Self-interactions in the dark matter and neutrino sectors: Impact on galaxy clustering

New Physics from Galaxy Clustering II
November 9, 2023

Francis-Yan Cyr-Racine

Department of Physics and Astronomy, University of New Mexico

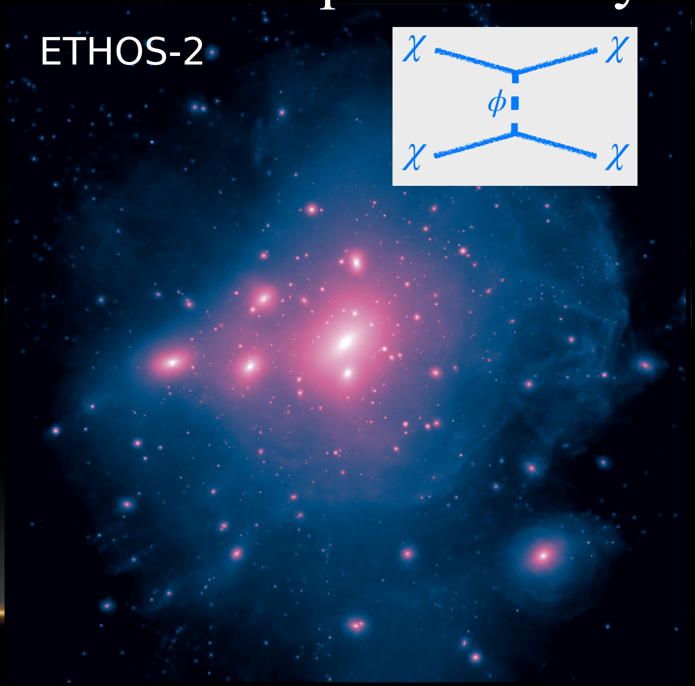
David Camarena

John Houghteling

Birendra Dhanasingham

The ultimate sin…

- The theme of this talk is self-interaction. I'll discuss two aspects of it:
  - Neutrino self-interactions and their impact on LSS.
  - Dark matter self-interactions and their impact on very small scales.

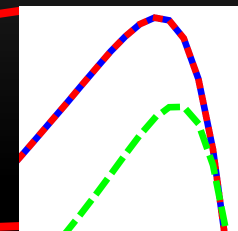


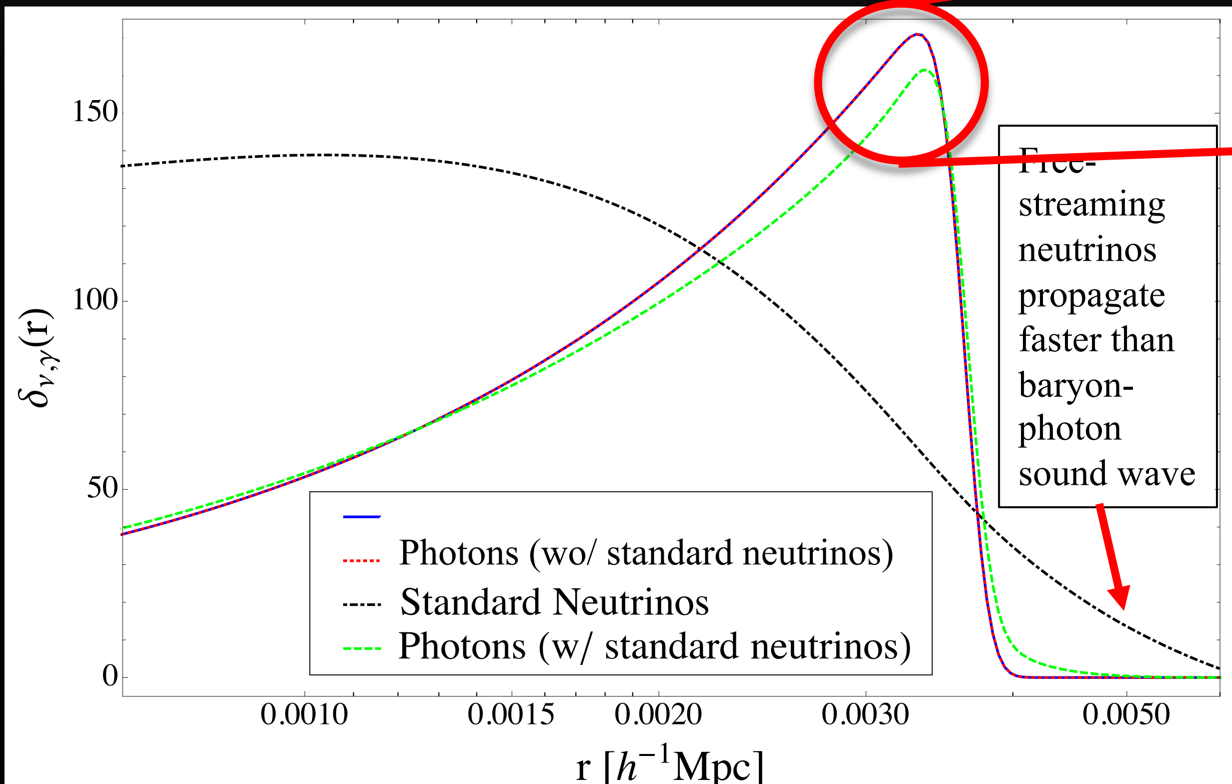
The importance of neutrinos in cosmology

- Deep in the radiation-dominated epoch, neutrinos account for 41% of the energy density of the Universe.
- Prior to the epoch of recombination (when neutral atoms form in the Universe), Standard Model neutrinos are the only free-streaming radiation in the Universe.
- Detailed evolution of matter and CMB fluctuations are sensitive to this radiation free-streaming fraction.

Free-streaming Radiation and the CMB

Neutrinos give rise to a phase shift and amplitude suppression to CMB fluctuations





Cyr-Racine & Sigurdson (2014)

$$d_\gamma(\tau, k) = 3\zeta_{\rm in}(1+\Delta_\gamma)\cos(\varphi_s + \delta\varphi) + O(\varphi_s^{-1}),$$

where

$$\Delta_\gamma \simeq -0.2683 R_\nu + O(R_\nu^2),$$

$$\delta\varphi \simeq 0.1912\,\pi R_\nu + O(R_\nu^2).$$

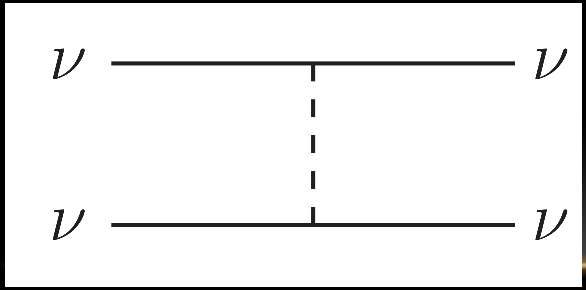
$$R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu} \simeq 0.403$$

for $N_{\rm eff} \simeq 3.046$

Bashinsky & Seljak (2004)
Baumann et al. (2016)

Neutrinos and the CMB

- This phase shift and amplitude suppression are very robust signatures of free-streaming radiation as they rely only on gravitational interactions.
- Key question: Is this simple picture consistent with observations? Or is yet-unknown neutrino physics modifying this picture?
- The simplest phenomenology that can suppress neutrino free-streaming is neutrino self-interactions.



- Hannestad (2005)
- Trotta & Melchiorri (2005)
- Melchiorri & Serra (2006)
- Bell, Pierpaoli & Sigurdson (2006)
- De Bernardis et al. (2008)
- Basboll, Bjaelde, Hannestad &Raffelt (2009)
- Smith, Das & Zahn (2012)
- Cyr-Racine & Sigurdson (2014)
- Archidiacono & Hannestad (2014)
- Forastieri, Lattanzi & Natoli (2015)
- Baumann, Green, Meyers & Wallisch (2016)
- Brust, Cui & Sigurdson (2017)
- Lancaster, Cyr-Racine, Knox, Pan (2017)
- Choi, Chiang & Loverde (2018)
- Song, Gonzalez-Garcia & Salvado (2018)
- Venzor et al. (2020, 2022, 2023)
- Brinkmann et al. (2021)
- Das & Ghosh (2021,2023)

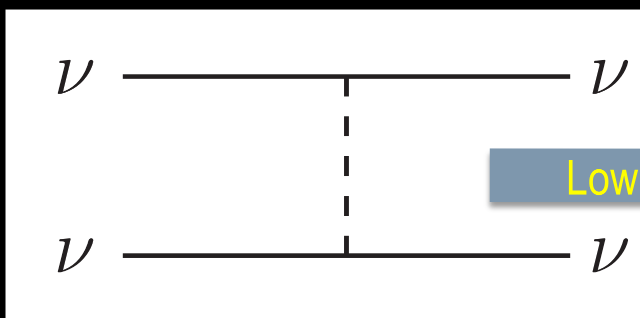
And many more!

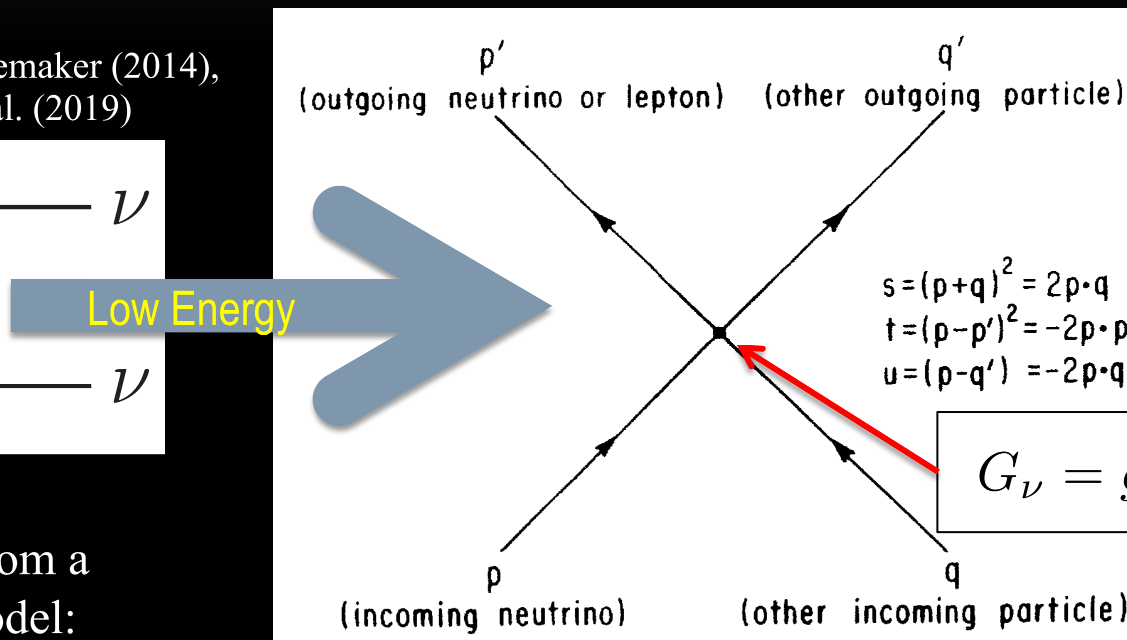
Beyond Free-streaming Neutrinos

New Unknown Interaction with massive mediator at low energies:

$$\mathcal{L}_{\rm phen} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + {\rm h.c.})$$

See e.g. Cherry, Friedland & Shoemaker (2014), Ng & Beacom (2014), Blinov et al. (2019)





$$G_\nu = g_\nu^2/M_\phi^2$$

Could be generated from a leptophilic scalar model:

$$\mathcal{L} = \frac{1}{\Lambda^2}(LH)^2\phi$$

See e.g. Berryman et al. (2022)

4-Fermion Interaction stronger than Fermi constant

$$G_\nu > G_{\rm F}$$

Delayed Neutrino Decoupling

Neutrino Opacity:

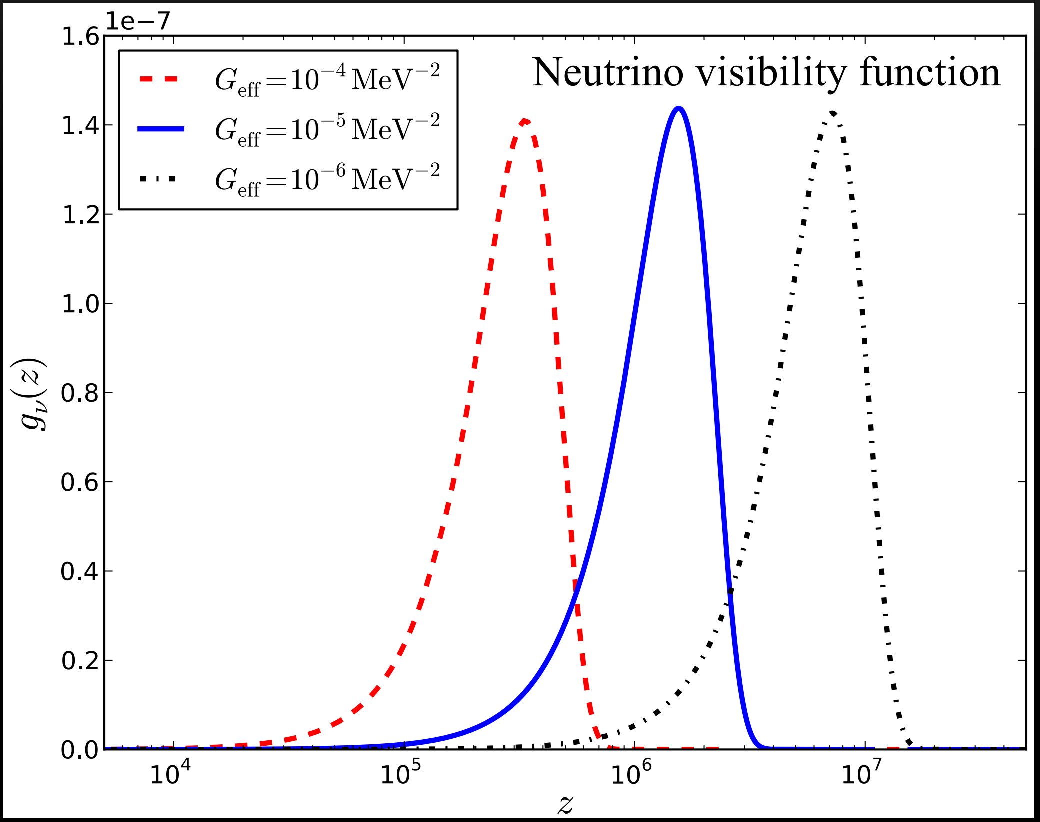
$$\dot{\tau}_\nu \propto -aG_{\rm eff}^2 T_\nu^5$$

$$G_{\rm eff} \propto G_\nu$$

$$G_\nu = g_\nu^2/M_\phi^2$$

$$g_\nu(\tau) \equiv -\dot{\tau}_\nu e^{-\tau_\nu}$$

New Neutrino Interactions → Delayed Neutrino free streaming!



Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)

Massive Neutrino Boltzmann Hierarchy

Simplified Boltzmann Hierarchy (assume decoupling in relativistic regime):

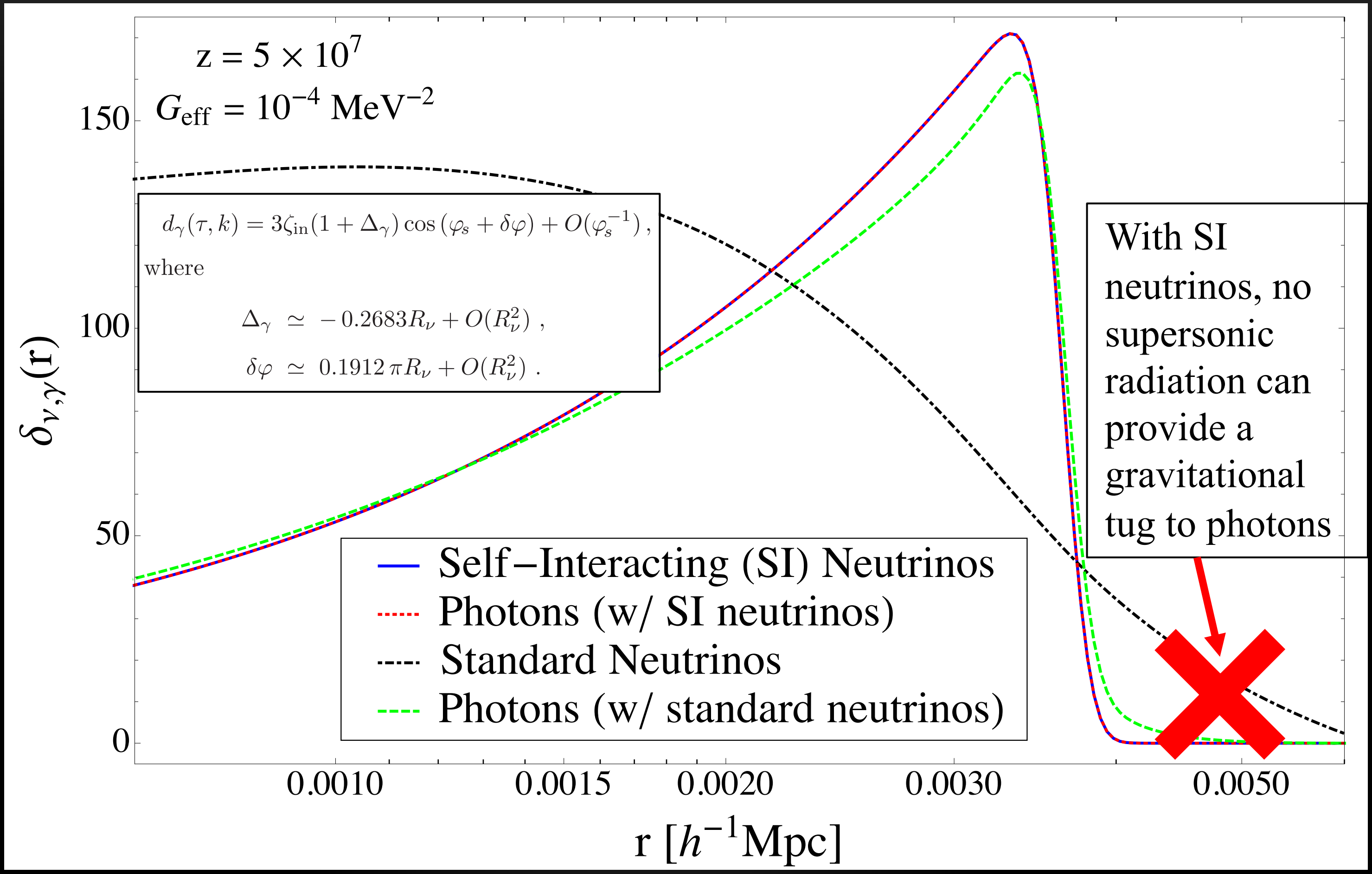
$$\frac{\partial \nu_l}{\partial \tau} + k\frac{q}{\epsilon}\left(\frac{l+1}{2l+1}\nu_{l+1} - \frac{l}{2l+1}\nu_{l-1}\right) - 4\left[\frac{\partial \phi}{\partial \tau}\delta_{l0} + \frac{k}{3}\frac{\epsilon}{q}\psi\delta_{l1}\right] = -a\frac{G_{\rm eff}^2 T_\nu^5 \nu_l}{f_\nu^{(0)}(q)}\left(\frac{T_{\nu,0}}{q}\right)\left(A\left(\frac{q}{T_{\nu,0}}\right) + B_l\left(\frac{q}{T_{\nu,0}}\right) - 2D_l\left(\frac{q}{T_{\nu,0}}\right)\right)$$

Relaxation-time approximation

$$\epsilon = \sqrt{q^2 + a^2 m_\nu^2},$$

Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)
Choi, Chiang & Loverde (2018)
Kreisch, Cyr-Racine & Doré (2020)
Brinkmann et al. (2021)
Venzor et al. (2022, 2023)

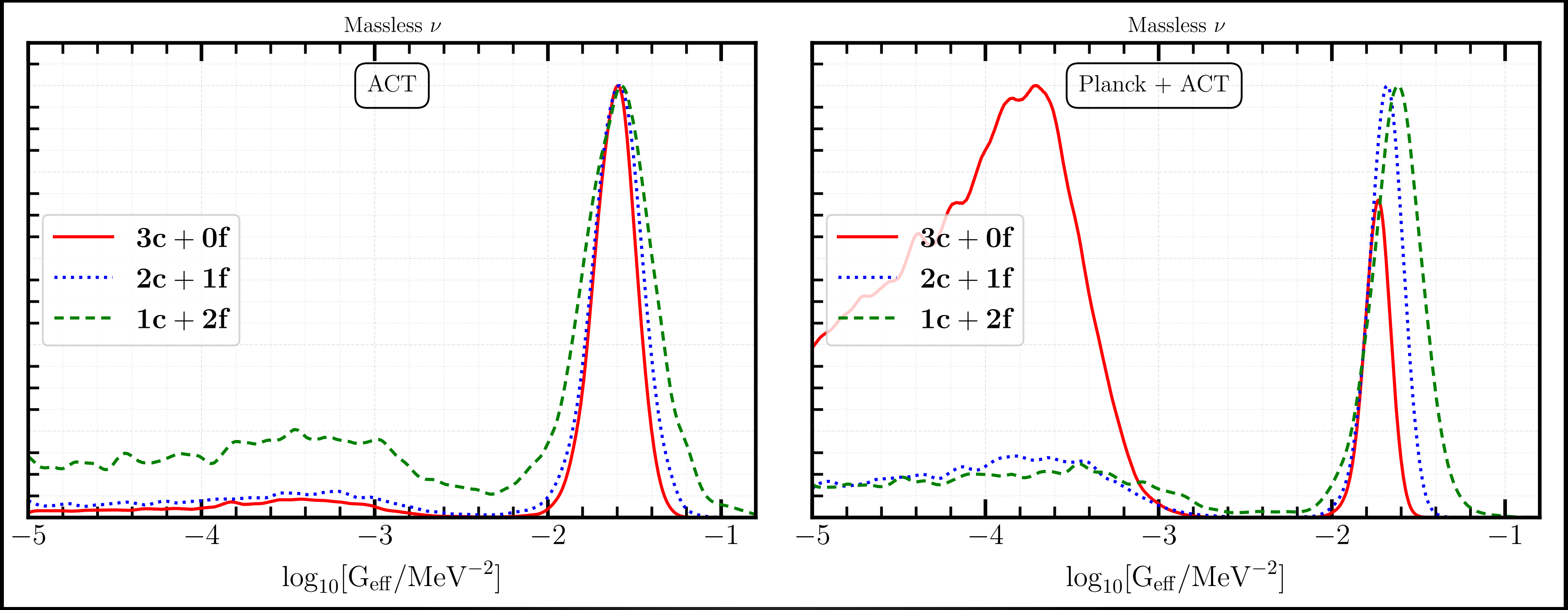
Impact of self-interacting Neutrinos on CMB



Cyr-Racine & Sigurdson (2014)

Some outrageous CMB results…

- ACT data also displays significant preference for neutrino self-interactions. Planck does not like it so much.

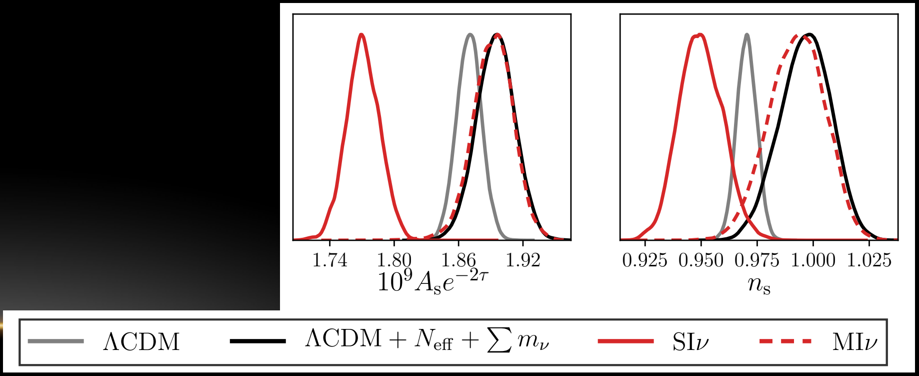


Das & Ghosh (2023)
Kreisch et al. (2023)

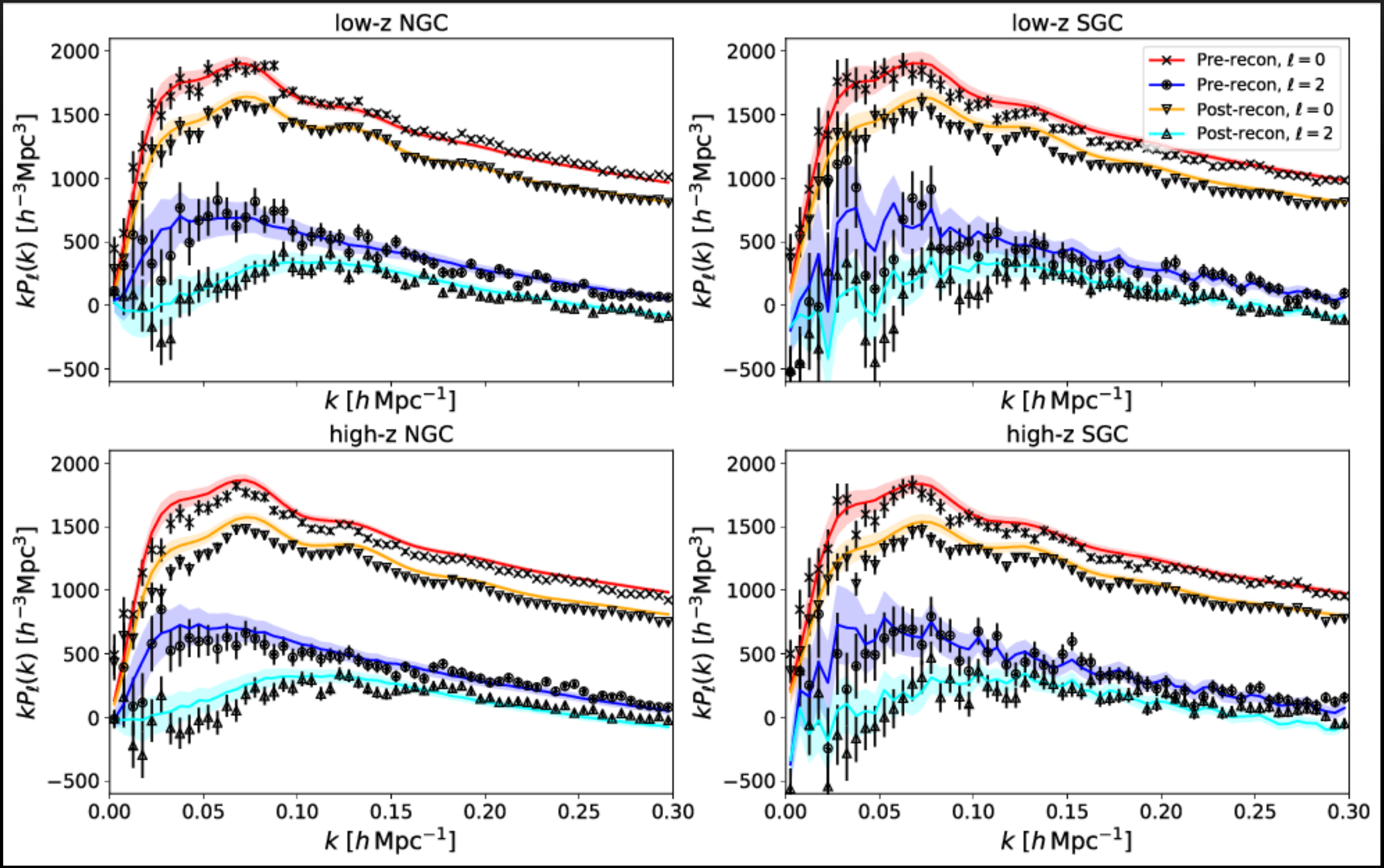
The SIν and the CMB

- The SIν is possible because of a multi-parameter degeneracy between the impact of neutrinos and changes in the primordial spectrum of fluctuations (n_s, A_s).
- Planck CMB temperature data, BAO, and ACT data show a marked preference for a delayed onset of neutrino free-streaming.
- However, Planck CMB polarization data tend to dislike the presence of new neutrino self-interactions.

Need an independent observable that can help confirm or rule out this signal.



Full Shape to the rescue



Philcox et al. (2020)

Impact of self-interacting Neutrinos on matter clustering

- Dark matter perturbation equation can be written as:

$$\ddot{d}_{\rm c} + \frac{\dot{a}}{a}\dot{d}_{\rm c} = -k^2\psi,$$

$$d_{\rm c} \equiv \delta_{\rm c} - 3\phi,$$

where $ds^2 = a^2(\tau)[-(1+2\psi)d\tau^2 + (1-2\phi)d\vec{x}^2],$

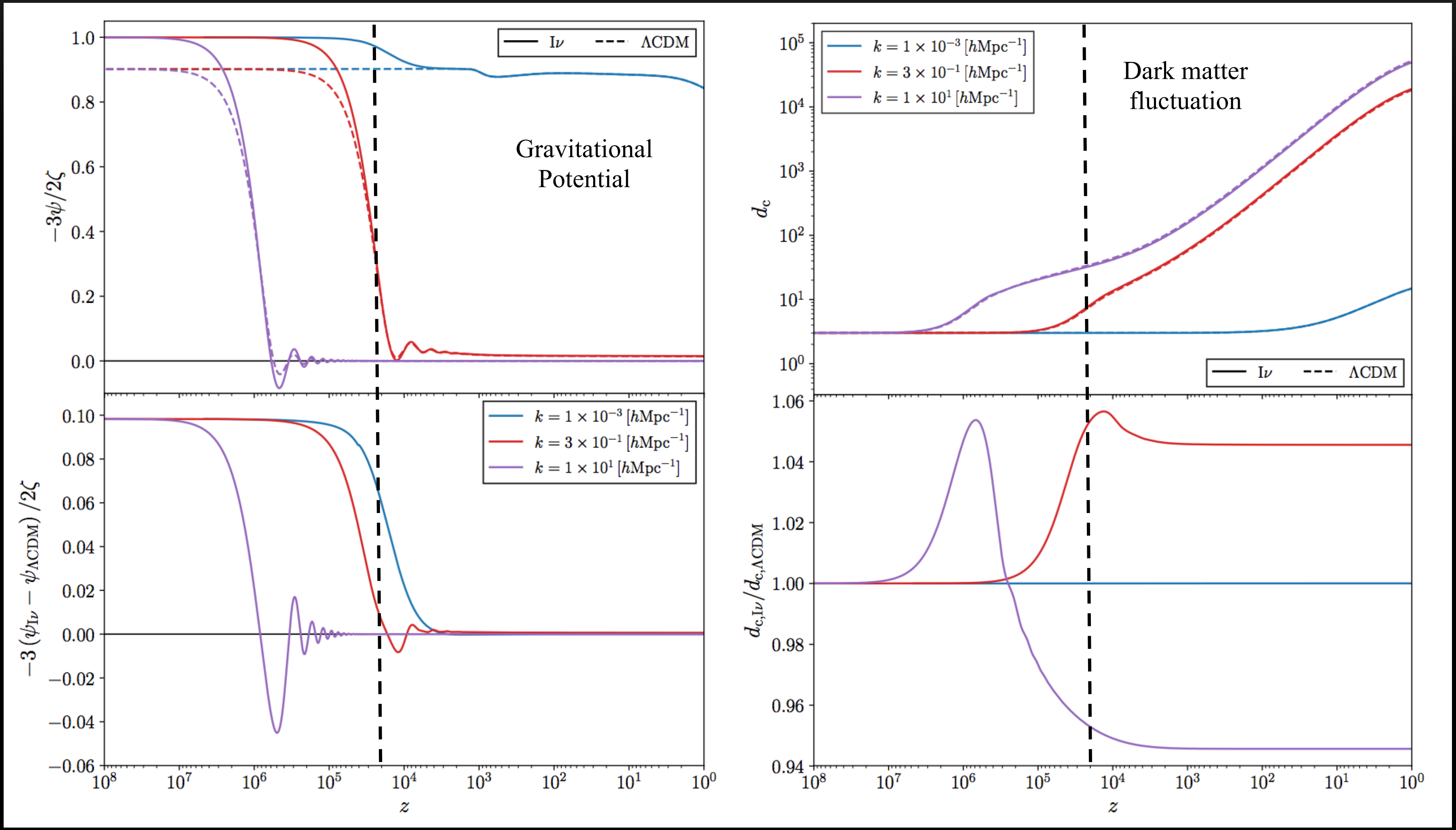
- The general solution (in radiation domination):

$$d_{\rm c}(k,\tau) = -\frac{9}{2}\phi_{\rm p} + k^2\int_0^\tau d\tau'\tau'\psi(k,\tau')\ln(\tau'/\tau),$$

- Without free-streaming neutrinos, we have:

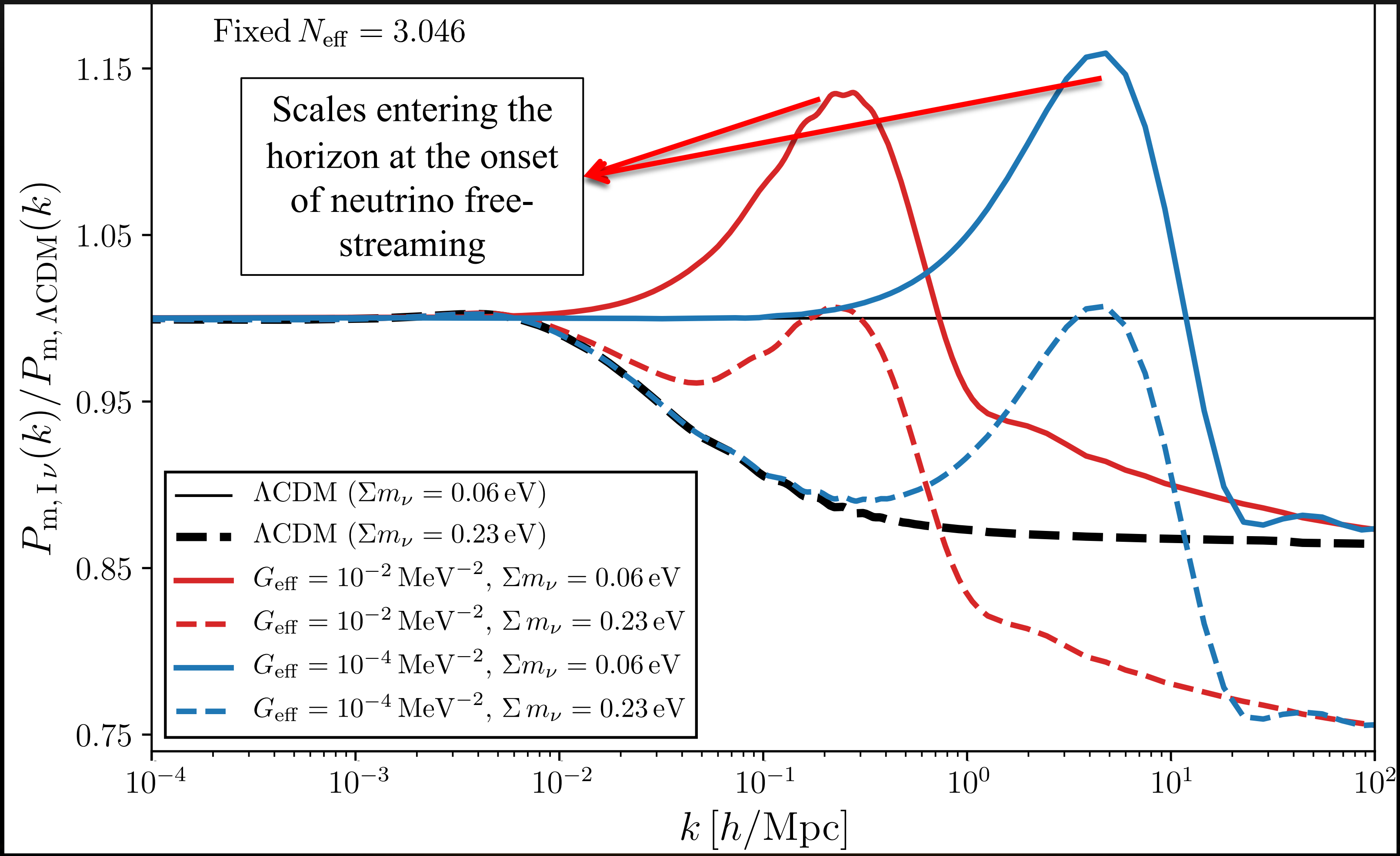
$$\phi - \psi = 0$$ instead of $$\phi = (1+2R_\nu/5)\psi$$

Impact of self-interacting Neutrinos on matter clustering



Kreisch, Cyr-Racine, Doré (2020)

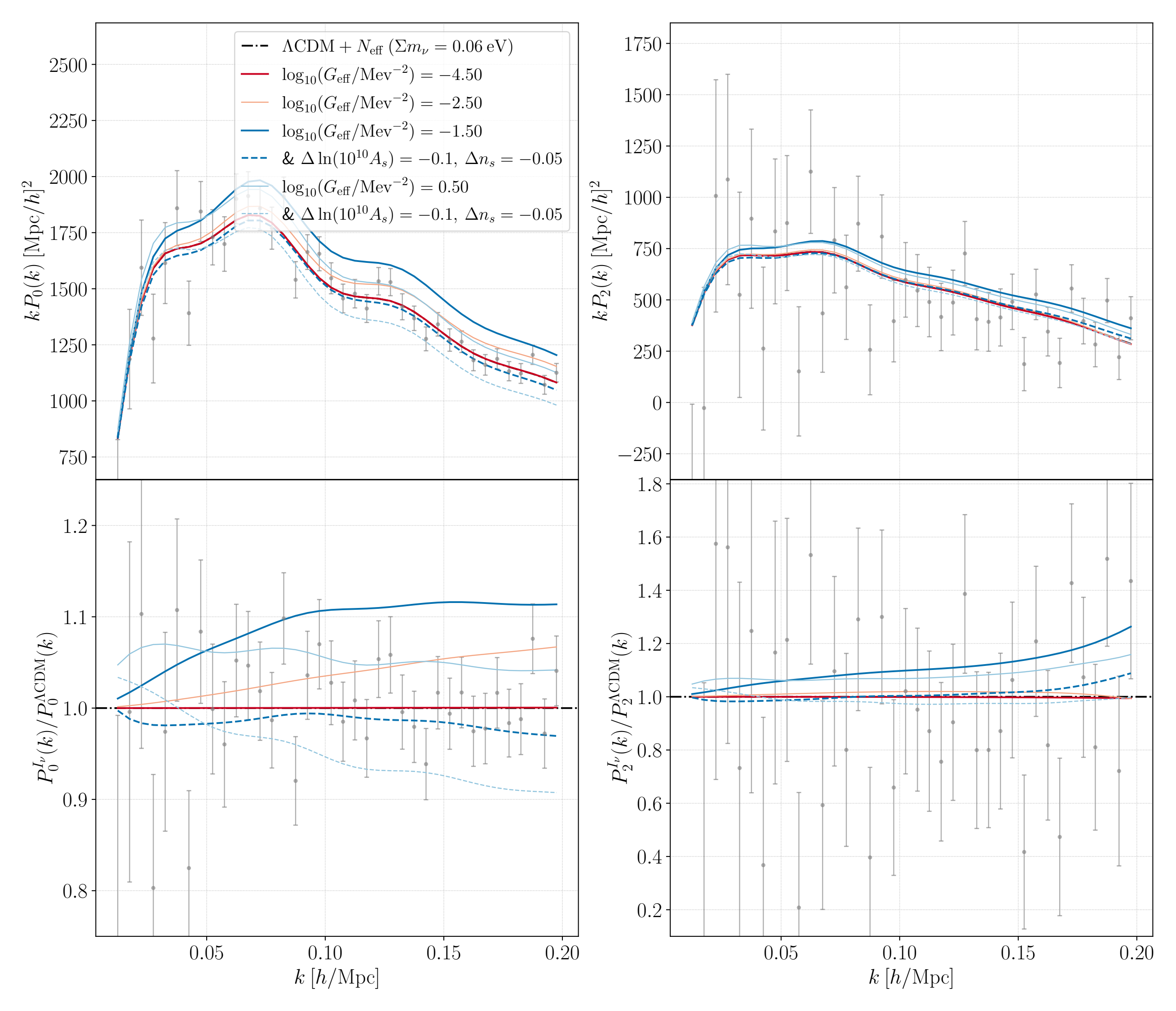
Impact of self-interacting Neutrinos on matter clustering



Kreisch, Cyr-Racine, Doré (2020)

Galaxy power spectra and interacting neutrinos

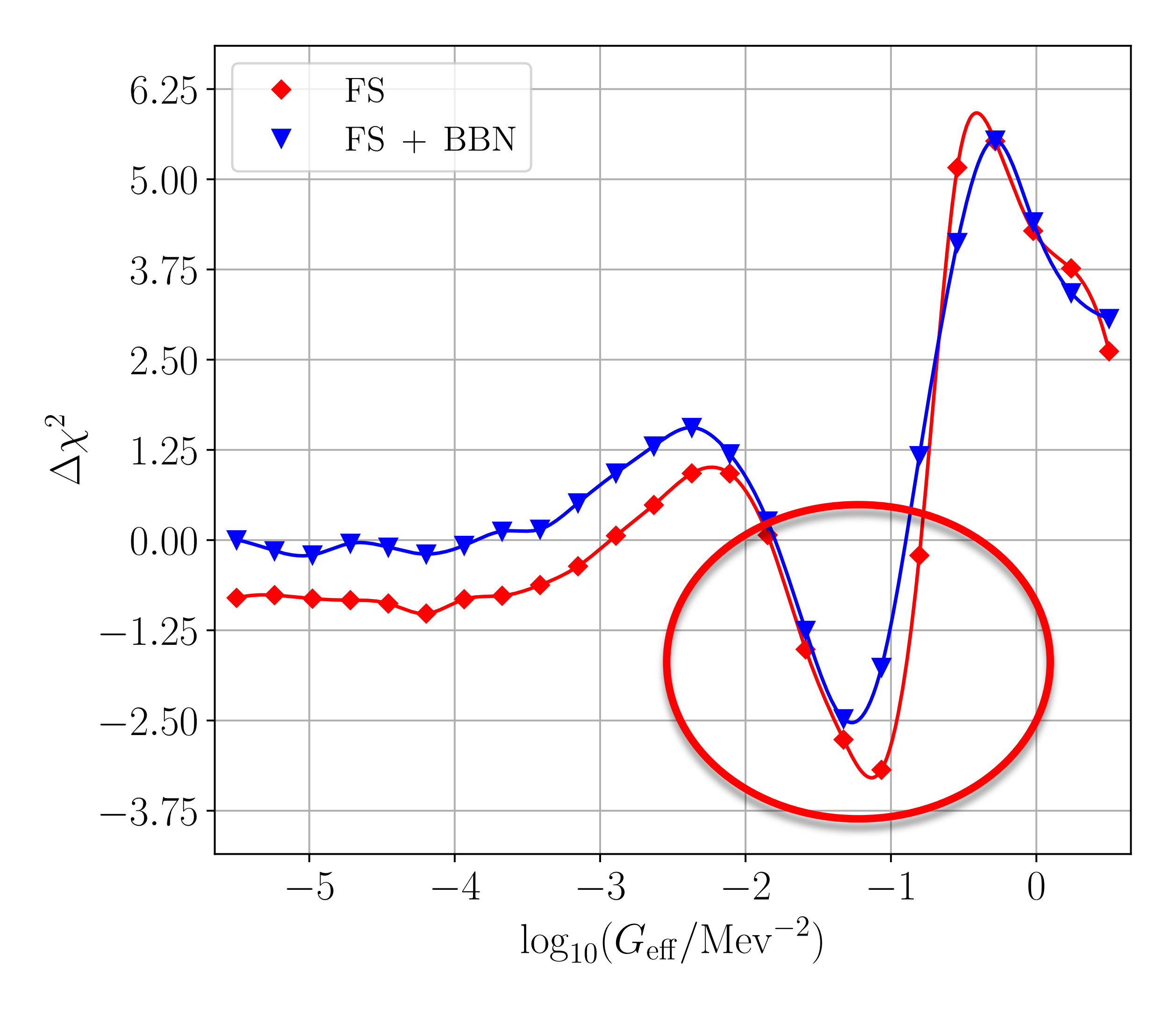
- Interacting neutrinos can in principle provide a good fit to the galaxy power spectra when the primordial spectrum of fluctuations is also modified.



Camarena, Cyr-Racine, Houghteling (2023)

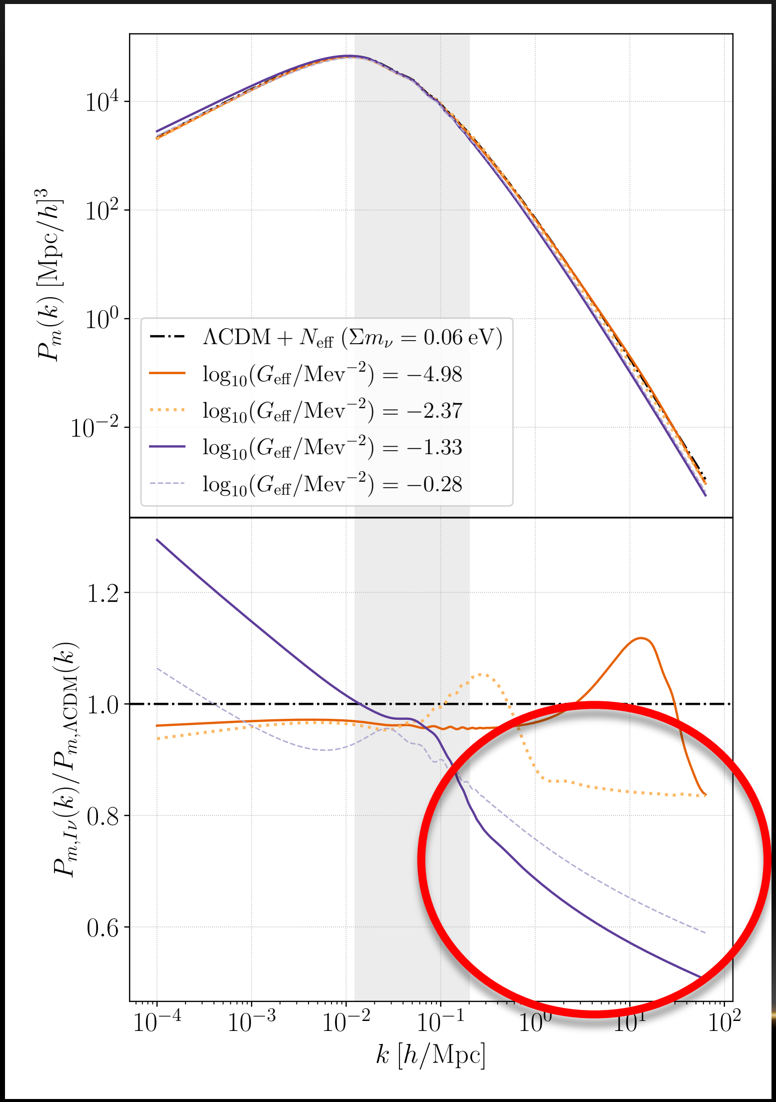
Galaxy power spectra: Profile likelihood

- By minimizing the full-shape likelihood, we see that the galaxy power spectra also shows some preference for the SIν!



Camarena, Cyr-Racine, Houghteling (2023)

Preferred shape for the matter power spectrum

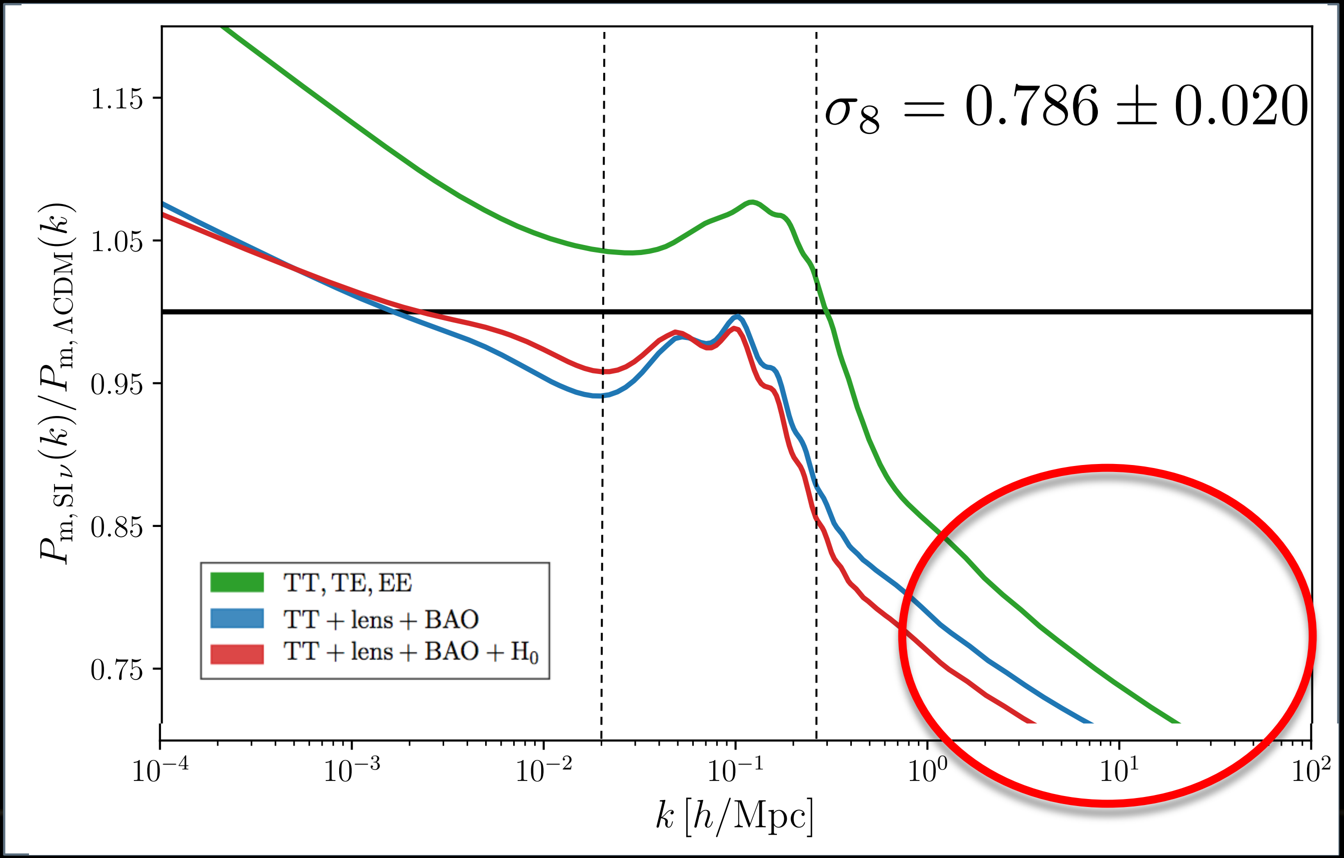


- The preferred neutrino interaction model has a matter power spectrum that is significantly suppressed on small scales.
- This is a key prediction of such models!

Camarena, Cyr-Racine, Houghteling (2023)

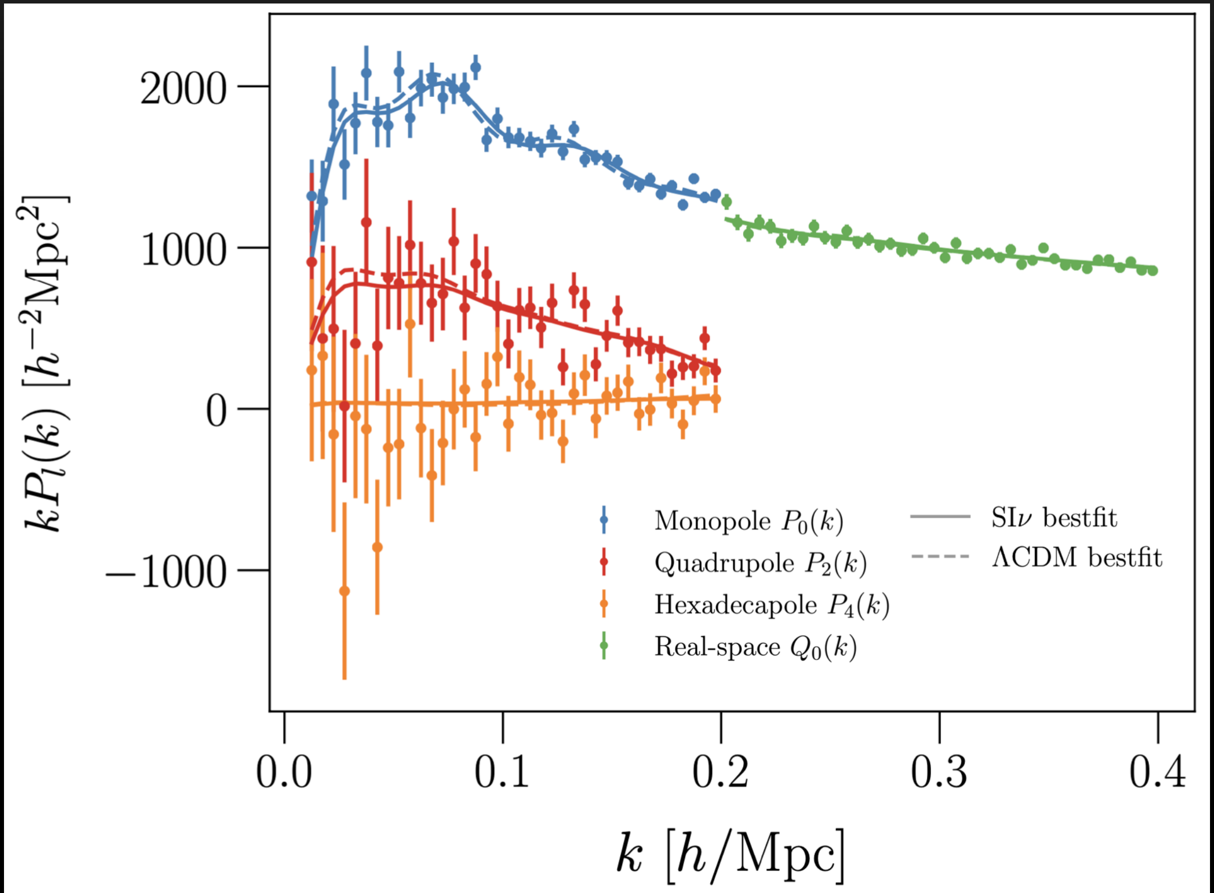
Preferred shape for the matter power spectrum

- Interestingly, similar matter power spectrum shapes seen for models preferred by the CMB.



Kreisch, Cyr-Racine, Doré (2020)

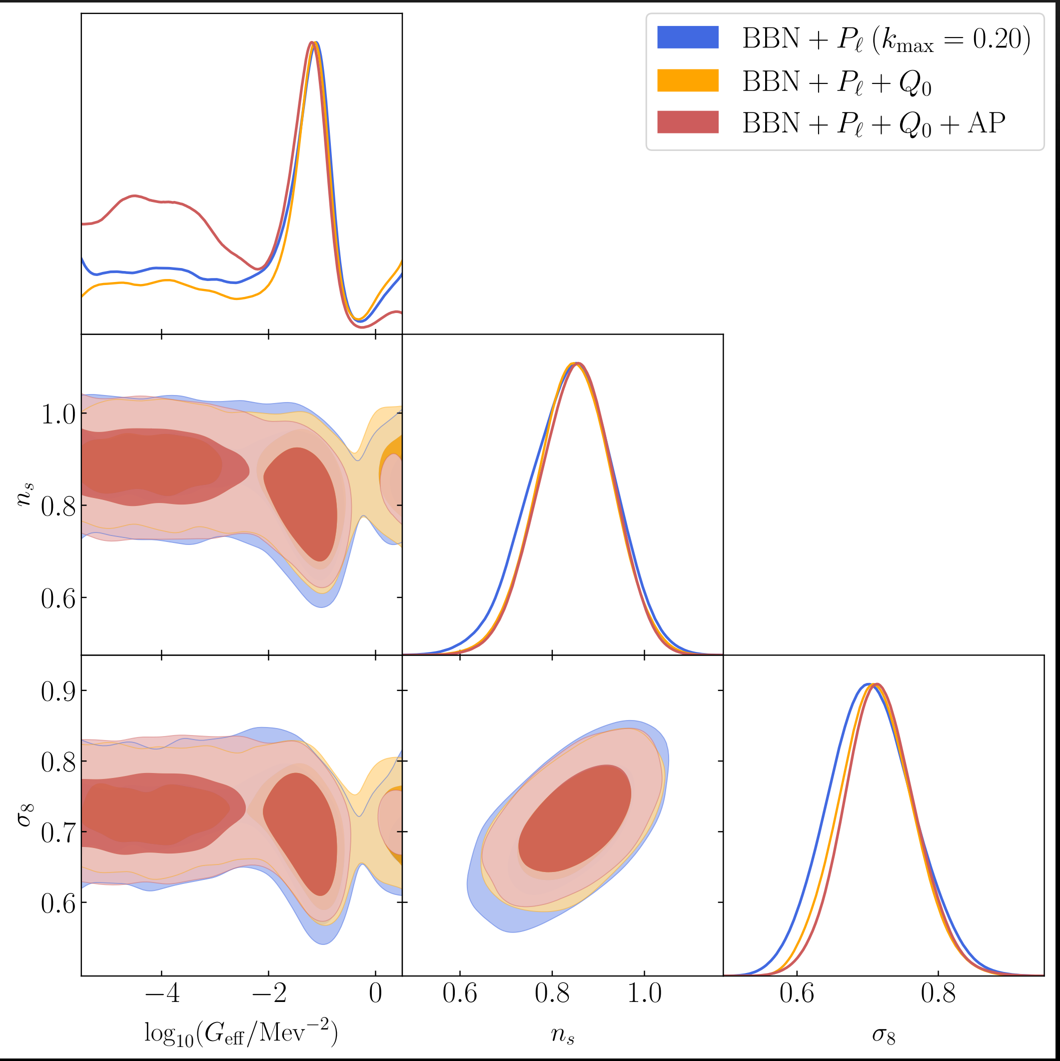
Our results are consistent with other analysis



He, An, Ivanov & Gluscevic (2023)

Galaxy power spectra: Bayesian analysis

- We see consistent results, in which the full-shape data show a preference for the SIν. This is the same model favored by some CMB analyses.

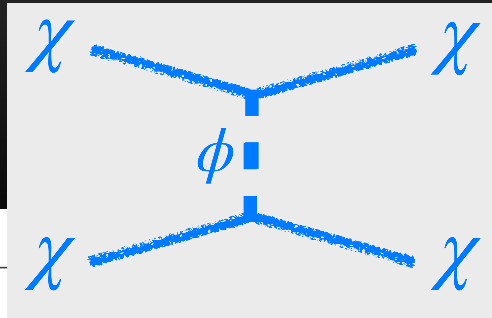


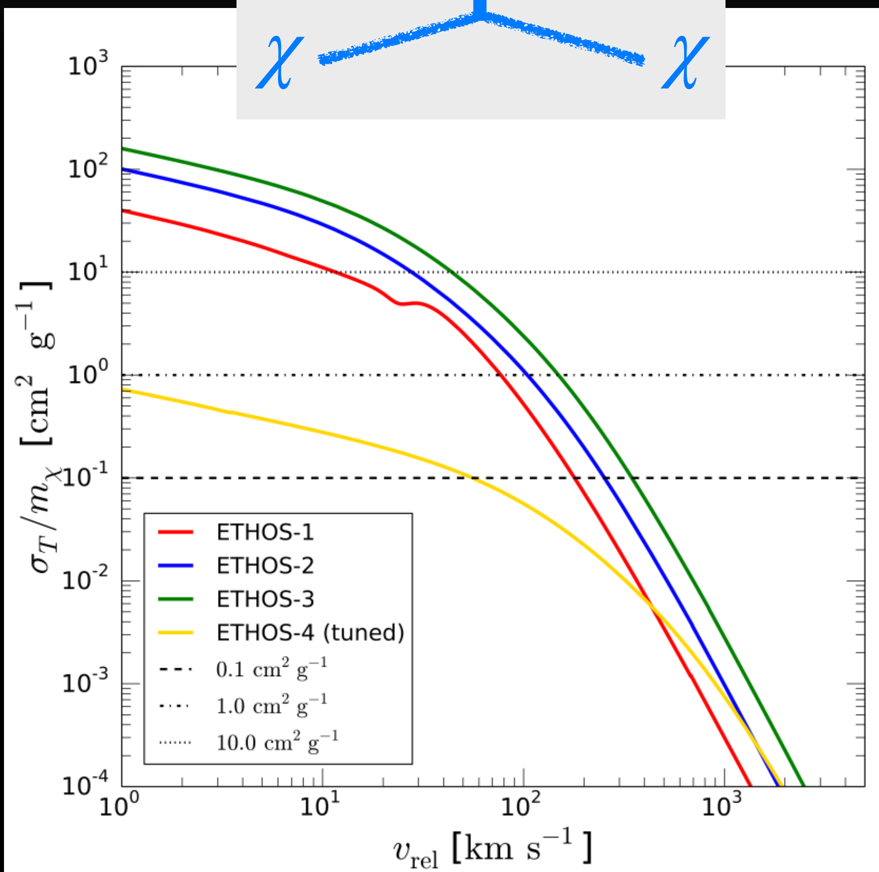
Camarena, Cyr-Racine, Houghteling (2023)

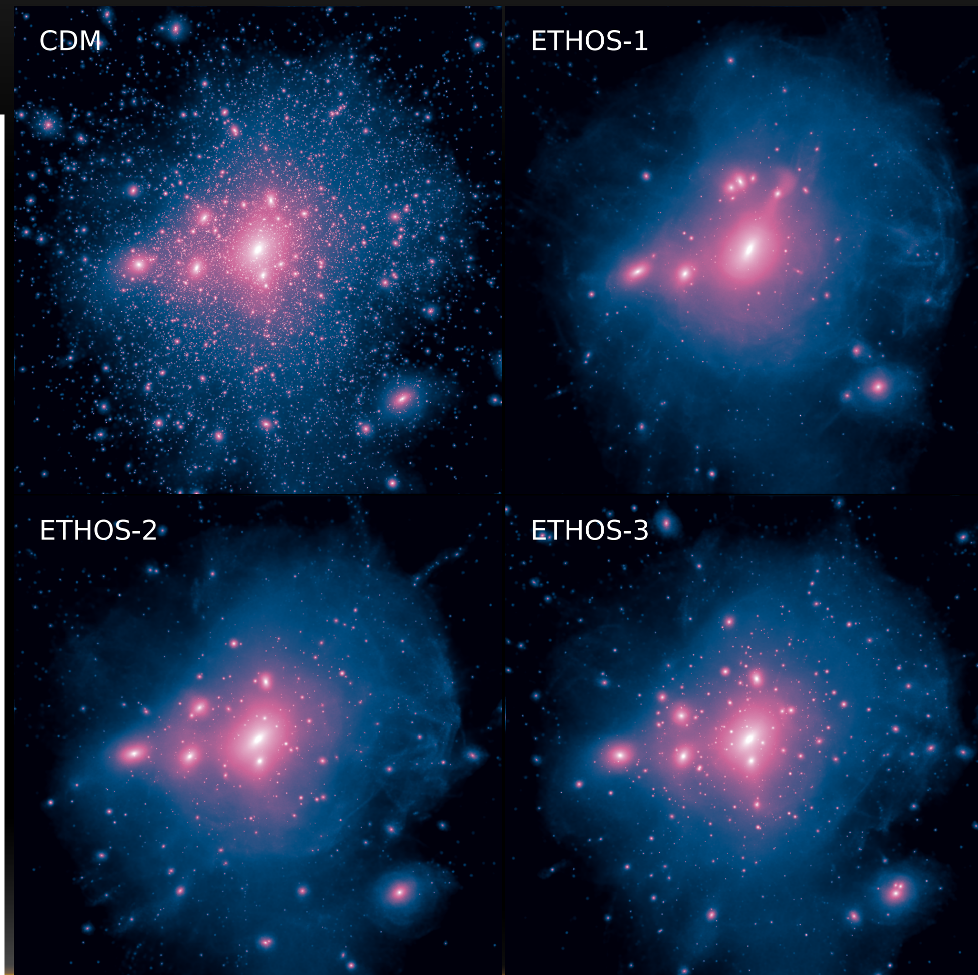
SIν Cosmology: The current situation

- We now have two independent types of datasets showing the existence of the SIν cosmology.
- This implies that this is a physical feature present in the data, and not the results of a spurious feature in the CMB sky.
- The statistical significance is however not overwhelming, and I would say that, at best, there is a mild preference for a delayed onset of neutrino free-streaming.
- Another possibility is that the SIν is picking a feature in the data that has nothing to do with neutrinos but is caused by other physics.
- Either way, this points to the existence of something we do not yet understand, which is exciting!

Self-interacting dark matter and halo structure



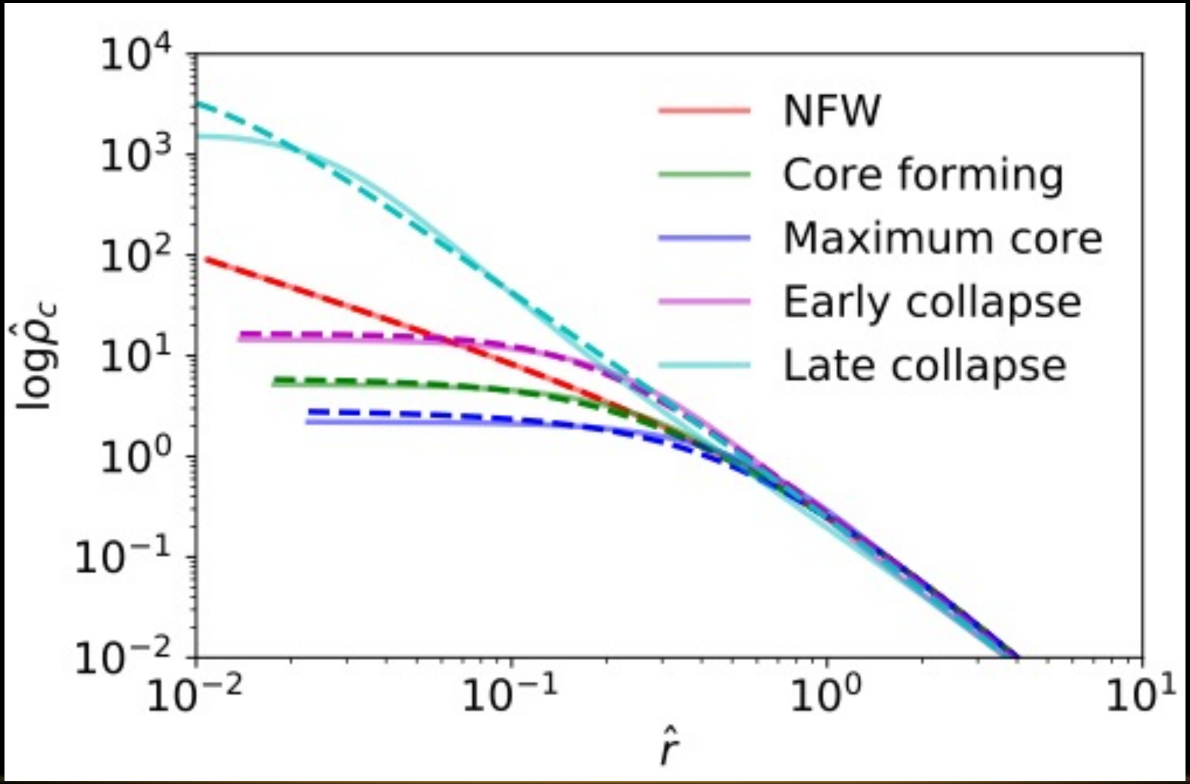




Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

Self-interacting dark matter halo: Diversity of density profiles

- SIDM predicts a broad diversity of halo density profiles, that is absent in standard cold dark matter.

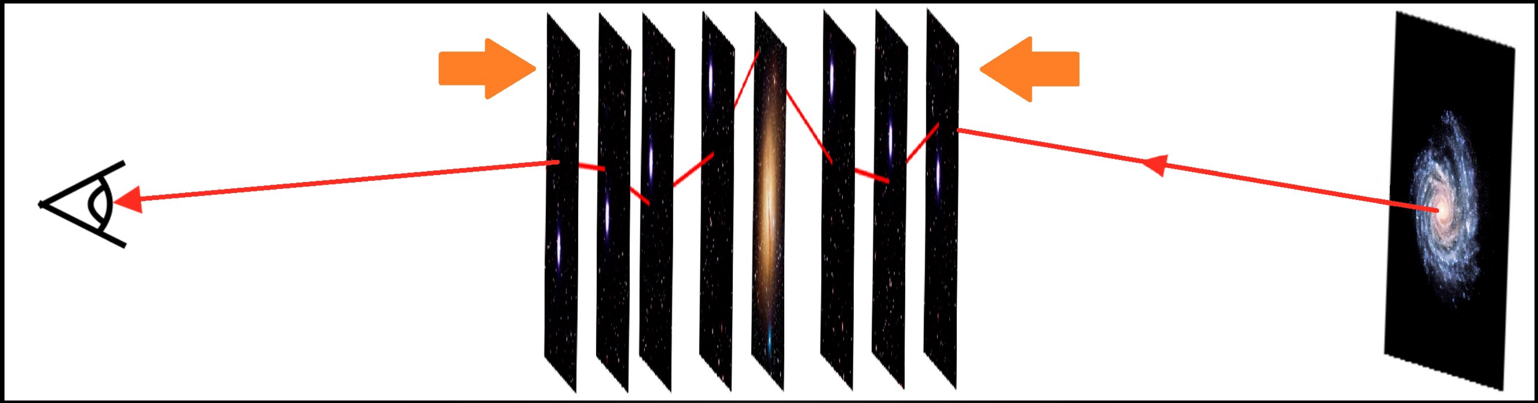


Yang et al. (2022)

Probing SIDM: Effective Multiplane Lensing

- Since lensing is just a mapping between a source plane and an image plane, compress everything to a single function: $$\mathbf{u} = \mathbf{x} - \boldsymbol{\alpha}_{\rm eff}(\mathbf{x})$$

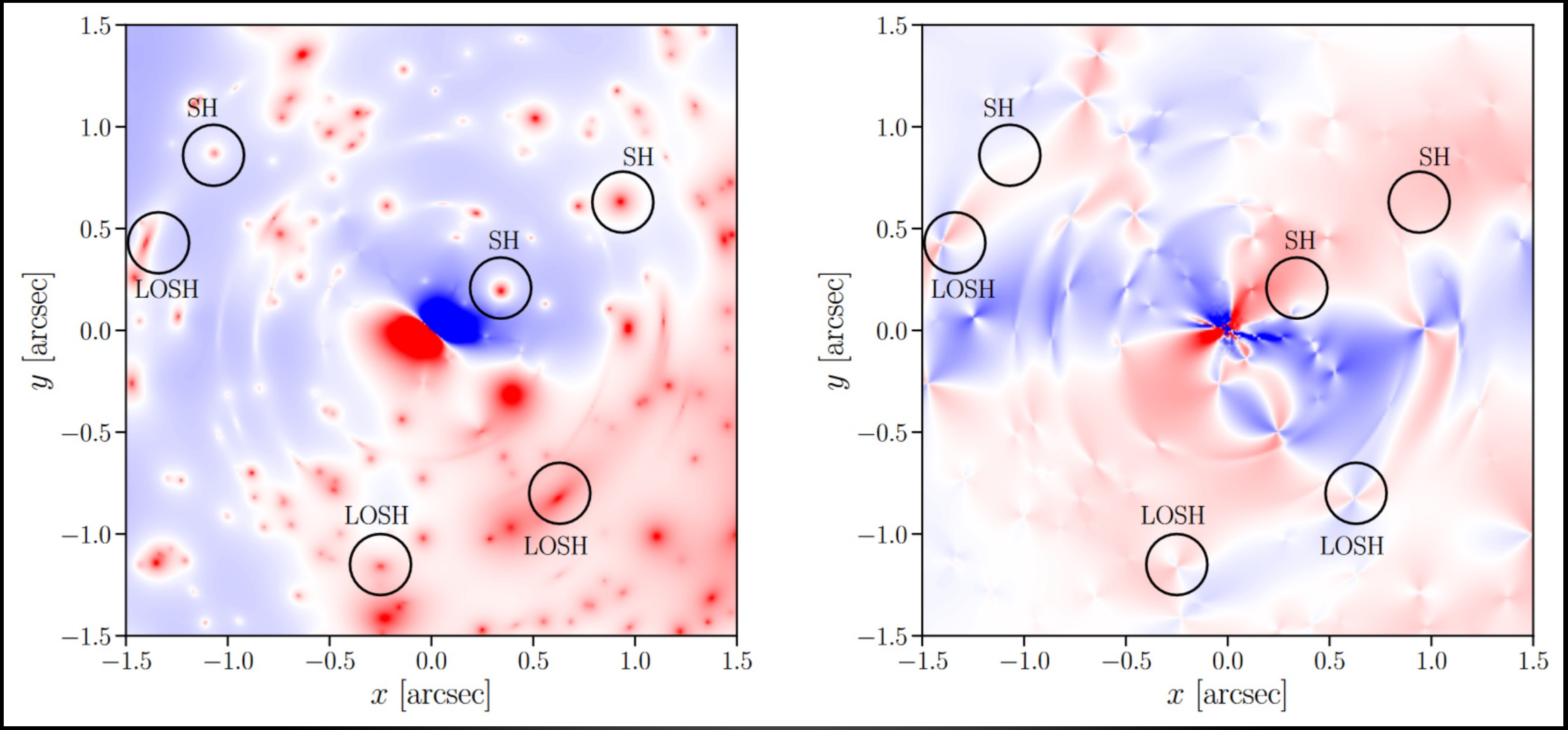
where
u - coordinate in the source plane
x - coordinate in the image plane



Divergence Component: $\kappa_{\rm div} \equiv \frac{1}{2}\nabla \cdot \boldsymbol{\alpha}_{\rm eff} - \kappa_0$
Curl Component: $\kappa_{\rm curl} \equiv \frac{1}{2}\nabla \times \boldsymbol{\alpha}_{\rm eff} \cdot \hat{\mathbf{z}}$

Effective deflection field

- Divergence and curl of the effective deflection field: Anisotropies between the radial and angular direction

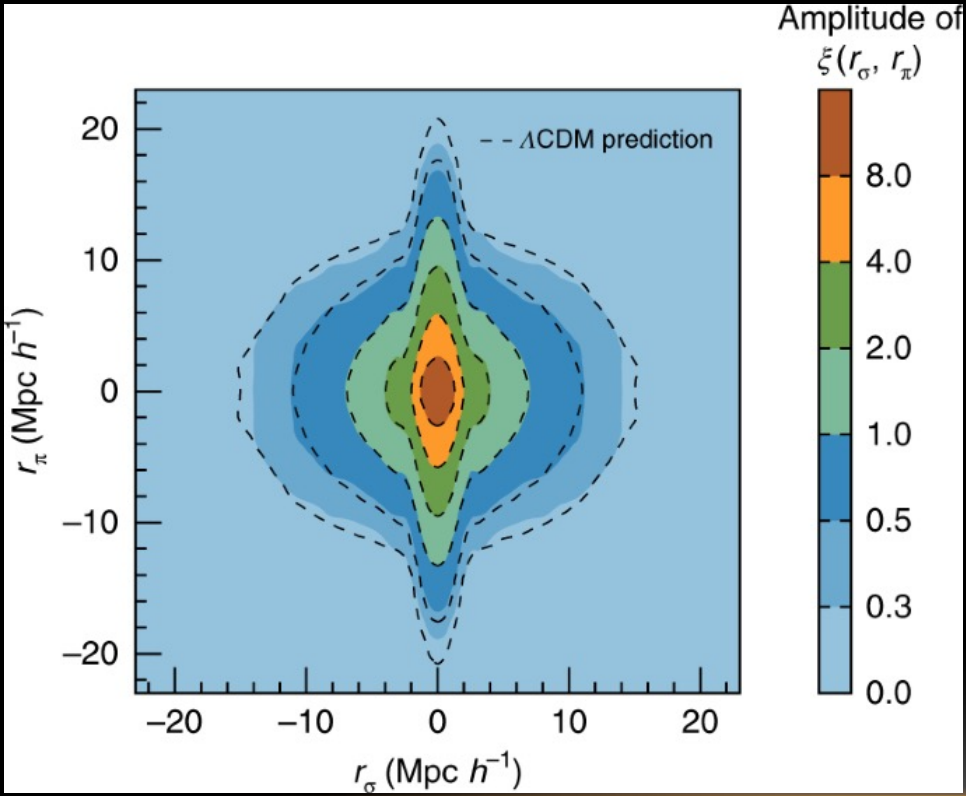


Dhanasingham, Cyr-Racine + (2023)

Thank you, Daniel Gilman!

Inspiration from large-scale structure

- Galaxy peculiar velocities give rise to a quadrupole moment in the galaxy two-point correlation function.

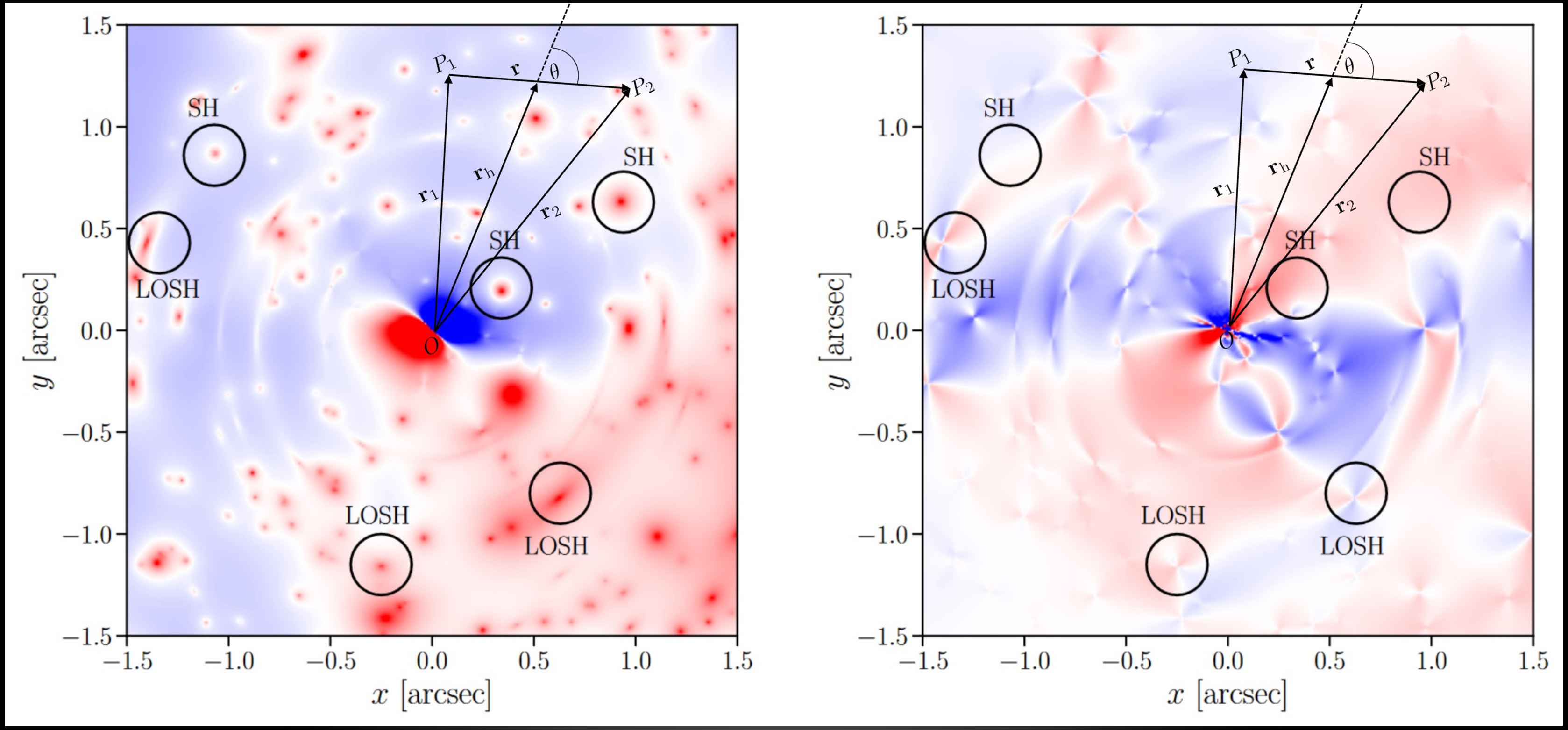


- In strong lensing, presence of main galaxy break translation symmetry, giving rise to anisotropies.

He et al. (2018)

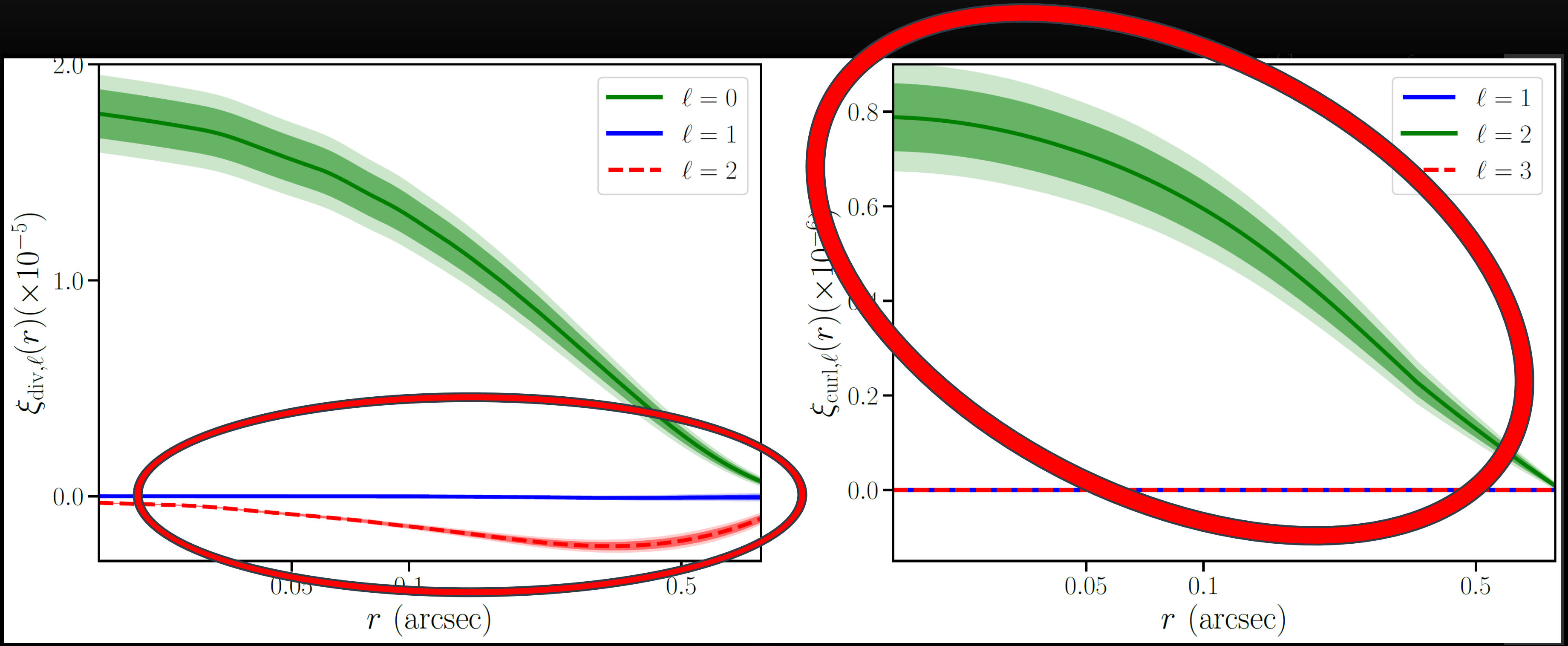
Capturing Anisotropies

- Compute the two-point function of the effective deflection field. $\xi(\mathbf{r}) = \xi(\mathbf{r}_2 - \mathbf{r}_1) = \frac{1}{A}\int_A d^2\mathbf{r}_1\ \kappa_{\rm div}(\mathbf{r}_1)\ \kappa_{\rm div}(\mathbf{r}+\mathbf{r}_1)$



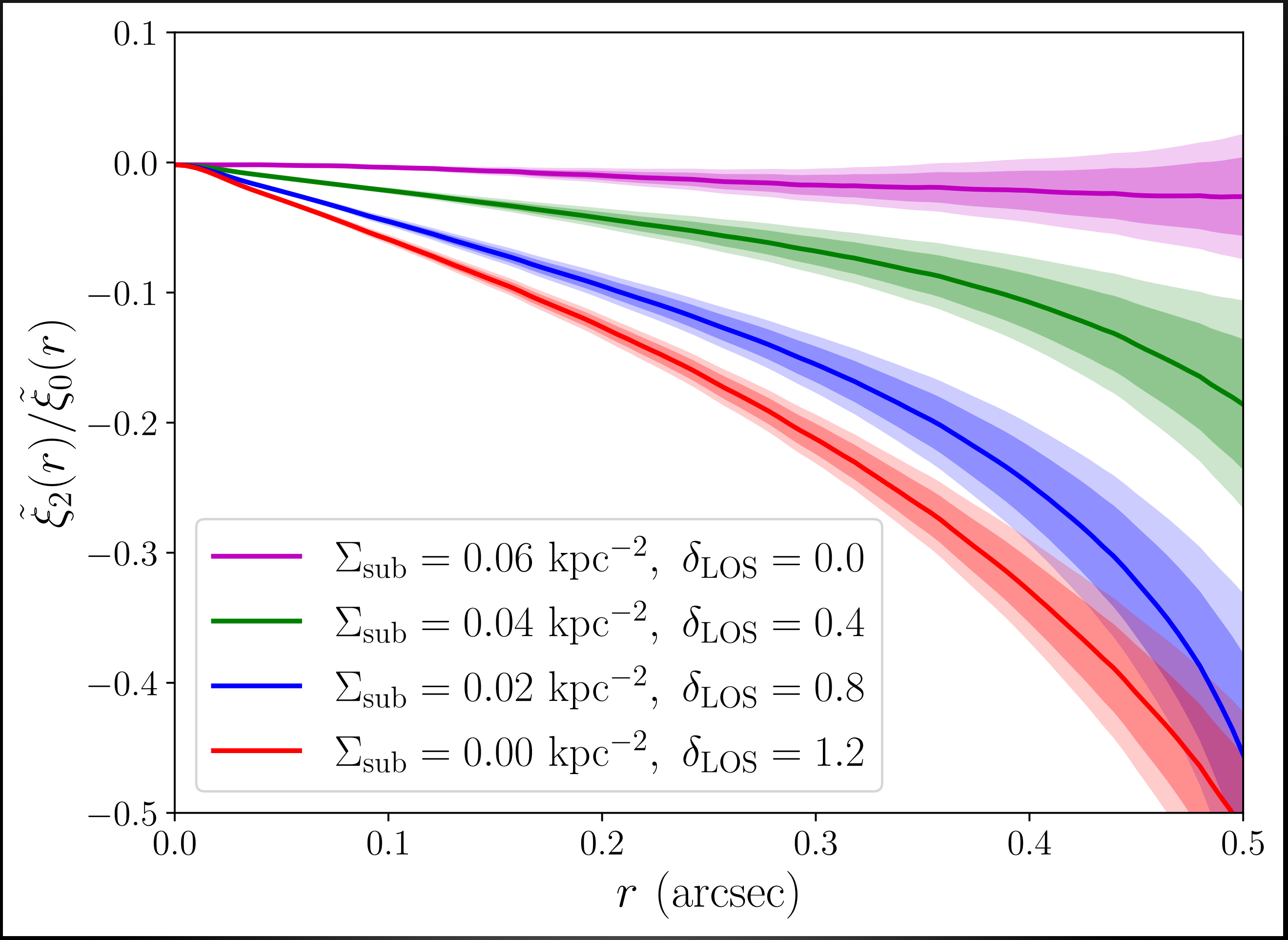
Dhanasingham, Cyr-Racine + (2023)

Correlation function: Nonzero quadrupole moments



(see also, Hezaveh et al. 2016b; Chatterjee & Koopmans 2018; Díaz Rivero et al. 2018a,b; Brennan et al. 2019; Cyr-Racine et al. 2019; Çagan Şengül et al. 2020; Bayer et al. 2023a,b)

The quadrupole is probing line-of-sight halos

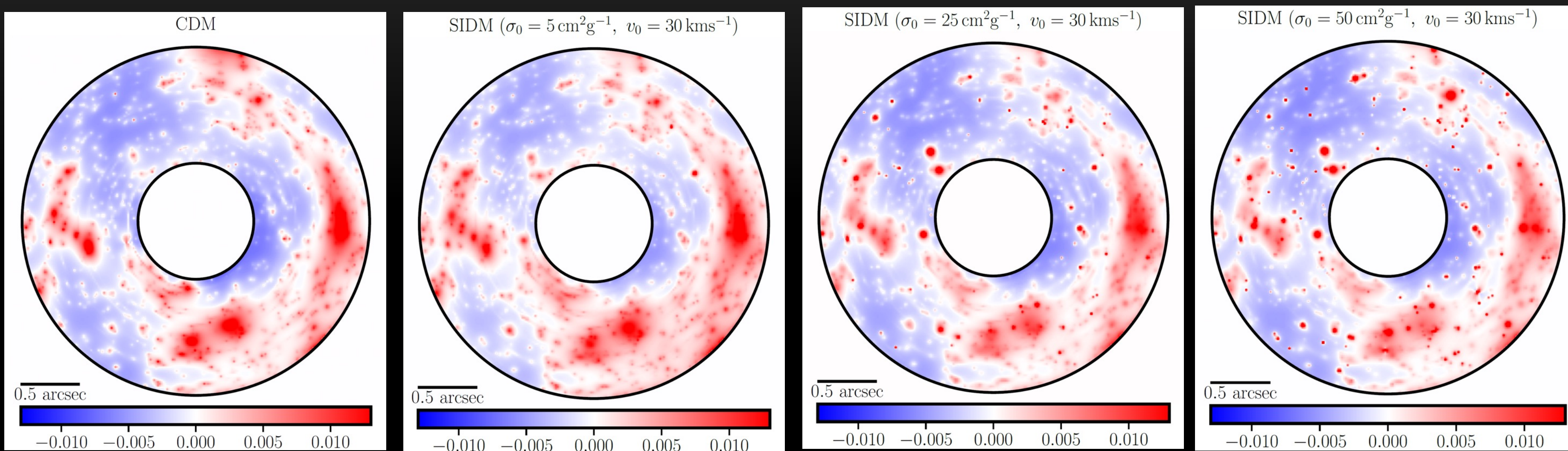


Dhanasingham, Cyr-Racine + (2022)

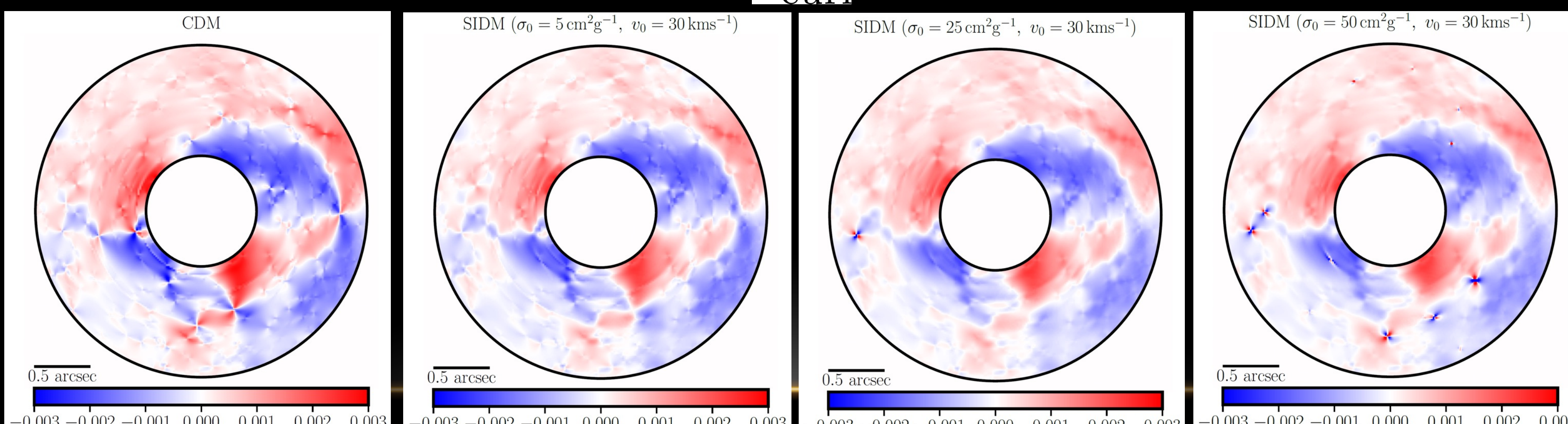
$\kappa_{\rm div}$

Self-interacting Dark Matter

$\kappa_{\rm div}$

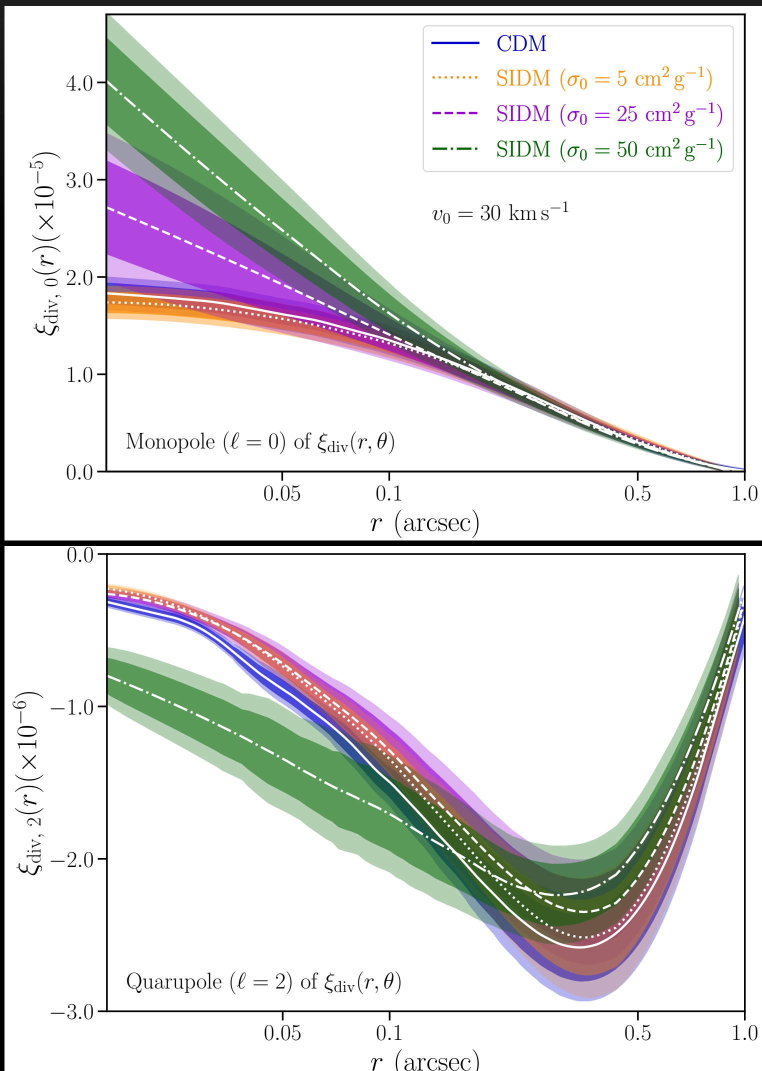


$\kappa_{\rm curl}$



Dhanasingham, Cyr-Racine + (2023)

Self-interacting Dark Matter

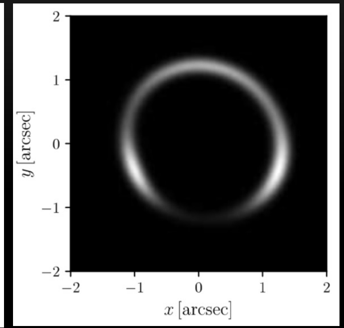


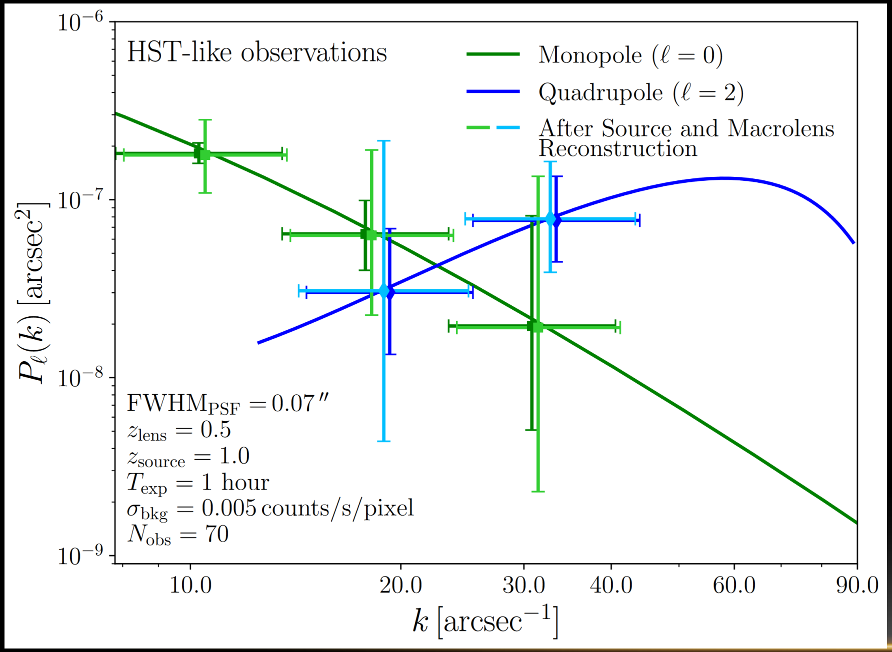
	Div Monopole	Div Quadrupole	Curl Quadrupole
Small cross section			
Medium cross section			
Large cross section			

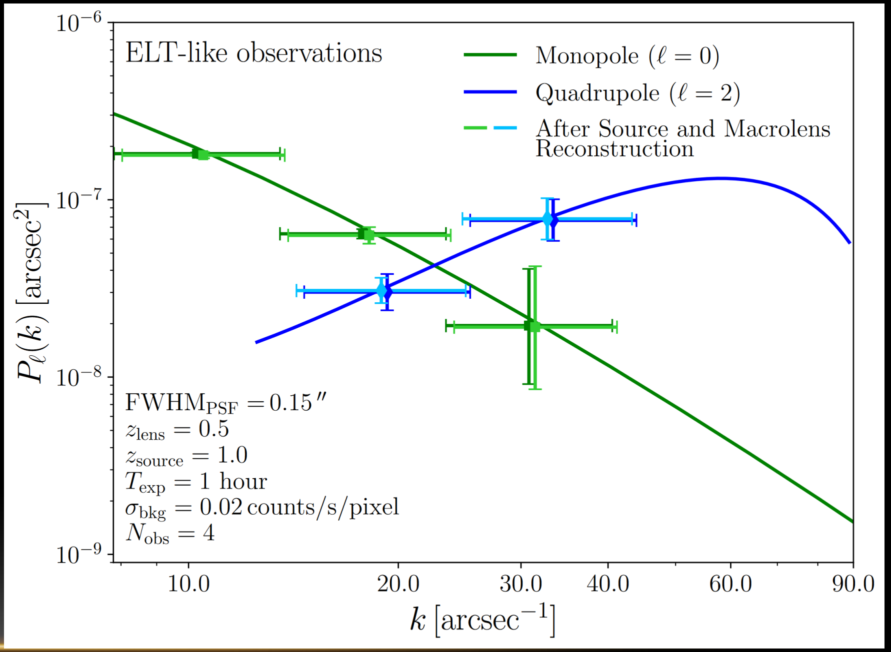
Dhanasingham, Cyr-Racine + (2023)

Assessing detectability in ideal case

	HST-like	ELT-like
Resolution (arcsec/pixel)	0.05	0.01
$\mathrm{FWHM_{PSF}}$ (arcsec)	0.07	0.15
T_{exp} (hours)	1.0	1.0
σ_{bkg} (counts/s/pixel)	0.005	0.02
N_{obs}	70	4







Dhanasingham, Cyr-Racine + (2022)

Self-interacting Conclusions

- Neutrinos:
  - Due to neutrinos' importance in the early Universe, cosmological data offer great sensitivity to new physics affecting neutrino free-streaming.
  - Both CMB and the galaxy power spectrum show some preference for neutrino self-interactions.
- Dark Matter:
  - Anisotropies in the two-point correlation function of the $\kappa_{\rm div}$ and $\kappa_{\rm curl}$ fields allow us to separate line-of-sight halos from main-lens substructure.
  - By measuring both the quadrupole and monopole of the $\xi_{\rm div}$ function, get sensitivity to the SIDM cross section.