Sterile Neutrinos

Some Recent Developments

Joachim Kopp
HEP Seminar | University of Bielefeld | January 25th, 2018

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In this Talk

- The Reactor Anomaly: A Hint for Sterile Neutrinos?
- Sterile Neutrinos: Global Status
- Cosmological Constraints (and how to evade them)

The Reactor Anomaly

A Hint for Sterile Neutrinos?

The Reactor Anomaly

$\overline{\nu}_e$ flux from nuclear reactors is ~ 3.5% below prediction

Mueller *et al.* 1101.2663, Huber 1106.0687

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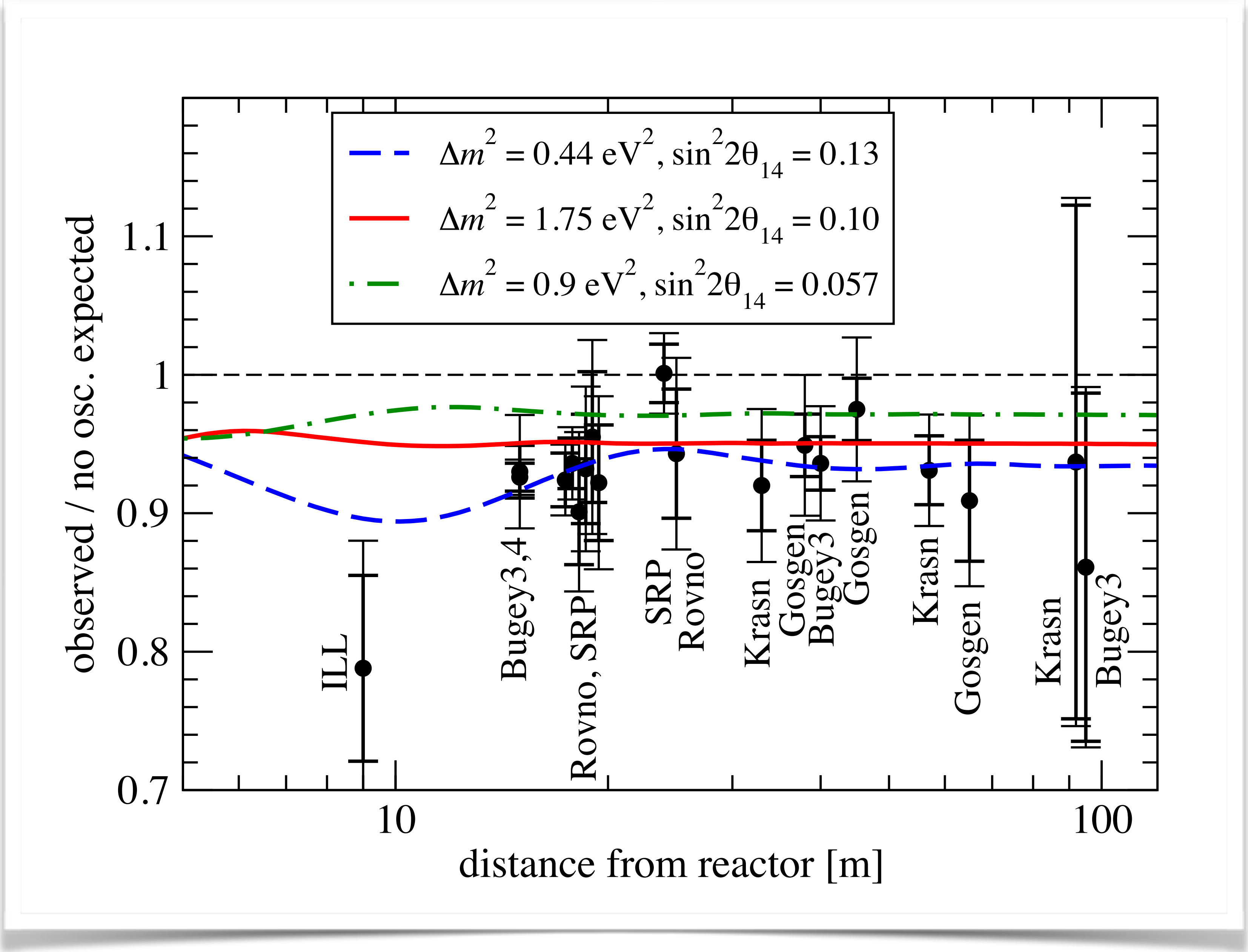
The Reactor Anomaly

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

Mueller *et al.* 1101.2663, Huber 1106.0687

The Reactor Anomaly

$\overline{\nu}_e$ flux from nuclear reactors is ~ 3.5% below prediction



The Reactor Anomaly

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

- Predicting reactor $\bar{\nu}_e$ fluxes:
  - 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

The Reactor Anomaly

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

- Important corrections
  - Finite size of nucleus
  - Weak magnetism $\mathcal{L} \supset (\bar{e}_L \sigma^{\mu\nu} \nu_L) W_{\mu\nu}$
  - Screening of nuclear charge: $Z \to Z_{eff}$
  - Radiative corrections (γ emission)
  - Non-equilibrium effects in measured β spectra
  - Neutron lifetime uncertainty
- see next talk by Patrick Huber for details

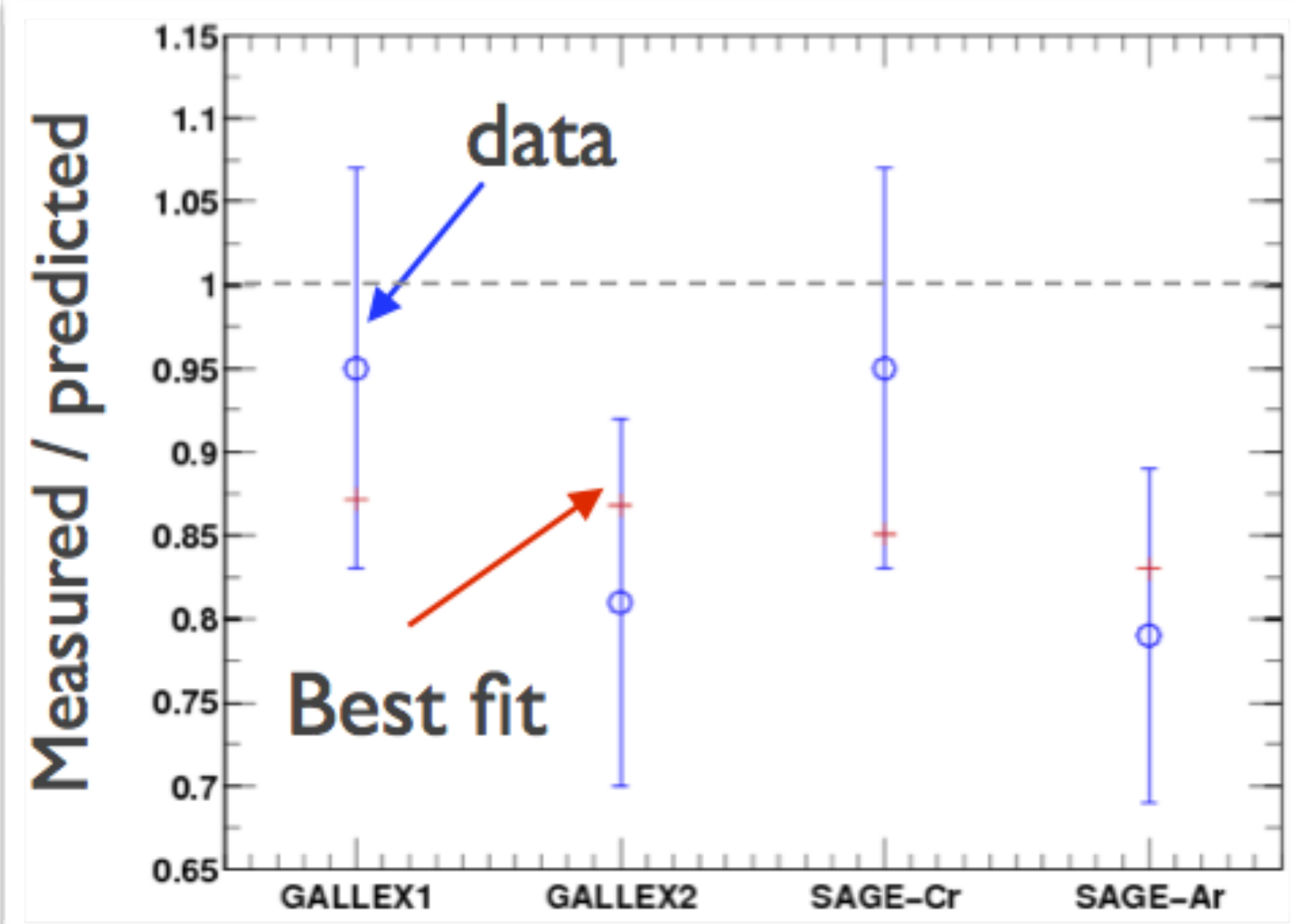
Mueller *et al.* 1101.2663, Huber 1106.0687

The Gallium Anomaly: A Vindication?

- Experiments with intense radioactive sources
- Neutrino detection via

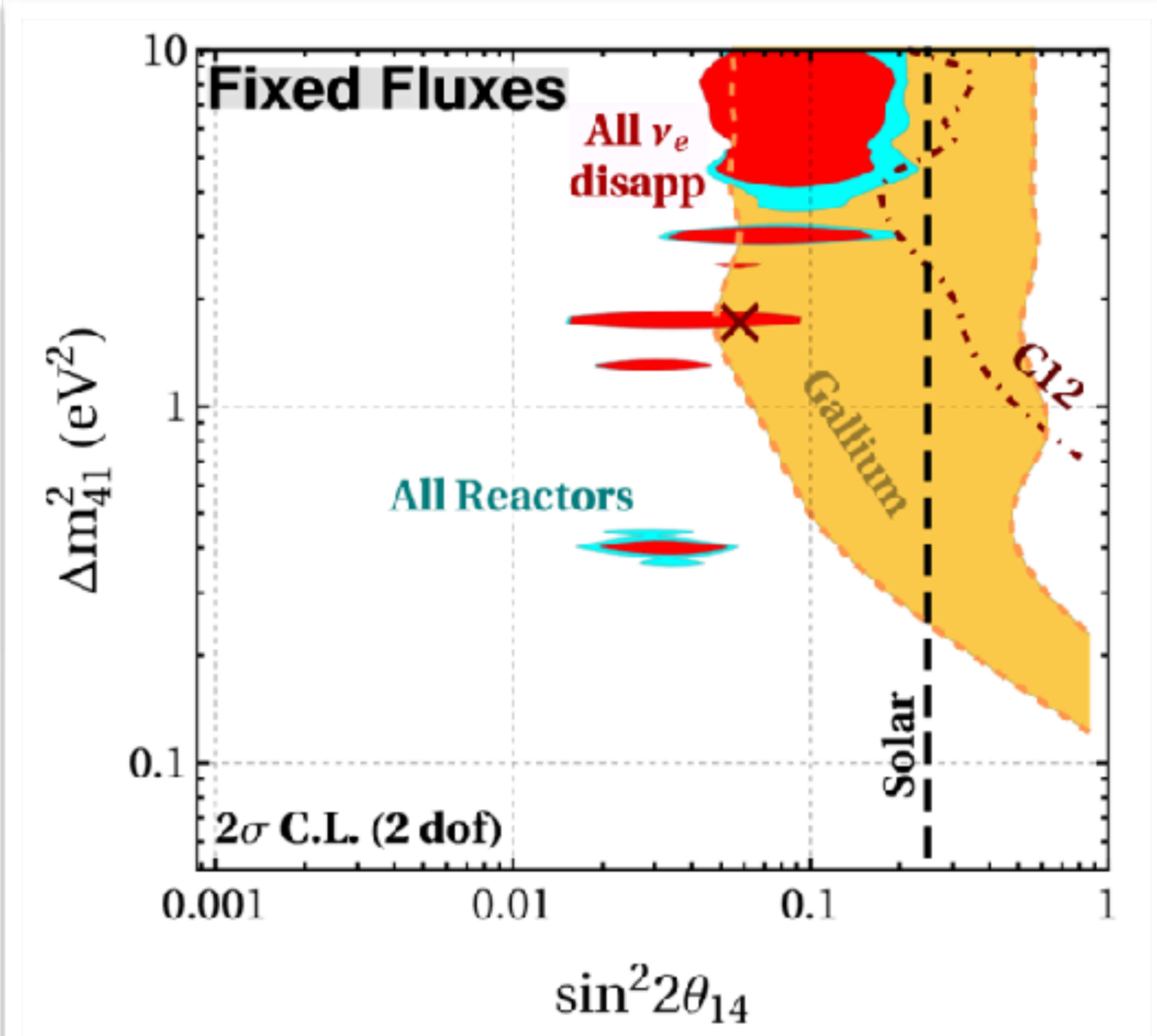
$$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$$

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



Giunti Laveder 1006.3244

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



Dentler Hernández JK Maltoni Schwetz 1709.04294

Isotope-Dependent Fluxes

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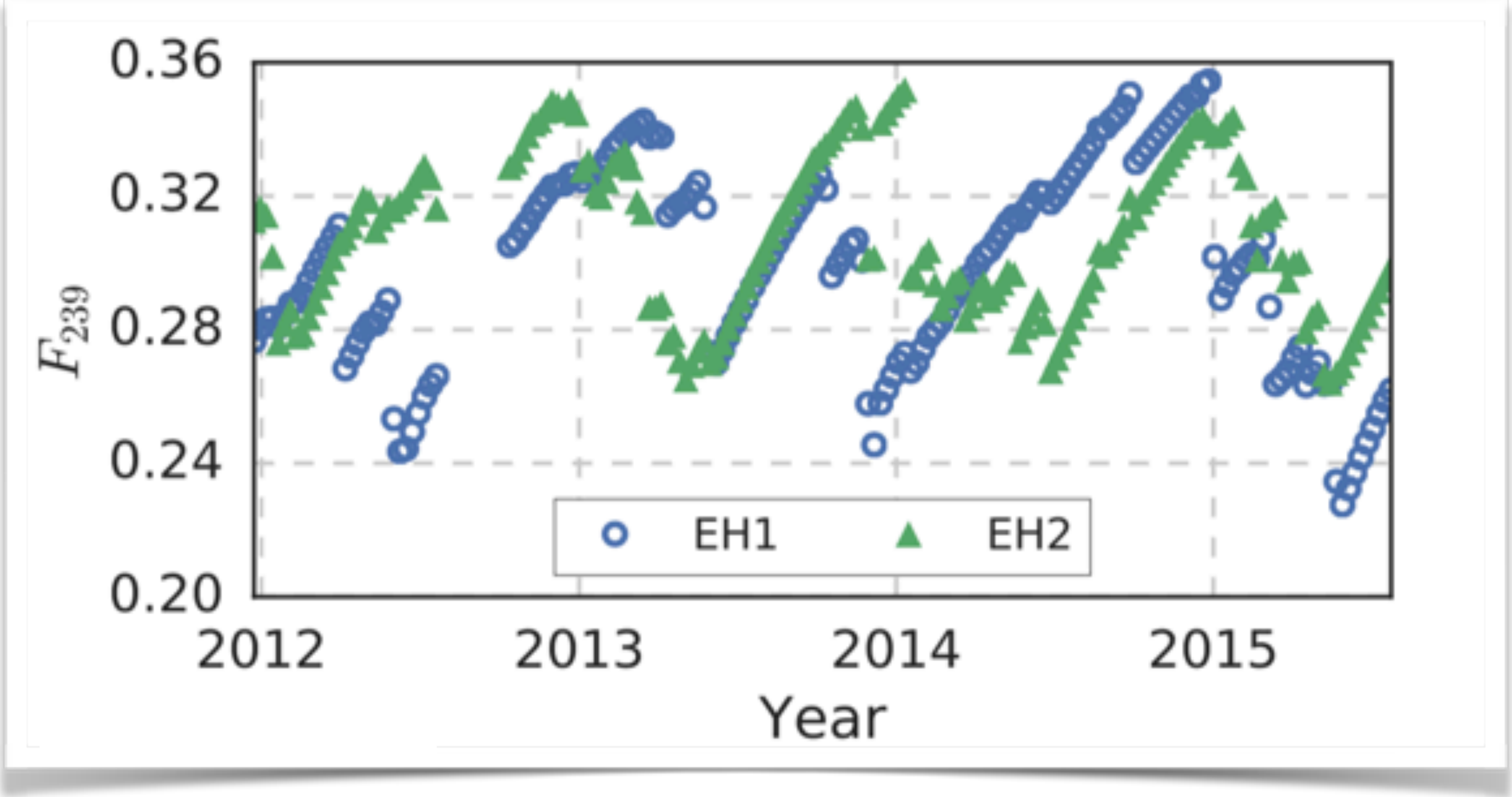
- ☑ Reactor fuel composition evolves with time ("burnup")



Daya Bay 1704.01082

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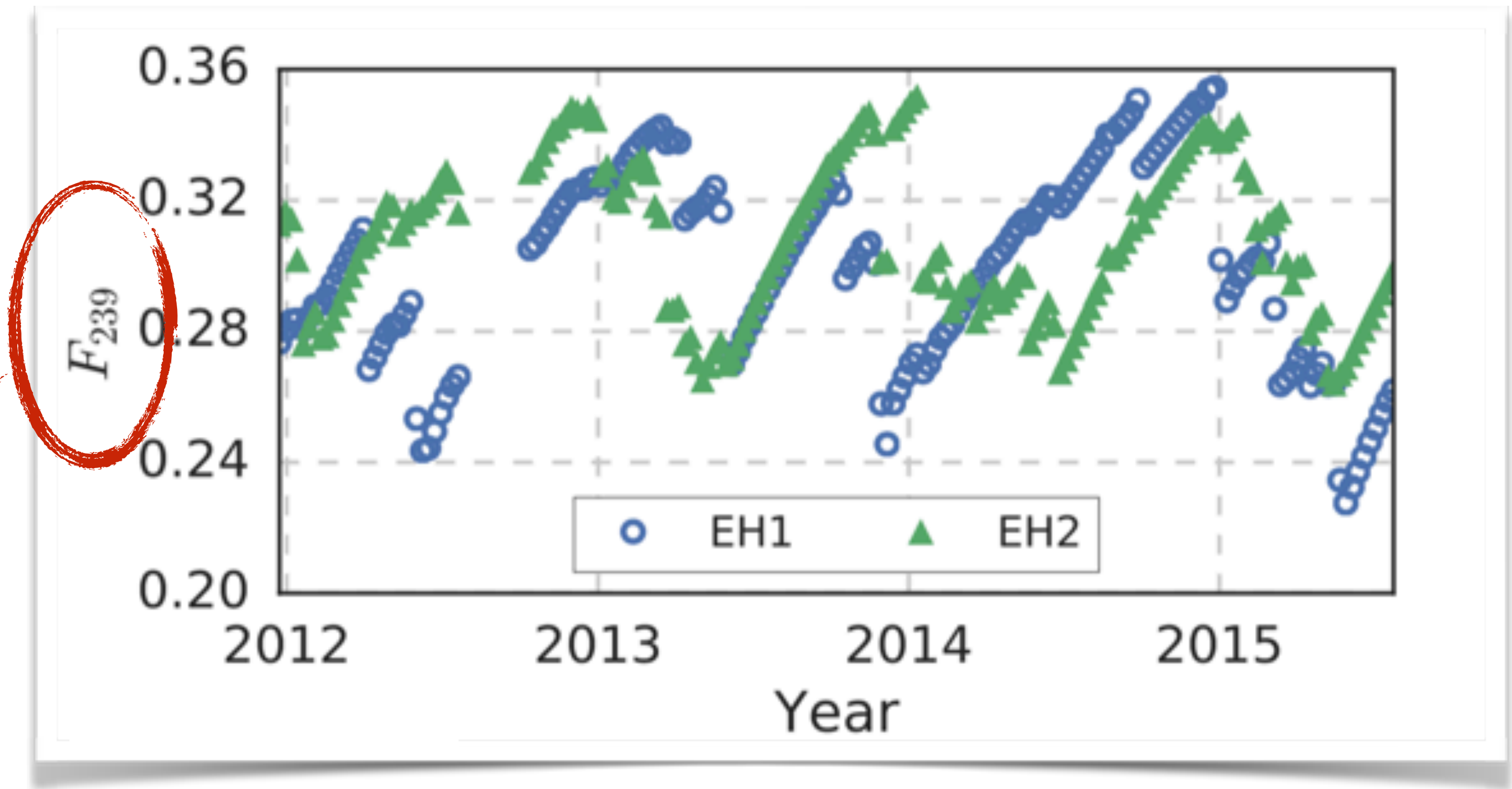

Effective fraction of ^{239}Pu fissions

$$F_i(t) = \frac{\sum_{r=1}^{6} \frac{W_{\mathrm{th,r}} \bar{P}_{ee,r} f_{i,r}(t)}{L_r^2 \overline{E}_r(t)}}{\sum_{r=1}^{6} \frac{W_{\mathrm{th,r}} \bar{P}_{ee,r}}{L_r^2 \overline{E}_r(t)}}$$

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Isotope-Dependent Fluxes

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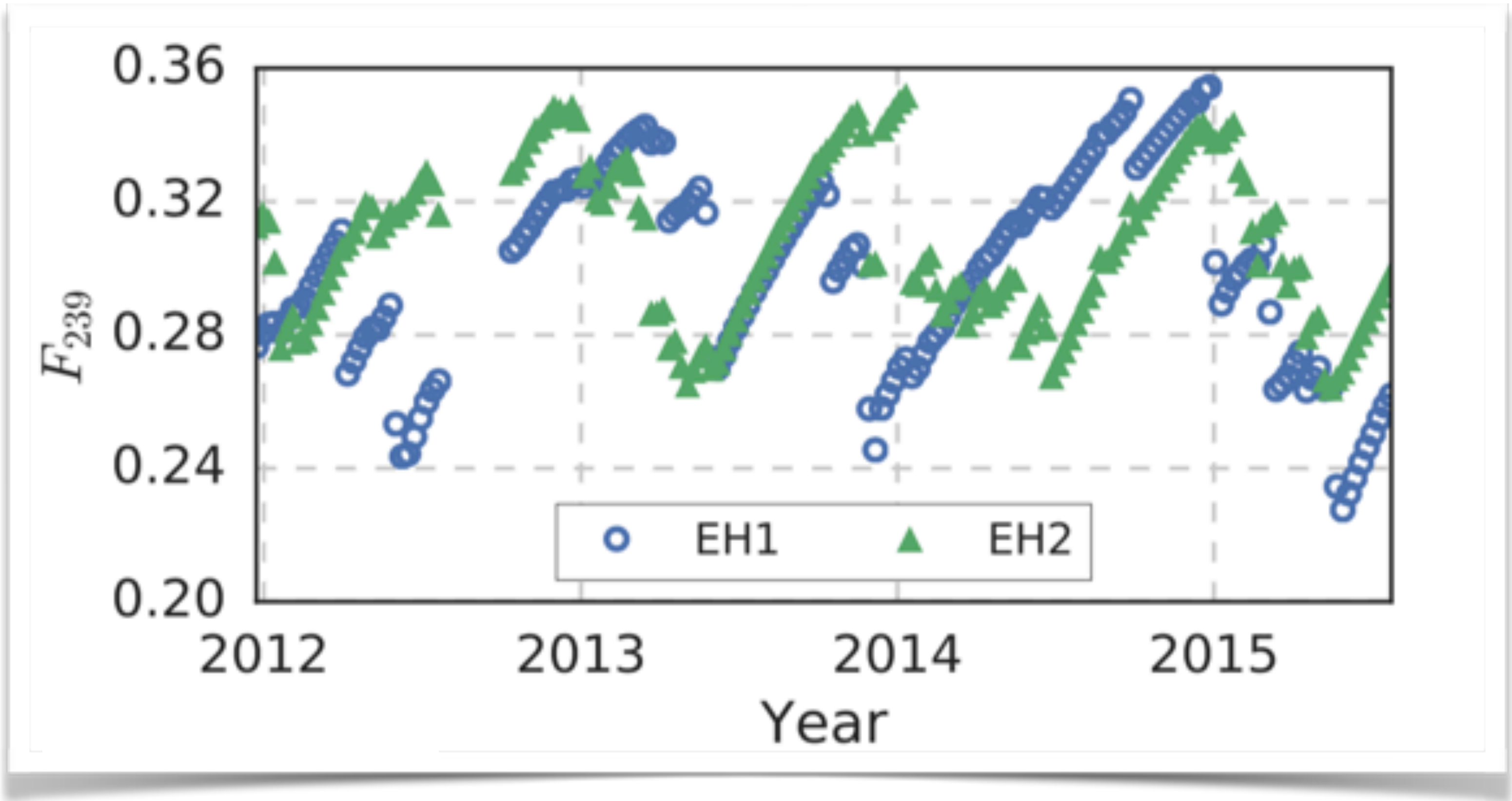

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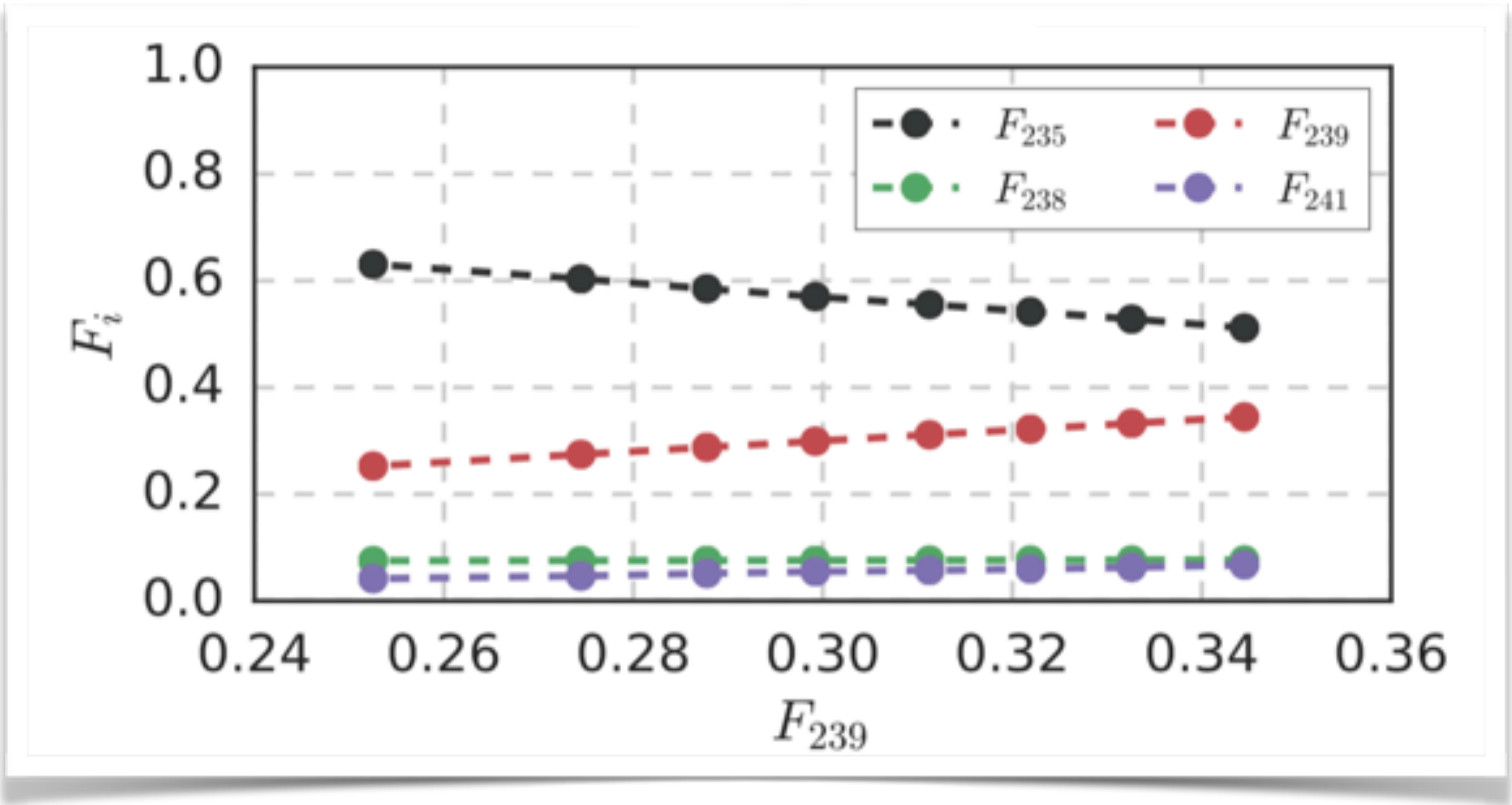

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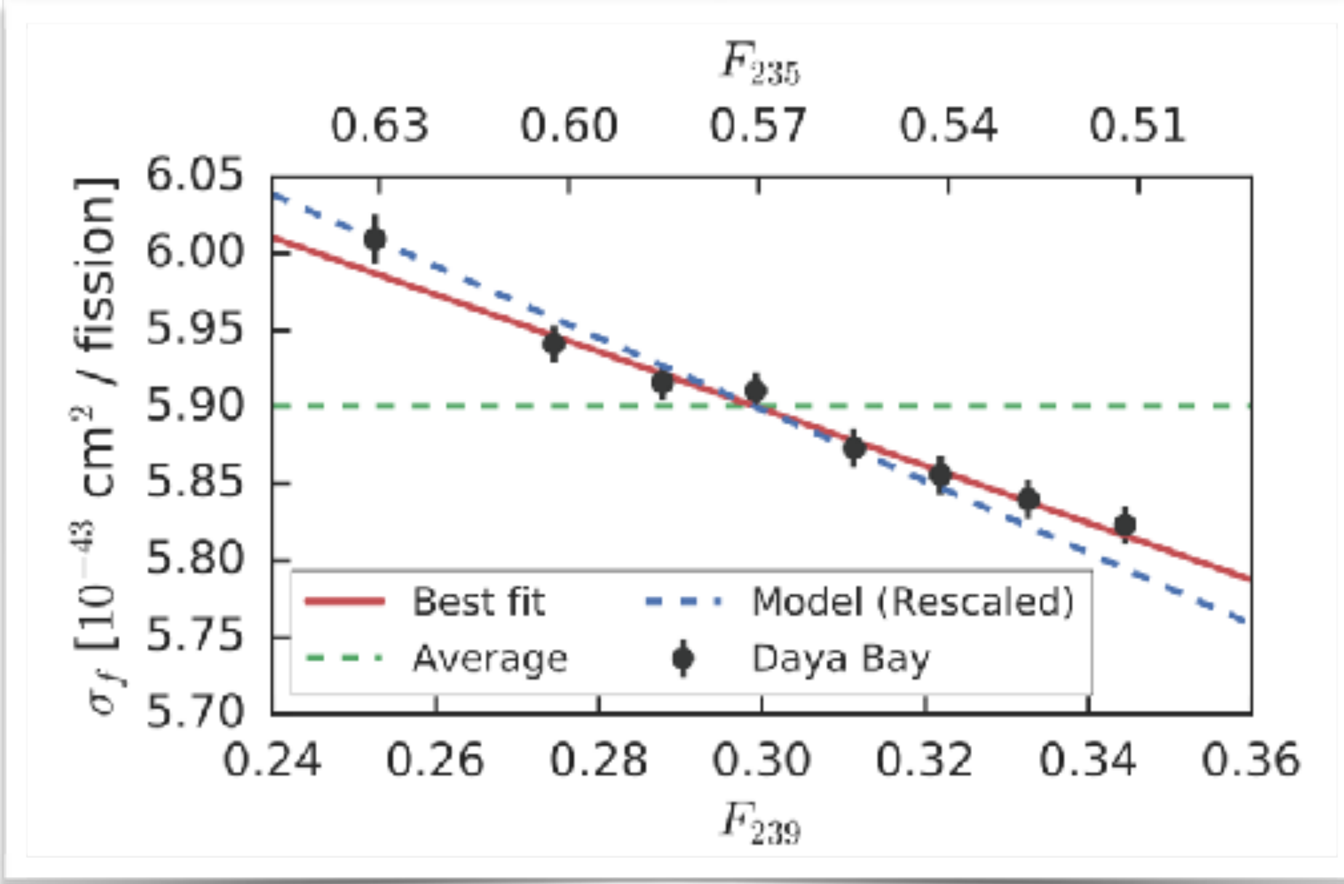
Isotope-Dependent Fluxes

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure inverse β decay rate as function of F_{239}



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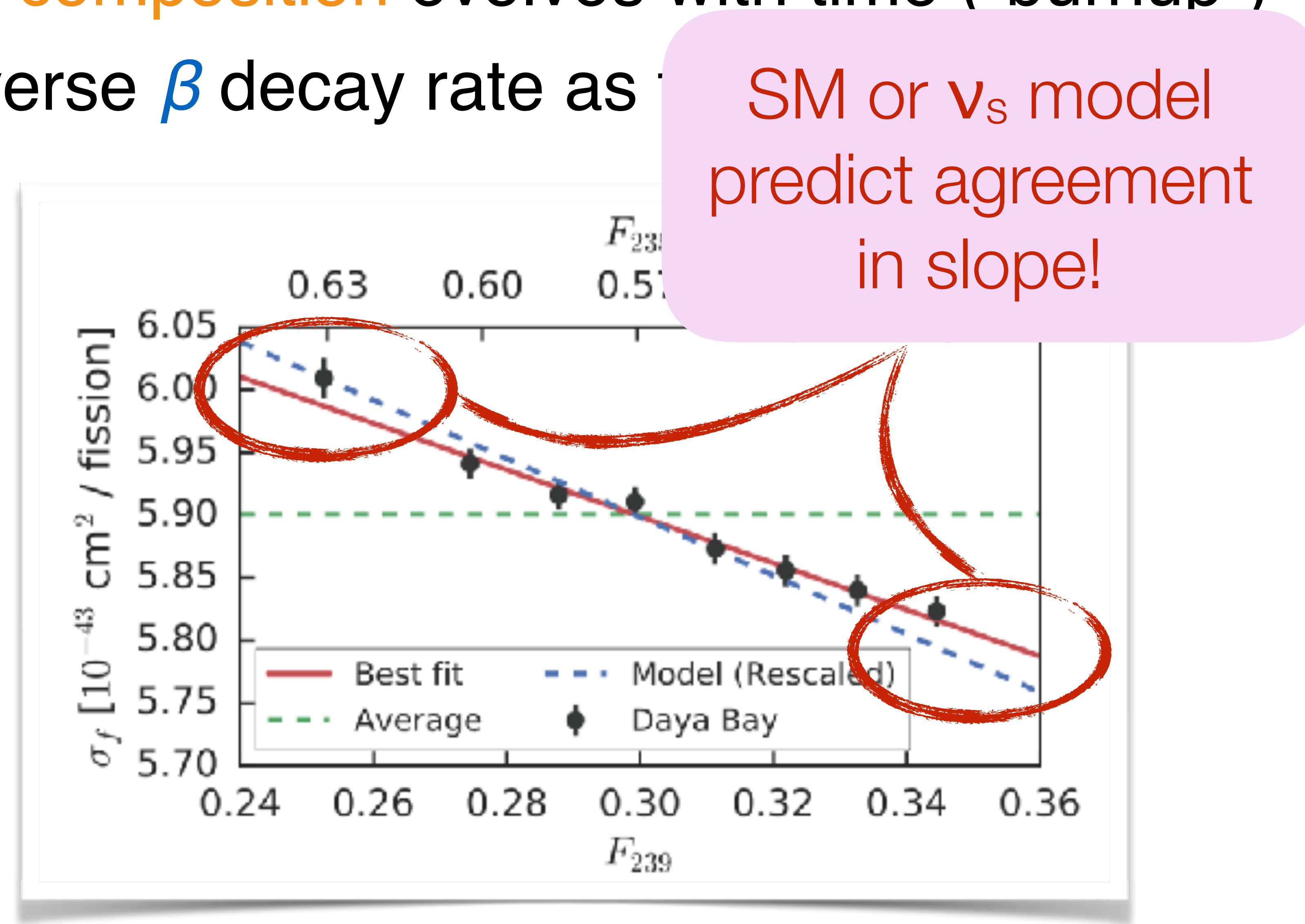
Isotope-Dependent Fluxes

- Reactor fuel composition evolves with time ("burnup")
- Measure inverse β decay rate as f



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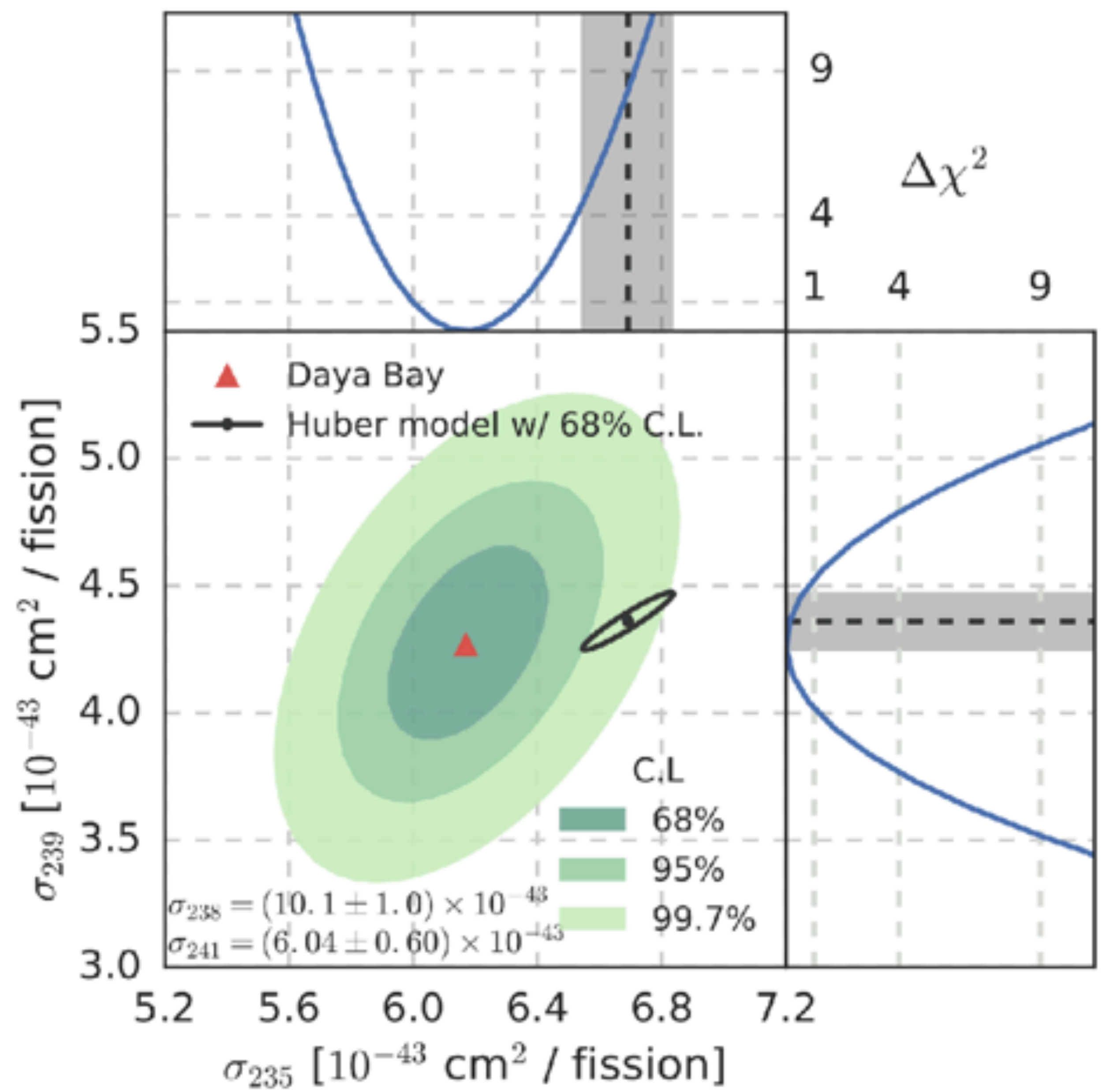
Sterile Neutrinos or Flux Uncertainty?



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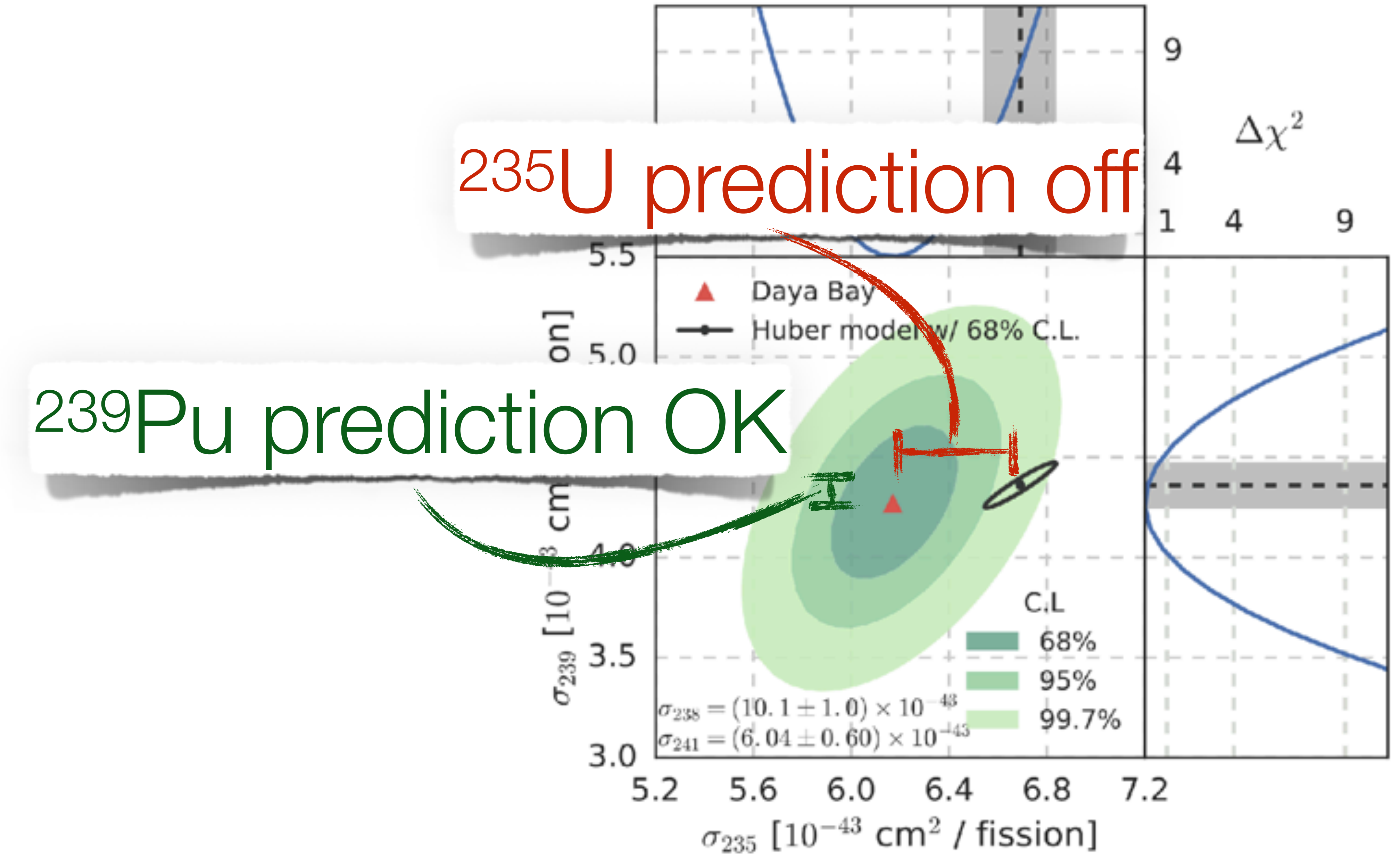

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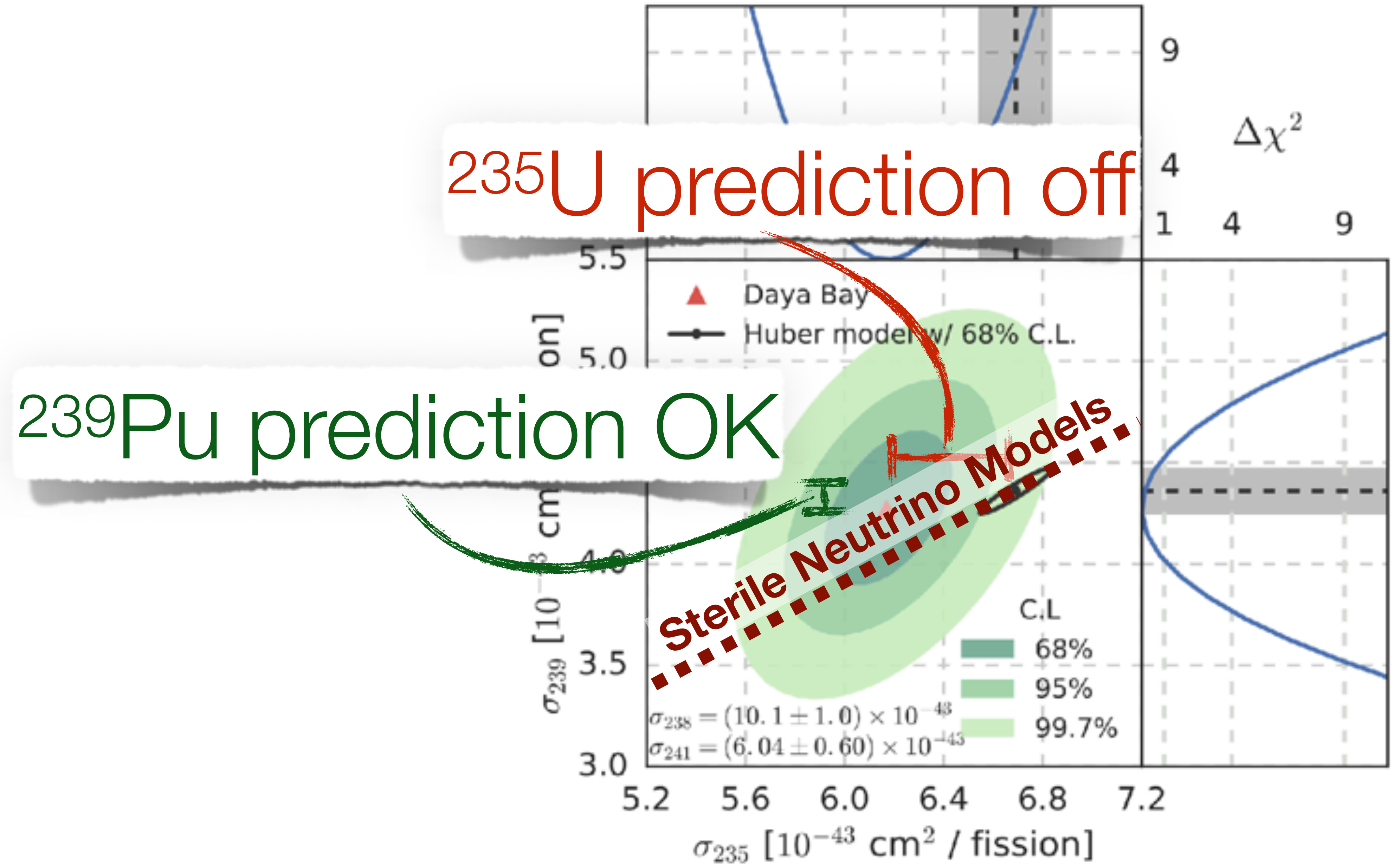

Daya Bay [1704.01082](1704.01082)

Sterile Neutrinos or Flux Uncertainty?

Sterile Neutrinos or Flux Uncertainty?

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

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

Sterile Neutrinos or Flux Uncertainty?

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  - 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)

Dentler Hernández JK Maltoni Schwetz 1709.04294

Sterile Neutrinos or Flux Uncertainty?

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

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

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

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Fixed vs. Free Flux Normalization

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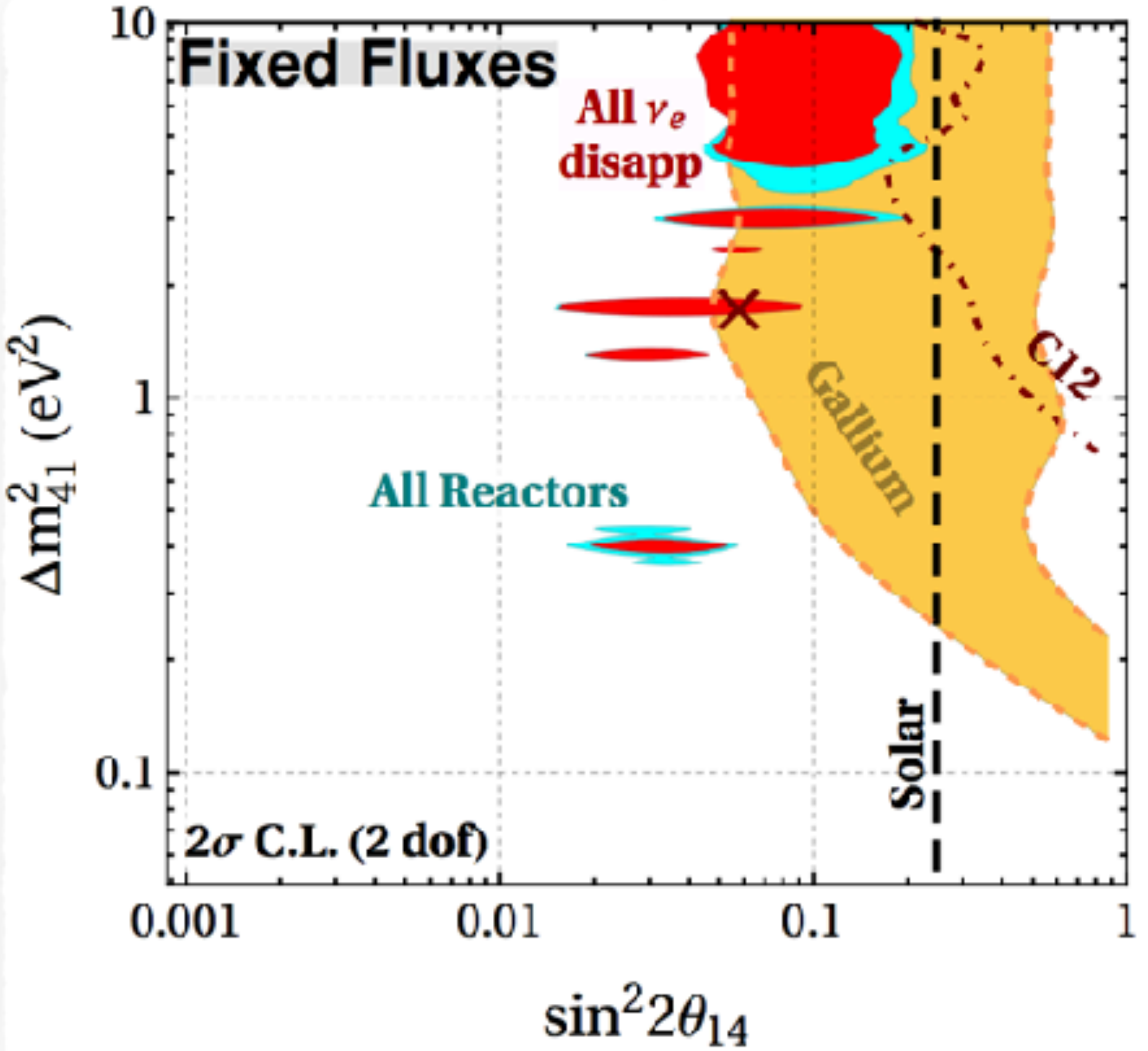
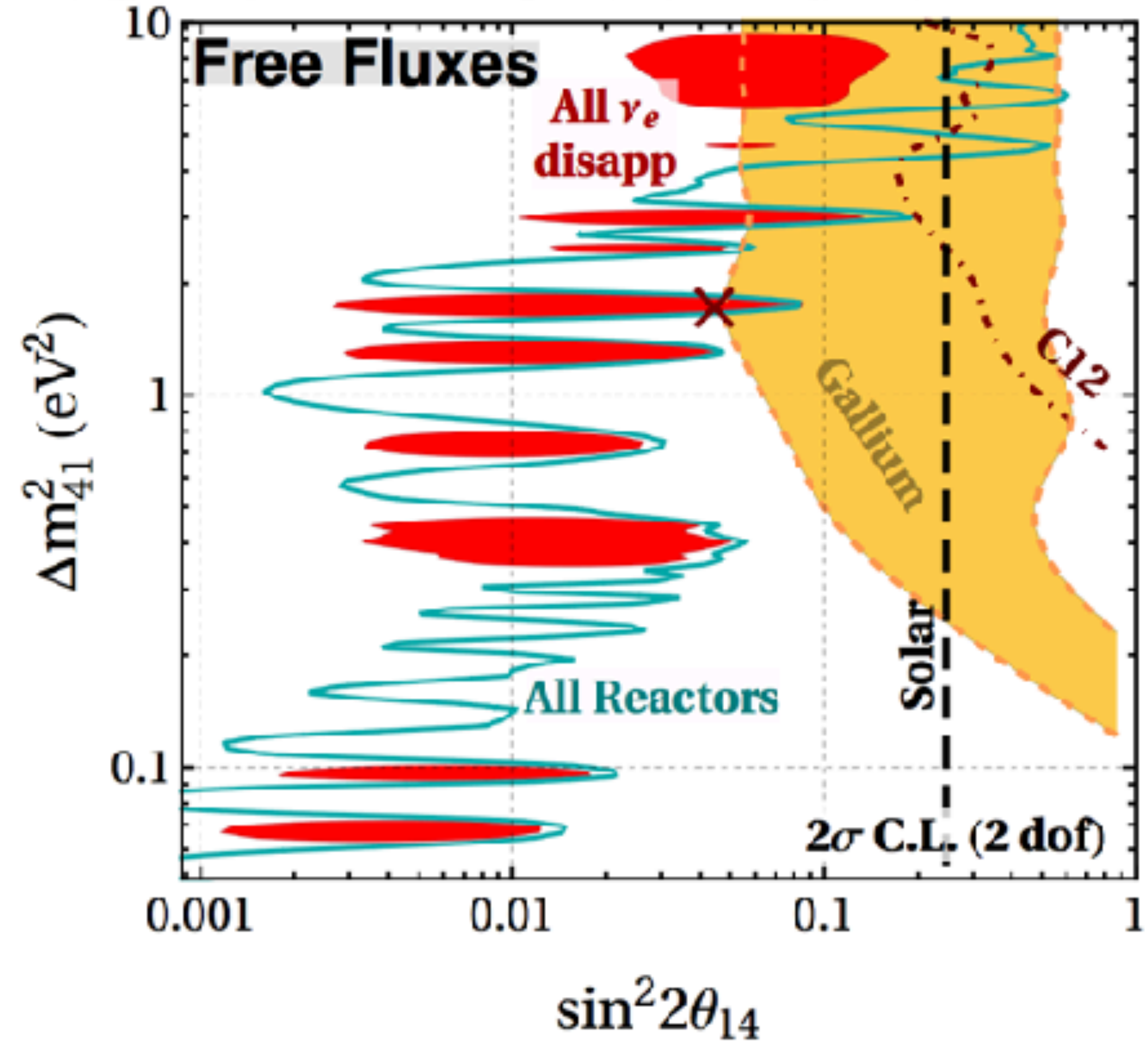
Fixed vs. Free Flux Normalization





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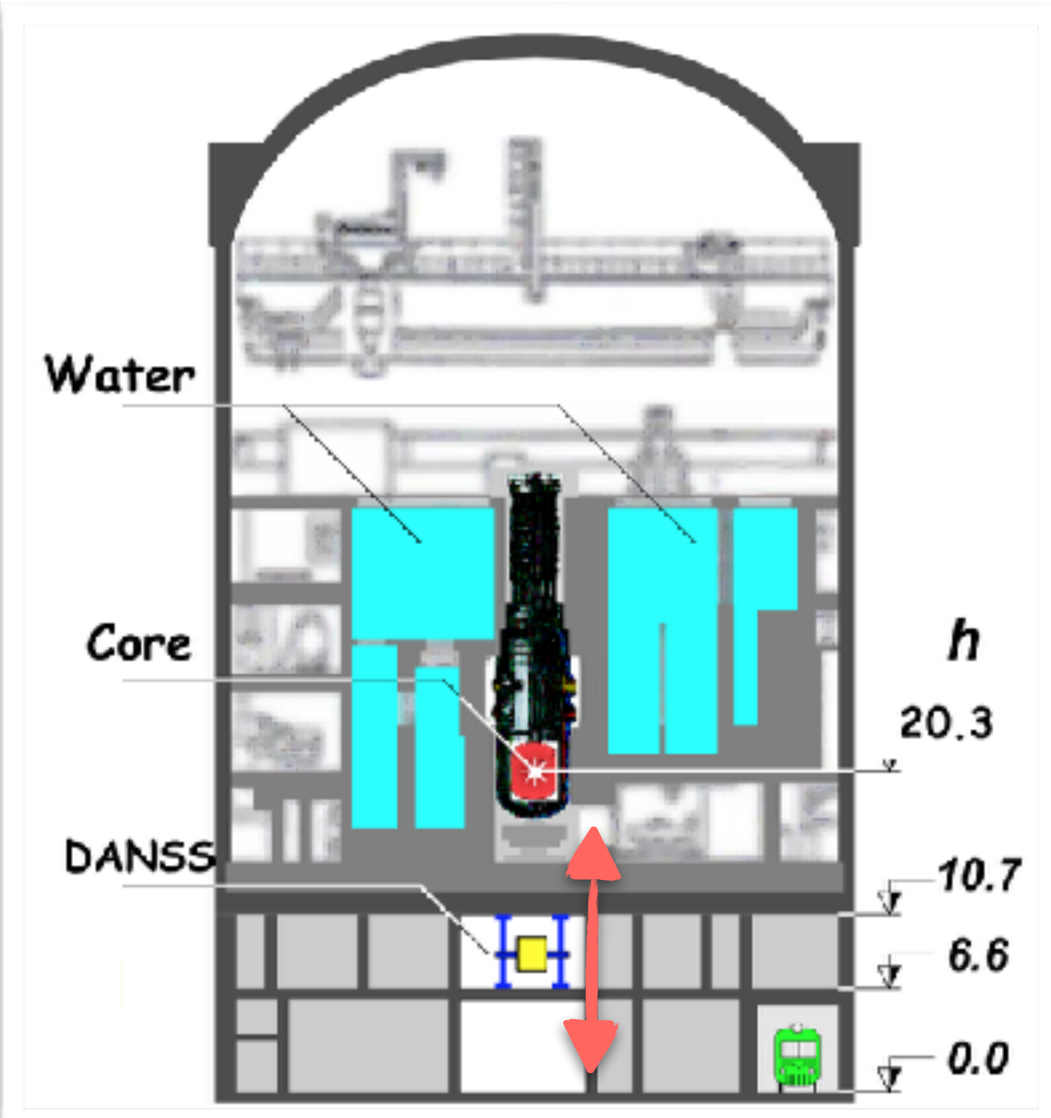
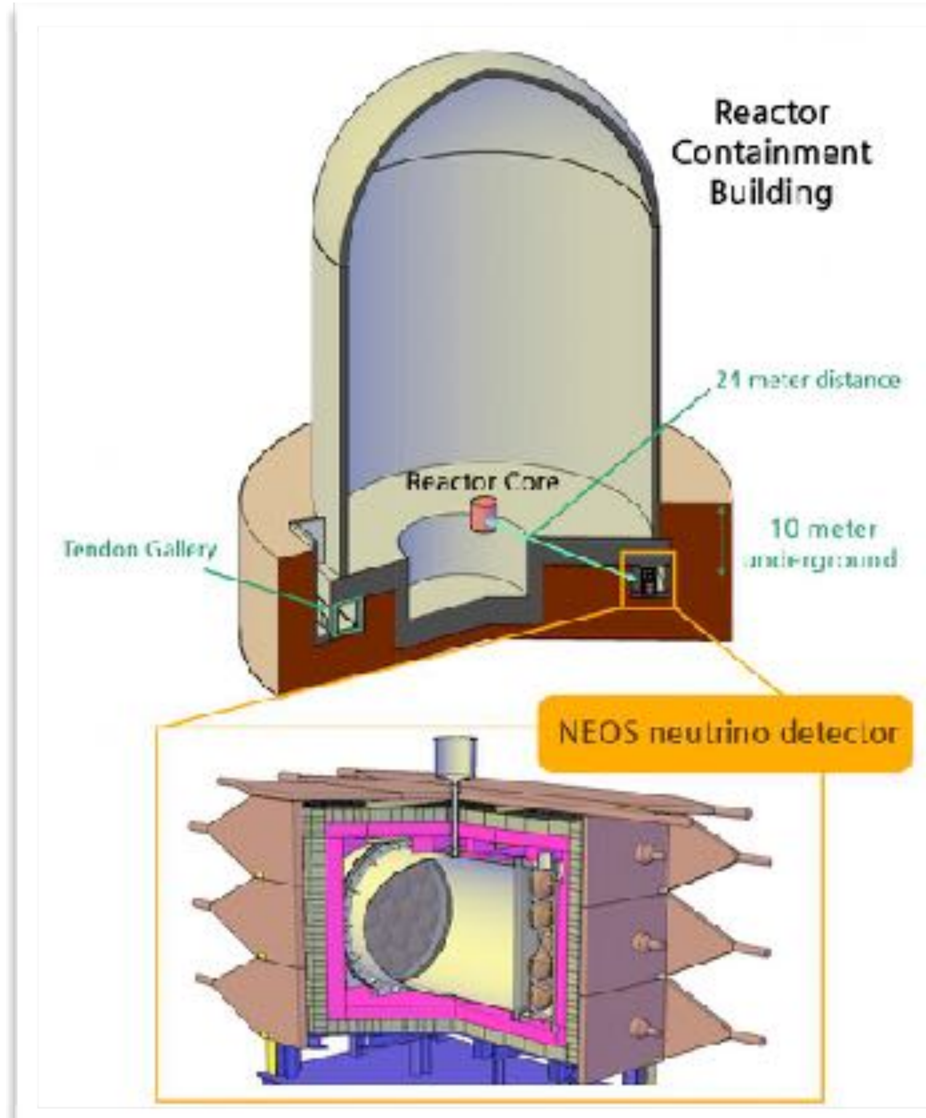
DANSS and NEOS



DANSS

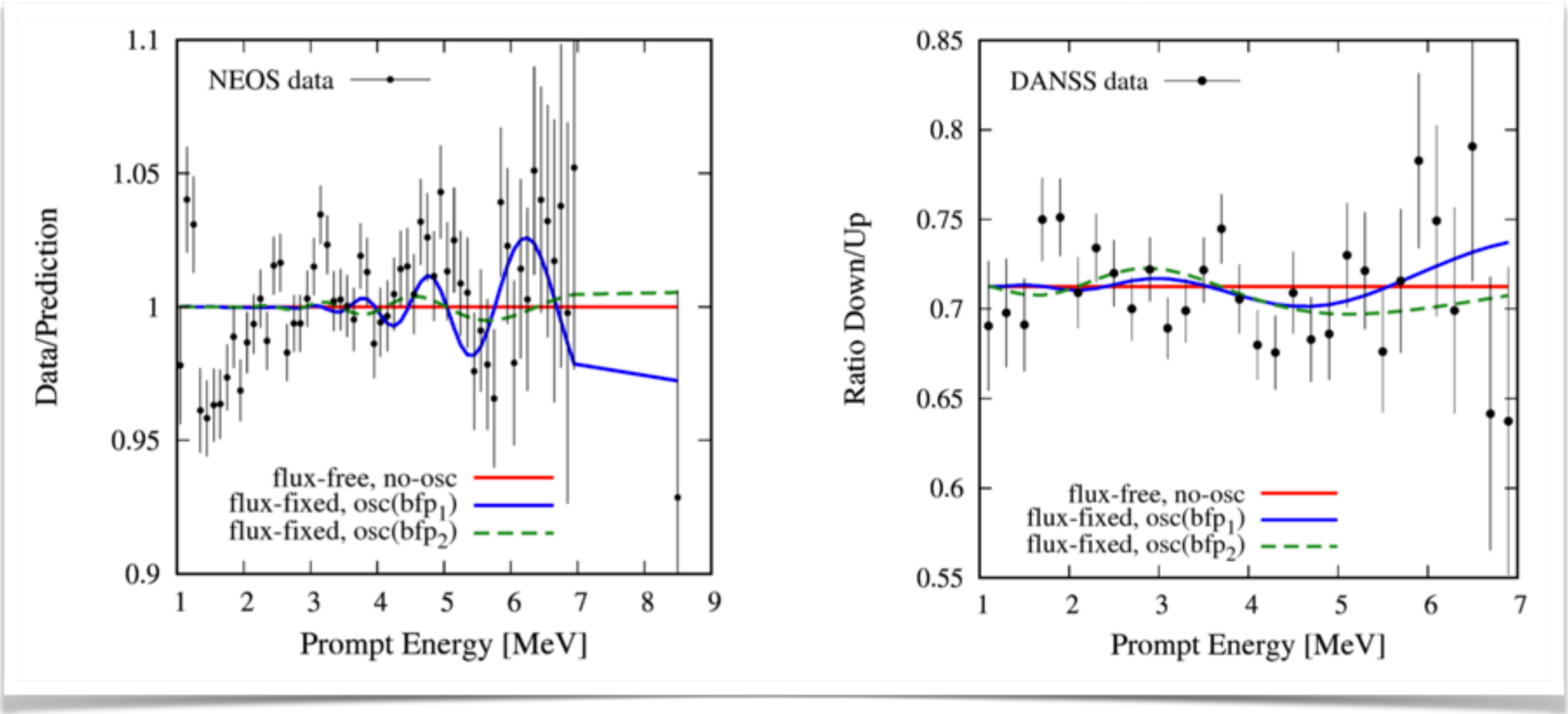
Danilov, Moriond 2017



NEOS

Ko *et al.* 1610.05134
Daya Bay 1607.05378

NEOS and DANSS



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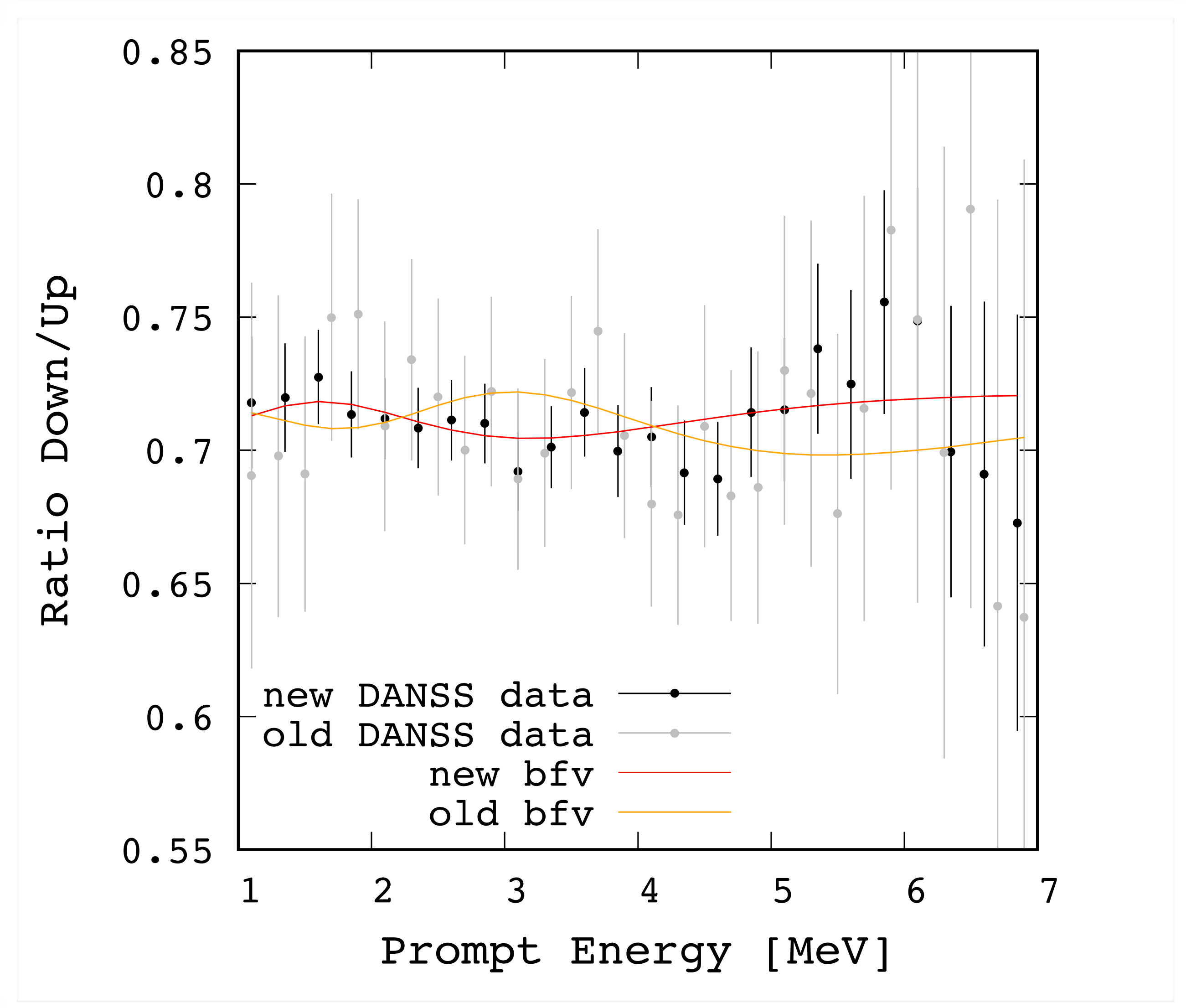
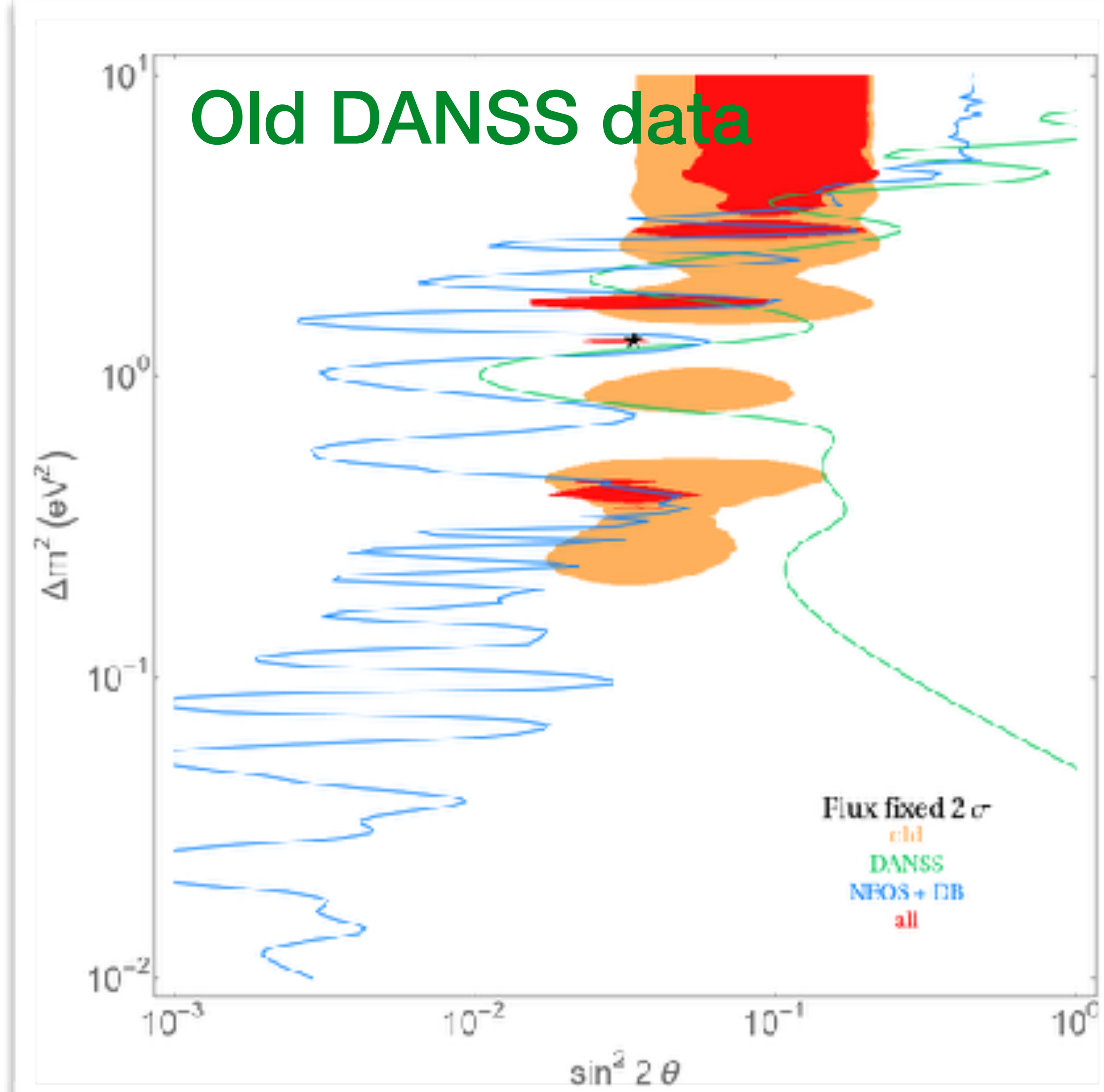
News from DANSS





plots courtesy of Álvaro Hernández
Danilov, Solvay Workshop Dec 2017
Gariazzo Giunti Laveder Li 1801.06467

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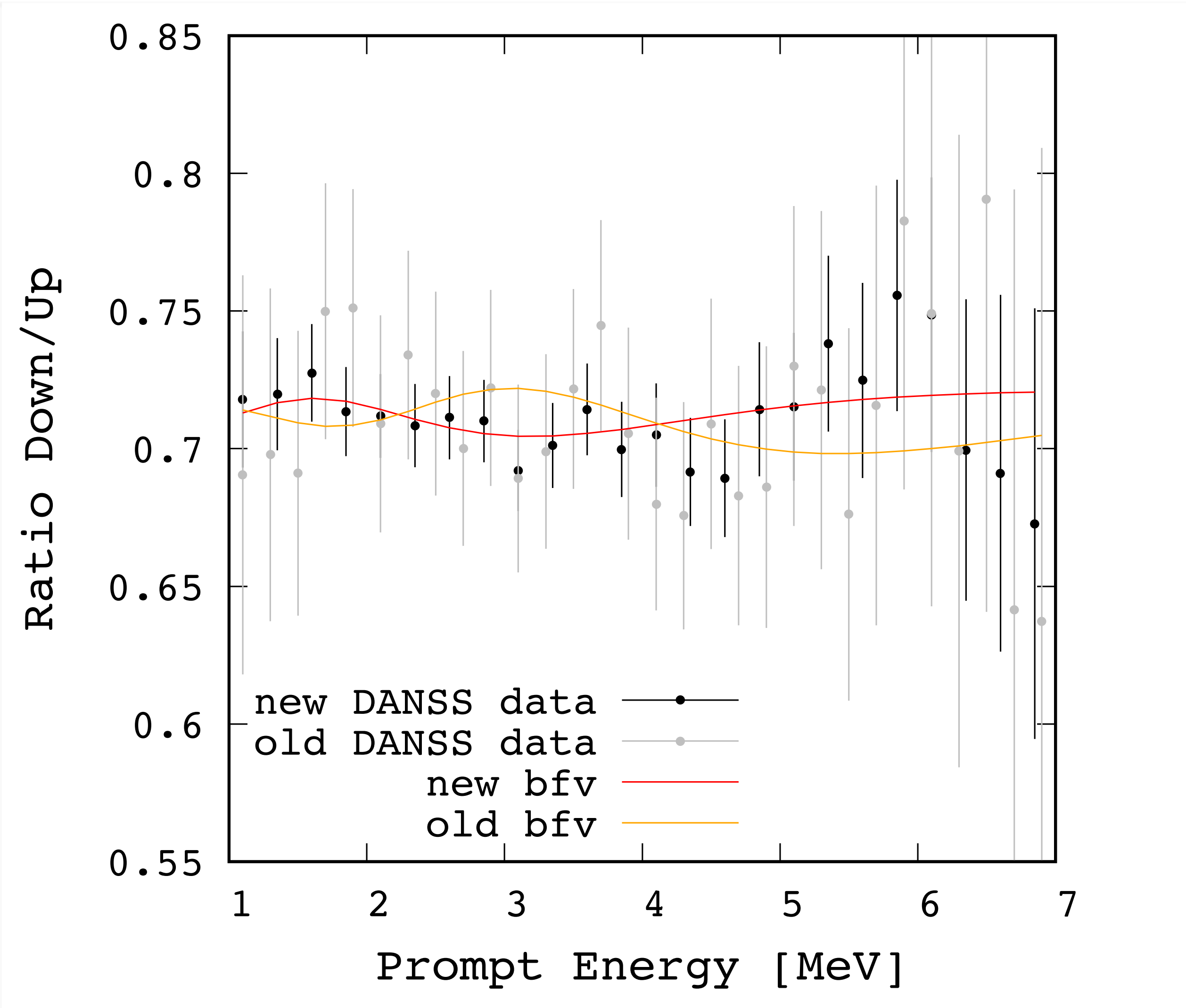

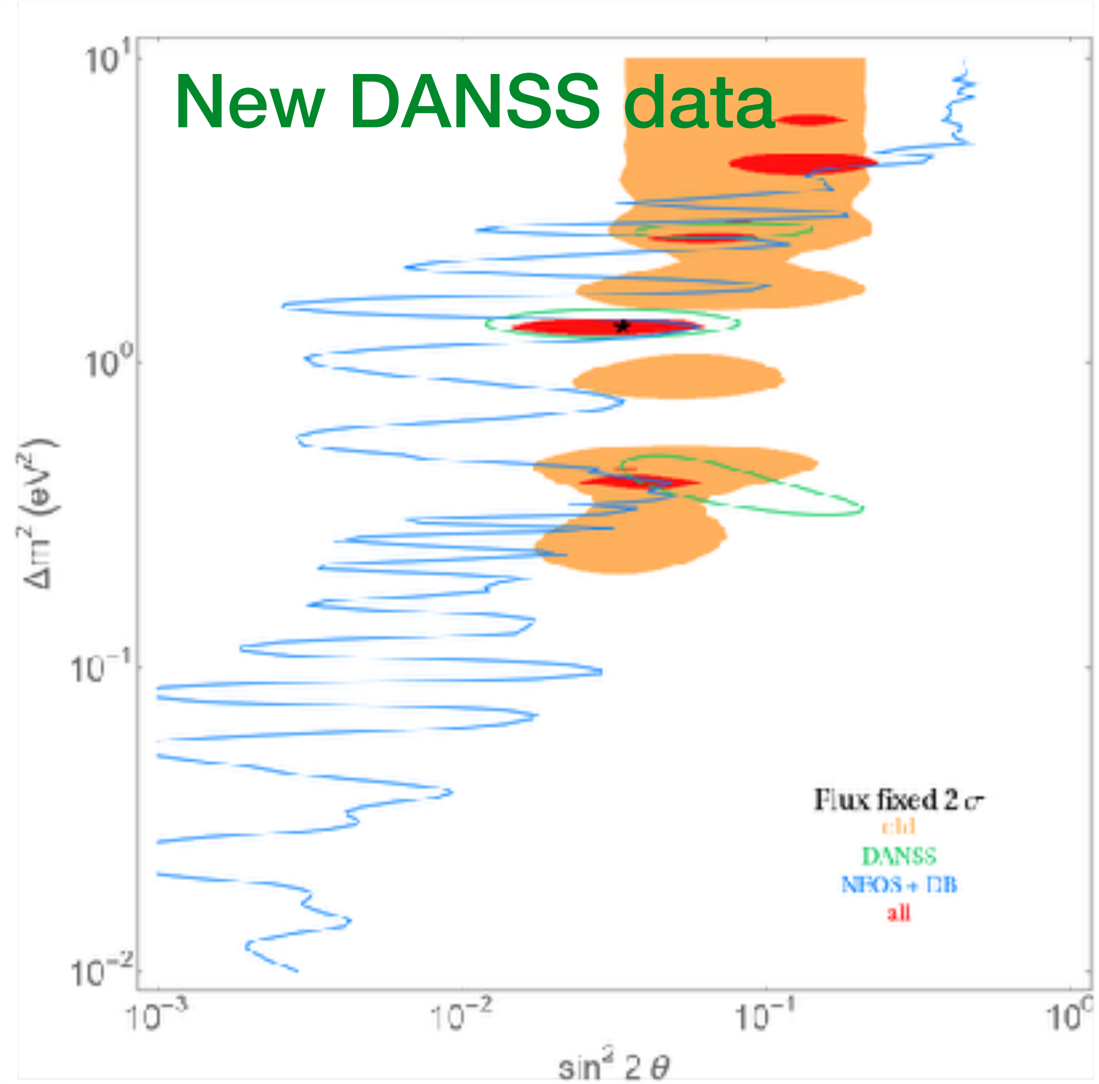

plots courtesy of Álvaro Hernández
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Gariazzo Giunti Laveder Li 1801.06467

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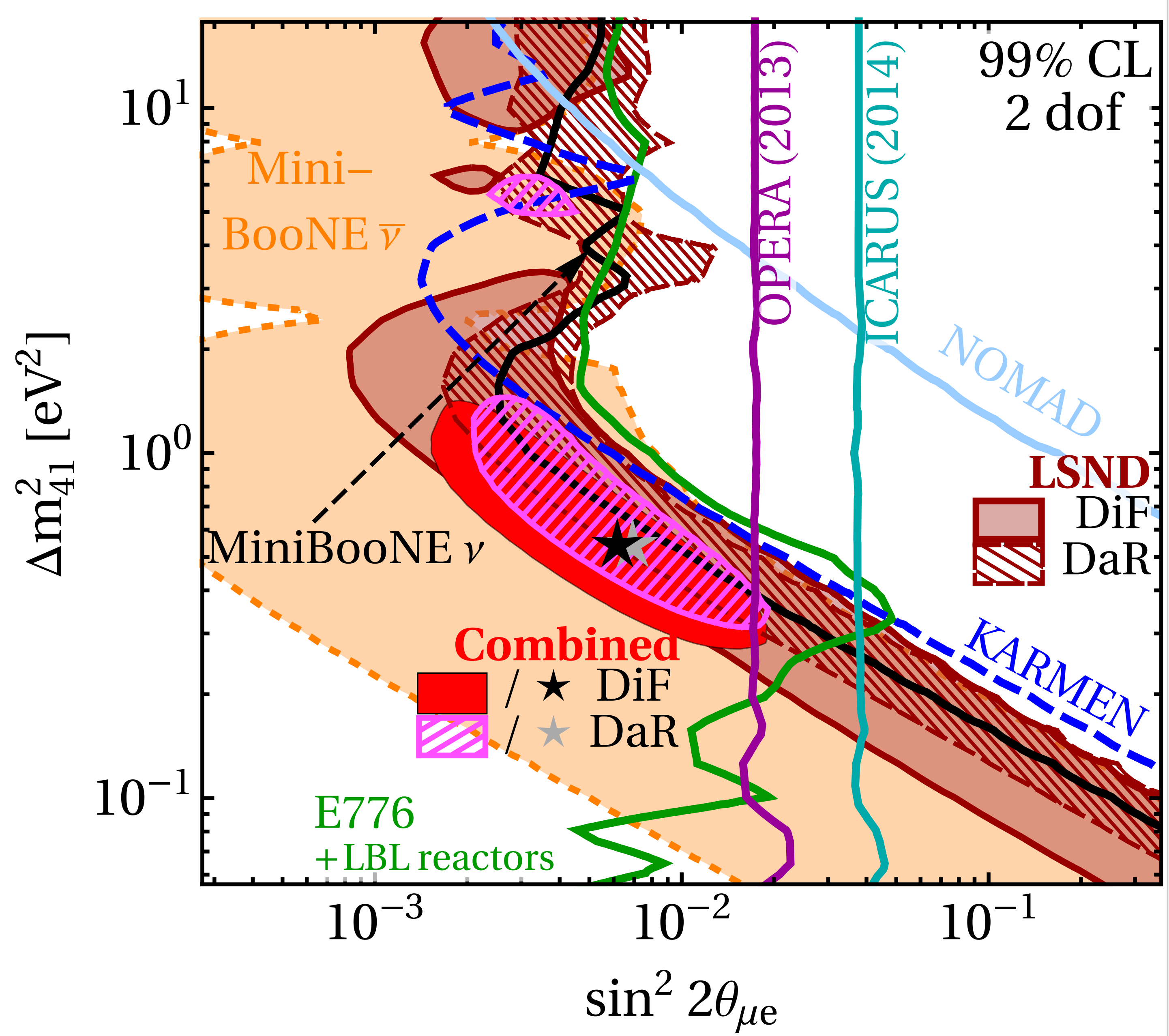
Sterile Neutrinos

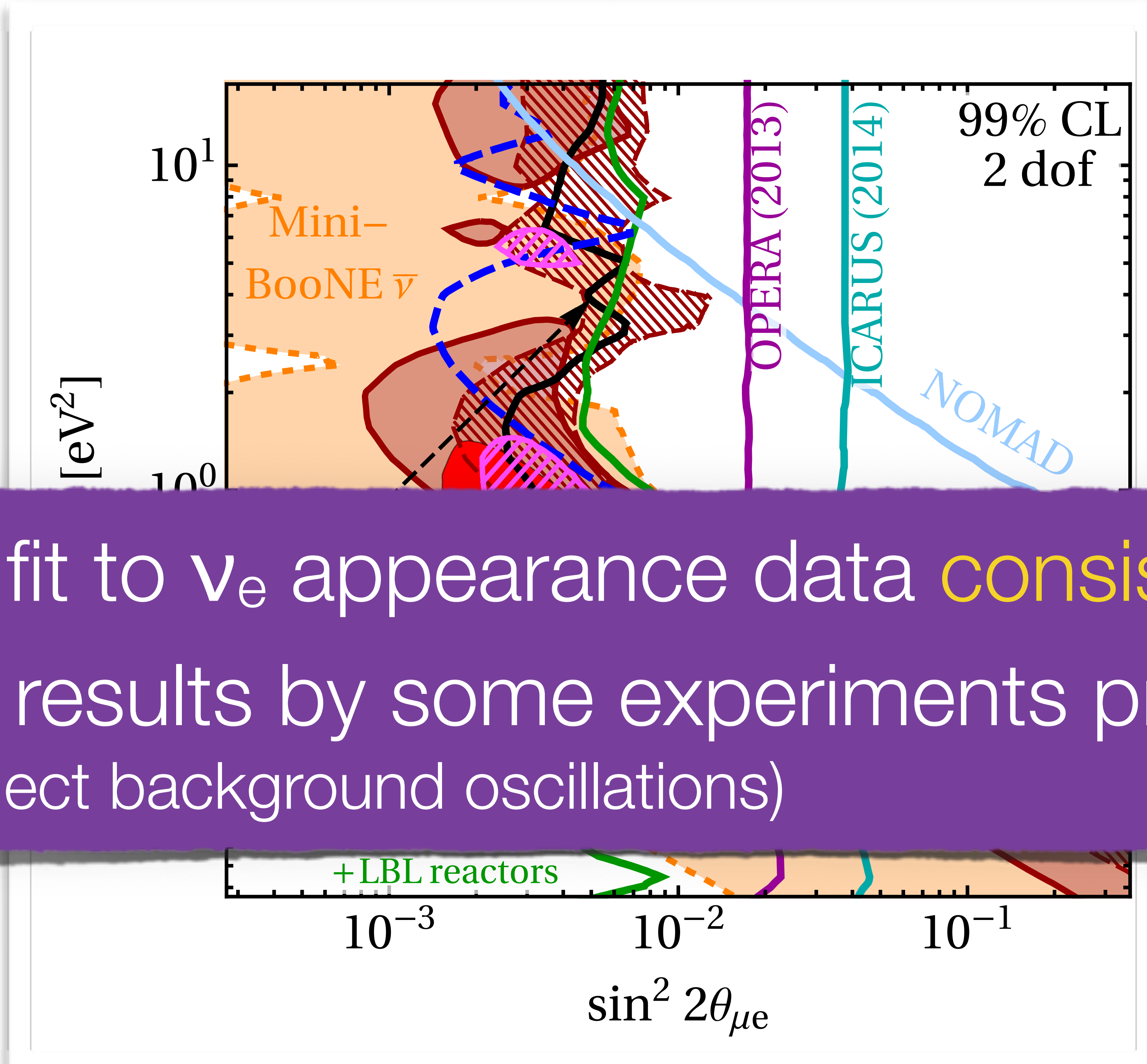
Global Status

$\nu_\mu \to \nu_e$ 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*

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Relation Between Oscillation Channels

- Oscillation channels are related:

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

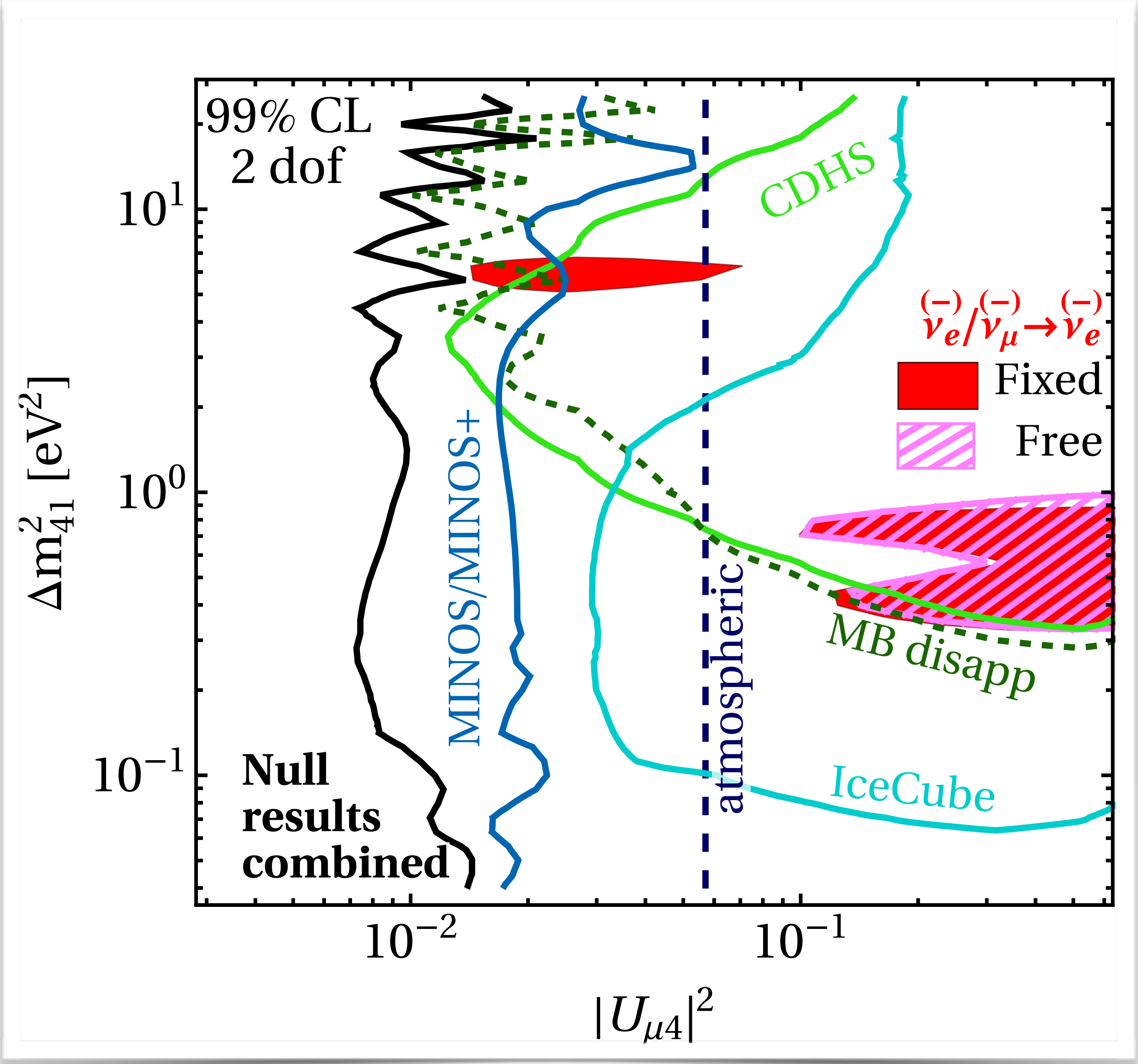
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

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

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

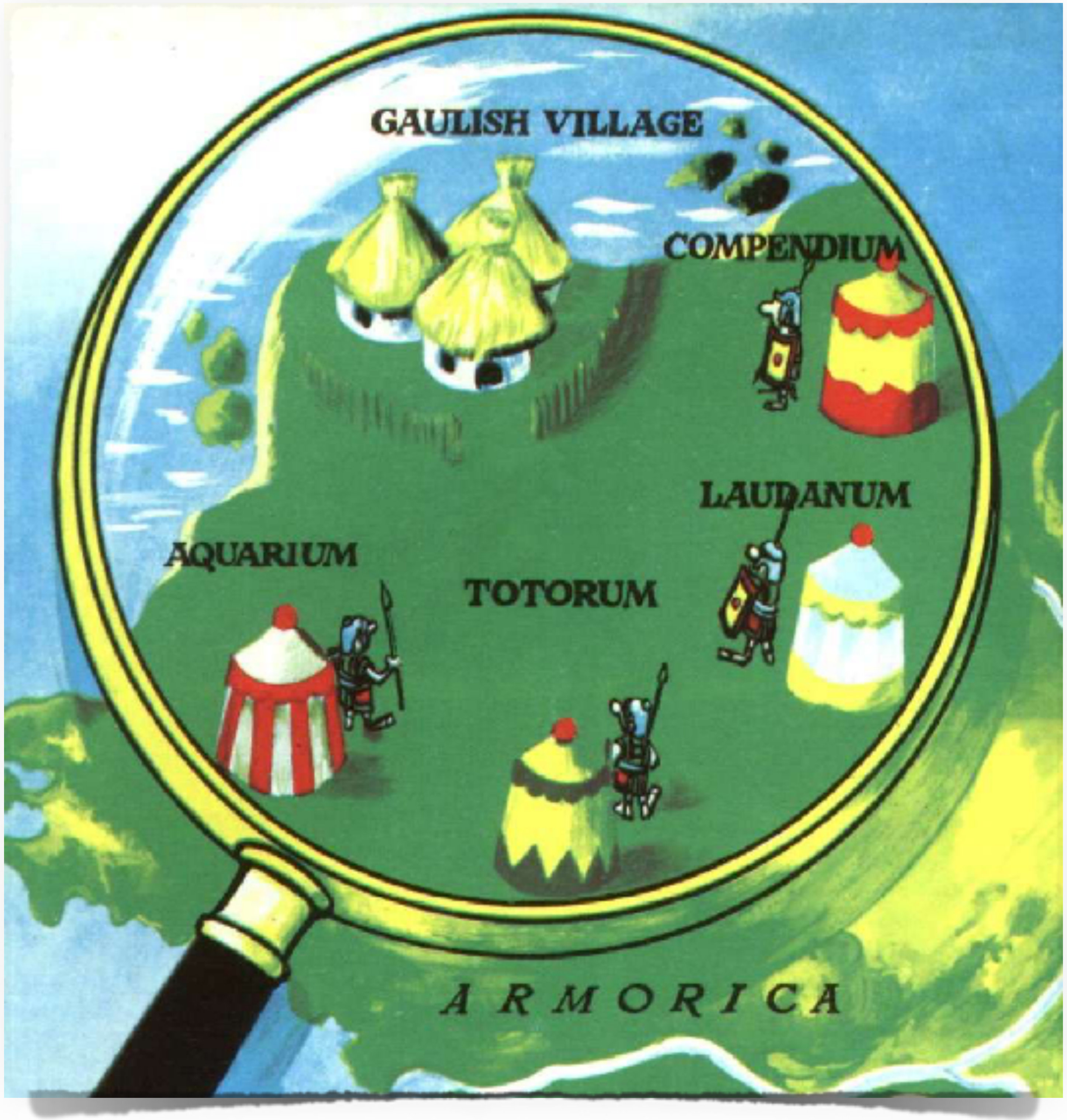
- Models can be over-constrained.

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



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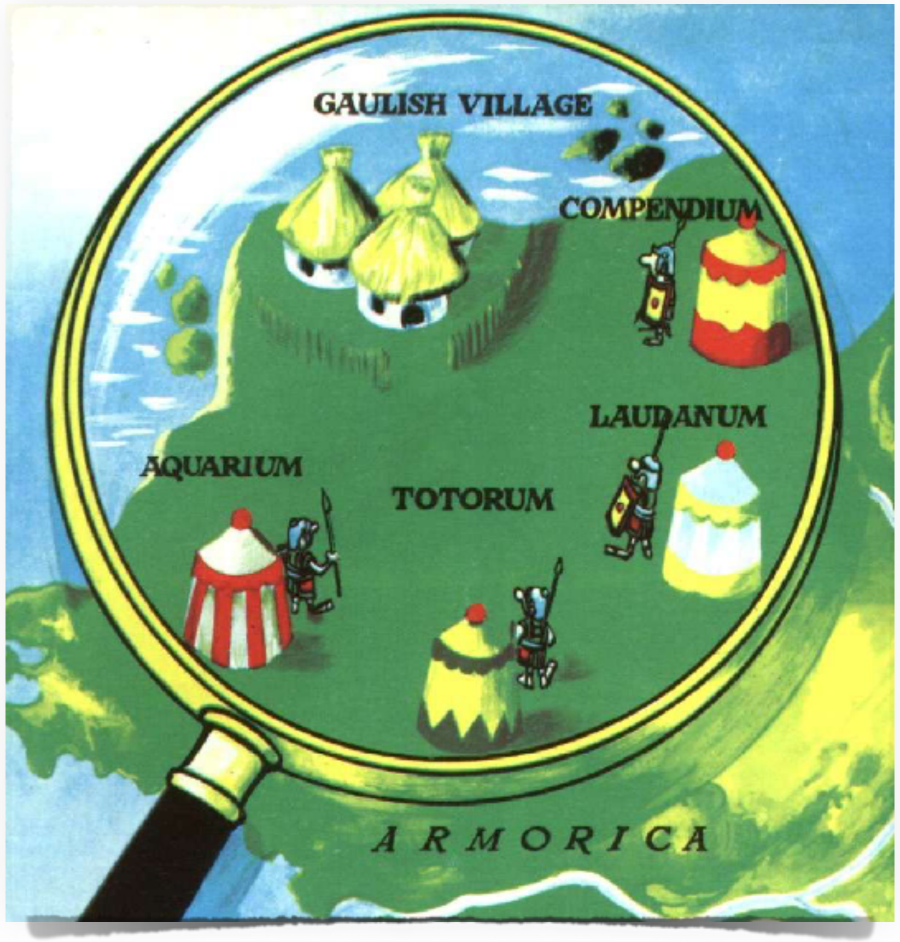


severe tension ($p < 10^{-4}$)

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

Cosmological Constraints

and how to evade them

Sterile Neutrinos in Cosmology

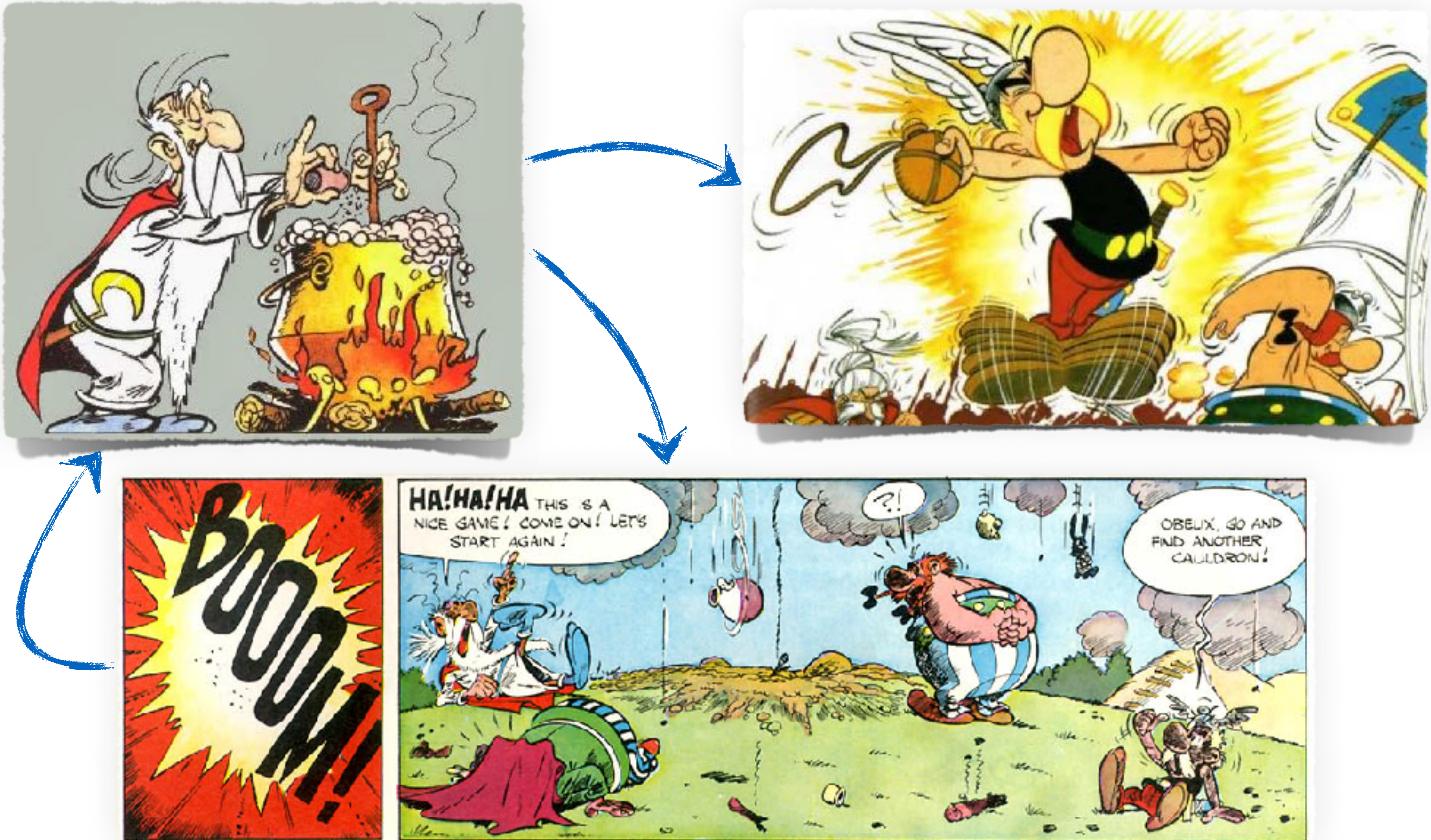
Standard picture: ν_s production via oscillation at T ≳ MeV

- ☑ $\nu_{e,\mu,\tau}$ 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:

$\Sigma m_\nu \lesssim 0.23$

$N_{eff} \lesssim 3.38$

BSM Model Building Flowchart

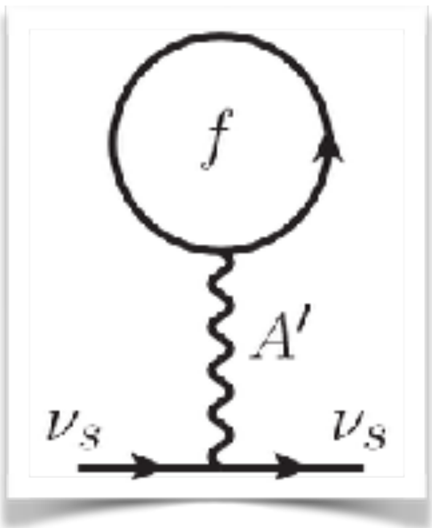


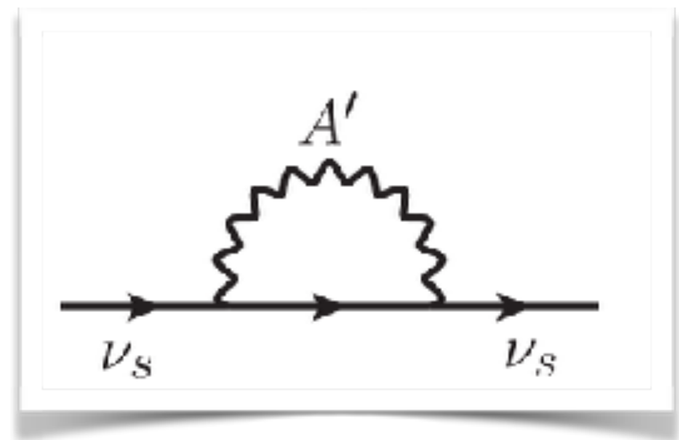
Reconciling Sterile Neutrinos with Cosmology

- Entropy production at $T < \text{MeV}$
  - ν_s diluted — Fuller Kishimoto Kusenko, 1110.6479; Ho Scherrer, 1212.1689
- New interactions in the ν_s sector
  - production suppressed by thermal potential
    Hannestad et al. 1310.5926; Dasgupta JK, 1310.6337
  - minimal scenario now disfavored
    Cherry Friedland Shoemaker 1605.06506
    Chu Dasgupta Dentler JK Saviano, in preparation
- ν_s properties change in late phase transition
  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}





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

thermal correction $V \sim T^a$

- ☑ Effective mixing angle

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

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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 $V \sim T^a$

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

- ☑ Effective mixing angle

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

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Suppressed ν_s Production

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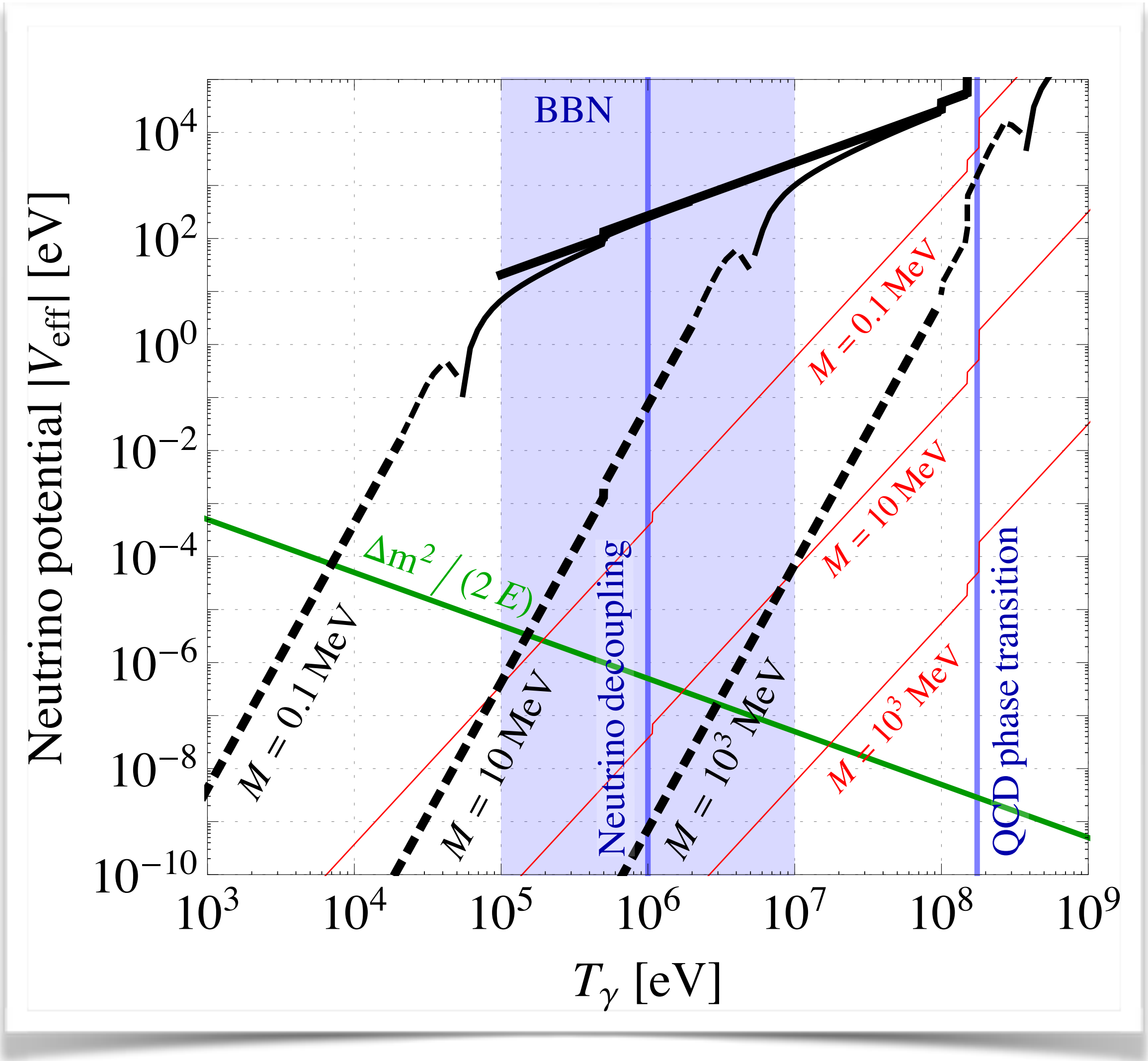

- ☑ If $V_{\rm eff} \gg \Delta m^2/(2T)$: ν_s production suppressed Hannestad *et al.* 1310.5926
Dasgupta JK 1310.6337

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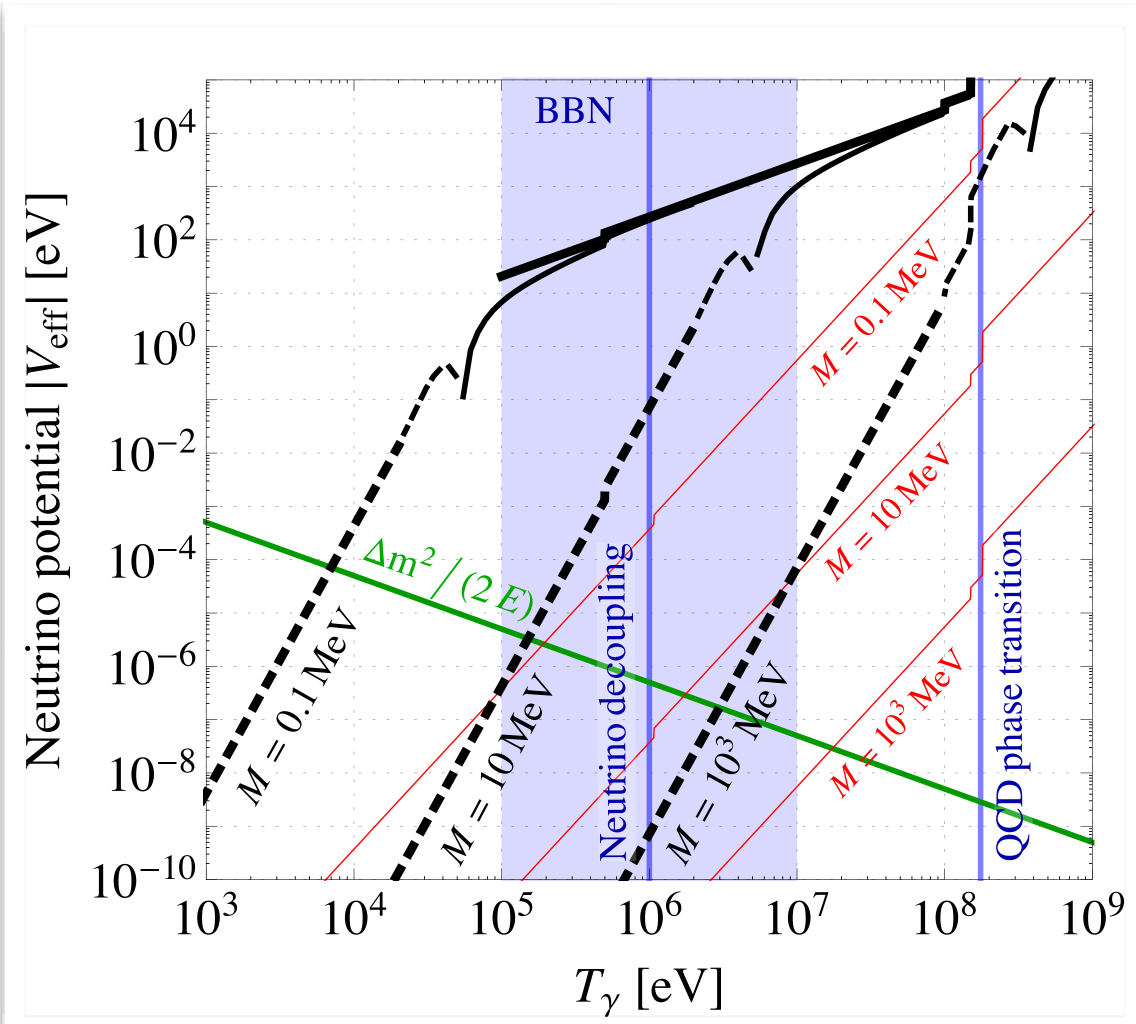
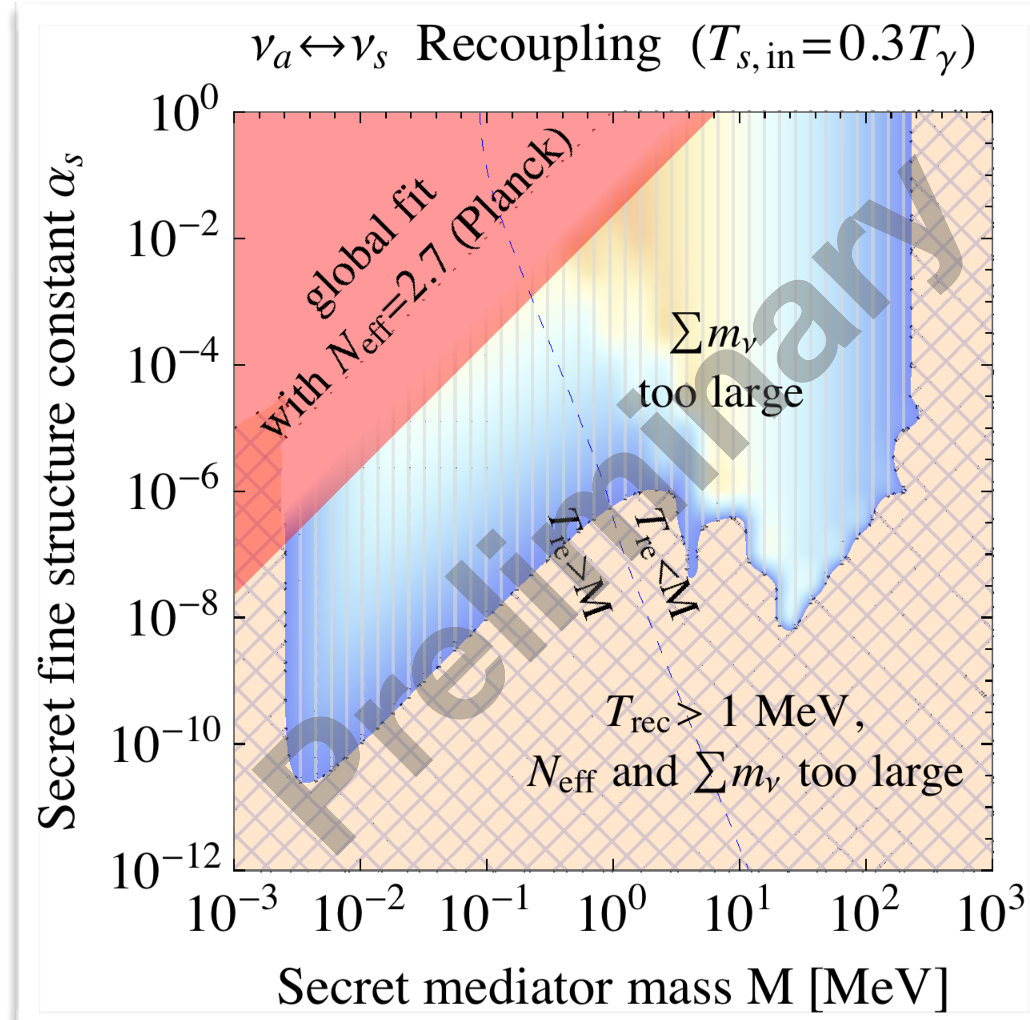
Suppressed ν_s Production





- ☑ If $V_{\rm eff} \gg \Delta m^2/(2T)$: ν_s production suppressed Hannestad *et al.* 1310.5926, Dasgupta JK 1310.6337
- ☑ Problem: late equilibration between $\nu_{e,\mu,\tau}$ and ν_s

Chu Dasgupta JK 1505.02795, Cherry Friedland Shoemaker 1605.06506
Chu Dasgupta Dentler JK Saviano, *in preparation*

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Suppressed ν_s Production

Bezrukov Chudaykin Gorbunov, 1705.02184
Chu Dasgupta Dentler JK Saviano, *in preparation*

☑ Basic idea

- large ν_s mass at early times ➠ production kinematically suppressed
- late phase transition reduces mass to ~ eV

☑ Toy model

$$V(\phi_1, \phi_2) = \frac{\lambda_1}{4}\phi_1^4 + \frac{\lambda_2}{4}\phi_2^4 + \frac{\lambda_p}{2}\phi_1^2\phi_2^2 + \frac{\mu_1^2}{2}\phi_1^2 + \frac{\mu_2^2}{2}\phi_2^2$$

$$\mathcal{L}_{\text{Yukawa}} = -y\phi_1\overline{\nu_{sL}}\nu_{sR} - \frac{1}{2}m_{sL}\overline{\nu_{sL}^c}\nu_{sL} - \frac{1}{2}m_{sR}\overline{\nu_{sR}^c}\nu_{sR} + h.c.$$

☑ Possible behavior: inverse symmetry breaking

Weinberg 1974

- large T: $\langle\phi_1\rangle \neq 0$, $\langle\phi_2\rangle = 0$ (V_{eff} dominated by thermal corrections)
- small T: $\langle\phi_1\rangle = 0$, $\langle\phi_2\rangle = 0$ ➠ ν_s mass given by m_{sL}, m_{sR}

Summary

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Summary

- Reactor anomaly: significant $\overline{\nu}_e$ deficit
  - hint for sterile neutrinos?
  - or systematic uncertainty in the prediction?
- Daya Bay: fluxes functions of isotope composition
  - preference for ^{235}U misprediction
  - but ν_s hypothesis gives good fit as well
  - even for unconstrained fluxes, preference for ν_s persist
- Global Fit: severe tension with ν_μ disappearance
- Cosmology: constraints evaded in non-minimal models

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Thank you!