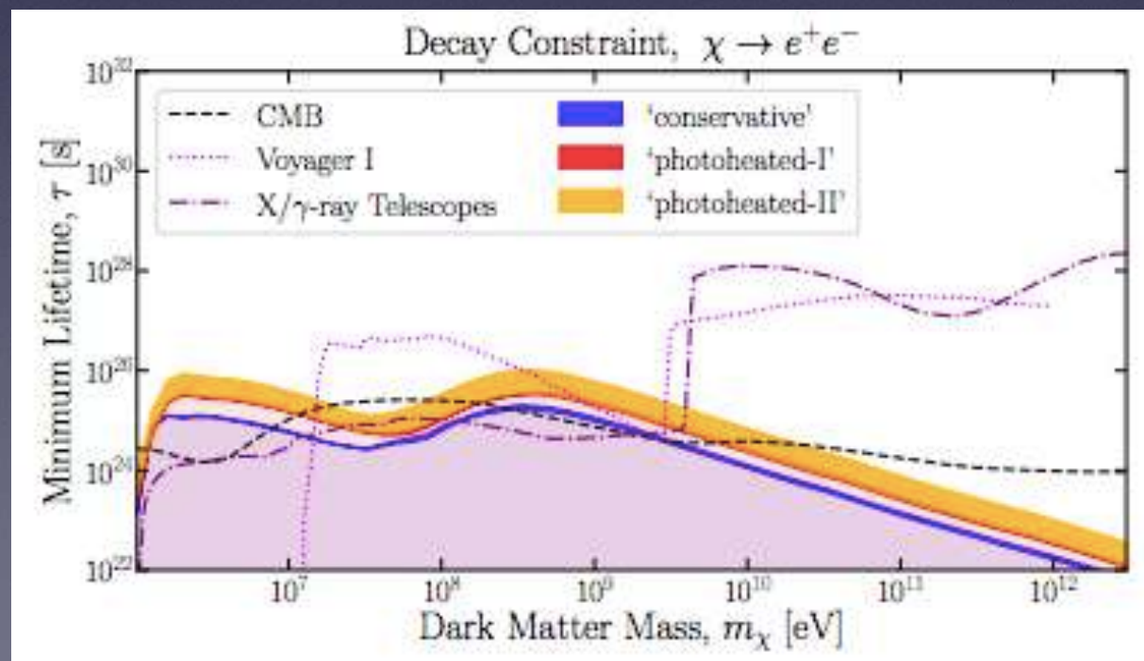
- The effect of DM annihilation on the CMB is <u>universal</u> in the keV-TeV+ range [TRS '16]: for <u>every</u> model where DM annihilates with ~constant cross section during dark ages, effect on CMB can be captured by a universal shape with a model-dependent normalization factor (which can be computed 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 <u>ruled out</u> for masses below ~10 GeV. Light DM needs a different origin mechanism, or suppressed annihilation.



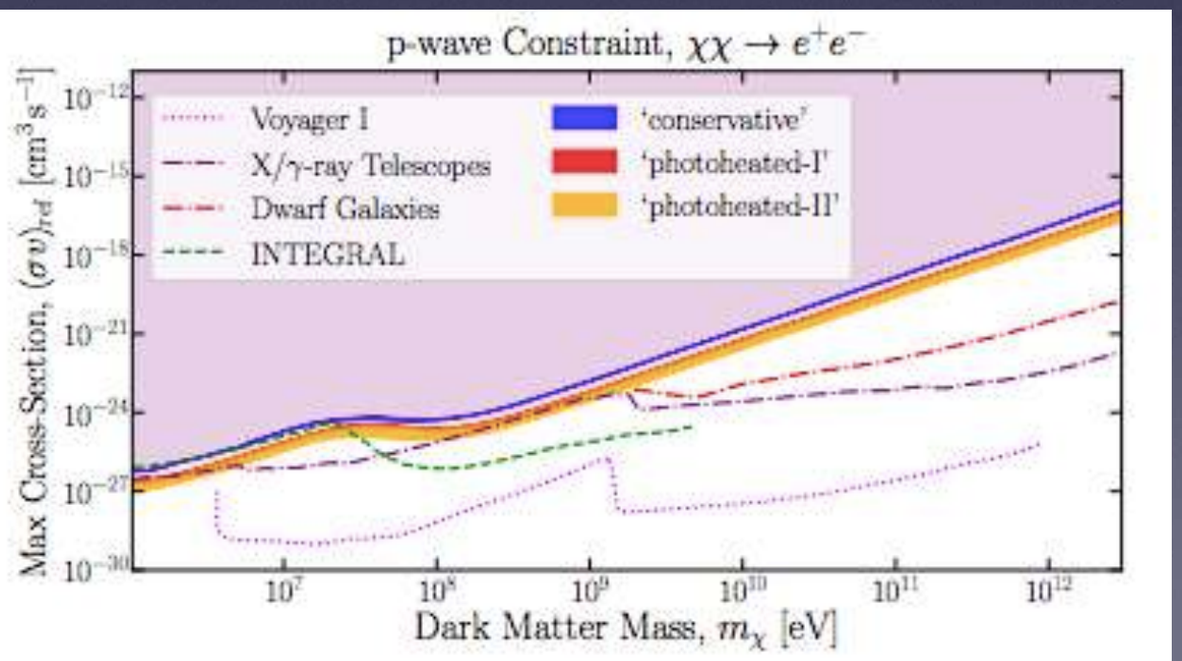
Planck Collaboration '18 1807.06209 based on results of TRS PRD '16

Decay limits from CMB and Lyman-alpha

- For decaying dark matter, comparable bounds from ionization/CMB and heating/Lyman-alpha constraints.
- 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)



Liu et al '20



Eventual goal: a comprehensive map of the full space of possible early-universe signatures of exotic energy injections, allowing us to easily translate arbitrary energy injection models into observables and constraints

(We already have something very close to this for CMB anisotropy signals from DM annihilation/decay - I would like to extend it to other observables)

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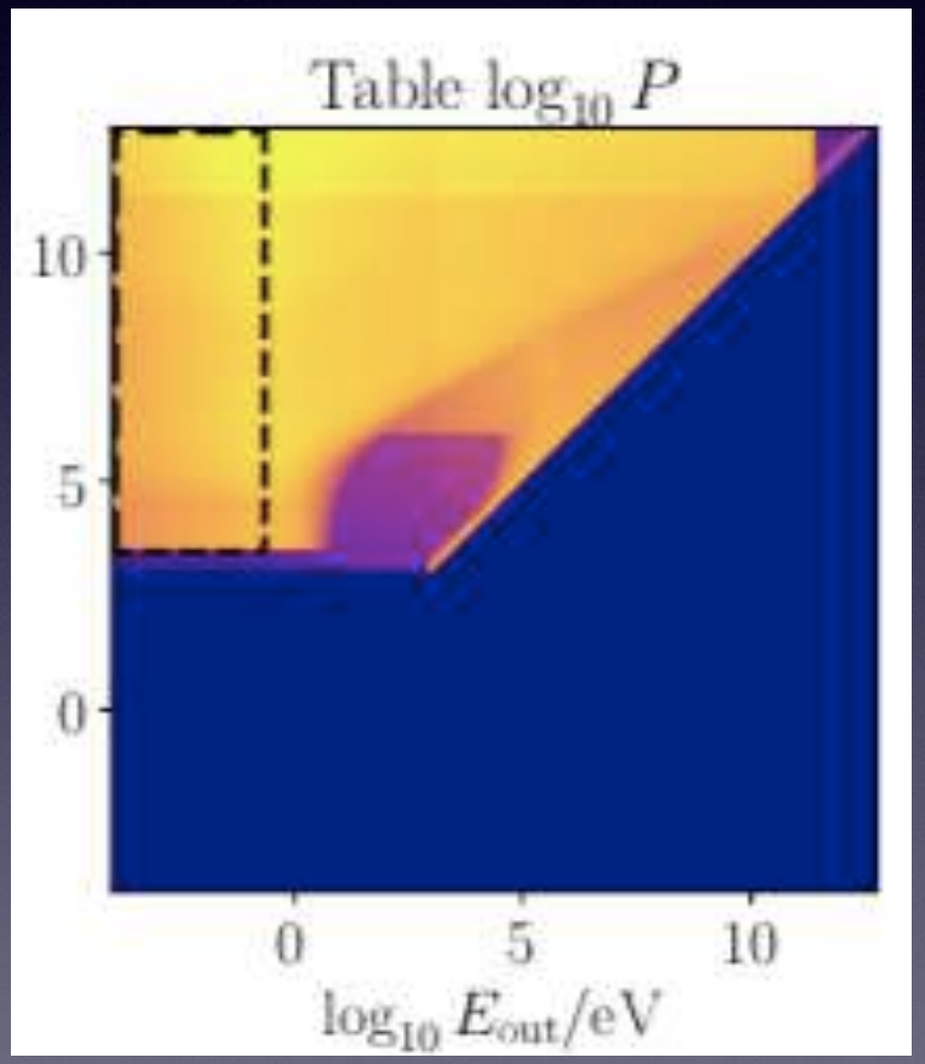
DarkHistory with neural networks

[Yitian Sun & TRS, 2207.06425]

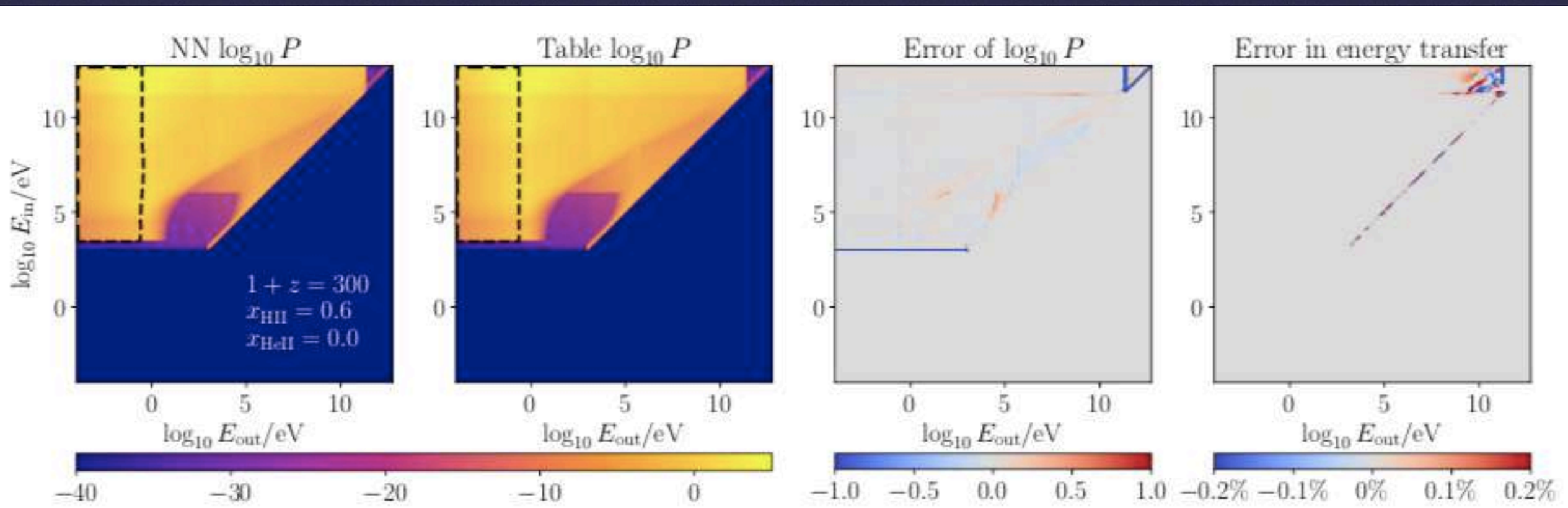
- Goal: store the transfer functions in a more efficient/ compact way
  - improve usability
  - facilitate adding extra parameter dependences (e.g. on gas density, for future inhomogeneity studies + factorizing out Ω_b dependence)
- Observation:
  - neural networks can serve as general function approximators
  - the transfer functions have features and structure, but have significant regions where they are quite smooth - much less information than # of pixels



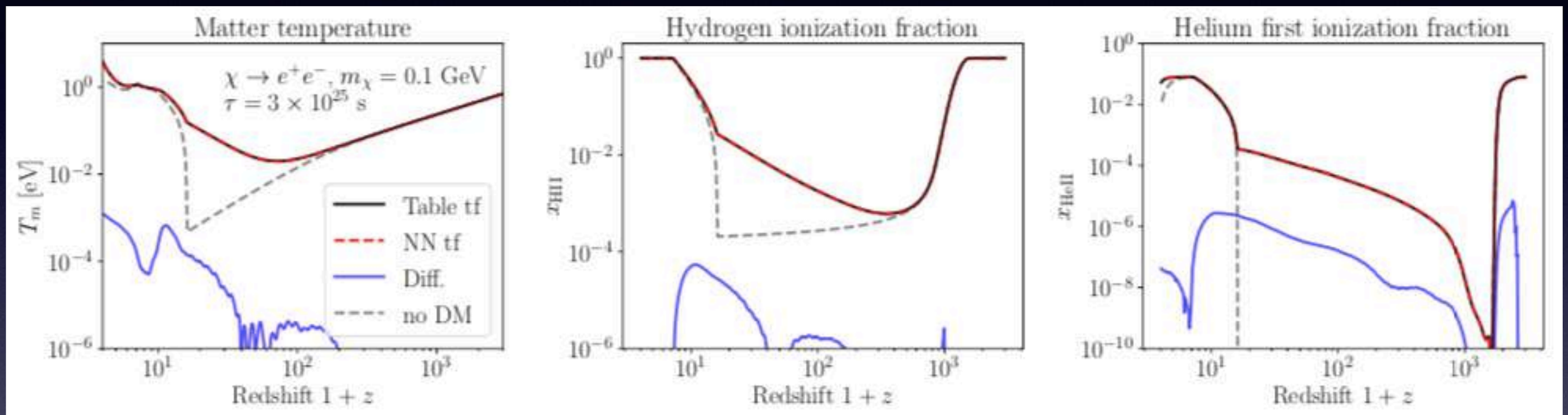
Example slice through a transfer function at $1+z=300$, $x_{HII}=0.6$

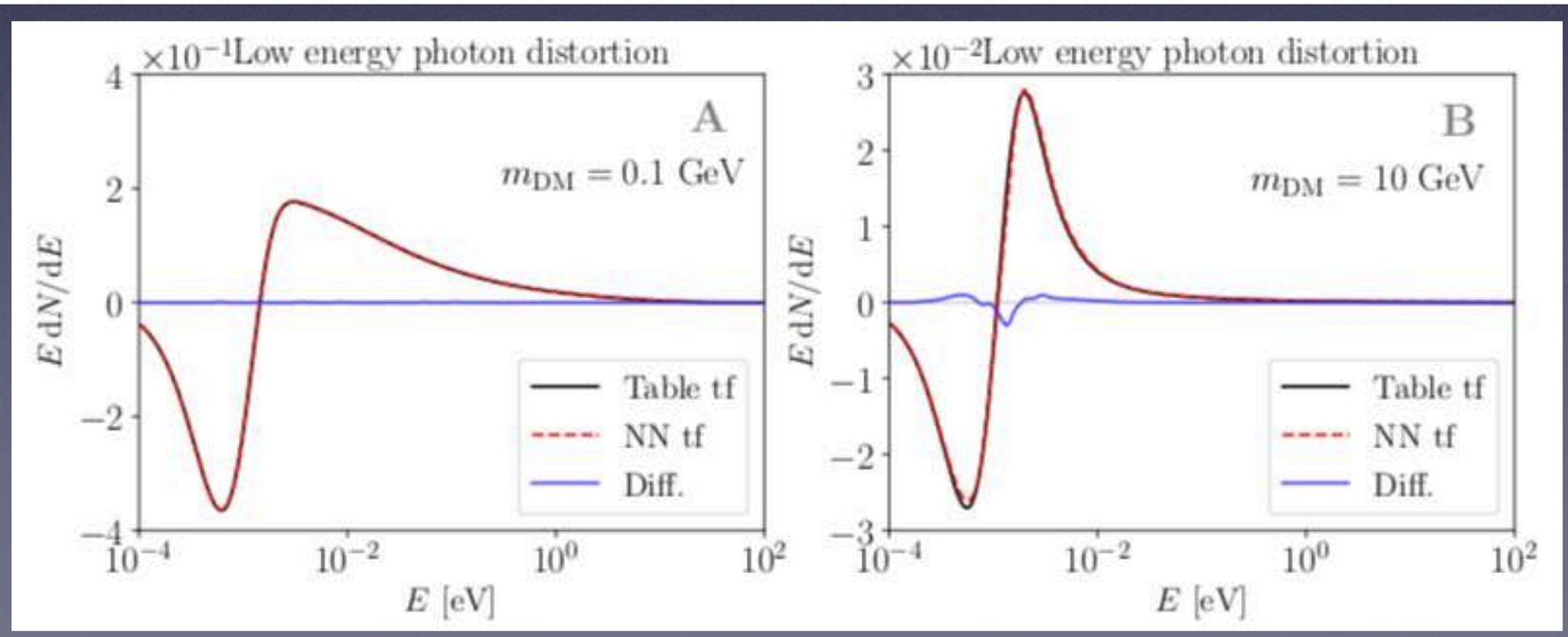
Results

- Network is ~400x smaller than tables (may be possible to do even better)
- Speed of code with NN evaluation is comparable to that with table lookup
- Accuracy in temperature/ionization histories is <2% (often much lower)
- DarkHistory also predicts a component of the CMB spectral distortion - also well reproduced, although with larger errors (up to 10%)



Comparison of histories + spectral distortion





Detailed treatment of the low-energy cascade

[Hongwan Liu, Wenzer Qin, Greg Ridgway, TRS, to appear]

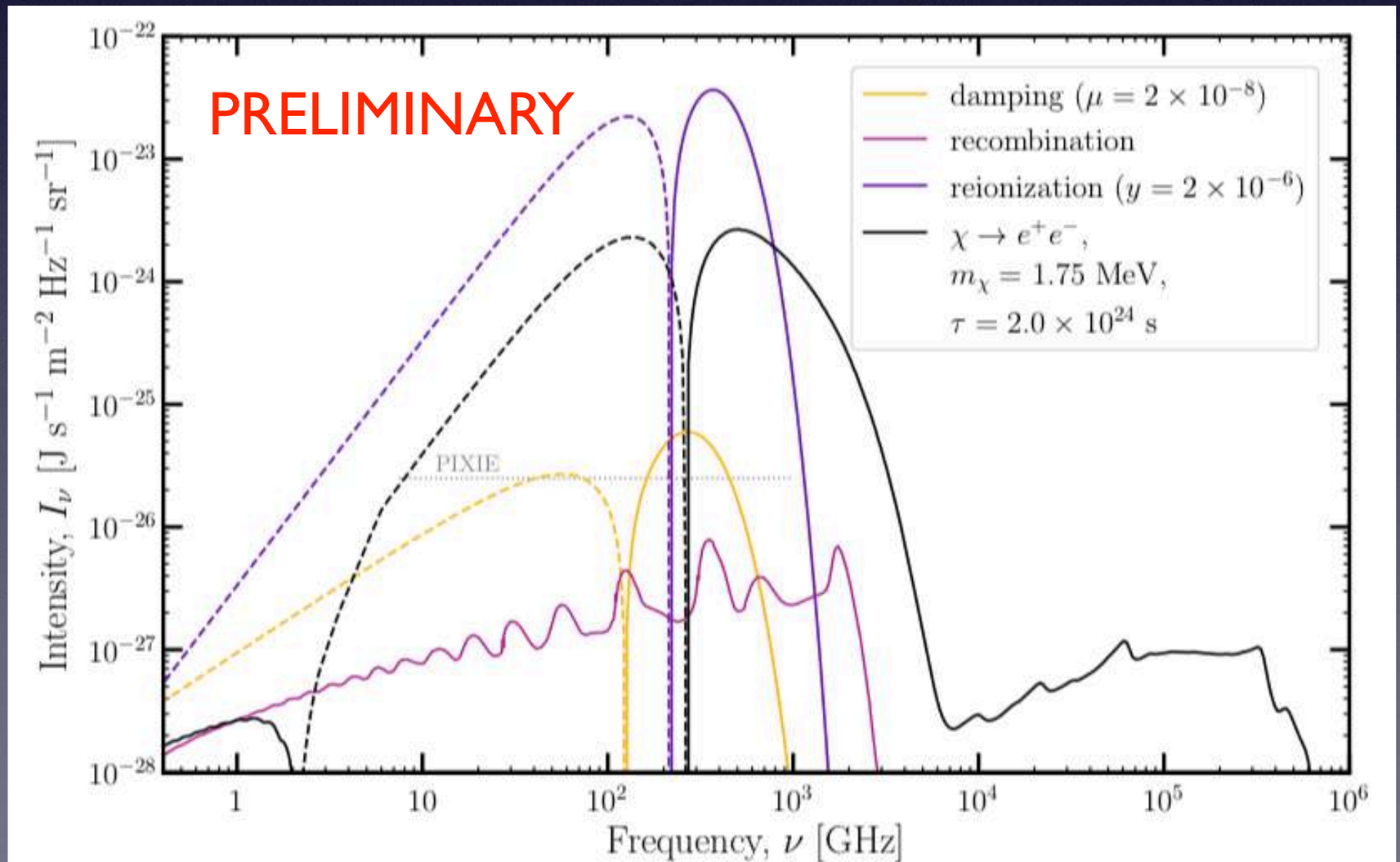
- Present status: once particles cool below 3 keV,
  - for electrons/positrons, we interpolate the published results of the MEDEA code over energy - but only 7 energies for interpolation + only evaluates integrated energy in spectral distortion, not spectrum
  - we track photons until they ionize or fall below 13.6 eV; we assign photons in the 10.2-13.6 eV range to hydrogen excitation and assume they free-stream below 10.2 eV
- We also use the three-level atom approximation (with fudge factors) to study the evolution of the ionization history, and assume a blackbody radiation field - may not be accurate in the presence of energy injection

Goals of upcoming work

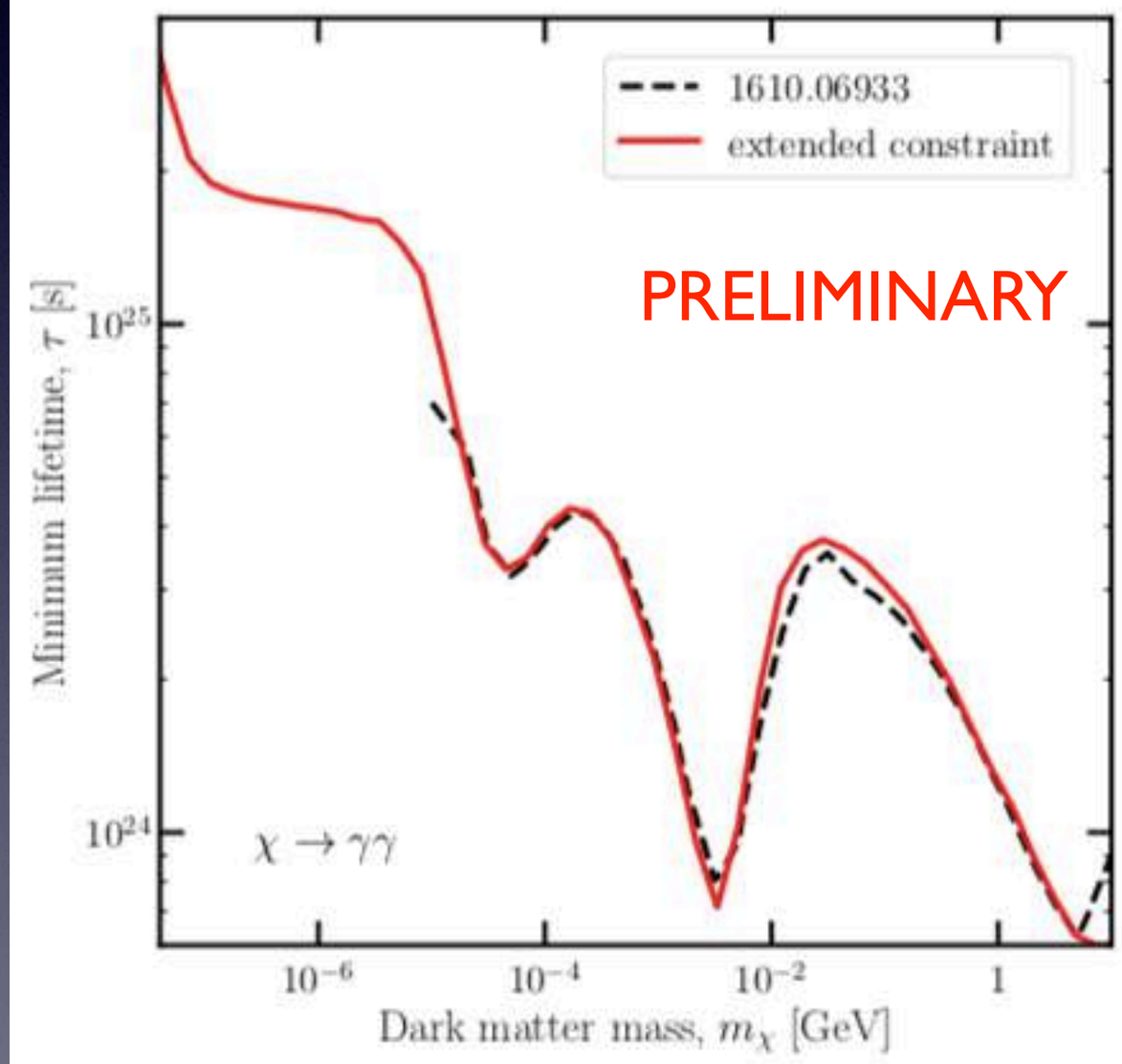
- Carefully track the joint evolution of the H/He atoms and the radiation field after recombination, taking into account a large number of atomic levels
- Take into account high-frequency distortions to the blackbody spectrum that can affect ionization/recombination/excitation rates
- Extend our code for electron/positron energy losses down to energies where the electrons thermalize with the CMB (cross-checked against existing MEDEA code at sample points)
- Predict the final distortion to the CMB blackbody spectrum produced by energy injection

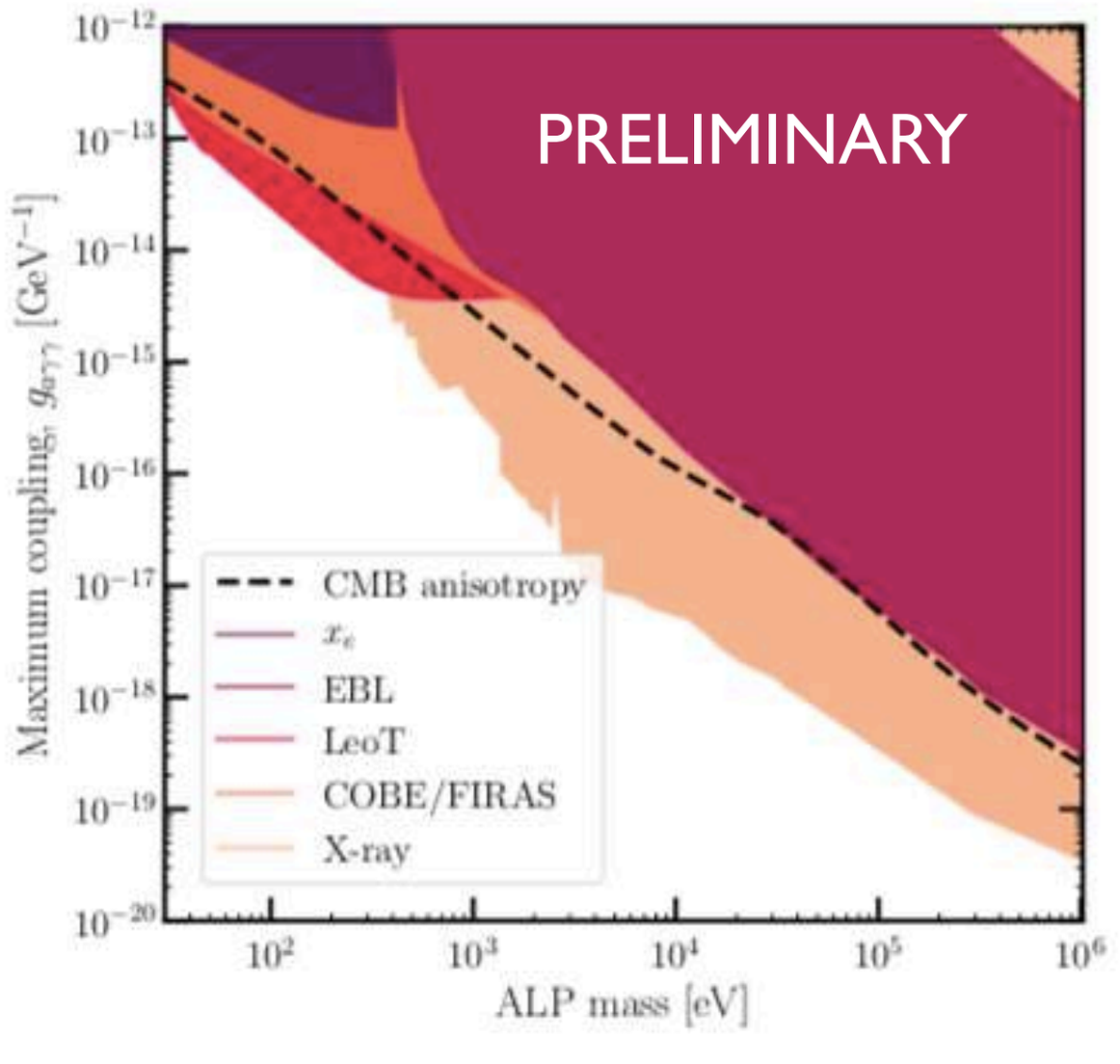
Preliminary spectral distortion results

- Previous studies have examined the spectral distortion from the high-redshift, fully ionized universe (e.g. Chluba et al '19, Acharya & Khatri '19)
- We have checked we agree with their results when we match assumptions
- We have also confirmed we accurately reproduce the Standard Model spectral distortion from recombination
- We can now predict the full distortion including energy injection



Preliminary constraints on low-mass DM





Summary

- Cosmological datasets can provide powerful probes of the non-gravitational properties of dark matter, and other exotic physics
- We already have stringent and broadly applicable limits on annihilating and decaying DM, especially at sub-GeV mass scales, from the cosmic microwave background, and complementary+competitive bounds from Lyman-alpha for leptonically decaying light DM
- 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
- DarkHistory now includes a compact version relying on neural networks, which should also facilitate further upgrades (including additional parameter dependence, inhomogeneity, etc)
- Work is in progress to fully treat the low-energy particle cascade and predict the full space of possible CMB spectral distortions from energy injection