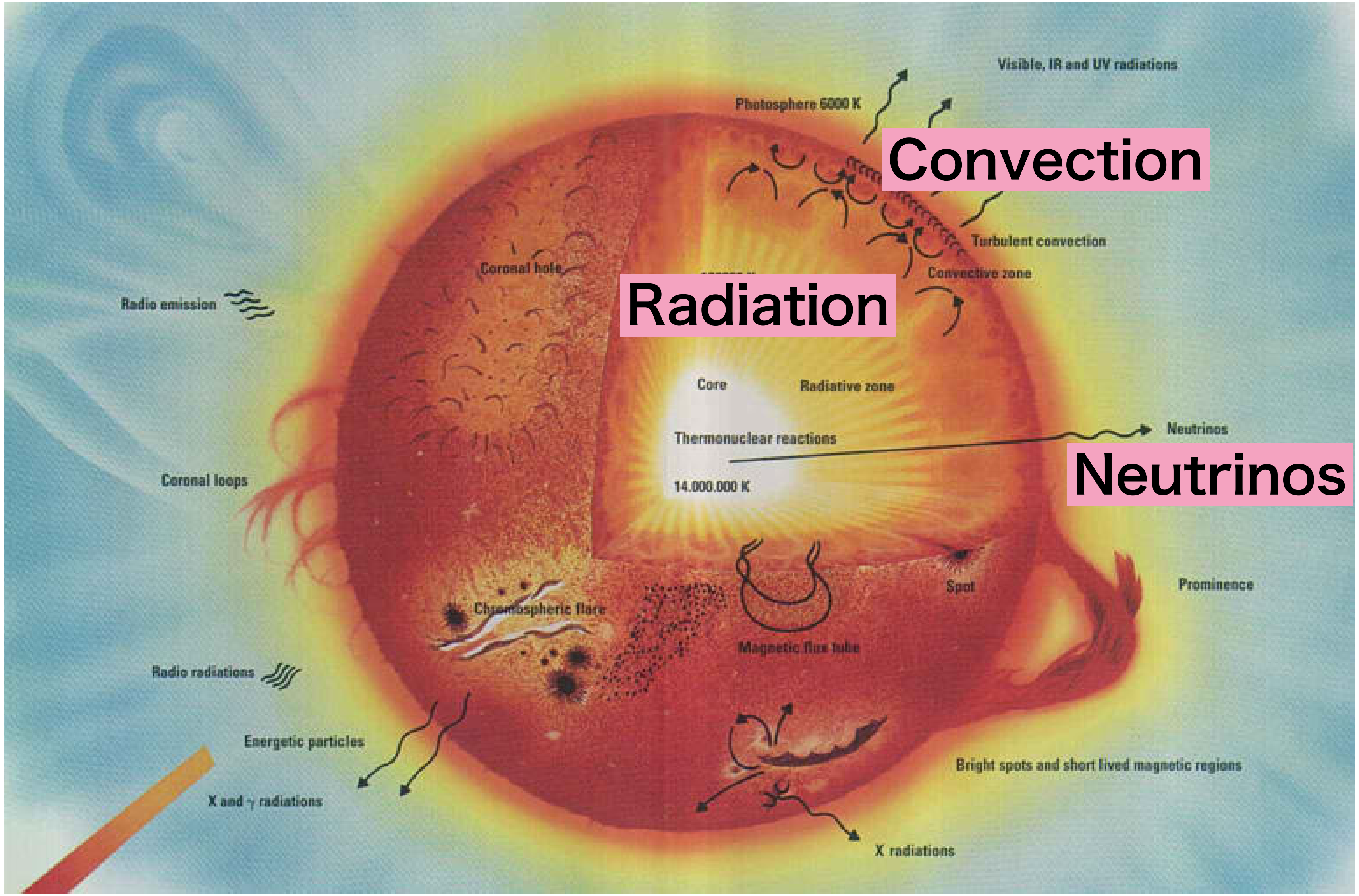
Helioseismology and Solar Neutrinos

H. Shibahashi

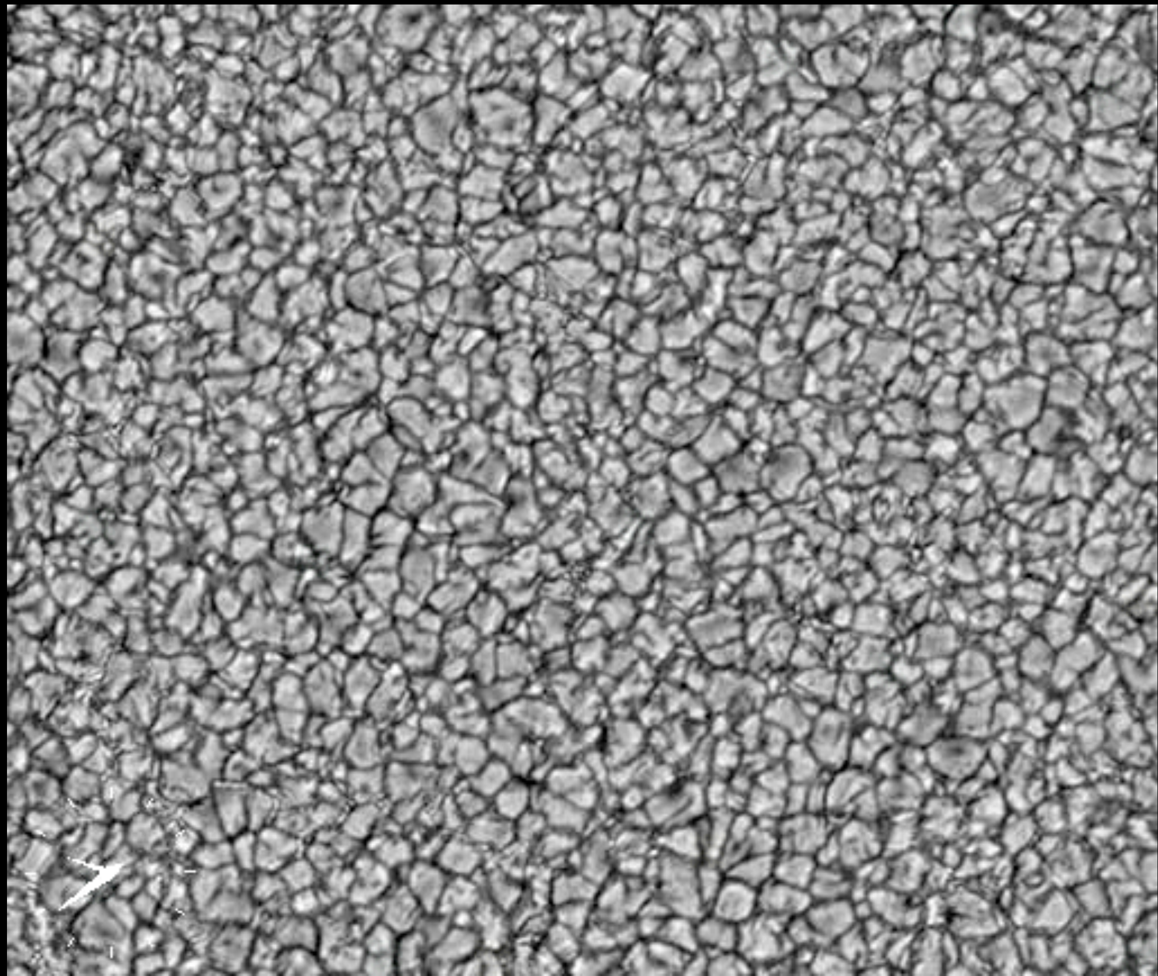
(University of Tokyo)

Outline

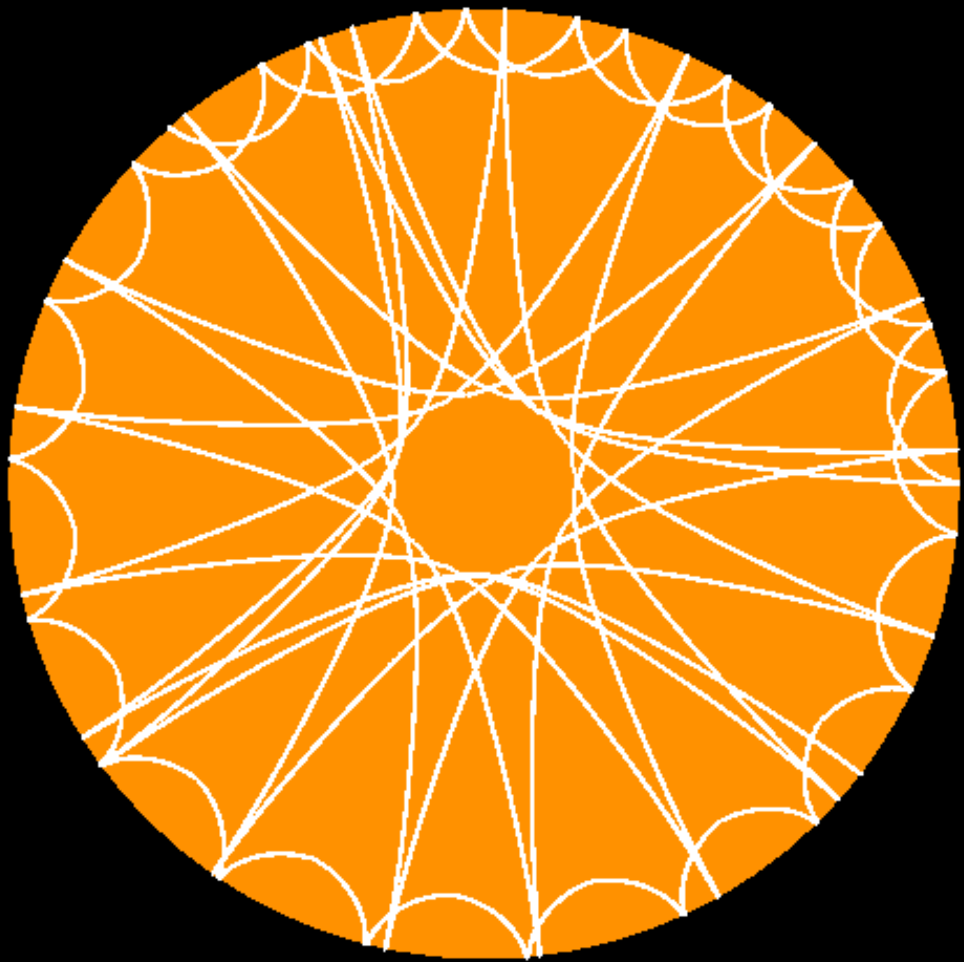
- Helioseismology
- Solar Evolutionary Model
- Solar Seismic Model
- Impact of the New Solar Abundance
- Solar Neutrino Problems: revisited


Visible, IR and UV radiations
Photosphere 6000 K
Convection
Turbulent convection
Convective zone
Coronal hole
Radiation
Radio emission
Core
Radiative zone
Thermonuclear reactions
14.000.000 K
Neutrinos
Neutrinos
Coronal loops
Spot
Prominence
Chromospheric flare
Magnetic flux tube
Radio radiations
Energetic particles
Bright spots and short lived magnetic regions
X and γ radiations
X radiations

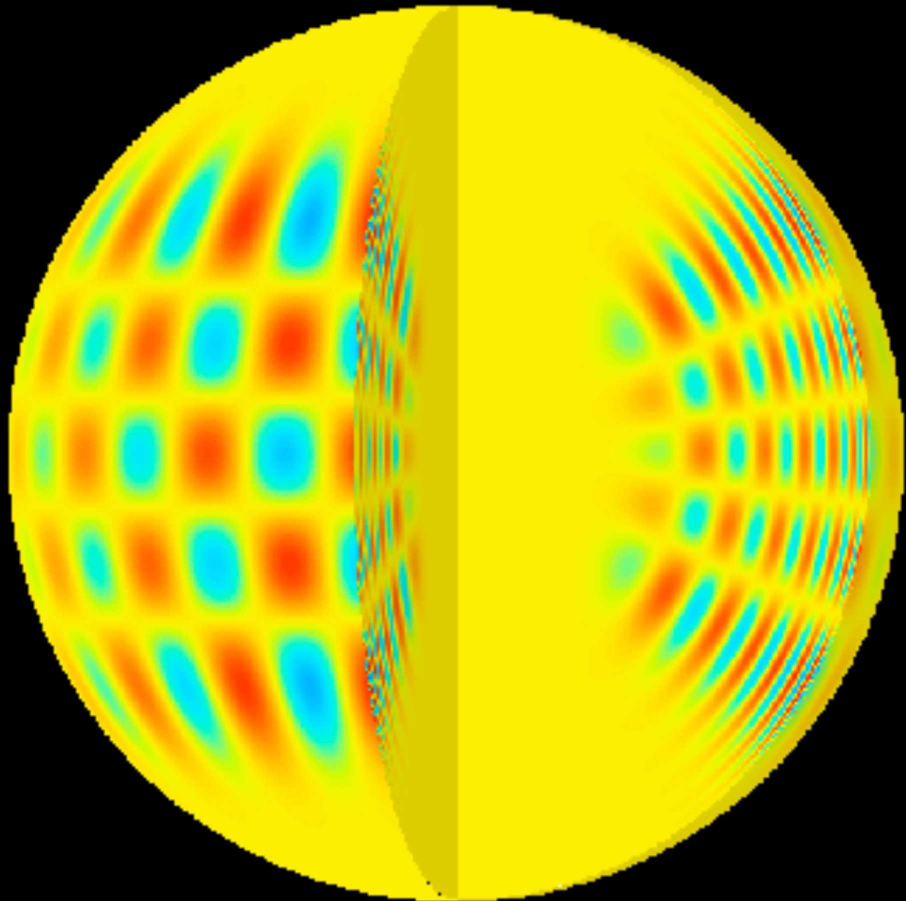
Turbulence generates acoustic noise.

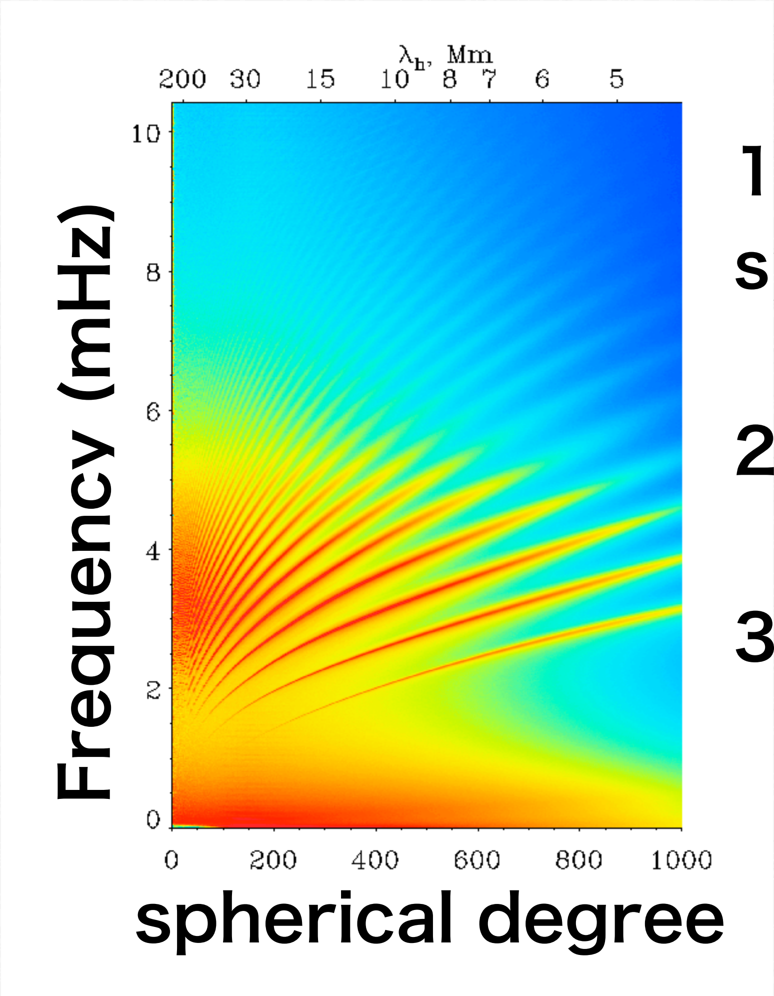


Acoustic waves propagate in the Sun.



Only the waves resonating the cavity survive as eigenoscillations.





1. oscillation pattern:
spherical harmonic analysis

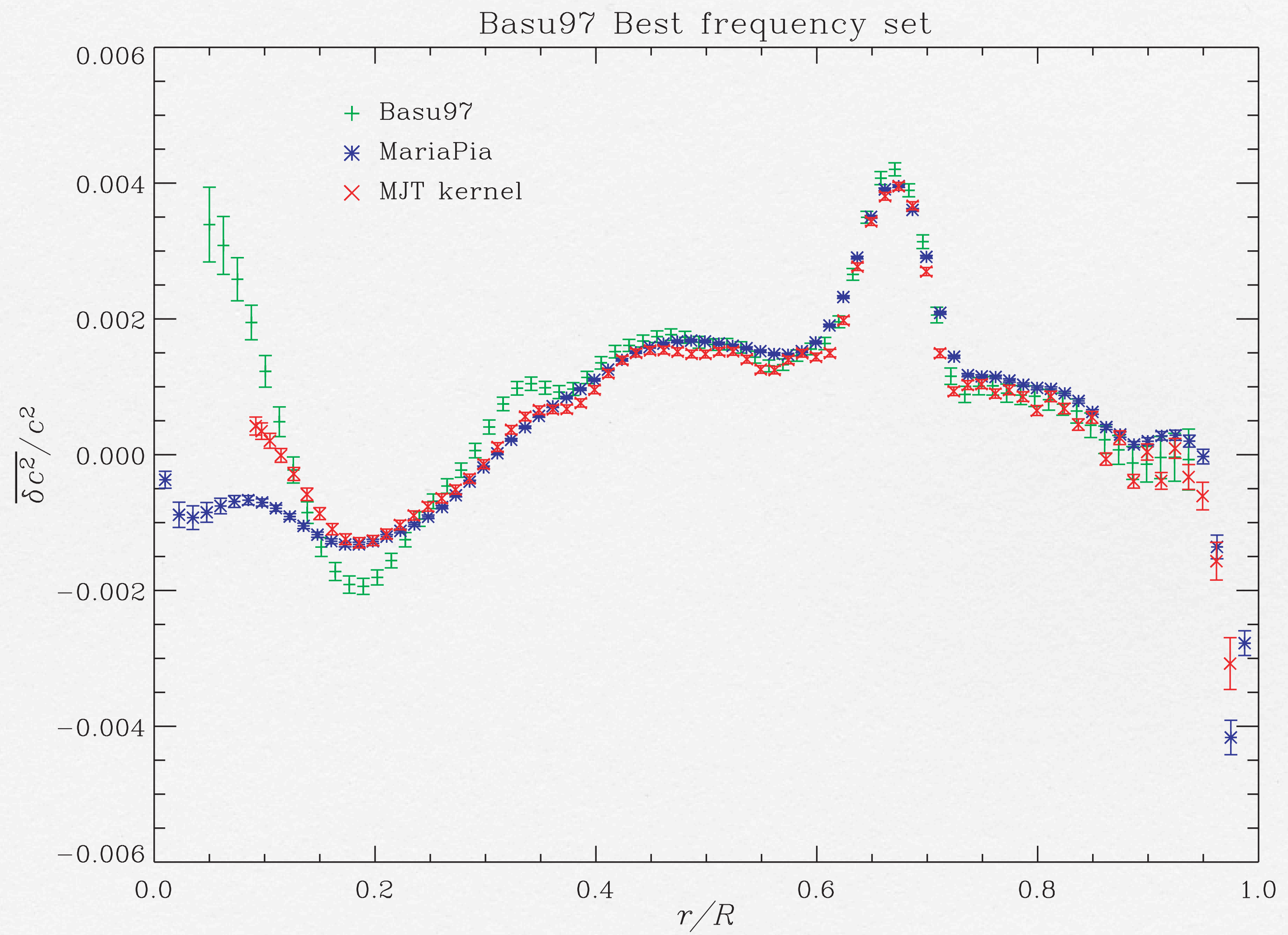
2. FT --> frequency analysis

3. eigenfrequencies

frequency of acoustic mode

=

sound speed / cavity size



Basu97 Best frequency set
Basu97
MariaPia
MJT kernel
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
0.0
0.2
0.4
0.6
0.8
1.0
r/R
$\overline{\delta c^2}/c^2$

Evolutionary Solar Model

Constraints:

Present mass of the Sun : time independent

Present radius of the Sun : treatment of convection

Present luminosity of the Sun : dependent on initial abundance

Present age of the Sun

Chemical abundances in the photosphere (Z/X)

Assumption : standard evolution

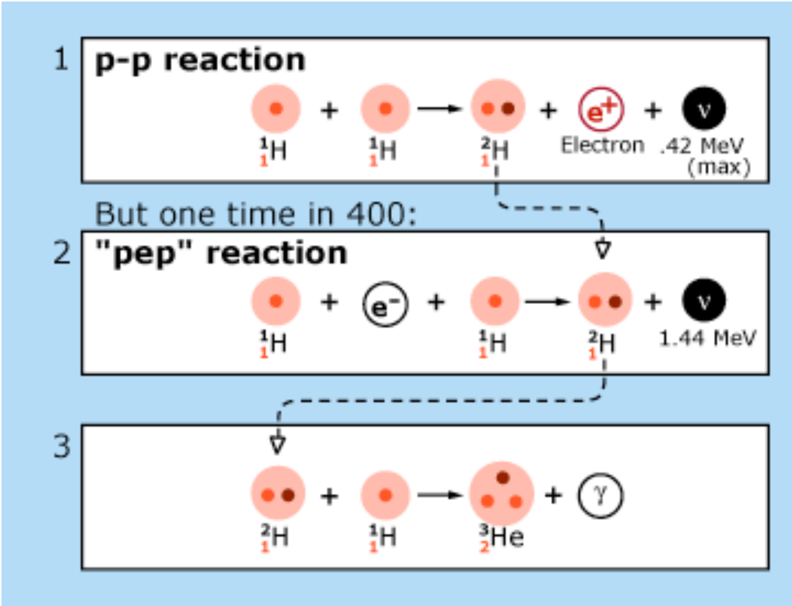
Parameters : mixing length, initial helium abundance

Seismic Solar Model

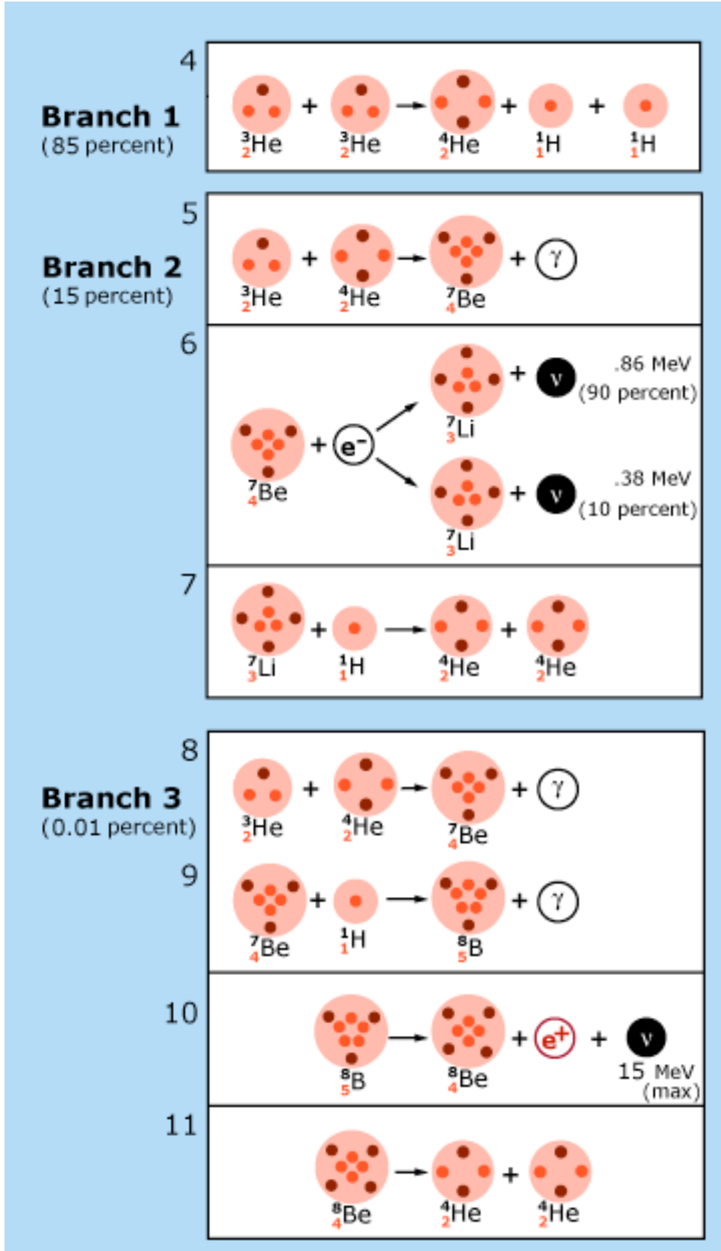
Constraints:
Seismically determined sound speed
Seismically determined depth of the convection zone
Mass, radius, luminosity of the Sun : snapshot
Chemical abundances in the photosphere (Z/X)

Snapshot : No need to follow stellar evolution

X(r) : obtained as a solution



$1\ \mathrm{MeV} = 1.6\ 10^{-13}\ \mathrm{J}$

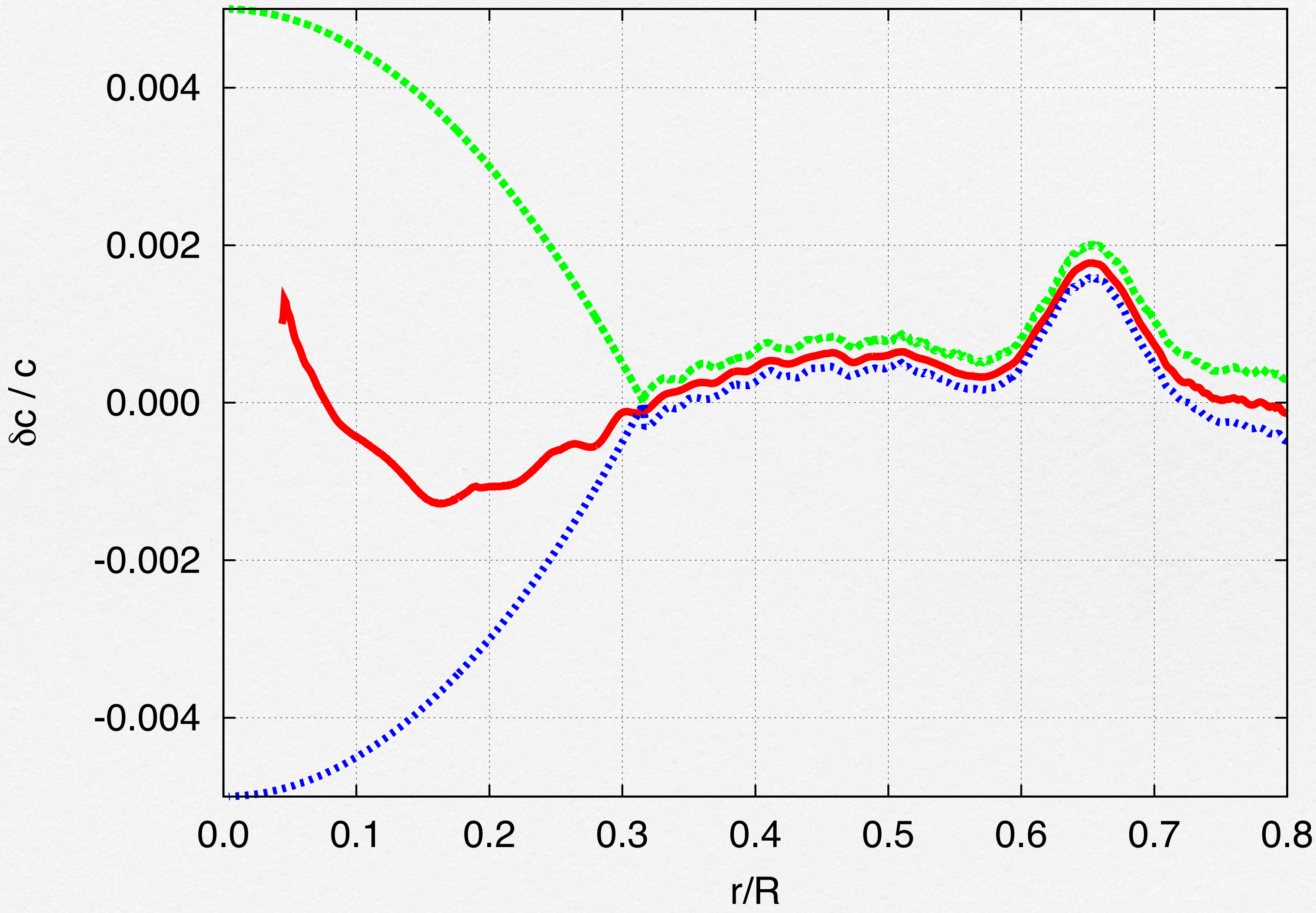


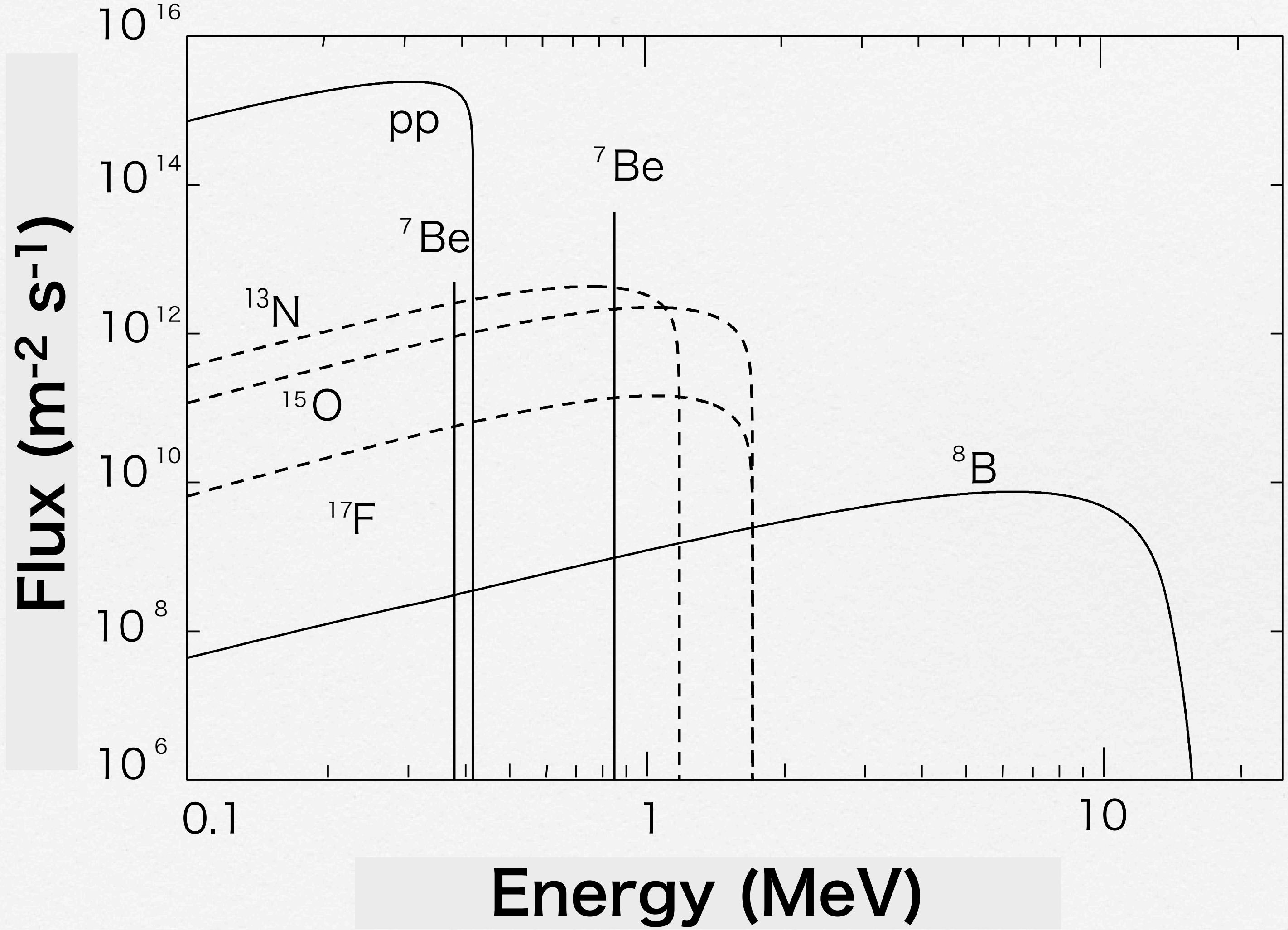
pp-chain

J.N. Bahcall,

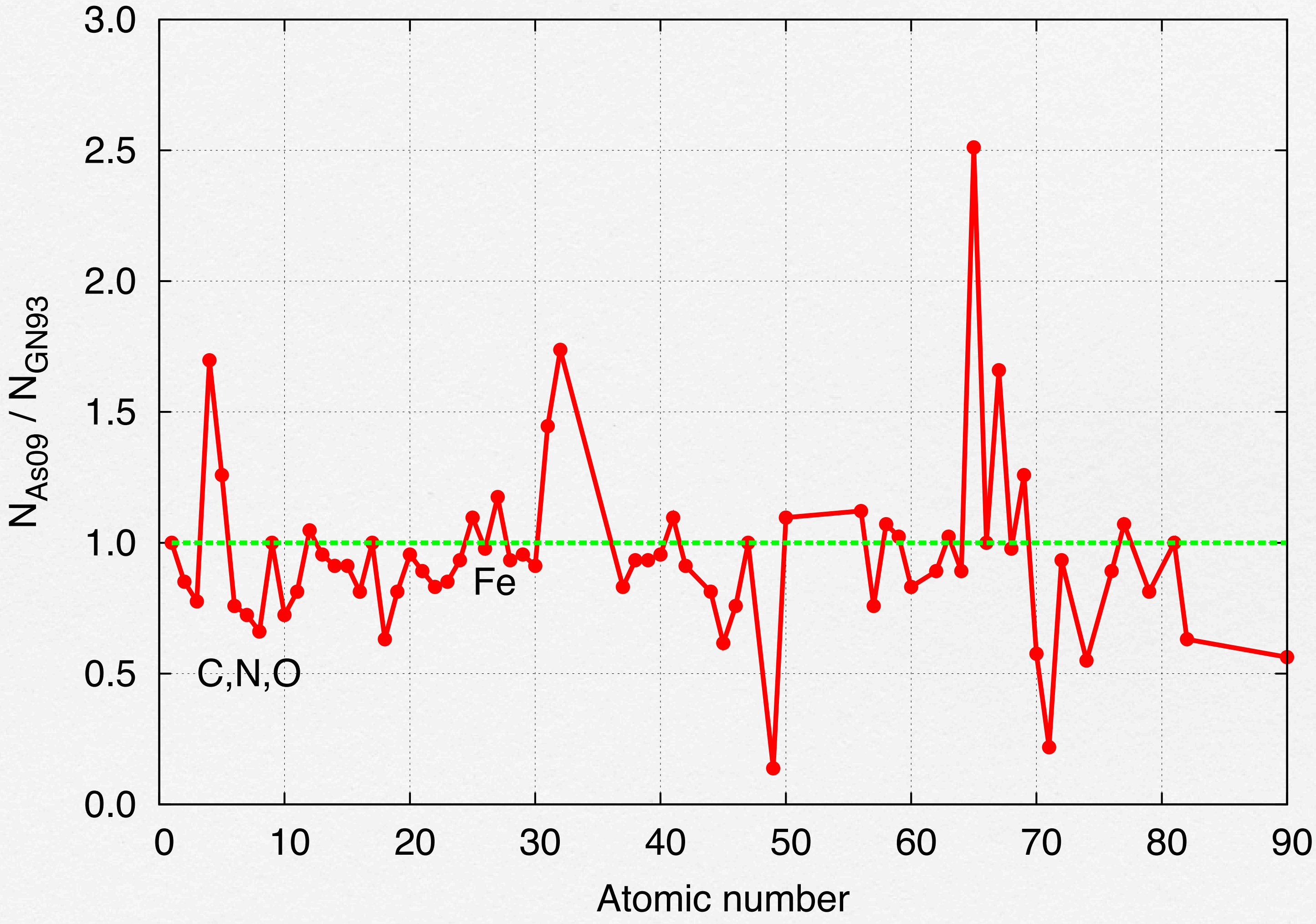
Neutrinos from the Sun, Scientific American,

Volume 221, Number 1, July 1969, pp. 28-37.

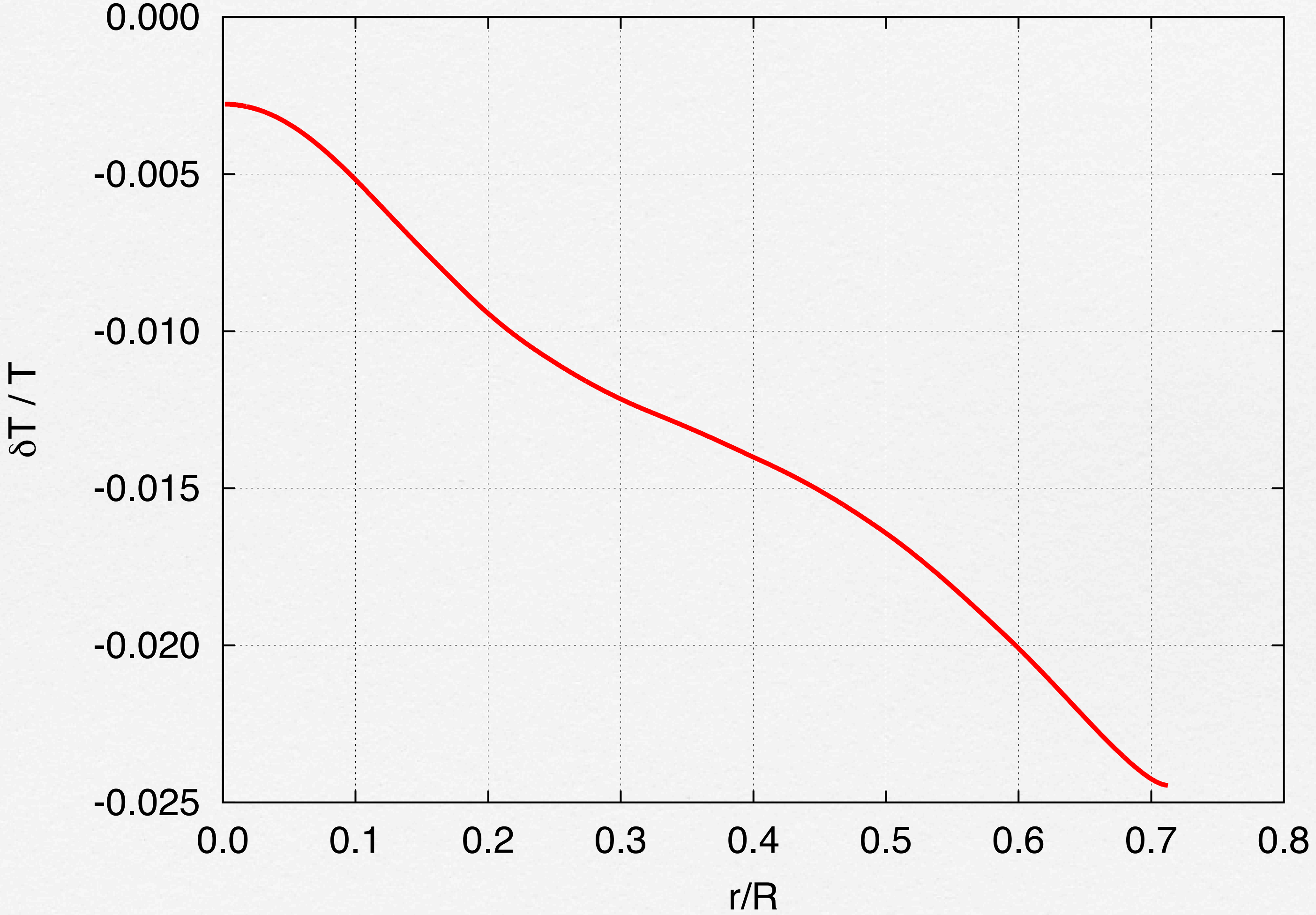

0.004
0.002
0.000
-0.002
-0.004
δc / c
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
r/R


Flux (m-2 s-1)
Energy (MeV)
10 16
10 14
10 12
10 10
10 8
10 6
0.1
1
10
pp
7 Be
7 Be
13N
15O
17F
8B

Impact of the new solar abundances


3.0
2.5
2.0
1.5
1.0
0.5
0.0
N_{As09} / N_{GN93}
0
10
20
30
40
50
60
70
80
90
Atomic number
C,N,O
Fe

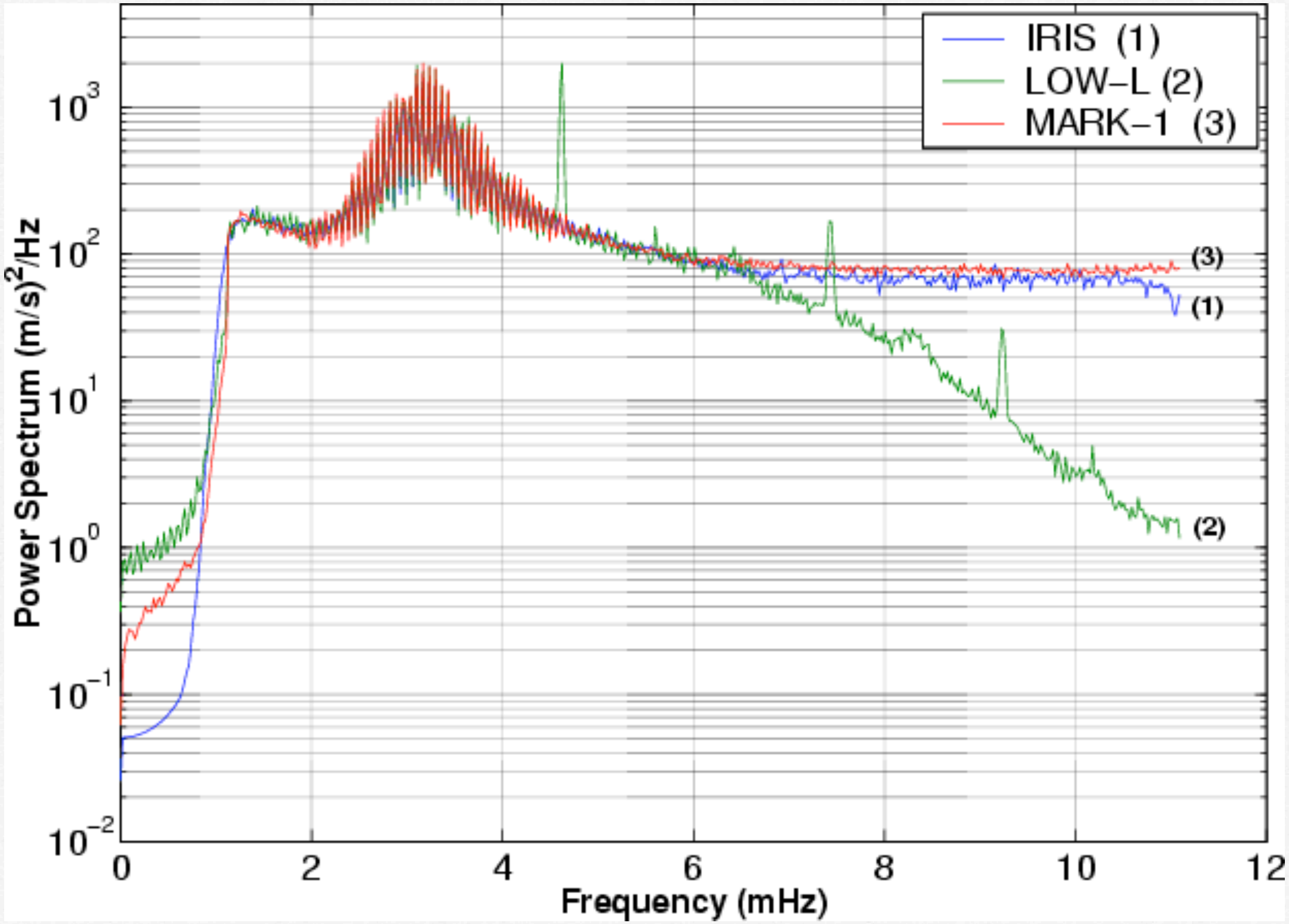
- low metalicity
- low opacity
- low central temperature
- low ^{8}B neutrino flux


0.000
-0.005
-0.010
-0.015
-0.020
-0.025
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
δT / T
r/R

	GN93	As09
pp $(10^{10}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	5.83 ± 0.07	5.85 ± 0.07
pep $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$1.41^{+0.02}_{-0.01}$	$1.44^{+0.01}_{-0.02}$
hep $(10^{3}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$8.19^{+0.24}_{-0.23}$	$8.33^{+0.24}_{-0.23}$
^{7}Be $(10^{9}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	4.56 ± 0.67	$4.46^{+0.67}_{-0.68}$
^{8}B $(10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.22^{+1.30}_{-1.09}$	$3.99^{+1.25}_{-1.08}$
^{13}N $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$1.82^{+0.38}_{-0.33}$	$1.31^{+0.28}_{-0.24}$
^{15}O $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$1.54^{+0.41}_{-0.34}$	$1.10^{+0.29}_{-0.25}$
^{17}F $(10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.19^{+1.24}_{-1.02}$	$2.61^{+0.78}_{-0.65}$

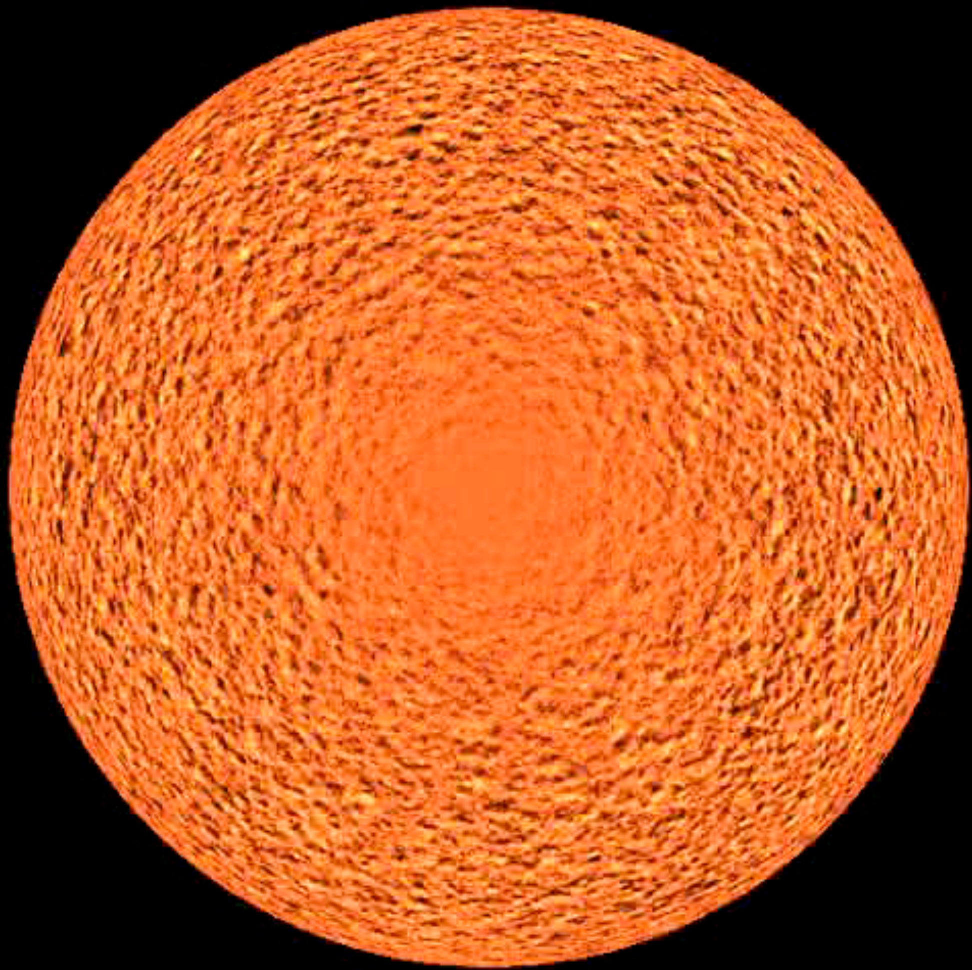
Summary

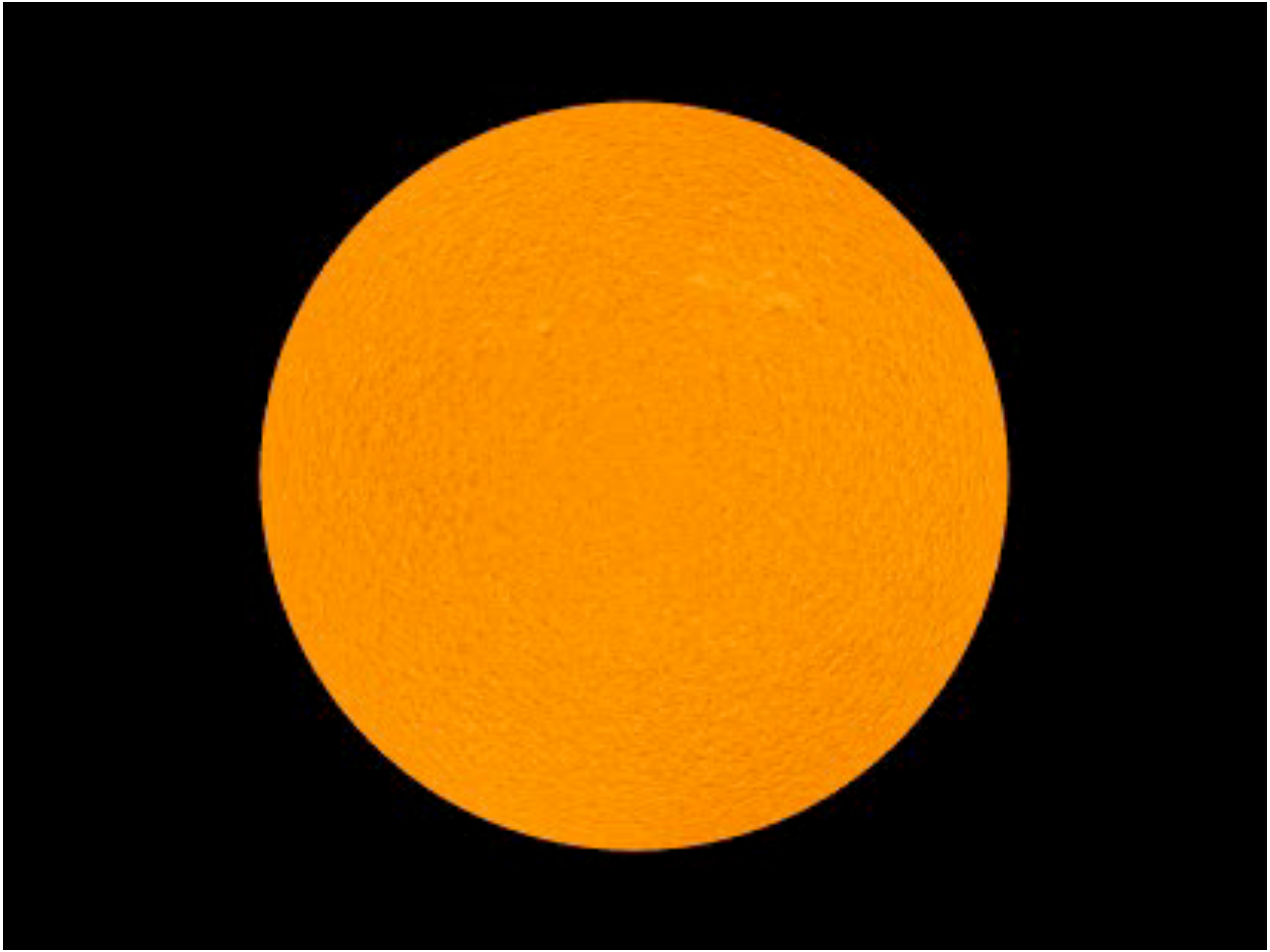
- Helioseismology provides us a new eye to see the invisible interior of the Sun.
- Seismic solar models can be made as a snapshot model without following stellar evolution.
- Newly revised solar abundances breaks harmony with helioseismology.

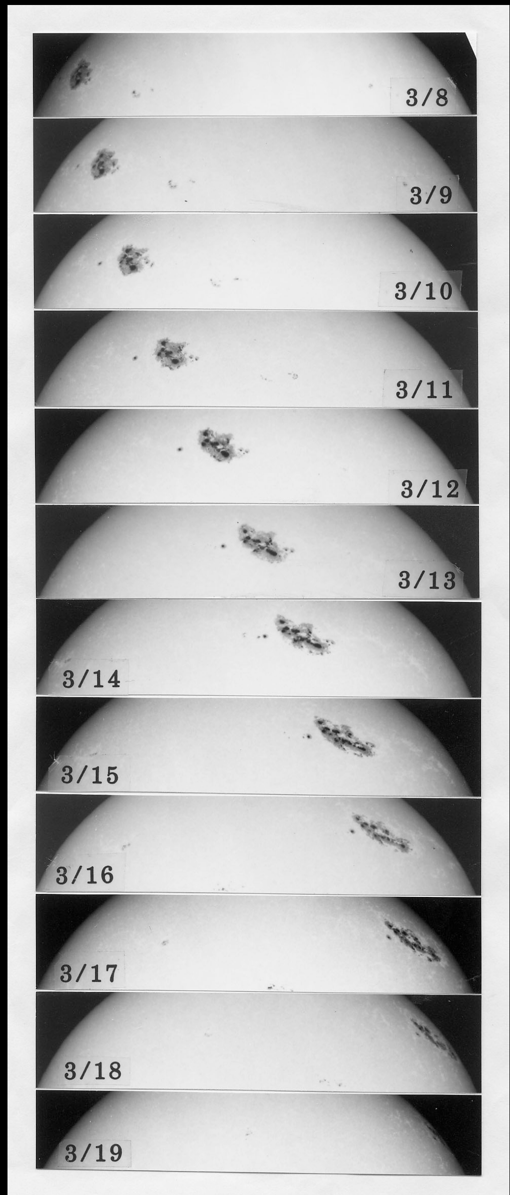


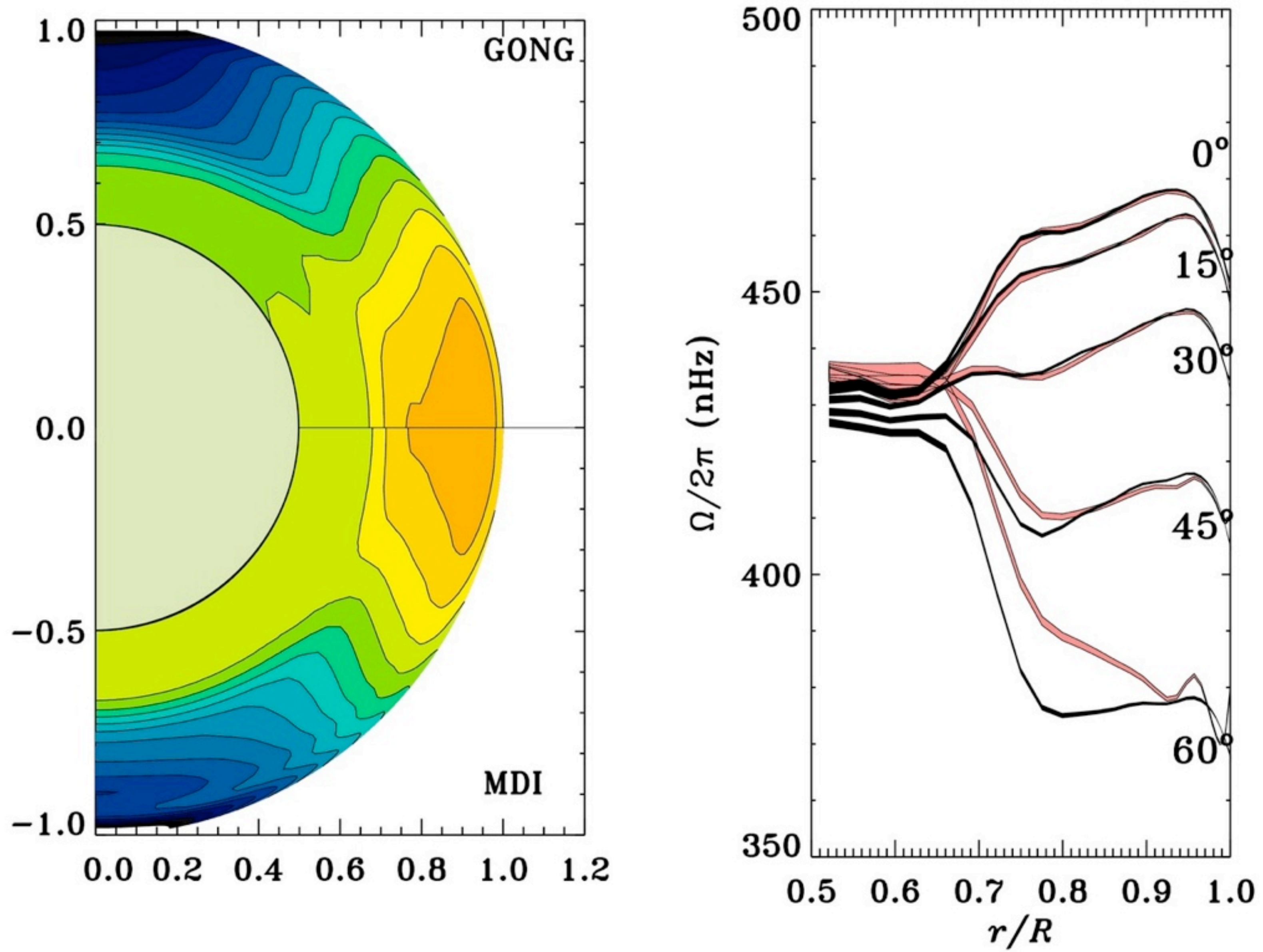
IRIS (1)
LOW–L (2)
MARK–1 (3)
Power Spectrum (m/s)^2/Hz
10^3
10^2
10^1
10^0
10^−1
10^−2
0
2
4
6
8
10
12
Frequency (mHz)
(3)
(1)
(2)

A snapshot of surface velocity field

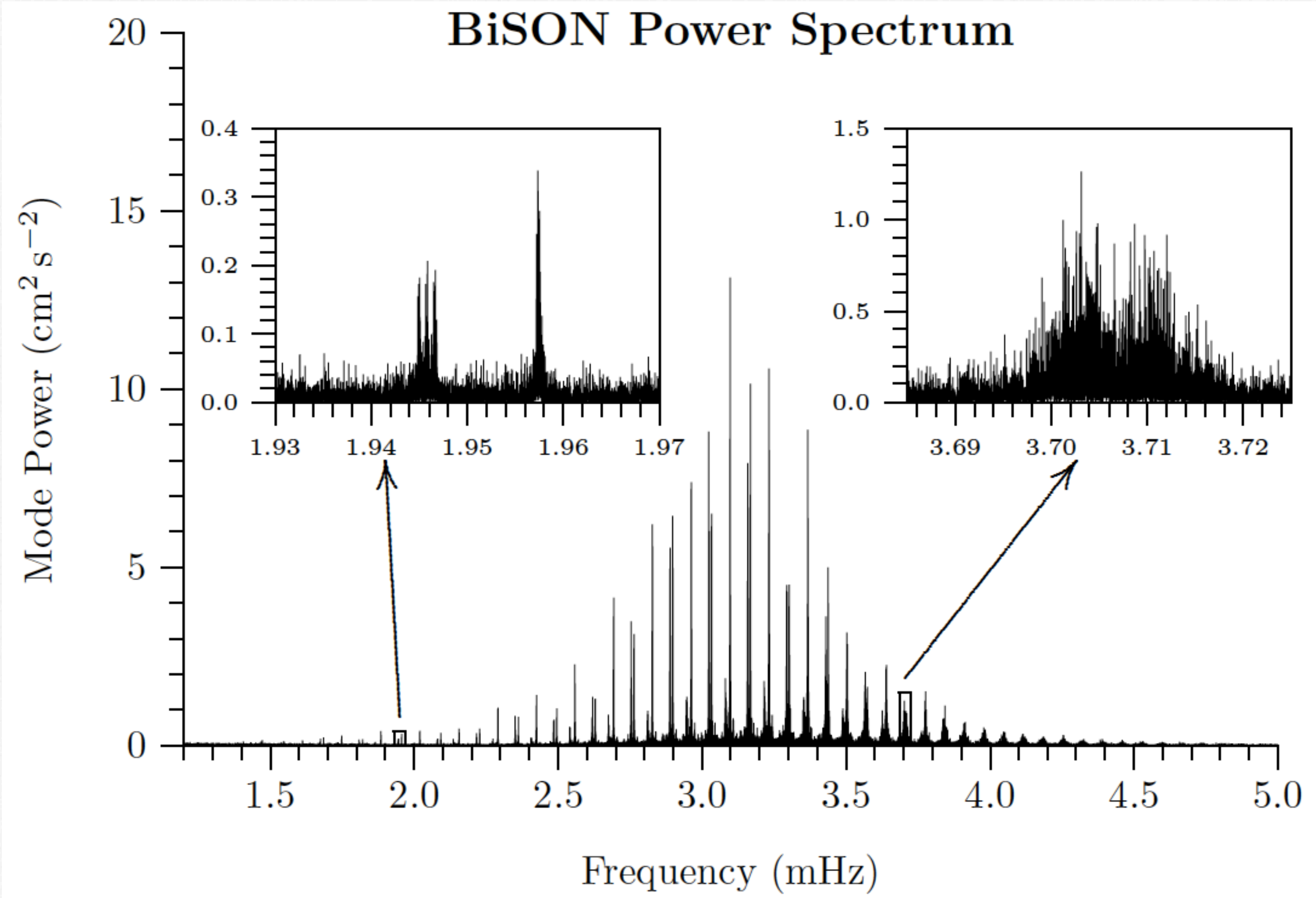


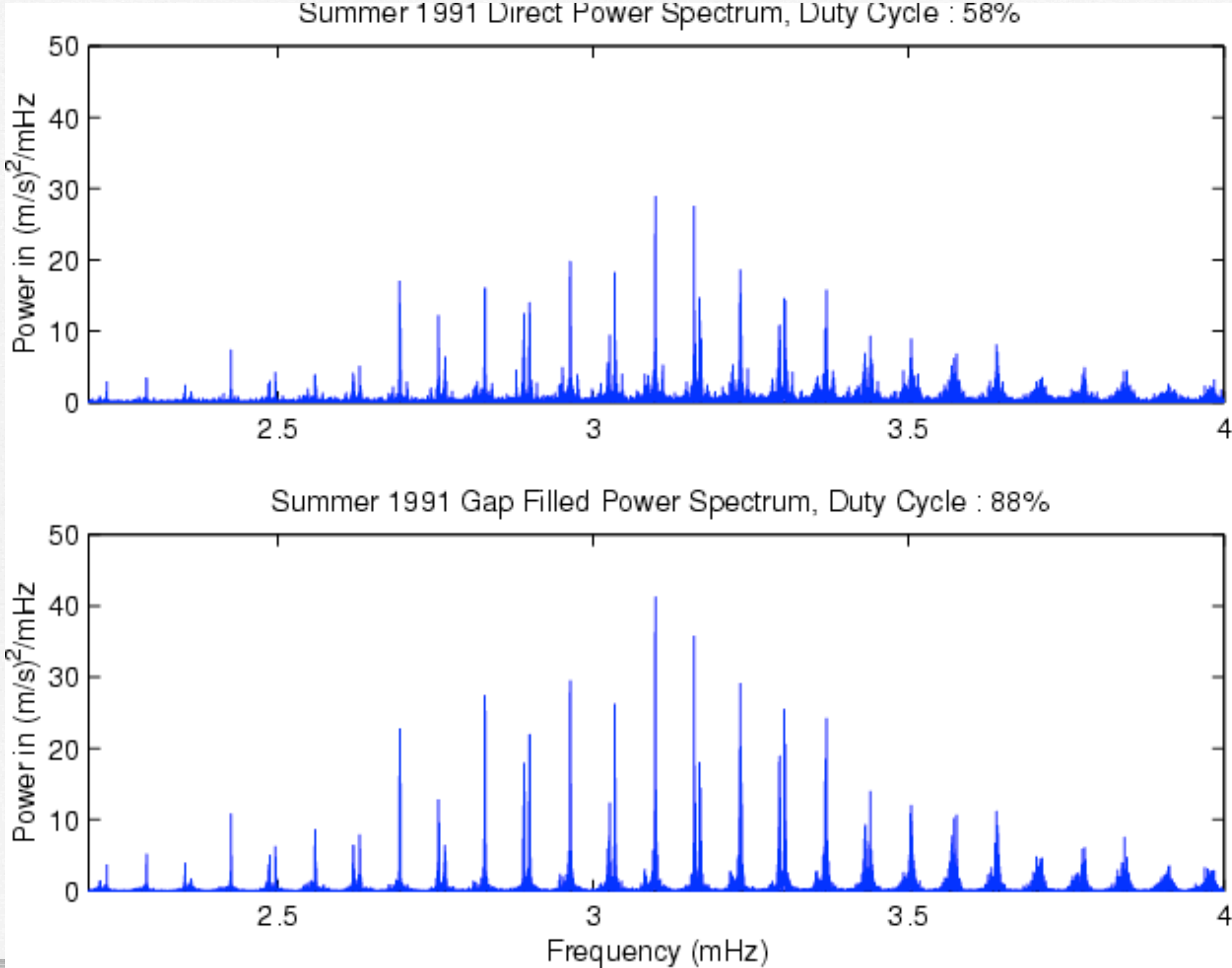



3/8
3/9
3/10
3/11
3/12
3/13
3/14
3/15
3/16
3/17
3/18
3/19



GONG
MDI
1.0
0.5
0.0
−0.5
−1.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
500
450
400
350
Ω/2π (nHz)
0°
15°
30°
45°
60°
0.5 0.6 0.7 0.8 0.9 1.0
r/R


BiSON Power Spectrum
Mode Power (cm^2 s^{-2})
Frequency (mHz)
0
5
10
15
20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.1
0.2
0.3
0.4
1.93
1.94
1.95
1.96
1.97
0.0
0.5
1.0
1.5
3.69
3.70
3.71
3.72



Summer 1991 Direct Power Spectrum, Duty Cycle : 58%
Power in (m/s)2/mHz
50
40
30
20
10
0
2.5
3
3.5
4
Summer 1991 Gap Filled Power Spectrum, Duty Cycle : 88%
Power in (m/s)2/mHz
50
40
30
20
10
0
2.5
3
3.5
4
Frequency (mHz)

	Watanabe(2001)	This work
pp $(10^{10}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$5.98^{+0.05}_{-0.04}$	$5.84^{+0.07}_{-0.08}$
pep $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	1.44 ± 0.02	1.38 ± 0.01
hep $(10^{3}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2.11 ± 0.06	$2.15^{+0.07}_{-0.06}$
^{7}Be $(10^{9}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.72^{+0.39}_{-0.43}$	4.33 ± 0.64
^{8}B $(10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.77^{+1.04}_{-0.72}$	$3.77^{+1.16}_{-0.99}$
^{13}N $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.43^{+0.49}_{-1.26}$	$3.43^{+0.80}_{-0.70}$
^{15}O $(10^{8}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.15^{+0.49}_{-1.26}$	$3.37^{+0.88}_{-0.75}$
^{17}F $(10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$5.22^{+1.08}_{-1.16}$	$3.88^{+1.13}_{-0.96}$