Ultralight dark matter: From small-scale structure to dynamic neutrino mass

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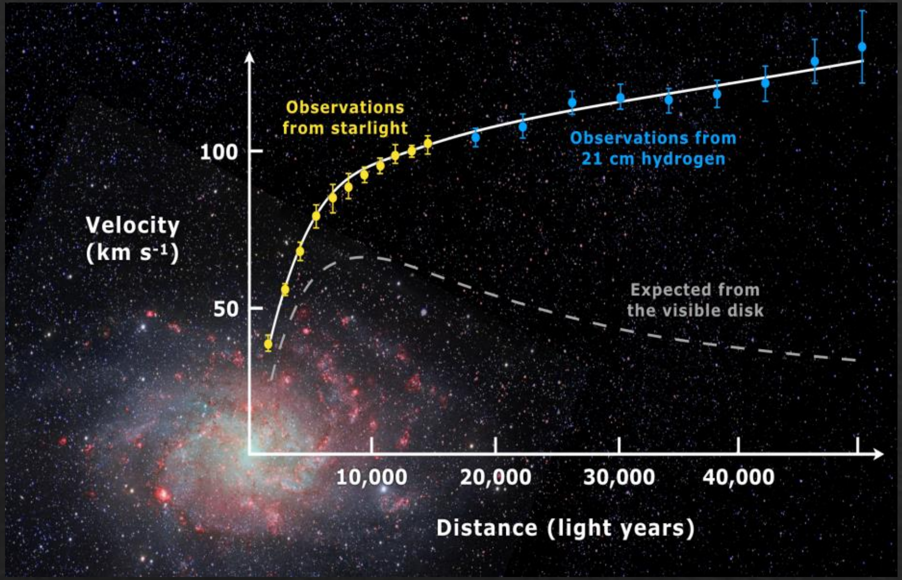
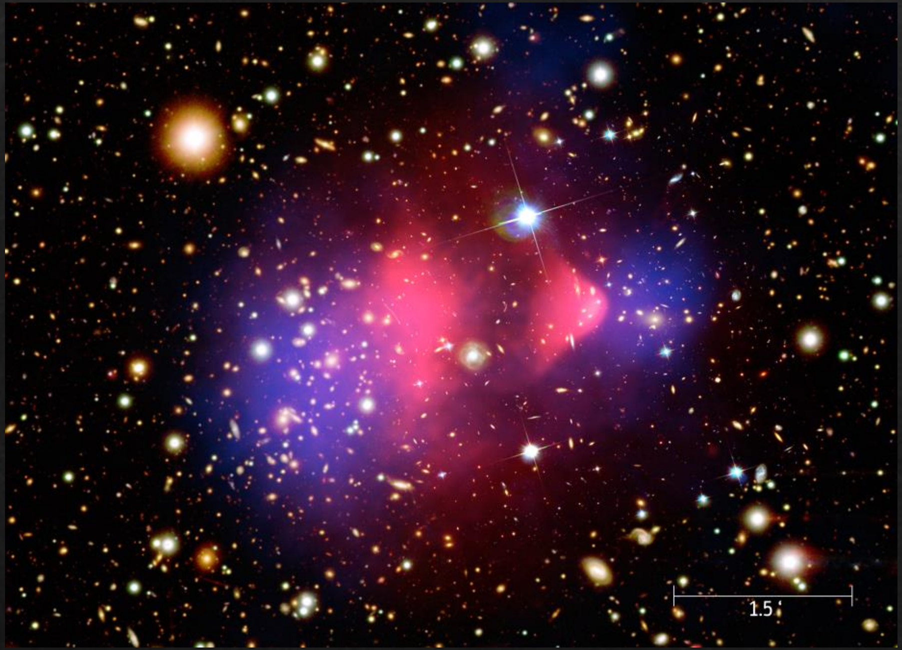
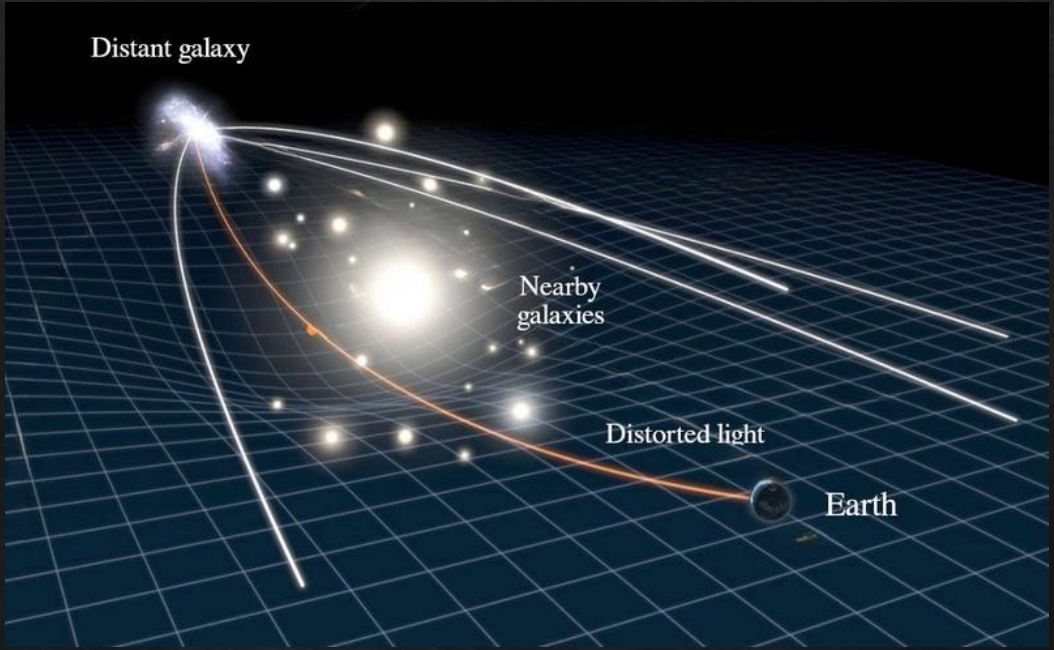
Jun 10, 2025

Evidence of dark matter



Velocity dispersion of galaxy clusters
Galaxy rotation curves
Gravitational lensing
Bullet cluster
Cosmic microwave background
Large scale structure
Baryon acoustic oscillations
Type Ia supernovae, ...





How light could dark matter particles be?

Uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$m \gtrsim 4.8 \times 10^{-21}\text{eV} \underbrace{\left(\frac{10\ \text{km/s}}{v}\right)\left(\frac{0.02\ \text{kpc}}{\Delta x}\right)}_{}$$

Willman 1 (dSph, discovered in 2018)

$$\lambda_{\text{dB}} = 0.25\ \text{kpc} \left(\frac{4.8 \times 10^{-21}\text{eV}}{m}\right)\left(\frac{10\ \text{km/s}}{v}\right)$$

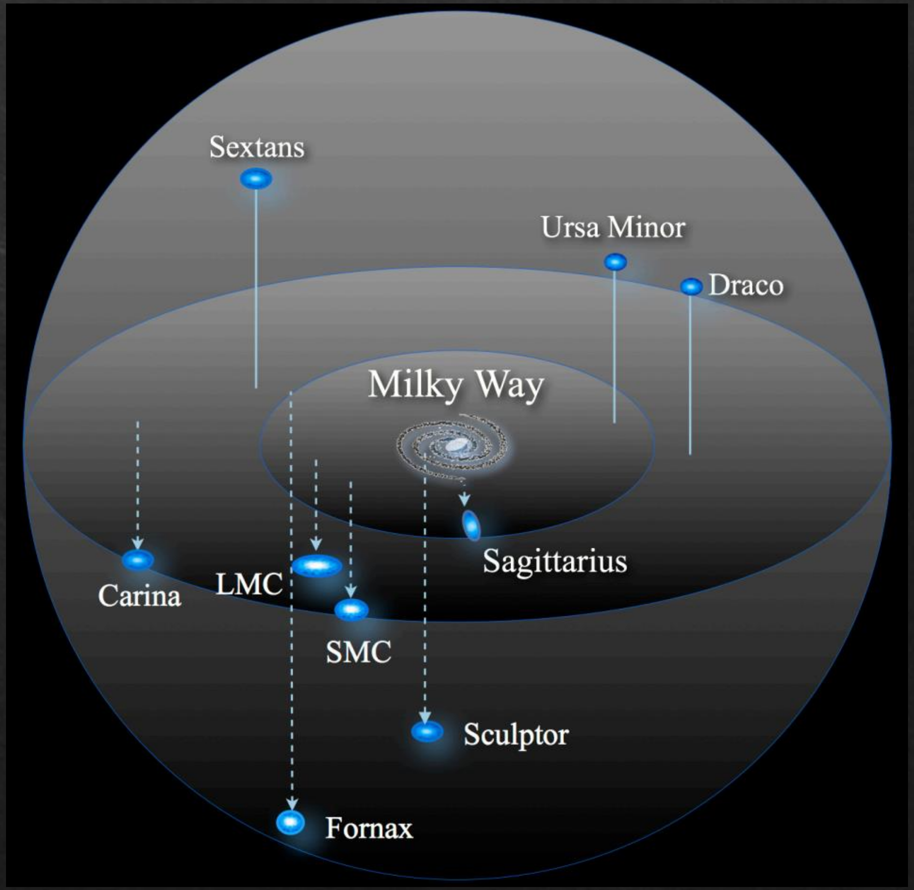


Figure from D. H. Weinberg et al. (PNAS, 2013)

If dark matter particles are fermions …

Pauli exclusion principle

$$n = g \int \frac{d^3p}{(2\pi)^3} f \lesssim \frac{g}{(2\pi)^3} \frac{4\pi}{3} (mv)^3$$

$$m \gtrsim 24 \text{ eV} \left(\frac{2}{g}\right)^{\frac{1}{4}} \underbrace{\left(\frac{\rho_{DM}}{0.4 \text{ GeV/cm}^3}\right)^{\frac{1}{4}} \left(\frac{200 \text{ km/s}}{v}\right)^{\frac{3}{4}}}_{\text{Solar neighborhood}}$$

$$\lambda_{\rm dB} = 7.7 \times 10^{-5} \text{ m} \left(\frac{24 \text{ eV}}{m}\right) \left(\frac{200 \text{ km/s}}{v}\right)$$

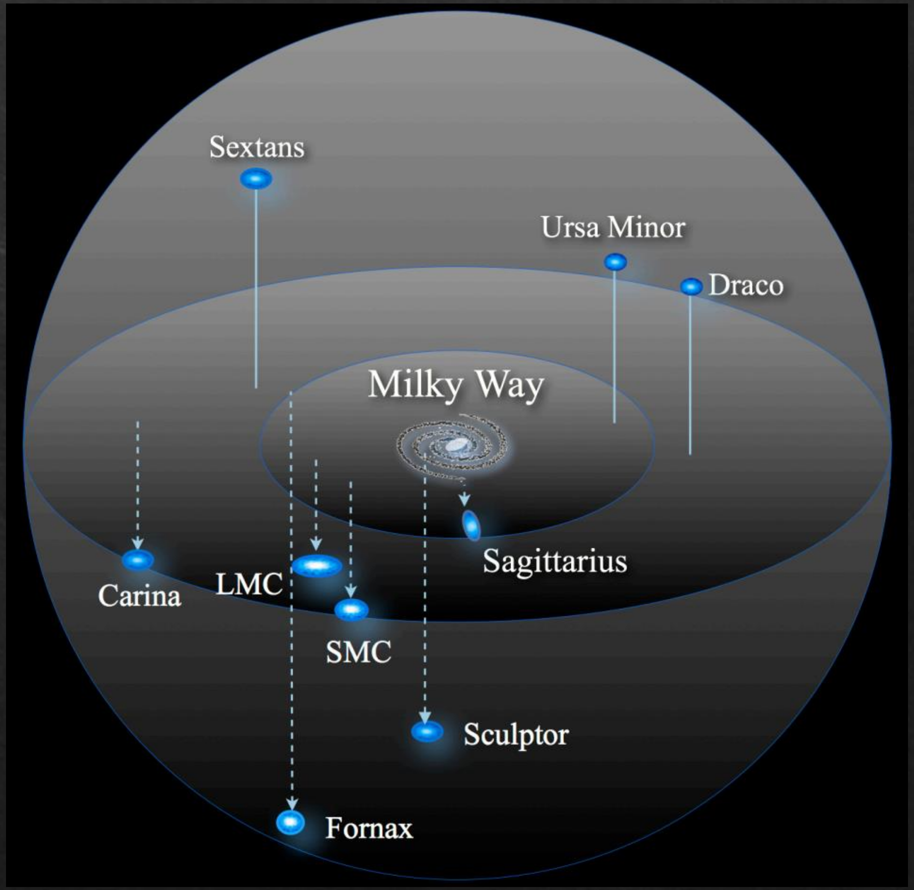


Figure from D. H. Weinberg et al. (PNAS, 2013)

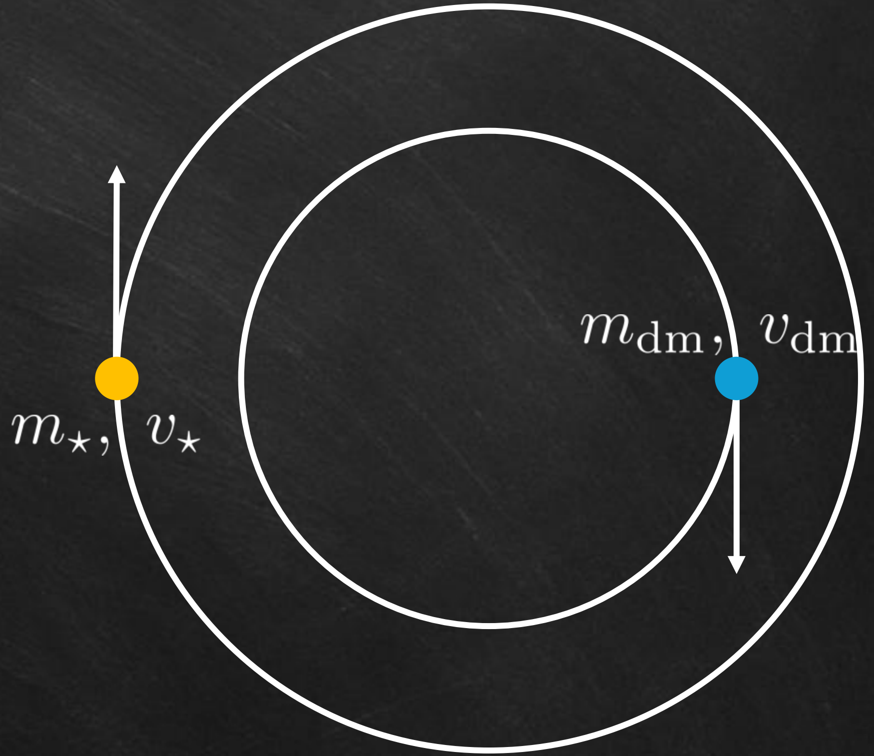
S. Tremaine & J. E. Gunn (PRL, 1979)

How heavy could dark matter "particles" be?

$$v_\star = \frac{m_{\rm dm}}{m_\star} v_{\rm dm} \sim \frac{m_{\rm dm}}{m_\star}\sqrt{\frac{GM_{\rm gal}}{R_{\rm gal}}}$$

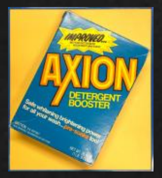
↓

Virial/escape velocity



Too heavy dark matter ($\gg M_\odot$) → Stellar heating

Dark matter mass landscape



Wavelike vs. particlelike?

Ultralight dark matter

- Large occupation number ➡ Classical fields

$$n\lambda_{\rm dB}^3 \sim \left(\frac{40\ \mathrm{eV}}{m}\right)^4 \sim 3\times 10^{82}\left(\frac{10^{-19}\ \mathrm{eV}}{m}\right)^4$$

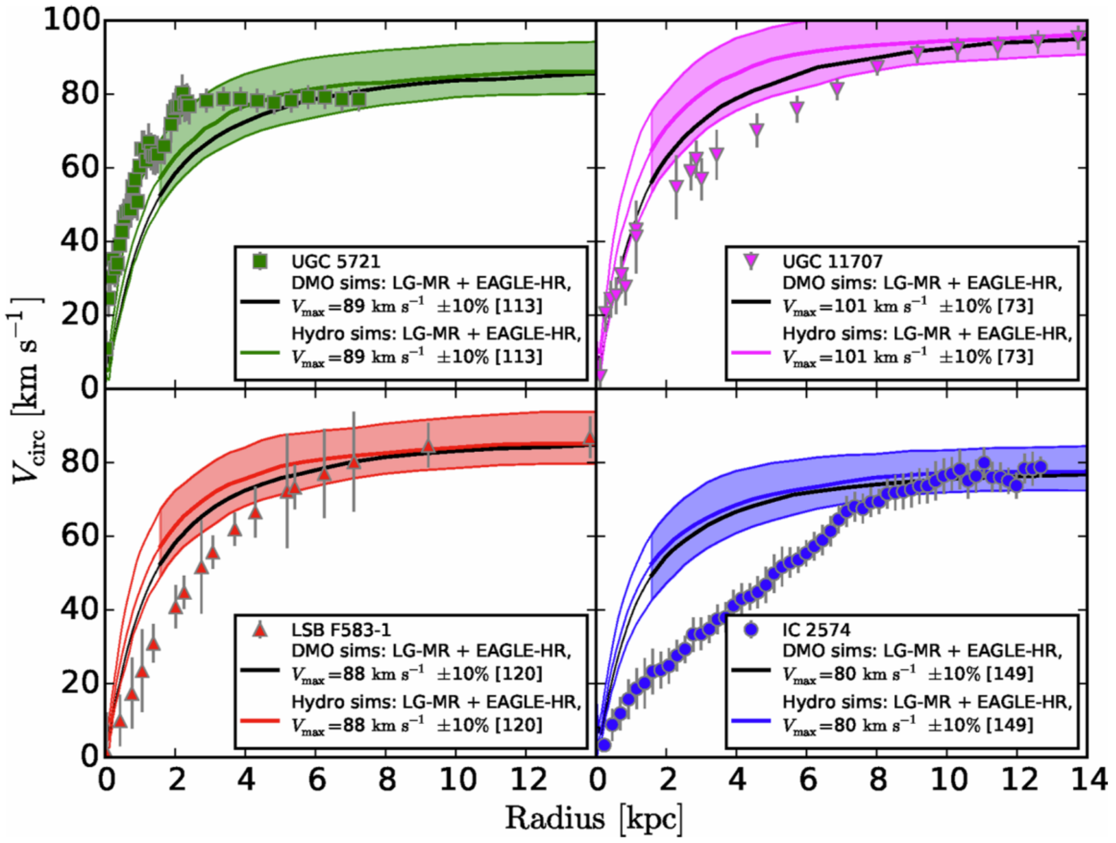
- Macroscopic/astrophysical scales

$$\lambda_{\rm dB} \sim 50\ \mu\mathrm{m}\left(\frac{40\ \mathrm{eV}}{m}\right) \sim 0.6\ \mathrm{pc}\left(\frac{10^{-19}\ \mathrm{eV}}{m}\right)$$

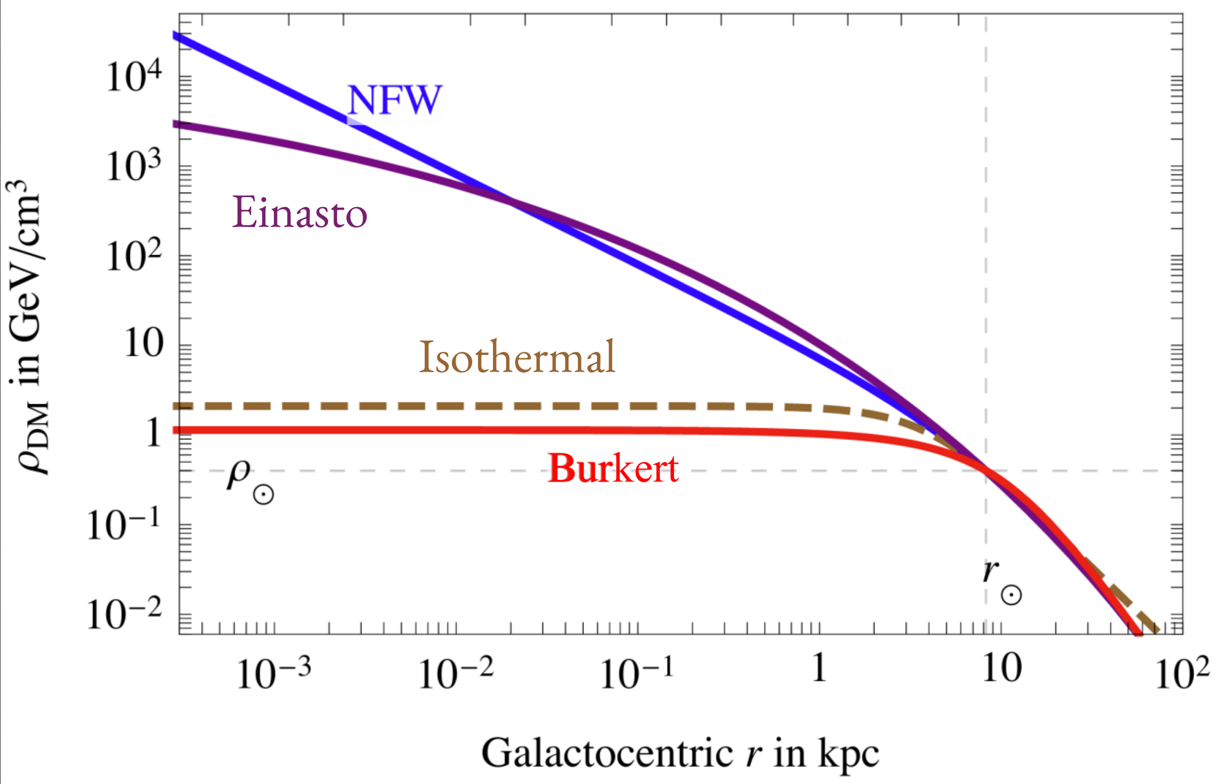
- Wave dynamics, rich phenomenology

Interference, Bose-Einstein condensation, polarization, modulation of standard model constants, etc.

Diversity of dark matter profiles



K. A. Oman et al. (MNRAS, 2015)



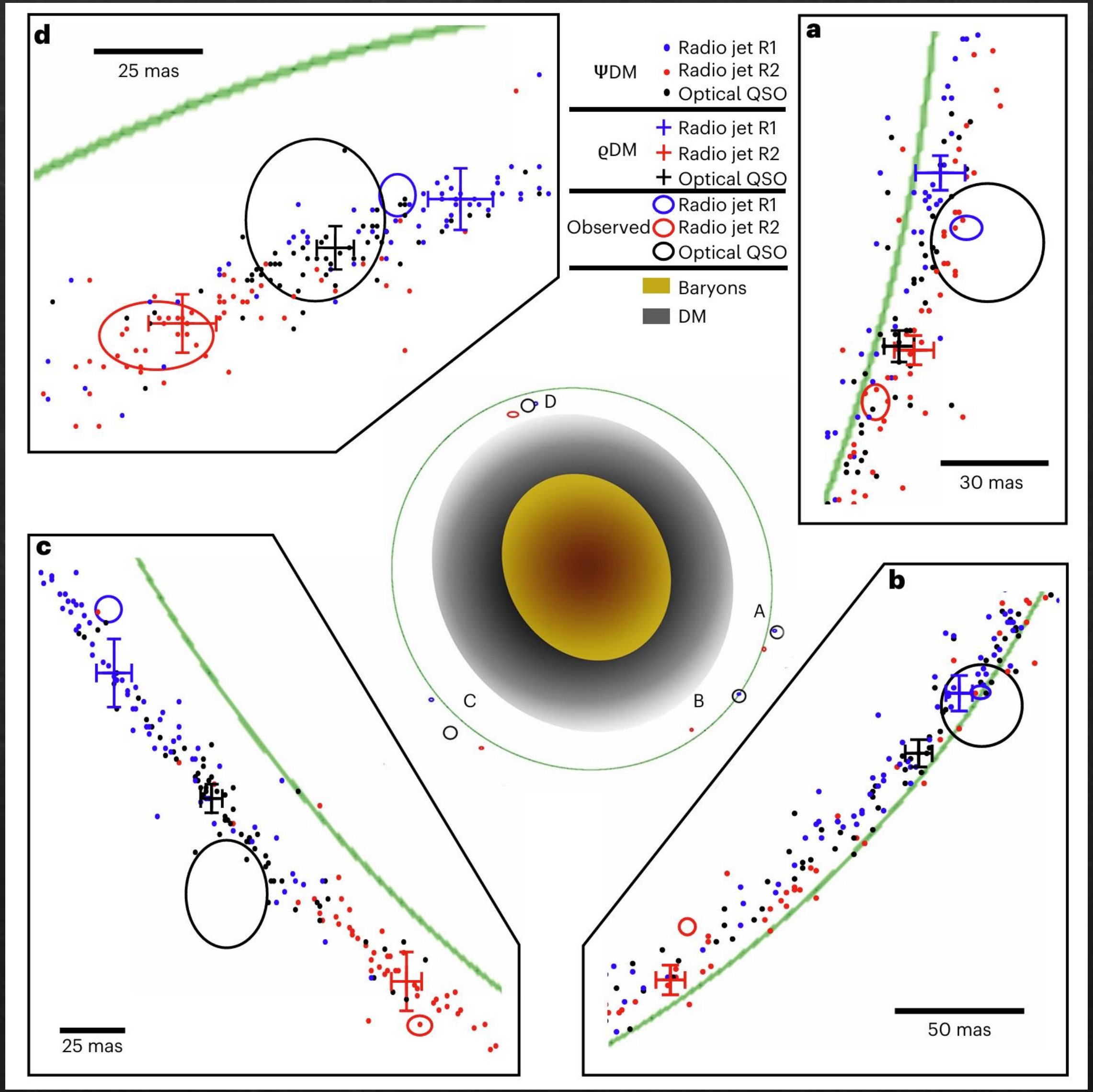
M. Cirelli et al. (2024)

Strong lensing anomalies in HS 0810+2554

Big circles: Observed locations of a quasi-stellar object and two radio jets

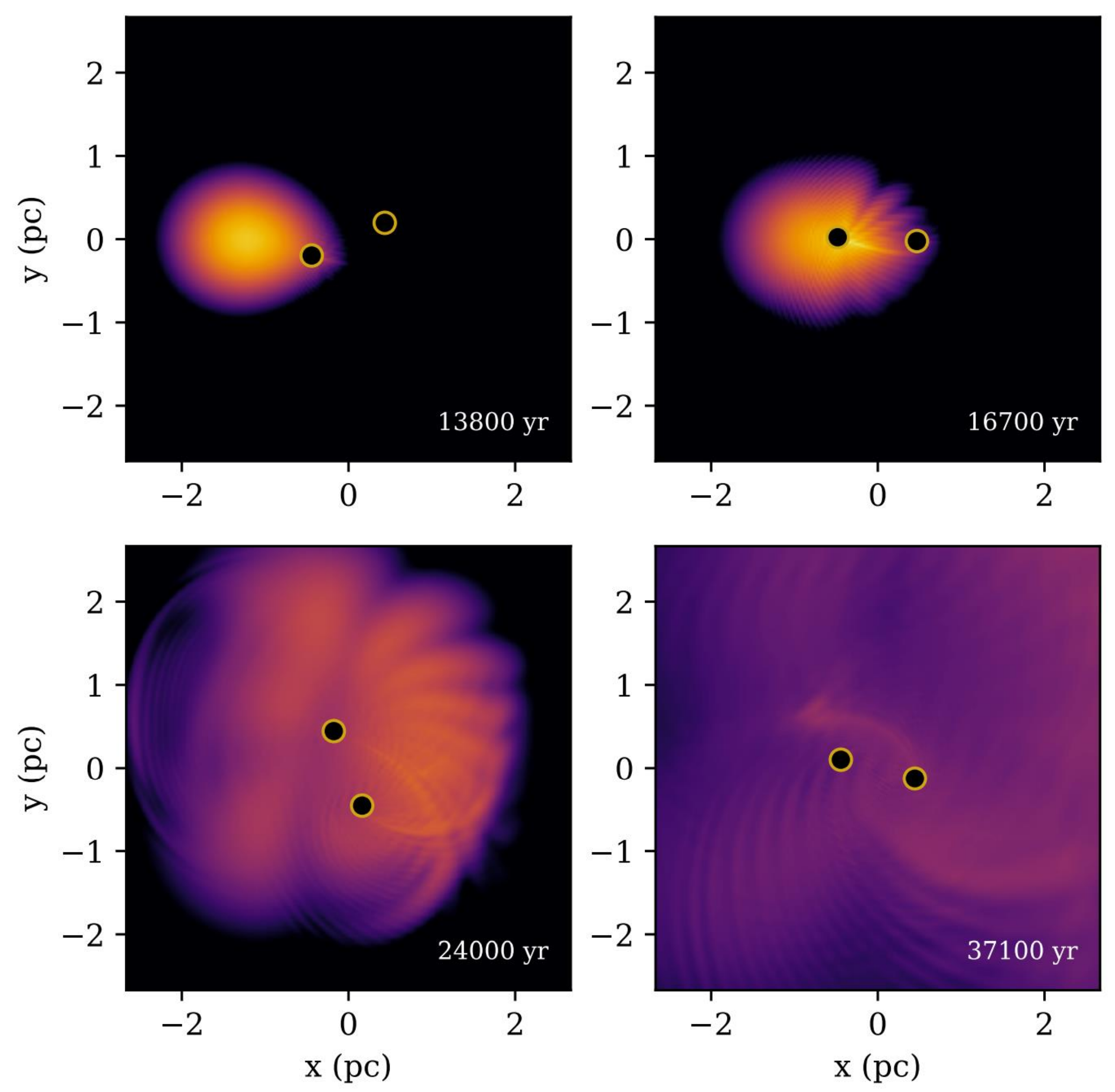
Cross points: NFW profile

Points: 75 Gaussian realizations of fuzzy DM fluctuations



A. Amruth et al. (Nature Astronomy, 2023)

Final parsec problem



B. C. Bromley et al. (PRD, 2024)
H. Koo et al. (PLB, 2024)

Mathematical prescriptions

$$i\partial_t \psi = -\frac{\nabla^2}{2ma^2}\psi + \frac{m}{a}\Phi\psi$$

$$\nabla^2 \Phi = \frac{1}{2M_{\mathrm{P}}^2}(\rho - \overline{\rho})$$

$$\rho = m|\psi|^2$$

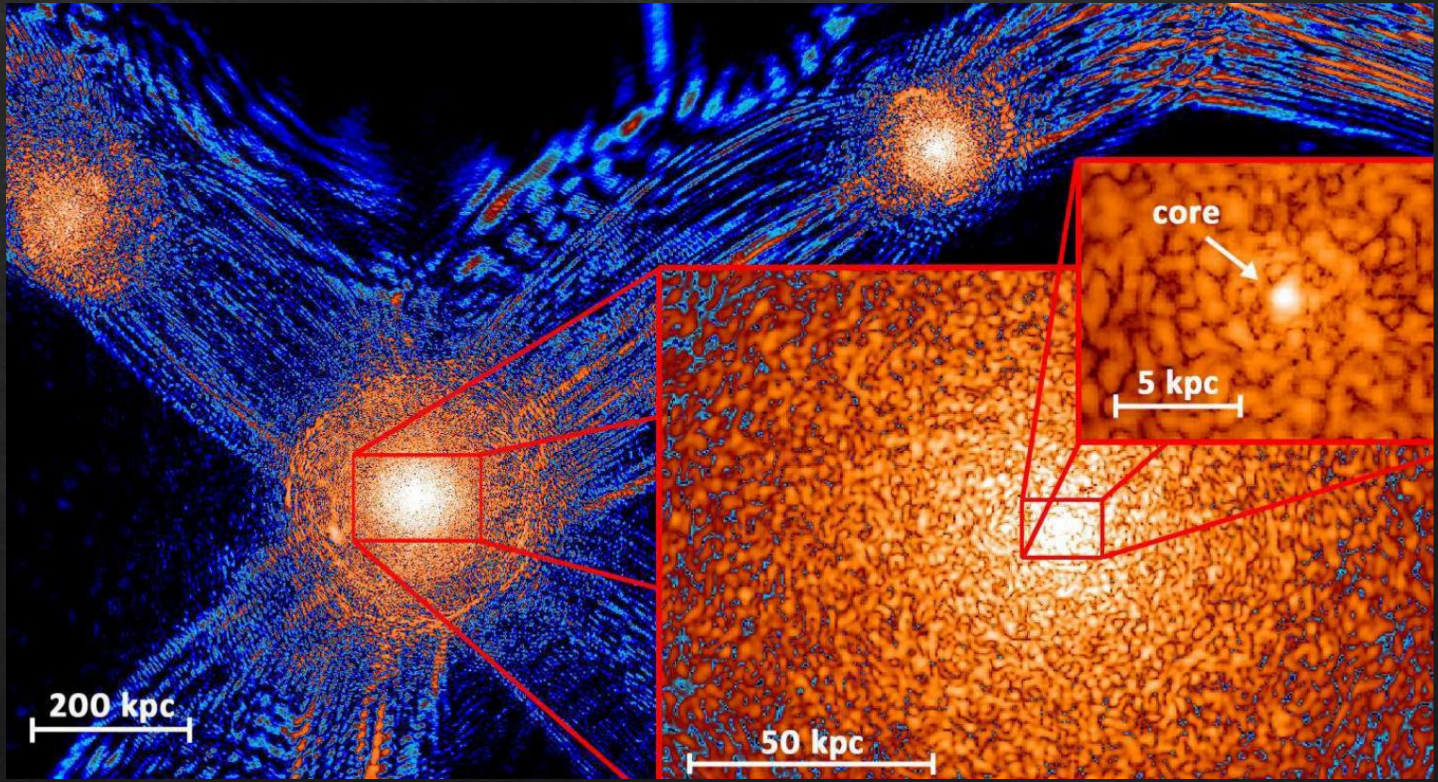
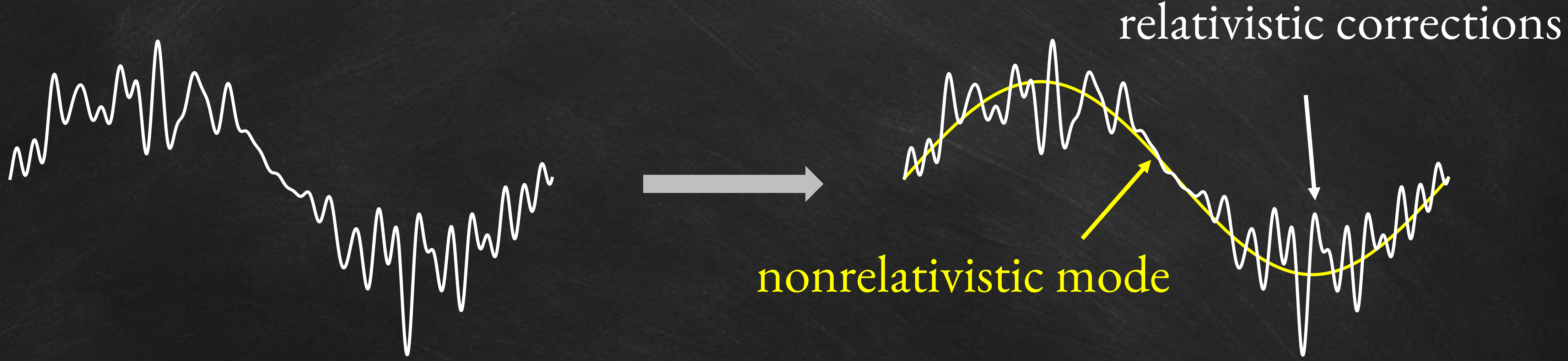


Figure from H.-Y. Schive et al. (Nature Physics, 2014)

Nonrelativistic effective field theory

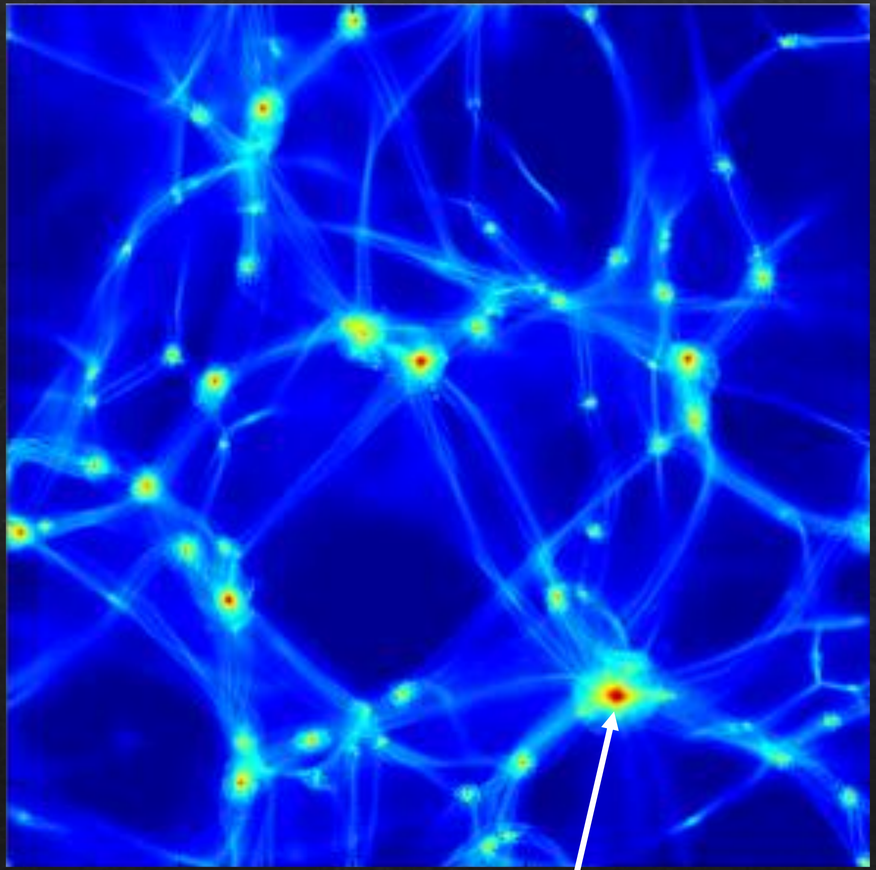


$$\phi(t, \boldsymbol{x}) = \frac{1}{\sqrt{2ma^3}} \left[\psi(t, \boldsymbol{x}) e^{-imt} + \text{c.c.}\right]$$

B. Salehian et al. (JHEP, 2020)
B. Salehian, **HYZ** et al (JHEP, 2021)

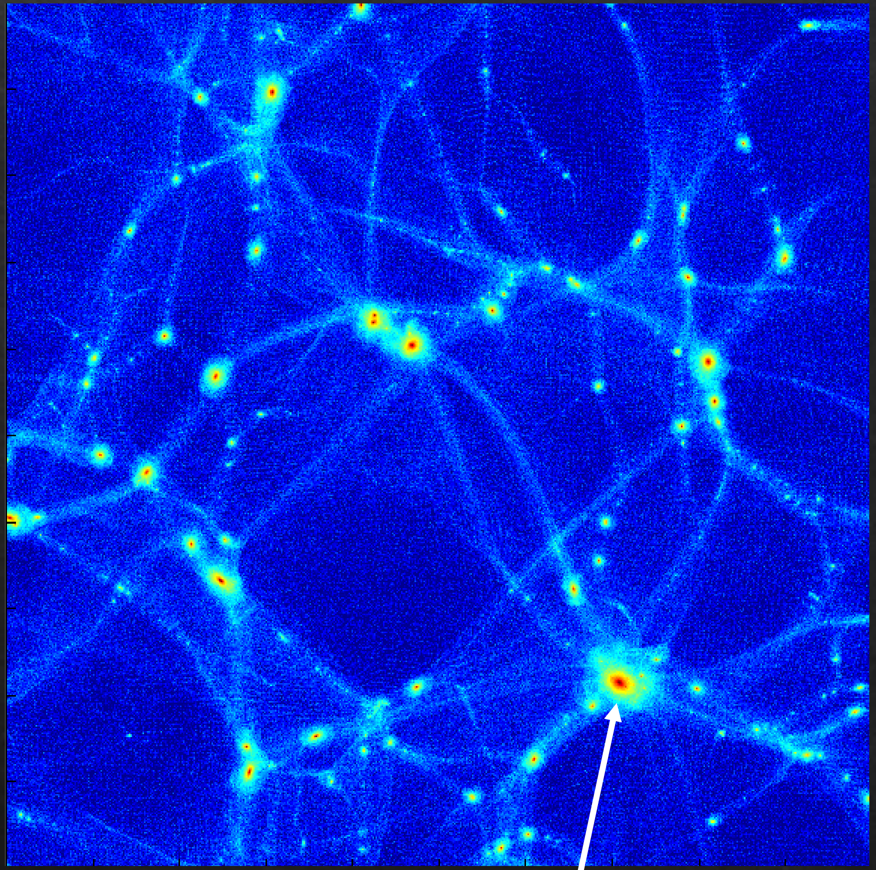
Large- and small-scale structure

Wavelike dark matter



Solitons, cored profiles

Particlelike dark matter

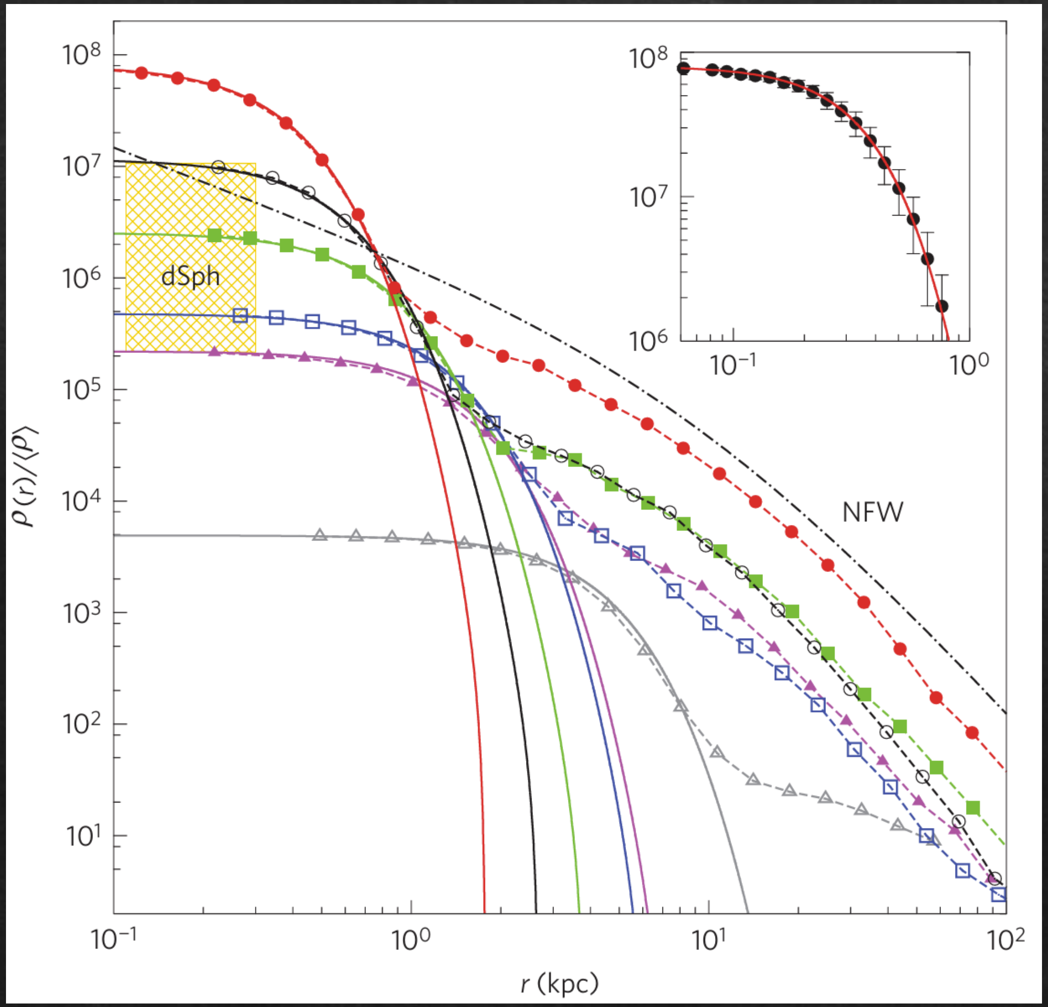


NFW, cuspidal profiles

H.-Y. Schive et al. (Nature Physics, 2014)

Density profiles of ultralight dark matter halos

Soliton core + NFW profile

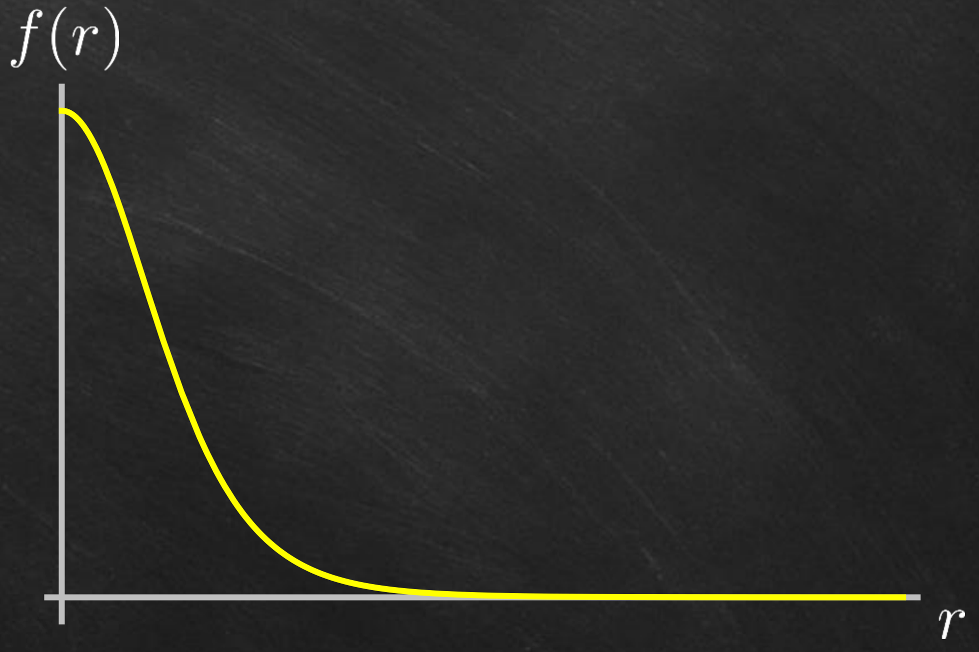


H.-Y. Schive et al. (Nature Physics, 2014)

Solitons

$$\psi(t, \boldsymbol{x}) = f(r)e^{i\mu t} \ , \quad \mu \ll m$$

$$\phi(t, \boldsymbol{x}) \approx \sqrt{\frac{2}{m}} f(r) \cos(\omega t) \ , \quad \omega = m - \mu$$



Ground state of the SP equations

Soliton profile solver in Mathematica: DMSolitonFinder

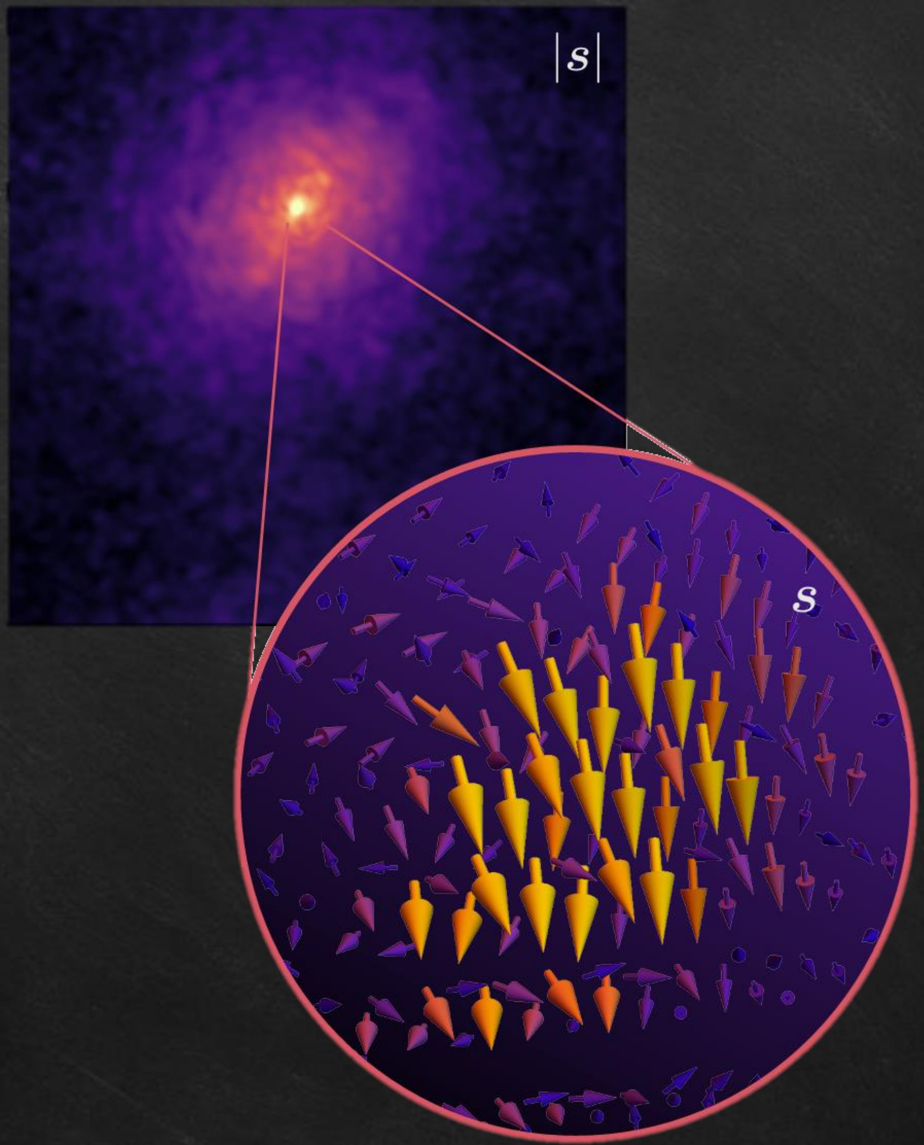
HYZ (JHEP, 2025)

Spin in vector solitons

$$\psi_i(t, \boldsymbol{x}, \sigma) = f(r) e_i(\sigma) e^{i\mu t}$$

$$e_i(0) = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad , \qquad e_i(\pm 1) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm i \\ 0 \end{pmatrix}$$

Linearly polarized   Circularly polarized

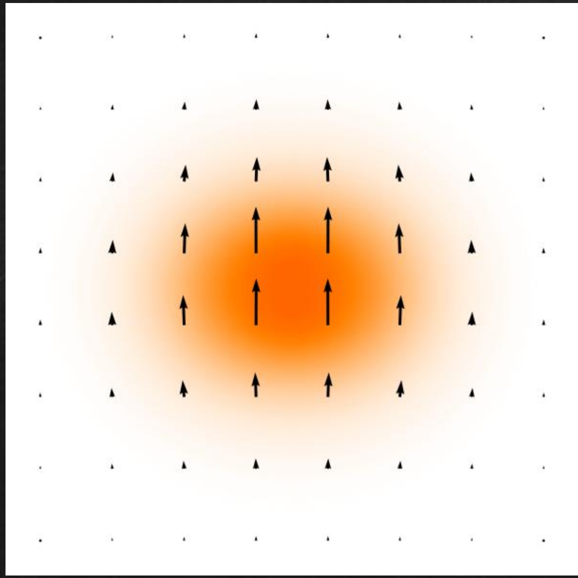


M. Jain & M. A. Amin (PRD, 2022)
HYZ, M. Jain, and M. A. Amin (PRD, 2022)

Figure from M. A. Amin et al. (JCAP, 2022)

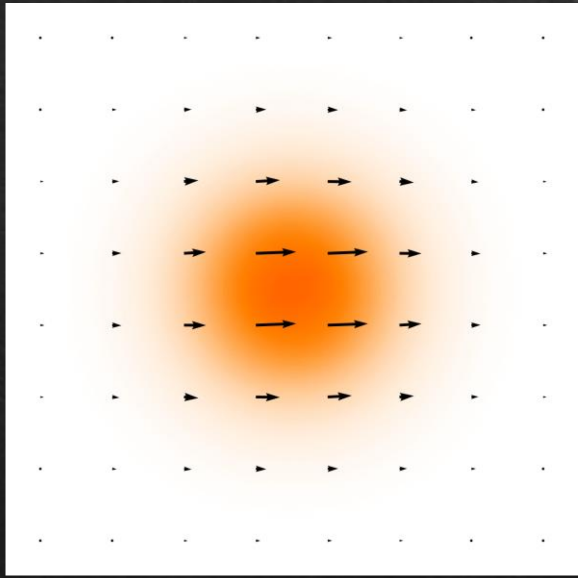
Vector solitons

$$X_i \approx \sqrt{\frac{2}{m}} f(r) \begin{pmatrix} 0 \\ 0 \\ \cos(\omega t) \end{pmatrix}$$



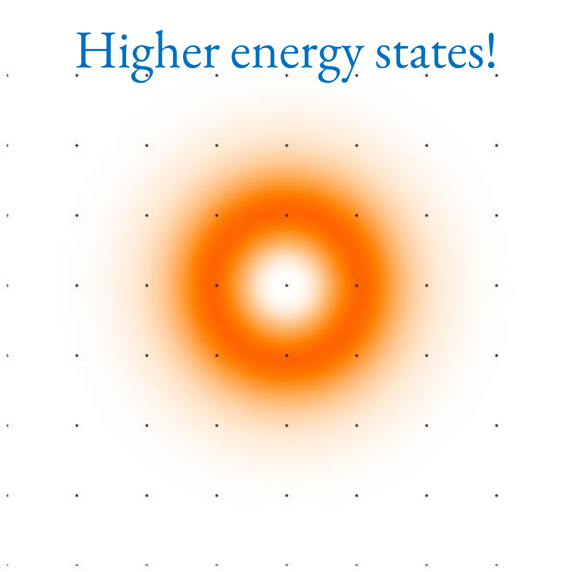
Linearly polarized

$$X_i \approx \frac{1}{\sqrt{m}} f(r) \begin{pmatrix} \cos(\omega t) \\ \sin(\omega t) \\ 0 \end{pmatrix}$$



Circularly polarized

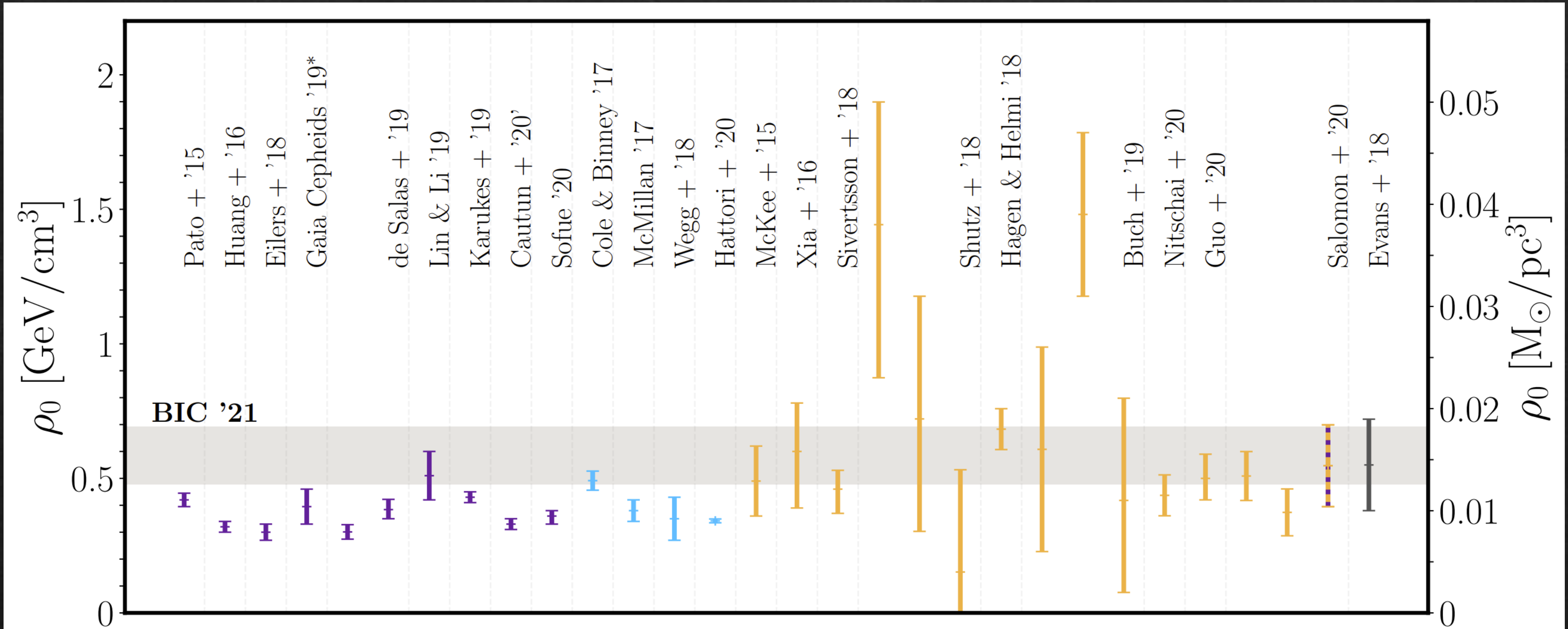
$$X_i \propto g(r)\cos(\omega t)\hat{\boldsymbol{r}}$$



Spherically symmetric
(Solutions with a node)

HYZ, M. Jain, and M. A. Amin (PRD, 2022)

Local dark matter density

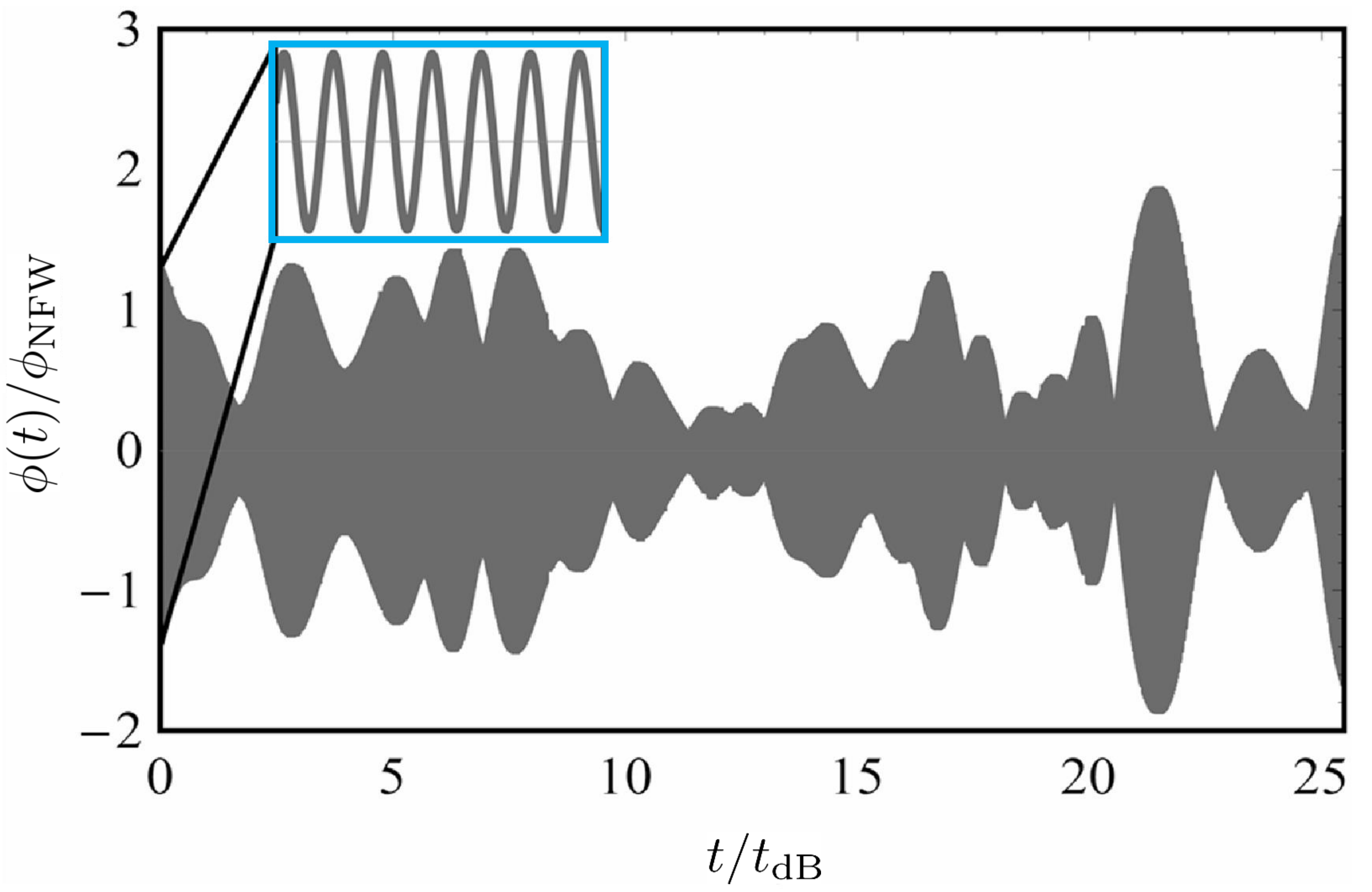


$$\rho_{\rm local} \approx 0.4 \mathrm{GeV/cm^3}$$

M. Benito et al. (Phys.Dark Univ., 2021)

Stochastic fluctuations

Constant amplitude within a de Broglie time

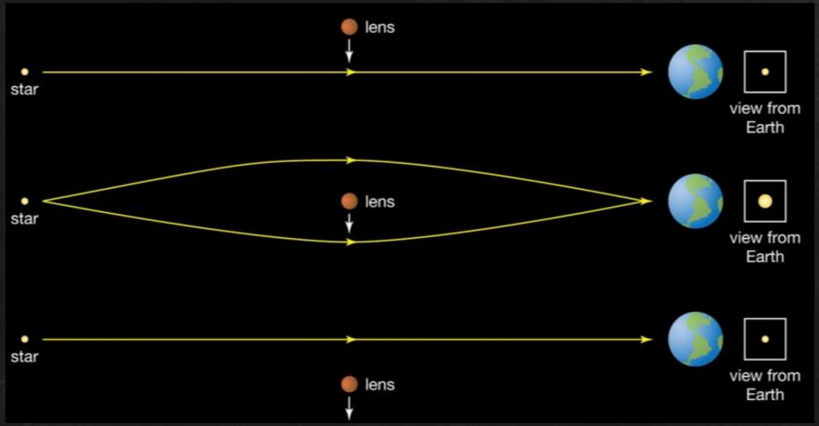


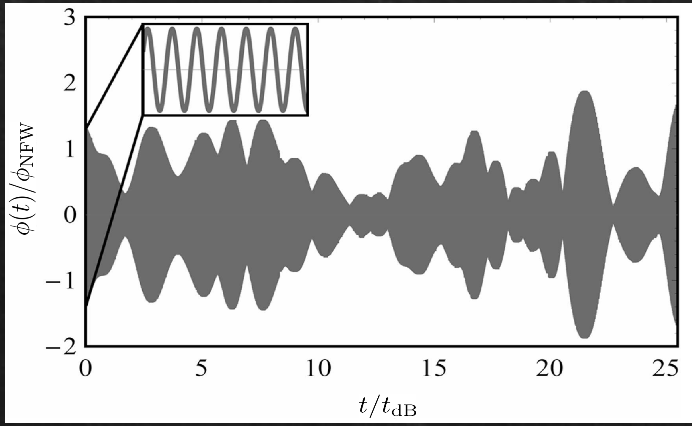
$$t_{\mathrm{dB}} \sim \frac{\lambda_{\mathrm{dB}}}{v}$$

Highly random on long time scales

G. P. Centers et al. (Nature Commun., 2021)

Rich phenomenology



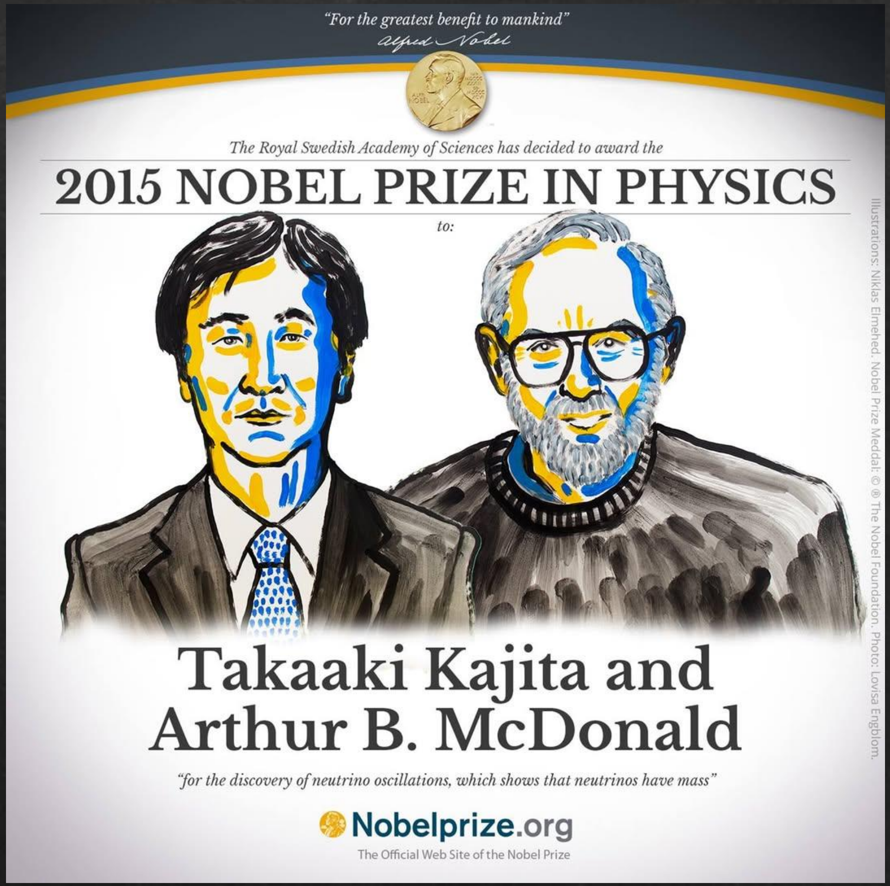


Neutrino mass?

The standard model and neutrino mass

The standard model:

- Minimal lepton sector
- No right-handed neutrino
- Massless neutrinos
- Accidental lepton number symmetry



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

The seesaw mechanism

Mass matrix for ν_L, ν_R

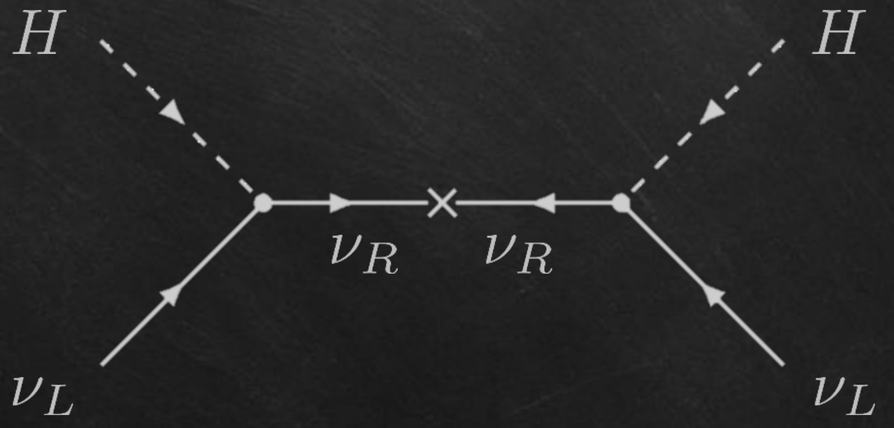
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

$$\Big\downarrow\, m_D \ll m_R$$

$$m_l \simeq \frac{m_D^2}{m_R} \ , \quad m_h \simeq m_R$$

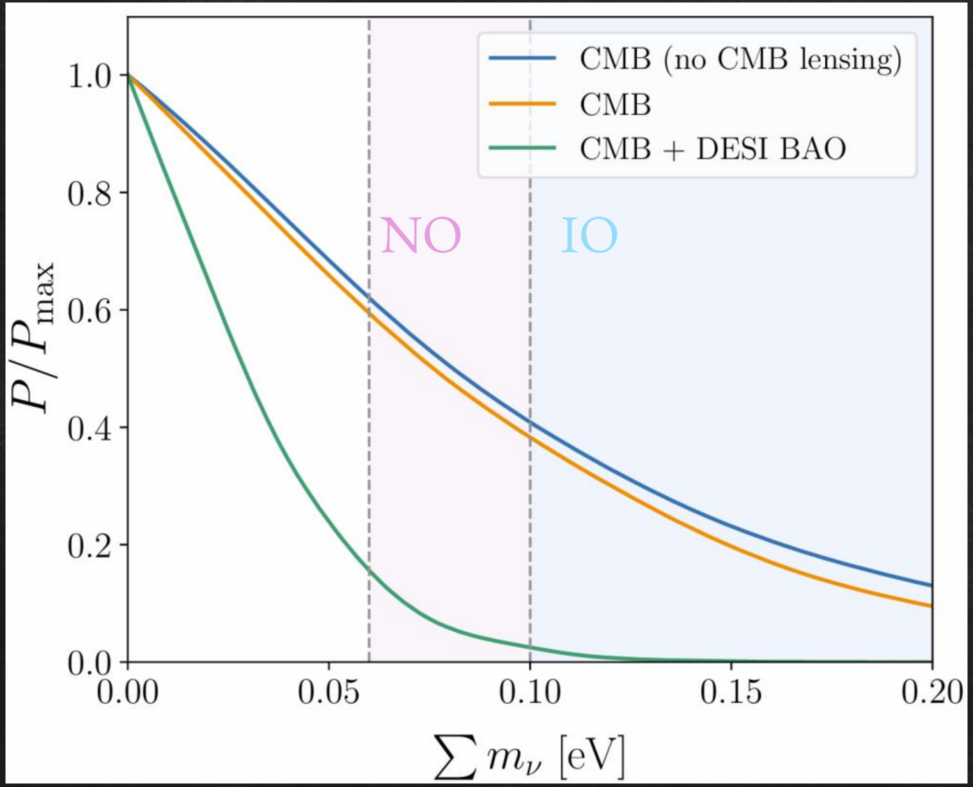
$$\mathcal{L} \supset -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \overline{\nu_M^c} \nu_M + h.c.$$

$$\nu_D = \nu_L + \nu_R \ , \quad \nu_M = \nu_R + \nu_R^c$$



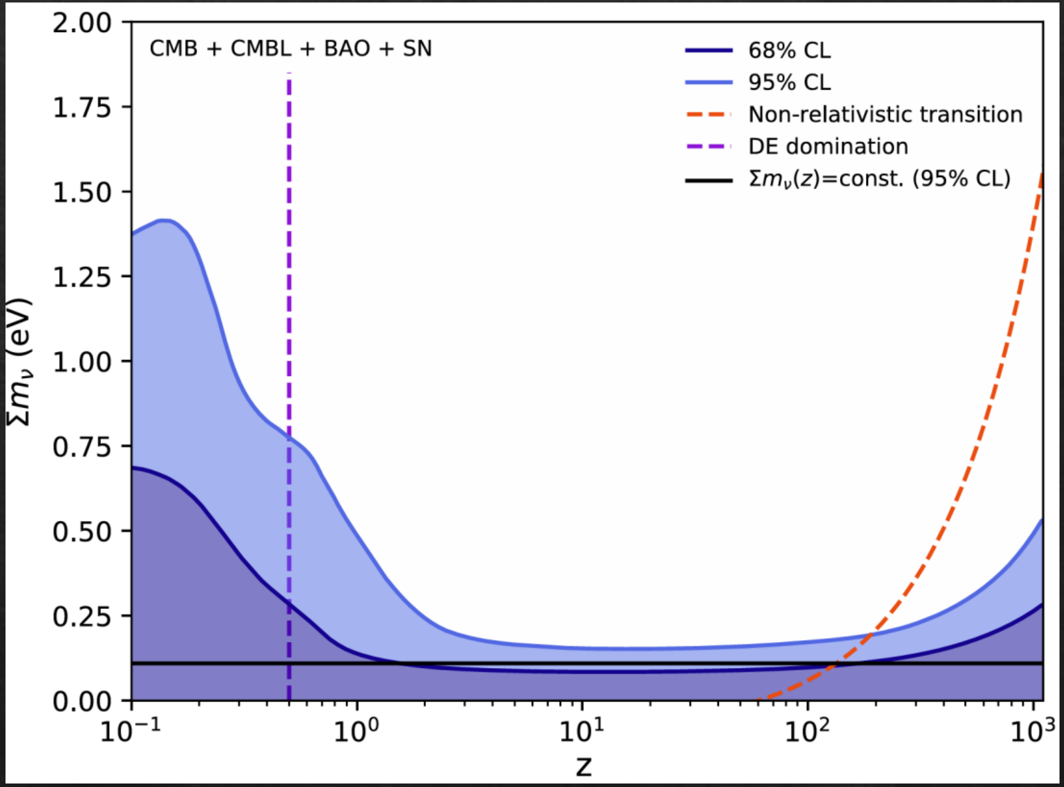
Dynamic neutrino mass? Some motivations

Some tension in $\sum m_\nu$?



DESI Collaboration (JCAP, 2025)

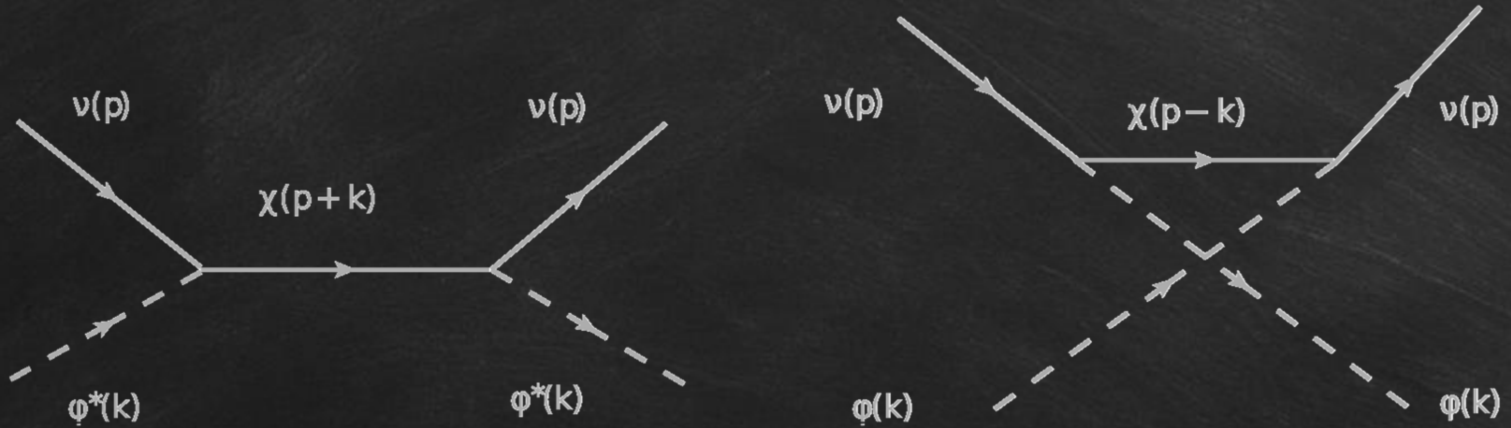
Redshift-dependent $\sum m_\nu$?



C. S. Lorenz et al. (PRD, 2021)

Can DM explain m_ν?

A specific realization of "dark" neutrino mass



ν : Neutrinos

χ : Fermionic mediators

φ : Scalar dark matter

ν, χ have zero bare mass

Cold gas of dark matter particles: (Forward scattering)

$$m_\nu^2 \propto \frac{\rho_\phi}{m_\phi^2}\frac{y(y-\epsilon)}{y^2-1}\,, \quad y = \frac{2E_\nu m_\phi}{m_\chi^2}\,, \quad \epsilon = \frac{n_\phi - \bar{n}_\phi}{n_\phi + \bar{n}_\phi}$$

Classical scalar field background:

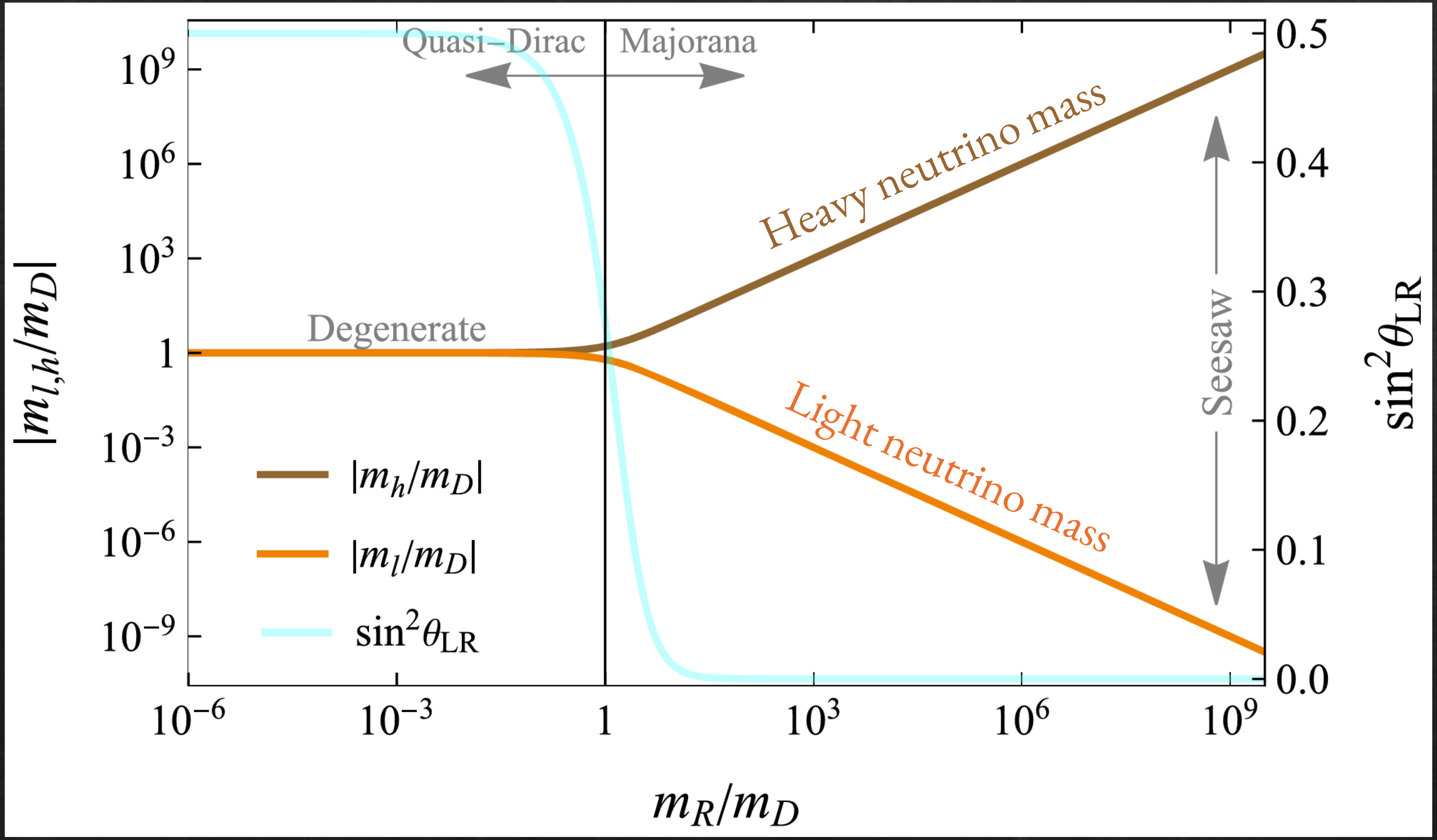
$$m_\nu^2 \propto \frac{\rho_\phi}{m_\phi^2}\cos^2(m_\phi t)$$

(Relevant to ultralight dark matter)

M. Sen and A. Y. Smirnov (JCAP, 2024)

Another realization of "dark" neutrino mass

If the Majorana mass is $m_R = g\phi_0 \cos(m_\phi t)$ in the seesaw



Y. ChoeJo, Y. Kim, and H.-S. Lee (PRD, 2023)

$$\begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} = \begin{pmatrix} \cos\theta_{LR} & \sin\theta_{LR} \\ -\sin\theta_{LR} & \cos\theta_{LR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{H.c.}$$


I WANT YOU
BUILD YOUR MODEL!

Testing the mass origin with supernova neutrinos

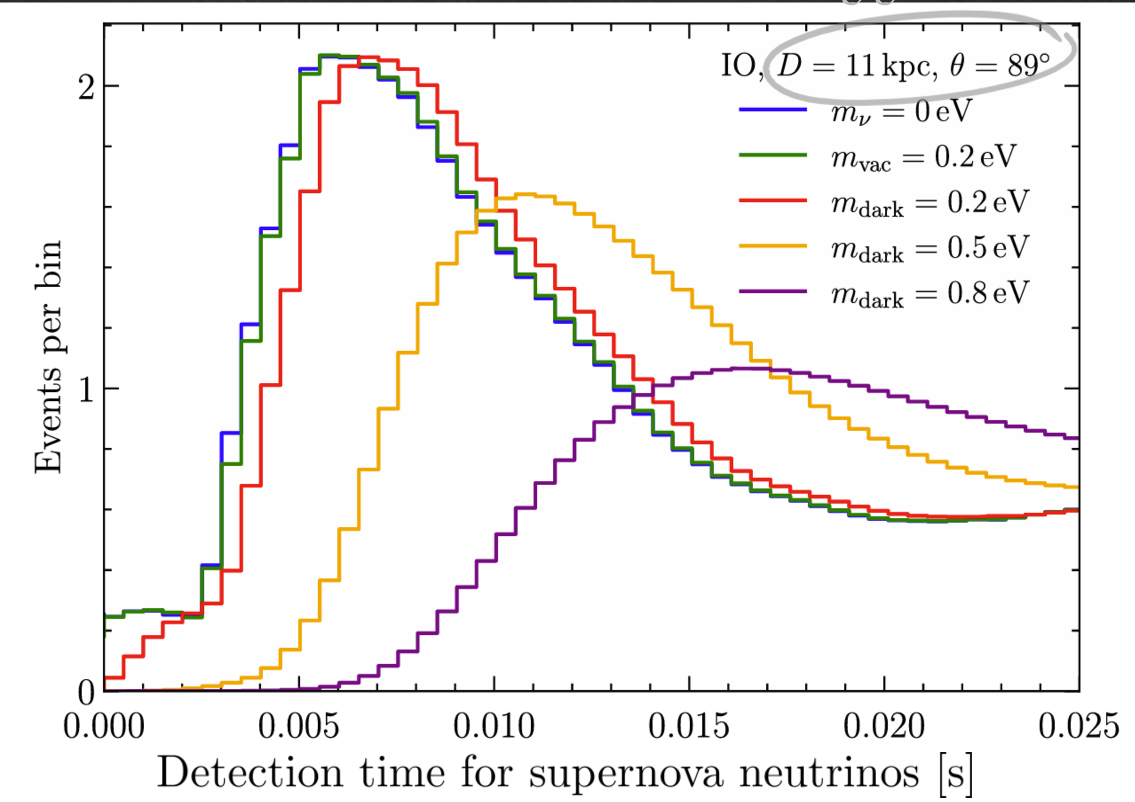
Galactic core-collapse supernovae rate ~O(1)/century

S. M. Adams et al. (ApJ, 2013)

Arrival time delay effect is pronounced for:

- Large "dark" mass
- Supernovae near galactic center (even lower rate)

Neutrinos crossing galactic center



S.-F. Ge, C.-F. Kong, and A. Y. Smirnov (PRL, 2024)

Assuming NFW profile for dark matter, neglecting time dependence and density fluctuations

Tests with oscillation experiments?

For ultralight DM $10^{-19} \lesssim m_\phi \ll 10\text{eV}$

$$\Delta m^2_{ij} \sim \Delta m^2_{ij\,D}(\boldsymbol{x}) \cos^2(m_\phi t)$$

DM density-dependent

Time modulation

assuming relativistic neutrinos

Several time and length scales

Modulation period $\quad T_\phi = \frac{\pi}{m_\phi} = 5.7\text{hr}\left(\frac{10^{-19}\text{eV}}{m_\phi}\right)$

Time scale for experiments $\quad T_{\text{exp}} \gtrsim \mathcal{O}(10)\text{days}$

➡ Time-averaged probabilities

Coherence length $\quad \lambda_{\text{dB}} = 1.24\text{au}\left(\frac{10^{-14}\text{eV}}{m_\phi}\right)\left(\frac{200\text{km/s}}{v}\right)$

Earth crossing distance $\quad l_\oplus = 1.16\text{au}\left(\frac{T_{\text{exp}}}{10\text{days}}\right)\left(\frac{v_\oplus}{200\text{km/s}}\right)$

➡ Space-averaged probabilities for $m_\phi \gg 10^{-14}\text{eV}$

Strategy

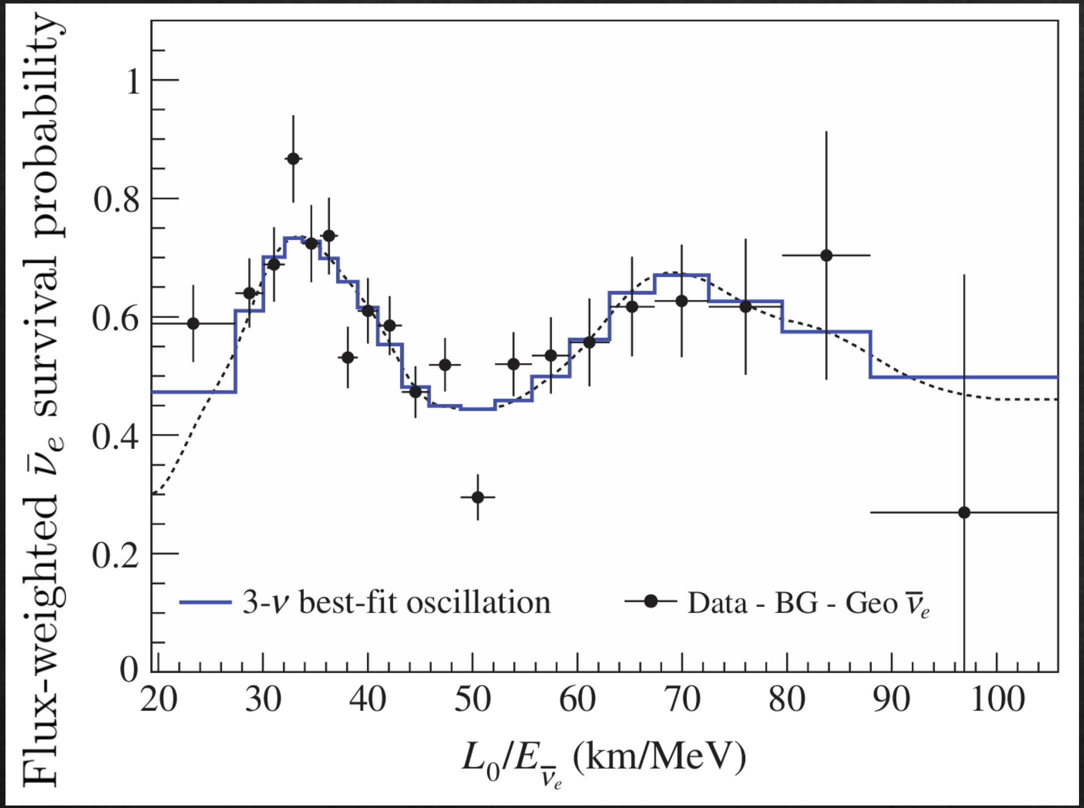
For $m_\phi \ll 10^{-14}\text{eV}$, constant m_ν:

1. Take time average
2. Compare with data

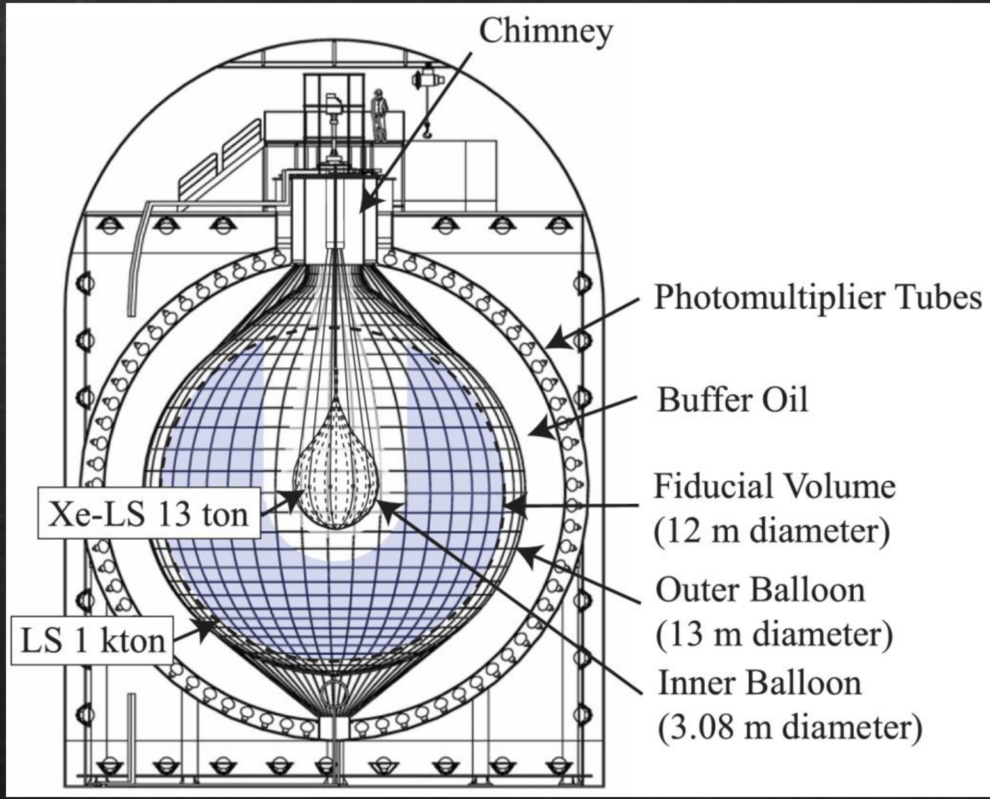
For $m_\phi \gg 10^{-14}\text{eV}$, varying m_ν:

1. Model DM density fluctuations
2. Take time + spatial average
3. Compare with data

Long-baseline reactor experiment: KamLAND



$L_0 = 180\text{km}$ (flux-weighted average baseline)

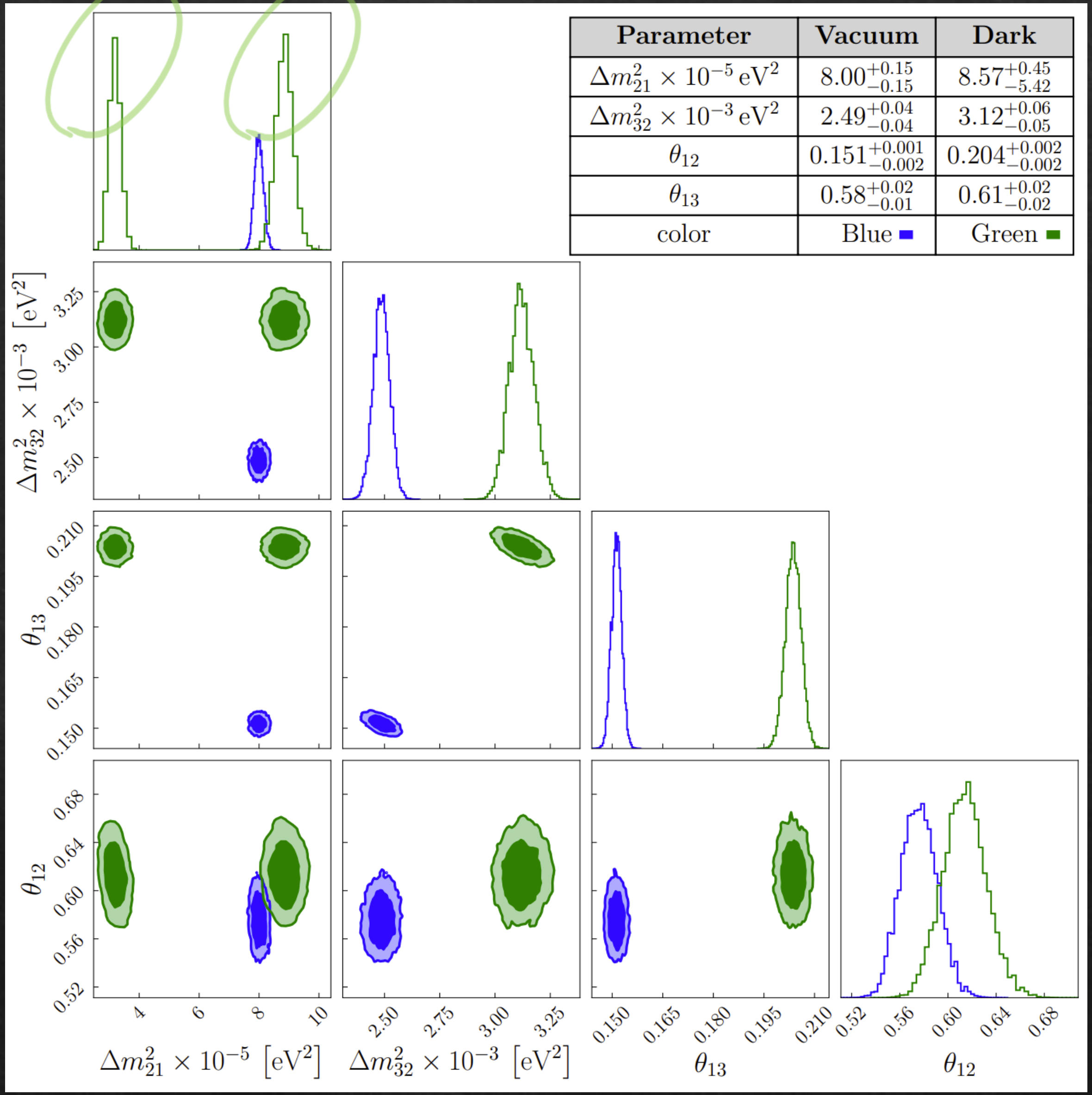


Located at 1km underground, Hida, Japan
Detected antineutrinos from >50 reactors (before 2013)
Sensitive to Δm^2_{21} , θ_{12} , θ_{13}

KamLAND Collaboration (2013)

Chi-square analysis

“Dark 1” “Dark 2”

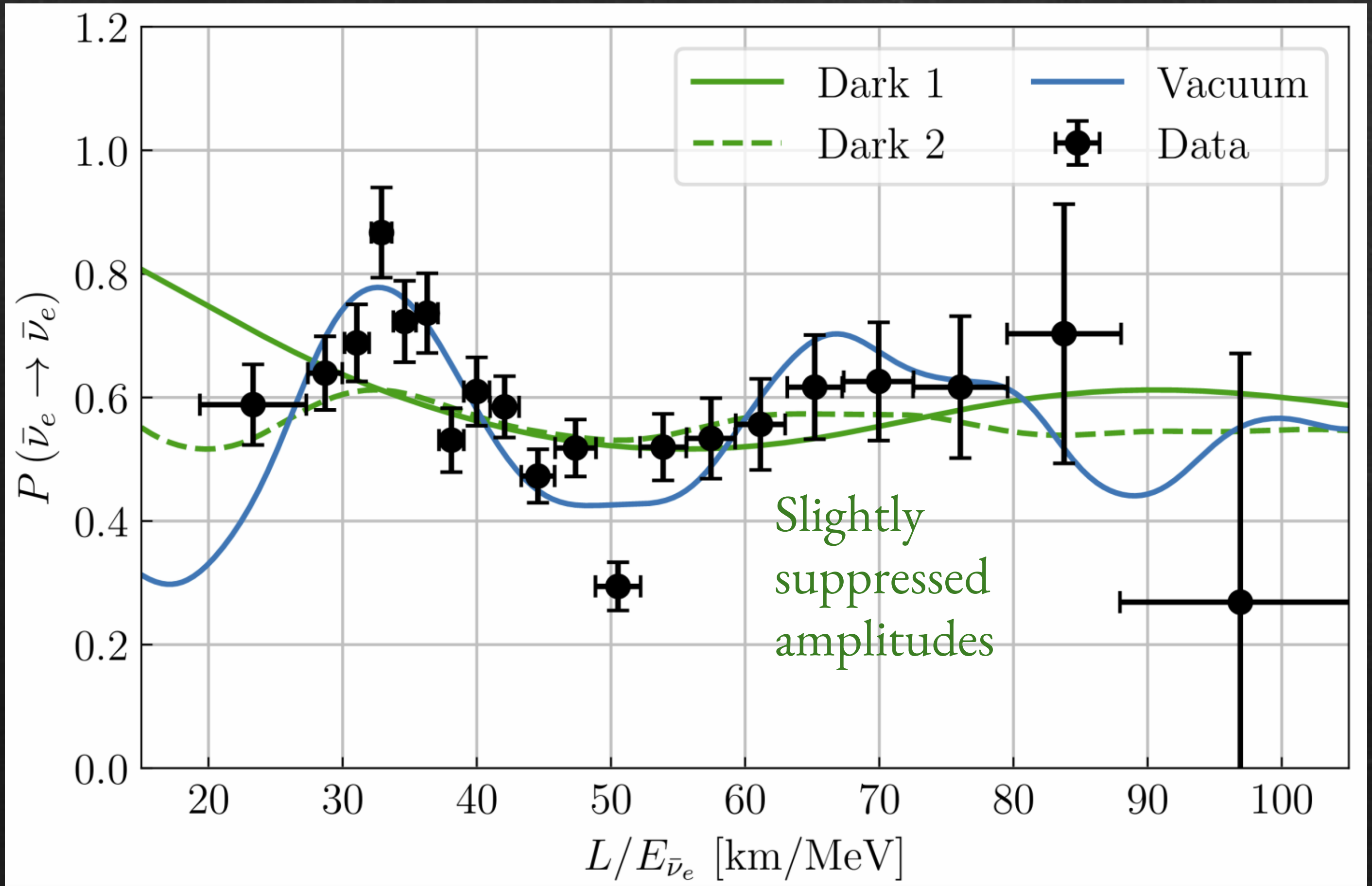


Parameter	Vacuum	Dark
$\Delta m^2_{21} \times 10^{-5}\,\mathrm{eV}^2$	$8.00^{+0.15}_{-0.15}$	$8.57^{+0.45}_{-5.42}$
$\Delta m^2_{32} \times 10^{-3}\,\mathrm{eV}^2$	$2.49^{+0.04}_{-0.04}$	$3.12^{+0.06}_{-0.05}$
θ_{12}	$0.151^{+0.001}_{-0.002}$	$0.204^{+0.002}_{-0.002}$
θ_{13}	$0.58^{+0.02}_{-0.01}$	$0.61^{+0.02}_{-0.02}$
color	Blue	Green

KamLAND (main dataset)
+ RENO + Double Chooz
(short baseline experiments)
+ Solar θ12

A. Cheek, L. Visinelli, and **HYZ** (2025)

Survival probabilities with best-fit parameters



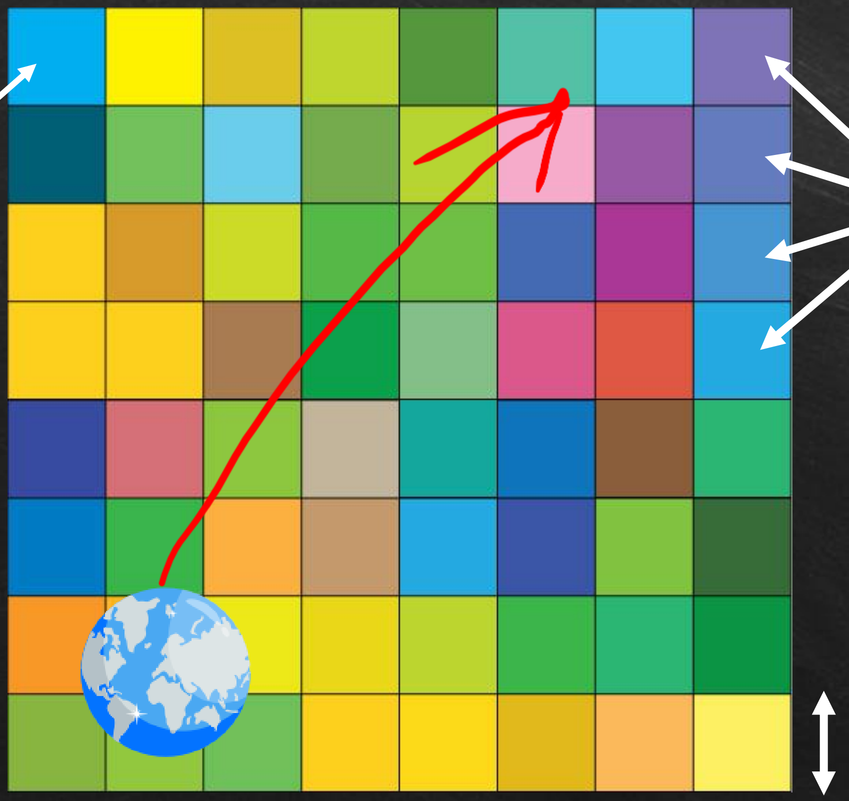
"Dark" mass is disfavored at $> 4\sigma$.

A. Cheek, L. Visinelli, and **HYZ** (2025)

Earth crossing through different de Broglie patches

Spatial average ≈ Ensemble average

Constant density within a patch



$$\frac{\rho_{\rm dm}}{\rho_{\rm NFW}} \sim \text{random}$$

$\lambda_{\rm dB}$

Colors: DM density

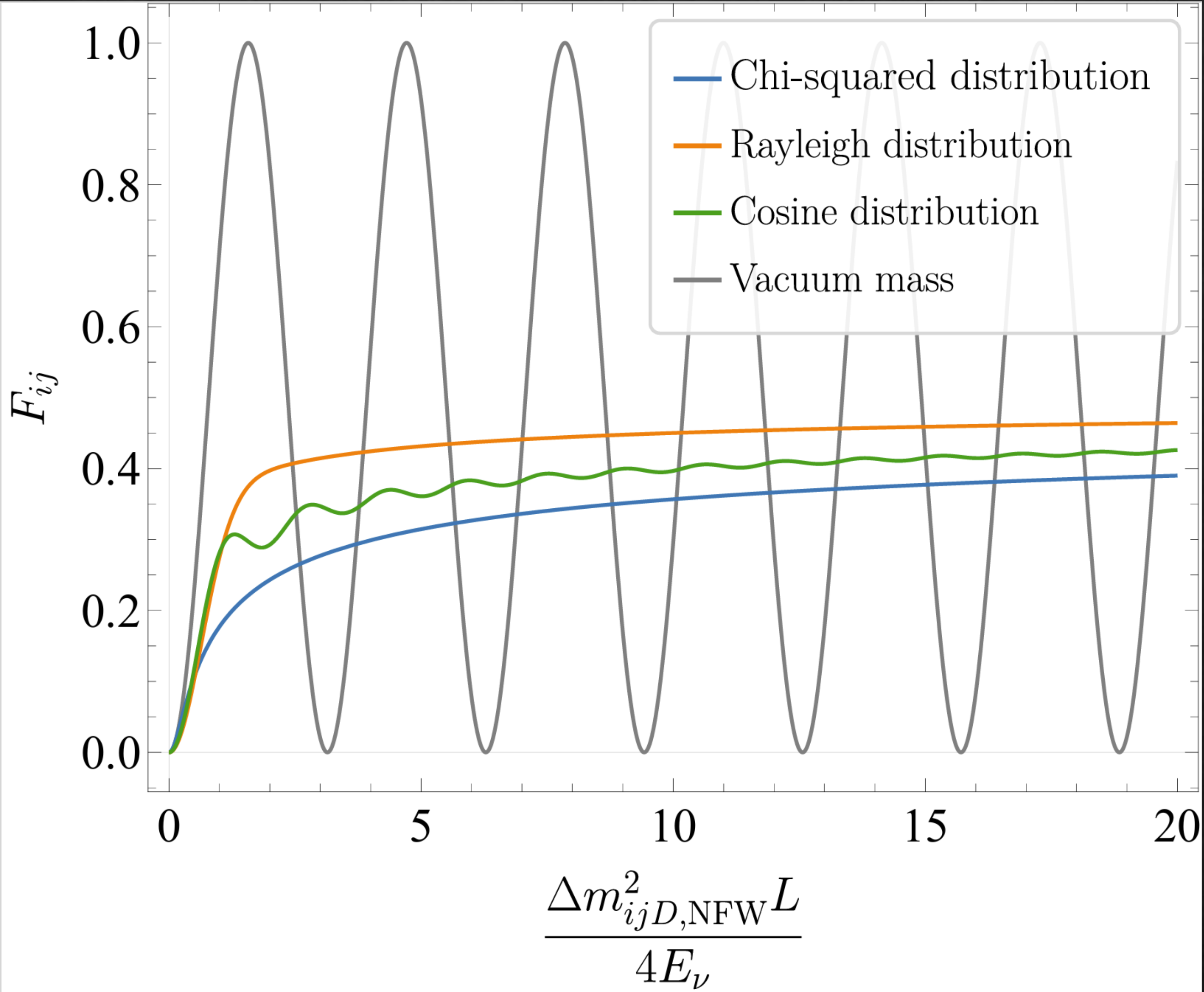
Suppressed oscillation behaviors

Distributions of mass-squared differences in different patches:

$$\frac{\Delta m^2_{ijD}}{\Delta m^2_{ijD}|_{\rm NFW}} \sim \chi^2(1),\ \text{Rayleigh}$$

$$\sim 1 - \cos(k_\theta \theta)$$

Flavor oscillations in terms of distances are suppressed in a model-independent way!



For vacuum mass: $F_{ij} = \sin^2 \frac{\Delta m^2_{ij} L}{4E_\nu}$

A. Cheek, L. Visinelli, and **HYZ** (2025)

Summary

- Ultralight DM density on small scales
  - Soliton + NFW
  - Stochastic fluctuations
- Dynamic m_ν due to ultralight DM?

  - For $10^{-19} \lesssim m_\phi \ll 10^{-14}\mathrm{eV}$

    KamLAND disfavors "dark" mass by $> 4\sigma$
  - For $10^{-14}\mathrm{eV} \ll m_\phi \ll 10\mathrm{eV}$

    Stochastic fluctuations suppress neutrino oscillations
- Ultralight DM is unlikely to account for m_ν