Sterile Neutrinos at the eV Scale

Whence, Where, and Whither?

Joachim Kopp (CERN & University of Mainz, Germany)

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In this Talk

- **The Neutrino Flavor Anomalies**
  - LSND & MiniBooNE: Anomalous $\nu_\mu \to \nu_e$ oscillations?
  - Reactor and Gallium Anomalies: Where are the missing ν_e?
- **Sterile Neutrinos:** Global Status
- **Cosmological Constraints** (and how to evade them)

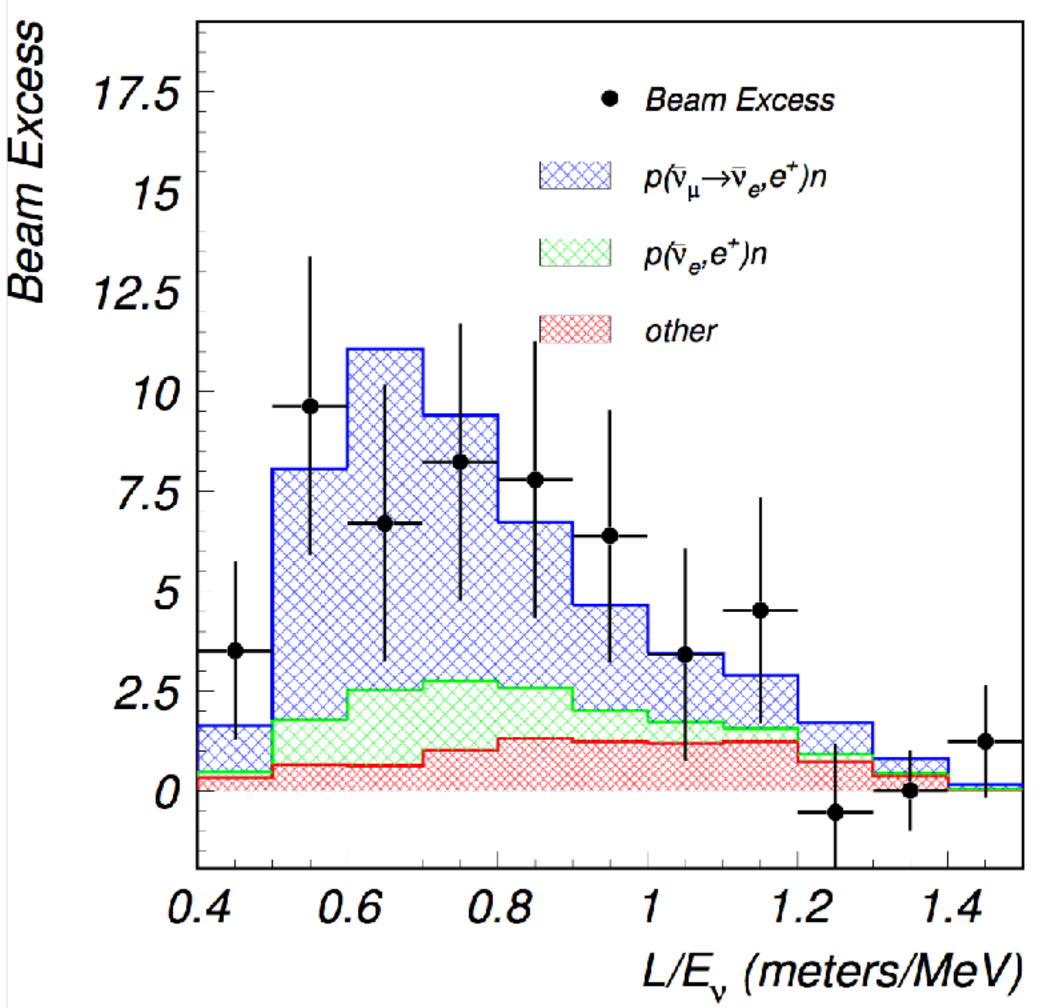
The Neutrino Flavor Anomalies

A Hint for Sterile Neutrinos?

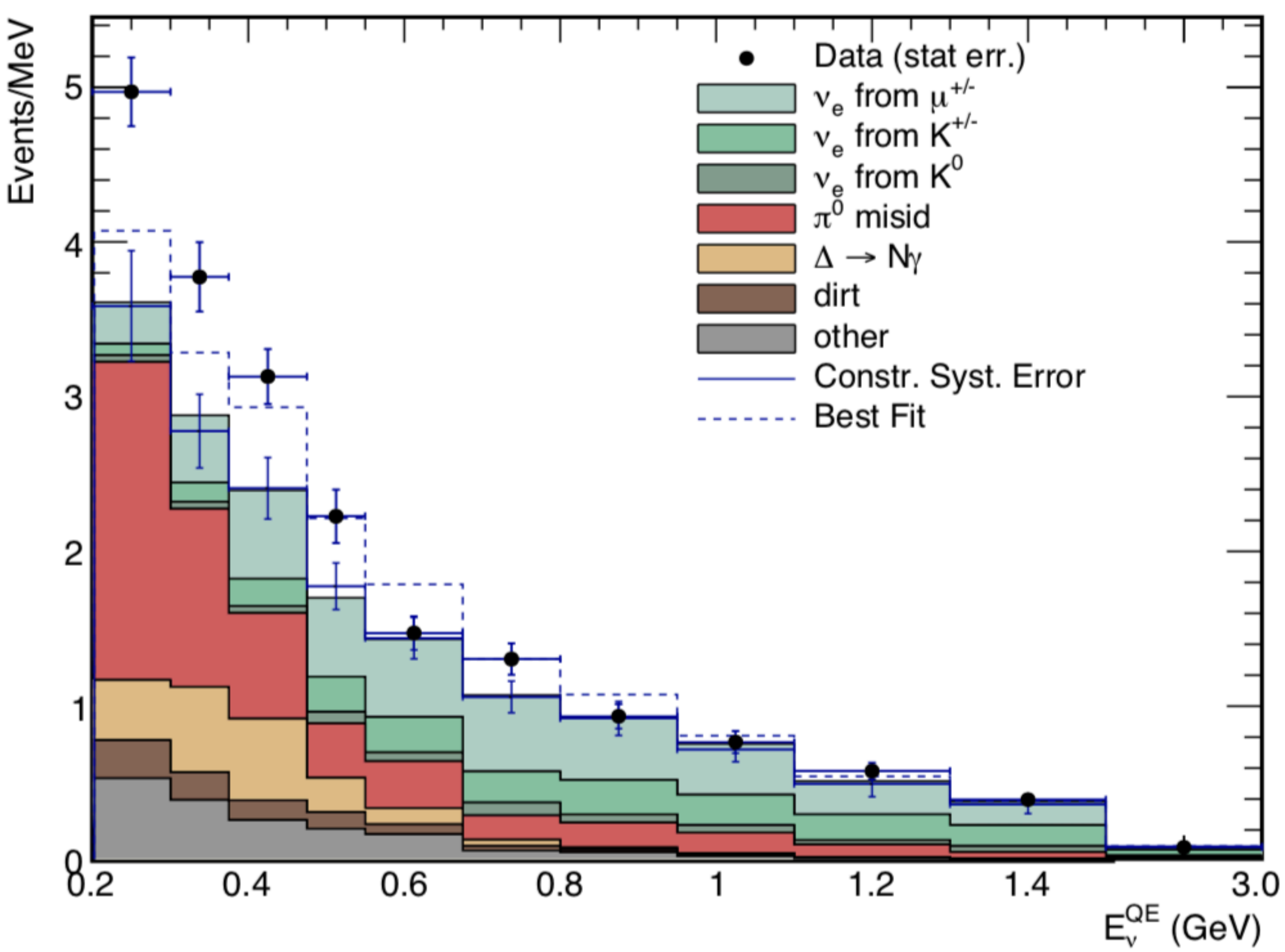
Anomalies in Short Baseline Oscillations

Anomalies in Short Baseline Oscillations

☑ LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations



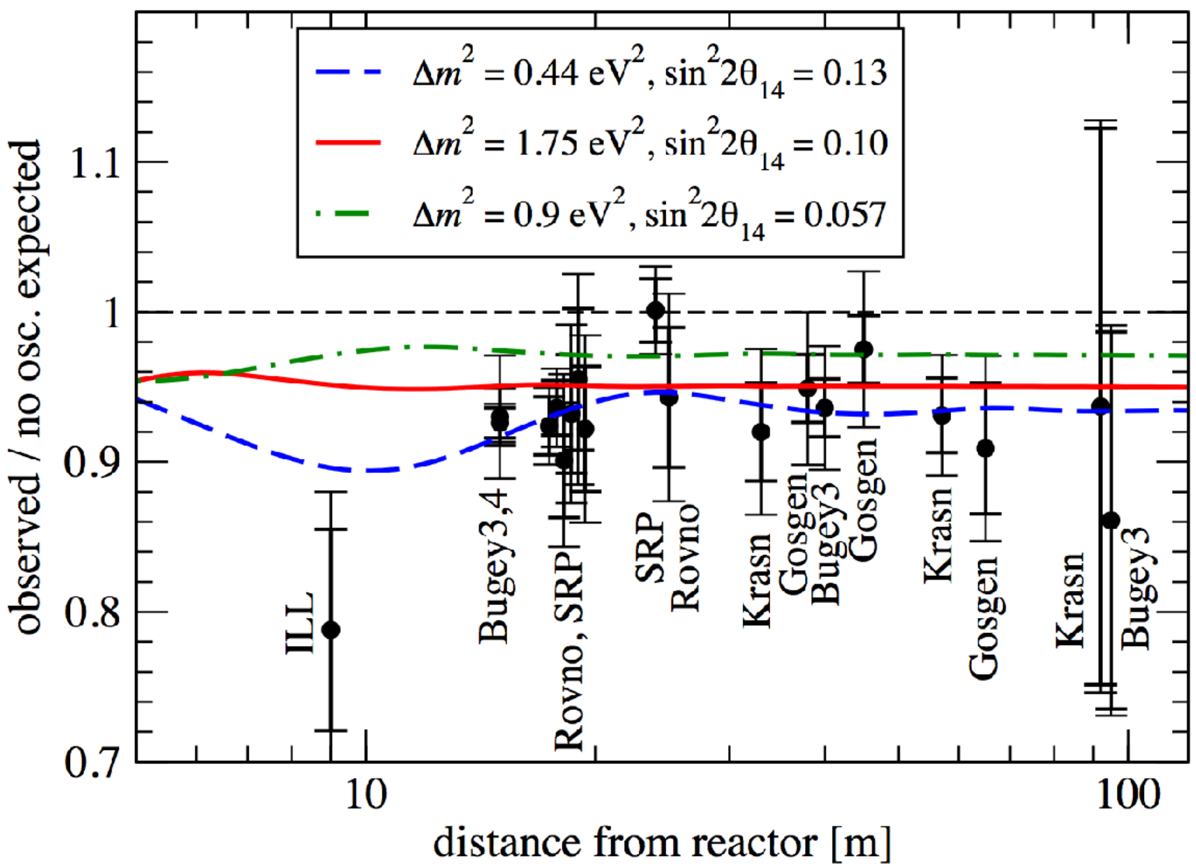
LSND 2001



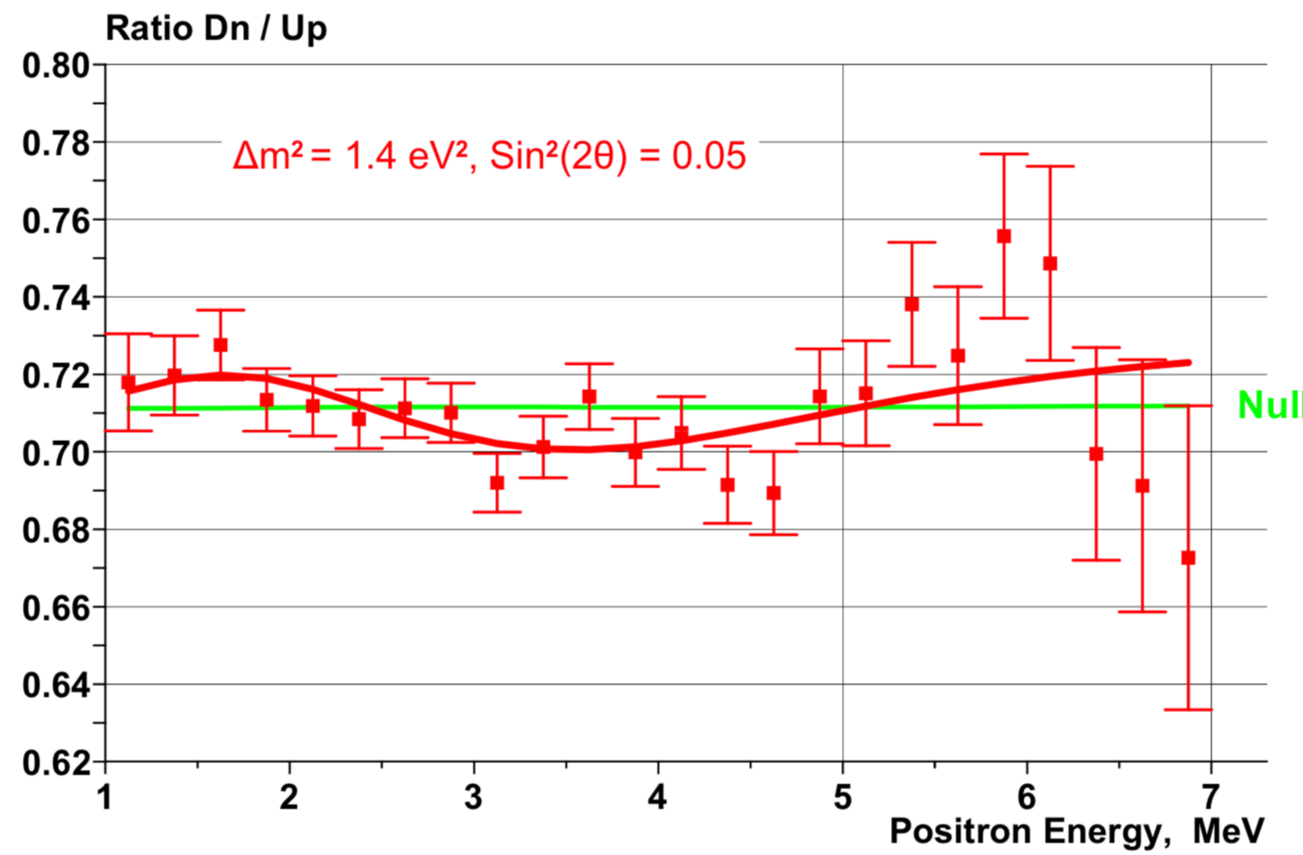
MiniBooNE 2018

Anomalies in Short Baseline Oscillations

- **LSND / MiniBooNE:** anomalous $\nu_\mu \to \nu_e$ oscillations
- **Reactor & Gallium Experiments:** anomalous ν_e disappearance



Mention et al., 1101.2755



DANSS Collaboration @ Neutrino 2018

Anomalies in Short Baseline Oscillations

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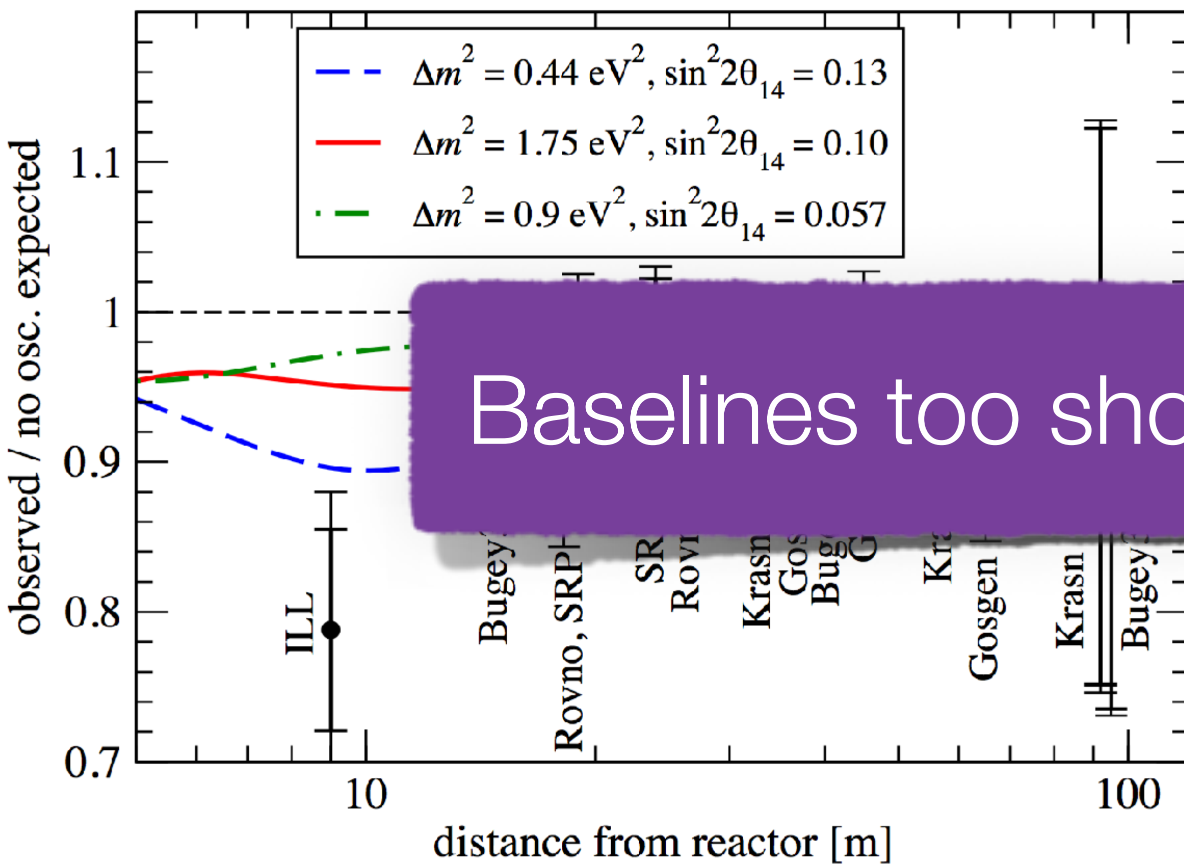

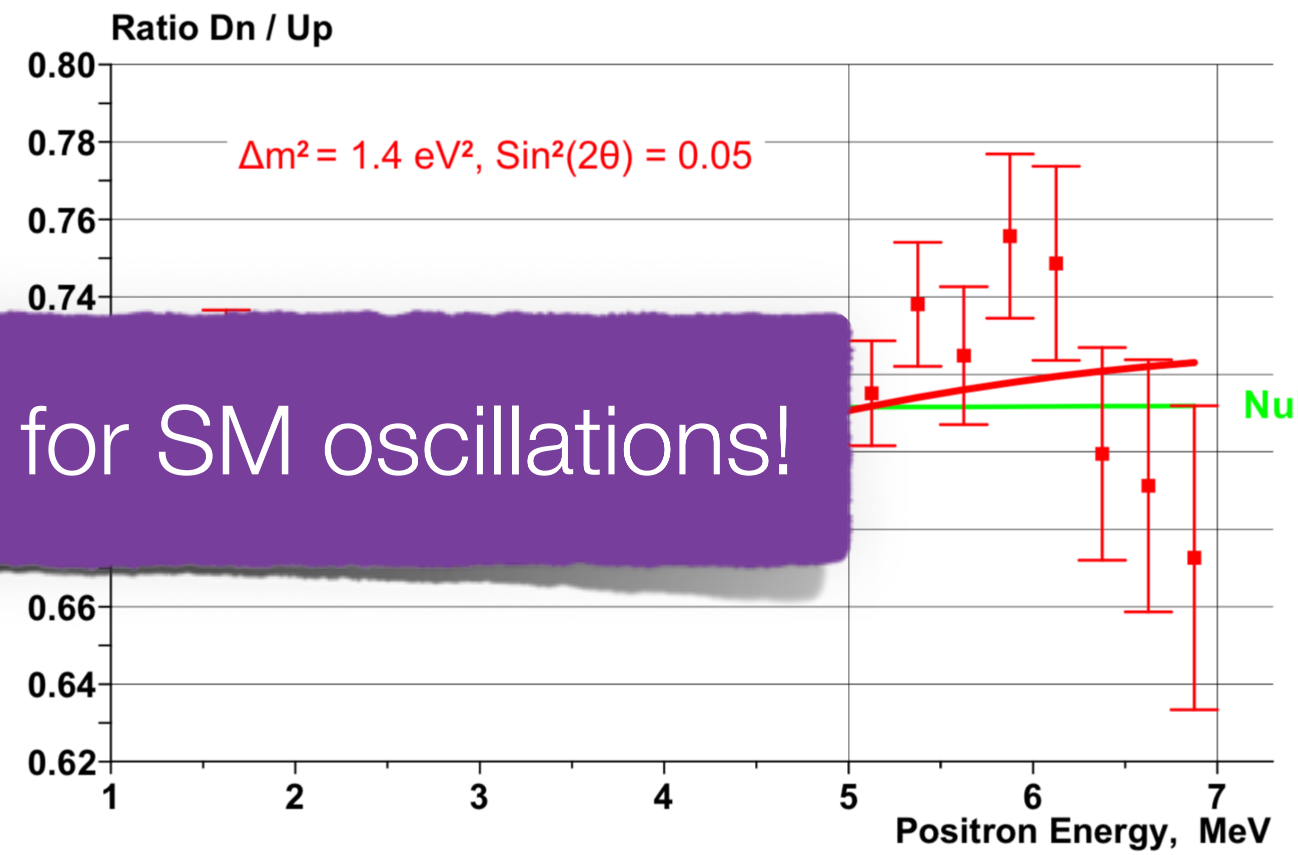

Baselines too short for SM oscillations!

Mention et al., 1101.2755

DANSS Collaboration @ Neutrino 2018

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, $m \sim$ TeV…M_{Pl})
  - can explain cosmic baryon asymmetry (leptogenesis, $m \gg 100$ GeV)
  - can explain dark matter ($m \sim$ keV)
  - can explain oscillation anomalies ($m \sim$ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

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

The Reactor Anomaly

$\overline{\nu}_e$ flux from nuclear reactors is $\sim 3.5\%$ ($\sim 3\sigma$) below prediction

➟ oscillations of $\overline{\nu}_e$ into sterile neutrinos $\overline{\nu}_s$?

Mueller *et al.* 1101.2663, Huber 1106.0687

The Reactor Anomaly

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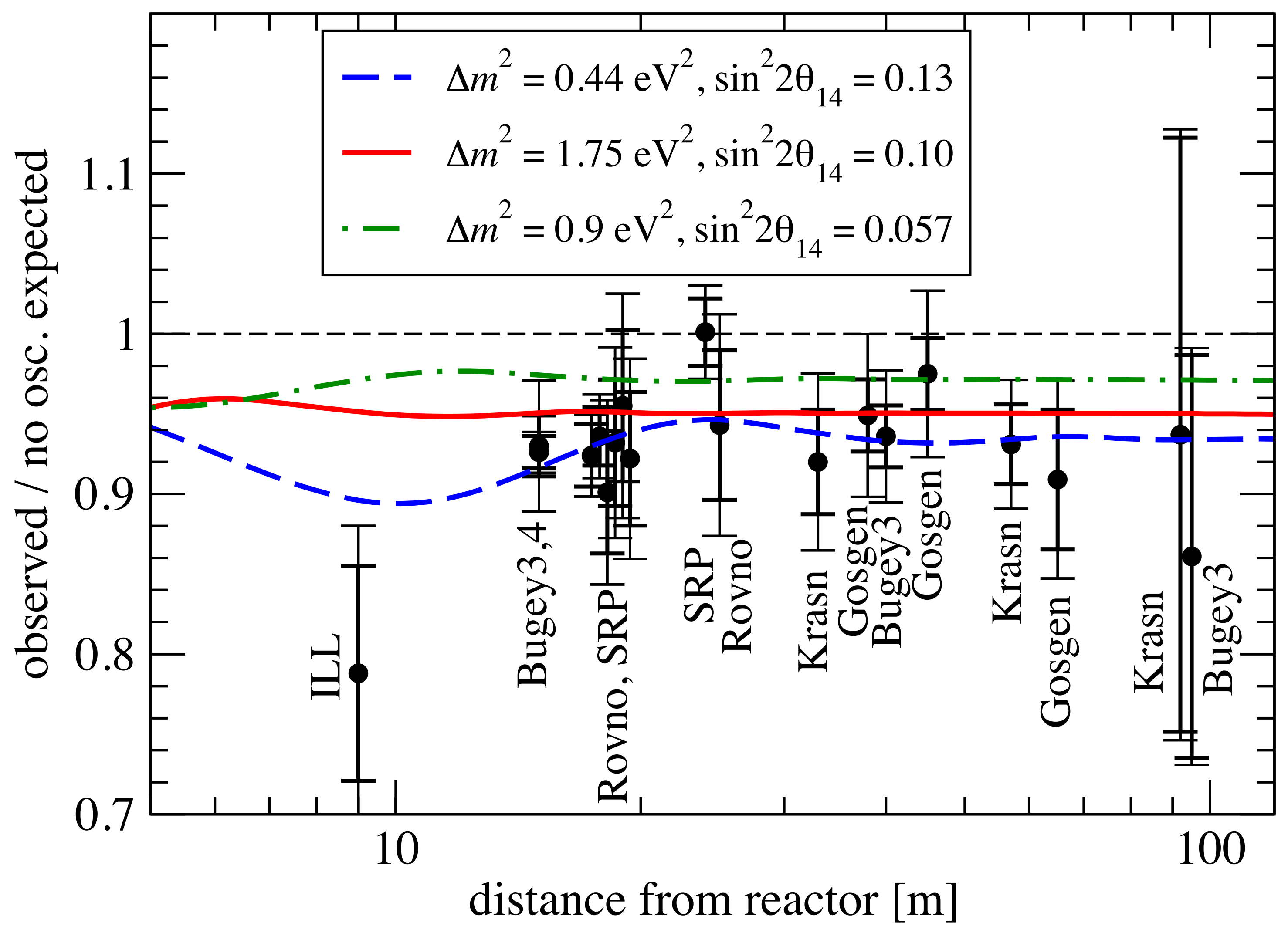

Predicting Reactor Neutrino Fluxes

$\overline{\nu}_e$ flux from nuclear reactors is $\sim$ 3.5% ($\sim 3\sigma$) below prediction

➟ oscillations of $\overline{\nu}_e$ into sterile neutrinos $\overline{\nu}_s$?

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

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

Mueller *et al.* 1101.2663, Huber 1106.0687

Corrections to Reactor Neutrino Fluxes

$\bar{\nu}_e$ flux from nuclear reactors is $\sim$ 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

Mueller *et al.* 1101.2663, Huber 1106.0687

Isotope-Dependent Fluxes

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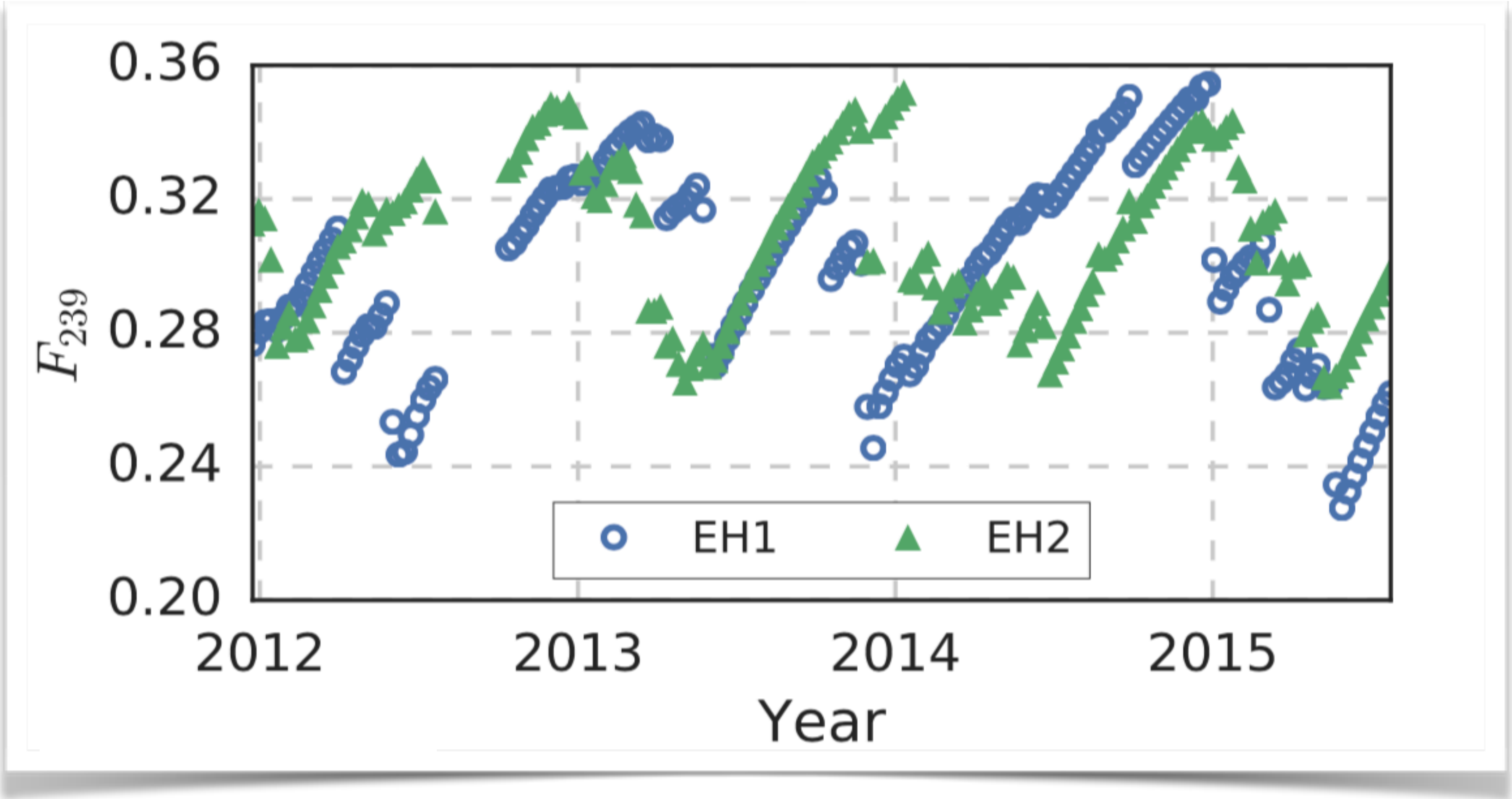
☑ Reactor fuel composition evolves with time ("burnup")



Daya Bay 1704.01082

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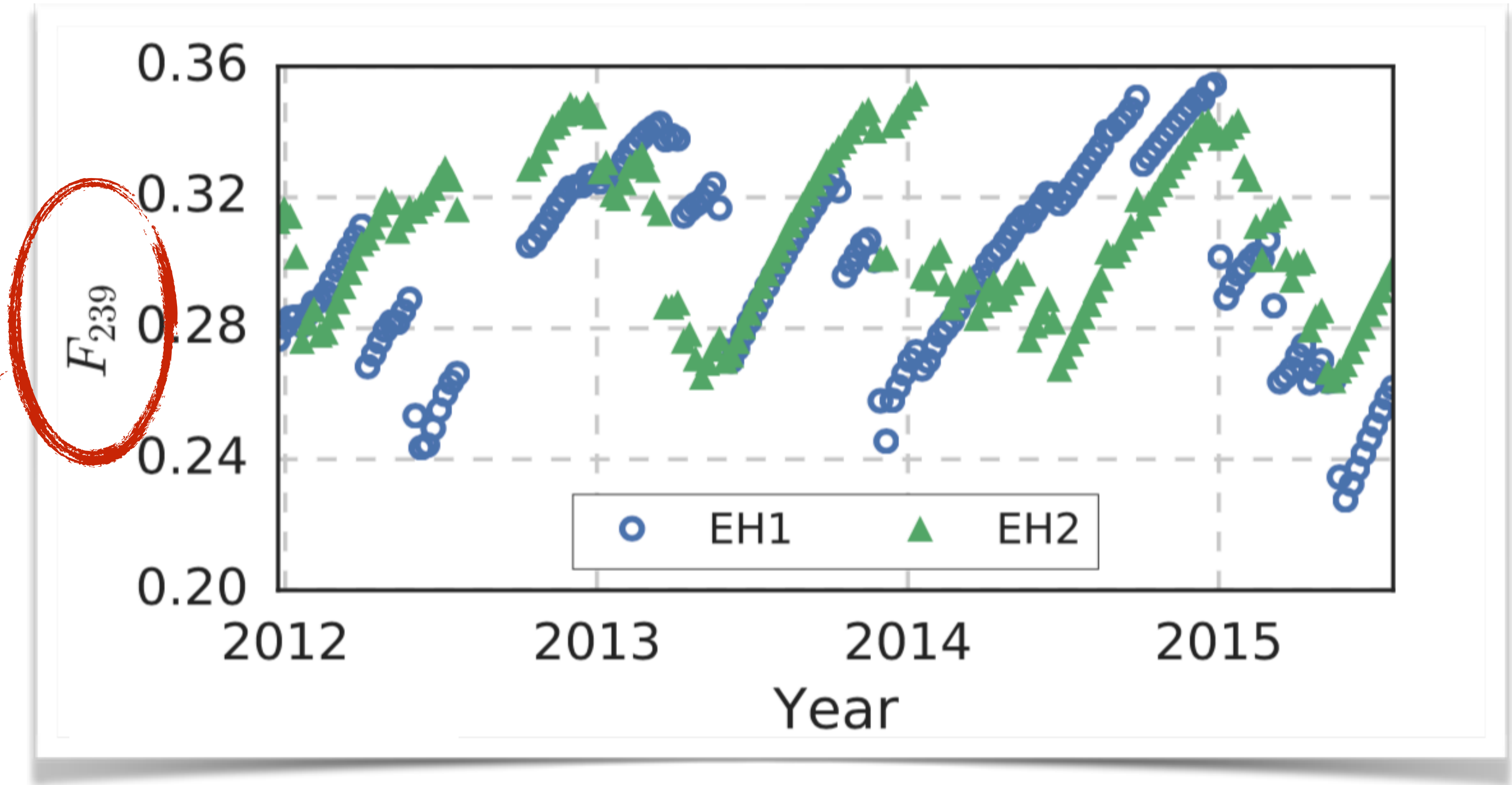

Effective fraction of ^{239}Pu fissions

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

)4.01082

Isotope-Dependent Fluxes

- Reactor fuel composition evolves with time (“burnup”)
- Measure inverse β decay rate as function of F_{239}
- Sterile Neutrino: same deficit for all isotopes
  Flux Misprediction: isotope-dependent deficits

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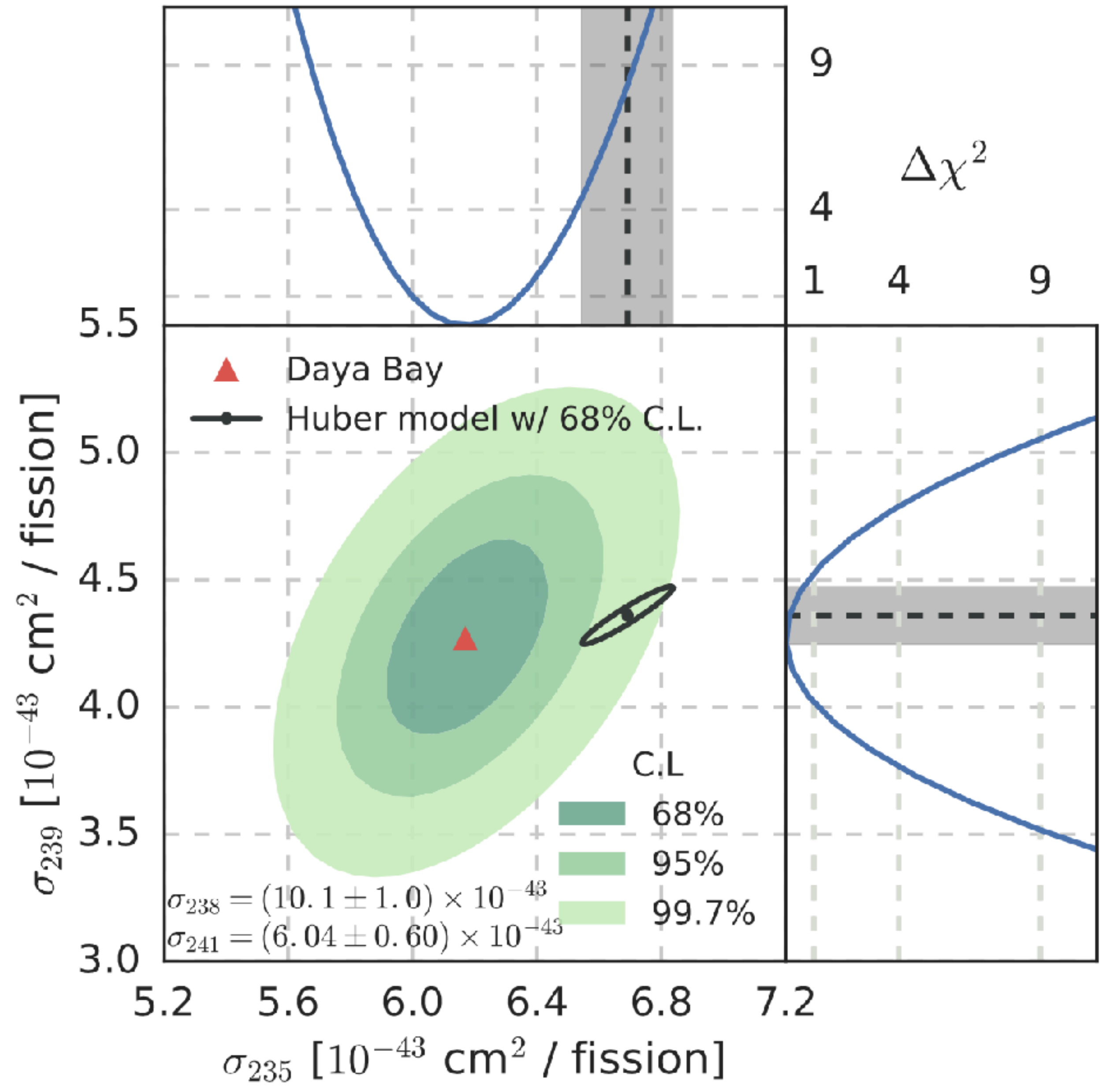
Sterile Neutrinos or Flux Uncertainty?



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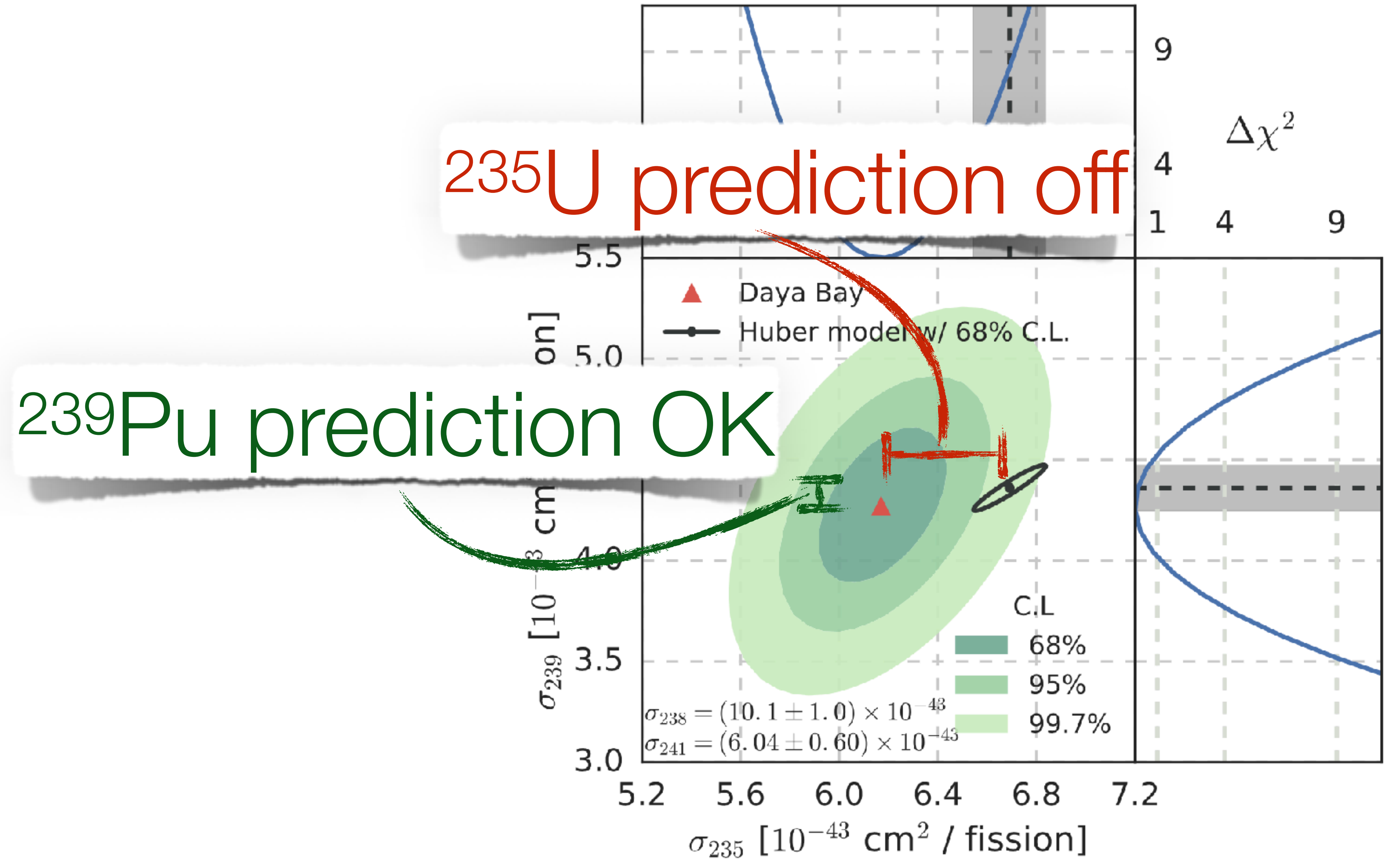

Daya Bay [1704.01082]

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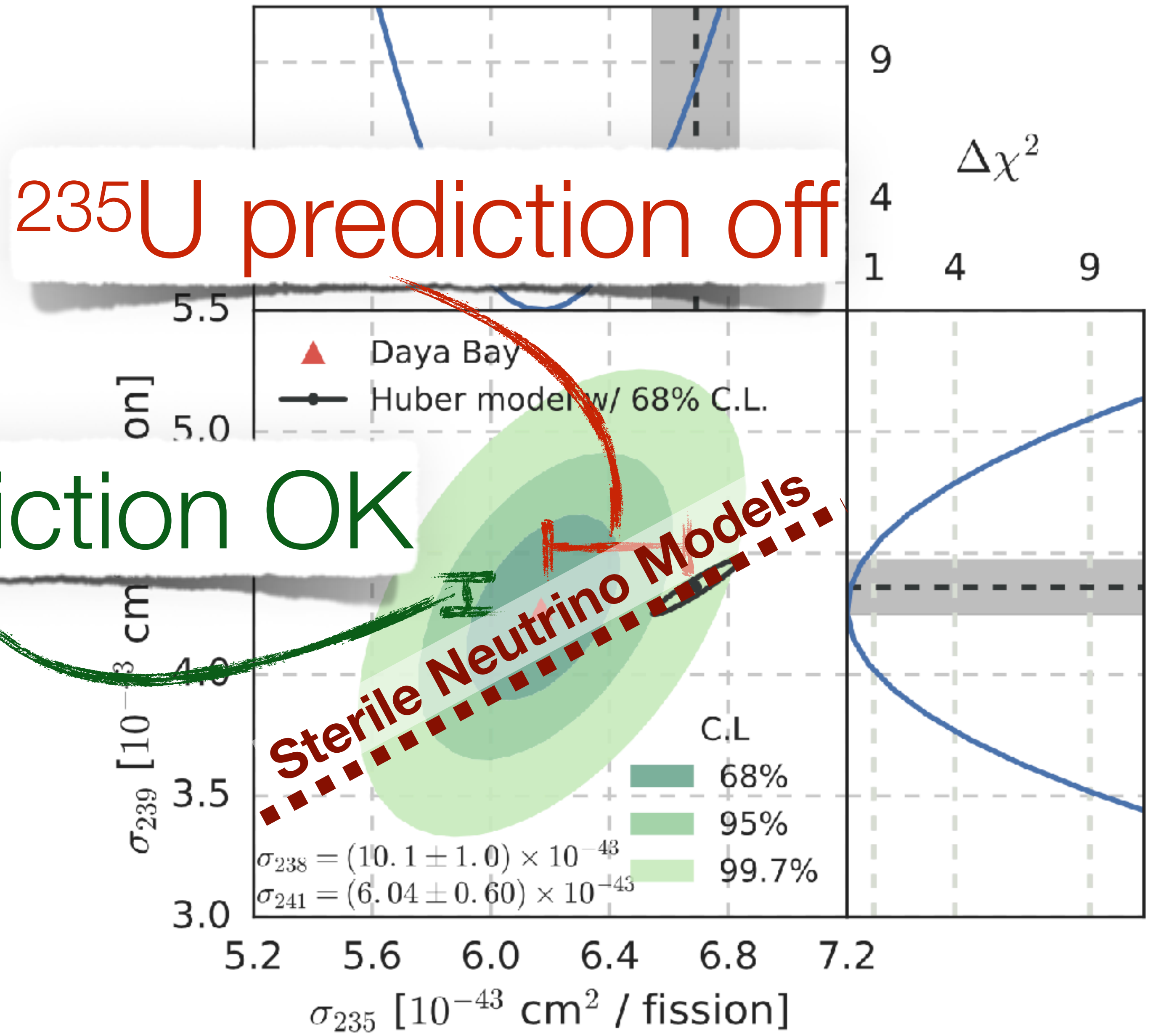

Daya Bay [1704.01082]

Sterile Neutrinos or Flux Uncertainty?

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- Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + ν_s

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

Sterile Neutrinos or Flux Uncertainty?

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$\Delta\chi^2 = 6.3$ (with theoretical uncertainties)

Dentler Hernández JK Maltoni Schwetz 1709.04294

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$\Delta\chi^2 = 6.3$ (with theoretical uncertainties)

- But both hypothesis yield excellent goodness of fit

Fluxes within errors + ν_s	: $p = 0.18$
Fluxes free	: $p = 0.73$
$\Delta\chi^2$ (sterile neutrino vs. free fluxes)	: $p = 0.007$

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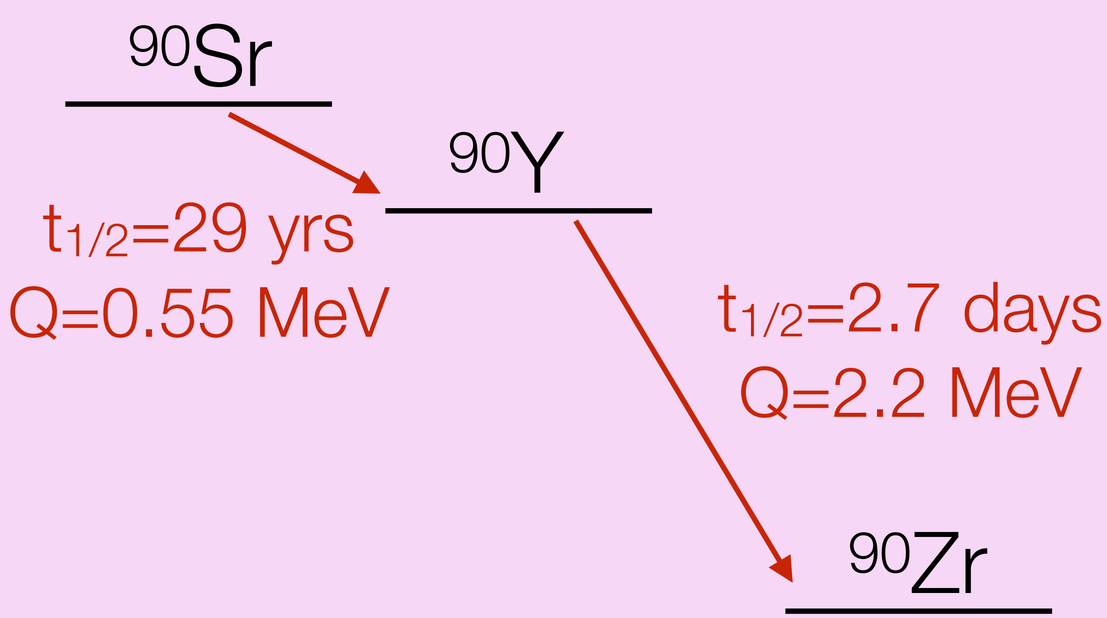
Caveats

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

Caveats

Non-Equilibrium Effects

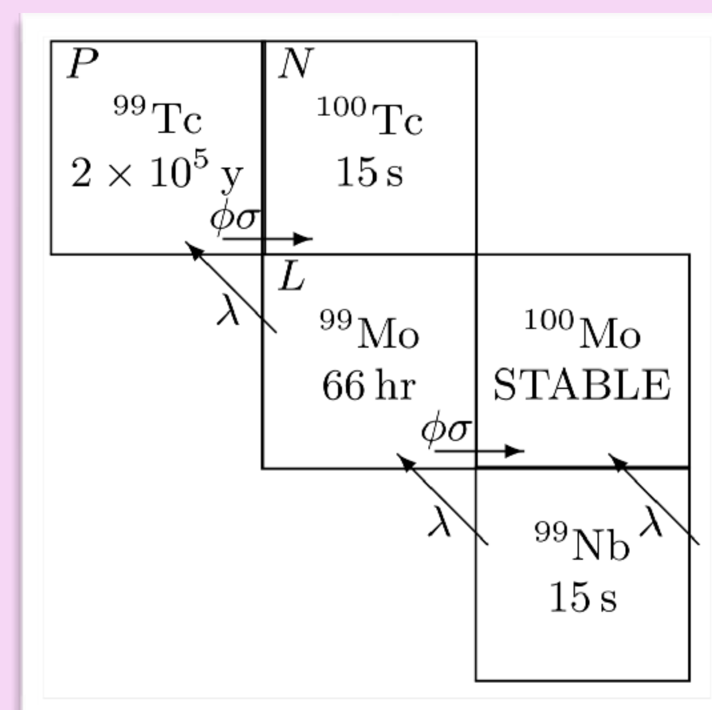
- ☑ Some relevant decays are out of equilibrium



- ☑ Extra *t*-dependence in ν flux

Non-Linear Isotopes

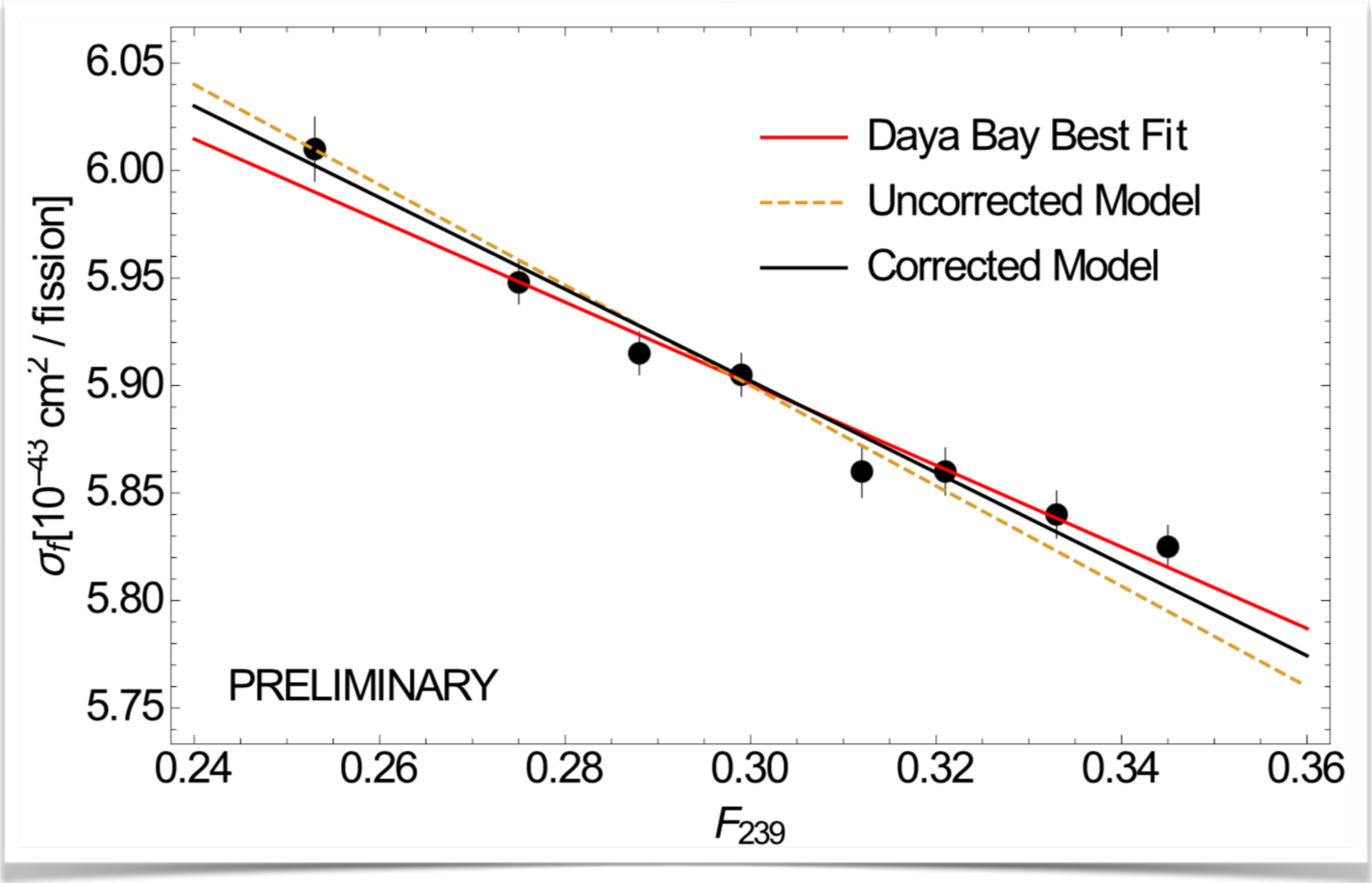
- ☑ Neutron capture on fission products



- ☑ Extra neutron flux/burnup dependence in ν flux

Jaffke Huber 1510.08948, Huber Sharma, *in preparation*

Improved Analysis



Huber Sharma, *in preparation*

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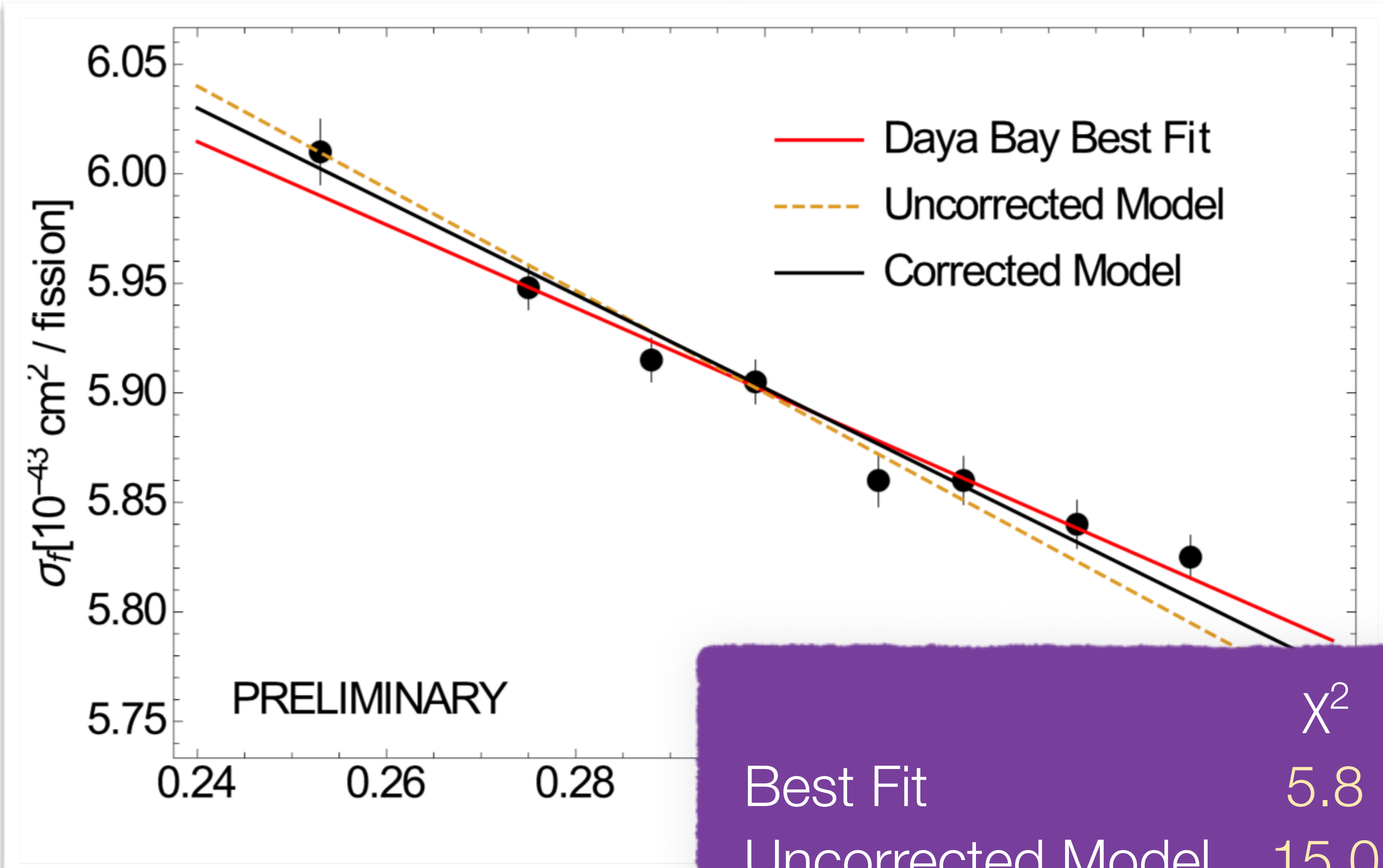


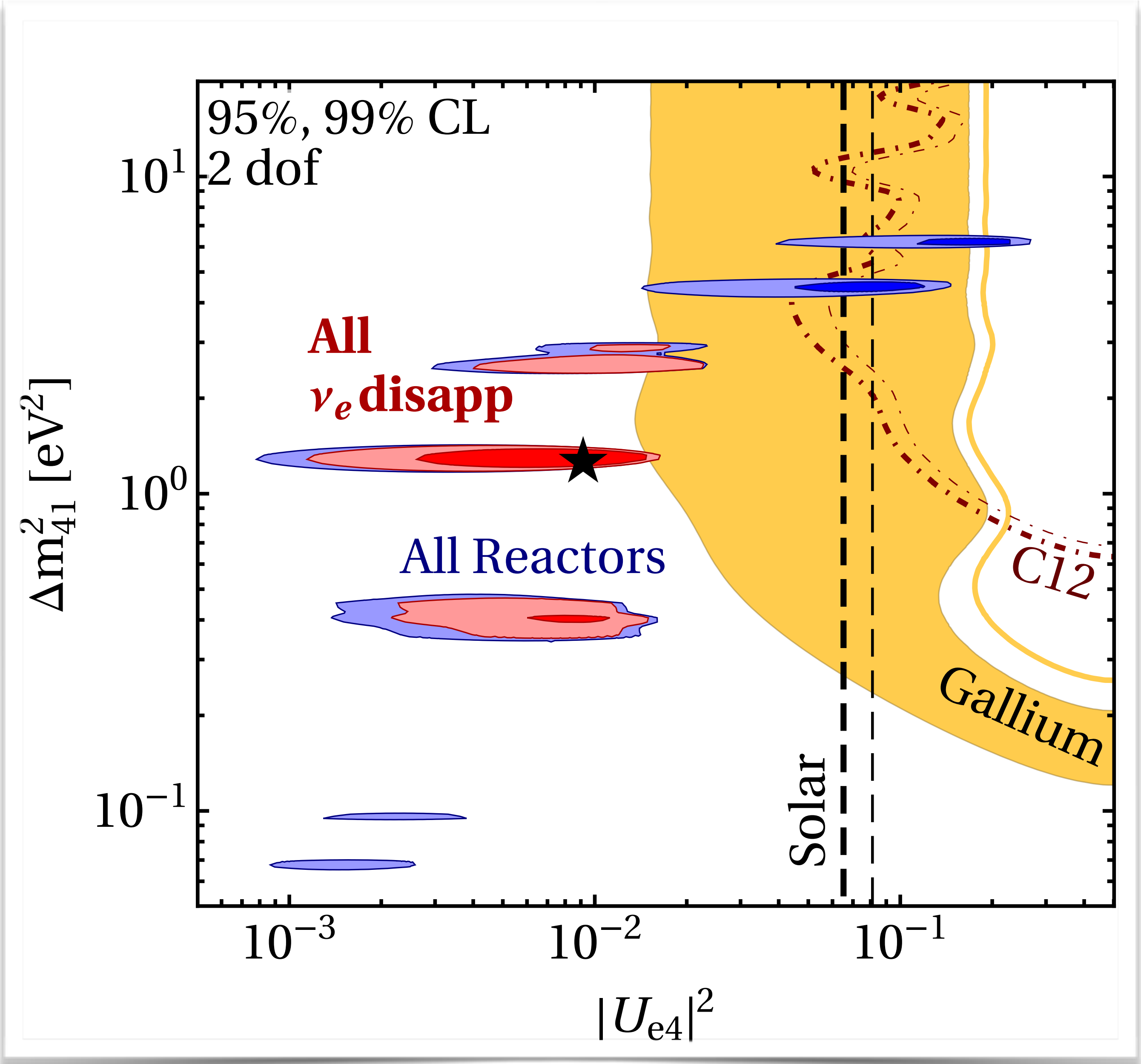
Huber Sharma, *in preparation*

	χ^2	$(\Delta\chi^2)^{1/2}$
Best Fit	5.8	
Uncorrected Model	15.0	3σ
Corrected Model	8.5	1.6σ

Sterile Neutrinos

Global Status

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



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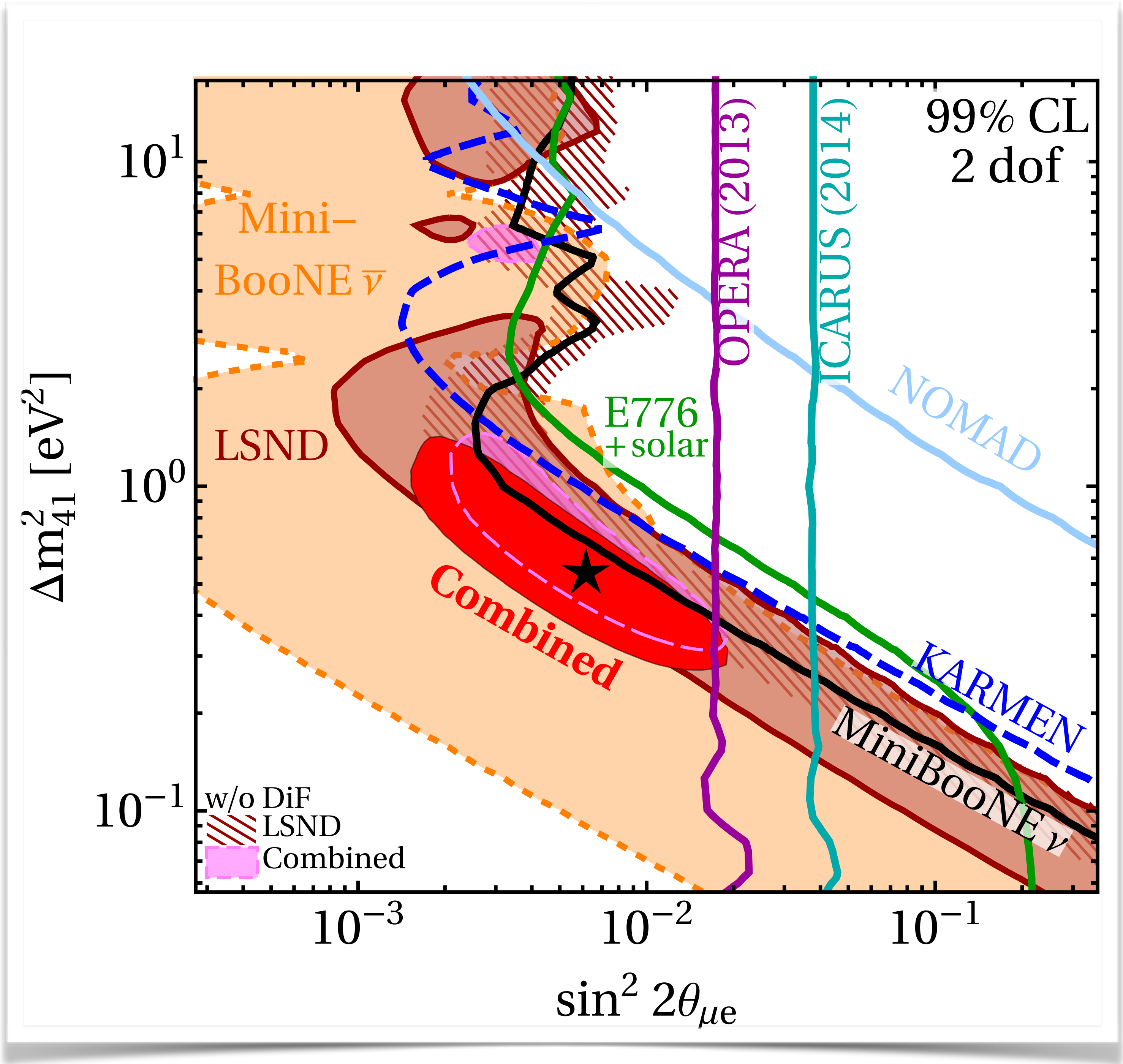
Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

$\nu_\mu \rightarrow \nu_e$ appearance



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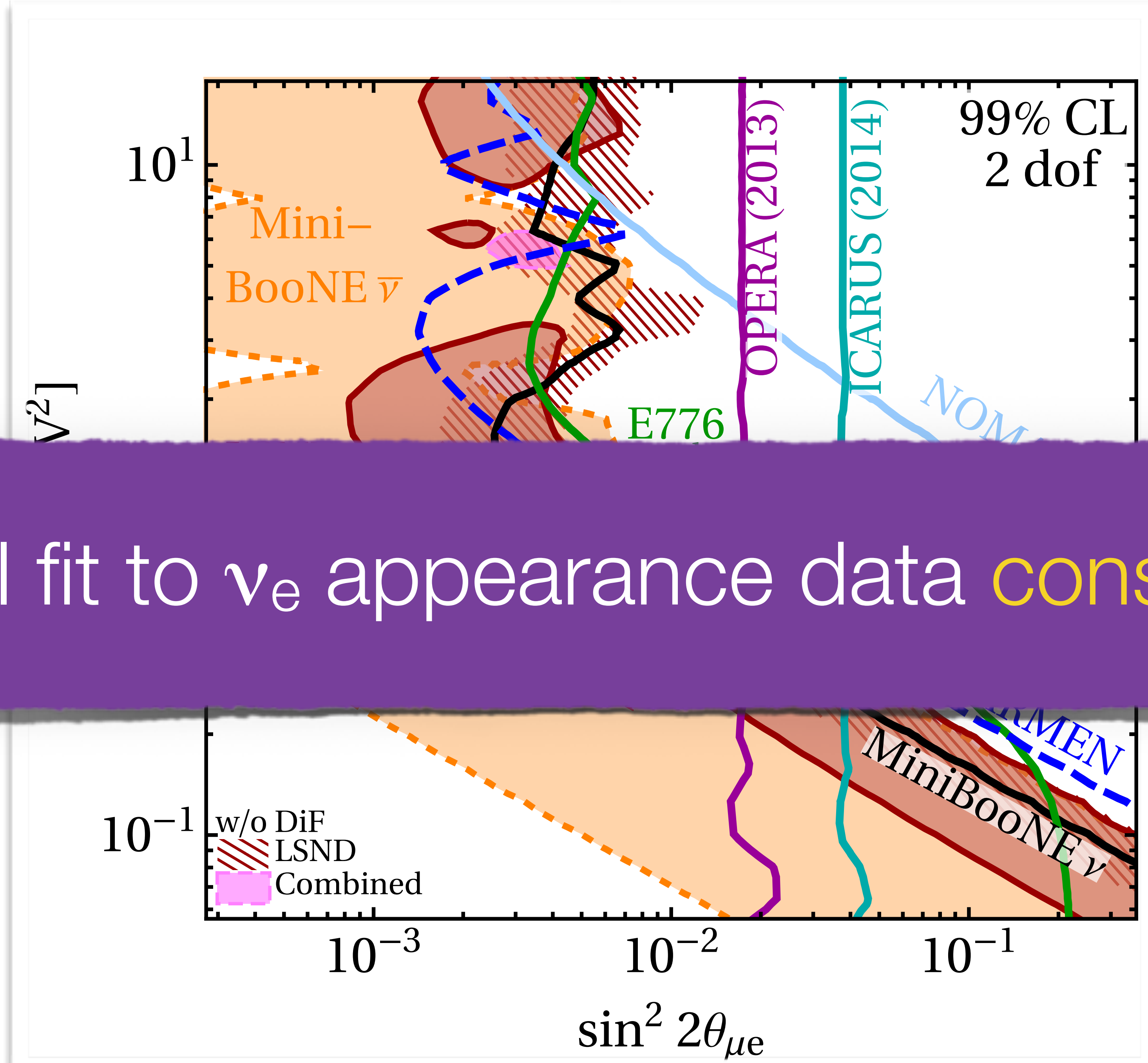
$\nu_\mu \to \nu_e$ appearance



Global fit to ν_e appearance data consistent.

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

Relation Between Oscillation Channels

- Oscillation channels are related:

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

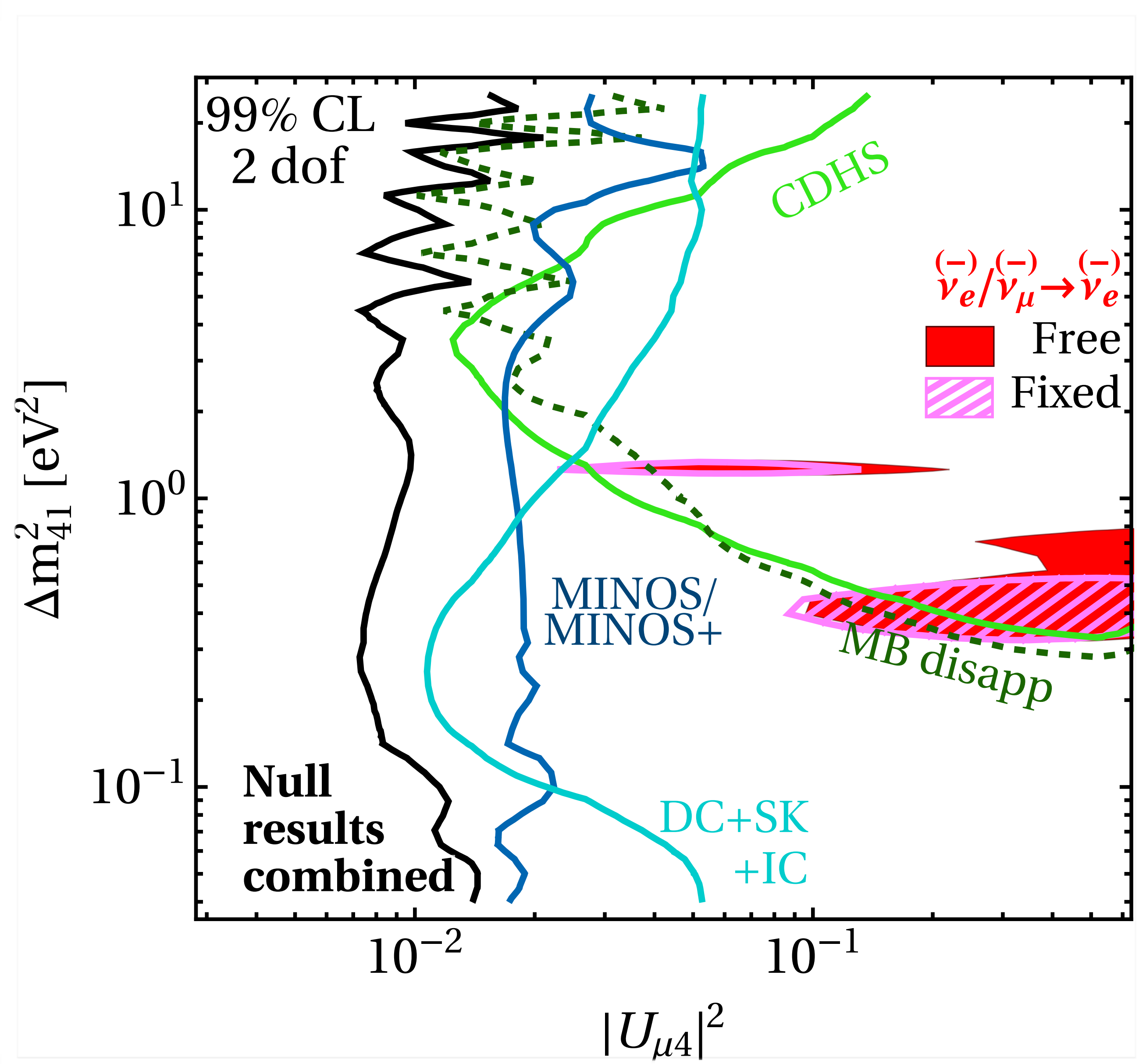
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

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

(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 Hernández 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

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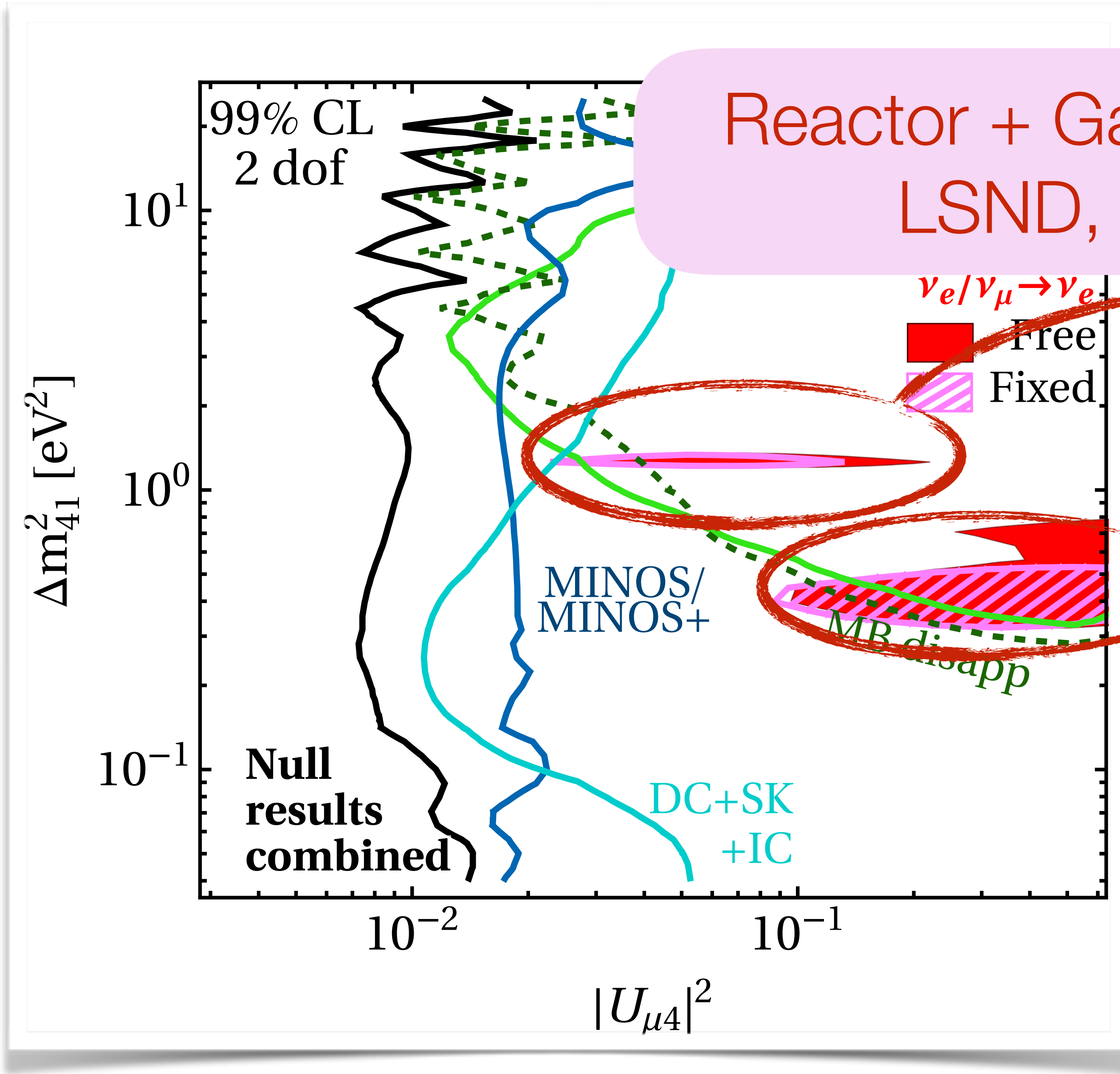

Reactor + Gallium Anomalies, LSND, MiniBooNE

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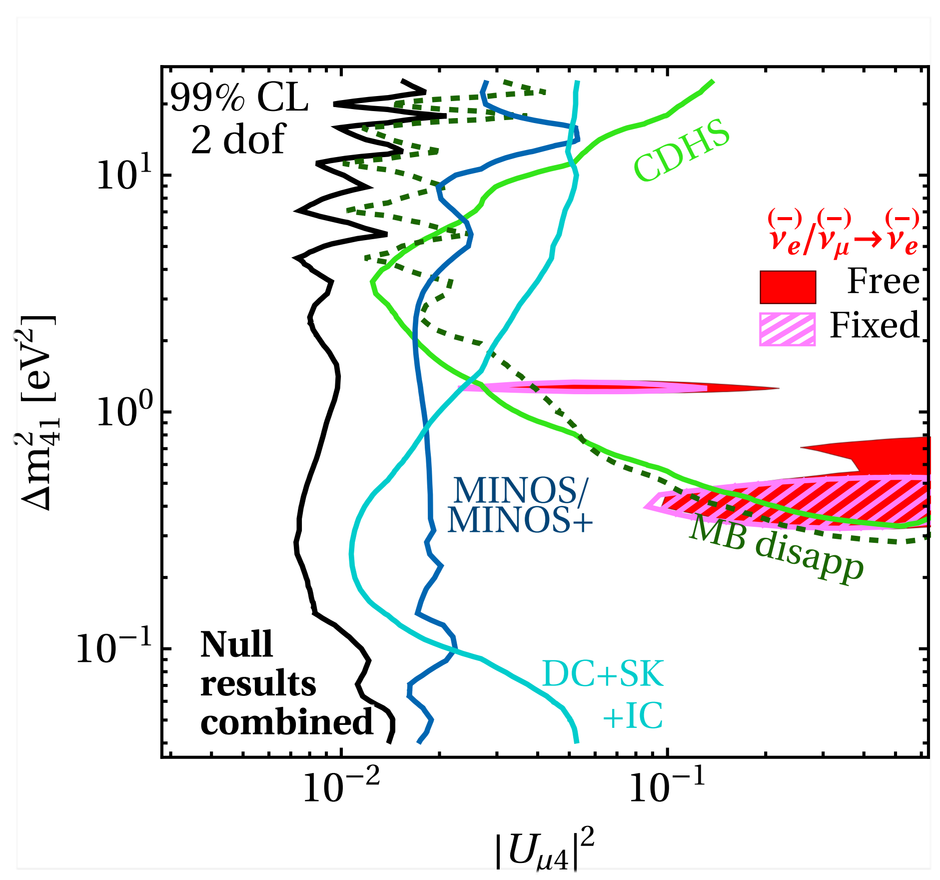

Dentler et al.
in preparation

	χ^2 / dof	$\Delta\chi^2_{glob}$	$\Delta\chi^2_{PG}$ / dof	p_{PG}
ν_μ disapp	468.9 / 504	5.9		
ν_e app+disapp	628.6 / 537	17.5		
Combined	**1120.9 / 1109**		**23.4 / 2**	**8.3×10^{-6}**

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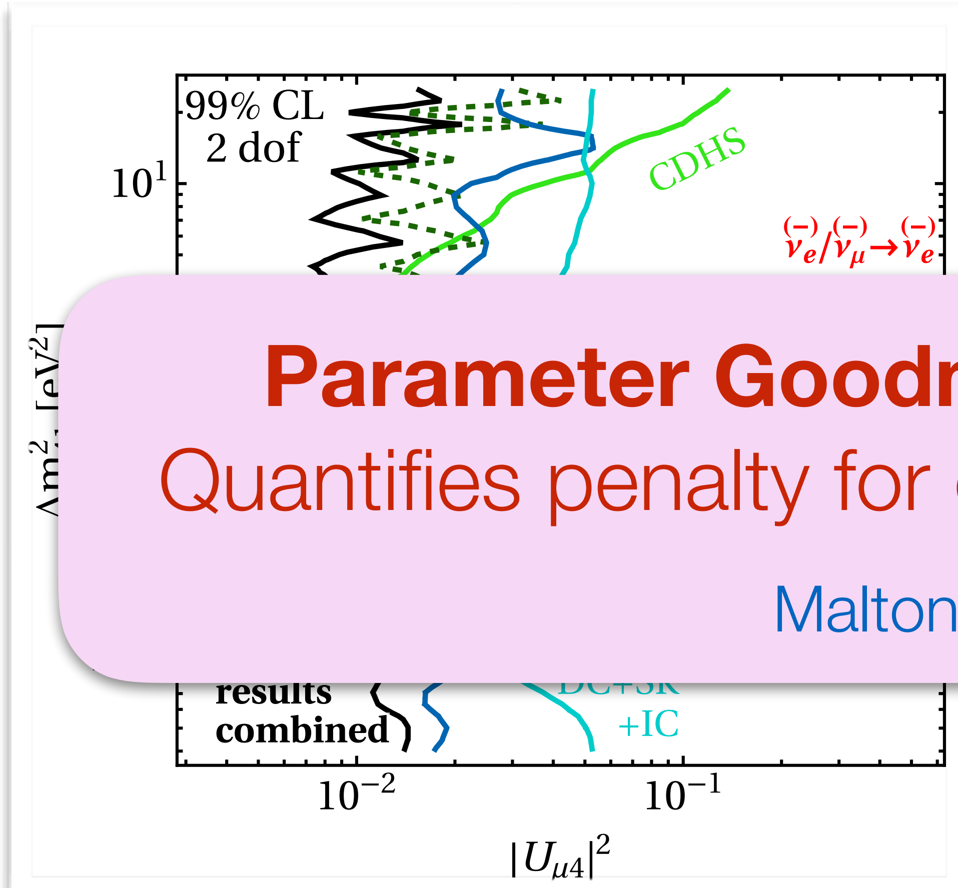
Global Fit in 3+1 Model



Dentler et al.
in preparation

Parameter Goodness-of-Fit Test:
Quantifies penalty for combining data sets

Maltoni Schwetz [hep-ph/0304176]

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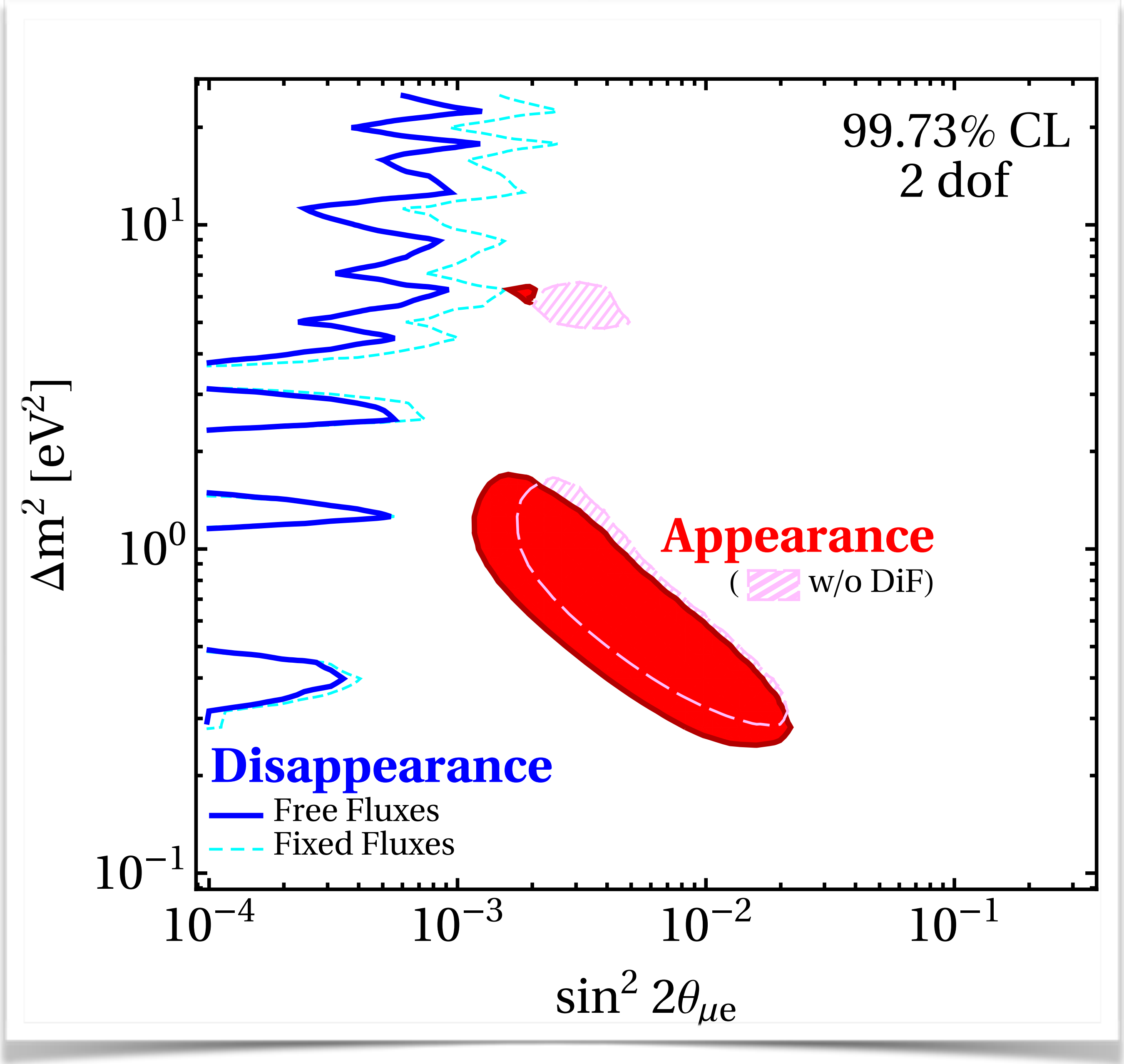
Appearance vs. Disappearance



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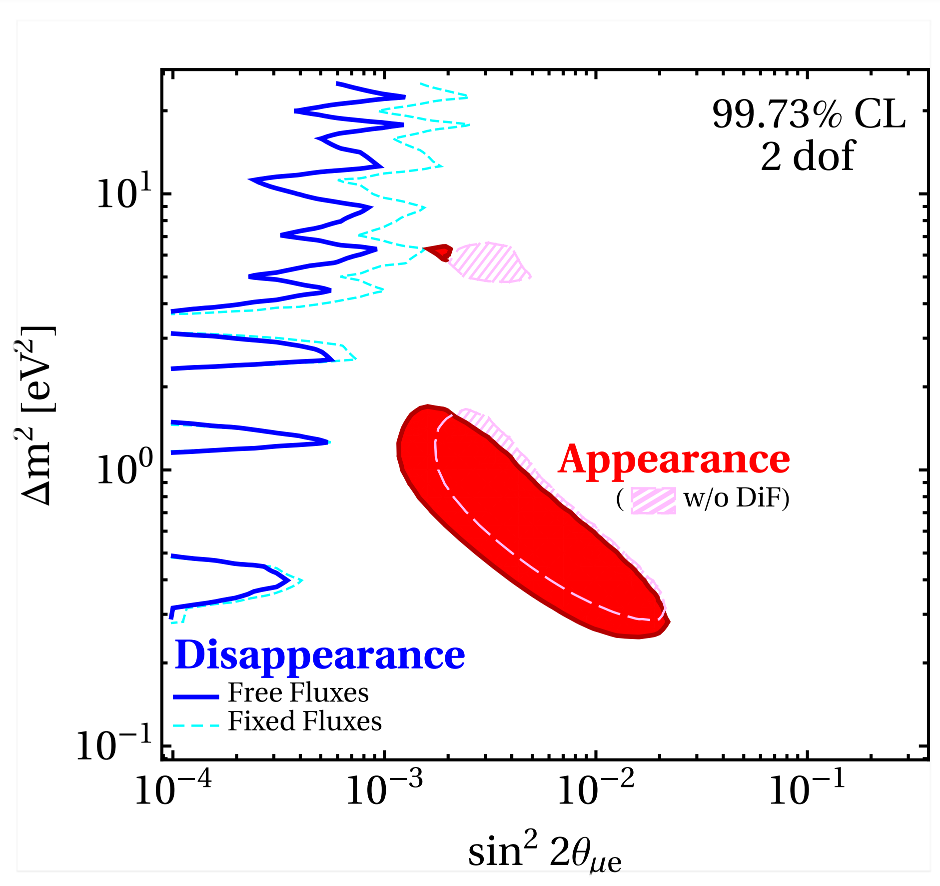

Dentler et al.
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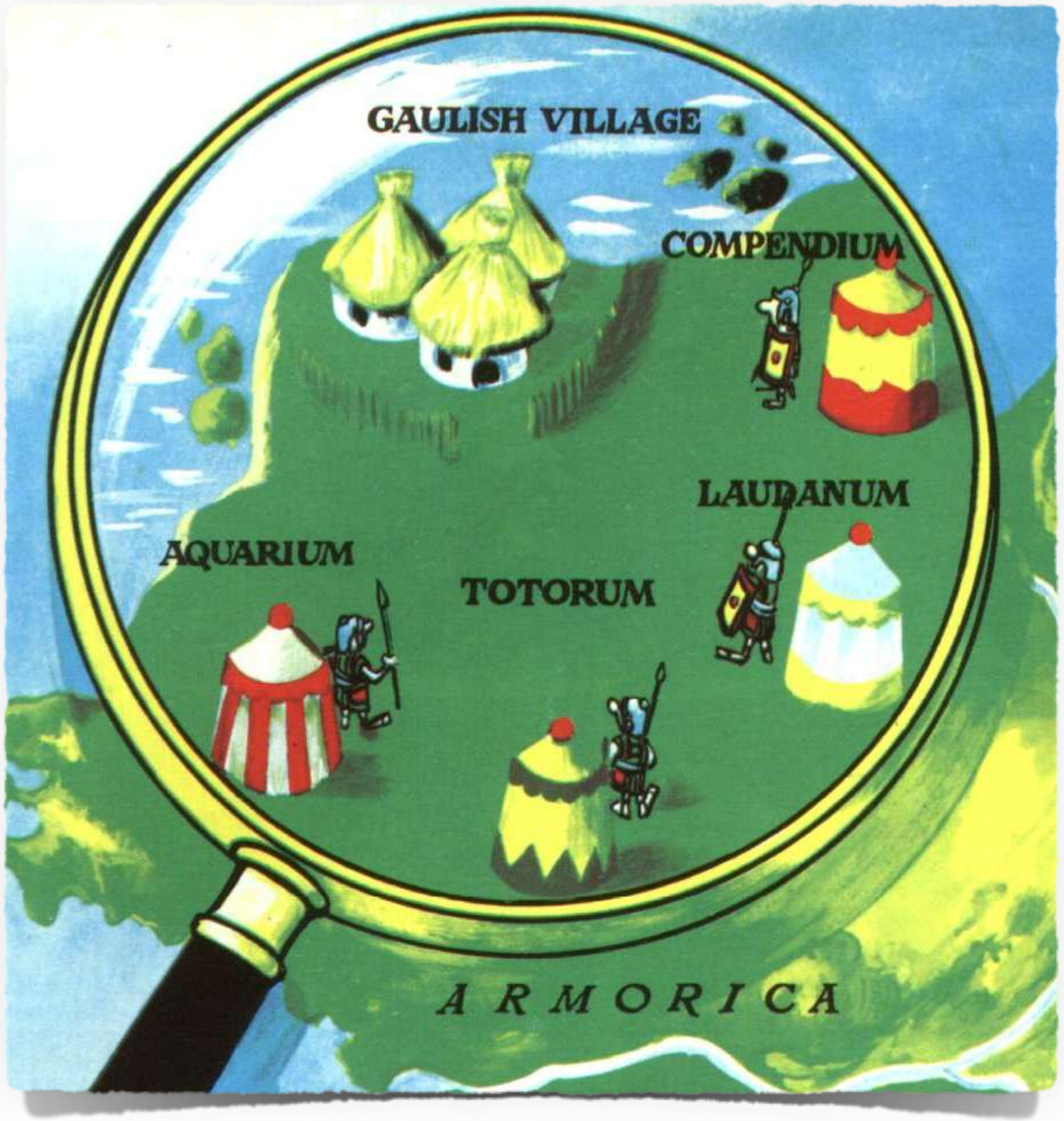
	χ^2 / dof	$\Delta\chi^2_{glob}$	$\Delta\chi^2_{PG}$ / dof	p_{PG}
Appearance	79.1 / 69	11.9		
Disappearance	1012.2 / 1040	17.7		
Combined	**1120.9 / 1109**		**29.6 / 2**	**3.7×10^{-7}**

Can Sterile Neutrinos Explain All Anomalies?



Can Sterile Neutrinos Explain All Anomalies?

severe tension ($p < 10^{-5}$)

- ν_S can't explain all anomalies (but could well explain some!)
- scrutinize anomalies for unknown systematics (need 4 independent effects!)
- scrutinize also null results!
- Many experiments under way to test the ν_S hypothesis

Cosmological Constraints

and how to evade them

Sterile Neutrinos in Cosmology

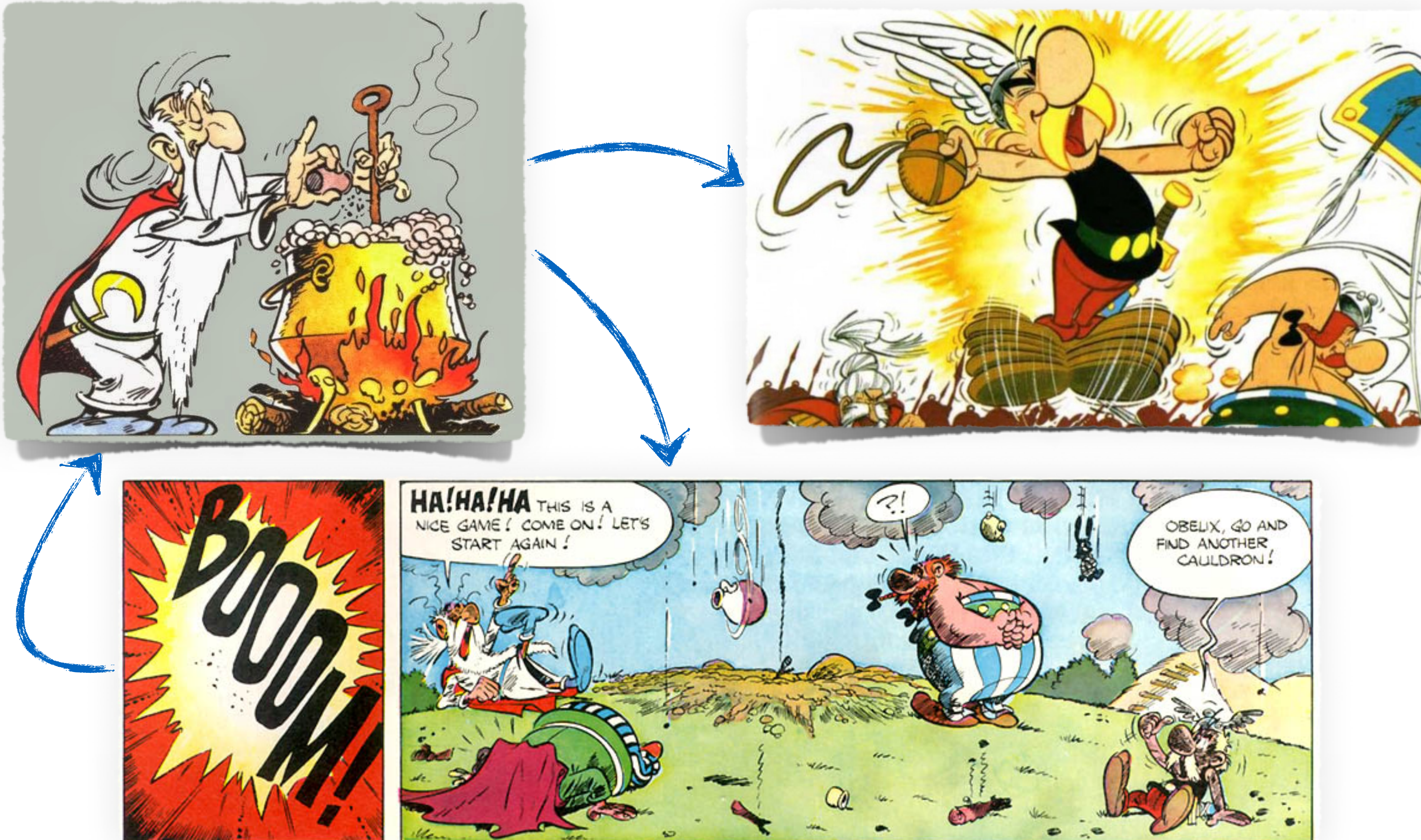
Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV

- ☑ $\nu_{e,\mu,\tau}$ 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:

$\Sigma m_\nu \lesssim 0.23$ ⚡

$N_{eff} \lesssim 3.38$ ⚡

BSM Model Building Flowchart



Reconciling Sterile Neutrinos with Cosmology

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

$\sum m_\nu \lesssim 0.12$ eV ⚡

$N_{eff} \lesssim 3.16$ ⚡

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- ☑ New interactions in the ν_s sector
  - production suppressed by thermal potential
  - avoids N_{eff} constraint, weakens Σm_ν constraint

Hannestad et al. 1310.5926
Dasgupta JK, 1310.6337

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- ☑ ν_s properties change in late phase transition

Bezrukov Chudaykin Gorbunov, 1705.02184
Chu et al., 1806.10629

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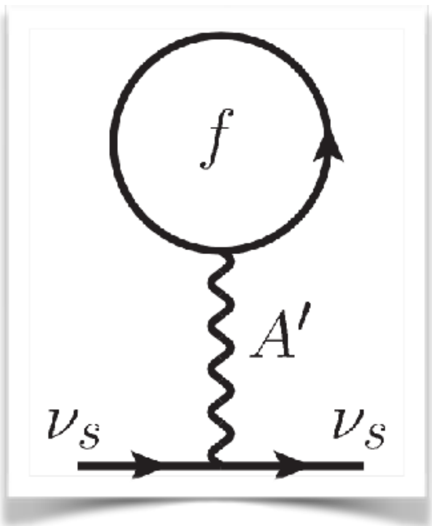
Bezrukov Chudaykin Gorbunov, 1705.02184
Chu et al., 1806.10629

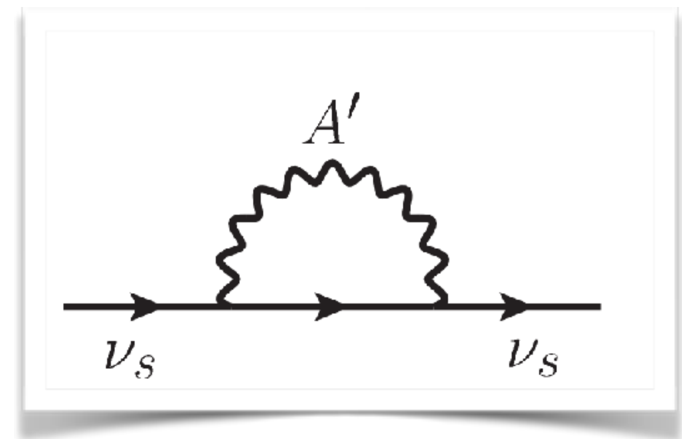
- ☑ Coupling to slow-rolling scalar field

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}





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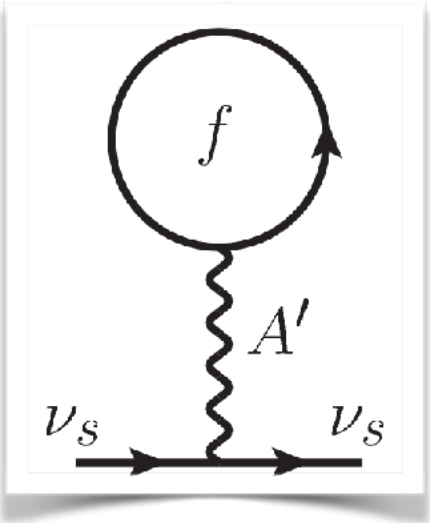

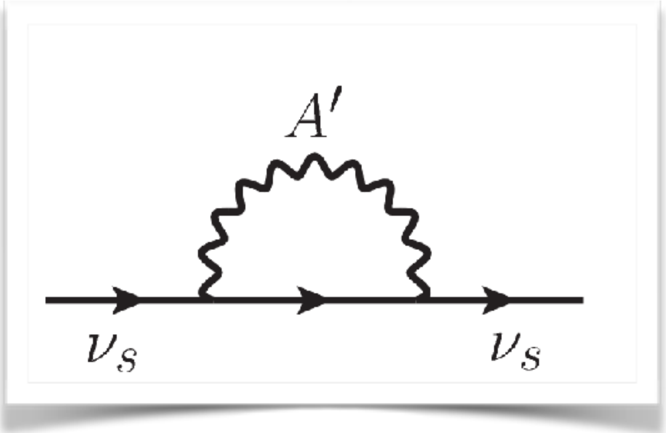

- Thermal propagators

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

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

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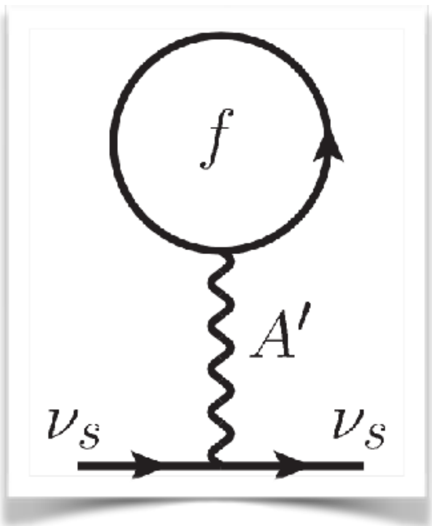

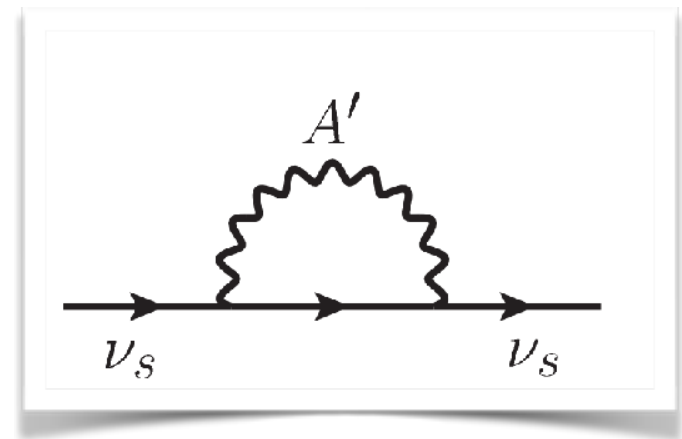

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$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)n_{f,b}(p)$$

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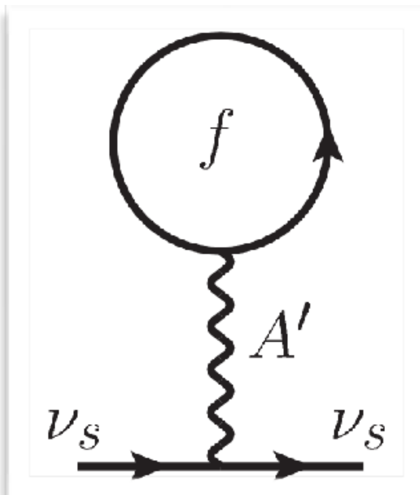
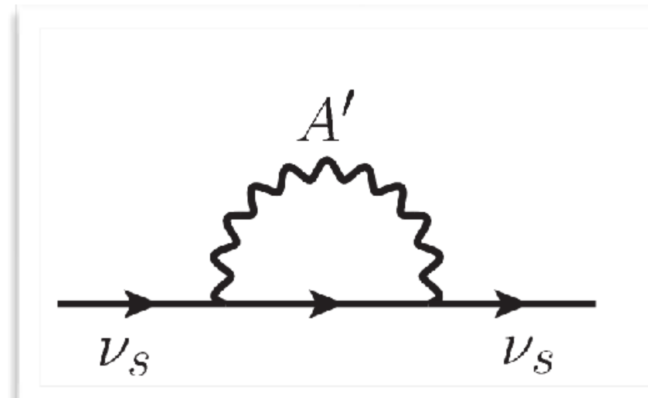




- Thermal propagators

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

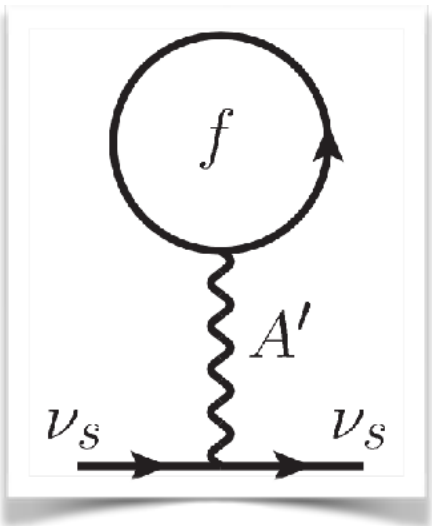
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

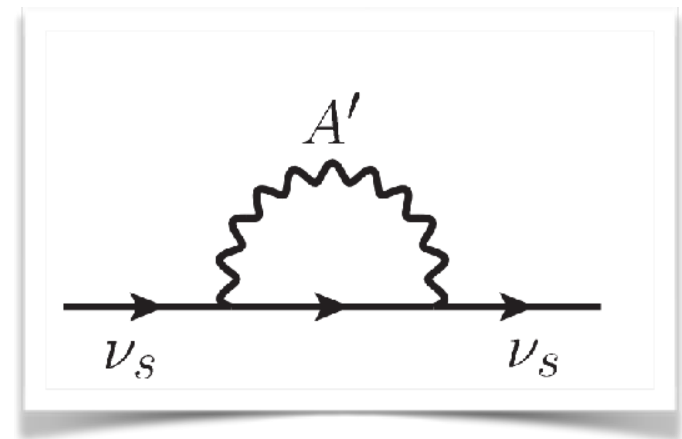
$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)\, n_{f,b}(p)$$

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

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:

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

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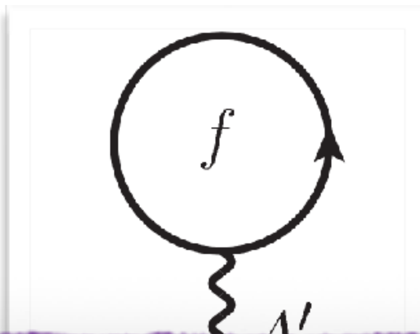

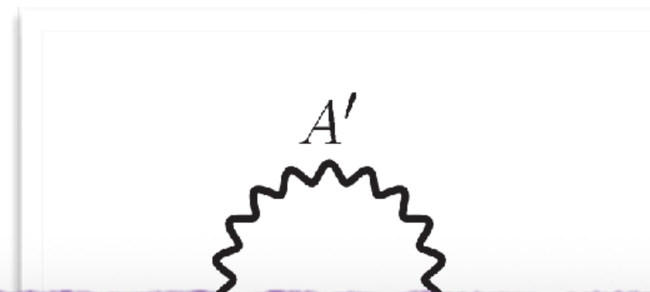

- ★ ν_s production strongly suppressed at high T
- ★ cosmological constraints avoided

- Effective mixing angle:

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

New Interaction in the Sterile Sector

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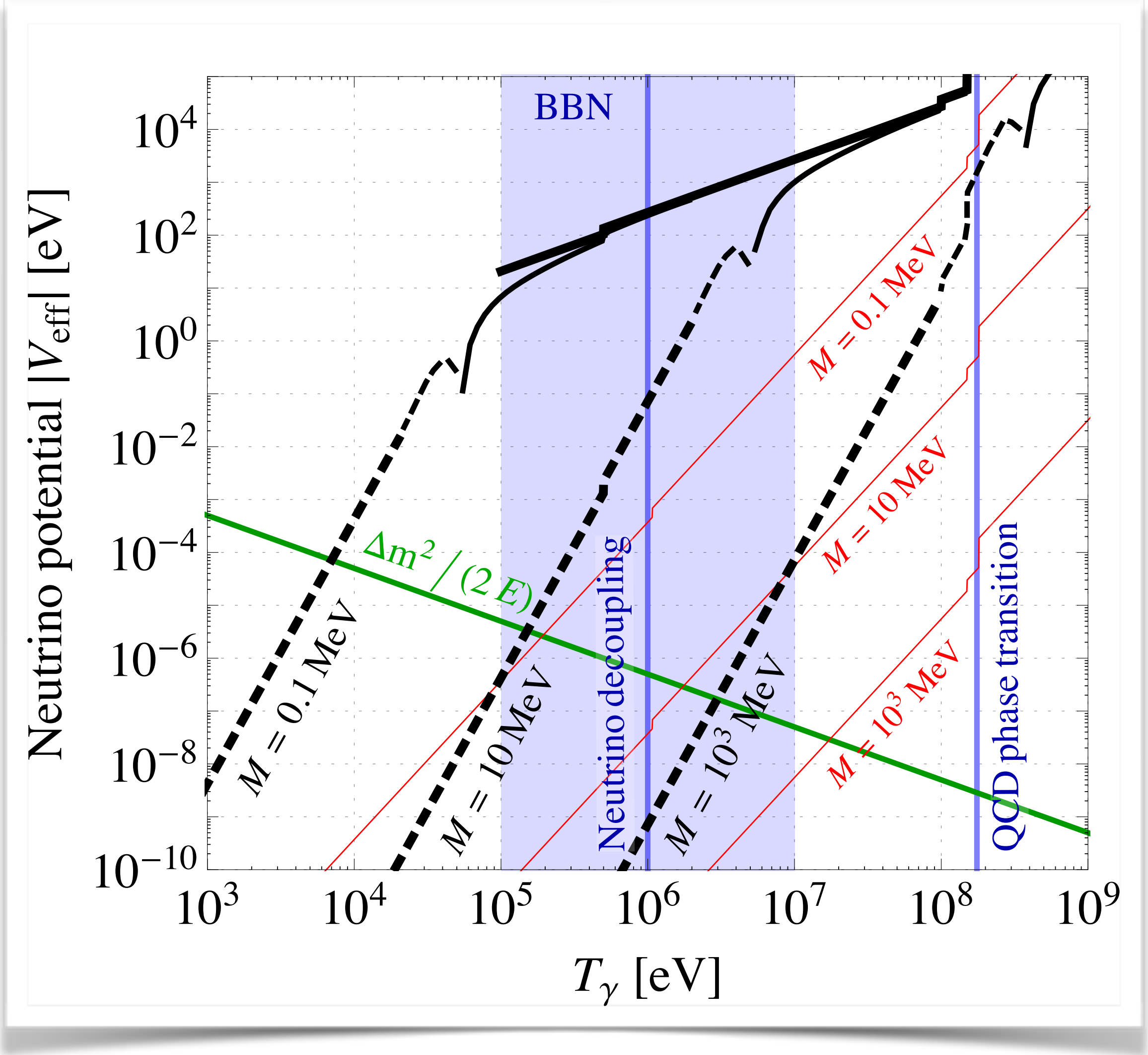

- If $V^{eff} \gg \Delta m^2/(2T)$: ν_s production suppressed Hannestad *et al.* 1310.5926
  Dasgupta JK 1310.6337
- Problem: late equilibration between $\nu_{e,\mu,\tau}$ and ν_s

Chu Dasgupta JK 1505.02795, Cherry Friedland Shoemaker 1605.06506
Forastieri *et al.* 1704.00626, Chu Dasgupta Dentler JK Saviano, *in preparation*

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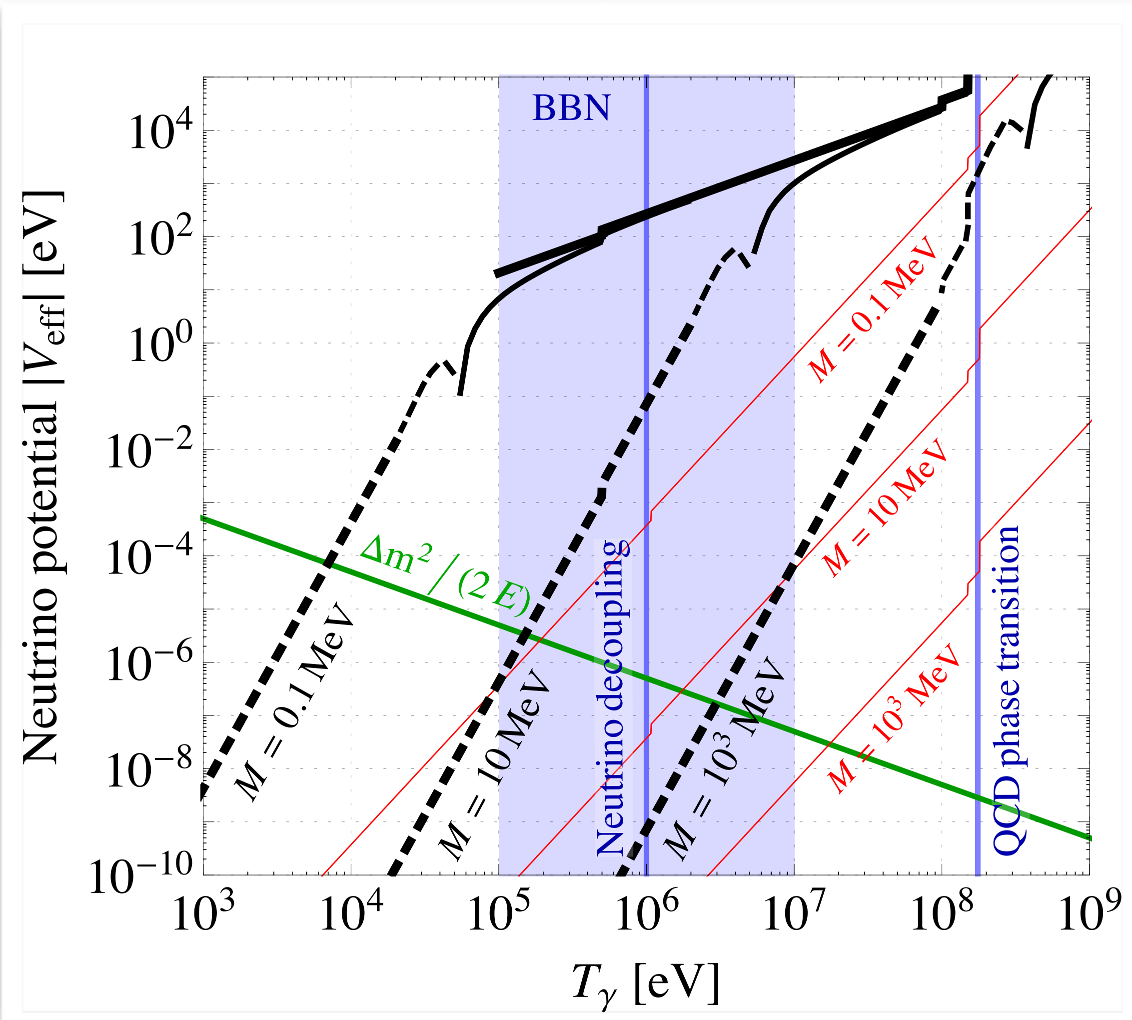

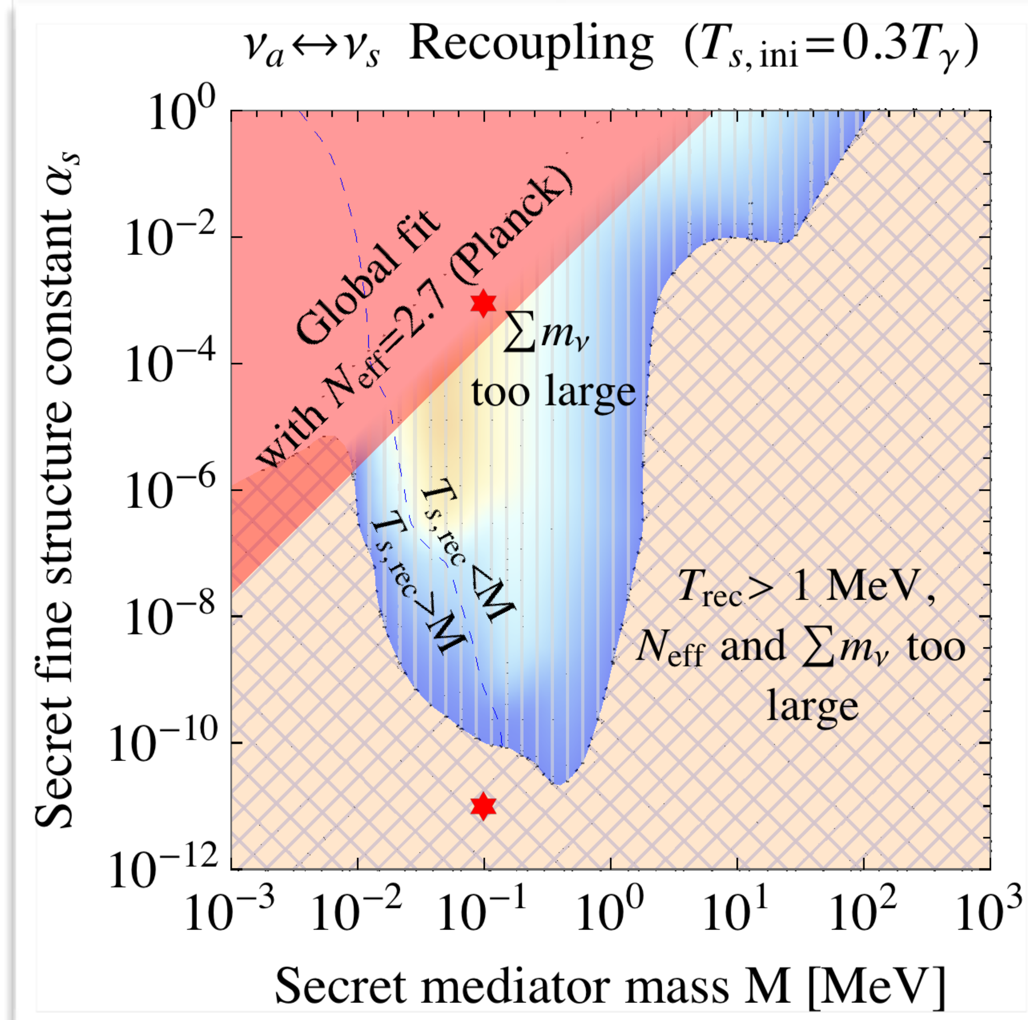

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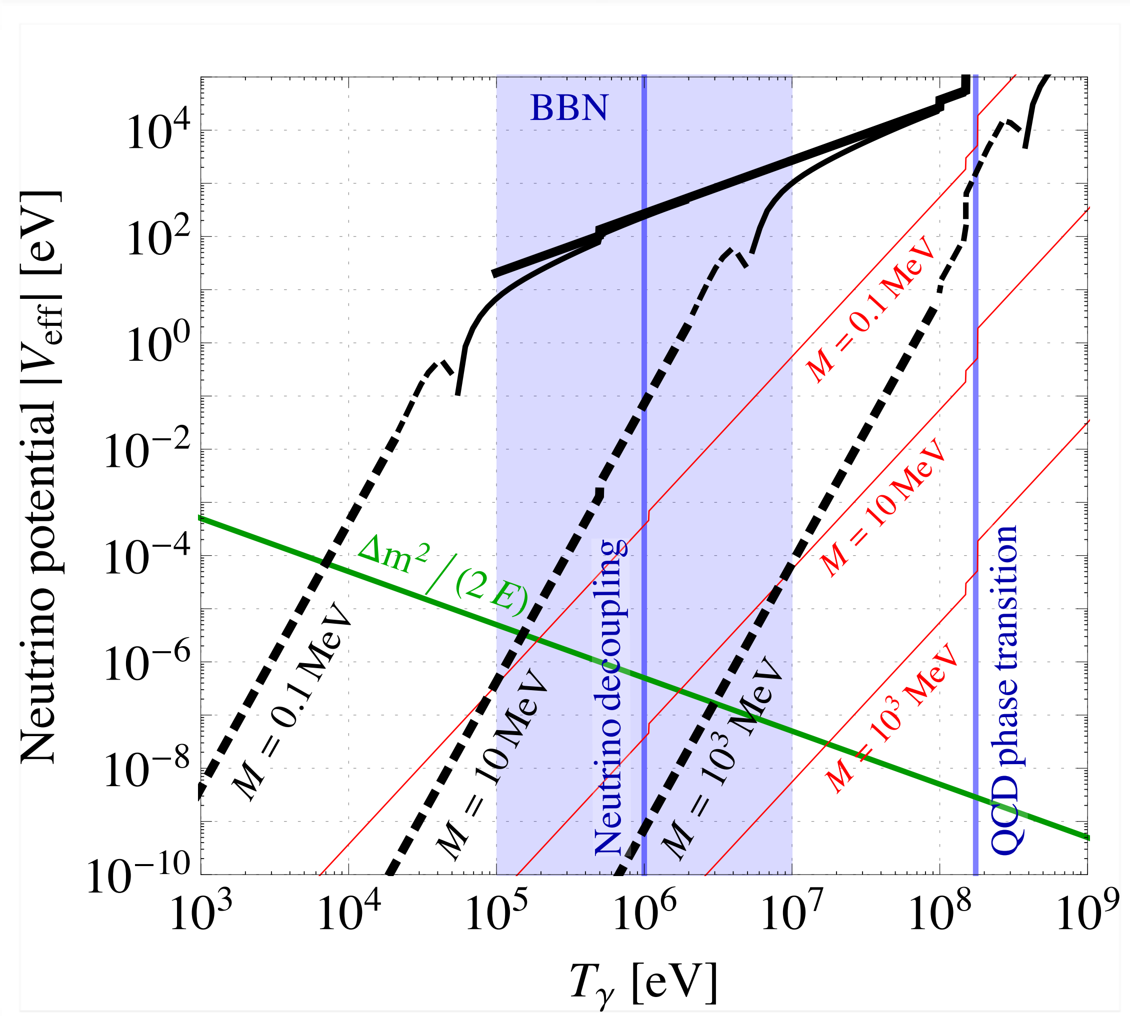

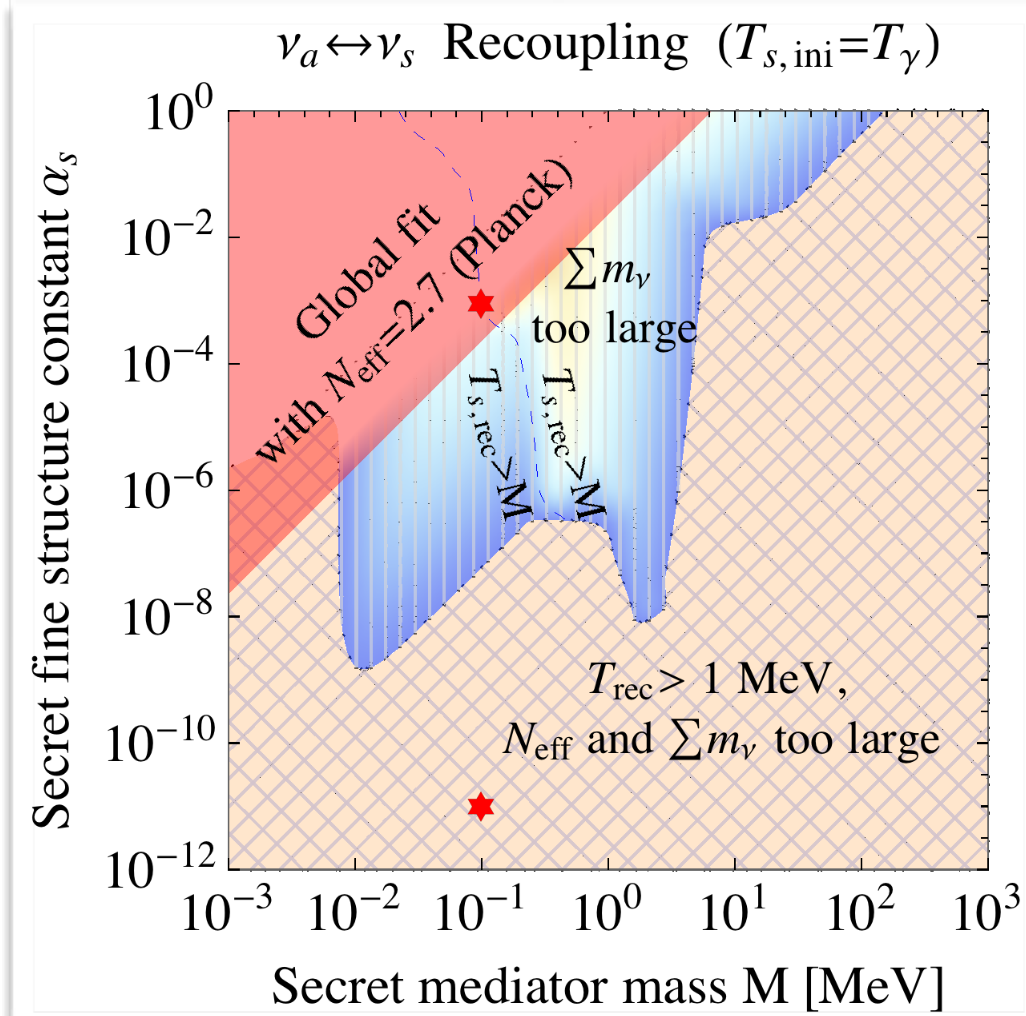

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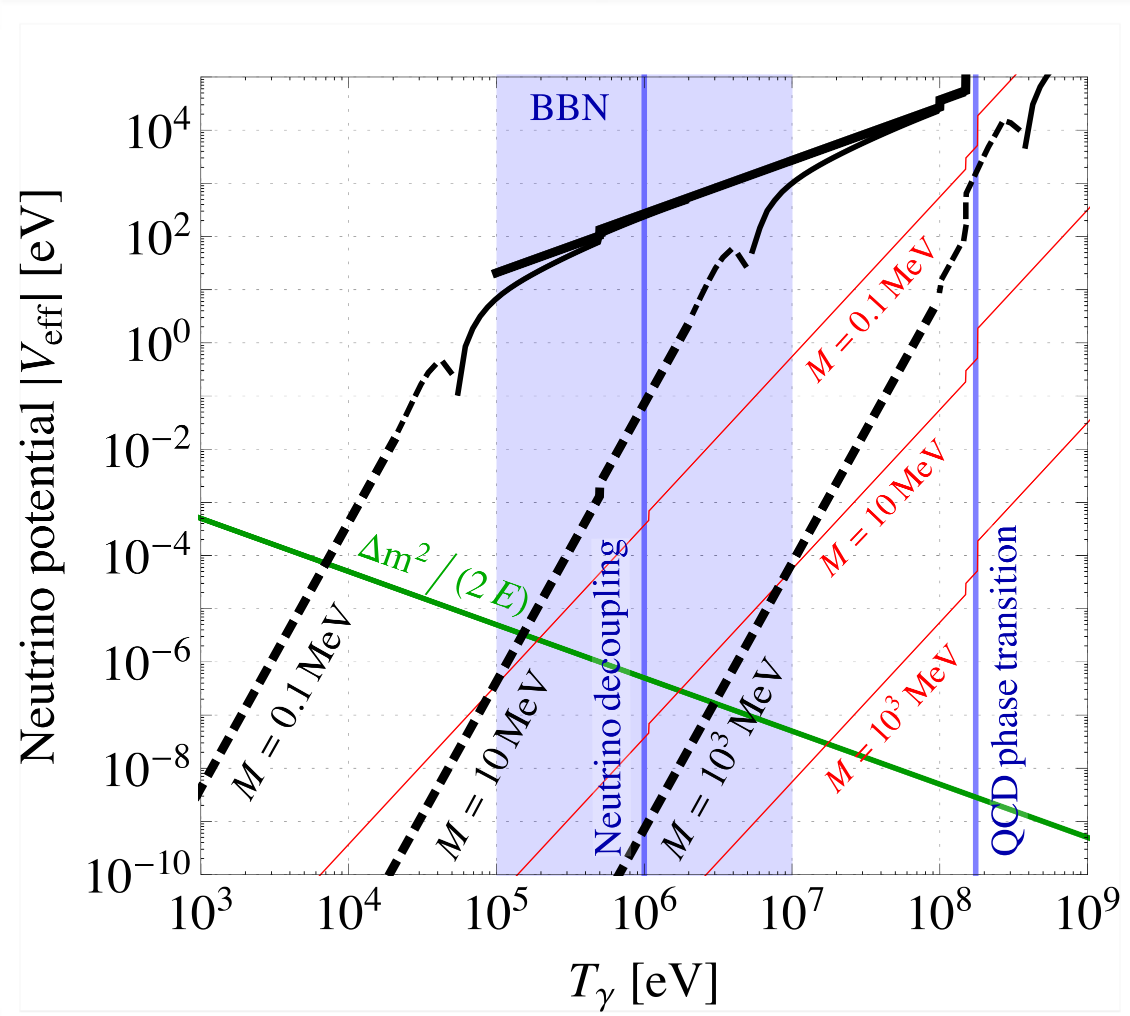

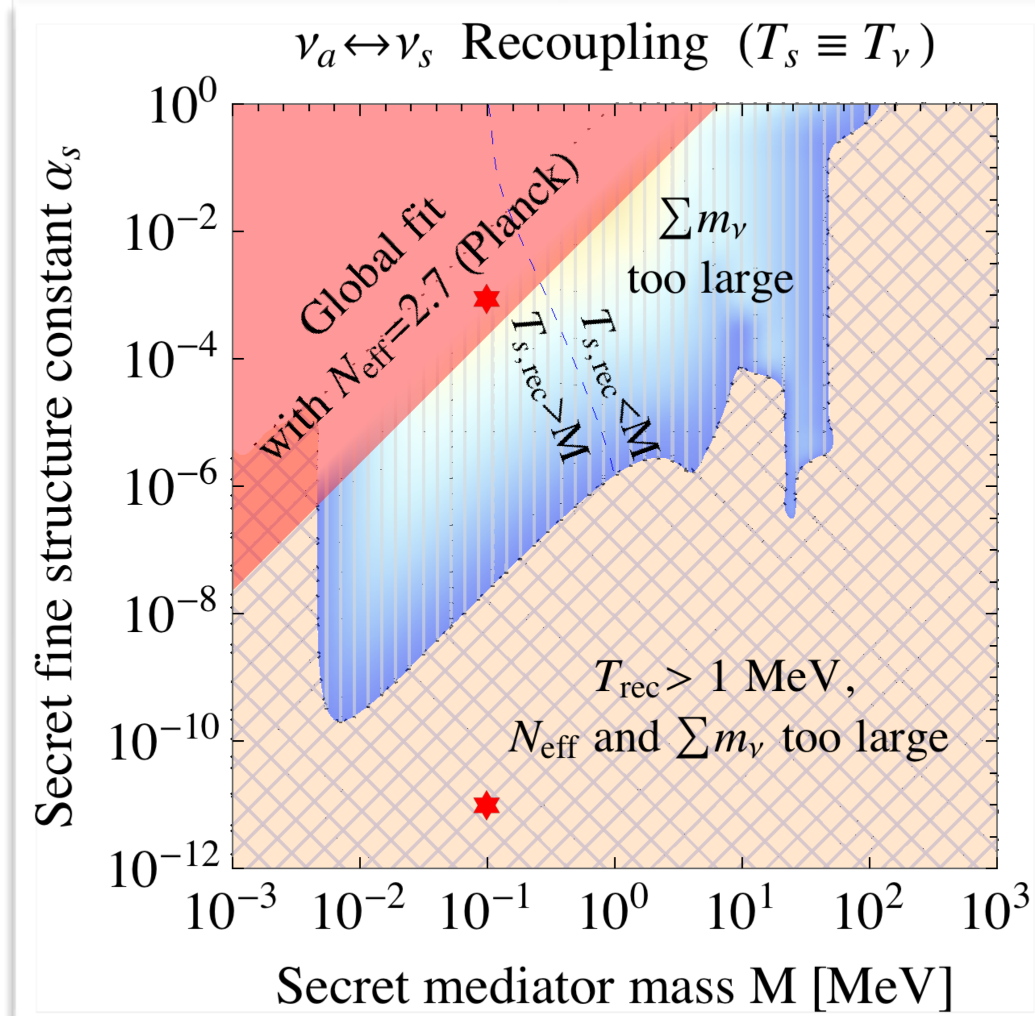

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Change of ν_s Properties in a Phase Transition

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

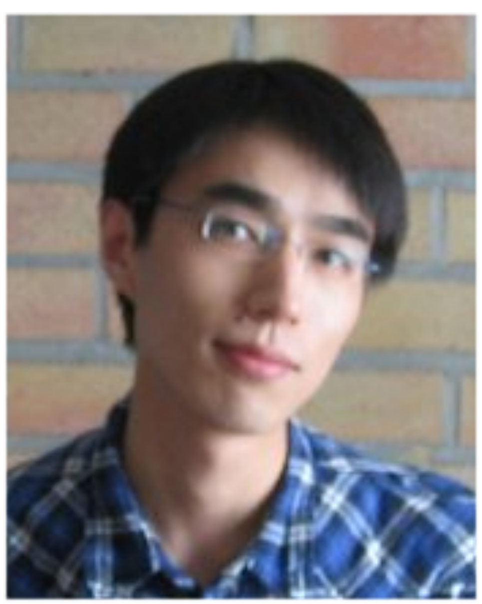
Weinberg 1974

- 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}

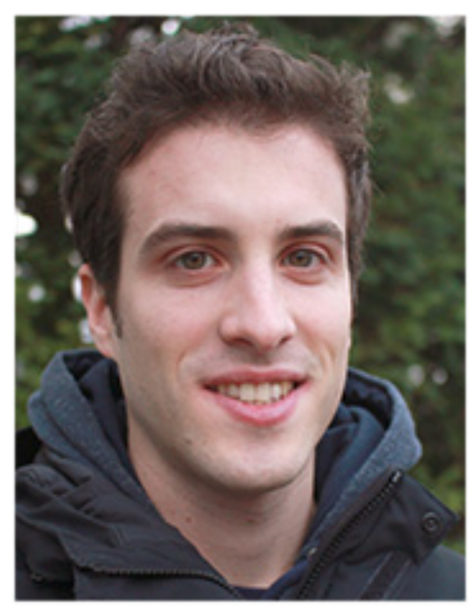
Summary

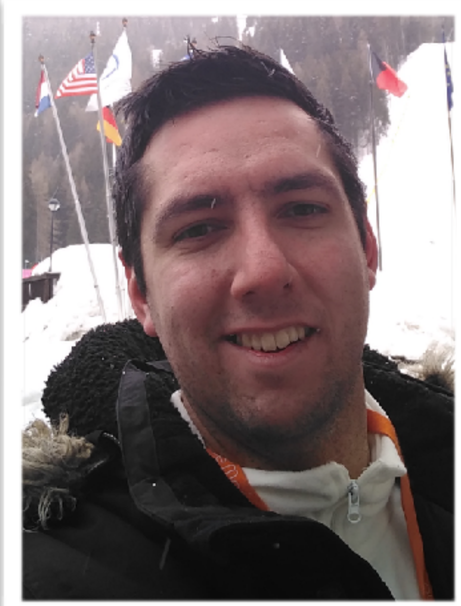
Summary

- Four independent oscillation anomalies
- Daya Bay: flux as function of isotope composition
  - mild preference ($< 2\sigma$) for flux misprediction over sterile neutrino
  - non-equilibrium effects and non-linear isotopes previously neglected
- Global Fit: severe tension with ν_μ disappearance
- Cosmology: constraints evaded in non-minimal models


Xiaoyong Chu


Mona Dentler


Álvaro Hernández


Ivan Martinez


Ninetta Saviano

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Thank You!