Rethinking Recombination: Primordial magnetic fields and their implications for the Hubble tension

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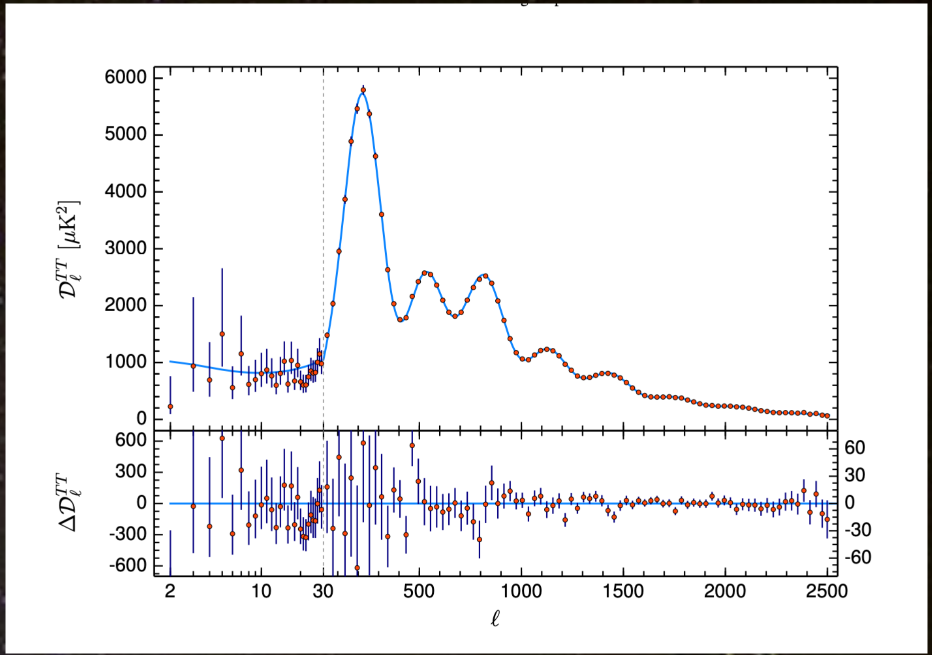
Outline

- Hubble tension basics/background
- Recombination basics/background
- PMFs and modified recombination schemes

Hubble Tension

- CMB measurements:
  - Measure BAO angular size, θ_s, in CMB power spectrum
  - Compute comoving sound horizon, r_s, and distance to surface of last scattering, $D_s[H_0]$, which is a function of H_0
  - Infer H_0: $\theta_s \sim \frac{r_s}{D_s[H_0]}$
    - Planck 18: $H_0 \sim (67 \pm 0.5)\,\frac{km}{s\,Mpc}$
    - $> 5\sigma$ tension with SH0ES collaboration



Planck Collaboration 2018

Recombination Basics

- Recombination models and codes presuppose it is a local process
  - Saha (local thermal equilibrium)
  - Peebles three level atom (3LA)
  - State of the art codes – HYREC, RECFAST
- The ionization fraction in all these models and codes is determined by the local baryon density and local physics
  - Inhomogeneities in the baryon density locally modify the recombination rate

Three Level Atom

$$\dot{x}_e = -C\left(n_H x_e^2 \alpha_B - 4 x_{1s} \beta_B e^{-\frac{E_{21}}{k_B T}}\right)$$

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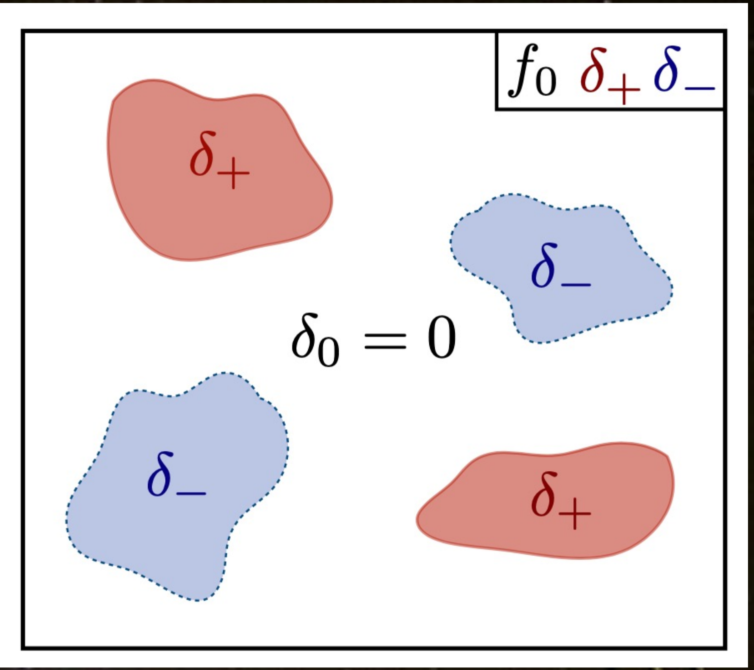
$$\langle n_e^2 \rangle \geq \langle n_e \rangle^2$$

Inhomogeneities lead to an overall speedup in average rate of recombination

Inhomogeneous recombination

- Karsten Jedamzik and collaborators: PMFs can source small-scale inhomogeneities

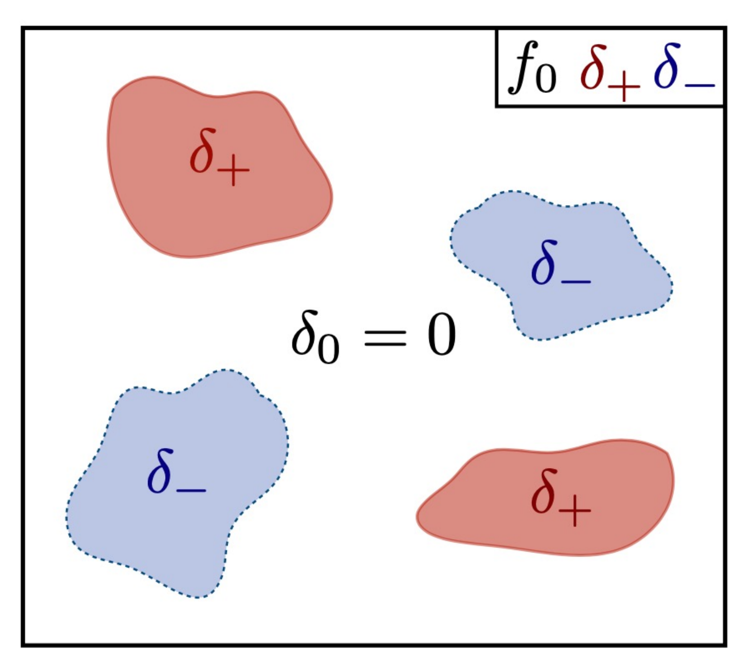
- Assessments of proposal to date:
    - Simple three-zone model of homogeneous recombination taking place in regions of
        - Overdensity, undersdensity, background density
        - Take volume weighted average of recombination in each region



Rashkovetskyi, Muñoz, Eisenstein, Dvorkin 2021

Inhomogeneous recombination

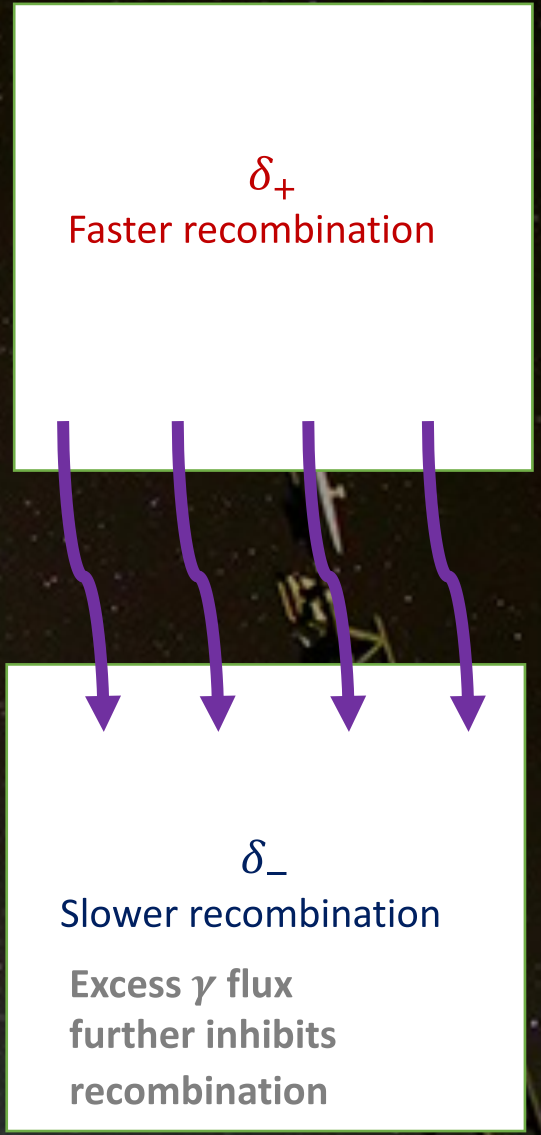
- Shortcomings of three-zone model of inhomogeneous recombination:
  - Does not account for spatial and temporal evolution of inhomogeneities
  - Ignores non-local radiative transfer on small-scales



Rashkovetskyi, Muñoz, Eisenstein, Dvorkin 2021

Radiative Transfer & Recombination

- On small-scales, non-local transport of diffusing radiation becomes important (Venumadhav & Hirata 2015)
- Need detailed account of non-local dynamics that govern PMF induced small-scale inhomogeneities



Radiative Transfer & Recombination

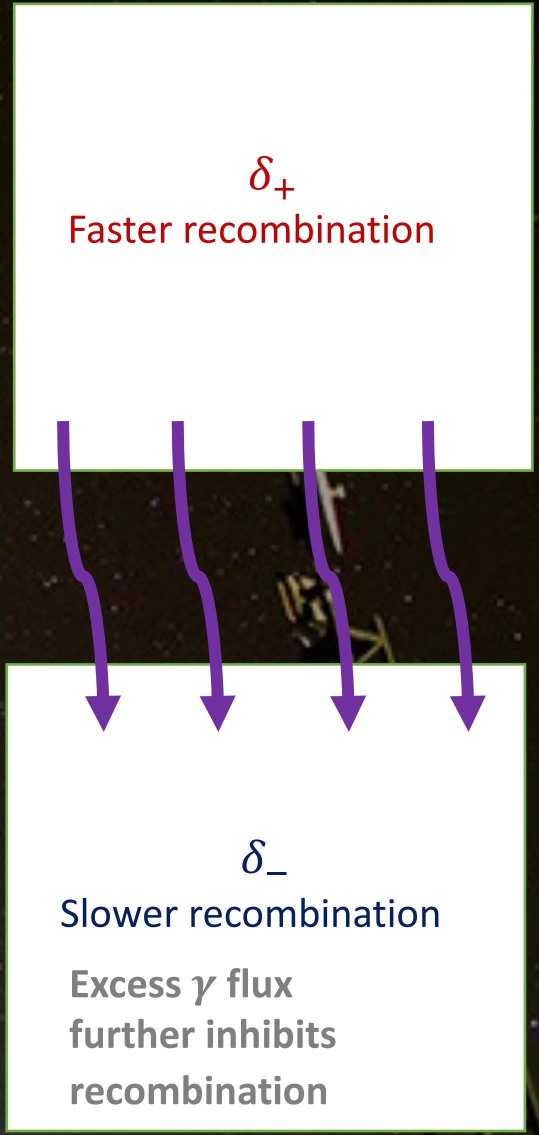
- Solve perturbed Boltzmann equation:
  - Contributions from continuum and Ly-α channels

$$\frac{\partial f}{\partial t} - \left[H + \frac{n_i n_j}{a}\frac{\partial v_i}{\partial x_j}\right]\nu\frac{\partial f}{\partial \nu} + \frac{c}{a}\hat{\mathbf{n}}\cdot\nabla f = \sum_{\text{process}} \dot{f}|_{\text{process}}. \qquad (23)$$

Venumadhav & Hirata 2015

- Continuum: perturb detailed balance between absorption and emission of continuum photons

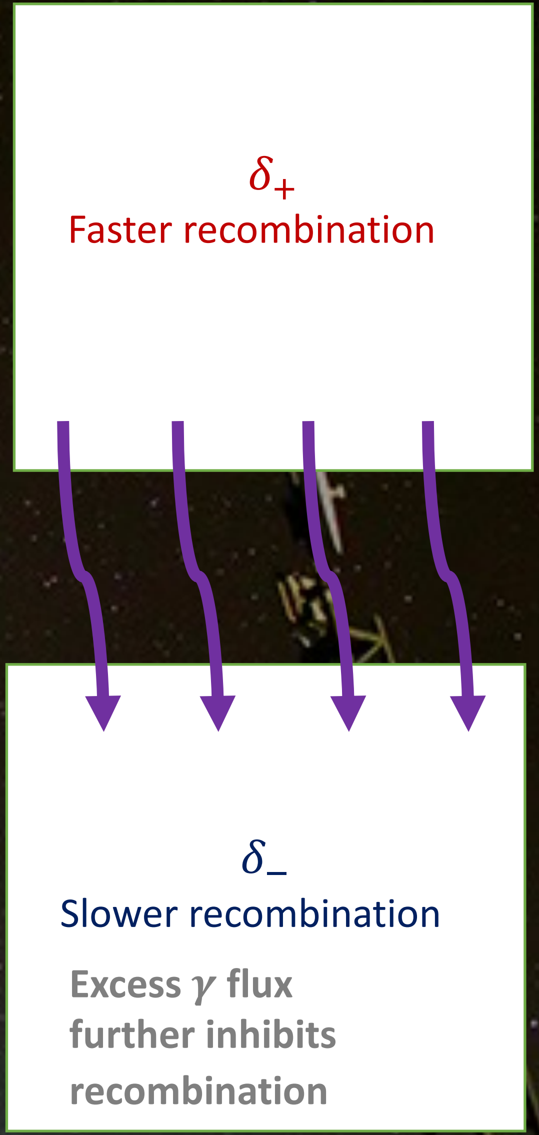
- Ly-α, 2s1s: perturb homogeneous Sobolev solution



Radiative Transfer & Recombination

- Solve perturbed Boltzmann equation:
  - Contributions from continuum and Ly-α, 2s1s channels

$$\delta \dot{x}_e \Big|_{cont} + \delta \dot{x}_e \Big|_{Ly\alpha,2s1s} \sim A\delta x_e + B\delta_m + C(\vec{k} \cdot \vec{v})$$



Numerical evolution scheme

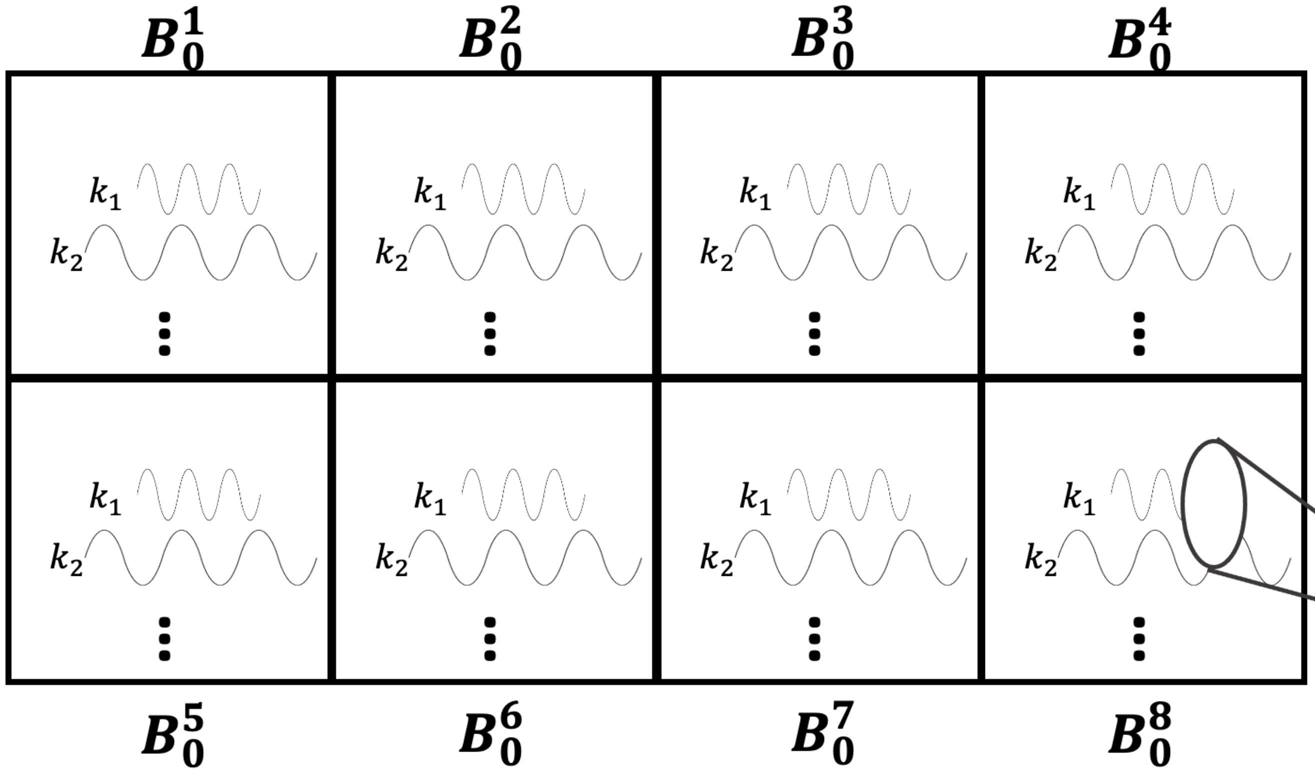
- Magnetogenesis at some very redshift z_o with power spectrum $\mathrm{P}_B(k, z_o)$
  - Potential sources:
    - Inflation, electroweak phase transition, etc.
- Magnetic field couples to velocity and energy density fields via Maxwell/Fluid equations (ideal MHD)
- Linear perturbation theory through several different regimes

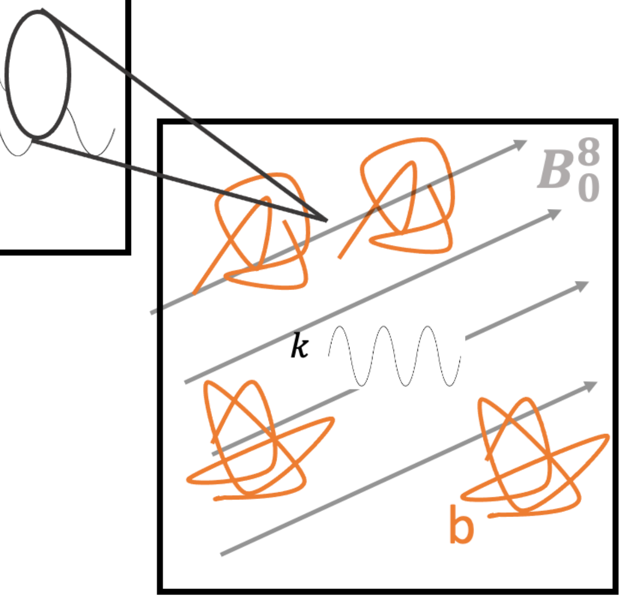
Linear Maxwell-Fluid Equations

- MHD contribution in Euler equation is non-linear:
- Non-Relativistic Euler equation:

$$\dot{v} + \frac{\nabla P}{\rho} + \nabla\varphi + \frac{1}{4\pi\rho} B \times (\nabla \times B) = F_d$$

Linear Maxwell-Fluid Equations





<u>MHD term:</u>

$$B\times(\nabla\times B) = (B_0 + b)\times\big(\nabla\times(B_0 + b)\big)$$
$$\approx B_0\times(\nabla\times b)$$

Linear Maxwell-Fluid Equations

$$\dot{\vec{r}} = M\vec{r}$$

- Convention: $\hat{k} = \hat{x}, \;\; B_0 = B_x\hat{x} + B_y\hat{y}, \;\;\; \hat{k} \cdot \widehat{B_0} = cos\phi$

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$$\frac{\partial}{\partial t}\begin{pmatrix} \delta \\ v_x \\ v_y \\ b \\ \delta x_e \end{pmatrix} = \begin{pmatrix} 0 & A & 0 & 0 & 0 \\ B & C & 0 & D & E \\ 0 & 0 & F & G & 0 \\ 0 & 0 & H & I & 0 \\ J & K & 0 & 0 & L \end{pmatrix}\begin{pmatrix} \delta \\ v_x \\ v_y \\ b \\ \delta x_e \end{pmatrix}$$

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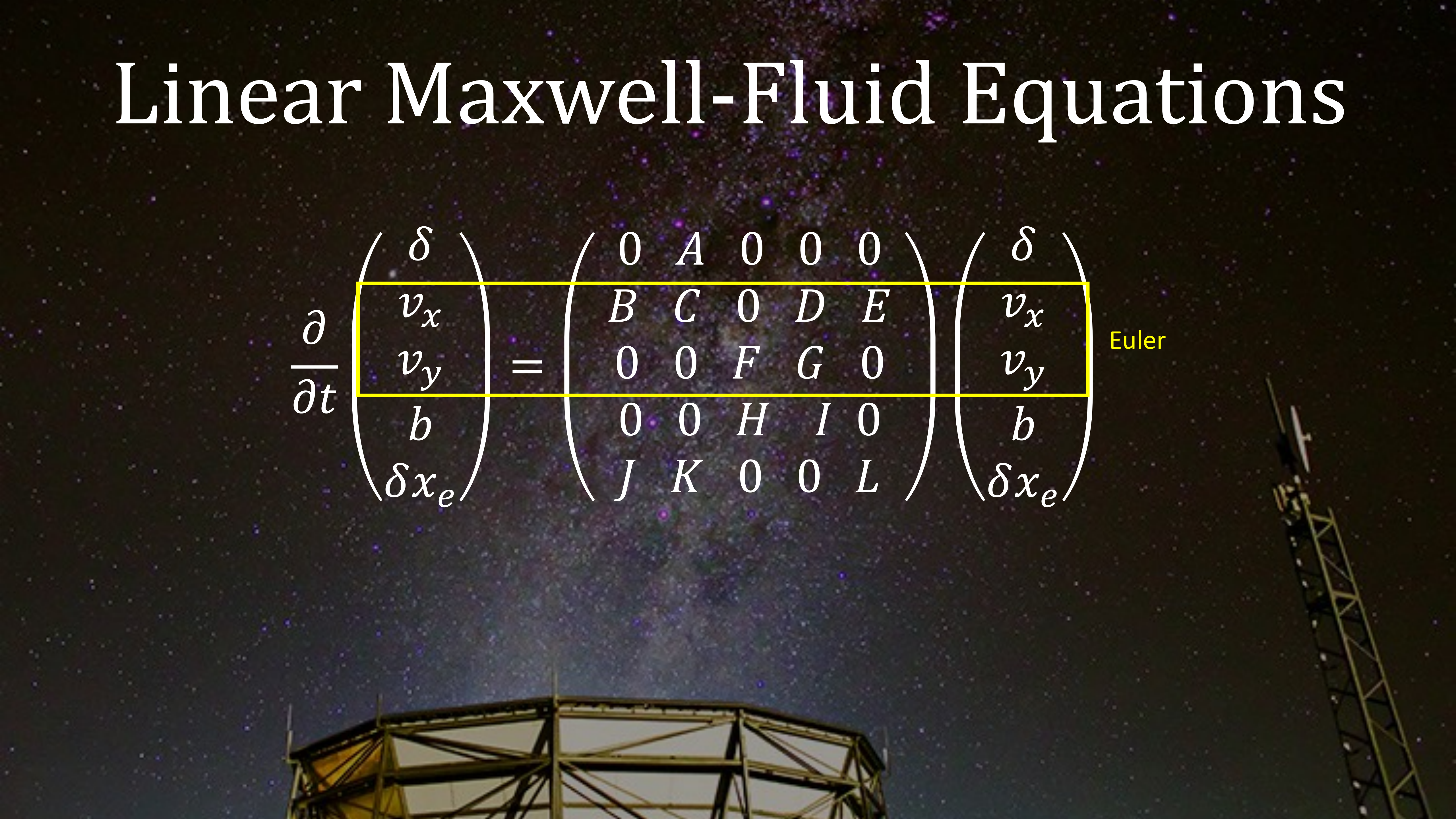
Continuity



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Euler

Linear Maxwell-Fluid Equations

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Induction

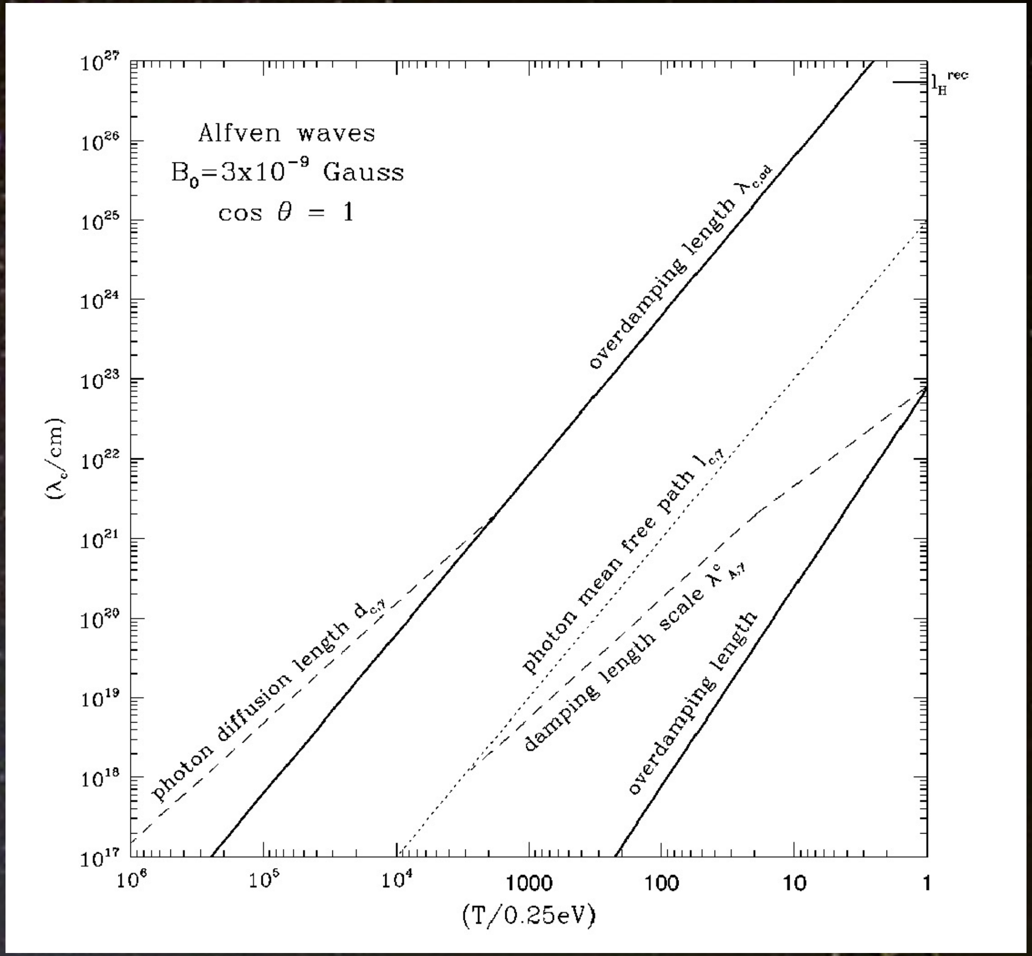
Linear Maxwell-Fluid Equations

$$\frac{\partial}{\partial t}\begin{pmatrix} \delta \\ v_x \\ v_y \\ b \\ \delta x_e \end{pmatrix} = \begin{pmatrix} 0 & A & 0 & 0 & 0 \\ B & C & 0 & D & E \\ 0 & 0 & F & G & 0 \\ 0 & 0 & H & I & 0 \\ J & K & 0 & 0 & L \end{pmatrix}\begin{pmatrix} \delta \\ v_x \\ v_y \\ b \\ \delta x_e \end{pmatrix}$$

Perturbed Boltzmann

Stages of evolution of modes

1. Mode crosses horizon, typically enters during neutrino diffusion or free streaming
   - (mostly ignore) - not as important as photon processing
2. Neutrino decoupling ($T \sim 1\ MeV$) – photon diffusion
3. Mode falls below photon MFP – photon free-streaming



Jedamzik, Katalaníc, Olinto, 1998

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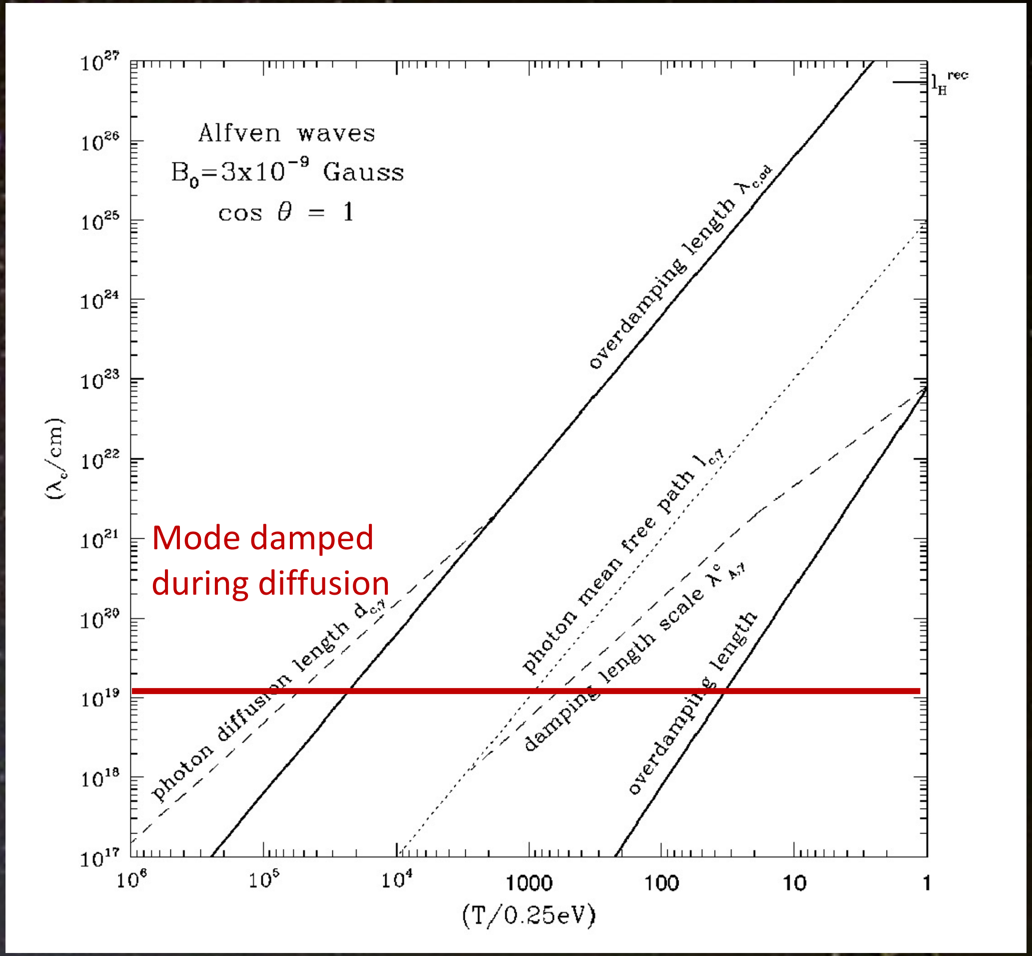

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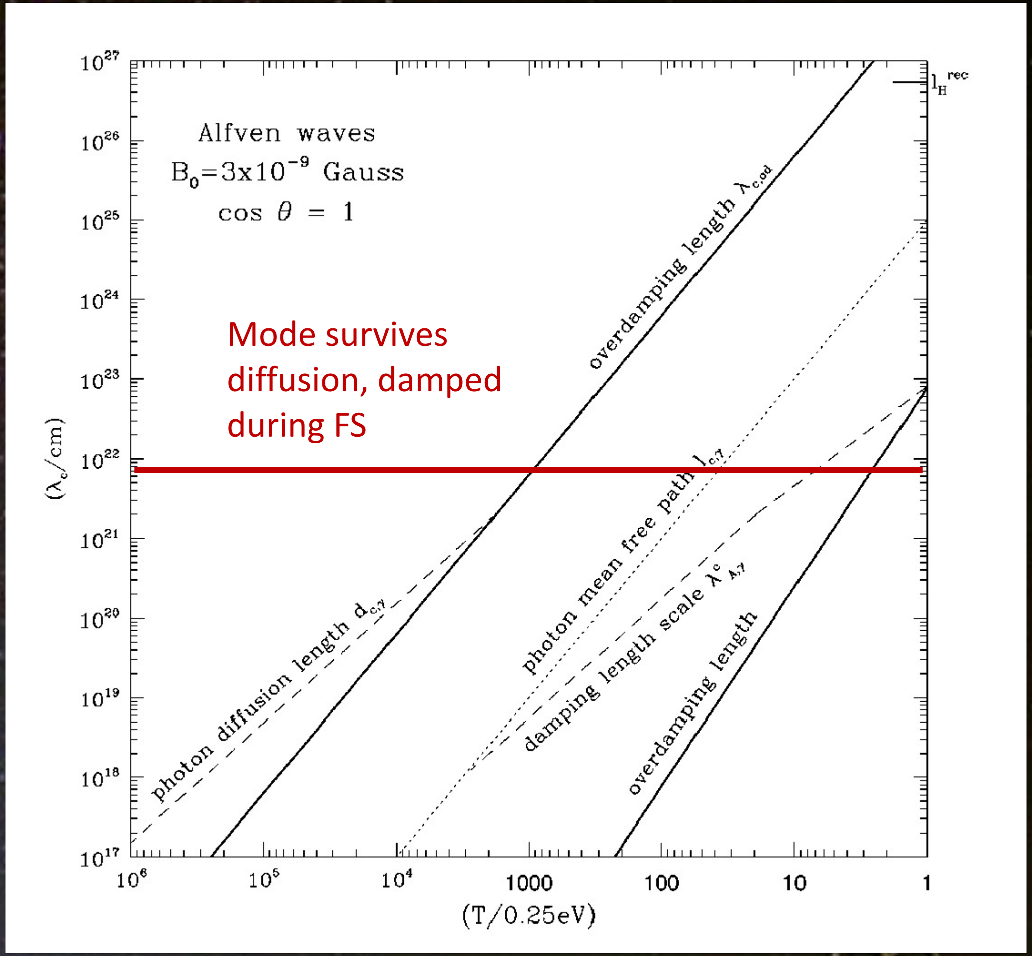

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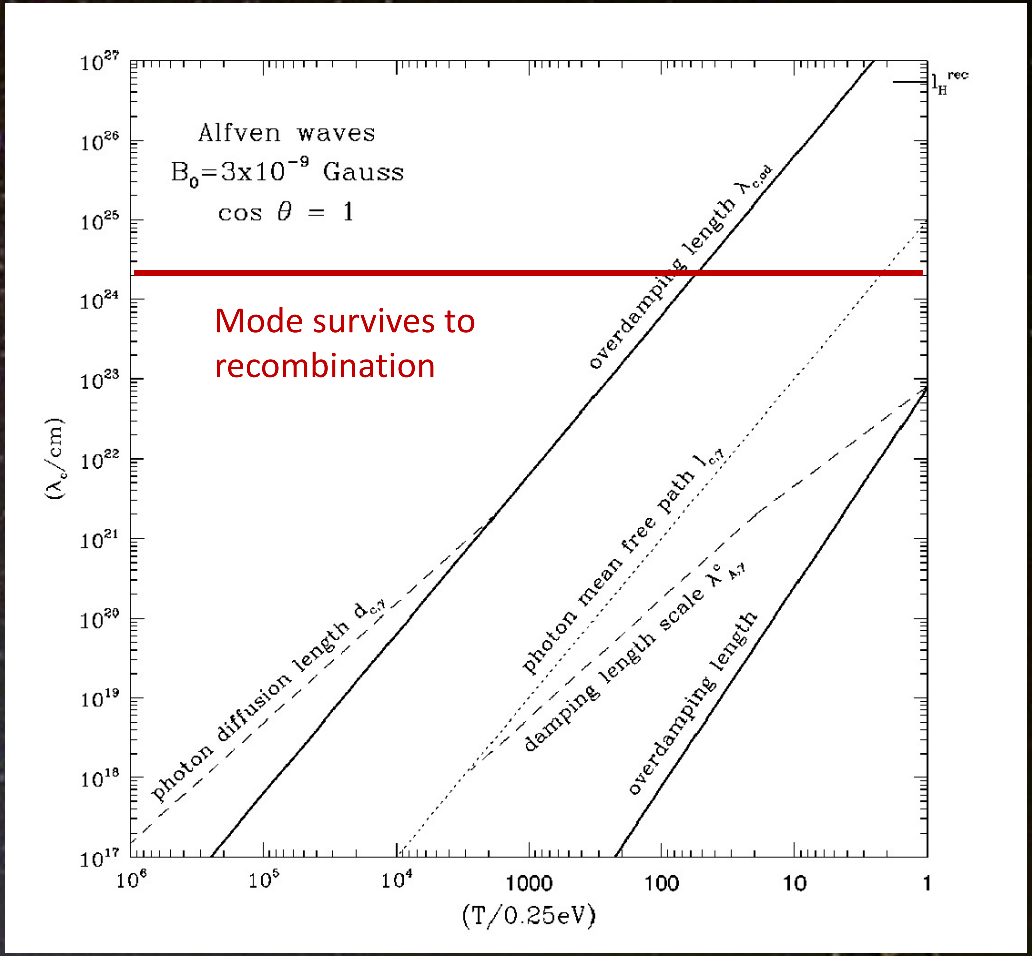


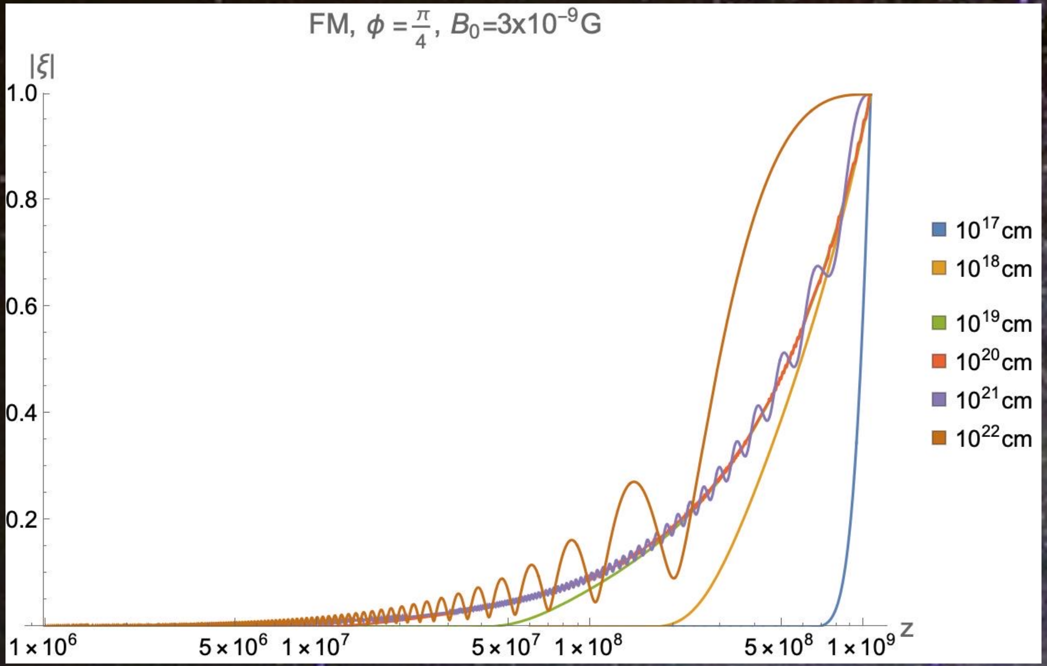
Jedamzik, Katalaníc, Olinto, 1998

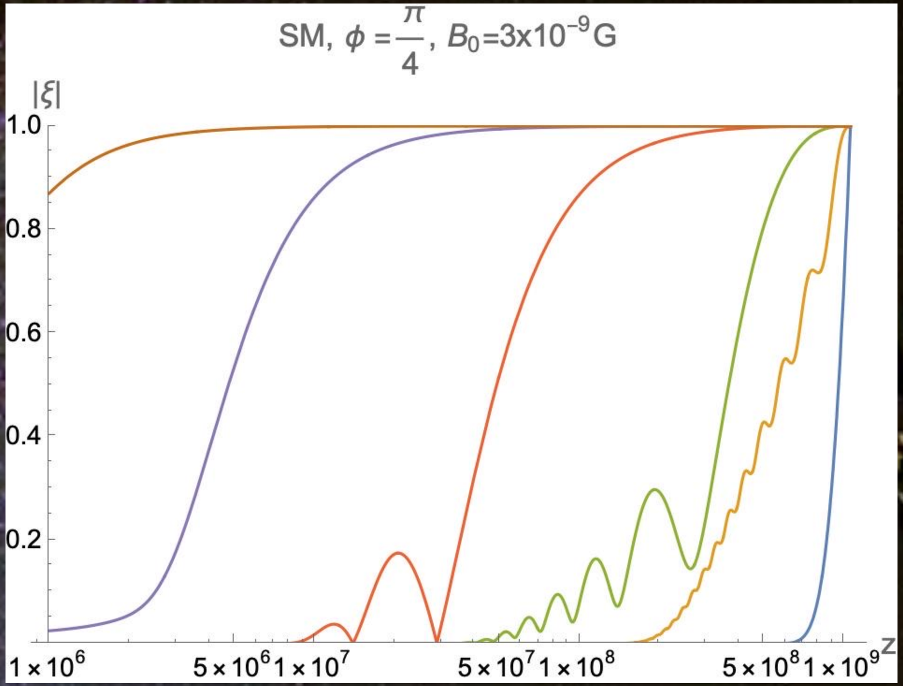
Photon diffusion regime

- Neutrino-decoupling ($T \sim 1\ MeV$): photon-diffusion regime
    - Define comoving displacement of fluid: $v = \mathrm{a}\dot{\xi}$
        - Integrate continuity and induction equation and substitute into Euler equation
            - Coupled damped harmonic oscillators for x and y displacements

Photon diffusion regime

- Neutrino-decoupling ($T \sim 1\ MeV$): photon-diffusion regime
  - Modified silk damping with PMF source

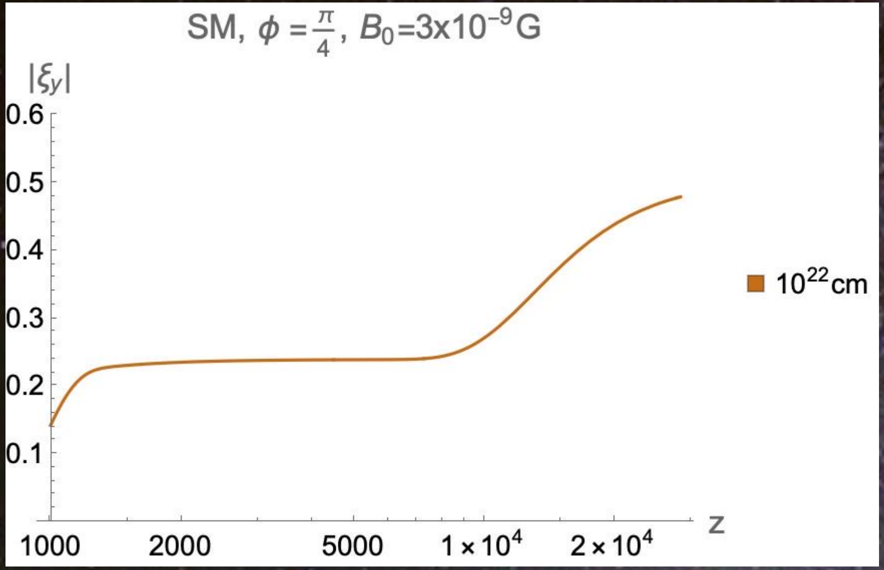


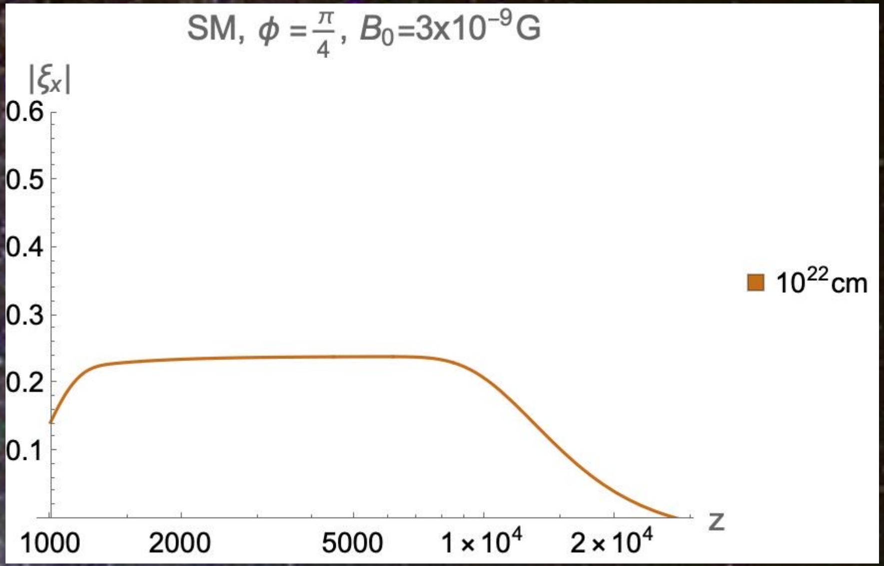


- Surviving modes are almost purely transverse
- Only compressible modes couple to matter density field (continuity equation)

Free Streaming Saha

- Mode falls below photon MFP: photon free streaming regime
  - Surviving SM modes are mostly transverse

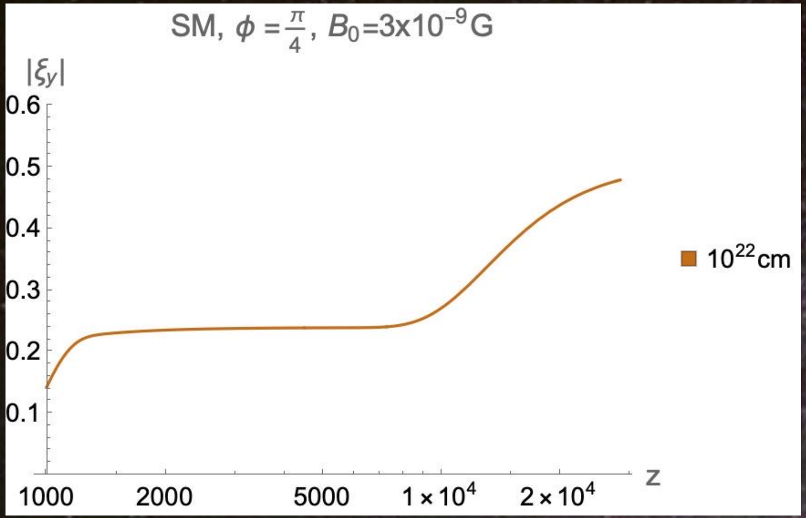


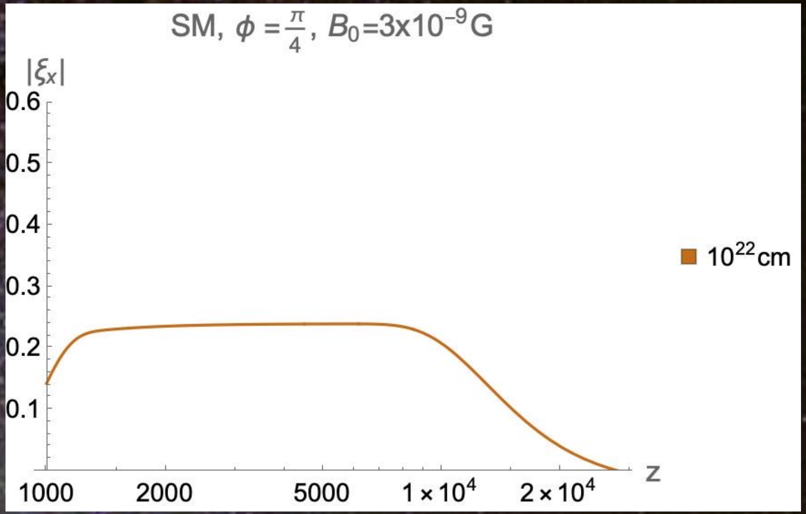


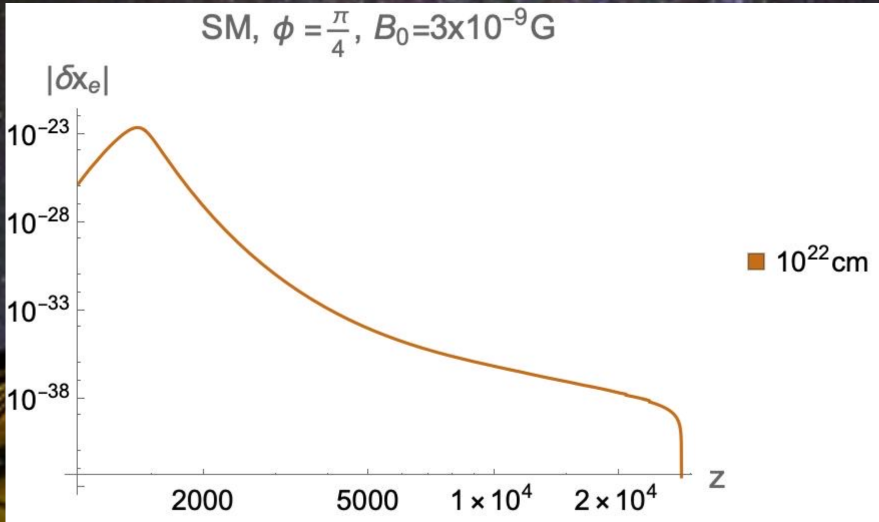
  - Power converted to compressible direction

Free Streaming Saha

- Can this significantly modify recombination?







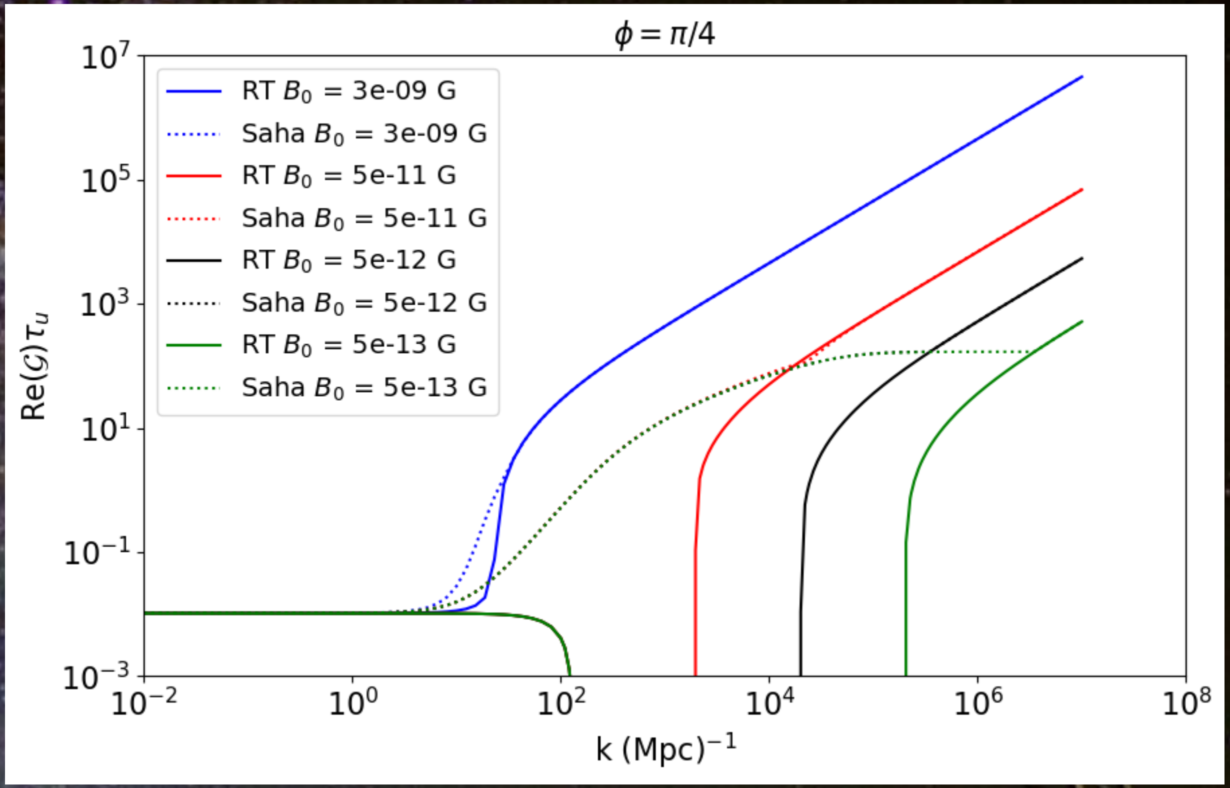
Saha vs. Radiative Transport

- Radiative transfer further suppresses growth across a wide range of length scales
  - Largest positive eigenvalue of system:

$$\dot{\vec{r}} = M\vec{r}$$

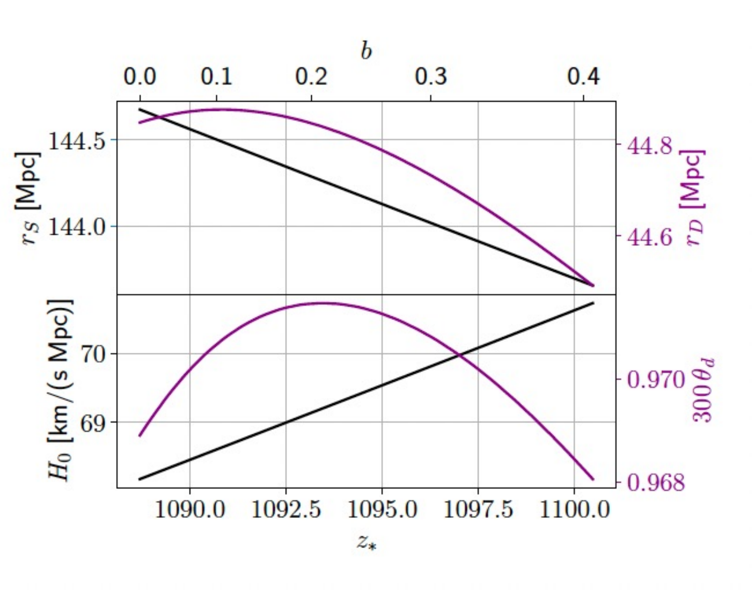
- Investigations ongoing

$z \approx 1100$

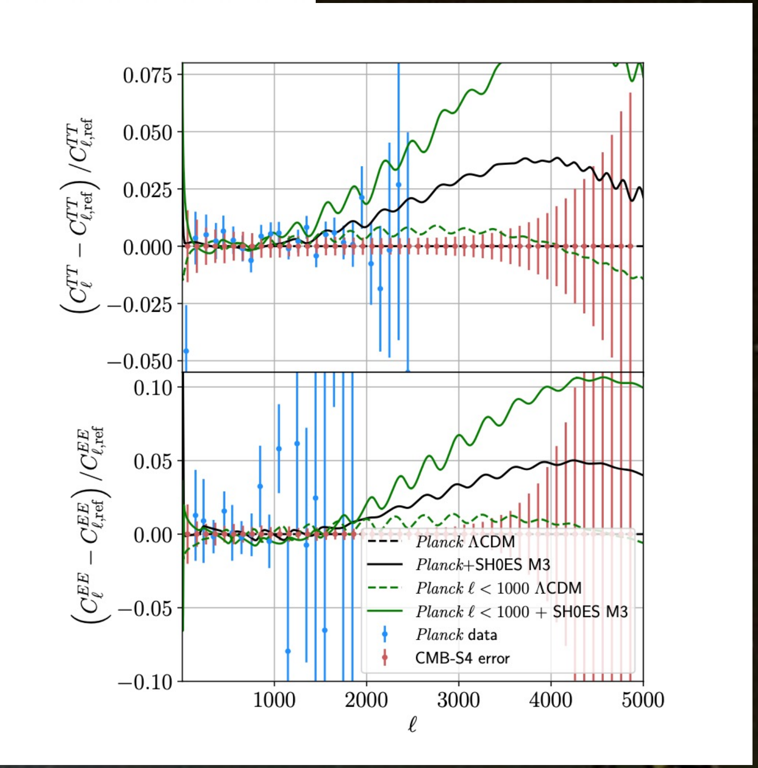


CMB constraints

- Sound horizon and damping scale respond differently to shift in surface of last scattering
- Can have differential shift in angular scale of each for a change in sound horizon
- Better damping tale data can constrain how much one can even shift recombination while respecting constraints



Rashkovetskyi, Muñoz, Eisenstein, Dvorkin (2021)



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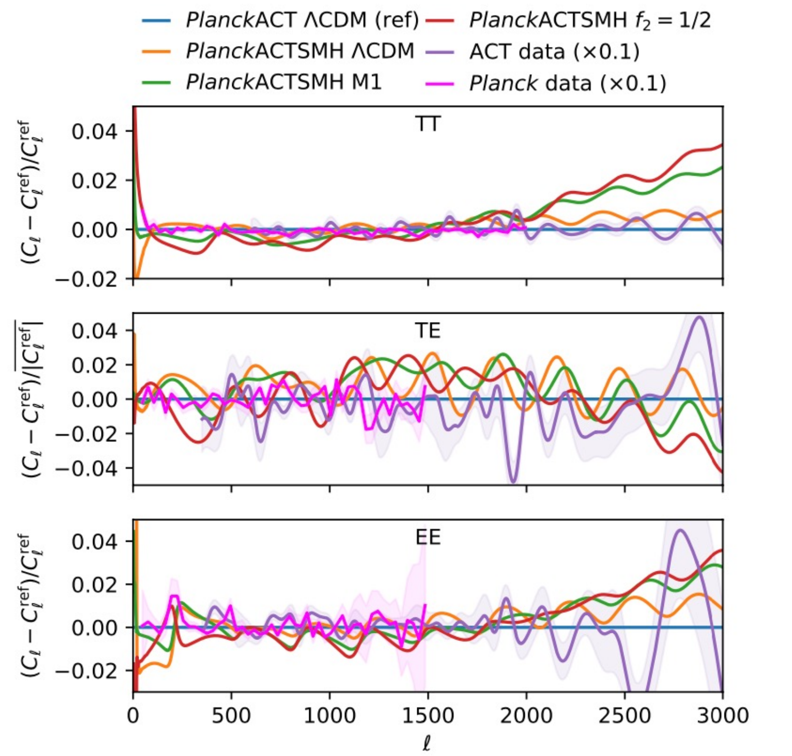
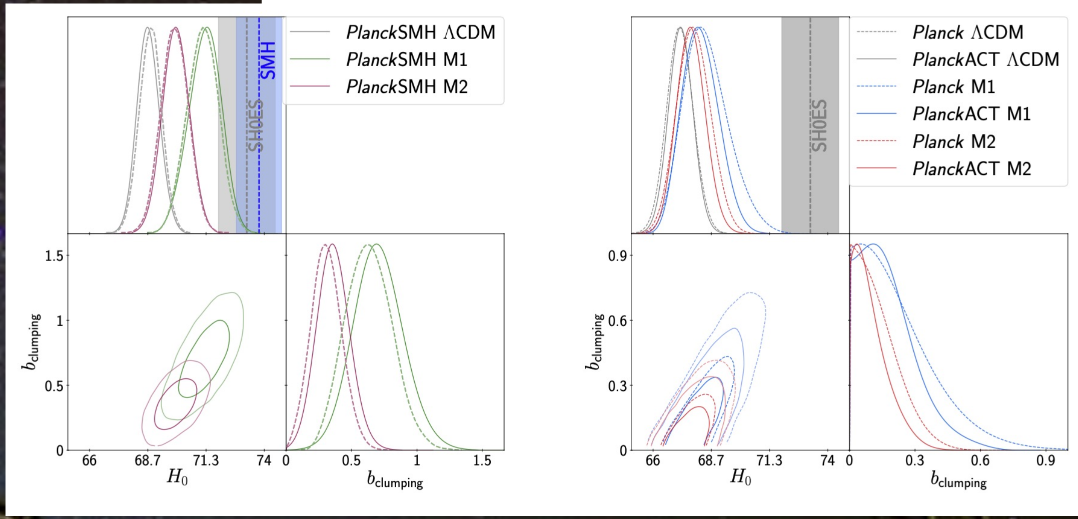
- Including ACT data to Planck likelihoods starts to disfavor models that shift recombination too much



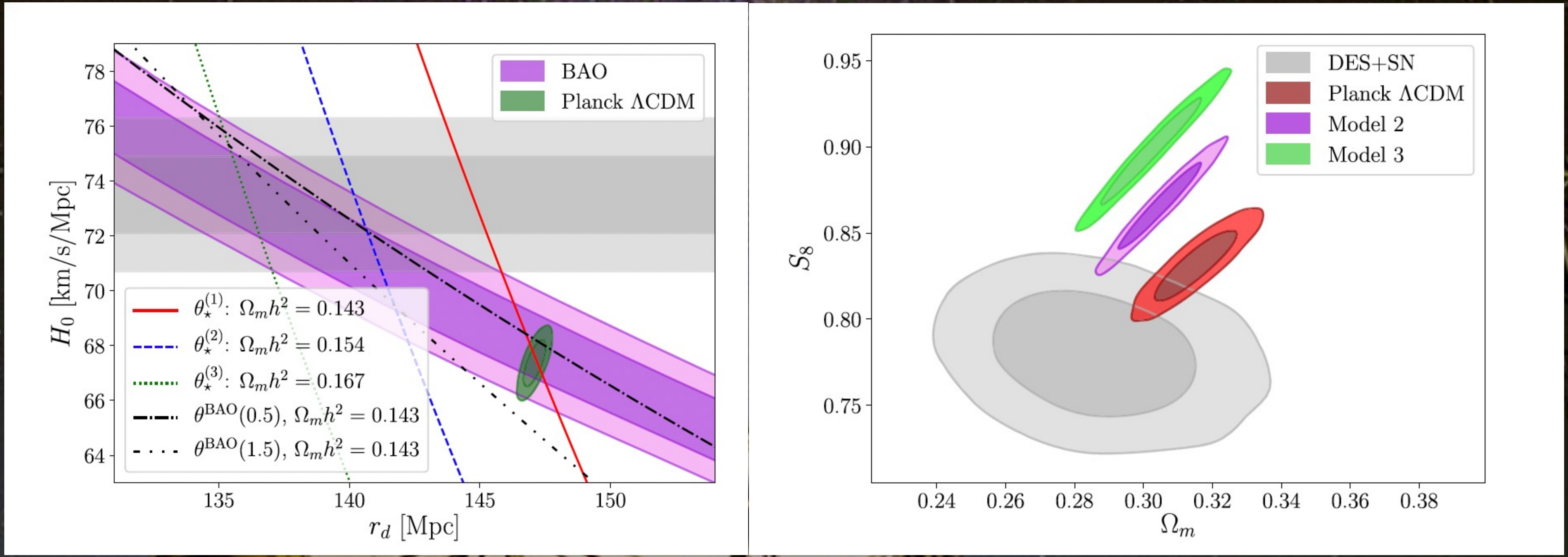


Thiele, Guan, Hill, Kosowsky, Spergel (2021)

Other constraints

- Cannot shrink sound horizon too far without worsening other S8 tension
  - $r_s - H_0$ slope fixed for given $\Omega_m h^2$
  - BAO slopes differ from CMB slope
- Currently, not possible to fully resolve the Hubble tension with a modified recombination history

Jedamzik, Pogosian, Zhao (2021)



Conclusions

- Inhomogeneities speed up recombination
- PMFs could be source of yet unaccounted for small-scale inhomogeneities that could resolve Hubble tension
- Linear perturbation theory using local recombination schemes already constrains how much one can expect to shift the surface of last scattering
- Including non-local radiative transport seems to slow down recombination
- Constraints from CMB and other cosmological probes already cast doubt on the ability of modified recombination schemes fully resolving the Hubble tension