Nuclear reactions for Standard Solar Models

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Schools on Nuclear Astrophysics Questions
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Powering the Sun

$$4p \longrightarrow {}^{4}\mathrm{He} + 2\nu_e + \gamma$$

$$\gamma \leq 26.7\mathrm{MeV} = c^2(4m_p - m_{^4\mathrm{He}})$$

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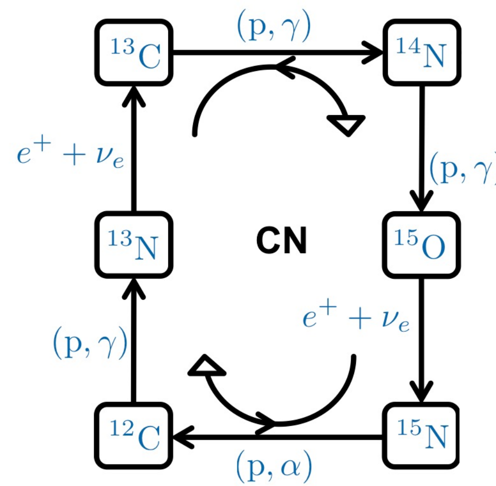
CN-cycle initially proposed in the 1930s



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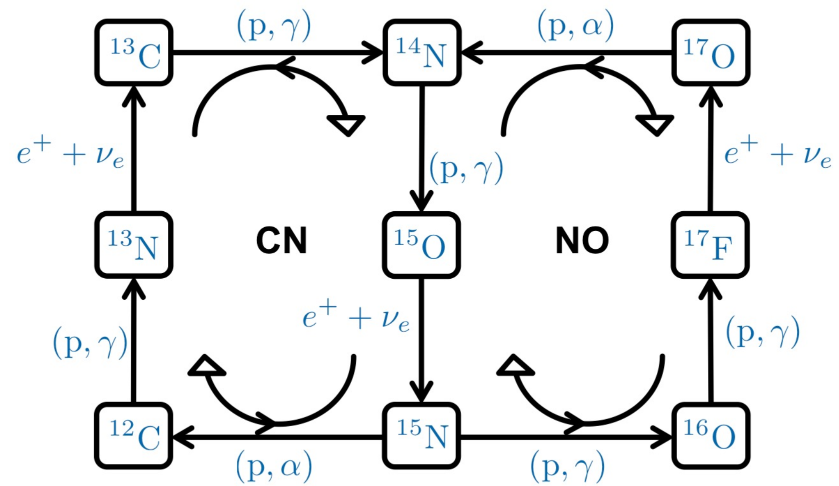
CNO-(bi)cycle

Part of the larger CNO-cycle



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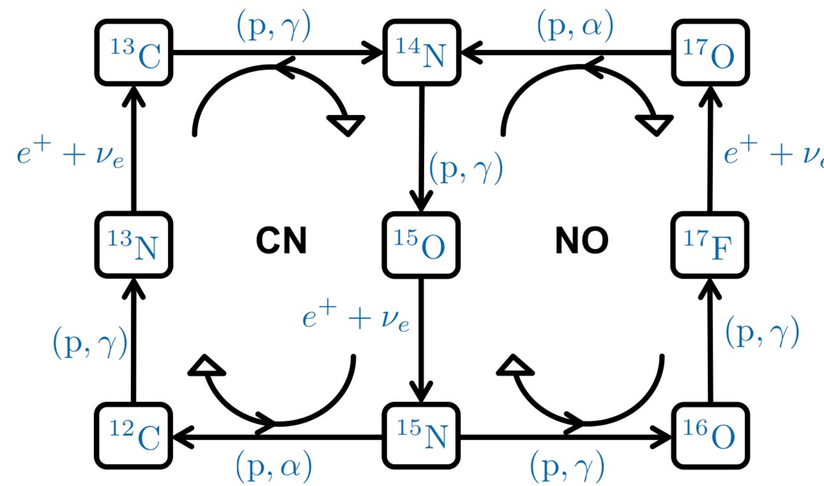

Part of the larger CNO-cycle

CN-cycle ~ 50 NO-cycle (Sun)

Powering the Sun

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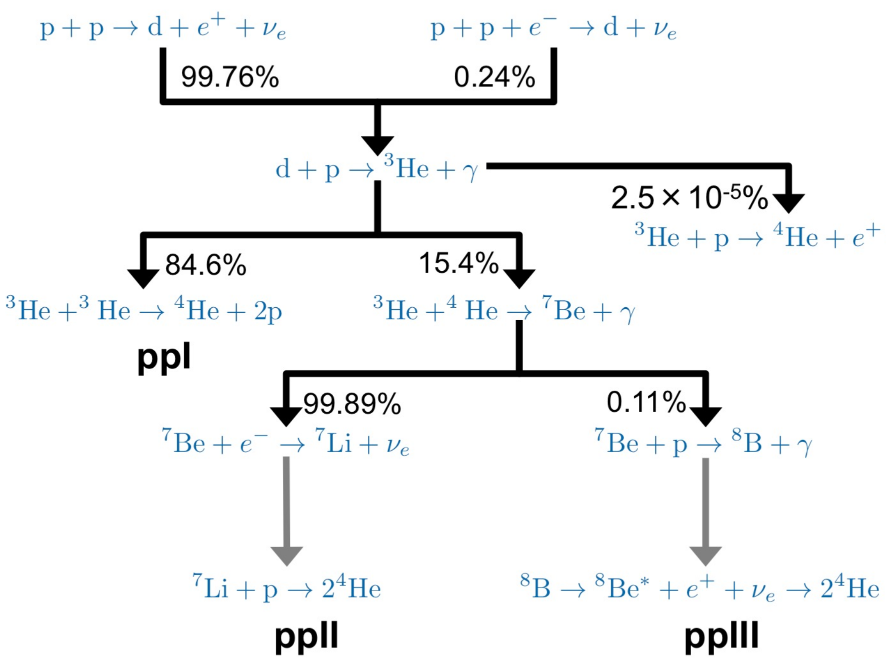

proton-proton chains

Powering the Sun

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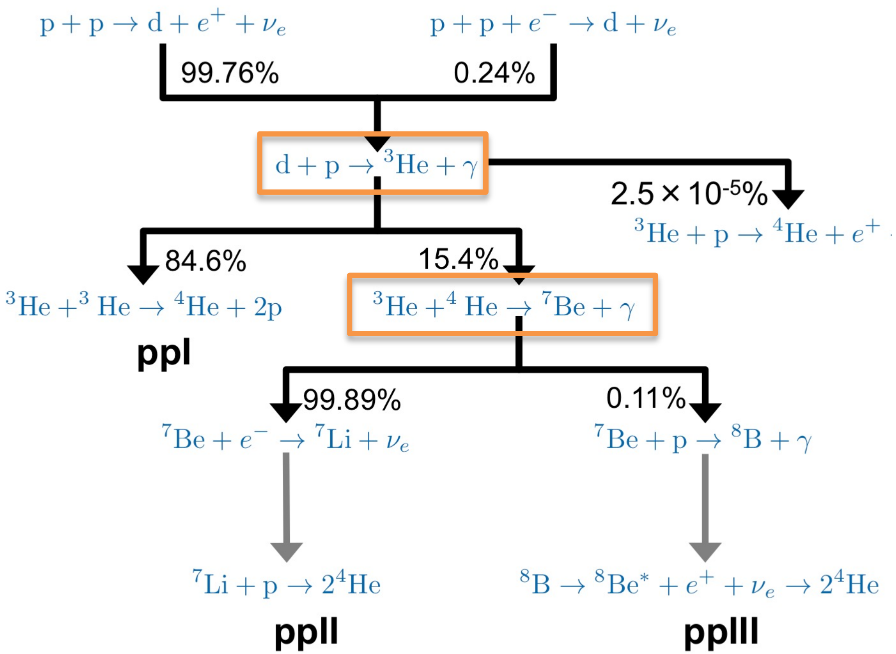
pp-chains



proton-proton chains

two main branching points

Powering the Sun

$$4p \longrightarrow {}^4\mathrm{He} + 2\nu_e + \gamma$$

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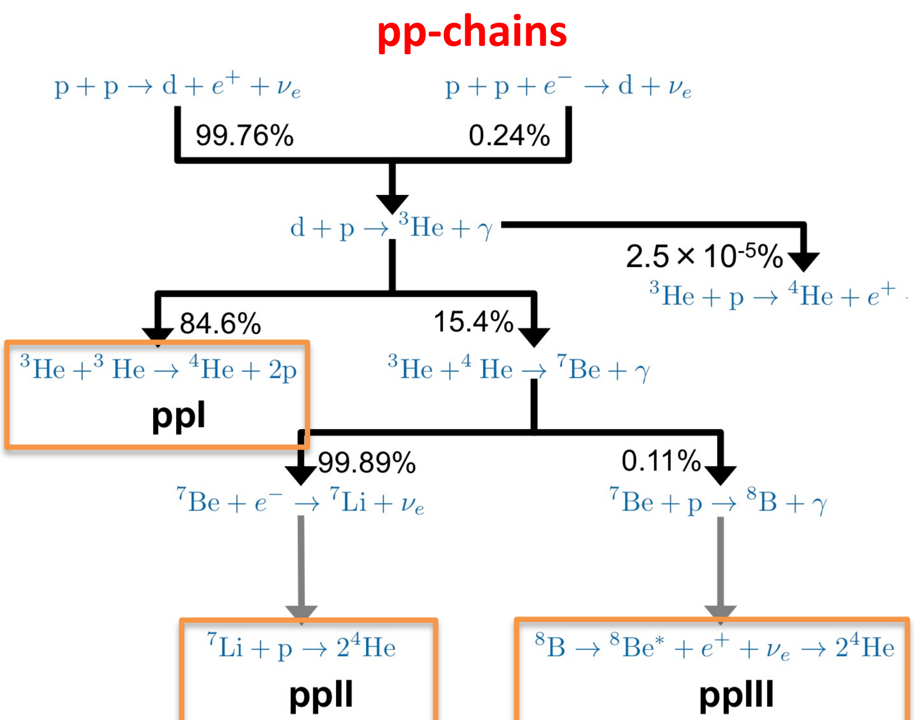

proton-proton chains

ppI:ppII:ppIII (& ^{3}He+p)
85:15:1e-4

Powering the Sun

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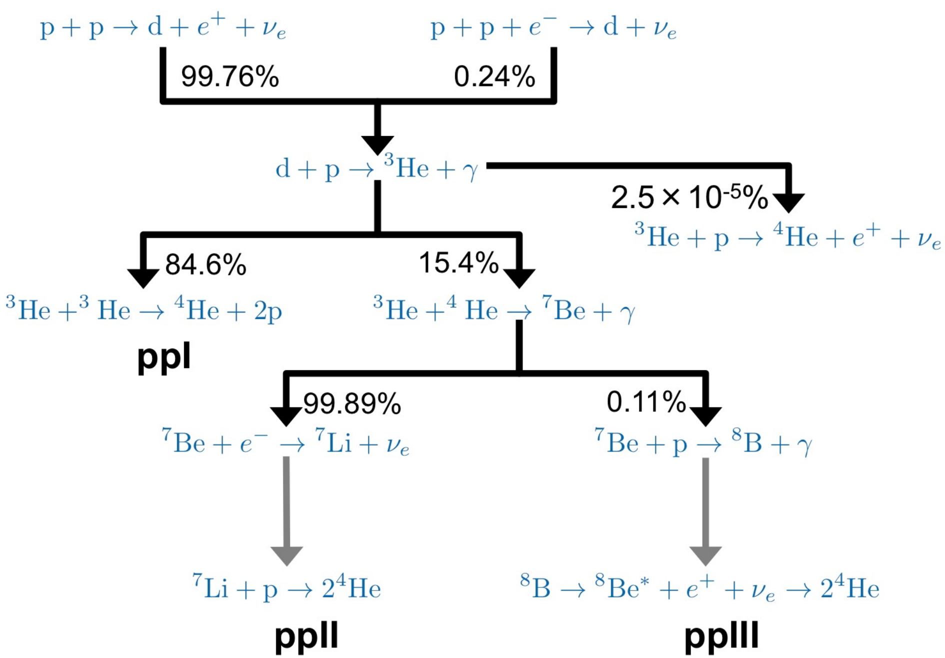
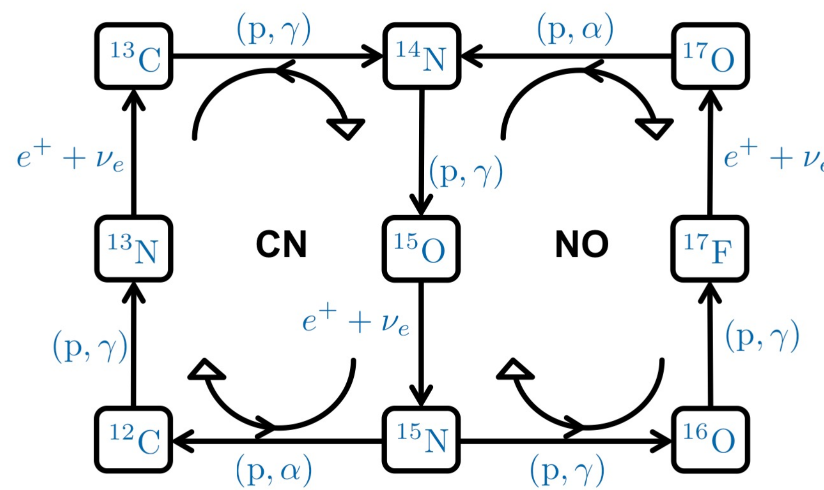
pp-chains

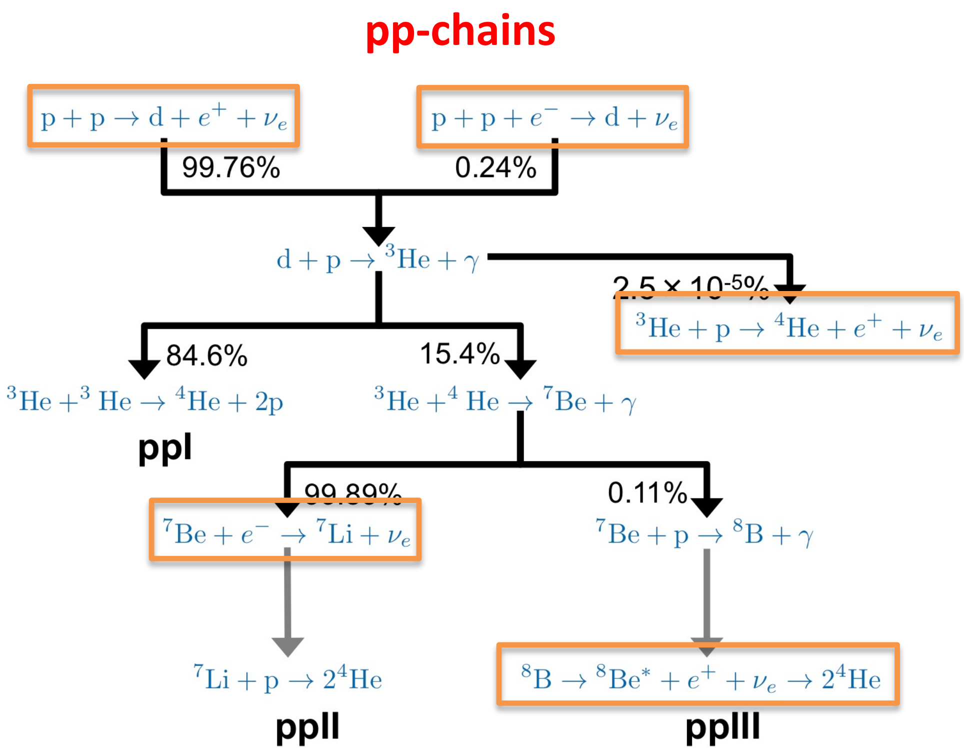


CNO-(bi)cycle

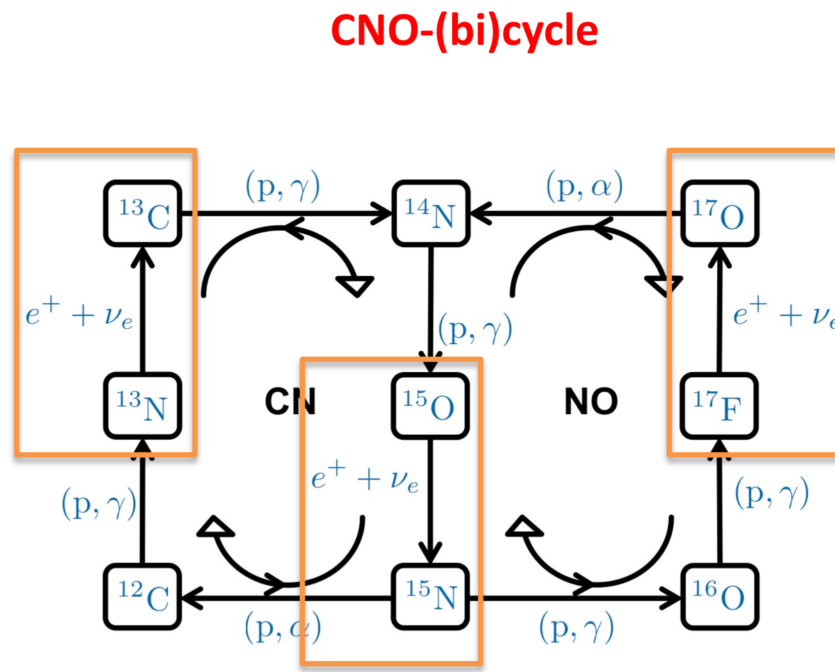


Villante & AS 2021

Eight fundamental neutrino sources can probe solar interior/physics

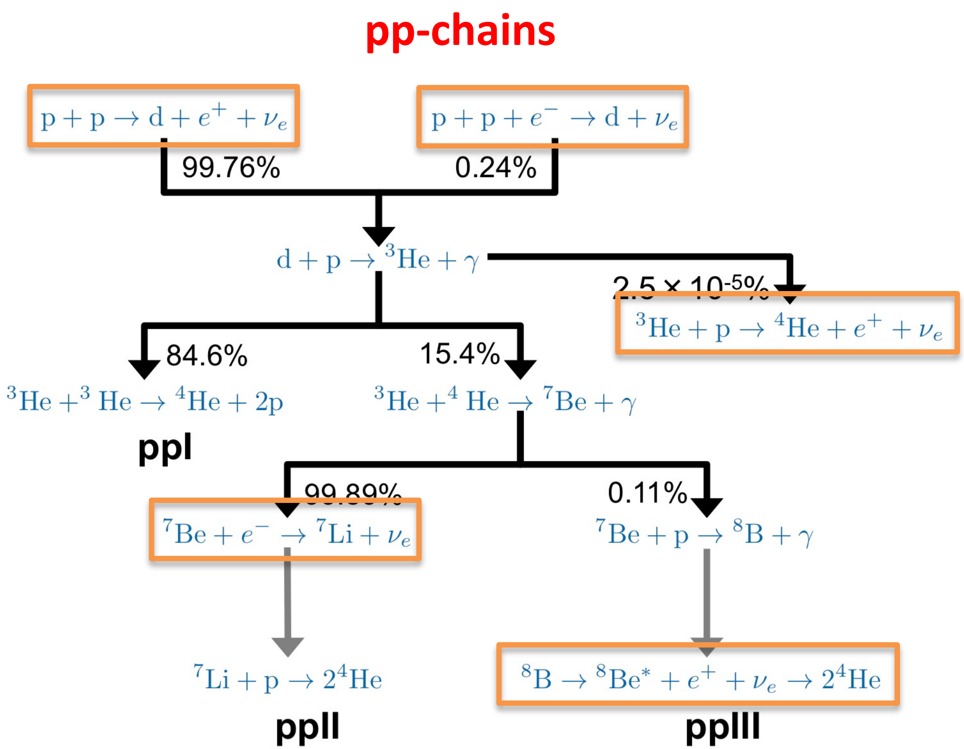


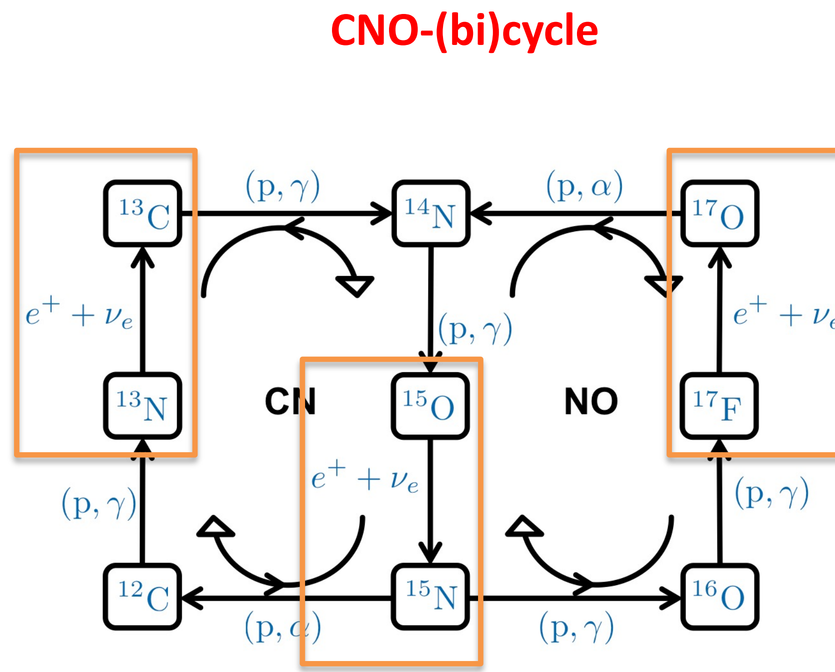
pp – pep – ^{7}Be – ^{8}B - hep



^{13}N – ^{15}O – ^{17}F

Eight fundamental neutrino sources can probe solar interior/physics





A framework (physical model) for quantitative predictions is needed (standard) solar models

Standard solar models

stellar evolution - physical processes (equations)
constitutive physics (nuclear rates, EOS, opacity, etc.)
initial composition of the star

Reaction	Uncertainty	Ref.
$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \nu_\mathrm{e} + \mathrm{e}^+$	1%	A16
$^3\mathrm{He} +^3 \mathrm{He} \rightarrow 2\mathrm{p} +^4 \mathrm{He}$	5.2%	A11
$\mathrm{p} +^3 \mathrm{He} \rightarrow^4 \mathrm{He} + \nu_\mathrm{e} + \mathrm{e}^+$	30%	A11
$^3\mathrm{He} +^4 \mathrm{He} \rightarrow^7 \mathrm{Be}$	5.2%	A11
$\mathrm{p} +^7 \mathrm{Be} \rightarrow^8 \mathrm{B}$	4.7%	Z15
$\mathrm{e}^- +^7 \mathrm{Be} \rightarrow^7 \mathrm{Li}$	2%	A11
$^\mathrm{p} +^{14} \mathrm{N} \rightarrow^{15} \mathrm{O}$	7.5%	M11
$^\mathrm{p} +^{16} \mathrm{O} \rightarrow^{17} \mathrm{F}$	7.6%	A11

Adelberger et al. 2011, Marta et al. 2011, Zhang et al. 2015, Acharya et al. 2016
Other reactions have small influence on outcome of solar models

Standard solar models

stellar evolution - physical processes (equations)
constitutive physics (nuclear rates, EOS, opacity, etc.)
initial composition of the star

3 observational constraints imposed at present age $\tau_{\odot}$=4.57 Gyr

*** photospheric $(Z/X)_{\odot}$ + solar mixture (fractional abundance of all metals)**
*** solar radius $R_{\odot}$**
*** solar luminosity $L_{\odot}$= 3.8418 x 10^{33} erg s^{-1}**

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* photospheric $(Z/X)_\odot$ + solar mixture (fractional abundance of all metals)
* solar radius $R_\odot$
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3 free parameters for the initial (pre-main sequence) model

*** Initial helium Y_{ini} ($L_\odot$)**
*** Initial metallicity Z_{ini} (X+Y+Z=1), so all composition determined $(Z/X)_\odot$**
*** Efficiency of convection in mixing length α_{MLT} ($R_\odot$)**

Evolve until solar age $\tau_\odot$ and adjust free parameters until observational constraints are satisfied (iterative process)

Standard solar models

A standard solar model imposes a strong constraint on solar energetics

$$L_\odot = \int_0^M \left(\varepsilon_{\rm nuc} - \varepsilon_\nu + \varepsilon_{\rm eg}\right) dm$$

gravothermal energy
(contraction/expansion/internal energy)
Negligible in main sequence star

Standard solar models

A standard solar model imposes a strong constraint on solar energetics

$$L_\odot = \int_0^M (\underbrace{\varepsilon_{\rm nuc} - \varepsilon_\nu}_{\text{nuclear energy production and associated neutrino losses}} + \varepsilon_{\rm eg})\, dm$$

$$\varepsilon_{\rm nuc} = \sum_{\rm H-burn} \varepsilon_i(T, \rho, \vec{X}) \qquad \varepsilon_\nu = \sum_{\rm i=1,8} \langle \varepsilon_\nu \rangle_i$$

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A linear relation between neutrino fluxes and solar luminosity can be obtained known as "Luminosity constraint" (Bahcall 2002, Vescovi et al. 2021)

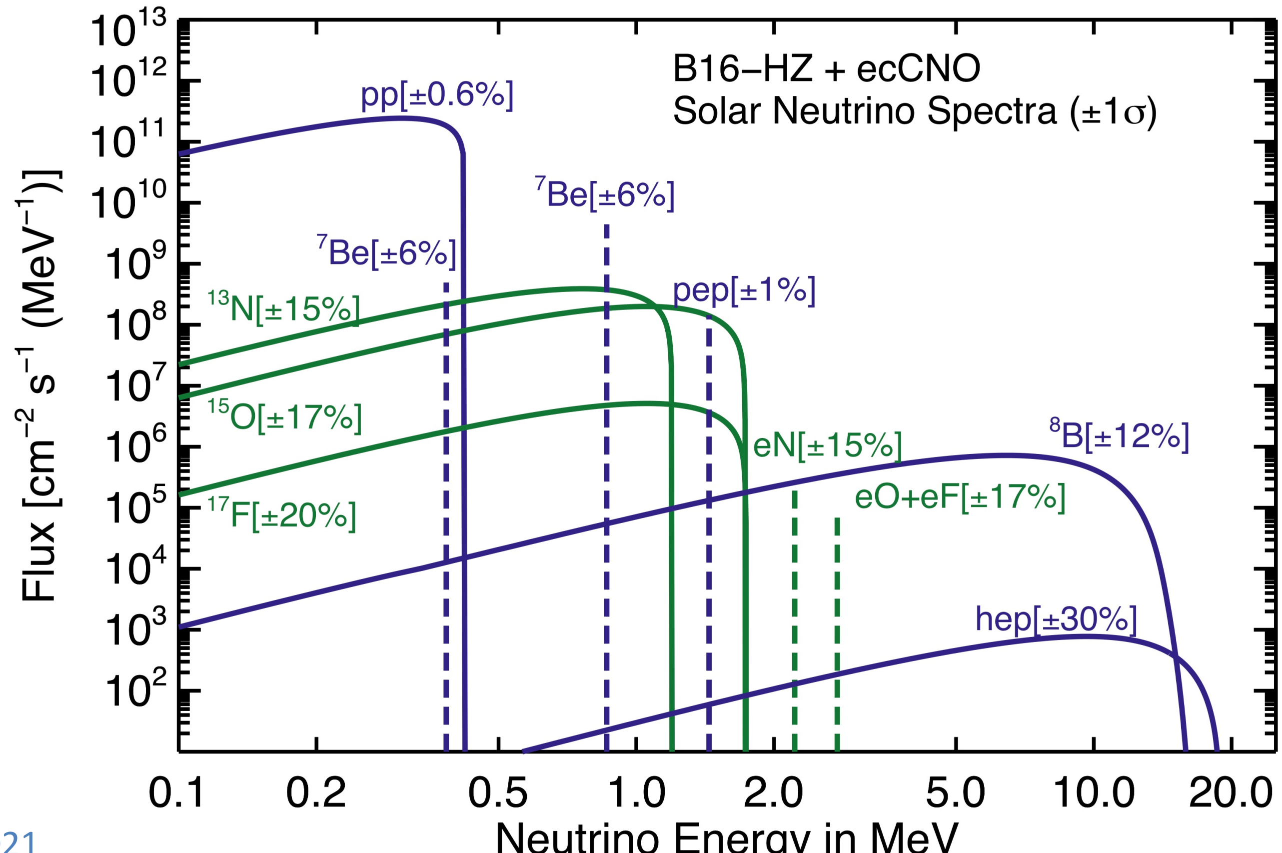
$$L_\odot = \sum_{i=1,8} \alpha_i \Phi_i$$

where α_i are given by **nuclear physics** and fluxes by the structure of the Sun (or model)

Solar neutrino spectrum

Spectral shape of neutrino fluxes well known (weak interactions)

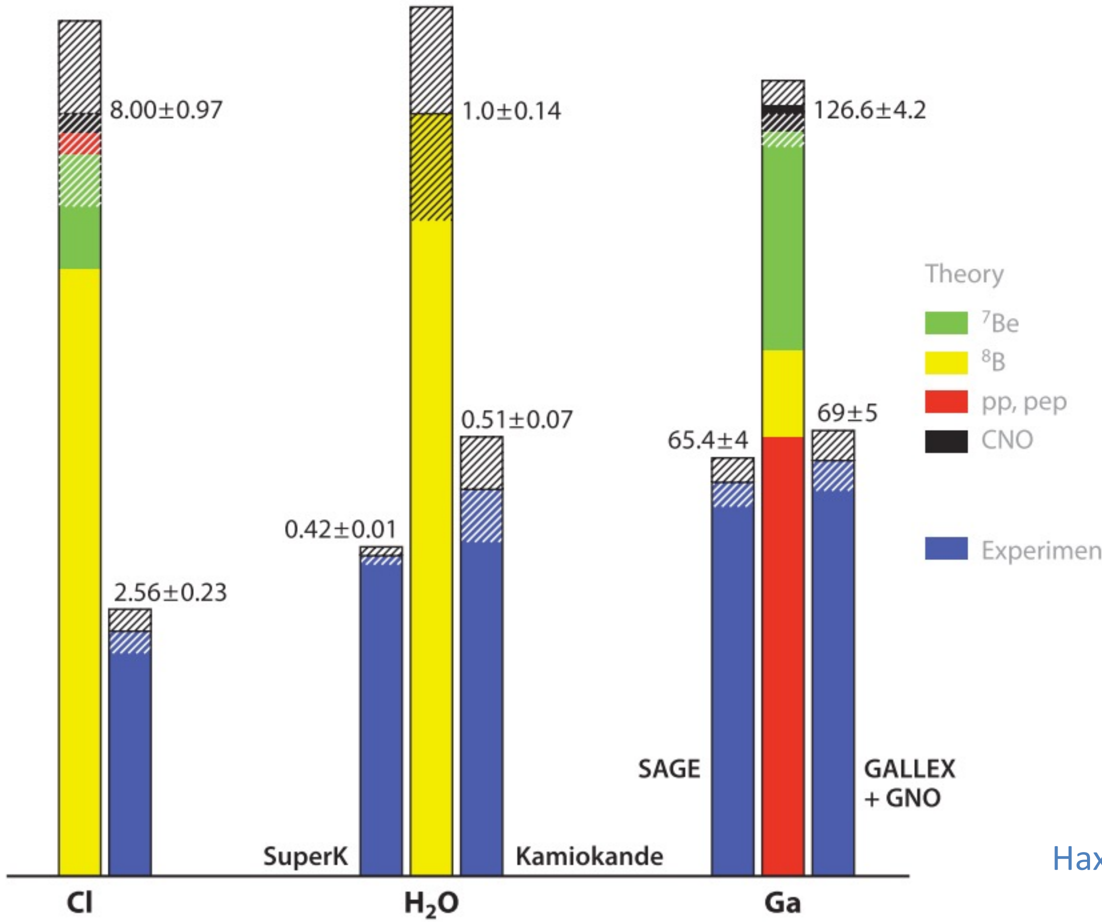
Absolute fluxes depend on model



Villante & AS 2021

Solar neutrino problem

For ~30 years – ν_e only experiments showed a solar ν deficit



Haxton et al. 2013

Solar neutrino problem

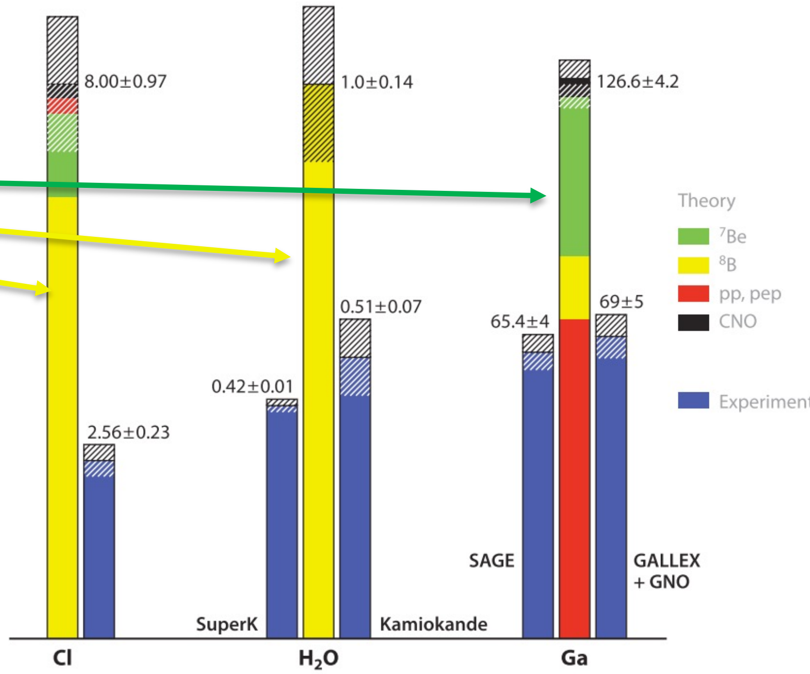
Two classes of astrophysical solution

Modification of SSM:
solar dynamics, dark matter, etc, etc
(to lower ^{8}B and ^{7}Be)

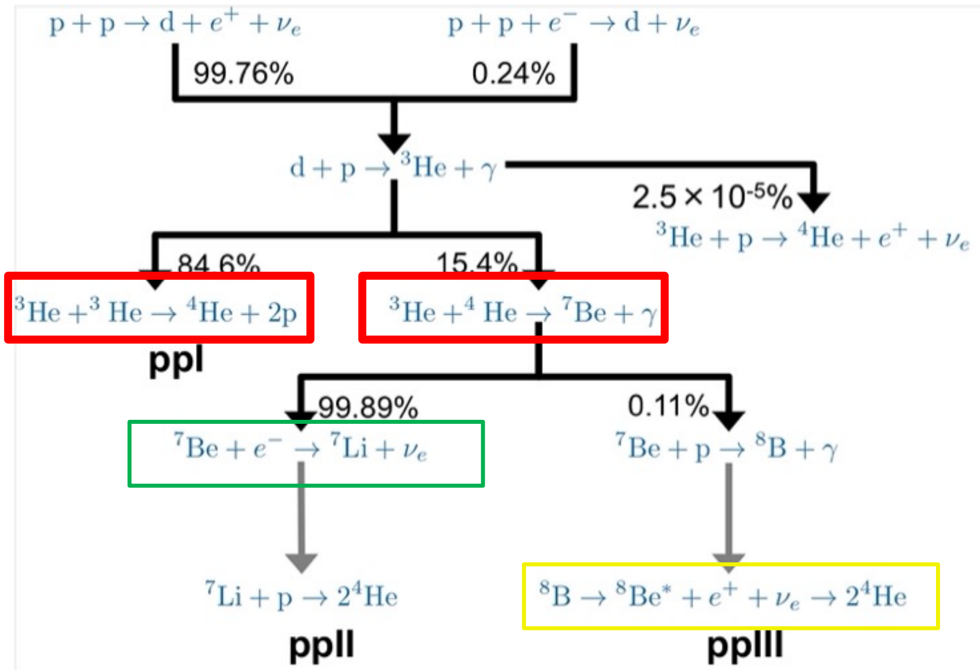
$$L_\odot = \int_0^M (\varepsilon_{\rm nuc} - \varepsilon_\nu + \boxed{\varepsilon_{\rm X}})\, dm$$

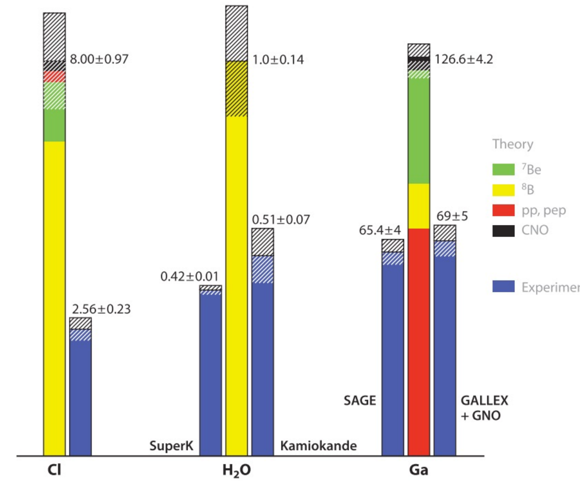
Different ν-fluxes

$$L_\odot = \sum_{i=1,8} \alpha_i \Phi_i$$



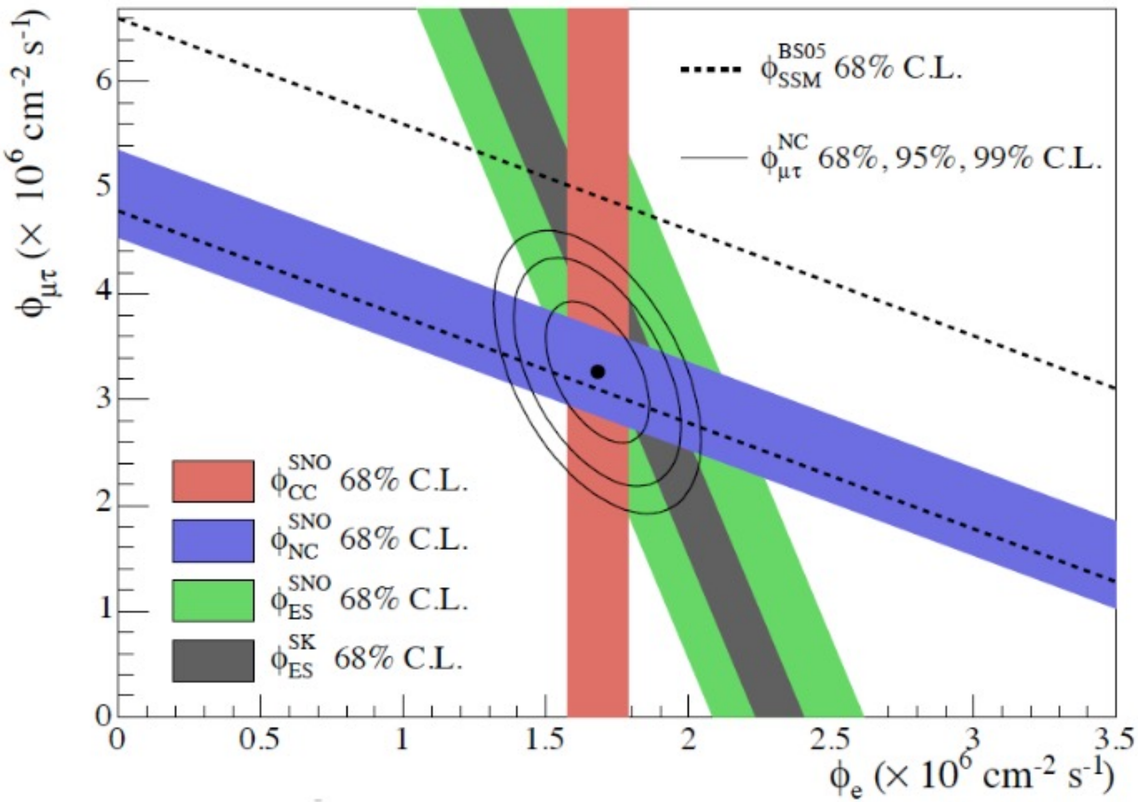
Solar neutrino problem





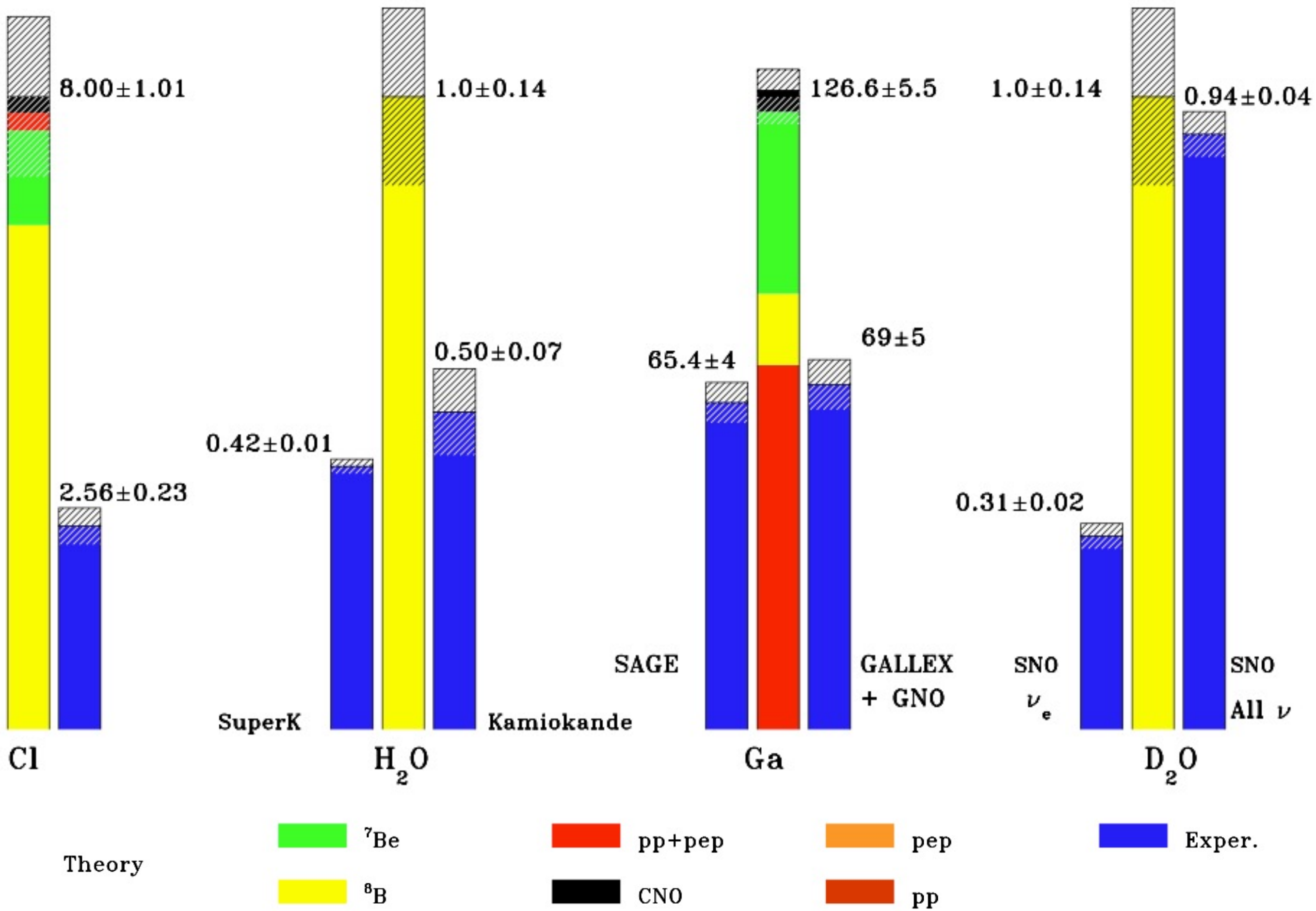
Accurate and precise ^{3}He+^{4}He, ^{3}He+^{3}He, p+^{7}Be rates became crucial
lengthy coverage of literature – Adelberger et al. 2011

SNO (and SuperK) discovery of neutrino oscillations

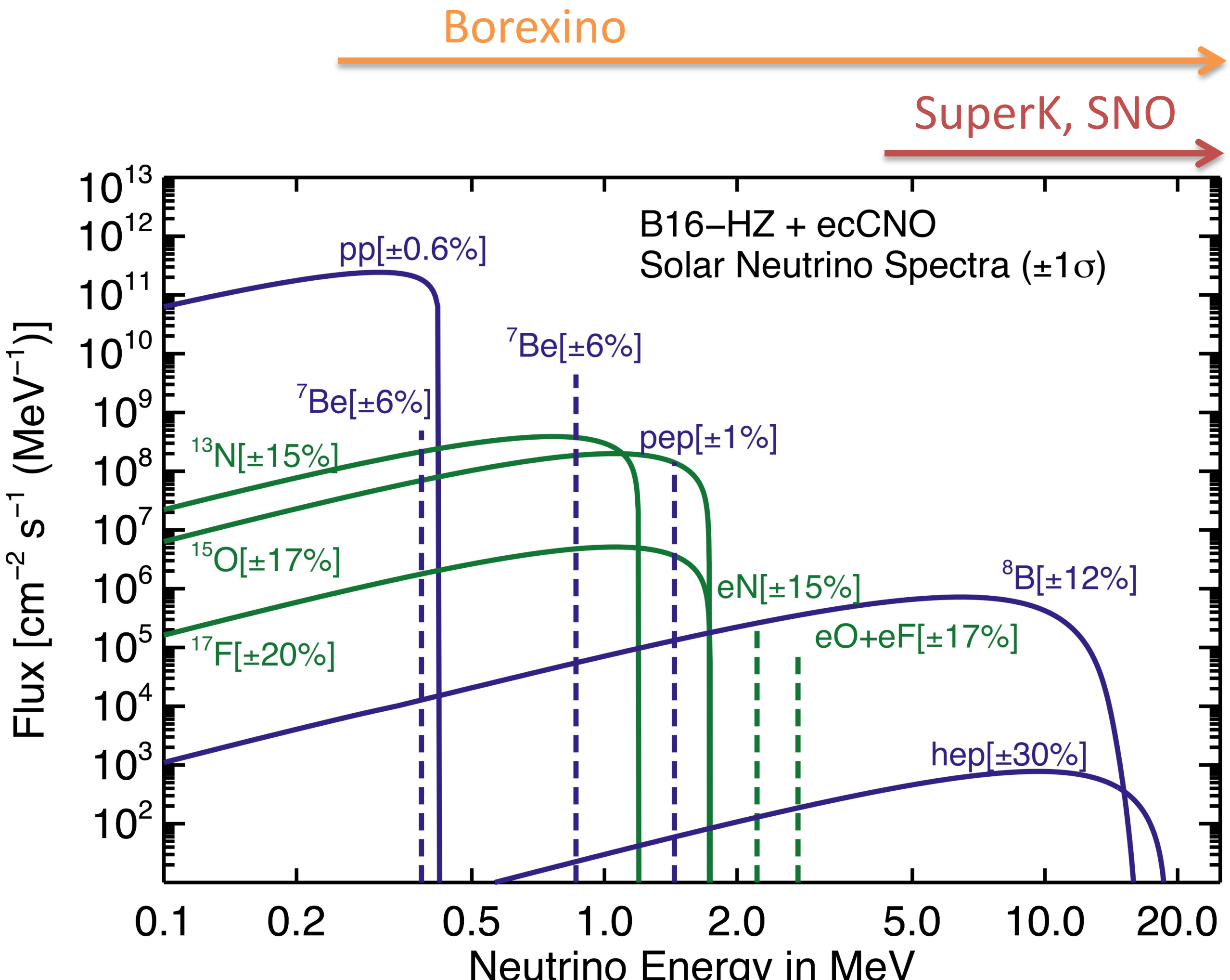


SNO coll.

SNO (and SuperK) discovery of neutrino oscillations



Towards spectroscopy of solar neutrinos - Borexino



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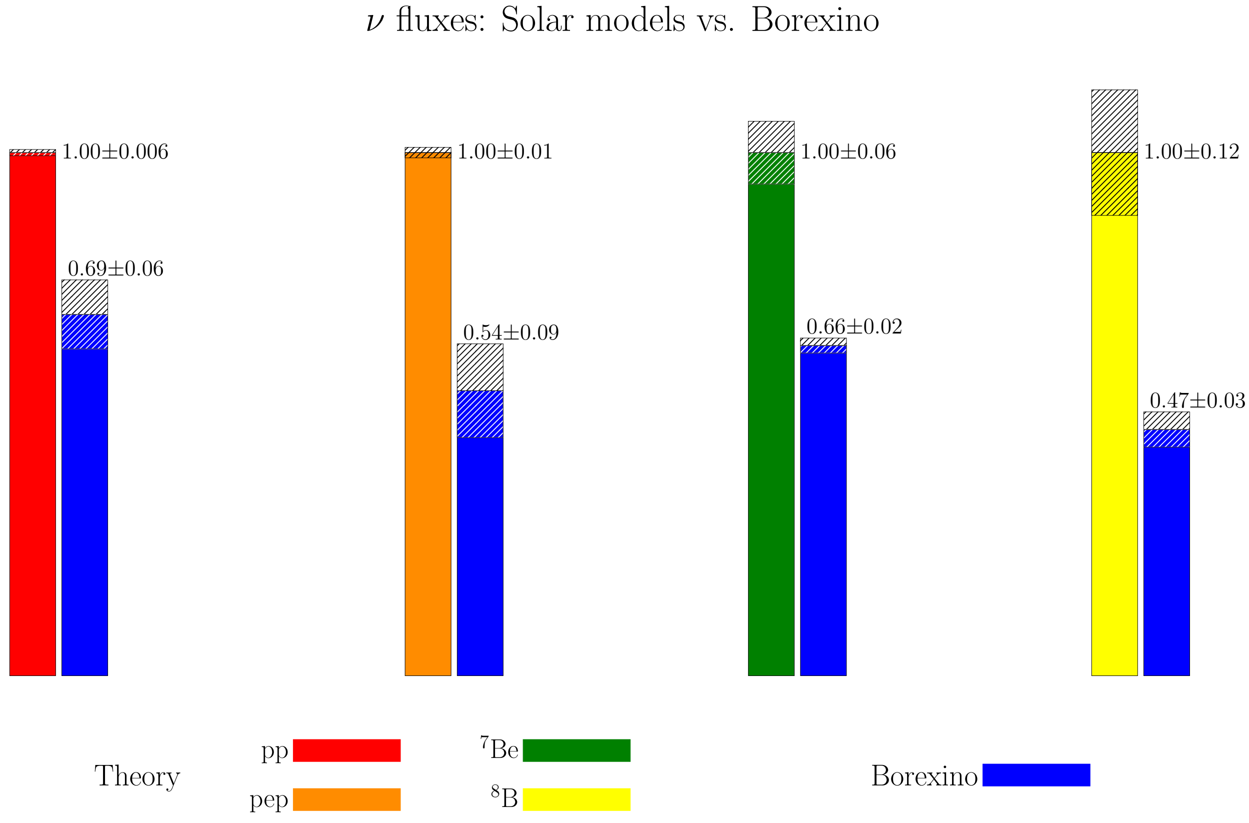


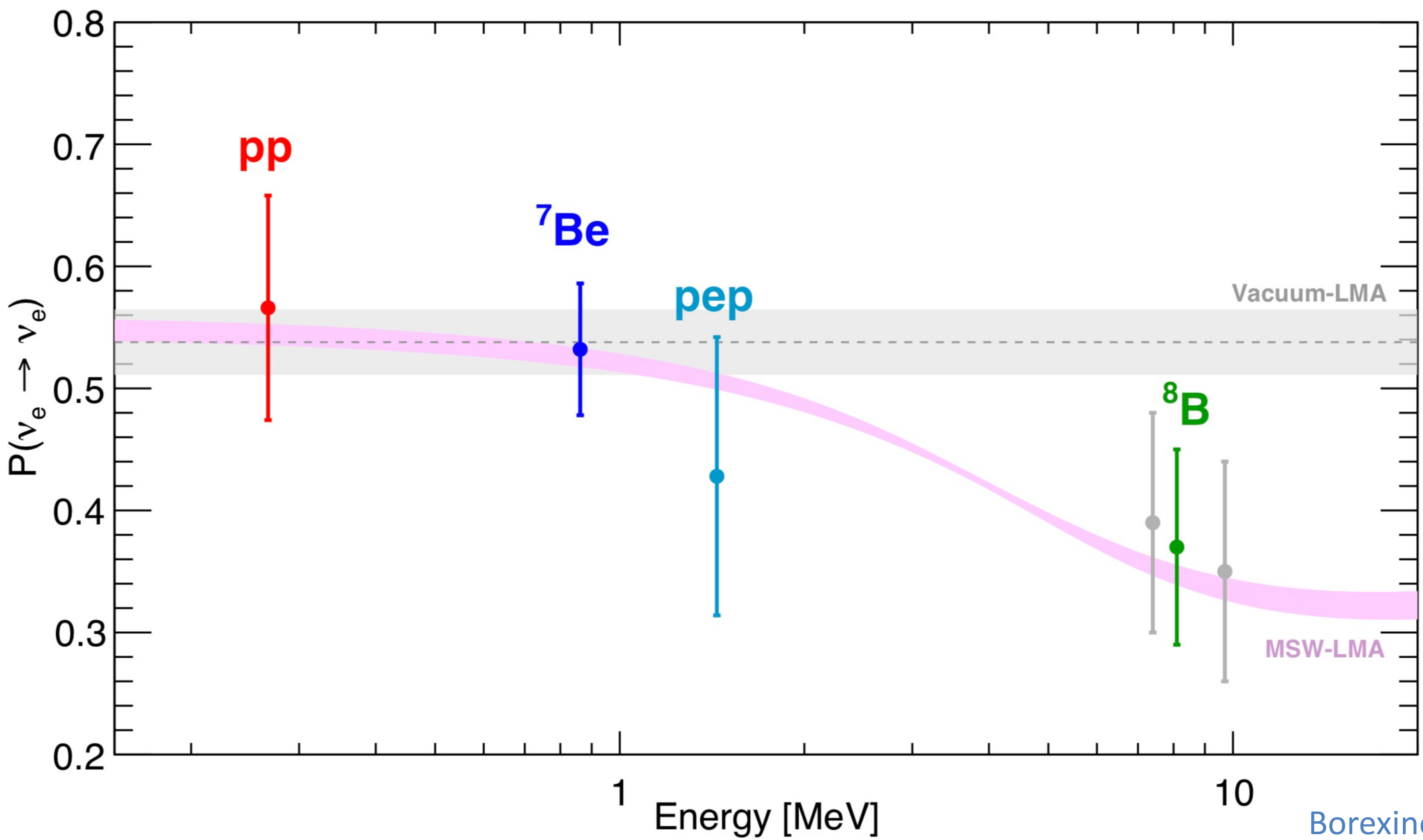
Once ν-oscillations are accounted for → **good agreement with SSM** (Borexino coll. 2018)

$$L = 3.89^{+0.35}_{-0.42} \times 10^{33}\,\mathrm{erg/s}$$

$$L_\odot = 3.842 \times 10^{33}\,\mathrm{erg/s}$$

Neutrino oscillations – survival probability

ν-physics and solar models remain associated
survival probability computed using SSMs as reference fluxes



Borexino coll. 2018

Testing source of solar energy

Detailed tests of solar physics

$$L = 3.89^{+0.35}_{-0.42} \times 10^{33}\,\mathrm{erg/s}$$

$$L_\odot = 3.842 \times 10^{33}\,\mathrm{erg/s}$$

In agreement, but 10% uncertainty

$$L_\odot = \int_0^M (\varepsilon_{\mathrm{nuc}} - \varepsilon_\nu + \varepsilon_{\mathrm{eg}})\, dm$$

still room for non-standard energy sources

The need for model precision fluxes

Individual fluxes

Flux	Solar (Global) (no LC)		SSM - B16 high-Z
$\Phi(pp)$	6.21 ± 0.50		5.98(0.6%)
$\Phi(pep)$	1.51 ± 0.12		1.44(1%)
$\Phi(hep)$	19^{+12}_{-9}		7.98(30%)
$\Phi(^7Be)$	4.85 ± 0.19	3%	4.93(6%)
$\Phi(^8B)$	$5.16^{+0.13}_{-0.09}$	2%	5.46(12%)

Experiments

Solar model

The need for model precision fluxes

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Experiments

Solar model

Experiment better than models

Nuclear reactions a limiting factor

S_{34} – 5%

S_{17} – 5%

The need for model precision fluxes

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Experiments — Solar model

Experiment better than models

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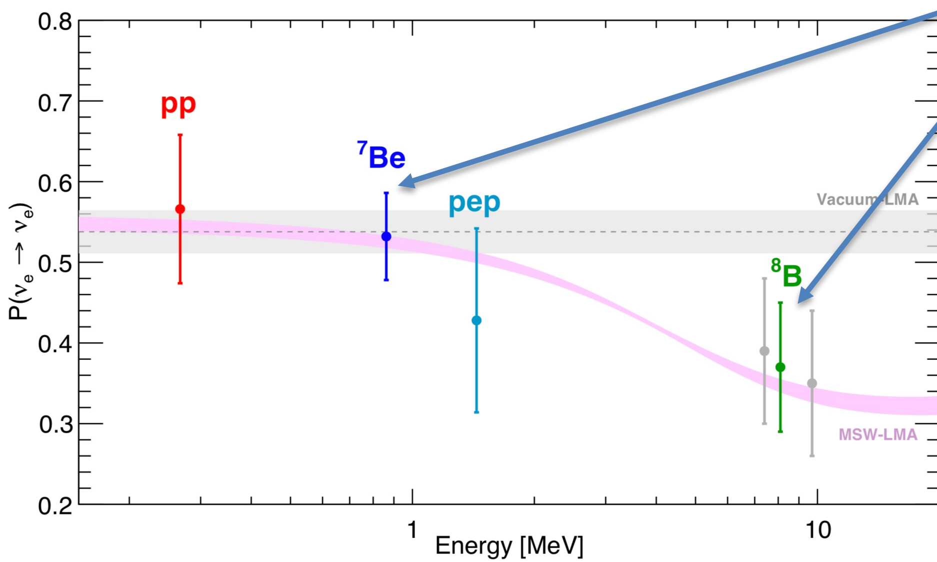
S_{34} – 5%

S_{17} – 5%

This affects, e.g. P(ee), model dominated errors



The need for model precision fluxes

Individual fluxes

Flux	Solar (Global) (no LC)		SSM - B16 high-Z	SSM - B16 low-Z
$\Phi(pp)$	6.21 ± 0.50		5.98(0.6%)	6.03(0.5%)
$\Phi(pep)$	1.51 ± 0.12		1.44(1%)	1.46(1%)
$\Phi(hep)$	19^{+12}_{-9}		7.98(30%)	8.25(30%)
$\Phi(^7Be)$	4.85 ± 0.19	3%	4.93(6%)	4.50(6%)
$\Phi(^8B)$	$5.16^{+0.13}_{-0.09}$	2%	5.46(12%)	4.50(12%)

Also solar studies

Two solar models – different solar composition

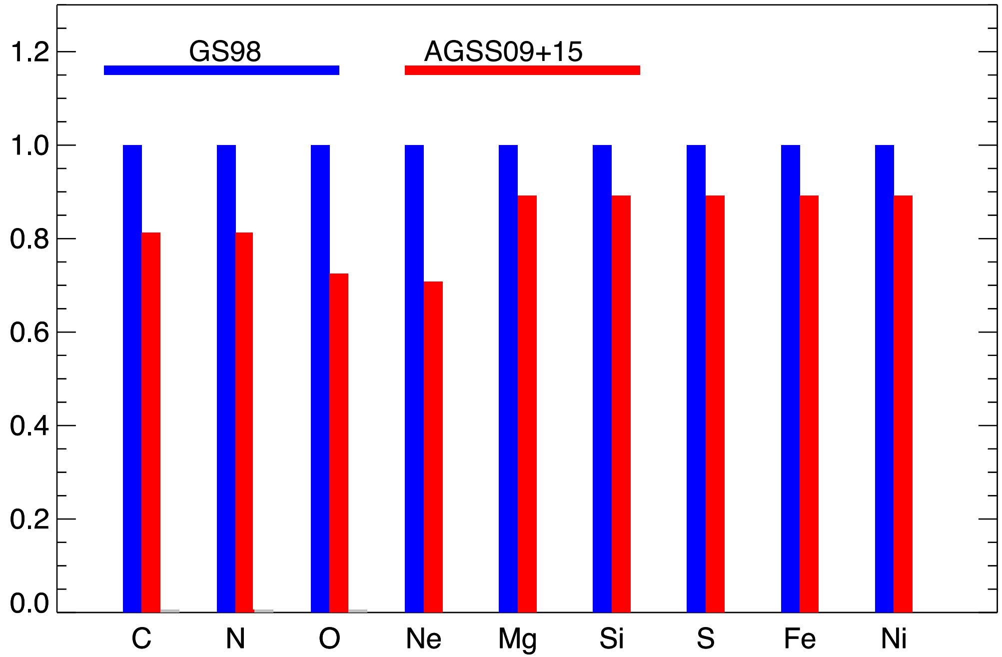
^{7}Be and ^{8}B different by 10% and 20%

Discrimination between them depends crucially on reducing model uncertainties

Solar abundance problem

3 observational constraints imposed at present age $\tau_{\odot}$=4.57 Gyr

*** photospheric $(Z/X)_{\odot}$ + solar mixture (fractional abundance of all metals)**
* solar radius $R_{\odot}$
* solar luminosity $L_{\odot}$= 3.8418 x 10^{33} erg s^{-1}



Spectroscopic analysis

new (AGSS09) vs old (GS98)

3D vs 1D model atmospheres
NLTE vs LTE line formation
identification of line blends

CNO(Ne) < 30-40%

Solar abudance problem

"Modern" solar composition: low in metals

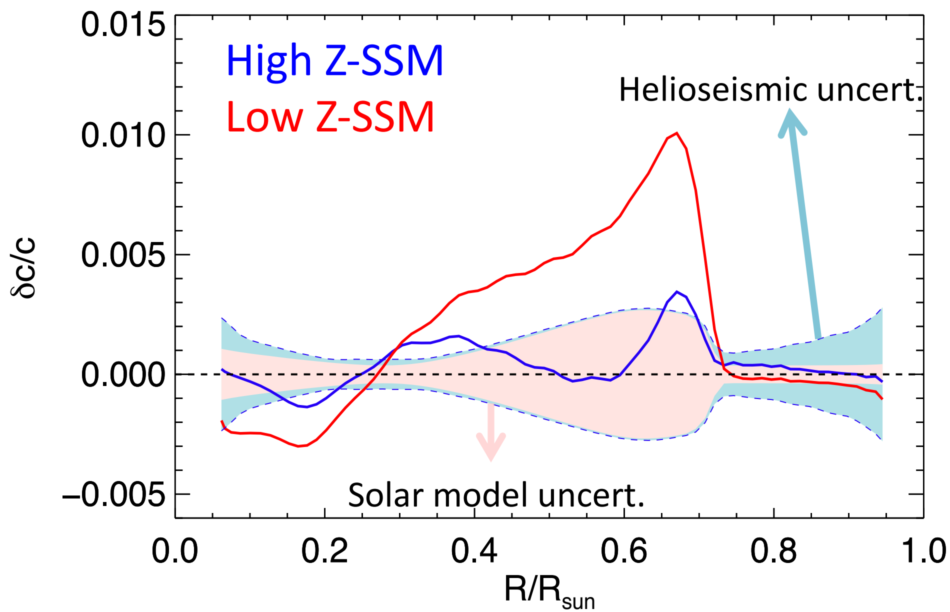
→ smaller radiative opacity in solar interior

→ impact on radiative energy transport (degeneracy with uncertain opacities)

→ changes internal solar structure

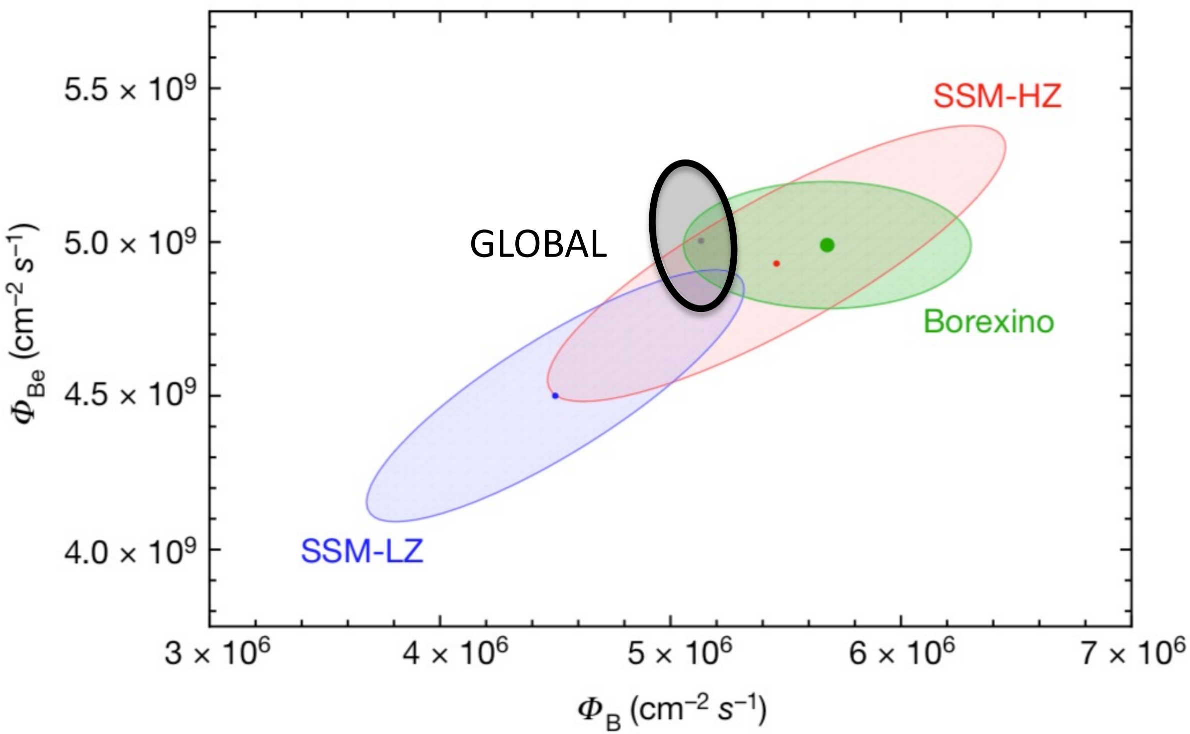
Most clear evidence – solar sound speed profile

(measurable by studying solar oscillations – global sound waves – helioseismology)



Solar abundance problem – no solution so far: limit in modeling Sun/stars?

Solar abudance problem



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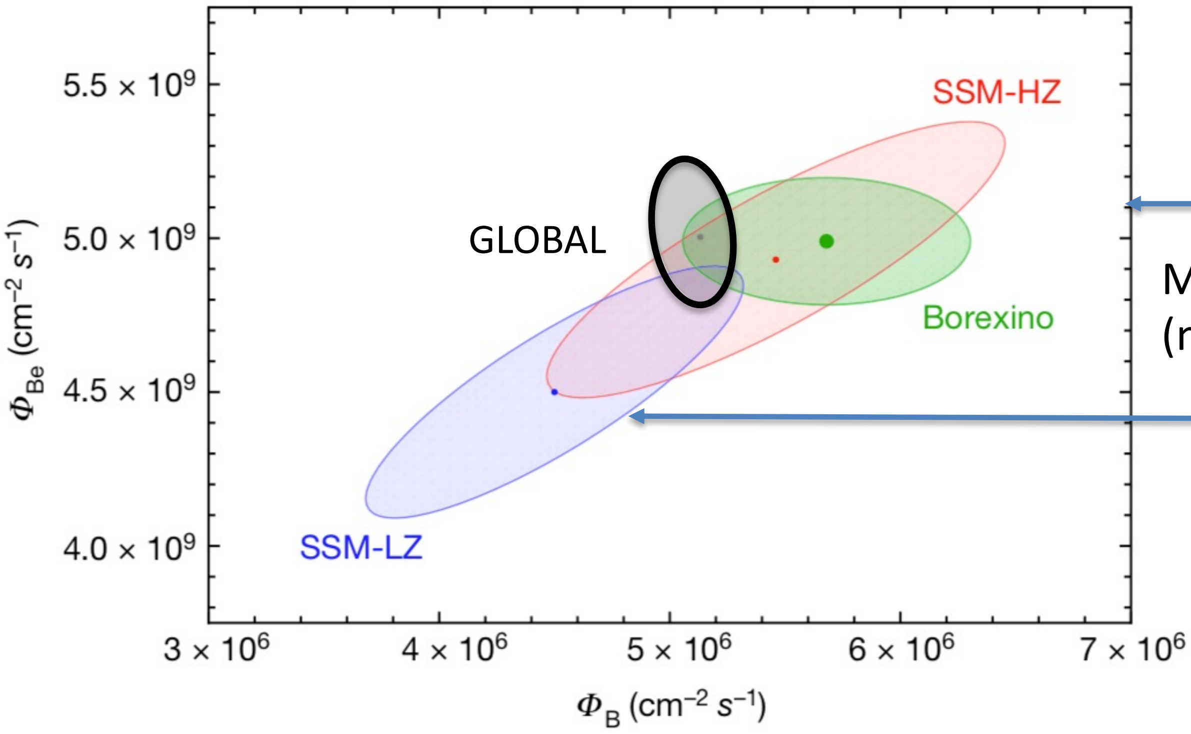

Model uncertainties (nuclear) should be reduced

Solar abundance problem

Fluxes on Earth cm^{-2}s^{-1}

Flux	B16-GS98	B16-AGSS09met	
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	x10^{10}
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	x10^{8}
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	x10^{3}
$\Phi(^{7}Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	x10^{9}
$\Phi(^{8}B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	x10^{6}
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	x10^{8}
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	x10^{8}
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	x10^{6}

CNO fluxes reflect linearly the CNO abundances
30-40% differences
15-20% uncertainties

Can we exploit ν-fluxes to learn about solar core composition and point towards a solution of solar abundance problem?

Solar composition from solar neutrinos

Uncertainties in model ν-fluxes separated qualitatively in:

- environmental (thermal): factors contributing to temperature in solar core (T_c)
  radiative opacities, solar luminosity, abundance of metals (but CNO)

- nuclear rates: affect individual or a few fluxes (e.g. $^3He+^4He$)

- CN(O) abundances: affect directly CN(O) fluxes

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Flux dependences

$$\frac{\Phi_i}{\Phi_{i,0}} = \prod_{\mathrm{j=env}} \left(\frac{p_j}{p_{j,0}}\right)^{\beta_{ij}} \prod_{\mathrm{j=nuc}} \left(\frac{p_j}{p_{j,0}}\right)^{\beta_{ij}} \prod_{\mathrm{j=CNO}} \left(\frac{p_j}{p_{j,0}}\right)^{\beta_{ij}}$$

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$$\delta\Phi_i = \sum_{\mathrm{j=env}} \beta_{ij}\delta p_j + \sum_{\mathrm{j=nuc}} \beta_{ij}\delta p_j + \sum_{\mathrm{j=CNO}} \beta_{ij}\delta p_j$$

1st order approximation

β_{ij} obtained from solar models (Serenelli et al. 2013) or linear perturbation (Villante & AS 2021)

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

In linear regime, it is reasonable that for any two fluxes (i,k), a coefficient c_{ik}

$$\delta\Phi_i - c_{ik}\delta\Phi_k = \sum_{\mathrm{j=env}} (\beta_{ij} - c_{ik}\beta_{kj})\delta p_j + \sum_{\mathrm{j=nuc}} (\beta_{ij} - c_{ik}\beta_{kj})\delta p_j + \sum_{\mathrm{j=CNO}} (\beta_{ij} - c_{ik}\beta_{kj})\delta p_j$$

That will give $\displaystyle\sum_{\mathrm{j=env}} (\beta_{ij} - c_{ik}\beta_{kj})\delta p_j \approx 0$

i.e. build a combination of ν-fluxes that minimizes environmental uncertainties

Solar composition from solar neutrinos

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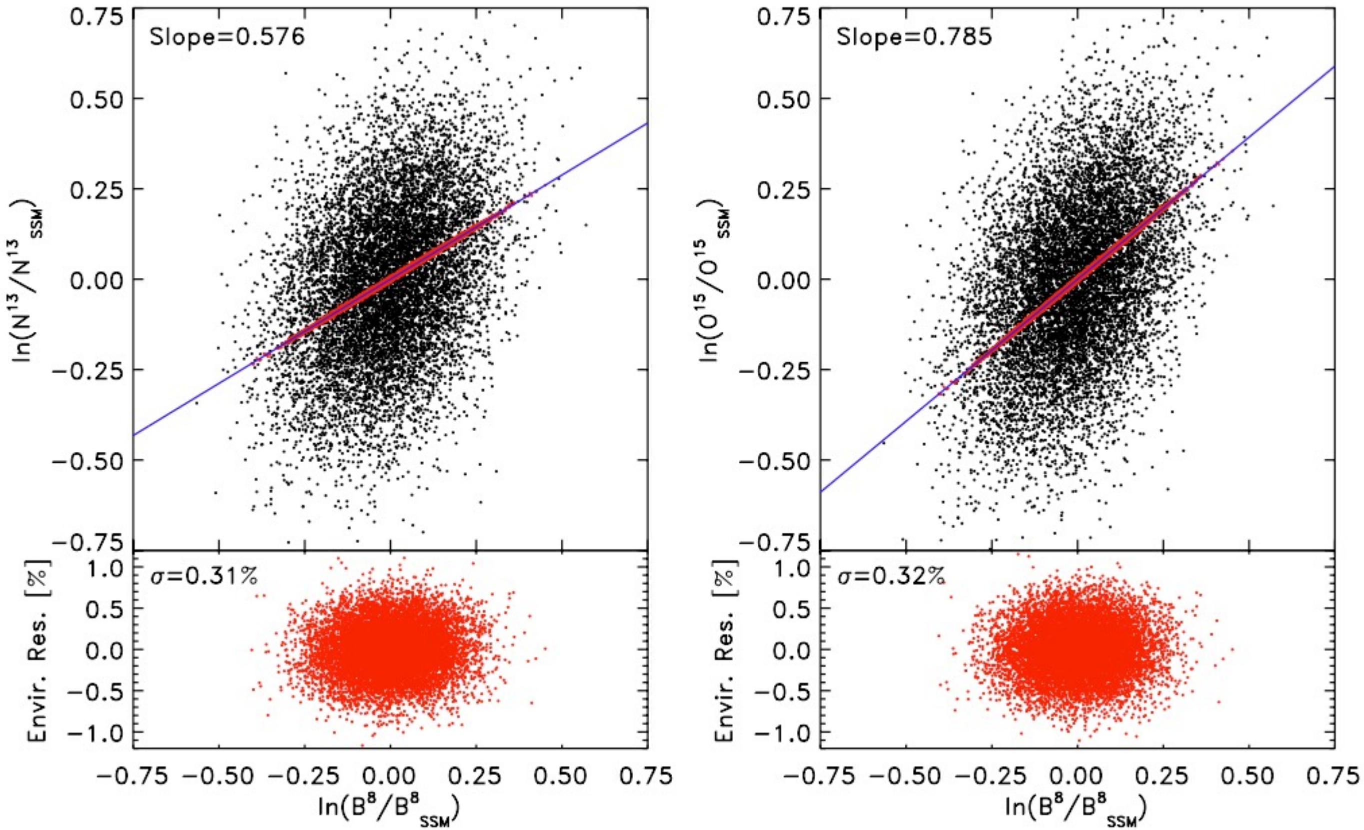

Serenelli et al. 2013

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

$$\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576} = x_C^{0.840} x_N^{0.161} D^{0.183} [L_\odot^{0.553} O^{-0.017} A^{0.157}] \times [\mathrm{S}_{11}^{-0.639} \mathrm{S}_{33}^{0.264} \mathrm{S}_{34}^{-0.526} \mathrm{S}_{17}^{-0.576} \mathrm{S}_{e7}^{0.576} \mathrm{S}_{114}^{0.743}] \times [x_{\mathrm{O}}^{0.002} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.004} x_{\mathrm{Si}}^{0.0} x_{\mathrm{S}}^{0.0} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.005}]$$

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172} [L_\odot^{0.515} O^{-0.016} A^{0.308}] \times [\mathrm{S}_{11}^{-0.831} \mathrm{S}_{33}^{0.342} \mathrm{S}_{34}^{-0.685} \mathrm{S}_{17}^{-0.785} \mathrm{S}_{e7}^{0.785} \mathrm{S}_{114}^{0.995}] \times [x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}]$$

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

$$\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}}\Big/\left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576}$$
$$= x_C^{0.840}\, x_N^{0.161}\, D^{0.183} \cancel{[L_\odot^{0.553}\, O^{-0.017}\, A^{0.157}]}$$
$$\times [\mathrm{S}_{11}^{-0.639}\, \mathrm{S}_{33}^{0.264}\, \mathrm{S}_{34}^{-0.526}\, \mathrm{S}_{17}^{-0.576}\, \mathrm{S}_{e7}^{0.576}\, \mathrm{S}_{114}^{0.743}]$$
$$\cancel{\times [x_{\mathrm{O}}^{0.002}\, x_{\mathrm{Ne}}^{-0.005}\, x_{\mathrm{Mg}}^{-0.004}\, x_{\mathrm{Si}}^{0.0}\, x_{\mathrm{S}}^{0.0}\, x_{\mathrm{Ar}}^{0.001}\, x_{\mathrm{Fe}}^{0.005}]}$$

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}}\Big/\left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785}$$
$$= x_C^{0.794}\, x_N^{0.212}\, D^{0.172} \cancel{[L_\odot^{0.515}\, O^{-0.016}\, A^{0.308}]}$$
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$$\frac{\Phi(^{13}\mathrm{N})}{\Phi(^{13}\mathrm{N})^{\mathrm{SSM}}} = \left(\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.576} \approx \mathrm{X}_{\mathrm{C+N}}\,[0.5\%(\mathrm{env}) + 9\%(\mathrm{nuc}) + 2\%(\mathrm{diff})]$$

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

$$\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576} = x_C^{0.840} x_N^{0.161} D^{0.183} \cancel{[L_\odot^{0.553} O^{-0.017} A^{0.157}]} \times [S_{11}^{-0.639} S_{33}^{0.264} S_{34}^{-0.526} S_{17}^{-0.576} S_{e7}^{0.576} S_{114}^{0.743}] \cancel{\times [x_{\mathrm{O}}^{0.002} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.004} x_{\mathrm{Si}}^{0.0} x_{\mathrm{S}}^{0.0} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.005}]}$$

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$$\frac{\Phi(^{13}\mathrm{N})}{\Phi(^{13}\mathrm{N})^{\mathrm{SSM}}} = \left(\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.576} \approx \mathrm{X}_{\mathrm{C+N}}\,[0.5\%(\mathrm{env}) + 9\%(\mathrm{nuc}) + 2\%(\mathrm{diff})]$$

$\Phi(^{8}\mathrm{B})$ Fixed by experiments (SNO, SuperK) to 2%

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

$$\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576} = x_C^{0.840} x_N^{0.161} D^{0.183} \cancel{[L_\odot^{0.553} O^{-0.017} A^{0.157}]} \times [\mathrm{S}_{11}^{-0.639} \mathrm{S}_{33}^{0.264} \mathrm{S}_{34}^{-0.526} \mathrm{S}_{17}^{-0.576} \mathrm{S}_{e7}^{0.576} \mathrm{S}_{114}^{0.743}] \cancel{\times [x_{\mathrm{O}}^{0.002} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.004} x_{\mathrm{Si}}^{0.0} x_{\mathrm{S}}^{0.0} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.005}]}$$

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$$\frac{\Phi(^{13}\mathrm{N})}{\Phi(^{13}\mathrm{N})^{\mathrm{SSM}}} = \left(\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.576} \approx \mathrm{X}_{\mathrm{C+N}}\,[0.5\%(\mathrm{env}) + \boxed{9\%(\mathrm{nuc})} + 2\%(\mathrm{diff})]$$

Dominant uncertainty – nuclear cross sections from several reactions (S_{114}, S_{34}, S_{17})

Solar composition from solar neutrinos

Environmetal uncertainties are fully correlated among fluxes

$$
\begin{aligned}
&\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576} \\
&= x_C^{0.840} x_N^{0.161} D^{0.183} \cancel{[L_\odot^{0.553} O^{-0.017} A^{0.157}]} \\
&\times [\mathrm{S}_{11}^{-0.639} \mathrm{S}_{33}^{0.264} \mathrm{S}_{34}^{-0.526} \mathrm{S}_{17}^{-0.576} \mathrm{S}_{e7}^{0.576} \mathrm{S}_{114}^{0.743}] \\
&\cancel{\times [x_{\mathrm{O}}^{0.002} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.004} x_{\mathrm{Si}}^{0.0} x_{\mathrm{S}}^{0.0} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.005}]}
\end{aligned}
$$

$$
\begin{aligned}
&\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} \\
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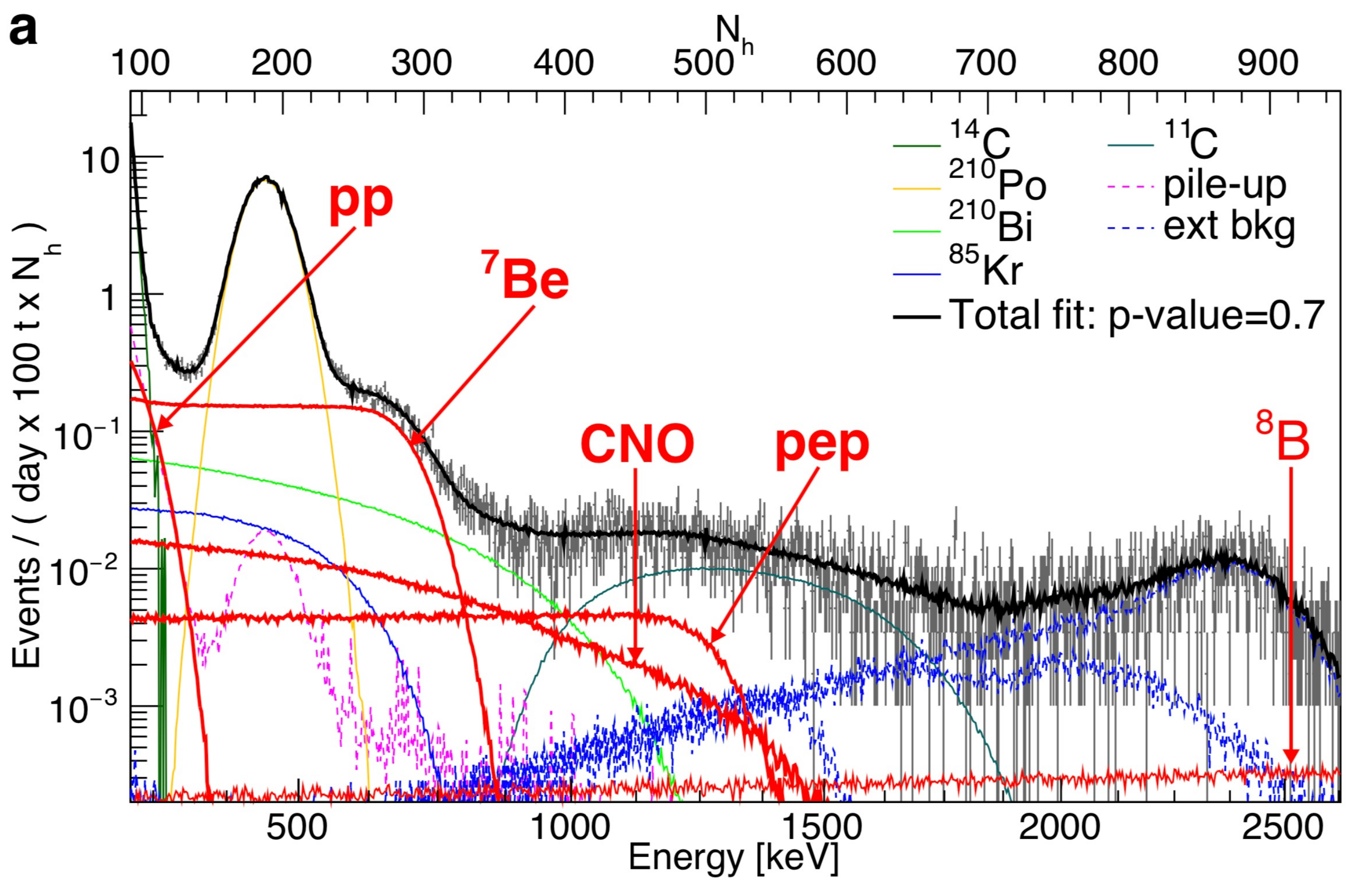
&\cancel{\times [x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}]}
\end{aligned}
$$

$$
\frac{\Phi(^{13}\mathrm{N})}{\Phi(^{13}\mathrm{N})^{\mathrm{SSM}}} = \left(\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.576} \approx \mathrm{X}_{\mathrm{C+N}} \, [0.5\%(\mathrm{env}) + 9\%(\mathrm{nuc}) + 2\%(\mathrm{diff})]
$$

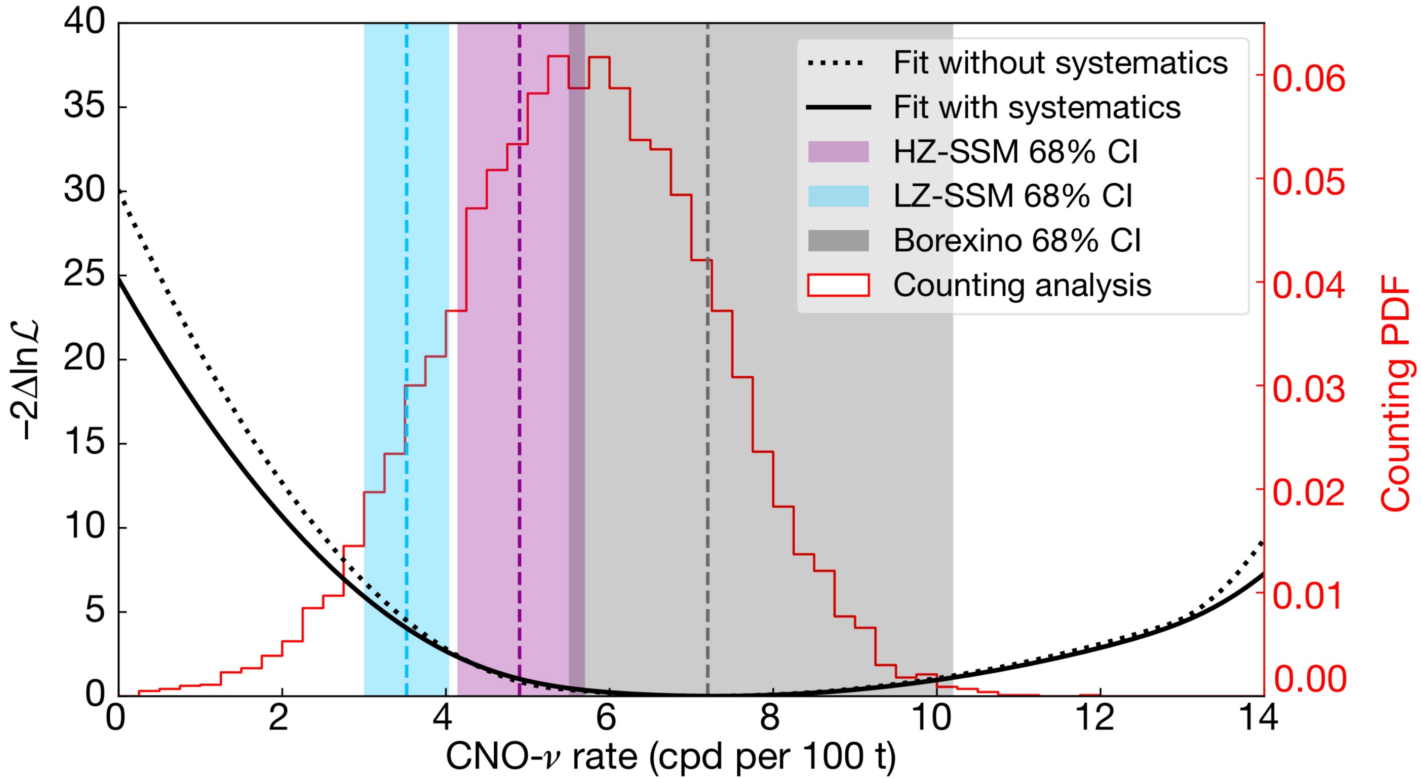
Provided a ^{13}N (or ^{15}O, or a combination of them) is available we obtain X_{C+N} in the solar core!

CN measurement at Borexino



Borexino coll. 2020

CN measurement at Borexino



Borexino coll. 2020

Still large experimental uncertainty – further improvements in data analysis

Pioneering study for future experiments

In solar models, reducing nuclear uncertainties is required

Summary

Solar models:

- reference neutrino fluxes for neutrino physics – survival probability
  - vacuum limit
  - potentially in transition region (CNO fluxes)
- neutrino inferred luminosity tests solar energy source and non-standard mechanisms
- learning about solar properties
  - CN composition in the core – solar abundance problem
  - breaking degeneracy with radiative opacities
  - surface vs core composition → tests of chemical mixing in stars
    non-standard events (e.g. accretion in early solar system)

Underlying these topics is the requirement of accurate and precise nuclear reaction rates
Fundamental physics (and astrophysics) requires excellent nuclear physics

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