SSM and Solar Abundances Problem

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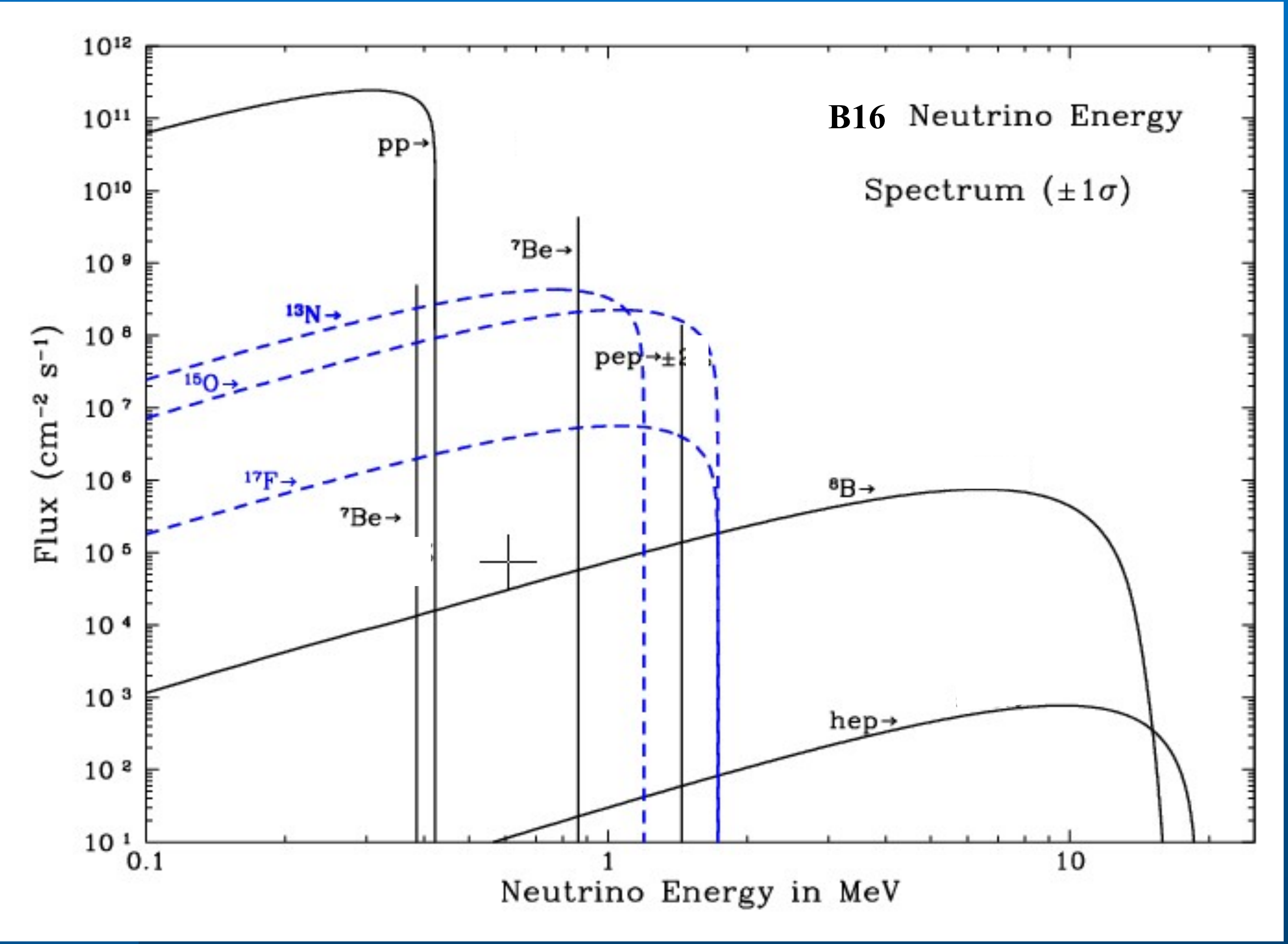
SSM: 50+ years of th-ex efforts



B16 SSM

Vinyoles et al, ApJ 2017

Improvements:
Treatment of radiative opacities uncertainties
ES with mixtures consistent with metal abundances
Nuclear reaction rates:

	$S(0)$	Uncert. %	$\Delta S(0)/S(0)$	Ref.
S_{11}	$4.03 \cdot 10^{-25}$	1	$0.5\%^{\dagger}$	1,2,3
S_{17}	$2.13 \cdot 10^{-5}$	4.7	+2.4%	4
S_{114}	$1.59 \cdot 10^{-3}$	7.5	-4.2%	5

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Ne	8.08 ± 0.06	7.93 ± 0.10
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Ar	6.40 ± 0.06	6.40 ± 0.13
Fe	7.50 ± 0.01	7.45 ± 0.01
$(Z/X)_{\odot}$	0.02292	0.01780

Abundances choice (10+ yr)
Photospheric (volatiles) +
Refractories (meteoritic)

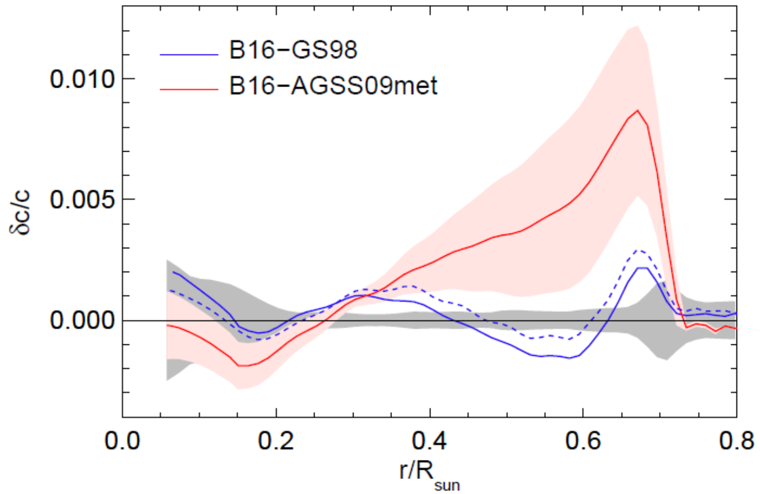
B16 SSM

Results:

Vinyoles et al, ApJ 2017 Bergstrom et al, JHEP 2016

Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

Solar Abundances Problem:



		GS98		AGSS09met	
Case	dof	χ^2	p-value (σ)	χ^2	p-value (σ)
$Y_S + R_{CZ}$ only	2	0.9	0.5	6.5	2.1
$\delta c/c$ only	30	58.0	3.2	76.1	4.5
$\delta c/c$ no-peak	28	34.7	1.4	50.0	2.7
$\Phi(^7Be) + \Phi(^8B)$	2	0.2	0.3	1.5	0.6
all ν-fluxes	8	6.0	0.5	7.0	0.6
global	40	65.0	2.7	94.2	4.7
global no-peak	38	40.5	0.9	67.2	3.0

S-factors in action: CNO

Serenelli, PG, Haxton PRD (2013)

CN fluxes are linearly proportional to:
- the C+N abundances
- S_{114}

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

A measurement of 15O neutrinos (10%), will challenge S_{17} & S_{114} to infer abundances and distinguish GS-AGS

S-factors in action: B/Be

Serenelli, PG, Haxton PRD (2013)

$$S_{17} = S_{34} S_{e7} \left[\frac{S_{11}}{S_{33}}\right]^{0.5} \left[F_{\rm SSM}^{\rm nonnuclear}\right]^{2.08} \times \frac{\phi(^8\mathrm{B})}{\phi^{\rm SSM}(^8\mathrm{B})} \Big/ \left[\frac{\phi(^7\mathrm{Be})}{\phi(^7\mathrm{Be})^{\rm SSM}}\right]^{2.08}$$

(In 2013) Current laboratory precision can be reached (7.5%) if both solar 7Be flux and S_{34} uncertainties are reduced to 3%

Borexino can make it, could S_{34} be improved?

Qnt.	Central value	σ (%)	Ref.
^{3}He(^{3}He, 2p)^{4}He	5.21 MeV b	5.2	1
^{3}He(^{4}He, γ)^{7}Be	$5.6 \cdot 10^{-4}$ MeV b	5.2	1
^{7}Be(e$^-$, ν_e)^{7}Li	Eq (40) SFII	2.0	1
^{3}He(p, e$^+\nu_e$)^{4}He	$8.6 \cdot 10^{-20}$ MeV b	30.2	1
^{16}O(p, γ)^{17}F	$1.06 \cdot 10^{-2}$ MeV b	7.6	1
$\tau_\odot$	$4.57 \cdot 10^9$ yr	0.44	2
diffusion	1.0	15.0	2
$L_\odot$	$3.8418 \cdot 10^{33}$ erg s^{-1}	0.4	2

SSM through the looking glass

Solar neutrinos Direct problem:
- **Neutrino fluxes and seismic from several input sets**
- **Verify predictions with observations**

Solar neutrinos Inverse problem:
- **Infer solar neutrino fluxes from neutrino observations**
- **Infer seismic properties from helioseismology**
- **Compute 10000n SSM connecting neutrino fluxes and seismic with SSM inputs**
- **Use Bayes to infer neutrino parameter distributions directly from observations**

In progress, Gonzalez-Garcia, PG, Serenelli, Villante et al

Uncertainties: 20 inputs + opacity function

- Sun luminosity $L_\odot$
- Sun difussion
- Sun age $\tau_\odot$
- 8 Nuclear Rates: S_{11}, S_{33}, S_{34}, S_{17}, S_{e7}, S_{114}, S_{hep}, S_{116}
- 9 Element Abundances: C, N, O, Ne, Mg, Si, S, A r, Fe
- Opacity profile $\kappa(\rho, T, X_i) = [1 + \delta\kappa(T)]\, \overline{\kappa}(\rho, T, X_i)$

Linear Opacitity (2)

$$\delta\kappa_I(T) = a + b\,\frac{\log_{10}(T_C/T)}{\Delta}$$

Gaussian Process (11 points + correlation parameter)

40 Data Points: 2 + 8 + 30

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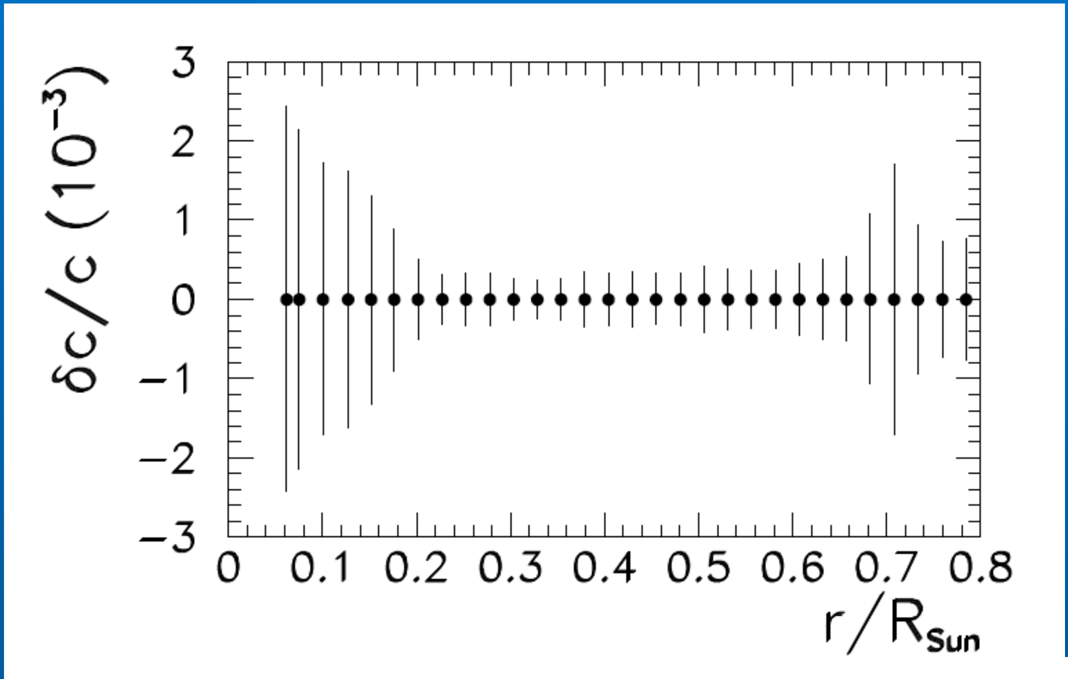
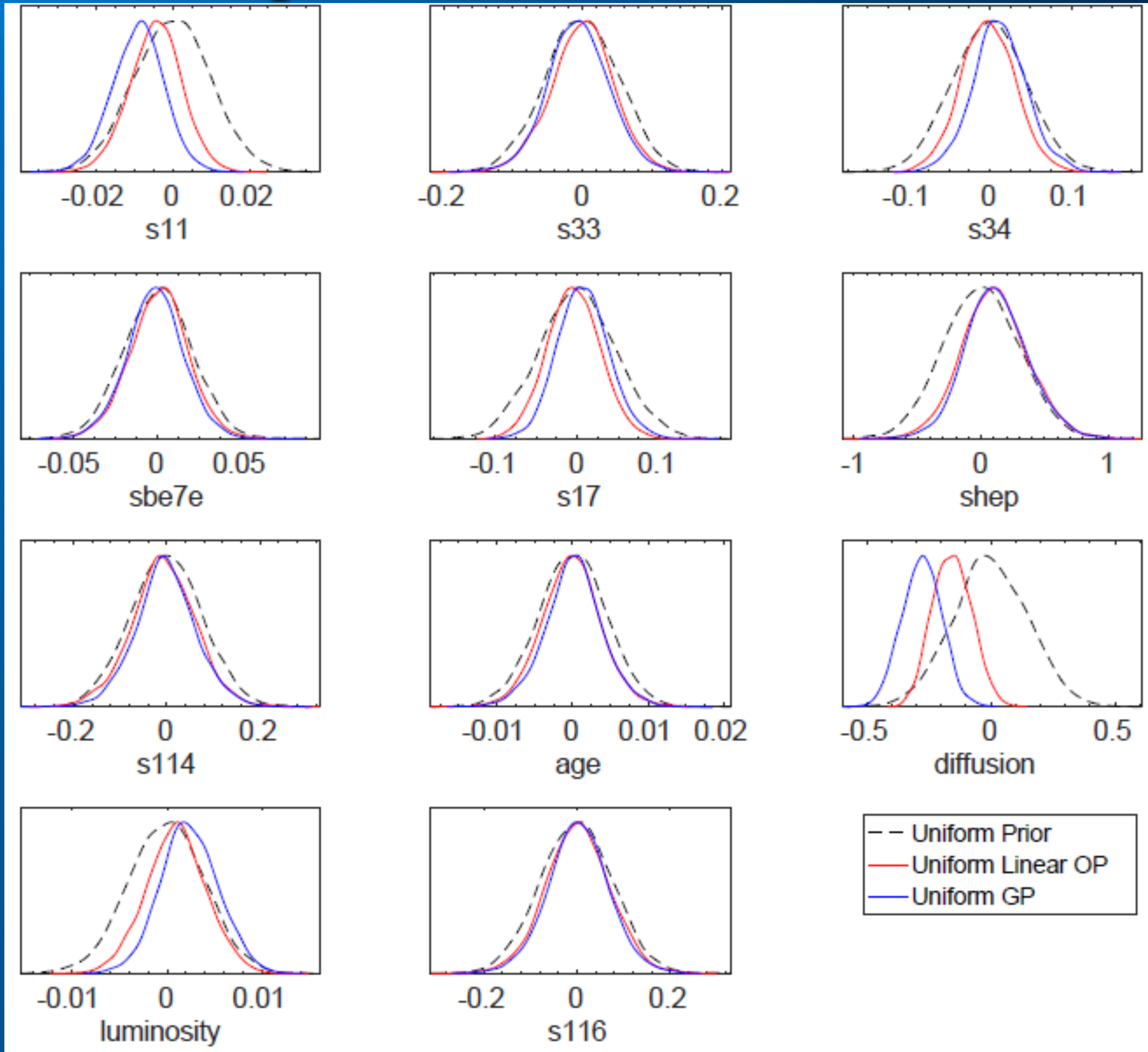
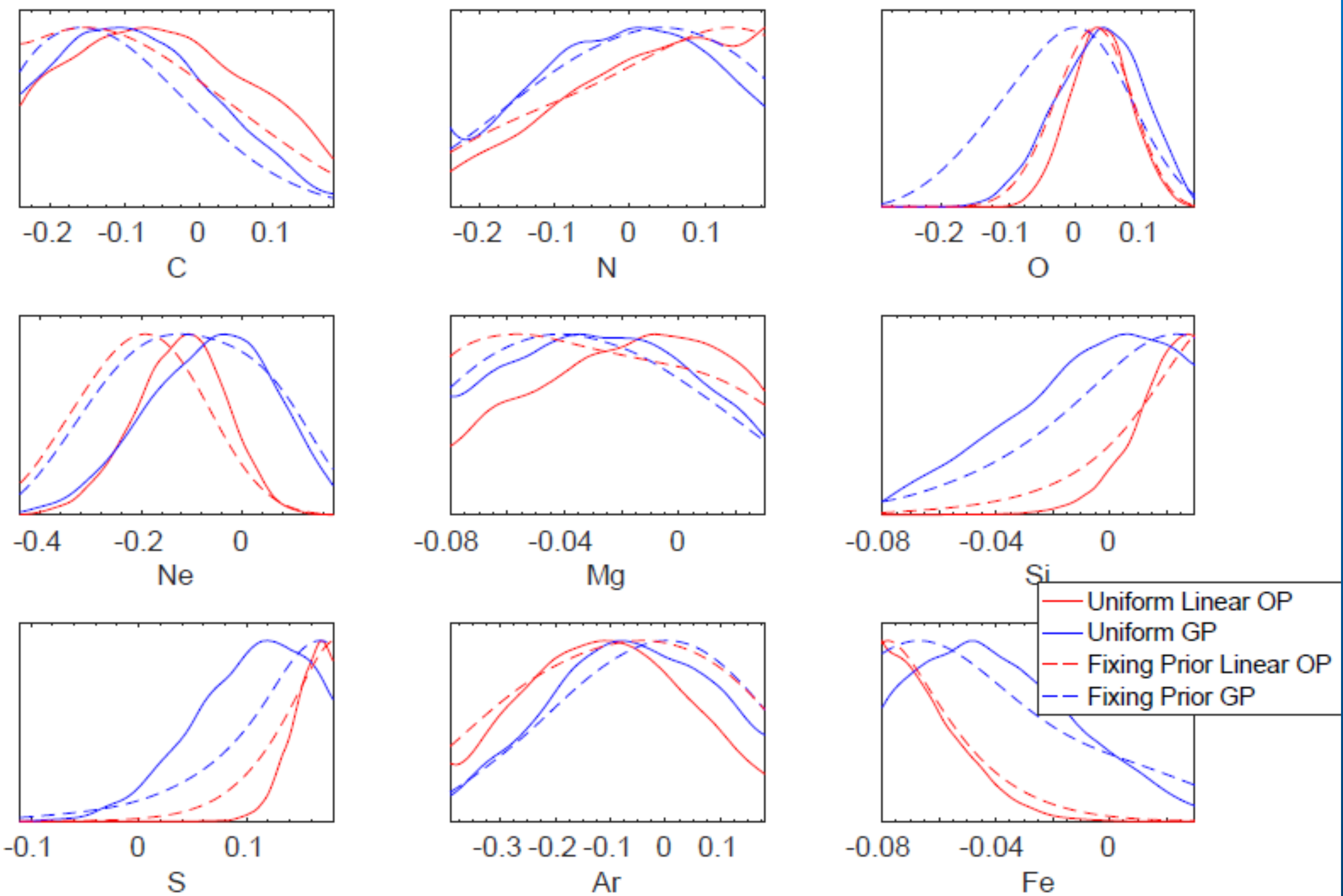


1	0.99	−0.05	0.08	−0.14	−0.20	−0.19	−0.11
0.99	1	−0.05	0.08	−0.14	−0.20	−0.19	−0.11
−0.05	−0.05	1	−0.08	0.10	−0.01	−0.00	−0.00
0.08	0.08	−0.08	1	−0.17	−0.31	0.09	0.10
−0.14	−0.14	0.10	−0.17	1	−0.02	−0.03	−0.01
−0.20	−0.20	−0.01	−0.31	−0.02	0	0.18	0.09
−0.19	−0.19	−0.00	0.09	−0.03	0.18	1	0.36
−0.11	−0.11	−0.00	0.10	−0.01	0.09	0.36	1

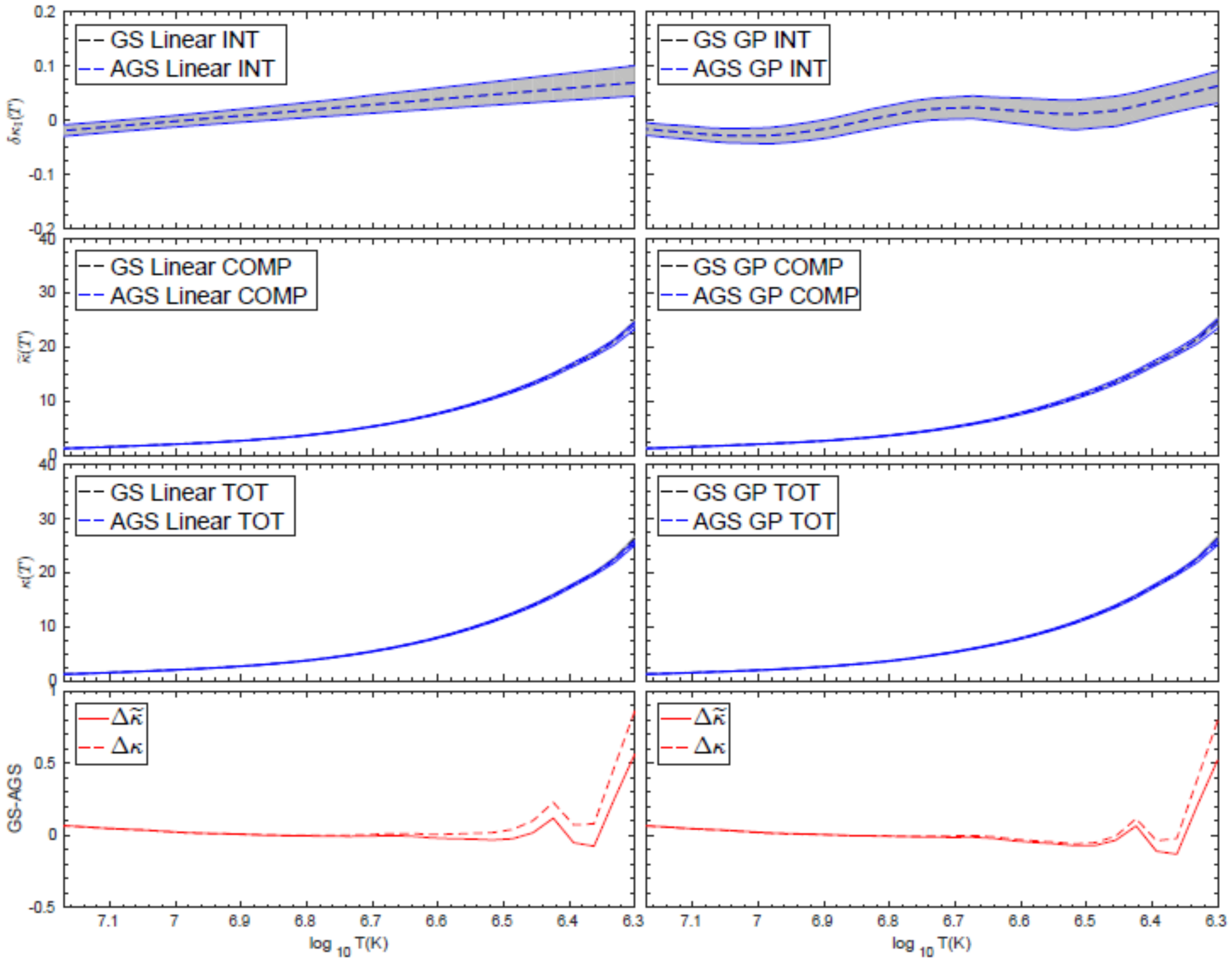
S-factors posteriors



Abundances posteriors



Opacity posteriors



Posteriors and model rejection

		LIN-OP				GP-OP			
		GS98		AGSS09met		GS98		AGSS09met	
$\vec{\mathcal{O}}$	n	$T(\vec{\mathcal{O}})$	p-value (σ)	$T(\vec{\mathcal{O}})$	p-value (σ)	$T(\vec{\mathcal{O}})$	p-value (σ)	$T(\vec{\mathcal{O}})$	p-value (σ)
$Y_S + R_{CZ}$	2	0.9	0.5	6.5	2.1	0.7	0.35	6.9	2.2
$\delta c/c$	30	58.0	3.2	76.1	4.5	35.6	1.2	40.2	1.6
all ν-fluxes	8	6.0	0.5	7.0	0.6	5.9	0.44	7.0	0.6
global	40	65.0	2.7	94.2	4.7	45.1	1.1	57.1	2.1

Element	GS98	AGSS09met	Linear OP	GP
C	8.52 ± 0.06	8.43 ± 0.05	[8.32, 8.56]	[8.31, 8.51]
N	7.92 ± 0.06	7.83 ± 0.05	[7.88, 8.10]	[7.81, 8.05]
O	8.83 ± 0.06	8.69 ± 0.05	[8.82, 8.91]	[8.80, 8.94]
Ne	8.08 ± 0.06	7.93 ± 0.10	[7.87, 8.06]	[7.90, 8.16]
Mg	7.58 ± 0.01	7.53 ± 0.01	[7.54, 7.60]	[7.52, 7.58]
Si	7.56 ± 0.01	7.51 ± 0.01	[7.57, 7.59]	[7.54, 7.59]
S	7.20 ± 0.06	7.15 ± 0.02	[7.35, 7.38]	[7.27, 7.37]
Ar	6.40 ± 0.06	6.40 ± 0.13	[6.14, 6.44]	[6.20, 6.50]
Fe	7.50 ± 0.01	7.45 ± 0.01	[7.42, 7.44]	[7.42, 7.48]

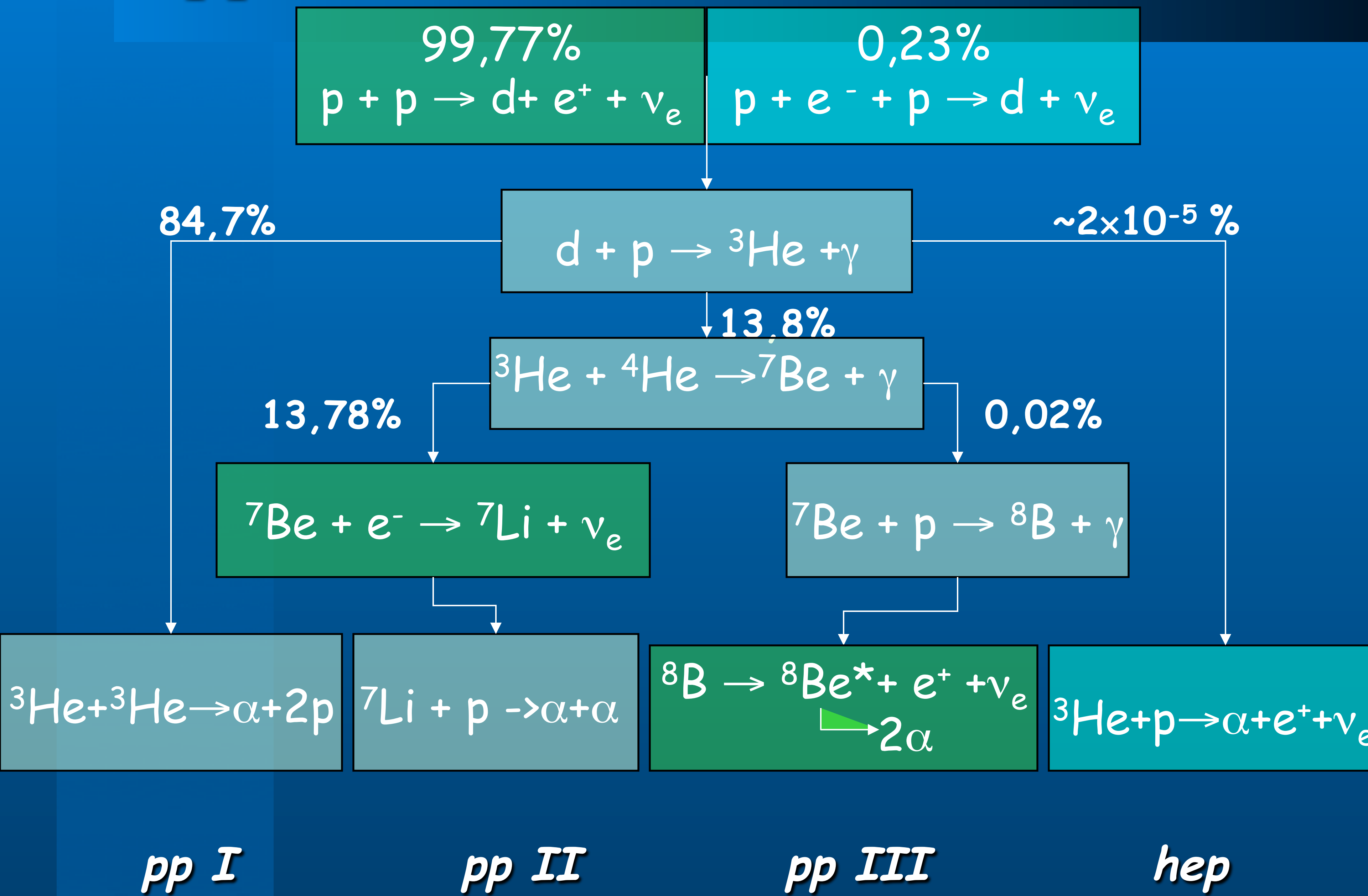
Concluding remarks

50 + years of SSM with improvements in opacities, solar abundances, astrophysical factors, … to understand Solar Neutrino Problem, with 10+ years facing Solar Abundances Problem

- S_{34}, S_{17}, S_{114}, are the most important S-factors to continue improving:
- S_{34}, S_{17} consistency check with 7Be/8B
- CNO neutrinos are linearly proportional to C+N abundances and S_{114}

- Solar neutrinos Inverse problem: with good S-factors, understand abundances problem or challenge opacity funcion.

pp chain



99,77%
$p + p \rightarrow d + e^{+} + \nu_e$
0,23%
$p + e^{-} + p \rightarrow d + \nu_e$
84,7%
$d + p \rightarrow {}^{3}He + \gamma$
~2×10^{-5} %
13,8%
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
13,78%
0,02%
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$
${}^{3}He + {}^{3}He \rightarrow \alpha + 2p$
${}^{7}Li + p \rightarrow \alpha + \alpha$
${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$
2α
${}^{3}He + p \rightarrow \alpha + e^{+} + \nu_e$
pp I
pp II
pp III
hep

CNO cycle

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$\varepsilon(^{13}N)=M(^{12}C)+M_p-M(^{13}C)-<E_\nu>(^{13}N)$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$
$$^{14}N + p \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$
$$^{15}N + p \rightarrow {}^{12}C + \alpha$$

$$\varepsilon(^{15}O)=M(^{13}C)+3M_p-M_\alpha-M(^{12}C)-<E_\nu>(^{15}O)$$

Local kinetic equilibrium

$$\frac{L_{SUN}}{4\pi(\mathrm{A.U.})^2} = \varepsilon_{CNO}\Phi_{CNO} + \varepsilon_{33}\Phi_{33} + (\varepsilon_{pp}\Phi_{pp} + \varepsilon_{pep}\Phi_{pep}) + \varepsilon_{^7Be}\Phi_{^7Be} + \varepsilon_{^8B}\Phi_{^8B} + \varepsilon_{hep}\Phi_{hep}$$

$$\frac{d\left[{}^2H\right]}{dt} = 0\ , \ \frac{d\left[{}^3He\right]}{dt} = 0 \quad \rightarrow$$

$$\Phi_{pp} + \Phi_{pep} = 2\Phi_{33} + \Phi_{^7Be} + \Phi_{^8B} + \Phi_{hep}$$