The Sun:
Past, Present, & Future

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in collaboration with

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Standard Solar Model (SSM)

Stellar model obtained by numerical integration of the equations describing the physical and chemical structure of the Sun as well as its time evolution.

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$$\frac{dL}{dm} = \varepsilon_{nuc} + \varepsilon_{grav} + \varepsilon_{\nu}$$

$$\frac{dT}{dr} = \frac{T}{H_P} \begin{cases} \nabla_{rad} \\ \nabla_{sad} \end{cases}$$

$$\frac{dX_j}{dt} = P_j - D_j + M_j + DG_j$$

Production Term

Destruction Term

Mixing Term

Gravitational Settling
Diffusion

SSM Computation: the Procedure

Constructing an initial model

P(m), T(m), ρ(m), R(m), L(m)

Chemically homogeneous

$$\{X_i(m)\} = constant$$

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$t_\odot = (4.570 \pm 0.006) Gyr$

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Comparing the results with solar observables

$L_\odot = 3.8275 \cdot 10^{33} (1 \pm 0.0004)\ erg \cdot s^{-1}$

$R_\odot = 6.9599 \cdot 10^{10} (1 \pm 0.000037)\ cm$

$\left(\frac{Z}{X}\right)_S = \left(\frac{Z}{X}\right)_\odot$

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Reliability/Accuracy of SSM

It depends on:

- The physical processes included in the model
- The precision of input physics

Reliability/Accuracy of SSM

The physical processes included in the model

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$$\frac{dX_j}{dt} = P_j - D_j + M_j$$

P_j: Production Term

D_j: Destruction Term

M_j: Mixing Term

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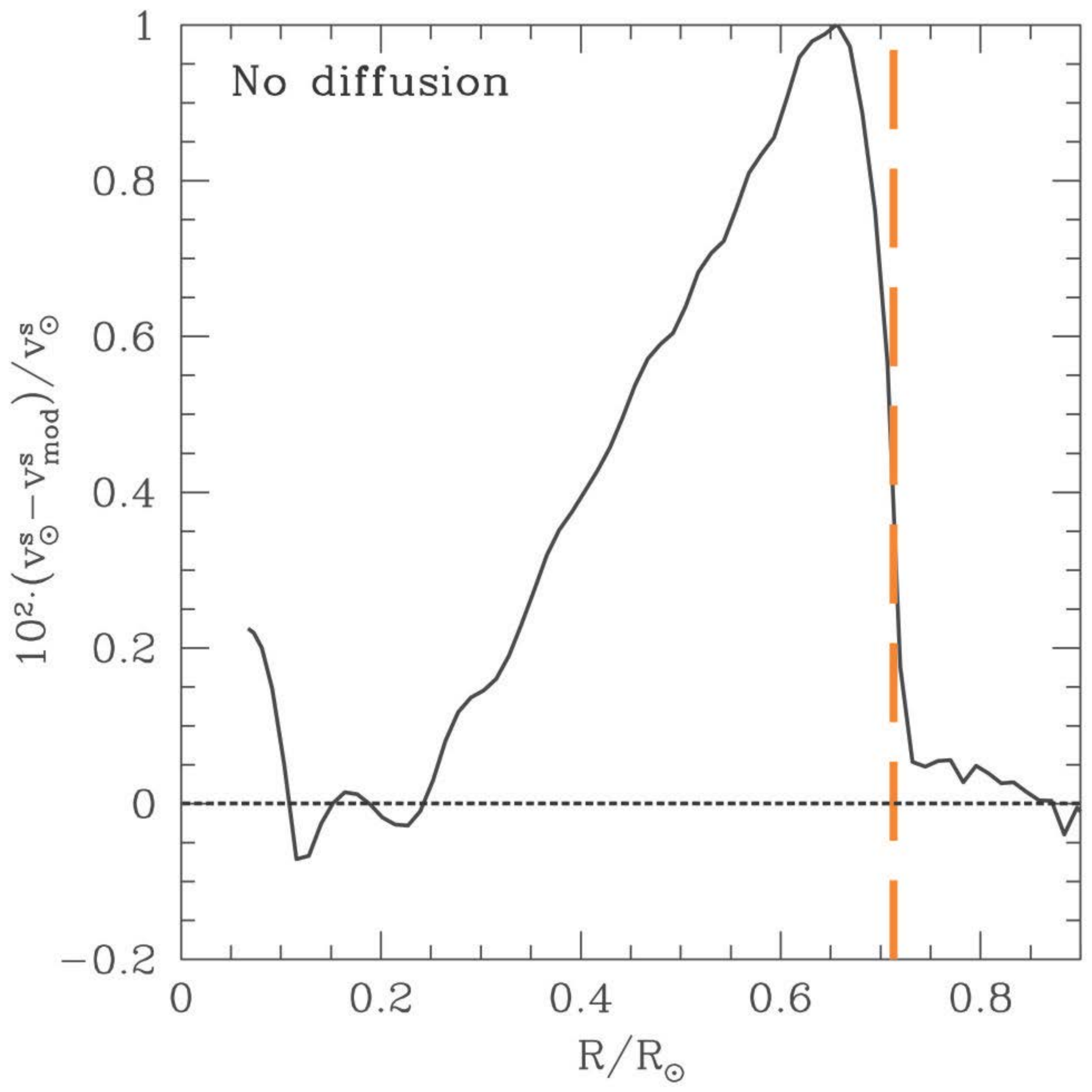

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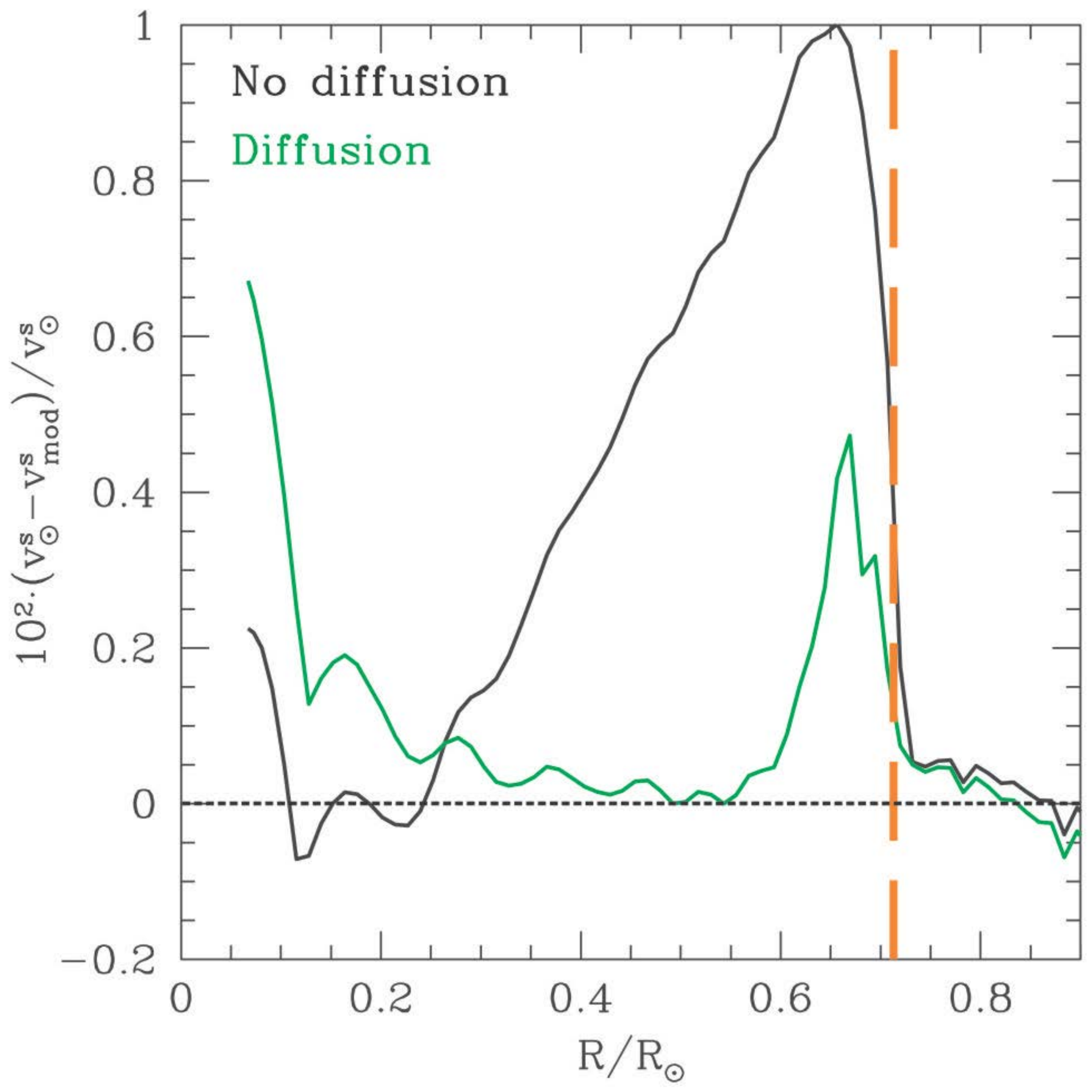

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- DG_j: Gravitational Settling Diffusion
- T_j: Rotation-Induced Mixing

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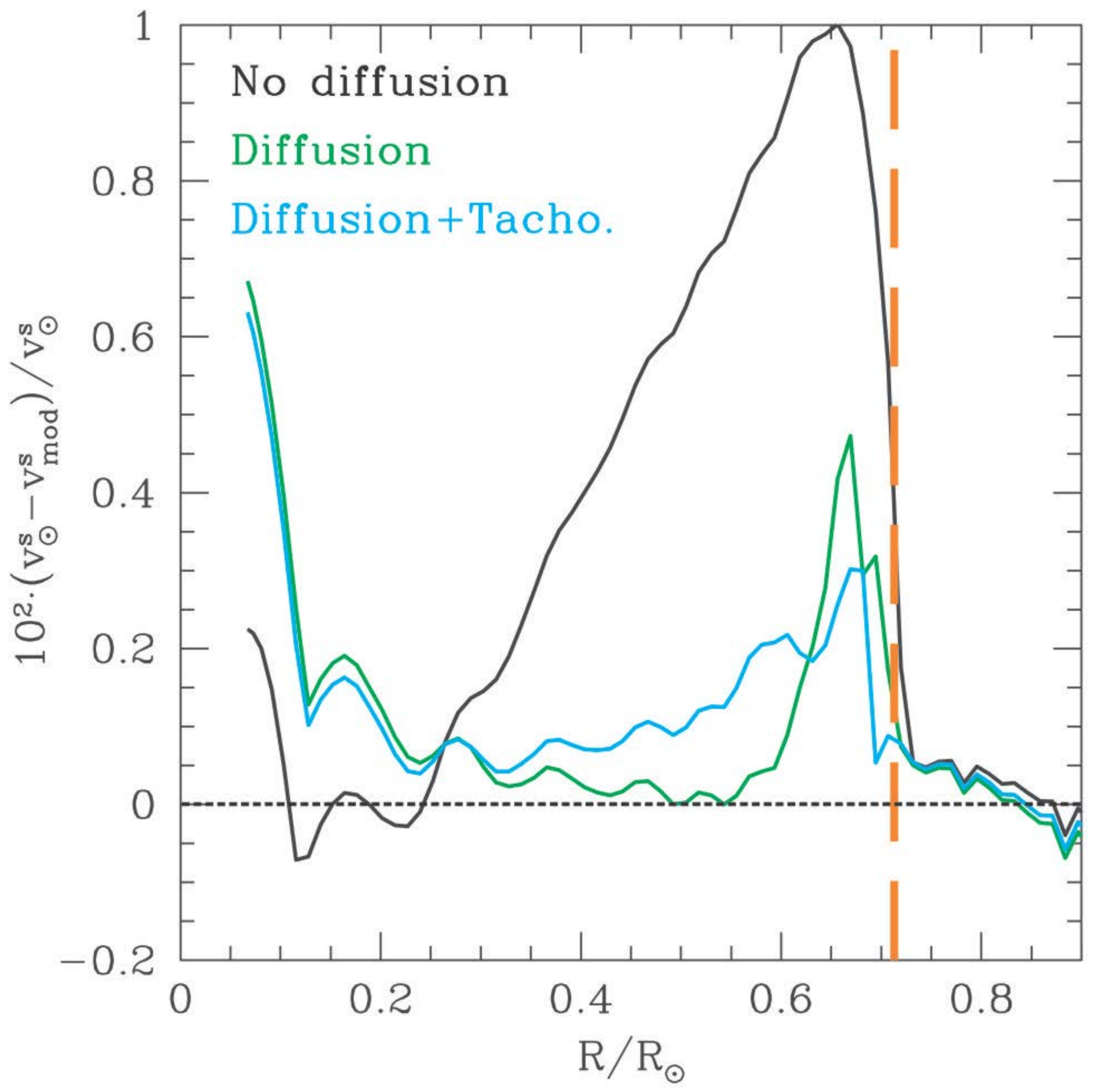

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OPAL2005

(Rogers & Nayfonov, 2002)

Physical picture based on ACTEX
Relativistic effects included

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FreeEos

(Cassisi+, 2003)

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OPAL 1996
(Iglesias & Rogers,1996)

OP 2005
(Seaton&Badnell 2004
Badnell+2005)

OPLIB
(Colgan+2016)

Reliability/Accuracy of SSM

The precision of input physics:
Nuclear reaction rate

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Reaction	S_0 (Mev b)	$\Delta S_0/S_0$	Reference
$p(p,e^+\nu)D$	$4.01 \cdot 10^{-25}$	1	Adelberger+2011
$D(p,\gamma)\ ^3He$	$2.14 \cdot 10^{-7}$	8	Adelberger+2011
$^3He(p,e^+\nu)\ ^4He$	$8.60 \cdot 10^{-20}$	30.2	Adelberger+2011
$^3He(\ ^3He,2p)\ ^4He$	5.21	5.2	Adelberger+2011
$^3He(\ ^4He,\gamma)\ ^7Be$	$5.6 \cdot 10^{-4}$	5.2	Adelberger+2011
$^7Be(p,\gamma)\ ^8B$	$2.13 \cdot 10^{-5}$	4.7	Zhang+2015
$^{12}C(p,\gamma)^{13}N$	$1.34 \cdot 10^{-3}$	15.6	Adelberger+2011
$^{13}C(p,\gamma)^{14}N$	$7.60 \cdot 10^{-3}$	13.2	Adelberger+2011
$^{14}N(p,\gamma)^{15}O$	$1.66 \cdot 10^{-3}$	7.2	Marta+2011
$^{15}N(p,\gamma)^{16}O$	$3.60 \cdot 10^{-2}$	16.7	Adelberger+2011
$^{15}N(p,\ ^4He)^{12}C$	73.00	6.8	Adelberger+2011
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The "solar abundance" problem

Constructing an initial model

Chemical homogeneous sphere

The “solar abundance” problem

SSMs depend on the adopted initial chemical composition

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SSMs depend on the adopted initial chemical composition

Photospheric Abundances

Current solar composition at the surface

$$\varepsilon(el) = log\left[\frac{n(el)}{n(H)}\right] + 12$$

Meteoritic Abundances

Protosolar nebula composition

$$N(el) = \frac{n(el)}{n(Si)} \times 10^6$$

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Ne, Ar from solar corona/wind

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He abundance undetermined in both the environments!

The “solar abundance” problem

Abundances from different sources are combined to obtain a complete compilation

$$\varepsilon(el) = log(N(el)) + R$$

Remapping factor

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Remapping factor

$$\frac{x_k}{X} = 10^{\varepsilon(k)-12}\frac{A_k}{A_H}$$

$$\frac{Z}{X} = \sum_k \frac{x_k}{X} = \sum_k 10^{\varepsilon(k)-12}\frac{A_k}{A_H}$$

$$z_k = \frac{x_k}{Z} = \frac{x_k}{X}\left(\frac{Z}{X}\right)^{-1}$$

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Free parameter:
Y and Z (X=1-Y-Z)

The "solar abundance" problem

HYPOTHESES:

$$\frac{z_k}{z_j} = costant$$

The "solar abundance" problem

<u>HYPOTHESES:</u>

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Photospheric solar abundance did not change

The "solar abundance" problem

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Diffusion is a democratic process

(Piersanti+2007)

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Tables of opacity and EOS with constant mixture and variable total Z and Y

The "solar abundance" problem

HYPOTHESES:

$$\frac{z_k}{z_j} = costant$$

Photospheric solar abundance did not change

Diffusion is a democratic process

(Piersanti+2007)

…but in the
innermost zones
of the Sun
$^{12}C \rightarrow {}^{14}N$ …

Tables of opacity and … ant mixture and variable To…

The “solar abundance” problem

“Old” photospheric abundances

2000

“New” photospheric abundances

The "solar abundance" problem

"Old" photospheric abundances

2000

"New" photospheric abundances

AG89	Anders & Grevesse 1989
GN93	Grevesse & Noels 1993
GS98	Grevesse & Sauvals 1993

"High metallicity" mixtures

$$\left(\frac{Z}{X}\right)_\odot = \begin{matrix} 0.02669 \\ 0.02439 \\ 0.02292 \end{matrix}$$

The "solar abundance" problem

2000

"Old" photospheric abundances	
AG89	Anders & Grevesse 1989
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"High metallicity" mixtures

$$\left(\frac{Z}{X}\right)_{\odot} = 0.02669,\ 0.02439,\ 0.02292$$

"New" photospheric abundances	
Lo03	Lodders 2003
AGSS09	Asplund+2009
Lo09	Lodders+2009
PLJ14	Palme+2014

"Low metallicity" mixtures

$$\left(\frac{Z}{X}\right)_{\odot} = 0.01762,\ 0.01780,\ 0.01903,\ 0.01995$$

The "solar abundance" problem

"Old" photospheric abundances

2000

"New" photospheric abundances

AG89 Anders & Grevesse 1989

GN93 Grevesse

GS98 Grevesse

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und+2009

ders+2009

e+2014

	Y_s	$R^{bcz}/R_\odot$
Lo03	0.234±0.007	0.725±0.006
AGSS09	0.232±0.006	0.722±0.005
Lo09	0.234±0.006	0.722±0.005
PLJ14	0.241±0.005	0.721±0.005
Solar	*0.2485±0.0034*	*0.713±0.001*

"High metallicity" r

tures

$\left(\frac{Z}{X}\right)_\odot =$ 0.02439, 0.02292

$\left(\frac{Z}{X}\right)_\odot =$ .01762, 0.01780, 0.01903, 0.01995

Constraints from neutrinos?

Flux	Exp.	Measured	Source
Φ_{pp}	10	6.1 (1±0.1)	BX
Φ_{pep}	8	1.27 (1±0:17)	BX
Φ_{hep}	3	8 (1±2)	BX
Φ_{Be}	9	4.99 (1±0.03)	BX
Φ_{B}	6	5.39 (1±0.015)	SK+SNO
Φ_{CNO}	8	$7.0^{+3.0}_{-2.0}$	BX

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Φ_{hep}	3	8 (1±2)	BX	8.15 (1±0.30)	8.28 (1±0.30)
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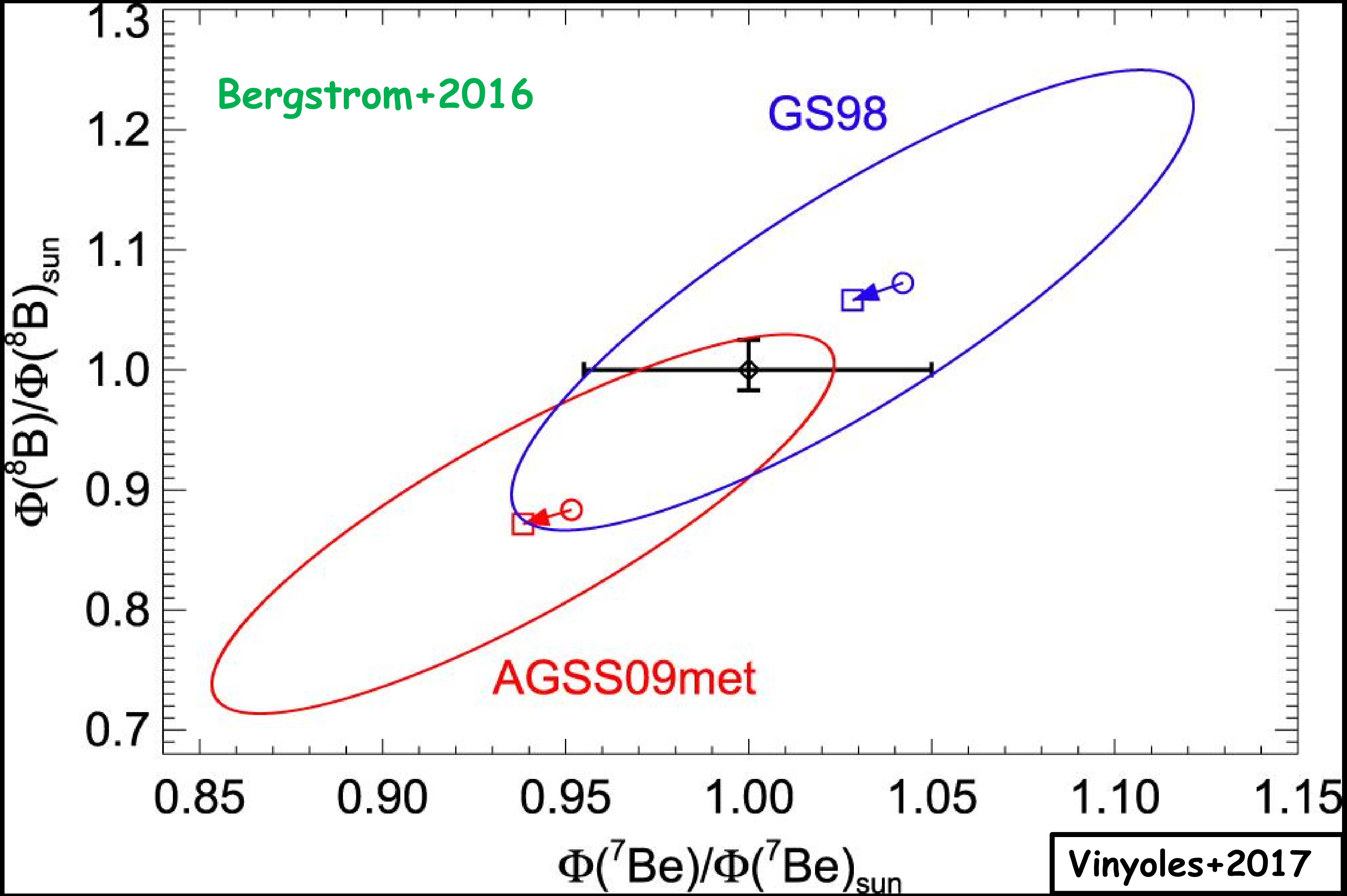

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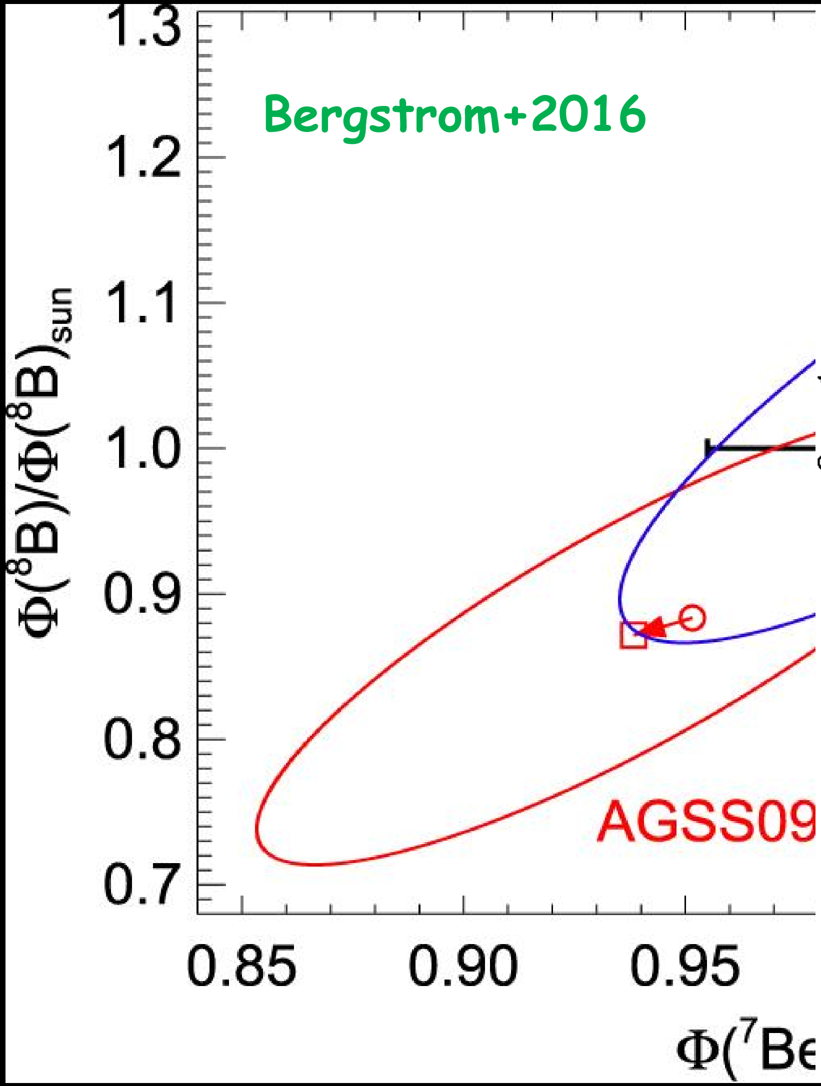

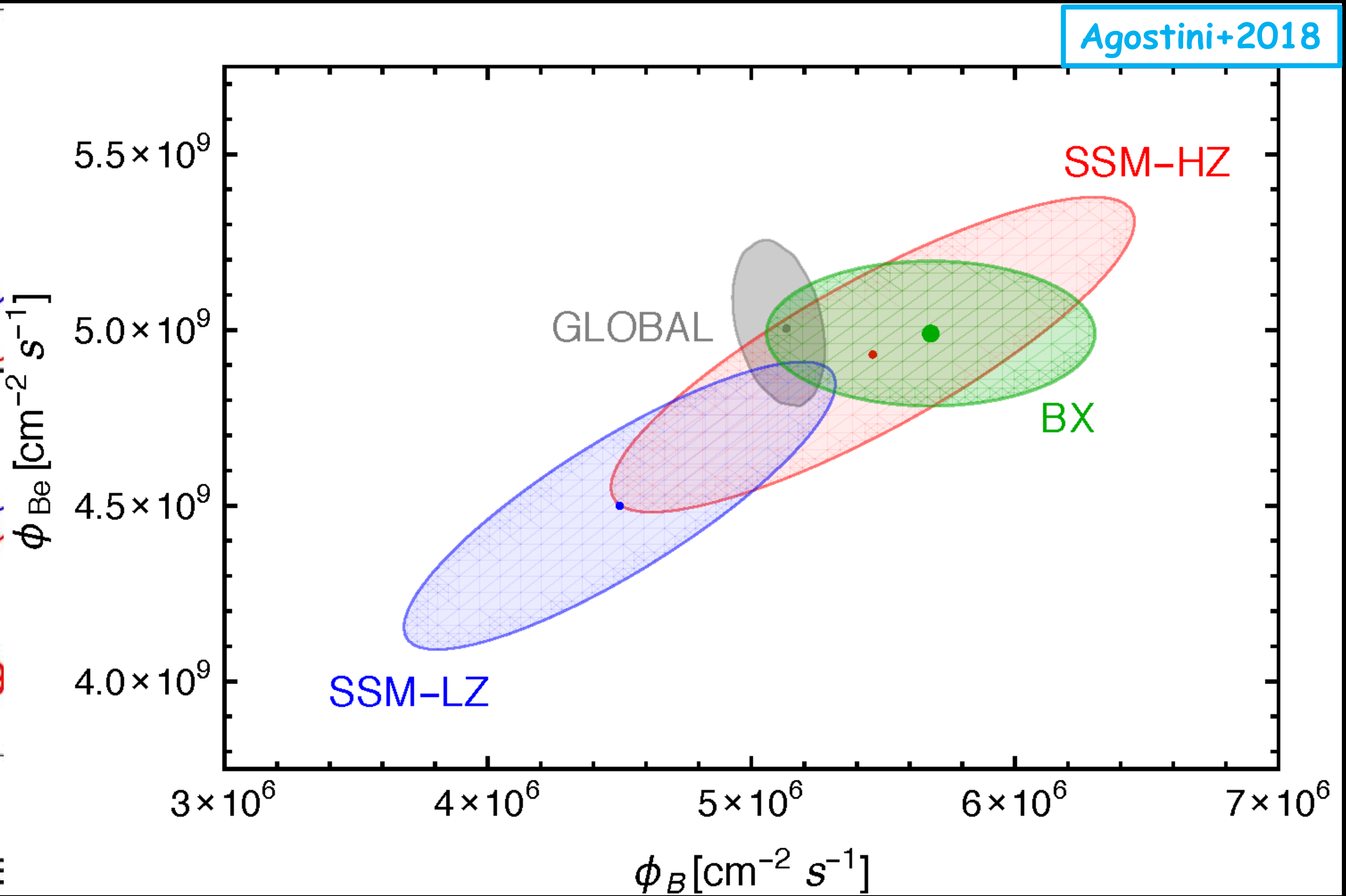

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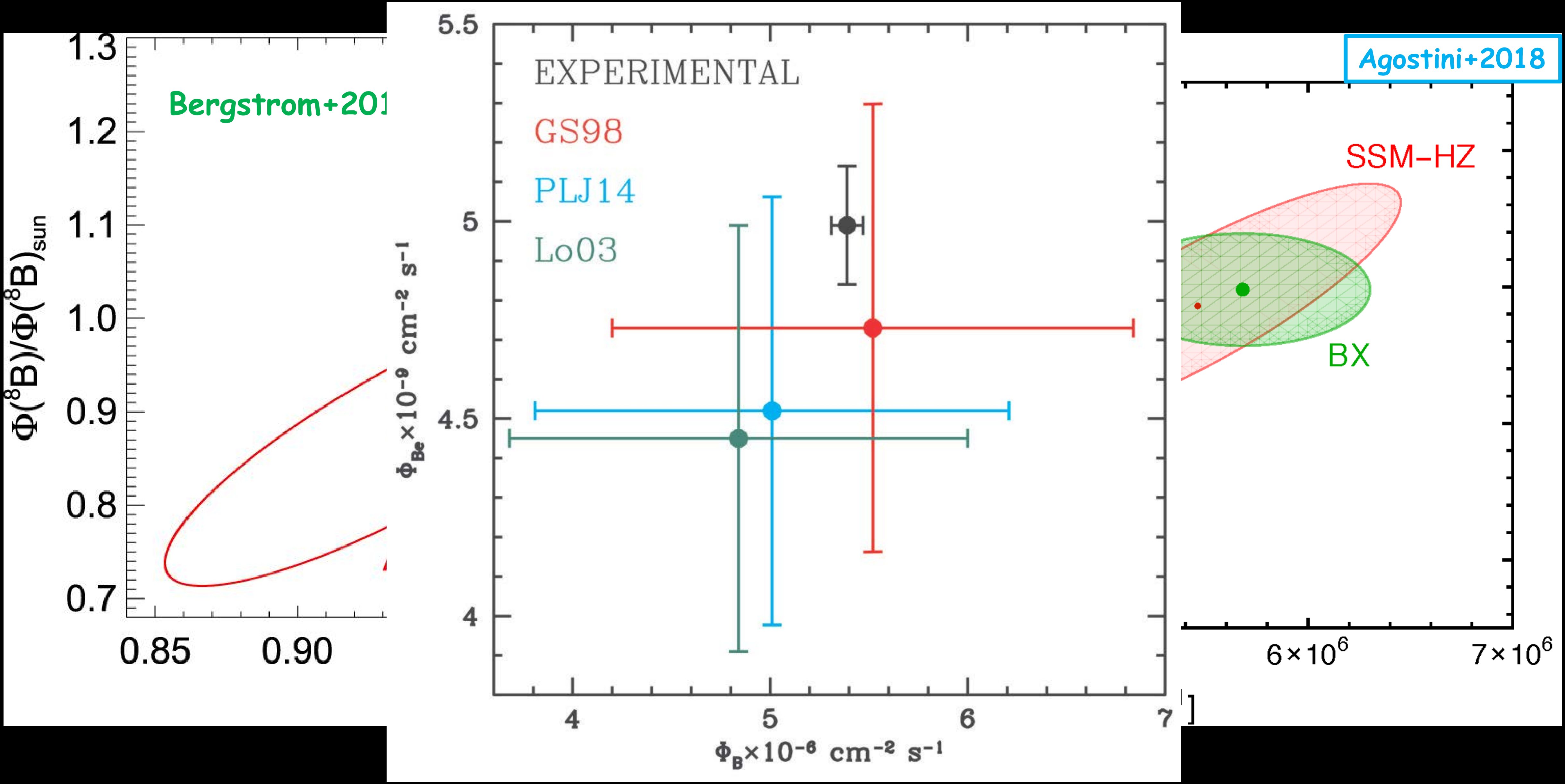

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$$\frac{dL}{dm} = \varepsilon_{nuc} + \varepsilon_{grav} - \varepsilon_{\nu}$$

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$$\Phi_{pp} + 0.946\Phi_{CNO} = 6.003\,(1 \pm 0.2\%) \times 10^{10} cm^{-2} s^{-1}$$

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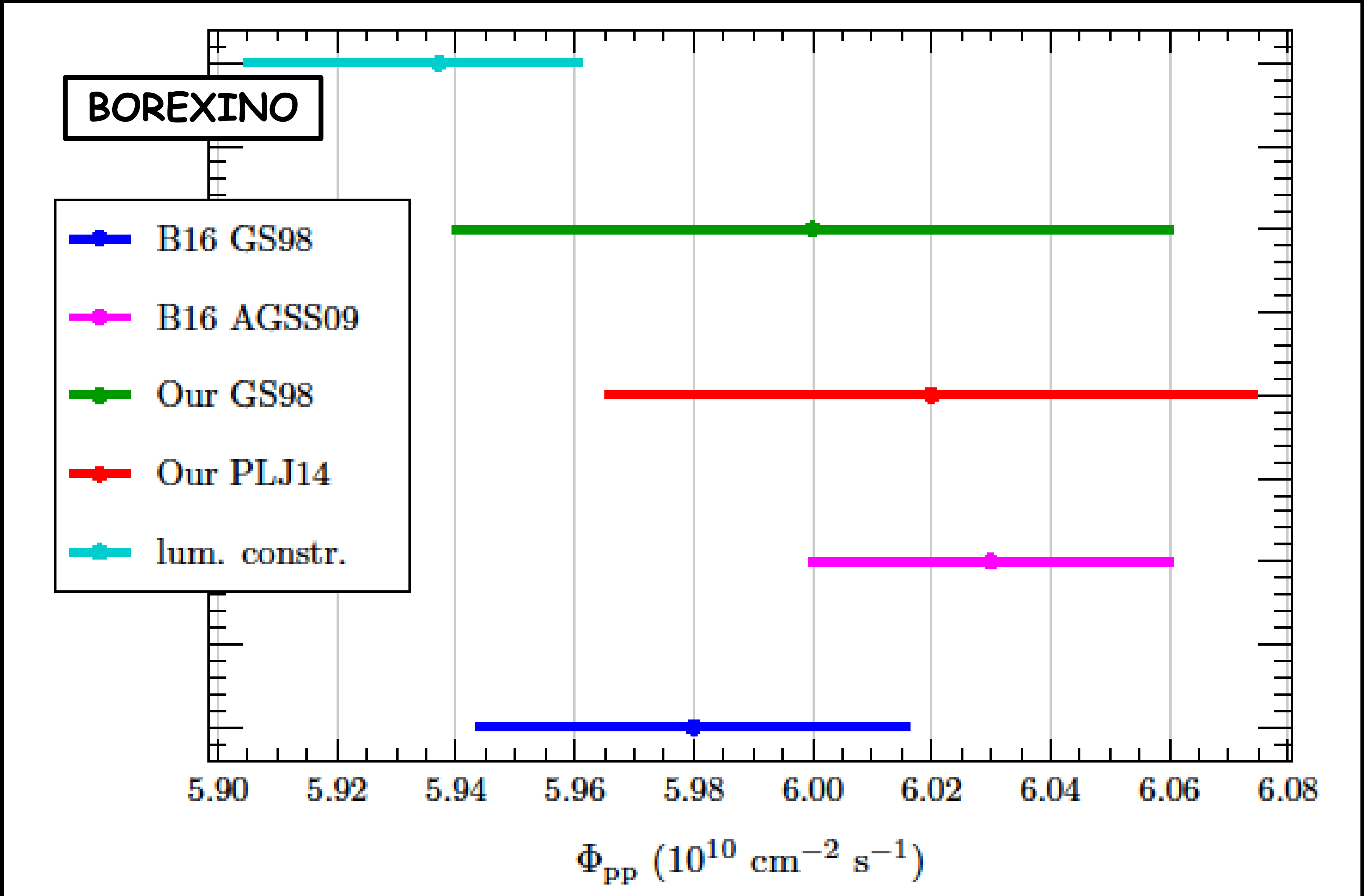

The metallicity at the Sun center

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Source	Z_C	Z_s
GS98	0.02020	0.0171
PLJ14	0.01751	0.0149

Conclusions

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Reaction rates $S_{3,4}$ $S_{7,1}$ $S_{14,1}$ → ^{8}B, ^{7}Be and CNO's ν-fluxes

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If Φ_{CNO} has an uncertainty of ~10% or lower CNO abundances can be checked!

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Opacity ➡ Temperature

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$$\frac{\Phi(^{13}\mathrm{N}+^{15}\mathrm{O})}{\Phi^{\mathrm{SSM}}(^{13}\mathrm{N}+^{15}\mathrm{O})} = \frac{X(C+N)}{X^{\mathrm{SSM}}(C+N)}\left[\frac{\Phi(^{8}\mathrm{B})}{\Phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.828} \times$$
$$[1 \pm 0.03(\mathrm{exp}) \pm 0.026(\mathrm{env}) \pm 0.035(\mathrm{LMA}) \pm 0.10(\mathrm{nucl})]\,.$$

Haxton_2008

THANK YOU FOR YOUR ATTENTION