Cosmological Probes of Absolute Neutrino Mass

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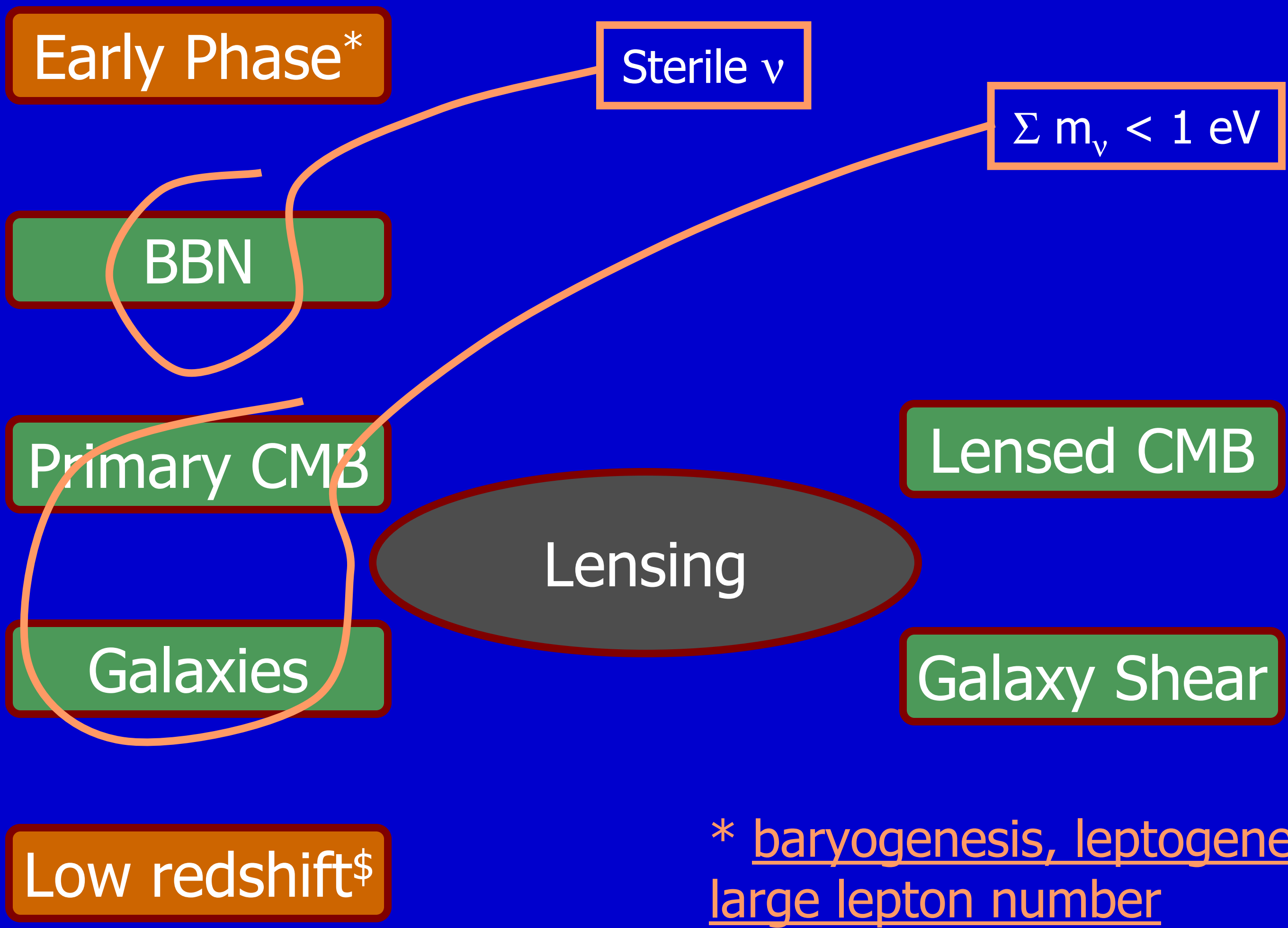
Neutrinos and Cosmology

	Cosmological Implications
How many?	Big Bang Nucleosynthesis (BBN), Cosmic Microwave Background (CMB)
What are their masses?	CMB, Large Scale Structure
How do they get massive?	BBN, CMB
Is the asymmetry large?	BBN, CMB

Massive Neutrinos and Cosmology: Outline



* baryogenesis, leptogenesis, large lepton number

$ SN ν, Relic SN ν bkgd, UHE cosmic rays (Z-burst)

Kinematic Constraints on Neutrino Mass

- Tritium decay

$$\bar{m}_{\nu_e} \equiv \sqrt{\Sigma_i |U_{ei}|^2 m_i^2} < 2\,\mathrm{eV}$$

(Mainz Collaboration, Bloom et al, Nucl. Phys. B91, 273, 2001)

- π and τ decay

$$\bar{m}_{\nu_\mu} < 0.17\,\mathrm{MeV}$$
$$\bar{m}_{\nu_\tau} < 18.2\,\mathrm{MeV}$$

WMAP constrains sum of neutrino masses to be less than 0.7 eV at 95% C.L.

Future of Laboratory Constraints

- Kinematic: KATRIN

  - Aim: $m_{\nu e} < 0.2$ eV at 95% CL.

- Double beta decay:
  - Importance: Probe whether ν is Majorana or Dirac
  - Proposed reach 0.05 eV (typical sources ~ 1 ton)
  - Many proposals: CUORE, EXO, GENIUS, MAJORANA, MOON, …
  - Different experiments ➔ Different nuclei ➔ Better handle on nuclear matrix element
  - Issue: Nuclear matrix element uncertain
  - Issue: Other new physics can lead to $0\nu 2\beta$

The Mass Window

- Super-Kamiokande, K2K (Atmospheric ν_μ oscillations)
  - $\delta m^2 \sim (0.07\ \text{eV})^2$
  - Mixing ~ Maximal

- At least one active neutrino with mass between 50 milli-eV and about 0.5 eV.

- Picture could change (mass schemes could) if LSND experiment is verified.

Massive Neutrinos and Cosmology: Outline

Early Phase*

Sterile ν

$\Sigma m_\nu < 1$ eV

BBN

Primary CMB

Lensed CMB

Lensing

Galaxies

Galaxy Shear

Low z$

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Neutrinos and Big Bang Nucleosynthesis

Increase N_ν

Speed-up Expansion rate

Larger n/p

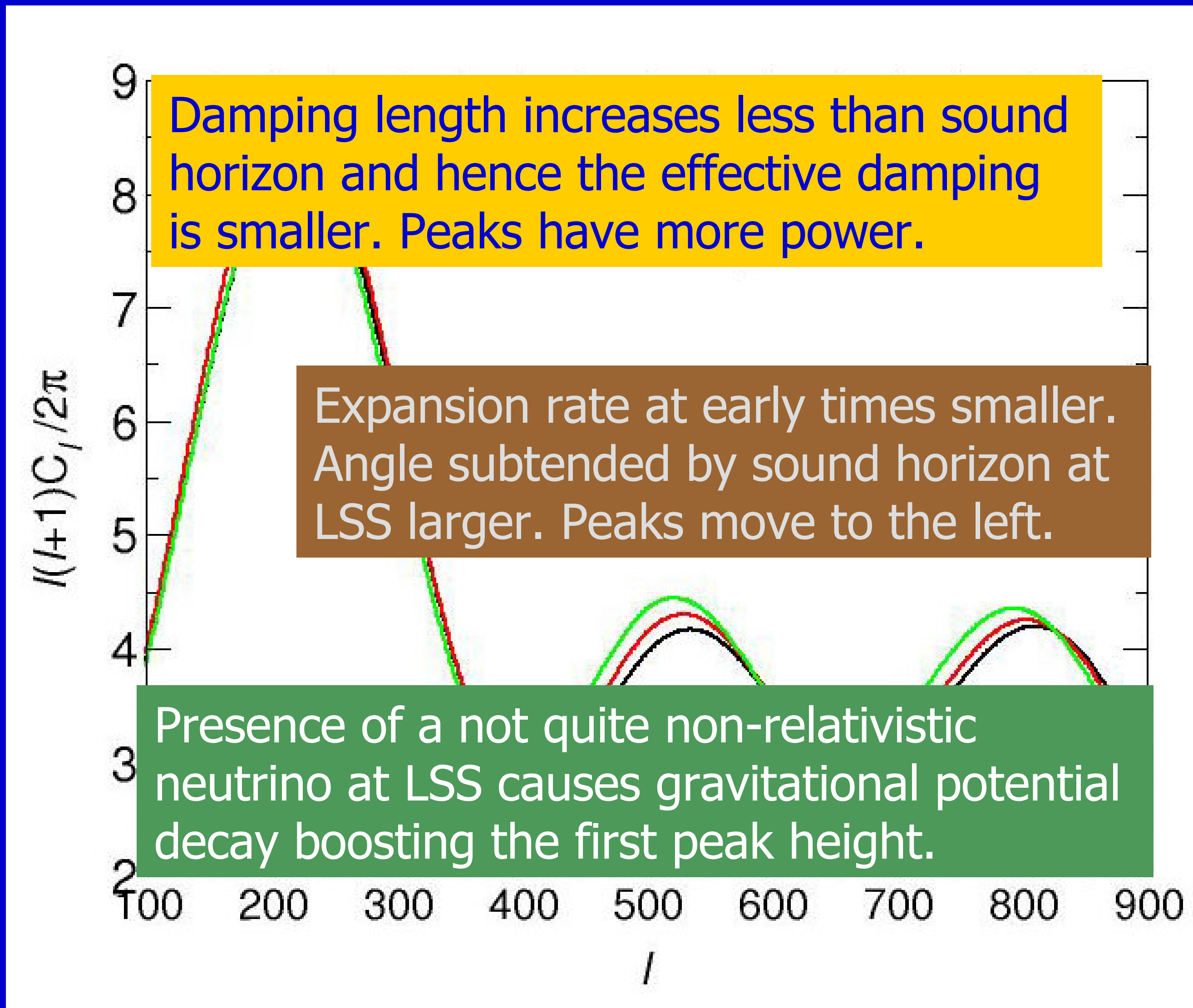
^{4}He and D/H increase

$1.7 < N_\nu < 3.5$ (95%) $\Rightarrow$ sterile ν (if it exists) must not thermalize.

Both 2+2 and 3+1 schemes disfavored.

K. N. Abazajian, Astropart. Phys. 19 (2003) 303

Massive Neutrino and Primary CMB



Neutrino Mass from Galaxies

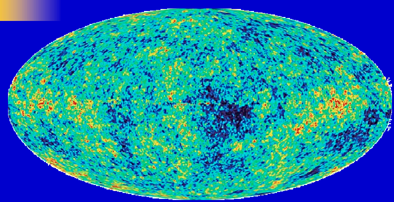
- The matter power spectrum measured using galaxy surveys can be used together with CMB experiments to determine the neutrino mass. Sloan Digital Sky Survey and WMAP together can measure the neutrino mass at 2σ if

$$m_\nu > 0.65\,\mathrm{eV}\left(\frac{\Omega_m h^2}{0.1N}\right)^{0.8}$$

where N is the number of neutrinos with degenerate mass m_ν.

Hu, Eisenstein and Tegmark, PRL 80 (1998) 5255

State of the Art



WMAP

Galaxy PS and bias, Lyα PS

Galaxy PS and bias

- WMAP+CBI+ACBAR+2dFGRS PS and bias gives

  $m_\nu < 0.24$ eV at 95% C.L. (Spergel et al 2004)

- WMAP+SDSS galaxy PS gives

  $m_\nu < 0.51$ eV at 95% C.L.

- WMAP+SDSS galaxy PS and bias+SDSS Lyα gives

  $m_\nu < 0.14$ eV at 95% C.L.

  (Seljak et al 2004, astro-ph/0407372)

Degeneracy

- Number of relativistic degrees of freedom or "number of neutrinos" labeled N_ν. For WMAP, allowing a free N_ν changes the 95% C.L. constraint to $m_\nu < 0.33$ eV (compared to 0.23 eV). $\sigma(N_\nu)$ is about unity when constrained along with m_ν.

  (Hannestad, 2003 astro-ph/0303076)

- Running of the scalar spectral index

- These will not be issues if we can get precise information about the primary CMB on small scales.

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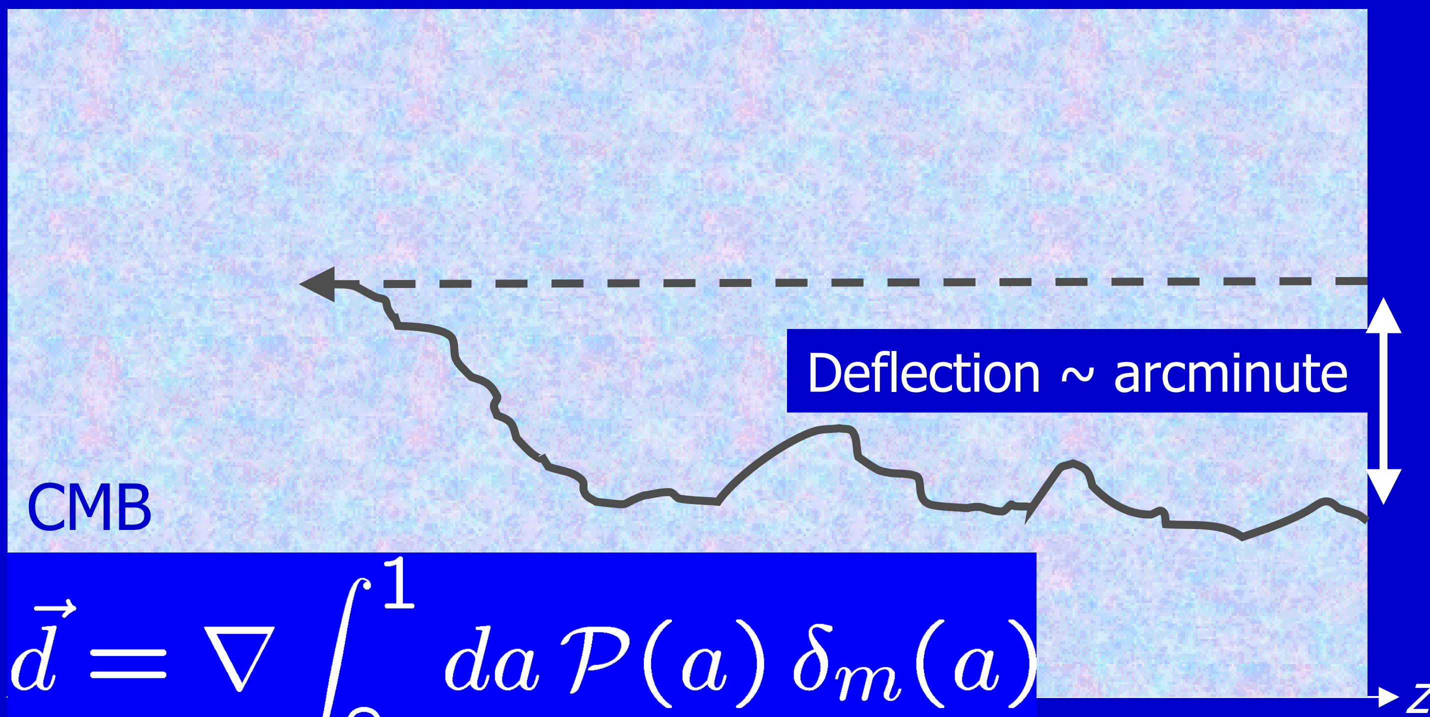
Effect of Lensing

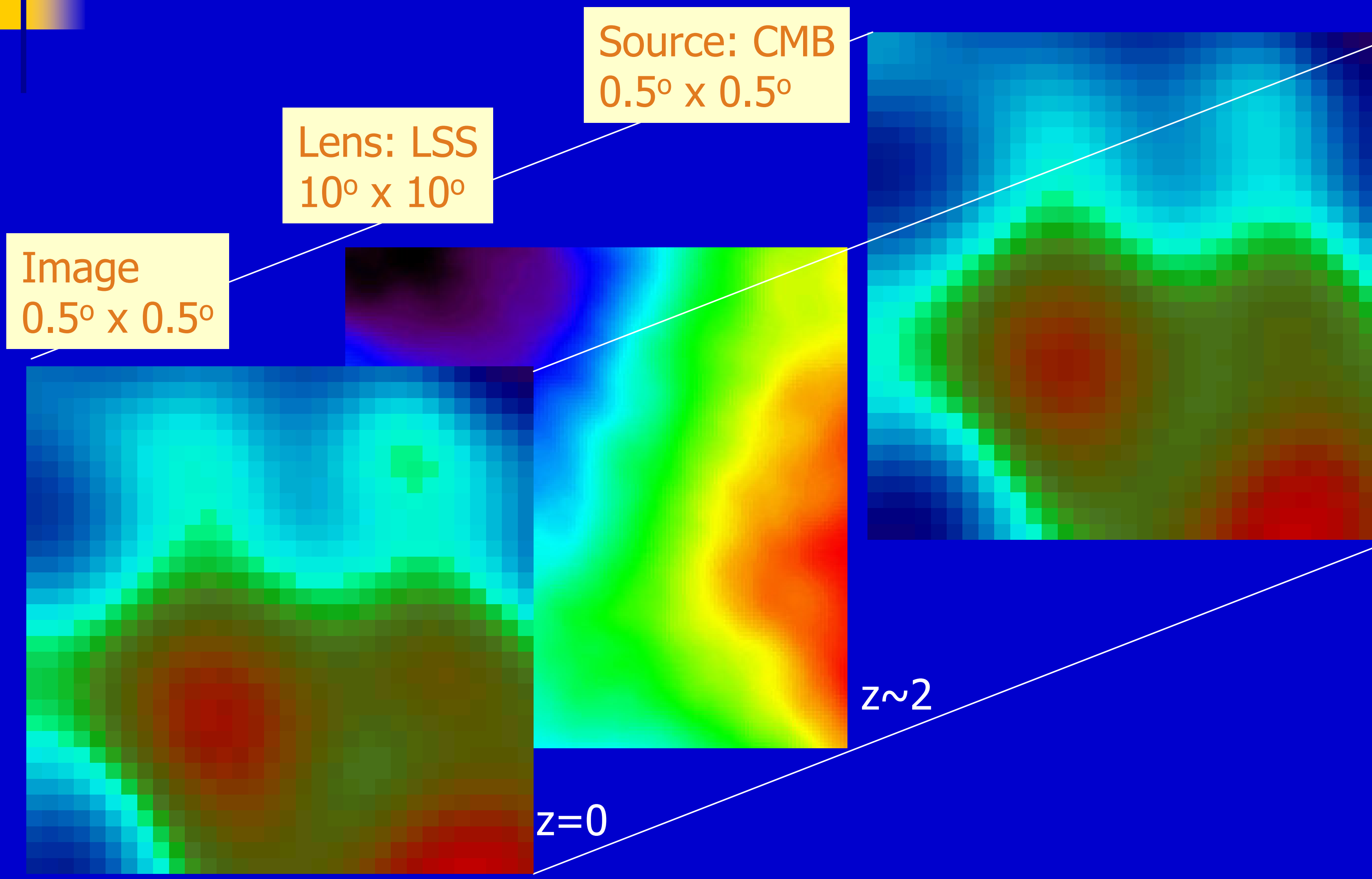


$$\vec{d} = \nabla \int_0^1 da\, \mathcal{P}(a)\, \delta_m(a)$$

Weak lensing of galaxies

Distortion matrix : $\nabla_i d_j$

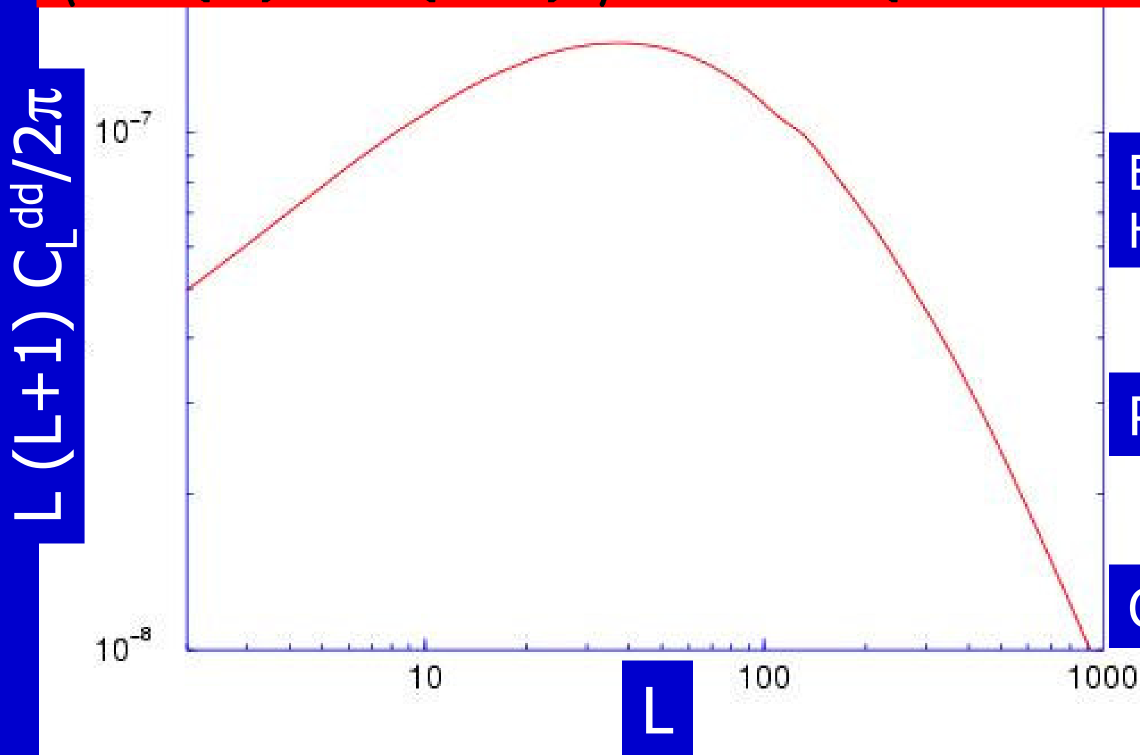
Lensing of the CMB



Coherence of CMB Lensing Deflection

$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$

$$\langle T(\vec{l})T(\vec{l}\,')\rangle \propto \vec{d}(\vec{l} - \vec{l}')$$



Estimate **d** from CMB maps
Hu and Okamoto, 2002

Peak sensitivity ~ z=2

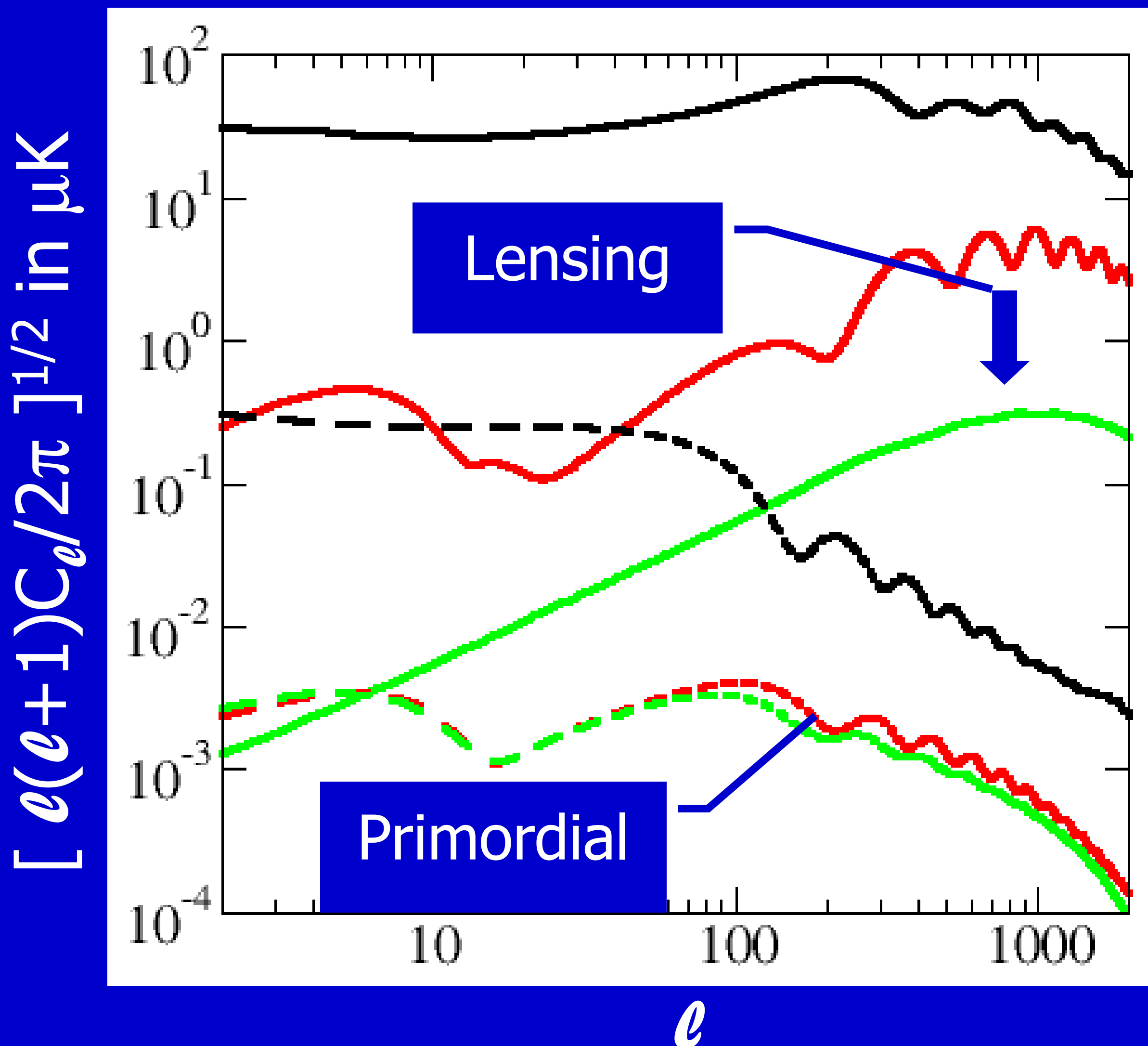
Coherence ~ 10 deg

Spectra

Black: TT
Red: EE
Green: BB

Solid: Scalar
Broken: Tensor

T/S = 10^{-4}



Jeans Instability for Neutrinos

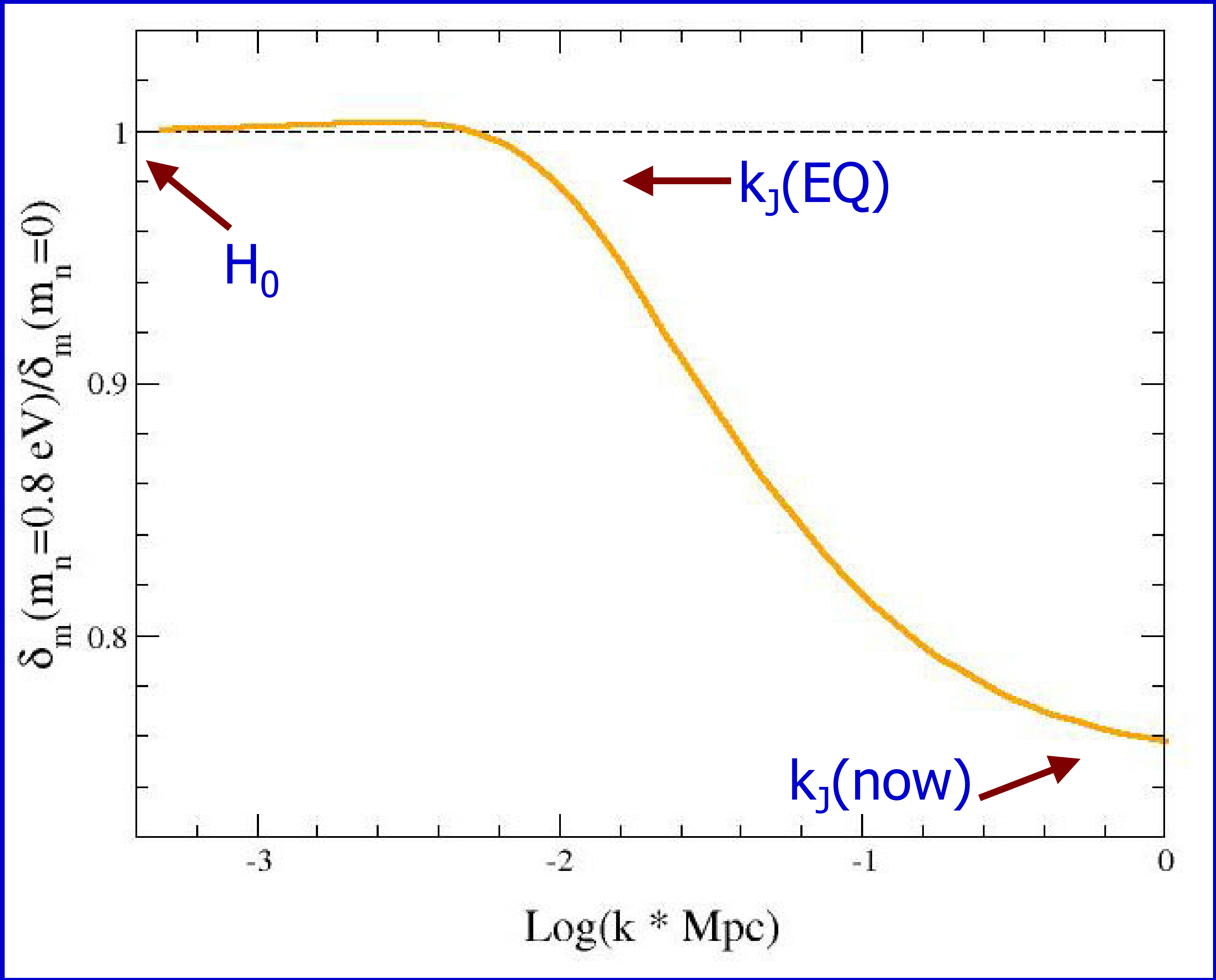
Neutrino perturbations on length scales larger than the Jeans length become unstable and collapse into dark matter potential wells.

$$\lambda_J(z) = \frac{v_\nu(1+z)}{\sqrt{4\pi G\rho_m}}$$

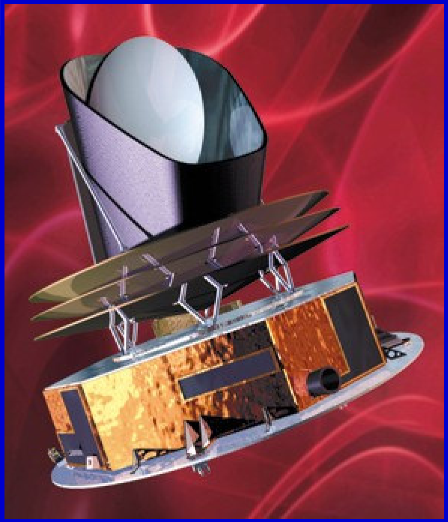
Bond and Szalay, ApJ 274, 443 (1983)
Hu and Eisenstein, ApJ 498, 497 (1998)

$$\lambda_J(z_{\mathrm{EQ}}) \sim 60\,\mathrm{Mpc}$$
$$\lambda_J(0) \sim 1\,\mathrm{Mpc}$$

Massive Neutrino and Matter Power Spectrum



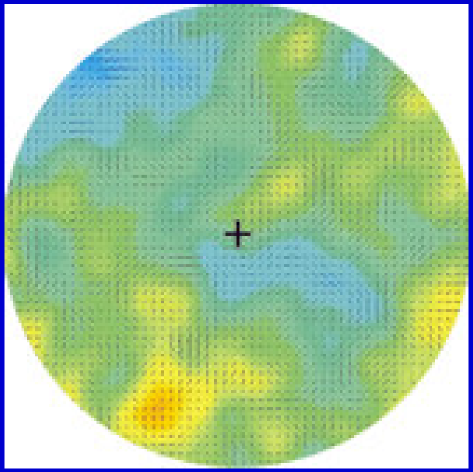
Prospects: CMB



Planck

- 100, 143 and 217 GHz channels

$\sigma(m_\nu) = 0.15$ eV



EPIC

- 1 μK per pixel
- Angular resolution 3 arcminutes
- Full Sky
- One channel at 217 GHz

$\sigma(m_\nu) = 0.05$ eV

Kaplinghat, Knox and Song, PRL 2003

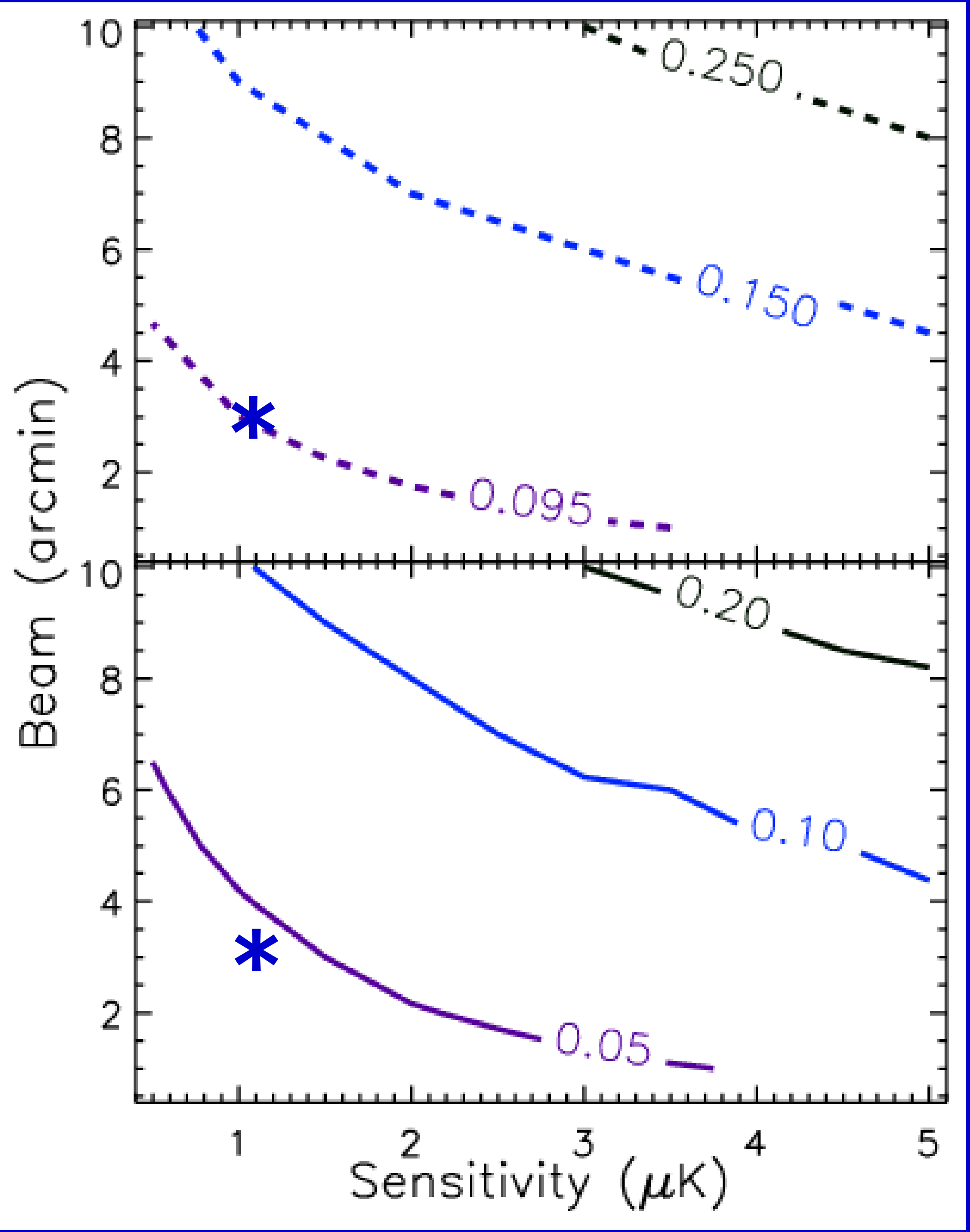
Neutrino

Top panel: $\sigma(N_\nu)$
Contours at 0.095, 0.15 and 0.25

Bottom panel: $\sigma(m_\nu)$
Contours at 0.05 eV, 0.1 eV and 0.2 eV

0.05 eV < Sum of active neutrino masses < 1 eV

* EPIC



Fundamental Physics with Future CMB Data Alone

Of Direct Relevance to Inflation:

- Gravity waves from Inflation.
- Precision measure of the amplitude of the scalar perturbations to 1%.
- Tilt and its variation with scale. Vital for differentiating between models of inflation.

Others:

- Detect the acceleration of the universe at perhaps 3σ independent of supernova Ia observations.
- Map reionization history.
- Precision cross-checks with BBN.

Kaplinghat, Knox and Song, PRL 2003

Secondary Science Goals and foregrounds

- To clean the scalar (lensed) B mode signal one would need to go down to about 5 arcmin resolution (perhaps lower). Secondary science goals listed above (and perhaps others) would then come for free. No need to optimize the experiment for secondary science goals.

- Could build an experiment sensitive only to the large angle signal for measuring primordial B modes. This would not be wise.

Prospects: Cosmic Shear

- With a deep survey over 10% of the sky, it is possible to constrain the mass of a single massive neutrino with a precision of

$$\sigma(m_\nu) = 0.1\,\mathrm{eV}$$

- Lensing tomography also provides an independent test of the acceleration of the universe

$$\sigma(w) = 0.1$$

Abazajian and Dodelson, 2003
Song and Knox, 2003

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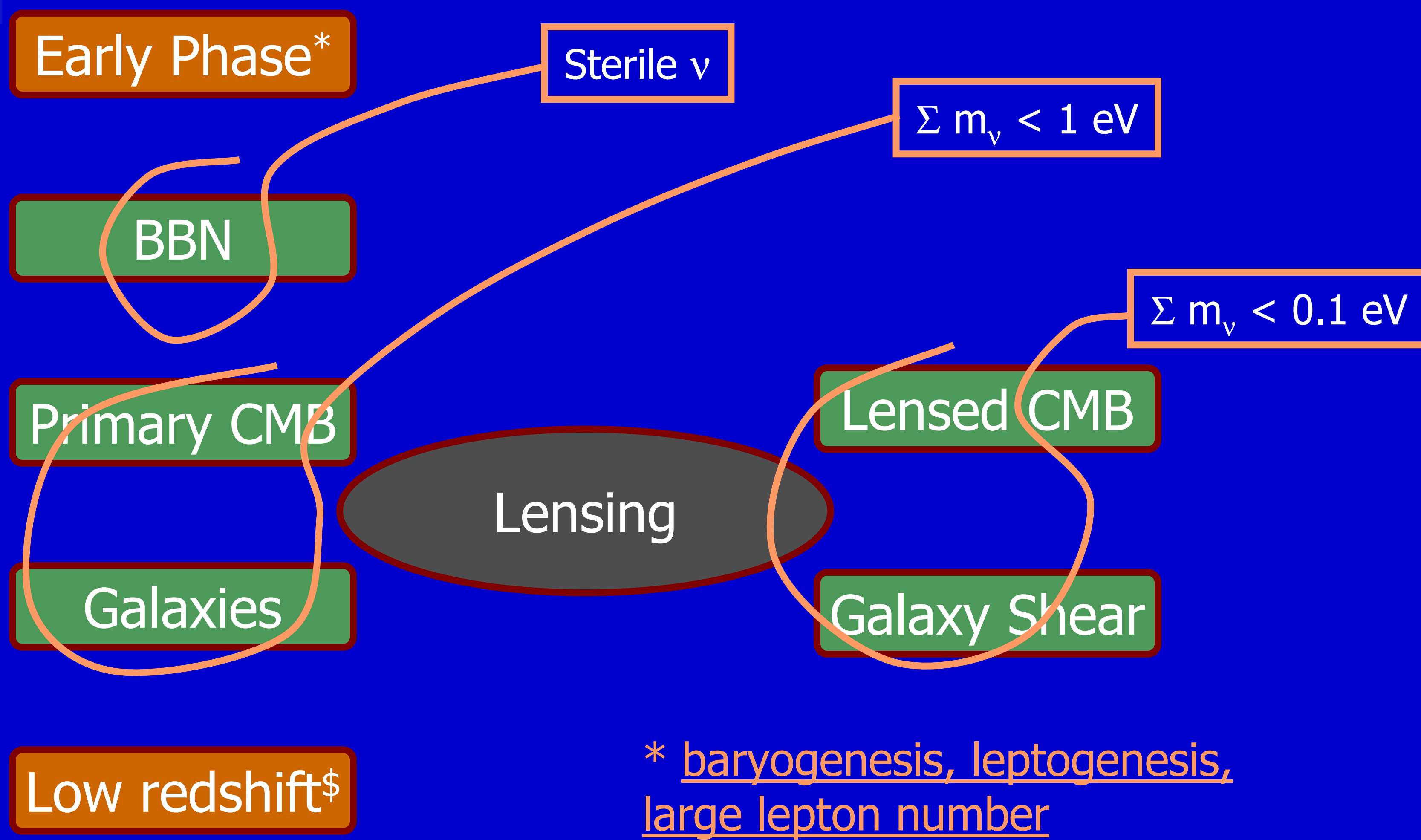

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