# Hydrogen mixing & the EDGES anomaly

Luke Johns
NASA Einstein Fellow
UC Berkeley

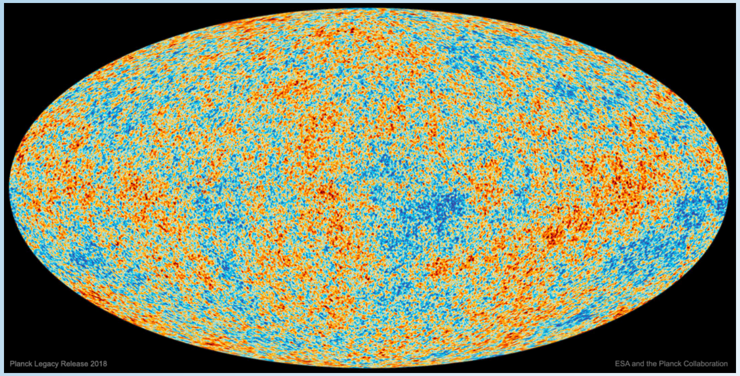
# Outline / takeaways

- In 2018 EDGES detected cosmic dawn at radio frequencies. According to one interpretation of their data, the hydrogen gas at $z \sim 17$ is **significantly colder than expected**.

- ***H-H′* oscillations and *H′*-DM scattering** could be responsible for the super-adiabatic cooling.

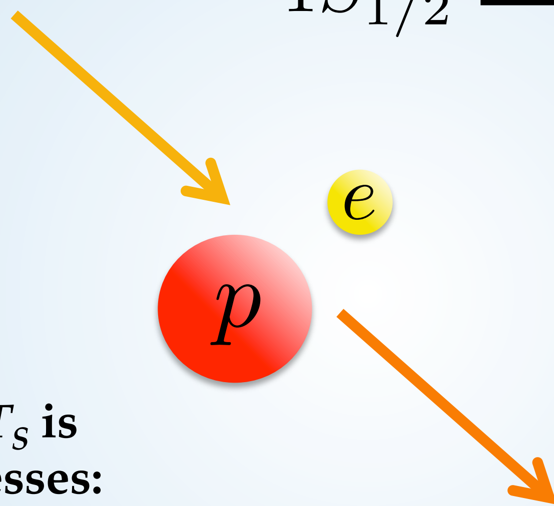
- The mixing strength picked out by cosmology is at an **interesting scale for colliders**, and the scenario as a whole has some **startling astrophysical implications**.

# 21 cm cosmology



Planck

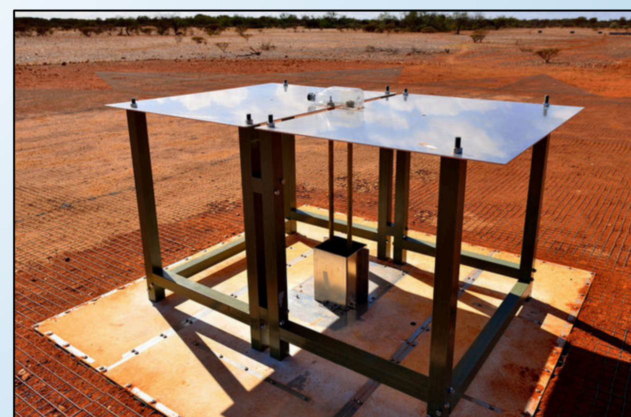
$$1S_{1/2} \longrightarrow \begin{cases} F = 1 \\ \Delta E = 6\ \mu\text{eV} \\ F = 0 \end{cases}$$



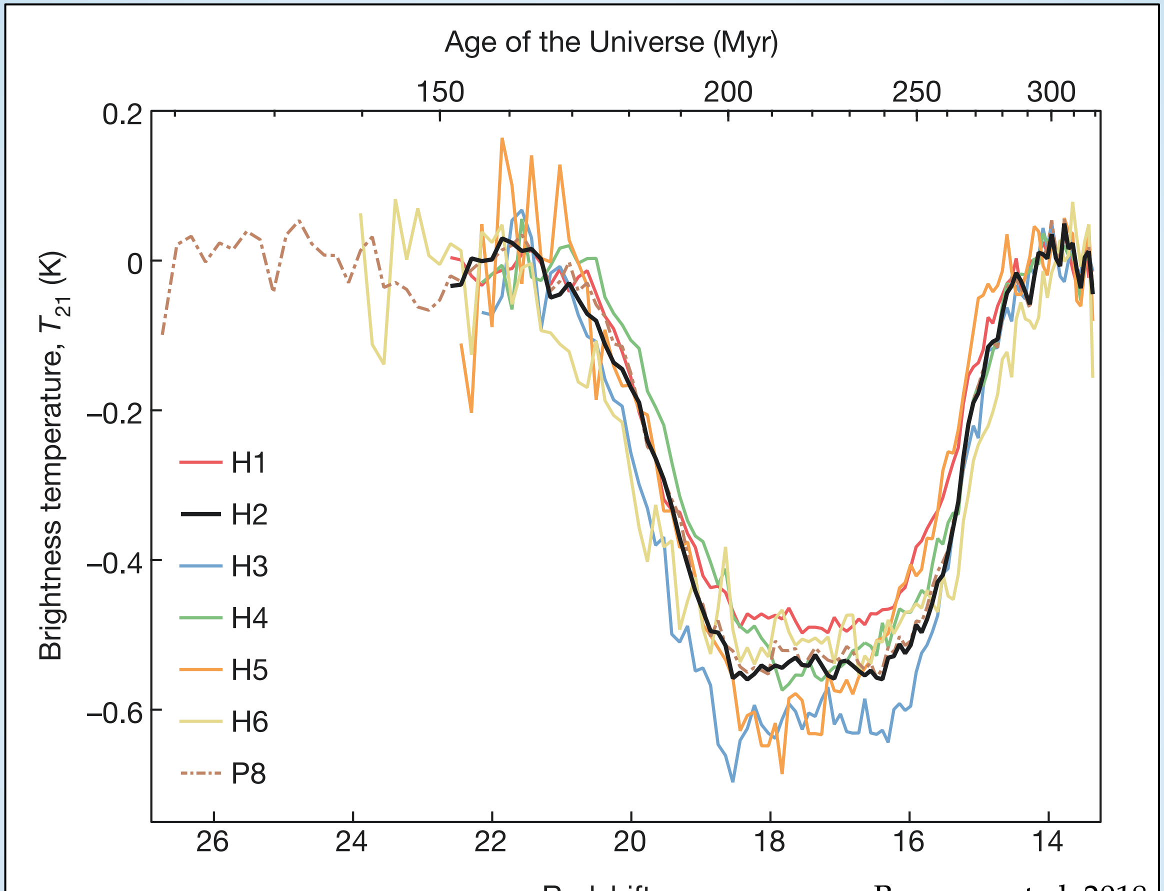

**The spin temperature $T_S$ is set by competing processes:**

$$T_S^{-1} = \frac{T_R^{-1} + x_c T_g^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha}$$

$T_R$ = brightness temp of *microwave background*
$T_g$ = kinetic temp of *hydrogen gas*
$T_\alpha$ = color temp of *Lyα radiation field*


EDGES

# The EDGES anomaly



Bowman et al. 2018

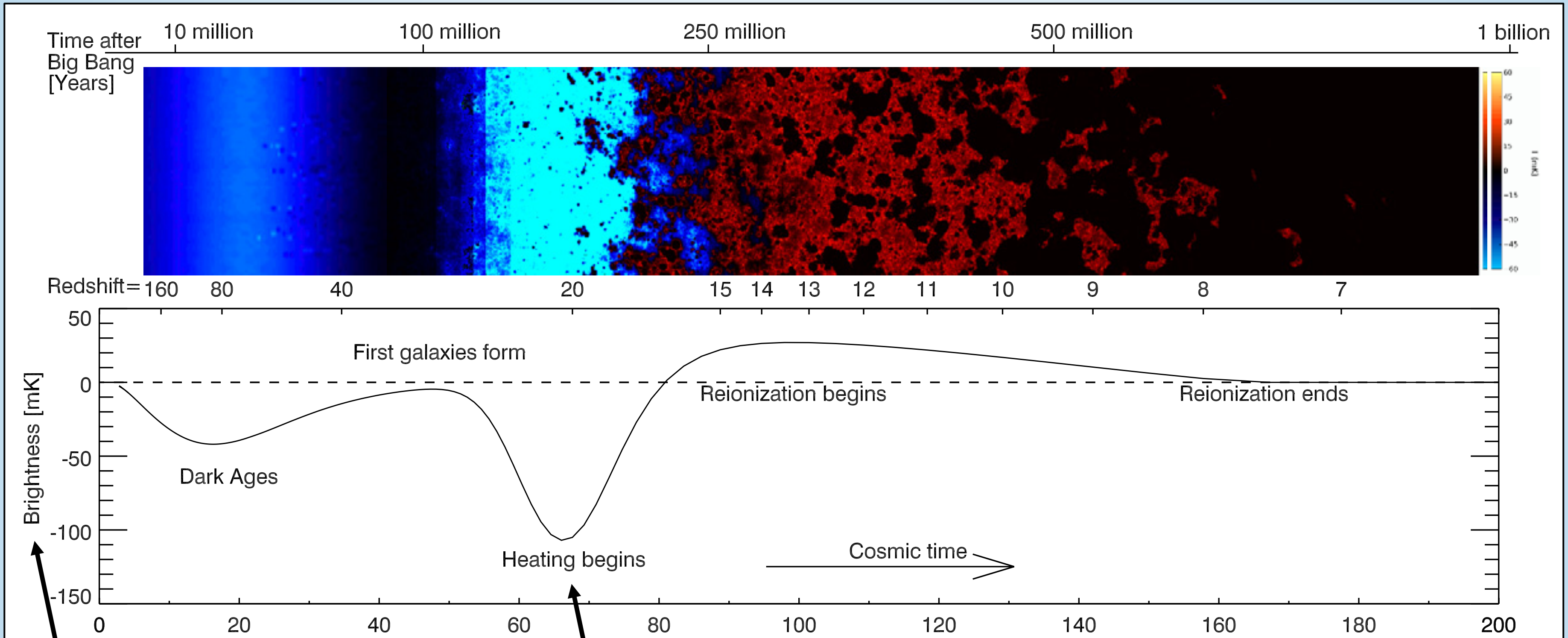
**Observed brightness temp** (depends on $T_S$)

$$T_{21} = \frac{T_{\mathrm{obs}} - T_R}{1+z}$$

$$T_{21}(z=17) \gtrsim -210 \text{ mK (expected)}$$

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

# The standard timeline



Pritchard & Loeb 2012

$T_{21}$

This dip corresponds to the EDGES absorption trough

## What could account for the anomalous depth?

- ✧ Systematics

  *e.g.*, modeling synchrotron emission, the ionosphere, etc.

  Hills et al. 2018

- ✧ Unexpected astrophysics (hotter background)

  *e.g.*, radio-loud accretion onto black holes

  Ewall-Wice et al. 2019

- ✧ BSM physics (colder gas)

  *e.g.*, scattering between SM particles and dark matter

  Barkana 2018

# SM-DM scattering

**Basic idea:**

The baryonic gas loses heat to DM
(which is assumed to be colder than the gas).

Tashiro et al. 2014; Muñoz et al. 2015

**Drawbacks:**

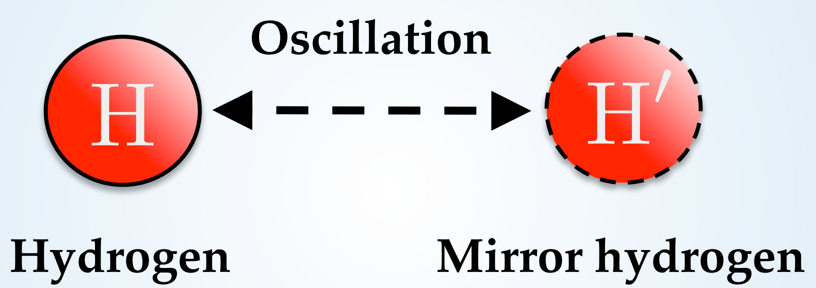
✧ The simplest scenario has DM coupling to H as a whole, but it's strongly constrained by 5th-force experiments.

Barkana et al. 2018

✧ The gas could cool by interacting with millicharged DM, but mDM would only be a small fraction of all DM—and even then it's highly constrained.

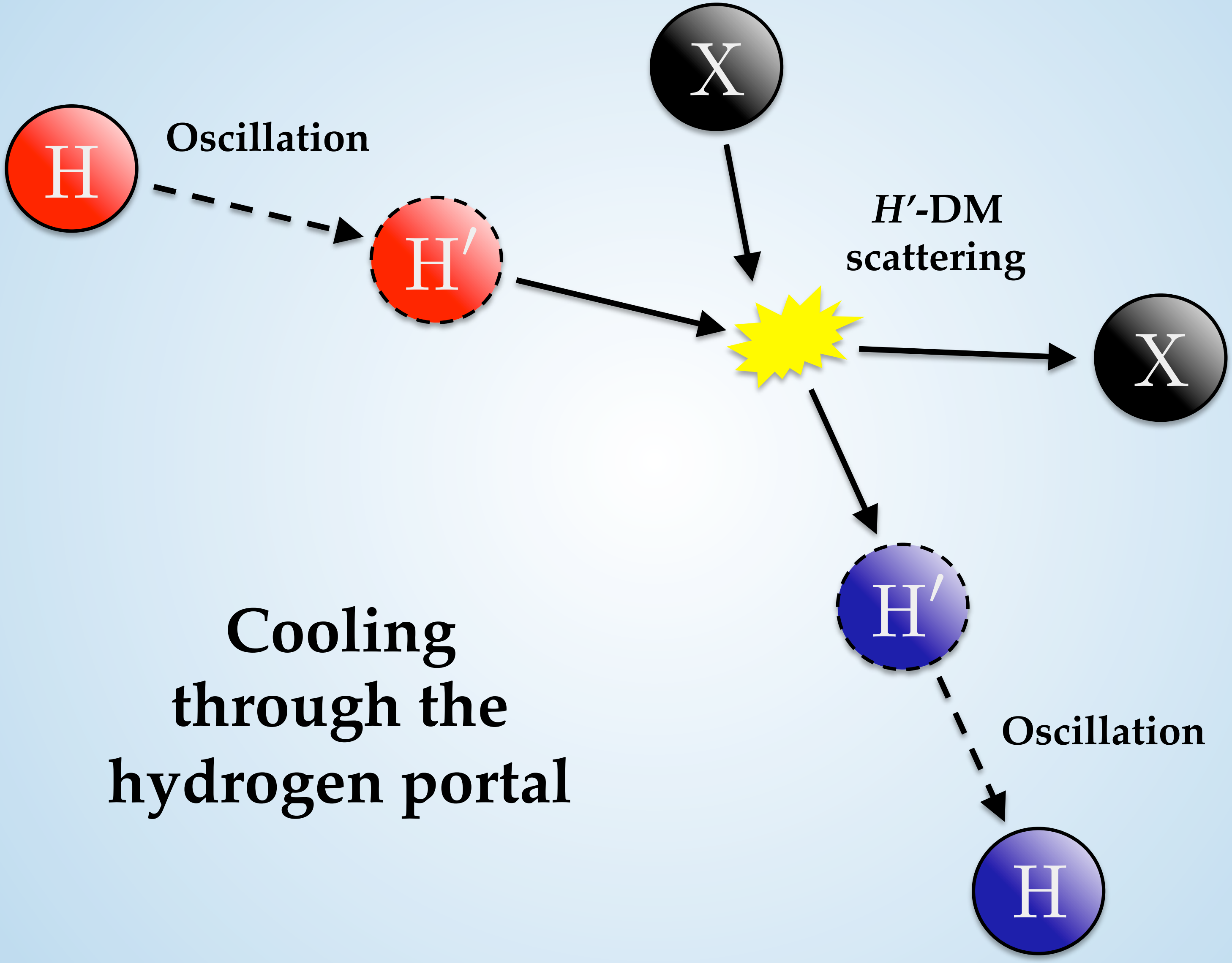
Muñoz & Loeb 2018; Berlin et al. 2018; Liu et al. 2019

Suppose that EDGES does indicate new physics. Maybe it's a hint that **the new physics has only shown up in connection to neutral hydrogen**…




- ✧ The SM & mirror sectors are related by a **$Z_2$ symmetry**.
- ✧ At a fundamental level, the sectors are connected by **leptoquarks**. (More on this later.)

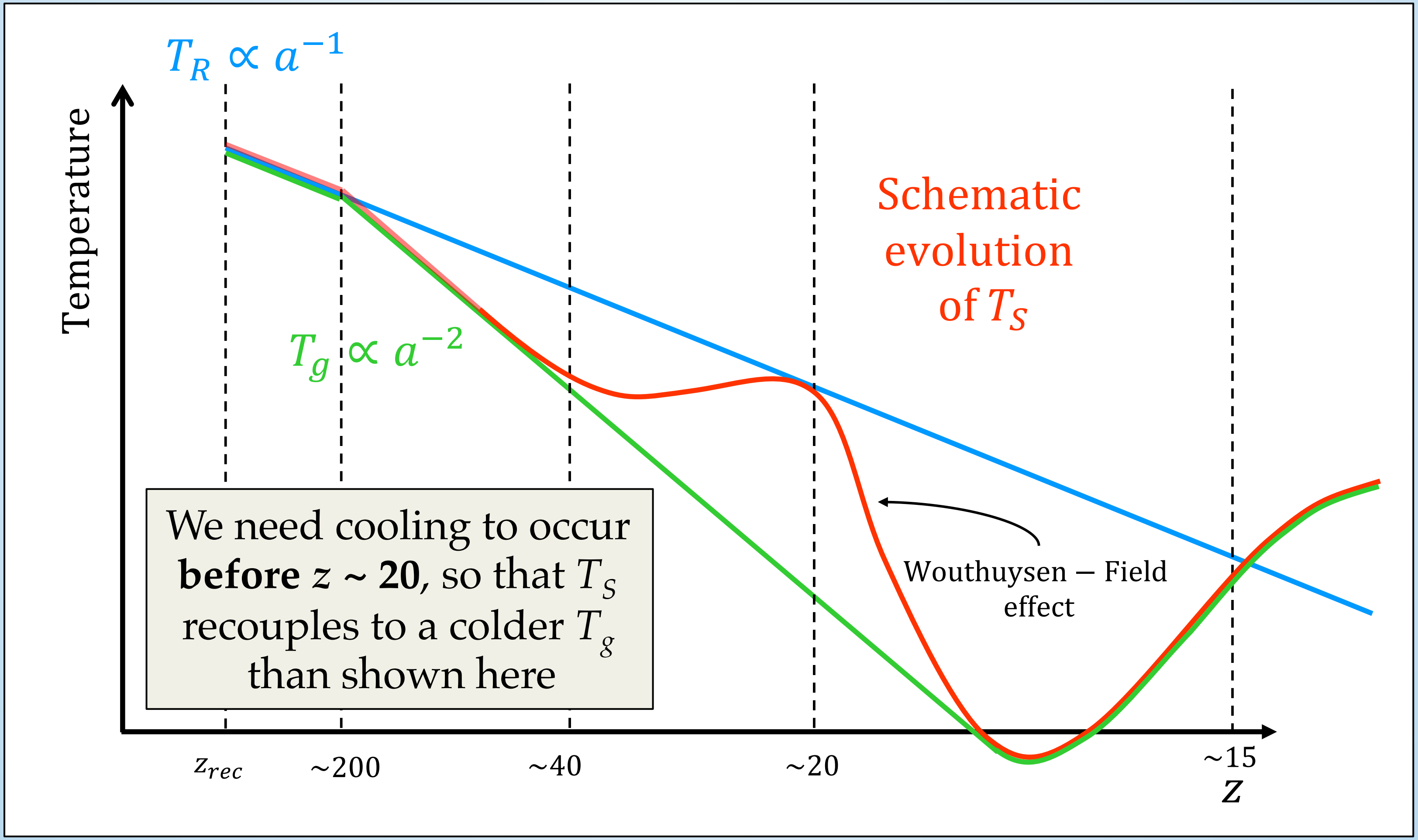
**Johns** & Koren, 2012.06584 (mixing/cooling scenario)
**Johns** & Koren, 2012.06591 (particle-physics model + other astro implications)


H
Oscillation
H′
X
H′-DM scattering
X
H′
Oscillation
H
Cooling through the hydrogen portal

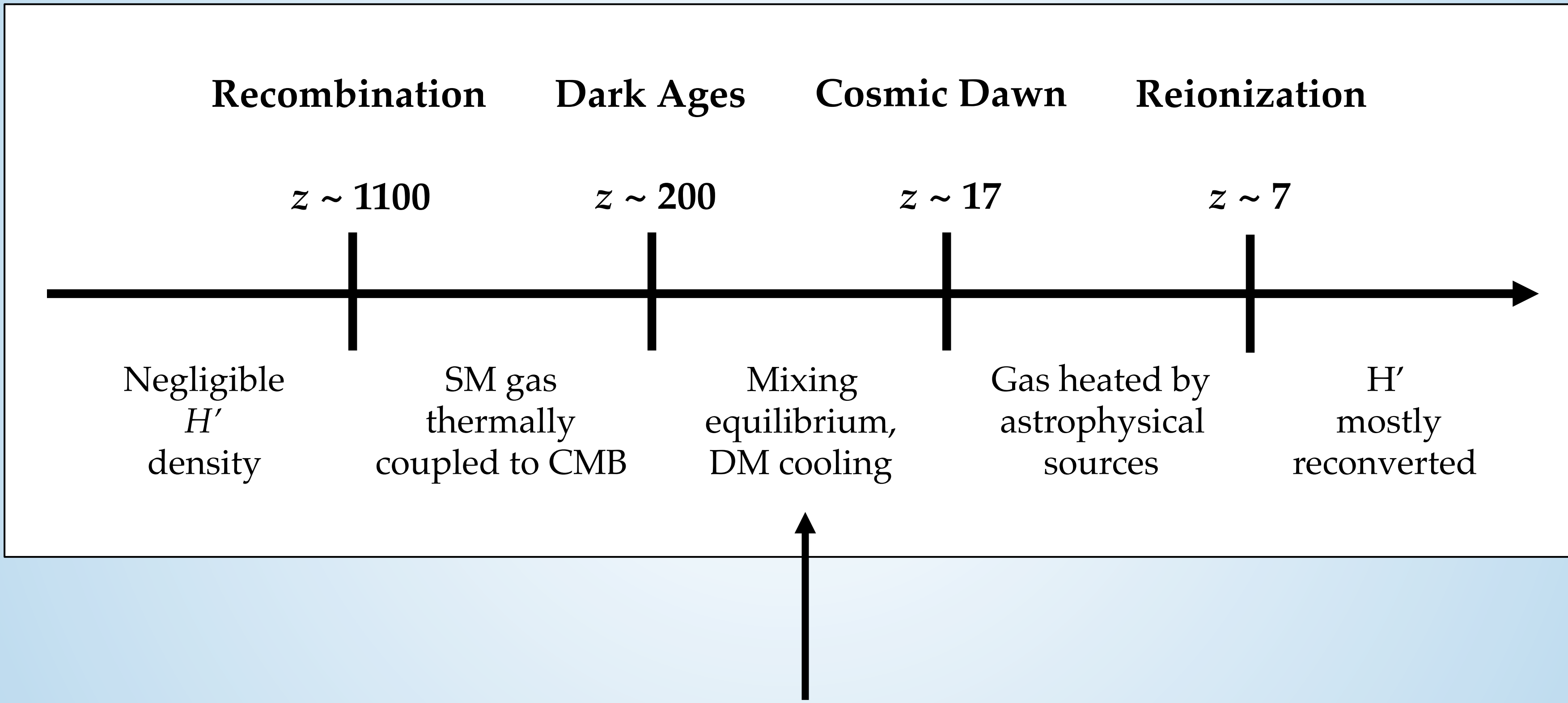
# The standard timeline (once more)

Collisional coupling of $T_S$ to $T_g$ is lost

Astro sources recouple $T_S$ to $T_g$, *and then* heat the gas



# Timeline of the hydrogen portal




Sequence from two slides back
(oscillations & heat transfer
must both be fast)

# Estimating the energy scale of mixing

Suppose that *H* **oscillates ~1 period between scattering events** during the late dark ages:

$$\delta \sim \Gamma_H$$

**Mixing parameter (oscillation frequency)**

***H* scattering rate**

$$\longrightarrow \quad z \sim 30: \quad \delta \sim \mathcal{O}\left(10^{-37}\right)\ \mathrm{GeV}$$

Mixing at this level is exquisitely sensitive to any physics that distinguishes $H$ and $H'$: **terrestrial experiments**, **mass splitting**, …

# *H*-*H′* mixing

A mass-degenerate, non-unitary, two-level quantum system with Hamiltonian

$$\mathcal{H} = \begin{pmatrix} \Delta V & \delta \\ \delta & -\Delta V \end{pmatrix}$$

Potential due to **forward scattering in the medium**

$$i\frac{d\rho}{dt} = [\mathcal{H}, \rho] + i\mathcal{C} \quad \Longrightarrow \quad \Gamma_{\text{osc}} \sim \frac{\Gamma_c}{4} \frac{\sin^2 2\theta_m}{1 + (\Gamma_c/2\omega_m)^2}$$

Quantum relaxation-time approximation

**Johns**, PRD (2019)

$\boldsymbol{\Gamma_c}$ = Total collision rate
$\boldsymbol{\theta_m}$ = In-medium mixing angle
$\boldsymbol{\omega_m}$ = In-medium osc. freq.

# Forward scattering & collisions

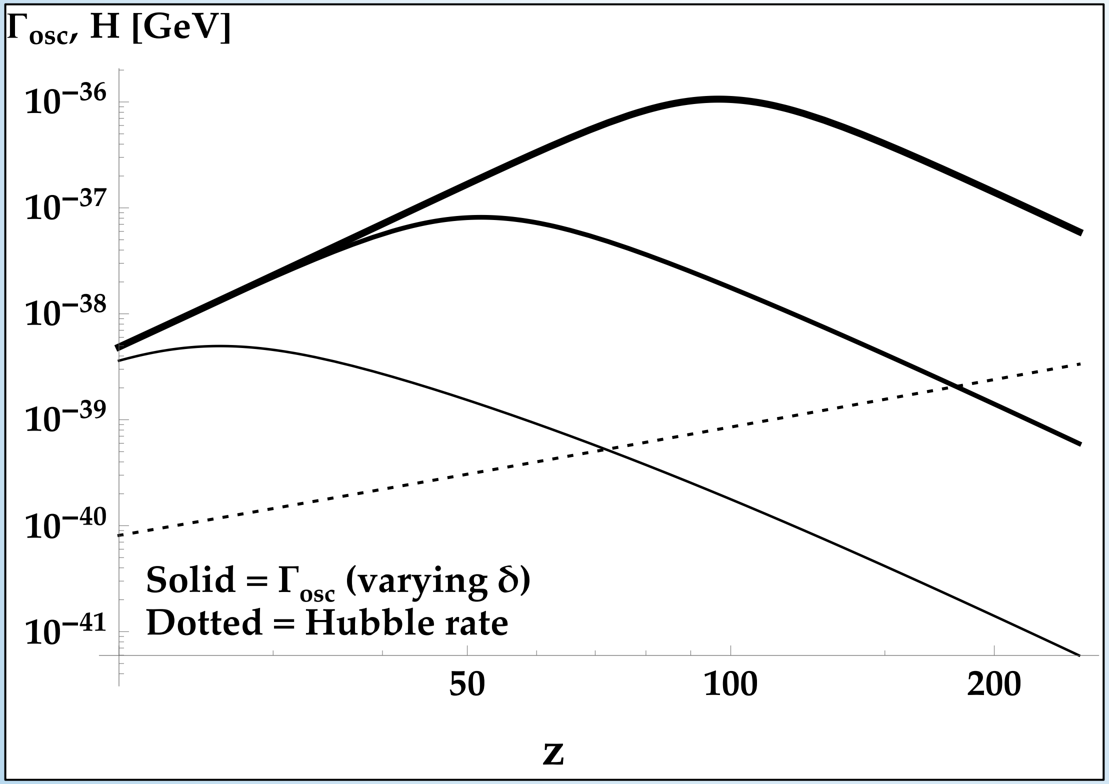
The viability of the *H-H′* mixing scenario hinges on hydrogen's interactions over cosmic history.

| | $\Gamma_H$ | $\Delta V_H$ |
|---|---|---|
| **Dark ages** | ***H-H*** **scattering** | ***H-H*** **scattering** |
| **Reionization** | **Photoionization** | ***H-H*** **scattering** |

Subdominant processes:
*H-e*$^-$ scattering, Rayleigh scattering, **B**-field coupling, …

# *H*-*H′* dynamics during the dark ages ("minimal mixing")

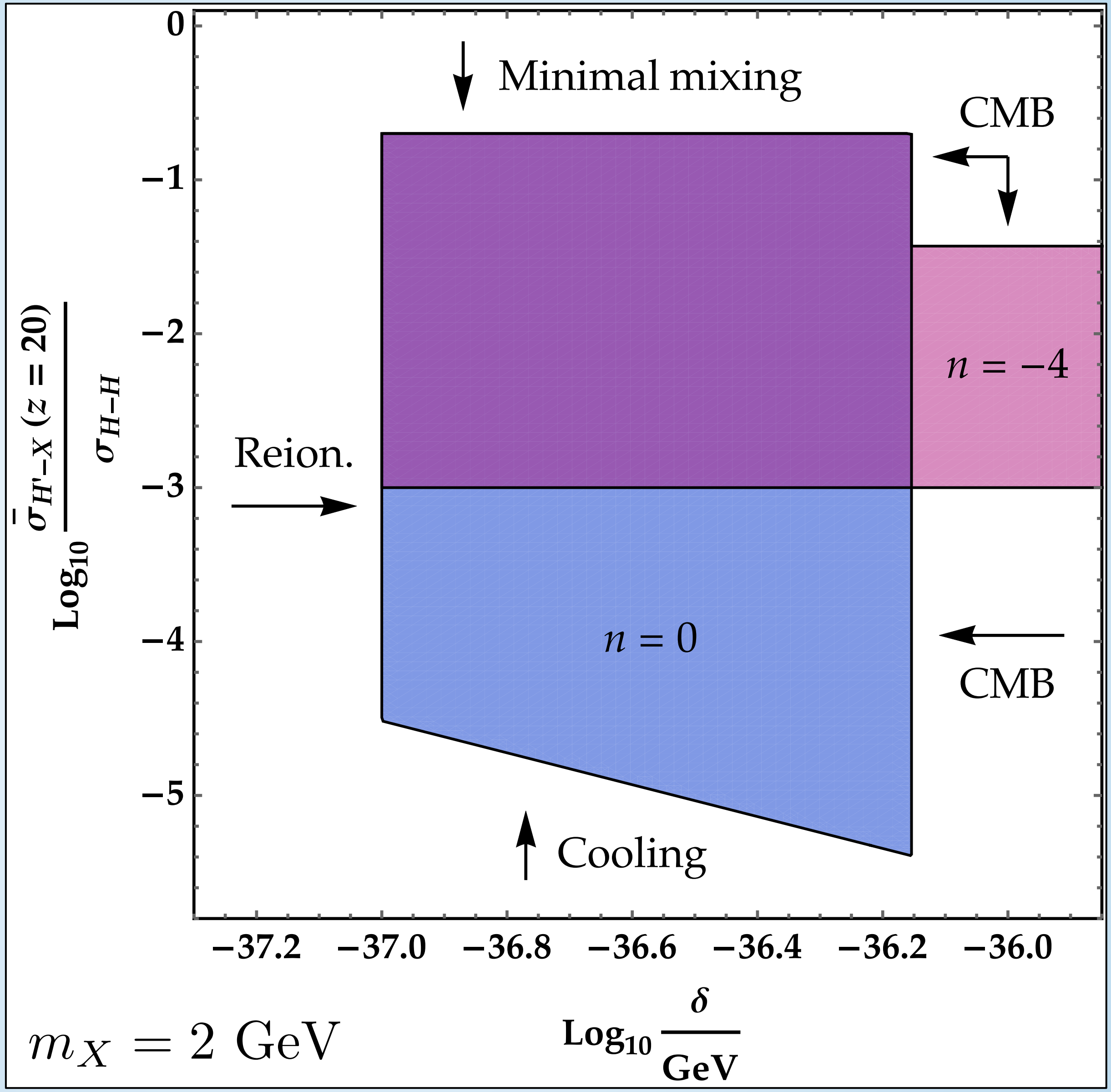
Assume *H′* interactions are always subdominant




When the solid curve is above the dashed one, mixing is in equilibrium.

# Viable parameter space

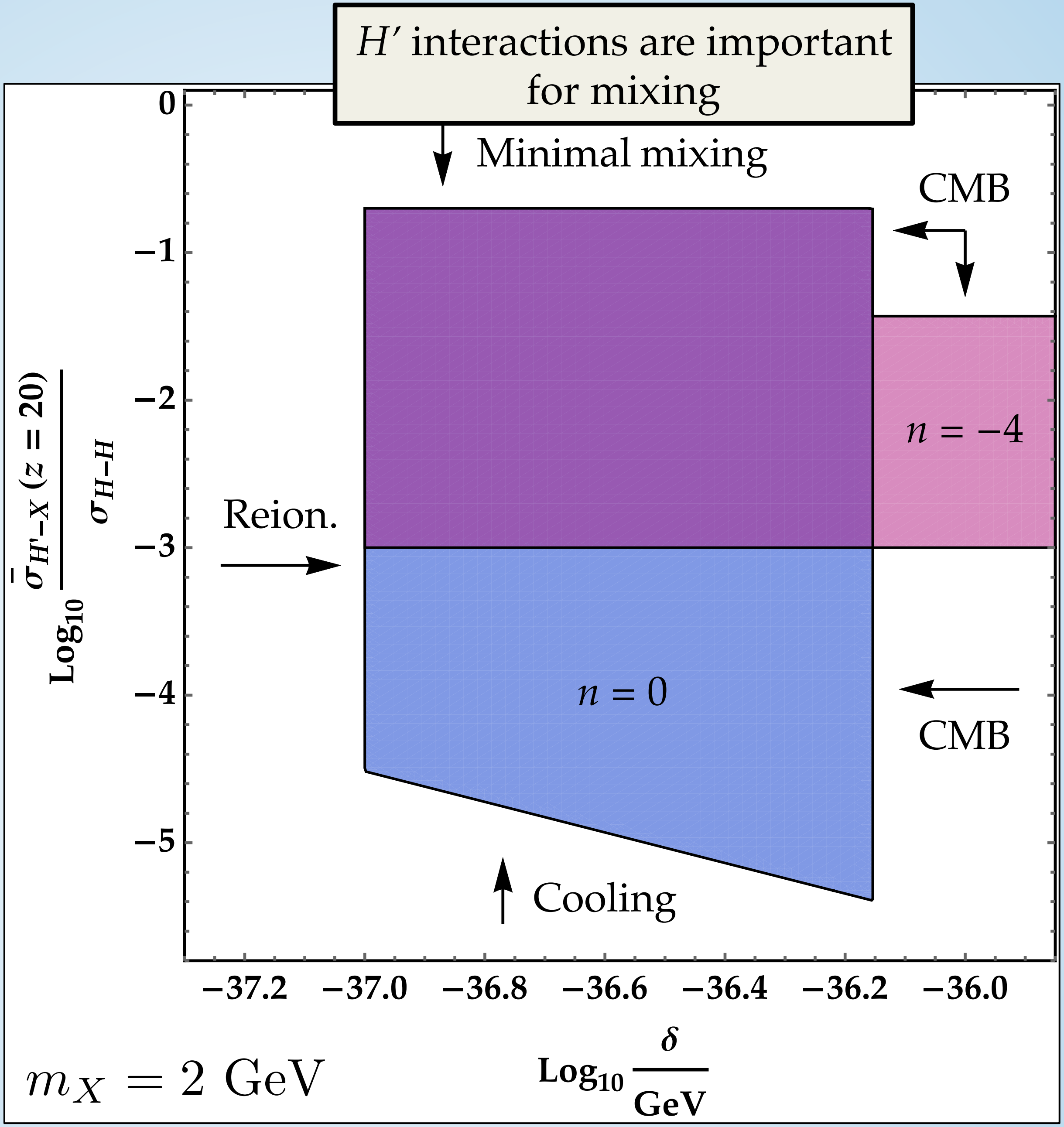
*H′*-DM cross section ($v^n$ scaling)




*H*-*H′* mixing parameter

# Viable parameter space

$H'$-DM cross section ($v^n$ scaling)




$H$-$H'$ mixing parameter

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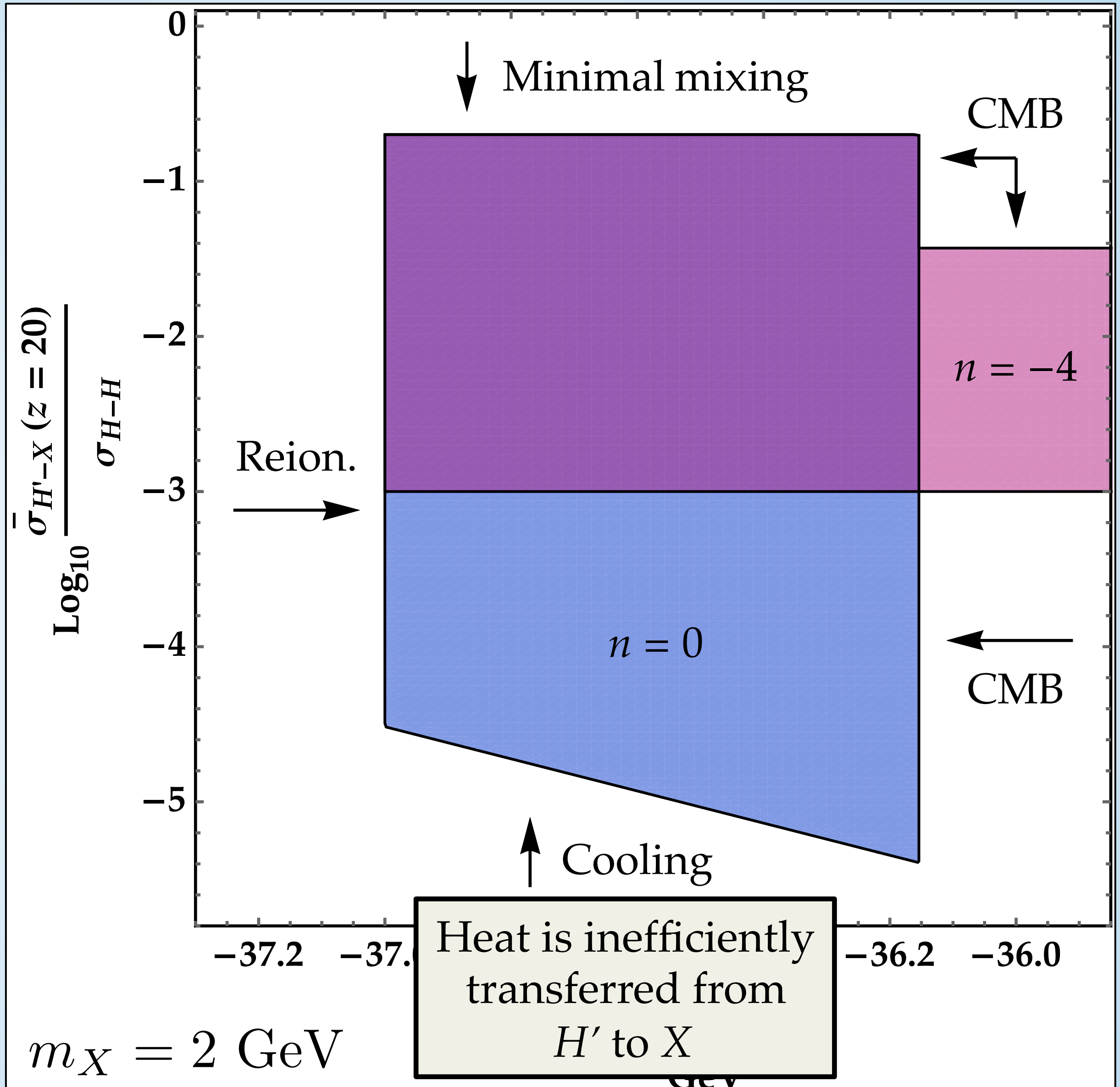


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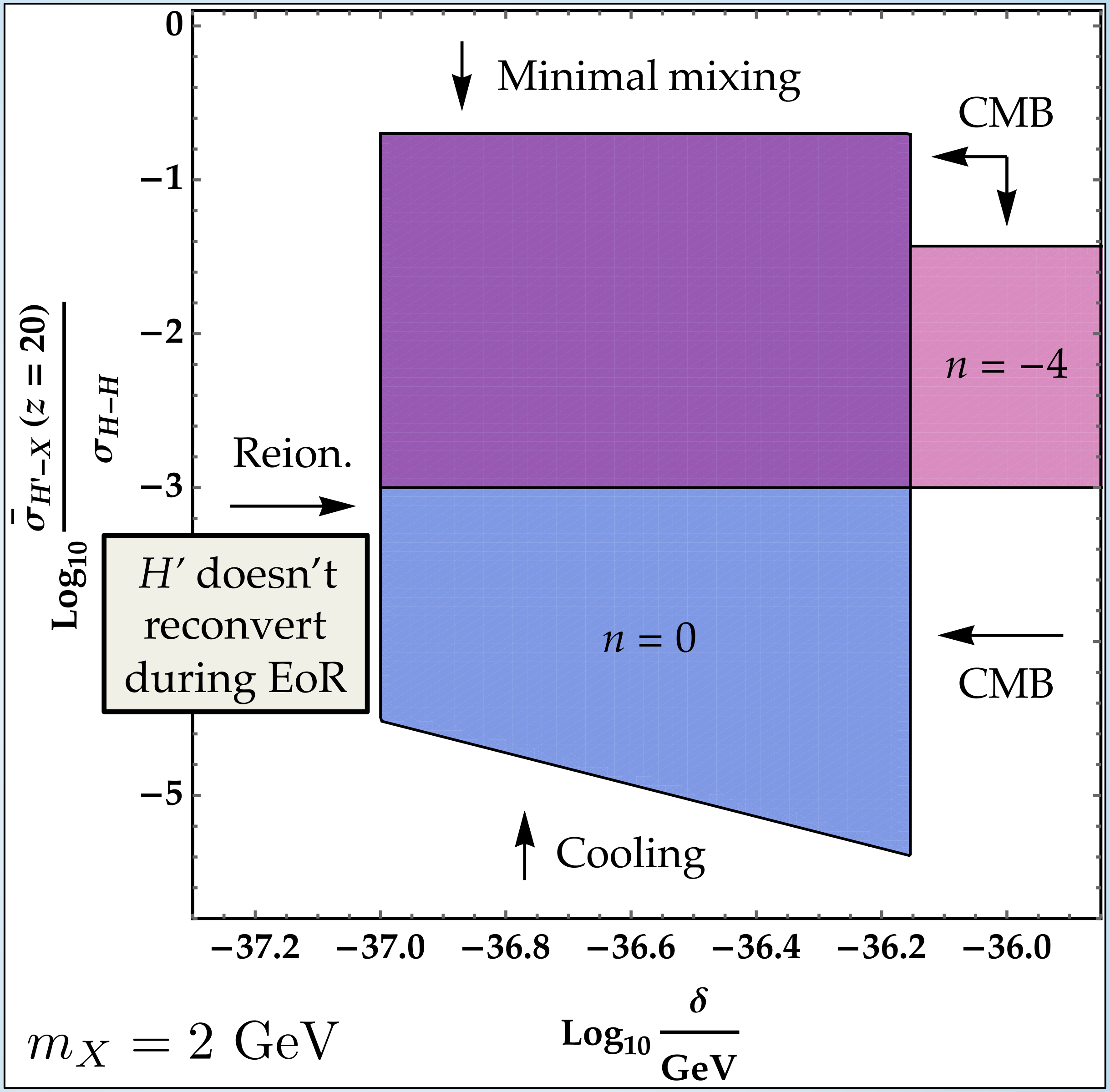


*H*-*H′* mixing parameter

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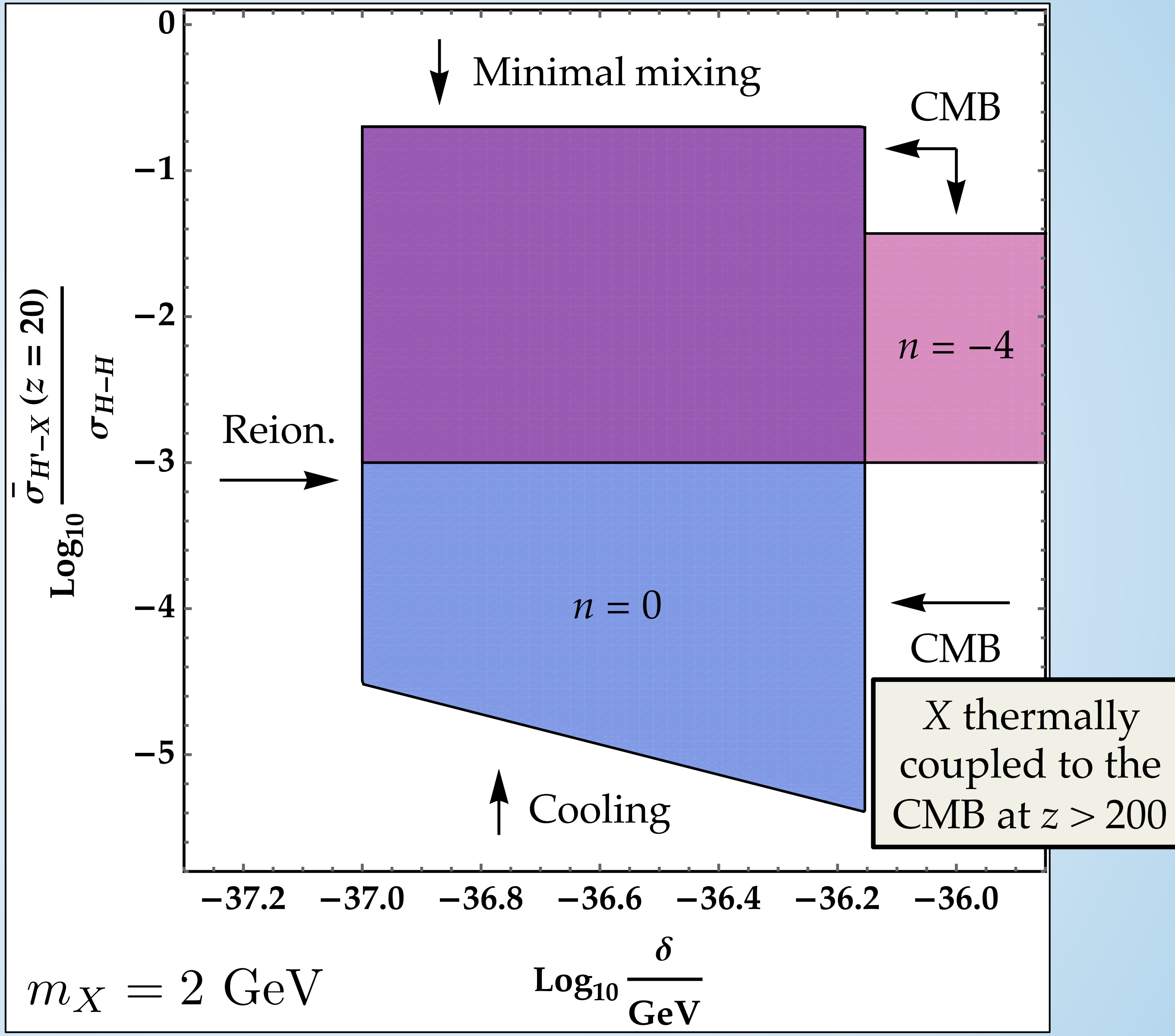
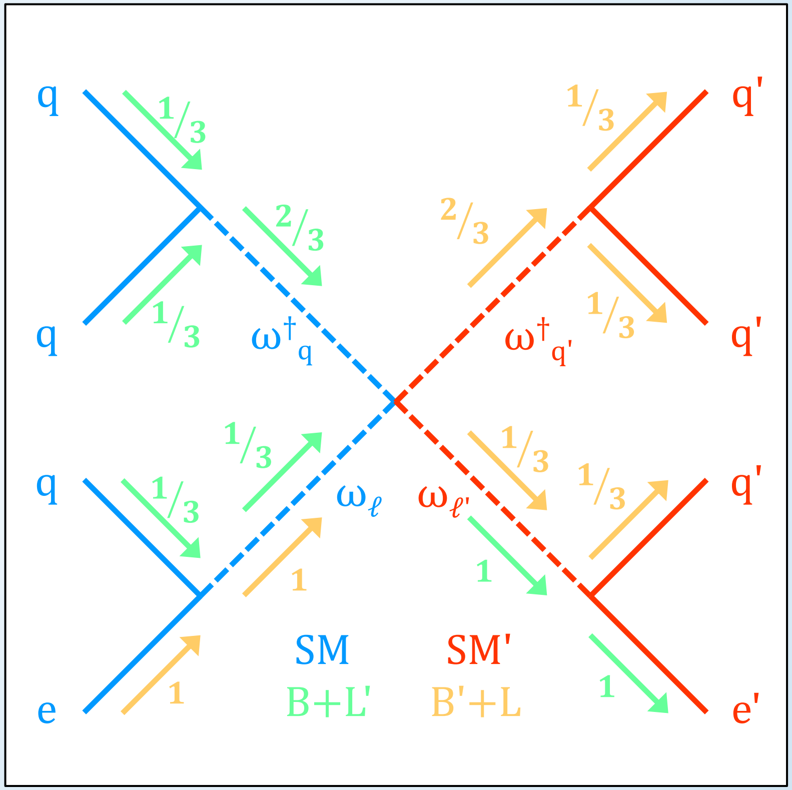



*H*-*H′* mixing parameter

# The origin of *H*-*H′* mixing

$$\mathcal{O}_{\rm part} \sim \frac{1}{\Lambda^8}\ \bar{e}'e\ \bar{u}'u\ \bar{u}'u\ \bar{d}'d \quad \longrightarrow \quad \mathcal{O}_{\rm had} \sim \frac{(4\pi)^2\,\Lambda_{\rm QCD}^6}{\Lambda^8}\ \bar{e}'\Gamma e\ \bar{p}'\Gamma p$$

Consider leptoquarks in a theory with ***B*+*L′*** **and *B′*+*L* symmetries:**



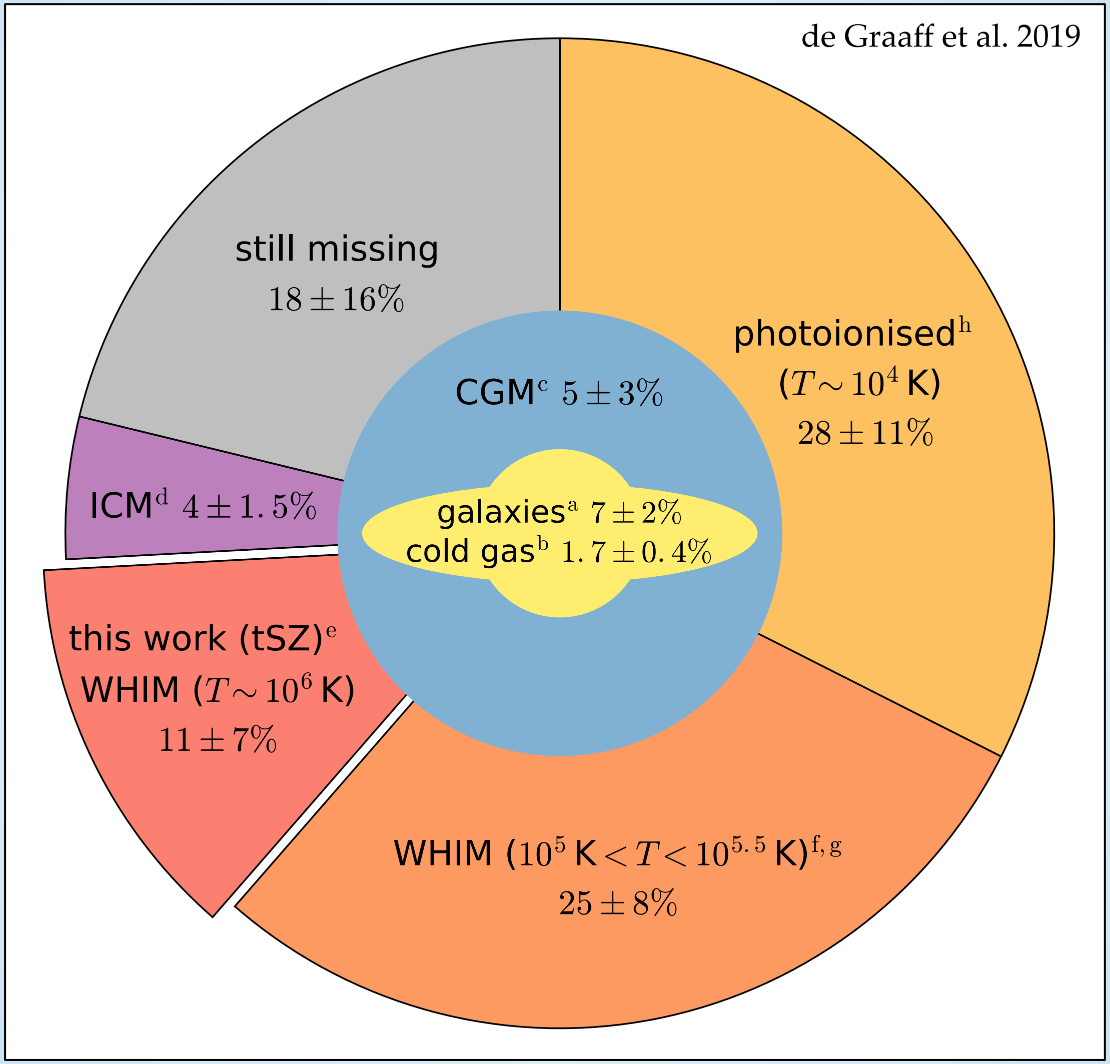

$$\delta = \langle H\,|\mathcal{O}_{\rm had}|\,H'\rangle$$

$$\sim \frac{(4\pi)^2\,\Lambda_{\rm QCD}^6}{\Lambda^8}\,\frac{1}{a_0^3}$$

$$\sim \underline{10^{-37}\ \text{GeV}}\ \left(\frac{\Lambda_{\rm QCD}}{250\ \text{MeV}}\right)^6 \left(\frac{250\ \text{GeV}\times\sqrt{N_\omega}}{M_\omega}\right)^8$$

Leptoquark multiplicity

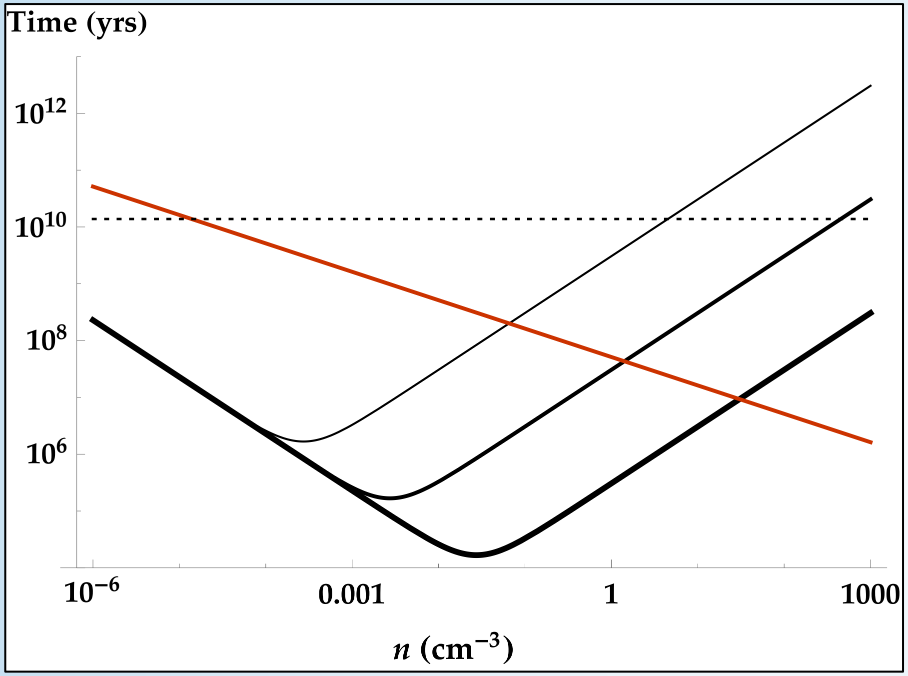
# The missing baryons problem




**Did a fraction of baryons never make it back?**

# Stars & black holes

Once a gas cloud reaches high enough density, mixing shuts off:




**Solid black = $\Gamma_{osc}$ (varying $\delta$)**
**Dashed = present age of universe**
**Red = gravitational free-fall time**

When the first stars are forming, the mirror sector lacks the free electrons that catalyze $H_2$ formation:

$$H + e^- \to H^- + \gamma$$

$$H^- + H \to H_2 + e^-$$

The absence of $H_2$ cooling may lead to mirror gas clouds directly collapsing to **SMBH seeds**.

D'Amico et al. 2017
Latif et al. 2019

**Mirror stars** are also possible.

Foot 1999
Curtin & Setford 2020

# Summary

- In 2018 EDGES detected cosmic dawn at radio frequencies. According to one interpretation of their data, the hydrogen gas at $z \sim 17$ is **significantly colder than expected**.
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