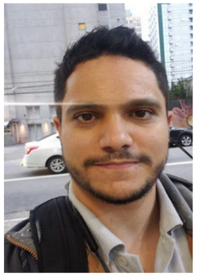
Neutrino Mass Measurement with Cosmic Gravitational Focusing

Shao-Feng Ge
葛韶锋
gesf@sjtu.edu.cn



Pedro Pasquini

Tan Liang

SFG, Pedro Pasquini, Liang Tan, **JCAP 05 (2024) 108** [arXiv:2312.16972]

上海交通大学 Shanghai Jiao Tong University

青岛高能大会
August 15, 2024

李政道研究所 Tsung-Dao Lee Institute

Outline

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1) Overview of ν Mass

2) 3rd Cosmological Way

Cosmic Gravitational Focusing

Dipole Structure in Galaxy Correlation Function

3) Summary

Neutrino Oscillation & Mass

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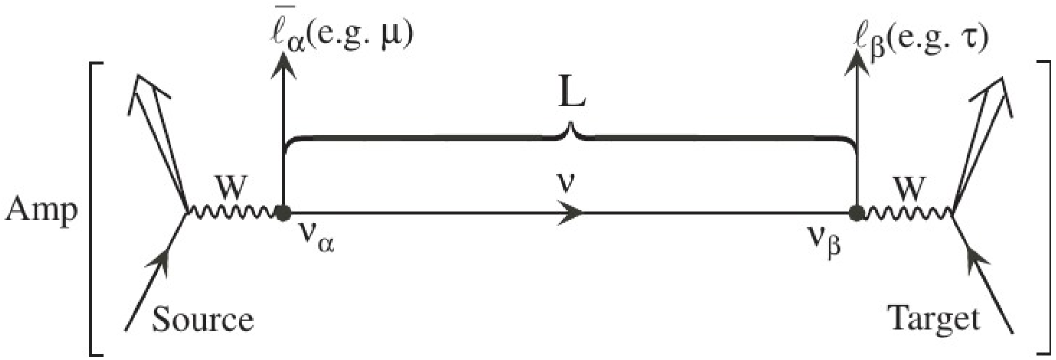
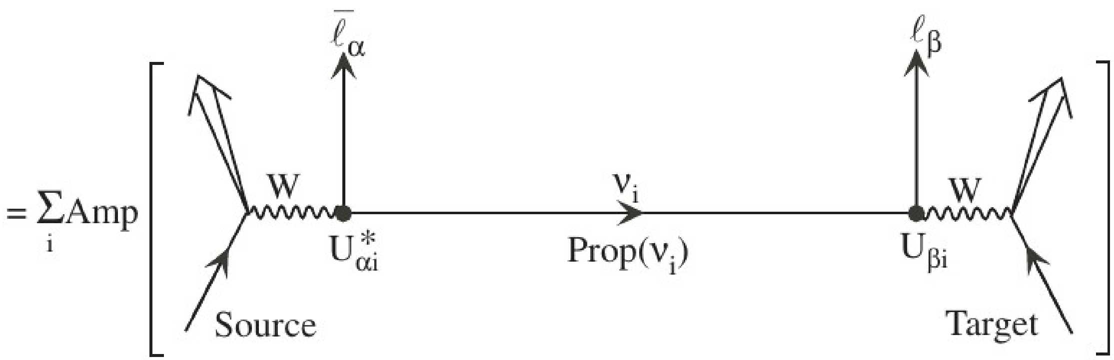




$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

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

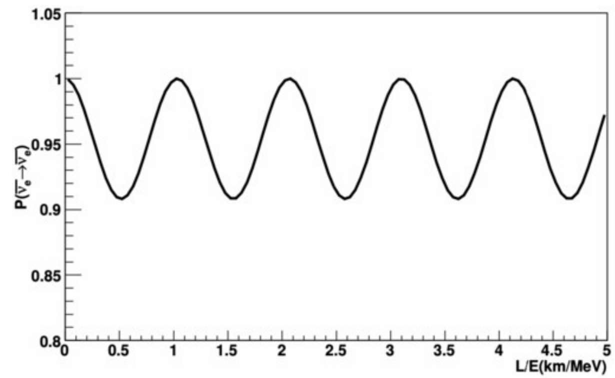
$$= \boxed{\sum_i U_{\alpha i} P_i U^\dagger_{\beta i} \nu_\beta}$$

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

B. Kayser, [hep-ph/0506165]

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

Mass



1st New Physics

Global Fit of Oscillation Parameters

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(for **NO**)	-1σ	Best Value	$+1\sigma$
$\Delta m_s^2 \equiv \Delta m_{21}^2\ (10^{-5}\mathrm{eV}^2)$	7.30	7.50	7.72
$\lvert\Delta m_a^2 \equiv \Delta m_{31}^2\rvert\ (10^{-3}\mathrm{eV}^2)$	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]

Seesaw Mechanism

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- **Heavy neutrinos (*N*)**

$$\bar{\nu} \mathrm{M_D} \mathcal{N} + h.c. + \overline{\mathcal{N}} \mathrm{M_N} \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & \mathrm{M_D} \\ \mathrm{M_D^T} & \mathrm{M_N} \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

required by **Grand Unification Theory (大统一理论)**

- **Seeaw Mechanism**

The diagonalization of the full mass matrix

$$\begin{pmatrix} 0 & \mathrm{M_D} \\ \mathrm{M_D^T} & \mathrm{M_N} \end{pmatrix} \Rightarrow M_\nu = -\mathrm{M_D} \frac{1}{\mathrm{M_N}} \mathrm{M_D^T}$$

$\mathrm{M_D} \sim O(100)$ GeV, $\mathrm{M_N} \sim O(10^{15})$ GeV $\to \mathrm{M}_\nu \sim O(0.01)$ eV

Light neutrino mass M_ν is suppressed by the heavy ones

Tsutomu Yanagida、Xiao-Gang He：
Let's play seesaw

Neutrino Mass Measurements

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ν Oscillation

Beta Decay

Radiative Emission of ν Pairs

SFG, Pedro Pasquini, **JHEP 12 (2023) 083** [arXiv:2306.12953]
Phys.Lett.B 841 (2023) 137911 [arXiv:2206.11717]
Eur.Phys.J.C 82 (2022) 3, 208 [arXiv:2110.03510]

Supernova ν Time Delay

SFG, Chui-Fan Kong, Alexei Smirnov, **accepted by PRL** [arXiv:2404.17352]

CνB Detection

CMB & LSS

SFG, Pedro Pasquini, Liang Tan, **JCAP 05 (2024) 108** [arXiv:2312.16972]

Neutrino Mass @ β Decay

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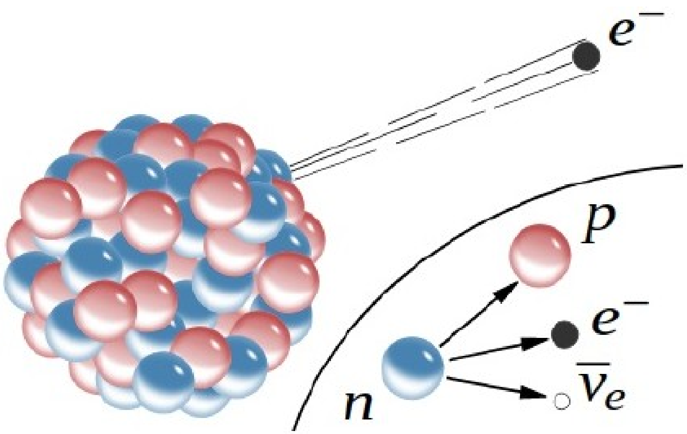

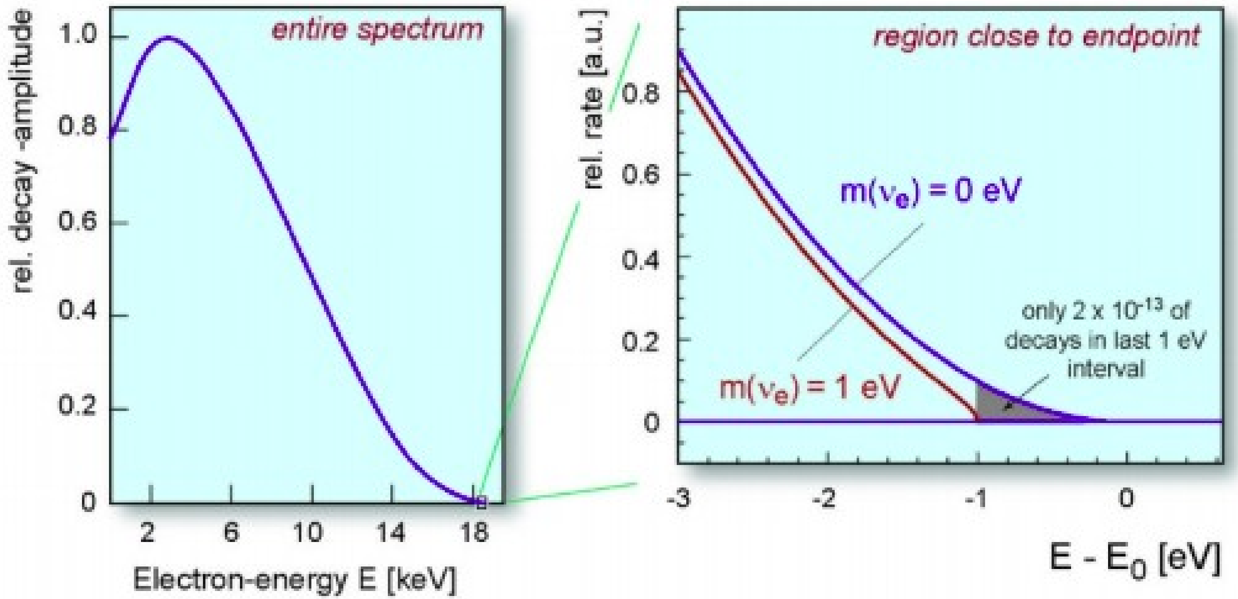

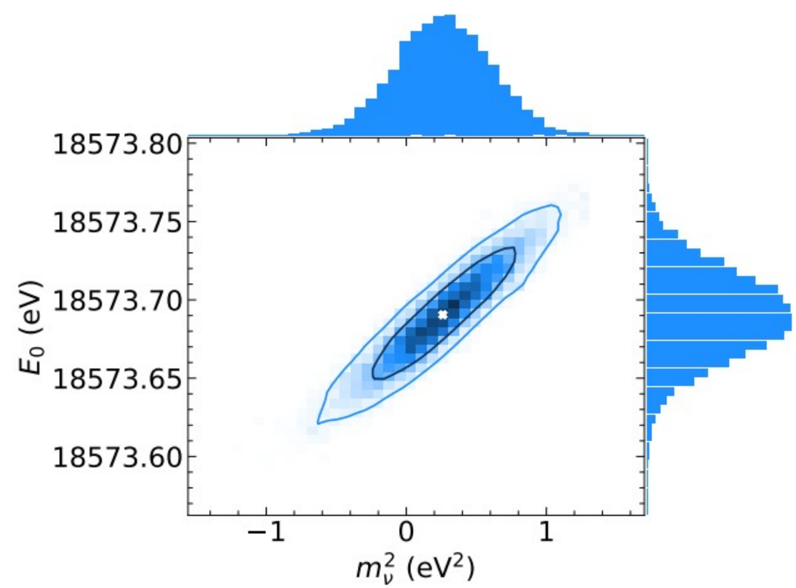

Nature Phys. 18 (2022) 2, 160-166

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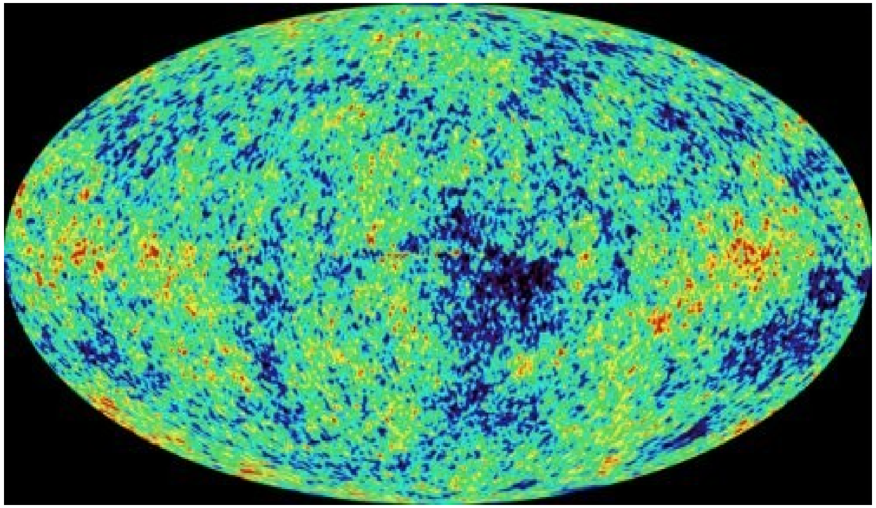
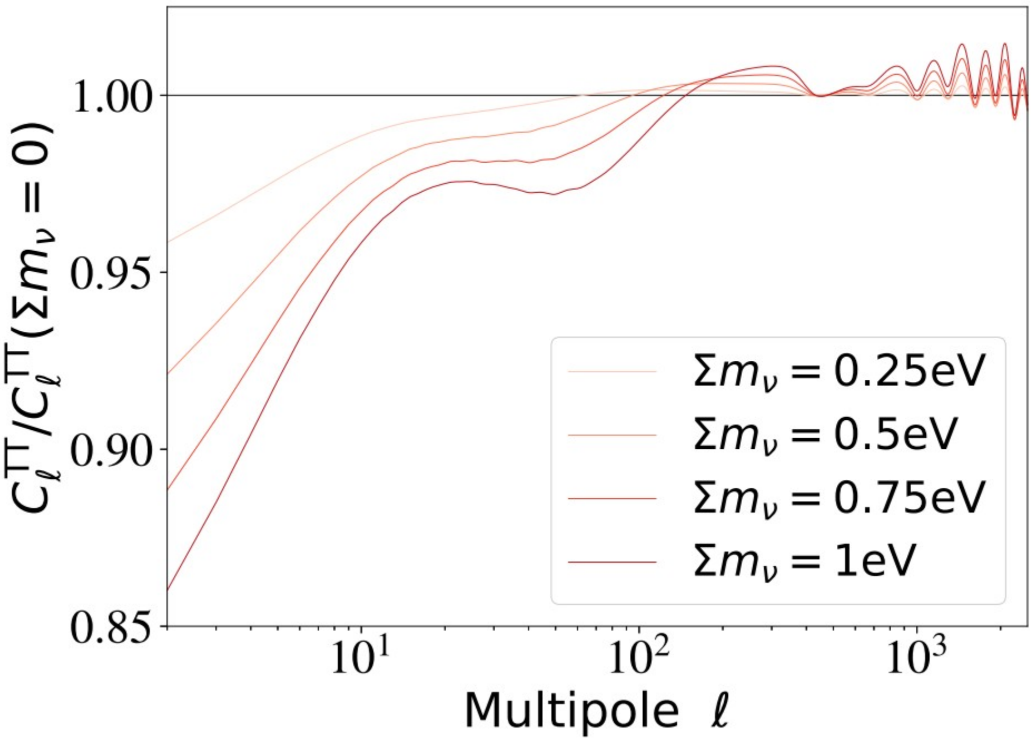
Massive neutrino decreasing CMB power spectrum



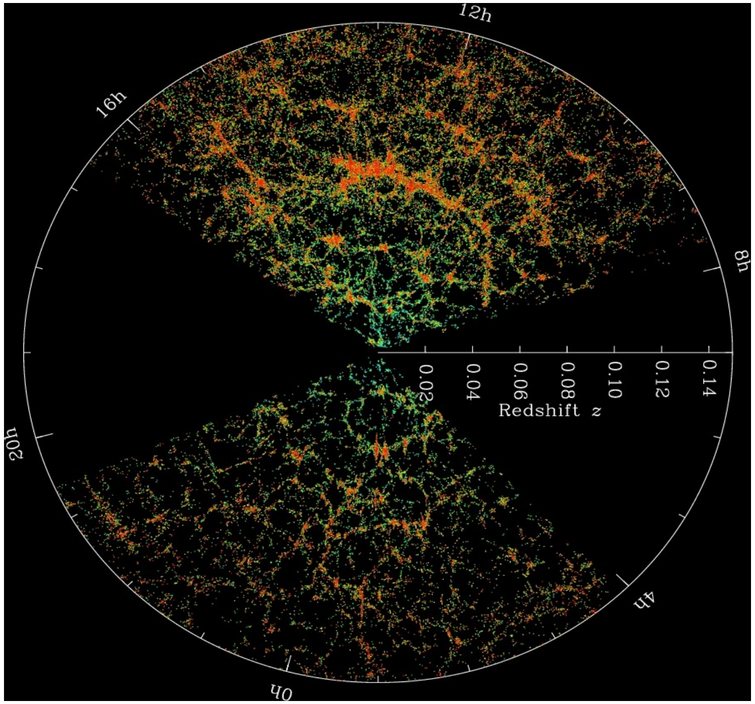


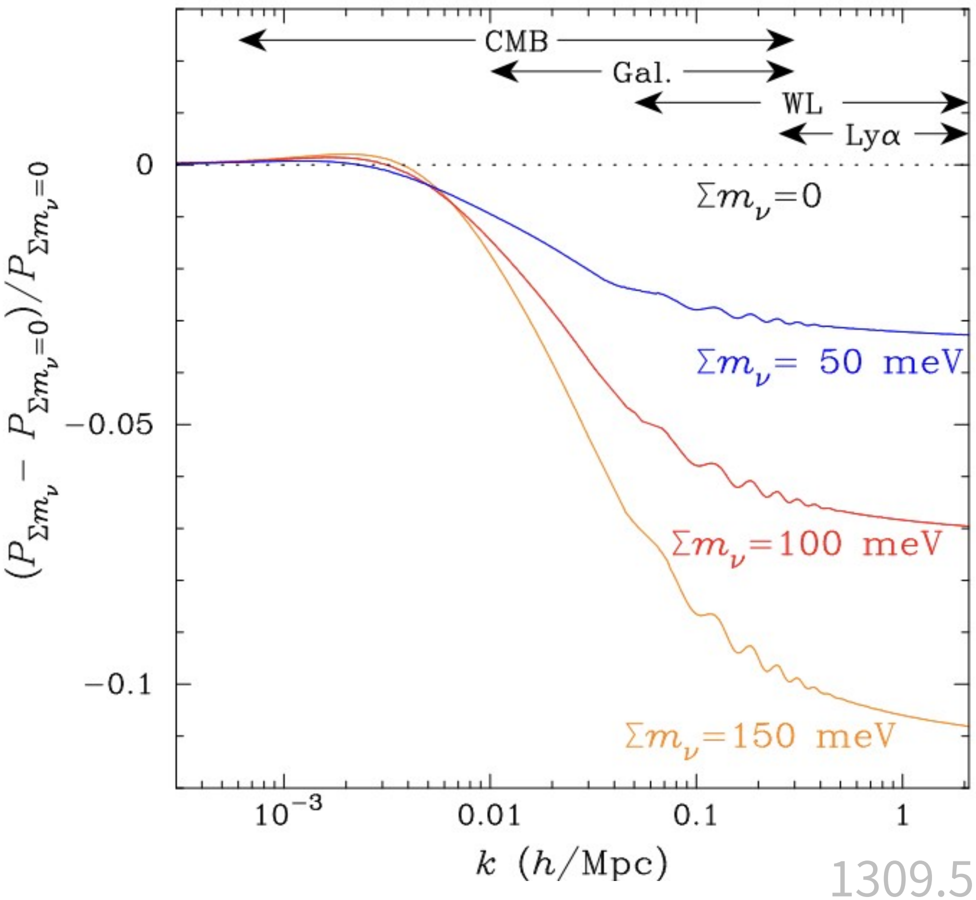
$$\rho_\nu = n_\nu \sum_i m_i$$

PDG 2022 Neutrino in Cosmology

LSS

Suppression matter power spectrum below neutrino free-streaming scale





1309.5383

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

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

Planck18+BAO

Cosmic ν Fluid (CνF) vs DM Halo

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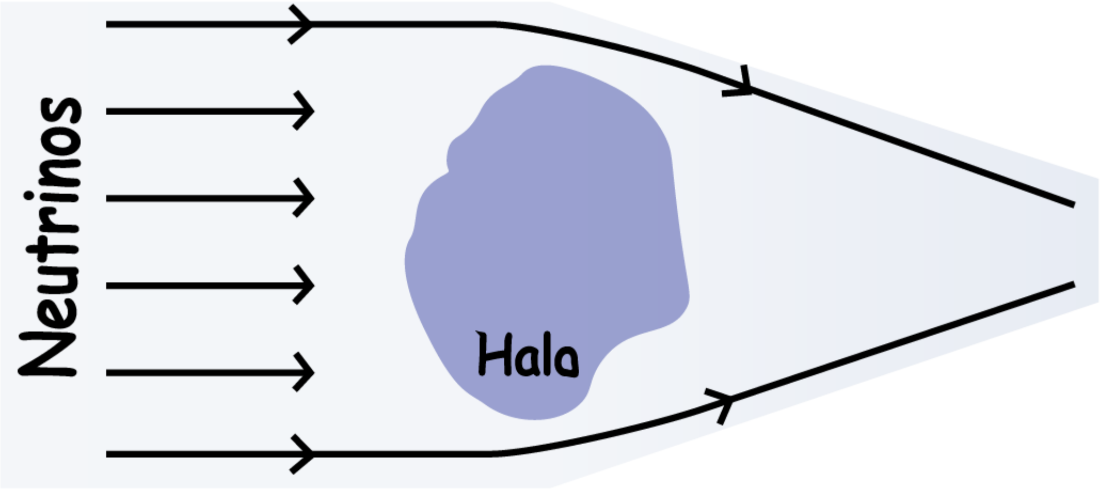
Gravitational attraction between DM halo & CνF



CνF

DM
Halo

vs Stone in Water Flow

Gravitational Deflection

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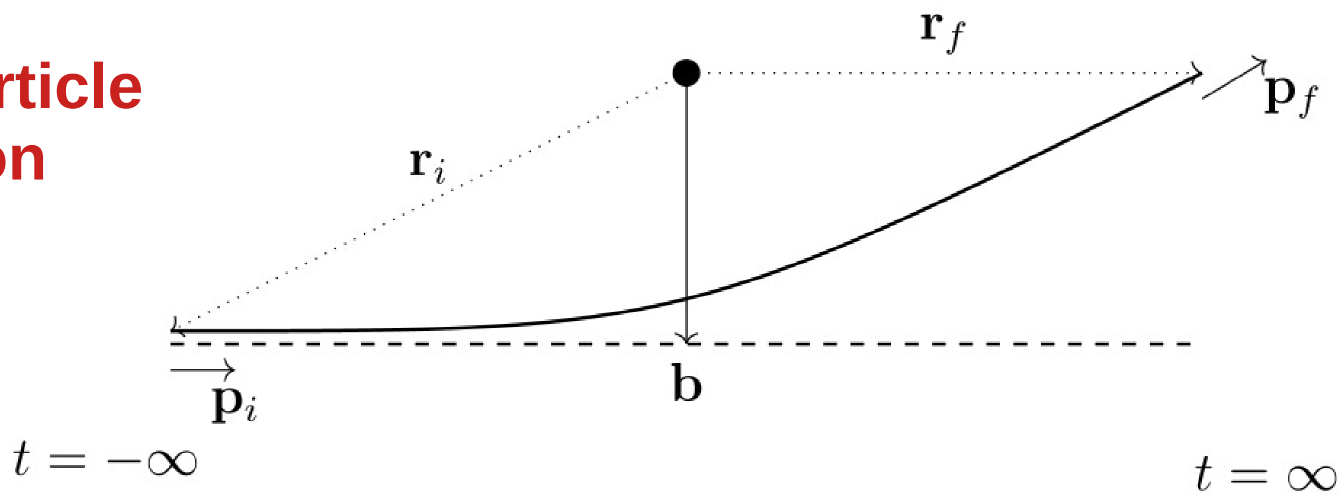
Single-particle description



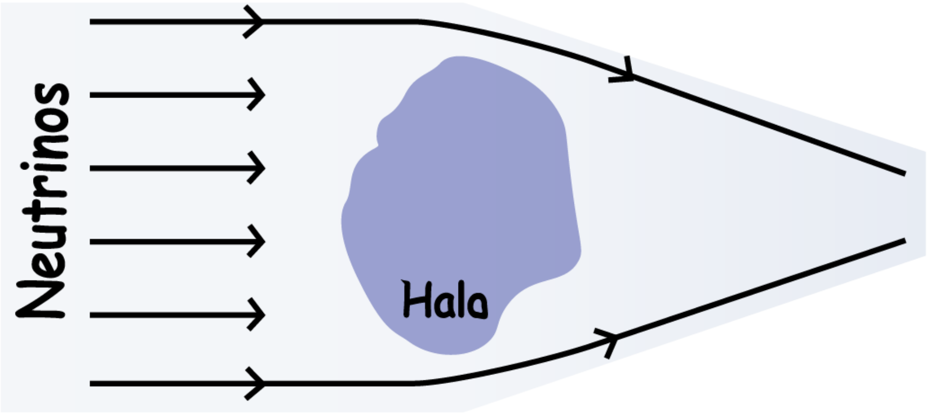
$$ds^2 \equiv -\left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

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

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

Dynamical Friction

Single-particle description



$$\Delta\phi \approx \pi + 2\frac{GM}{|\boldsymbol{b}|}\left(\frac{m_\nu^2}{|\boldsymbol{p}_i|^2}+2\right) \qquad f_\nu(\boldsymbol{p}_i,\boldsymbol{v}) \approx \frac{2}{e^{|\boldsymbol{p}_i - E_{\boldsymbol{p}_i}\boldsymbol{v}_{\nu c}|/T}+1}$$

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

Gravitational Focusing

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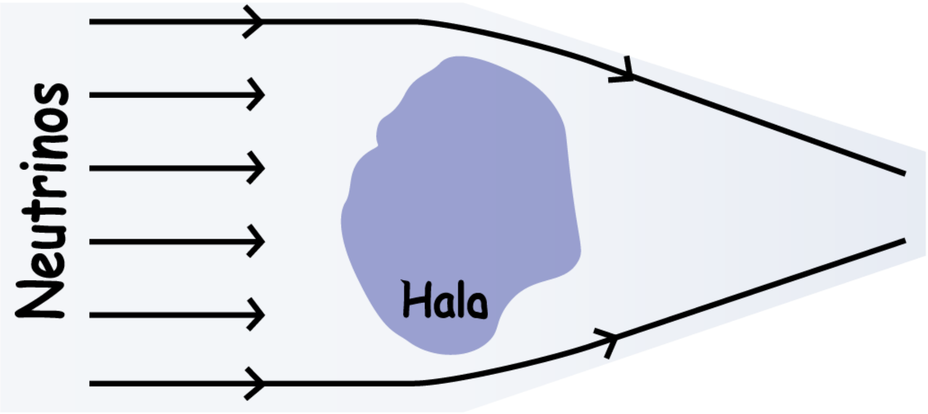

Boltzmann description

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

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

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

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

Cosmic Gravitational Focusing

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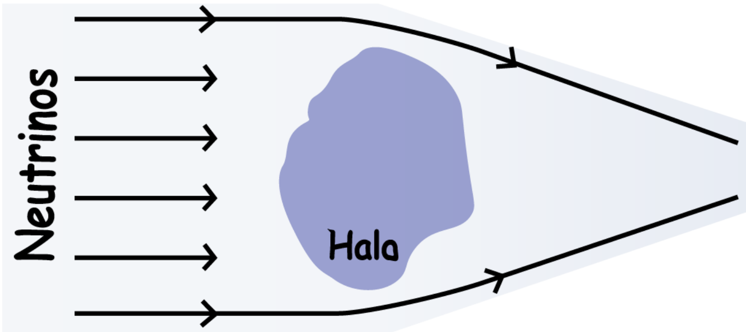
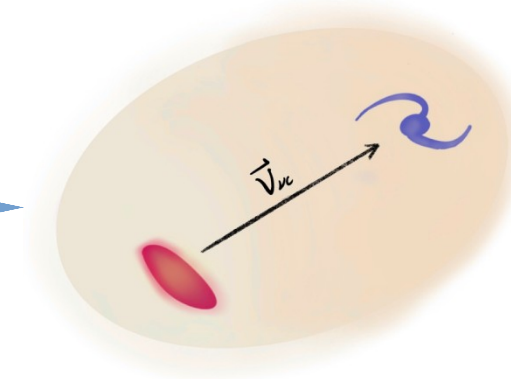




$$\delta_m = \delta_{m0} + \sum_{i=1}^{3} \frac{\delta\rho_{\nu_i}}{\rho_m}$$

Density enhancement downwind!

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

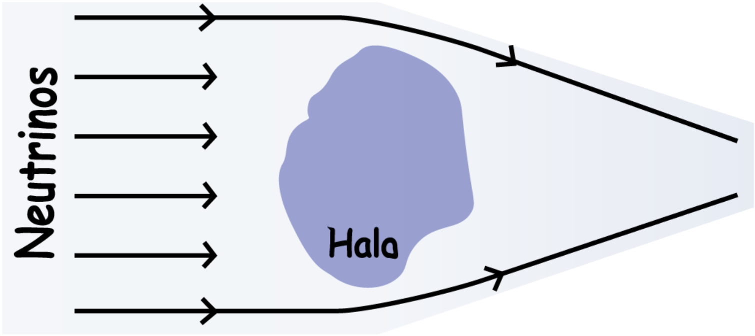
$$\widetilde{\delta}_m \equiv \widetilde{\delta}_{m0}(1 + i\widetilde{\phi})$$

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

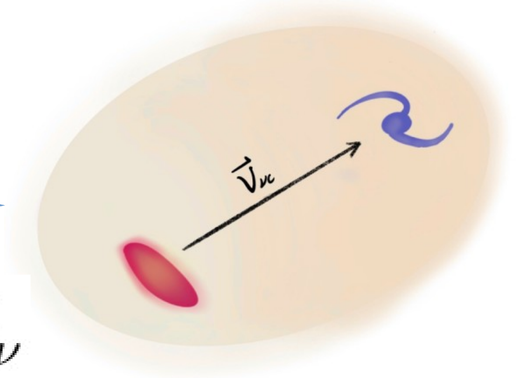
$$= -\int d\mathbf{x} e^{-i\mathbf{k}\cdot\mathbf{x}} A(\mathbf{x}) = -\widetilde{A}(\mathbf{k})$$

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

Galaxy Correlation & Bias



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



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

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

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

Galaxies with different bias $\Delta b \equiv b_c^\alpha - b_c^\beta$

Halo Mass Function & HOD for BGS

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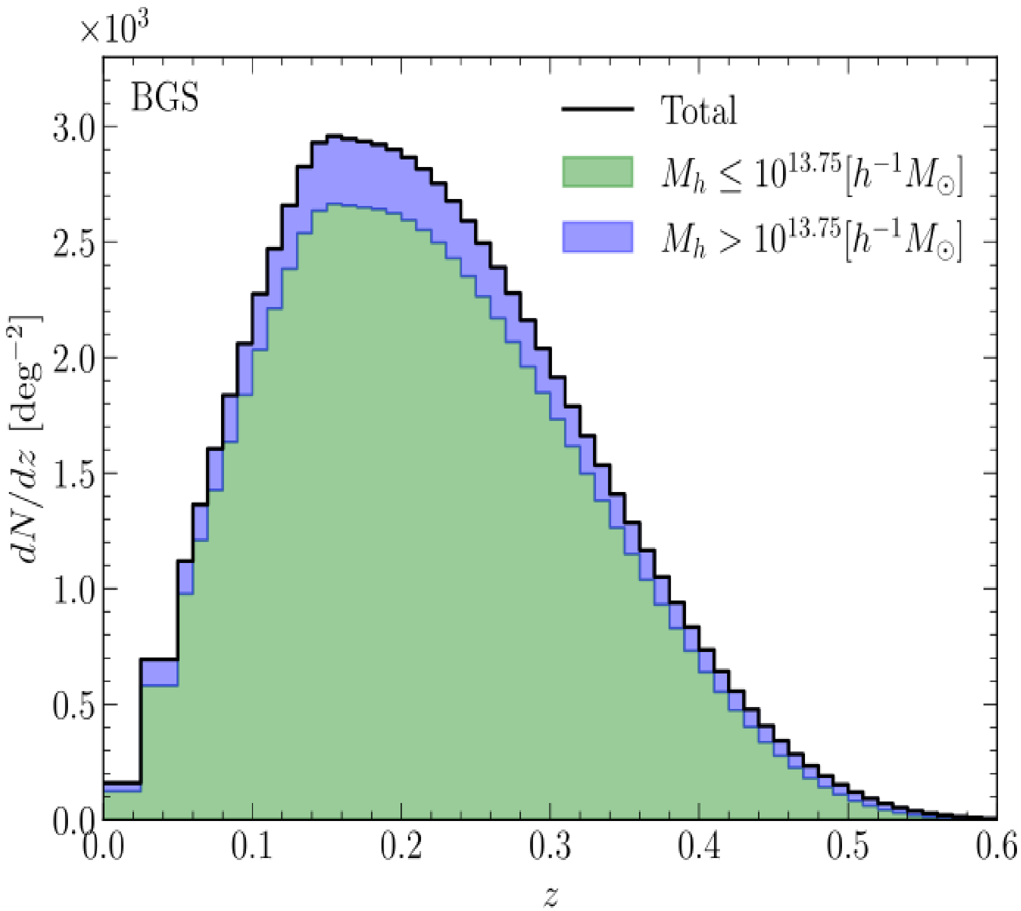

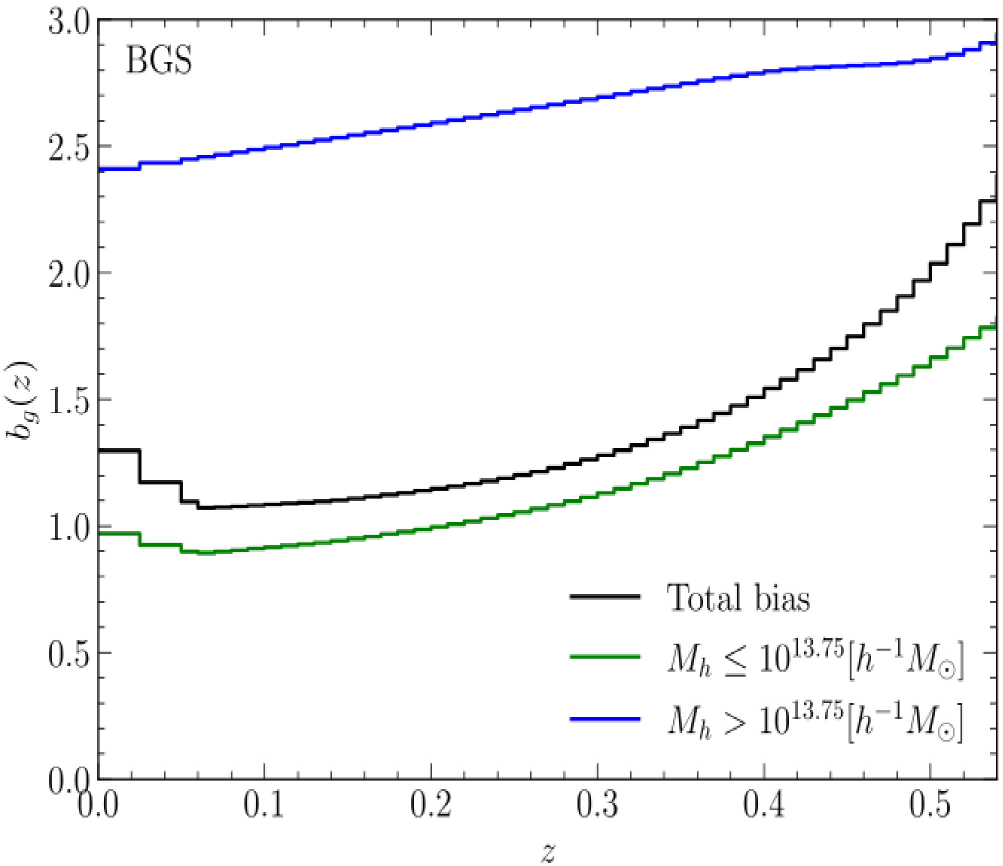

$$n_g(z) \equiv \int d\ln M_h \frac{dn(z)}{d\ln M_h} \langle N(M_h) \rangle \qquad b_g(z) \equiv \frac{1}{n_g} \int d\ln M_h \frac{dn(z)}{d\ln M_h} \langle N(M_h) \rangle b_h(M_h, z)$$

SNR @ DESI

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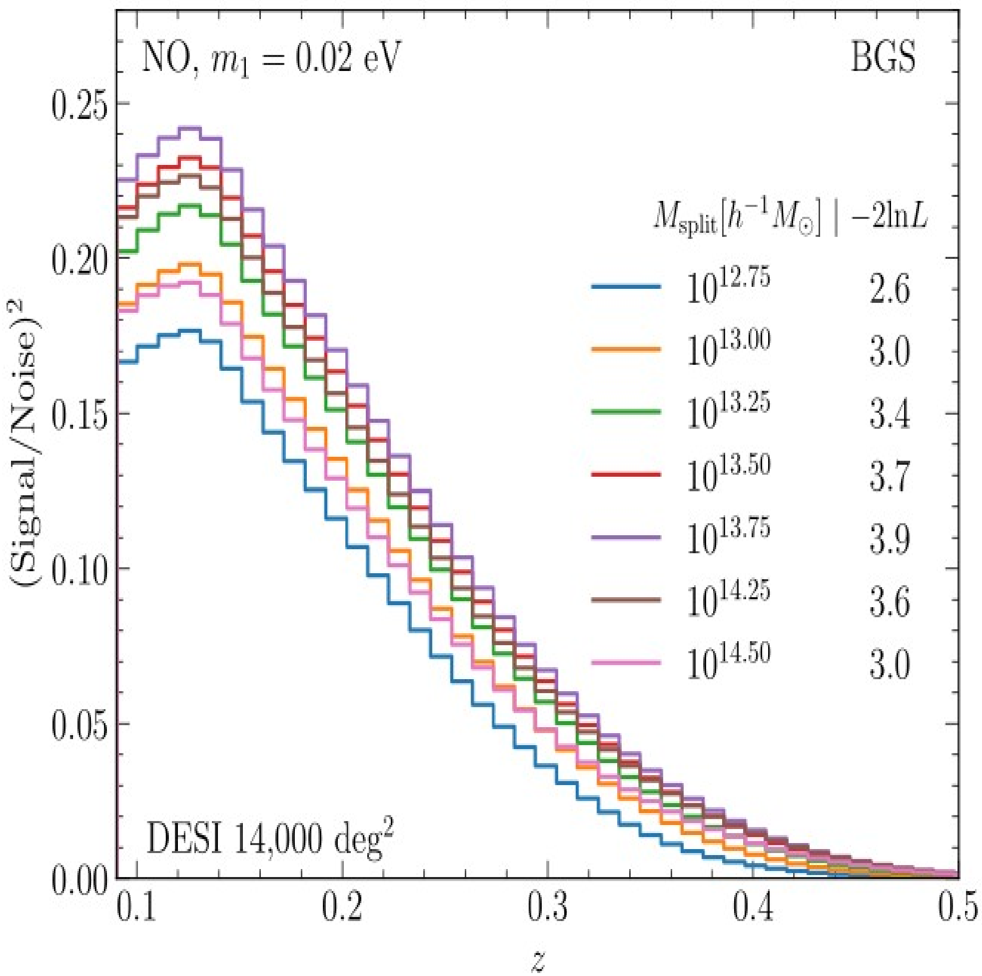
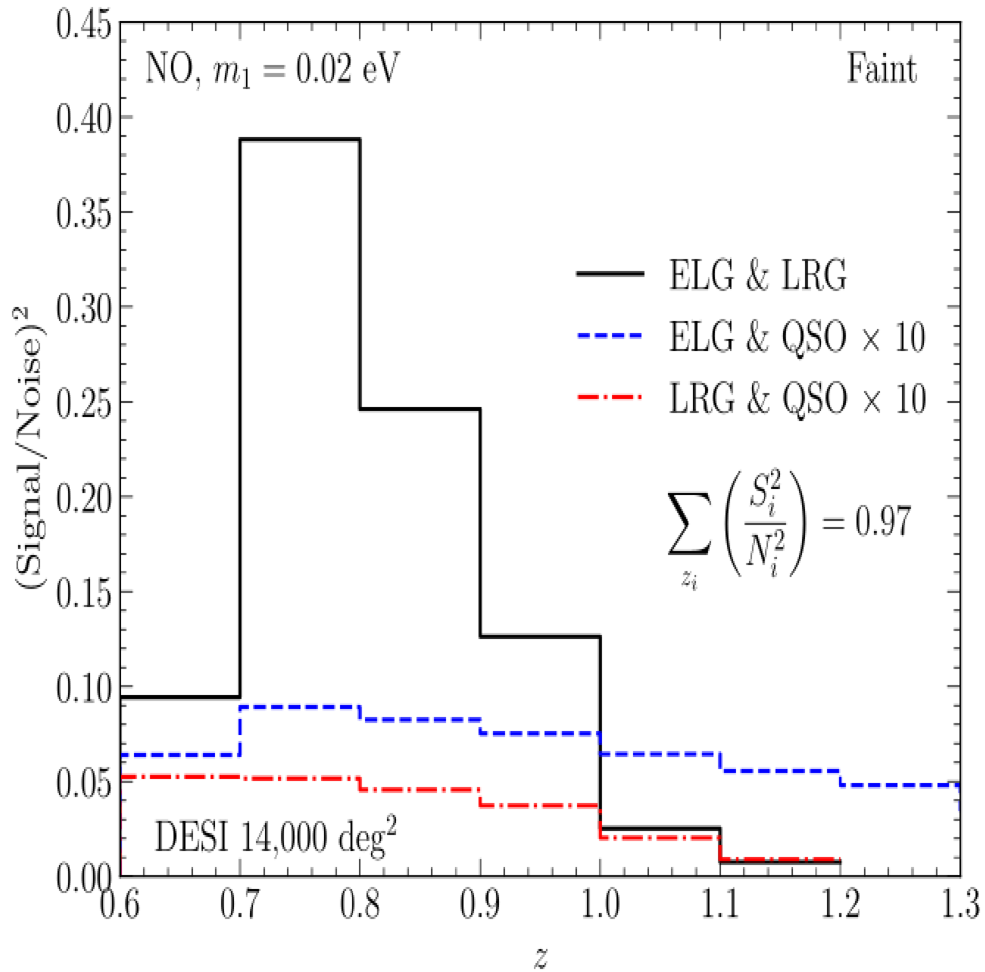
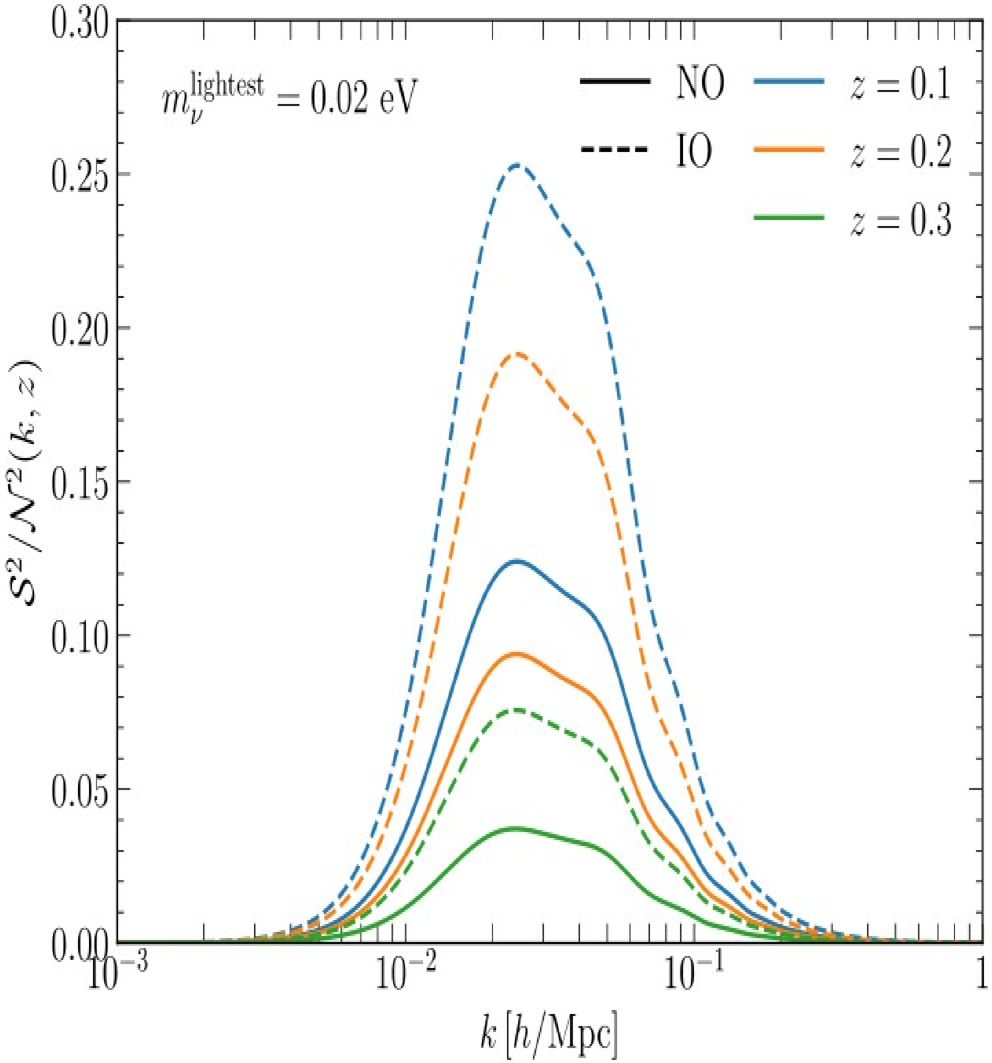
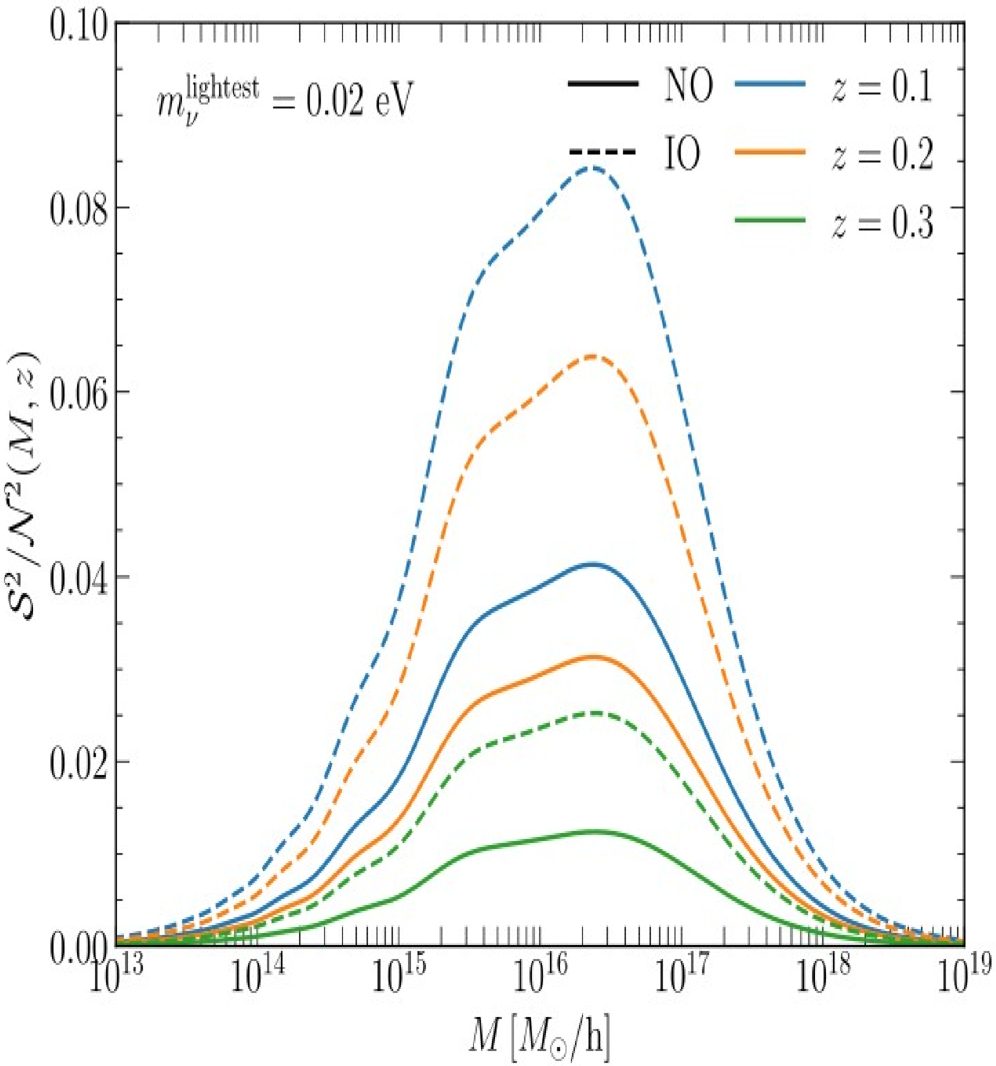




Redshift Distribution





3rd Cosmic Measurement of ν Masses

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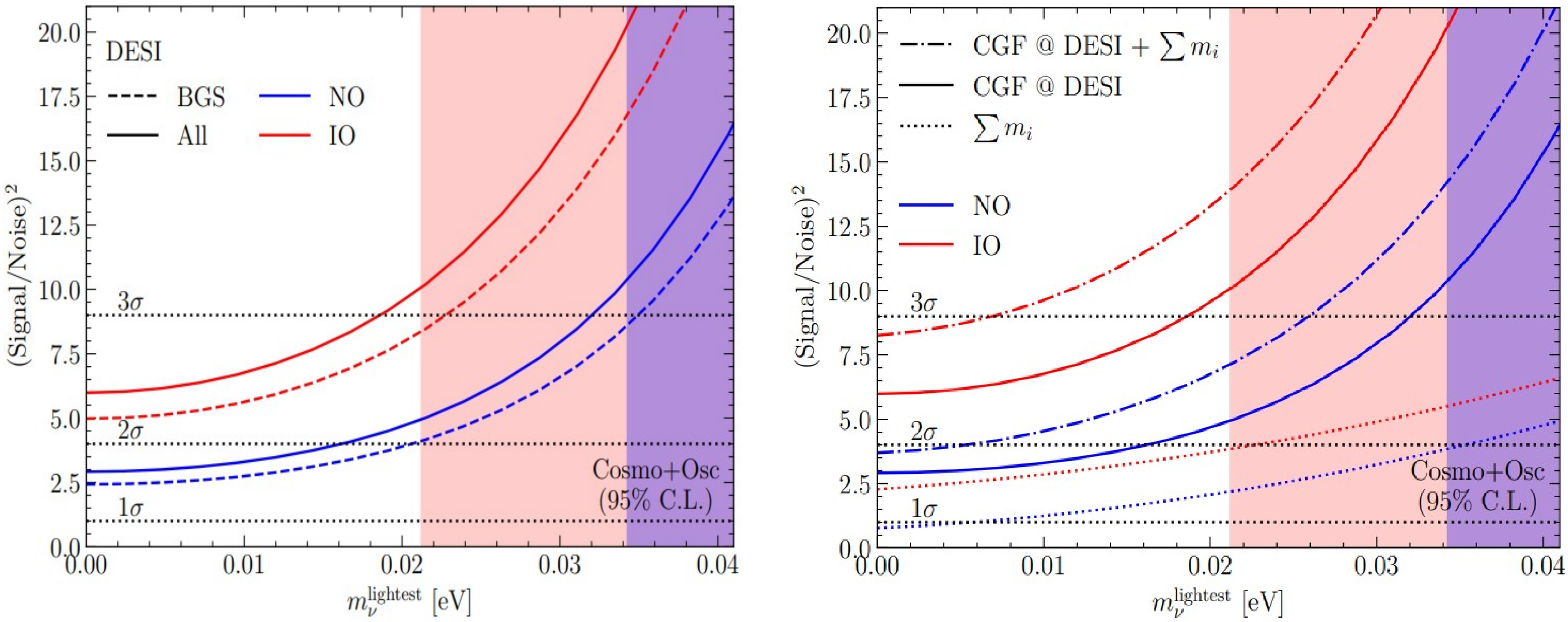
$$\mathrm{Im}\left[\tilde{\delta}_{g\alpha}\left(\tilde{\delta}_{g\beta}\right)^*\right] \propto \left(\mathbf{v}_{\nu c}\cdot\hat{\mathbf{k}}\right)\left(f_0 m_\nu^4 + f_1 m_\nu^2 T^2 + f_2 T^4\right)$$



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

3rd Cosmic Measurement of ν Masses

Tsung-Dao Lee Institute

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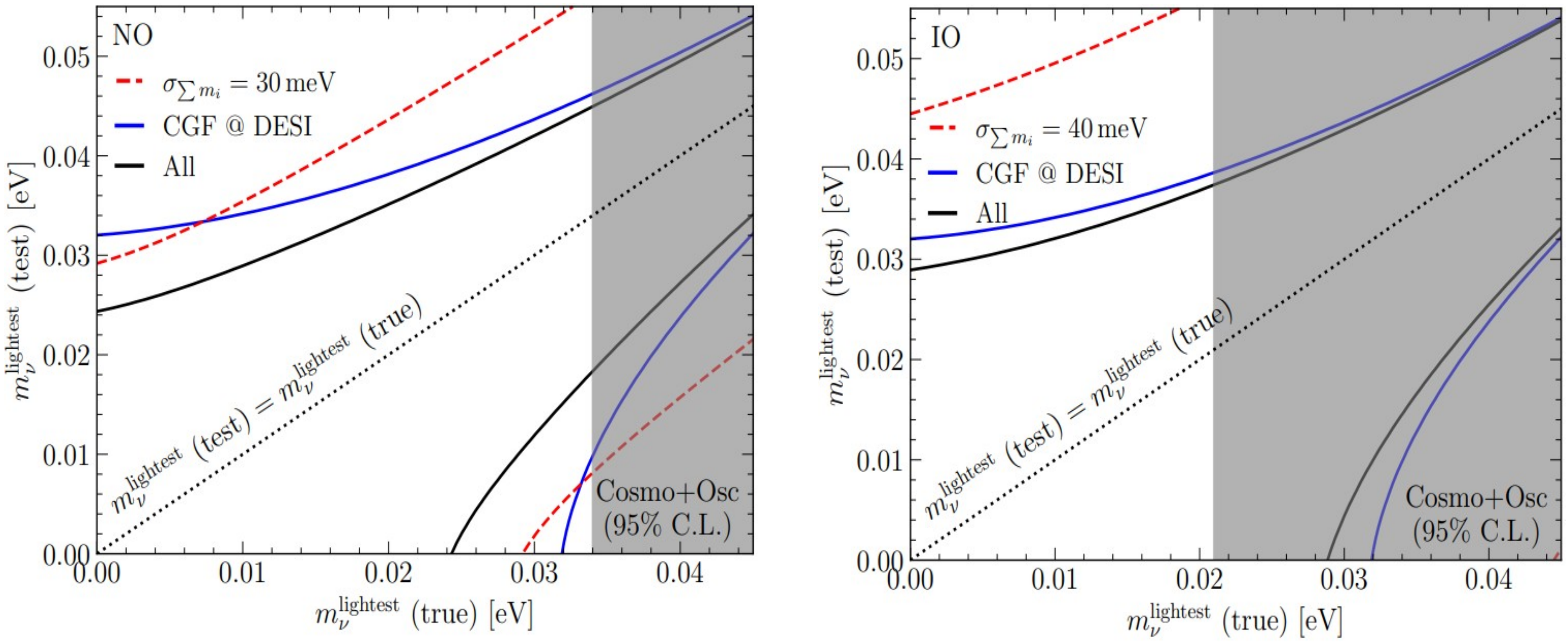


DESI, Euclid, Subaru PFS, **CSST**

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

Summary

1) Overview of Neutrino Mass

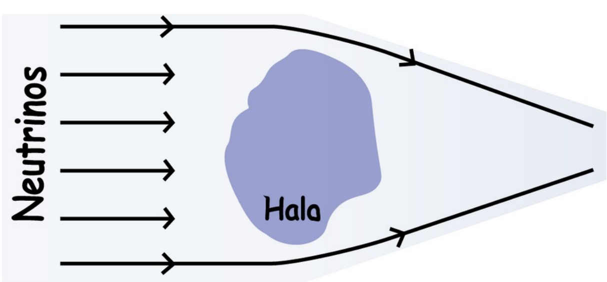
2) 3rd Cosmological Way

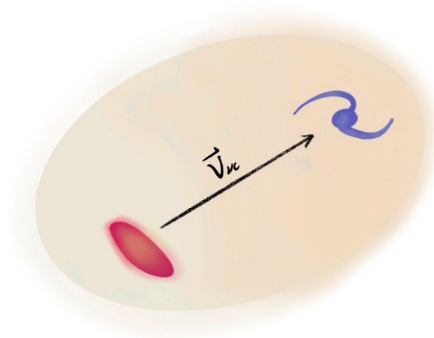
Dynamical Friction

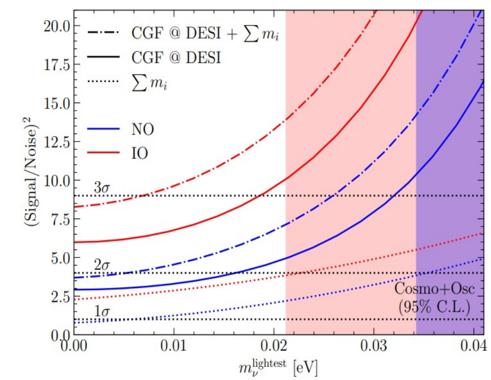
Cosmic Gravitational Focusing

Dipole Structure in Galaxy Correlation Function

Neutrino Mass Measurement @ DESI & CSST

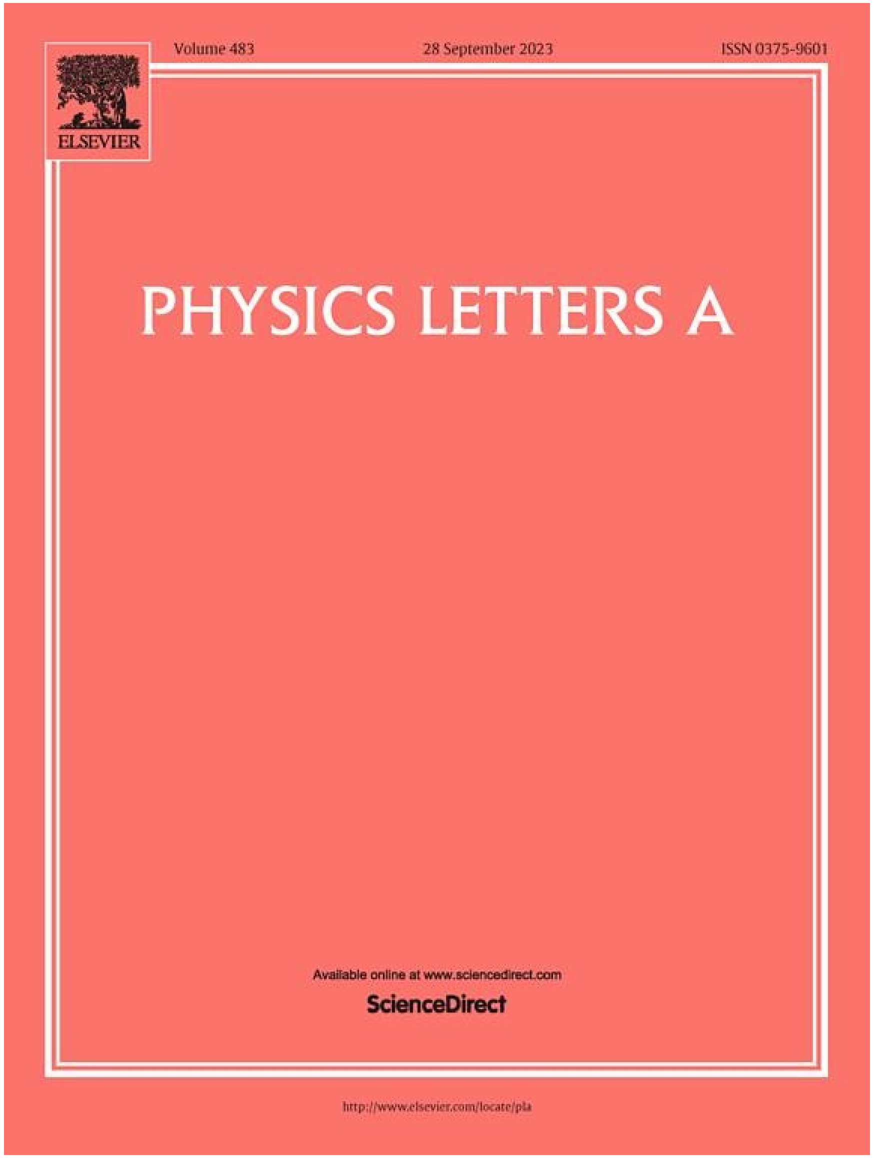






3) Summary

《 Physics Letters A 》



Aims & Scope

- Nonlinear science,
- Statistical physics,
- Mathematical and computational physics,
- AMO and physics of complex systems,
- Plasma and fluid physics,
- Optical physics,
- General and cross-disciplinary physics,
- Biological physics and nanoscience,
- Astrophysics, Particle physics and Cosmology.

Thank You

Minimal Neutrinos

Tsung-Dao Lee Institute

Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles

In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Neutrino vs Higgs

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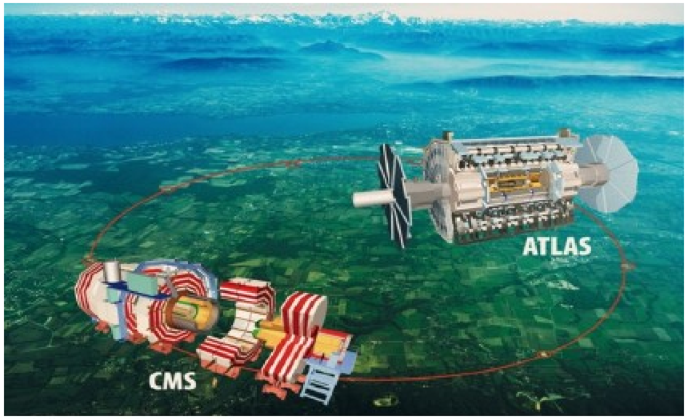
- **Higgs boson** ⇒ electroweak symmetry breaking & mass. ~ O(100)GeV
- **Chiral symmetry breaking** ⇒ majority of mass.
- The world seems not affected by the tiny neutrino mass?
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible **CP violation**
  - CP violation ⇒ **Leptogenesis**
  - ⇒ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - **EW Baryogenesis** is not enough.

Daya Bay @ **March 8, 2012**



LHC @ **July 4, 2012**

Decoherence & Non-Linear

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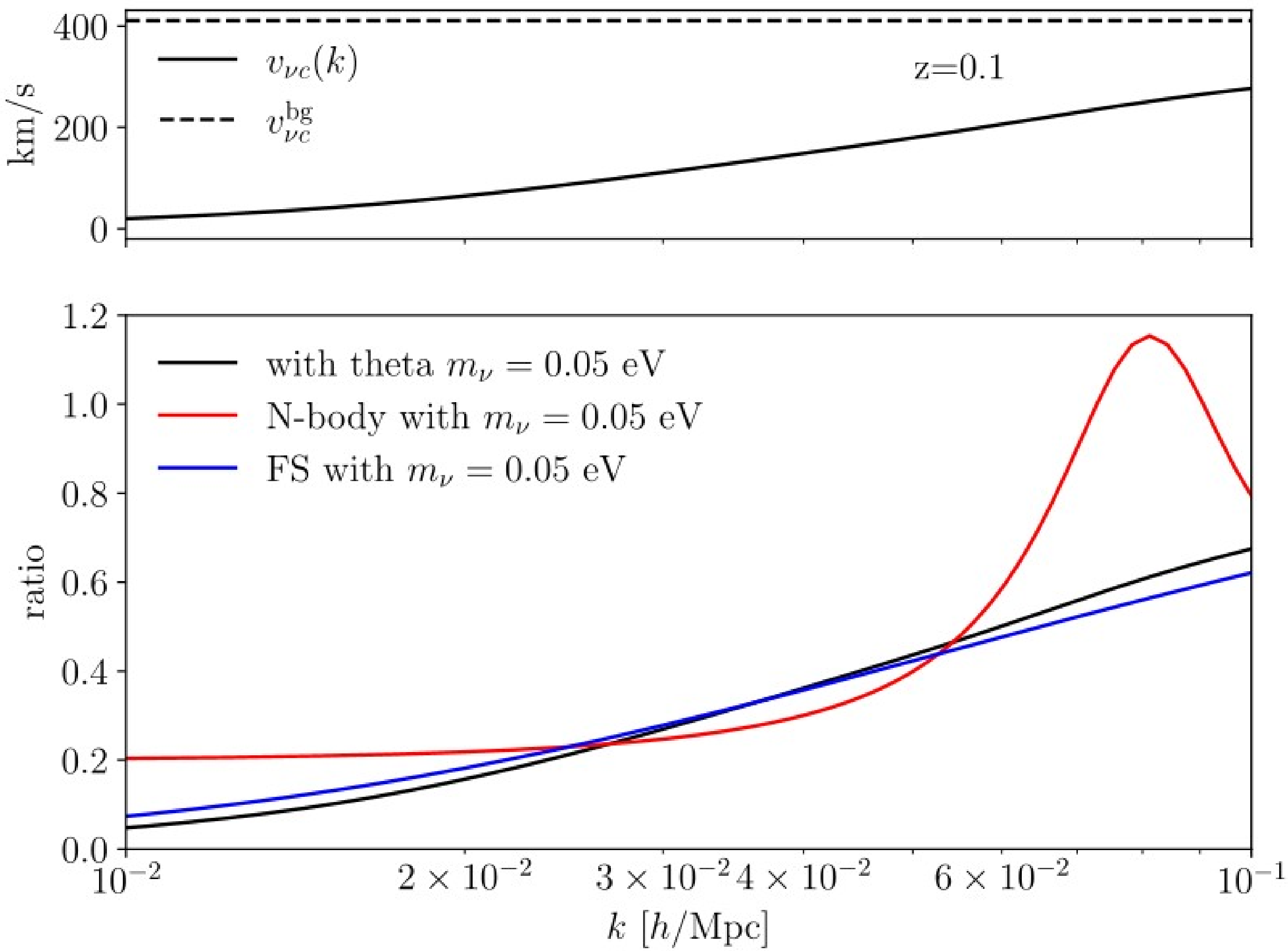
$$\langle(\boldsymbol{v}_{\nu c}\cdot\hat{\boldsymbol{k}})^2\rangle = \frac{1}{3}\int \frac{d|\boldsymbol{k}'|}{|\boldsymbol{k}'|}\Theta(|\boldsymbol{k}|-|\boldsymbol{k}'|)\left|\widetilde{W}(|\boldsymbol{k}'|R)\right|^2 \Delta_\zeta^2(\boldsymbol{k}')\left|\frac{T_{\theta_{\nu_i c}}(\boldsymbol{k}',z)}{|\boldsymbol{k}'|}\right|^2$$



DM Gravitational Focusing

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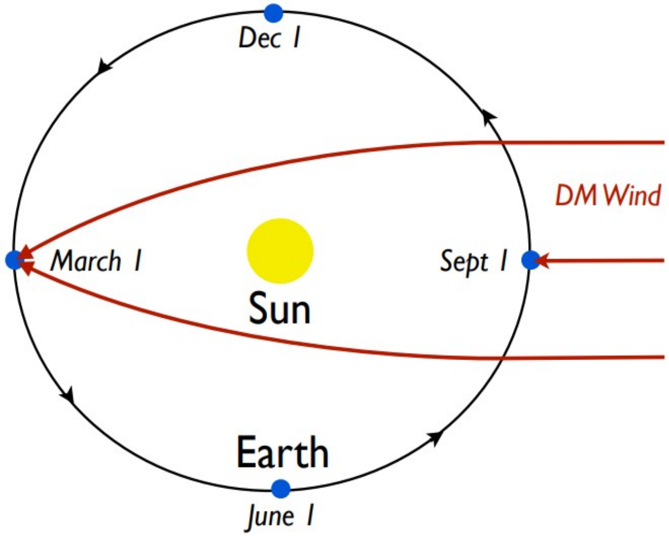
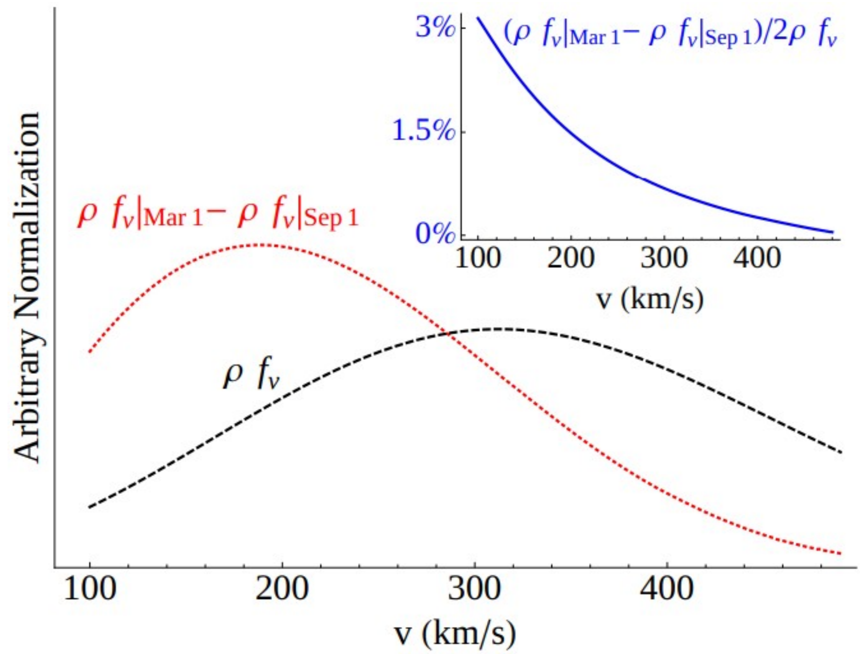
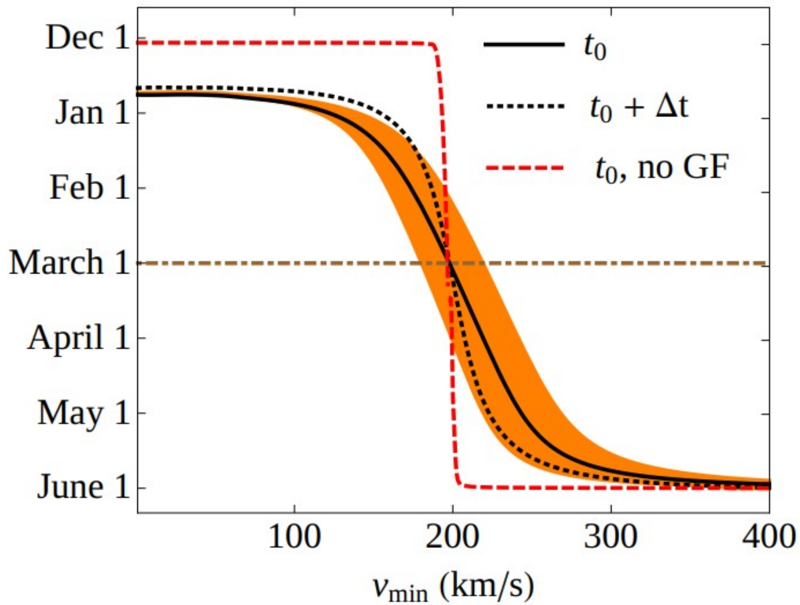


- **Density enhancement**



- **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]

ν Mass Ordering

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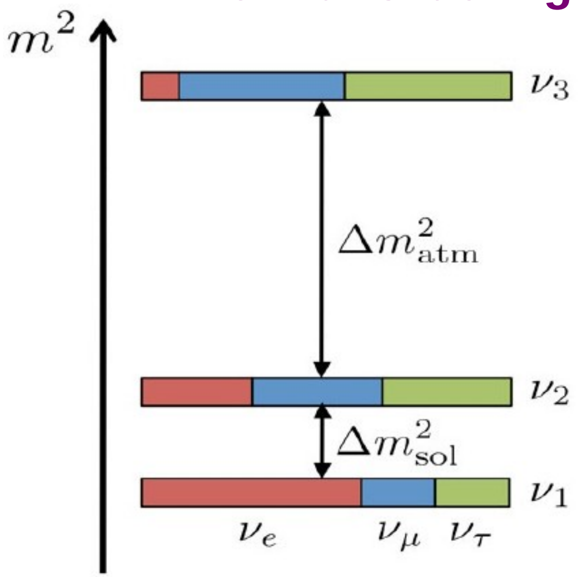
Normal Ordering (正序)



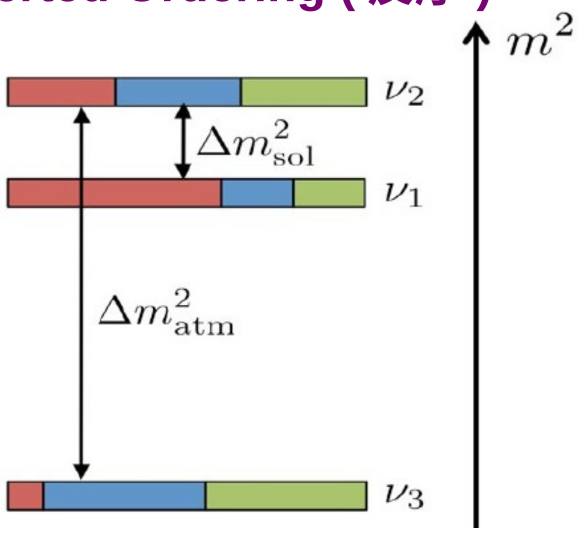
$$m_1 \lesssim m_2 < m_3$$

$$m_1$$

$$m_2 = \sqrt{m_1^2 + \Delta m_s^2}$$

$$m_3 = \sqrt{m_1^2 + \Delta m_a^2}$$

Inverted Ordering (反序)



$$m_3 < m_1 \lesssim m_2$$

$$m_1 = \sqrt{m_3^2 + \Delta m_a^2}$$

$$m_2 = \sqrt{m_3^2 + \Delta m_a^2 + \Delta m_s^2}$$

$$m_3$$

江门中微子实验 (JUNO)

However, ν oscillation experiment cannot measure the absolute mass!

ν Mass Hierarchy @ JUNO

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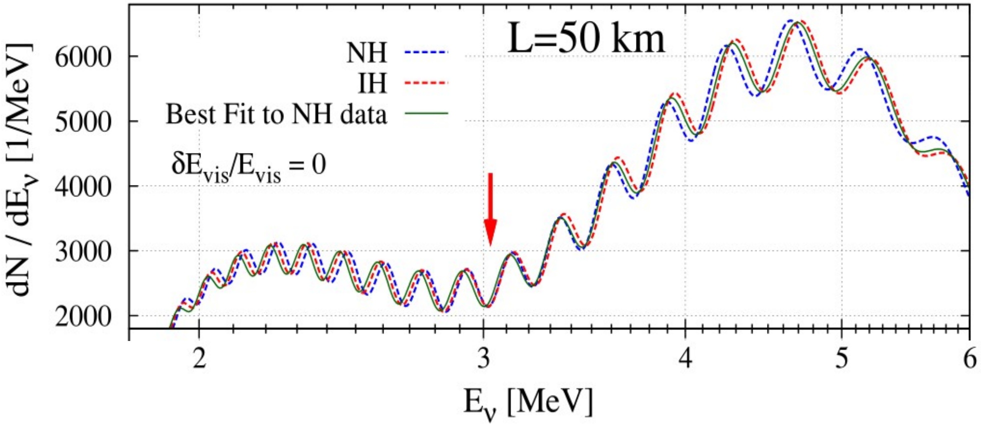
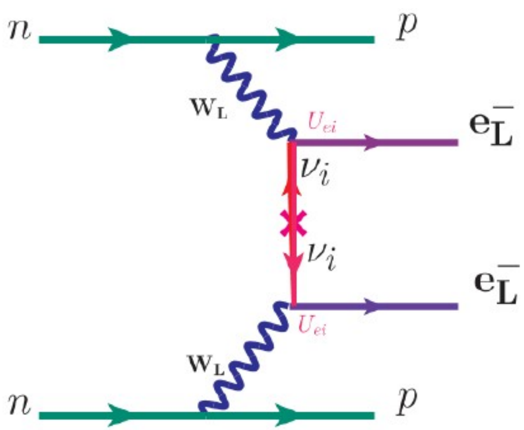
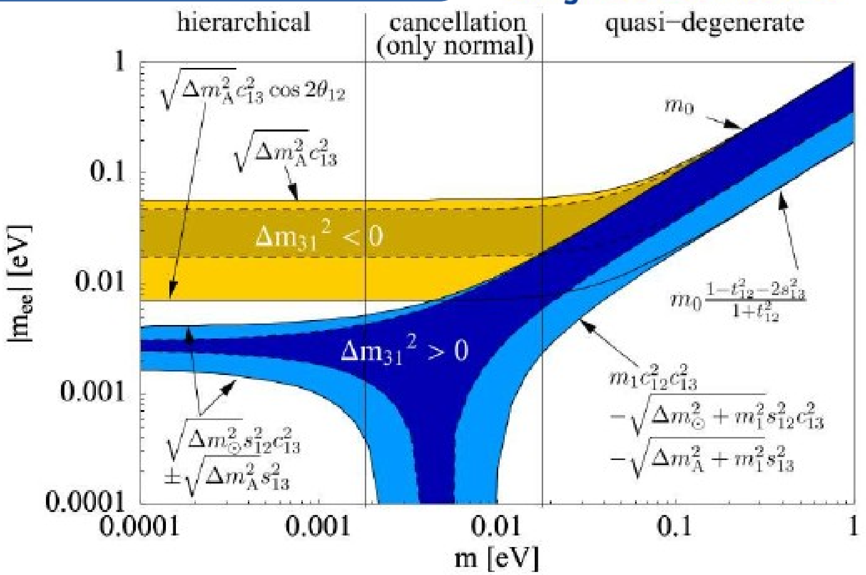


$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31}) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32})$$

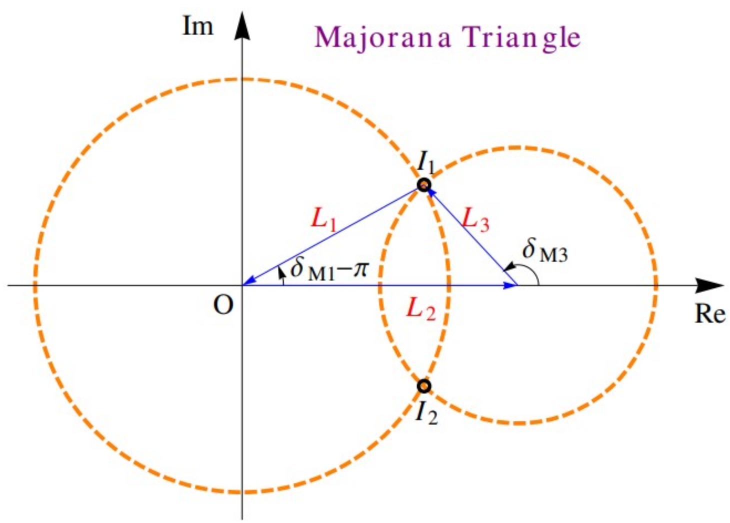
3 frequencies:

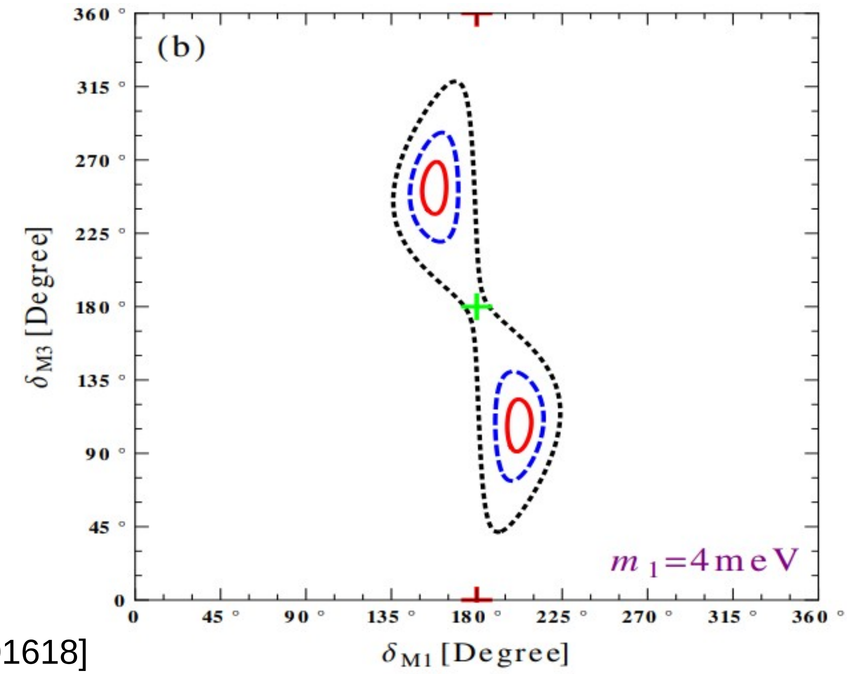
Neutrinoless Double Beta Decay





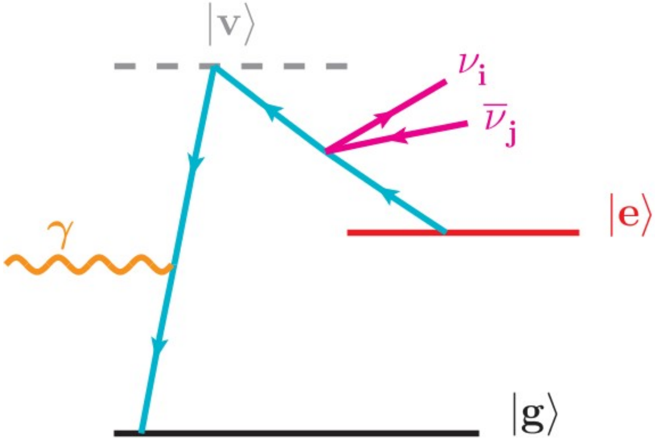
$$\langle m \rangle_{ee} \equiv \left| \sum_i m_i U_{ei}^2 \right| = \left| c_s^2 c_r^2 m_1 e^{i\delta_{M1}} + s_s^2 c_r^2 m_2 + s_r^2 m_3 e^{i\delta_{M3}} \right|$$





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

Radiative Emission of ν Pairs

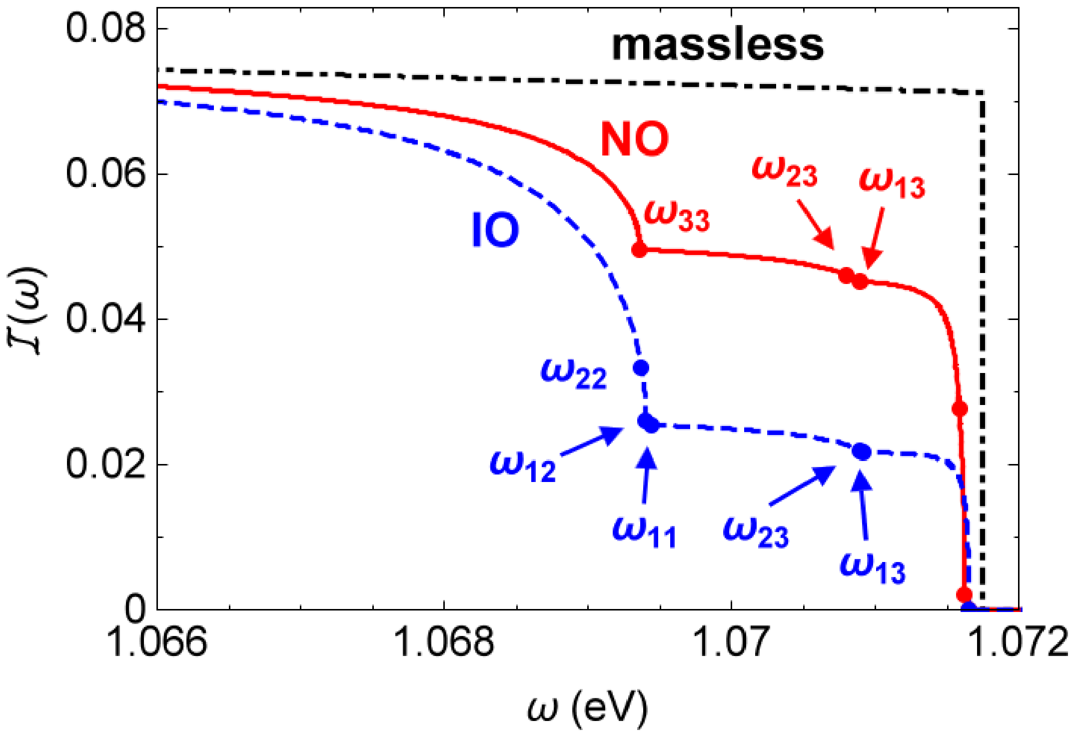


$$|e\rangle \to |v\rangle + \nu\bar{\nu}$$

$$\text{E1} \times \text{M1}$$

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

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

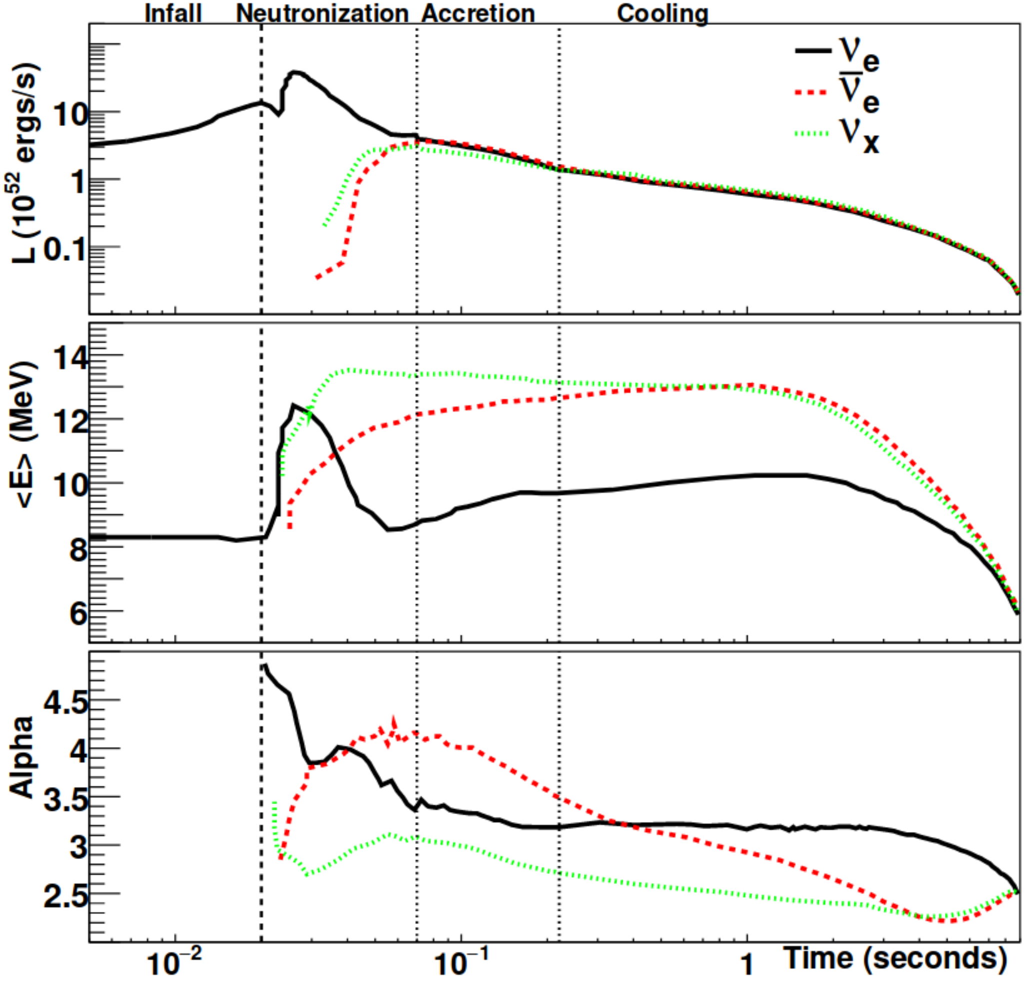


$$\omega_{ij}^{\max} \equiv \frac{E_e - E_g}{2} - \frac{1}{2}\frac{(m_i + m_j)^2}{(E_e - E_g)}$$

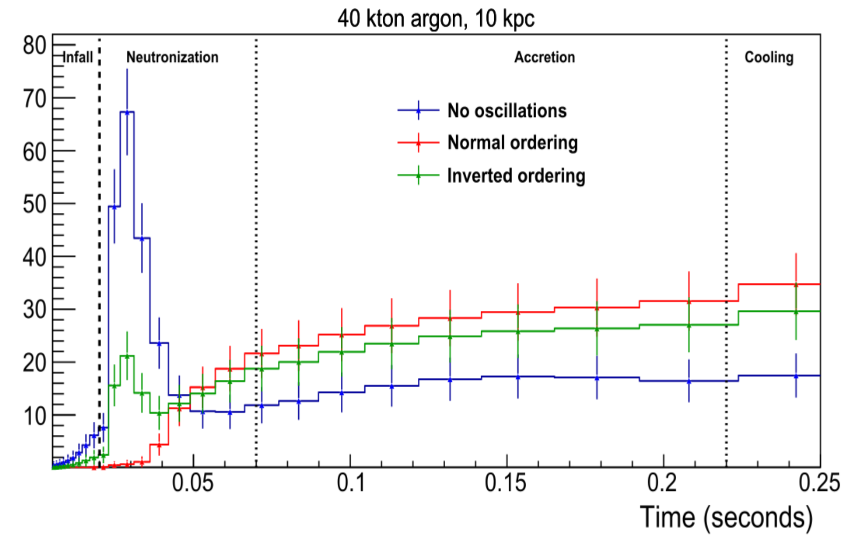
SFG & Pasquini
Eur.Phys.J.C 82 (2022) 3, 208;
Phys.Lett.B 841 (2023) 137911;
JHEP 12 (2023) 083

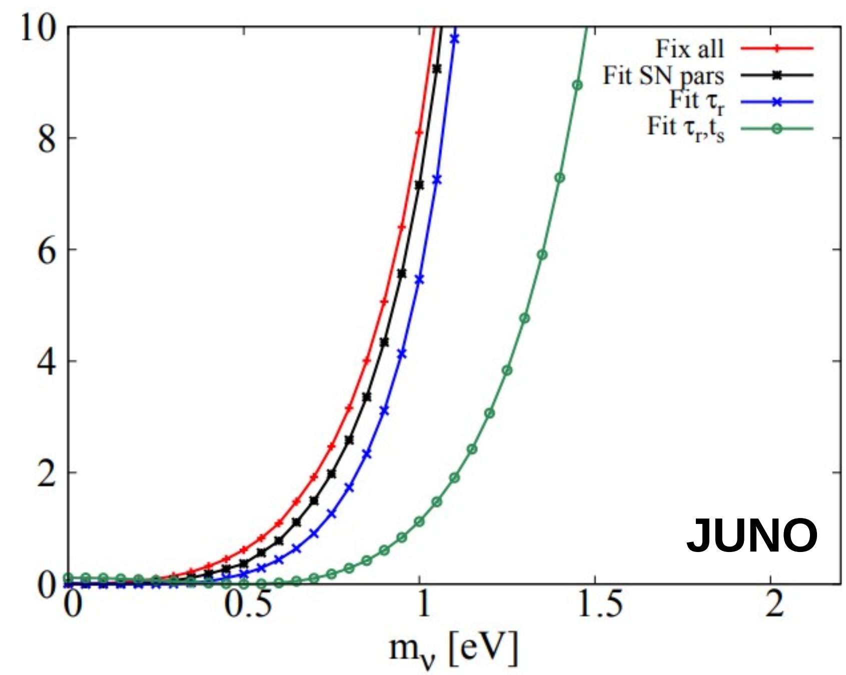
Time Delay in Supernova ν's

李政道研究所 Tsung-Dao Lee Institute



DUNE, 2008.06647

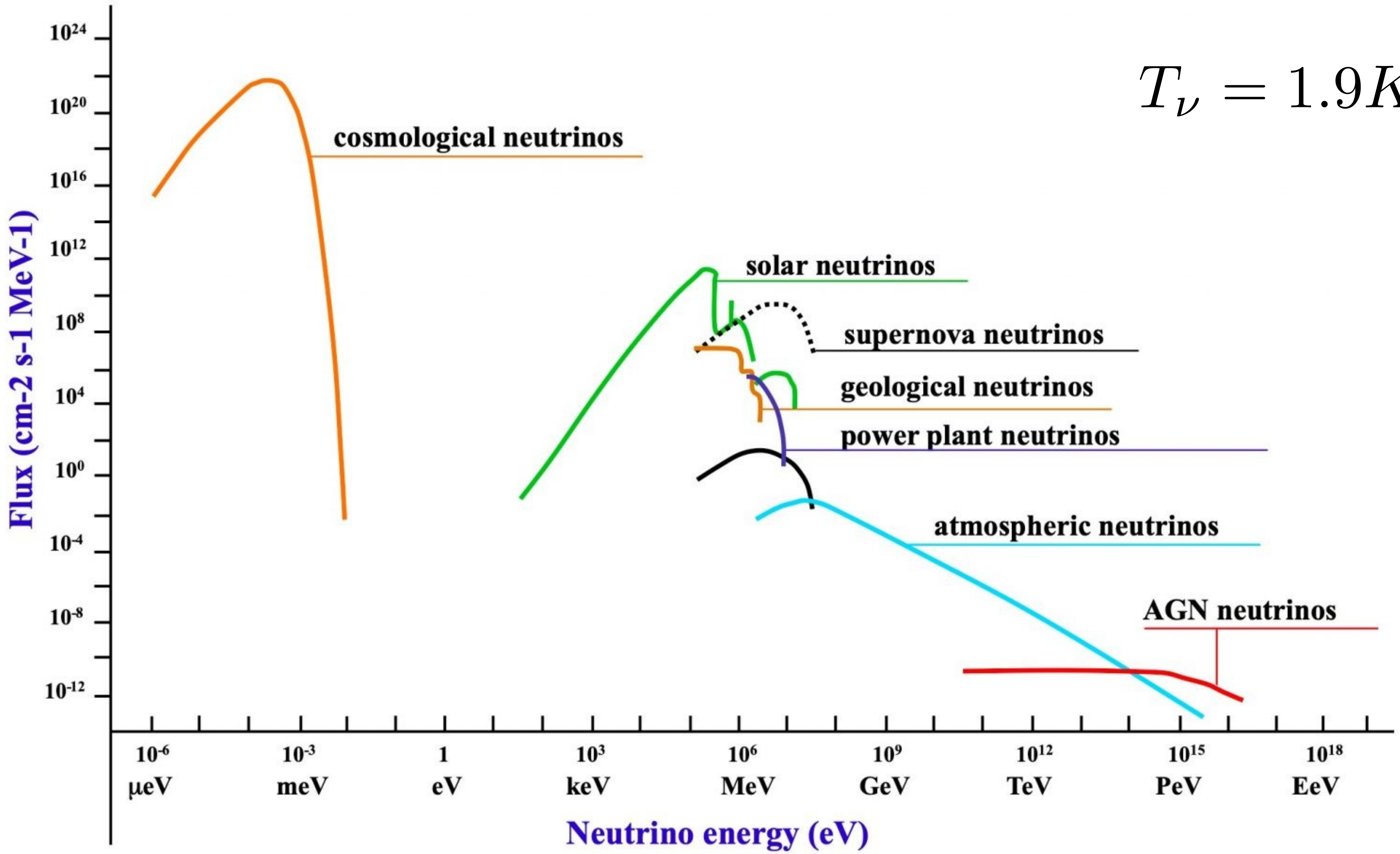




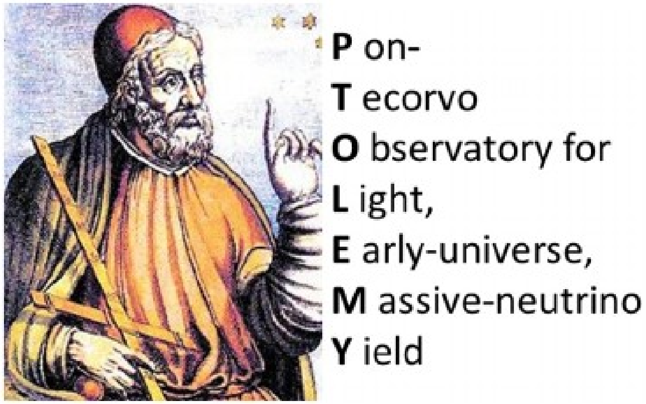
SFG, Chui-Fan Kong, Alexei Smirnov,
accepted by PRL [arXiv:2404.17352]

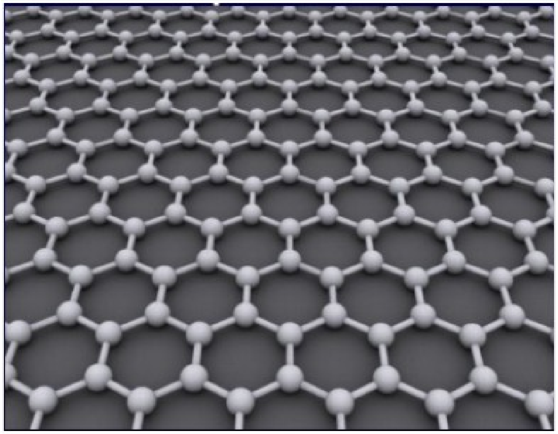
Lu, Cao, Li & Zhou [JCAP 05 (2015) 044]

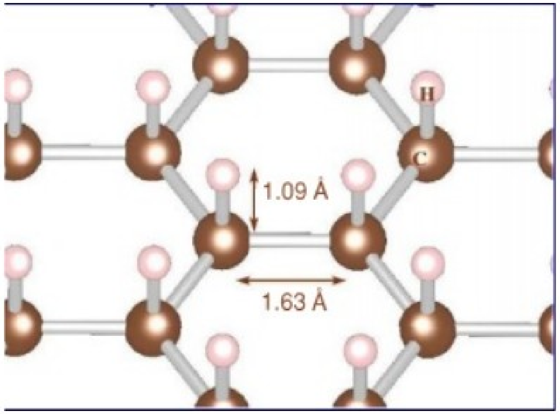
Cosmic ν Background



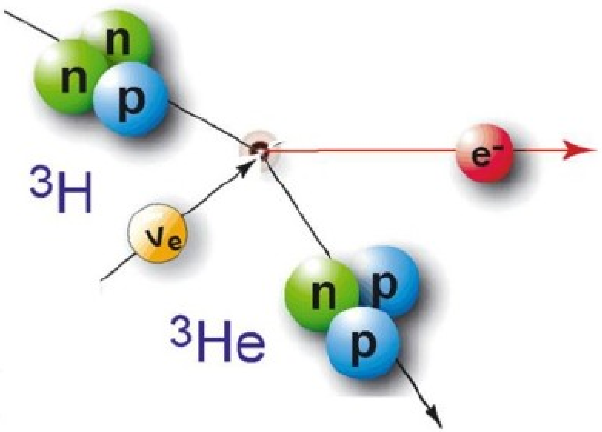
PTOLEMY Experiment

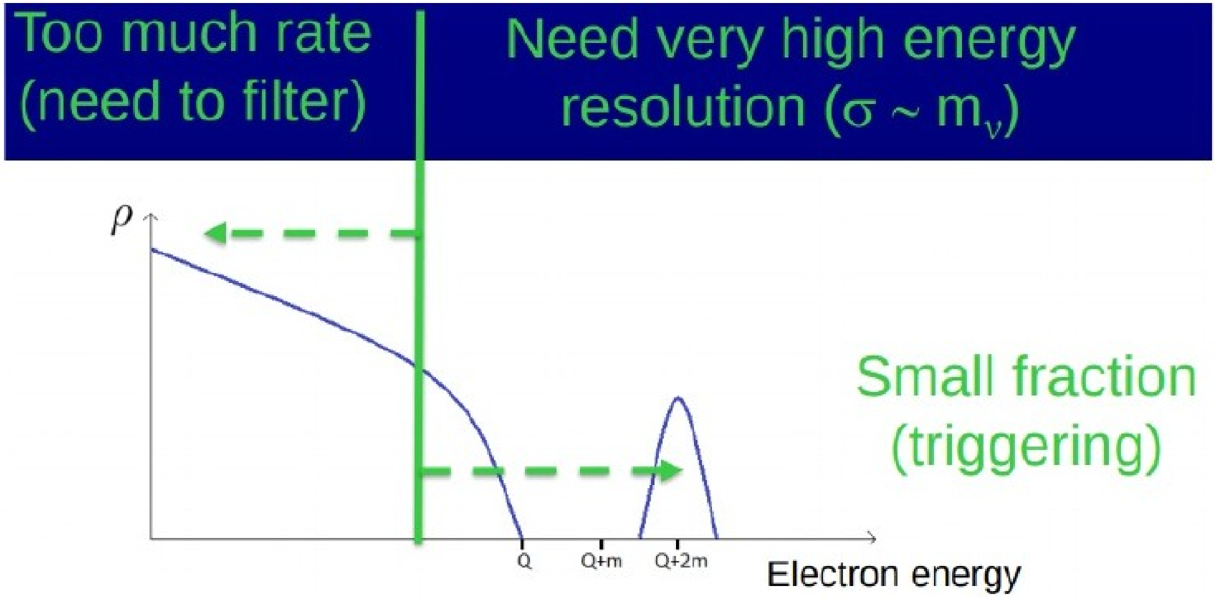






Graphene Substrate





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