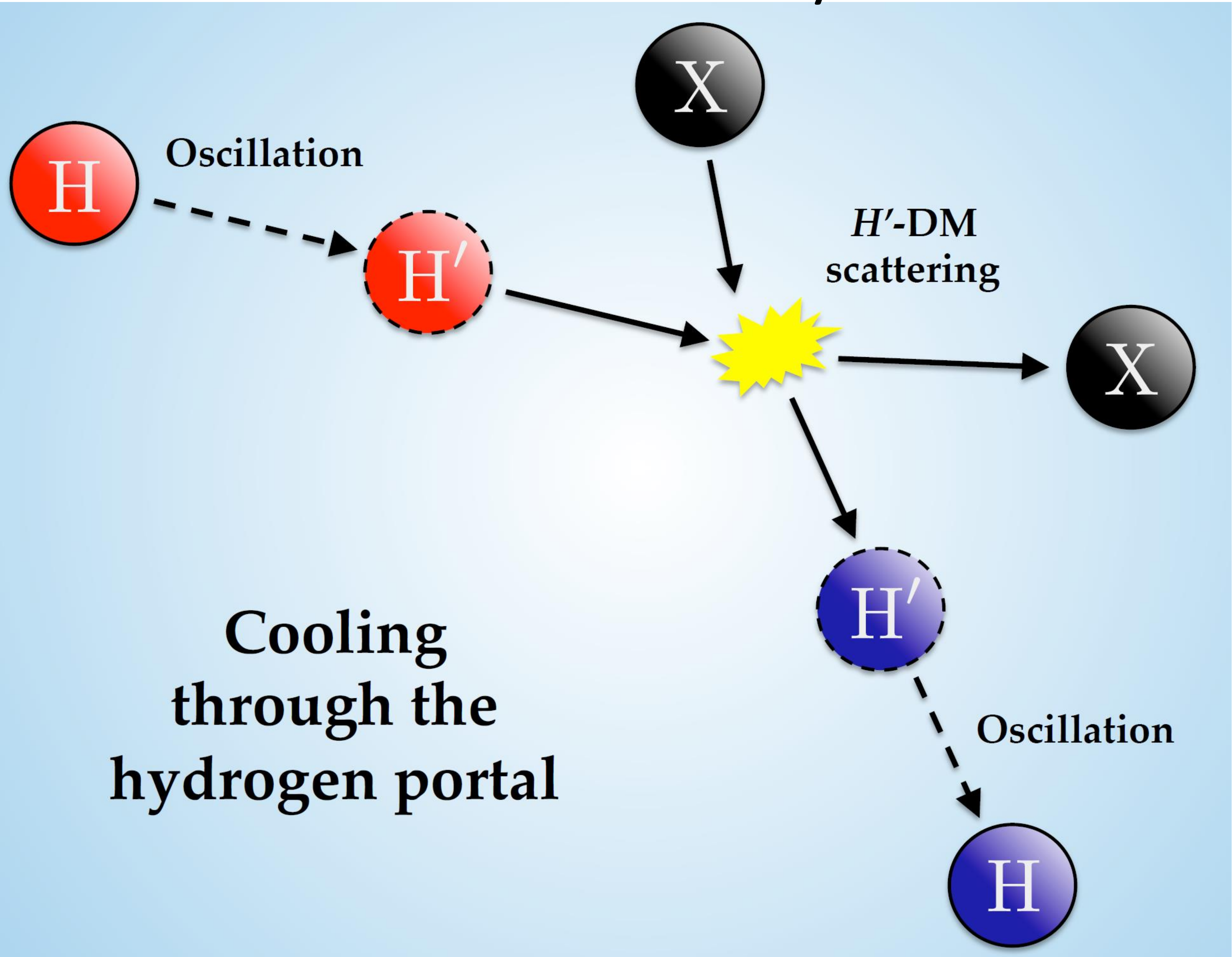
The Hydrogen Mixing Portal as a Novel Mechanism for Colder Baryons in 21 cm Cosmology



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Based on arXiv:2011.XXXXX
w/ Lucas Johns,
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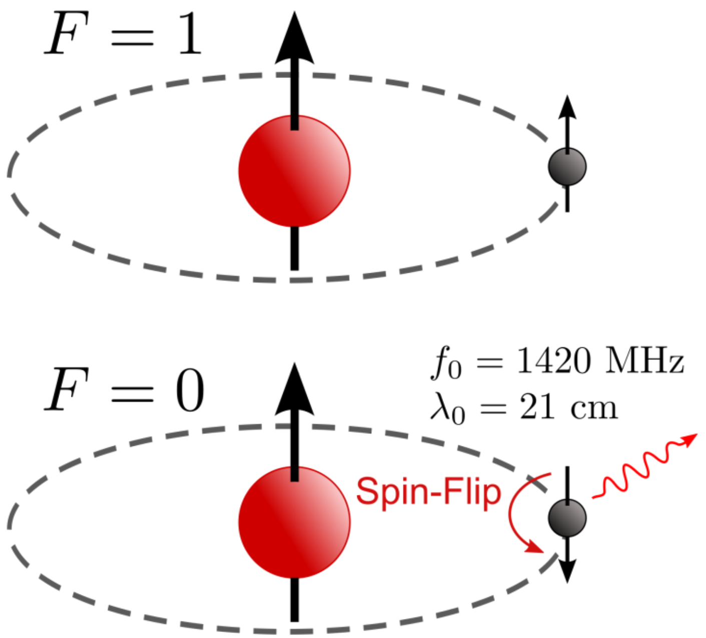
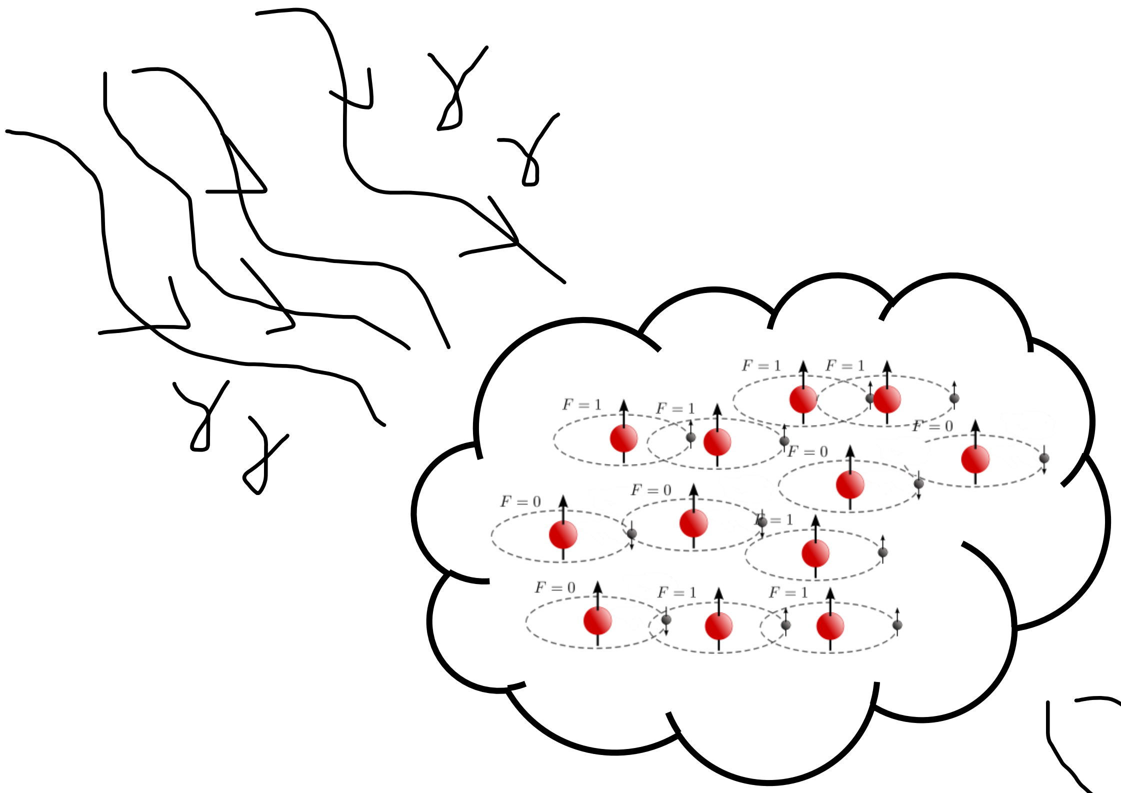
Fermilab Theory Seminar 11/19/2020

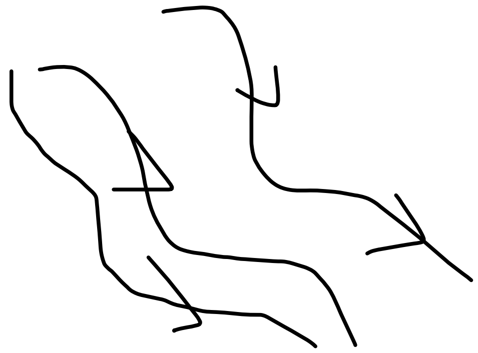
The Plan

1. The Standard Cosmology
   - 21 cm cosmology introduction
   - Hydrogen spin temperature in ΛCDM
   - EDGES anomaly
2. Can this lower the hydrogen spin temperature seen by EDGES?
   - Yes! The mixing and cooling are cosmologically viable.
3. Is there a sensible microphysical picture?
   - Yes! Necessary features symmetry-protected. Mixing operator can come from e.g. $\sim$TeV Leptoquarks.
4. Doesn't this violate… all later cosmology?
   - Apparently not!
   - Mixing *very* tiny and effectively turned off in structures.
   - Modified structure formation history differs between the sectors and SM stars form first
   - SM reionization shepherds the mixture back into SM baryons
   - Lots of interesting connections & directions for further work

21 cm physics





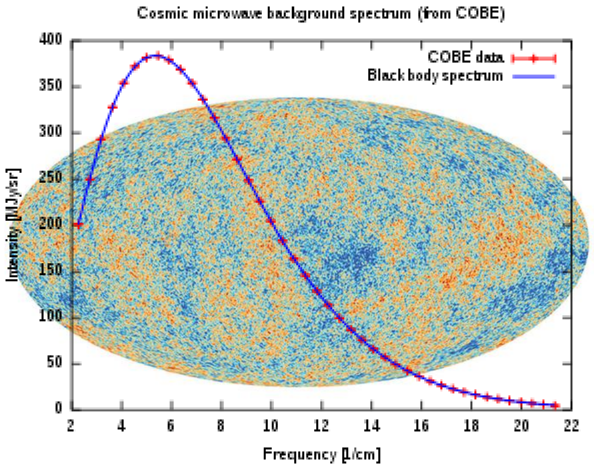


$$N_{\text{final}} - N_{\text{initial}} \sim N_{\text{emit}} - N_{\text{absorb}}$$

$$N_{\text{emit}} \propto N_{F=1}$$

$$N_{\text{absorb}} \propto N_{F=0}$$

The 21cm line to probe the dark ages



COBE, PLANCK

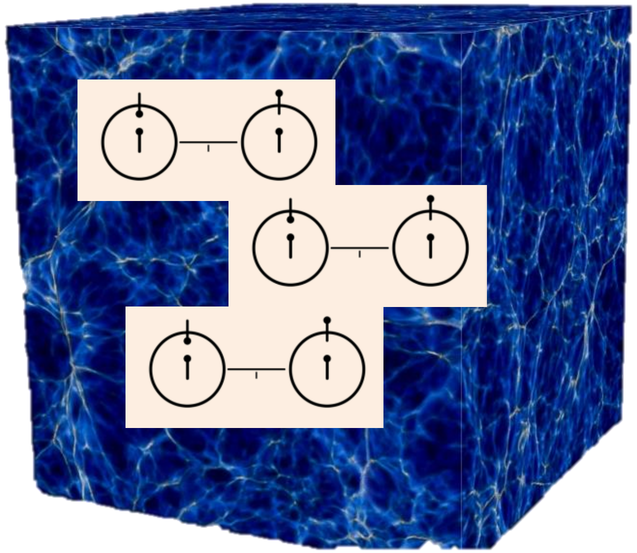
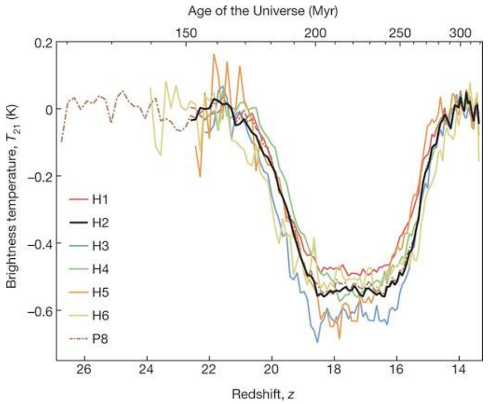
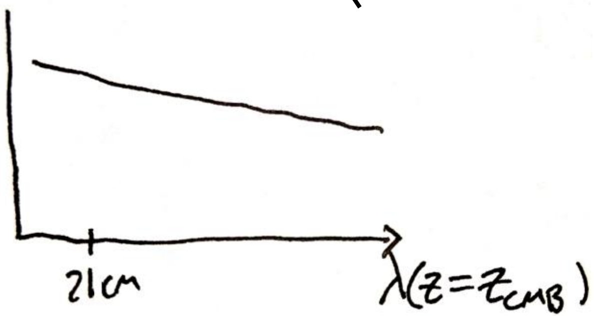


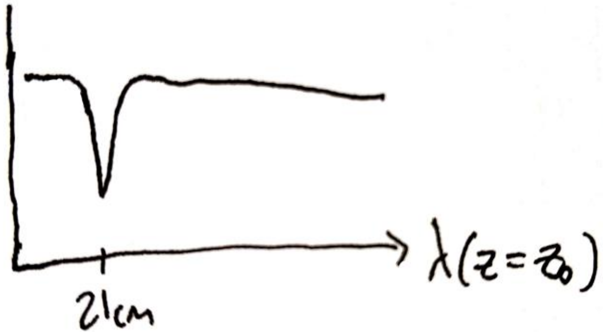
Image: J. Onorbe / MPIA

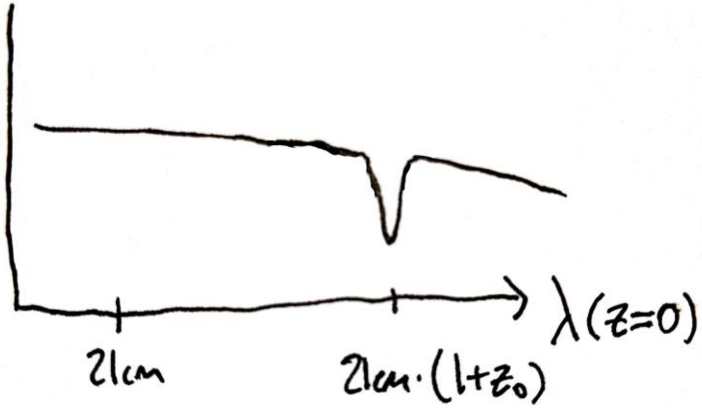


EDGES

$$\frac{N_{F=1}}{N_{F=0}} \equiv 3\exp\left(-\frac{E_{\mathrm{hf}}}{T_S}\right)$$



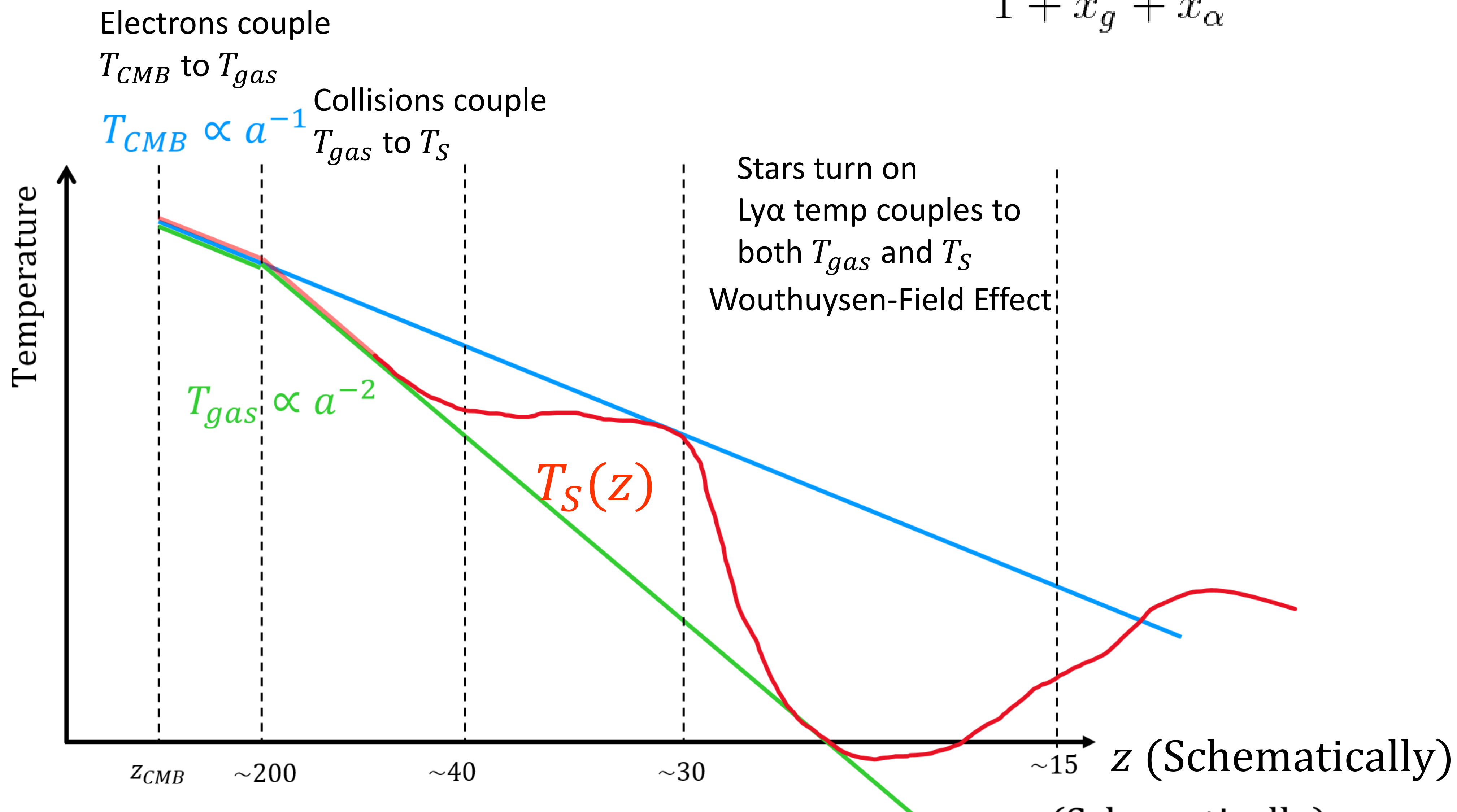


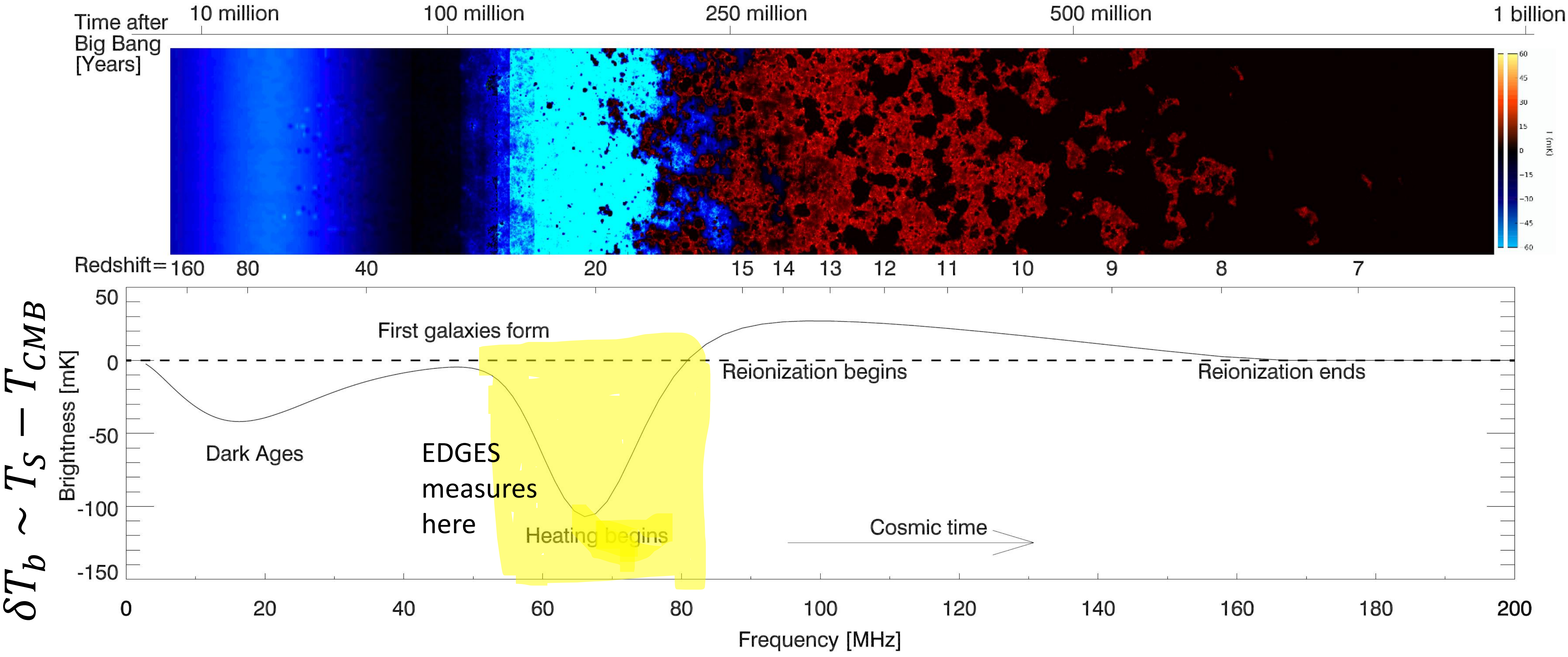


$T_S(z)$ in ΛCDM

Spin temperature set by competition between interactions

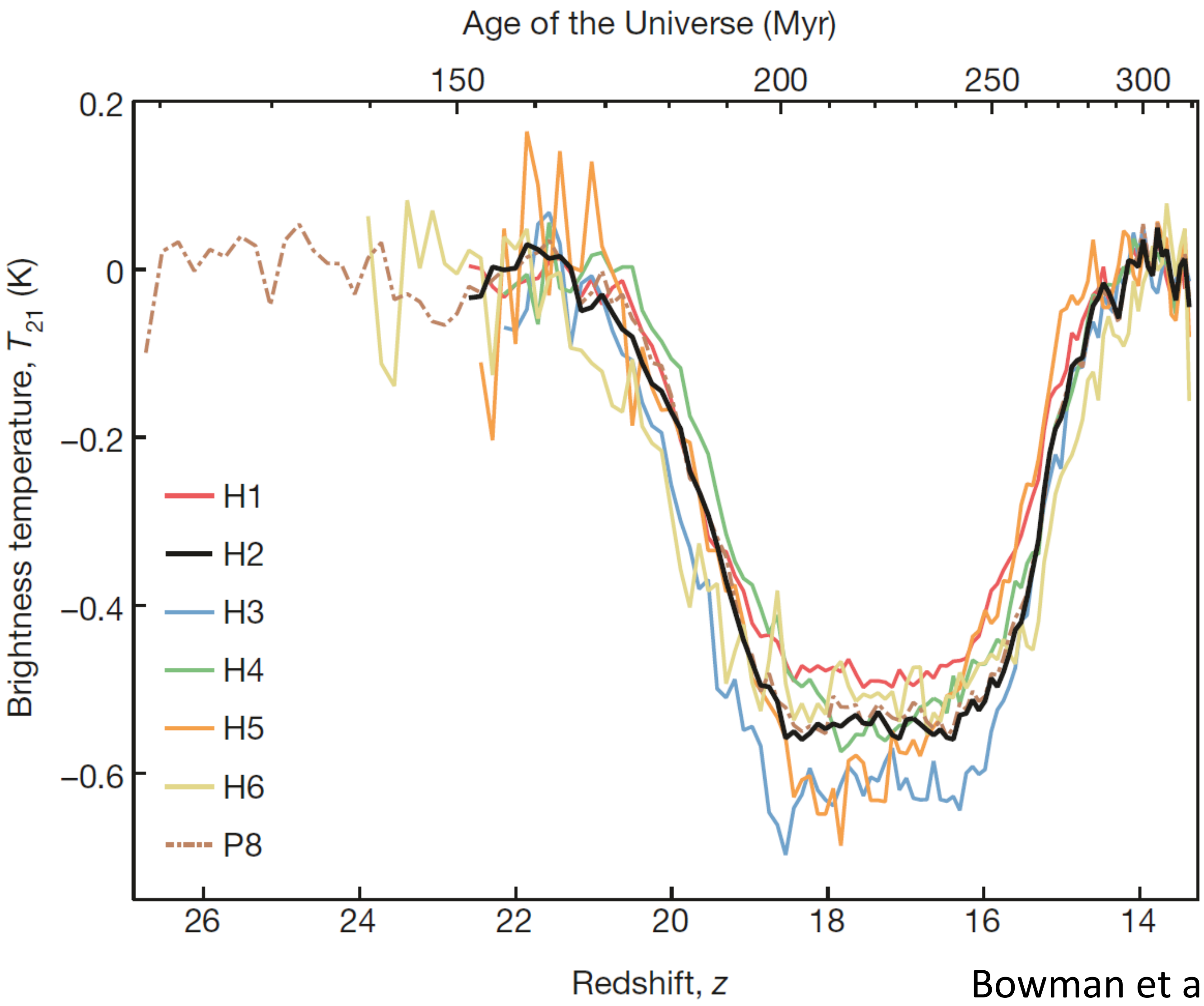
$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_g T_g^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_g + x_\alpha}$$





Rough timeline from Pritchard & Loeb, 2012

The Dataman Cometh



Coldest SM theory:

$$T_{21}^{SM}(z = 17) \gtrsim -220 \text{ mK}$$

Data:

$$T_{21}^{EDGES}(z \simeq 17) = -500^{+200}_{-500} \text{ mK}$$

A 3.8σ deviation!

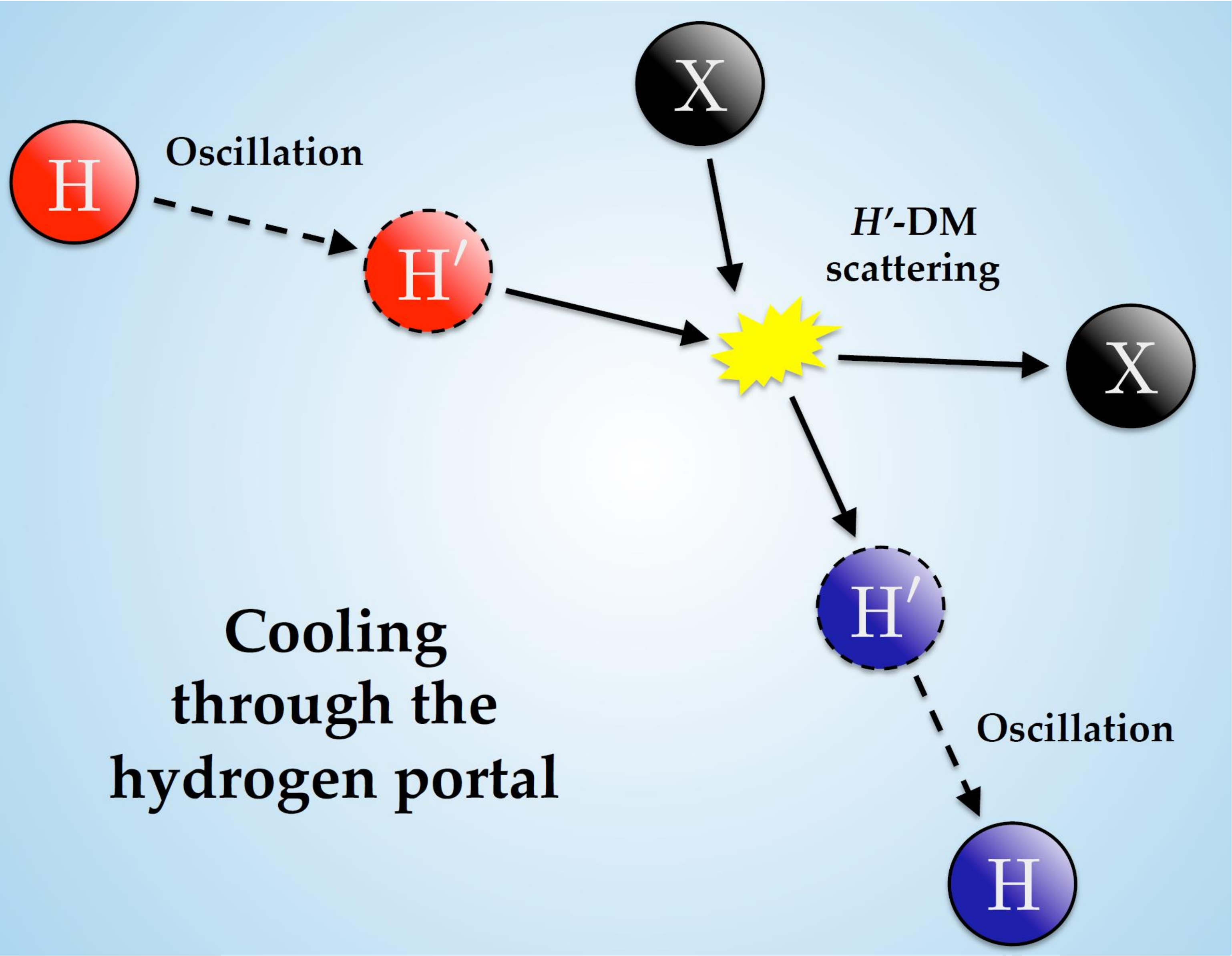
Bowman et al., 2018

Aside: Other suggestions

- Of course could be some other systematic. EDGES team have been very responsible and thorough and done lots of checks.

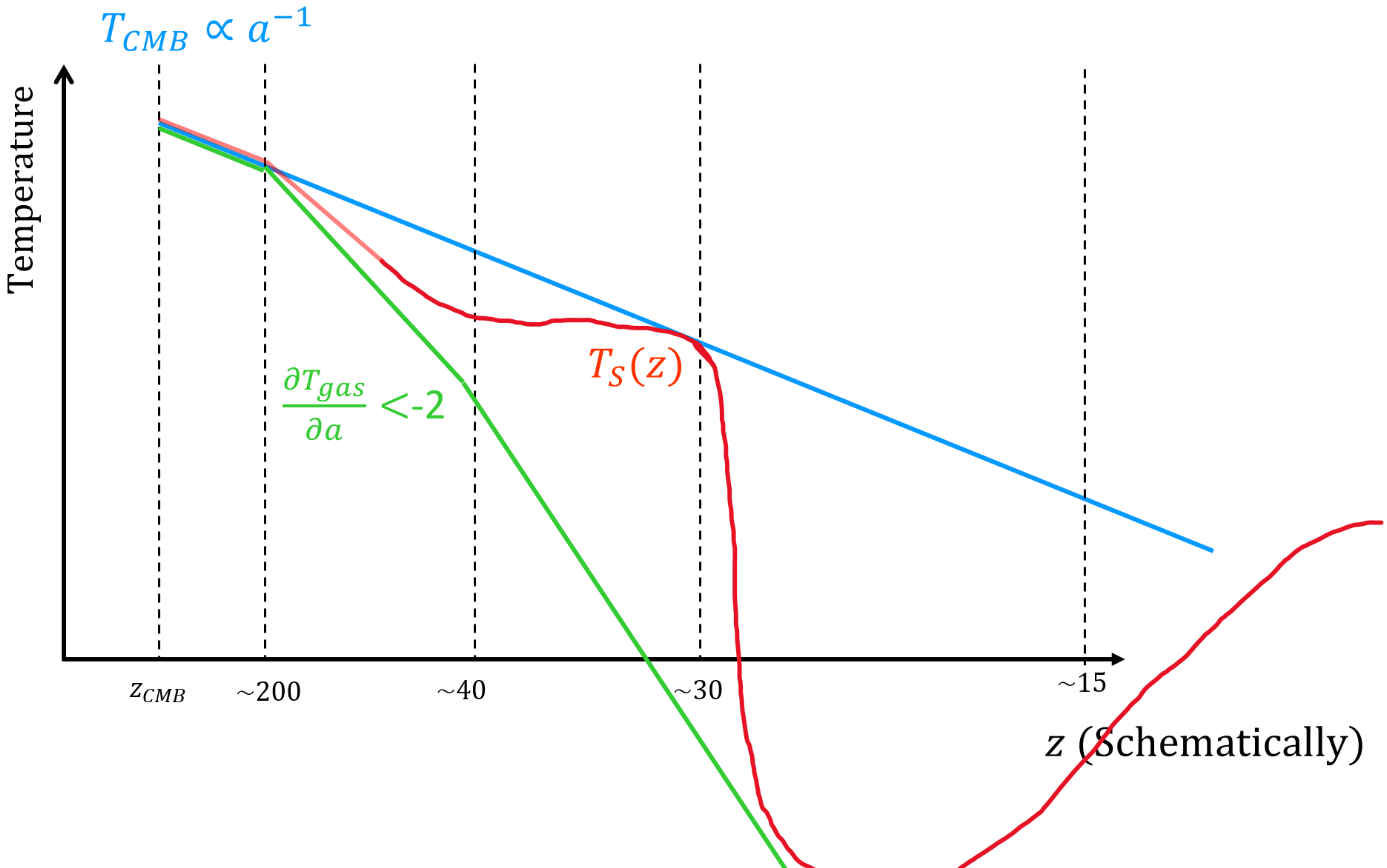
- As always with astroparticle stuff, perhaps new astrophysics. Must be *very* high-z sources. [Ewall-Wice et al ‘18,’19, …]
- Could also be a BSM mechanism to raise the CMB temp at very long wavelength [Pospelov et al, Moroi et al, Choi et al, Brandenberger et al, …]

- Obvious BSM models to cool H aren’t looking great. [Barkana, Muñoz & Loeb, Barkana et al, Liu et al, Berlin et al, …]



Can this lower the hydrogen spin temperature seen by EDGES?

Our timeline



In-Medium Mixing

$$\mathcal{H} = \begin{pmatrix} E_H^0 + \Delta V & \delta \\ \delta & E_{H'}^0 - \Delta V \end{pmatrix}$$

Difference of in-medium scattering potentials

$$\Gamma_{\mathrm{osc}} \sim \frac{\Gamma_c}{4} \frac{\delta^2}{\delta^2 + \Delta V^2 + (\Gamma_c/2)^2}$$

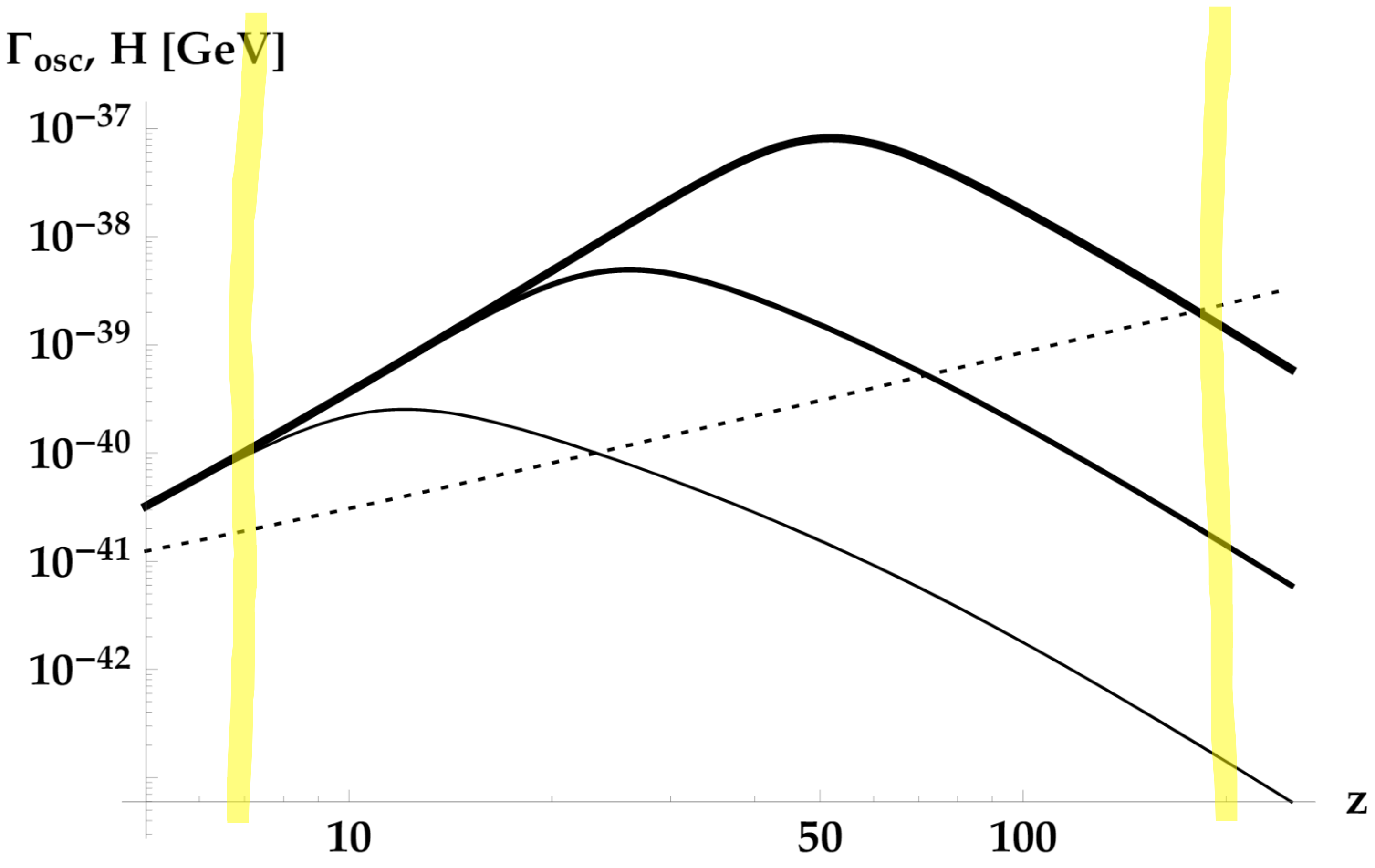
See Johns (2019) for derivation from quantum kinetics

Rate of decohering interactions very important

$$\Gamma_c = \Gamma_H + \Gamma_{H'}$$

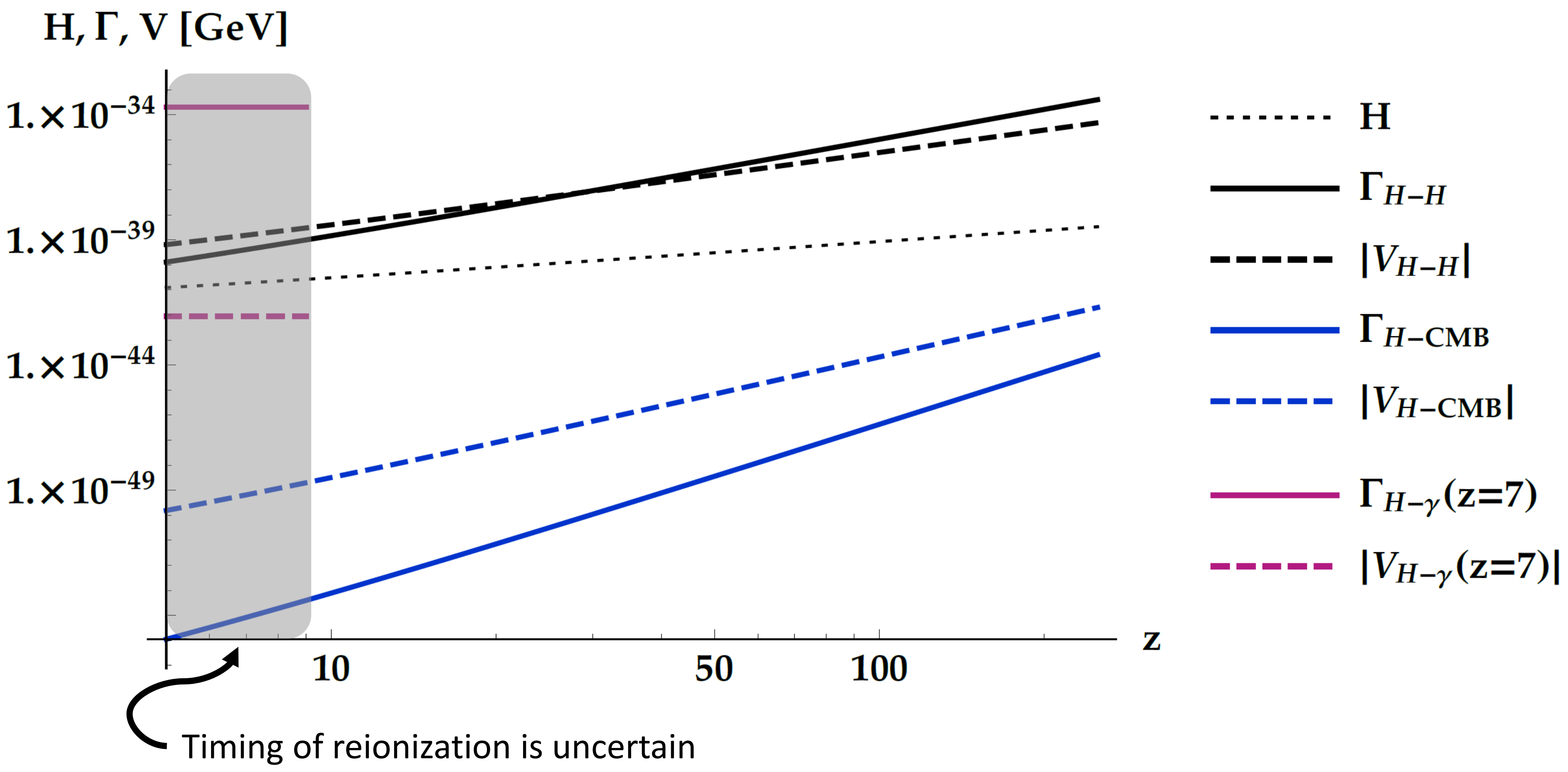
With $\delta \sim 10^{-38}\mathrm{GeV}$, ΔV turns off mixing in essentially any structure!

Timeline of mixing equilibration

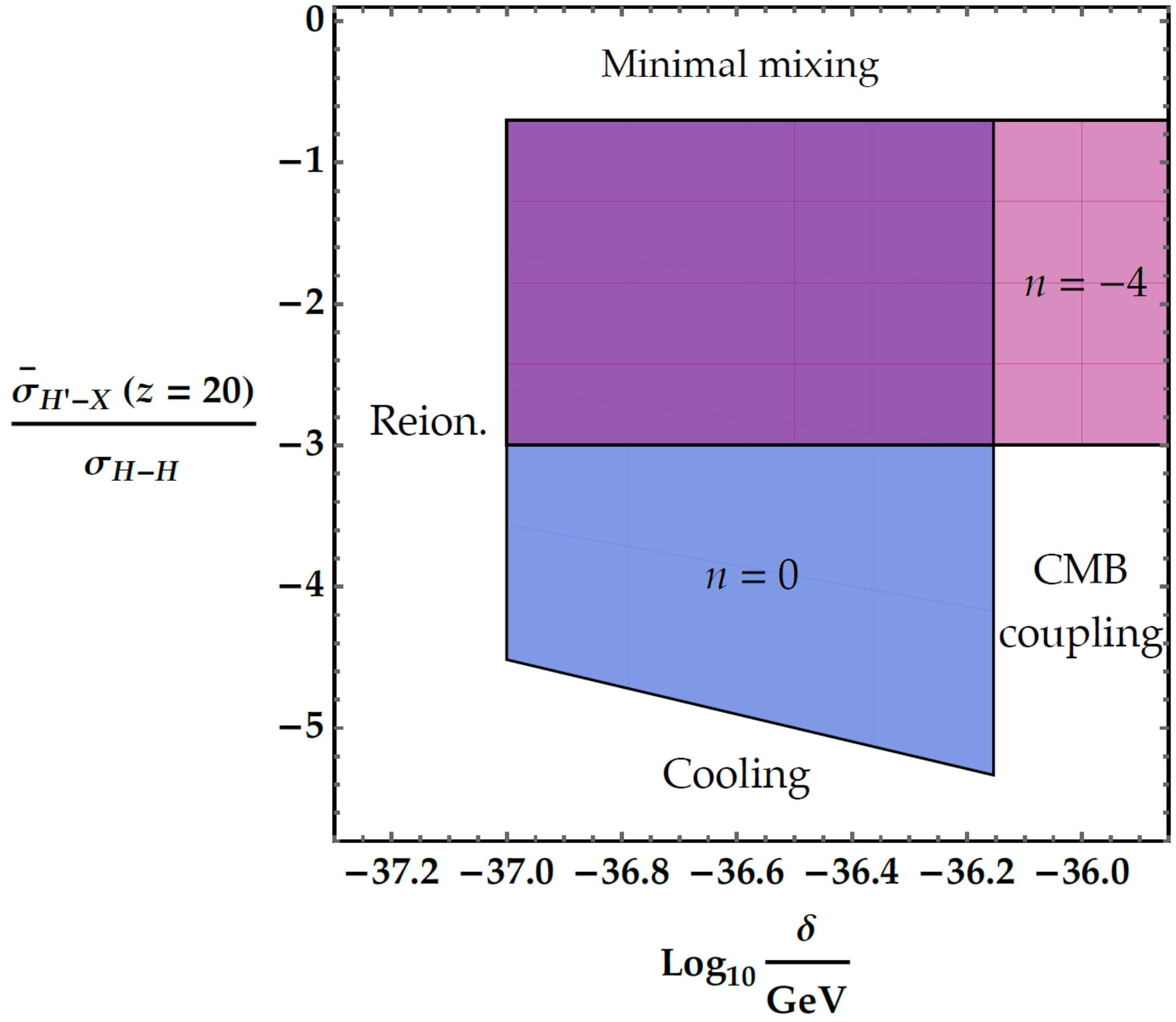


$$\delta = 5 \times 10^{-\{37,38,39\}}$$

Many tiny effects must be considered



Conservative parameter space



$m_X = 2$ GeV, thermal DM,
'maximal cooling' into thermal equil.
no 'backreaction' of cooling on mixing

$$\bar{\sigma}_{H'-X} = \int d\cos\theta\,(1-\cos\theta)\,\frac{d\sigma_{H'-X}}{d\cos\theta} = \sigma_0|\vec{v}_m|^n$$

$$\dot{Q}_g \sim -\frac{\rho_X \sigma_0 m_H}{(m_H+m_X)^2}\left(\frac{T_g}{m_H}\right)^{\frac{n+1}{2}}\frac{2^{\frac{5+n}{2}}\Gamma\left(3+\frac{n}{2}\right)}{\sqrt{\pi}}T_g$$

Is there a sensible microphysical picture?

Mirror Model EFT with $Z_2, B+L'$

RG ↓

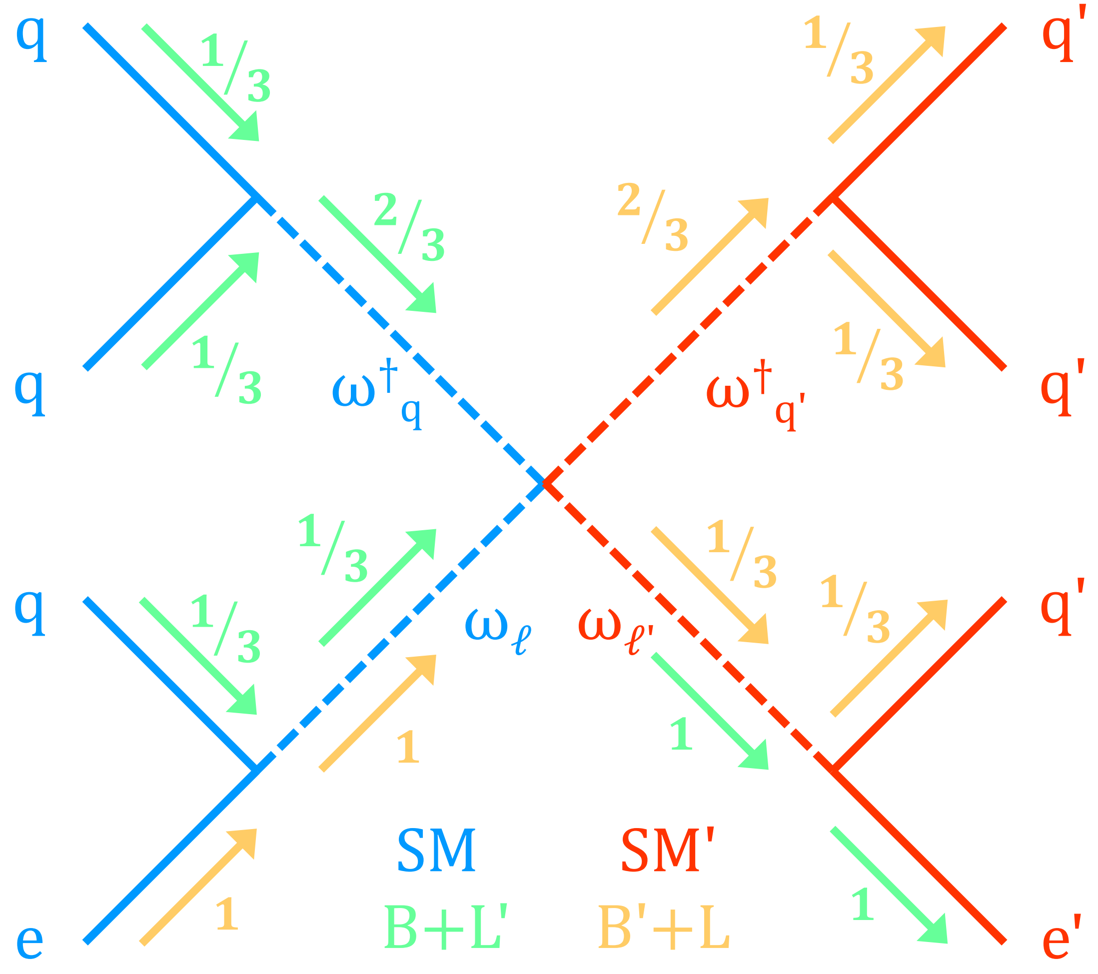
$$\mathcal{O}_{\text{partonic}} \sim \frac{1}{\Lambda^8}\, \bar{e}' e\; \bar{u}' u\; \bar{u}' u\; \bar{d}' d + \text{ h.c.},$$

$$\mathcal{O}_{\text{hadronic}} \sim \frac{(4\pi)^2 \Lambda_{\text{QCD}}^6}{\Lambda^8}\, \bar{e}' \Gamma e\; \bar{p}' \Gamma p + \text{ h.c.},$$

$$\delta \sim \langle H \left| \mathcal{O}_{\text{hadronic}} \right| H' \rangle \sim \frac{(4\pi)^2 \Lambda_{\text{QCD}}^6}{\Lambda^8} \frac{1}{a_0^3}$$

Bohr radius

Leptoquarks
A toy UV completion



Field	$SU(3)$	$SU(2)$	$U(1)$	$B+L'$	$B'+L$
ω_q	3	1	$-\frac{1}{3}$	$-\frac{2}{3}$	0
ω_ℓ	3	1	$-\frac{1}{3}$	$\frac{1}{3}$	1
ω'_q	$3'$	1	$-\frac{1}{3}'$	0	$-\frac{2}{3}$
ω'_ℓ	$3'$	1	$-\frac{1}{3}'$	1	$\frac{1}{3}$

$$\delta \gtrsim 10^{-38}\ \text{GeV}$$

$$M_\omega \lesssim 350\ \text{GeV}\ \left(\frac{\Lambda_{\text{QCD}}}{250\ \text{MeV}}\right)^6 \sqrt{N}$$

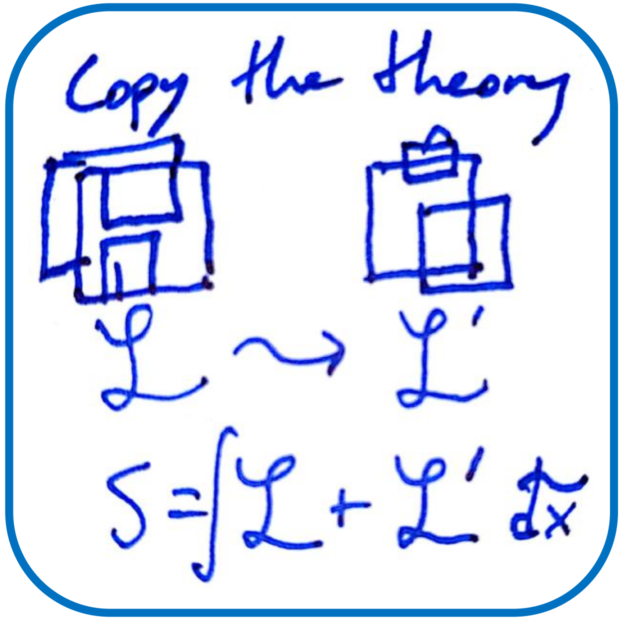
Ingredients are conventional and natural, though there is some non-minimality

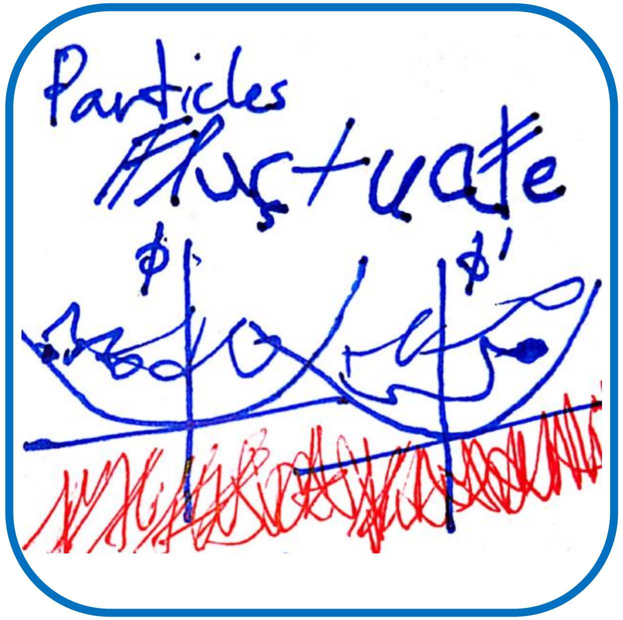
Early Mirror Cosmology

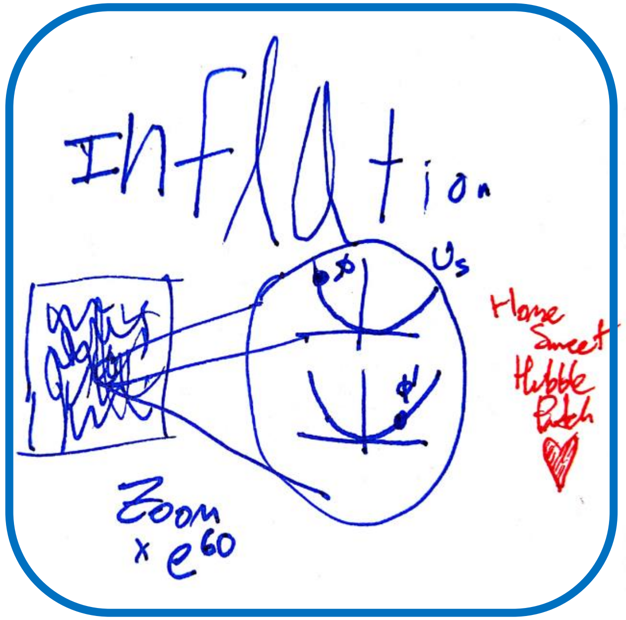
More challenging when Z_2 must be preserved

Simplest thing to do is rely on cosmic variance to effectively create asymmetric initial conditions

How to: Relic Asymmetry w/ Unbroken $\mathbb{Z}_2$



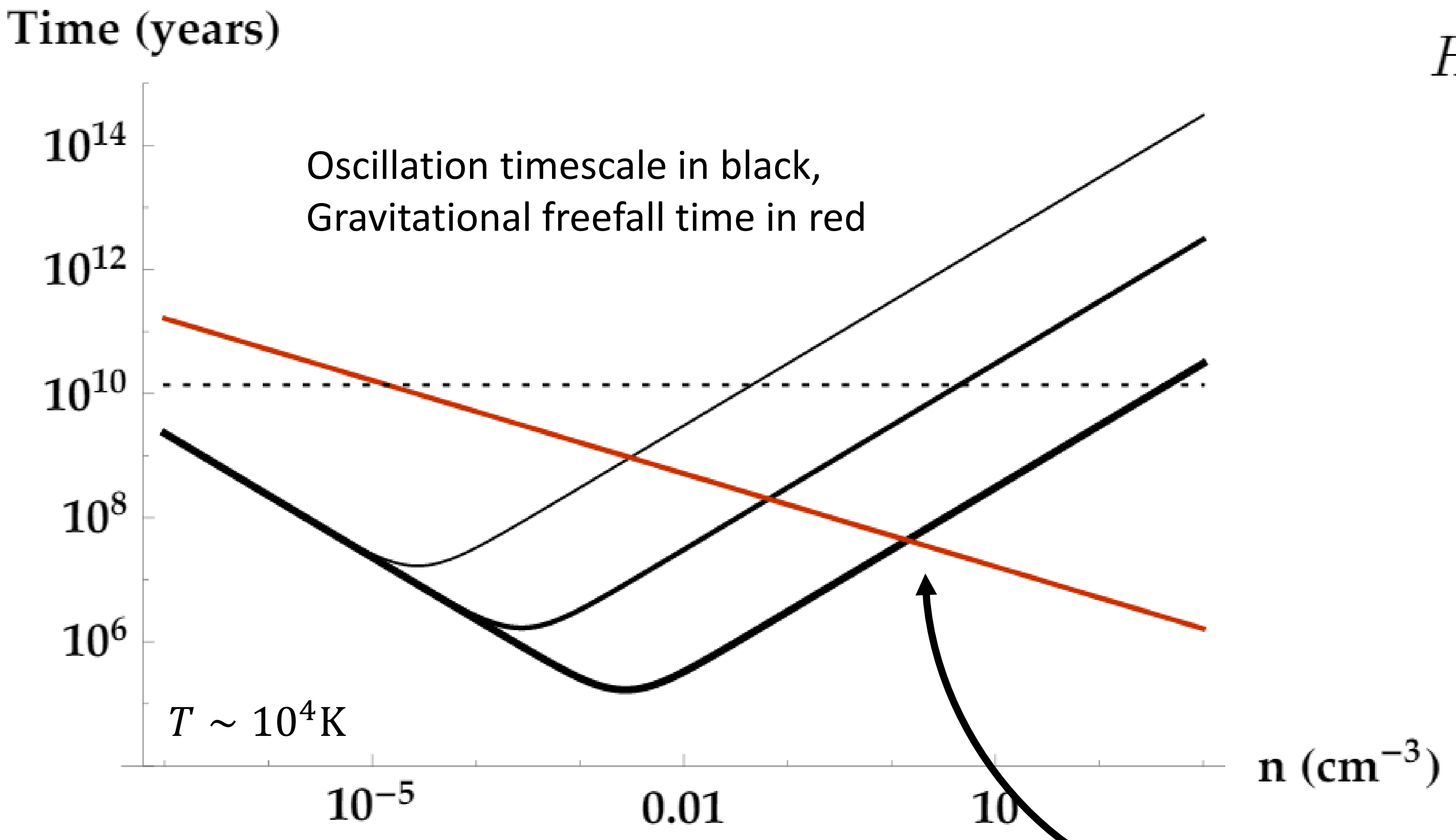




Doesn’t this violate… everything?

In particular, we can’t have half of baryons be H’ at z=0

Structure formation 1 - Linear collapse



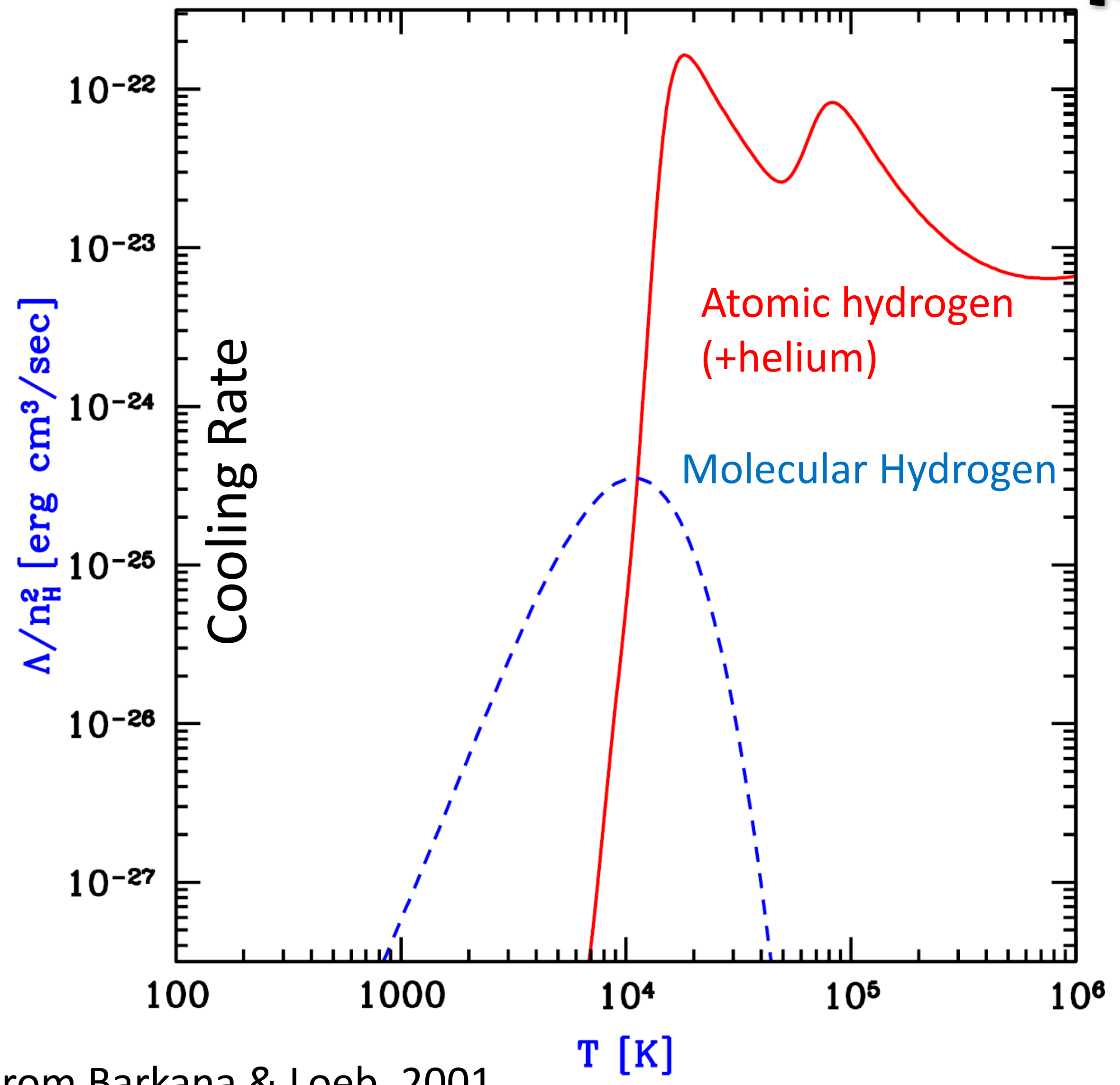
$H^{-1} \gtrsim t_{\rm grav}$ For collapse

$$\lambda_{\rm J} = \frac{2\pi}{k_{\rm J}}$$

Same in both sectors

Mixing turns off quickly in structures

Nonlinear collapse



From Barkana & Loeb, 2001

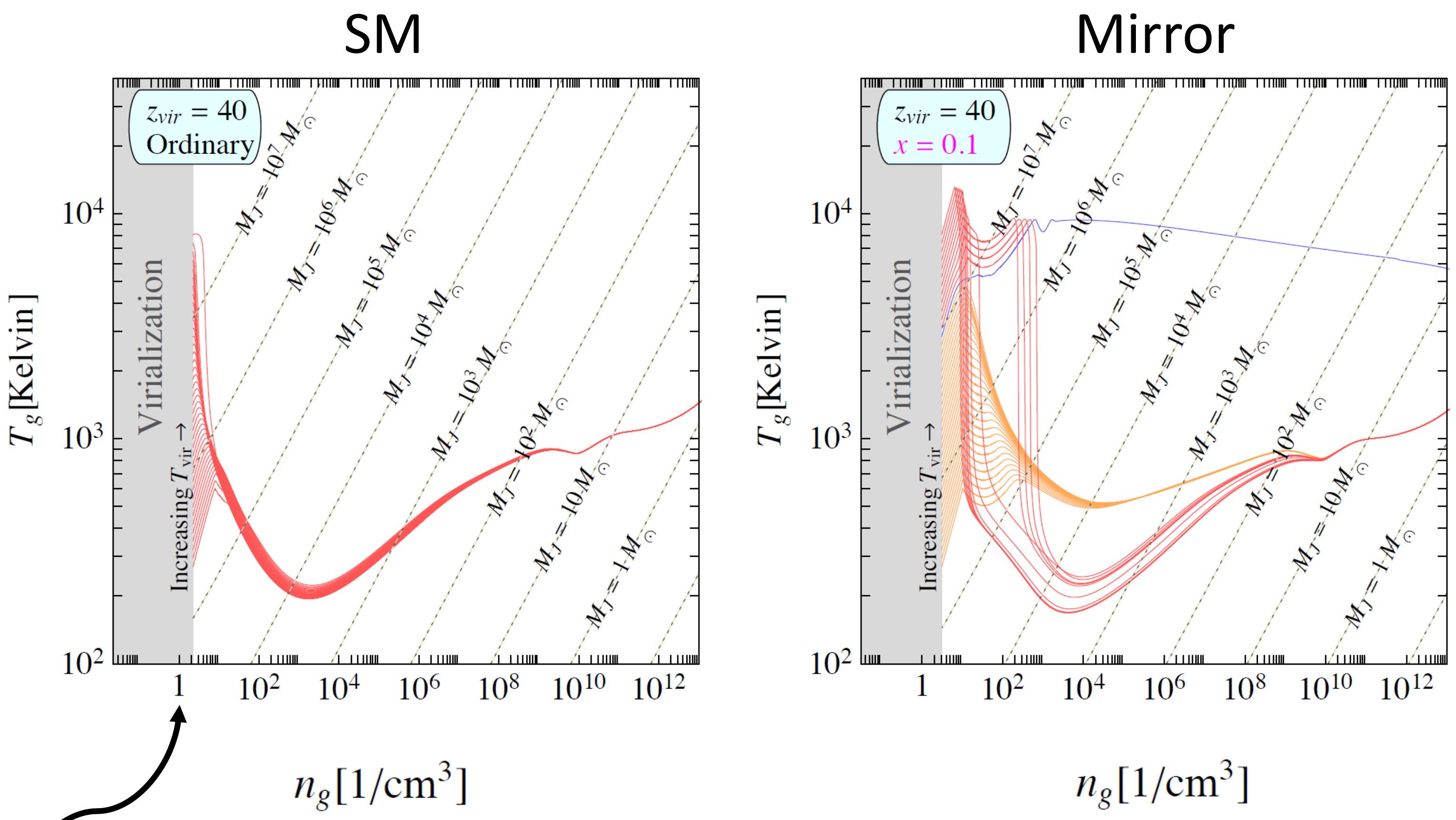
Need to cool quickly for star formation!

$$H^{-1} \gtrsim t_{\rm grav} \gtrsim t_{\rm cool}$$

$$H + e^- \rightarrow H^- + \gamma$$
$$H^- + H \rightarrow H_2 + e^-$$

Structure Formation

D'Amico, Panci, et al. 2017



Depending on initial size of overdensity, mirror cloud settles to temp

$T_{vir} \sim 200\text{K}$

$T_{vir} \sim 500 - 900\text{K}$

$T_{vir} \sim 9000\text{K}$

For fixed n at z=40, $T_{\rm vir} \propto R_{\rm vir}^2$ so think of beginning on left with same over-number-density, different physical size

Predicted mass function depends also on collapse timescales, not shown here

Reionization and baryon recovery

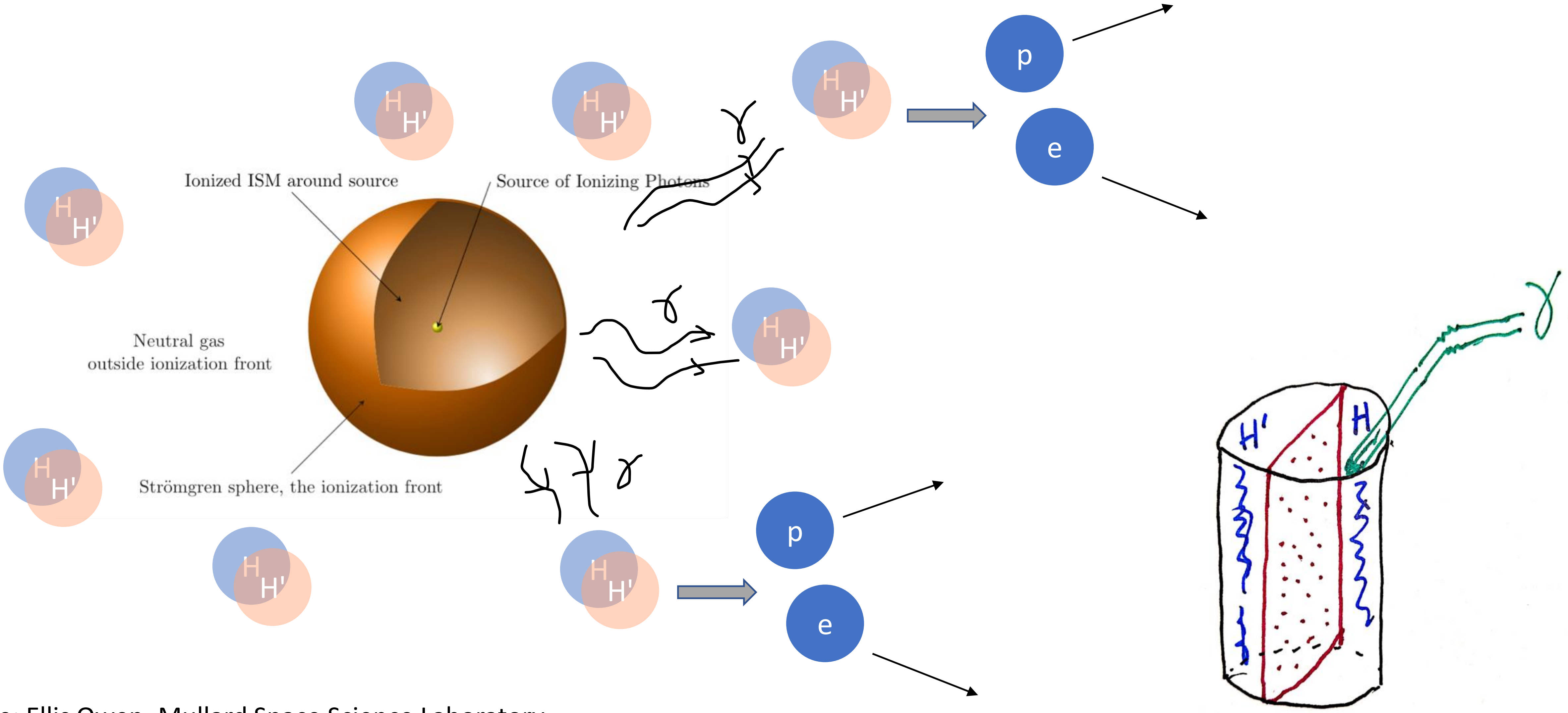
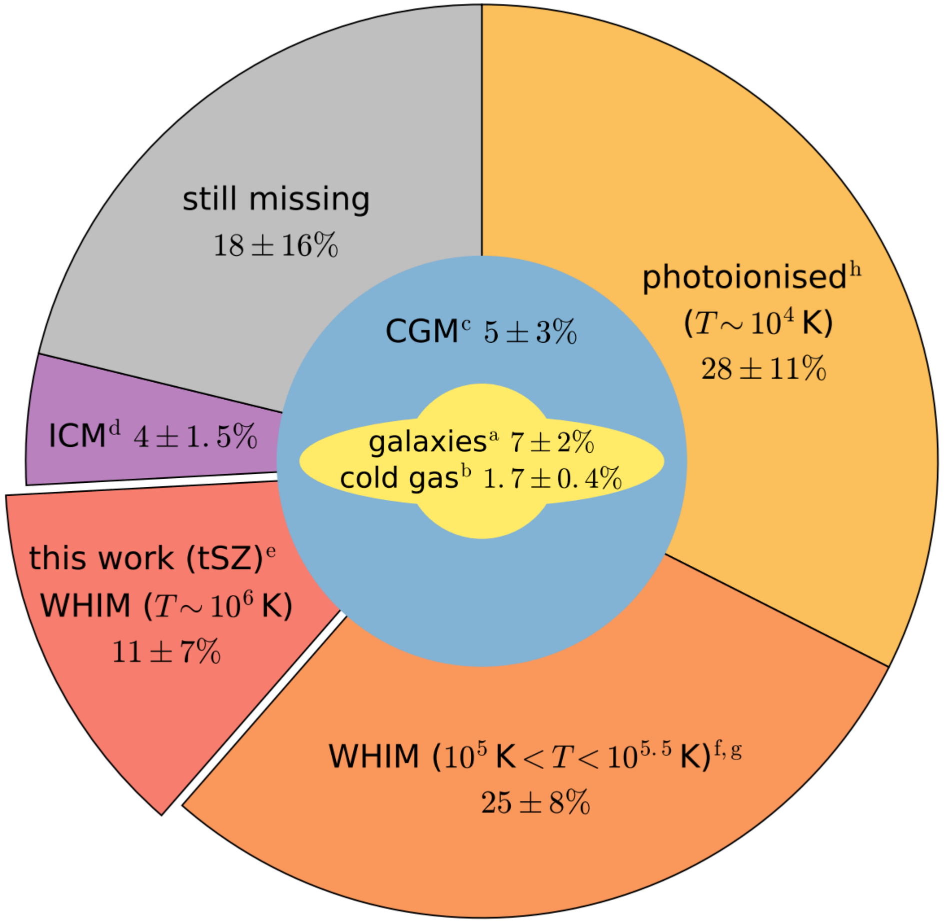


Image: Ellis Owen, Mullard Space Science Laboratory

Missing Baryons



Keep Looking!

de Graaff, Cai, Heymans, Peacock, A&A (2019)

Open questions – broader parameter space

Our parameter space was very conservative and restricted to region where we could semi-analytically compute

- **What if DM is not thermally distributed?**
- What if DM very cold and H' doesn't fully equilibrate?
- Can larger H'-DM interactions have interesting feedback on mixing?
- **What if H'-DM interactions are inelastic? [Tucker-Smith & Weiner, Graham et al., …]**
- **What if there's some nonzero initial mirror sector density?**
- What if mixing depends nontrivially on the hyperfine quantum number?

Open questions – cosmological evolution

There are many things we only considered qualitatively, if at all.

- How do superpositions of H & H’ behave while undergoing linear collapse? Nonlinear?
- **How does structure formation in SM change with only half of H?**
- How does structure formation in mirror sector work with only H’?
- Does the timeline work correctly to get the early SMBHs? [D’Amico, Panci et al.]
- **How about star formation and ionization rate?**
- How about *mirror* star formation? [Mohapatra & Teplitz, Foot, Berezhiani, …, Curtin & Setford]
- How quickly does H’ get reconverted to SM during reionization?
- **How many relic ‘missing baryons’ will there be precisely?**
- **How will these modifications show up in the non-sky-averaged signal?**
- **Can relic H’ be related to later small scale structure issues?**

Open questions – particle physics

We were only as explicit with the particle physics as we needed to be

- **Are there other interesting ways to generate that operator at weak coupling?**
- How about at strong coupling?
- **Are there UV scenarios which naturally lead to *many* leptoquarks?**
- Is there a simple embedding of this in mirror extension of MSSM and/or GUT?
- **Is there an exotic twin Higgs version in which this works? [Csaki, Guan, Ma, Shu '19]**
- What are the simplest/nicest DM candidates that work with this?
- Is it interesting to allow small n-n' mixing as well? [Berezhiani, …]
- How about including some freeze-in through portals?
- **Can you naturally get mixing for (mainly) only one hyperfine level?**

Conclusion

How in the #$@&% has this worked out so well‽

Please falsify this proposal!

Possible with no further theory effort:

- Increase the precision with which we know the modern cosmic energy budget by funding continued searches for baryons near $z = 0$, hopefully down to $\lesssim 5\%$.
- Image the dark ages with the hyperfine transition of another atom, e.g. ${}^{3}\mathrm{He}^{+}$ or deuterium, which would not see such an effect.
- Build a higher-energy proton-proton collider to rule out the entire plausible space of UV completions.

Once we understand the modified structure formation history:

- Image the 21cm sky ‘tomographically’ to get the angular power spectrum (e.g. with data from HERA, OVRO-LWA, SKA1-LOW)
- Look for signatures from early black holes, mirror stars, other dark bound structures, and their mass functions