Neutrino Physics Off the Beaten Paths

Joachim Kopp
LAUNCH 2017 | Heidelberg, Germany | September 14—15, 2017

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In this Talk

- Light Sterile Neutrinos
- Neutrinos and Dark Matter
- Mößbauer Neutrinos
- The GSI Anomaly

Light Sterile Neutrinos

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Anomalies in Short Baseline Oscillations

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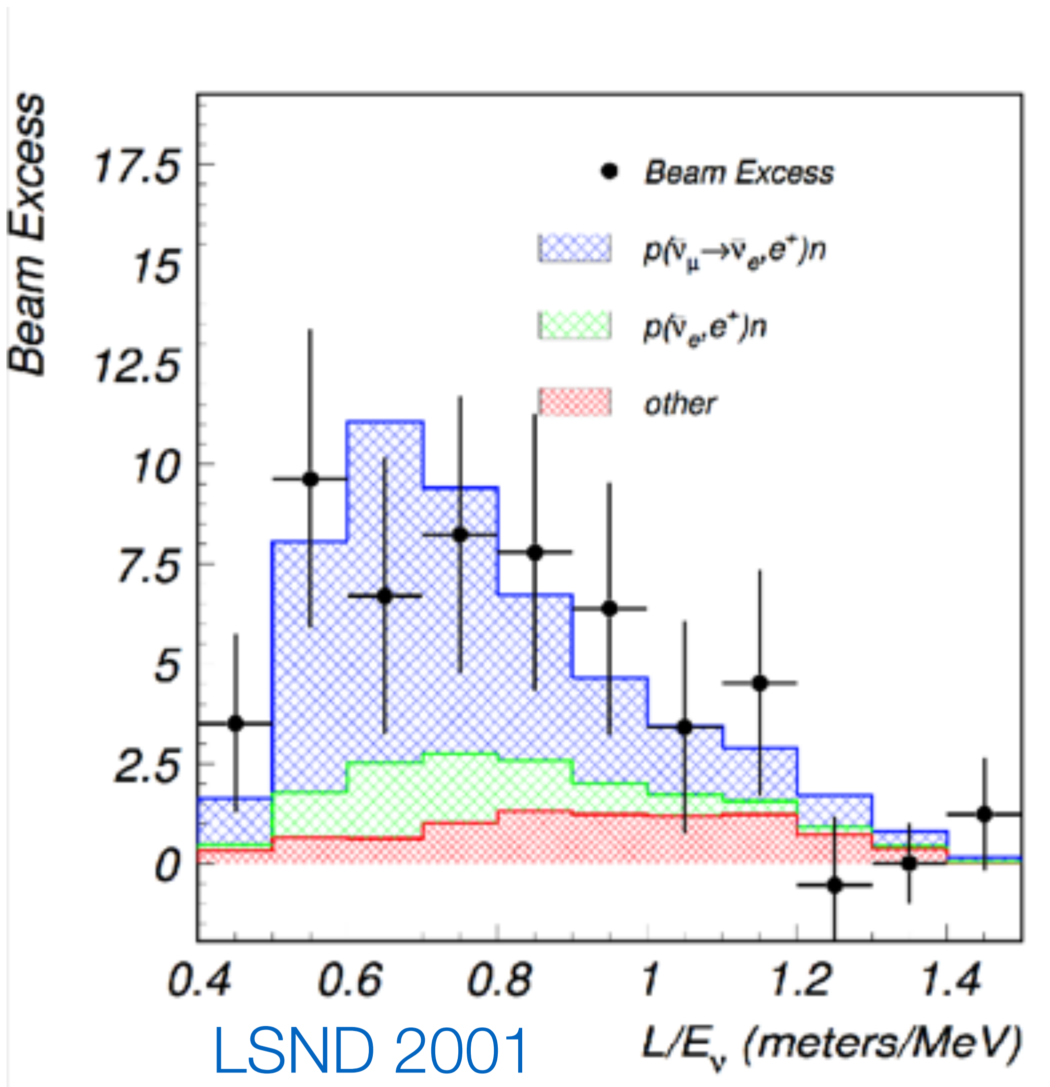
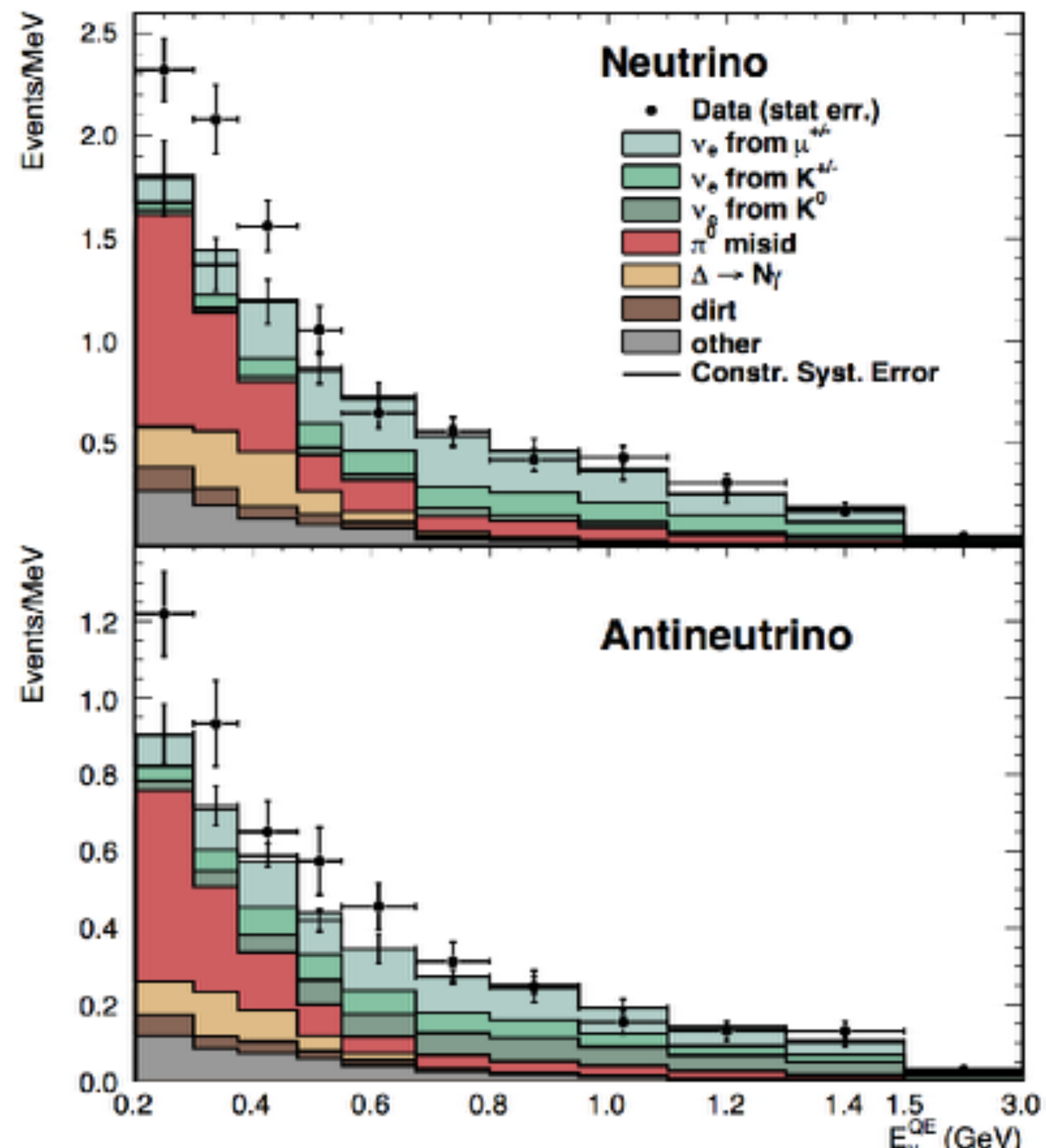
- LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations



LSND 2001



MiniBooNE 2001

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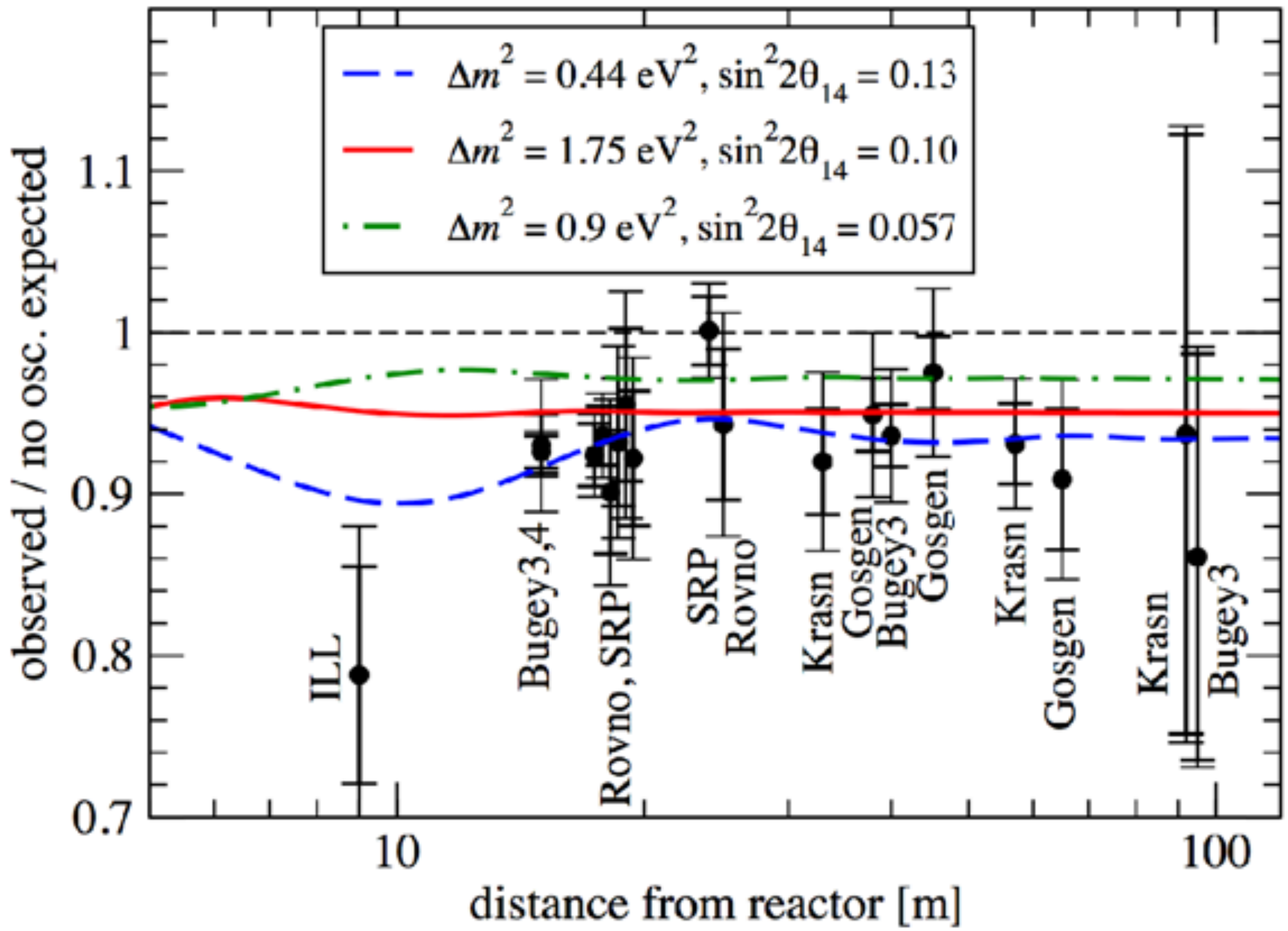
Anomalies in Short Baseline Oscillations

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



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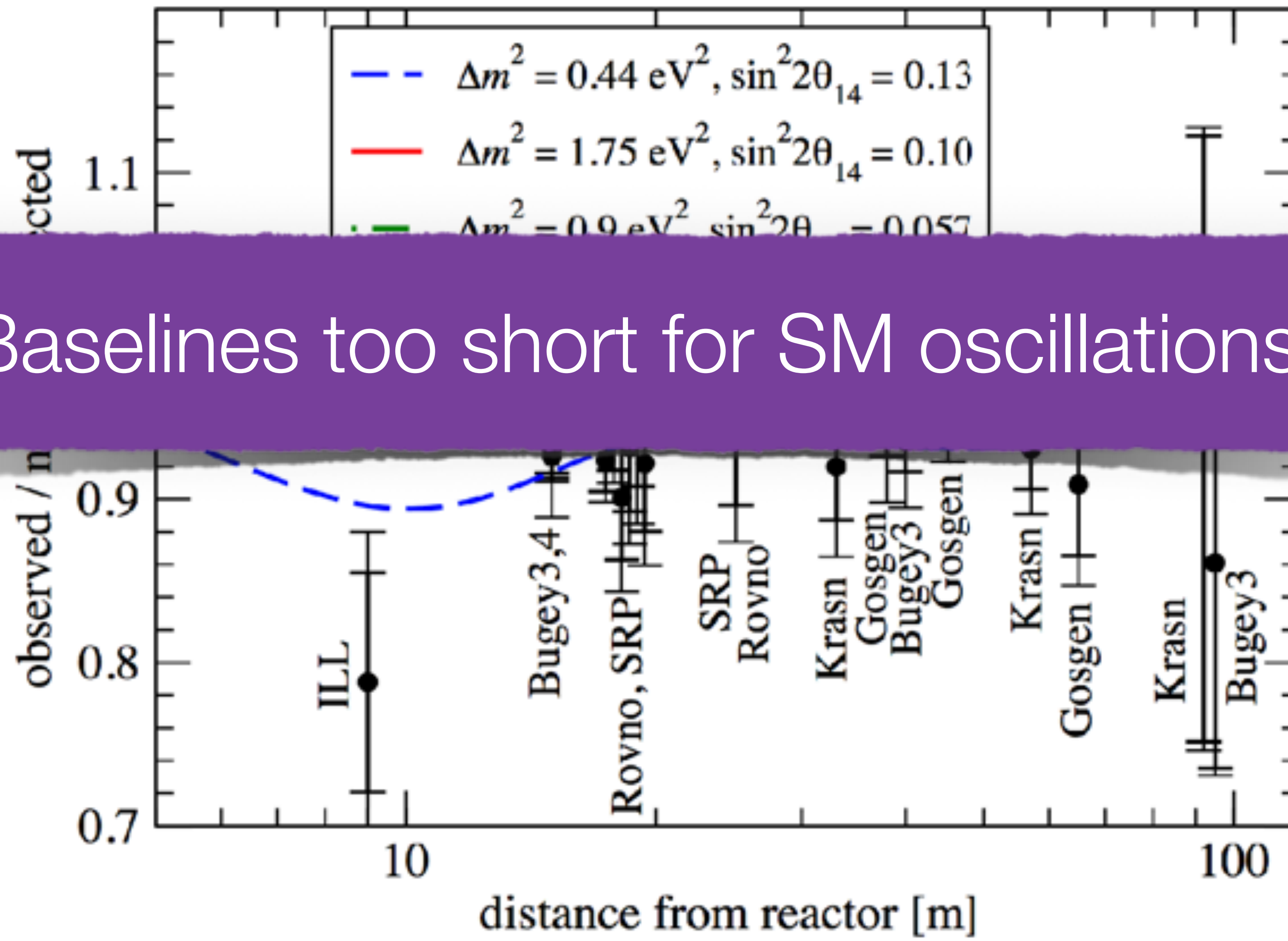
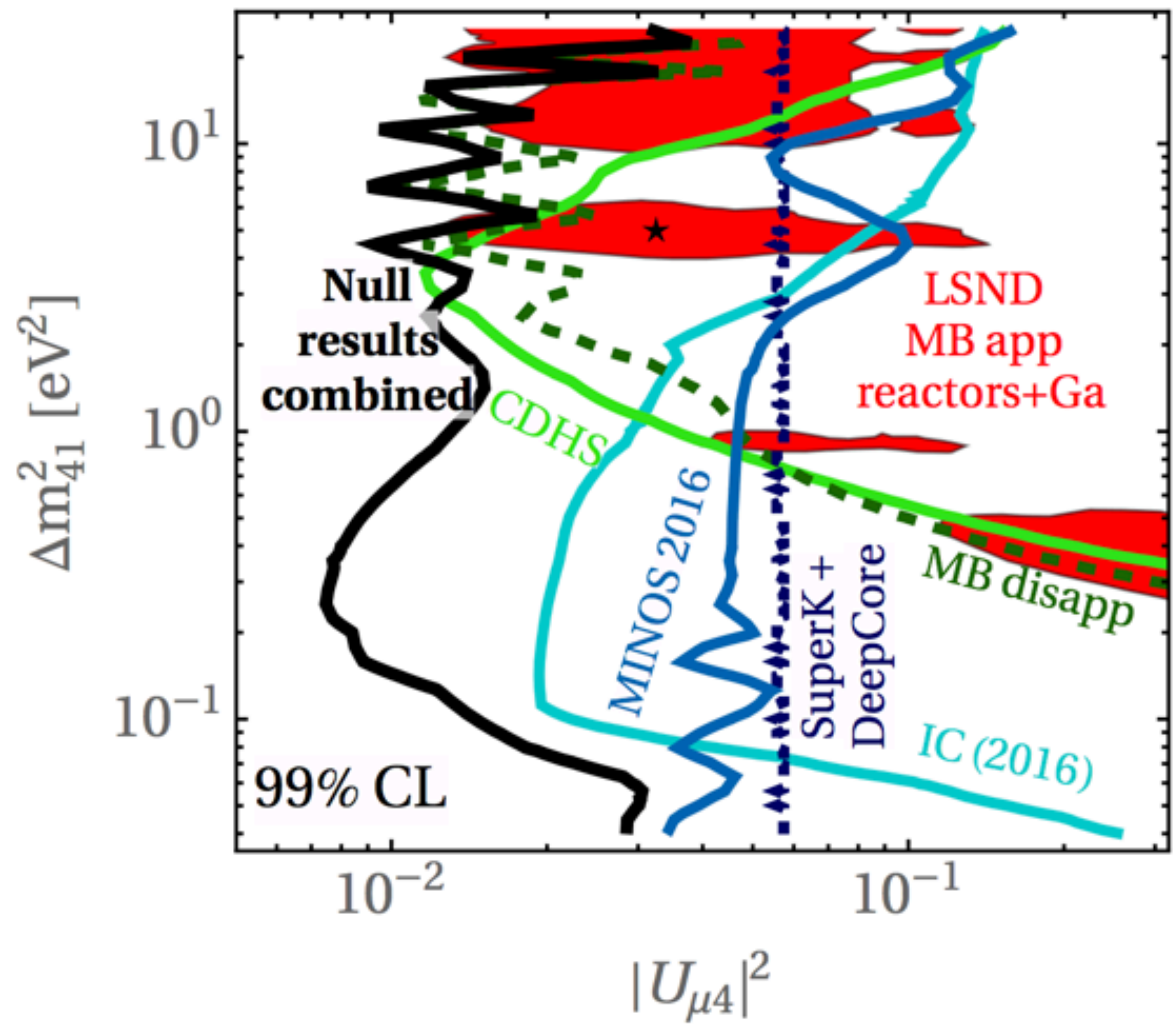


Baselines too short for SM oscillations!

Global Fit in 3+1 Model



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

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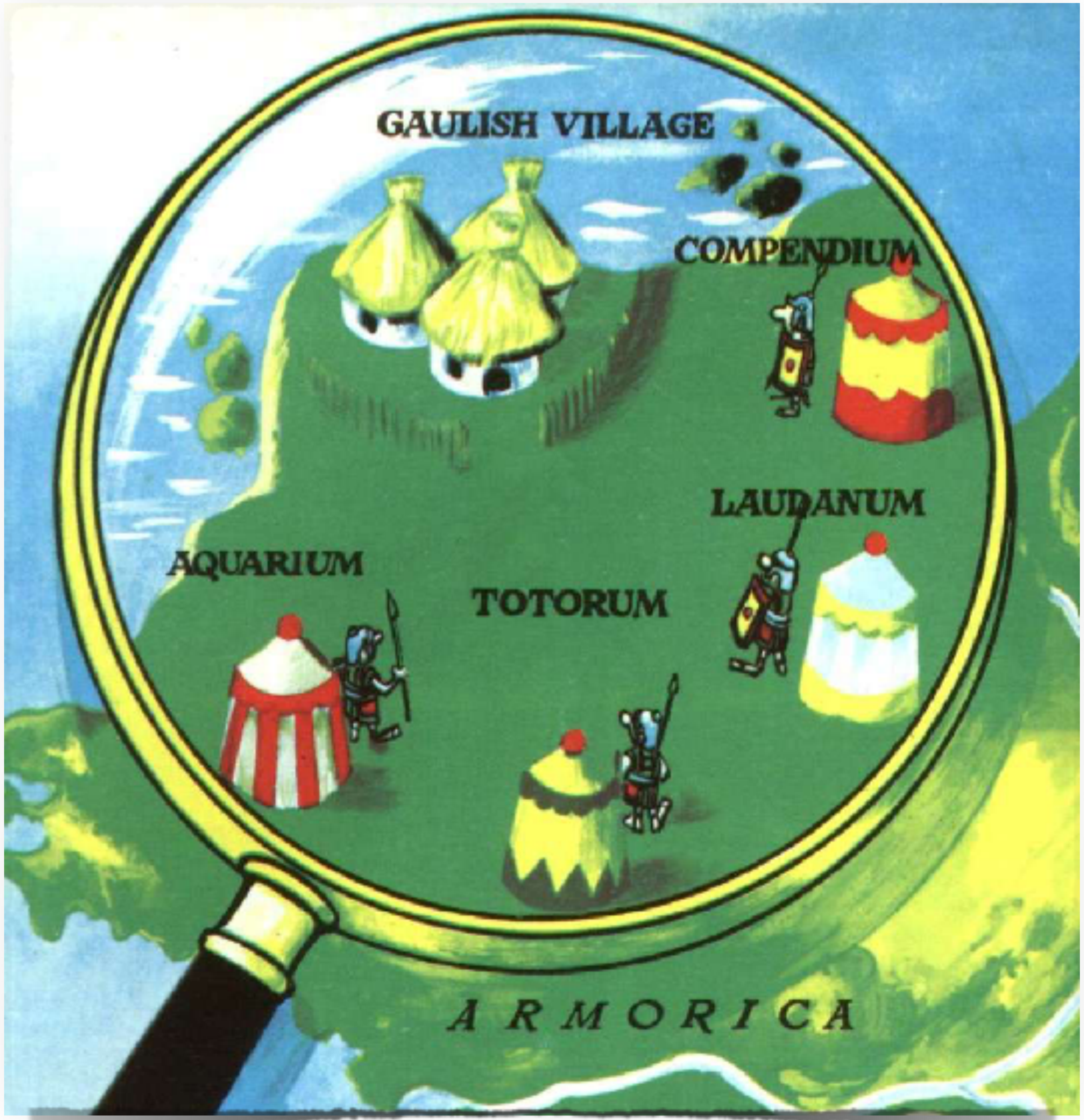
Status of Light Sterile Neutrinos



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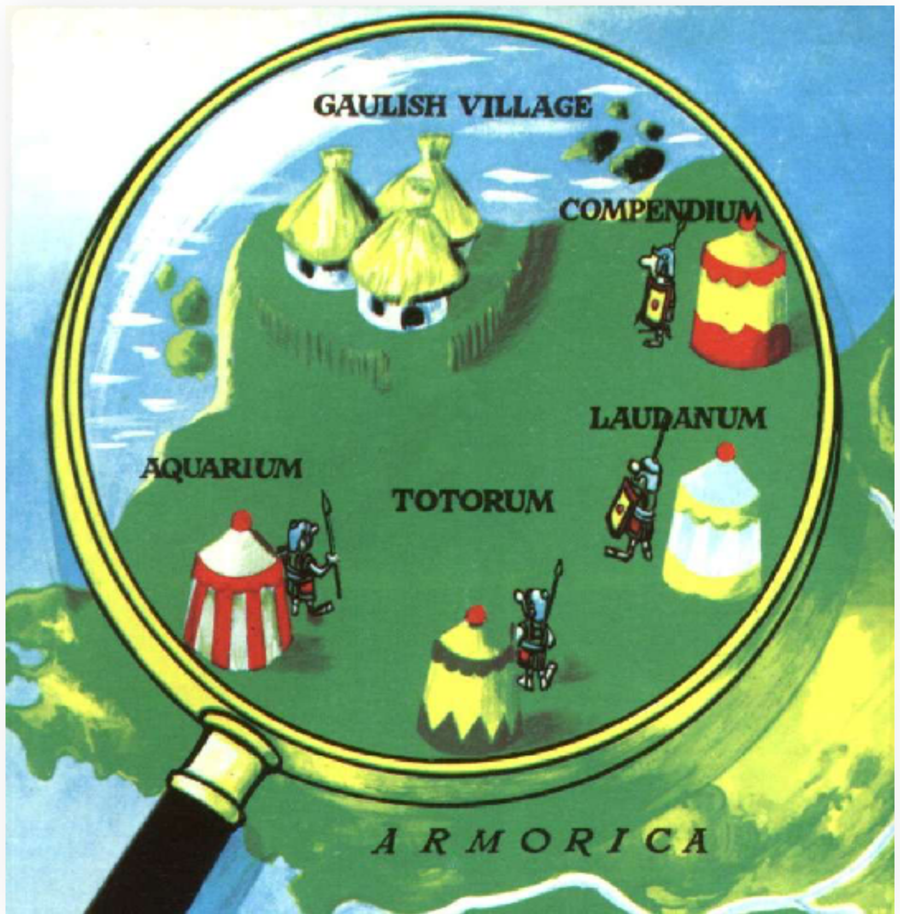

severe tension ($p < 10^{-4}$)

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

Reconciling Sterile Neutrinos with Cosmology

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

Constrained by N_{eff} and Σm_ν, but there are ways out:

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- ☑ 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

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- ☑ ν_s properties change in late phase transition

  Bezrukov Chudaykin Gorbunov, 1705.02184

Flux Measurement by Daya Bay

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

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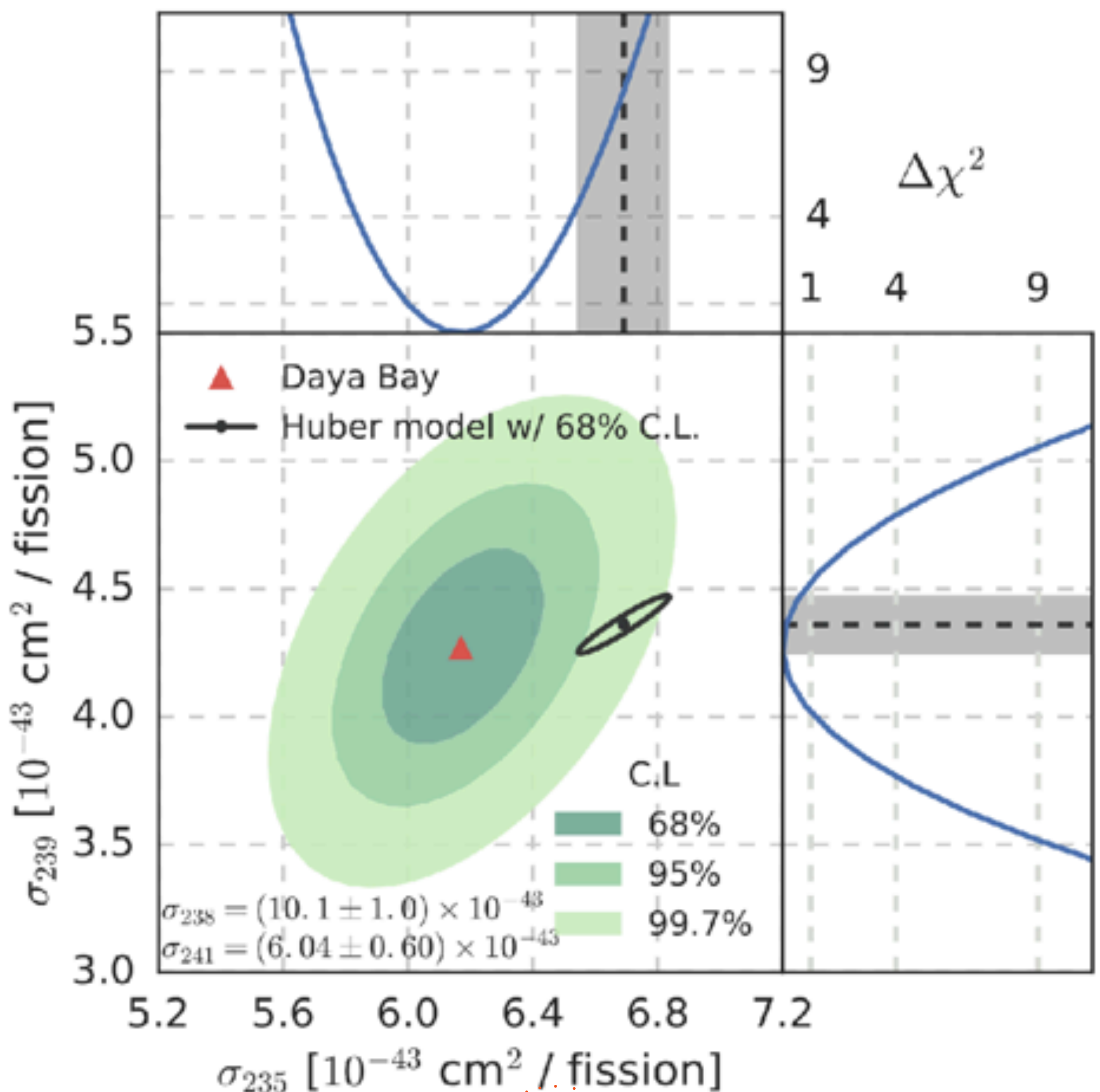

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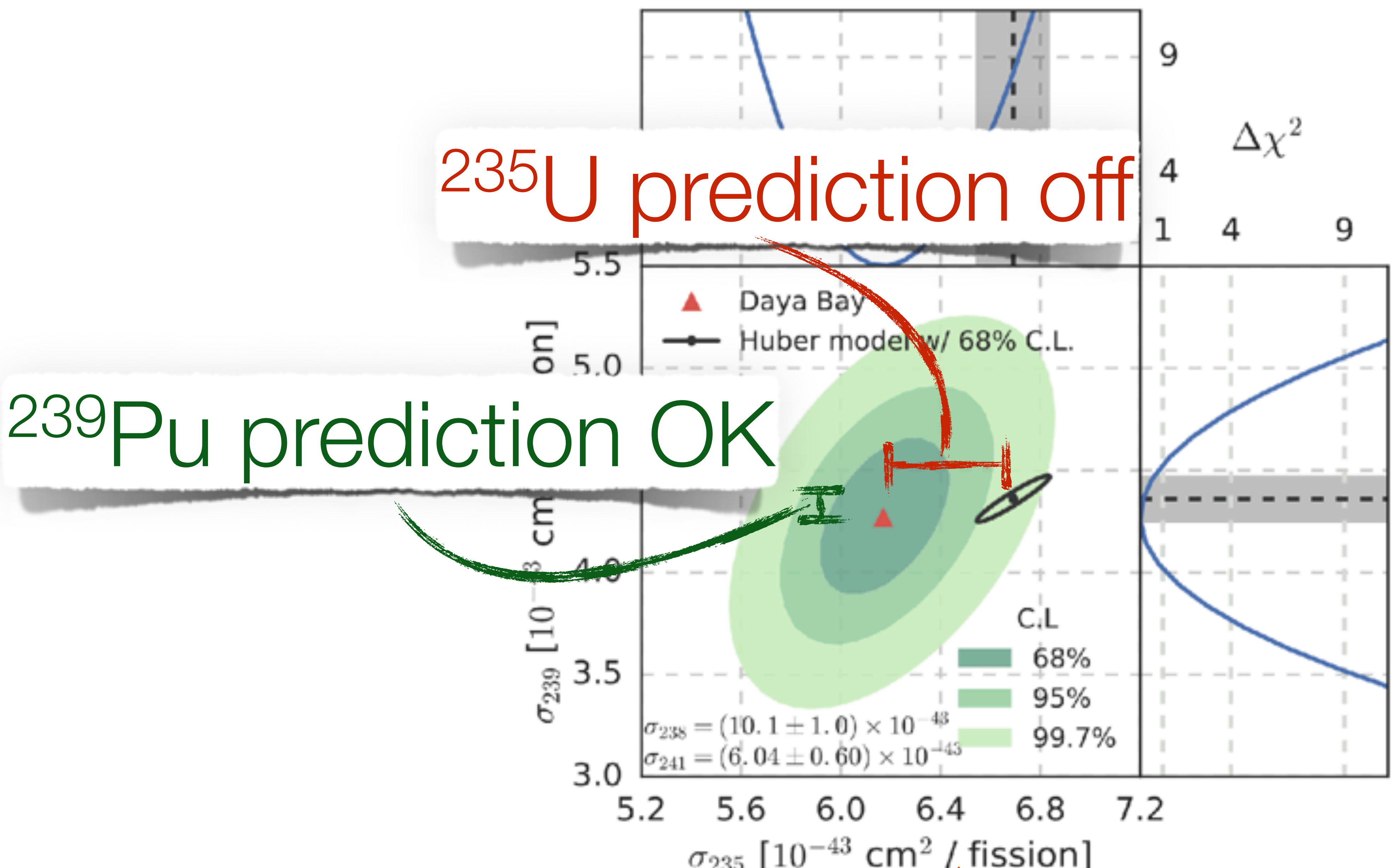

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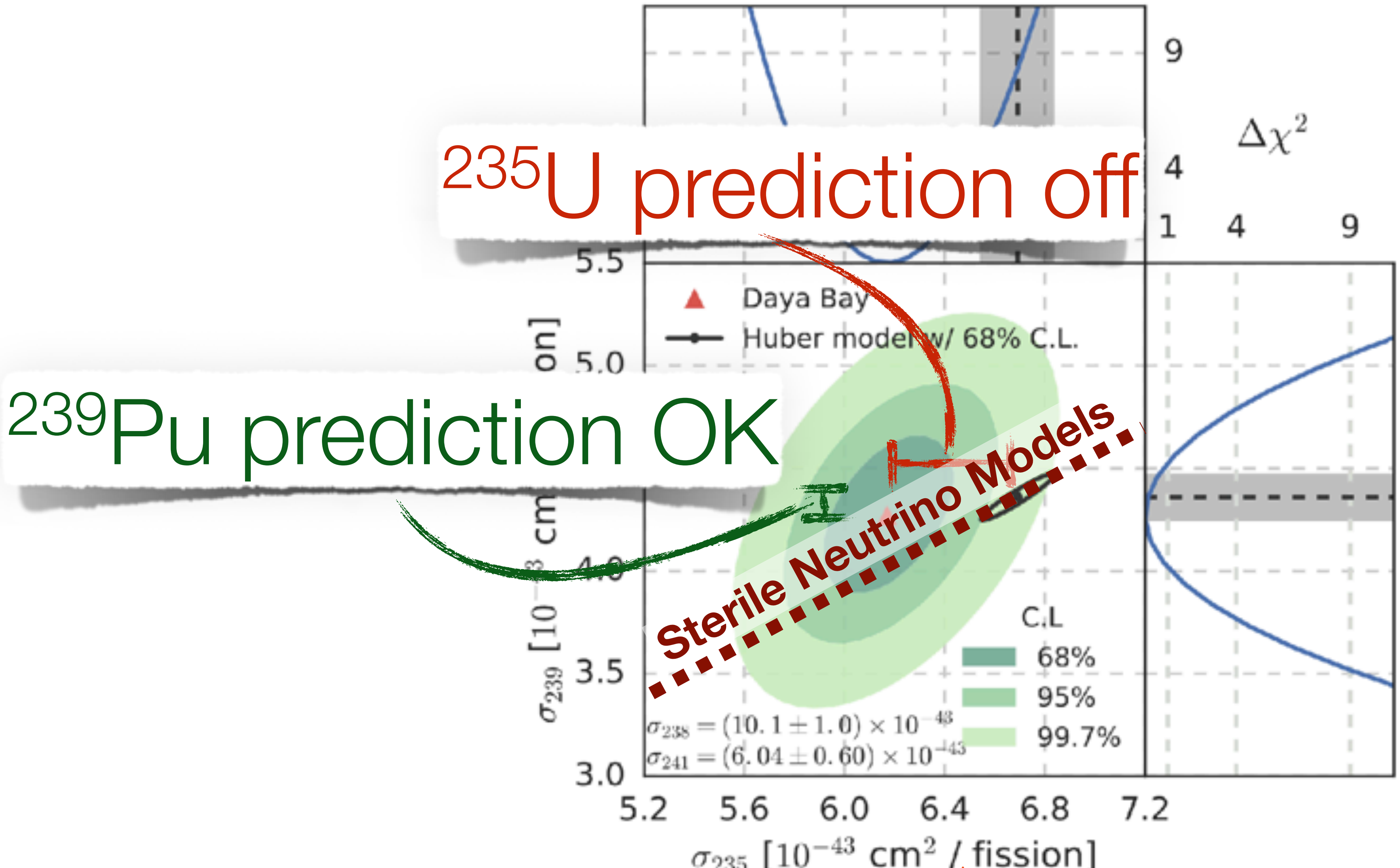

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  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + $\sin^2 2\theta_{14}$

$\Delta\chi^2 = 7.9$

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

Denter Hernández
JK Maltoni Schwetz
arXiv:1709.today

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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

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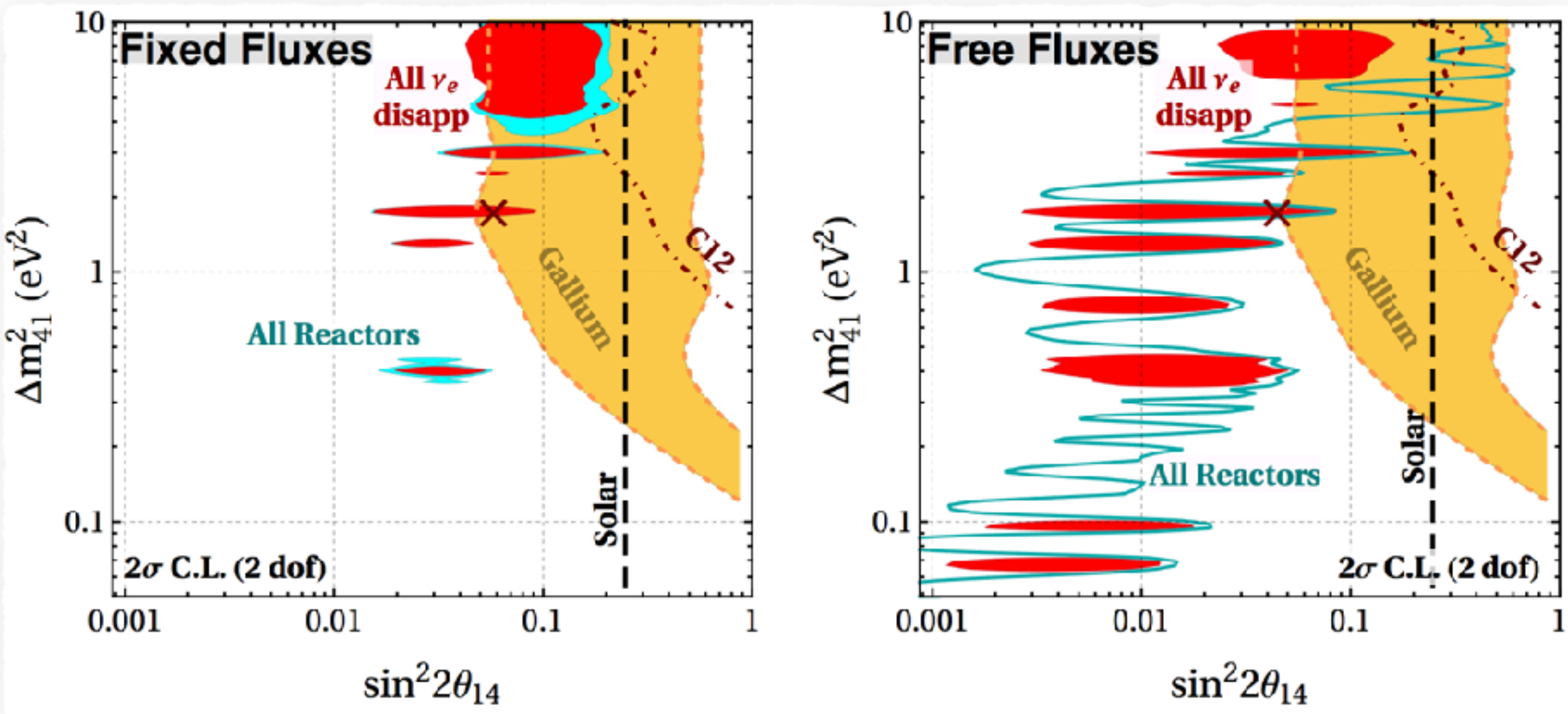

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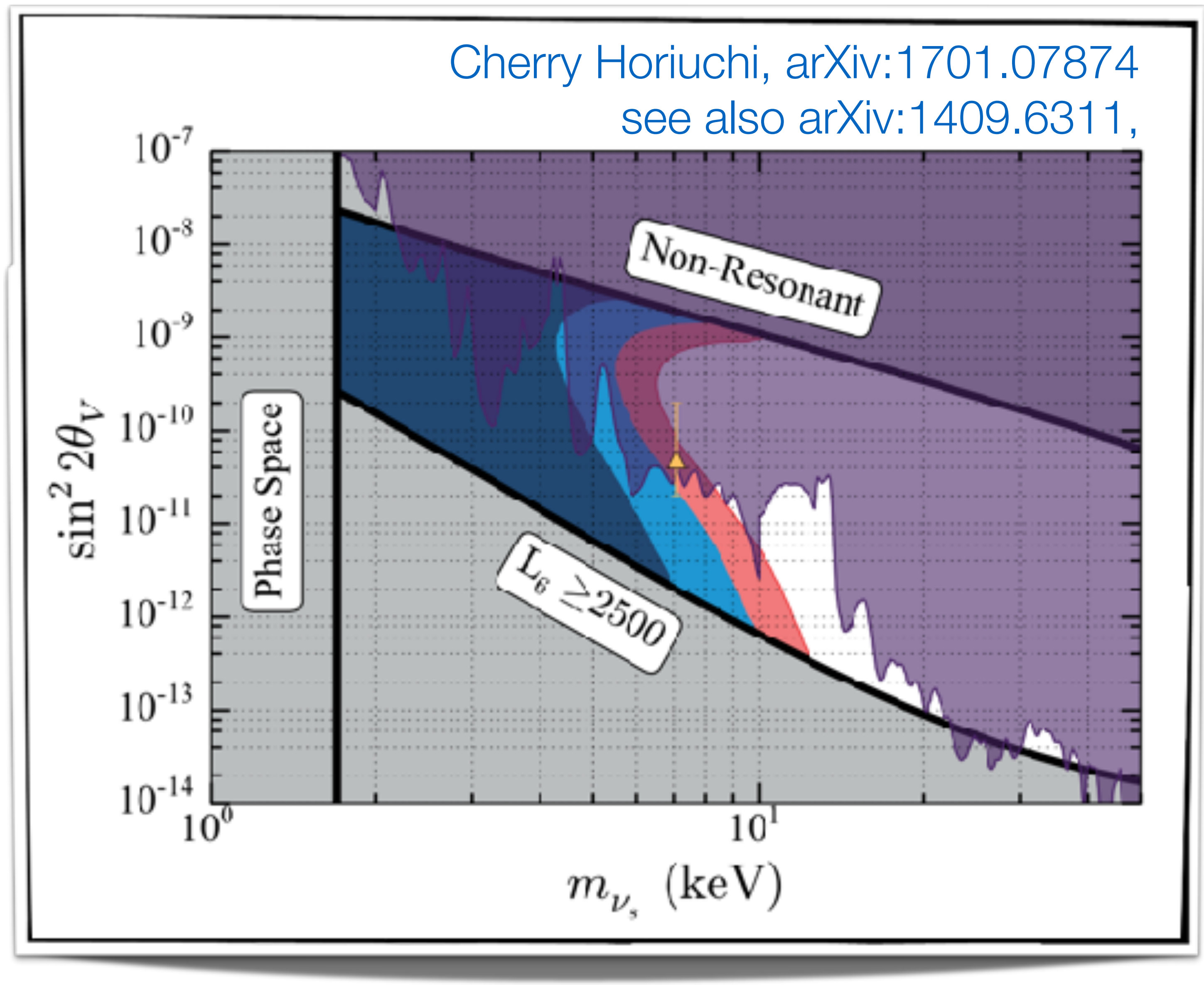
Neutrinos and Dark Matter

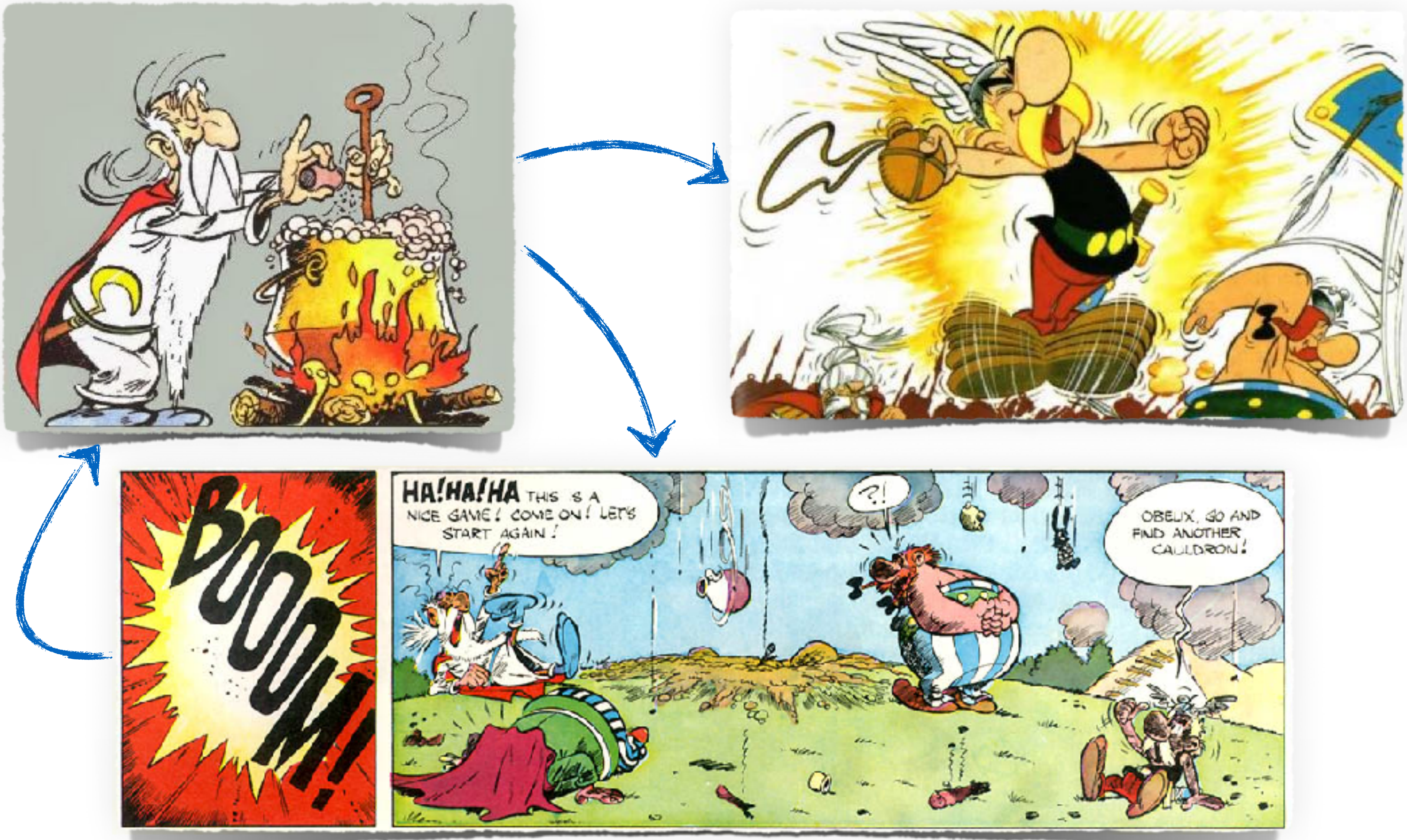
Recent Developments

Sterile Neutrinos as Dark Matter

- ☑ keV-scale sterile neutrinos are leading candidate for Warm Dark Matter
  - Improved small scale structure
  - x-ray line signature
- ☑ Production through oscillations challenged by e.g. Lyman-α data



Dark Matter Model Building Flowchart



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Production via Scalar Decays

- Decay of heavy scalars

$$\mathcal{L} \supset i\overline{N_\alpha}\not{\partial} N_\alpha + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{y_\alpha}{2} S \overline{N^c_\alpha} N_\alpha + 2\lambda(H^\dagger H)S^2$$

- S freezes in via $hh \leftrightarrow SS$, decays via $S \rightarrow NN$
- N produced with relatively cold spectrum

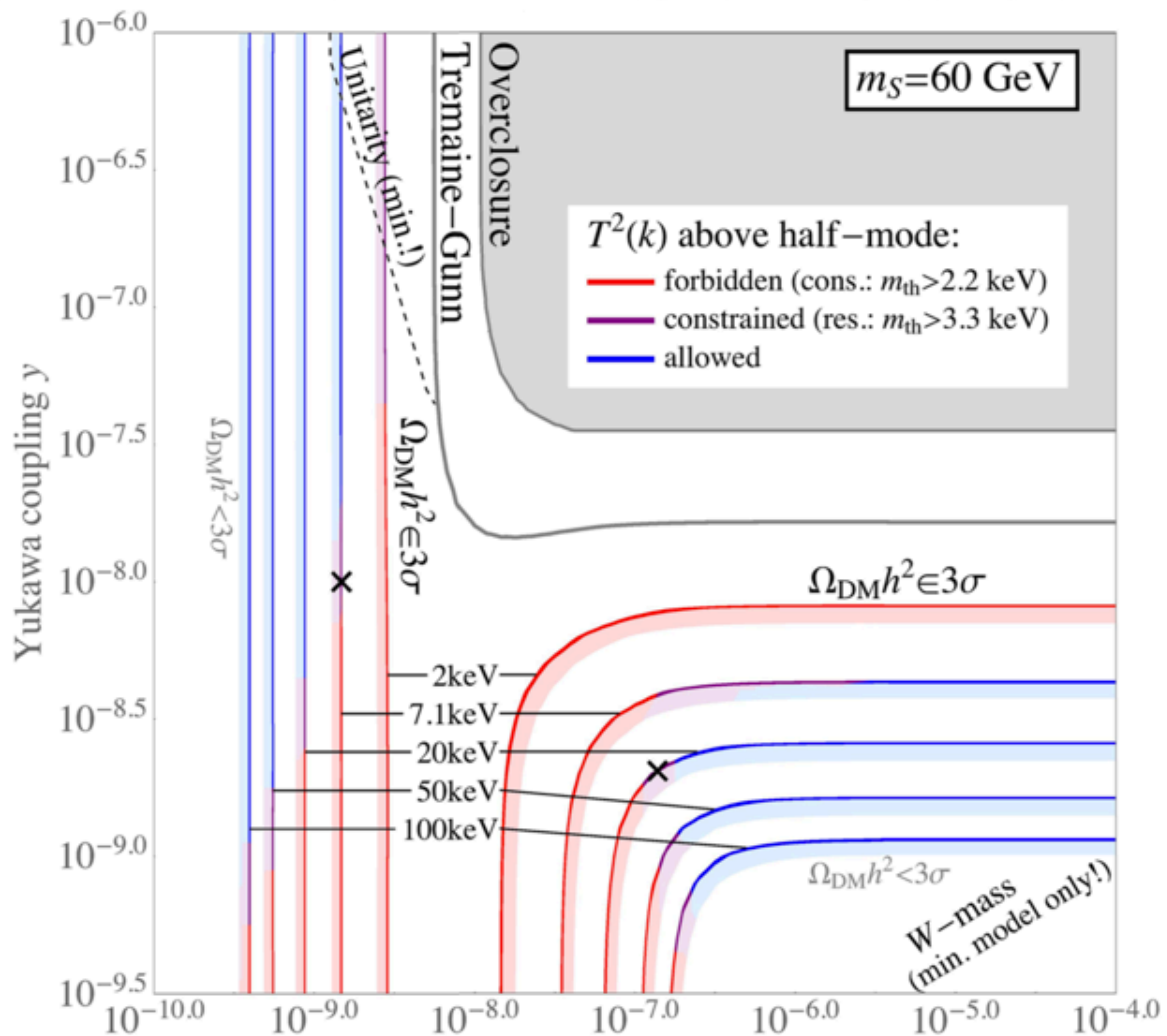
Shaposhnikov Tkachev hep-ph/0604236
Kusenko hep-ph/0609081
Merle Niro Schmidt 1306.3996
Merle Totzauer 1502.01011
König Merle Totzauer 1609.01289

Production via Scalar Decays

- Decay o

$\mathcal{L} \supset i\overline{N}_{\!\!\cdot}$ … $(H^\dagger H)S^2$

- S freeze
- N produ



König et al. [1609.01289](https://arxiv.org/abs/1609.01289)

…-ph/0604236
…-ph/0609081
…dt 1306.3996
…r 1502.01011
…r 1609.01289

Neutrino—DM Interactions

- Coherent forward scattering of neutrinos on DM
  - analogous to SM matter effects (“MSW effect”)
  - Observability requires huge DM number density
- Fuzzy Dark Matter
  - scalar or vector, $m < 10^{-20}\,\mathrm{eV}$
  - Compton wave length $\sim \mathrm{pc}$
  - Interesting for small scale structure

Krnjaic Machado Necib, 1705.06740
Brdar JK Liu Prass Wang, 1705.09455

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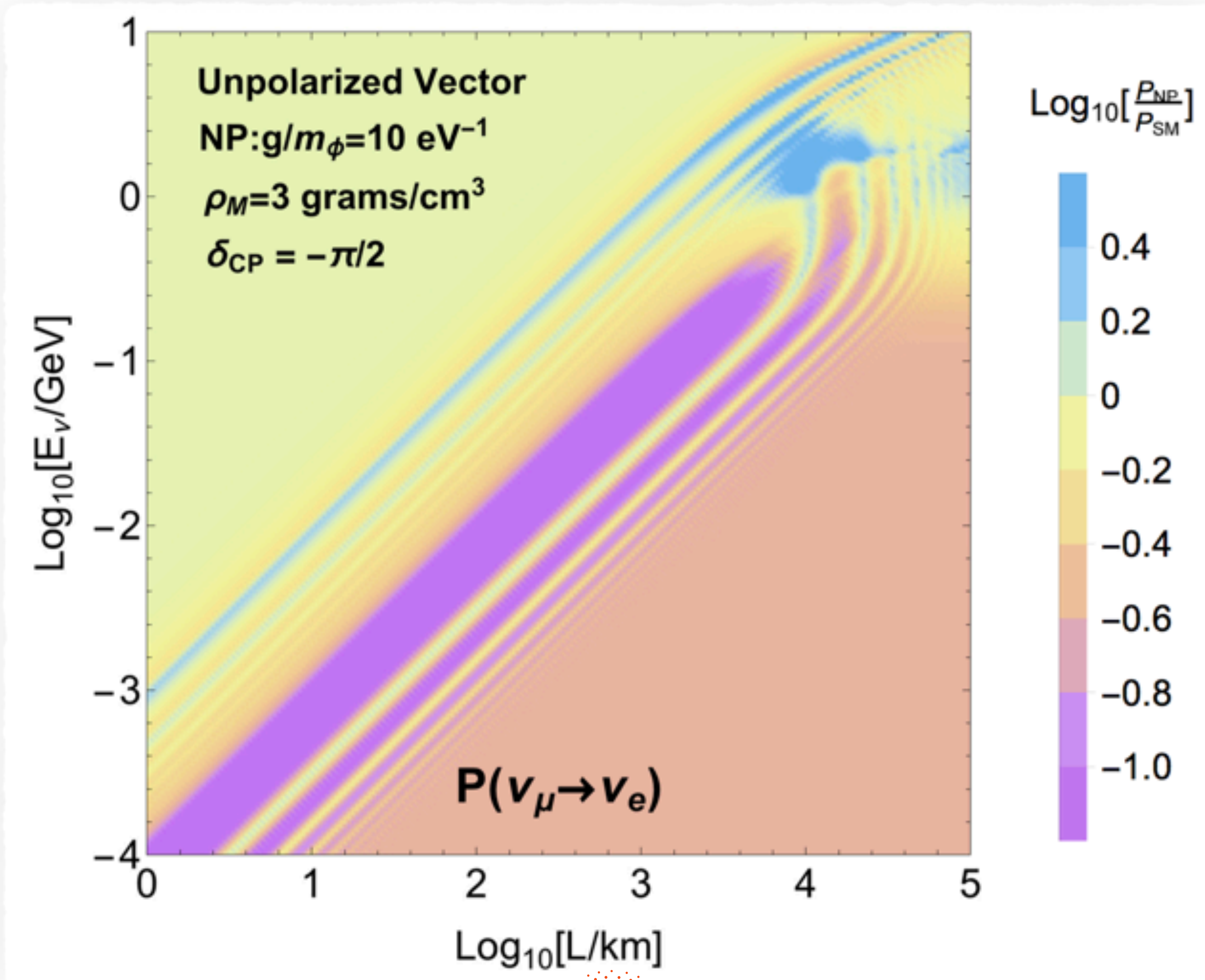
Neutrino—DM Interactions

Modified Oscillation Probabilities

- Coherent
  - anal
  - Obs
- Fuzzy
  - scal
  - Con
  - Inte



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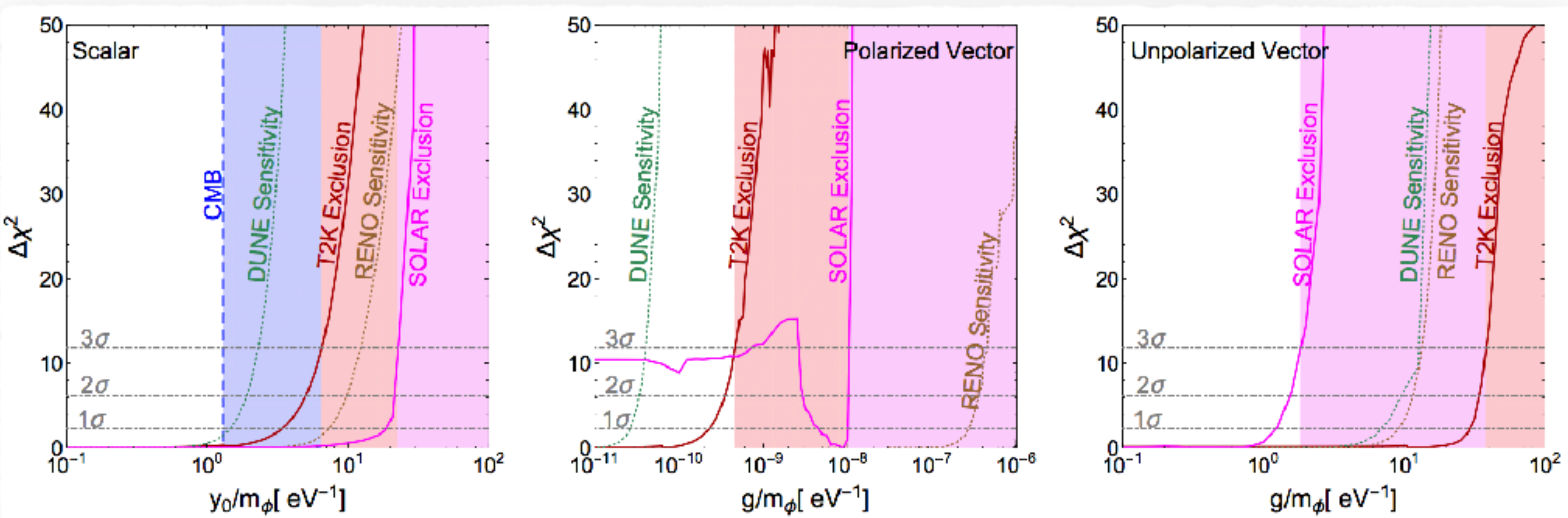
  - an
  - Ob

Limits from Long-Baseline Experiments



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Mößbauer Neutrinos

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The Neutrino Mößbauer Effect

- Classical Mößbauer Effect:
  Recoil-free emission / absorption of γ-rays by crystals
  - Extremely narrow emission / absorption lines
  - Observation of gravitational redshift in the lab
  - Determination of chemical environment of emitting nucleus
- Similar effect should exist for neutrinos

$$
\begin{aligned}
{}^3\mathrm{H} &\to {}^3\mathrm{He} + \bar{\nu}_e + e^-(\mathrm{bound}) \\
{}^3\mathrm{He} + \bar{\nu}_e + e^-(\mathrm{bound}) &\to {}^3\mathrm{H}
\end{aligned}
$$

^{3}H and ^{3}He embedded in crystals (metal hydrides)

Visscher 1959; Kells Schiffer 1983; Raghavan 2005

The Neutrino Mößbauer Effect

Neutrinos with very special properties

- Resonantly enhanced cross section
- Neutrino receives full decay energy: $Q = 18.6$ keV
- Natural line width: 1.17×10^{-24} eV
- Actual line width: $\sim 10^{-11}$ eV
  (broadening due to impurities, lattice defects, fluctuating B-fields)

Physics opportunities

- Neutrino oscillations in the lab: $L_{osc} \sim 20$ m
- Gravitational interactions of neutrinos
- Study of solid state effects

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Akhmedov JK Lindner, 0802.2513, 0803.1424, JK 0904.4346

The Mößbauer Neutrino Rate

$$\Gamma \propto \exp\left[-\frac{E_{S,0}^2 - m_2^2}{\sigma_p^2}\right] \exp\left[-\frac{|\Delta m^2|}{2\sigma_p^2}\right]$$
$$\cdot \frac{(\gamma_S + \gamma_D)/2\pi}{(E_{S,0} - E_{D,0})^2 + \frac{(\gamma_S+\gamma_D)^2}{4}}$$
$$\cdot \left\{1 - 2s^2c^2\left[1 - \frac{1}{2}(e^{-L/L_S^{\mathrm{coh}}} + e^{-L/L_D^{\mathrm{coh}}})\cos\left(\pi\frac{L}{L^{\mathrm{osc}}}\right)\right]\right\}$$

Akhmedov JK Lindner, 0802.2513, 0803.1424
JK 0904.4346

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Lamb-Mößbauer factor
(probability of recoil-free transitions)

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Akhmedov JK Lindner, [0802.2513](0802.2513), [0803.1424](0803.1424)
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Breit-Wigner

Akhmedov JK Lindner, 0802.2513, 0803.1424
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Wave packet decoherence

(depends on line width)

$L_{S,D}^{\rm coh} = 4E^2/(\Delta m^2 \Gamma_{S,D})$

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Oscillations

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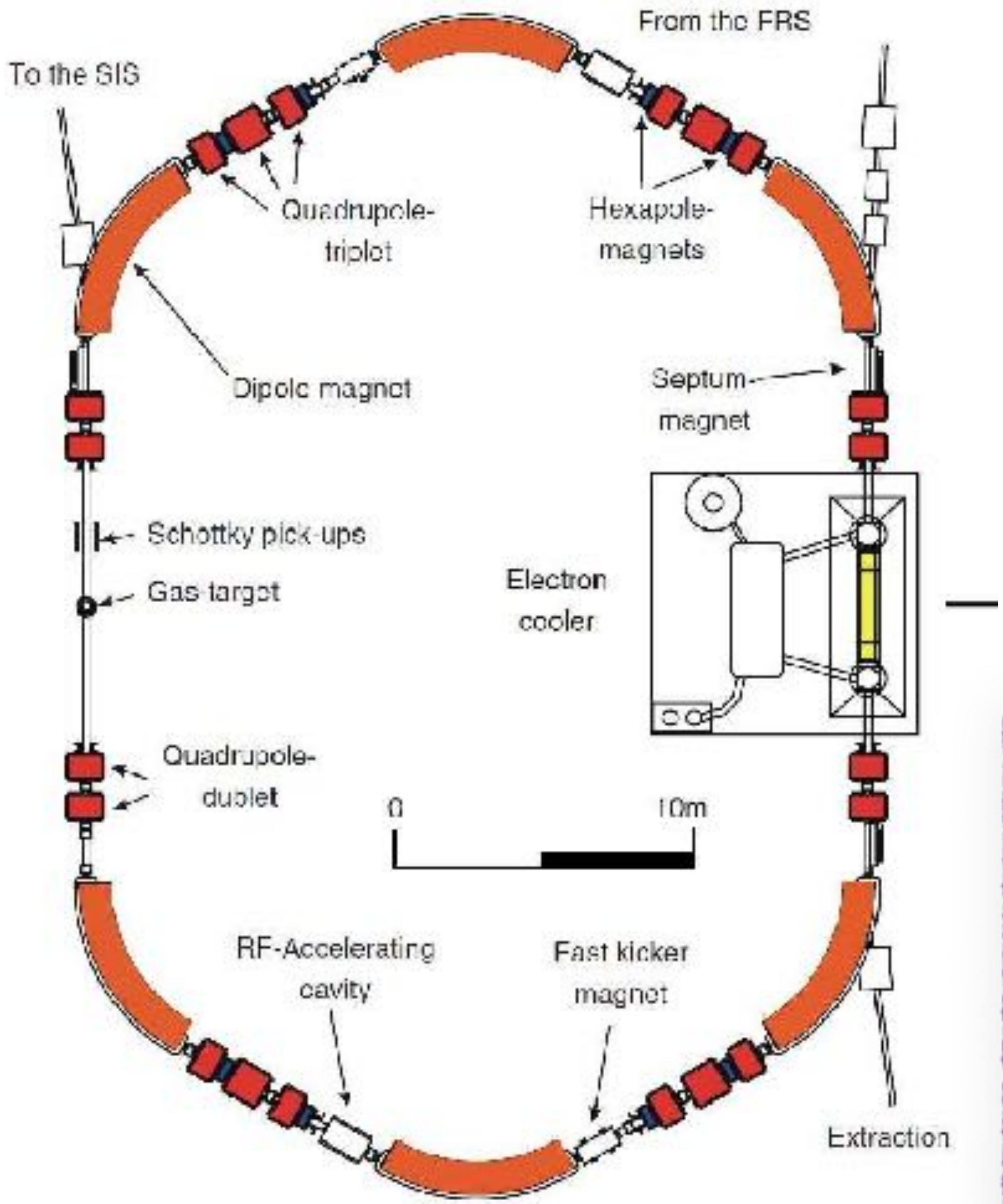
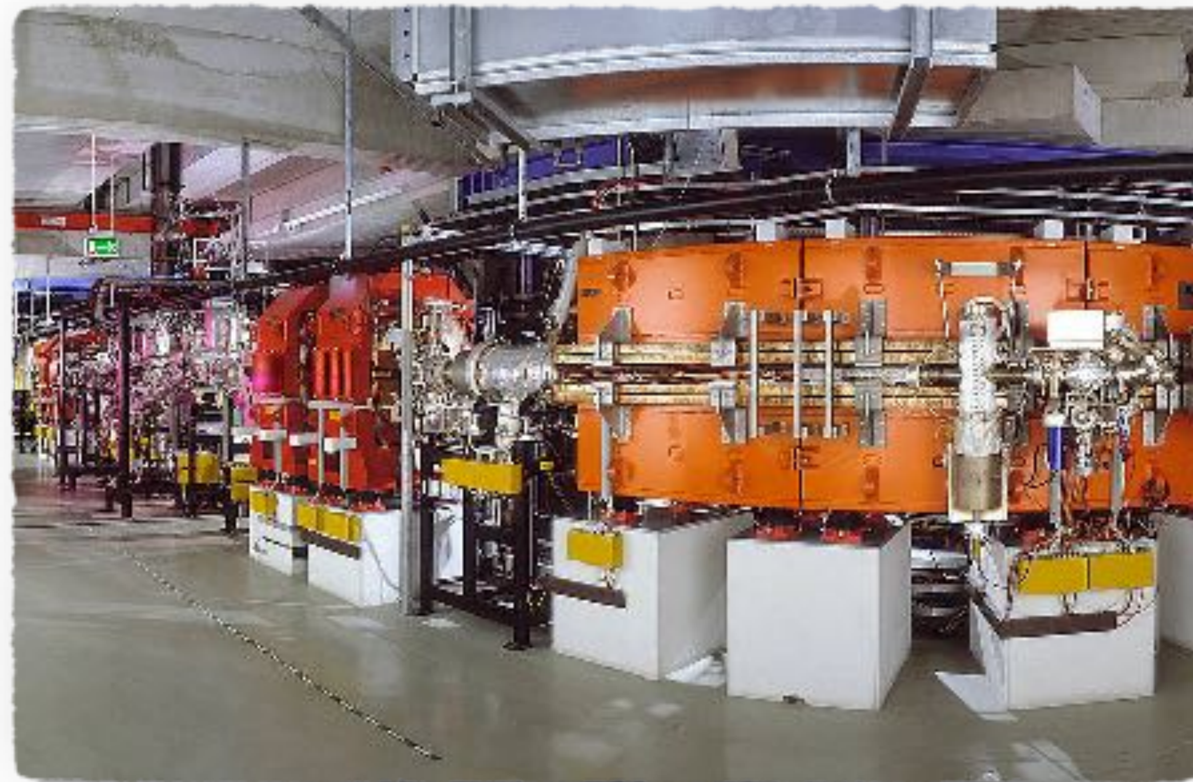
The GSI Anomaly

A Nuclear Physics Mystery





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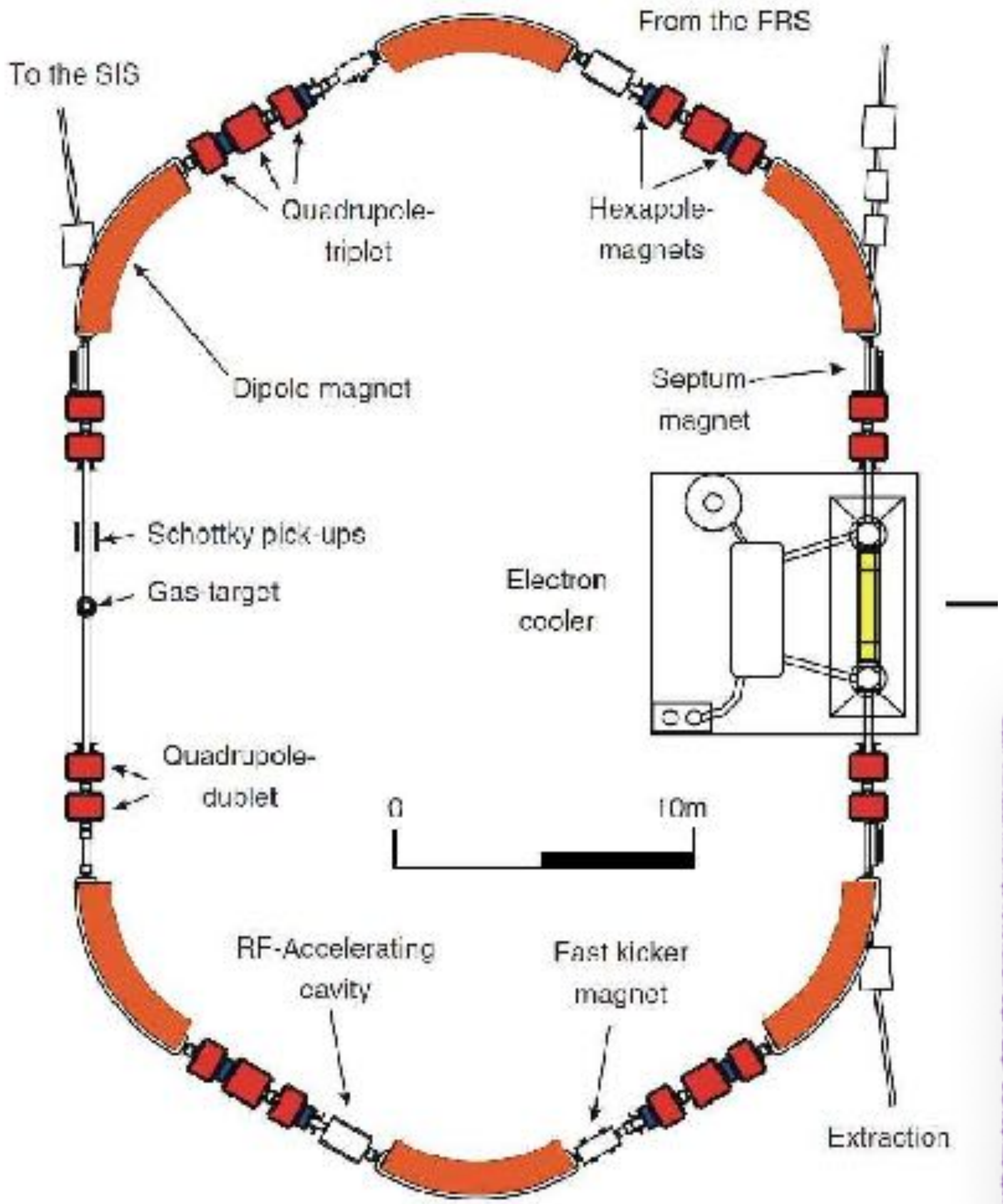

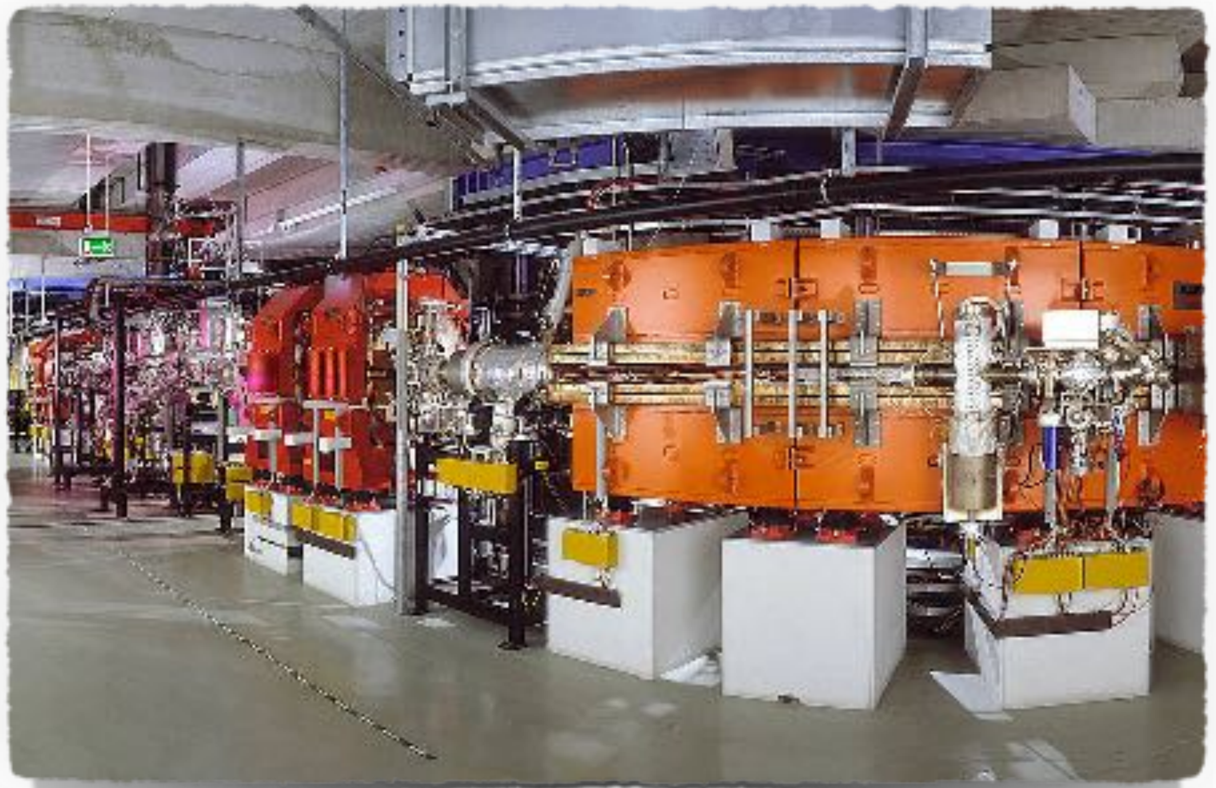

- Storage of H-like $^{140}Pr^{59+}$, $^{142}Pm^{60+}$ ions
- Electron capture to $^{140}Ce^{59+}$, $^{142}Nd^{60+}$

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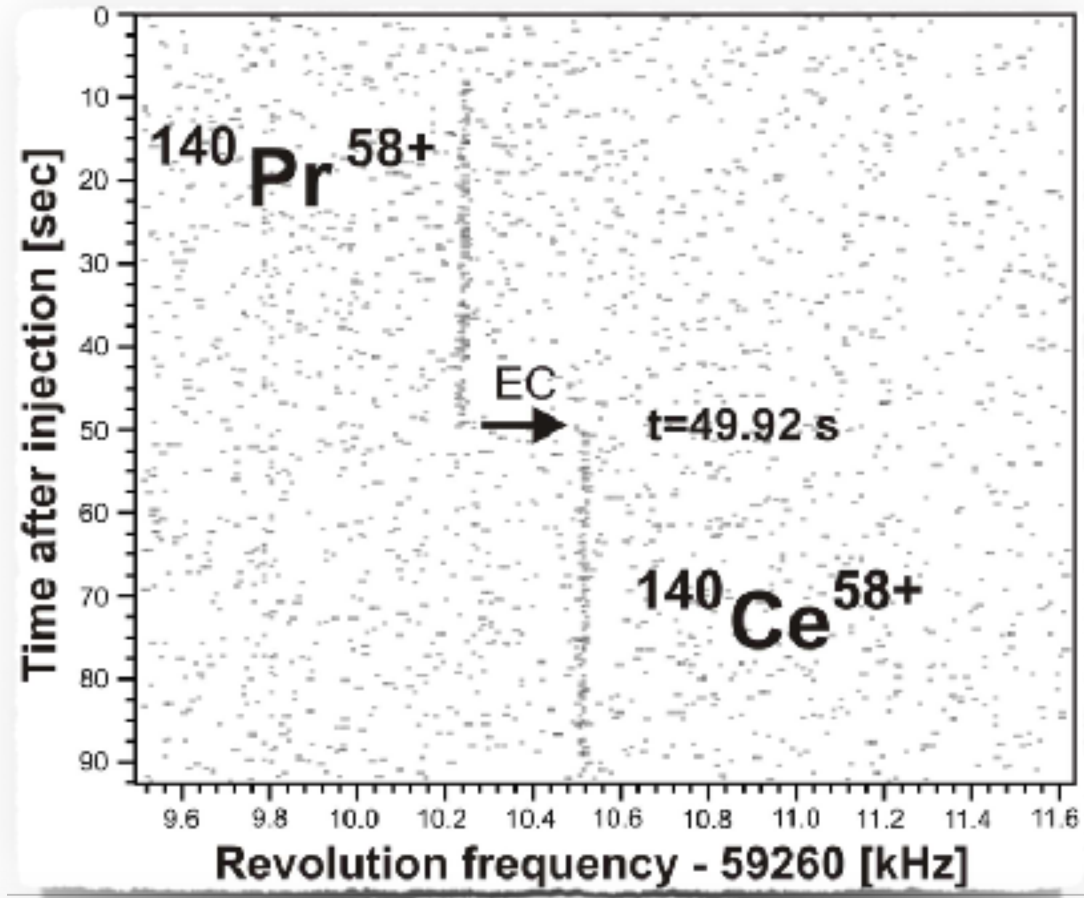

- Storage of H-like $^{140}Pr^{59+}$, $^{142}Pm^{60+}$ ions
- Electron capture to $^{140}Ce^{59+}$, $^{142}Nd^{60+}$
- Change in ion mass
  ➛ change in revolution frequency
- Measured in Schottky pick-up

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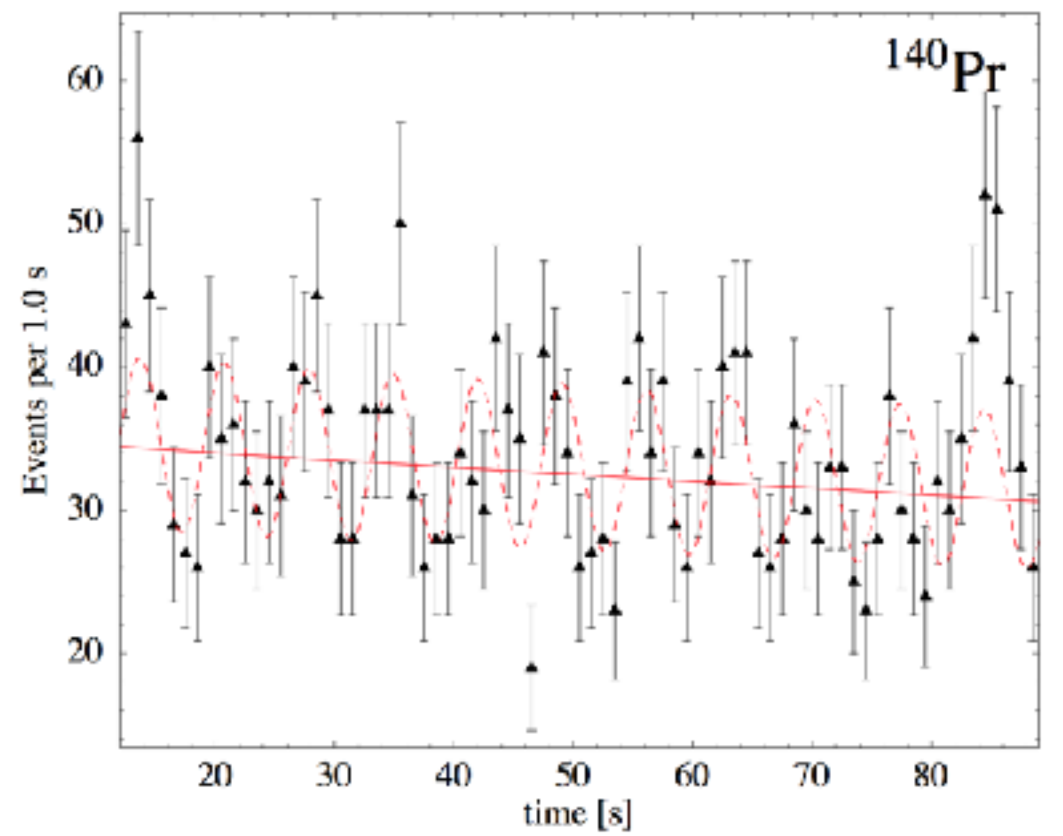
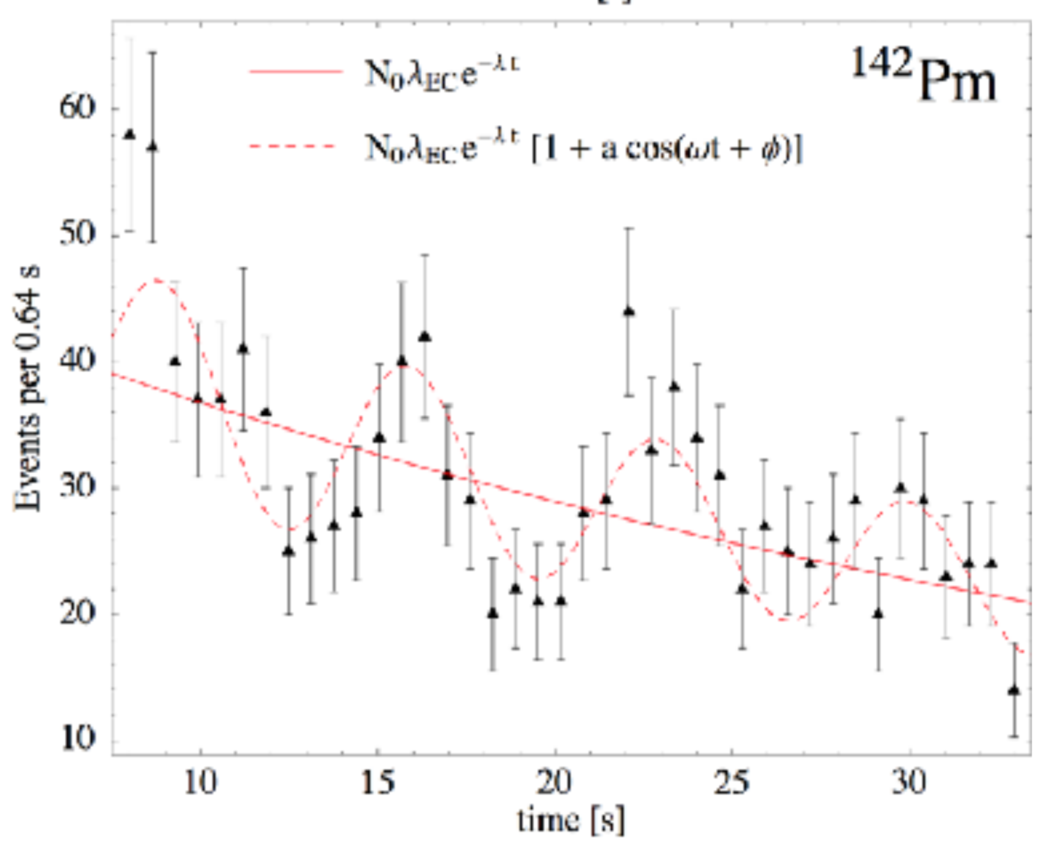
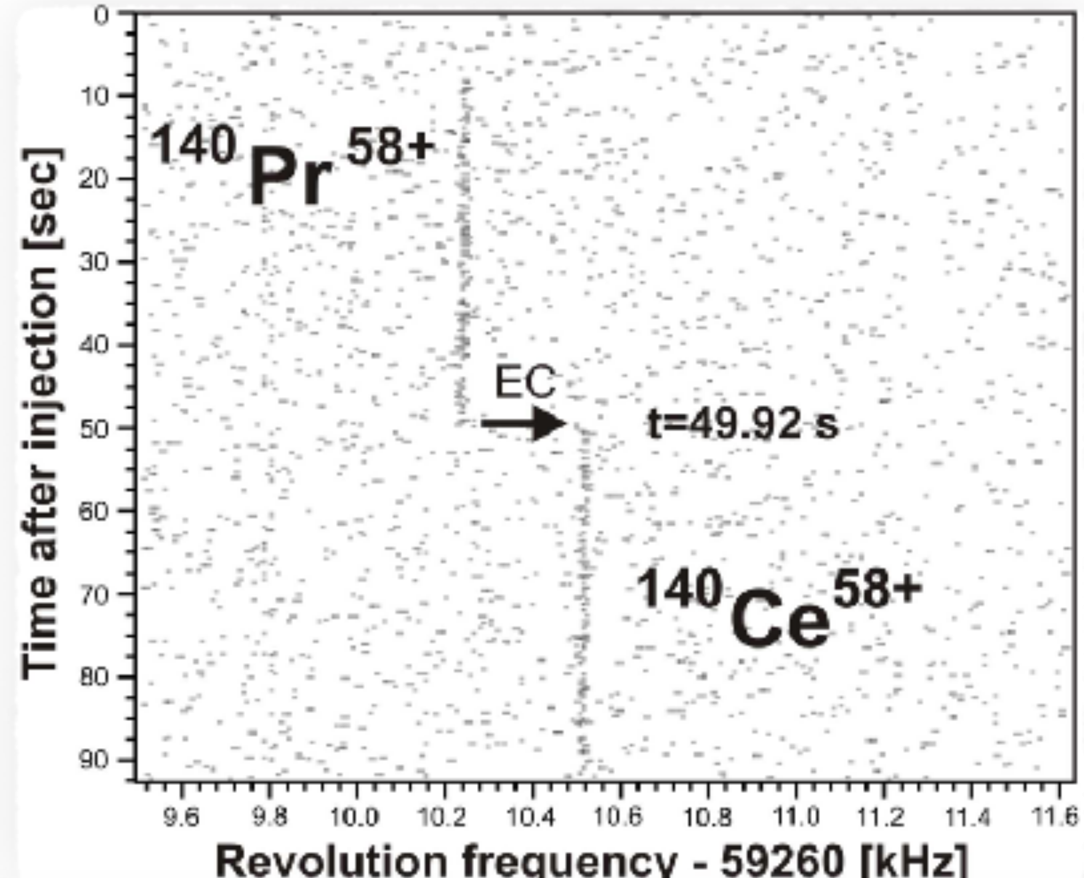
A Nuclear Physics Mystery







- ⋆ Storage of H-like $^{140}Pr^{59+}$, $^{142}Pm^{60+}$ ions
- ⋆ Electron capture to $^{140}Ce^{59+}$, $^{142}Nd^{60+}$
- ⋆ Change in ion mass
  ➛ change in revolution frequency
- ⋆ Measured in Schottky pick-up
- ⋆ Result: decay rate appears to oscillate!

Explanation Attempts

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- Interference of neutrino mass eigenstates
  - Numerically: $1\,/\,7\,\mathrm{sec} \sim \Delta m^2/(2E)$

Ivanov et al. 0801.2121
Kleinert Kienle 0803.2938

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Kienert JK Lindner Merle 0808.2389
Giunti 0801.4639, 0805.0431
Cohen Glashow Ligeti 0810.4602

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- Some discussions ensued …

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Thank you!