Sterile Neutrinos at the eV Scale
Theory and Phenomenology

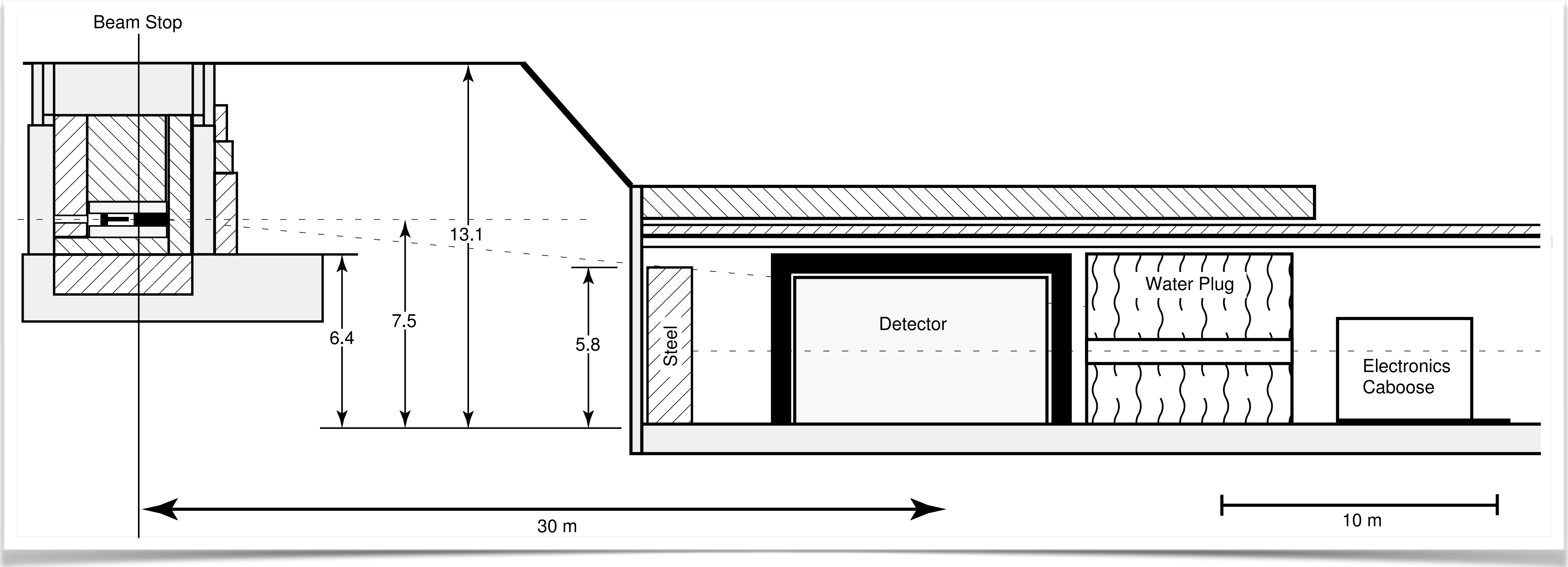
Joachim Kopp
TRISEP Summer School | TRIUMF, Vancouver, Canada | July 2019

In this Talk

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

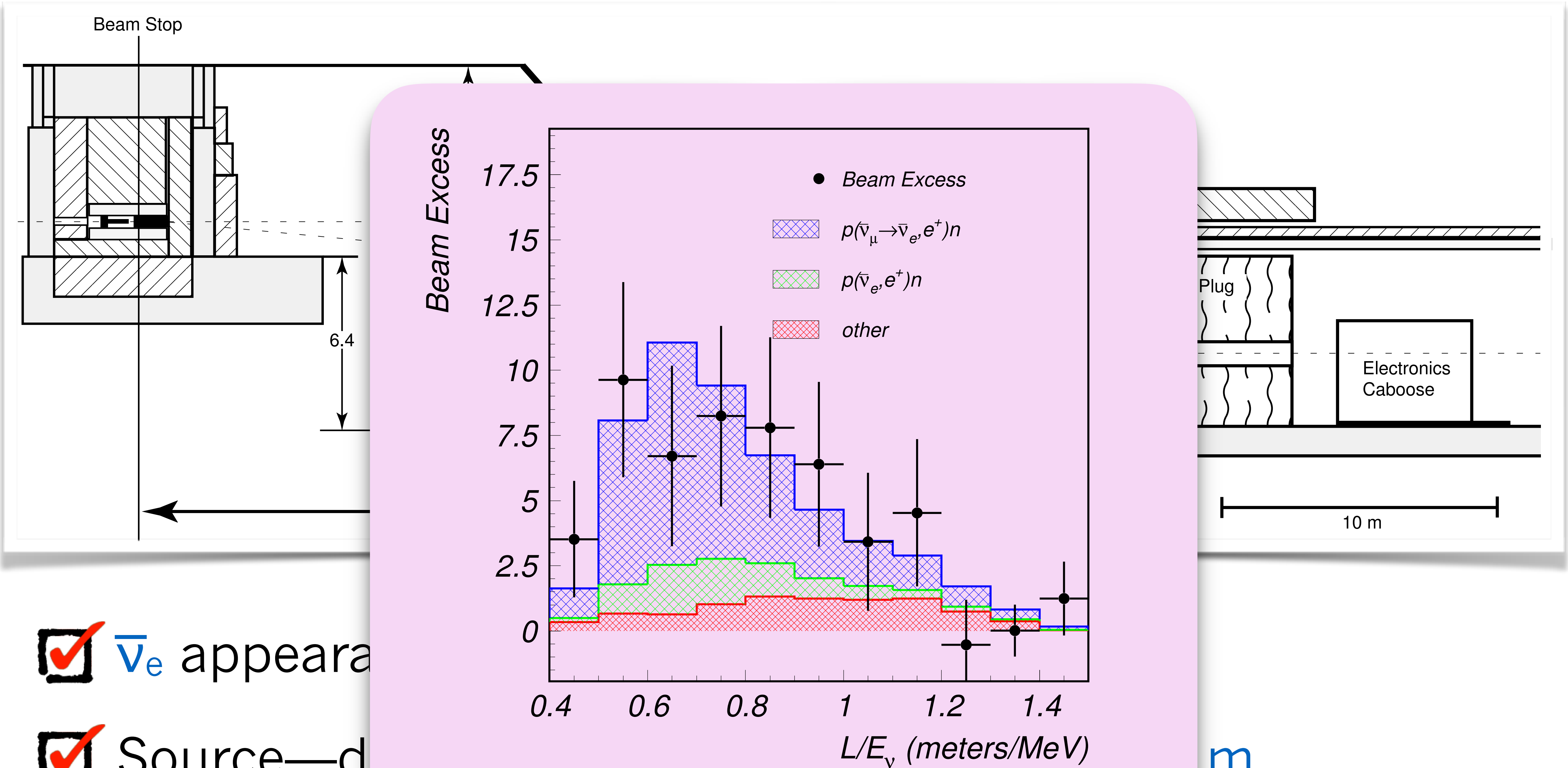
Oscillation Anomalies and Sterile Neutrinos

Anomaly #1: LSND



- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam
- ☑ Source—detector distance ("baseline") ~ 30 m

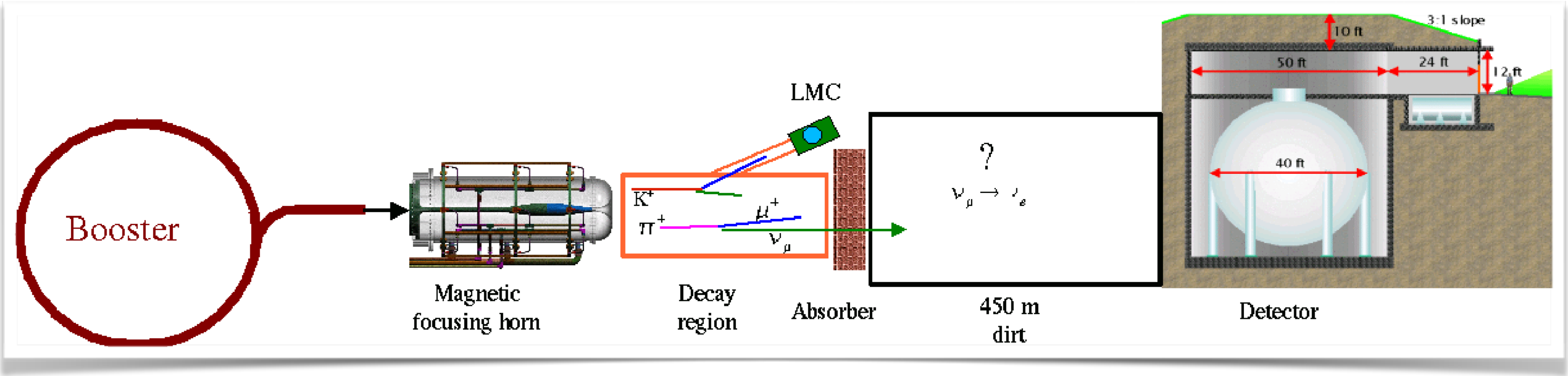
Anomaly #1: LSND



LSND Collaboration, hep-ex/0104049

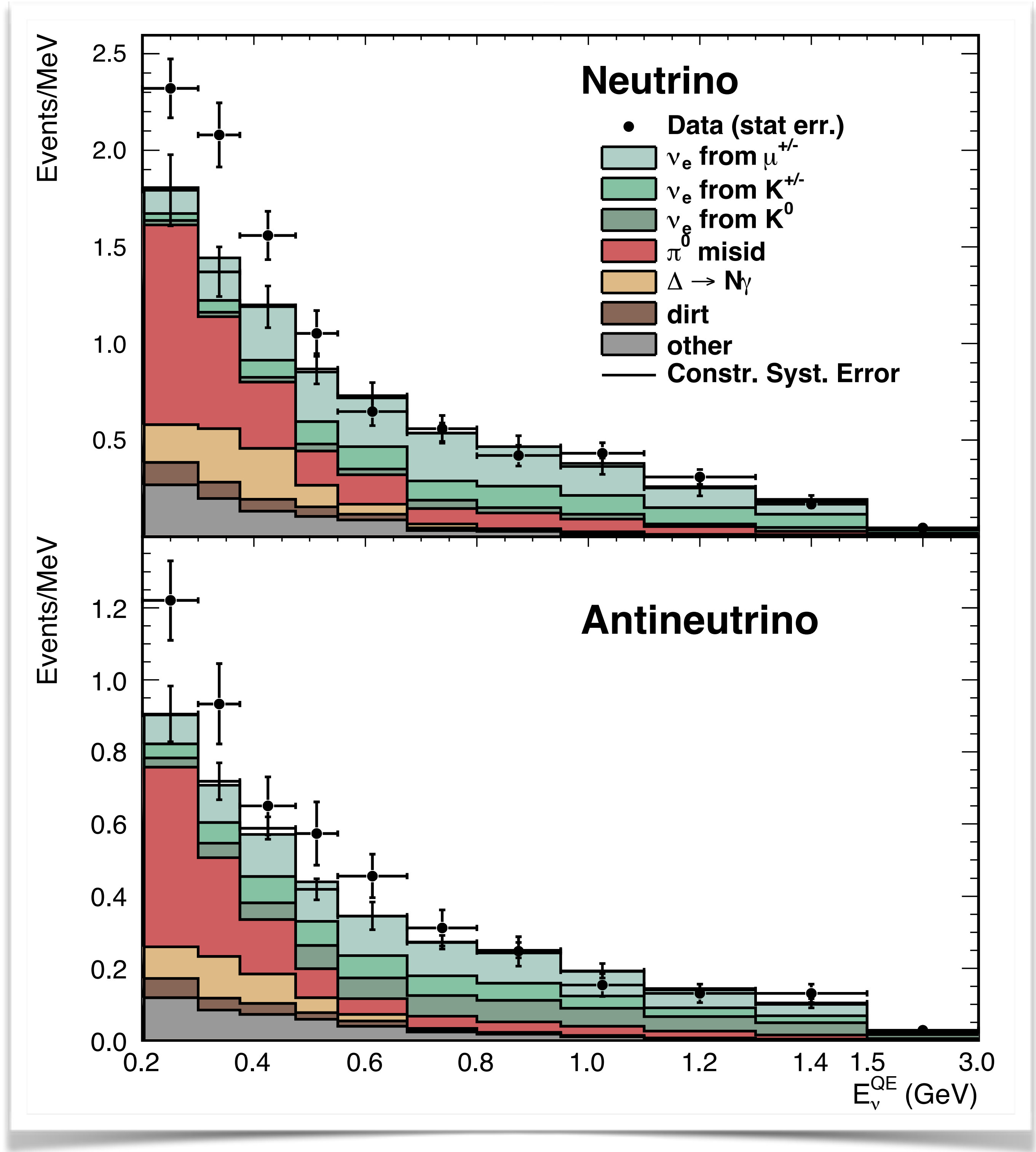
- ☑ $\bar{\nu}_e$ appeara
- ☑ Source—d … m

Anomaly #2: MiniBooNE



Anomaly #2: MiniBooNE

- No significant ν_e op $\bar{\nu}_e$ 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)



Sterile Neutrinos

Definition: sterile neutrino = SM singlet fermion

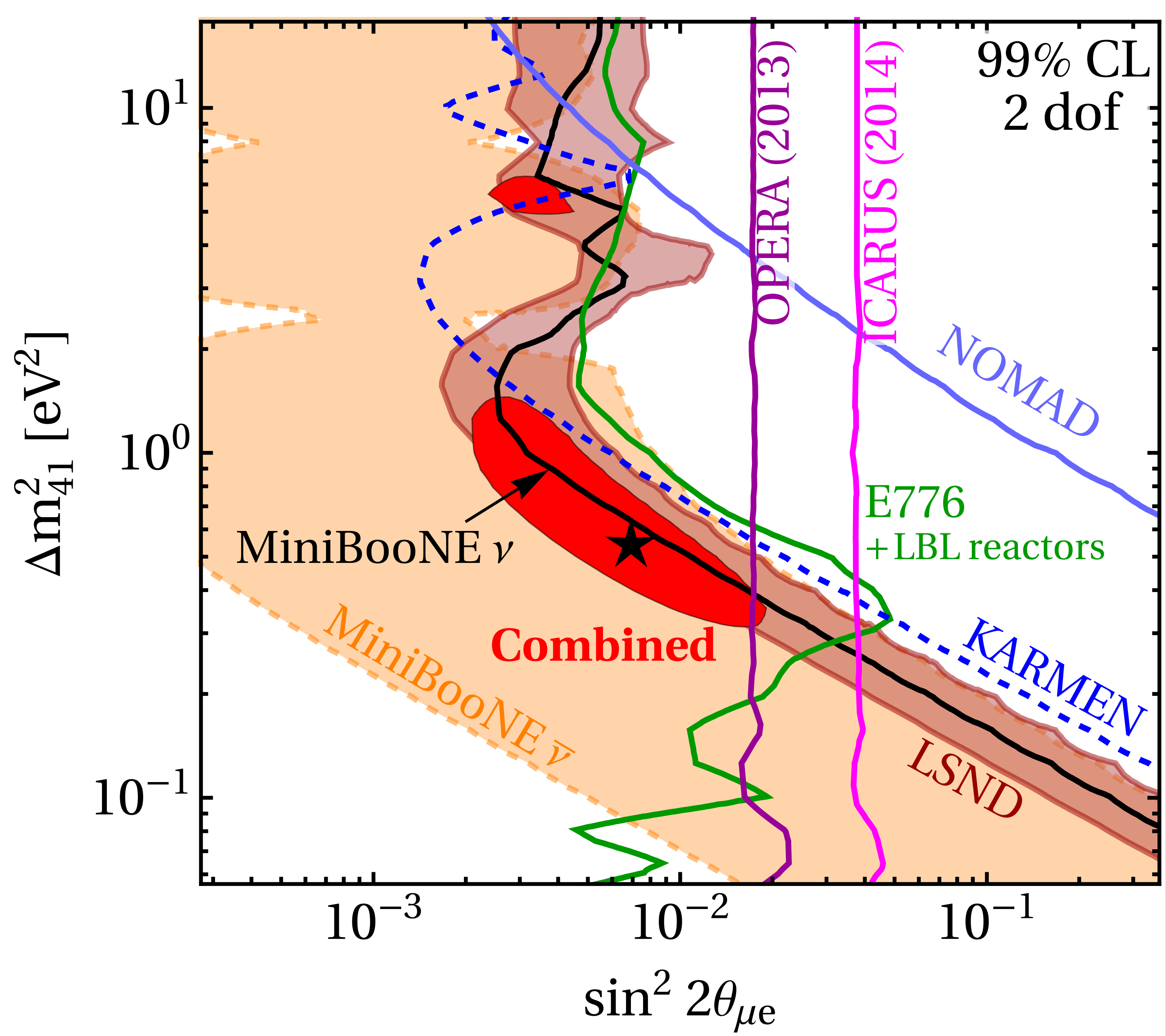
- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet

- ☑ Useful phenomenological tool
  - can explain ν masses (seesaw mechanism, m ~ TeV...M_{Pl})
  - can explain cosmic baryon asymmetry (leptogenesis, m≫100 GeV)
  - can explain dark matter (m ~ keV)
  - can explain oscillation anomalies (m ~ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

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

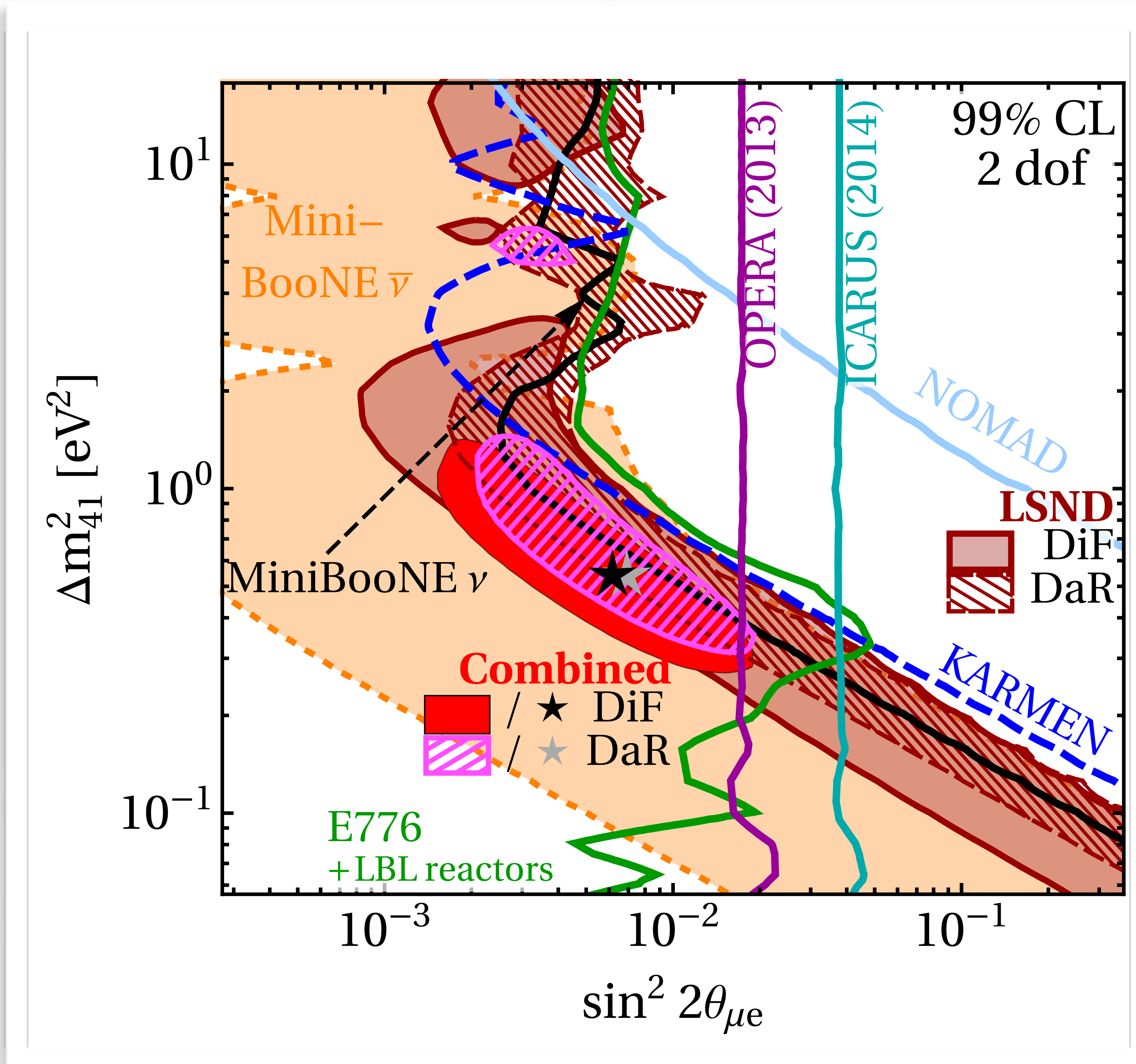
PRISMA CERN erc JG|U

$\nu_\mu \to \nu_e$ appearance



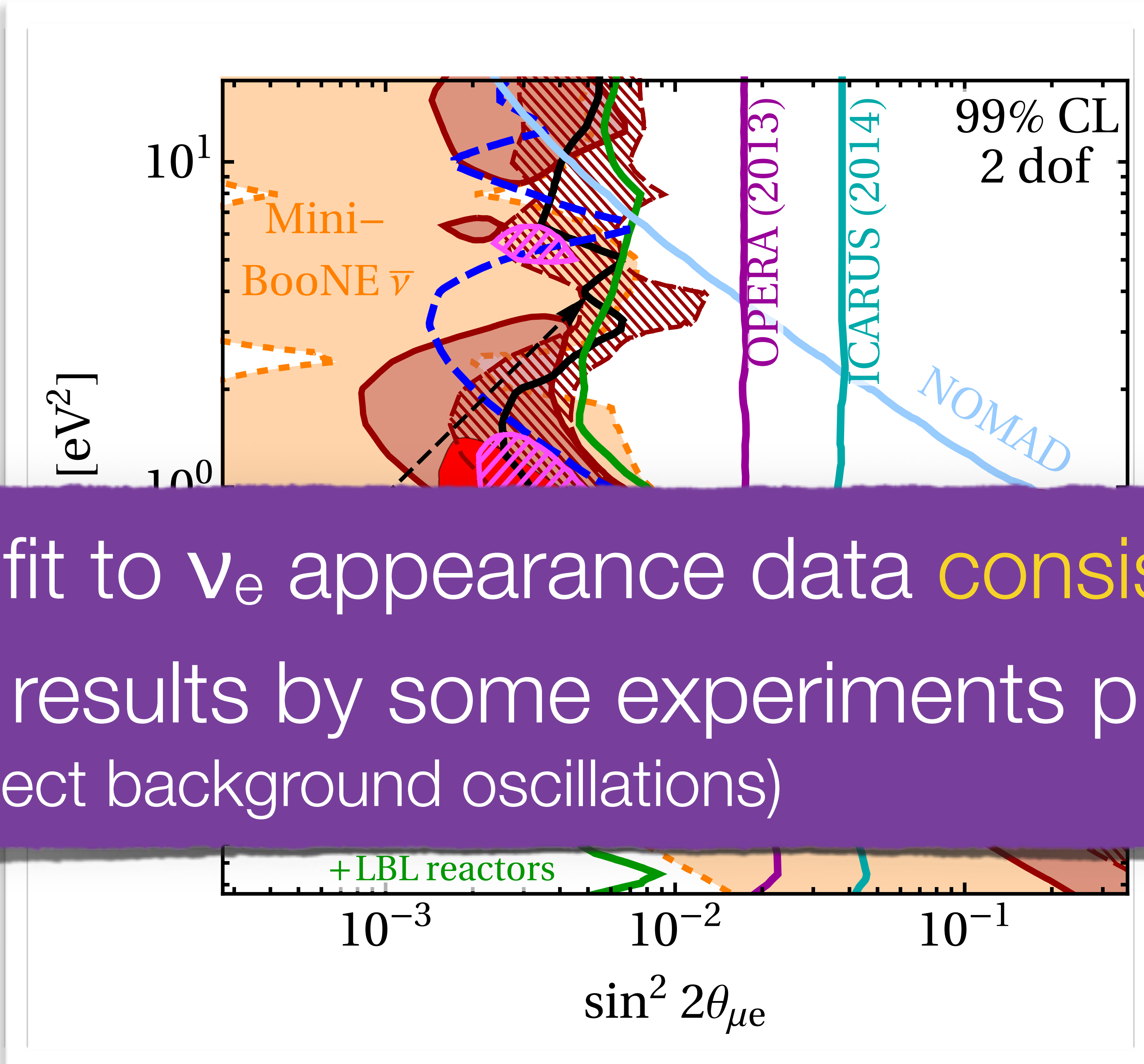
Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

$\nu_\mu \to \nu_e$ appearance



Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

$\nu_\mu \to \nu_e$ appearance



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

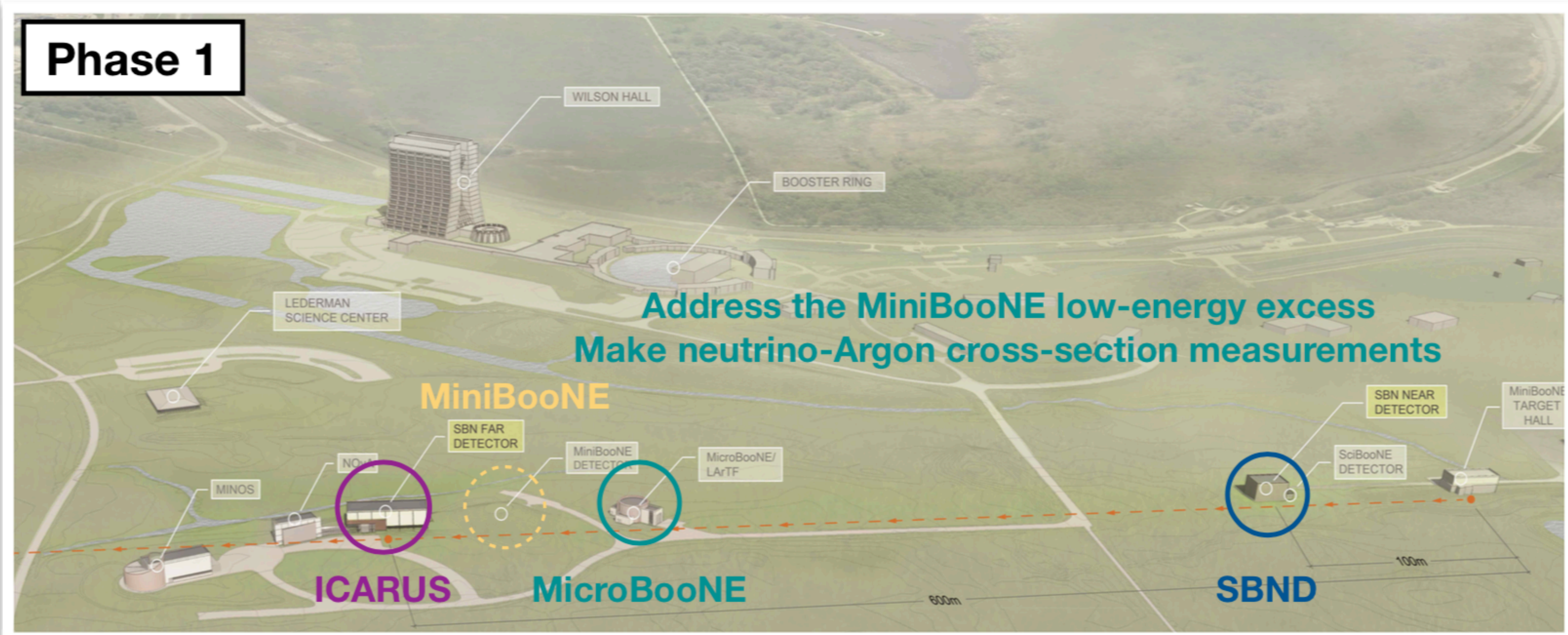
Dentler JK Machado Maltoni Martinez Schwetz, *in preparation*

PRiSMA CERN erc

JG|U

Testing the MiniBooNE Anomaly

Roxanne Guenette, Neutrino 2018



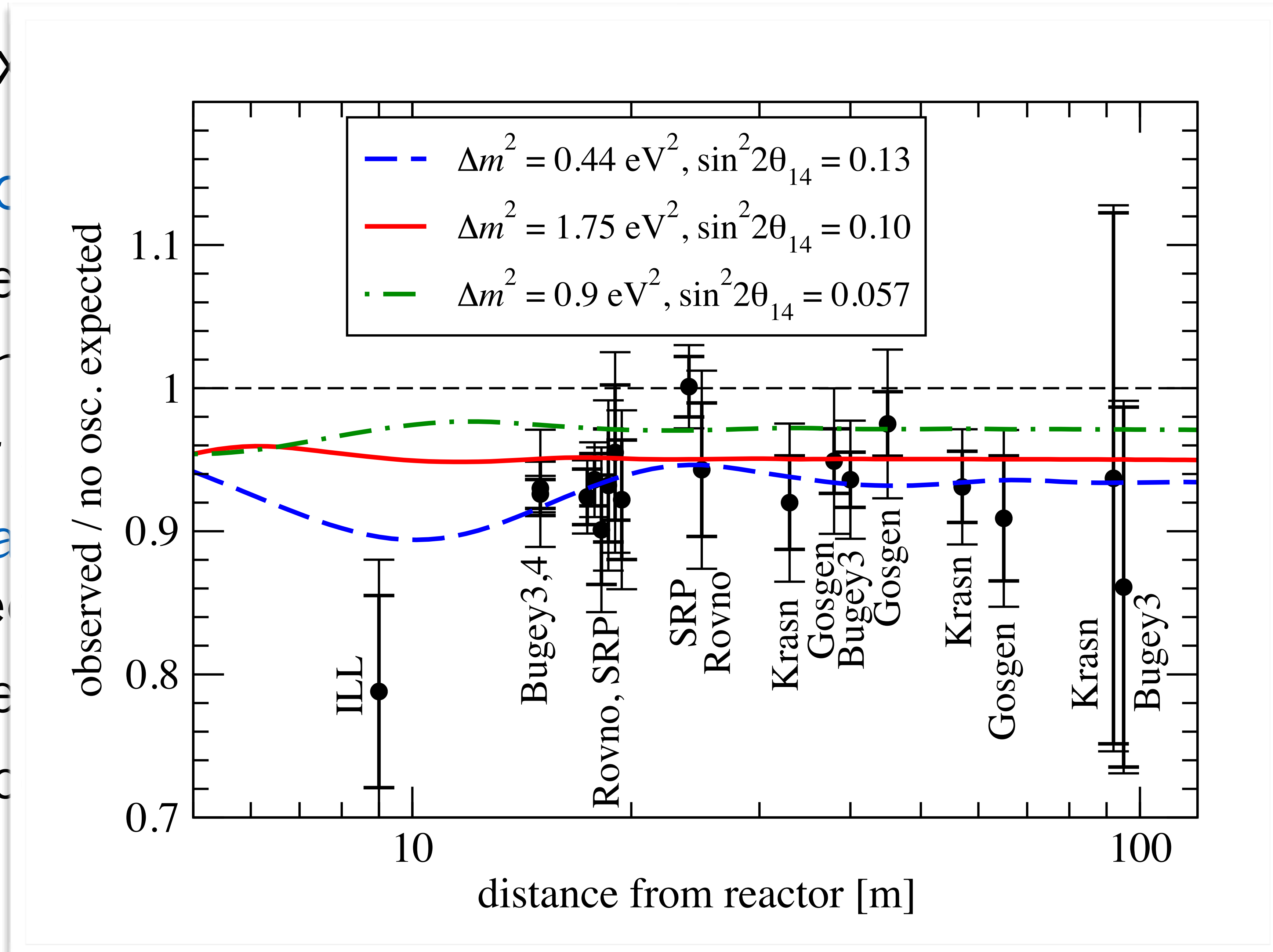
Anomaly #3: The Reactor Anomaly

- ☑ $\bar{\nu}_e$ flux from nuclear reactors is ~ 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

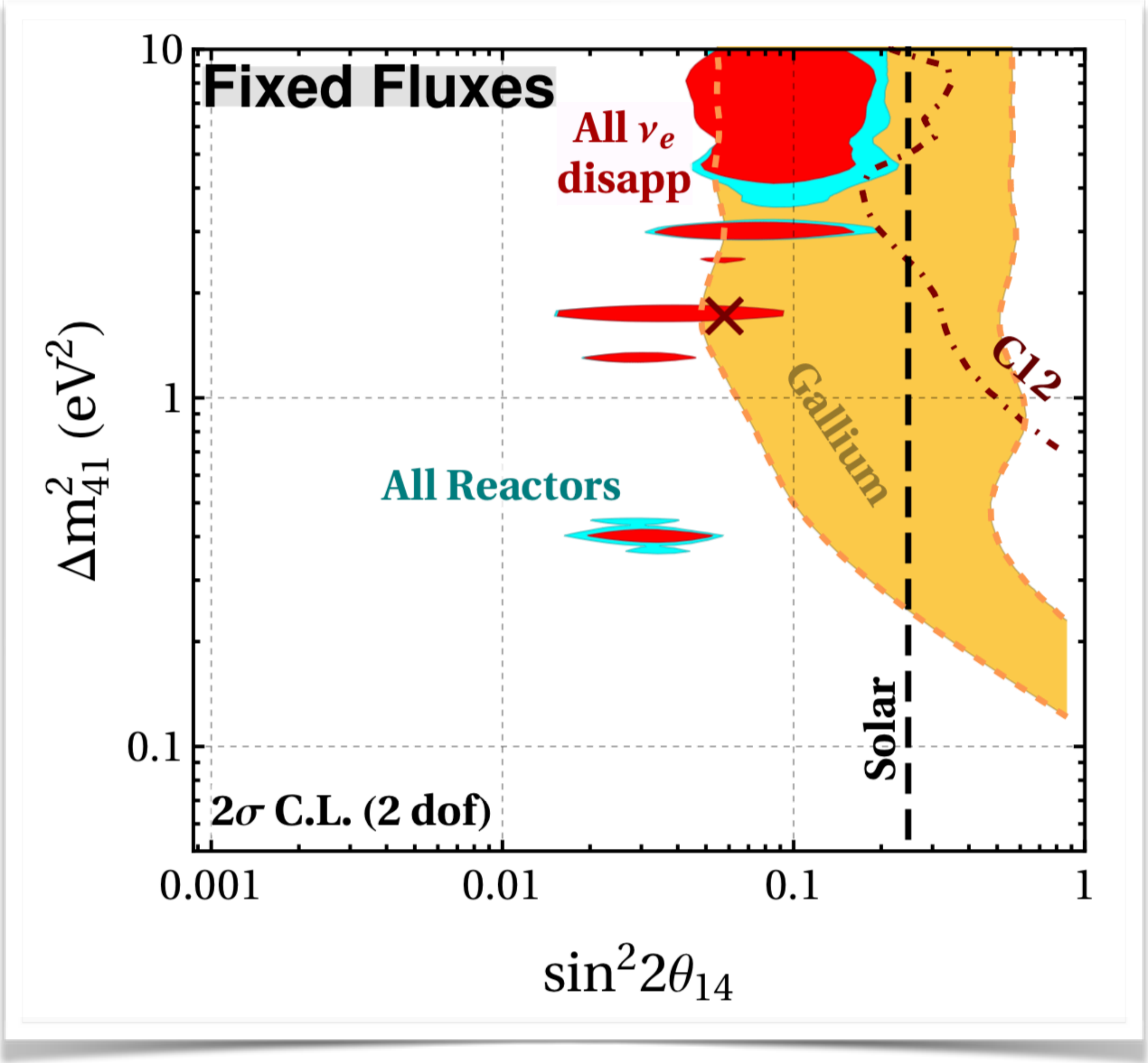
Anomaly #3: The Reactor Anomaly

- ☑ $\bar{\nu}_e$ flux … diction
- ☑ Metho…
  - Use … fission
  - Cor…
  - For…
  - Rea… …wn pre…
  - Use…
  - … c… …s”



Mueller *et al.* 1101.2663, Huber 1106.0687

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



Dentler Hernández JK Maltoni Schwetz 1709.04294

Flux Measurement by Daya Bay

Flux Measurement by Daya Bay

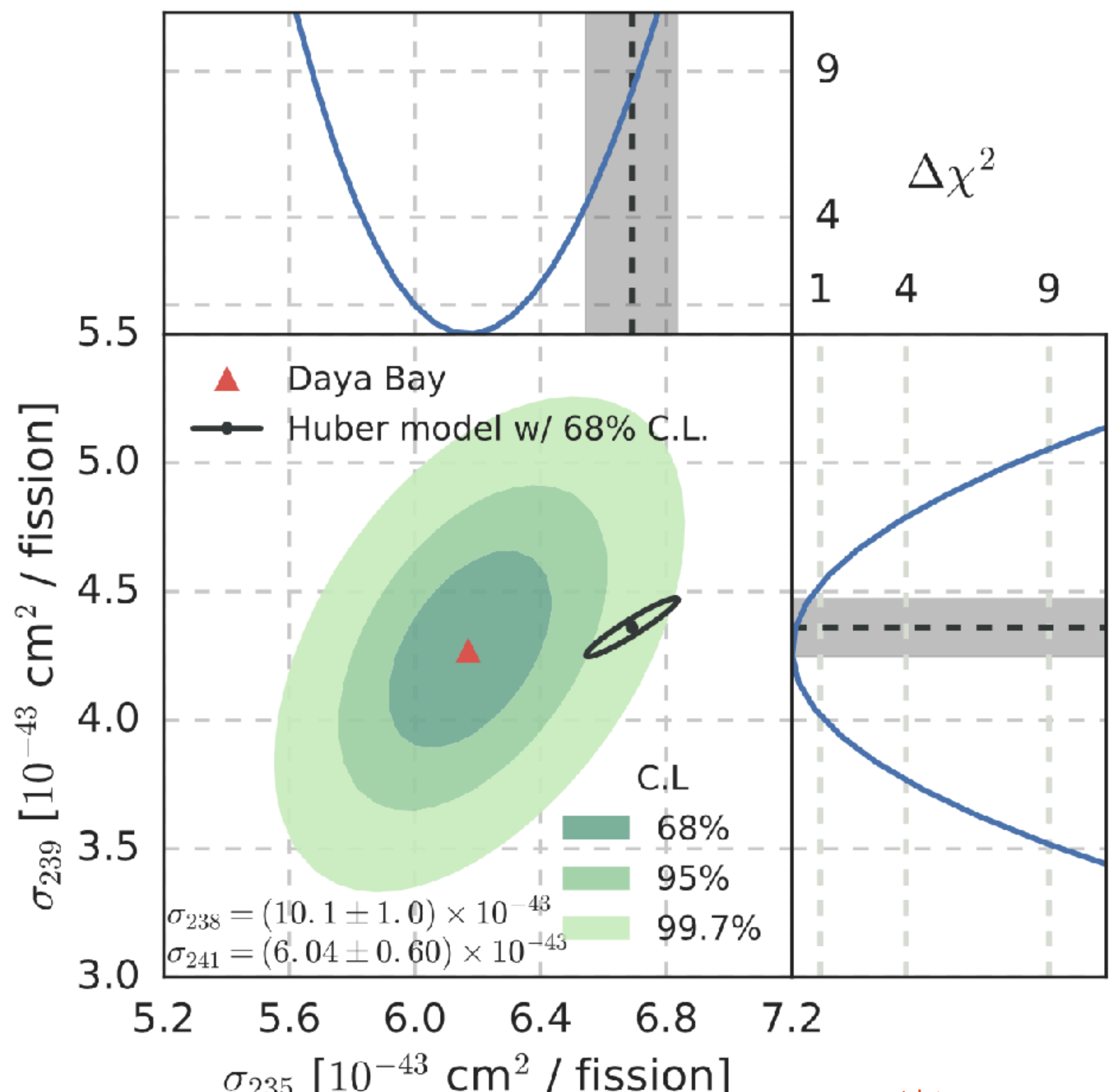
- ☑ Reactor fuel composition evolves with time ("burnup")

Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure inverse β decay rate *per isotope*

Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate *per isotope*

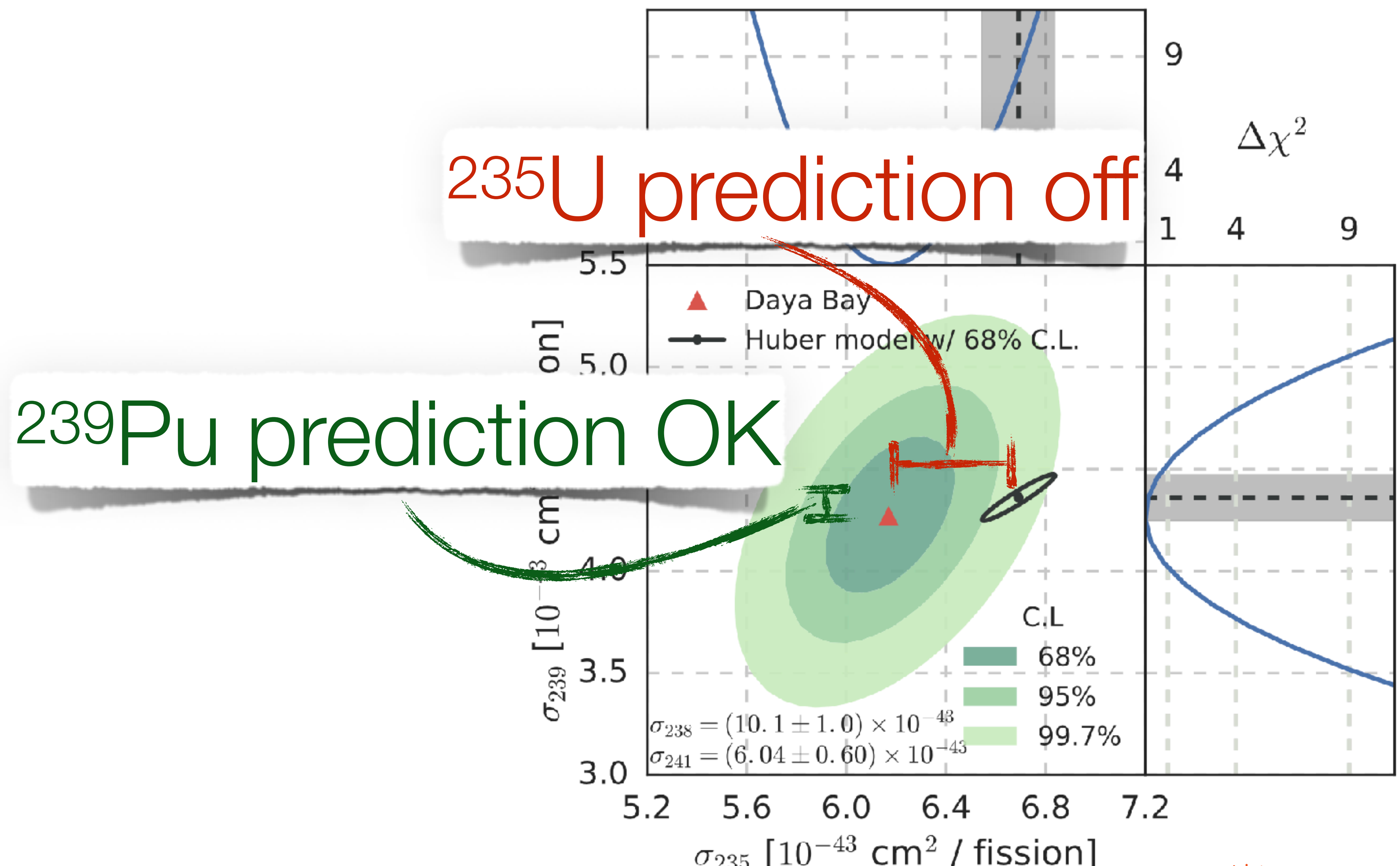


PRISMA CERN erc

JG|U

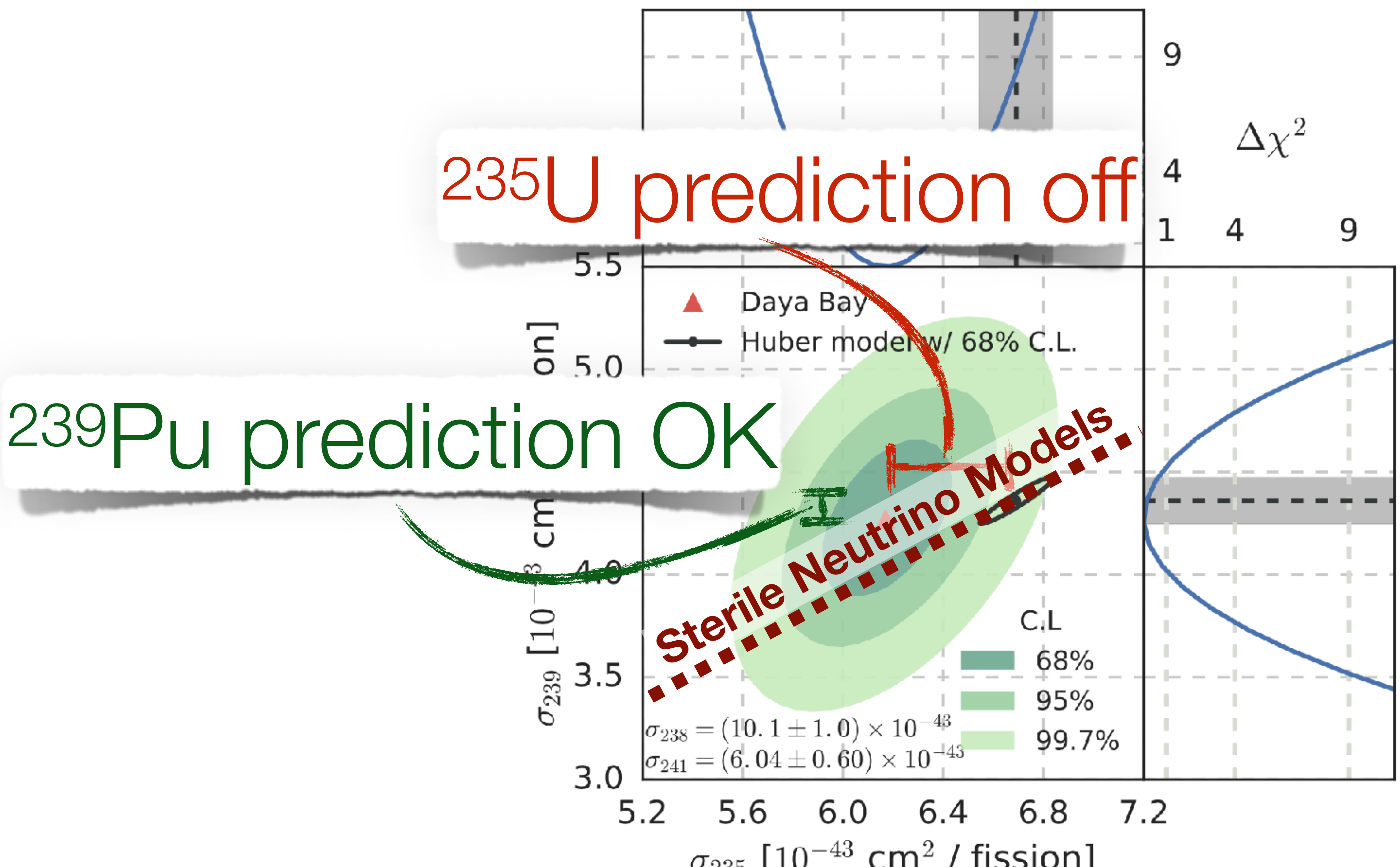
Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate *per isotope*



Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate *per isotope*



Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure inverse β decay rate *per isotope*
- ☑ Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + $\sin^2 2\theta_{14}$

$\Delta\chi^2 = 7.9$

PRISMA CERN erc

JG|U

Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure inverse β decay rate *per isotope*
- ☑ Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + $\sin^2 2\theta_{14}$

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

Denter Hernández
JK Maltoni Schwetz
arXiv:1709.today

Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate *per isotope*
- ☑ Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + $\sin^2 2\theta_{14}$

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

Denter Hernández
JK Maltoni Schwetz
arXiv:1709.today

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

Flux Measurement by Daya Bay

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate *per isotope*
- ☑ Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + $\sin^2 2\theta_{14}$

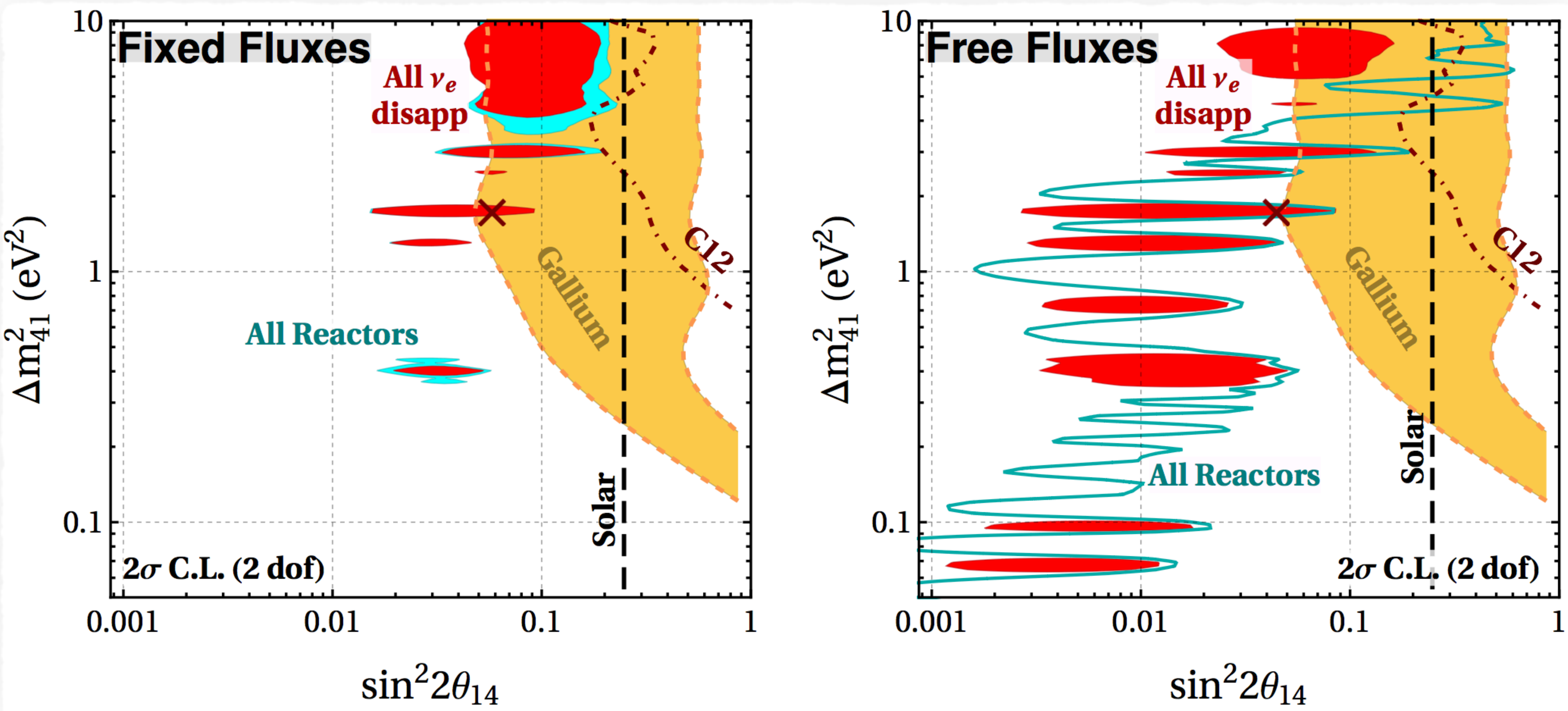
Denter Hernández
JK Maltoni Schwetz
arXiv:1709.today

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

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

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

Flux Measurement by Daya Bay



Fluxes within errors + $\sin^2 2\theta_{14}, \Delta m^2_{41}$: $p = 0.18$

Fluxes free : $p = 0.73$

$\Delta\chi^2$(sterile neutrino vs. free fluxes) : $p = 0.007$

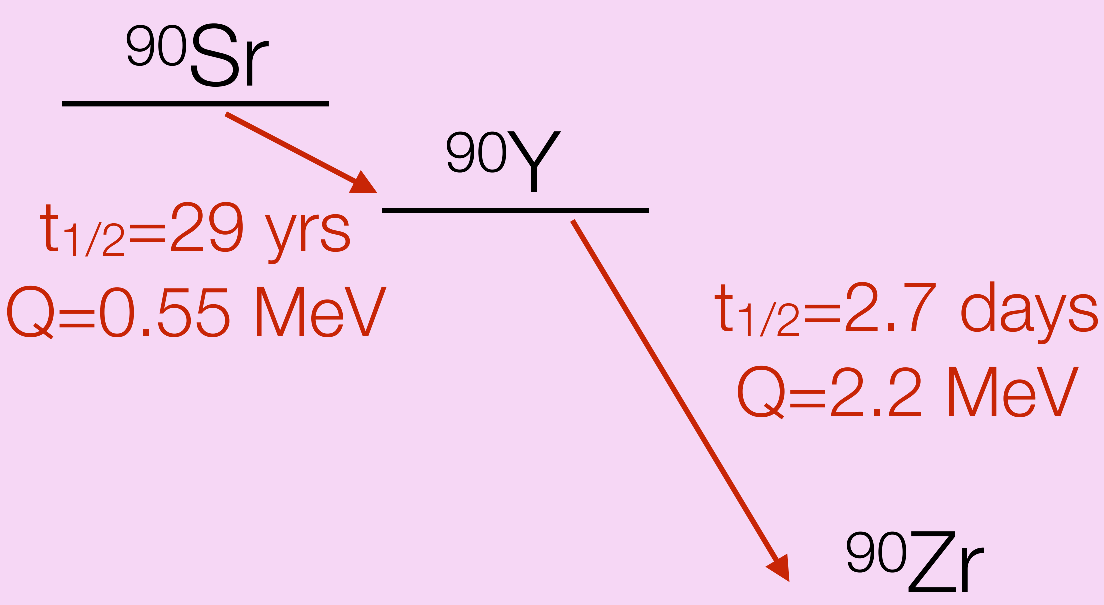
Caveats

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

Caveats

Non-Equilibrium

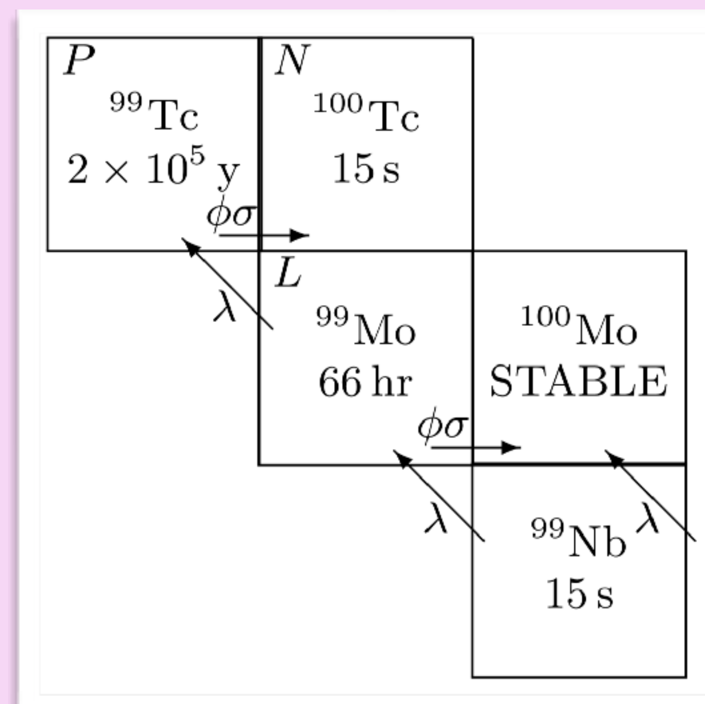
- ☑ Some relevant decays are out of equilibrium



- ☑ Extra *t*-dependence in ν flux

Non-Linear Isotopes

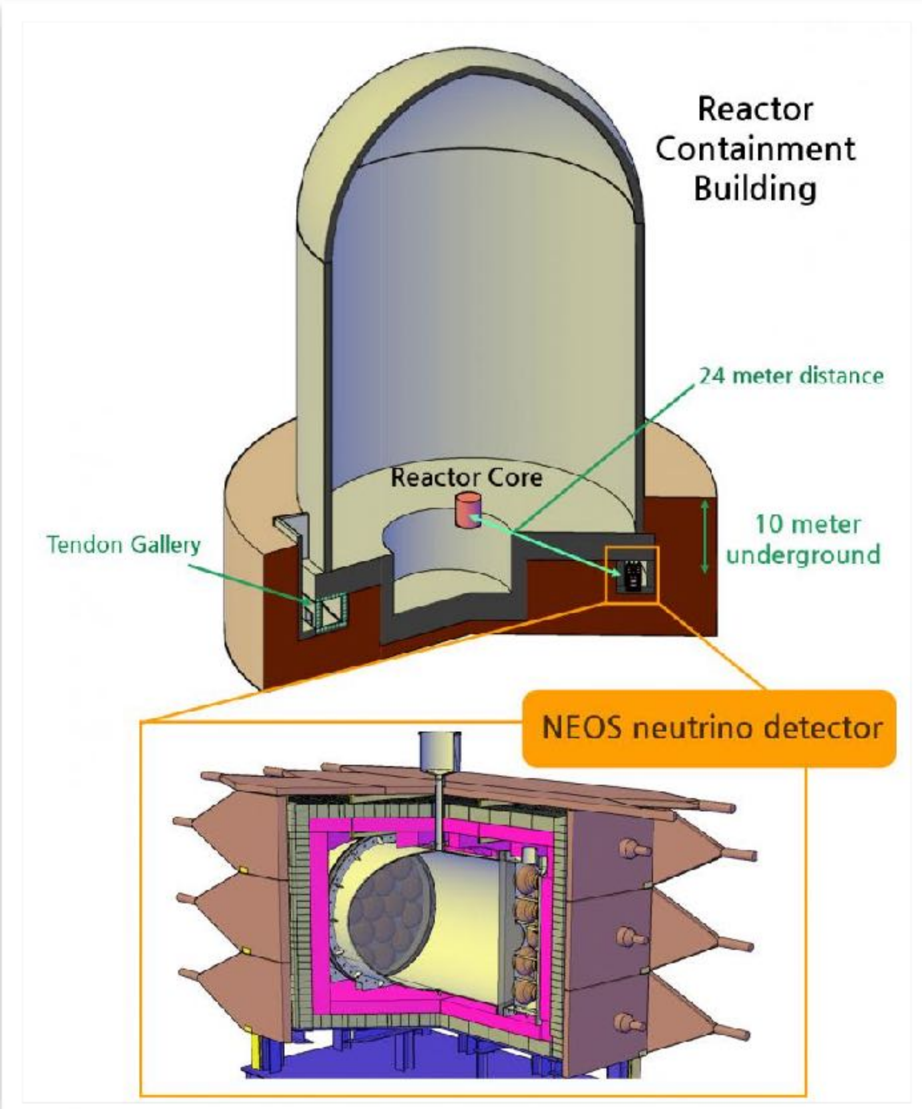
- ☑ Neutron capture on fission products

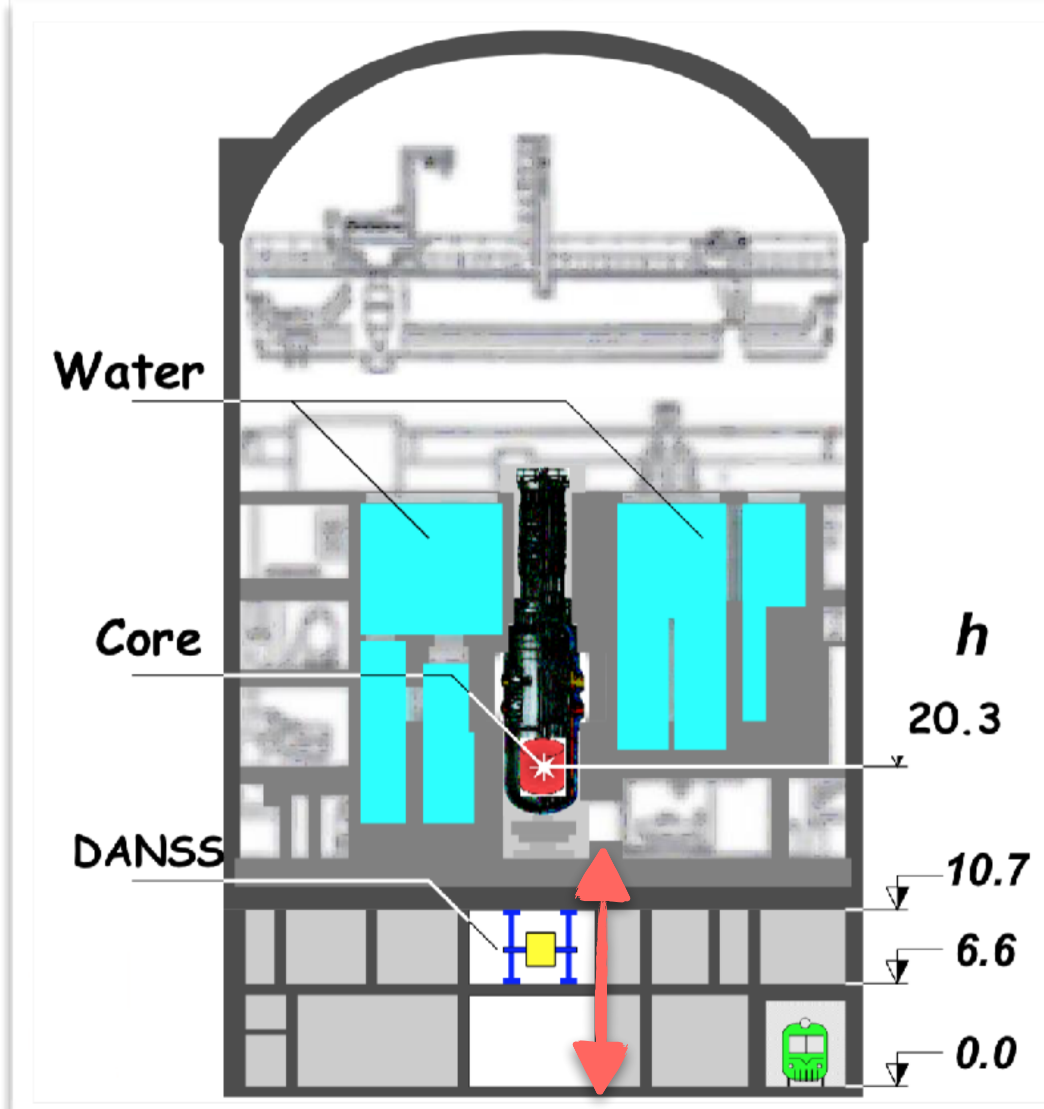


- ☑ Extra neutron flux/ burnup dependence in ν

Jaffke Huber 1510.08948, Huber Sharma, *in preparation*

Anomaly #3': NEOS and DANSS





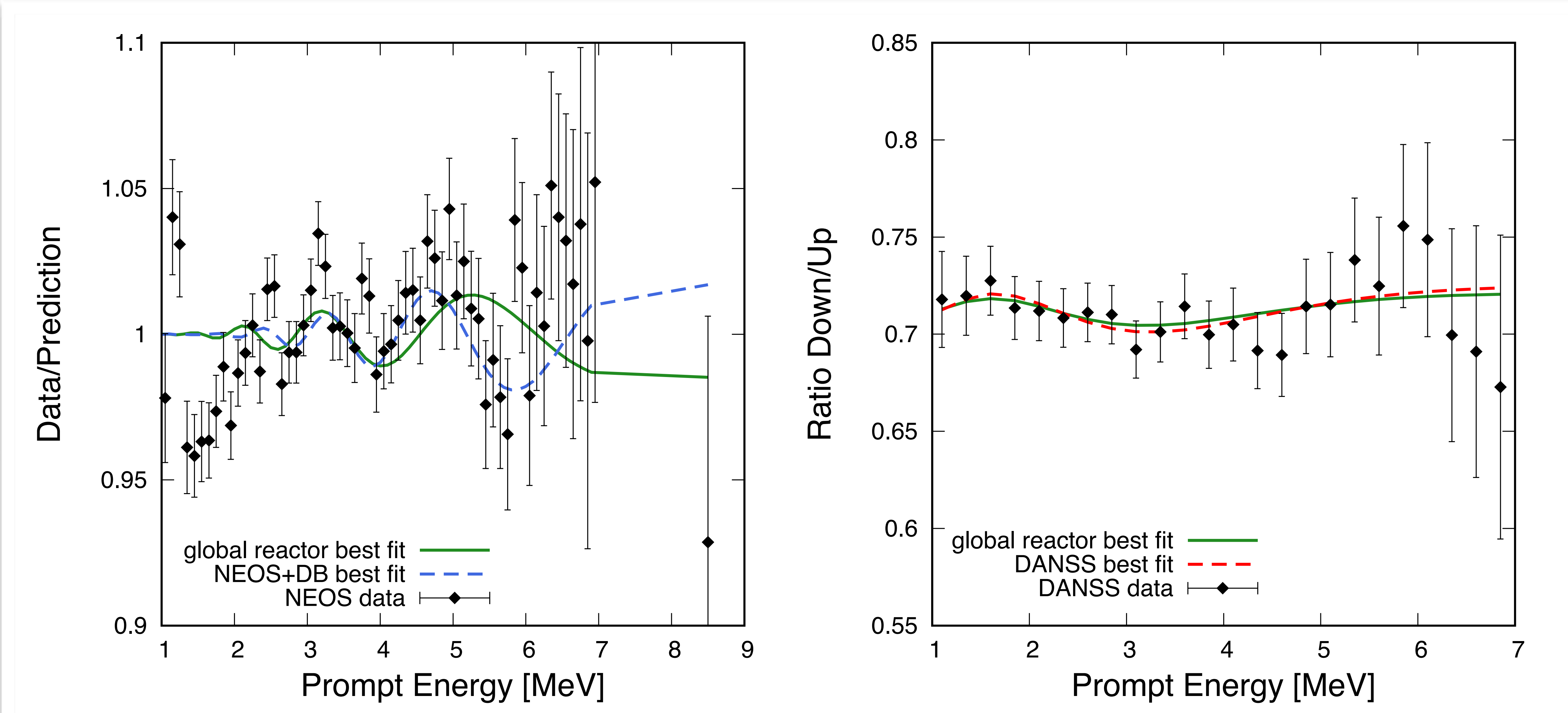
NEOS

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

PRiSMA CERN erc

 JG|U

Testing the Reactor Anomaly

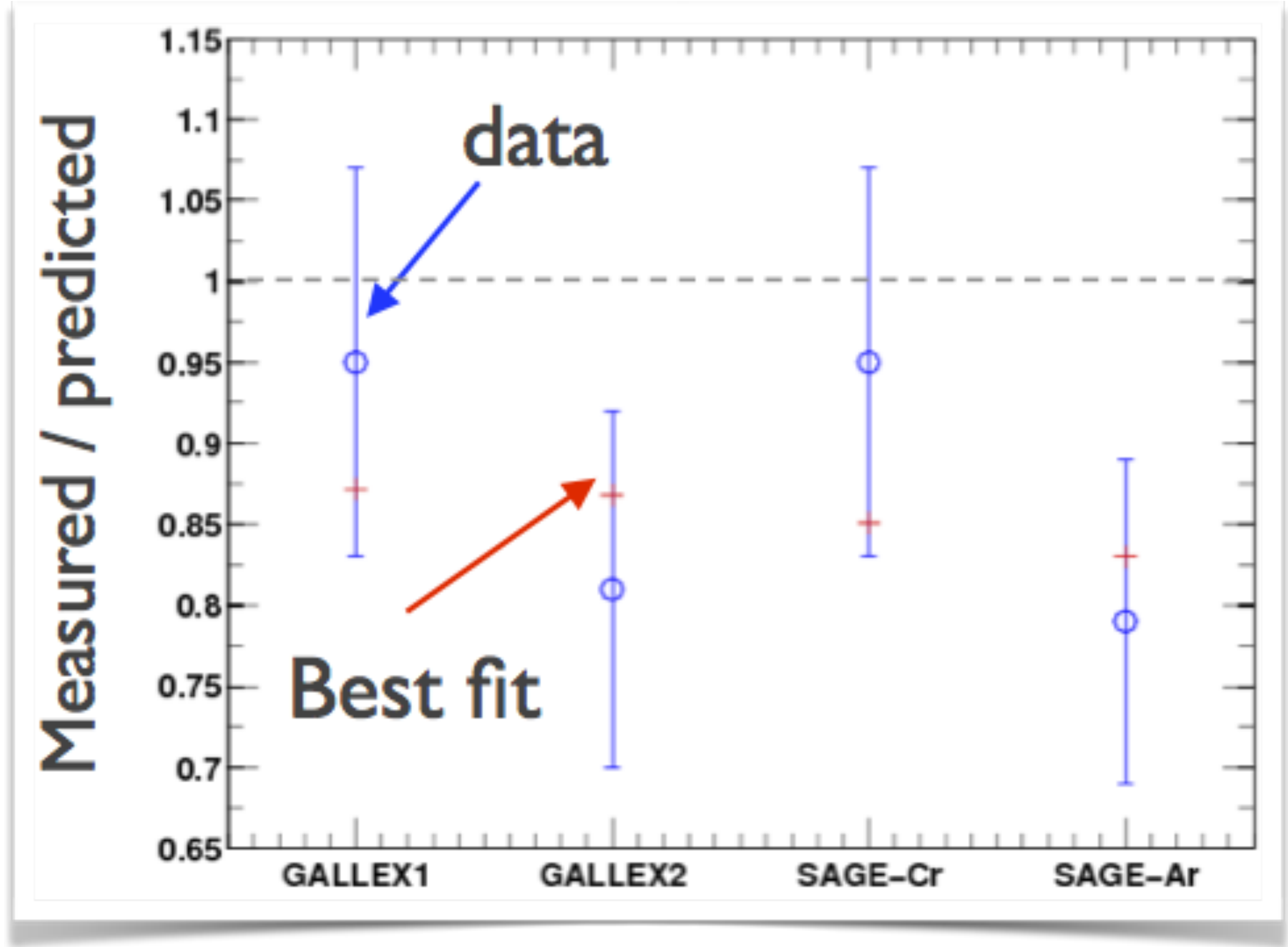
- ☑ Do we understand reactor neutrino fluxes?
- ☑ New short-baseline experiments
  - looking for spectral wiggles (smoking-gun oscillation signature)
- ☑ Analyze isotope-dependence of the anomaly
  - $\nu_e \to \nu_s$ oscillation are isotope-independent
  - Problems with flux prediction are typically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

Anomaly #4: The Gallium Anomaly

- Experiments with intense radioactive source
- Neutrino detection via

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- 3σ deficit
- ν_e disappearance into sterile state?



Giunti Laveder 1006.3244

Relation Between Oscillation Channels

- Oscillation channels are related:

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

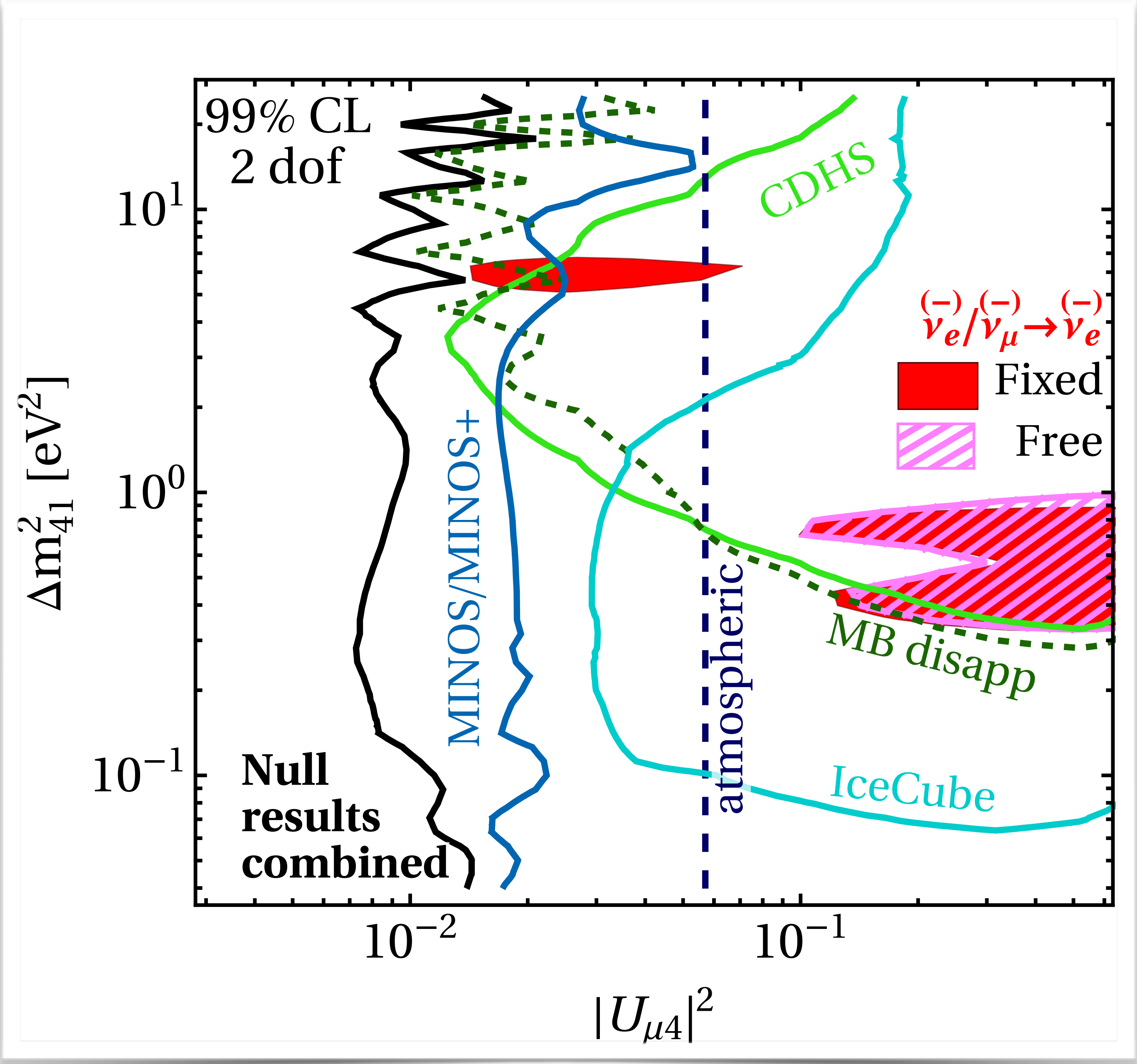
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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

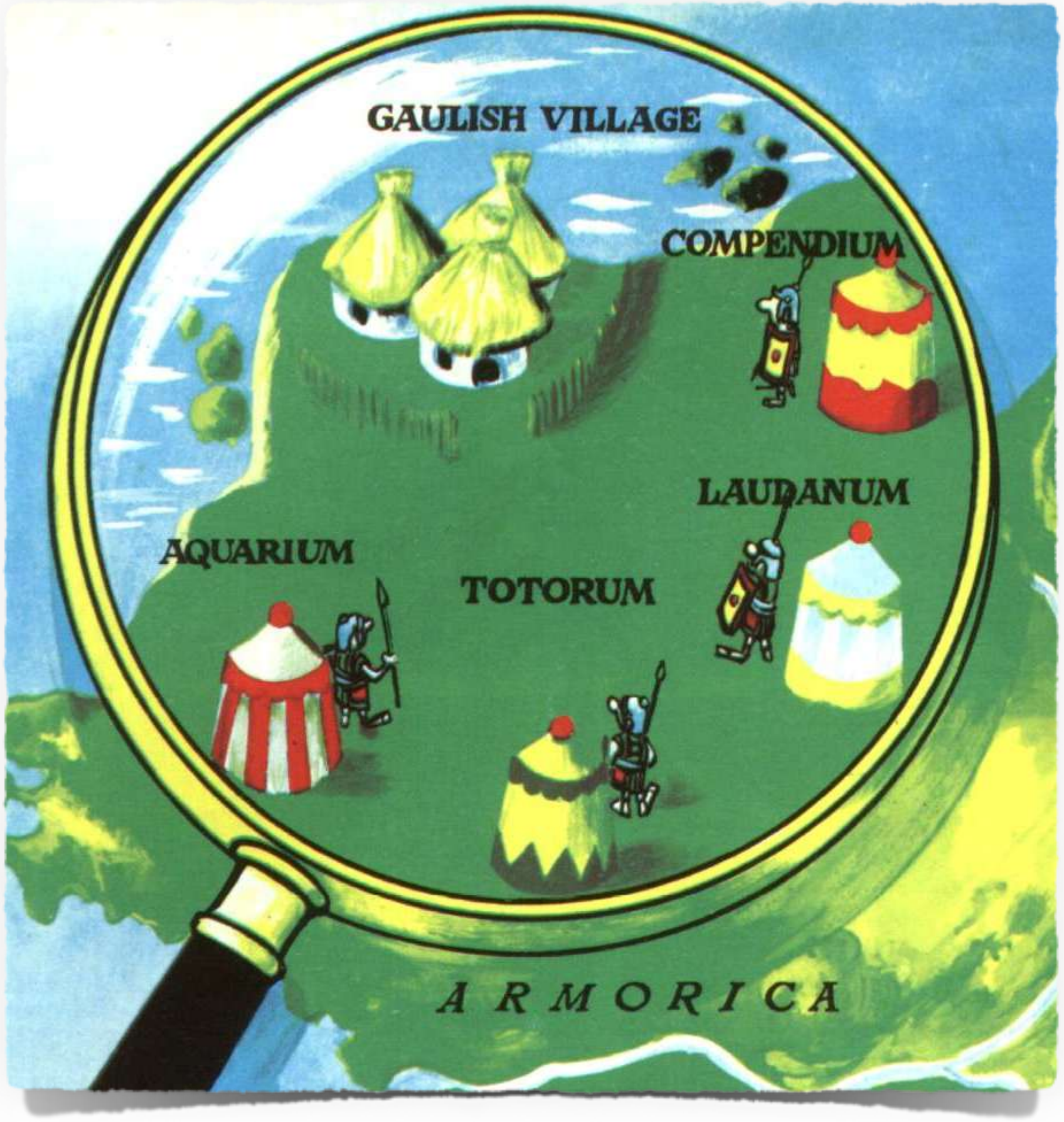
- Models can be over-constrained.

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



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

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

Sterile Neutrinos in Cosmology

Sterile Neutrinos in Cosmology

Standard picture: ν_s production via oscillation at $T \gtrsim$ 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:

$\Sigma m_\nu \lesssim 0.12$ eV ⚡

$N_{eff} \lesssim 3.16$ ⚡

PRiSMA CERN erc

Testing Neutrinos in Cosmology

N_{eff}

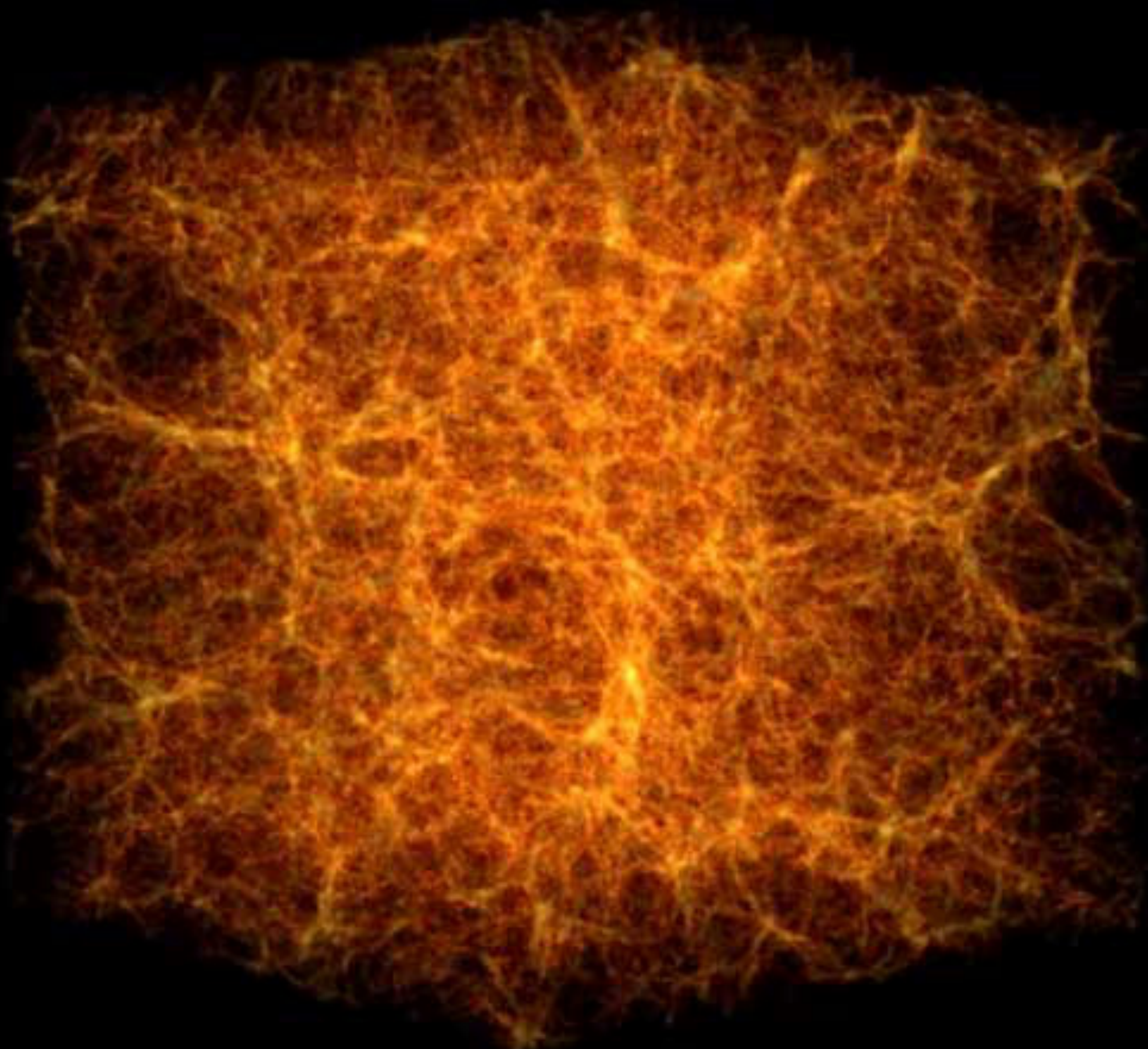
- "Effective number of neutrino species"
- Really just a measure of the energy density of relativistic particles
- affects expansion rate of the Universe

Σm_ν

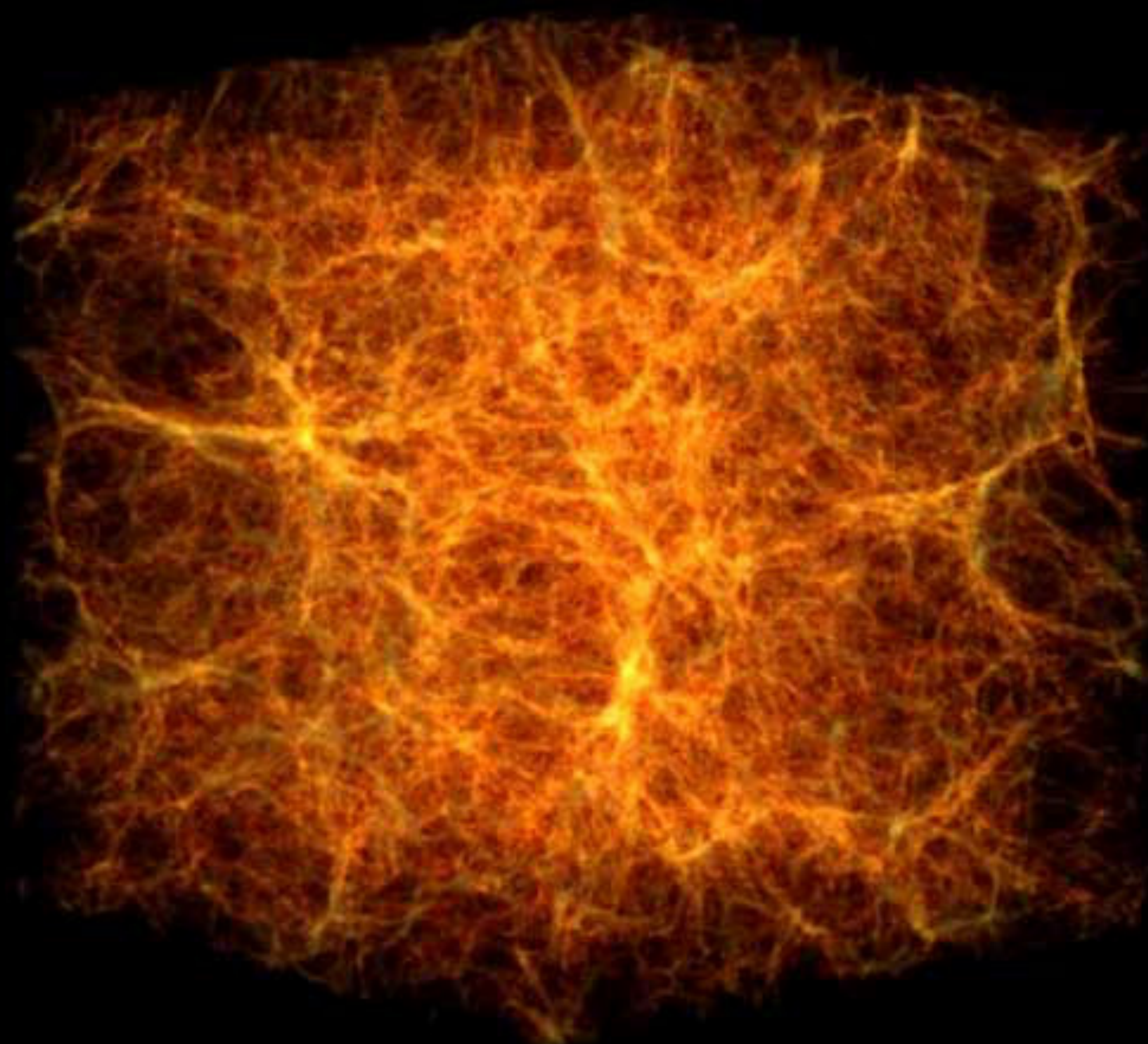
- "sum of neutrino masses"
- affects structure formation:
  - neutrinos do not form small structures
  - shallower gravitational wells for DM and baryons to fall into


z = 48.4
T = 0.05 Gyr
500 kpc


z = 48.4
T = 0.05 Gyr
500 kpc

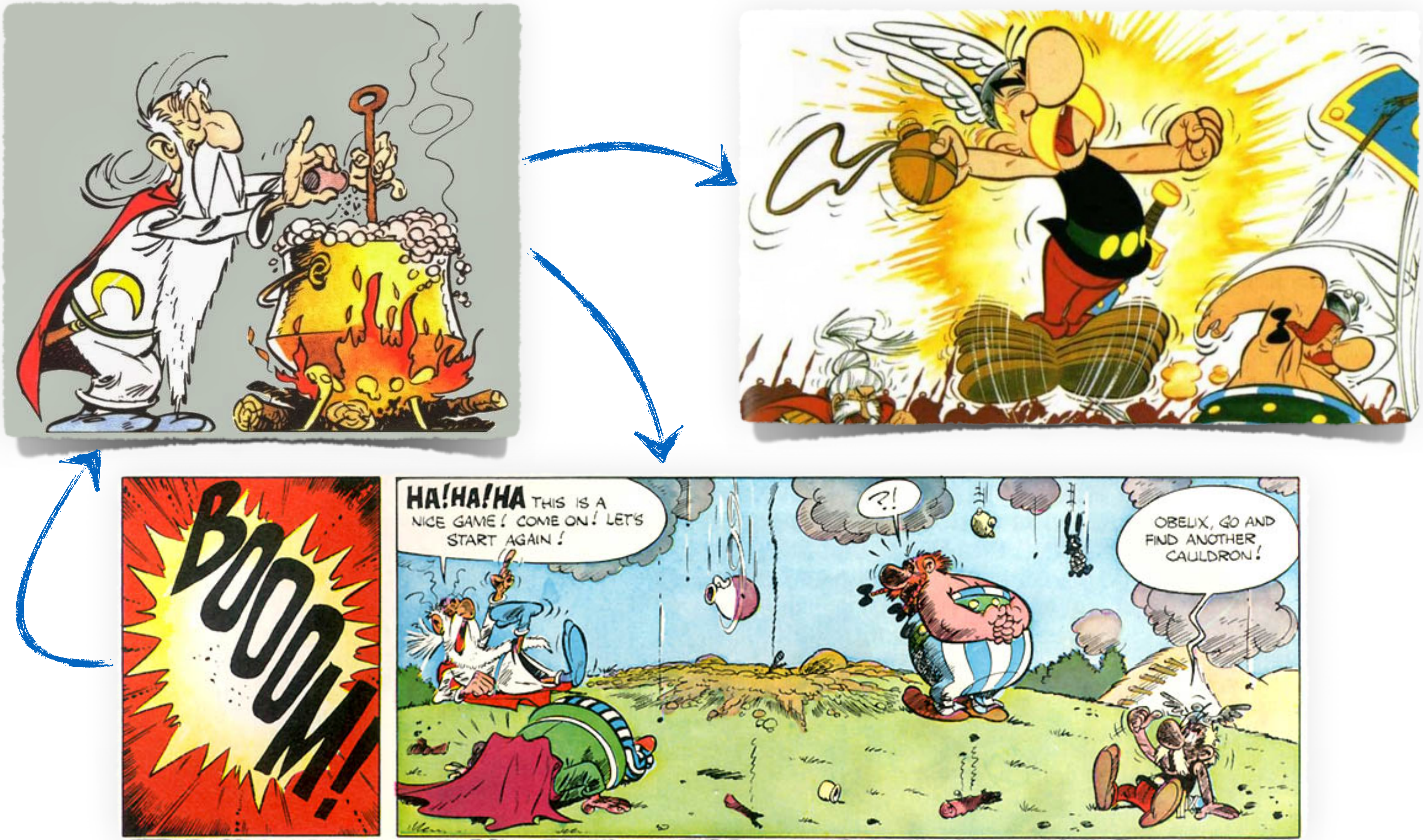


small neutrino mass



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 $\Sigma\, m_\nu$ 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
  - avoids N_{eff} constraint, weakens or avoids $\Sigma\, m_\nu$ constraint

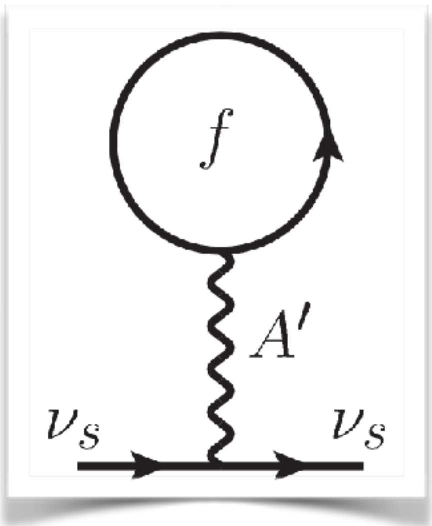
- ☑ ν_s properties change in late phase transition
  Bezrukov Chudaykin Gorbunov, 1705.02184
  Chu et al., 1806.10629

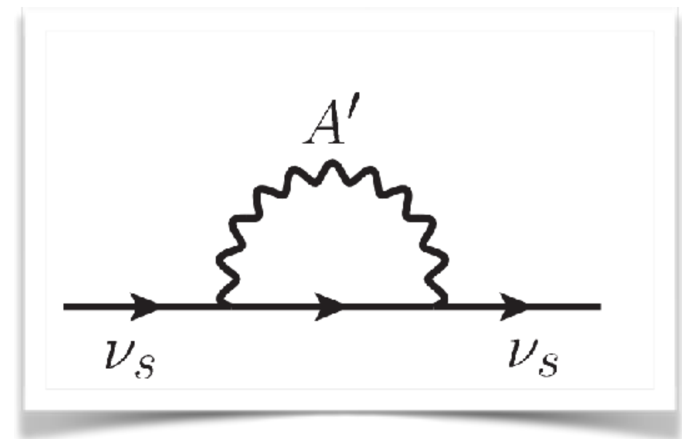
- ☑ Coupling to slow-rolling scalar field
  Fardon Nelson Weiner, astro-ph/0309800
  Bezrukov Chudaykin Gorbunov, 1705.02184

- ☑ …

New Interaction in the Sterile Sector

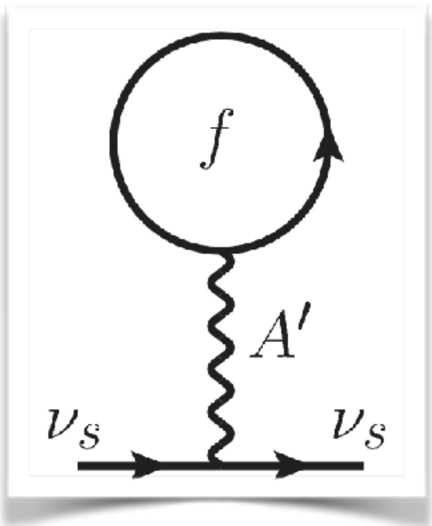
- ☑ Assume ν_s charged under a new *U(1)'* gauge group
- ☑ Neutrino self-energy contributes to effective potential V^{eff}

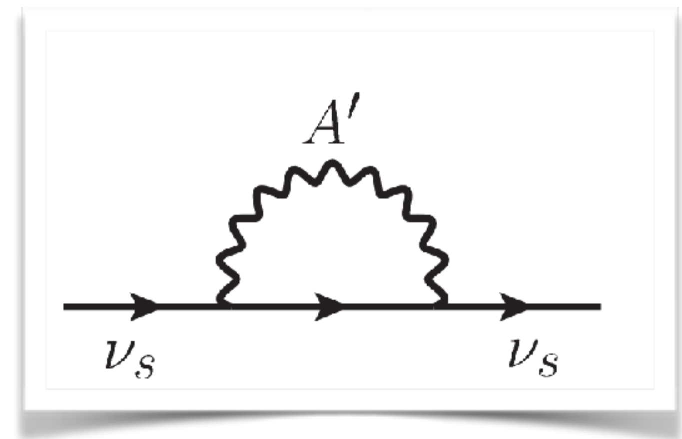




New Interaction in the Sterile Sector

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





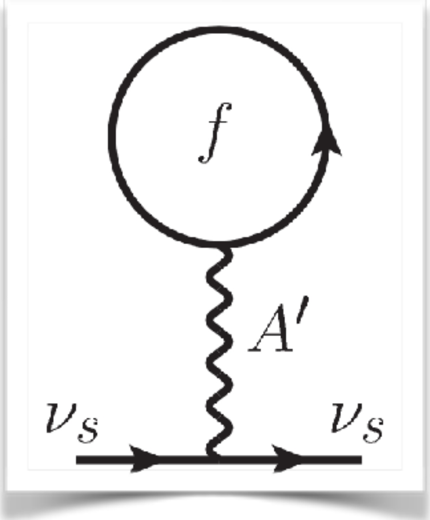
- Thermal propagators

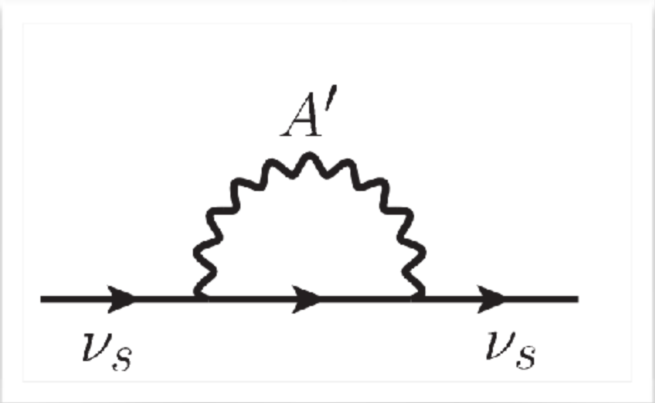
$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

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}





- Thermal propagators

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

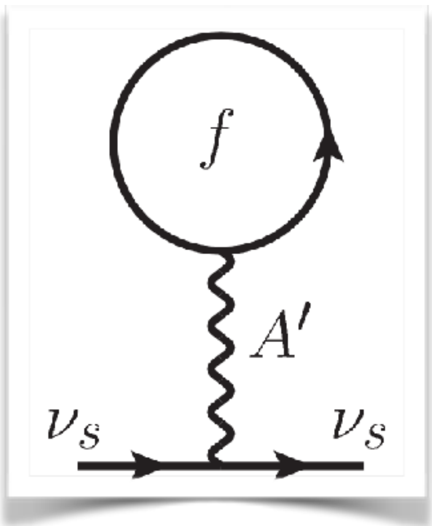
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

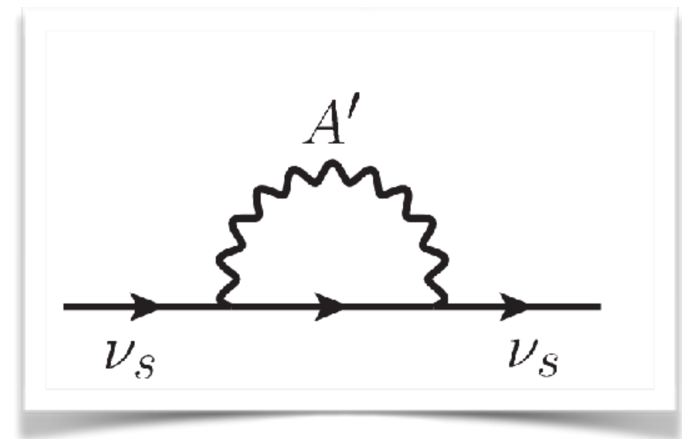
$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)n_{f,b}(p)$$

PRiSMA CERN erc JG|U

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}





- Thermal propagators

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

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

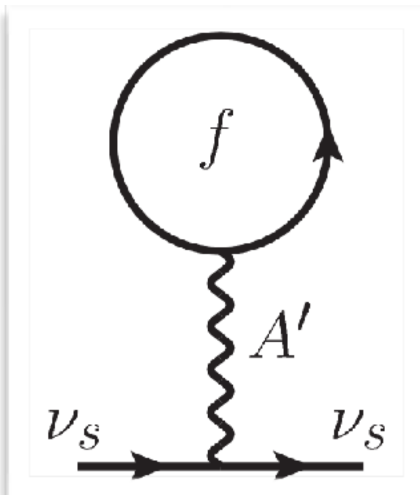
$$n_{f,b}(p) = [e^{|p\cdot u|/T_s} \pm 1]^{-1}$$

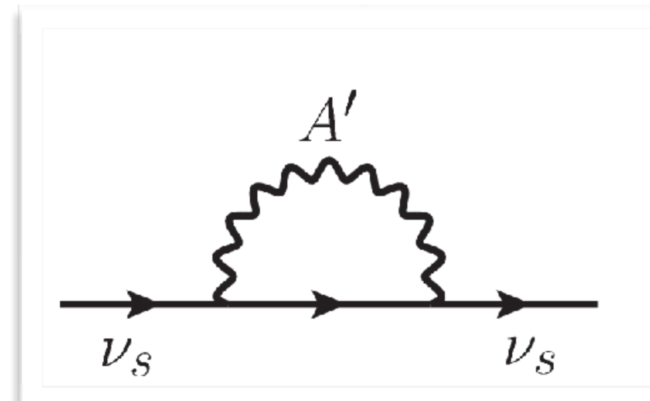
PRISMA CERN erc

JG|U

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 $V \sim T^a$

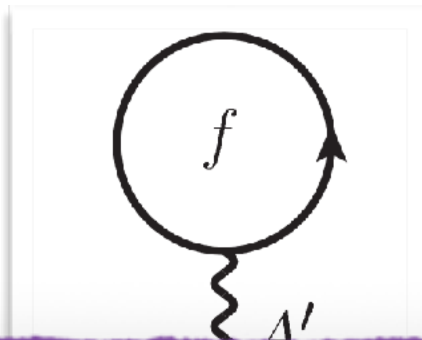
- ☑ Effective mixing angle:

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

PRISMA CERN erc JG|U

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

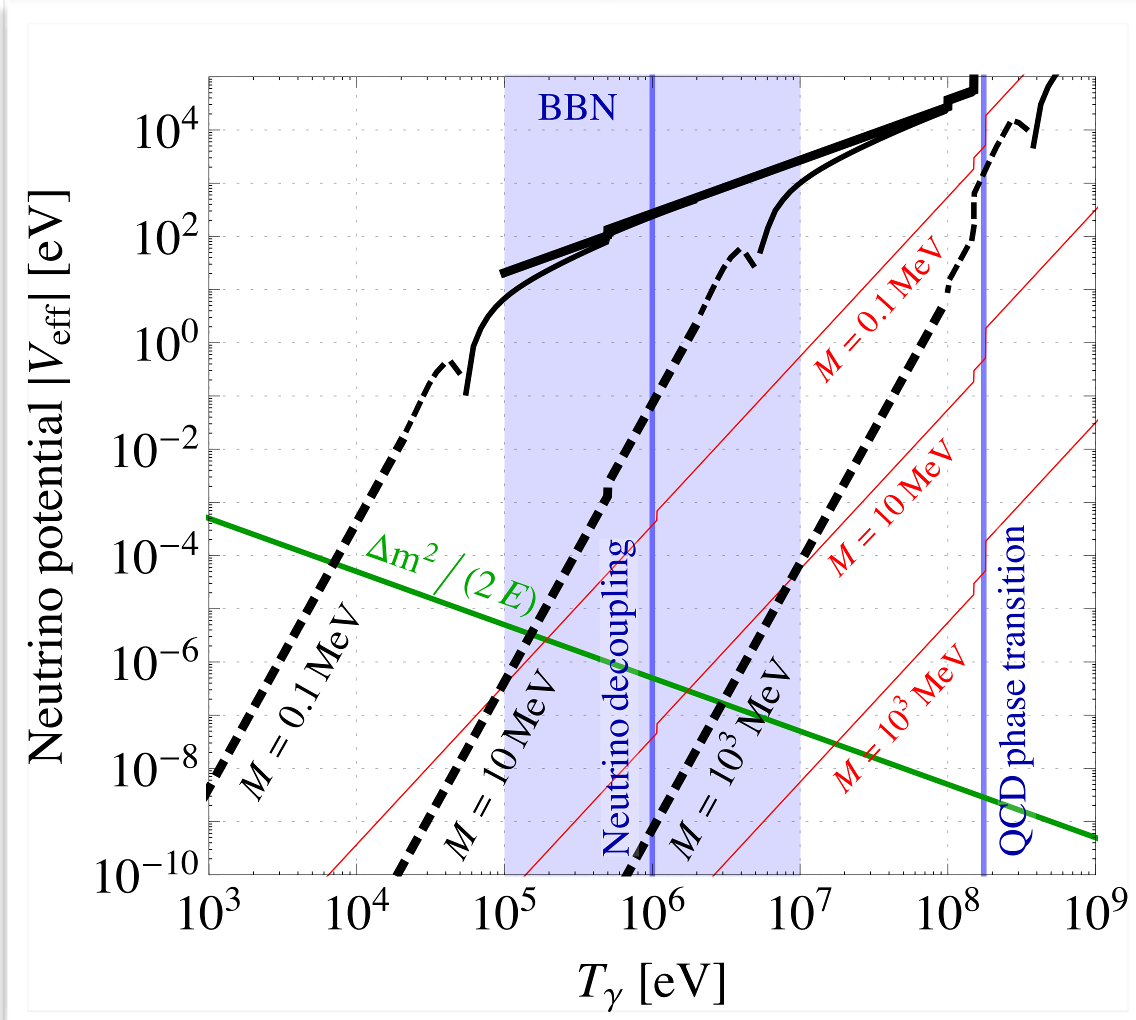
- ☑ Effective mixing angle:

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

PRISMA CERN erc

JG|U

New Interaction in the Sterile Sector



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

Hannestad *et al.* 1310.5926, Dasgupta JK 1310.6337

- ☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s
(*$N_{\rm eff}$* 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

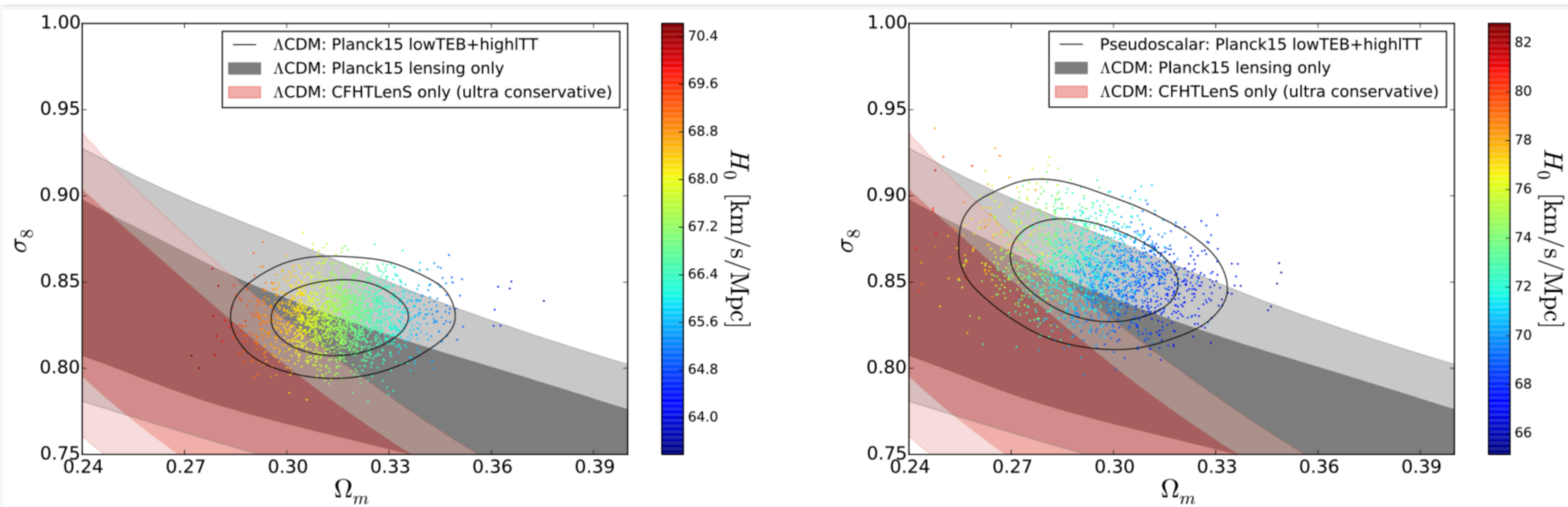
PRiSMA CERN erc

JG|U

New Interaction in the Sterile Sector

- While $V_{eff} \gg \Delta m^2/(2T)$: 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 $\nu_s \nu_s \to \varphi\varphi$ annihilation
  if mediator φ is a light pseudoscalar
- Could solve H_0 tension

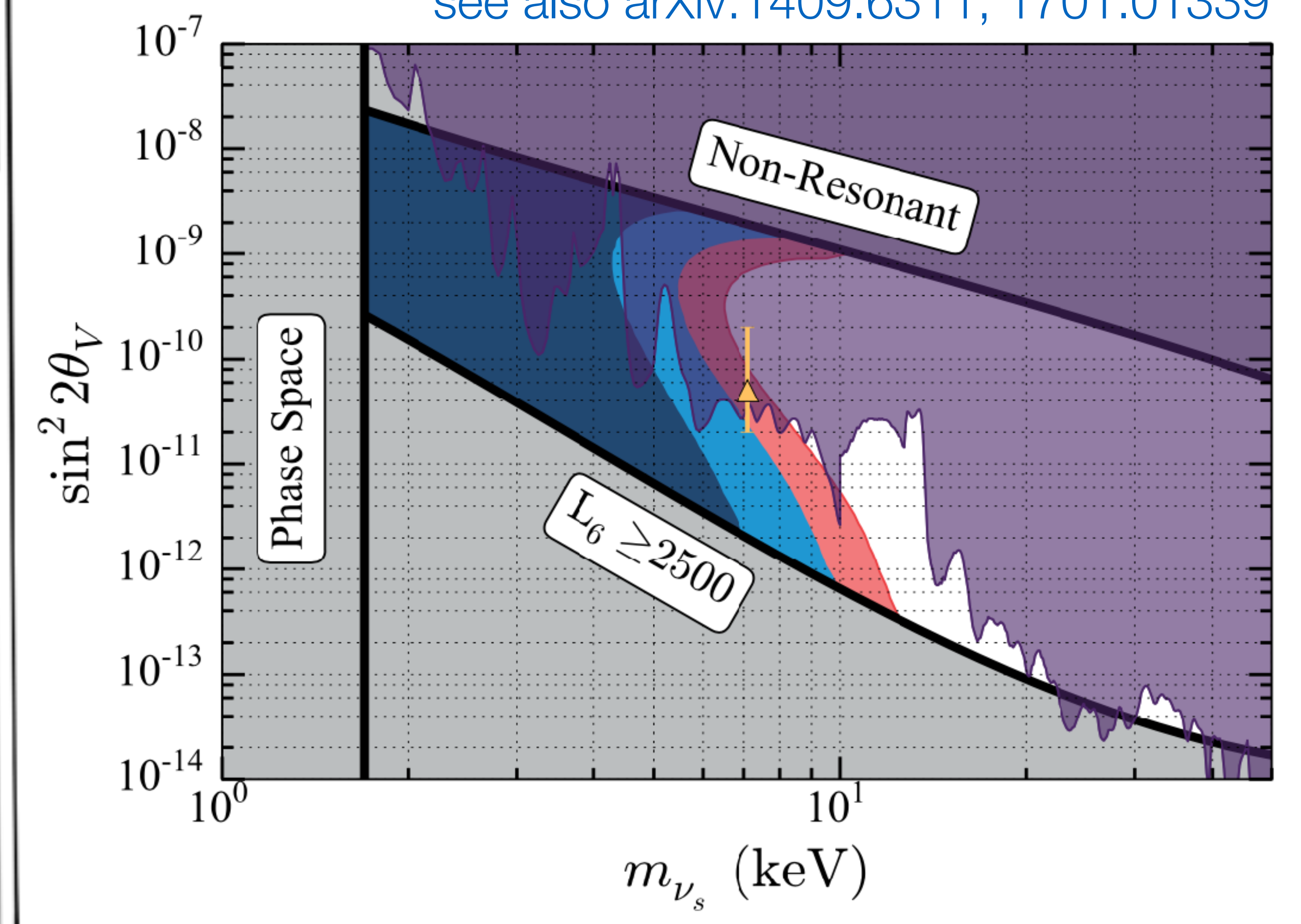
Archidiacono *et al.* 1606.07673



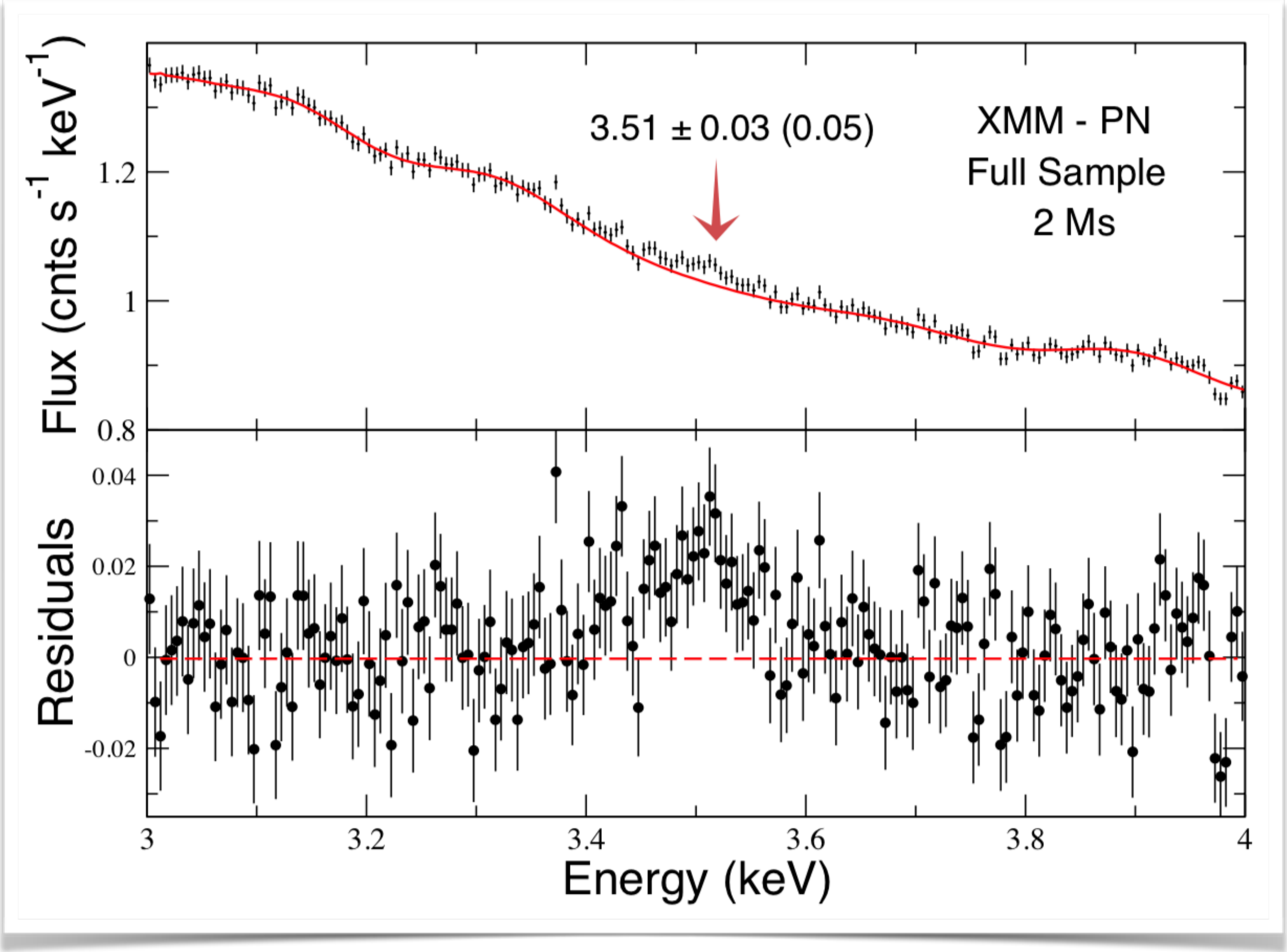
Sterile Neutrinos as Dark Matter

- ☑ 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

Cherry Horiuchi, arXiv:1701.07874
see also arXiv:1409.6311, 1701.01339



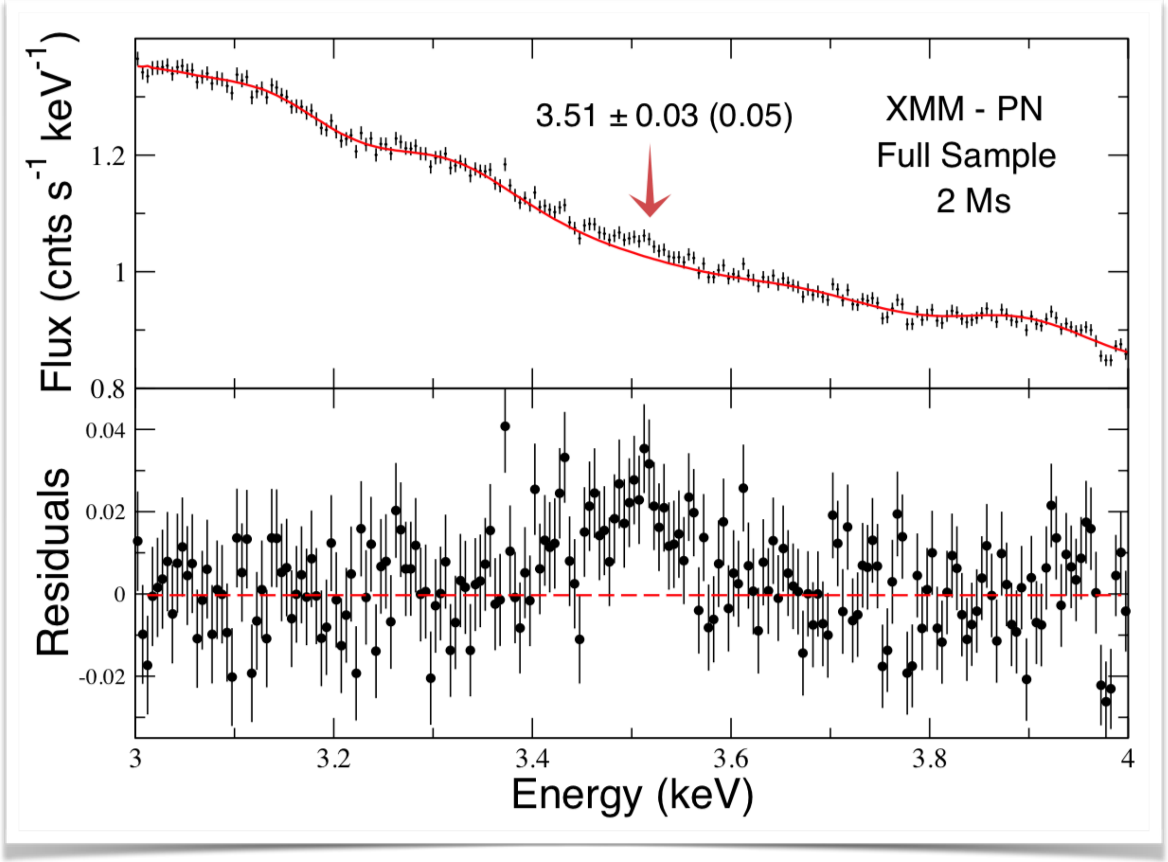
A Hint for Sterile Neutrino Dark Matter?



PRiSMA CERN erc

JG|U

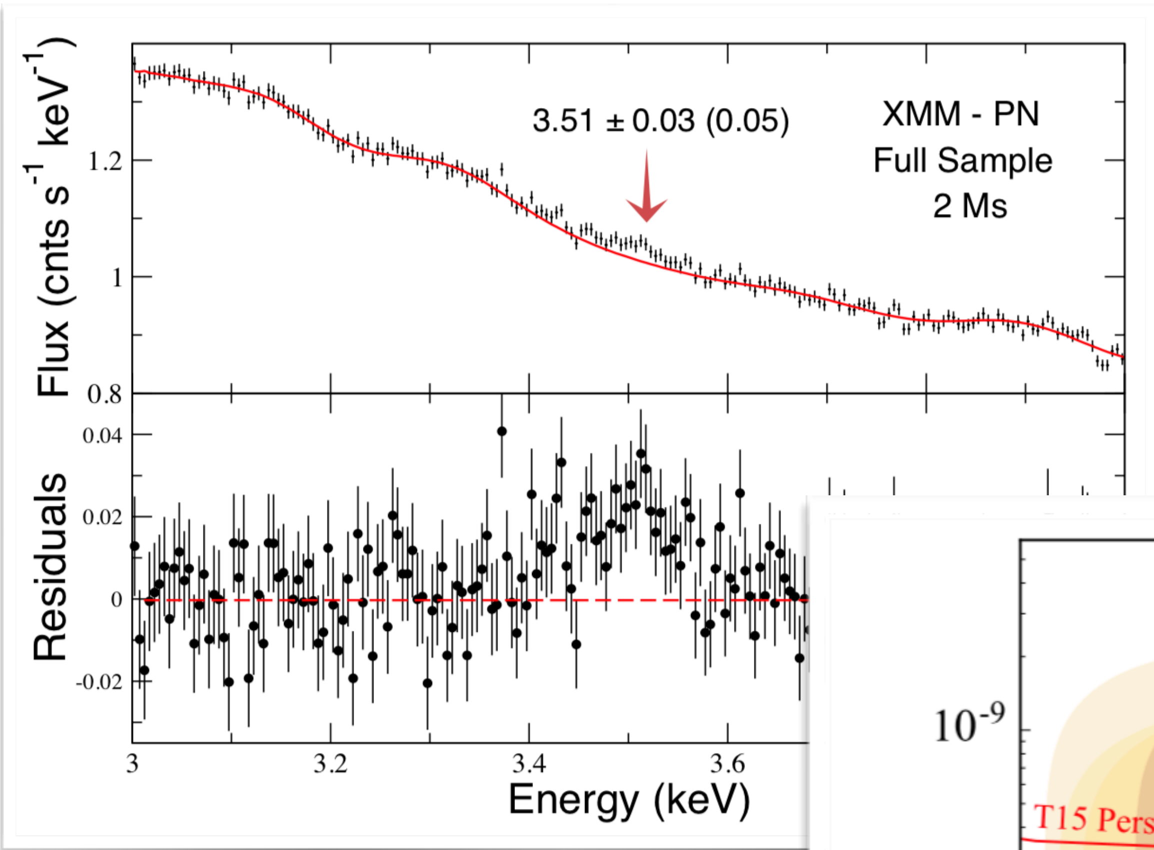
A Hint for Sterile Neutrino Dark Matter?



☑ From decay $\nu_s \to \nu_a + \gamma$?

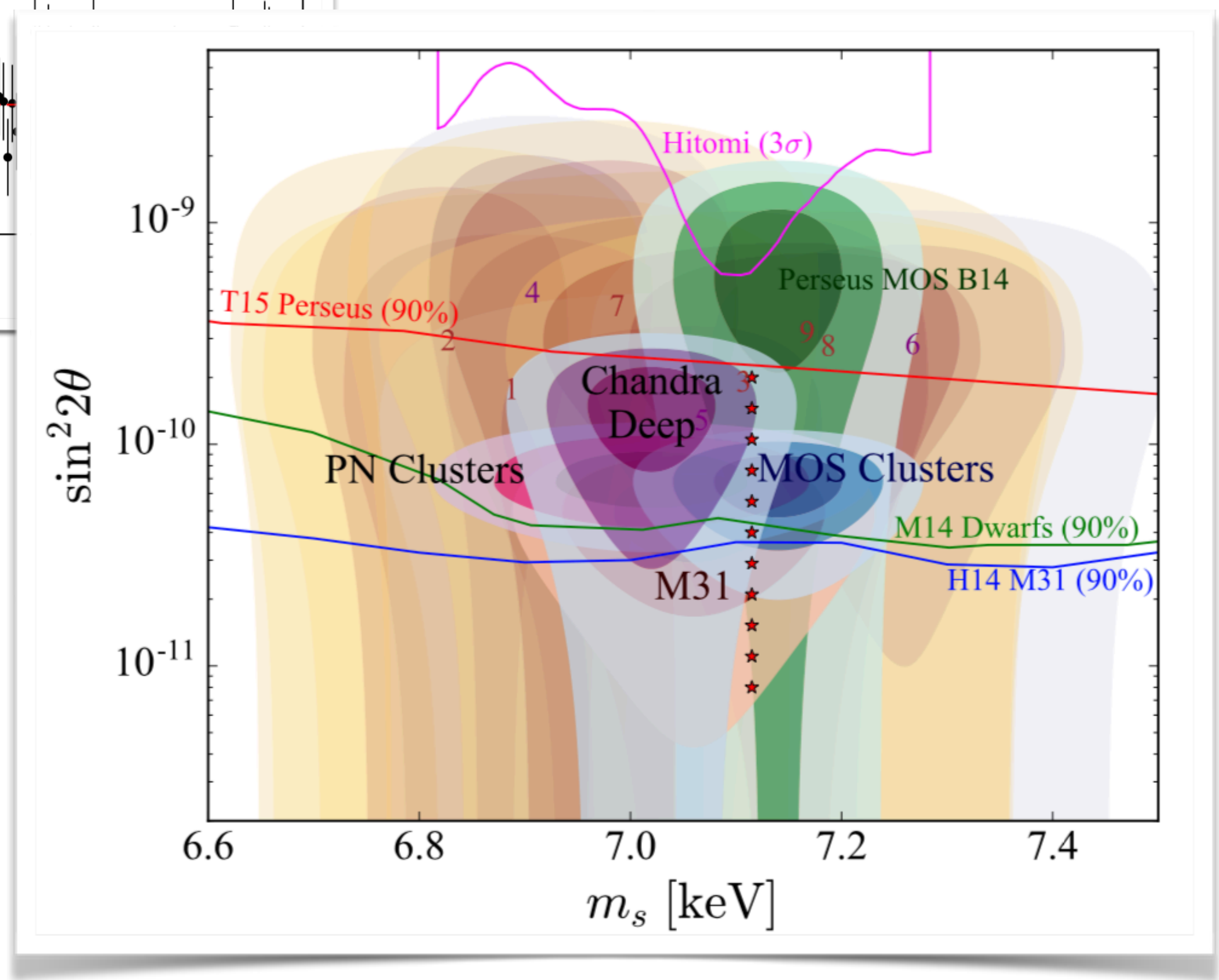
Abazajian 1705.01837

A Hint for Sterile Neutrino Dark Matter?



☑ From decay $\nu_s \to \nu_a + \gamma$?

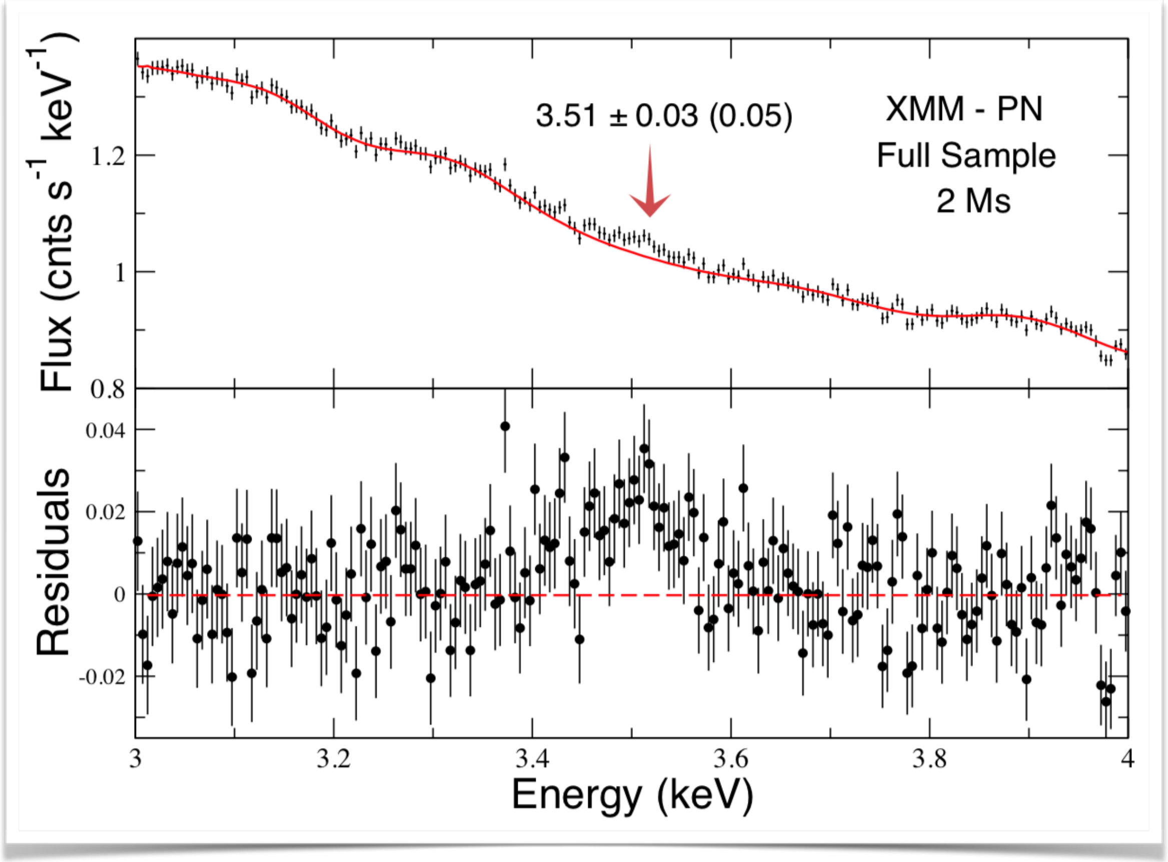
Abazajian 1705.01837



PRiSMA CERN erc

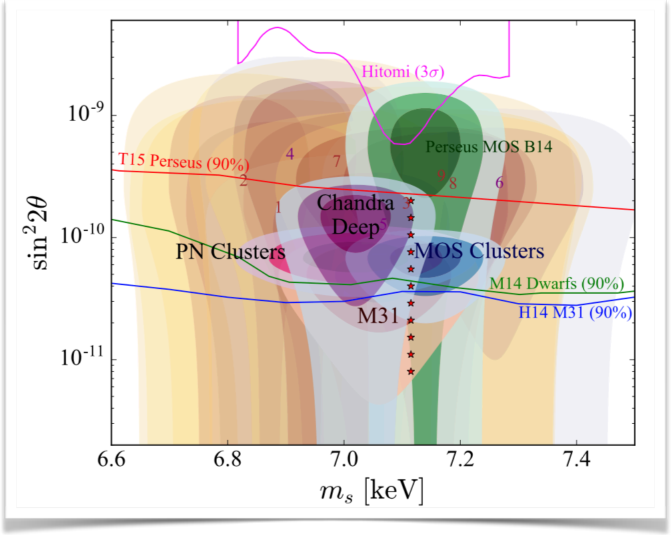
JG|U

A Hint for Sterile Neutrino Dark Matter?

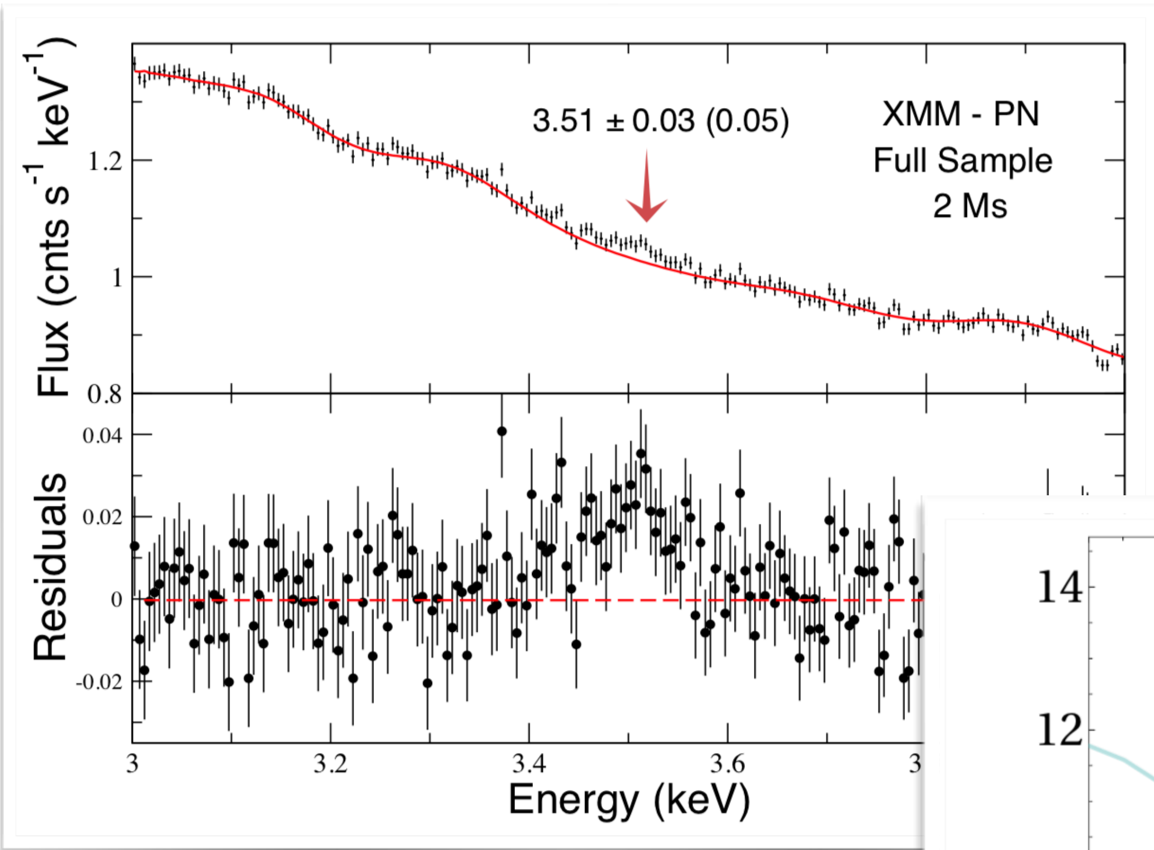


☑ From decay $\nu_s \rightarrow \nu_a + \gamma$?

Abazajian 1705.01837



A Hint for Sterile Neutrino Dark Matter?

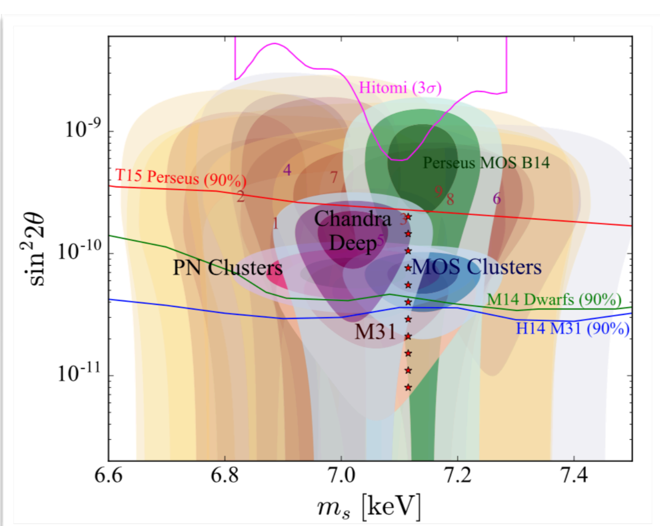


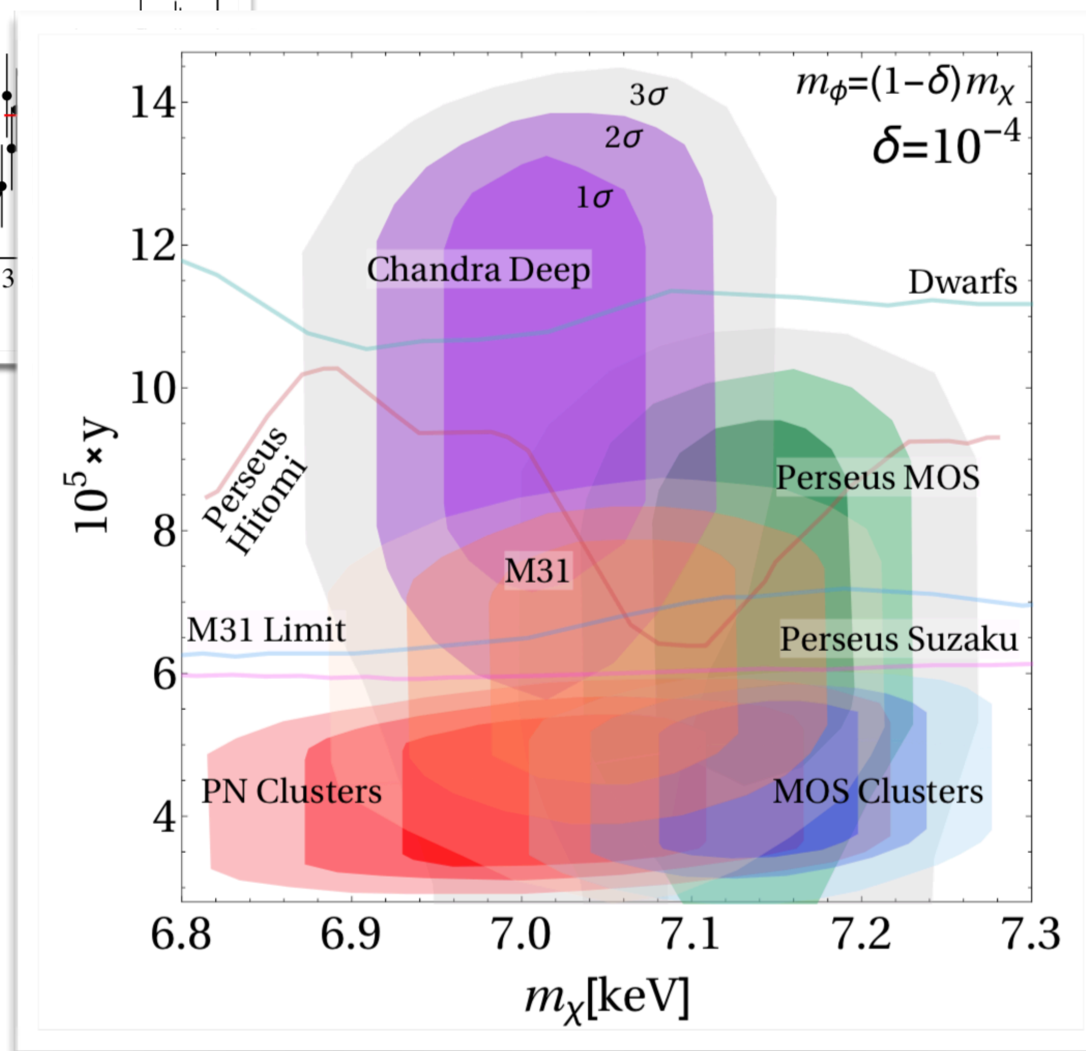
- ☑ From decay $\nu_s \to \nu_a + \gamma$?

  Abazajian 1705.01837

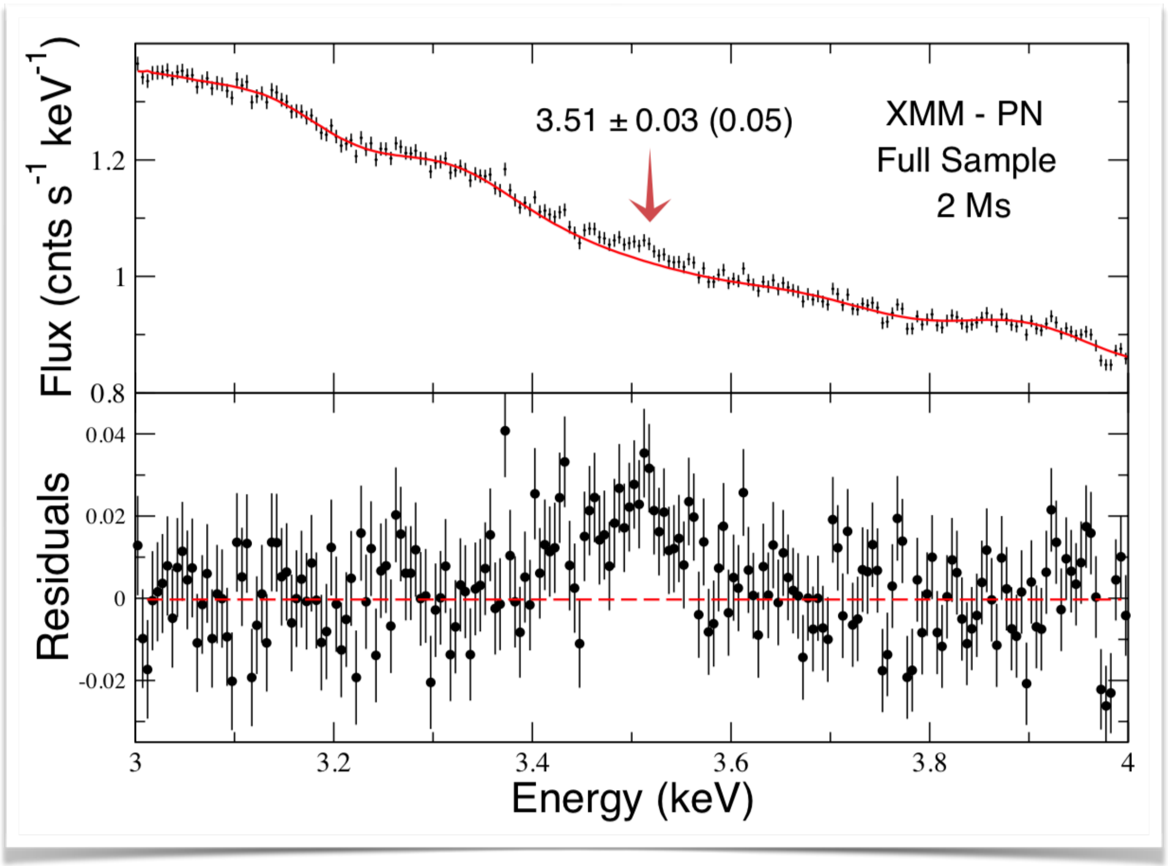
- ☑ Or from ν_s annihilation?

  Brdar JK Liu Wang 1710.02146





A Hint for Sterile Neutrino Dark Matter?

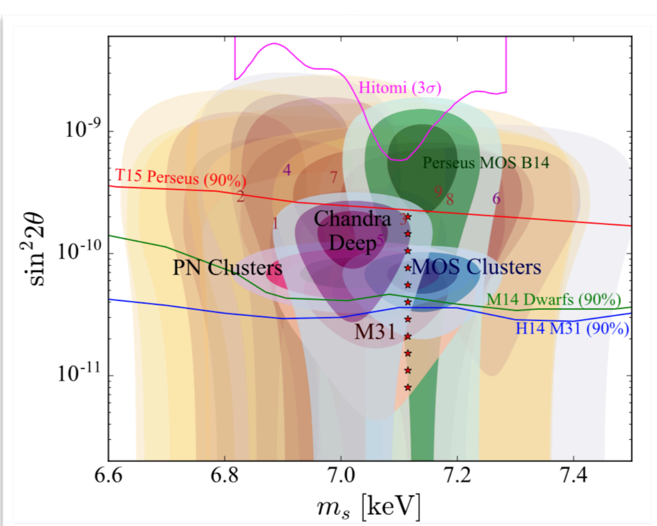


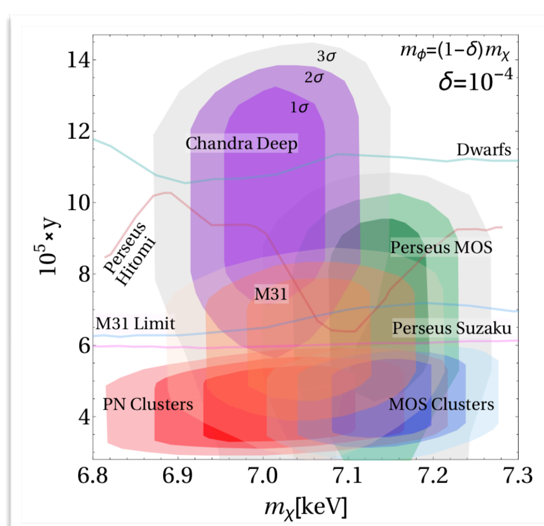
☑ From decay $\nu_s \rightarrow \nu_a + \gamma$?

Abazajian 1705.01837

☑ Or from ν_s annihilation?

Brdar JK Liu Wang 1710.02146

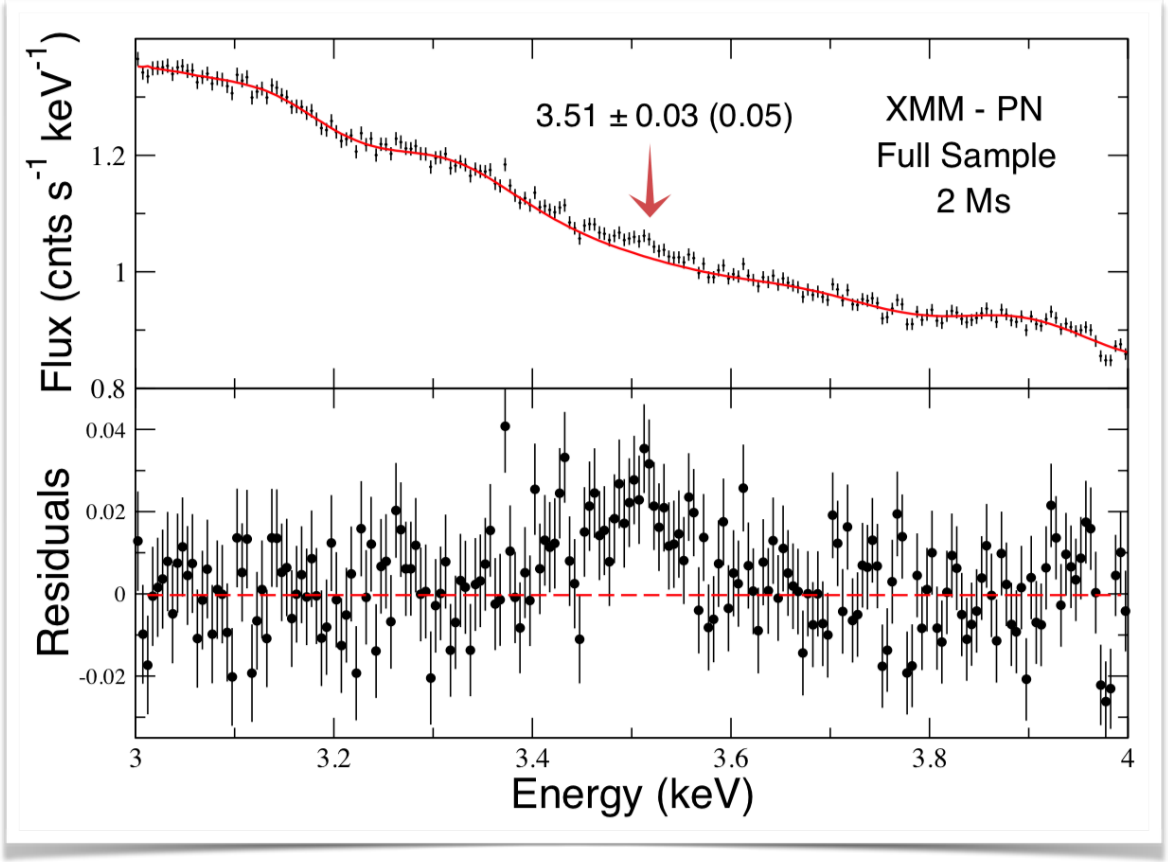




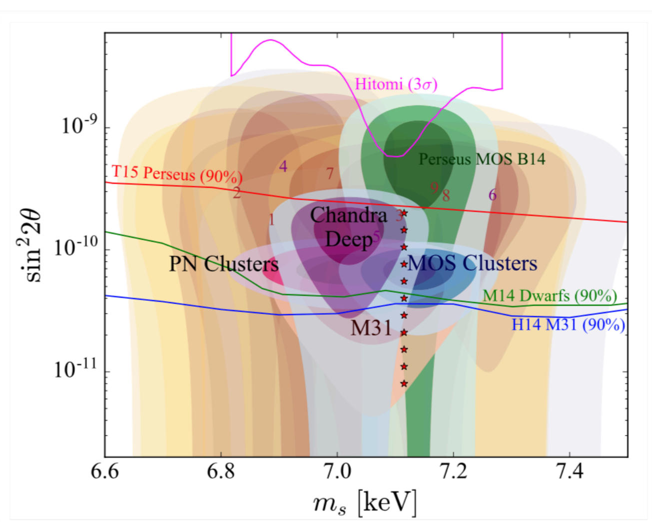
PRiSMA CERN erc

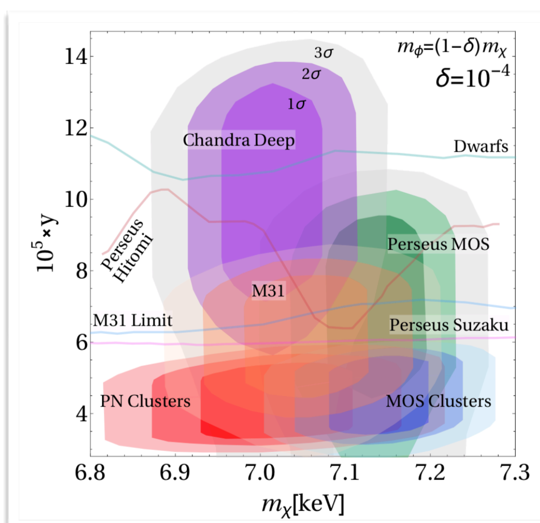
JG|U

A Hint for Sterile Neutrino Dark Matter?

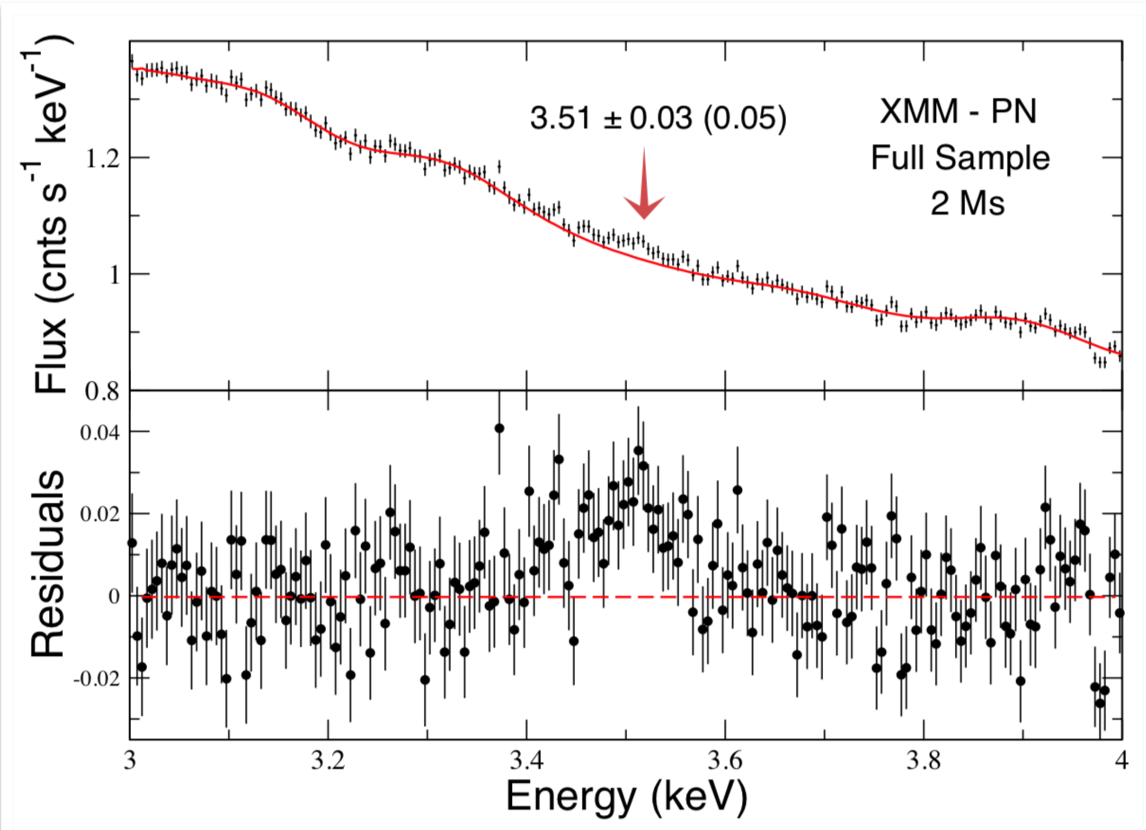


- ☑ From decay $\nu_s \to \nu_a + \gamma$?
  Abazajian 1705.01837
- ☑ Or from ν_s annihilation?
  Brdar JK Liu Wang 1710.02146
- ☑ Testable with sounding rockets

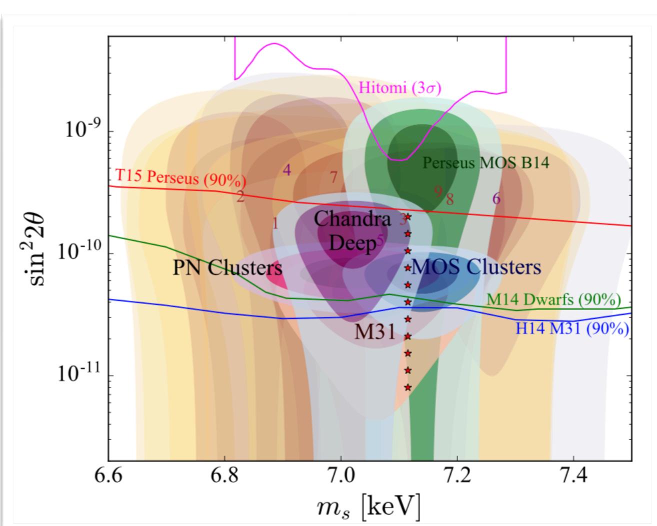


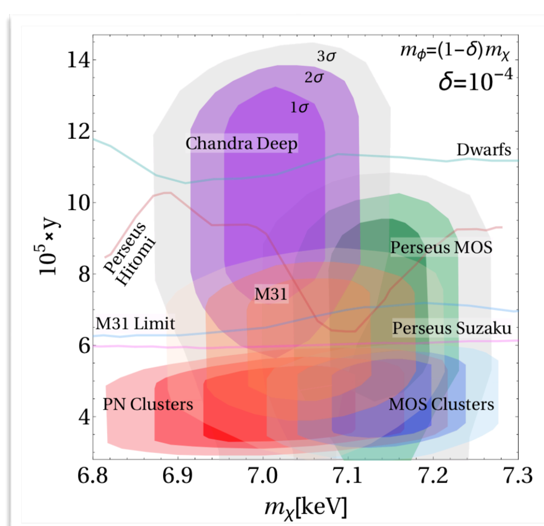


A Hint for Sterile Neutrino Dark Matter?



- ☑ 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



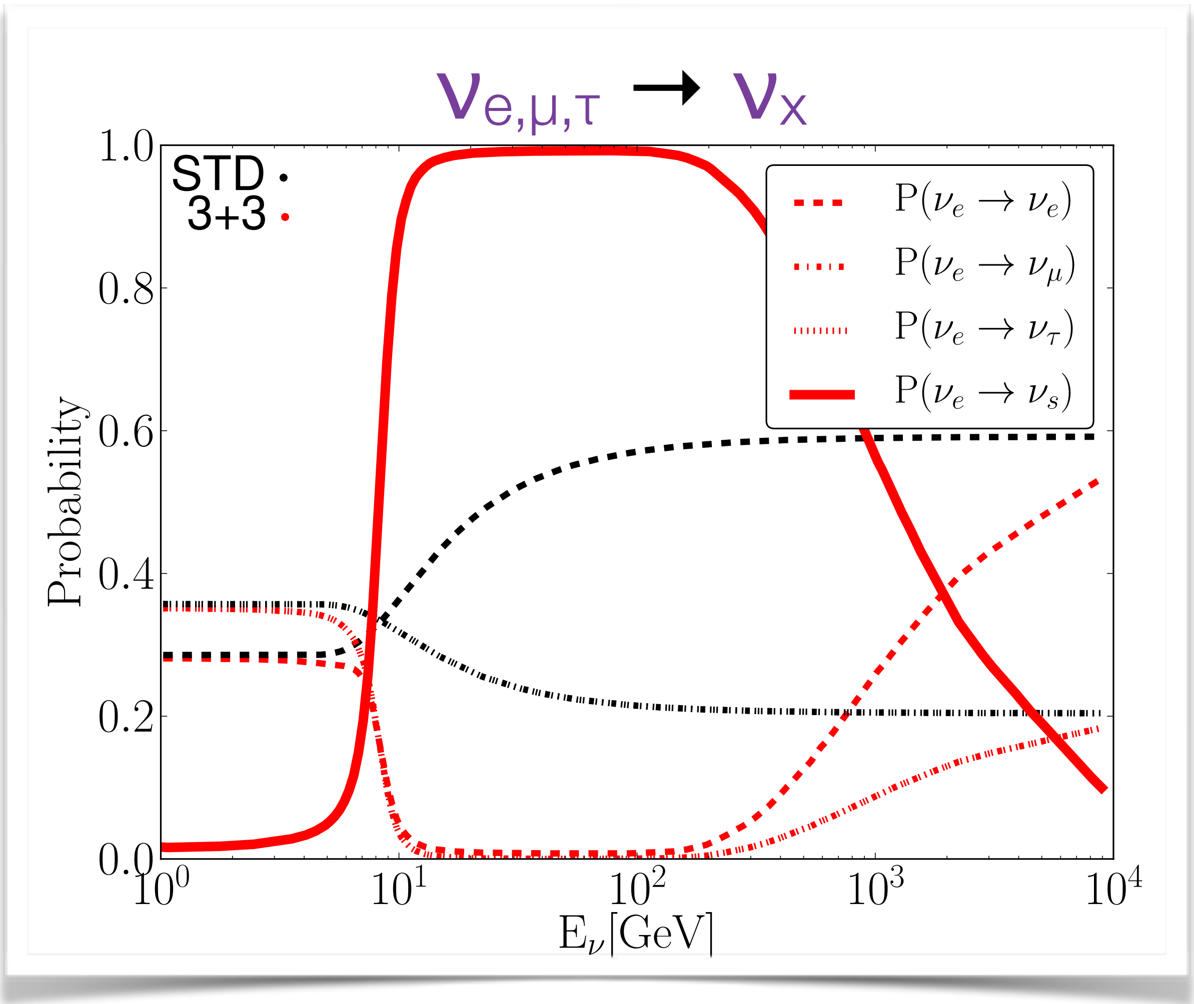


PRiSMA CERN erc

JG|U

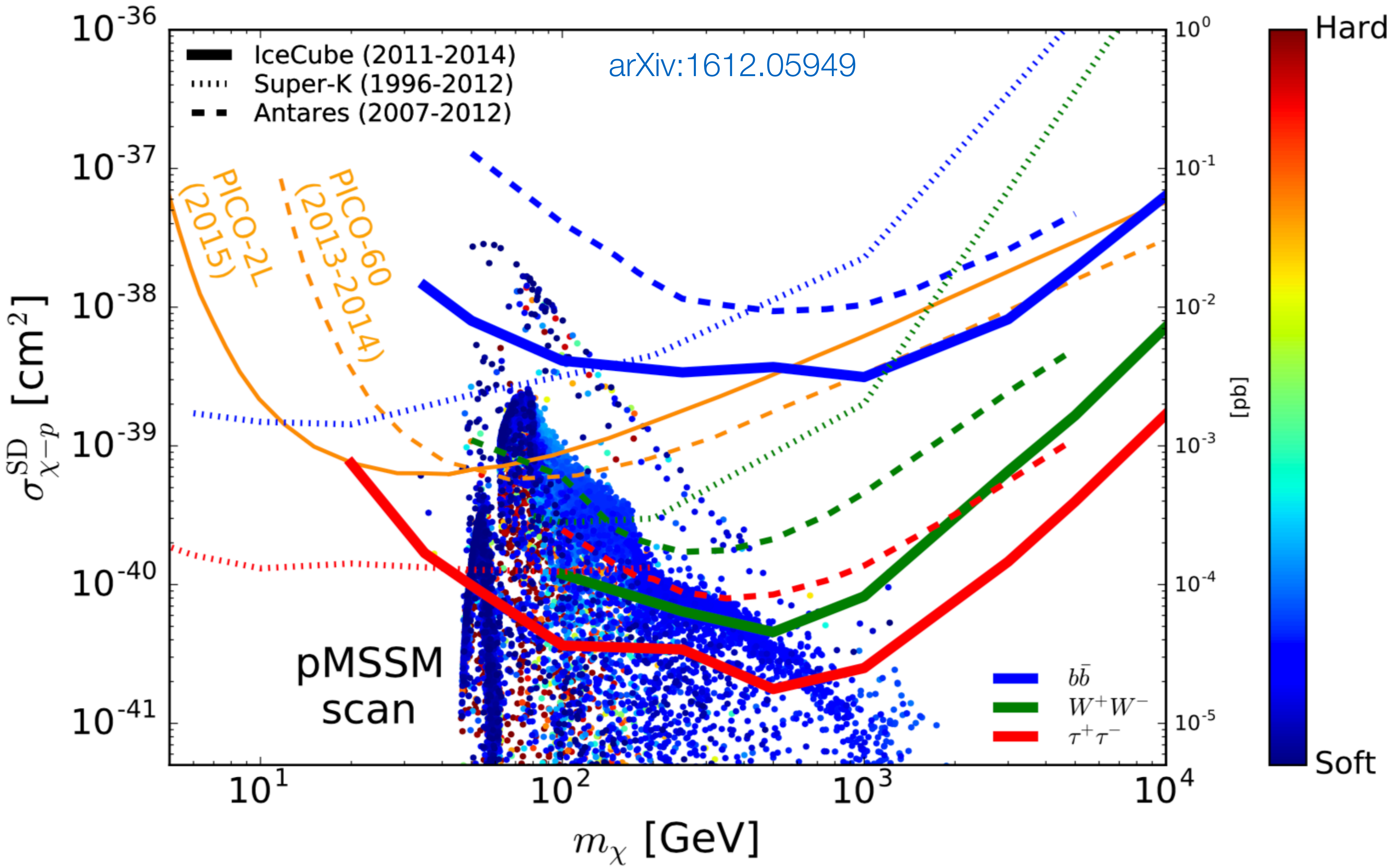
Sterile Neutrinos and DM Annihilation in the Sun

- 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 $\nu_{e,\mu,\tau} \to \nu_s$ conversion (for some ν / $\bar{\nu}$ flavors)

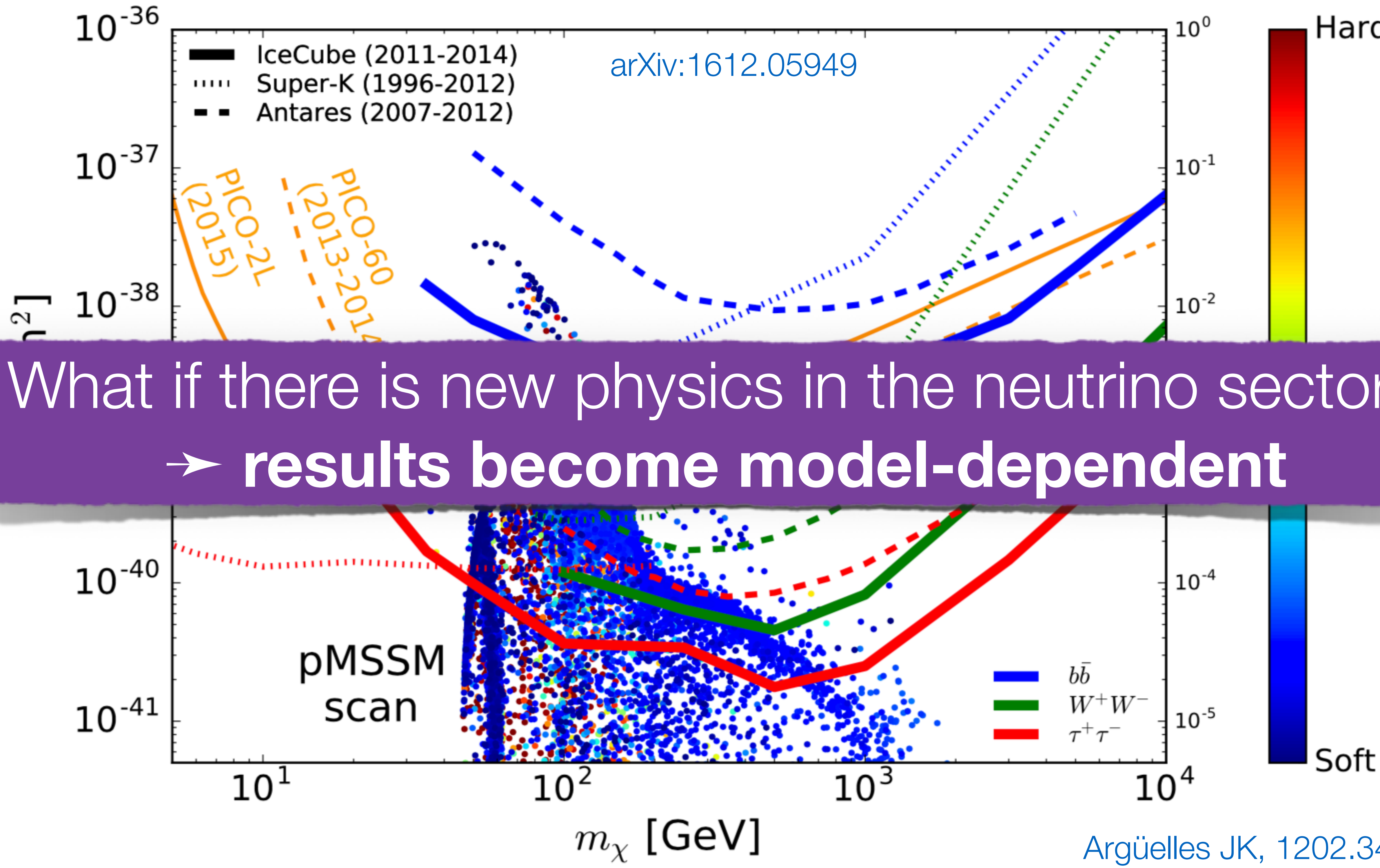


Argüelles JK [1202.3431](1202.3431)
Esmaili Peres [1202.2869](1202.2869)

DM Annihilation in the Sun



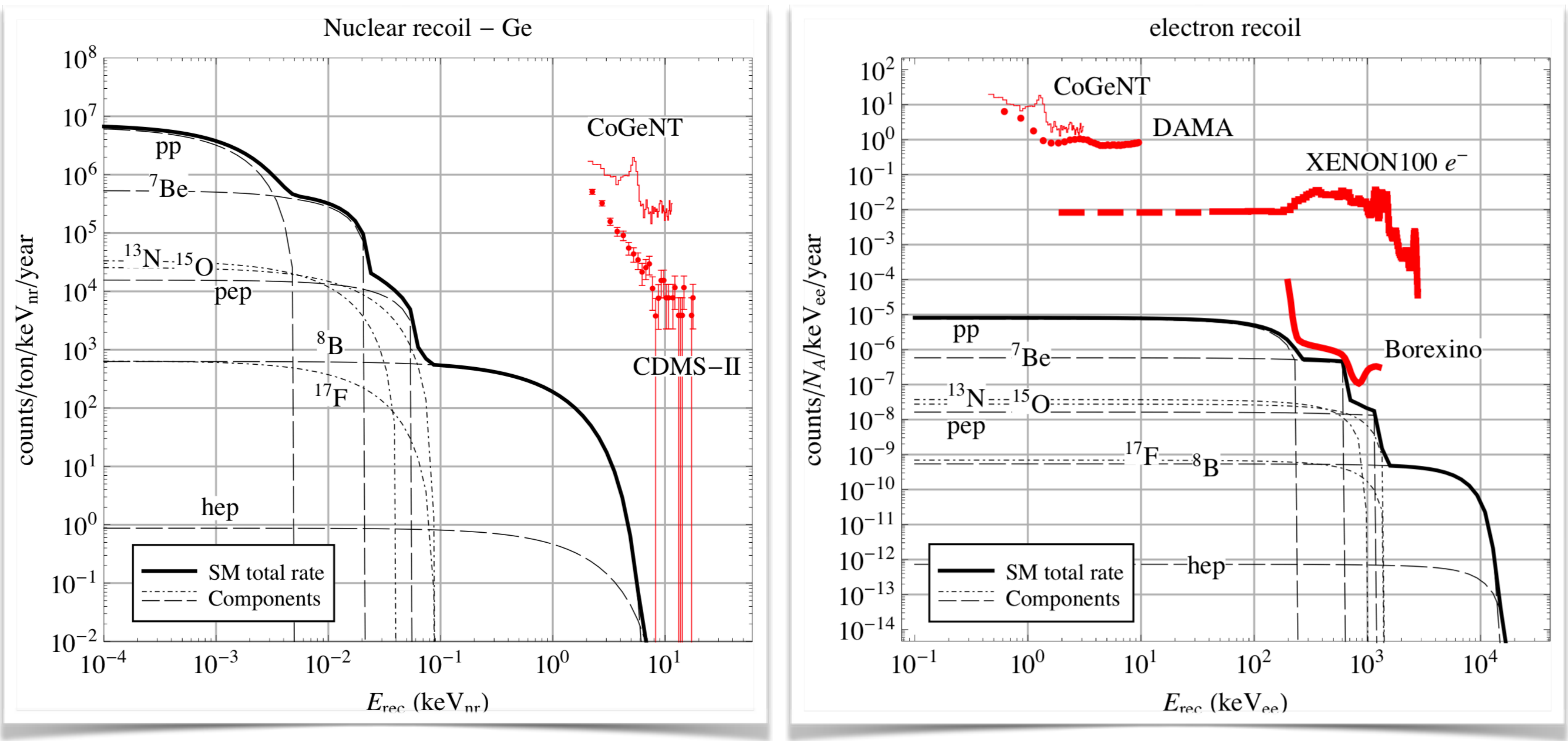
DM Annihilation in the Sun



What if there is new physics in the neutrino sector?
➛ **results become model-dependent**

Argüelles JK, 1202.3431

The Neutrino Floor in DM Searches

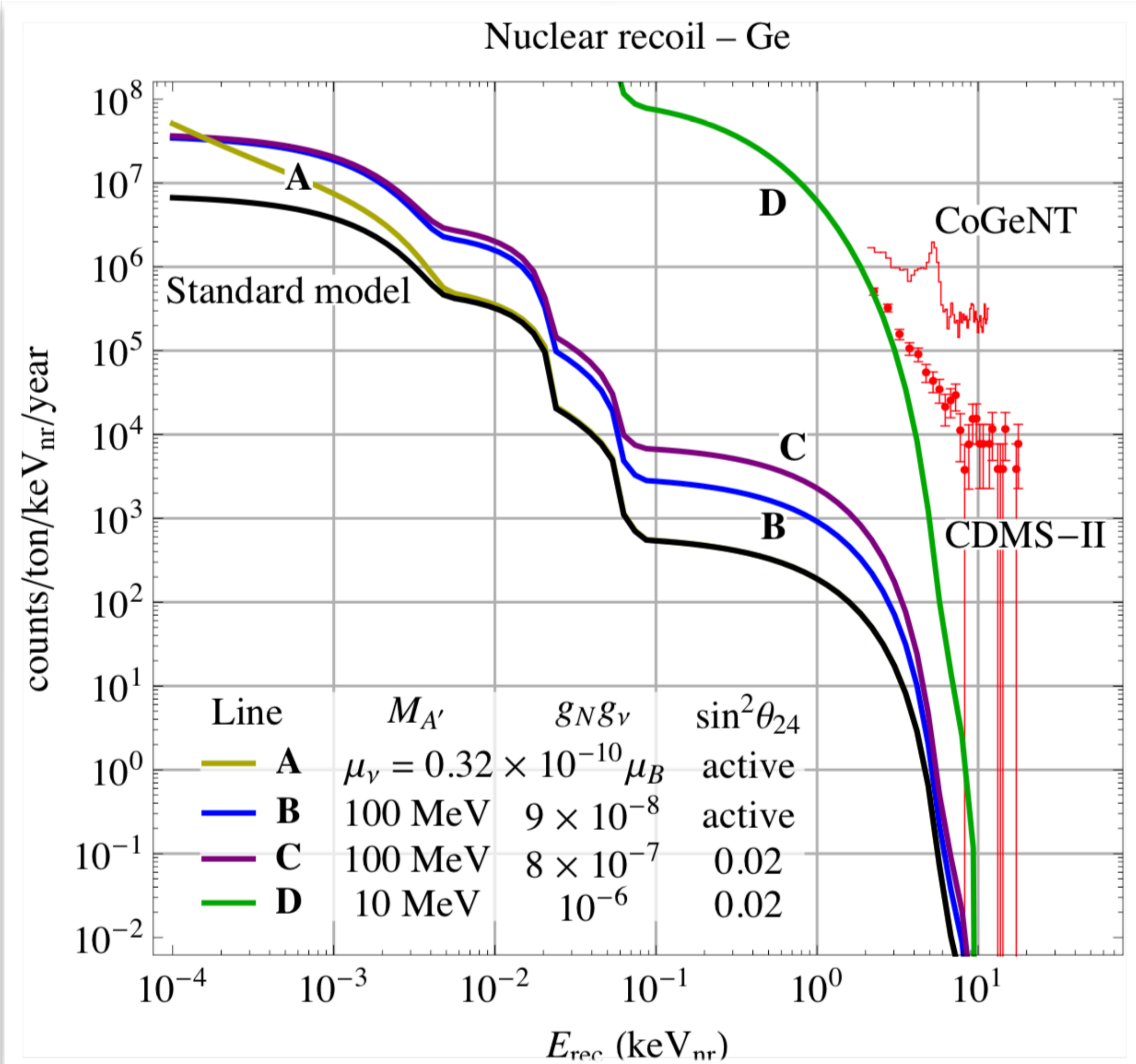


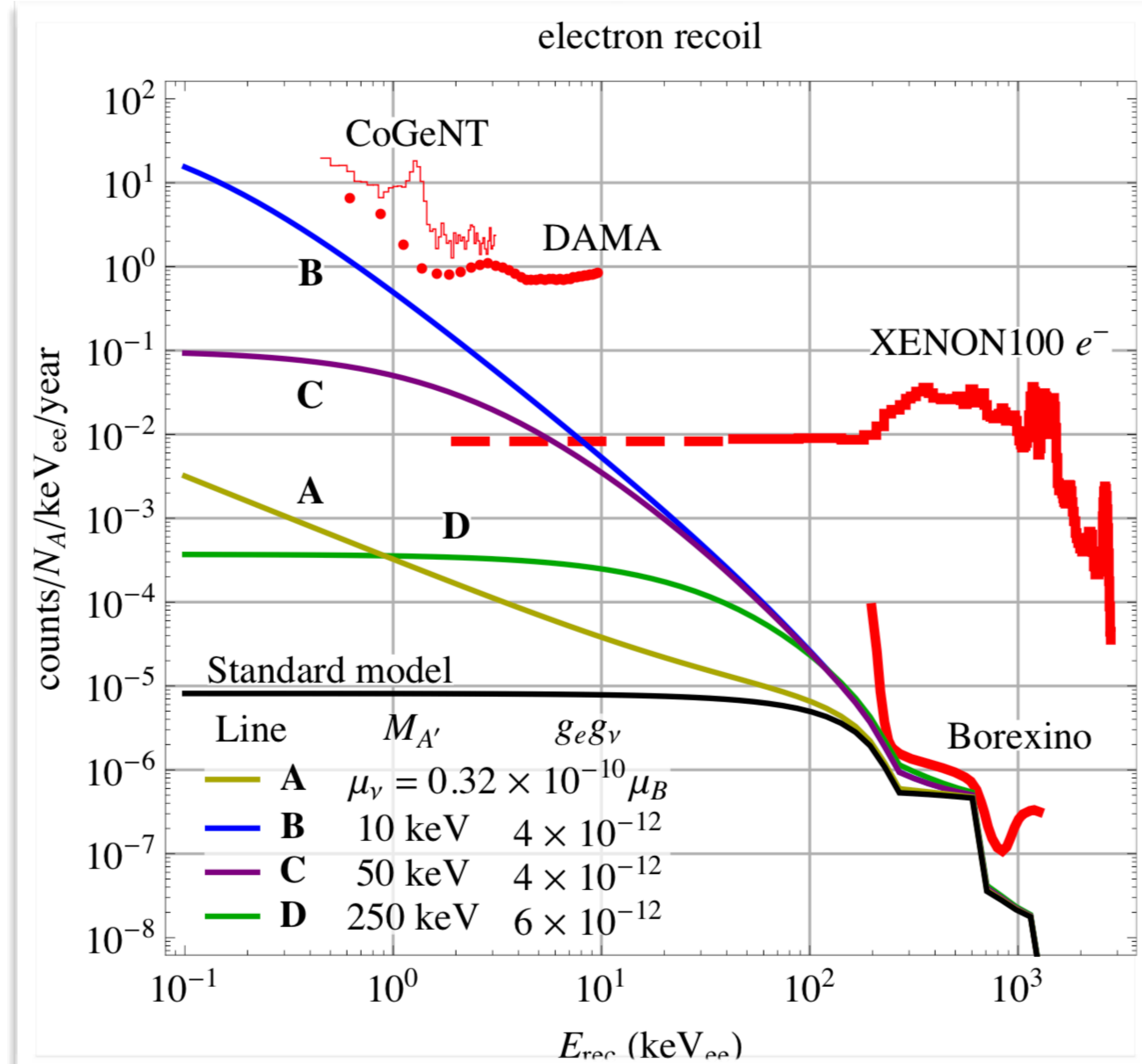
Harnik JK Machado, arXiv:1202.6073

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

PRiSMA CERN erc JG|U

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

PRISMA CERN erc

JG|U

Summary

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!