

Sterile ν : review of positive hints

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Milky Way Galaxy

**XXXI International Conference
on Neutrino Physics and Astrophysics**

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Positive hints. . .

- direct experiments (anomalies)
- other phenomena (including anomalies) and/or theoretical considerations



ν_s : positive experimental hints...

- LSND, MiniBooNE, IceCube...



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- LSND, MiniBooNE, IceCube...
- **Reactor antineutrino anomaly** ... disappears except the bump



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- LSND, MiniBooNE, IceCube...
- Reactor antineutrino anomaly ...
- Neutrino-4

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- LSND, MiniBooNE, IceCube...
- Reactor antineutrino anomaly ...
- Neutrino-4
- Gallium anomaly, mostly BEST

ν_s : other positive hints. . .

Do we need a 1-3 eV sterile neutrino ?

No !

- no other hints in particle physics
- contradicts to Standard Solar Model
- contradicts to Standard Cosmology

e.g. 2101.06785, 2109.14898

BBN, CMB+LSS, e.g. 2003.02289

How robust are two last statements ?

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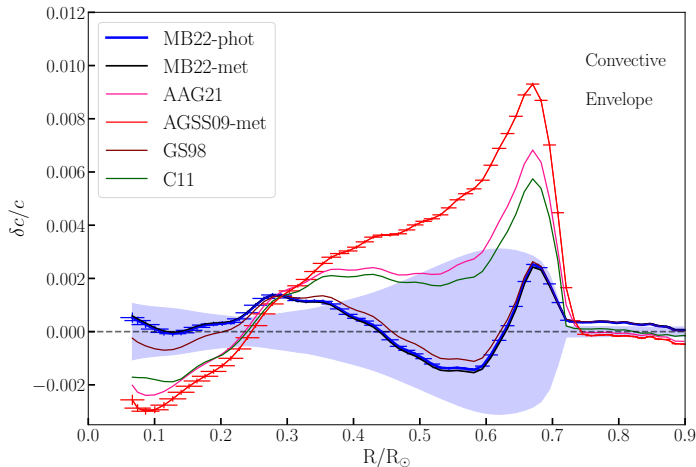
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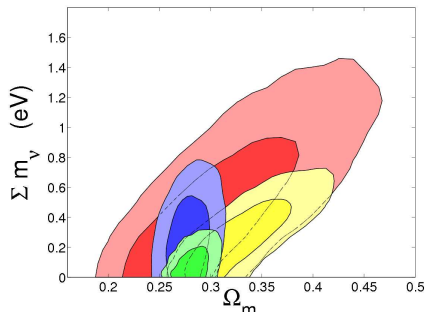
Limits from solar observation. . .

“solar composition problem”: higher metallicity models reproduce the Sun’s interior sound speed, while lower metallicity models explains photo-absorption lines

2203.02255



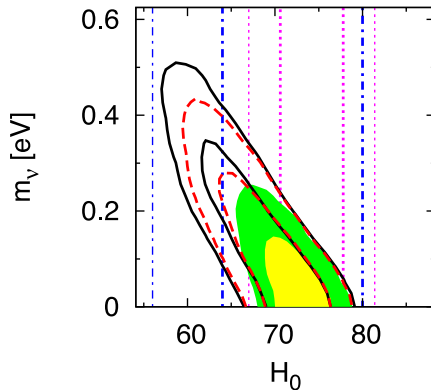
Cosmological limits: sub-eV scale... 15 years ago!!



LRG+BAO+WMAP5+SNe+BAO

$\Sigma m_\nu < 0.28 \text{ eV}$ (95% CL)

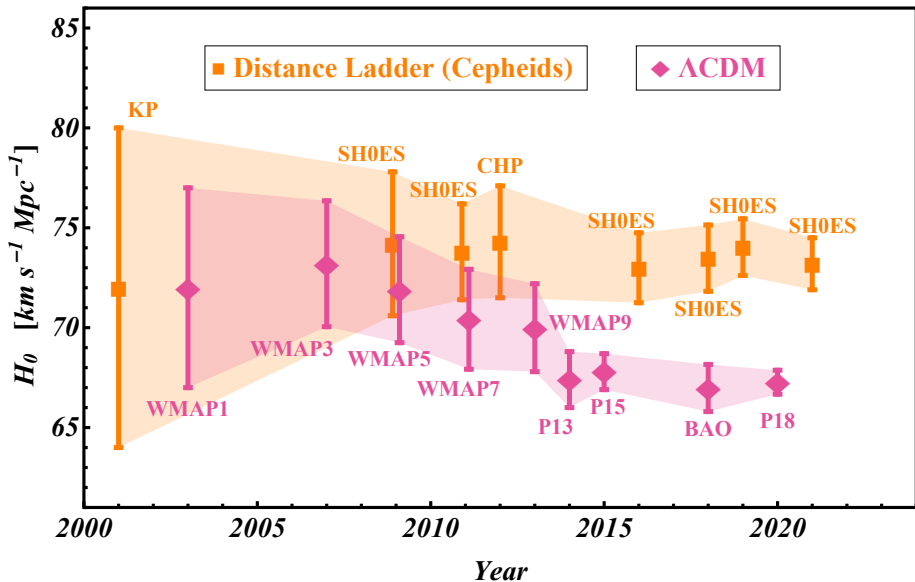
0911.5291



CMB+Hubble measurements

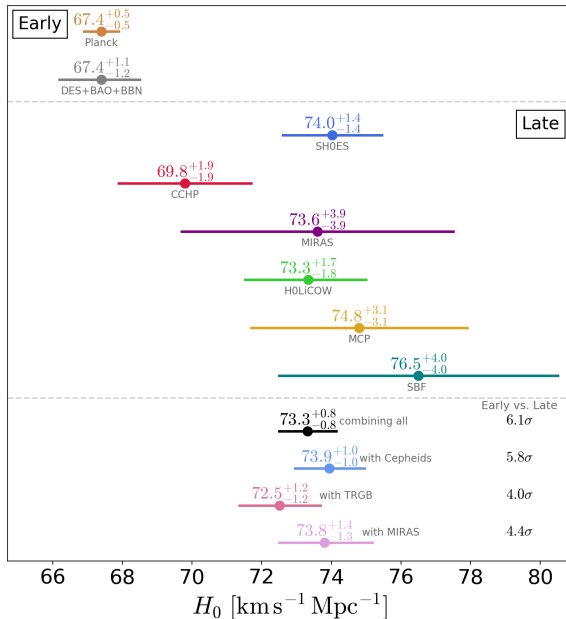
$\Sigma m_\nu < 0.20 \text{ eV}$ (95% CL)

0911.0976

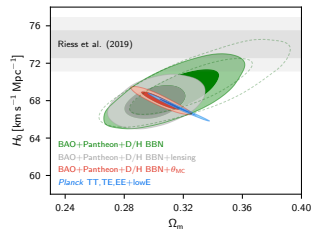


2105.05208

flat - Λ CDM

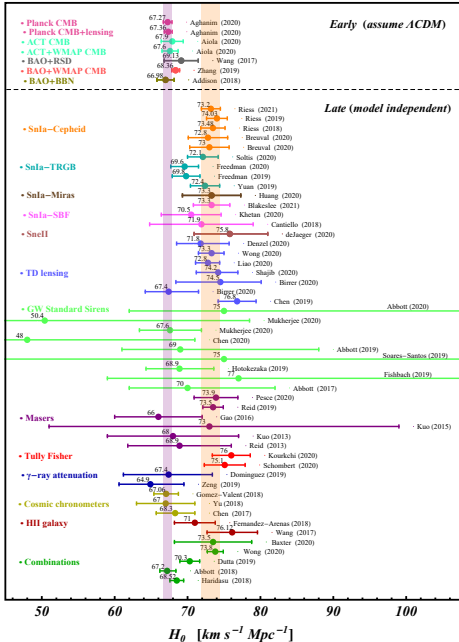


1807.06209

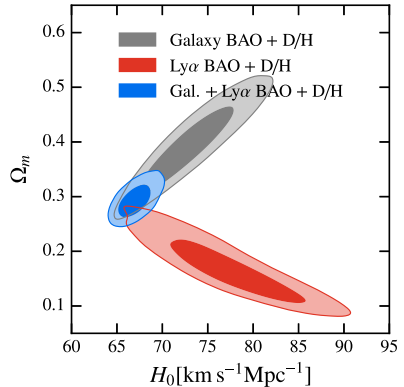


1907.10625

Constraints on H_0

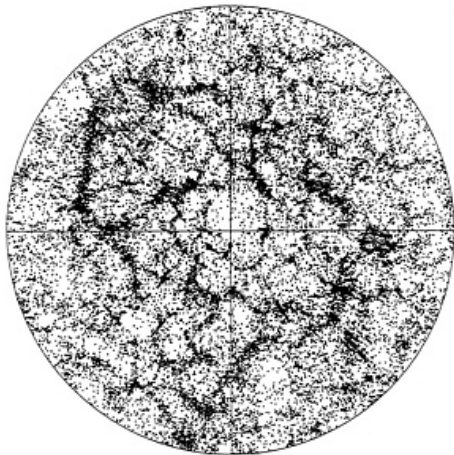


2105.05208

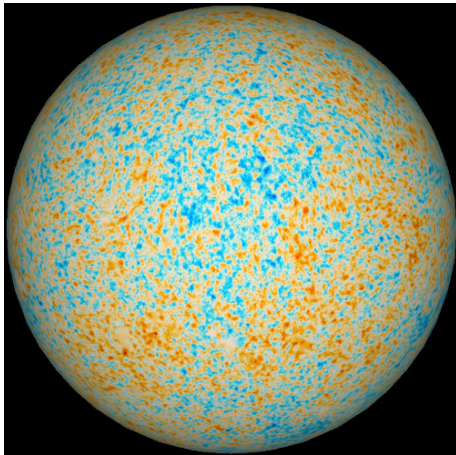


1707.06547

Inhomogeneous Universe

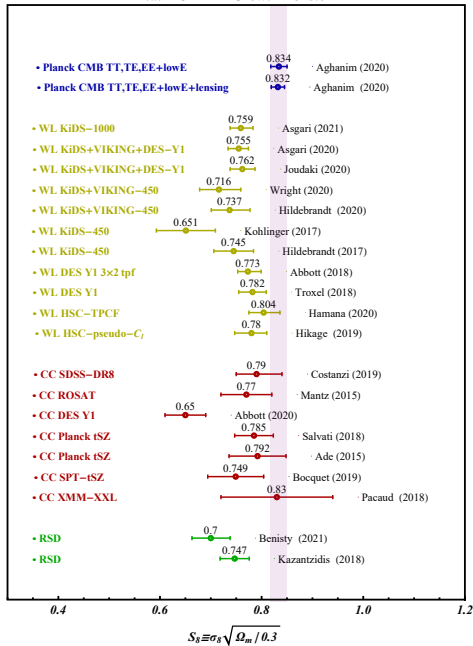


Large Scale Structure

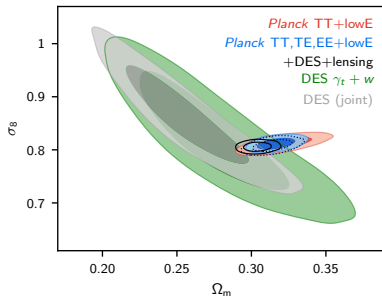


CMB anisotropy

Flat Λ CDM – Growth Tension



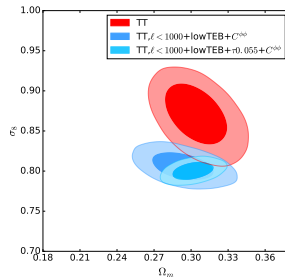
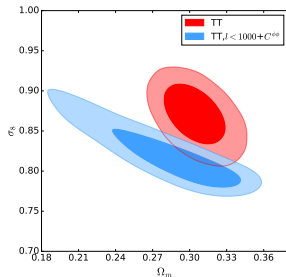
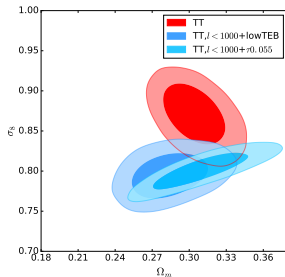
2105.05208



1807.06209

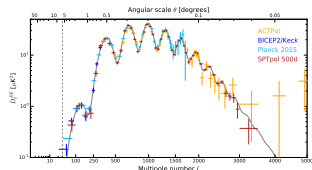
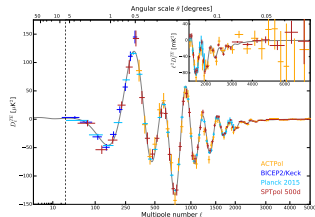
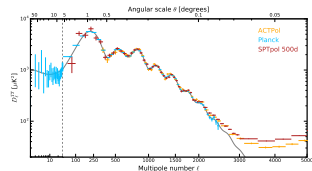
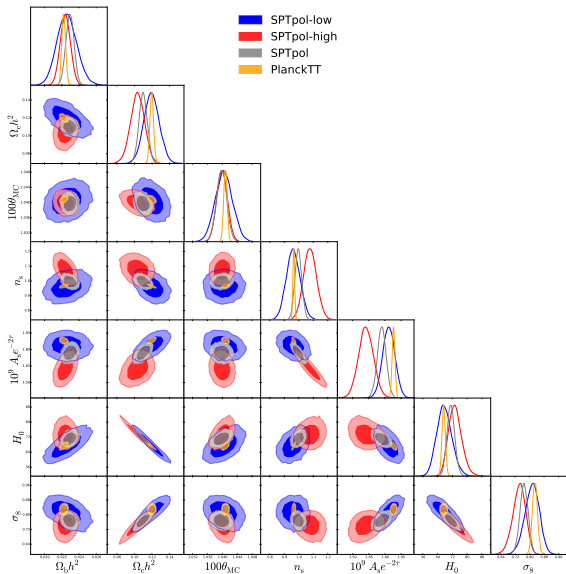
Neglecting Planck results with $l > 1000$

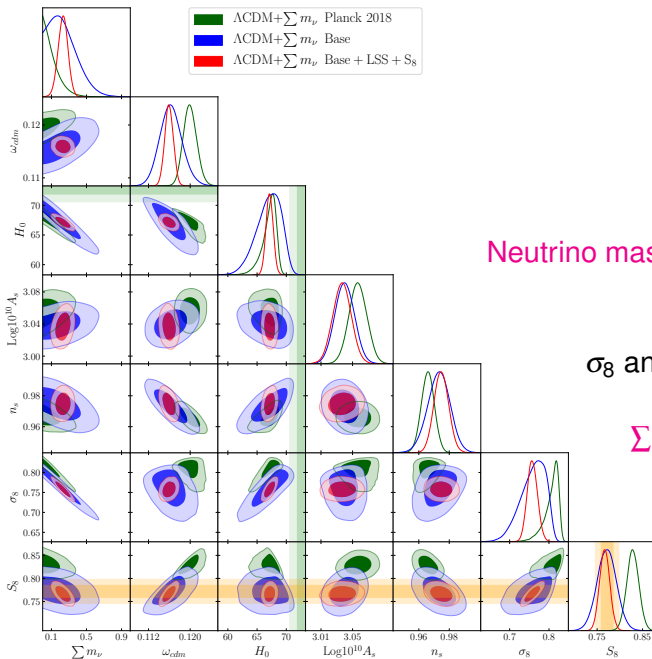
R. Burenin, 1806.03261



SPTpole with critical $I = 1000$

1707.09353





Neutrino masses: 4σ evidence...

2203.03666

σ_8 and to some extent H_0

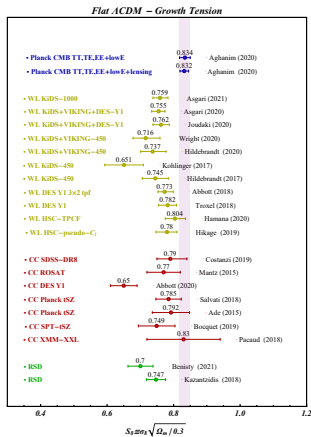
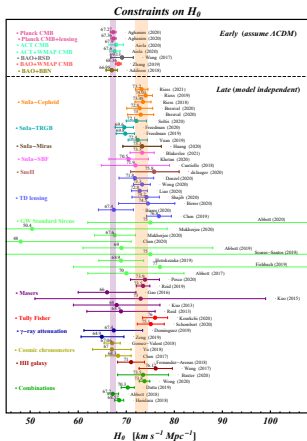
$\sum m_\nu = 0.23 \pm 0.06 \text{ eV}$

May the solution involve 1-3 eV ν_s ?

Data: It looks like a normalization...

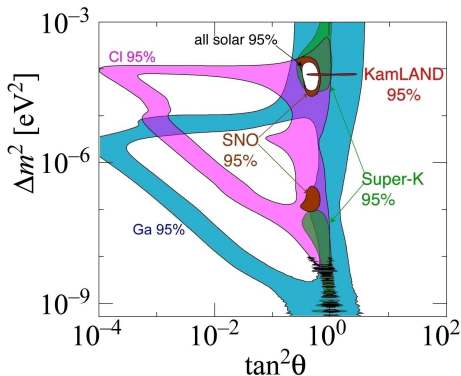
Solution: change smth “yesterday”
or between RD/MD, $T = 0.8$ eV, and recombination, $T = 0.25$ eV

nonrelativistic at $m = \langle p \rangle = 3T \rightarrow \Delta m^2 = 0.5 - 5 \text{ eV}^2$



Neutrino oscillations: masses and mixing angles

Solar 2×2 “subsector”

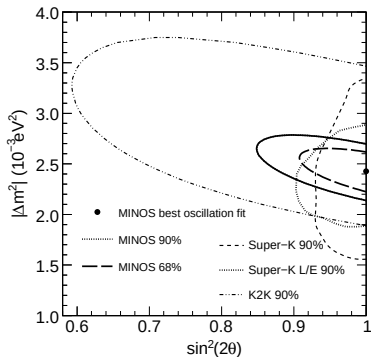


<http://hitoshi.berkeley.edu/neutrino/>

$$m_{\text{sol}}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

DAYA-BAY, RENO, T2K: $\sin^2 2\theta_{13} \approx 0.08$

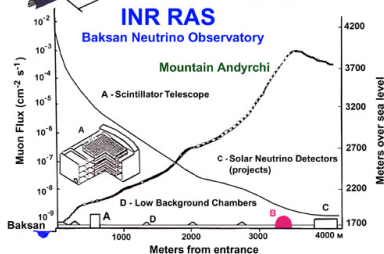
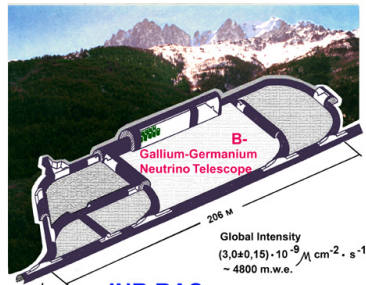
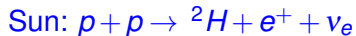
Atmospheric 2×2 “subsector”



arXiv:0806.2237

$$m_{\text{atm}}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$$

Measurement of the solar neutrino flux by SAGE



SAGE & GALLEX anomalies in numbers

1710.06326

Calibration sources

 ^{51}Cr

$$E_1 = 0.75 \text{ MeV } (f_1 = 96\%)$$

$$E_2 = 0.43 \text{ MeV } (f_2 = 4\%)$$

 ^{37}Ar

$$E_1 = 0.811 \text{ MeV}$$

$$E_2 = 0.813 \text{ MeV}$$

Experiments

SAGE

source $\approx$ sphere of $r = 6.3 \text{ cm}$
in the center of spherical vessel
 $r_1 = 25.3 \text{ cm}$ and $r_2 = 72.6 \text{ cm}$

GALLEX

source $\approx$ sphere of $r = 0.4 \text{ m}$
in the center of spherical vessel
 $r_1 = 0.45 \text{ m}$ and $r_2 = 2.5 \text{ m}$

$$R^{th} = \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} dr [P(E_1, |\vec{r} - \delta\vec{r}|) f_1 + P(E_2, |\vec{r} - \delta\vec{r}|) f_2]$$

$$(1998) R_{\text{SAGE}}^{obs} (^{51}\text{Cr}) = 0.93 \pm 0.12$$

$$(1994) R_{\text{GALLEX}}^{obs} (^{51}\text{Cr}) = 0.93 \pm 0.11$$

$$(2005) R_{\text{SAGE}}^{obs} (^{37}\text{Ar}) = 0.77 \pm 0.09$$

$$(1996) R_{\text{GALLEX}}^{obs} (^{51}\text{Cr}) = 0.80 \pm 0.11$$

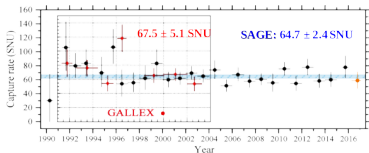
J.N.Abdurashitov et al (2009)

1710.06326

F.Kaether et al (2010)

The combined fit to SAGE+GALLEX

solar ν flux is stable...



minimizing

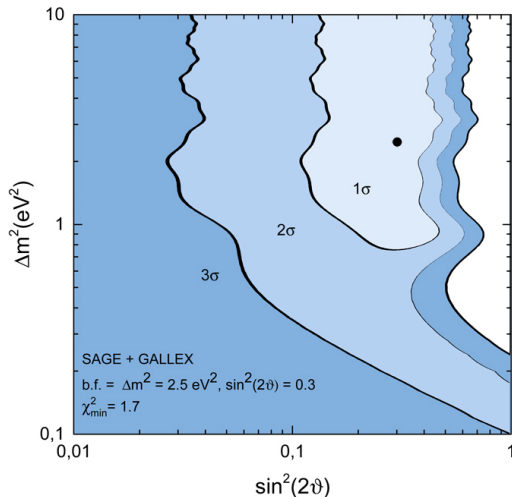
$$\chi^2 = \sum_{i=1}^4 \frac{\left(R_i^{obs} - R_i^{th}(\Delta m^2, \sin^2 2\theta)\right)^2}{\sigma_{R_i}^2},$$

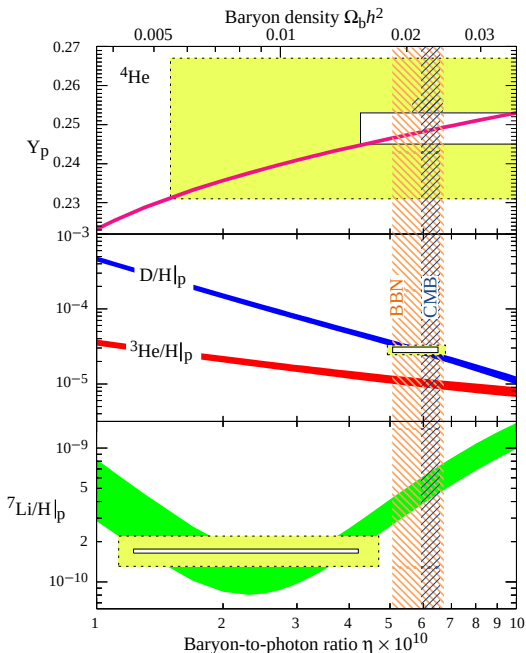
combined best fit

$$\Delta m^2 \approx 2.5 \text{ eV}^2, \quad \sin^2 \theta \approx 0.3$$

1710.06326

consistent with C.Giunti, M.Lavender (2011)

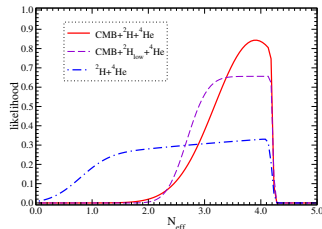




$$Y_p = 0.2581 \pm 0.025 ,$$

$$D/H|_p = (2.87 \pm 0.21) \times 10^{-5}$$

1103.1261



similar results from other studies

1001.4440, 1001.5218

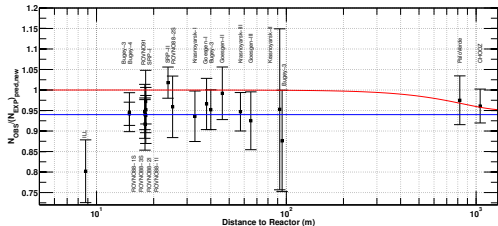
$$N_\nu < 4.2 \text{ @ } 95\% \text{CL}$$

$N_\nu < 4.3$ with shorter neutron's life...

Reactor anomaly: $\bar{\nu}_e \rightarrow N$?

1101.2663, 1106.0687

G.Mention et al. (2011)

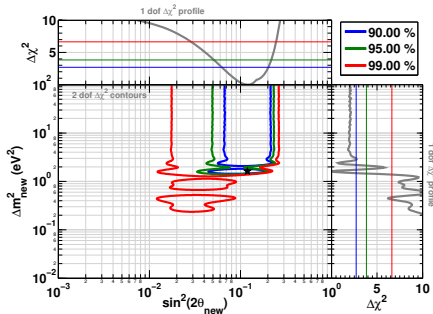


Deficit due to 6% correction to $\bar{\nu}_e$ budget

- new nuclear rates
- new neutron life-time:

$$\tau_n : 926\text{s} \rightarrow 886\text{s}$$

However: the value of uncertainty remains the same,
 $\sim 3\% \dots$



Combined fit to Reactor and Gallium data

Bunch of proposals to test the anomaly. . .

see 1204.5379

Reactor anomaly: new comers... new evidences?

NEOS (Korea, 2017-...)

$\bar{\nu}_e$ from 2.8 GW_{th} reactor

detector at $L = 24$ m

events normalized to Daya Bay

spectrum at 550 m

best fit

$$\Delta m^2 \simeq 1.5 \text{ eV}^2, \quad \sin^2 2\theta_{ee} \simeq 0.05$$

DANSS (Russia, 2017-...):

$\bar{\nu}_e$ from 3.1 GW_{th} reactor

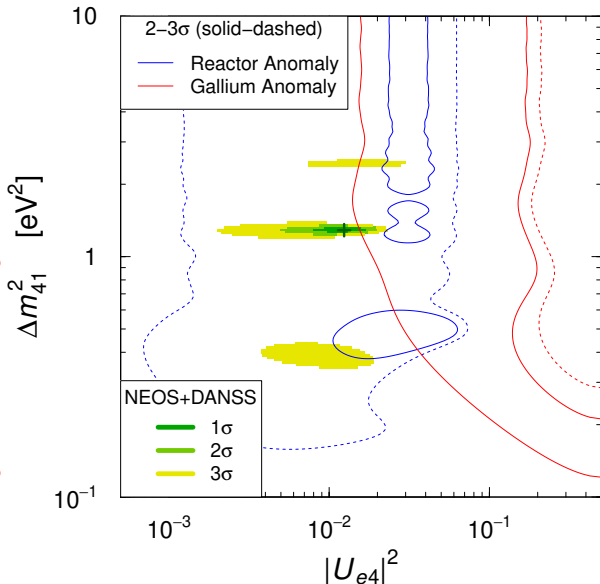
movable detector at

$L = 10.7 - 12.5$ m

best fit

$$\Delta m^2 \simeq 1.4 \text{ eV}^2, \quad \sin^2 2\theta_{ee} \simeq 0.05$$

1801.06467



Neutrino-4 results...

1809.10516

PROSPECT (USA, 2018-...)

85 MW_{th} compact reactor
segmented detector covering
 $L = 6 - 7.5$ m
measures flux ratios

STEREO (France, 2018-...):

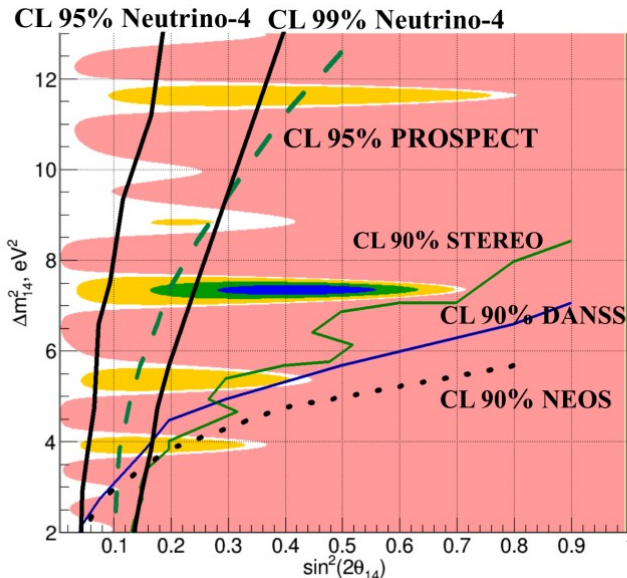
58 MW_{th} compact reactor
segmented detector covering
 $L = 9.4 - 11.1$ m
measures flux ratios

NEUTRINO-4 (Russia, 2018-...)

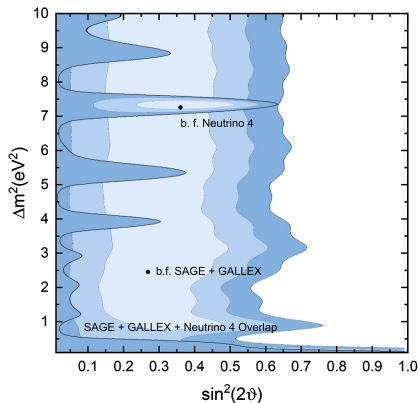
100 MW_{th} extracompact
reactor SM-3 (Dimitrovgrad)
segmented movable detector
 $L = 6 - 12$ m
measures flux ratios
best fit

$$\Delta m^2 \simeq 7.2 \text{ eV}^2$$

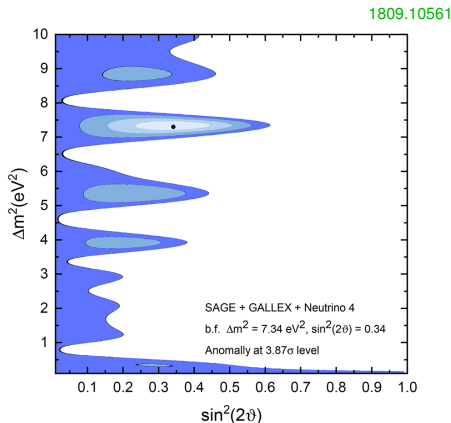
$$\sin^2 2\theta_{ee} \simeq 0.35$$



Consistency of Gallium and NEUTRINO-4 anomalies



1905.07437



1809.10561

almost 4σ anomaly

Baksan Experiment on Sterile Transition

proposal: 1006.2103, 1204.5379, ...

artificial dichromatic source:

^{51}Cr of 3 MCi ($\Delta W/W < 0.5\%$)

neutrino flux measurment:

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

2 detector volumes:
(7.5 t and 40 t of Ga)
for the flux cross check

geometry is chosen:

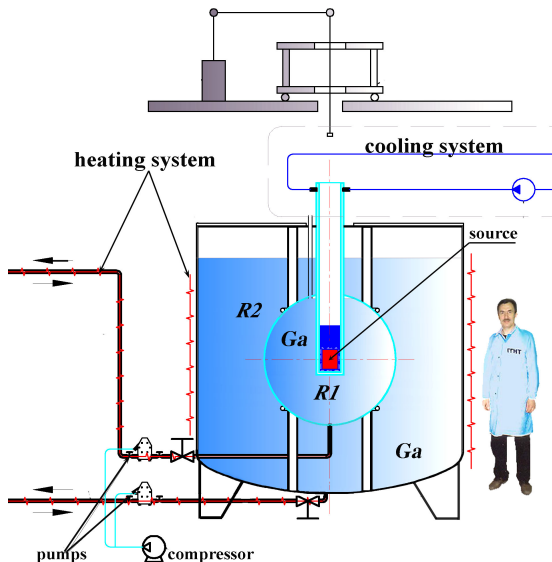
to search for $\simeq 1$ eV neutrino
with given amount ~ 50 t of Ga

data taking:

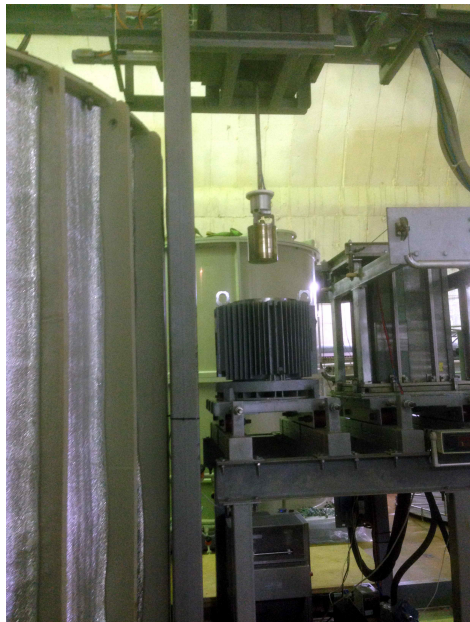
July–September 2019

$\tau_{^{51}\text{Cr}} = 27.7\text{d}$

$\tau_{^{71}\text{Ge}} = 11.4\text{d}$

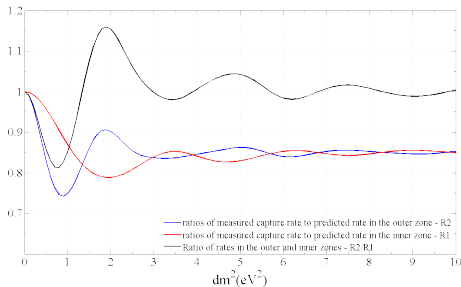
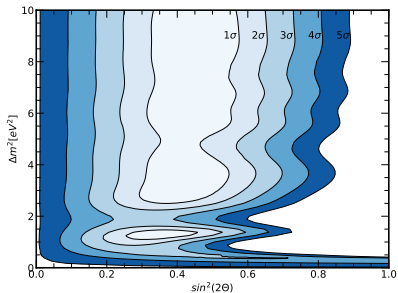






BEST: $R_1 = 0.791 \pm 0.050$, $R_2 = 0.766 \pm 0.050$

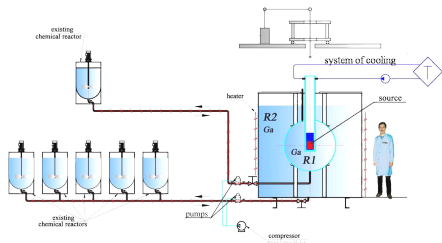
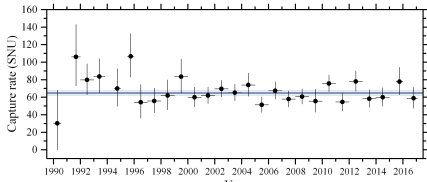
2109.11482



5- σ evidence for ν_s

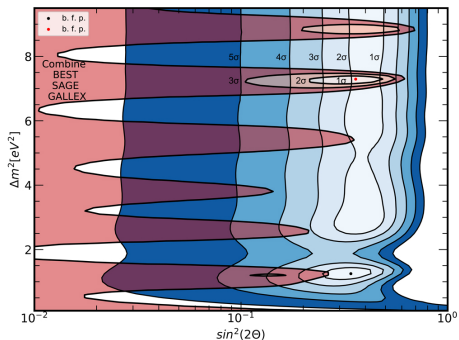
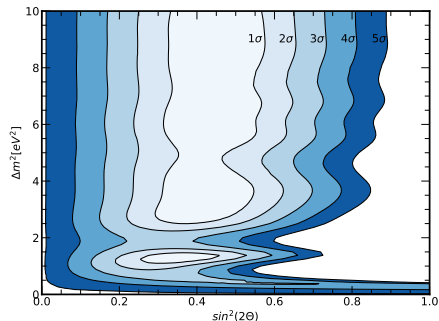
2109.14654

confirmation of Gallium anomaly



BEST: $R_1 = 0.791 \pm 0.050$, $R_2 = 0.766 \pm 0.050$

2109.11482

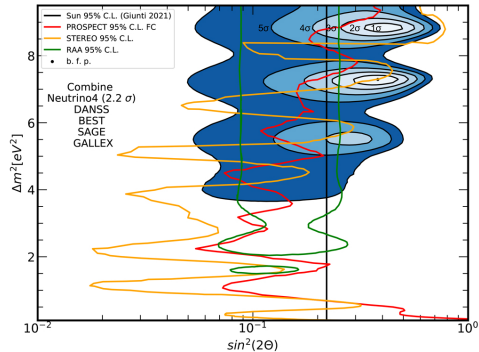
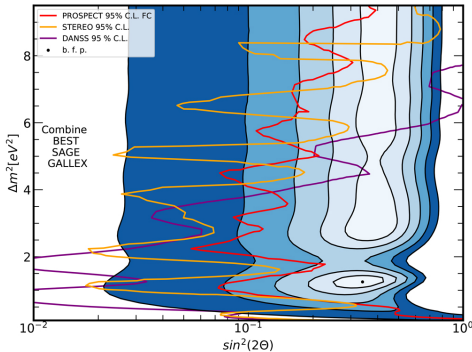


5- σ evidence for ν_s
 confirmation of Gallium anomaly
 consistent with NEUTRINO-4 $\sim 2.5\sigma$ anomaly

2109.14654

BEST combined with others

2109.14654



5.7- σ combined evidence for ν_s

BEST b.f.p. is excluded by reactor neutrino experiments

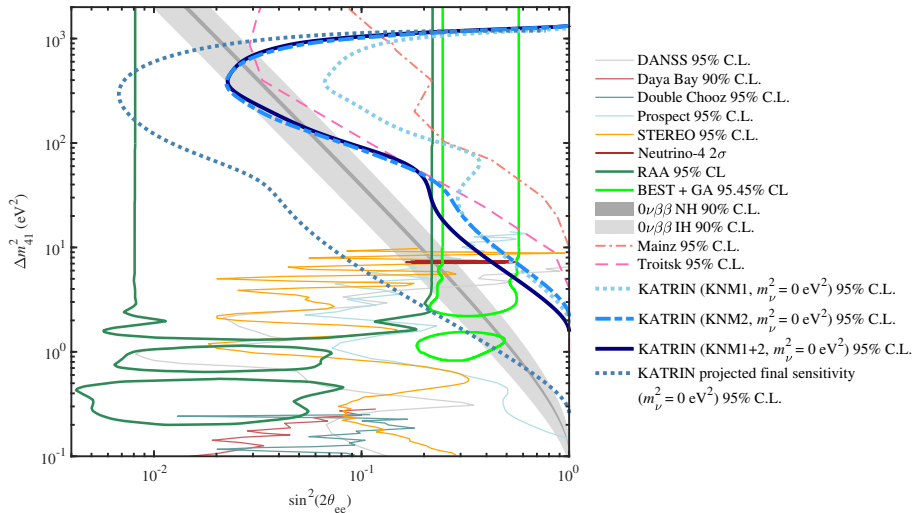
Combined 2- σ region is consistent with all reactor experiments

Combined 2- σ region is excluded

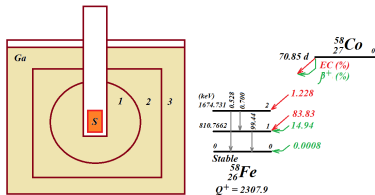
from solar neutrinos (SSM)
and from cosmology (Λ CDM)

More limits

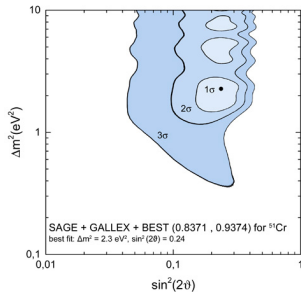
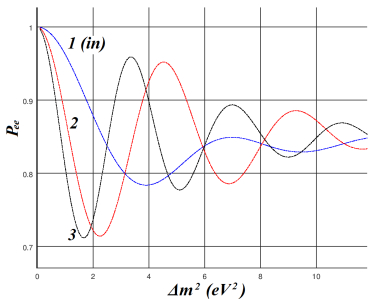
2201.11593



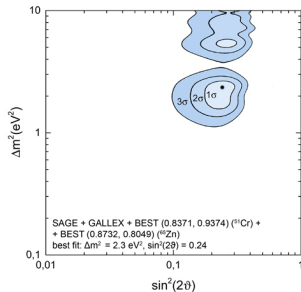
BEST2-? : heavier neutrino region



Split the outer region into two



with ^{51}Cr

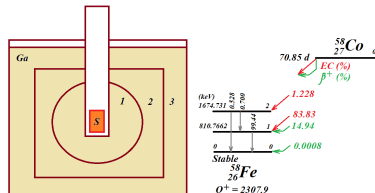
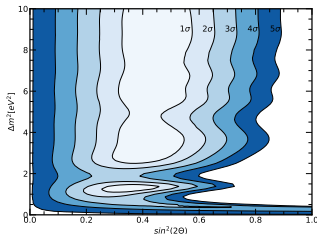


with ^{65}Zn

To summarize on positive hints...

- **BEST anomaly is at 5σ** (5.7σ with Neutrino-4)
see 2109.11482, 2109.14654, 2201.07364 for details
- It is consistent with previous Gallium anomaly and Neutrino-4 anomaly
- Many alternative explanations suggested, all failed so far...
- Can be tested with other sources and geometry
- “Indirect limits” are questionable and can be avoided with new ingredients

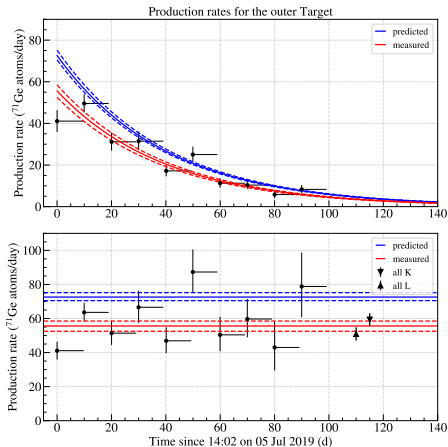
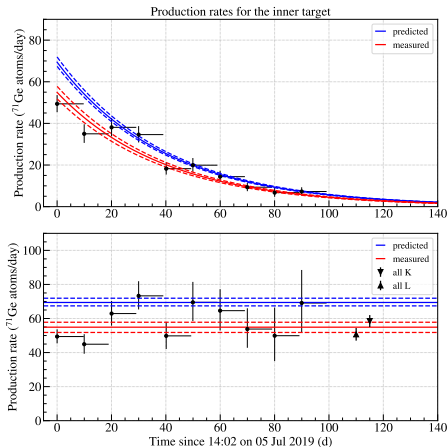
What is the origin?





BEST counts

2109.11482



Light (sterile) neutrinos in cosmology

Impact on processes

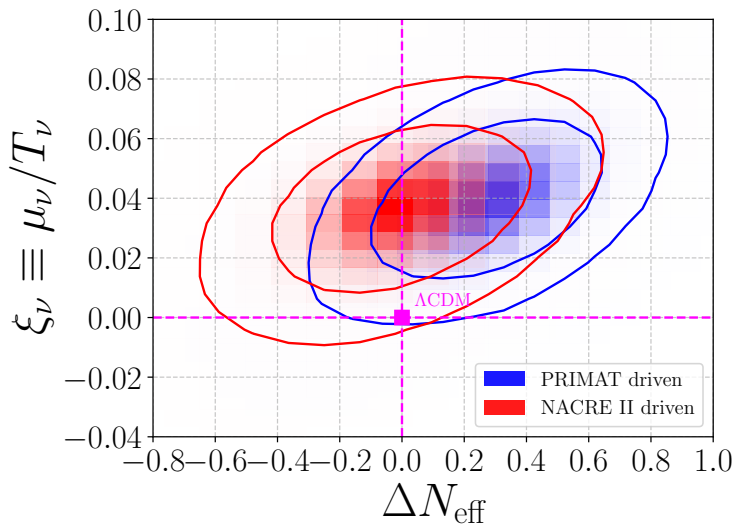
- **Big Bang Nucleosynthesis: increase of expansion rate**

$$H^2 = \frac{8\pi}{3} G\rho, \quad \rho = \frac{\pi^2}{30} \left(2 \times T_\gamma^4 + 2 \times (3 + \Delta N_\nu) \times T_\nu^4 \right)$$

with $\Delta N_\nu > 0$ higher H neutrons freeze out earlier giving more Helium

- **expansion rate at Equality, $\rho_{rad} = \rho_{mat}$, and at CMB epoch**
change of CMB anisotropy $-0.34 < \Delta N_\nu < 0.33$ (95% CL)
- **become non-relativistic, but have high velocity**
free streaming leads to washing out of low-scale perturbations
change galaxy spectrum **limits on ΔN_ν & neutrino masses**

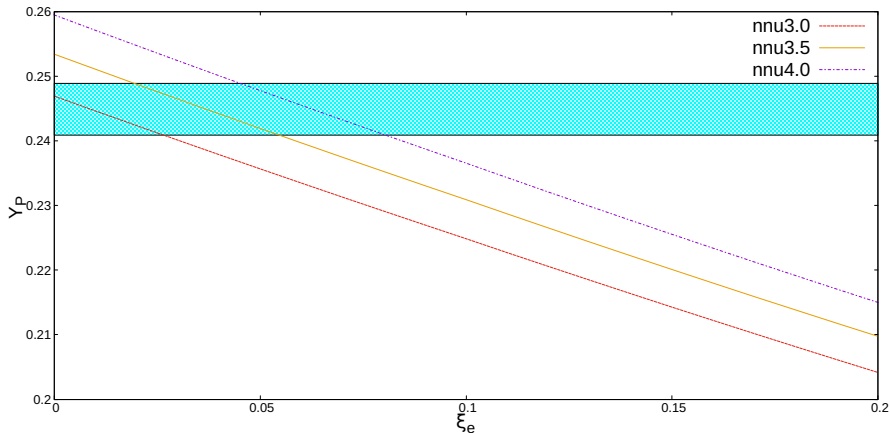
Nucleosynthesis: $n_n \propto e^{-\mu_\nu/T_\nu}$, $H_n^2 \propto (.. + \Delta N_\nu)$



2206.00693

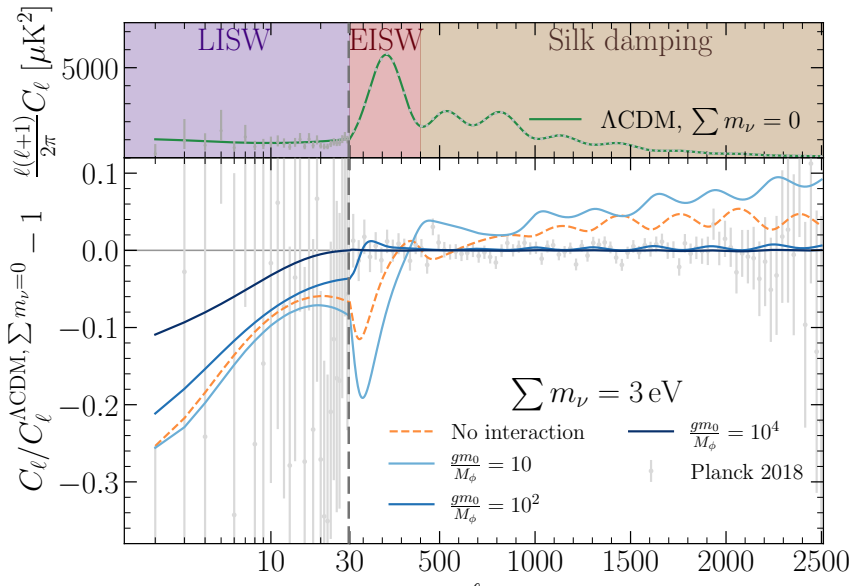
BBN: extra-radiation and lepton asymmetry

2104.04381



CMB: 'heavy' neutrinos with long-range force

2101.05804



Limits from solar observation. . .

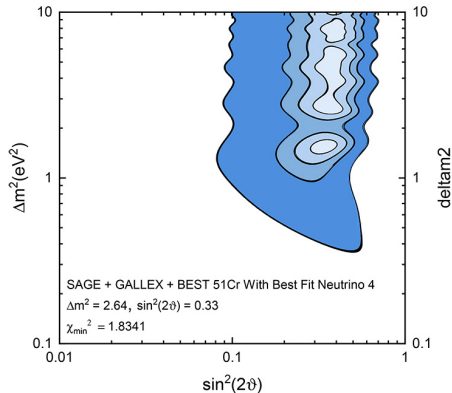
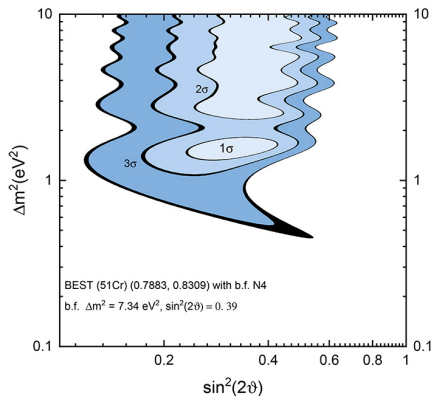
An additional source of uncertainty had arisen at the time, with the advent of three-dimensional (3D) radiative-hydrodynamic models of the Sun's atmosphere for determining element abundances from photo-absorption lines (Asplund et al., 2006, 2009). [This improved analysis, though, lowered the inferred metallicities, leading to tension with the Sun's interior sound speed profile determined from helioseismology \(Christensen-Dalsgaard, 2002\).](#) The discrepancy between higher metallicity models that accurately reproduce the Sun's interior sound speed and lower metallicity models based on the most current treatment of the photosphere was termed the [“solar composition problem”](#).

...

Similarly, uncertainties remain in our understanding of radiative transport in the Sun, including the continuing debate about the Sun's primordial composition. As changes in composition often can be mimicked by changes in radiative opacities, our imperfect knowledge of the latter has slowed resolution of the solar composition problem.

[Solar fusion III: New data and theory for hydrogen-burning stars, 2405.06470](#)

if BEST confirms Neutrino-4



BEST finds the Neutrino-4 best fit

all Gallium experiments after that

Description of neutrino oscillations (III)

- Two-neutrino oscillations: transition probability

$$P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2}{4E} L \right),$$

- Two-neutrino oscillations: survival probability

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

- Oscillation length

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5 \text{ m}) \cdot \frac{E}{\text{MeV}} \frac{\text{eV}^2}{\Delta m^2}$$