Neutrino Mass Measurement with Cosmic Gravitational Focusing

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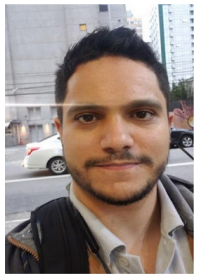


Pedro Pasquini

谭亮

Shao-Feng Ge, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

5th 粒子物理前沿研讨会

April 14, 2024

李政道研究所

Tsung-Dao Lee Institute

Outline

Tsung-Dao Lee Institute

1) Overview of ν Mass Measurements

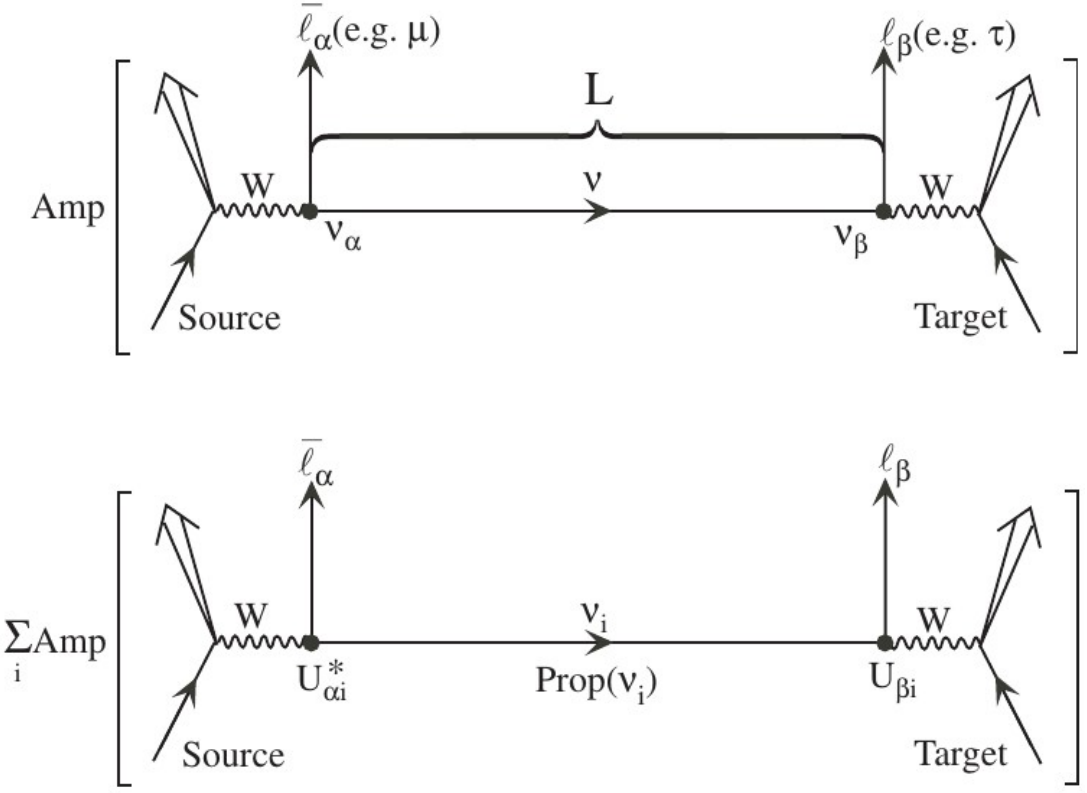
- ν Oscillation
- Beta Decay
- Radiative Emission of ν Pairs
- Supernova ν Time Delay
- CνB Detection
- CMB & LSS

2) 3rd Cosmological Way

- Cosmic Gravitational Focusing
- Dipole Structure in Galaxy Correlation Function

3) Summary

Neutrino Oscillation & Mass



$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$$\rightarrow \boxed{\sum_i U_{\alpha i} e^{i(E_i t - \vec{P}_i \cdot \vec{x})} \nu_i}$$

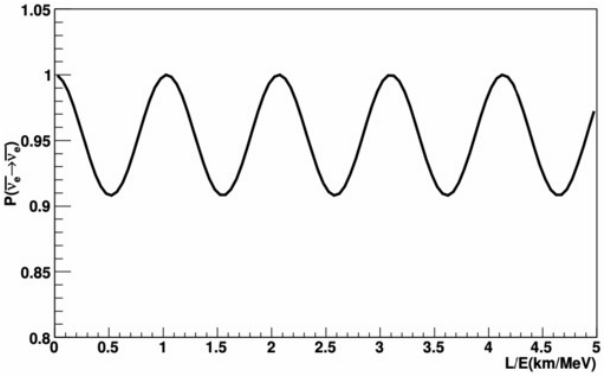
$$= \boxed{\sum_i U_{\alpha i} P_i U^\dagger_{\beta i} \nu_\beta}$$

$$\equiv \sum_\beta A_{\alpha\beta} \nu_\beta$$

B. Kayser, [hep-ph/0506165]

$$P_{\alpha\beta}|_{\alpha\neq\beta} \equiv |A_{\alpha\beta}|^2 = \sin^2 2\theta \sin^2\left(\delta m^2 \frac{L}{4E}\right)$$

1st New Physics **振幅** **频率**



Global Fit

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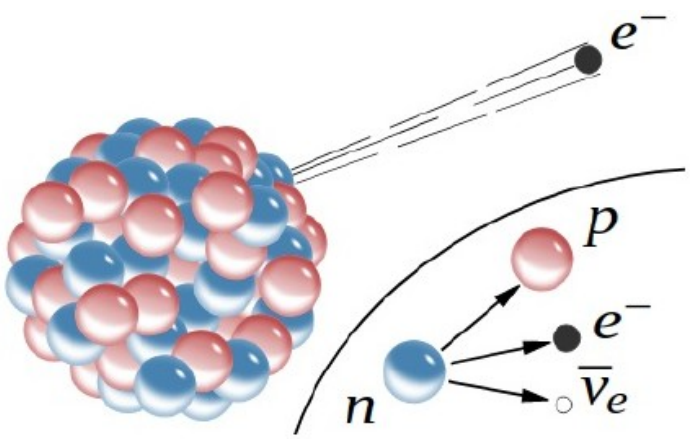
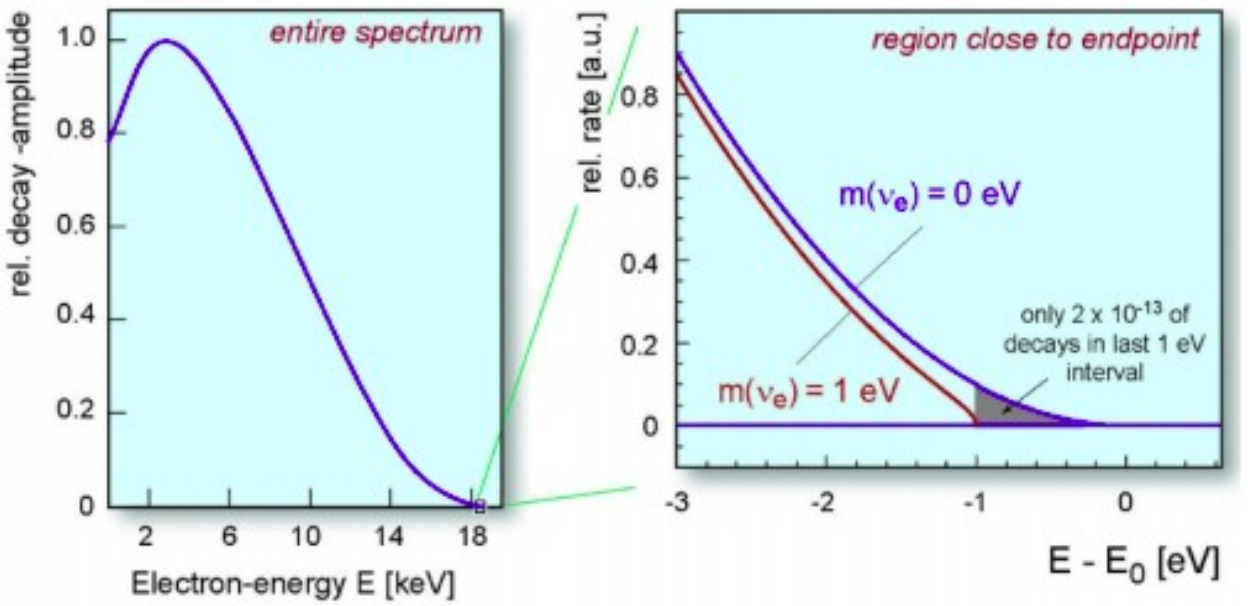
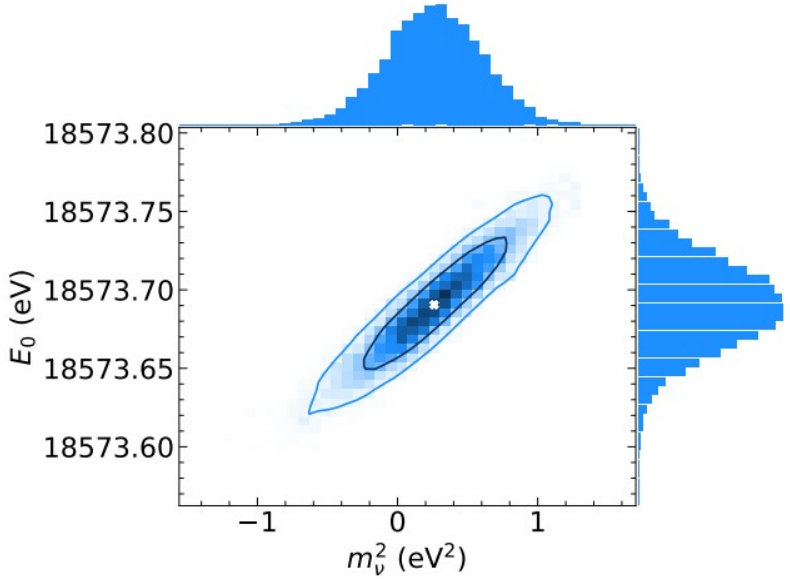
(for **NO**)	-1σ	Best Value	$+1\sigma$
$\Delta m^2_s \equiv \Delta m^2_{21}\,(10^{-5}\mathrm{eV}^2)$	7.30	7.50	7.72
$\lvert\Delta m^2_a \equiv \Delta m^2_{31}\rvert\ (10^{-3}\mathrm{eV}^2)$	2.52	2.56	2.59
$\sin^2\theta_s\ (\theta_s \equiv \theta_{12})$	0.302 (33.3°)	0.318 (34.3°)	0.334 (35.3°)
$\sin^2\theta_a\ (\theta_a \equiv \theta_{23})$	0.544 (47.54°)	0.566 (48.79°)	0.582 (49.72°)
$\sin^2\theta_r\ (\theta_r \equiv \theta_{13})$	0.02147 (8.43°)	0.02225 (8.58°)	0.02280 (8.69°)
δ_D	191°	216°	257°
δ_{Mi}	**??**	**??**	**??**

Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola & Valle, [arXiv:2006.11237]

Neutrino Mass @ β Decay

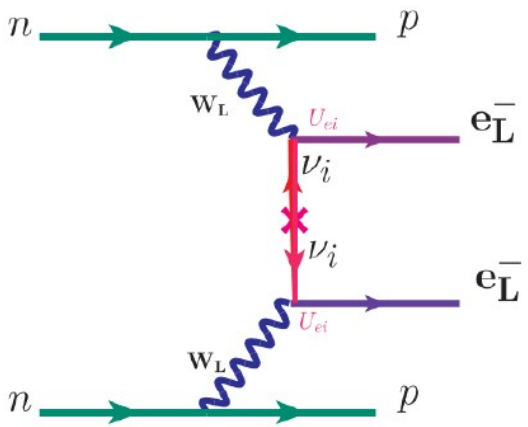


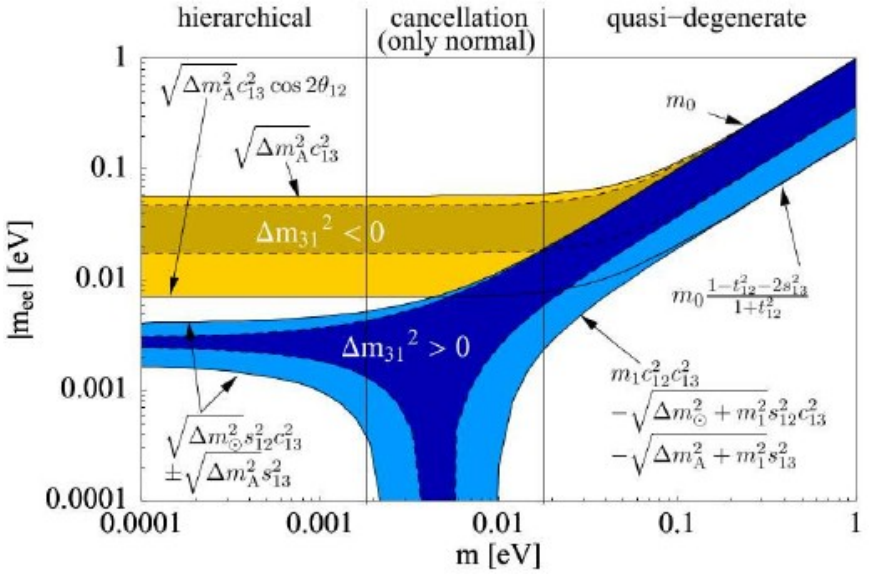




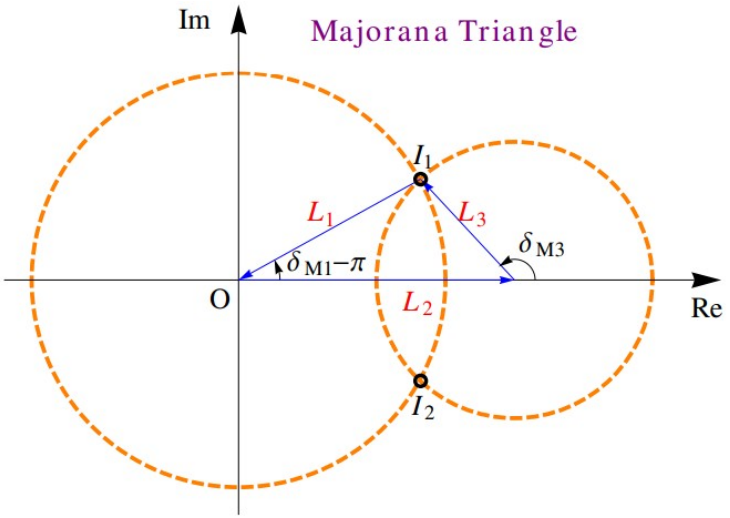
Nature Phys. 18 (2022) 2, 160-166

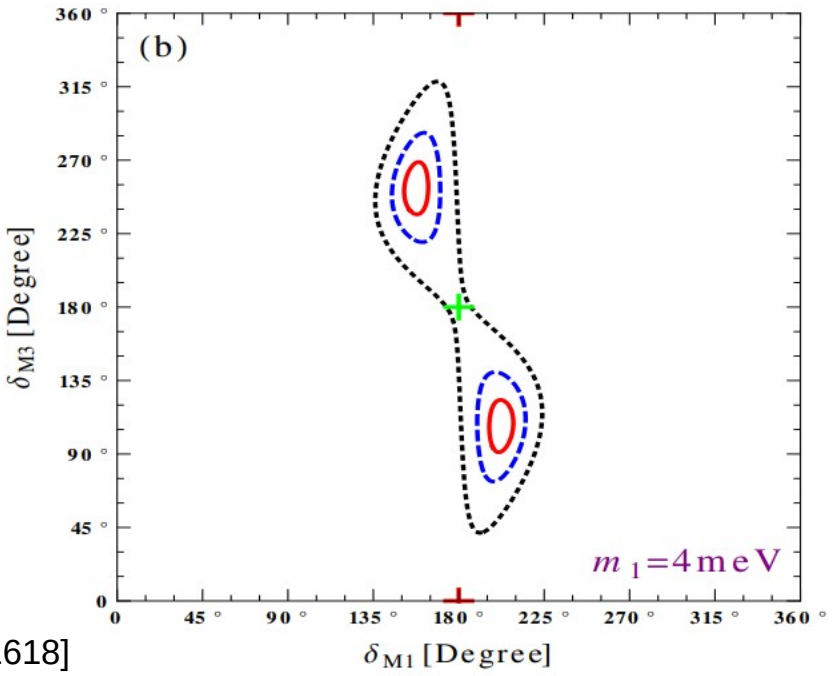
Neutrinoless Double Beta Decay





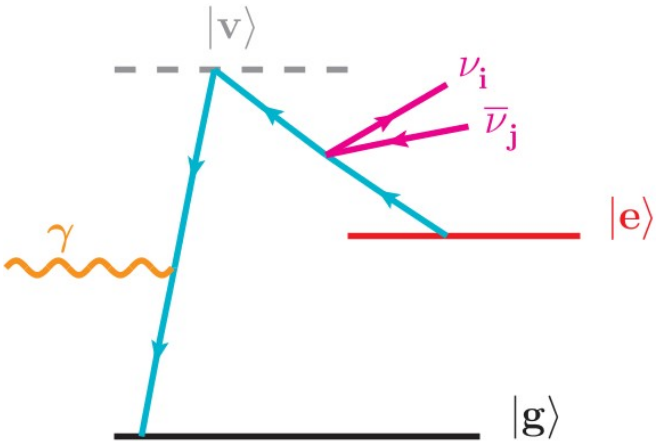
$$\langle m \rangle_{ee} \equiv \left| \sum_i m_i U_{ei}^2 \right| = \left| c_s^2 c_r^2 m_1 e^{i\delta_{M1}} + s_s^2 c_r^2 m_2 + s_r^2 m_3 e^{i\delta_{M3}} \right|$$





SFG & Manfred Lindner, PRD 95 (2017) No.3, 033003 [arXiv:1608.01618]

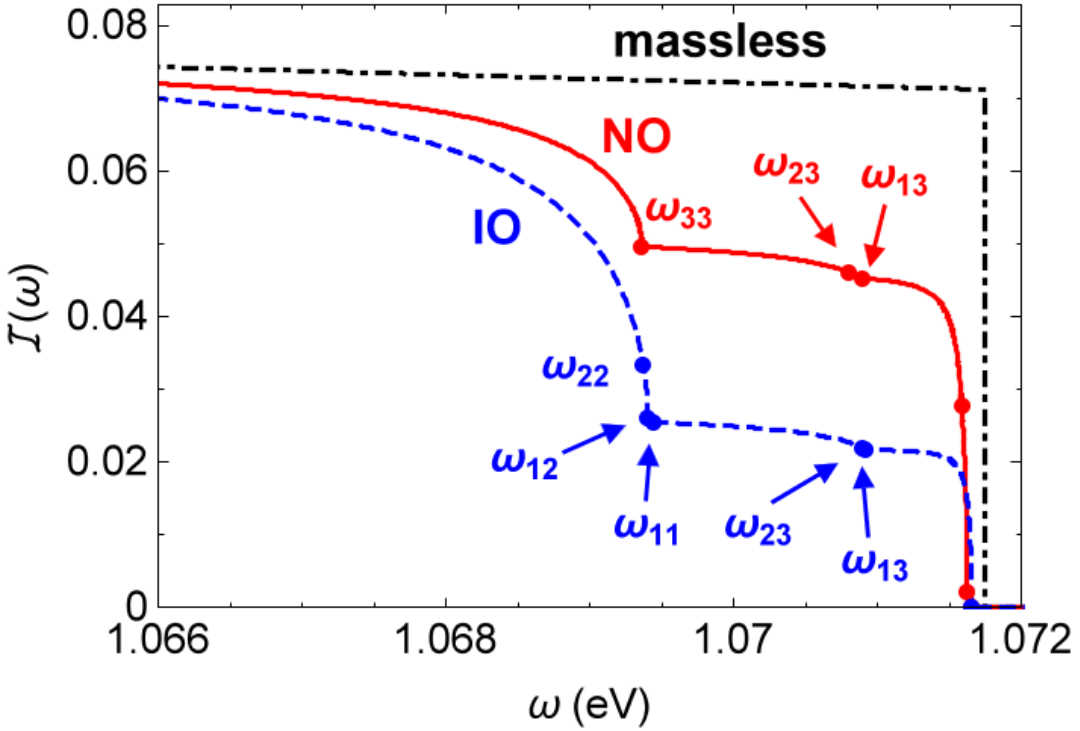
Radiative Emission of ν Pairs



$$|e\rangle \to |v\rangle + \nu\bar{\nu} \qquad \mathrm{E1} \times \mathrm{M1}$$

M. Yoshimura, Phys. Rev. D 75, 113007 (2007)

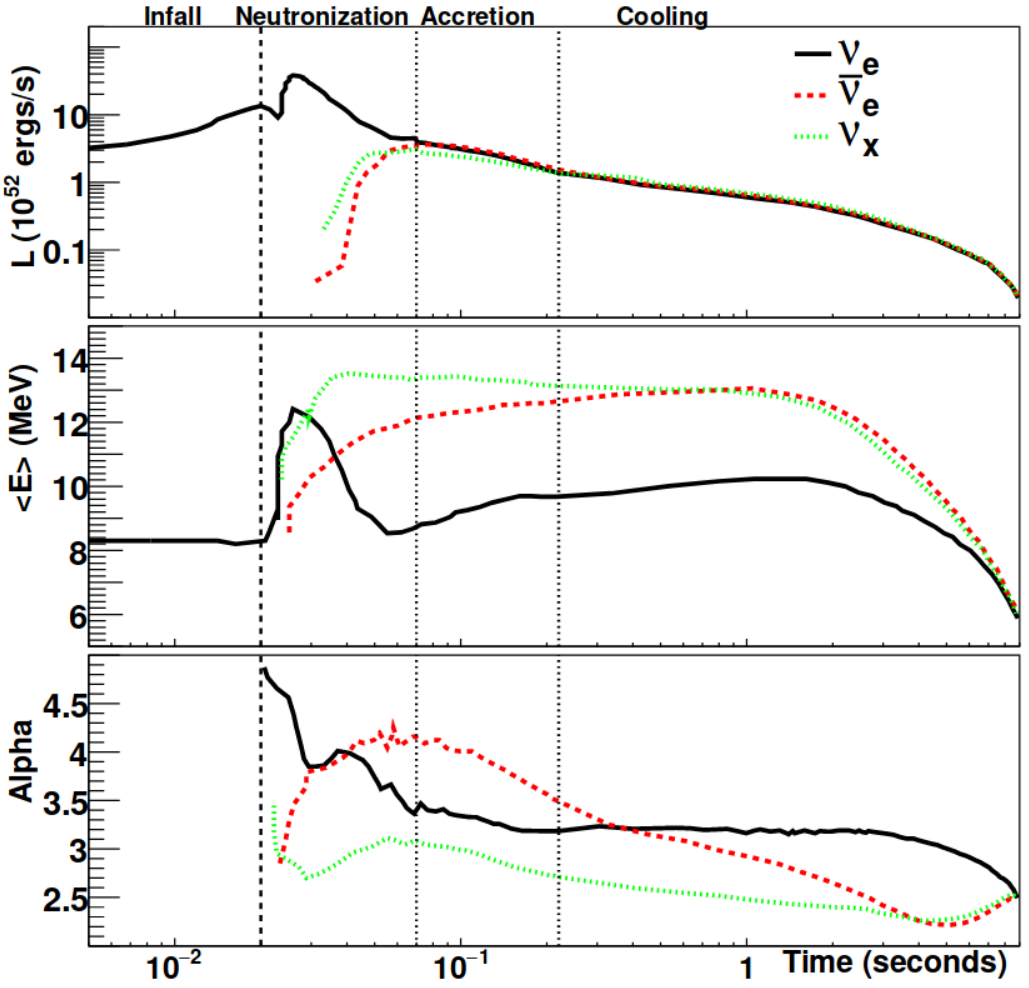
Jue Zhang & Shun Zhou, Phys.Rev.D 93 (2016) 11, 113020



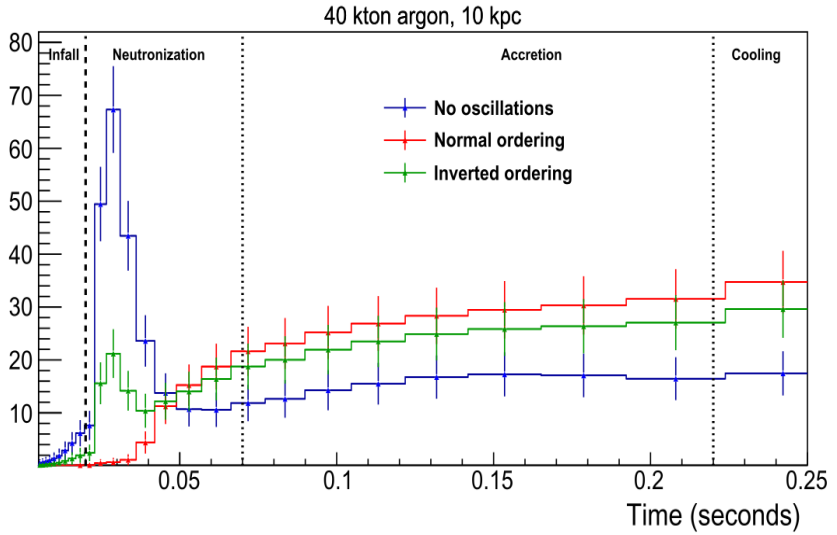
$$\omega_{ij}^{\max} \equiv \frac{E_e - E_g}{2} - \frac{1}{2}\frac{(m_i + m_j)^2}{(E_e - E_g)}$$

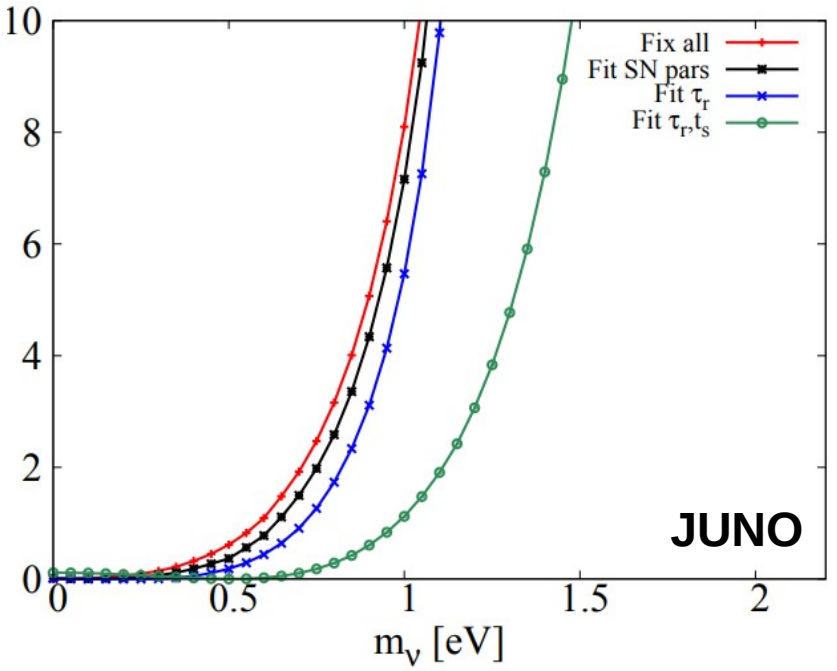
SFG & Pasquini
Eur.Phys.J.C 82 (2022) 3, 208;
Phys.Lett.B 841 (2023) 137911;
JHEP 12 (2023) 083

Time Delay in Supernova ν's



DUNE, 2008.06647





SFG, Kong, Smirnov, to appear

Lu, Cao, Li & Zhou [JCAP 05 (2015) 044]

Cosmic ν Background

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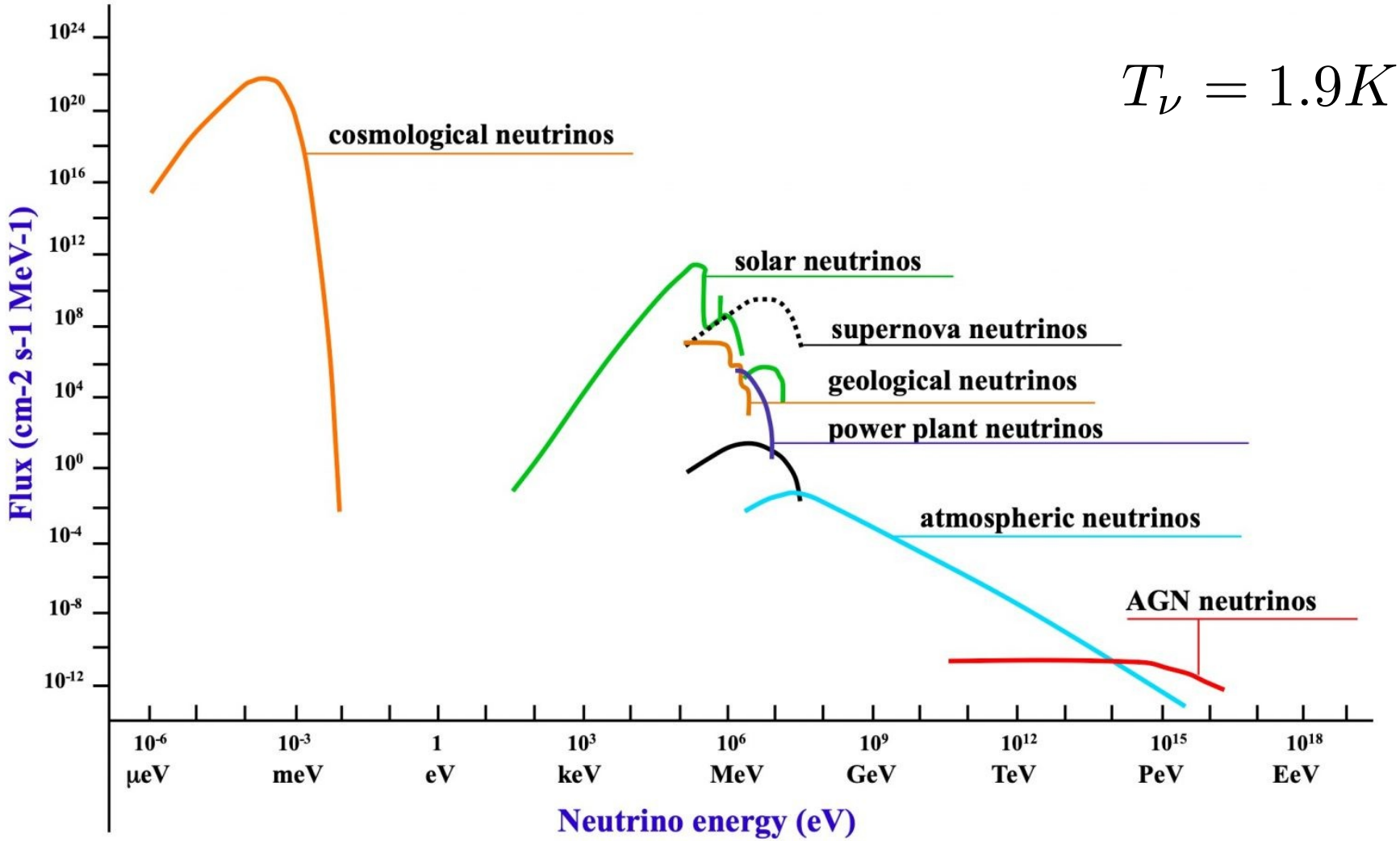
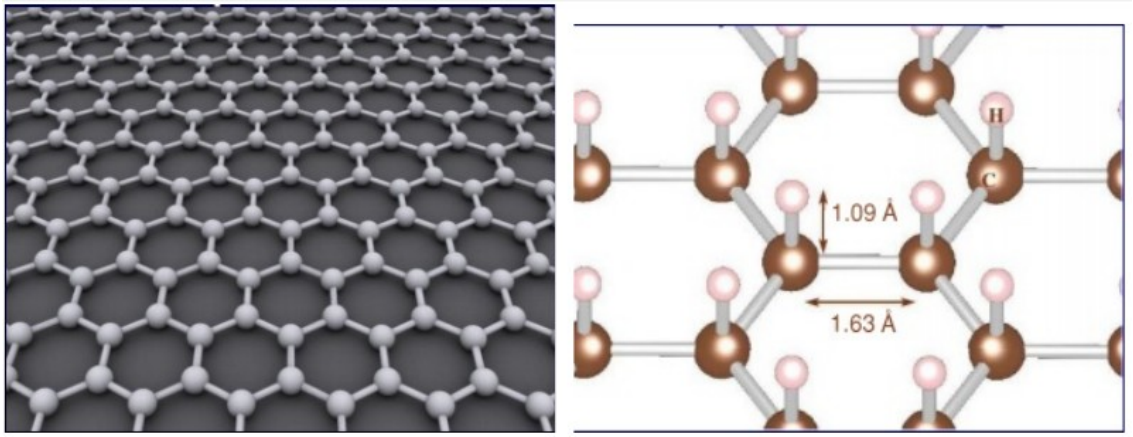
$$T_\nu = 1.9K$$

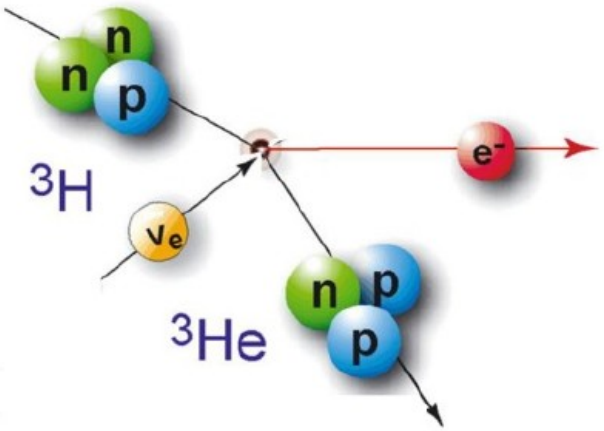


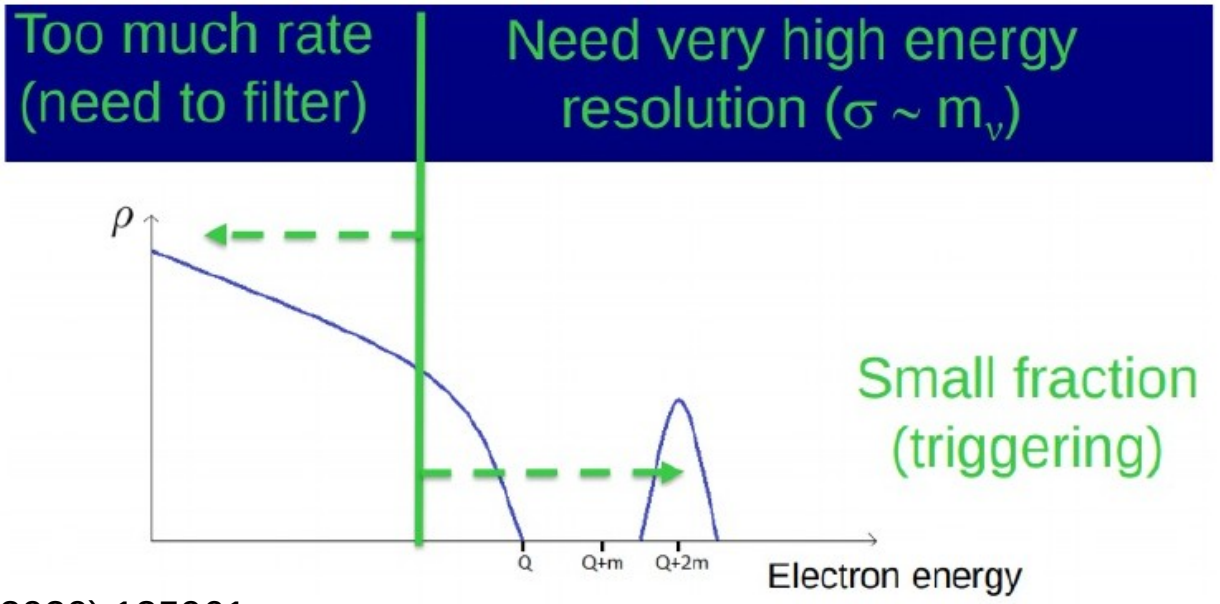
PTOLEMY Experiment

P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield



Graphene Substrate

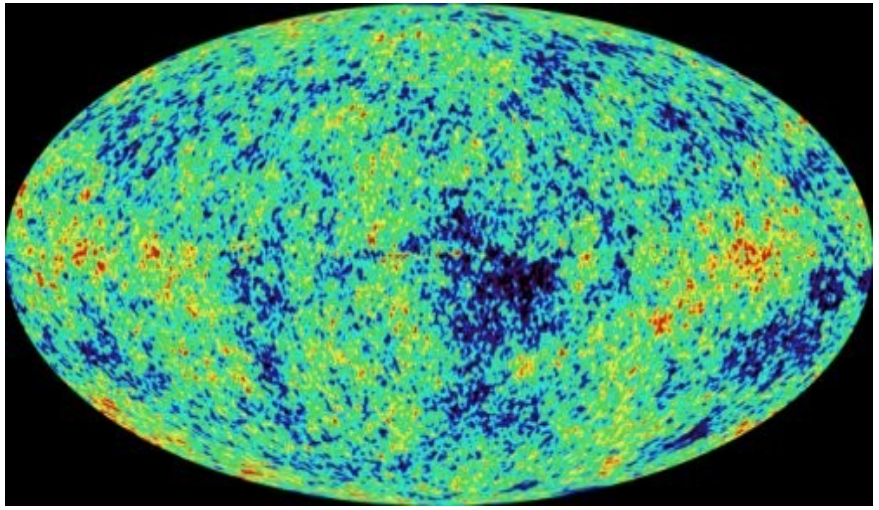




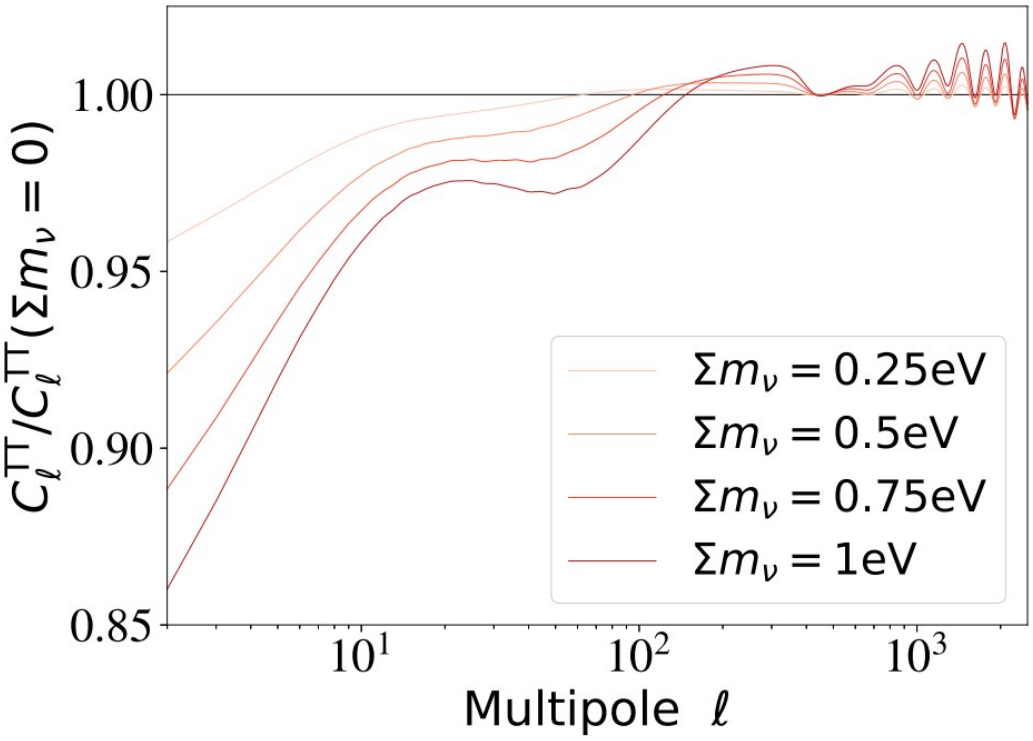
SFG & Pasquini, Phys.Lett.B 811 (2020) 135961

CMB

Massive neutrino Decreasing CMB power spectrum



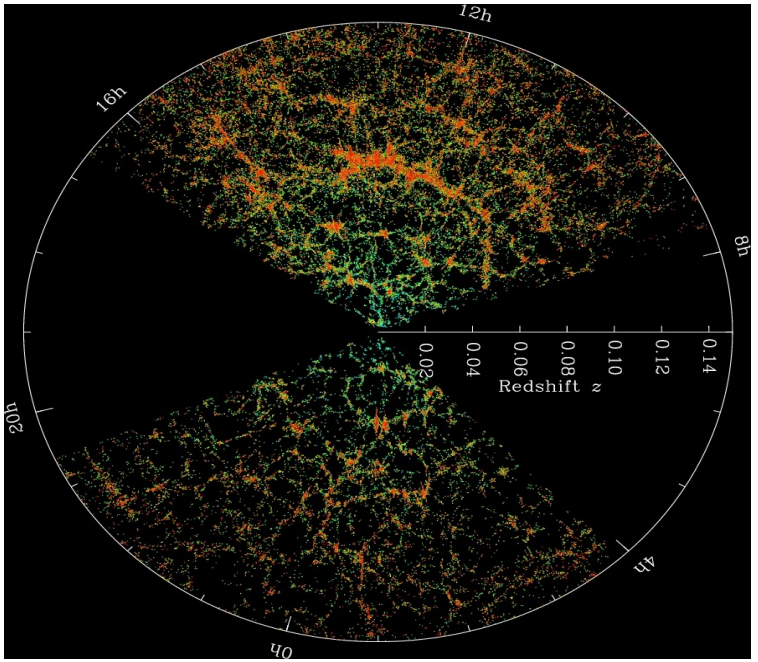
$$\rho_\nu = n_\nu \sum_i m_i$$

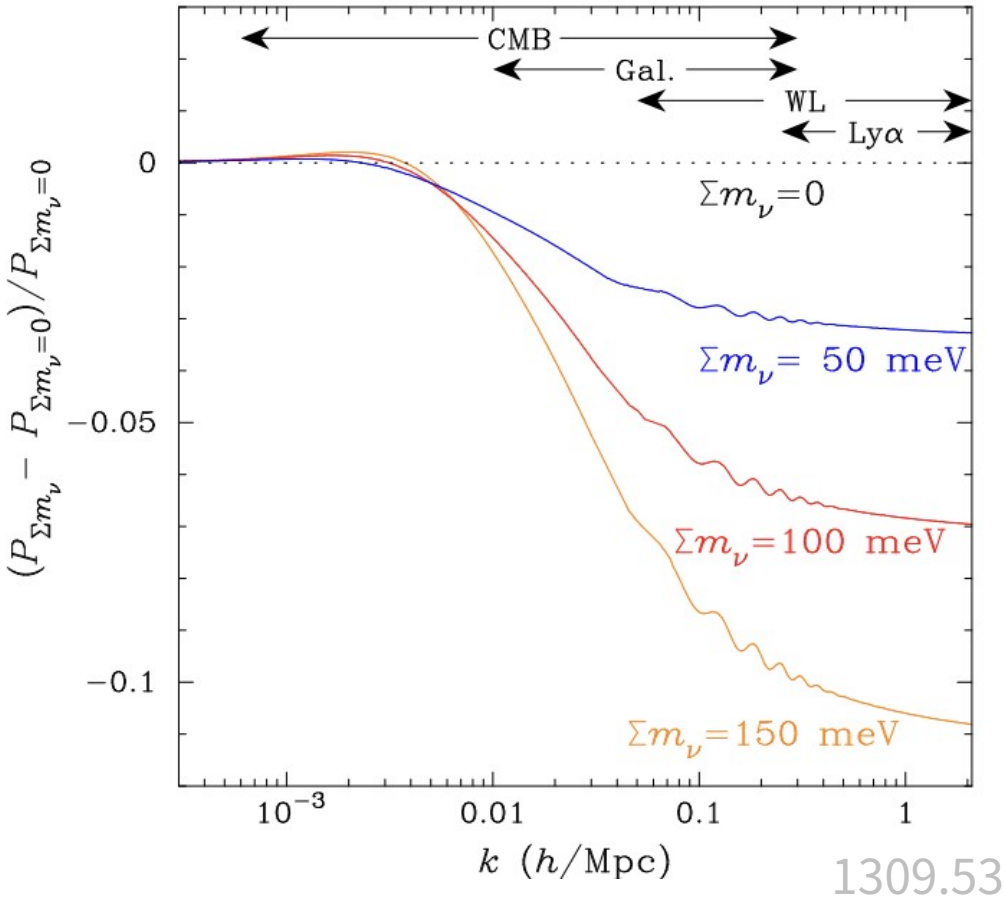


PDG 2022 Neutrino in Cosmology

LSS

Suppression matter power spectrum below neutrino free-streaming scale





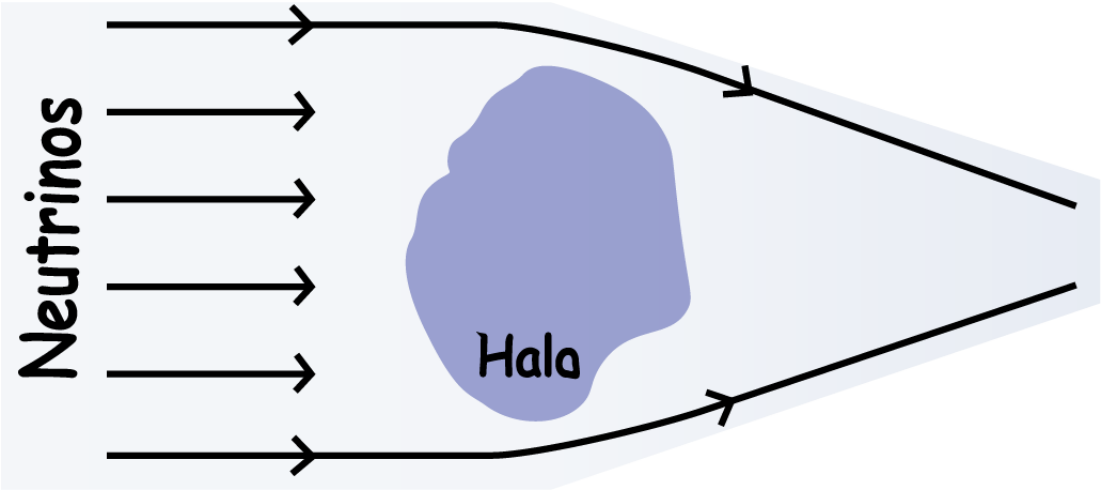
1309.5383

$$\rho_\nu = n_\nu \sum_i m_i$$

$$\sum m_\nu < 0.13 \text{ eV}$$

Planck18+BAO

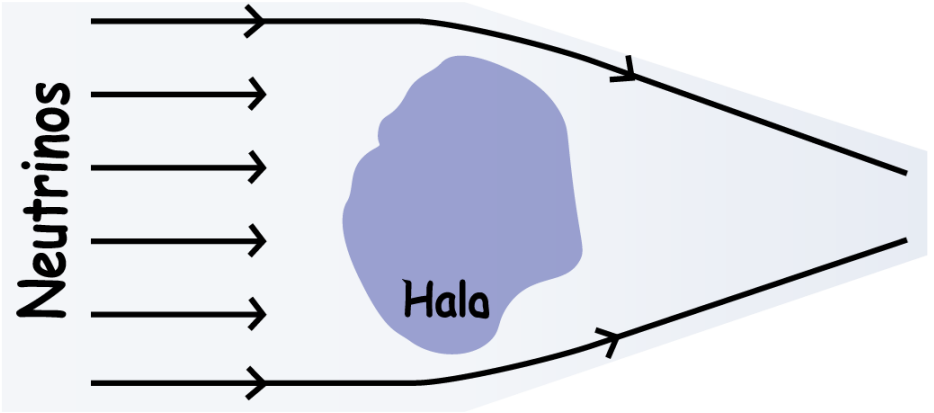
Cosmic ν Fluid (CνF) vs DM Halo



中微子流体 **暗物质晕** **vs 水流中的石头**

Dynamical Friction (动力学摩擦)

Deflection in Gravitational Potential

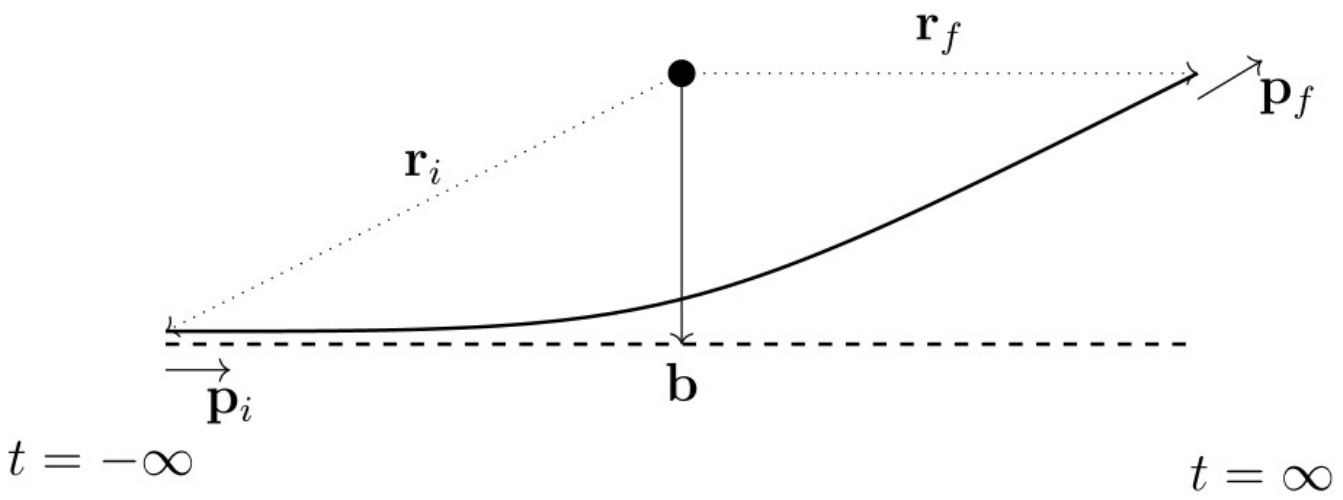


$$ds^2 \equiv -\left(1-\frac{2GM}{r}\right)dt^2 + \left(1-\frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

$$\Delta\phi = 2|\boldsymbol{b}| \int_{r_{\rm min}}^{\infty} \frac{dr}{r^2}\left[1+\frac{2b_{90}}{r}-\frac{|\boldsymbol{b}|^2}{r^2}+\frac{2GM|\boldsymbol{b}|^2}{r^3}\right]^{-1/2}$$

$$b_{90} \equiv GMm_\nu^2/|\boldsymbol{p}_i|^2 \qquad r_{\rm min}^3 + 2b_{90}r_{\rm min}^2 - |\boldsymbol{b}|^2 r_{\rm min} + 2GM|\boldsymbol{b}|^2 = 0$$

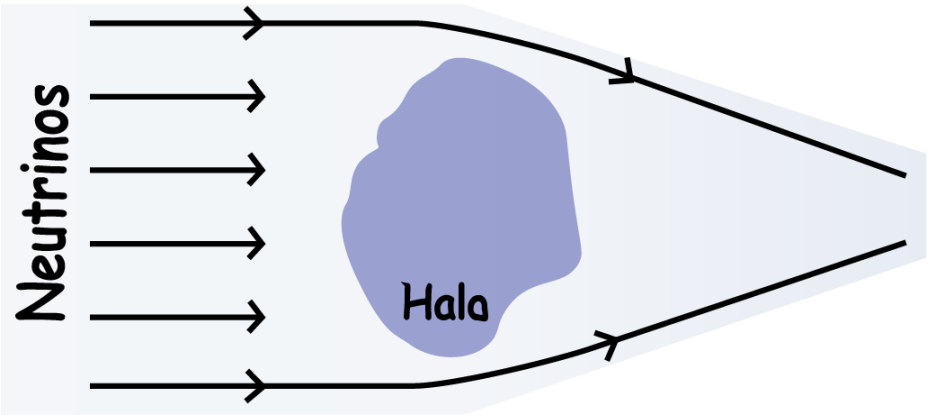
Dynamical Friction (动力学摩擦)



$$\Delta\phi \approx \pi + 2\frac{GM}{|\boldsymbol{b}|}\left(\frac{m_\nu^2}{|\boldsymbol{p}_i|^2} + 2\right)$$

$$\Delta\boldsymbol{p}^{\parallel} \equiv \boldsymbol{p}_f^{\parallel} - \boldsymbol{p}_i = (-\cos\Delta\phi - 1)\,\boldsymbol{p}_i \approx -\frac{2G^2M^2}{|\boldsymbol{b}|^2}\left(\frac{m_\nu^2}{|\boldsymbol{p}_i|^2} + 2\right)^2 \boldsymbol{p}_i$$

Gravitational Focusing



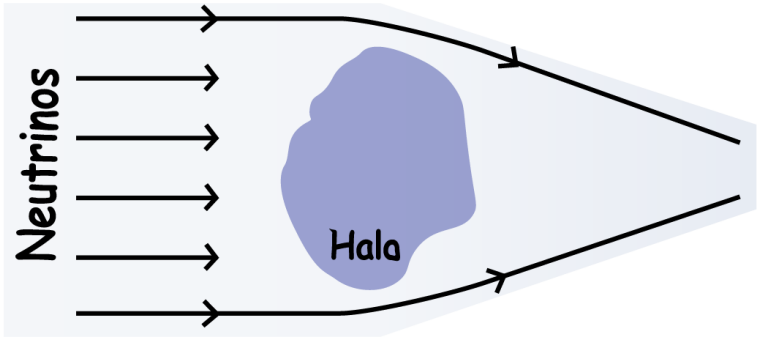
$$f_\nu(\boldsymbol{x},\boldsymbol{p}) \equiv \overline{f}_\nu(\boldsymbol{p}) + \delta f_\nu(\boldsymbol{x},\boldsymbol{p})$$

$$\left\{\partial_t + \frac{\boldsymbol{p}\cdot\nabla_{\boldsymbol{x}}}{aE_{\boldsymbol{p}}} - \left[(H+\dot{\Phi})\boldsymbol{p} + \frac{E_{\boldsymbol{p}}}{a}\nabla_{\boldsymbol{x}}\Psi - \frac{|\boldsymbol{p}|^2\nabla_{\boldsymbol{x}}\Phi - \boldsymbol{p}(\boldsymbol{p}\cdot\nabla_{\boldsymbol{x}}\Phi)}{aE_{\boldsymbol{p}}}\right]\cdot\nabla_{\boldsymbol{p}}\right\} f_\nu(\boldsymbol{x},\boldsymbol{p}) = 0$$

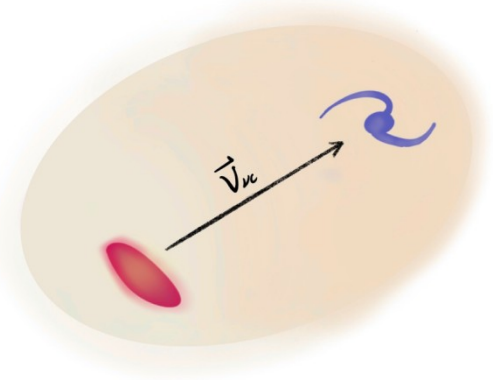
$$\delta\widetilde{f}_\nu(\boldsymbol{k},\boldsymbol{p}) = \widetilde{\Psi}(\boldsymbol{k})\left(\frac{m_\nu^2+2\boldsymbol{p}^2}{\boldsymbol{p}\cdot\boldsymbol{k}}\boldsymbol{k} - \boldsymbol{p}\right)\cdot\nabla_{\boldsymbol{p}}\overline{f}_\nu(\boldsymbol{p})$$

$$\mathrm{Im}[\delta\widetilde{\rho}_\nu] = -\frac{(\boldsymbol{v}_{\nu c}\cdot\hat{\boldsymbol{k}})\widetilde{\Psi}}{4\pi}\int d|\boldsymbol{p}'|\left(m_\nu^4 + 3m_\nu^2|\boldsymbol{p}'|^2 + 2|\boldsymbol{p}'|^4\right)\frac{d\overline{f}_\nu}{d|\boldsymbol{p}'|}\Theta(|\boldsymbol{p}'| - E_{\boldsymbol{p}'}|\boldsymbol{v}_{\nu c}\cdot\hat{\boldsymbol{k}}|)$$

Cosmic Gravitational Focusing



$$\delta_m = \delta_{m0} + \sum_{i=1}^{3} \frac{\delta\rho_{\nu_i}}{\rho_m}$$



Density enhancement downwind!

$$\delta\rho_\nu(-\mathbf{x}) = -\delta\rho_\nu(\mathbf{x})$$

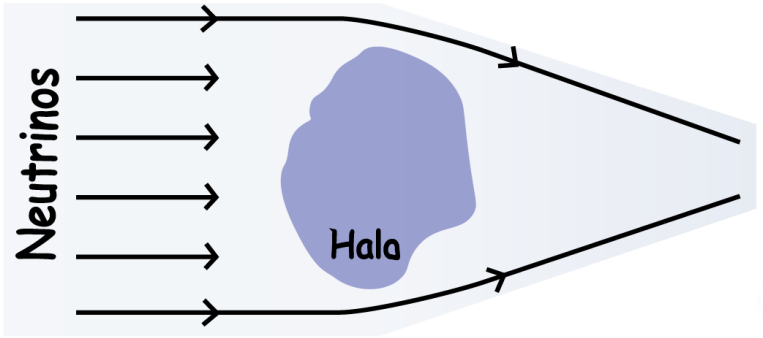
$$\widetilde{\delta}_m \equiv \widetilde{\delta}_{m0}(1 + i\widetilde{\phi})$$

$$[\widetilde{A}(\mathbf{k})]^* = \int d\mathbf{x} e^{i\mathbf{k}\cdot\mathbf{x}} A(\mathbf{x}) = \int d\mathbf{x} e^{-i\mathbf{k}\cdot\mathbf{x}} A(-\mathbf{x})$$

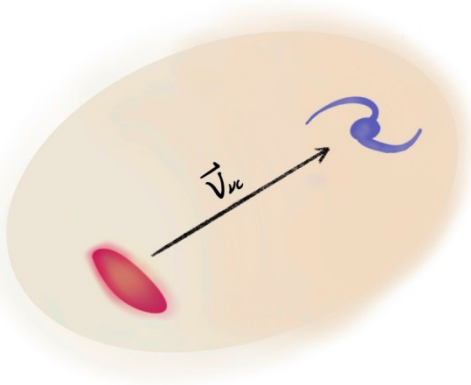
$$= -\int d\mathbf{x} e^{-i\mathbf{k}\cdot\mathbf{x}} A(\mathbf{x}) = -\widetilde{A}(\mathbf{k})$$

SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

Galaxy Correlation & Bias



$$\delta_m = \delta_{m0} + \sum_{i=1}^{3} \frac{\delta\rho_{\nu_i}}{\rho_m}$$



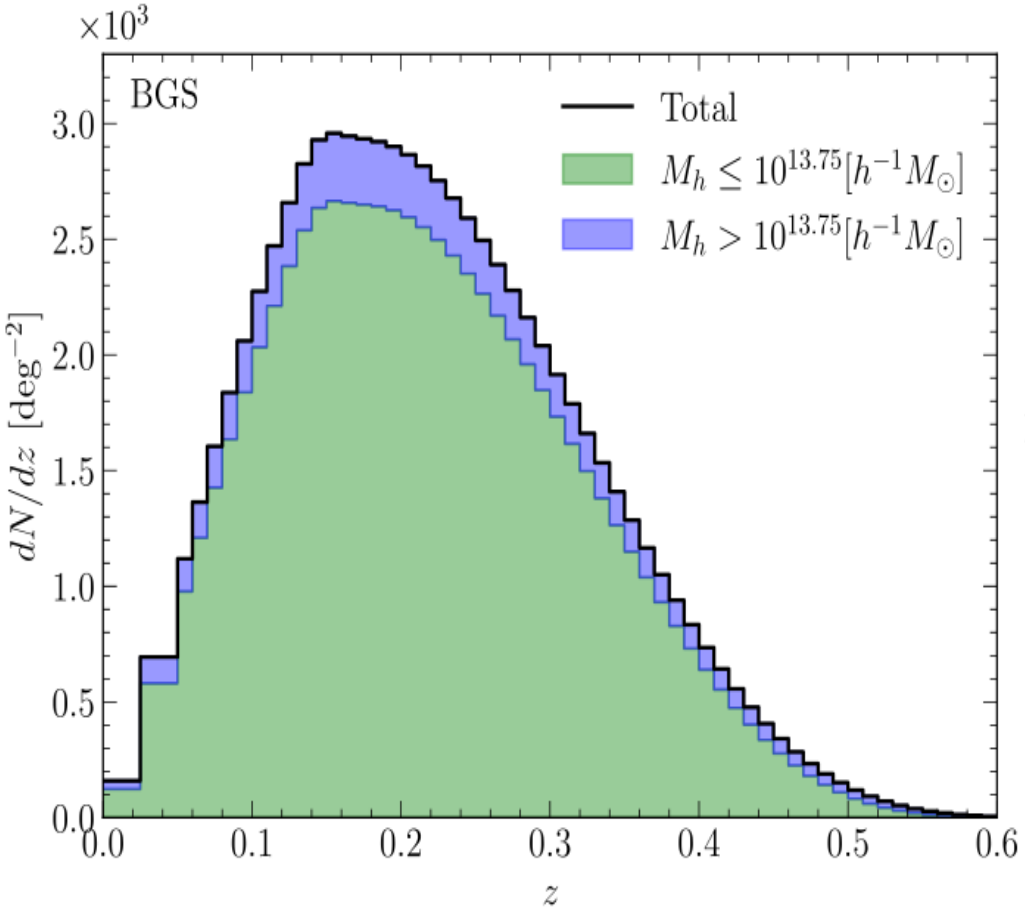
$$\delta_{g\alpha} = b_c^\alpha F_c \delta_c + b_\nu^\alpha F_\nu \delta_\nu$$

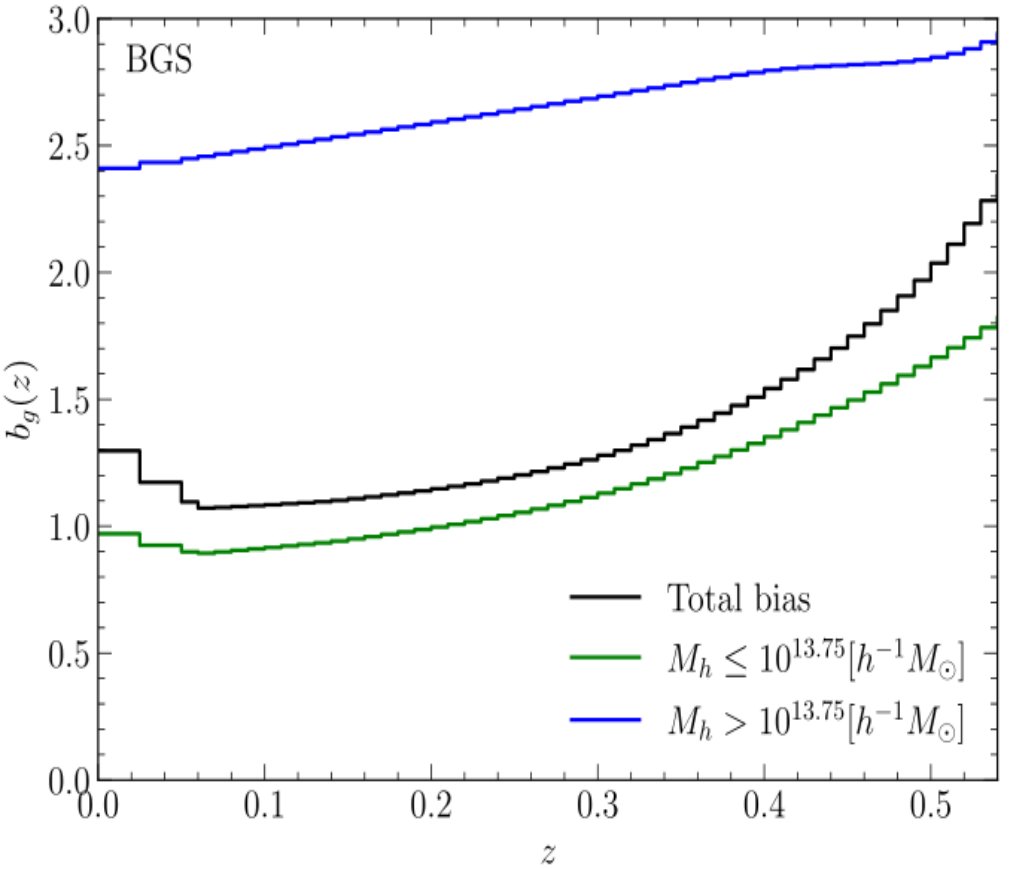
$$\delta_{g\alpha,\mathrm{RSD}}(\boldsymbol{x}) \equiv \delta_{g\alpha}(\boldsymbol{x}) - \frac{\partial}{\partial x}\left(\frac{\boldsymbol{u}_m \cdot \hat{\boldsymbol{x}}}{aH}\right)$$

$$\mathrm{Im}[\widetilde{\delta}_{g\alpha,\mathrm{RSD}}\widetilde{\delta}^*_{g\beta,\mathrm{RSD}}] = -i\Delta b \left[\mu_{\boldsymbol{k}}^2 \frac{\dot{\widetilde{\phi}}}{H} + (f\mu_{\boldsymbol{k}}^2 + 1)\widetilde{\phi}\right] \widetilde{\delta}^2_{m0}$$

需要考虑具有不同 bias 的星系类型 $\Delta b \equiv b_c^\alpha - b_c^\beta$

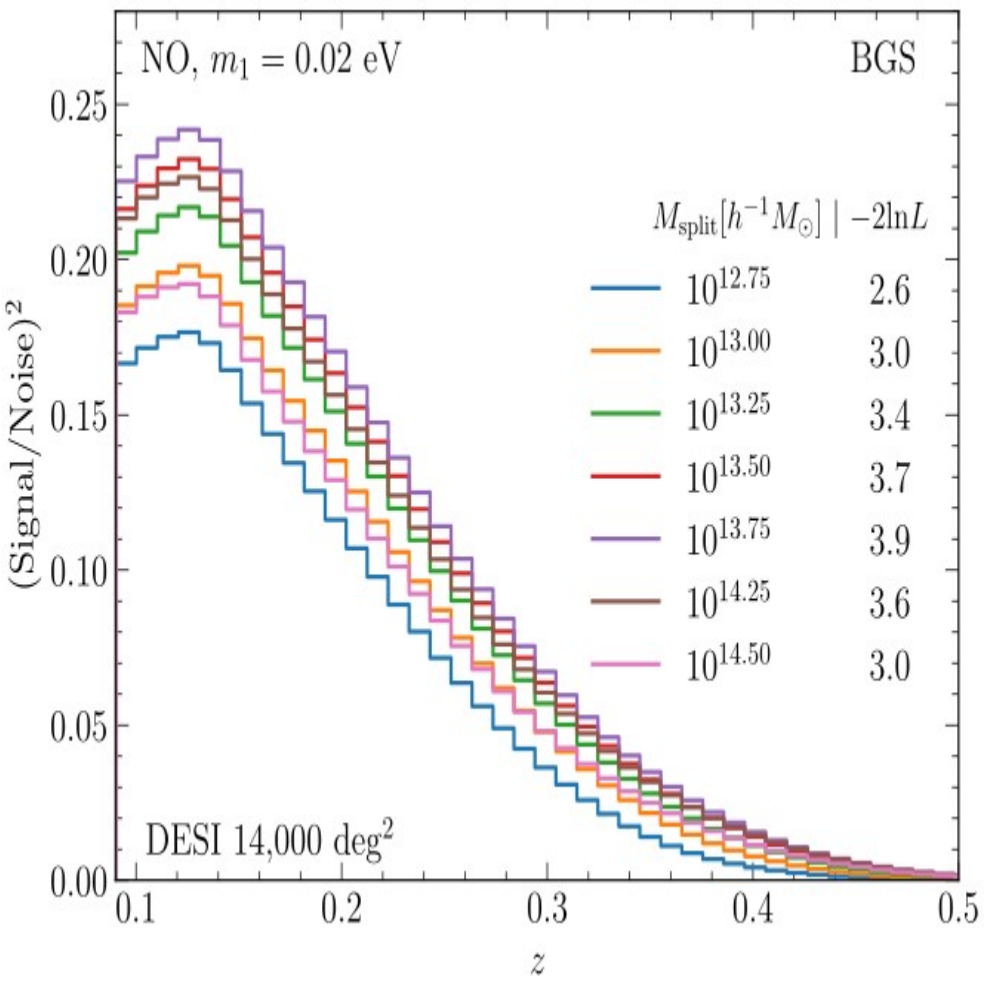
Halo Mass Function & HOD for BGS

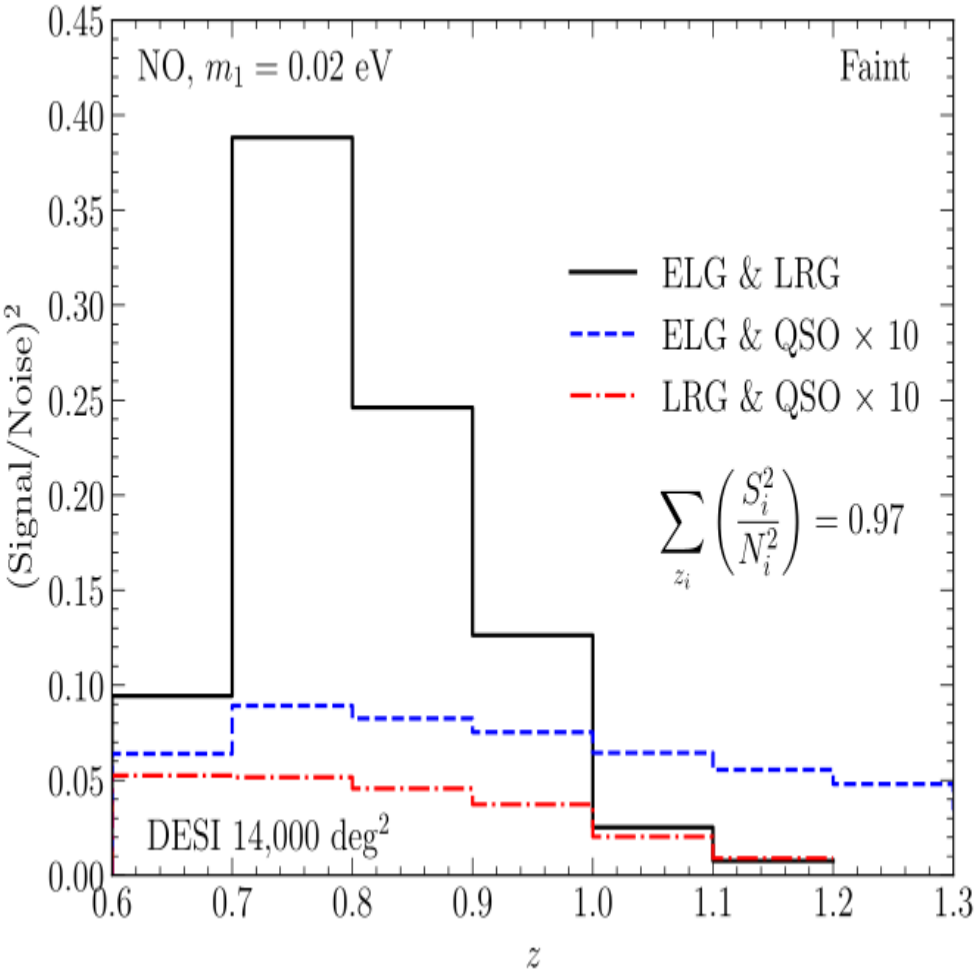




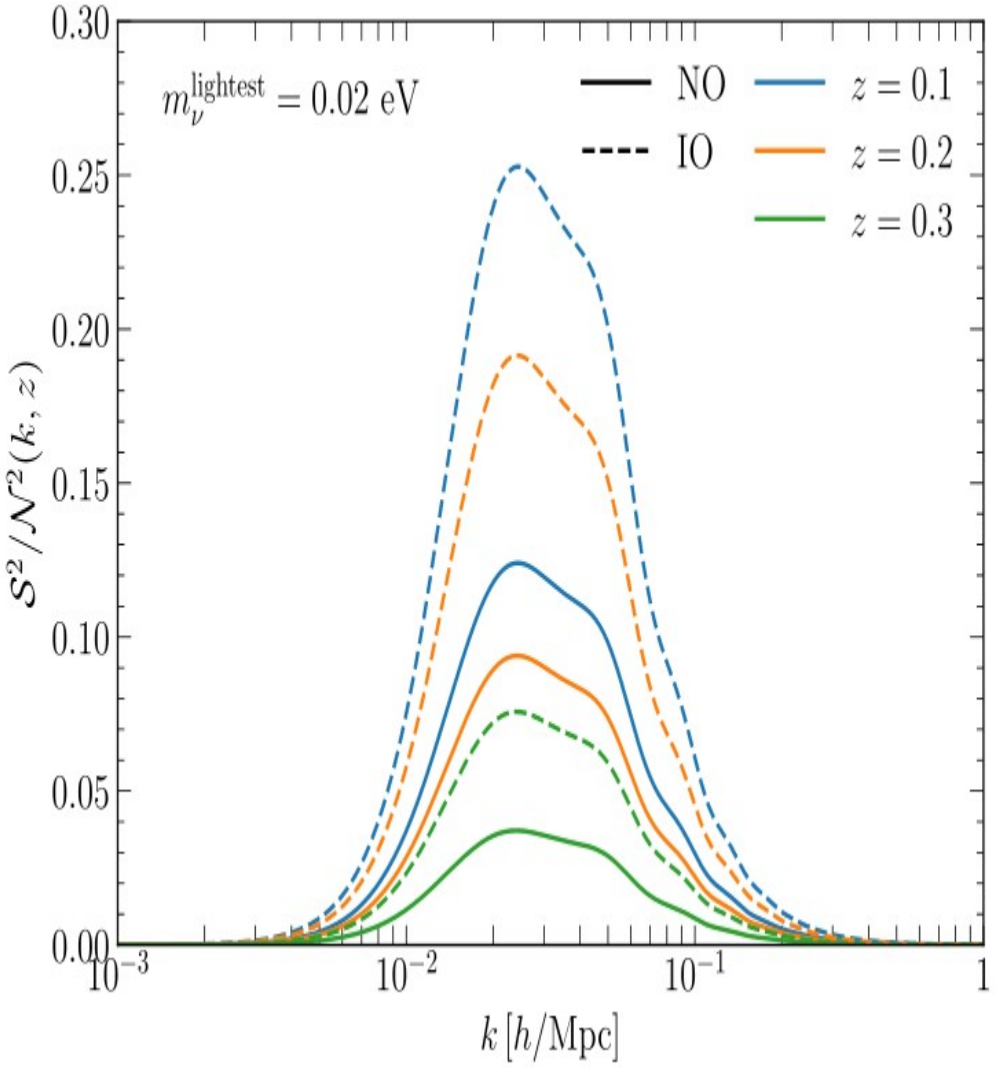
$$n_g(z) \equiv \int d\ln M_h \frac{dn(z)}{d\ln M_h}\langle N(M_h)\rangle \qquad b_g(z) \equiv \frac{1}{n_g}\int d\ln M_h \frac{dn(z)}{d\ln M_h}\langle N(M_h)\rangle b_h(M_h, z)$$

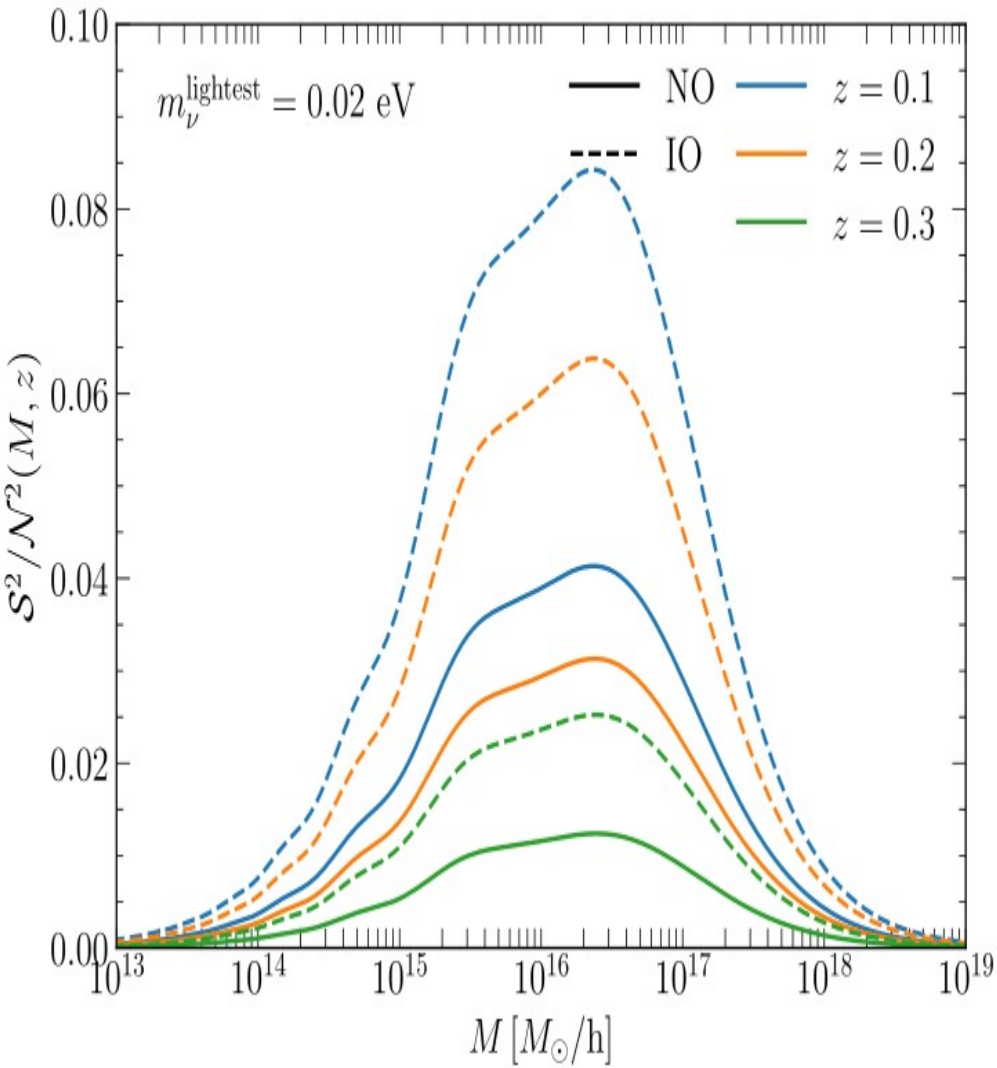
SNR @ DESI


NO, $m_1 = 0.02$ eV
BGS
$M_{\rm split}[h^{-1}M_\odot]$ | $-2\ln L$
$10^{12.75}$ 2.6
$10^{13.00}$ 3.0
$10^{13.25}$ 3.4
$10^{13.50}$ 3.7
$10^{13.75}$ 3.9
$10^{14.25}$ 3.6
$10^{14.50}$ 3.0
DESI 14,000 deg^2
(Signal/Noise)^2
z


NO, $m_1 = 0.02$ eV
Faint
ELG & LRG
ELG & QSO × 10
LRG & QSO × 10
$\sum_{z_i}\left(\frac{S_i^2}{N_i^2}\right) = 0.97$
DESI 14,000 deg^2
(Signal/Noise)^2
z

Redshift Distribution

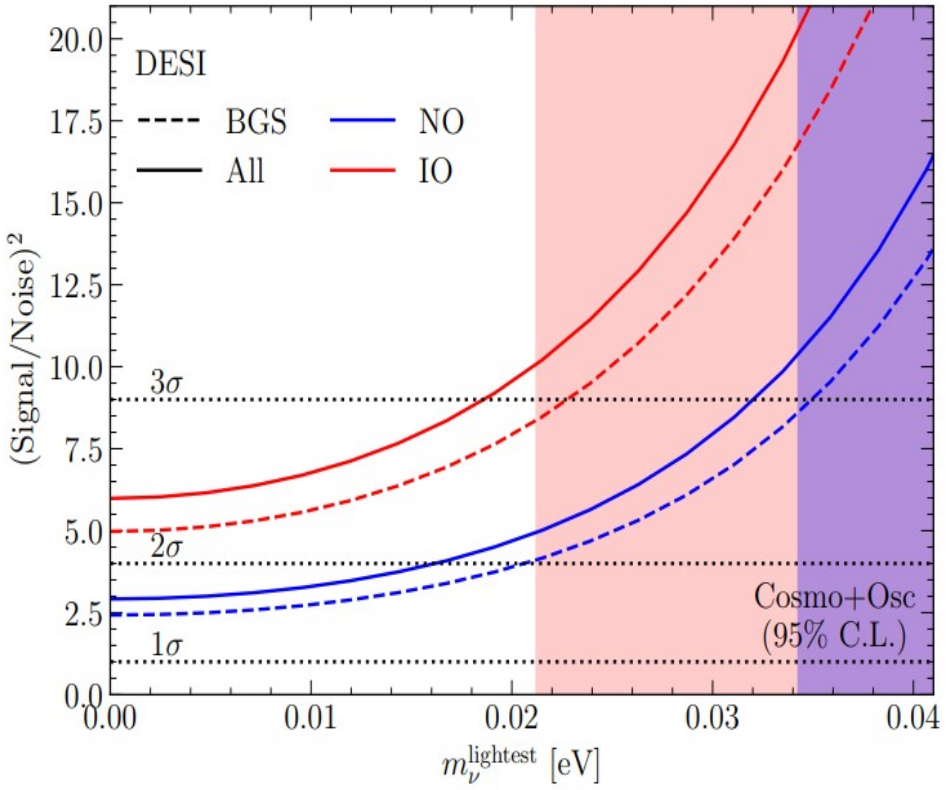


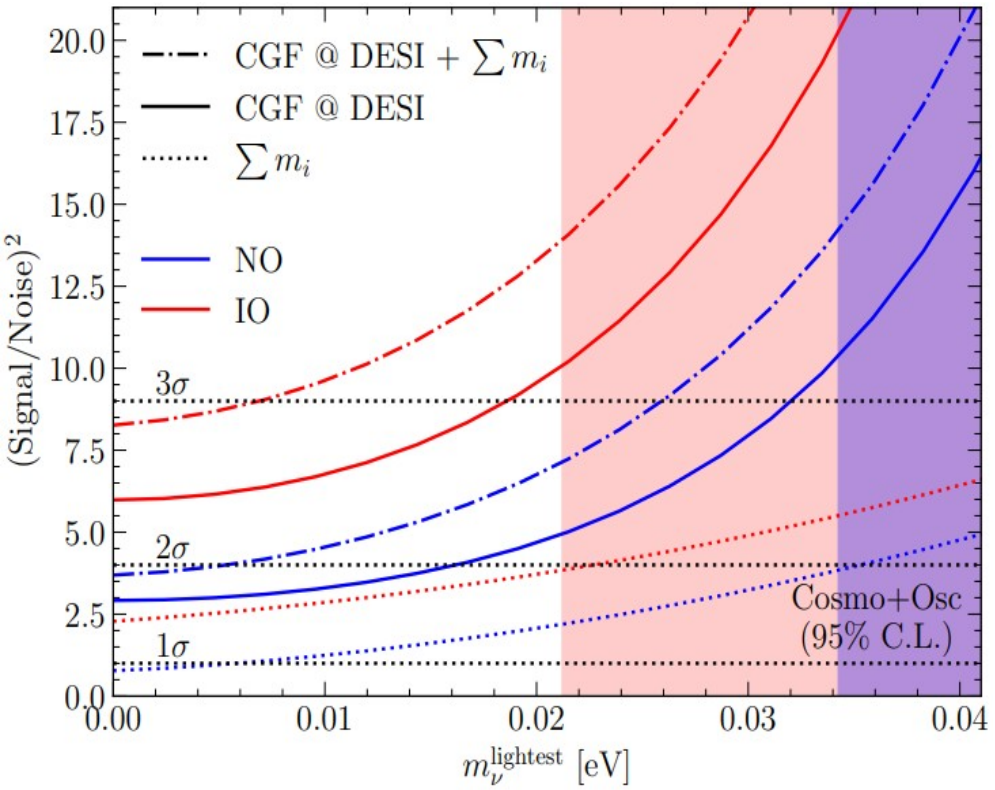


3rd Cosmic Measurement of ν Masses

Tsung-Dao Lee Institute

$$\mathrm{Im}\left[\tilde{\delta}_{g\alpha}\left(\tilde{\delta}_{g\beta}\right)^{*}\right] \propto \left(\mathbf{v}_{\nu c}\cdot\hat{\mathbf{k}}\right)\left(f_0 m_\nu^4 + f_1 m_\nu^2 T^2 + f_2 T^4\right)$$



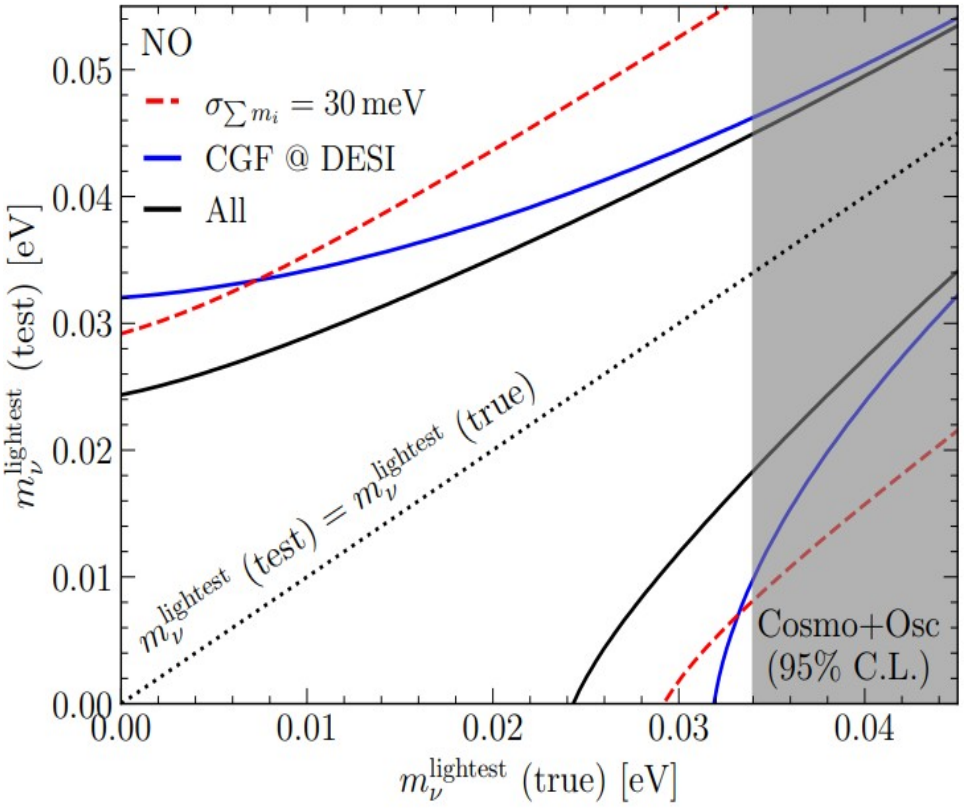


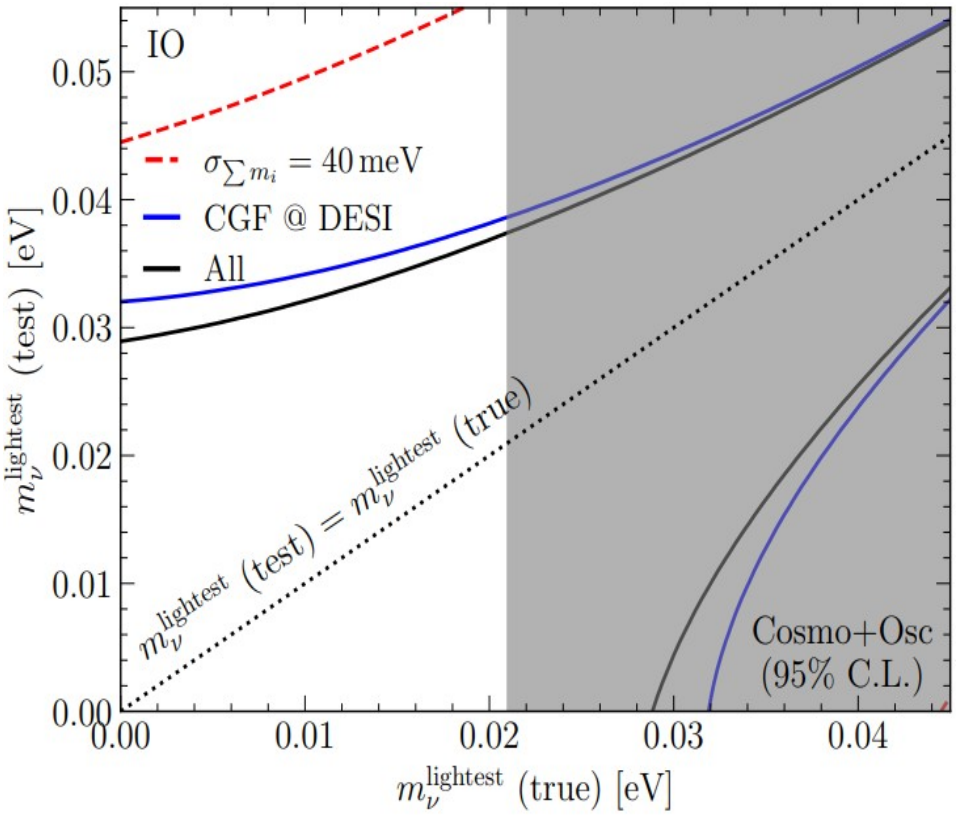
SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

3rd Cosmic Measurement of ν Masses

Tsung-Dao Lee Institute

$$\mathrm{Im}\left[\tilde{\delta}_{g\alpha}\left(\tilde{\delta}_{g\beta}\right)^*\right] \propto \left(\mathbf{v}_{\nu c}\cdot\hat{\mathbf{k}}\right)\left(f_0 m_\nu^4 + f_1 m_\nu^2 T^2 + f_2 T^4\right)$$





DESI, Euclid, Subaru PFS, **CSST**

SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

Summary

1) Overview of Neutrino Mass Measurements

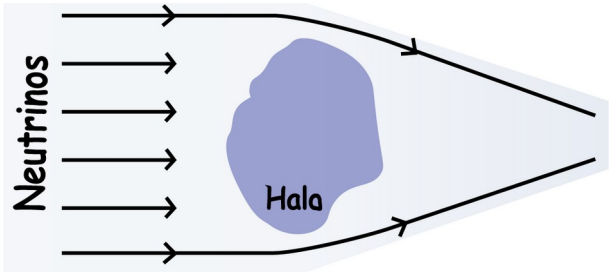
2) 3rd Cosmological Way

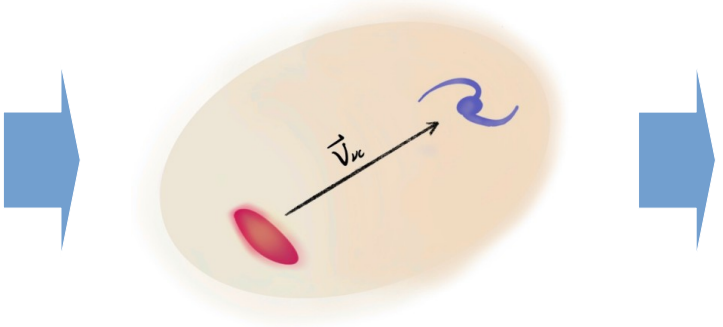
Dynamical Friction

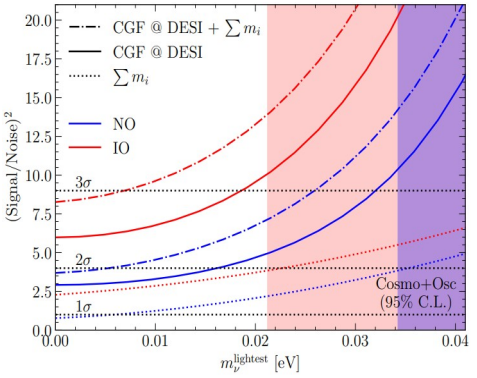
Cosmic Gravitational Focusing

Dipole Structure in Galaxy Correlation Function

Neutrino Mass Measurement @ DESI & CSST







3) Summary

Thank You

Backup Slides

Decoherence & Non-Linear

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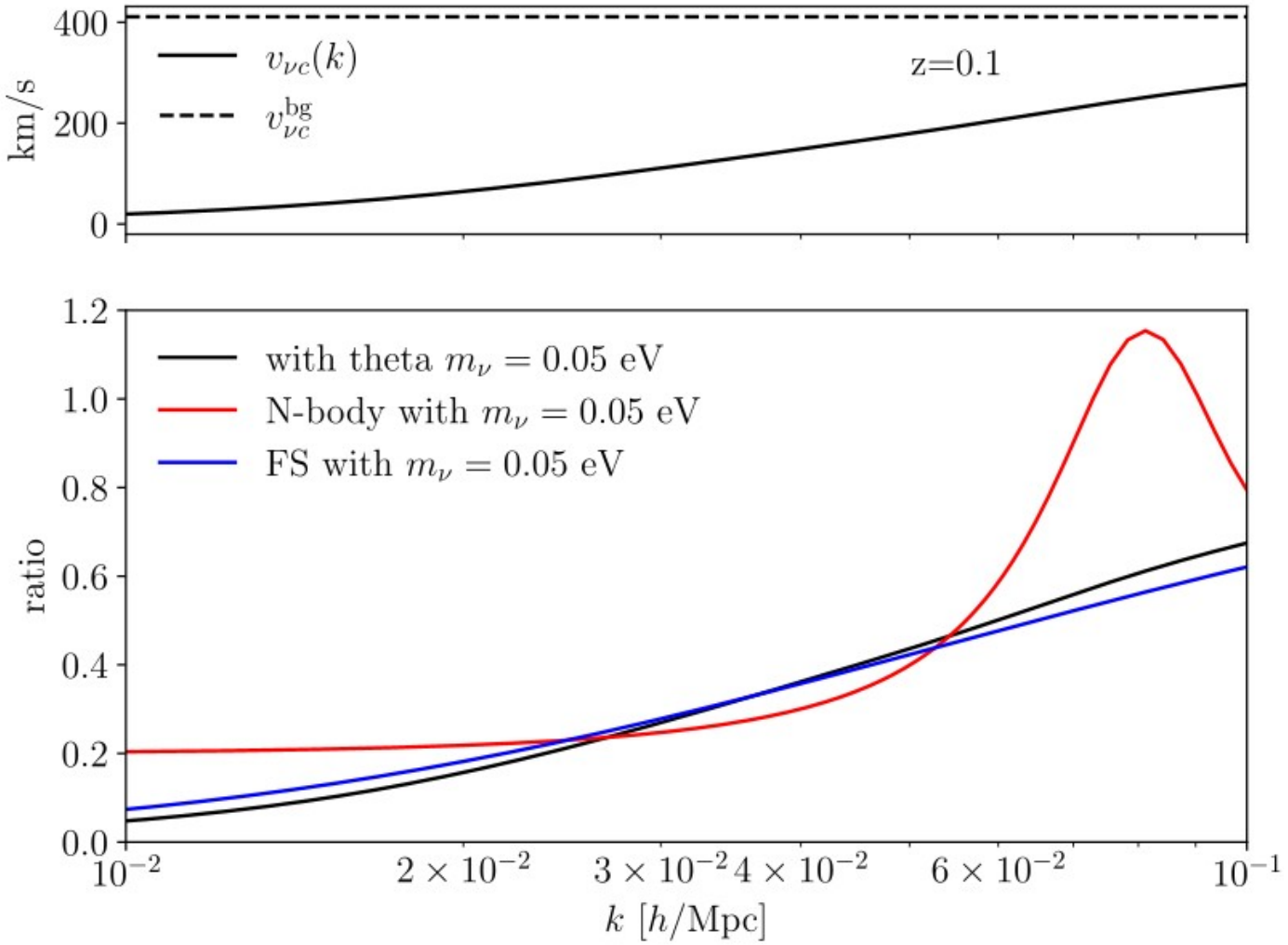
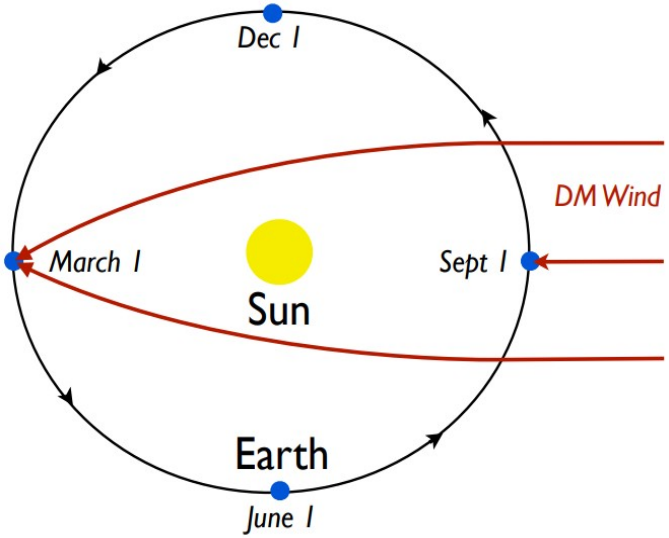
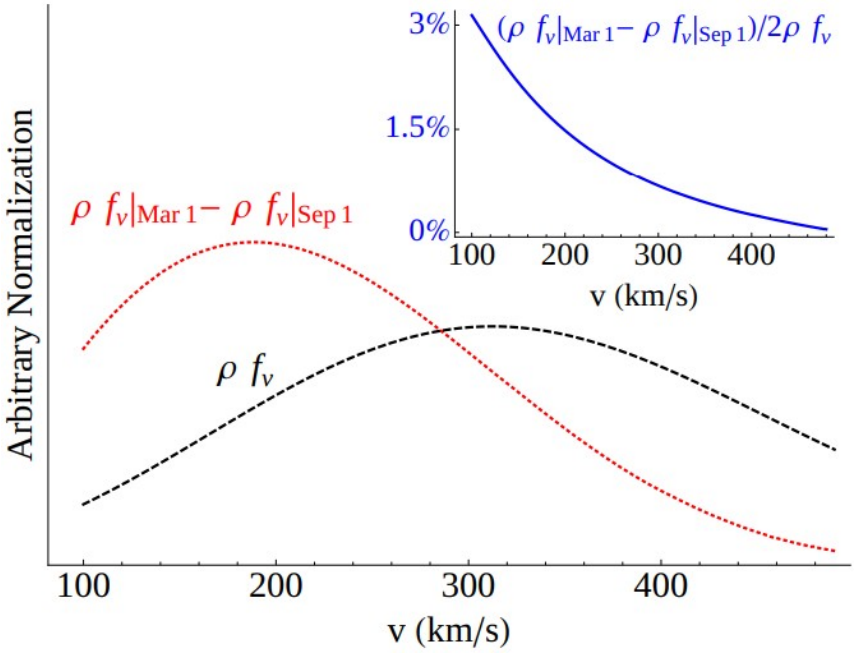
$$\langle (\boldsymbol{v}_{\nu c}\cdot\hat{\boldsymbol{k}})^2\rangle = \frac{1}{3}\int \frac{d|\boldsymbol{k}'|}{|\boldsymbol{k}'|}\Theta(|\boldsymbol{k}|-|\boldsymbol{k}'|)\left|\widetilde{W}(|\boldsymbol{k}'|R)\right|^2 \Delta^2_\zeta(\boldsymbol{k}')\left|\frac{T_{\theta_{\nu_i c}}(\boldsymbol{k}',z)}{|\boldsymbol{k}'|}\right|^2$$



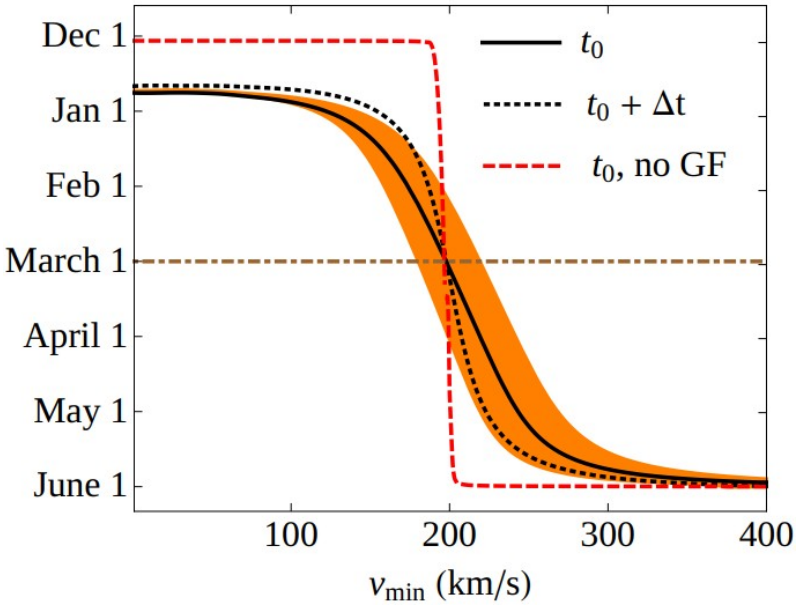
DM Gravitational Focusing



- **Density enhancement**



- **Modulation phase shift**



Lee, Lisanti, Peter, Safdi, Phys. Rev. Lett. 112, 011301 (2014) [arXiv:1308.1953]

Bozorgnia & Schwetz, JCAP 08 (2014) 013 [arXiv:1405.2340]