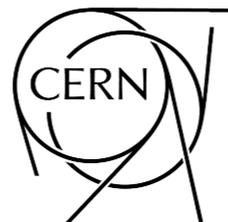


Sterile Neutrinos at the eV Scale

Theory and Phenomenology

Joachim Kopp

NBI Summer School | Copenhagen, Denmark | July 2021



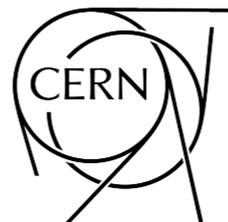
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In this Talk

- Neutrino Oscillations
- Short-Baseline Anomalies
- Global Fit Results
- Cosmology

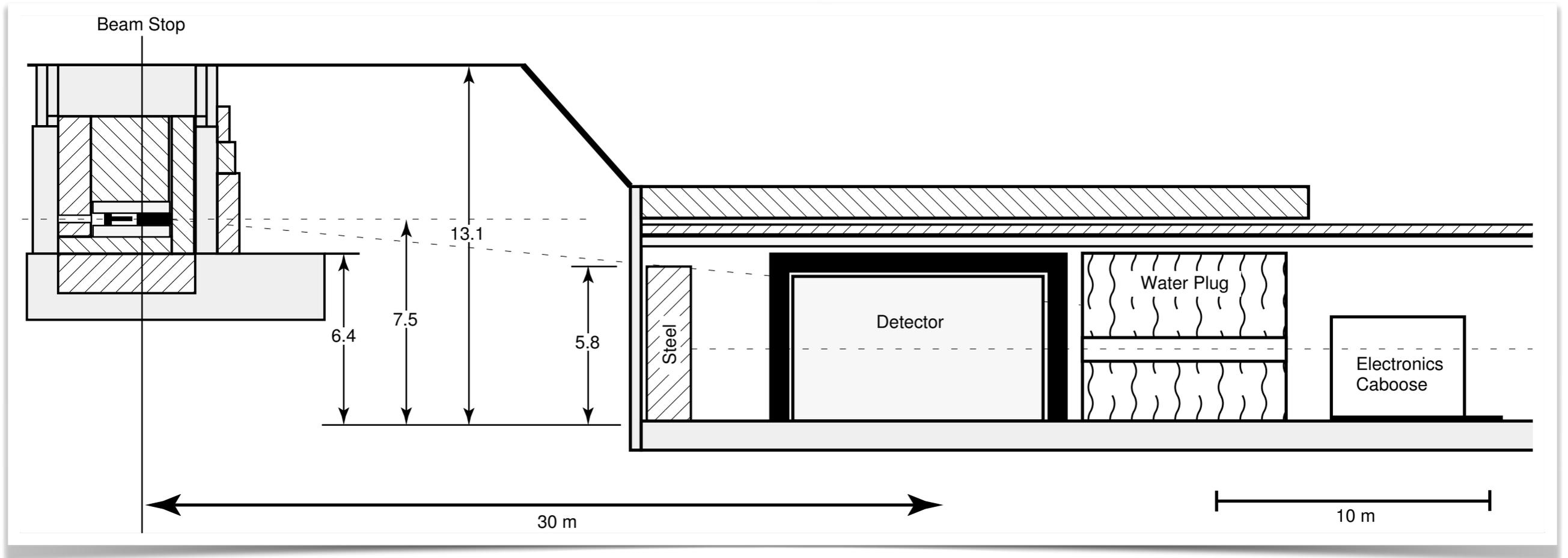
Oscillation Anomalies and Sterile Neutrinos



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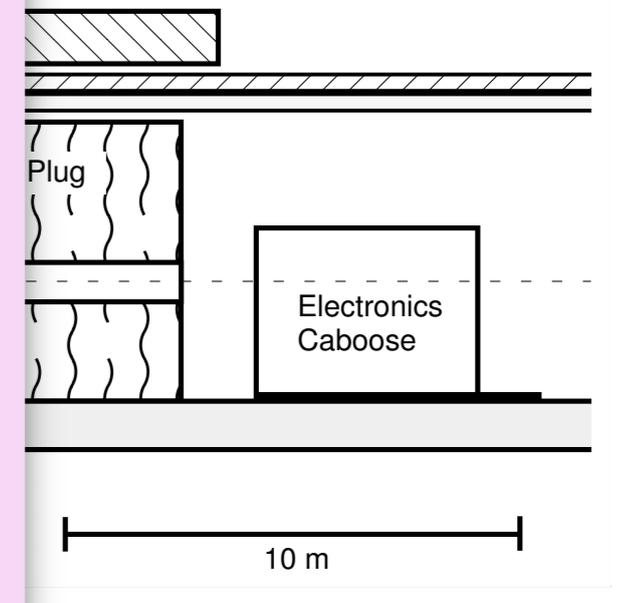
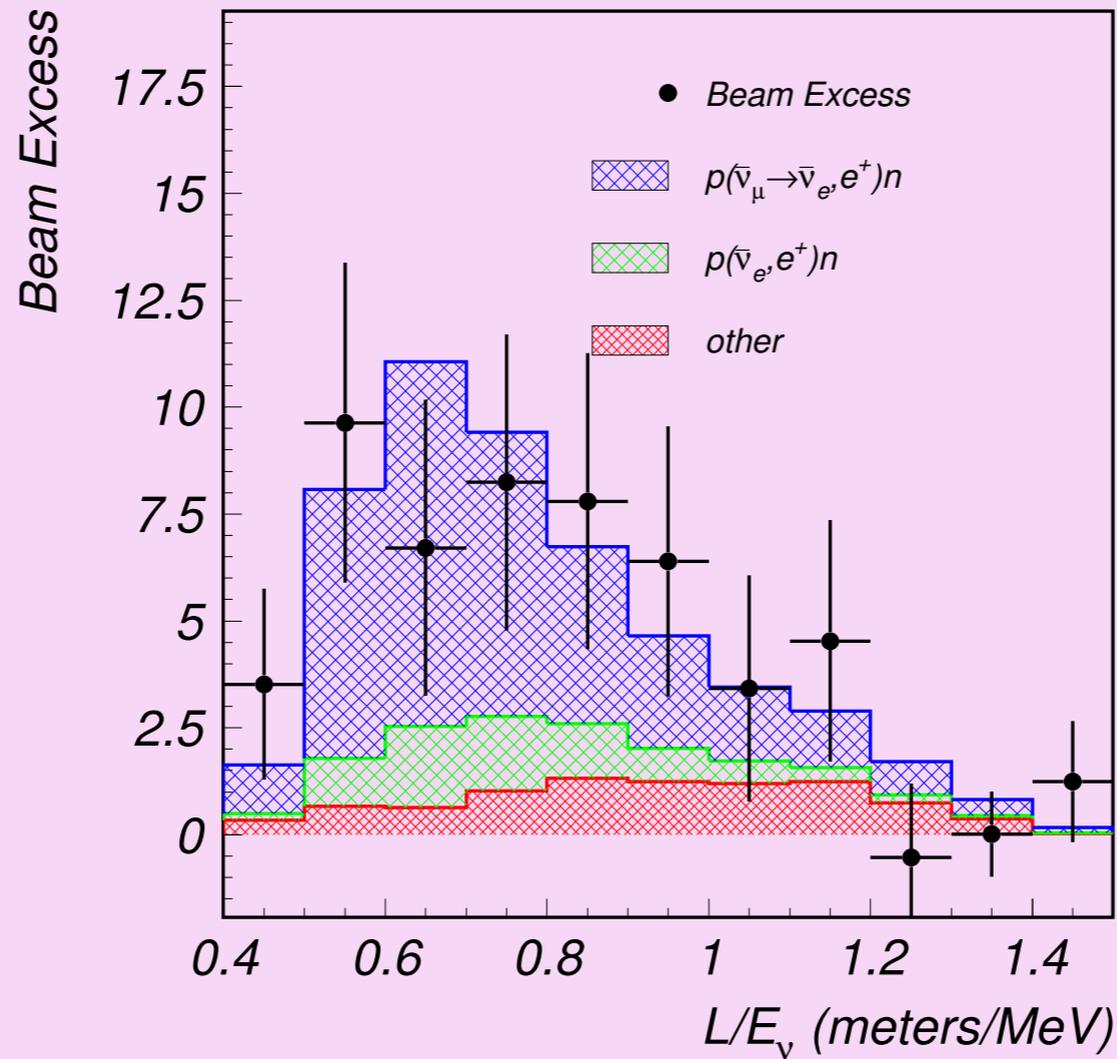
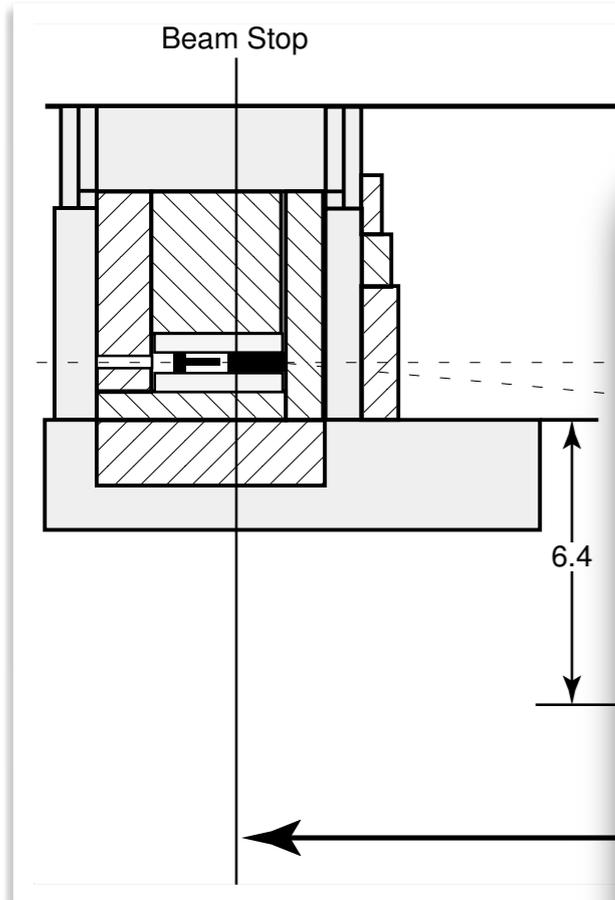
Anomaly #1: LSND



☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam

☑ Source—detector distance (“baseline”) ~ 30 m

Anomaly #1: LSND



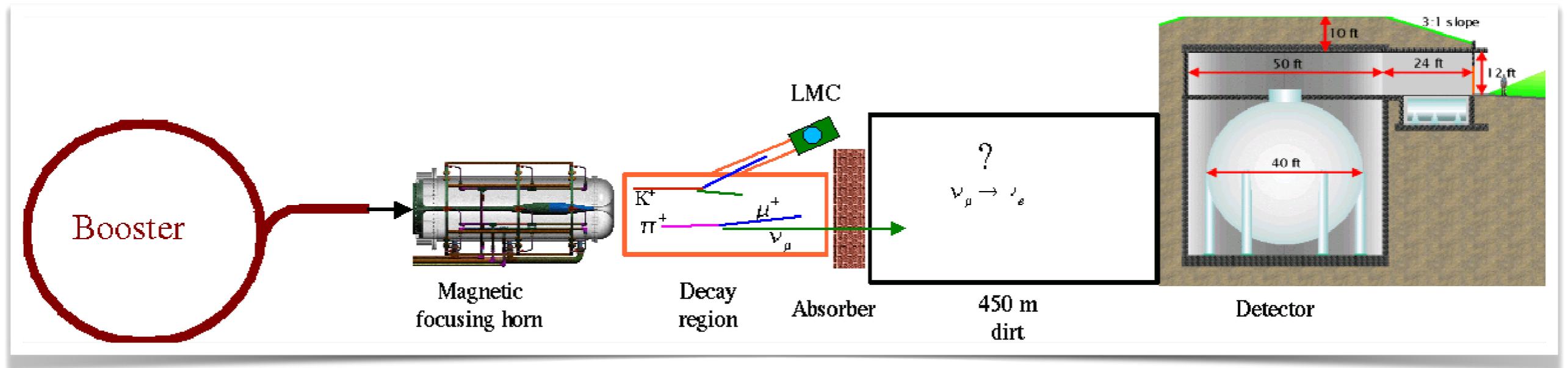
☑ $\bar{\nu}_e$ appearance

☑ Source—d

m

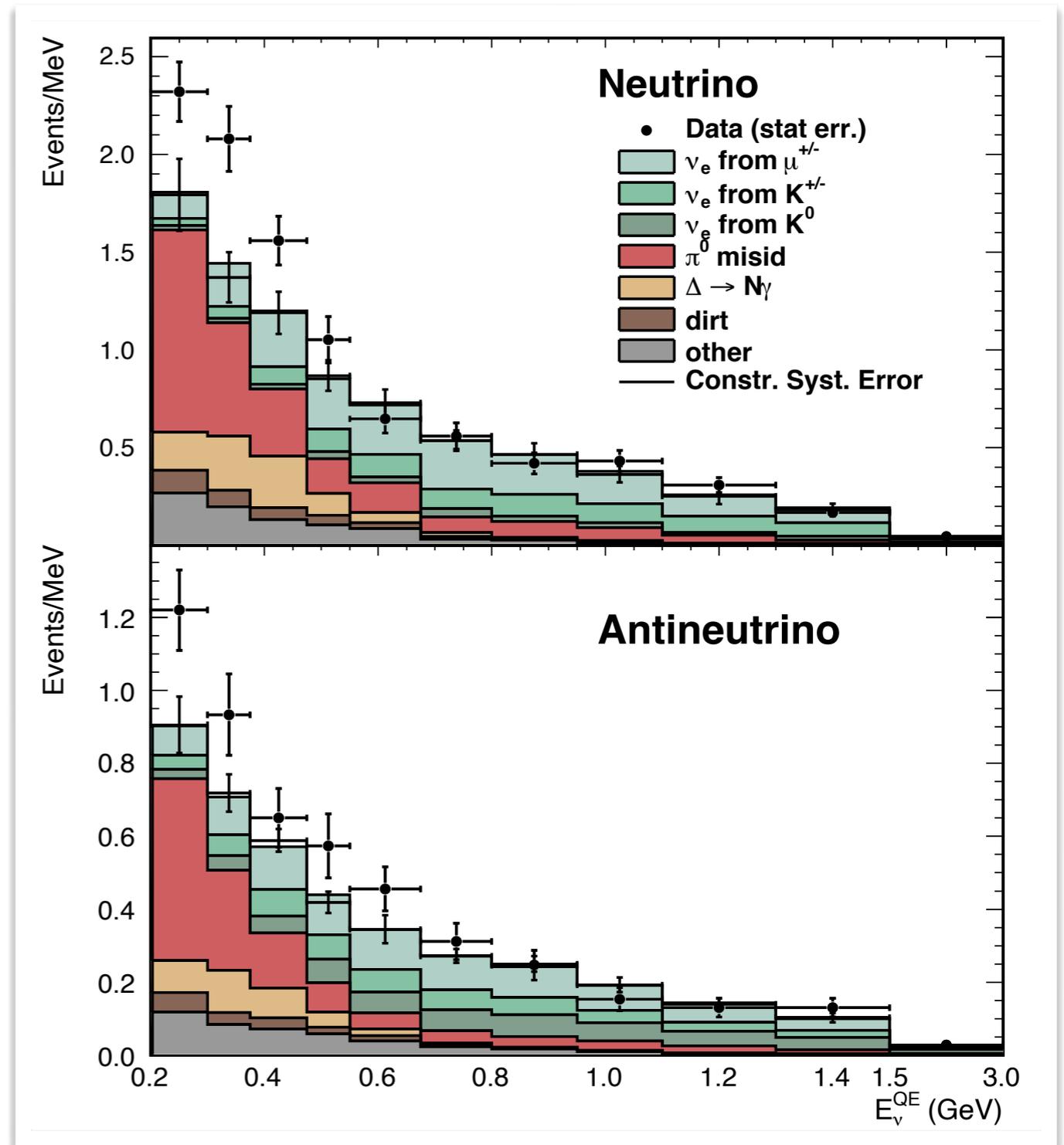
LSND Collaboration, [hep-ex/0104049](https://arxiv.org/abs/hep-ex/0104049)

Anomaly #2: MiniBooNE



Anomaly #2: MiniBooNE

- ✓ No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred L/E region
- ✓ But consistent with LSND
- ✓ Low-energy excess not understood
- ✓ L/E too small to be explained in 3-flavor framework (wrong Δm^2)



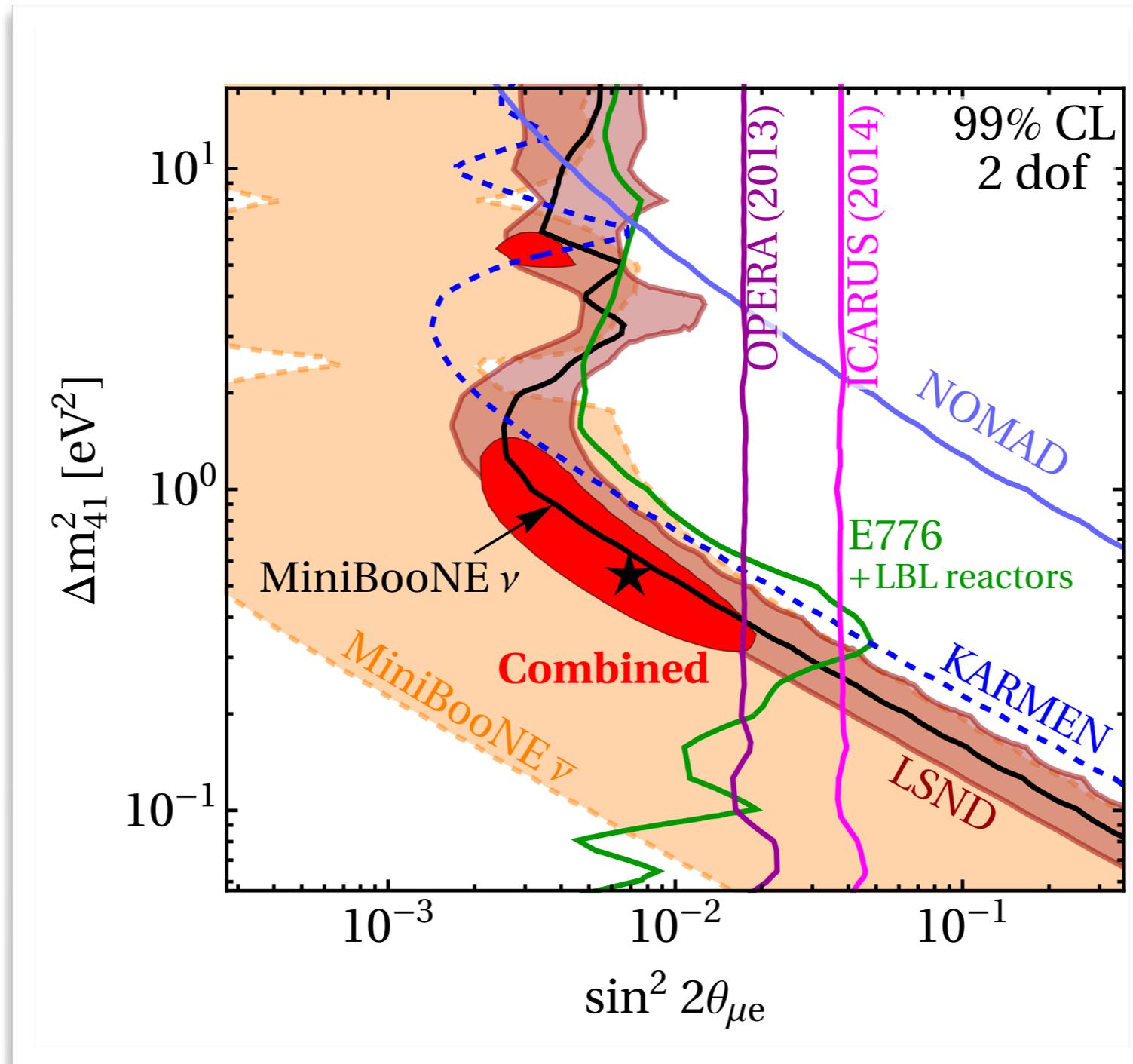
Definition: sterile neutrino = SM singlet fermion

- ☑ Very generic extension of SM
 - can be leftover of extended gauge multiplet
 - ☑ Useful phenomenological tool
 - can explain ν masses (seesaw mechanism, $m \sim \text{TeV} \dots M_{\text{Pl}}$)
 - can explain cosmic baryon asymmetry (leptogenesis, $m \gg 100 \text{ GeV}$)
 - can explain dark matter ($m \sim \text{keV}$)
 - can explain oscillation anomalies ($m \sim \text{eV}$)
- Promote mixing matrix to 4×4 , oscillation formula unchanged:

$$P_{\alpha \rightarrow \beta} = \sum_{j,k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp \left[-i(E_j - E_k)T \right]$$

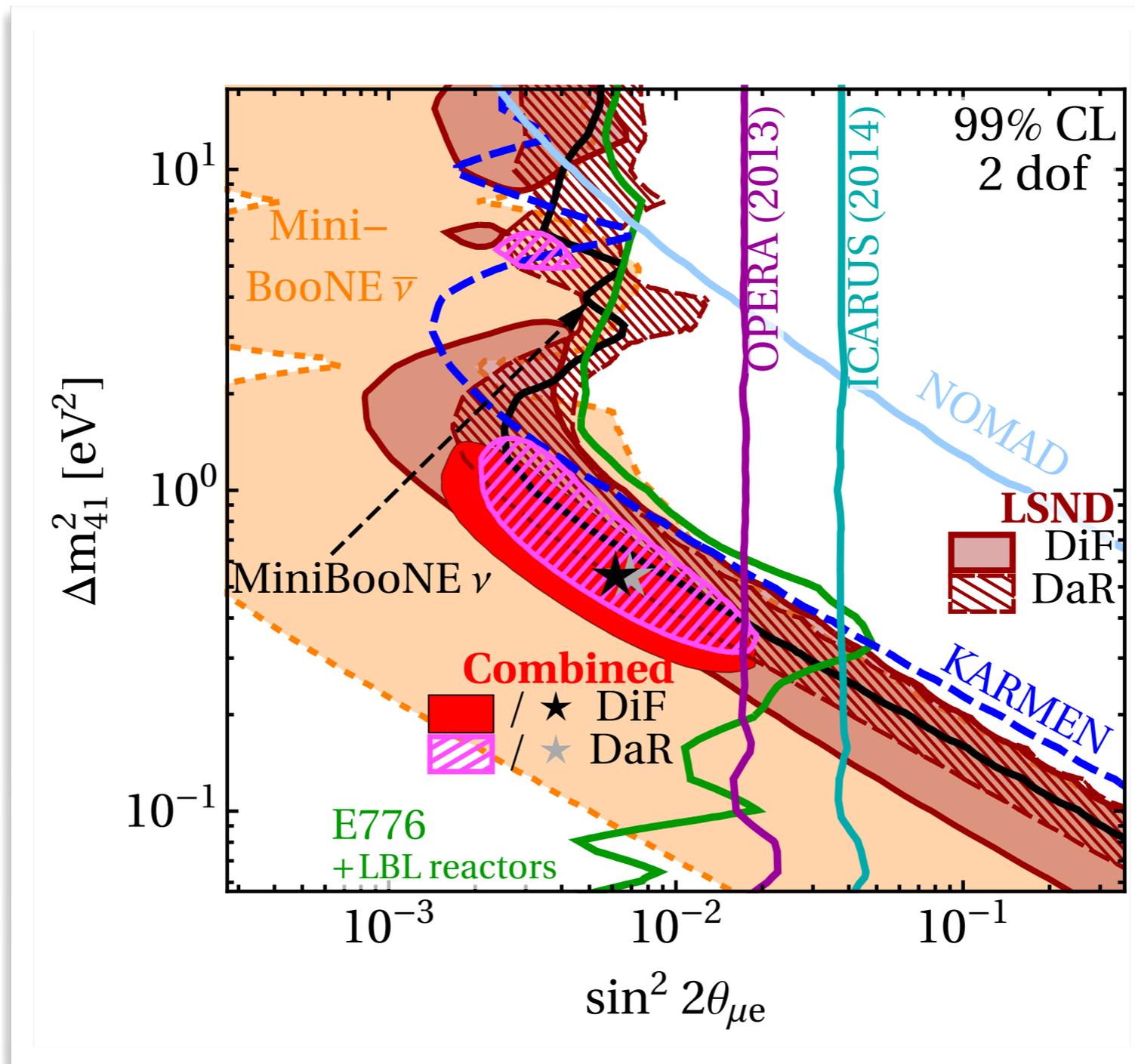


$\nu_\mu \rightarrow \nu_e$ appearance



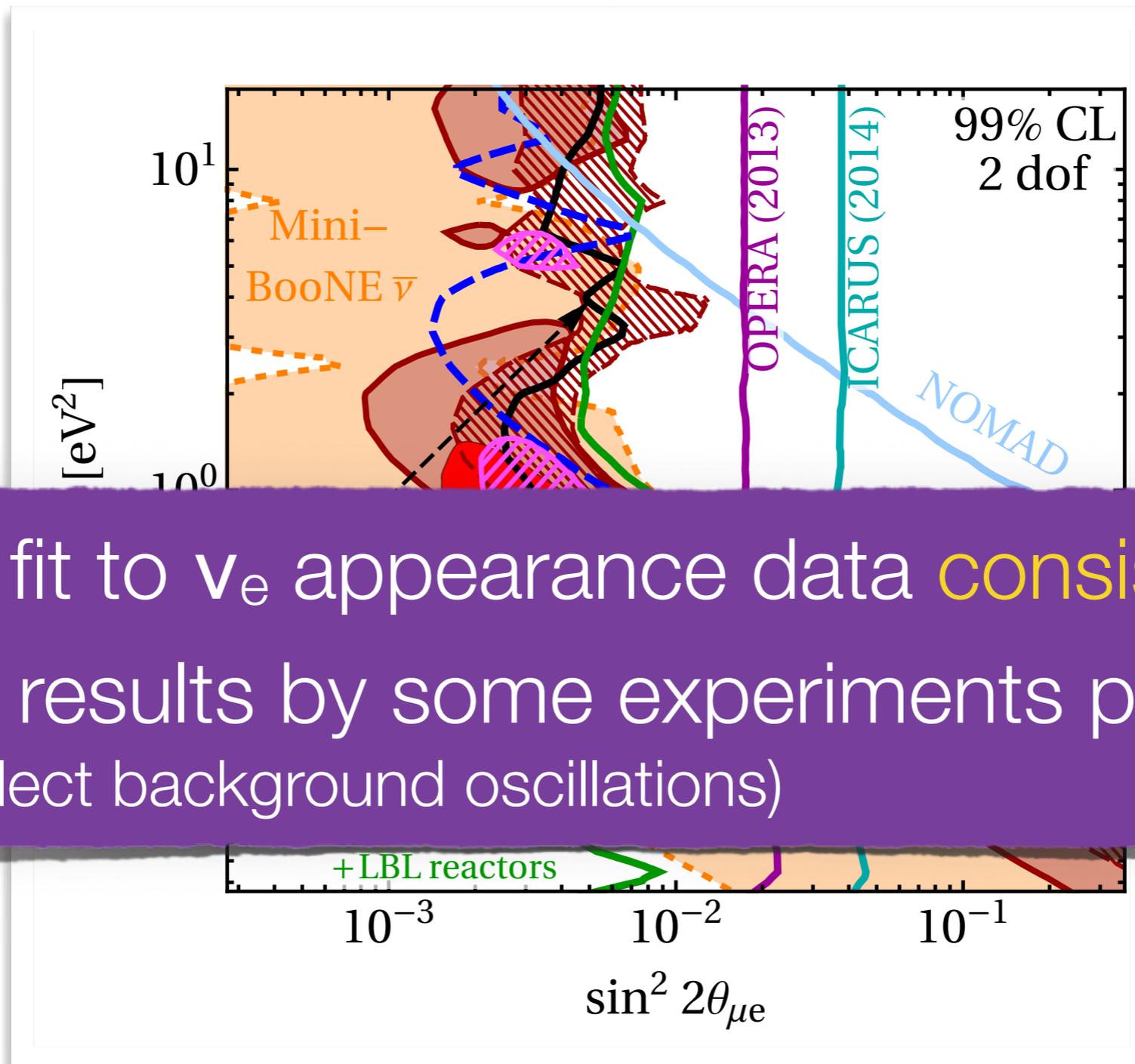
Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

$\nu_\mu \rightarrow \nu_e$ appearance



Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

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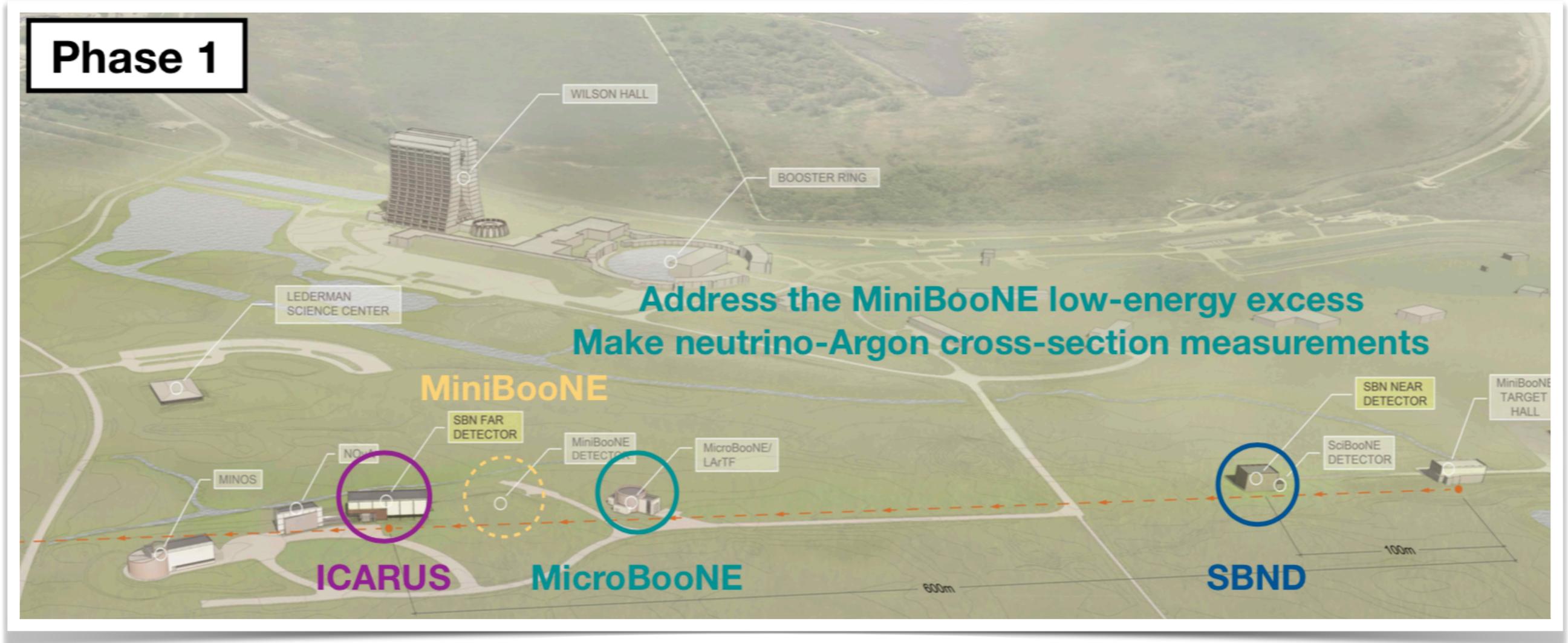


- ★ Global fit to ν_e appearance data **consistent**
- ★ Official results by some experiments problematic (e.g. neglect background oscillations)

Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

Testing the MiniBooNE Anomaly

Roxanne Guenette, Neutrino 2018



Anomaly #3: The Reactor Anomaly

☑ $\bar{\nu}_e$ flux from nuclear reactors is $\sim 3.5\%$ below prediction

☑ Method:

- Use measured β spectra from ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu fission
- Convert to $\bar{\nu}_e$ spectrum
- For single β decay: $E_\nu = Q - E_e$
- **Reality:** thousands of decay branches, many not known precisely
- Use information from nuclear data tables ...
- ... complemented by a fit to “effective decay branches”

Mueller *et al.* [1101.2663](#), Huber [1106.0687](#)

Anomaly #3: The Reactor Anomaly

$\bar{\nu}_e$ flux

Method

Use

Cor

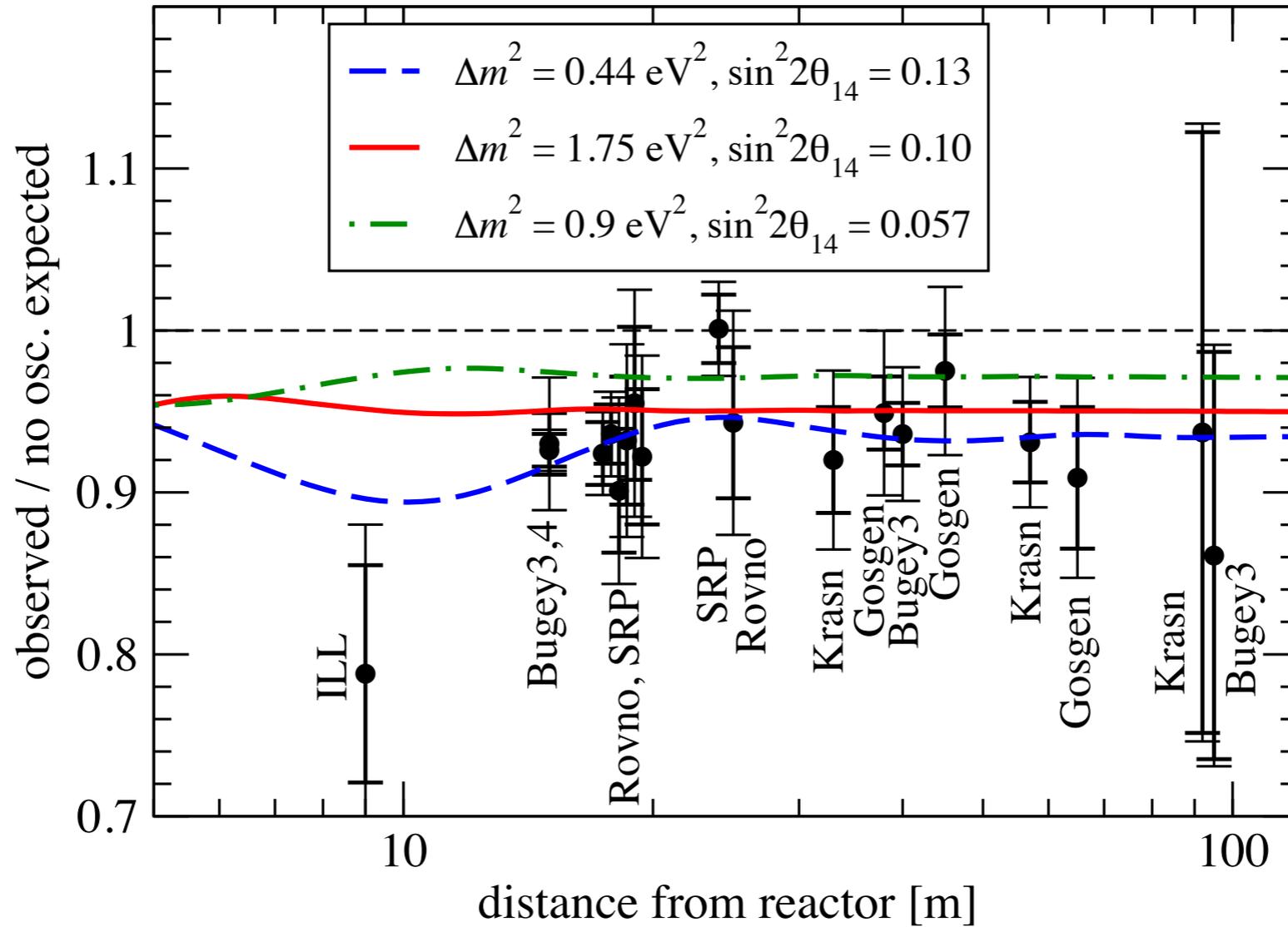
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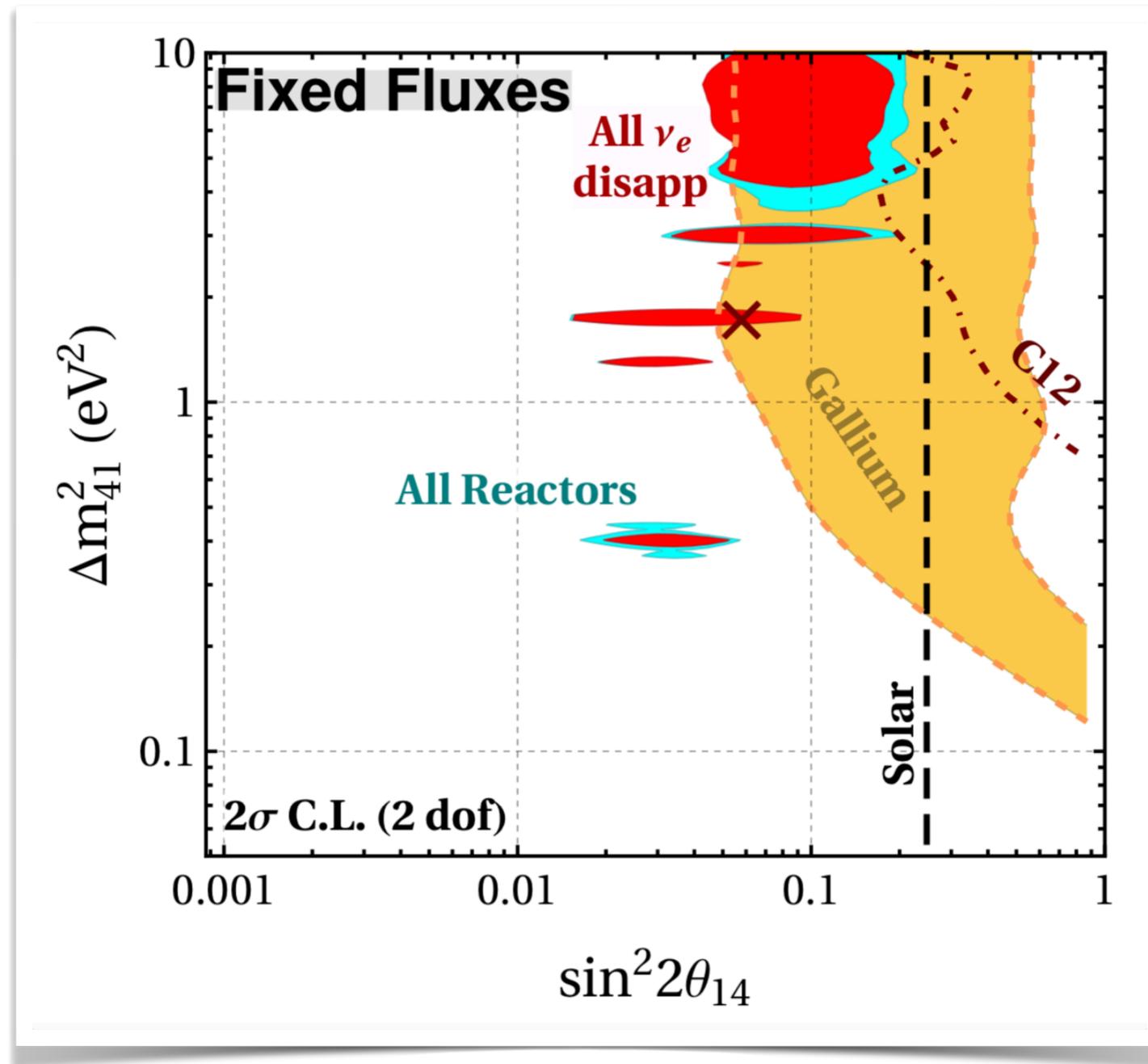
fission

νn

s''

Mueller *et al.* [1101.2663](#), Huber [1106.0687](#)

Global Fit to ν_e and $\bar{\nu}_e$ Disappearance



[Dentler Hernández JK Maltoni Schwetz_1709.04294](#)

Flux Measurement by Daya Bay

Flux Measurement by Daya Bay

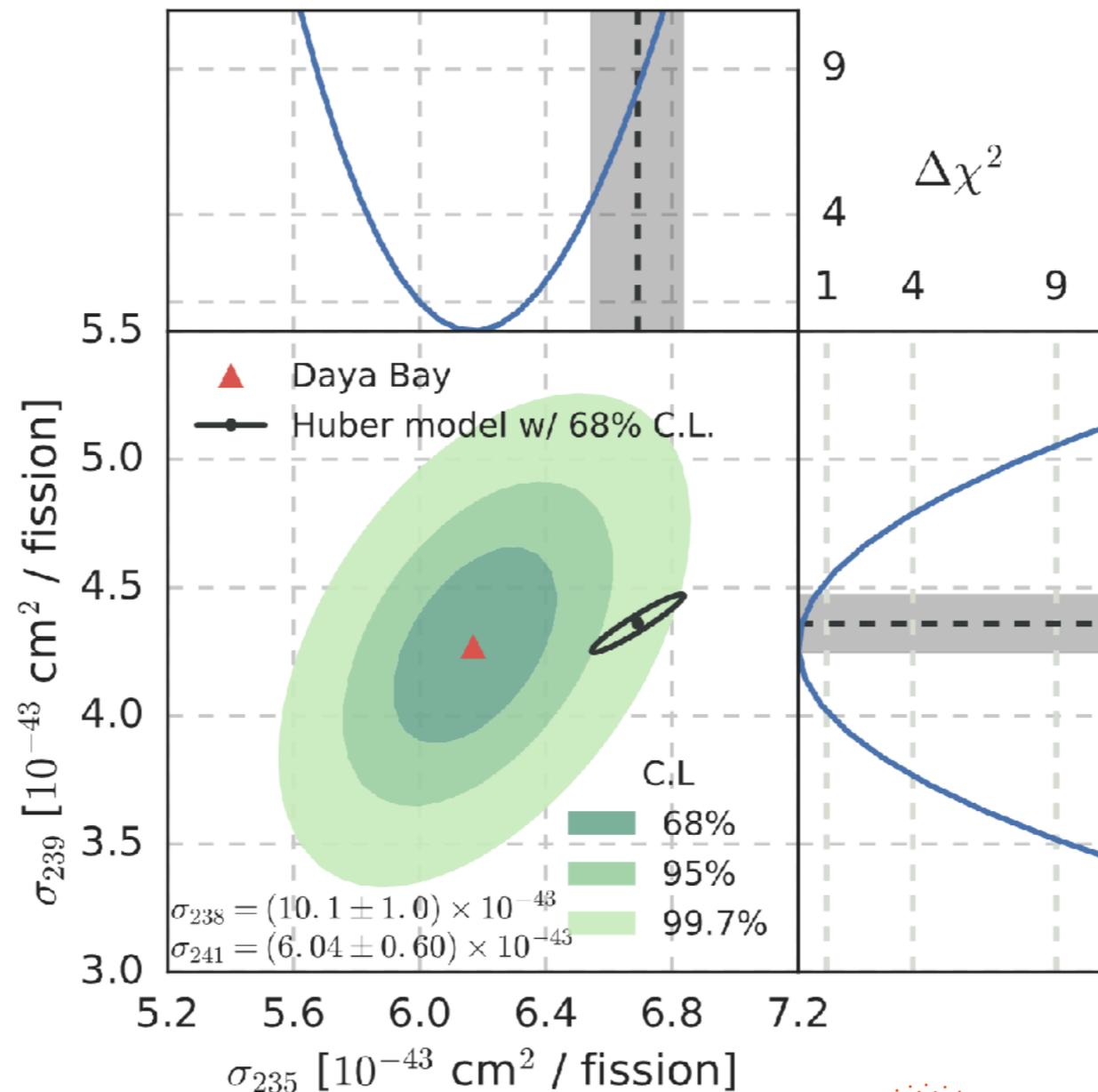
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Flux Measurement by Daya Bay

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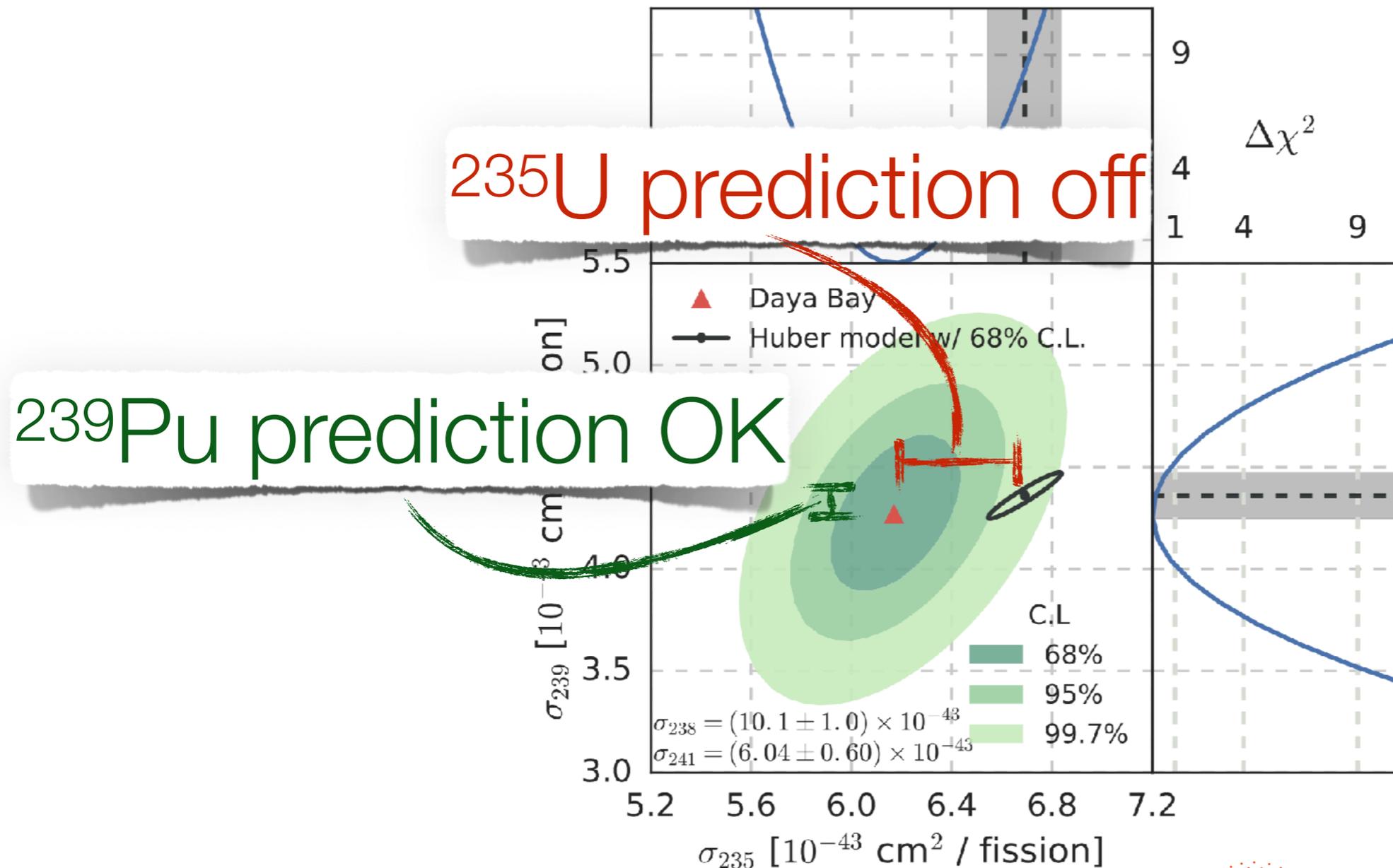
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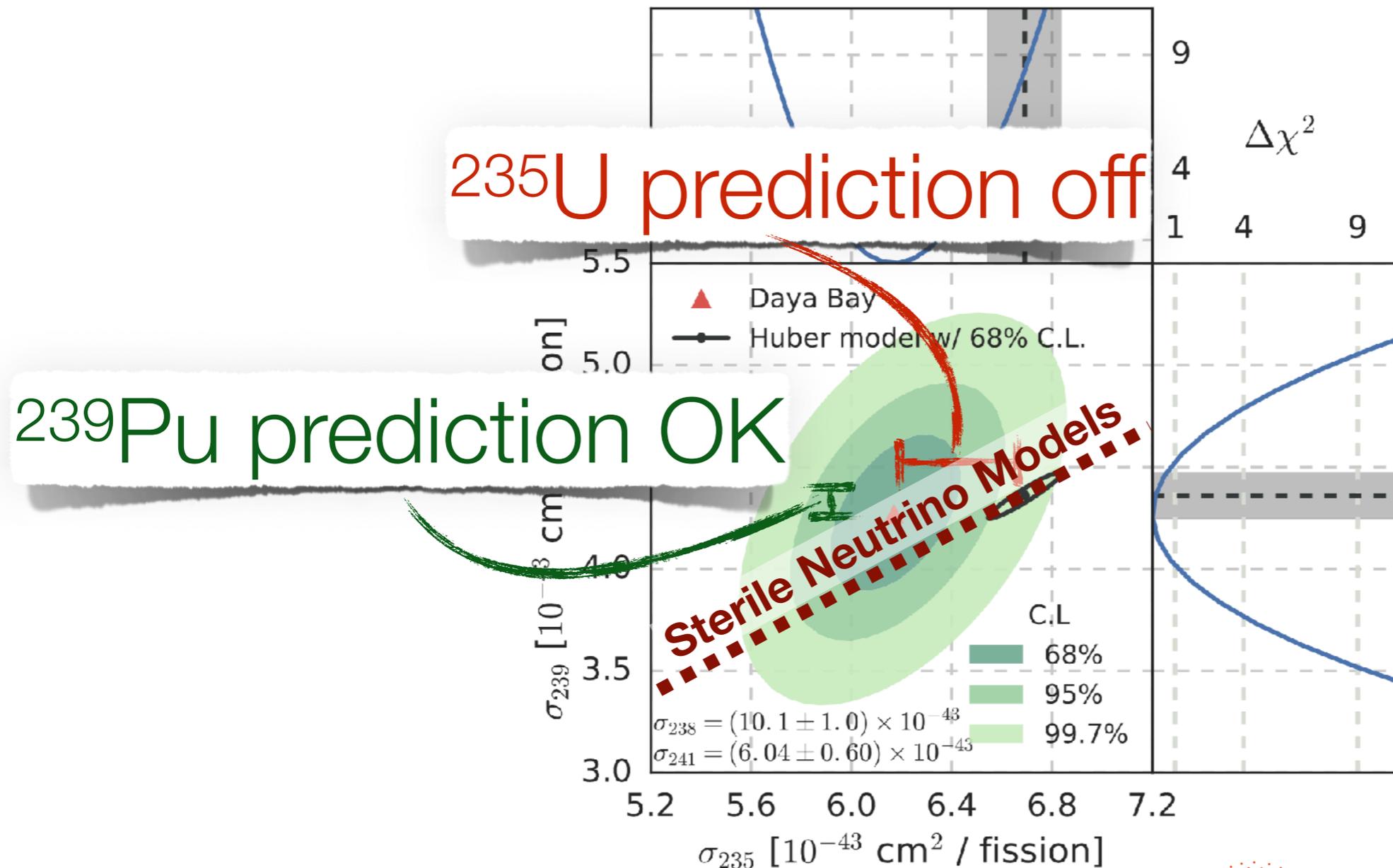
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- ☑ Full analysis:
 - Compare fit with **free** ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu fluxes to fit with **fixed fluxes** + $\sin^2 2\theta_{14}$

$$\Delta\chi^2 = 7.9$$

Flux Measurement by Daya Bay

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$$\Delta\chi^2 = 6.3 \text{ (with H-M uncertainties)}$$

Denter Hernández
JK Maltoni Schwetz
arXiv:1709.today

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- ☑ **Interpretation difficult**
 - Number of **degrees of freedom**?
 - Include uncertainties in fixed fluxes?

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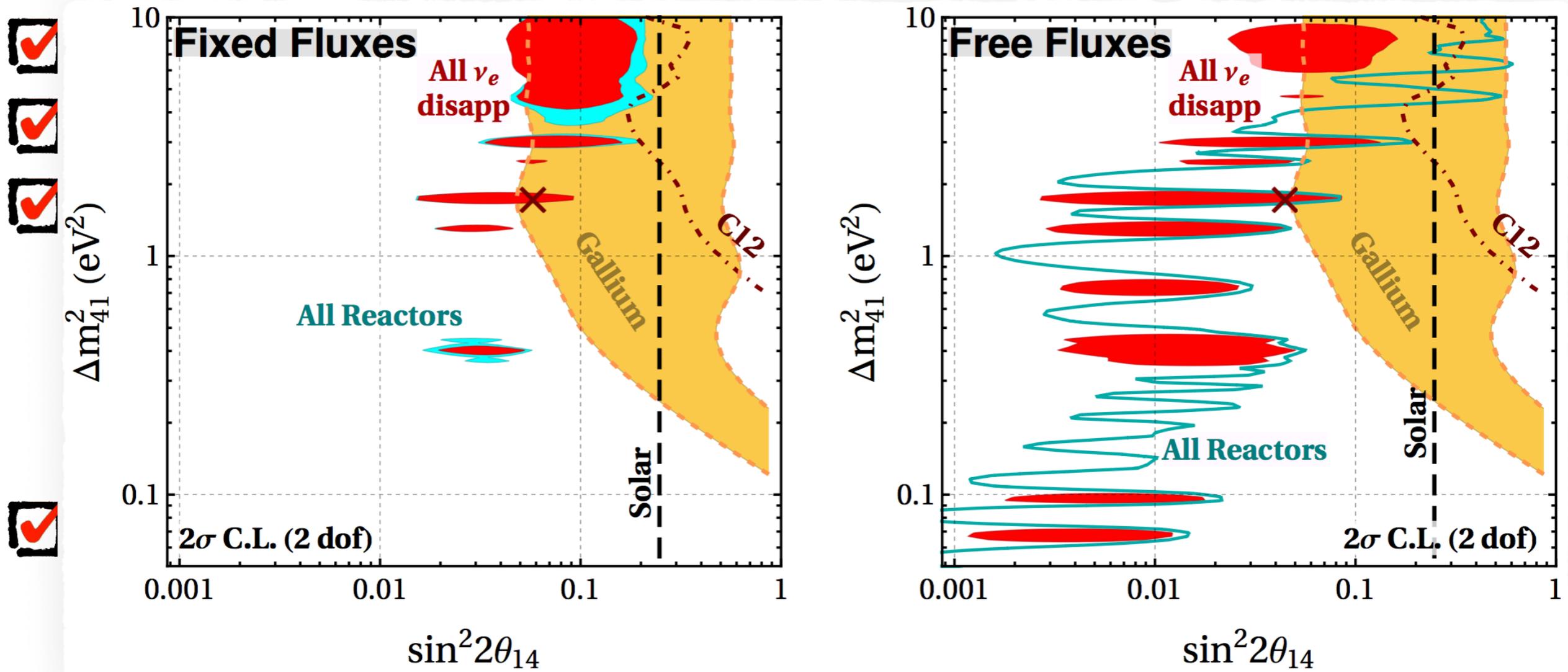
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Fluxes within errors + $\sin^2 2\theta_{14}$, Δm_{41}^2 : $p = 0.18$
Fluxes free : $p = 0.73$
 $\Delta\chi^2$ (sterile neutrino vs. free fluxes) : $p = 0.007$

Flux Measurement by Daya Bay



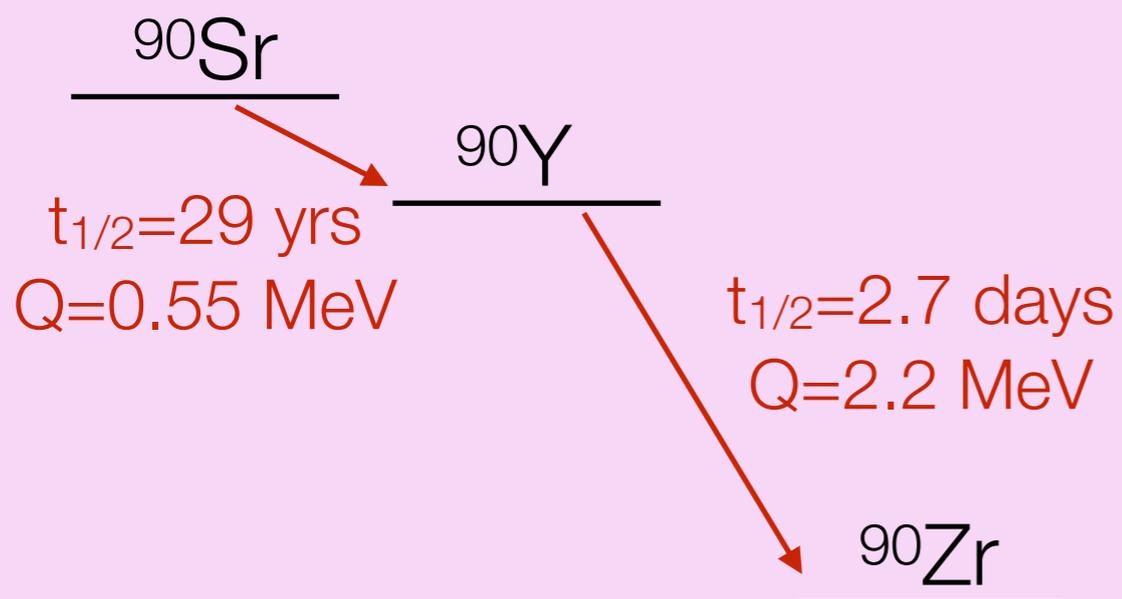
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Daya Bay method assumes
flux from each isotope is
time and burnup-independent.

Caveats

Non-Equilibrium

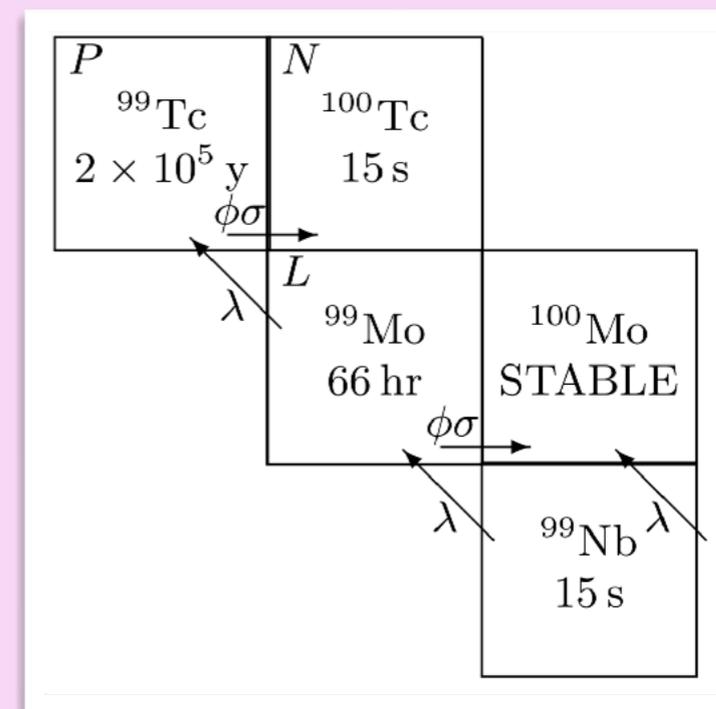
- ☑ Some relevant decays are **out of equilibrium**



- ☑ Extra **t -dependence** in **ν flux**

Non-Linear Isotopes

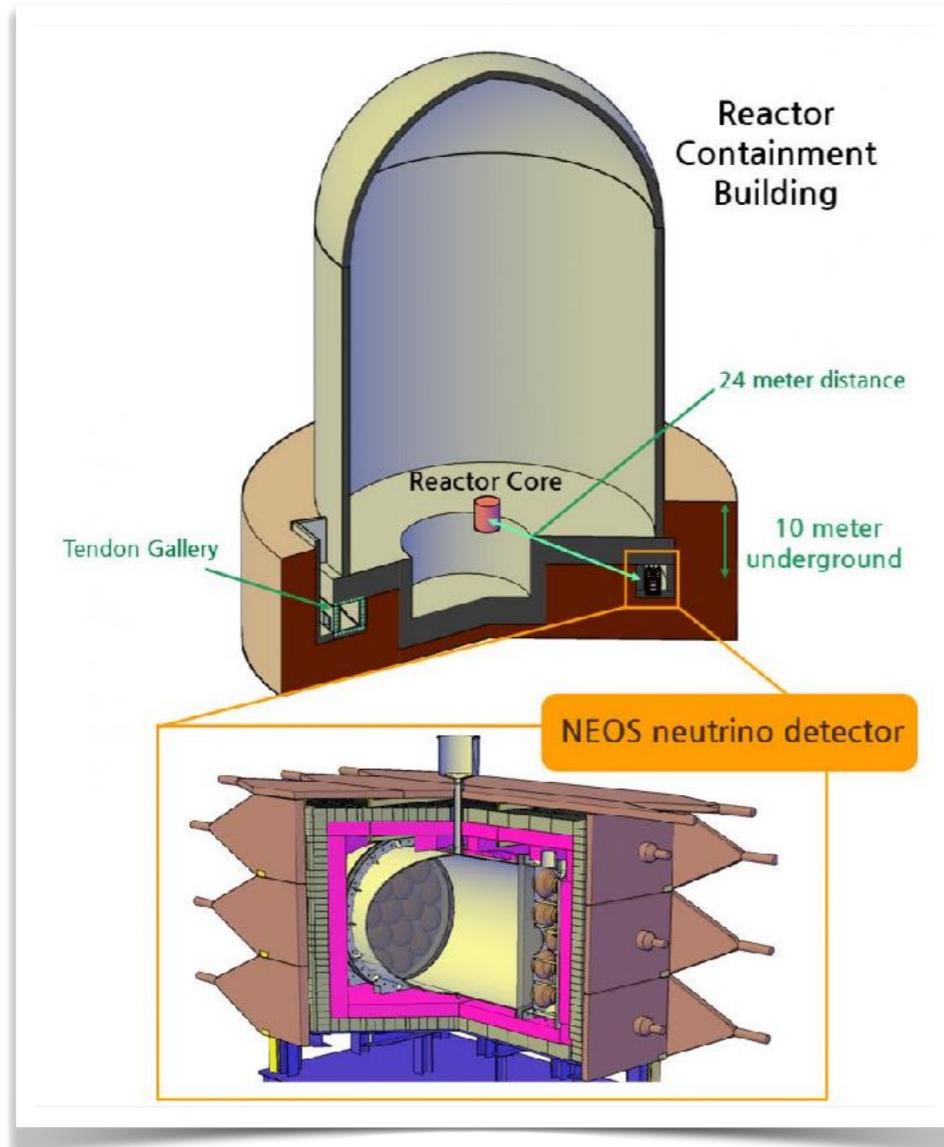
- ☑ **Neutron capture** on fission products



- ☑ Extra **neutron flux/ burnup dependence** in **ν**

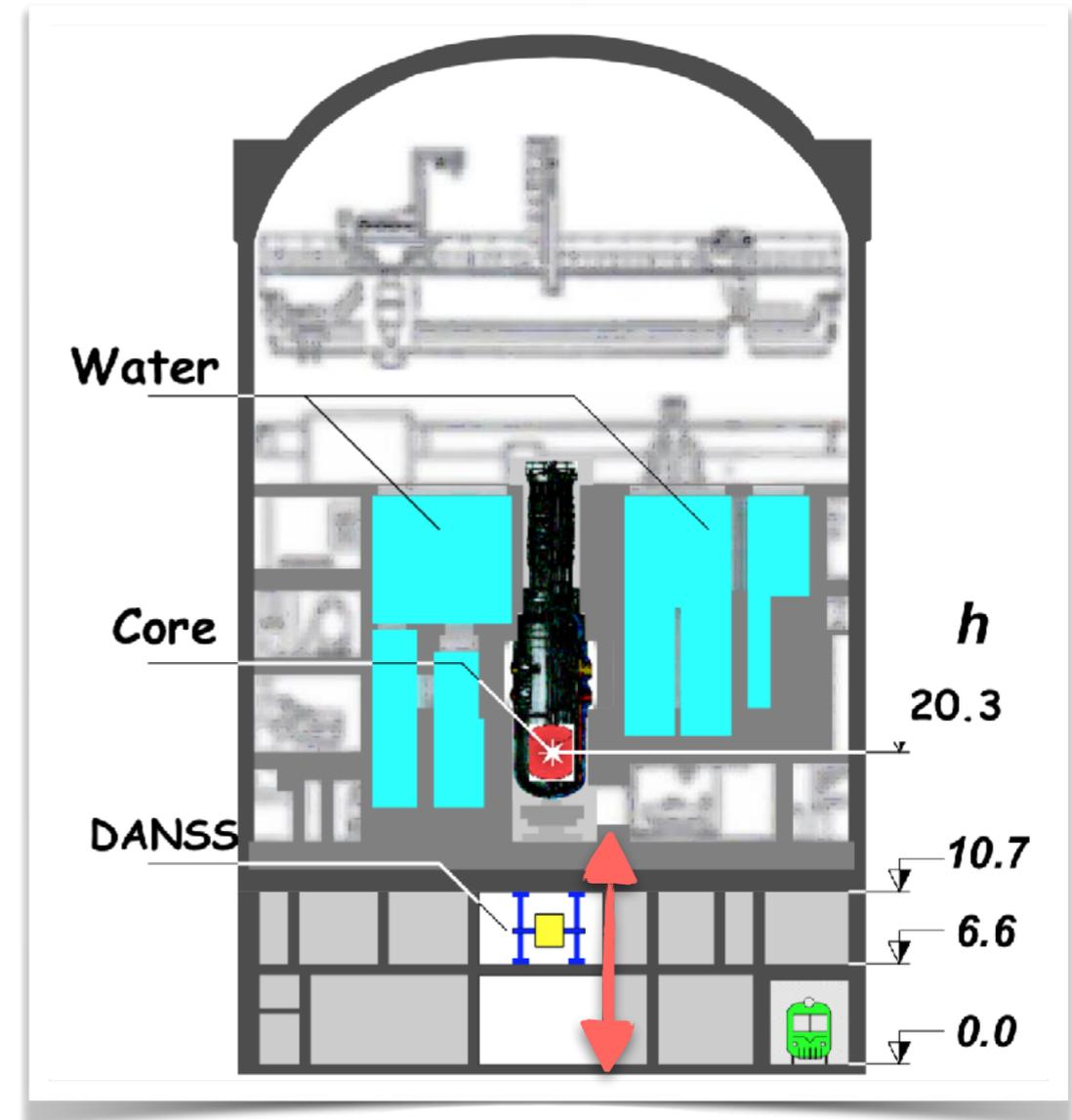
Jaffke Huber [1510.08948](#), Huber Sharma, *in preparation*

Anomaly #3': NEOS and DANSS



NEOS

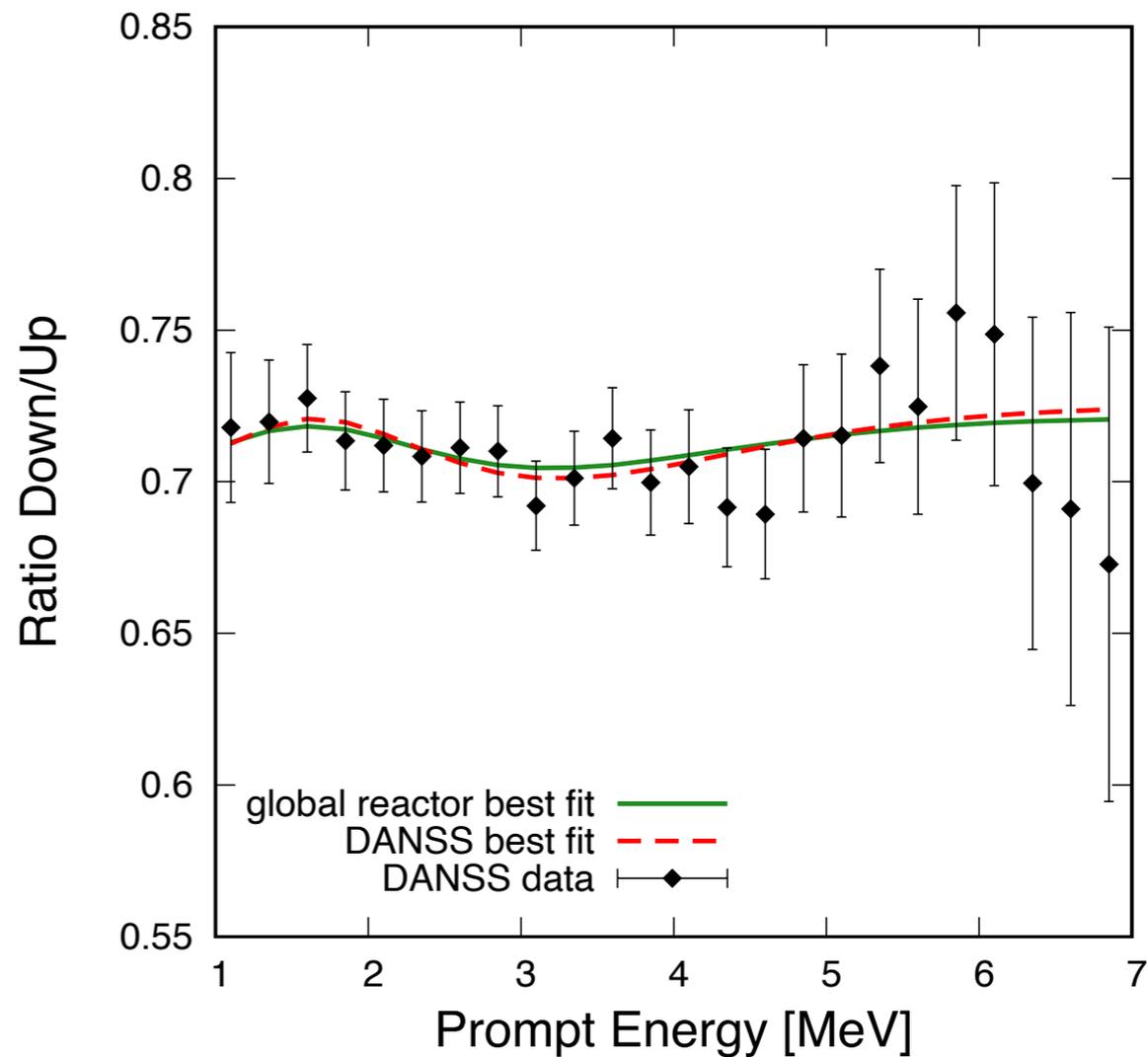
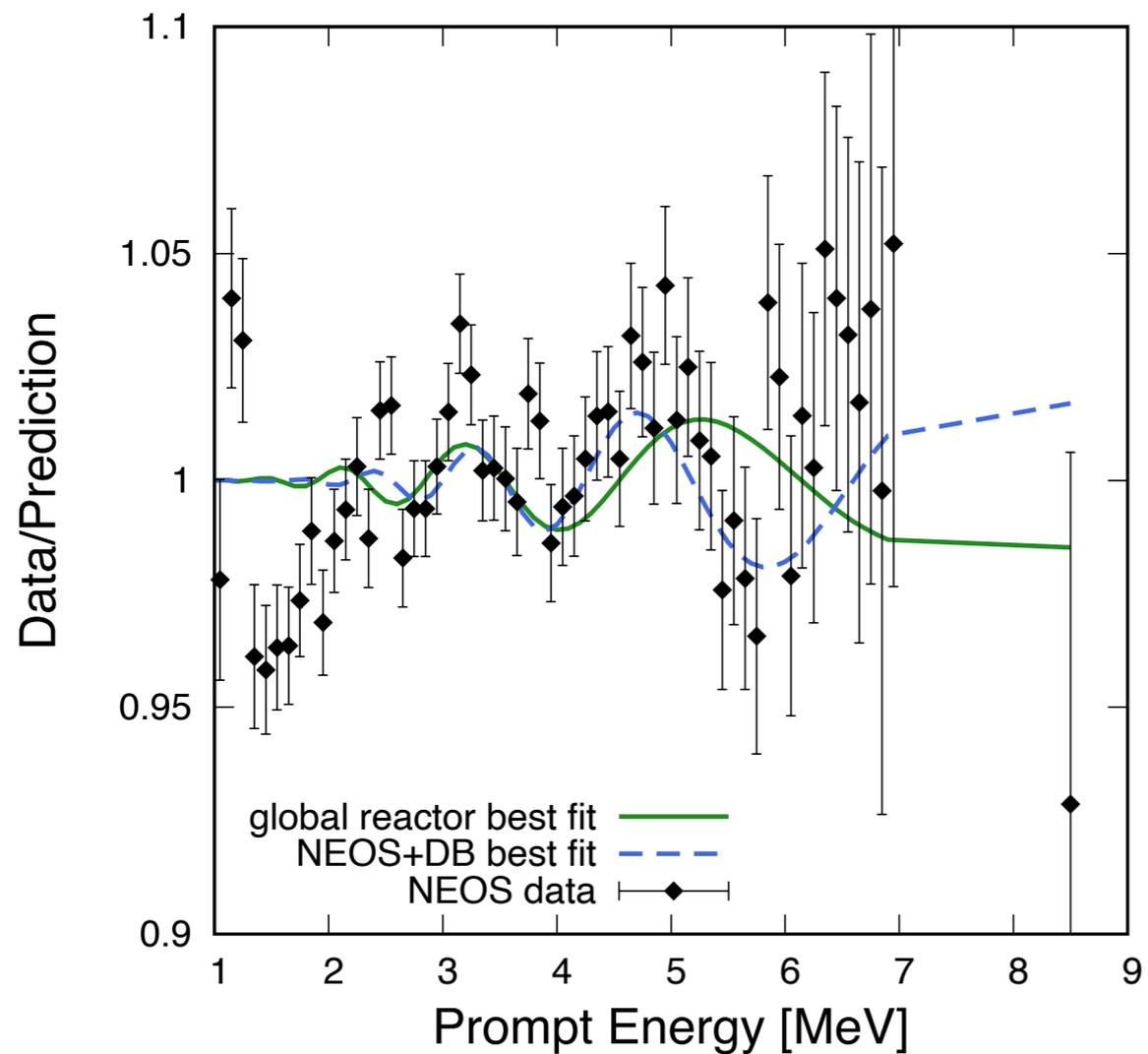
Ko *et al.* [1610.05134](#)
Daya Bay [1607.05378](#)



DANSS

Danilov *et al.* [Neutrino 2018](#),
[Moriond 2017](#), [Solvay Workshop Dec 2017](#)

Anomaly #3': NEOS and DANSS



NEOS

DANSS

Dentler Hernández JK Maltoni Schwetz [1709.04294](https://arxiv.org/abs/1709.04294)

Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

Testing the Reactor Anomaly

- ☑ Do we understand reactor neutrino fluxes?
- ☑ New short-baseline experiments
 - looking for spectral wiggles (smoking-gun oscillation signature)
- ☑ Analyze isotope-dependence of the anomaly
 - $\nu_e \rightarrow \nu_s$ oscillation are isotope-independent
 - Problems with flux prediction are typically different for different fissible isotopes

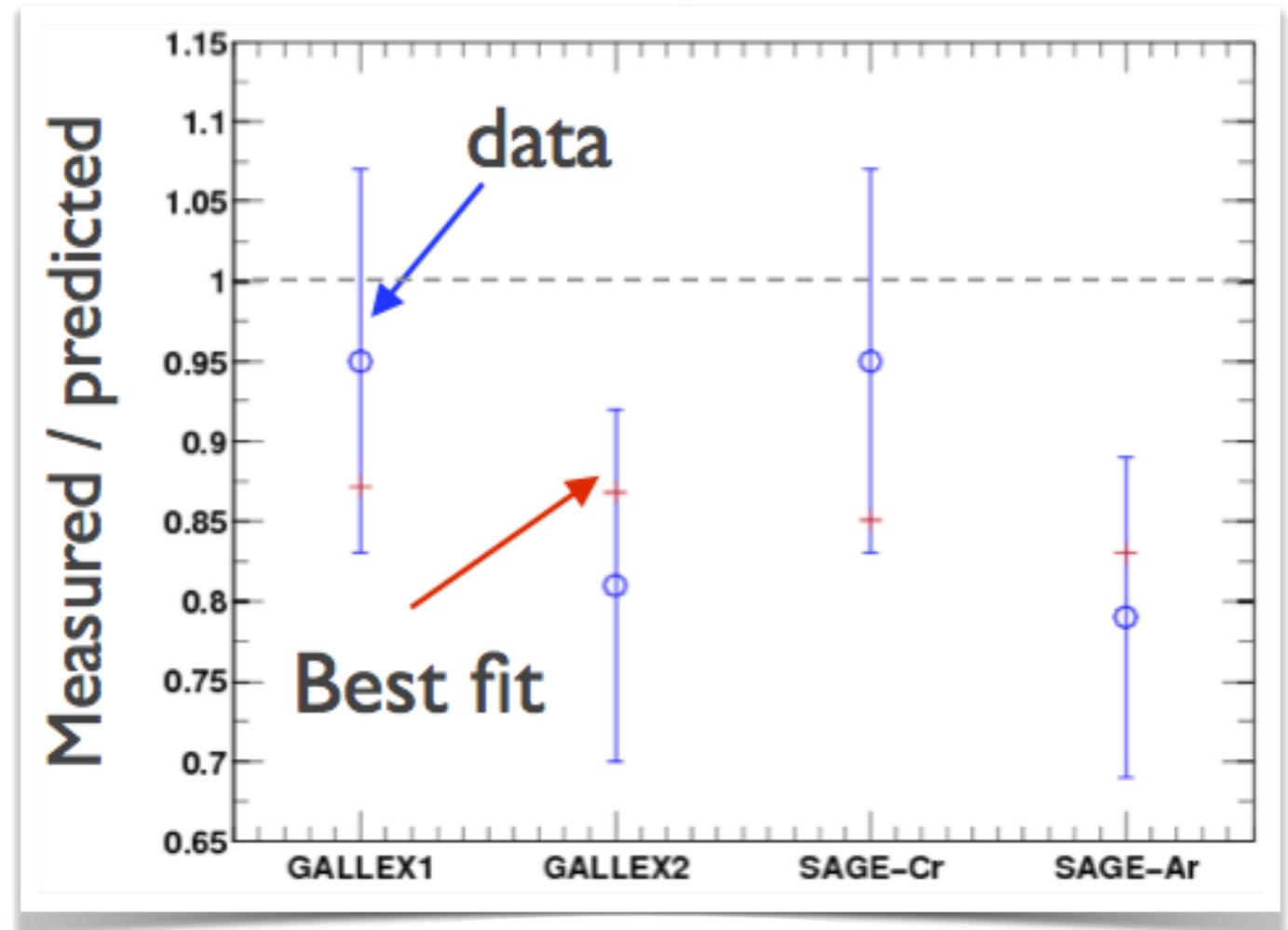
Anomaly #4: The Gallium Anomaly

- ☑ Experiments with intense radioactive source
- ☑ Neutrino detection via



- ☑ 3σ deficit
- ☑ ν_e disappearance into sterile state?

Giunti Laveder [1006.3244](#)



Relation Between Oscillation Channels

- ☑ Oscillation channels are related:

$$P_{\nu_e \rightarrow \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

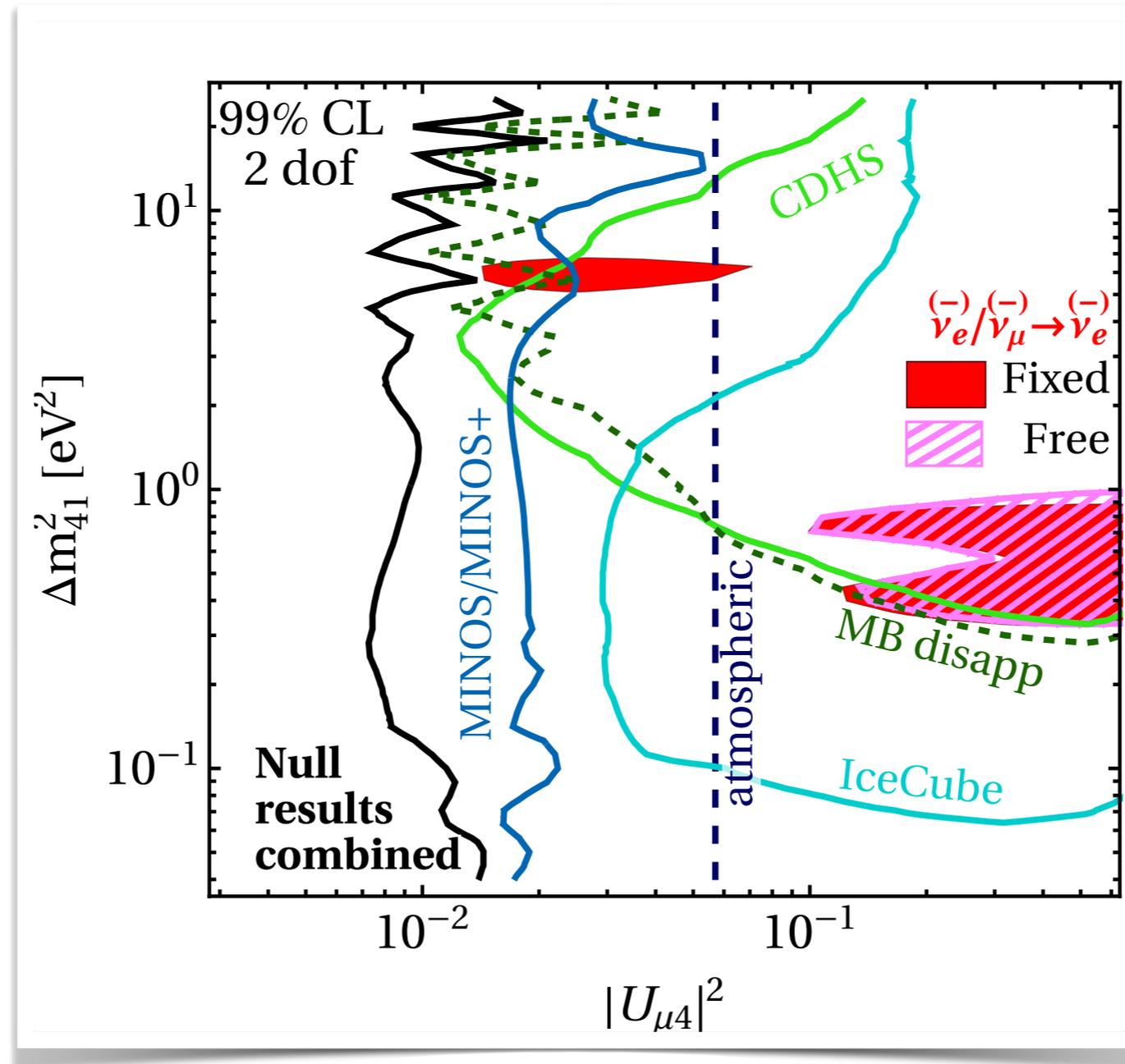
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{\nu_\mu \rightarrow \nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

(for $4\pi E / \Delta m_{41}^2 \ll L \ll 4\pi E / \Delta m_{31}^2$)

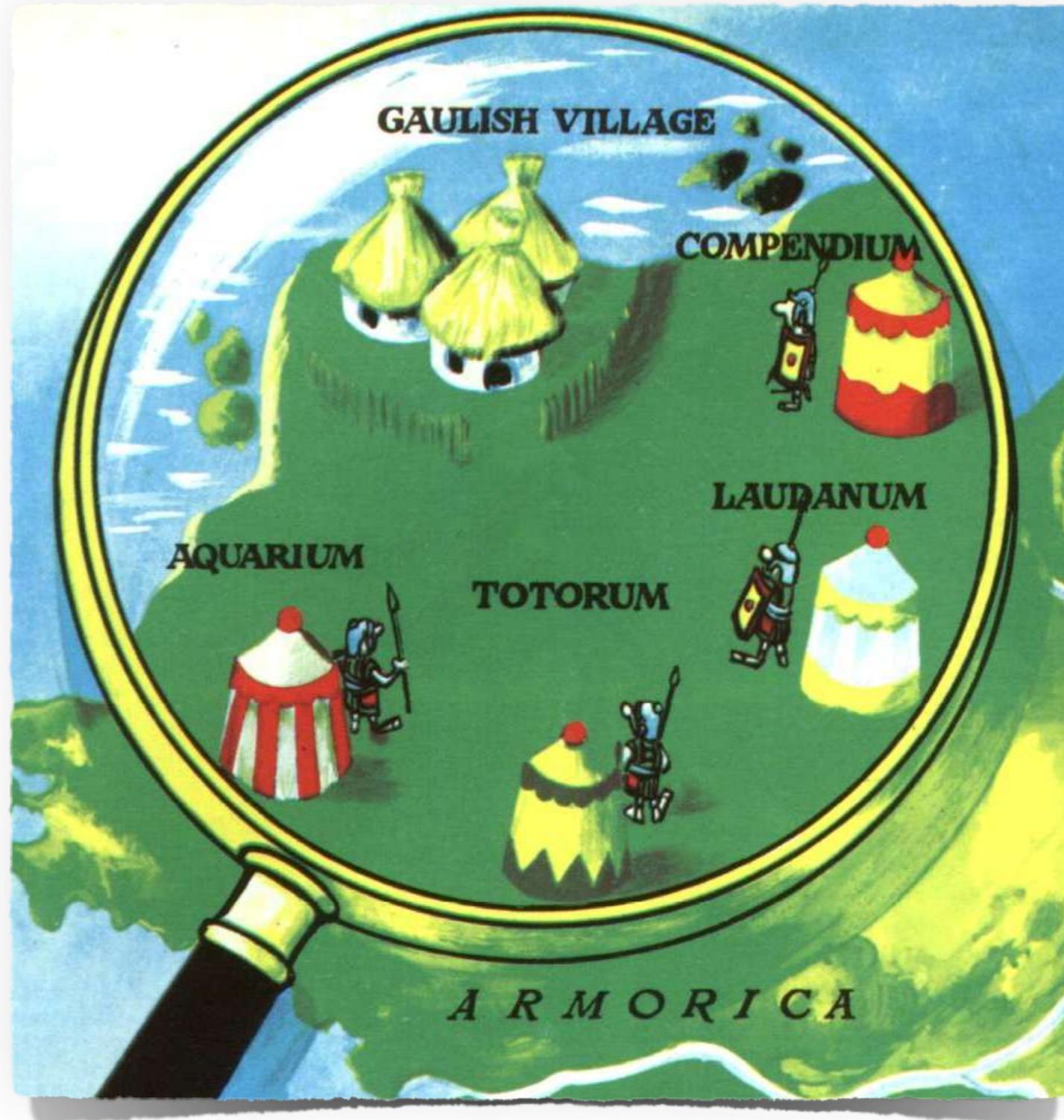
- ☑ Models can be **over-constrained**.

Global Fit in 3+1 Model

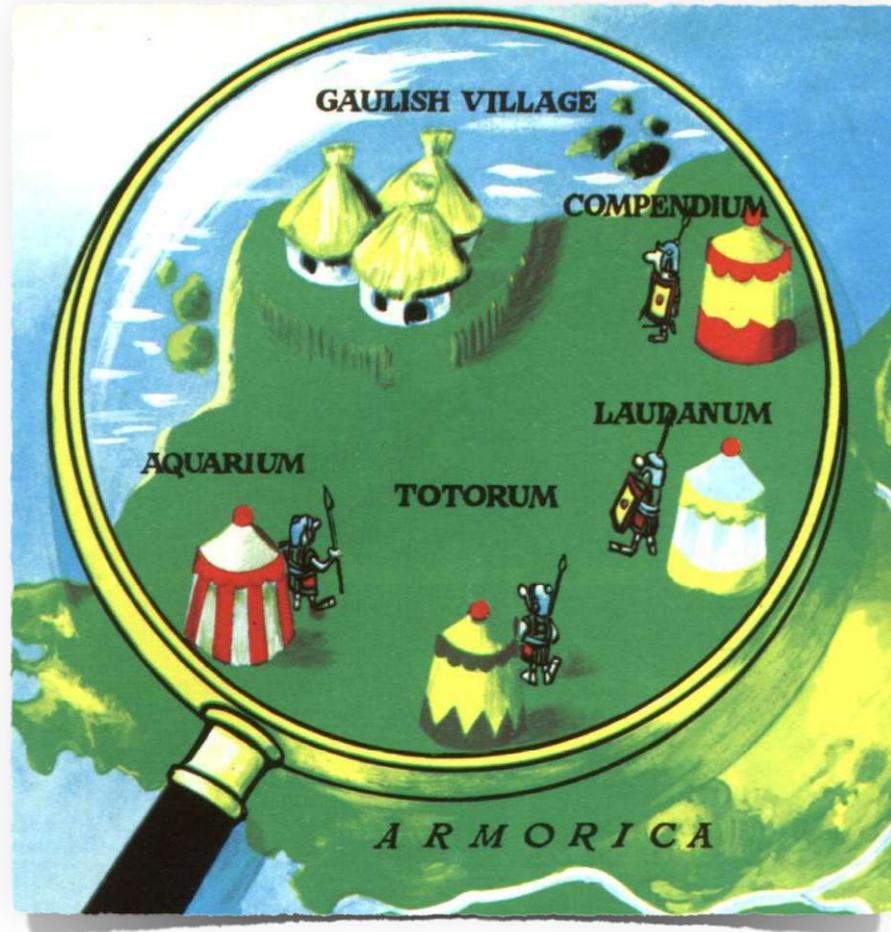


Dentler Hernandez JK Machado Maltoni Martinez Schwetz, in preparation
 see also works by Collin Argüelles Conrad Shaevitz, e.g. [1607.00011](#),
 Gariazzo Giunti Laveder Li, e.g. [1703.00860](#)

Status of Light Sterile Neutrinos



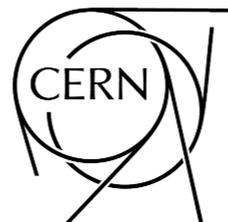
Status of Light Sterile Neutrinos



severe tension ($p < 10^{-4}$)

- ★ scrutinize anomalies for **unknown systematics** (need 4 independent effects!)
- ★ **scrutinize also null results!**

Sterile Neutrinos in Cosmology



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Sterile Neutrinos in Cosmology

Standard picture: ν_s production via oscillation at $T \gtrsim \text{MeV}$

- ☑ $\nu_{e,\mu,\tau}$ evolve into superposition with ν_s
- ☑ Hard interaction collapses ν wave function
 - $\frac{1}{2} \sin^2 2\theta$ of ν converted to ν_s
- ☑ Remaining $\nu_{e,\mu,\tau}$ start to oscillate again
- ☑ Constrained by **CMB, LSS, BBN**:

$$\Sigma m_\nu \approx 0.12 \text{ eV} \text{ ⚡}$$

$$N_{\text{eff}} \approx 3.16 \text{ ⚡}$$

Testing Neutrinos in Cosmology

N_{eff}

- ☑ “Effective number of neutrino species”
- ☑ Really just a measure of the **energy density** of **relativistic particles**
- ☑ affects **expansion rate** of the Universe

Σm_{ν}

- ☑ “sum of neutrino masses”
- ☑ affects structure formation:
 - neutrinos do not form small structures
 - shallower gravitational wells for DM and baryons to fall into

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

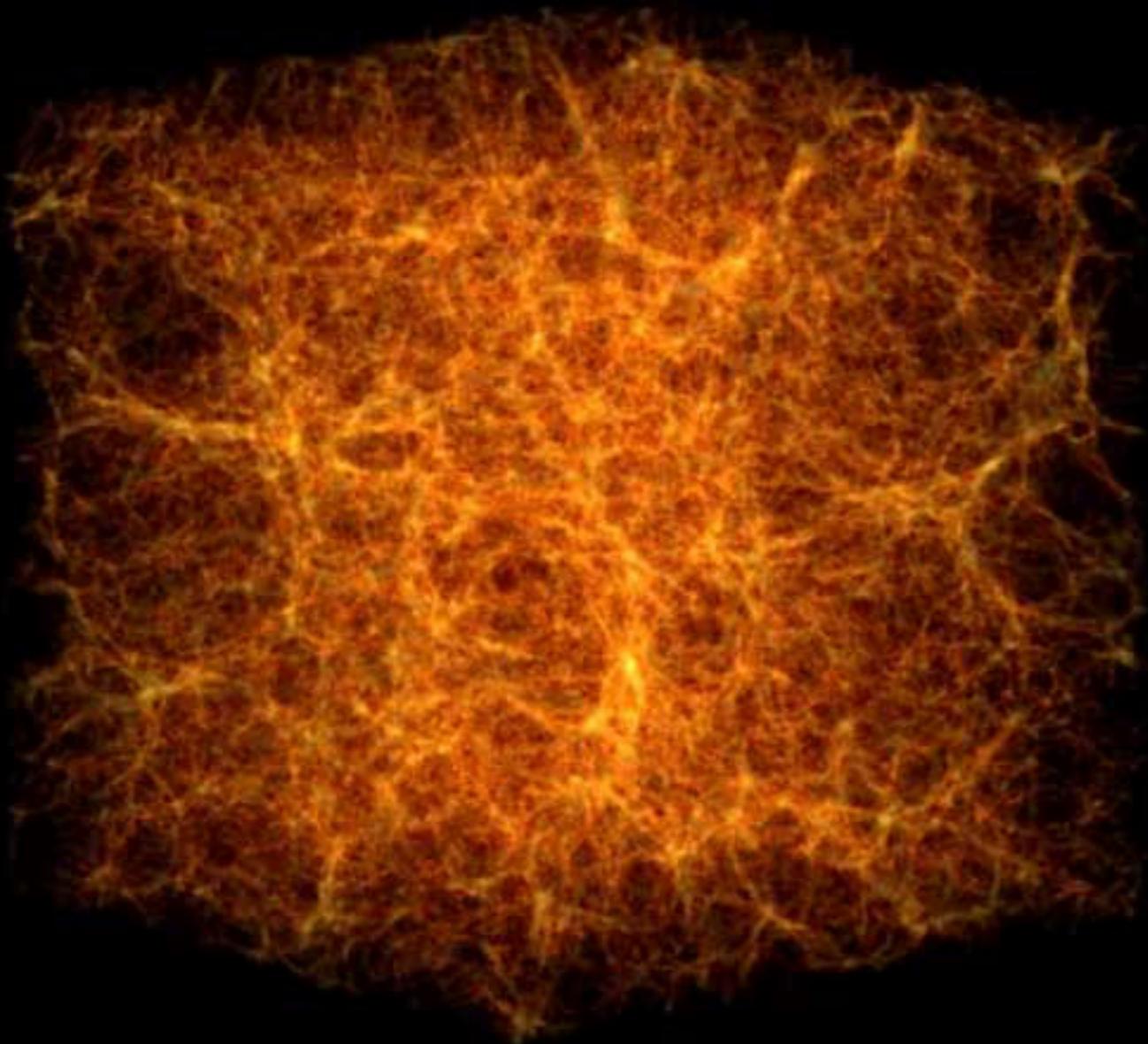


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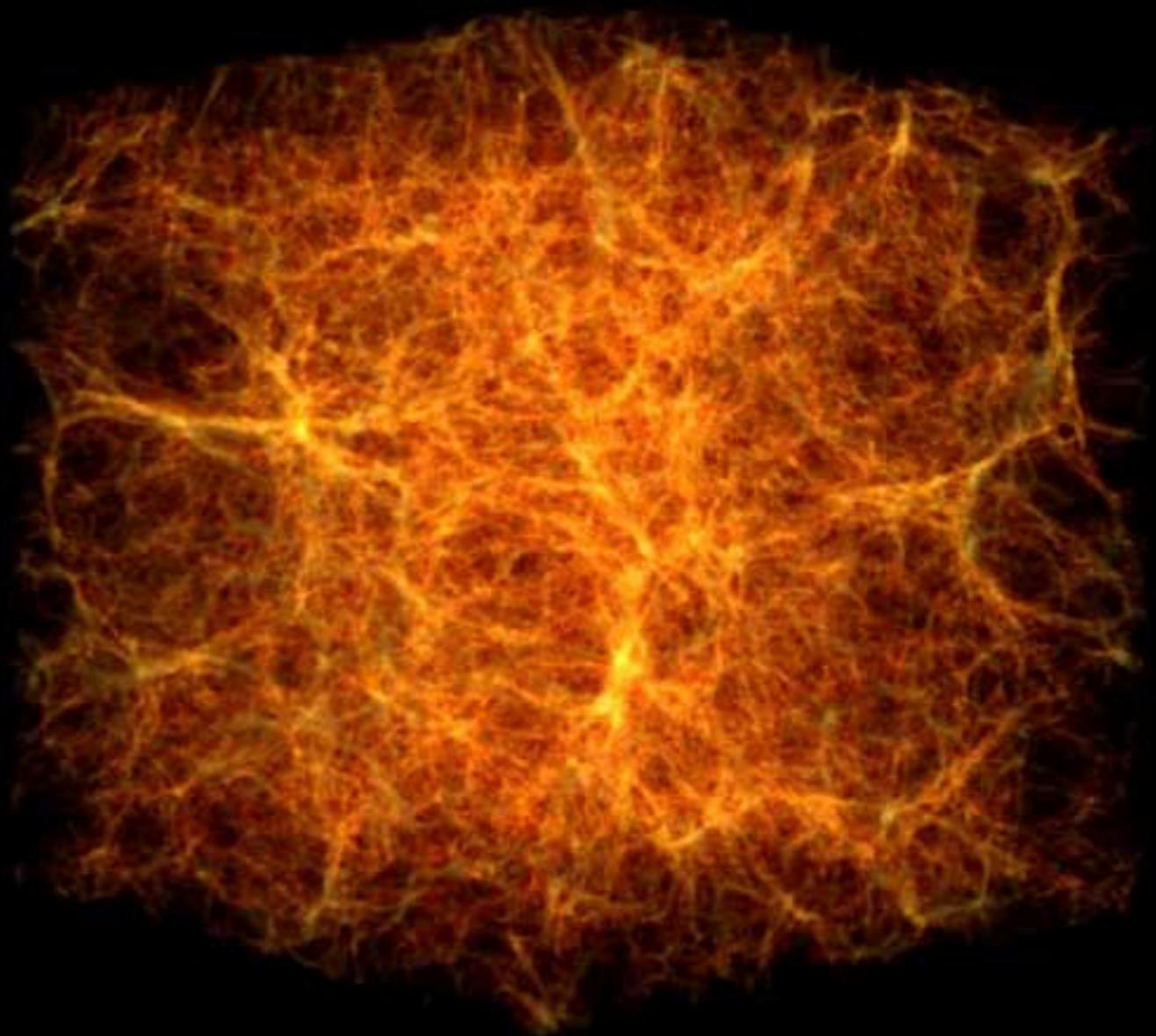
$T = 0.05 \text{ Gyr}$

500 kpc





small neutrino mass



large neutrino mass

BSM Model Building Flowchart



Reconciling Sterile Neutrinos with Cosmology

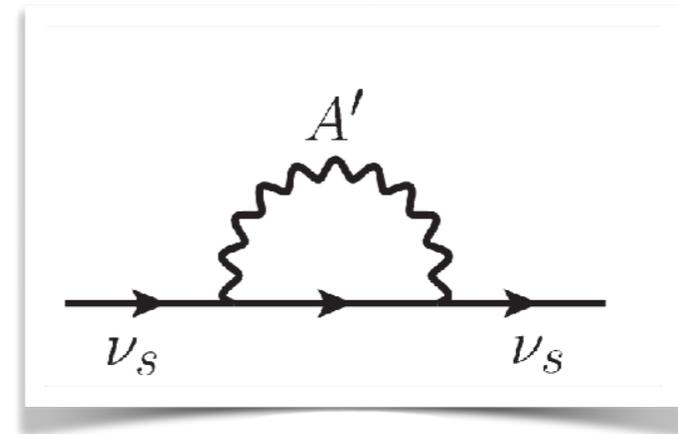
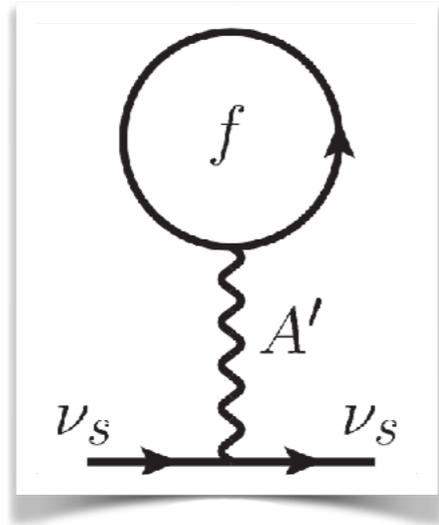
- ☑ New interactions in the ν_s sector
 - production suppressed by thermal potential
 - avoids N_{eff} constraint, weakens or avoids Σm_ν constraint
- ☑ ν_s properties change in late phase transition
- ☑ Coupling to slow-rolling scalar field
- ☑ ...

Reconciling Sterile Neutrinos with Cosmology

- ☑ New interactions in the ν_s sector Hannestad et al. [1310.5926](#)
Dasgupta JK, [1310.6337](#)
 - production suppressed by thermal potential
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Chu et al., [1806.10629](#)
- ☑ Coupling to slow-rolling scalar field Fardon Nelson Weiner, [astro-ph/0309800](#)
Bezrukov Chudaykin Gorbunov, [1705.02184](#)
- ☑ ...

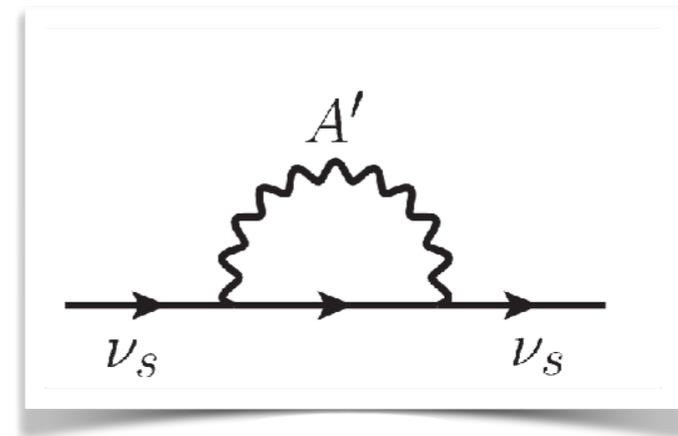
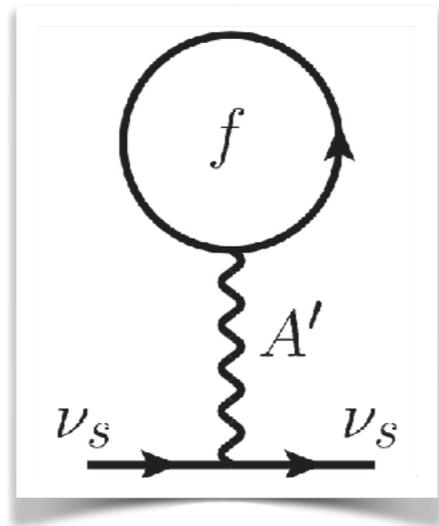
New Interaction in the Sterile Sector

- ✓ Assume ν_s charged under a new $U(1)'$ gauge group
- ✓ Neutrino self-energy contributes to effective potential V^{eff}



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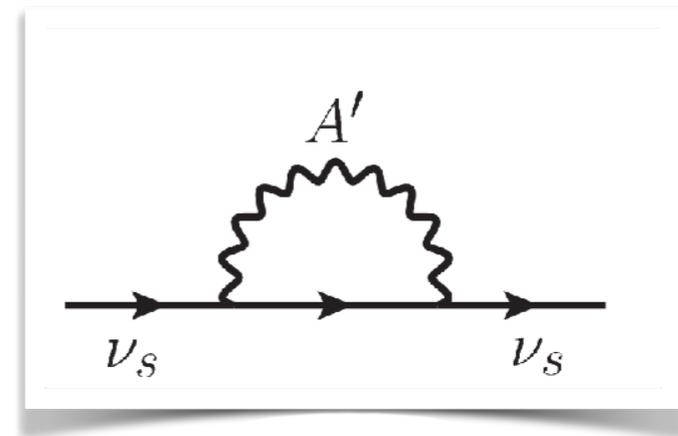
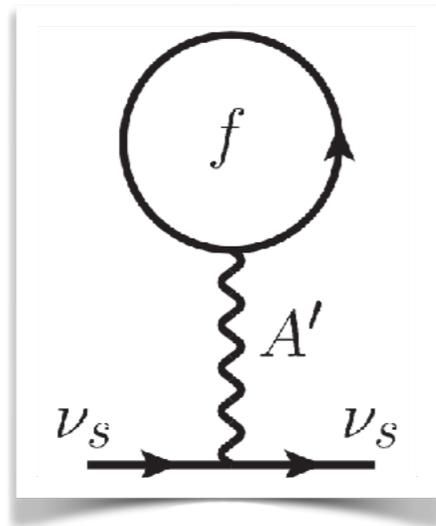


- ✓ Thermal propagators

$$S(p) = (\not{p} + m) \left[\frac{1}{p^2 - m^2} + i\Gamma_f(p) \right]$$
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2) \left[\frac{1}{p^2 - M^2} + i\Gamma_b(p) \right]$$

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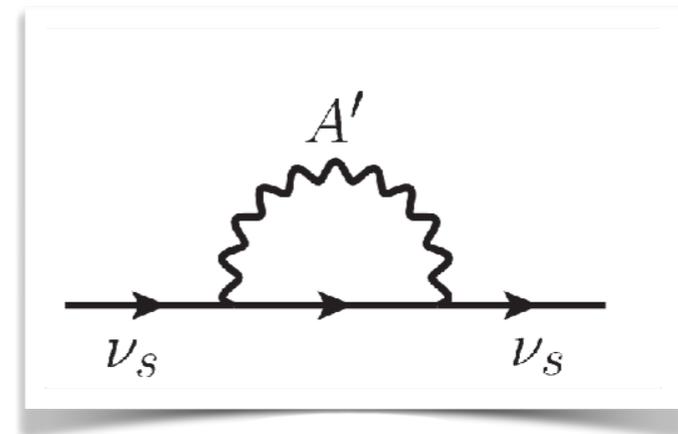
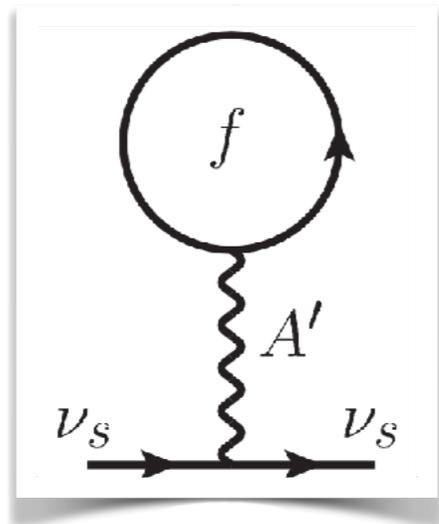
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$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)n_{f,b}(p)$$

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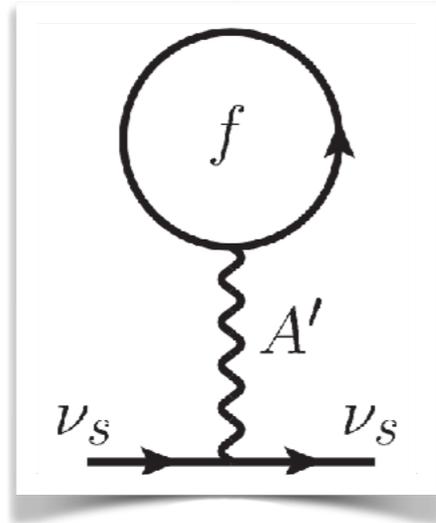
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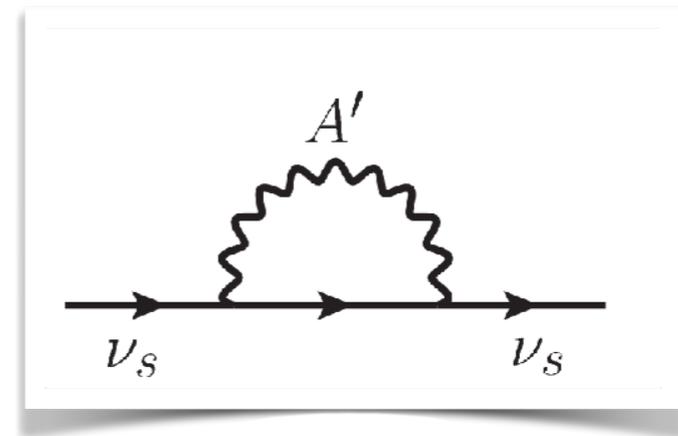
$$n_{f,b}(p) = [e^{|p \cdot u|/T_s} \pm 1]^{-1}$$

New Interaction in the Sterile Sector

- ✓ Assume ν_s charged under a new $U(1)'$ gauge group
- ✓ Neutrino self-energy contributes to effective potential V^{eff}



MSW potential $V \sim n_f - n_{\bar{f}}$



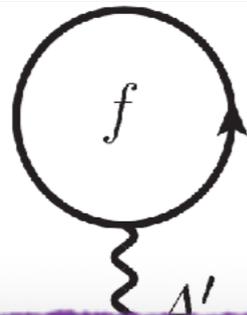
thermal correction $V \sim T^a$

- ✓ Effective mixing angle:

$$\sin^2 2\theta_{\text{eff}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV^{\text{eff}}}{\Delta m^2} \right)^2}$$

New Interaction in the Sterile Sector

- ✓ Assume ν_s charged under a new $U(1)'$ gauge group
- ✓ Neutrino self-energy contributes to effective potential V^{eff}



- ★ ν_s production strongly suppressed at high T
- ★ cosmological constraints avoided

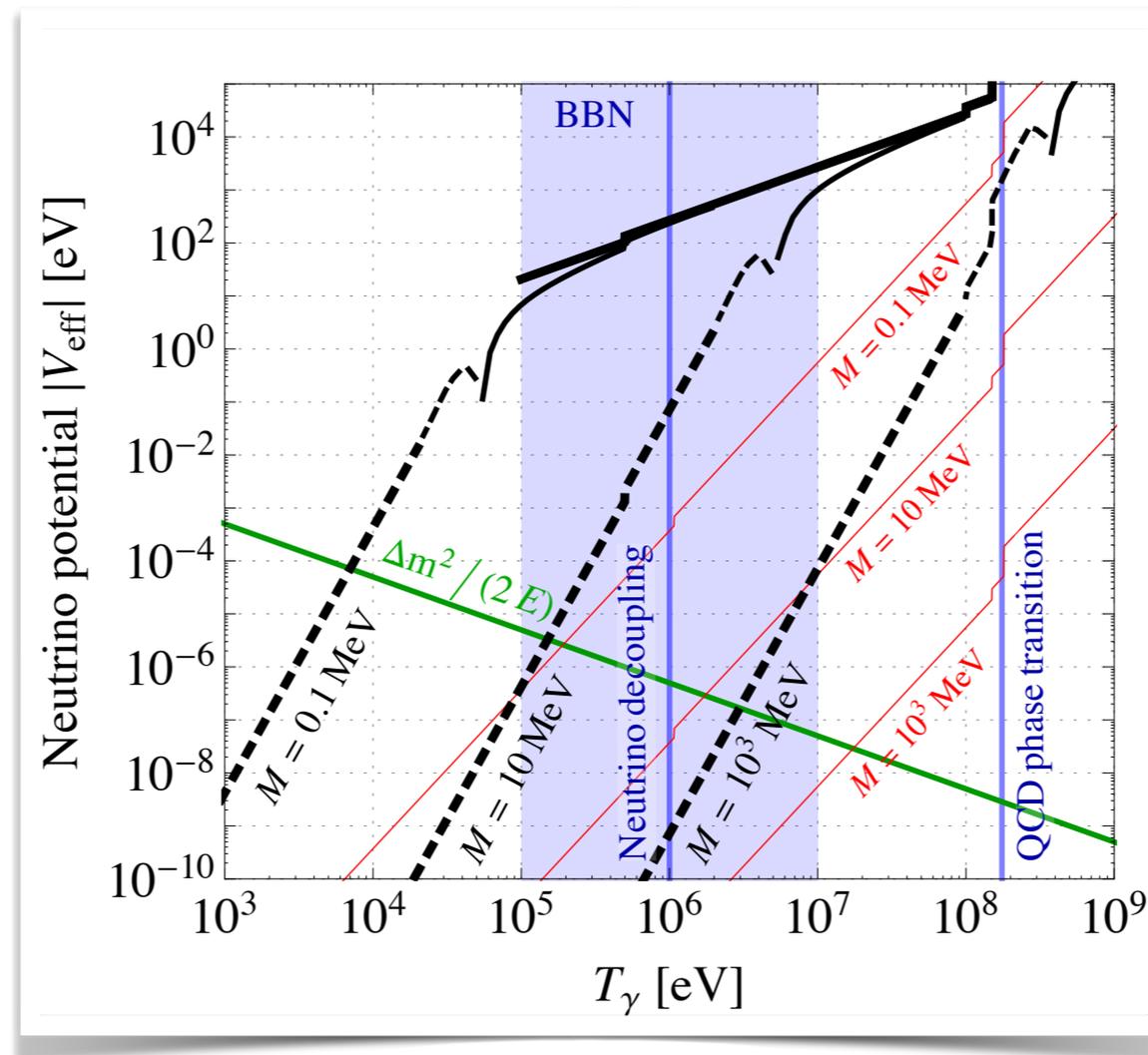
new potential $V^{\text{eff}} = \dots$

thermal correction $V^{\text{eff}} = \dots$

- ✓ Effective mixing angle:

$$\sin^2 2\theta_{\text{eff}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV^{\text{eff}}}{\Delta m^2} \right)^2}$$

New Interaction in the Sterile Sector



- ☑ While $V_{eff} \gg \Delta m^2 / (2T)$: ν_s production suppressed

Hannestad *et al.* [1310.5926](#), Dasgupta JK [1310.6337](#)

- ☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s

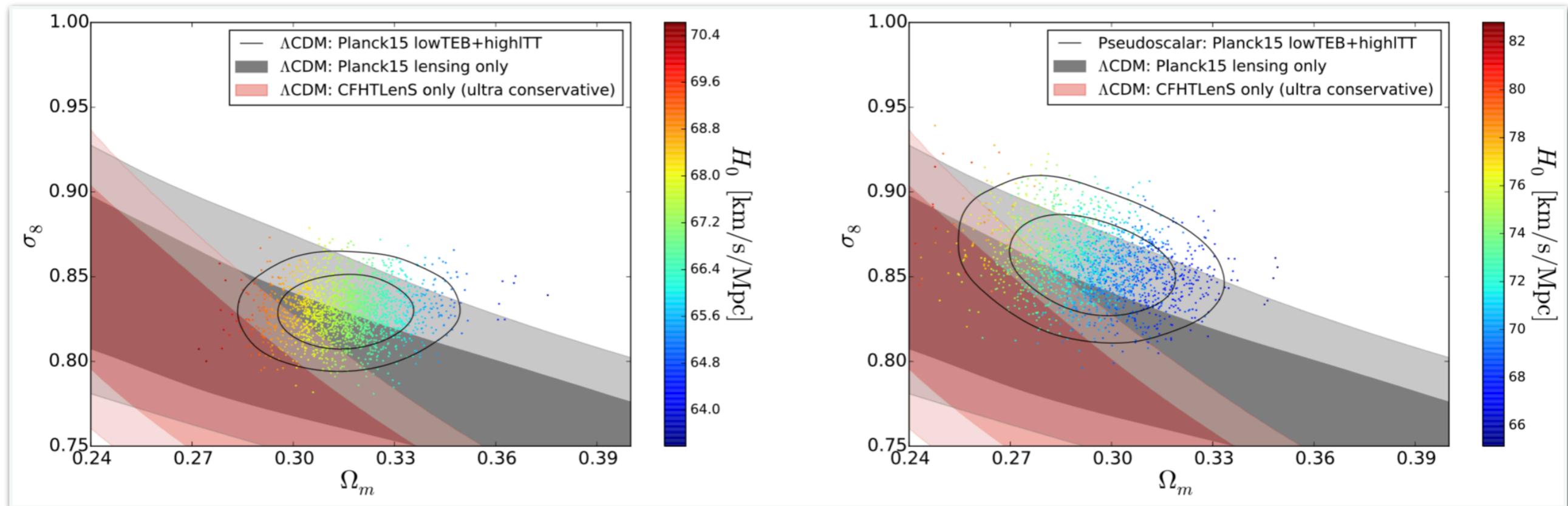
(N_{eff} is fixed by then, but Σm_ν still worrisome)

Chu Dasgupta JK [1505.02795](#), Cherry Friedland Shoemaker [1605.06506](#)
Forastieri *et al.* [1704.00626](#), Chu Dasgupta Dentler JK Saviano [1806.10629](#)

New Interaction in the Sterile Sector

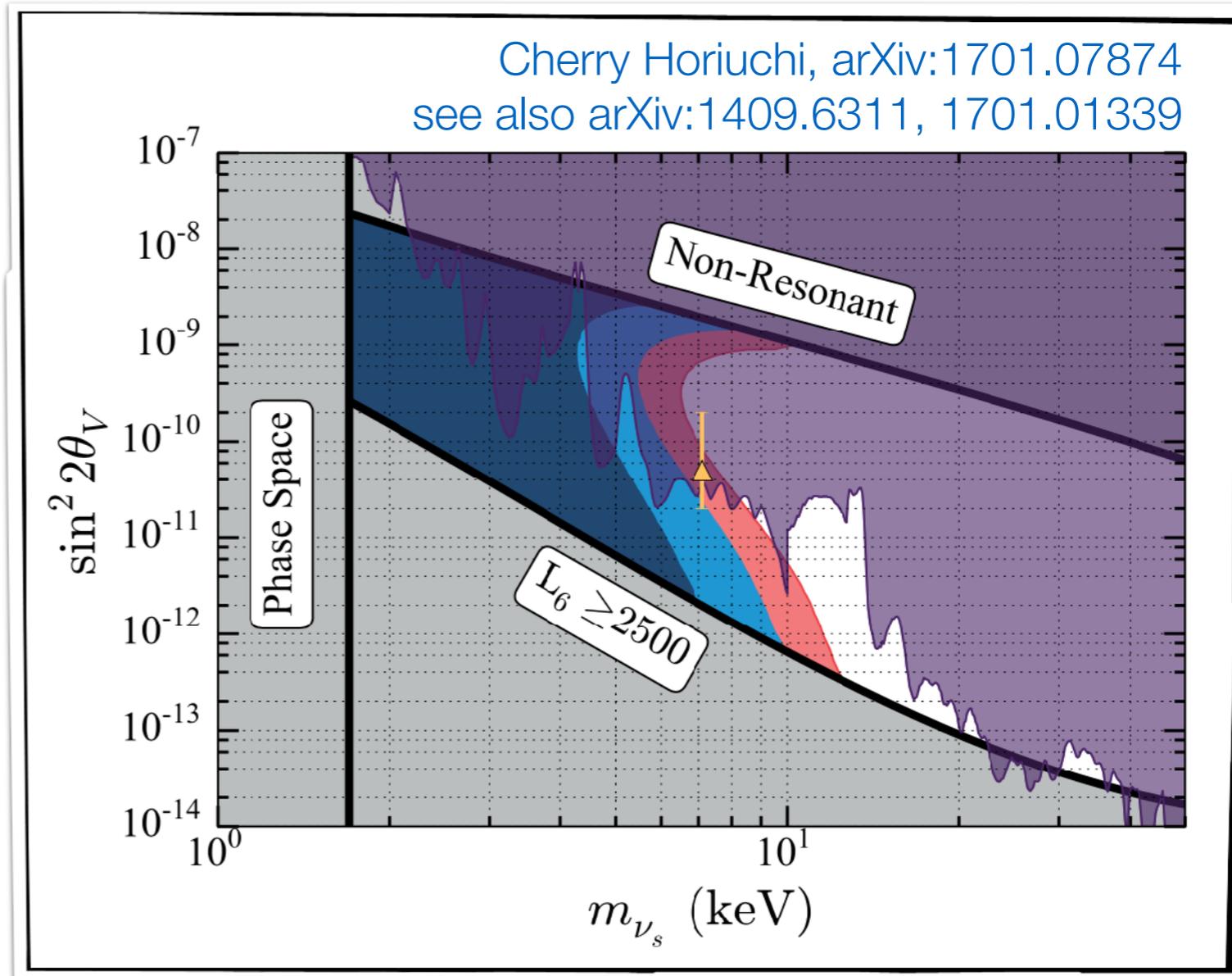
- ☑ While $V^{\text{eff}} \gg \Delta m^2 / (2T)$: ν_s production suppressed
- ☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s
(N_{eff} is fixed by then, but Σm_ν still worrisome)
- ☑ Can be solved by $\nu_s \nu_s \rightarrow \phi \phi$ annihilation
if mediator ϕ is a light pseudoscalar
- ☑ Could relax H_0 tension

Archidiacono *et al.* [1606.07673](https://arxiv.org/abs/1606.07673)

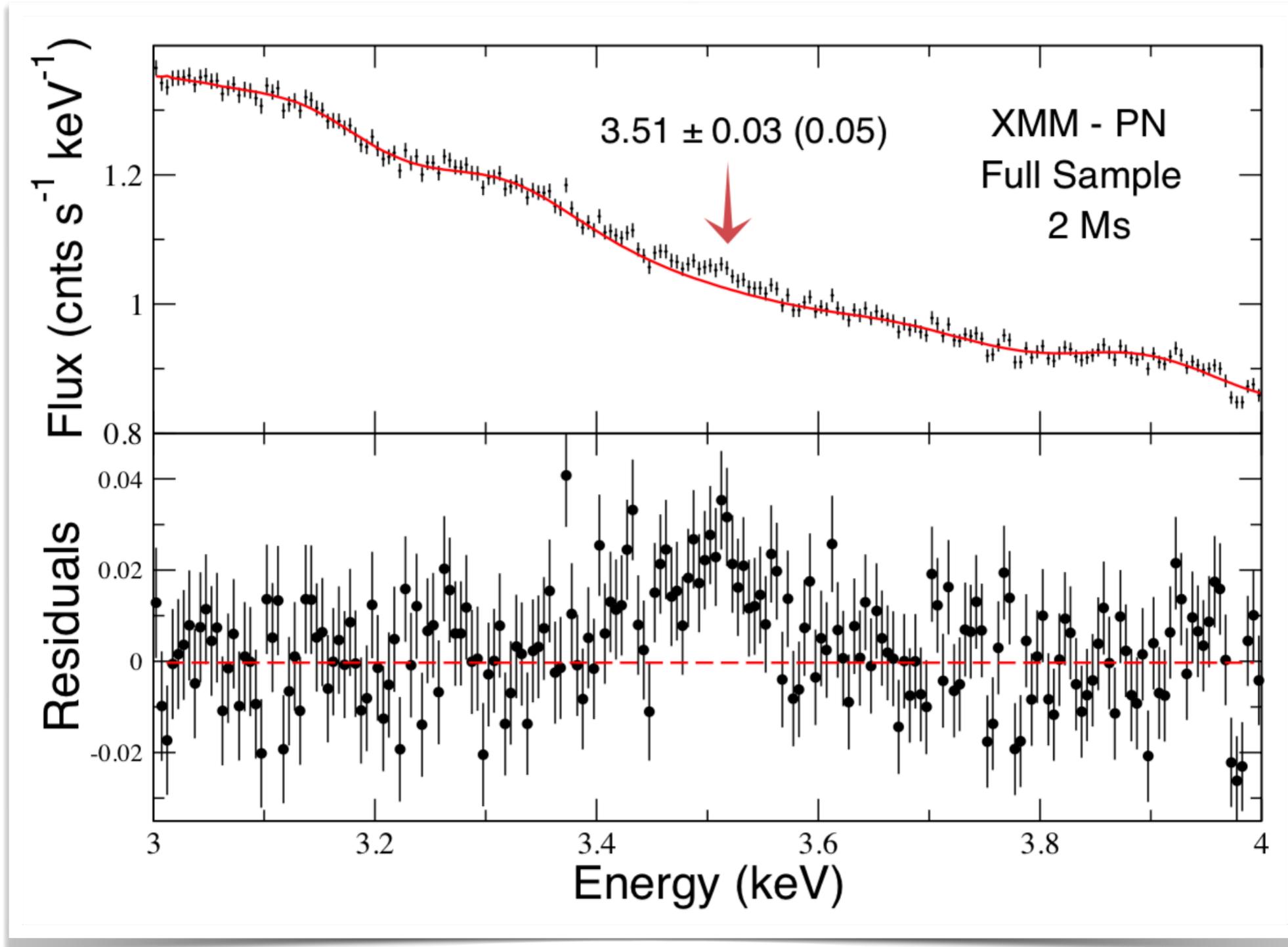


Sterile Neutrinos as Dark Matter

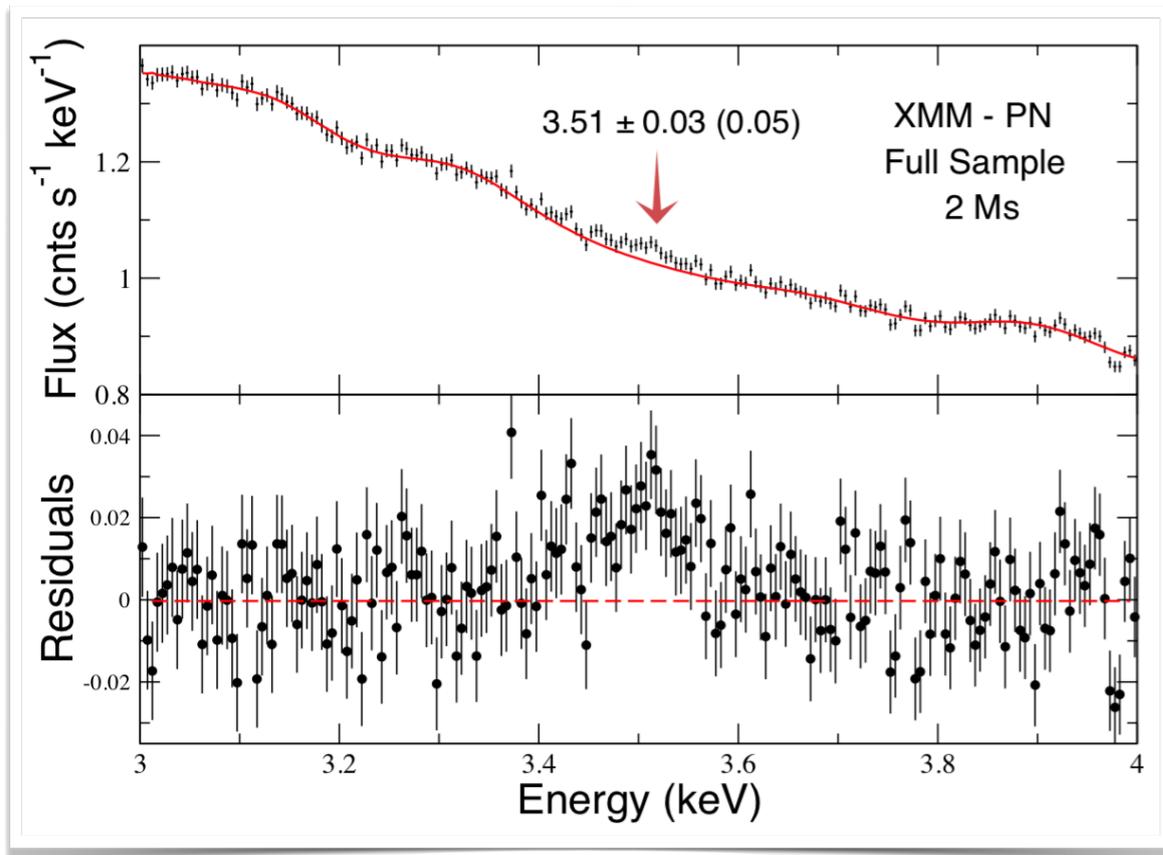
- ☑ Leading candidate for **Warm Dark Matter**
 - Improved **small scale structure**
- ☑ Production through oscillations challenged by e.g. **Lyman- α data**
- ☑ Promising alternative production mechanisms
 - Decays of heavy particles
 - High-T freeze-in



A Hint for Sterile Neutrino Dark Matter?

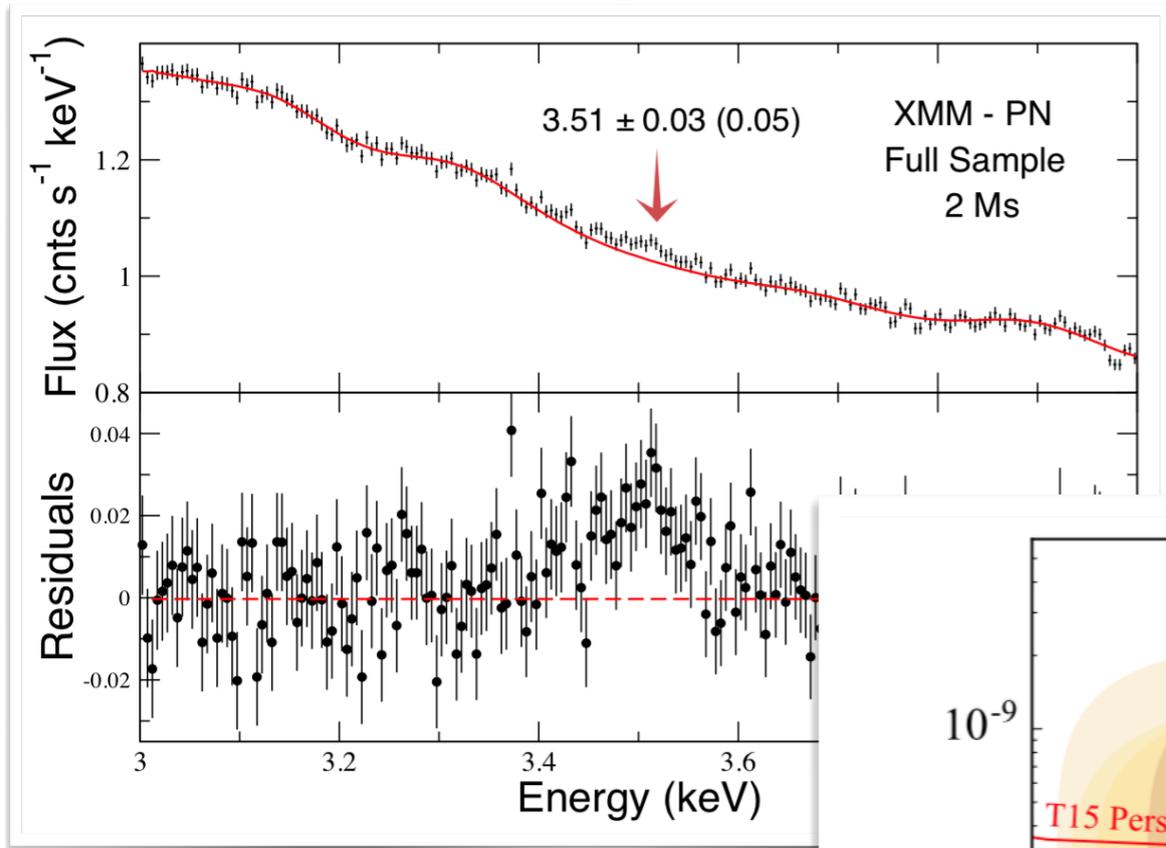


A Hint for Sterile Neutrino Dark Matter?

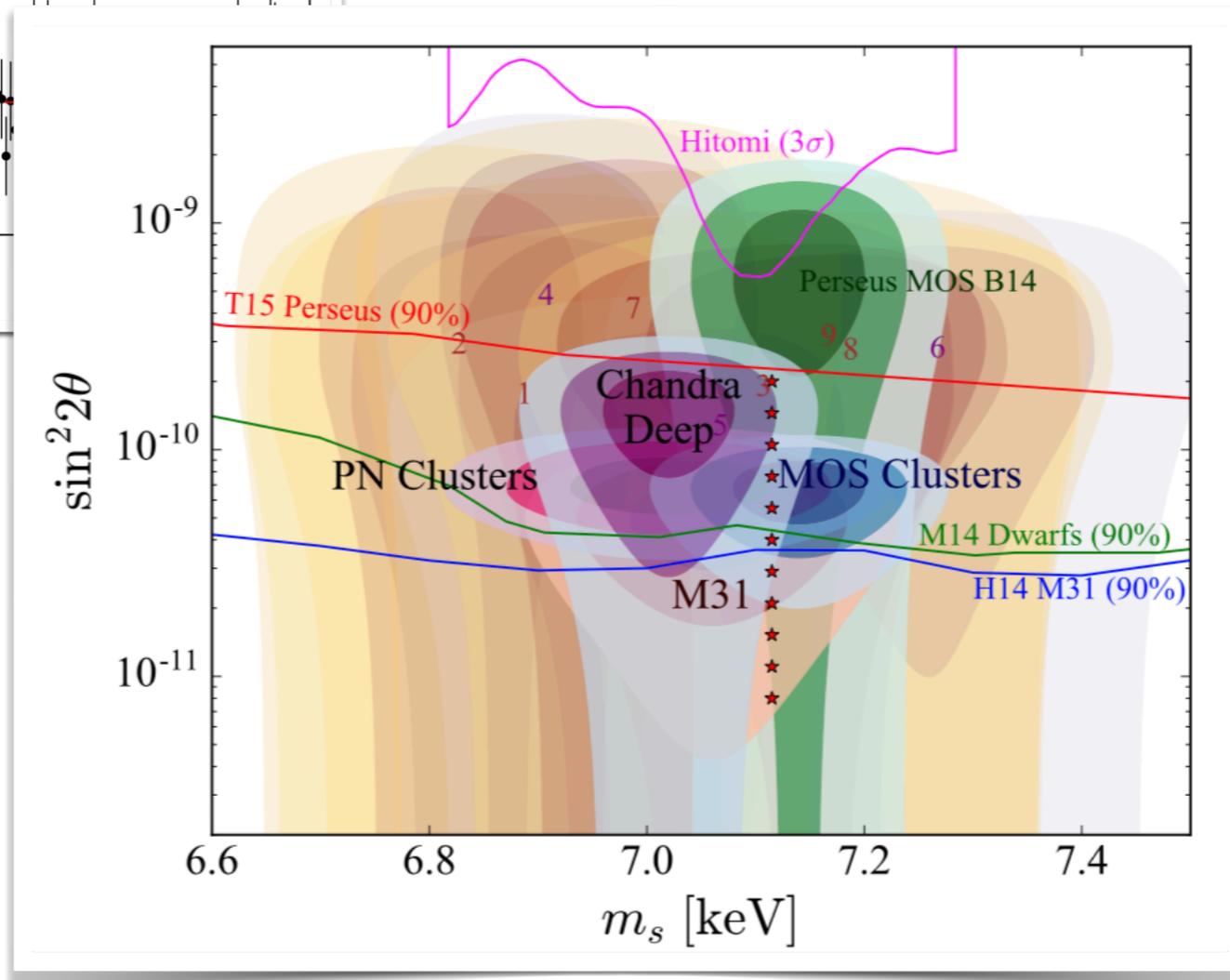


From decay $\nu_s \rightarrow \nu_a + \gamma$?
Abazajian 1705.01837

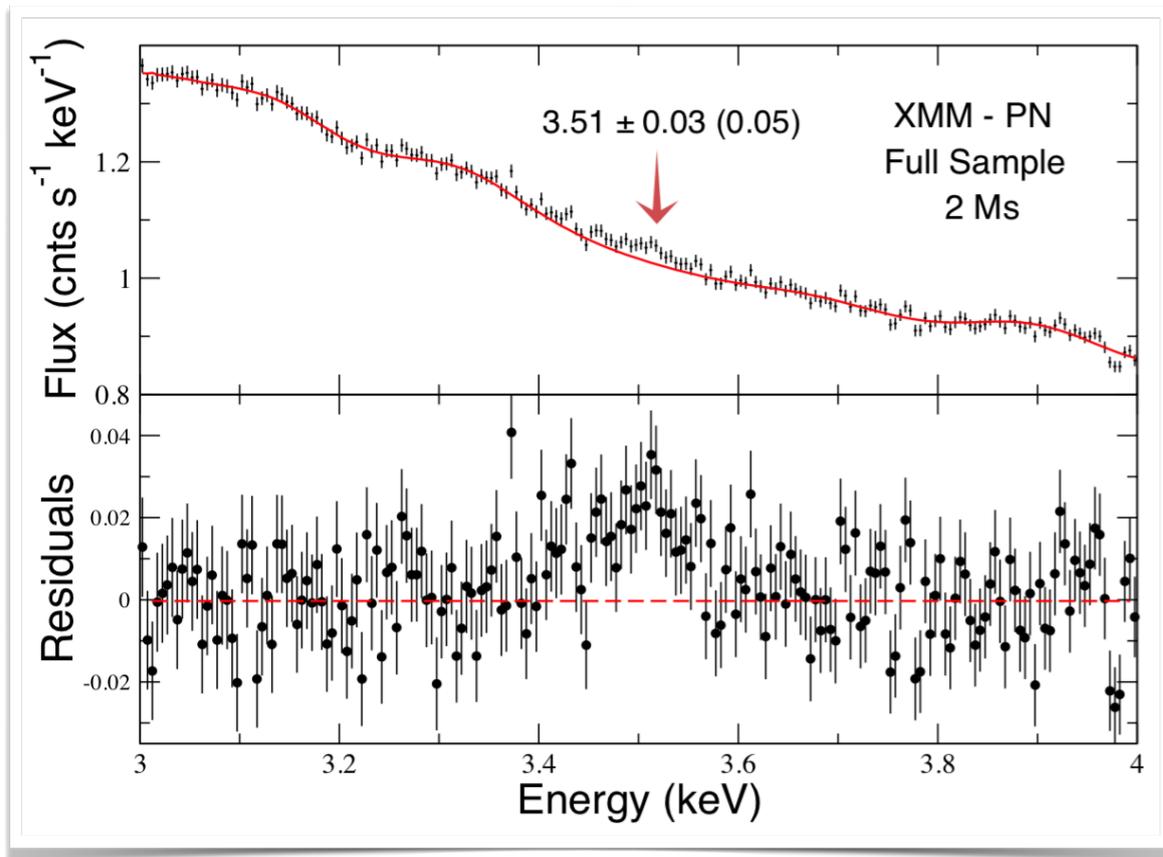
A Hint for Sterile Neutrino Dark Matter?



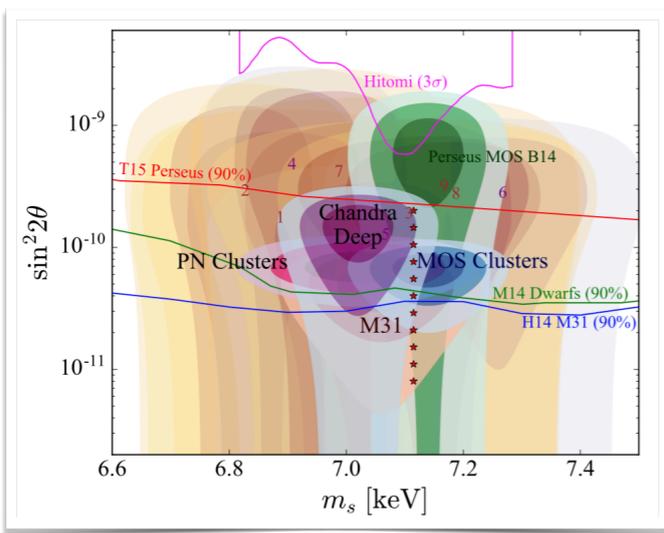
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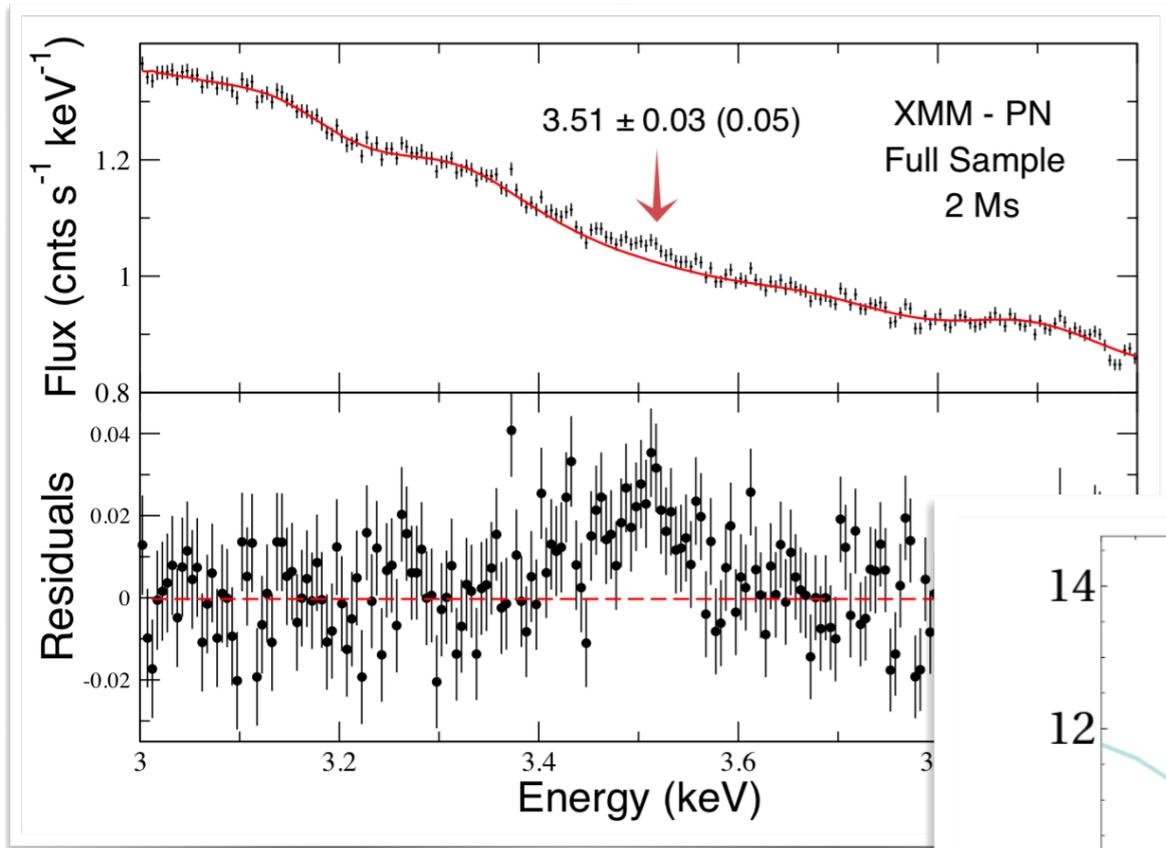
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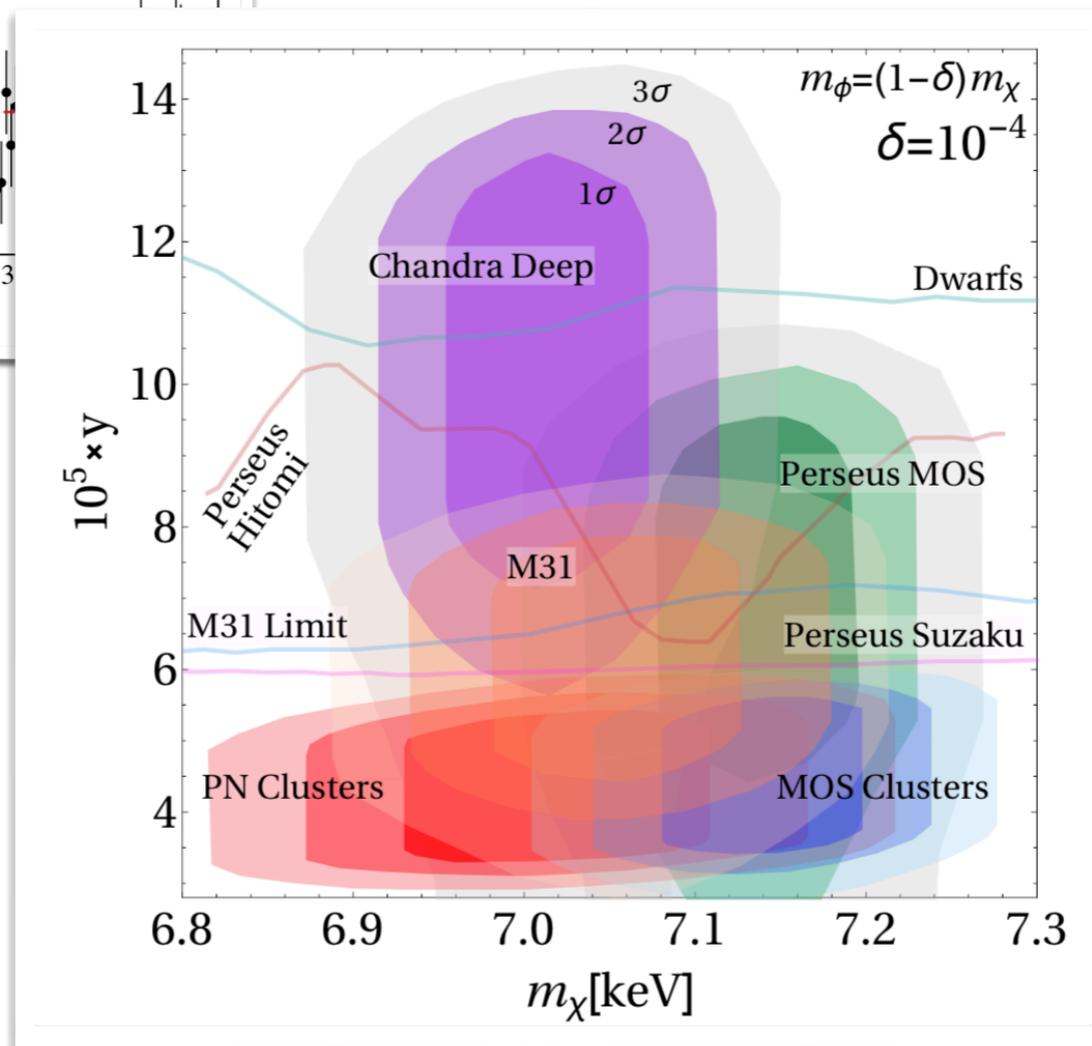
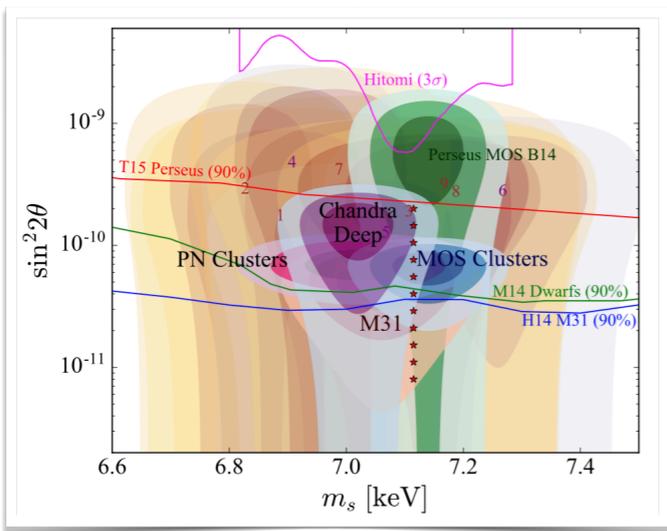


A Hint for Sterile Neutrino Dark Matter?

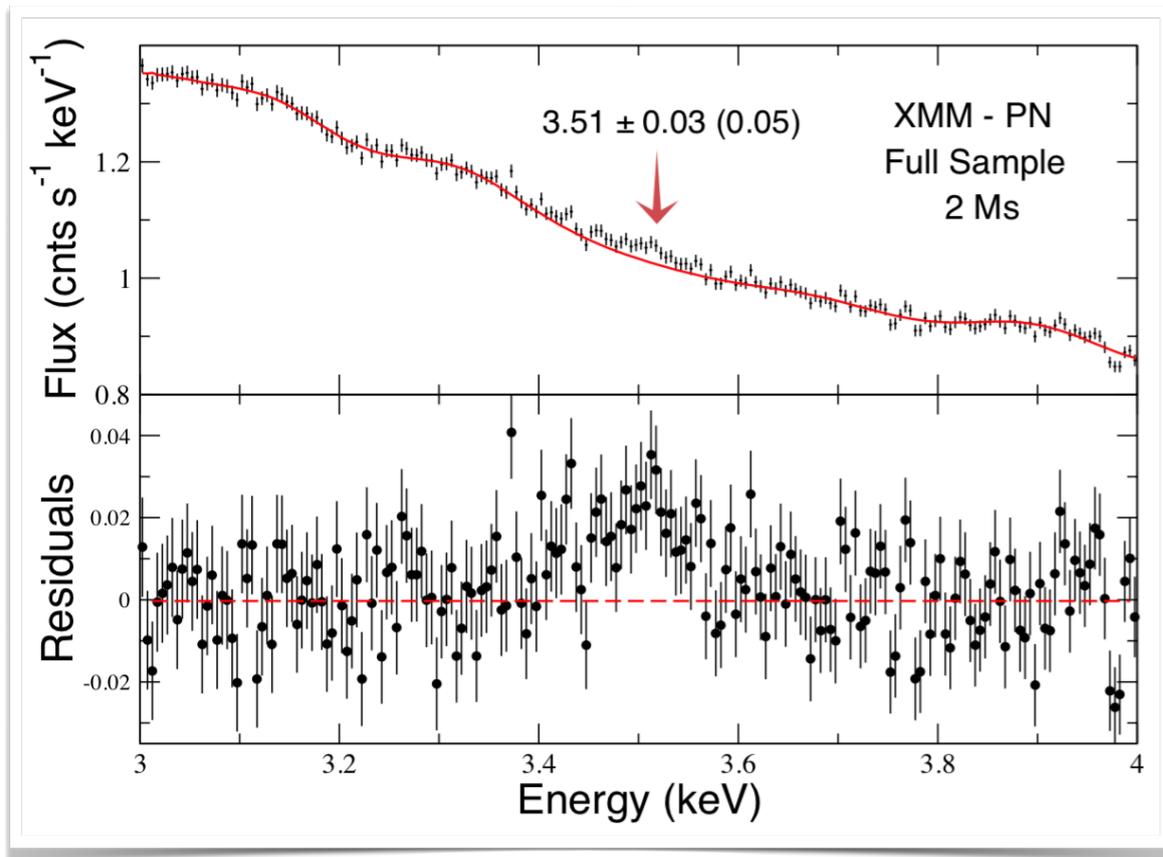


☑ From decay $\nu_s \rightarrow \nu_a + \gamma$?
Abazajian 1705.01837

☑ Or from ν_s annihilation?
Brdar JK Liu Wang 1710.02146

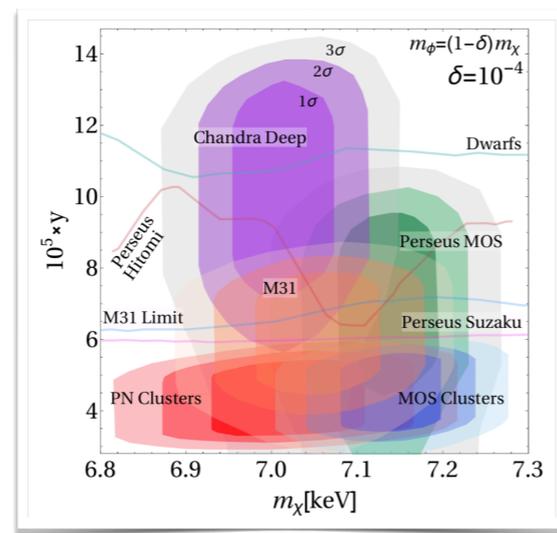
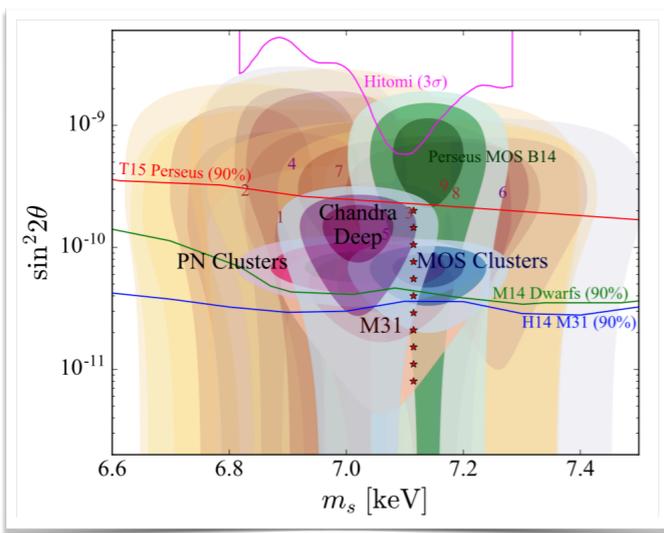


A Hint for Sterile Neutrino Dark Matter?

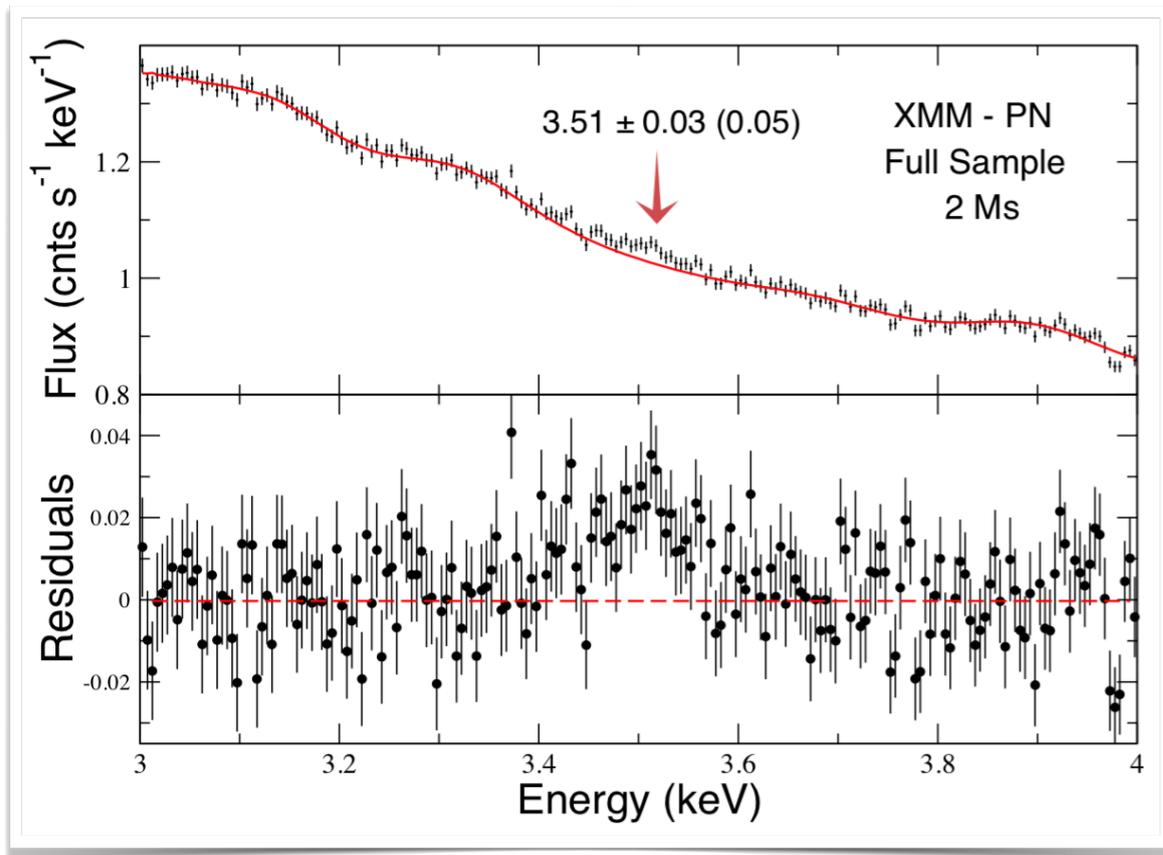


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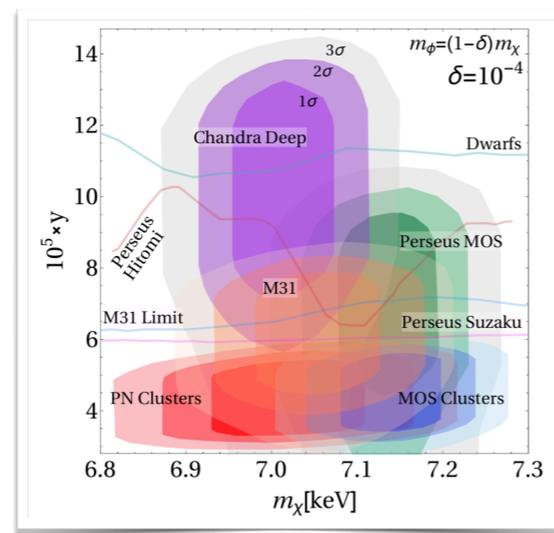
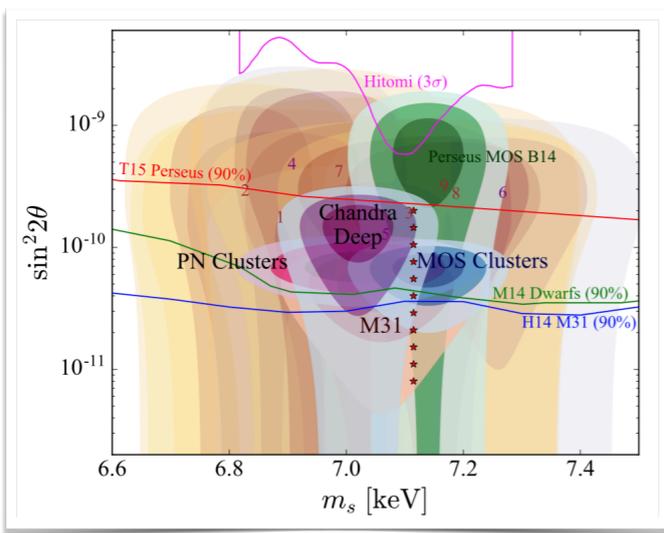
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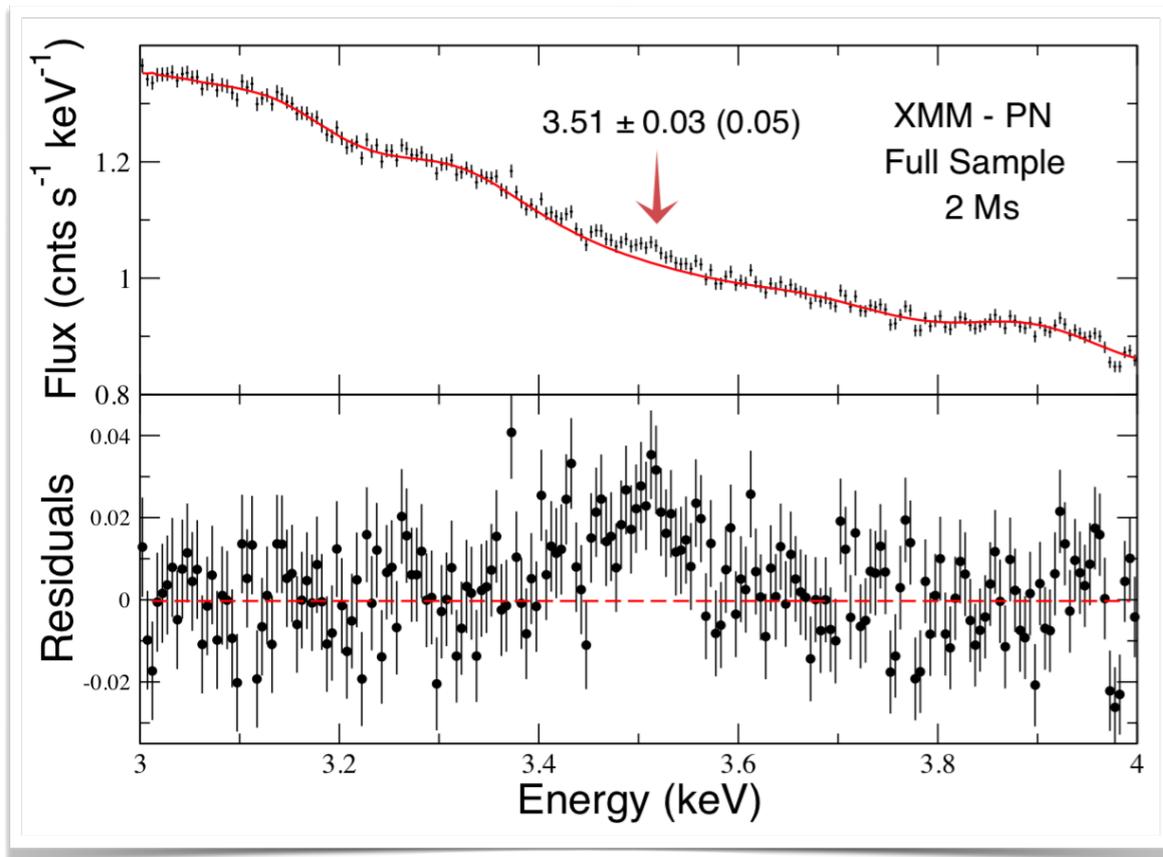
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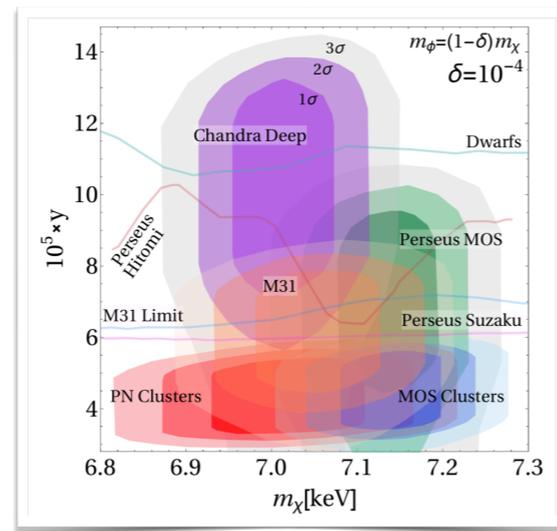
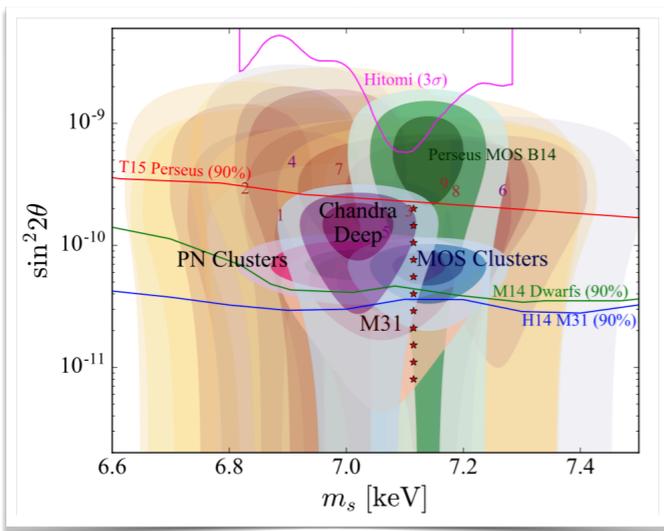
- From decay $\nu_s \rightarrow \nu_a + \gamma$?
 Abazajian 1705.01837
- Or from ν_s annihilation?
 Brdar JK Liu Wang 1710.02146
- Testable with sounding rockets



A Hint for Sterile Neutrino Dark Matter?

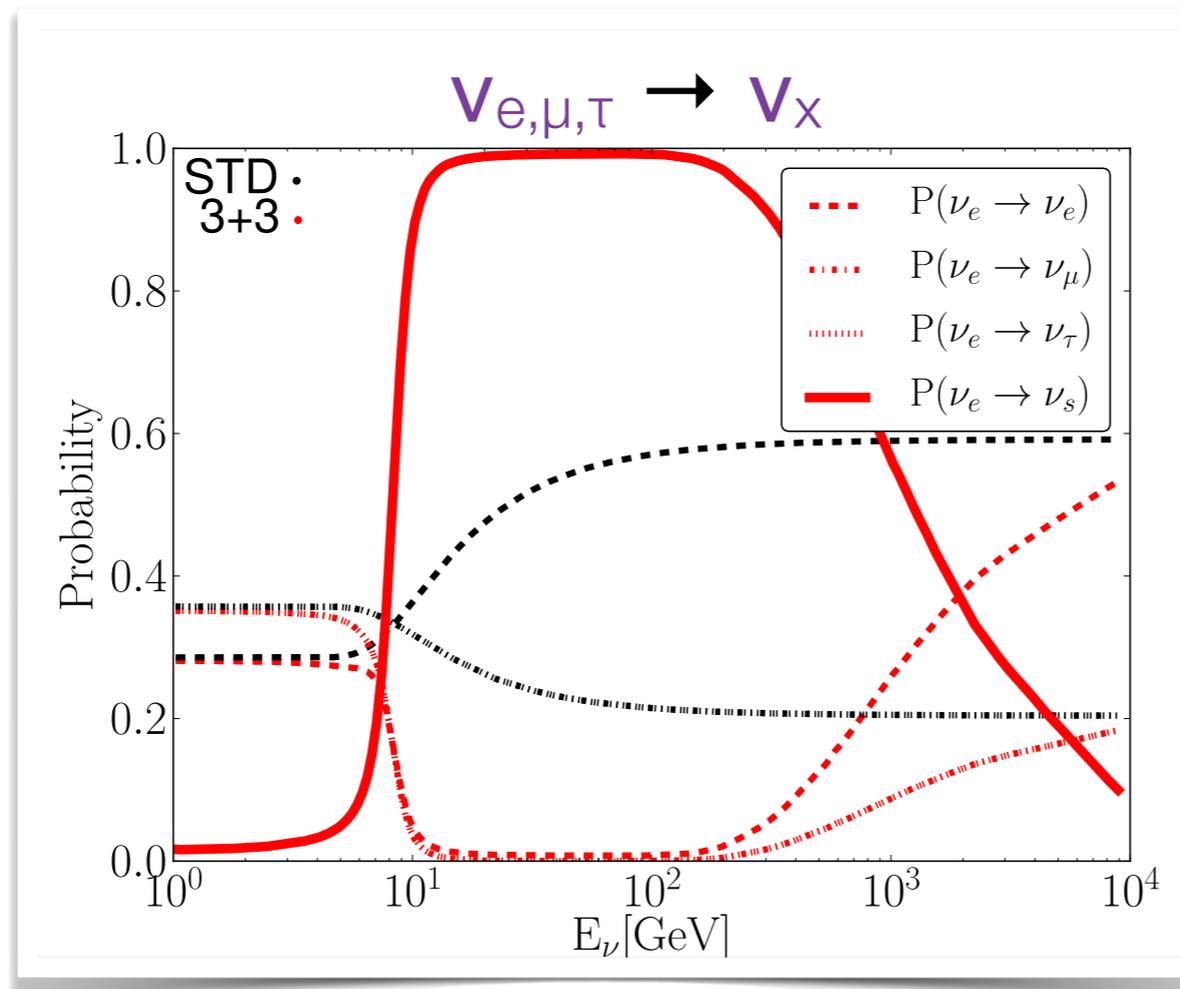


- From decay $\nu_s \rightarrow \nu_a + \gamma$?
 Abazajian 1705.01837
- Or from ν_s annihilation?
 Brdar JK Liu Wang 1710.02146
- Testable with sounding rockets
- Testable using
 DM velocity spectroscopy
 Speckhard Ng Beacom Laha 1507.04744



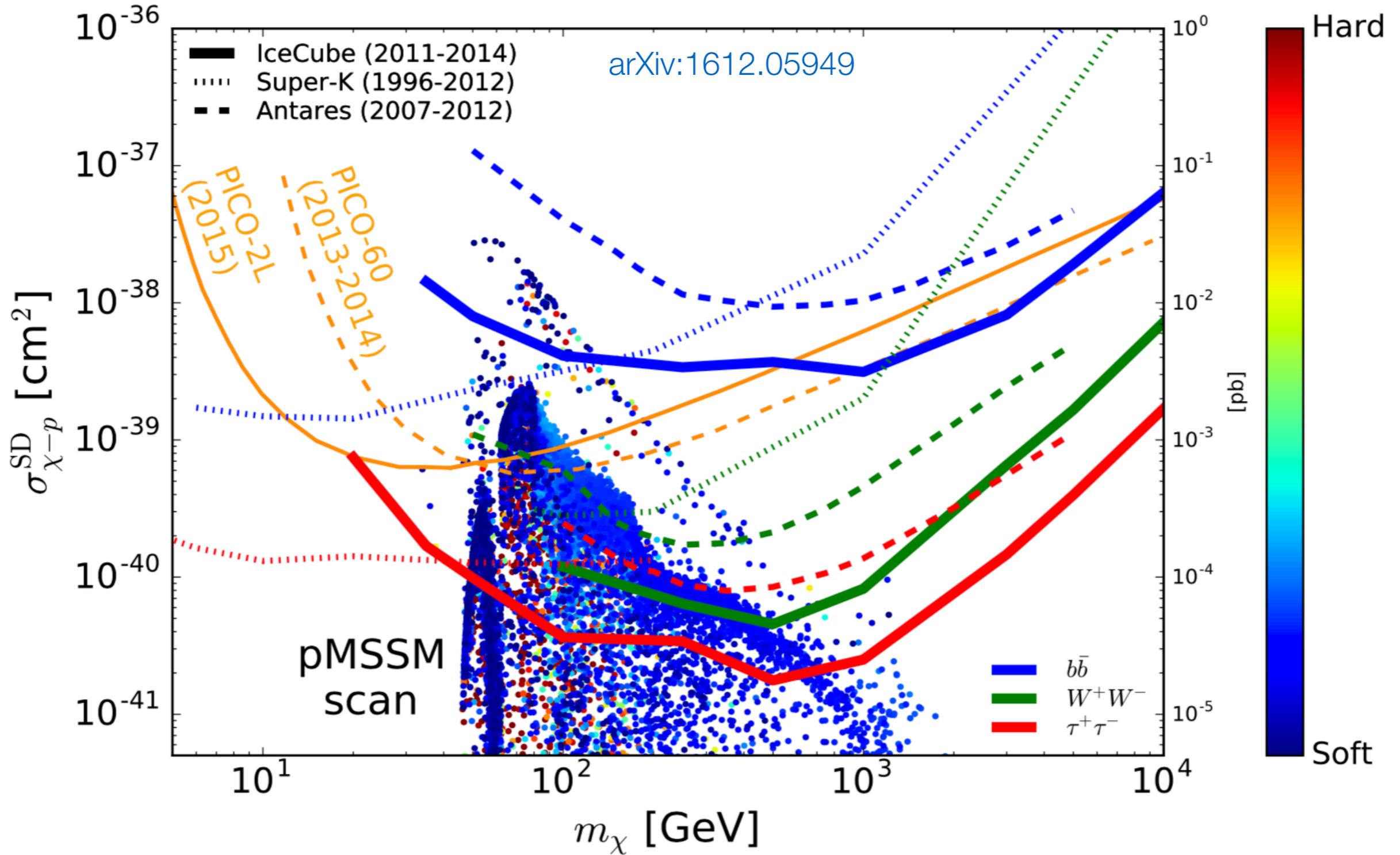
Sterile Neutrinos and DM Annihilation in the Sun

- ☑ Neutrino telescope limits on neutrinos from DM annihilation in the Sun depend crucially on oscillation physics
- ☑ In ν_s models, new MSW resonances can lead to strong $\nu_{e,\mu,\tau} \rightarrow \nu_s$ conversion (for some $\nu / \bar{\nu}$ flavors)

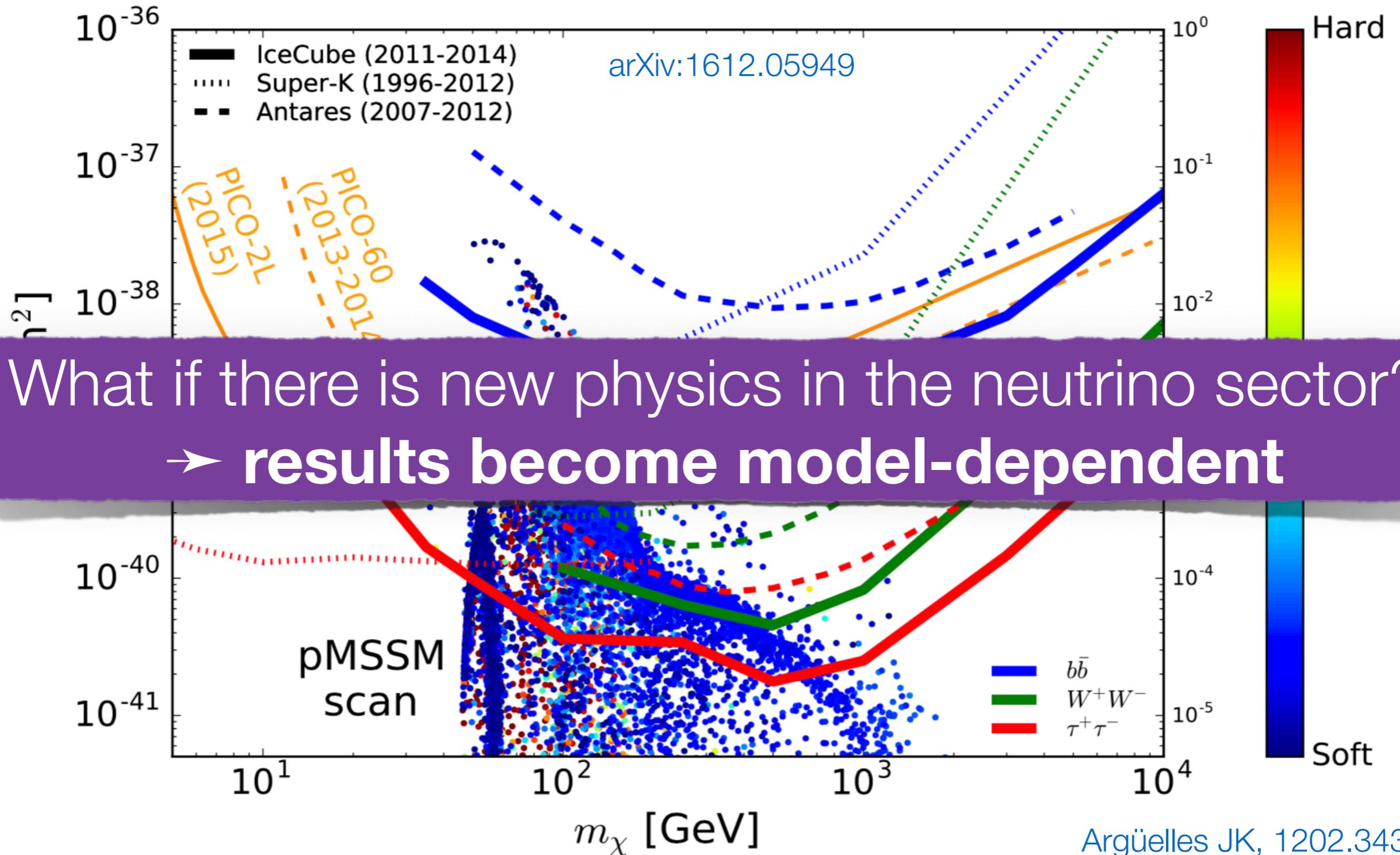


Argüelles JK [1202.3431](#)
Esmaili Peres [1202.2869](#)

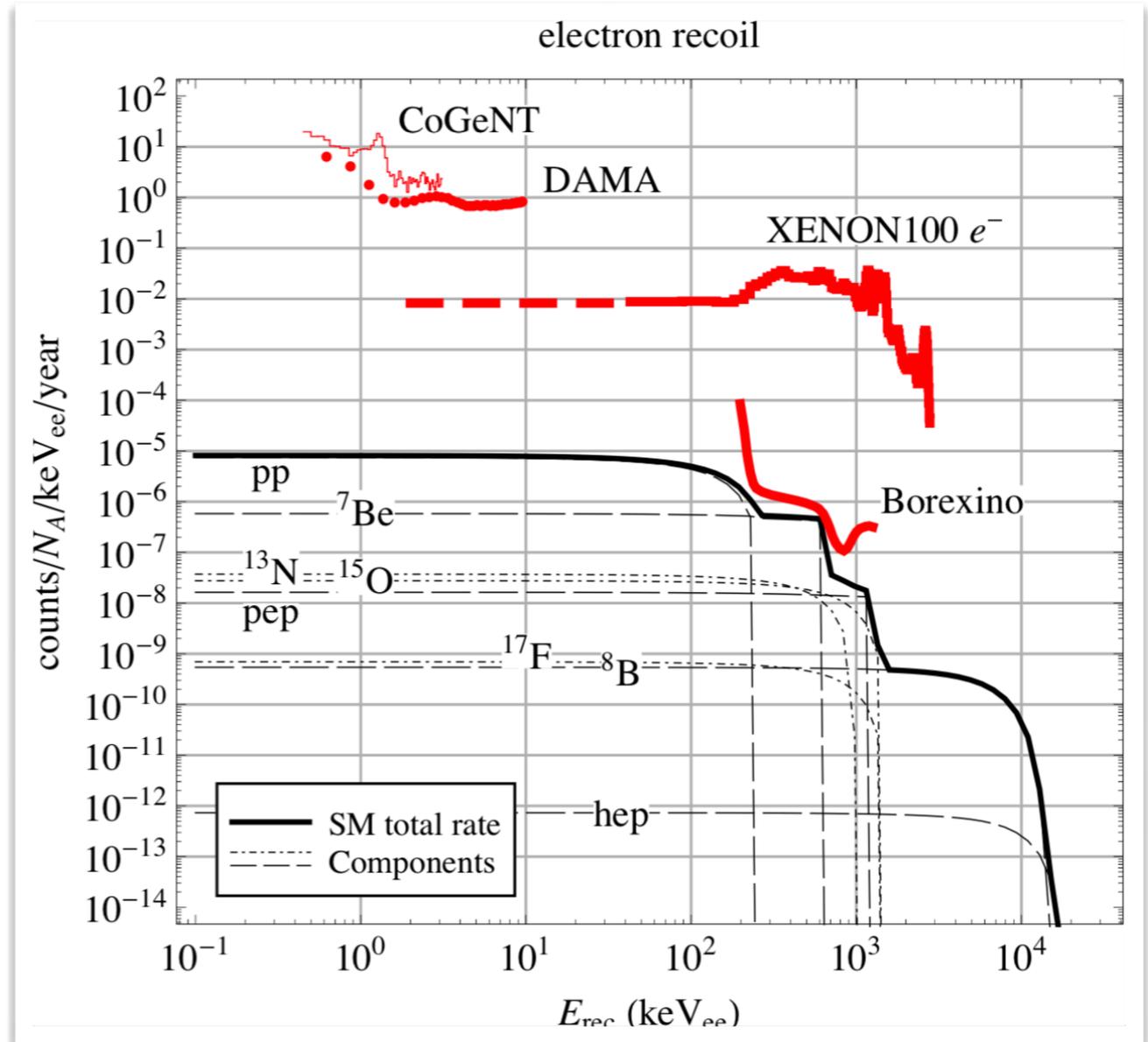
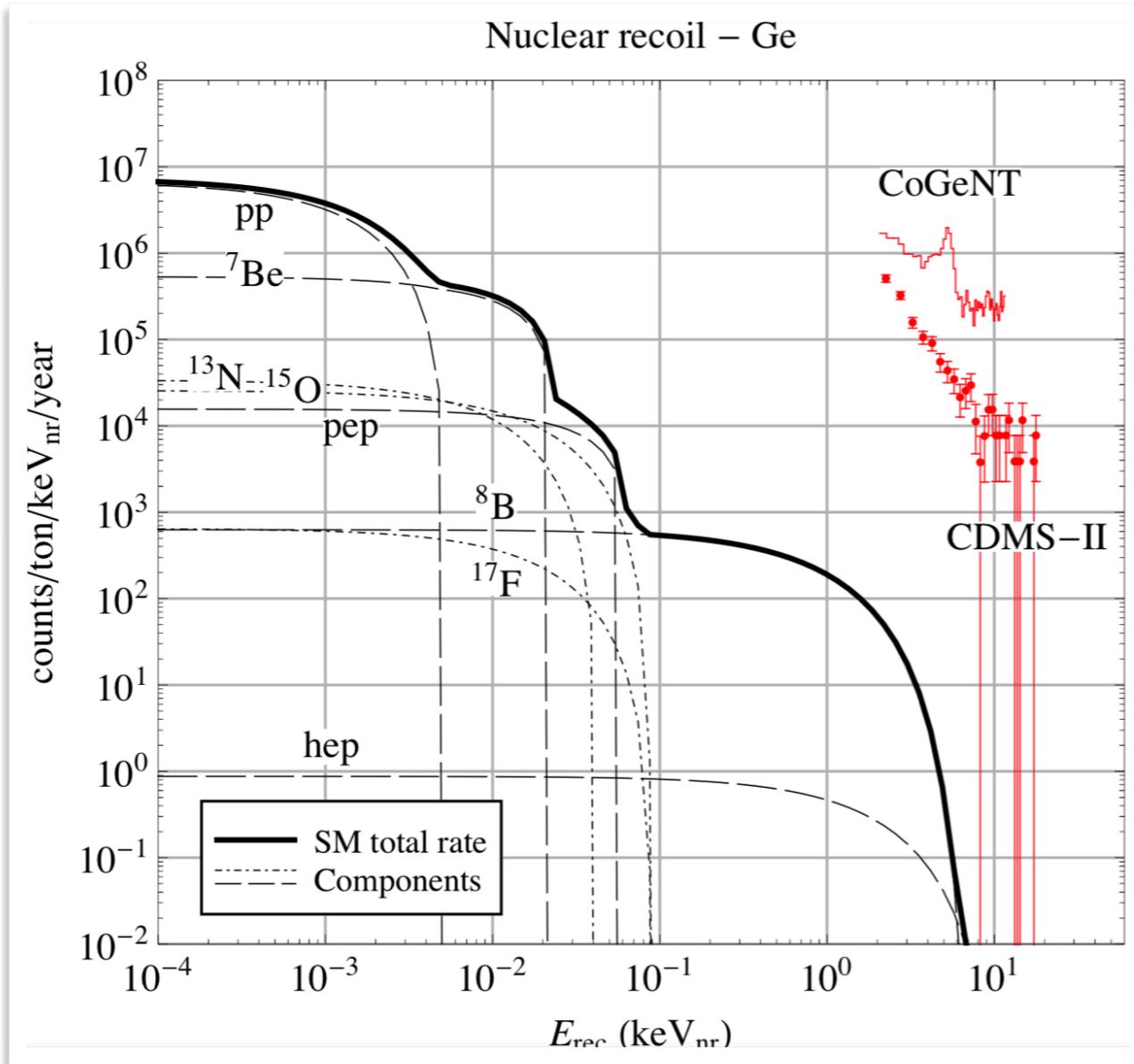
DM Annihilation in the Sun



DM Annihilation in the Sun



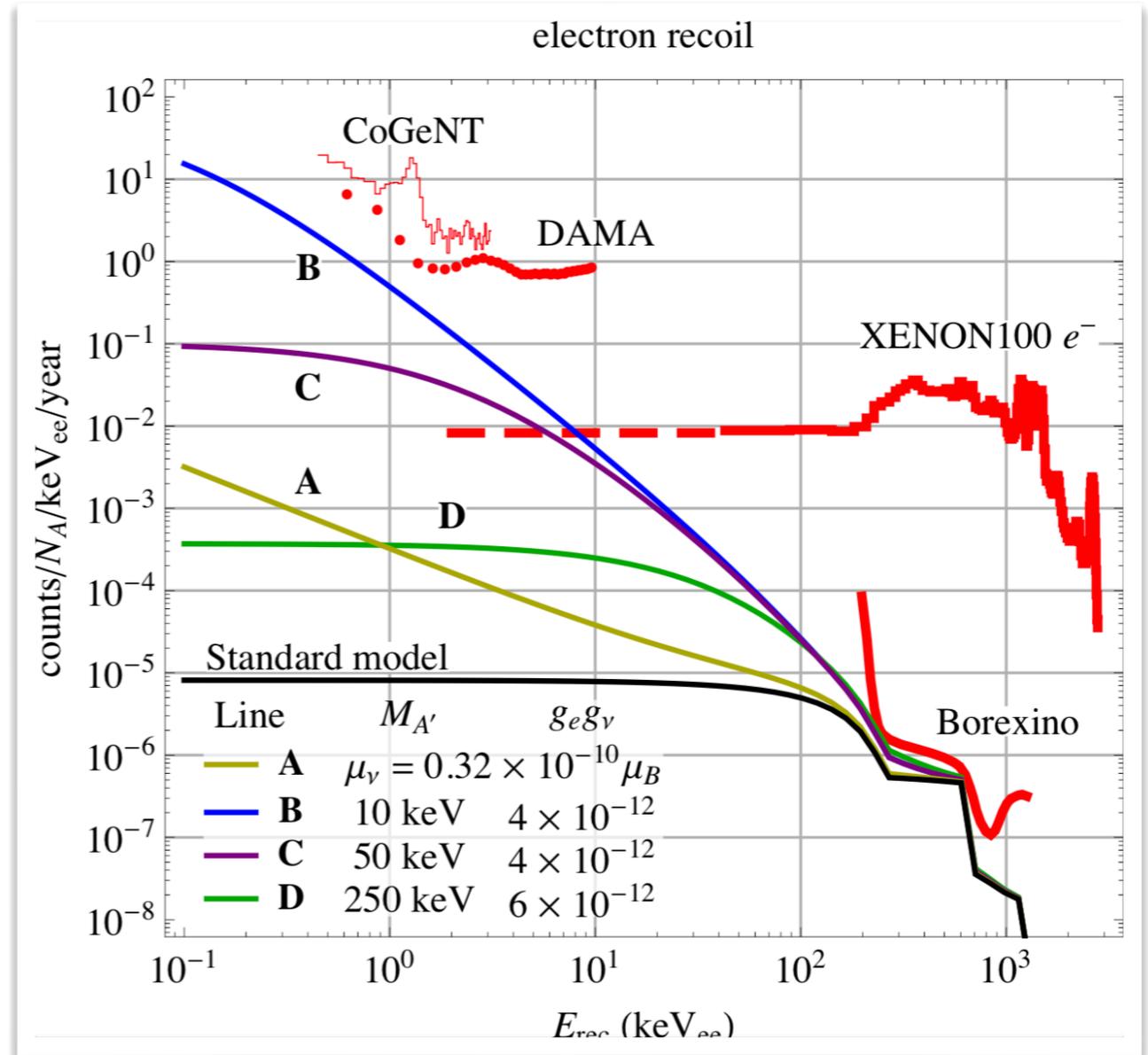
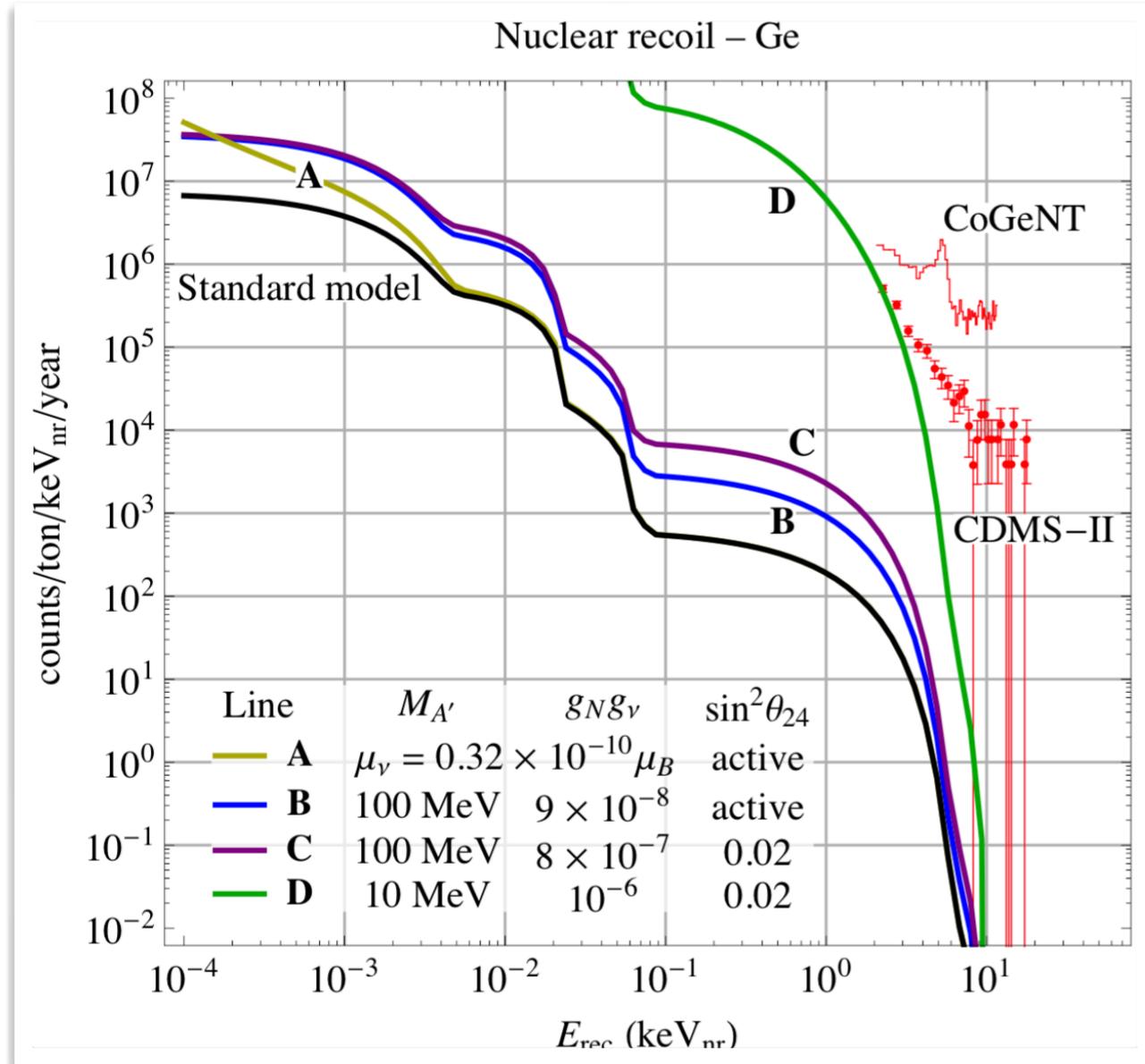
The Neutrino Floor in DM Searches



Harnik JK Machado, arXiv:1202.6073

- DM detectors are neutrino detectors
- Opportunity for dedicated neutrino research program

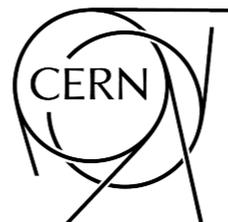
Probing New Physics in the Neutrino Sector



see works by Bertuzzo Billard Boehm Cerdeno Coloma Dent Deppisch Dutta Fairbairn Farzan Harnik Heeck Huber Jubb JK Liao Link Kulkarni Machado Newstead Perez Pospelov Pradler Strigari Vincent Walker Zukanovich-Funchal, ...

Similar opportunities in coherent ν –nucleus scattering

Summary



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



Summary

- ☑ **Four independent** short-baseline anomalies
 - LSND
 - MiniBooNE
 - gallium anomaly
 - reactor anomaly
- ☑ **Inconsistent** with null results
 - scrutinize anomalies as well as null results!
- ☑ **Cosmology**
 - strong constraints on the simplest models
 - can be avoided in more **baroque scenarios**
 - interesting consequences for dark matter physics

Thank you!

