Gravitational Lensing of Cosmic Neutrino Background

Lin & Holder (arXiv:1910.03550)

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In collaboration with Gilbert Holder

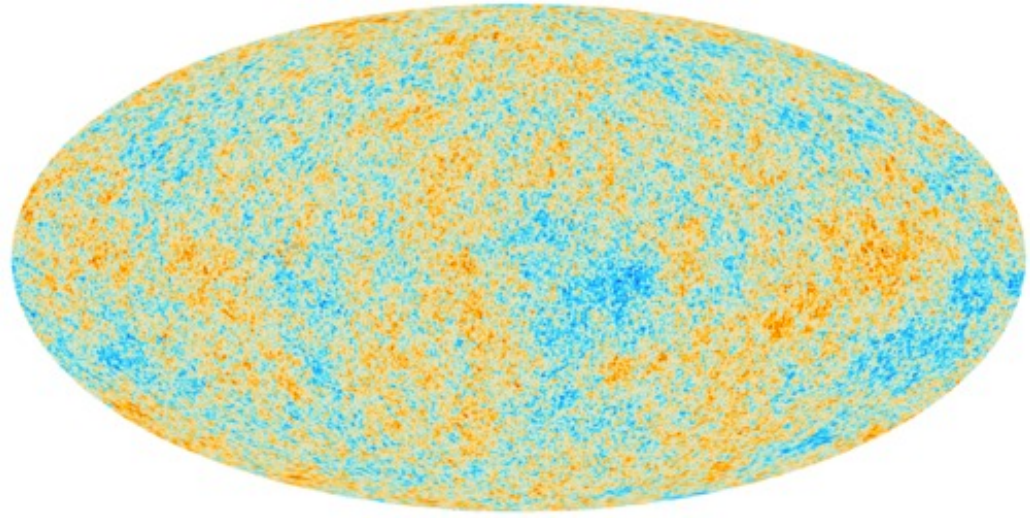
2019.10.9 Topics in Cosmic Neutrino Physics @FermiLab

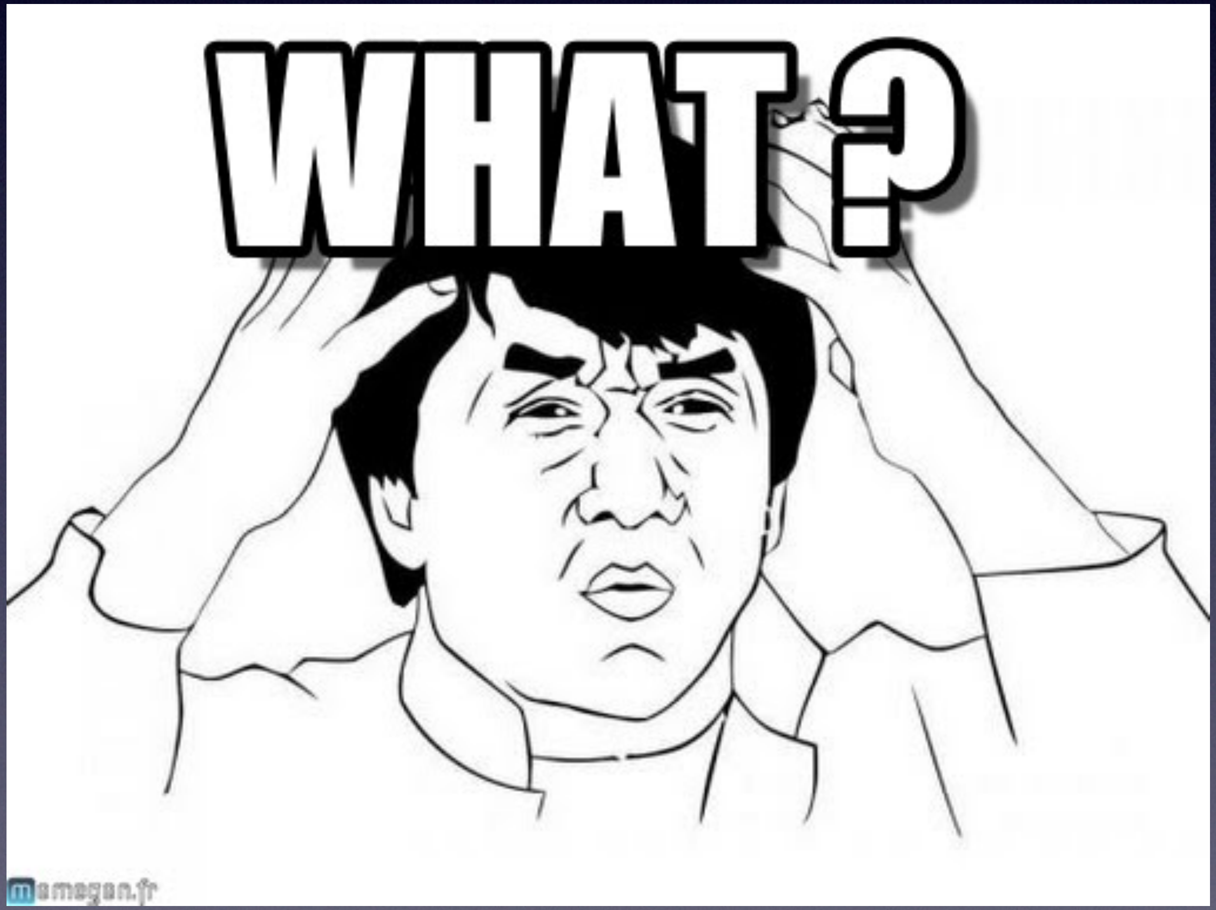
Lensing of CνB vs CMB

Similar:

Difference:

- Both (shall) have anisotropy and would be lensed by foreground gravitational potential





Thought Experiment!

Lensing of CνB vs CMB

Similar:

- Both (shall) have anisotropy and would be lensed by foreground gravitational potential

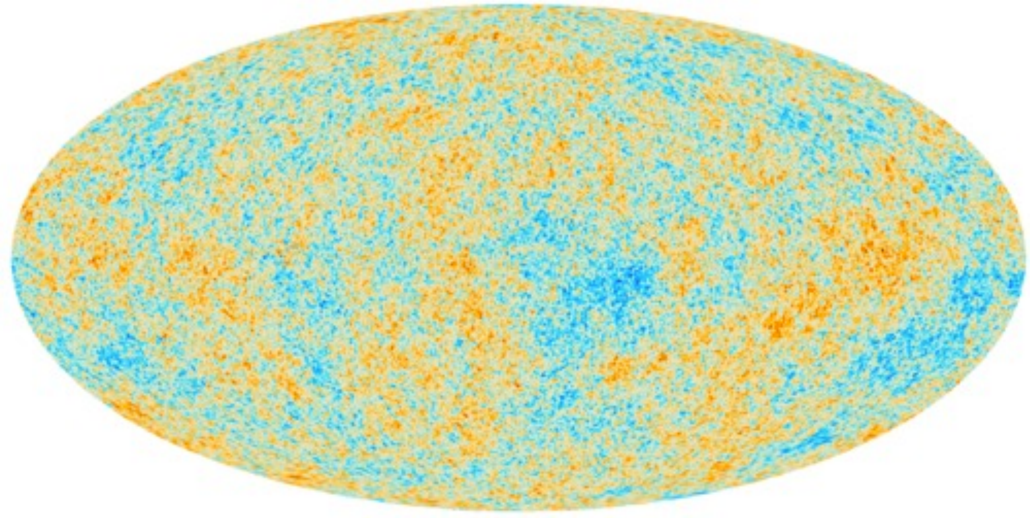
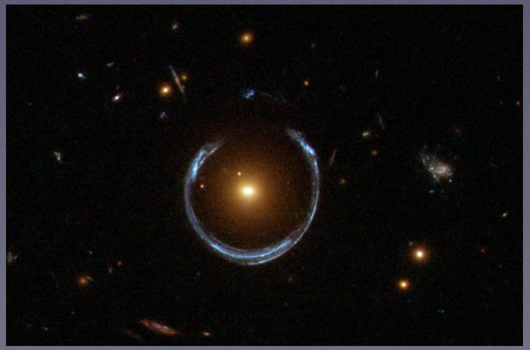


Image Credit: 1) Planck
2) ESA/NASA, Hubble



Difference:

- Neutrinos from the early universe will be non-relativistic today (massive neutrinos)
- Larger angles of deflection
- Closer surface of last scattering (compared to the cosmic microwave background)
- Could form multiple lensed images **[Strong gravitational lensing]**

Cosmic Neutrino Last Scattering Surface

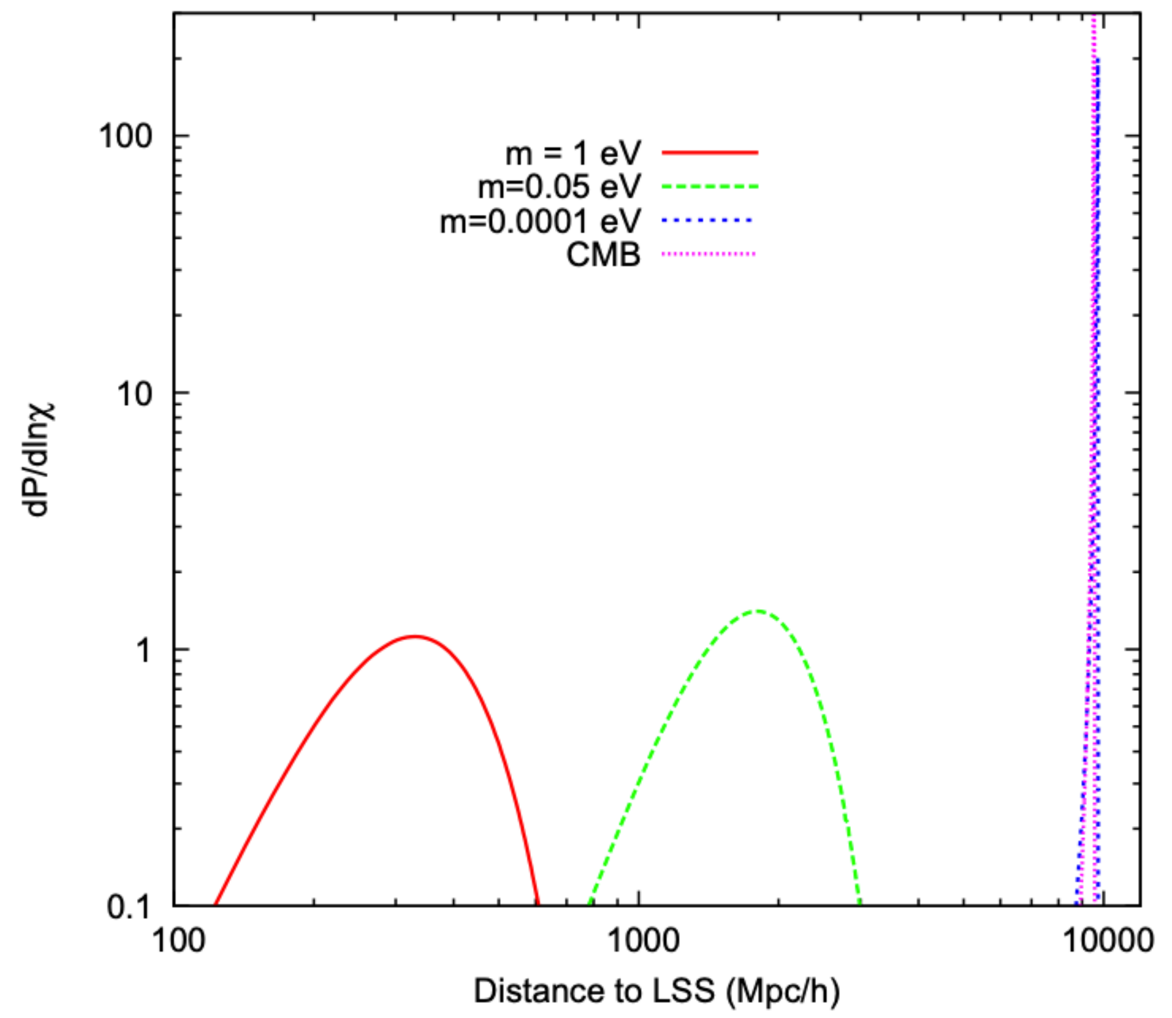


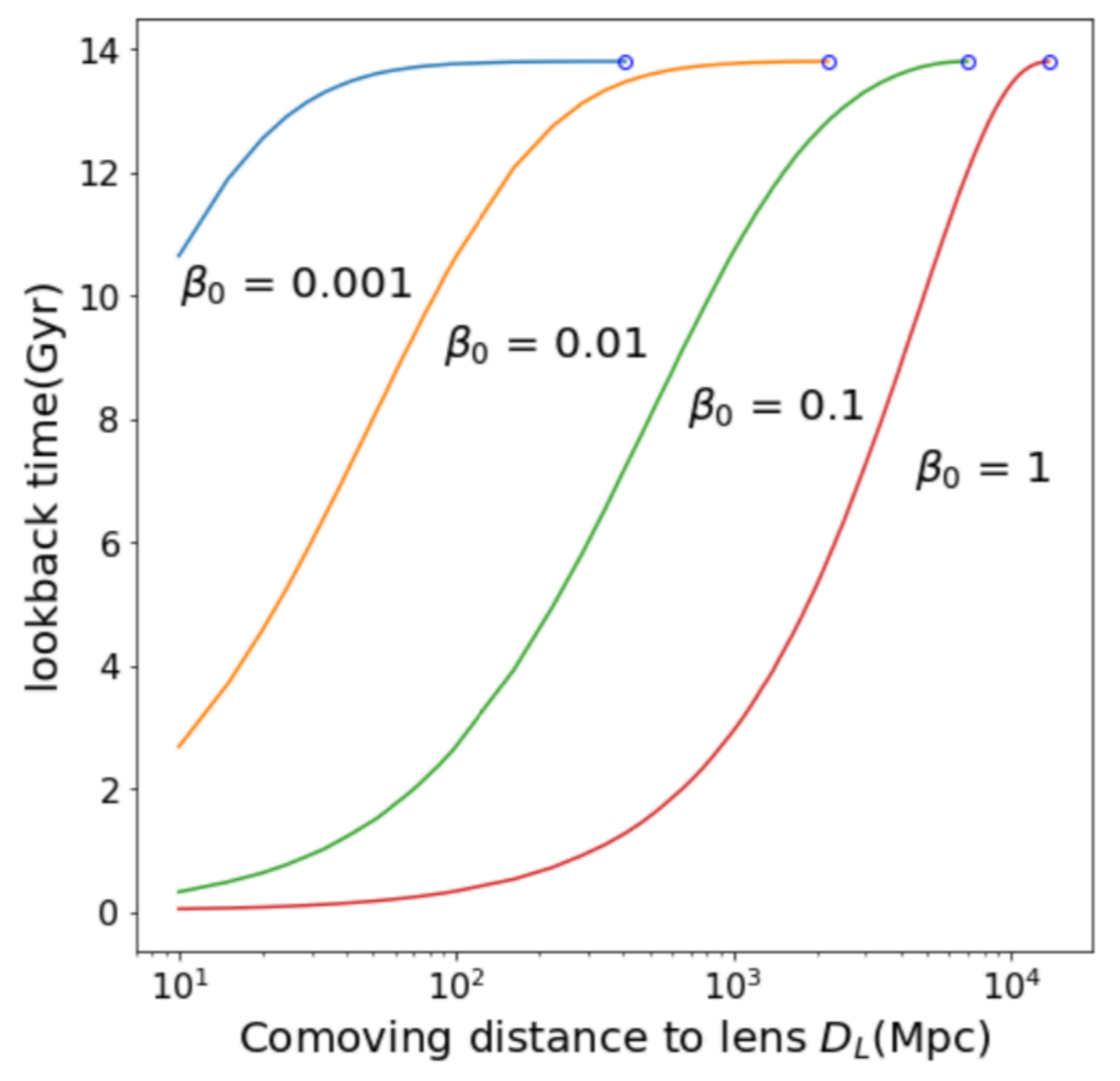
FIG. 2: The probability that a neutrino with mass m last scatters at a given comoving distance from us (the visibility function). Massive neutrinos travel more slowly than massless neutrinos so arrive here from much closer distances. Also shown is the last scattering surface of the cosmic microwave background, virtually indistinguishable from that of an $m_\nu = 10^{-4}$ eV neutrino.

$$v(a) = \frac{v_0}{\sqrt{a^2 + \frac{v_0^2}{c^2}(1 - a^2)}}$$

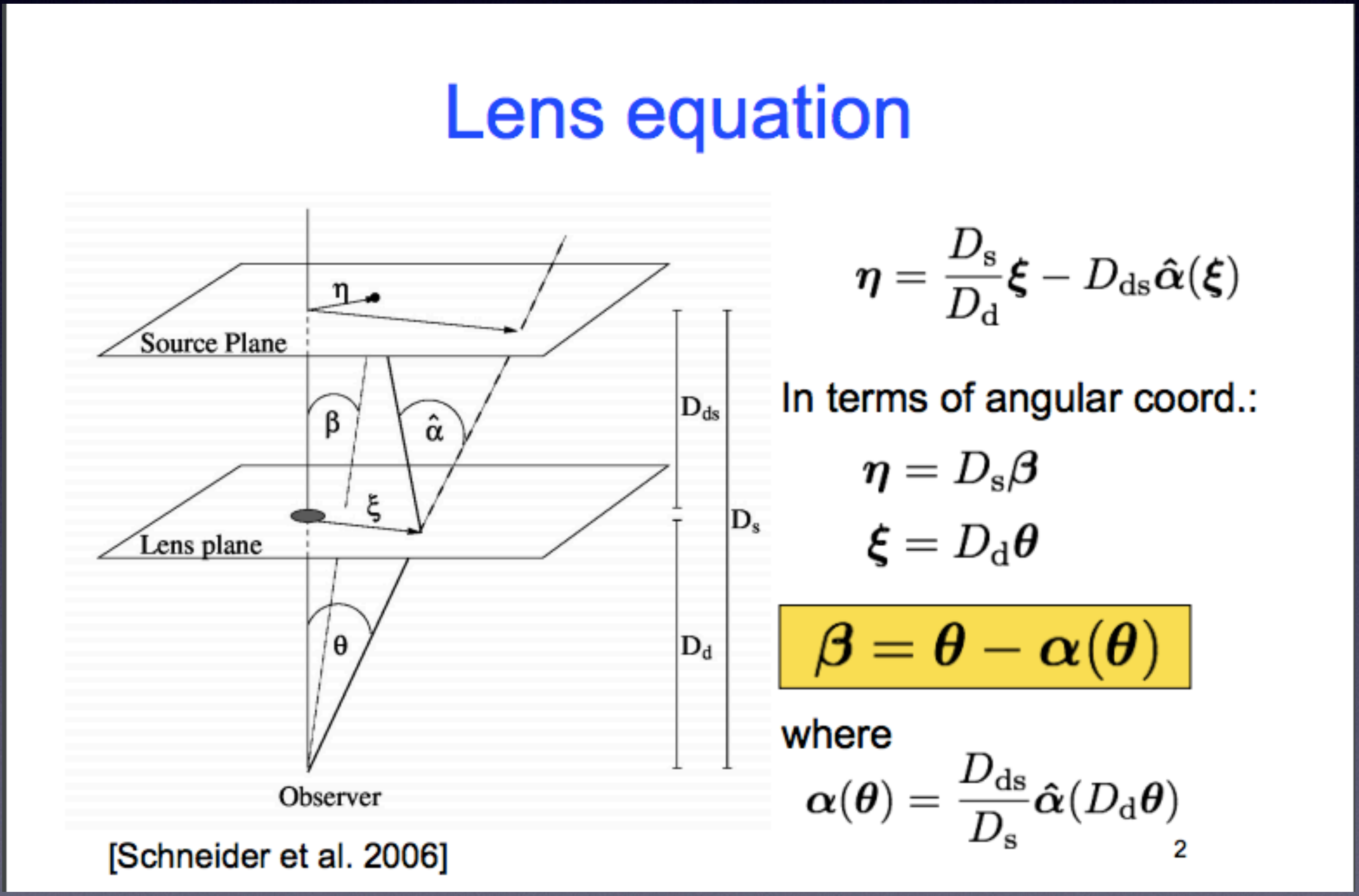
$$D_S(v_0) = \int_{a_s}^{1} \frac{da}{a^2 H(a)} v(a)$$

Dodelson & Vesterinen (PRL, 2009)

Cosmic Neutrino Last Scattering Surface



Strong lensing of cosmic neutrino



Lens equation

$$\boldsymbol{\eta} = \frac{D_s}{D_d}\boldsymbol{\xi} - D_{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

In terms of angular coord.:

$$\boldsymbol{\eta} = D_s\boldsymbol{\beta}$$

$$\boldsymbol{\xi} = D_d\boldsymbol{\theta}$$

$$\boxed{\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})}$$

where

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{D_{ds}}{D_s}\hat{\boldsymbol{\alpha}}(D_d\boldsymbol{\theta})$$

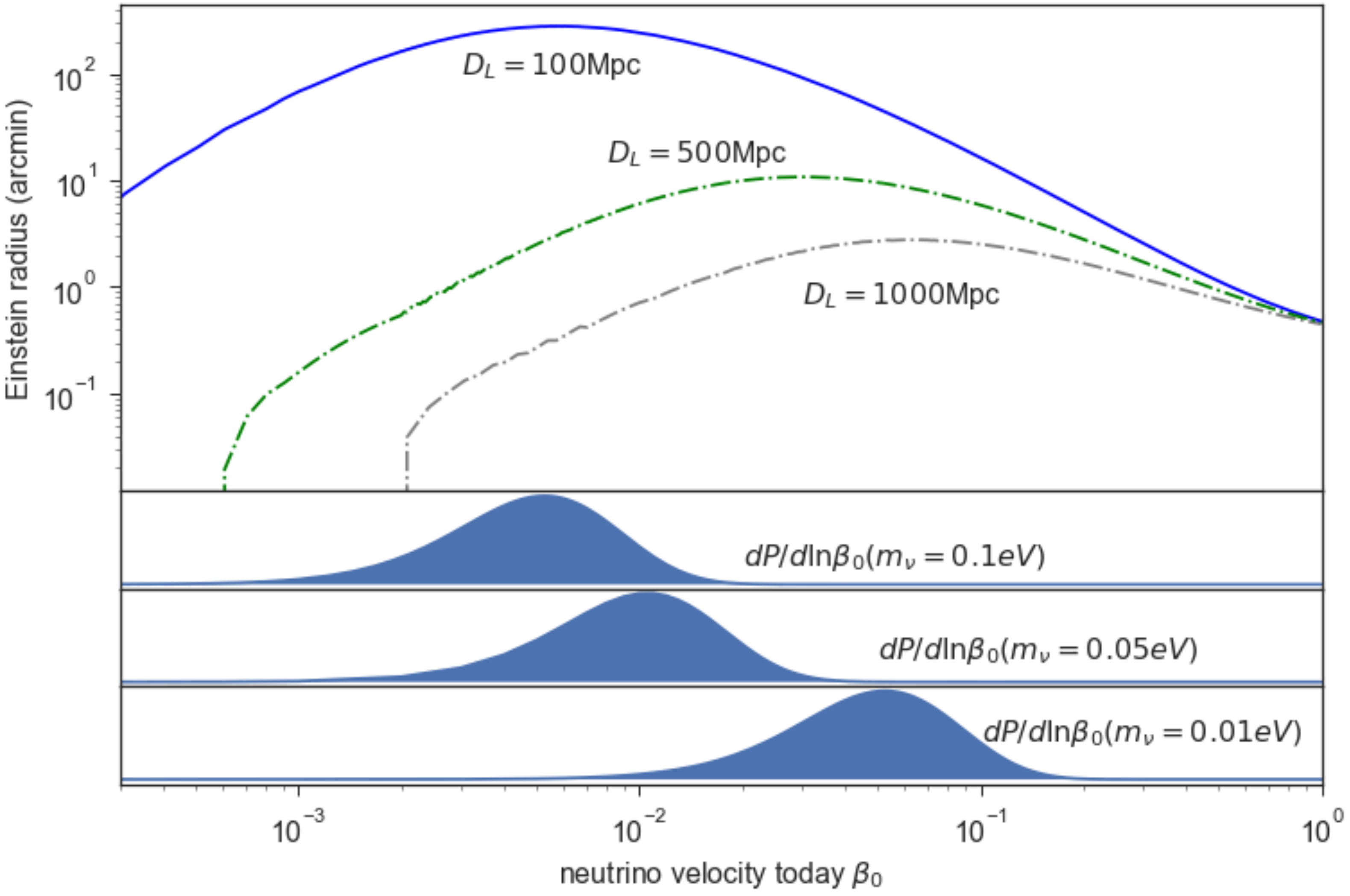
[Schneider et al. 2006]

Slides credit: Sherry Suyu

- Angle of deflection for cosmic neutrino (post-Newtonian)

$$\alpha(R) = \frac{4GM(R)}{Rc^2}\frac{c^2 + v_{lens}^2}{2v_{lens}^2},$$

Einstein Radius: function of neutrino velocity/ Distance to Lens



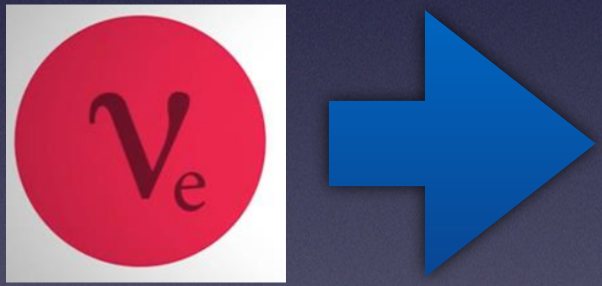
$$\frac{dP}{dp_0} = \frac{2}{3\zeta(3)k_B^3T_\nu^3}\frac{p_0^2/c^3}{e^{p_0/k_BT_\nu}+1}$$

Neutrinos momentum distribution

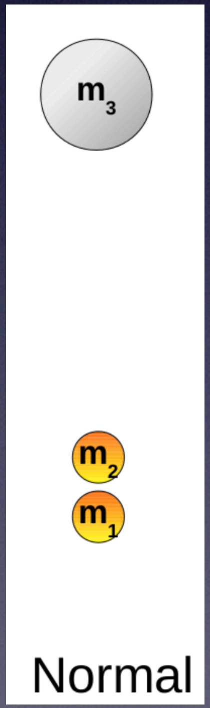
$$\theta_E^{\mathrm{SIS}} = \frac{4\pi\sigma_v^2}{c^2}\left(\frac{c^2+v_{lens}^2}{2v_{lens}^2}\right)\frac{D_{LS}(v_0,D_L)}{D_S(v_0)}$$

SIS lens model: σv = 1000 km/s

Mass eigenstates splitting via gravitational potential



Neutrino source (flavor)

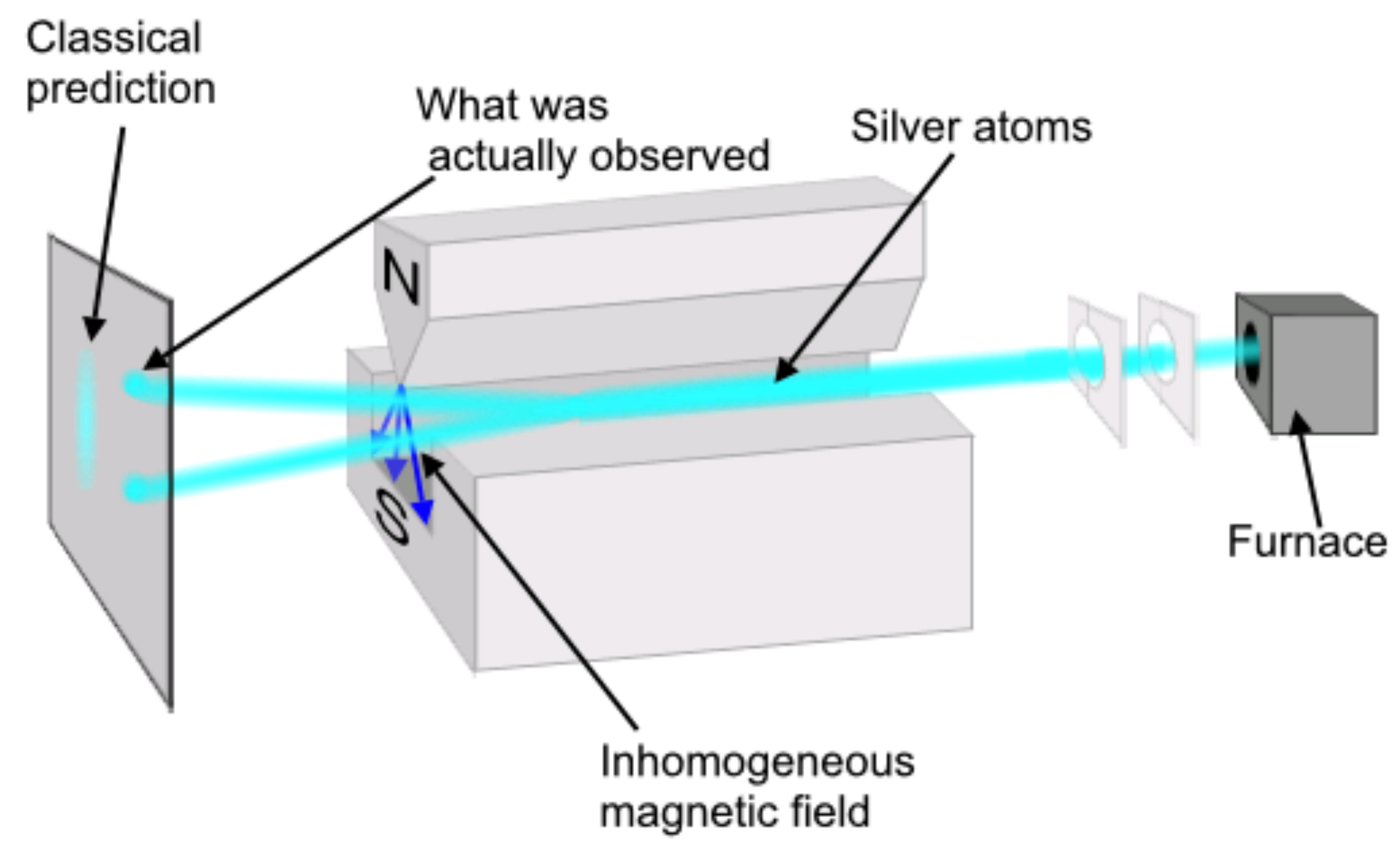


Mass eigenstates

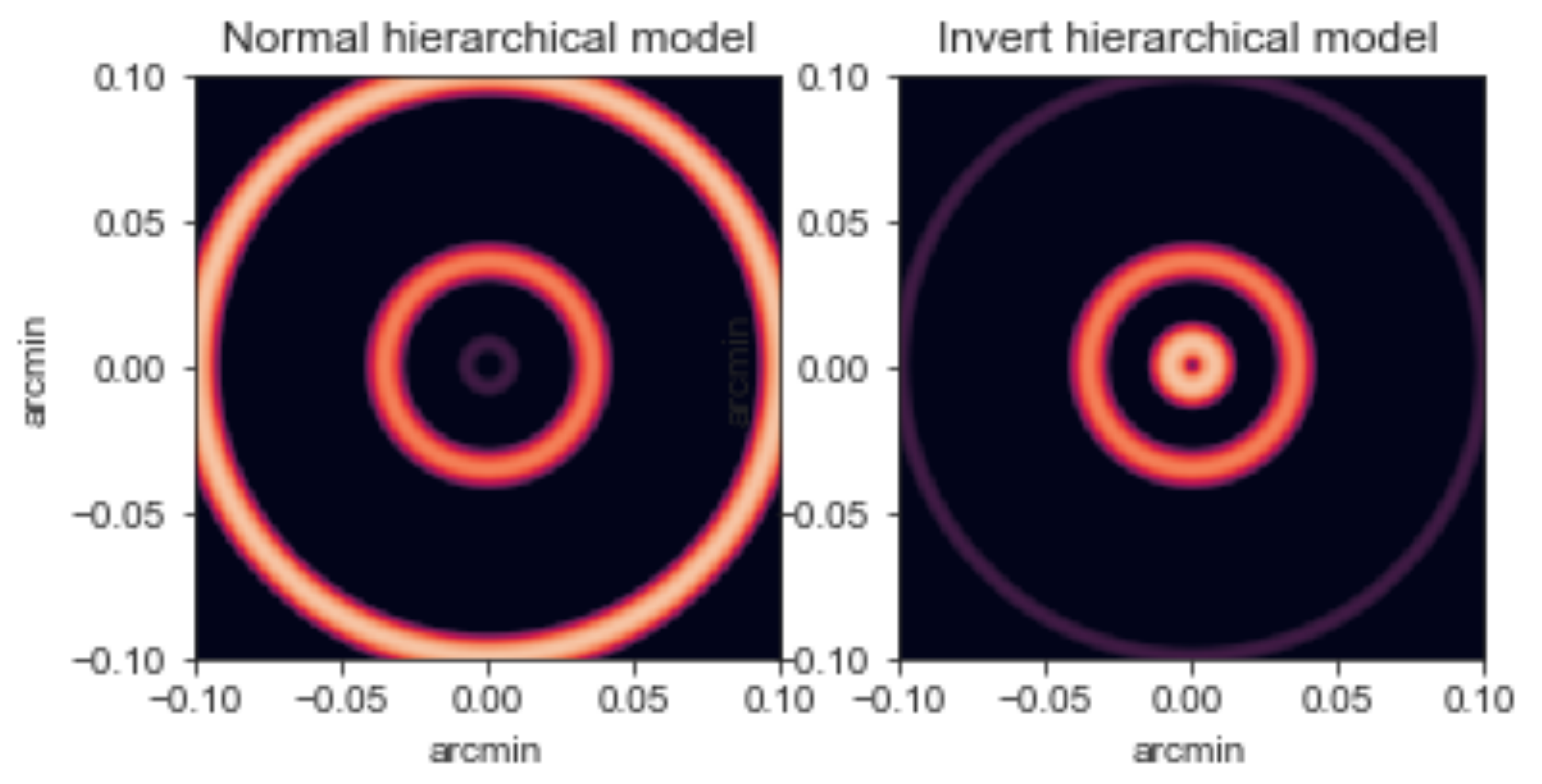
Gravitational Lens:
Spectrometer

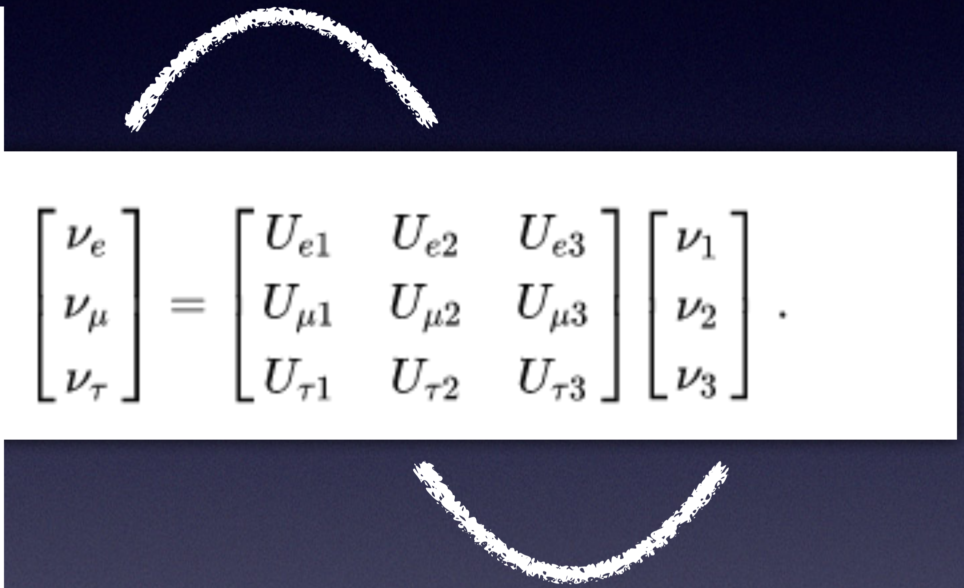
Mass eigenstates
splitting

Spectrometer:
Stern–Gerlach experiment



Mass eigenstates splitting via gravitational potential





$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$

Source: ν_e

Detector: ν_e

Discussion & Summary

- Strong lensing of CνB could be the largest Stern–Gerlach experiment in our universe
- Neutrino oscillations are not relevant in this case, as the mass eigenstates get dispersed in angular space
- Time evolution of the halo could also be probed
- Interesting, with extremely rich source of information: strong lensing, neutrino mass, quantum properties

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Thank you!

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Image credit: Aram Grigoryan/Getty Images