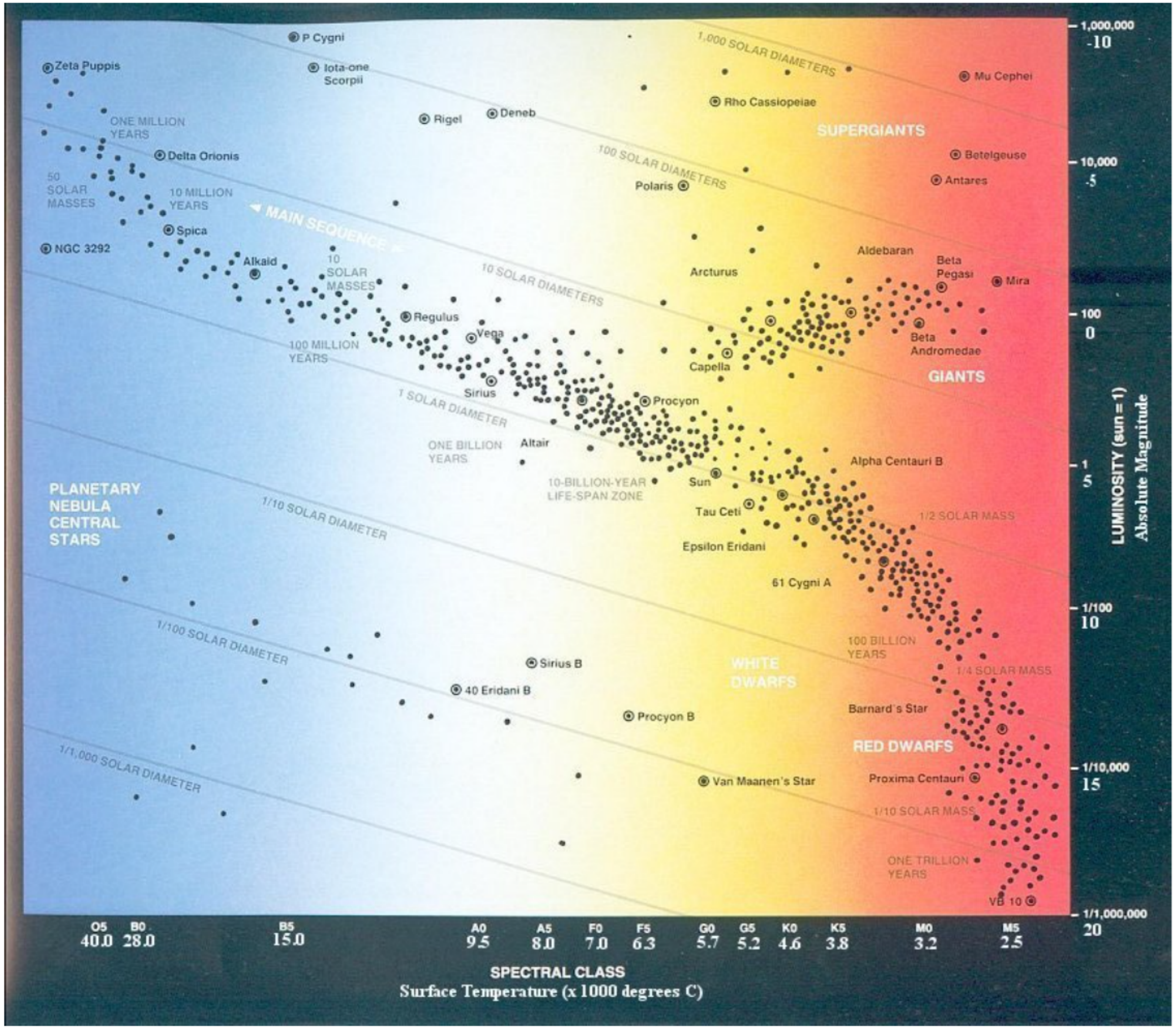
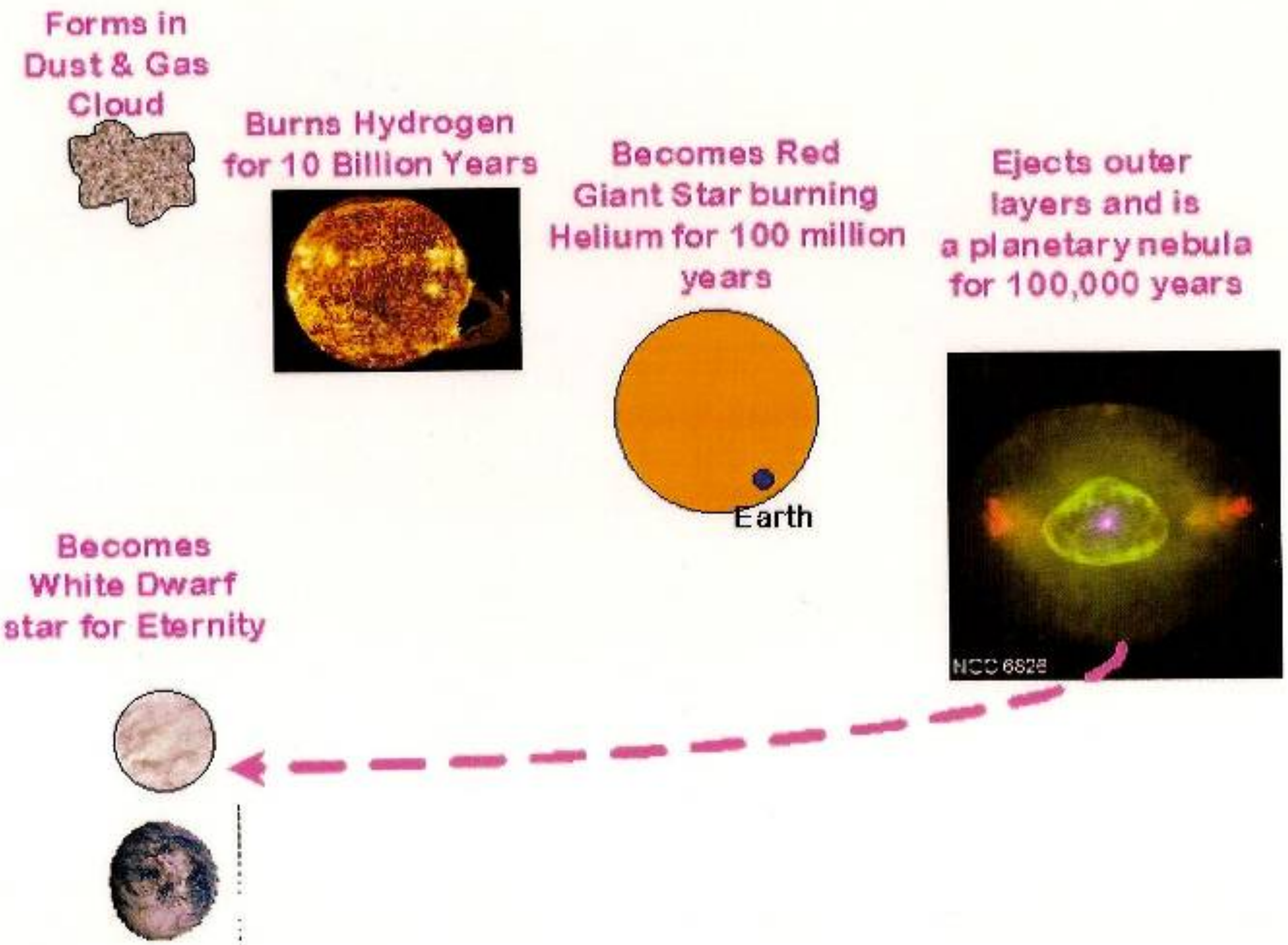
Astrofisica Nucleare e Subnucleare
Neutrino Astrophysics

Hertzspung-Russell diagram

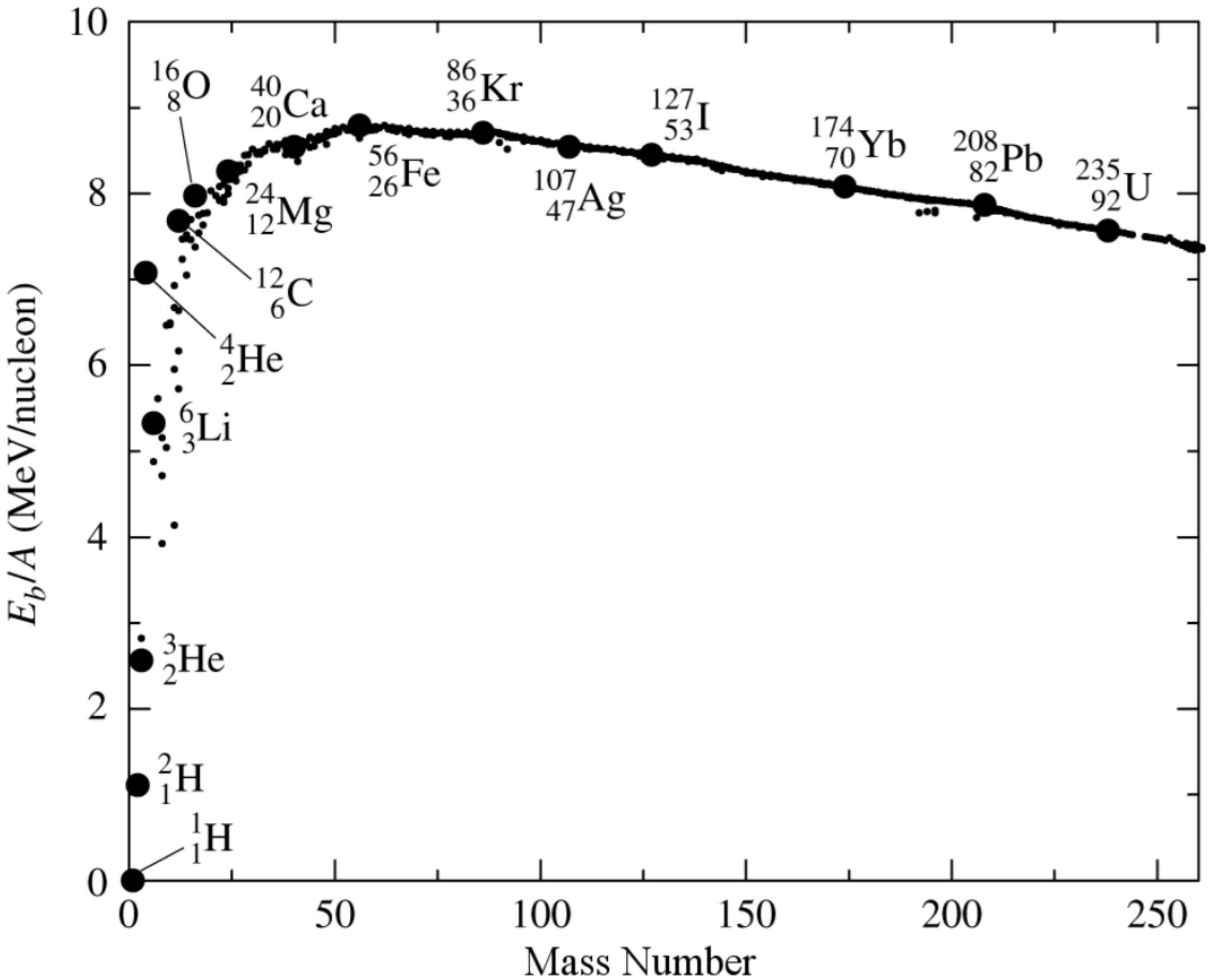


Life of small star $(< 1{,}4\ M_{\odot})$



Nuclear Binding Energy

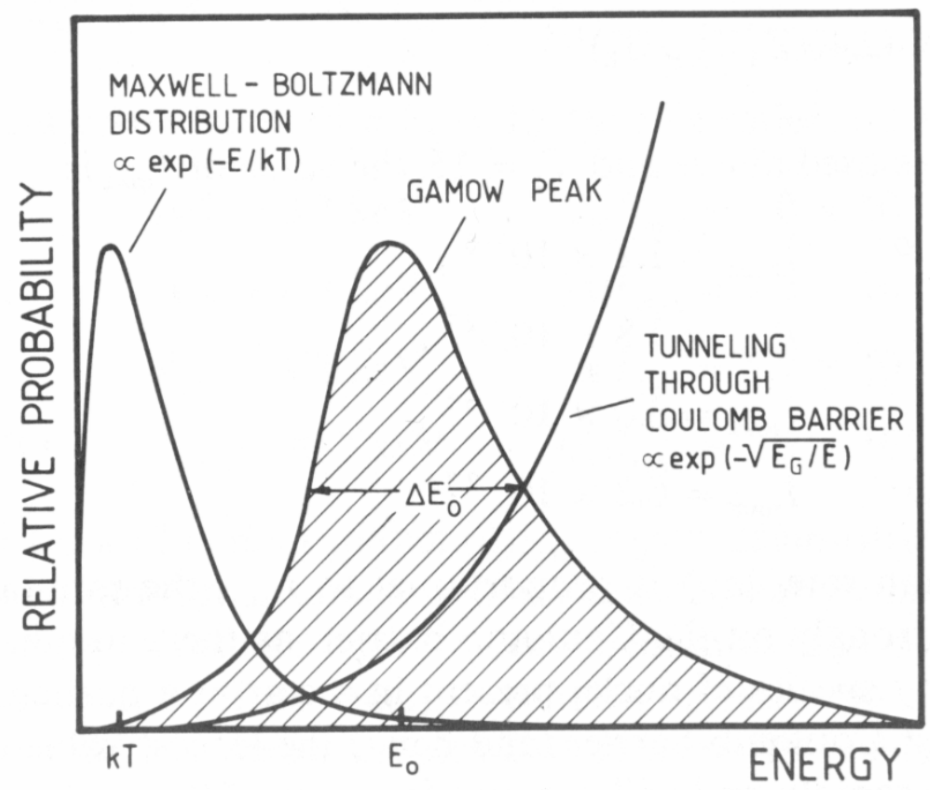
Liberated energy is due to the gain in nuclear binding energy.



Gamow window

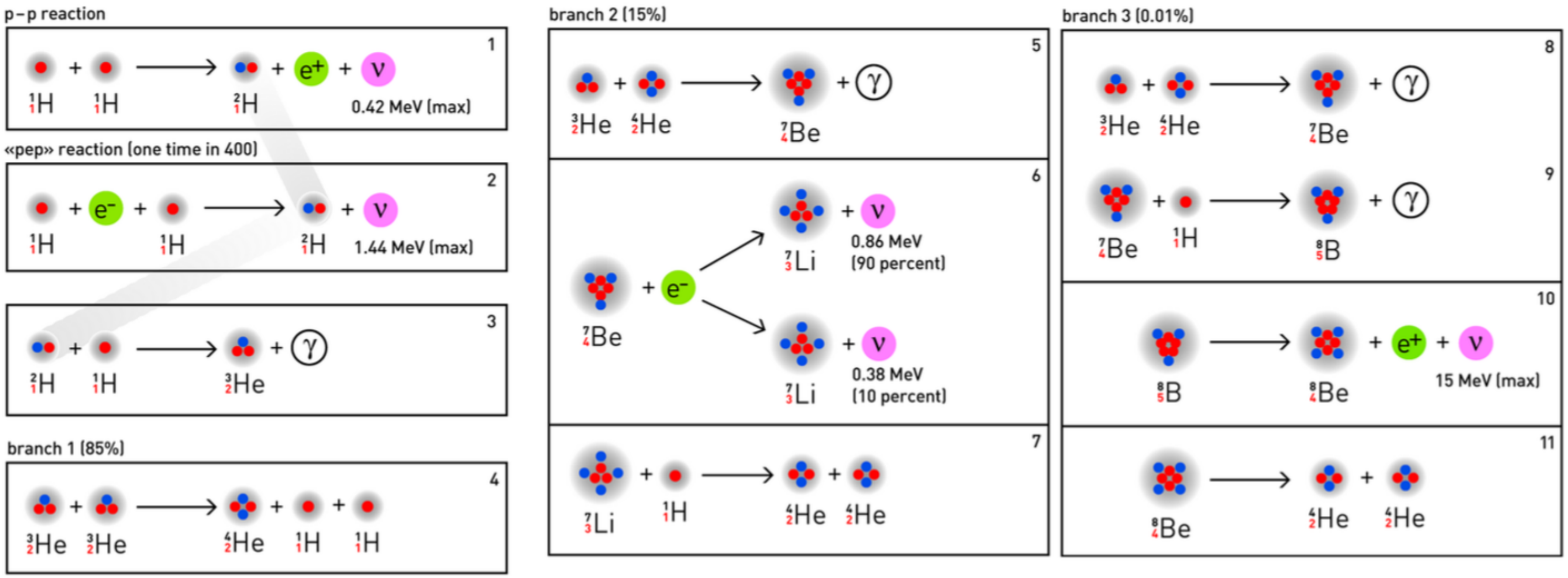
Using definition S factor:

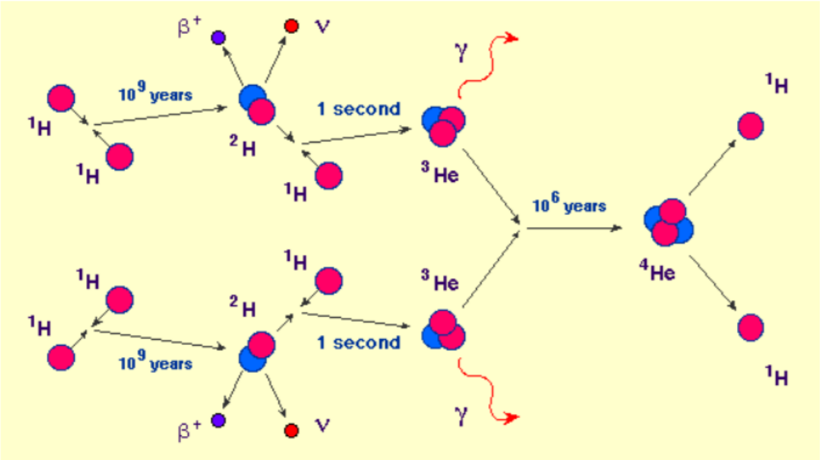
$$\langle \sigma v \rangle = \left(\frac{8}{\pi m}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$



pp chains

Once ^{4}He is produced can act as catalyst initializing the ppII and ppIII chains.





LUNA program: pp chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu$ [0.27 MeV] — 99.75%

$p + e^{-} + p \rightarrow {}^{2}H + \nu$ [1.44 MeV] — 0.25%

$^{2}H + p \rightarrow {}^{3}He + \gamma$ — 50 kV 2001

86%: $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ — 50 kV 1999

14%: $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ — 400 kV 2006

$2 \cdot 10^{-5}$%: $^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

99.89%: $^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$ [0.81 MeV]

0.11%: $^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow {}^{8}Be$

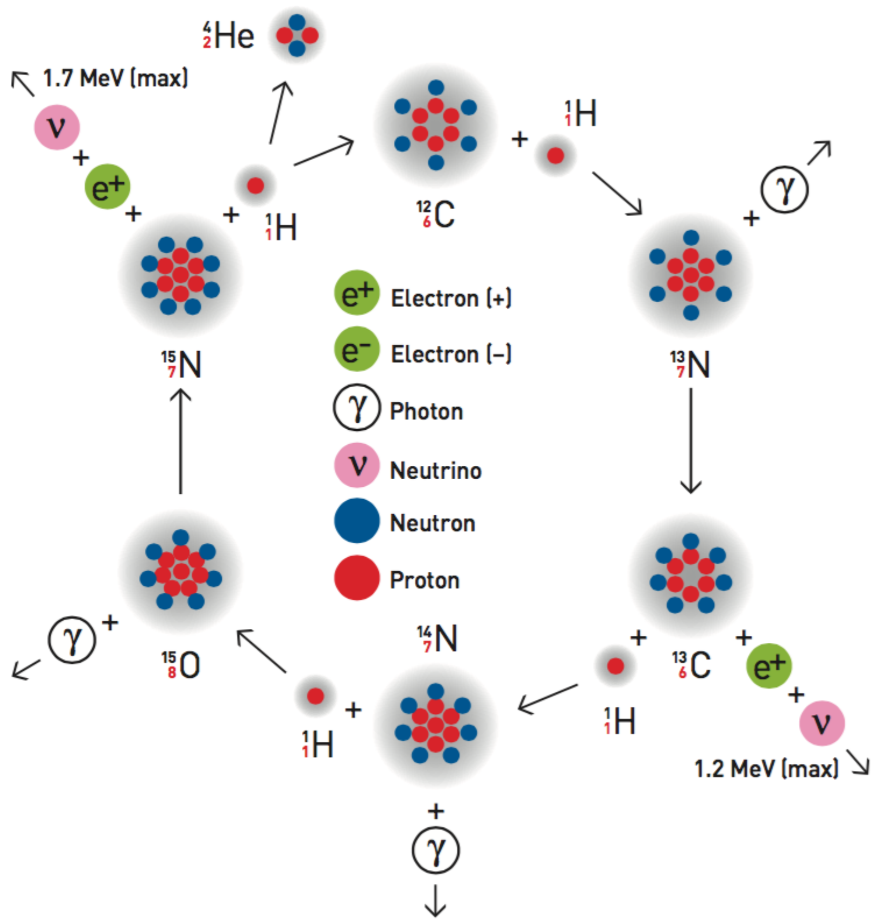
$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ [6.80 MeV]

$^{8}Be \rightarrow 2\ {}^{4}He$

$^{8}Be \rightarrow 2\ {}^{4}He$

CHAIN I	CHAIN II	CHAIN III	CHAIN IV
Q_{eff} = 26.20 MeV	Q_{eff} = 25.66 MeV	Q_{eff} = 19.67 MeV	Q_{eff} = 16.84 MeV

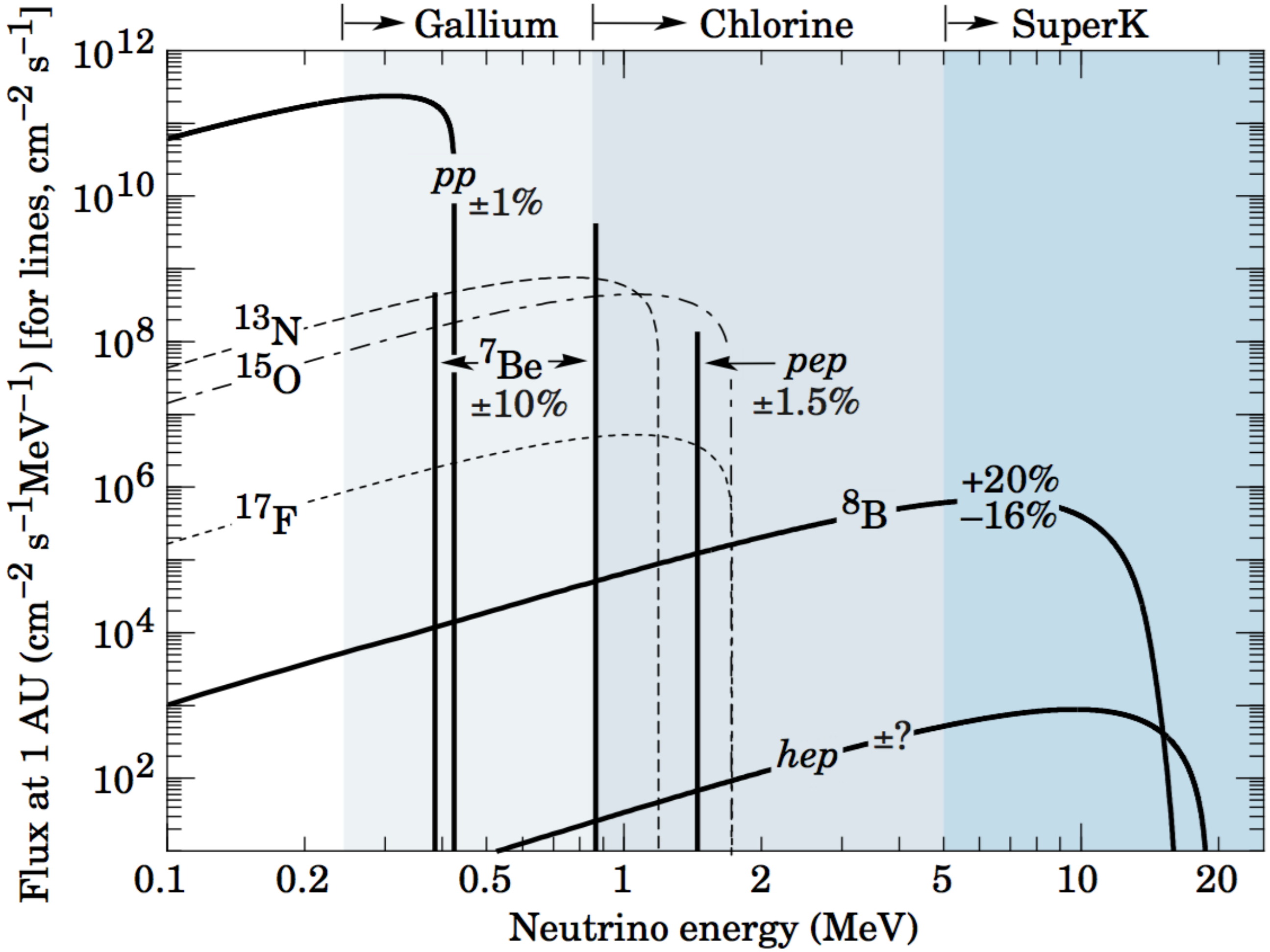
The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst.

Neutrino spectrum (Sun)

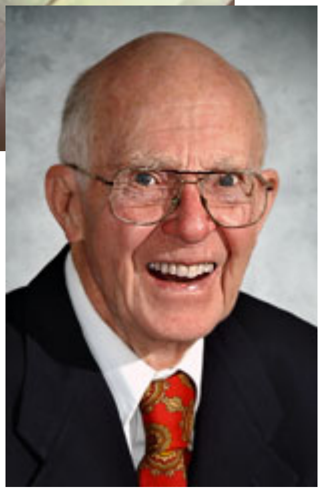
This is the predicted neutrino spectrum

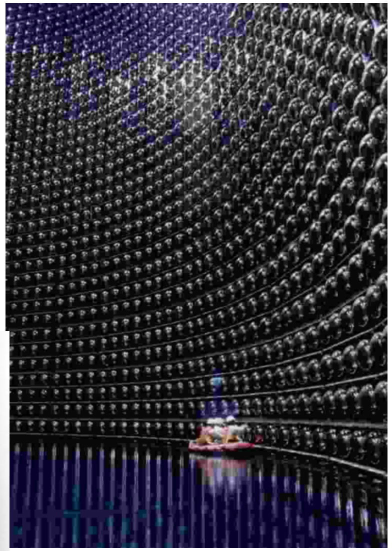


Astrofisica Nucleare e Subnucleare

Solar Neutrinos

The 2002 Nobel Prize for the Solar Neutrino Physics





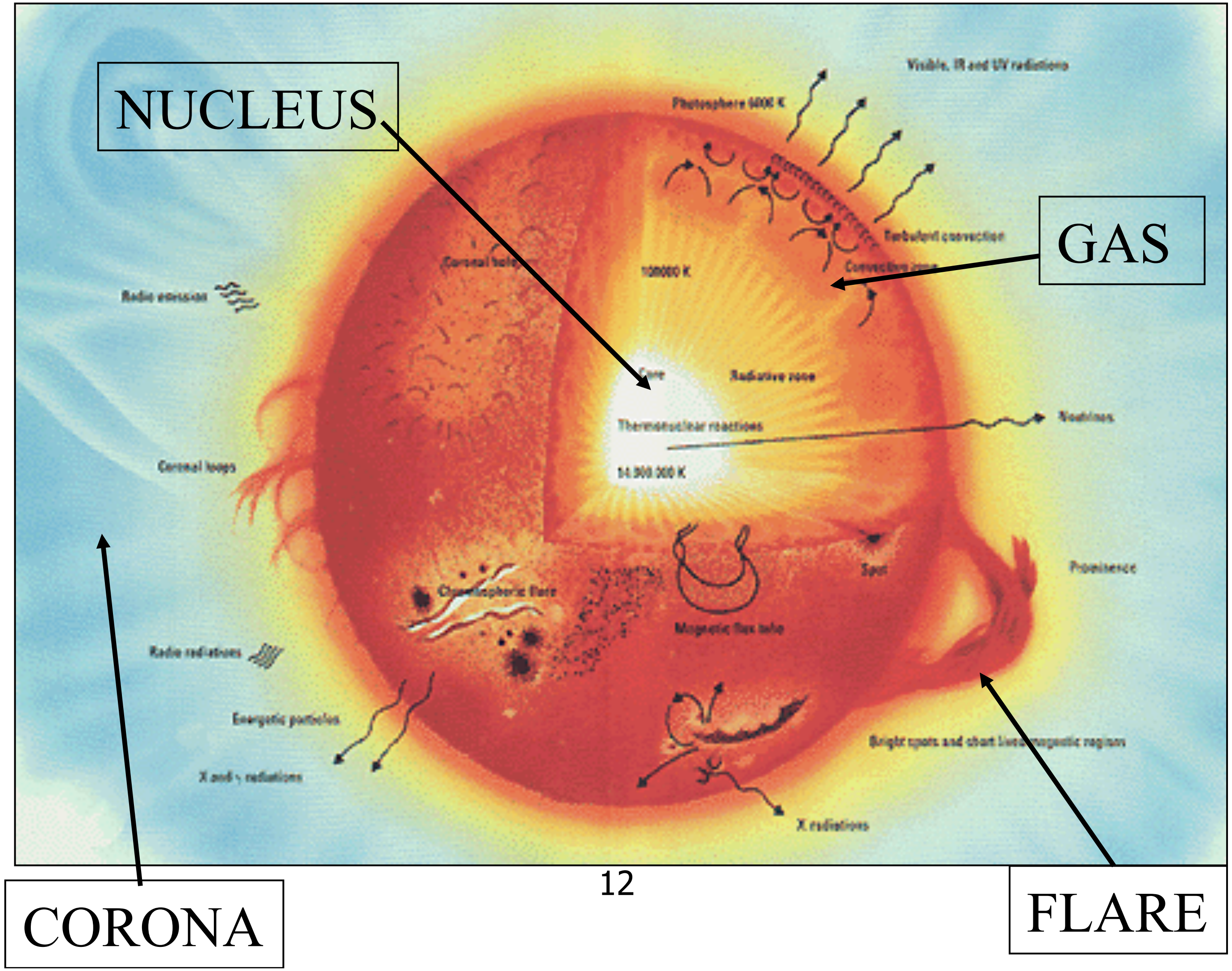
Masatoshi Koshiba

http://nobelprize.org/nobel_prizes/physics/laureates/2002/koshiba-lecture.pdf

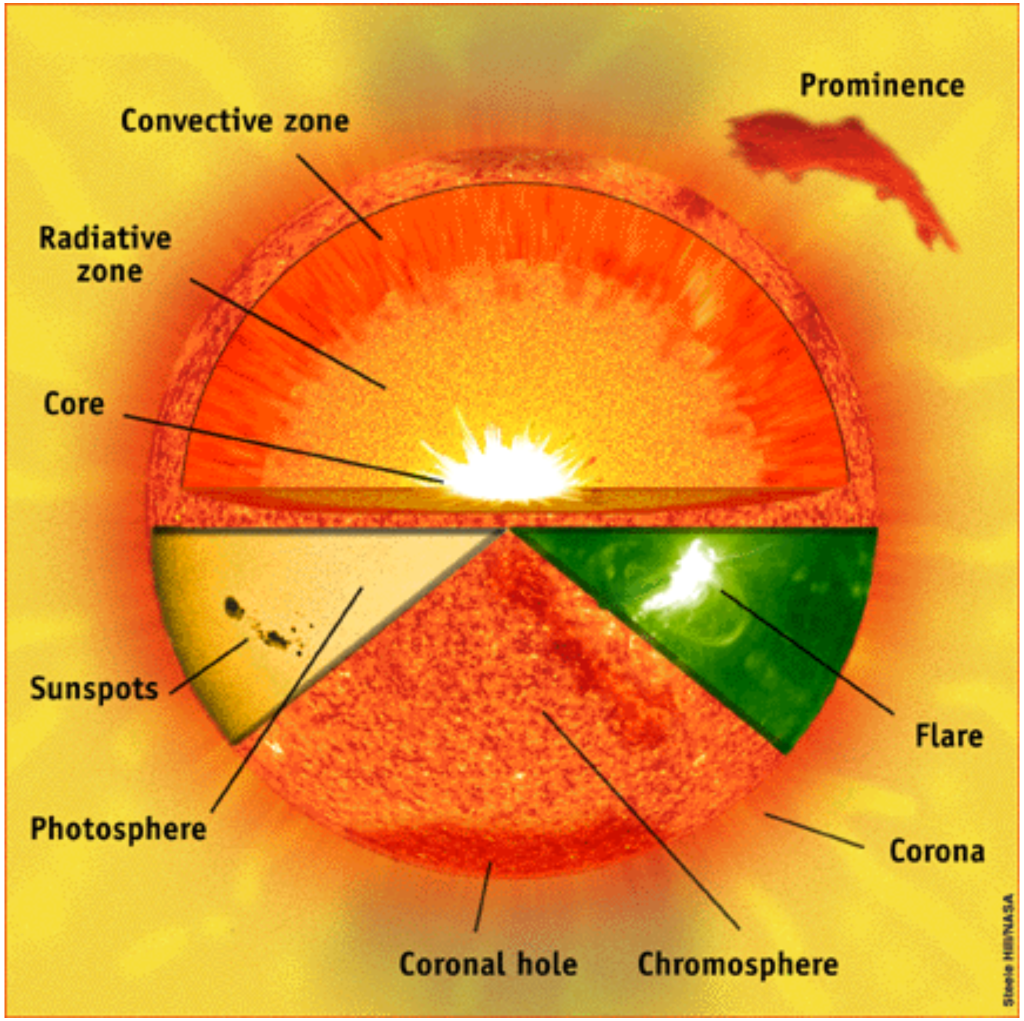
Raymond Davis Jr.

http://nobelprize.org/nobel_prizes/physics/laureates/2002/davis-lecture.pdf

The Standard Solar Model



The Standard Solar Model



The Standard Solar Model

http://www.sns.ias.edu/~jnb/

- J. Bahcall: The main author of the SSM
- The standard solar model is derived from the conservation laws and energy transport equations of physics, applied to a spherically symmetric gas (plasma) sphere
- Constrained by the luminosity, radius, age and composition of the Sun

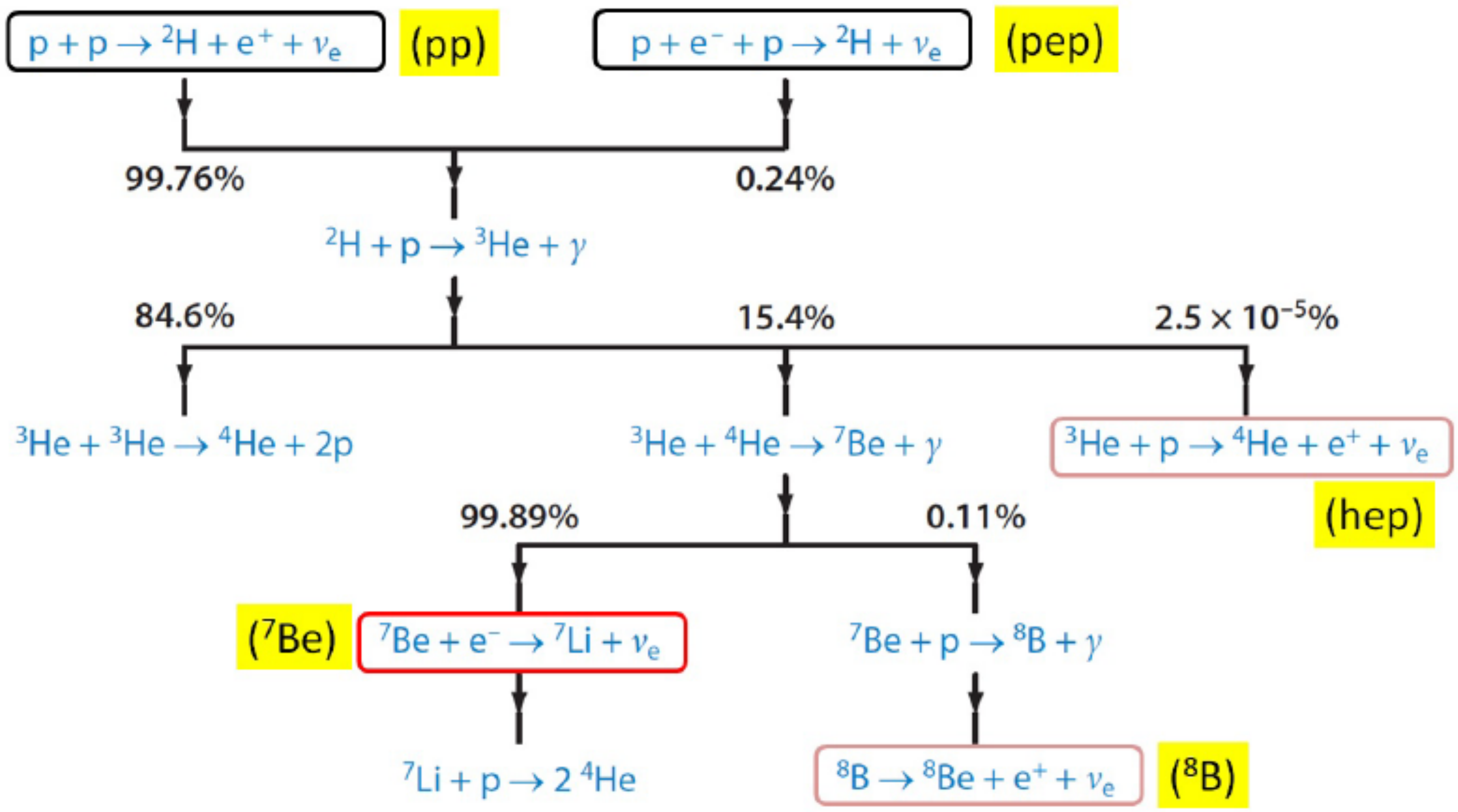
•Inputs for the Standard Solar Model
  –Mass
  –Age
  –Luminosity
  –Radius
•No free parameters
•Tested by helioseismology
•Fusion ⇒ neutrinos

Nota: Leggere l'articolo (tradotto anche in italiano)
http://www.sns.ias.edu/~jnb/Papers/Popular/Nobelmuseum/italianmystery.pdf

The predictions of the SSM

- Most of the neutrinos produced in the sun come from the first step of the pp chain.
- Their energy is so low (<0.425 MeV) → very difficult to detect.
- A rare side branch of the pp chain produces the "boron-8" neutrinos with a maximum energy of roughly 15 MeV
- These are the easiest neutrinos to observe, because the neutrino cross section increases with energy.
- A very rare interaction in the pp chain produces the "hep" neutrinos, the highest energy neutrinos produced in any detectable quantity by our sun.
- All of the interactions described above produce neutrinos with a spectrum of energies. The inverse beta decay of Be^7 produces mono-energetic neutrinos at either roughly 0.9 or 0.4 MeV.

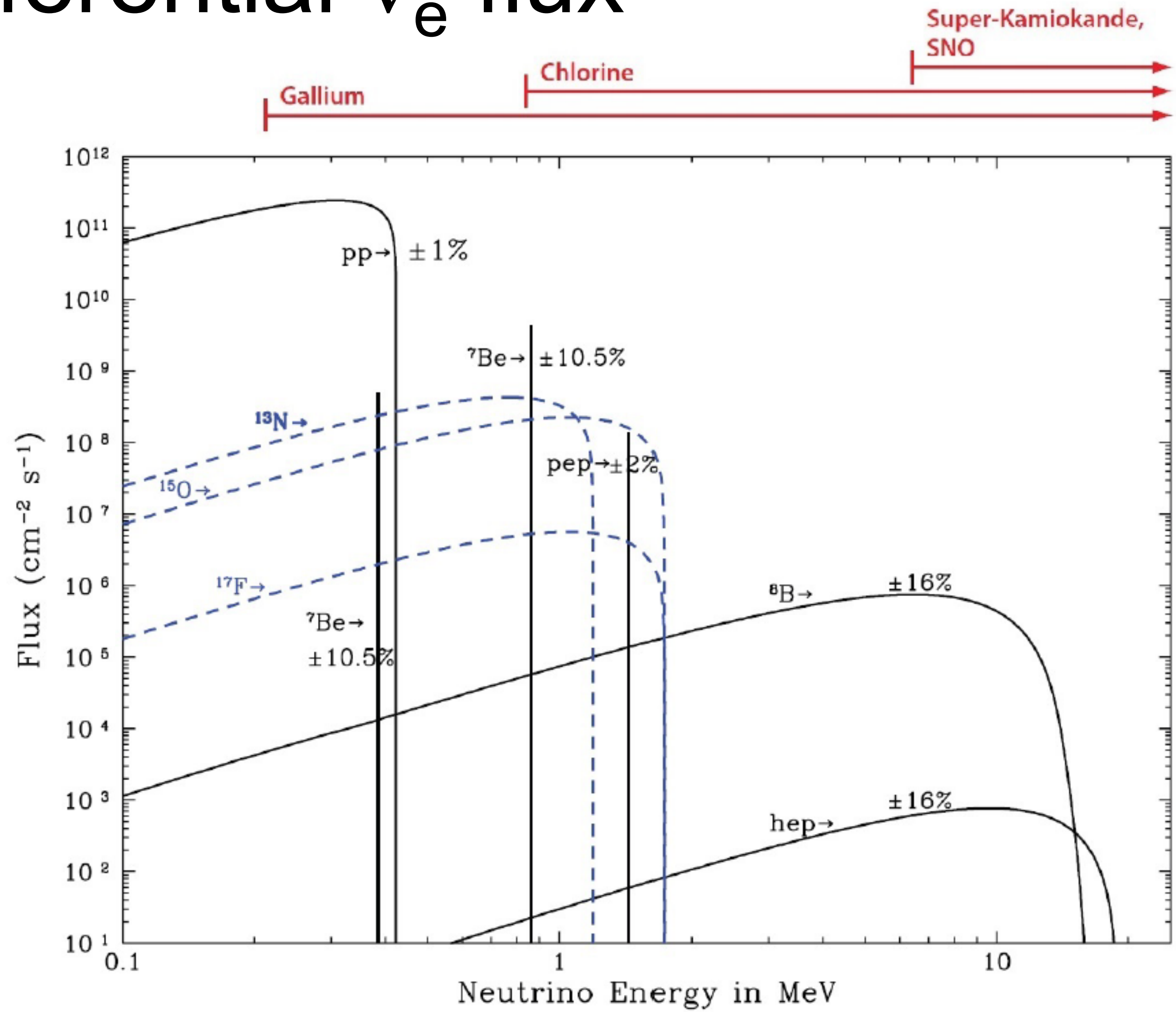
ν from the Sun: the proton cycle



$$4p \rightarrow^4 \text{He} + 2e^+ + 2\nu_e \qquad Q = 26.73 \text{ MeV} \quad \langle E_\nu \rangle \simeq 0.3 \text{ MeV}$$

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2} \frac{2L_\odot}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$$

Differential ν_e flux



Neutrino Emission

Source r	Reaction	Average Neutrino Energy $\langle E\rangle_r$ (MeV)	Maximum Neutrino Energy (MeV)
pp	$p + p \rightarrow d + e^+ + \nu_e$	0.2668	0.423 ± 0.03
pep	$p + e^- + p \rightarrow d + \nu_e$	1.445	1.445
^{7}Be	$e^- + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + \nu_e$	0.3855 0.8631	0.3855 0.8631
^{8}B	${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15
hep	${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$	9.628	18.778
^{13}N	${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e$	0.7063	1.1982 ± 0.0003
^{15}O	${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^+ + \nu_e$	0.9964	1.7317 ± 0.0005
^{17}F	${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^+ + \nu_e$	0.9977	1.7364 ± 0.0003

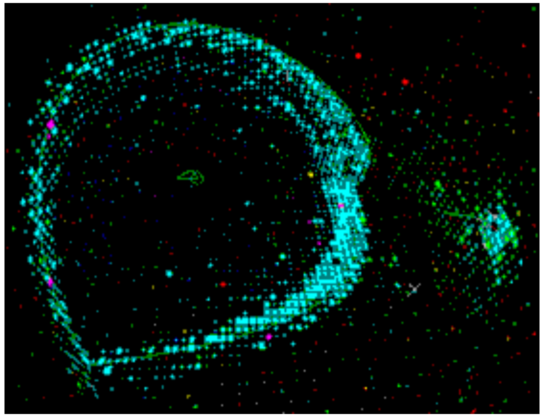
Experimental Techniques

Two detection techniques for the solar neutrinos:

1- elastic scattering

$$\nu_e + e \rightarrow \nu_e + e$$

SK



2- Neutron capture

$$\nu_e + n \rightarrow e + p$$

No free neutrons in nature:

$$(Z,A) + \nu_e \rightarrow e + (Z+1,A)$$

Example: $^{71}Ga + \nu \rightarrow {}^{71}Ge + e$

3- The SNO way:

- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + d \rightarrow \nu_x + n + p$

Solar Neutrino Detectors

- Neutrino Absorption Experiments
  - 37Cl
  - 71Ga
- Neutrino Scattering Experiments
  - SuperKamiokande
- Direct Counting experiments
  - SNO

- 'Davis'
- GALLEX/GNO < (radiochemical)
- SAGE
- SuperKamiokande (elastic scattering)
- SNO

•The Clorine or 'Davis' experiment

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e$$

- Pioneering experiment by Ray Davis at Homestake mine began in 1967
- Consisted of a 600 ton chlorine tank
- Experiment was carried out over a 20 year period, in an attempt to measure the flux of neutrinos from the Sun
- **Measured flux was only one third the predicted value !!**

^{37}Cl experiment

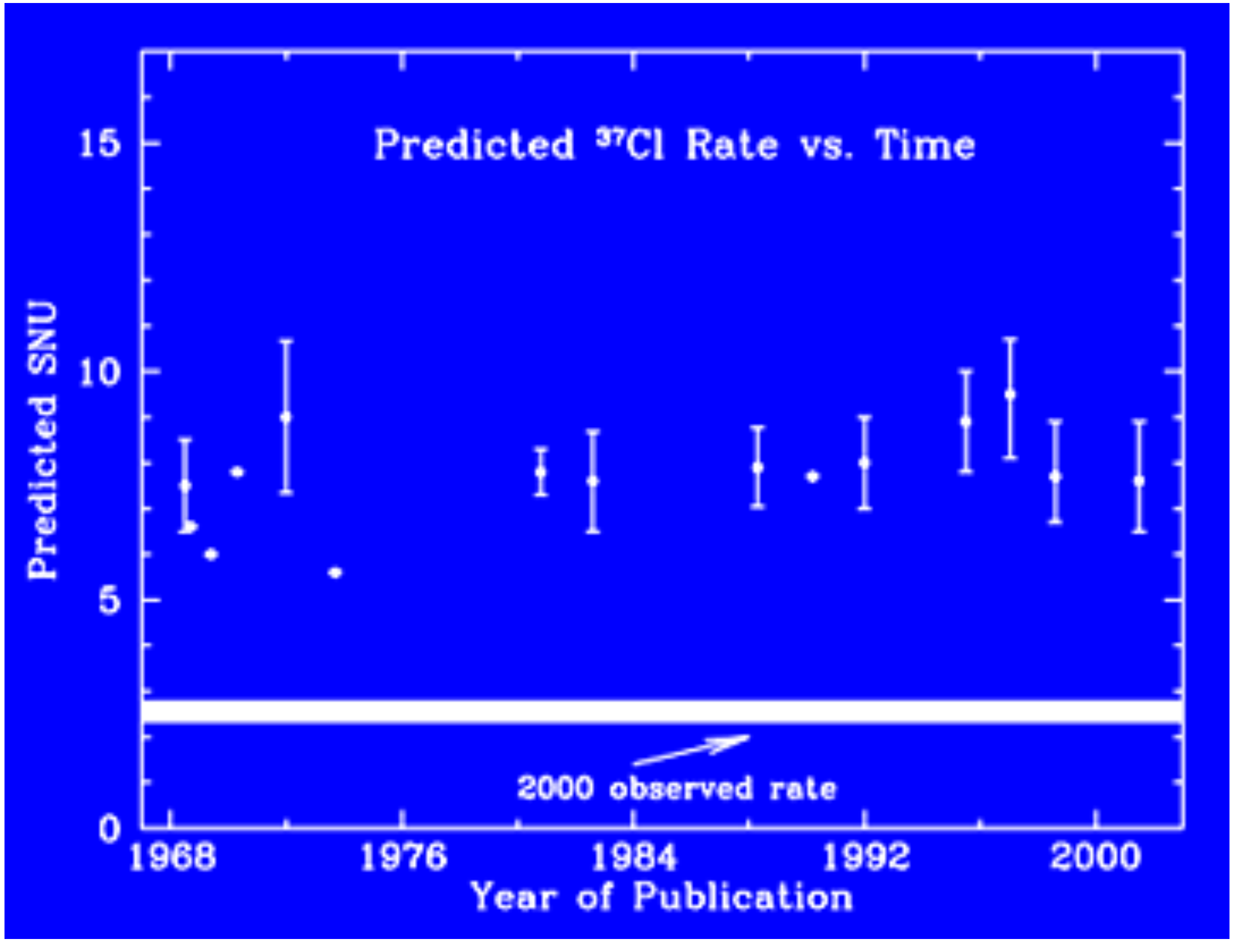
- The Clorine or 'Davis' experiment

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e$$

- Pioneering experiment by Ray Davis at Homestake mine began in 1967
- Consisted of a 600 ton chlorine tank
- Threshold E = 0.814 MeV
- Experiment was carried out over a 20 year period, in an attempt to measure the flux of neutrinos from the Sun
- Chemical extraction of Argon and direct counting of Argon decays (15 atoms over 130 tons of Cl every month!)
- Measured flux was only one third the predicted value

^{37}Cl experiment

^{37}Cl experiment



Radiochemical experiments: GALLEX/GNO and SAGE

- The main solar neutrino source is from the p-p reaction:

$$p + p \rightarrow d + e^{+} + \nu_e + 0.42\text{MeV}$$

- Solar neutrino experiment based on the reaction:

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

- Ability to detect the low-energy neutrinos from p-p fusion

- **SAGE:** Located at the Baksan Neutrino Observatory in the northern Caucasus mountains of Russia (1990-2000)

- **GALLEX/GNO:** Located at the Gran Sasso

- Energy threshold: 233.2 ± 0.5 keV, below that of the p-p ν_e (420 keV)

•GALLEX/GNO

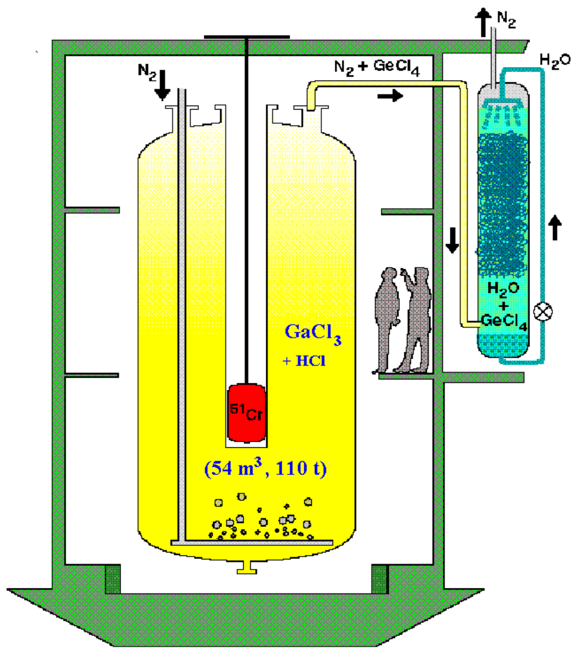
• 30.3 tons of gallium in form of a concentrated $GaCl_3$-HCl solution exposed to solar ν's

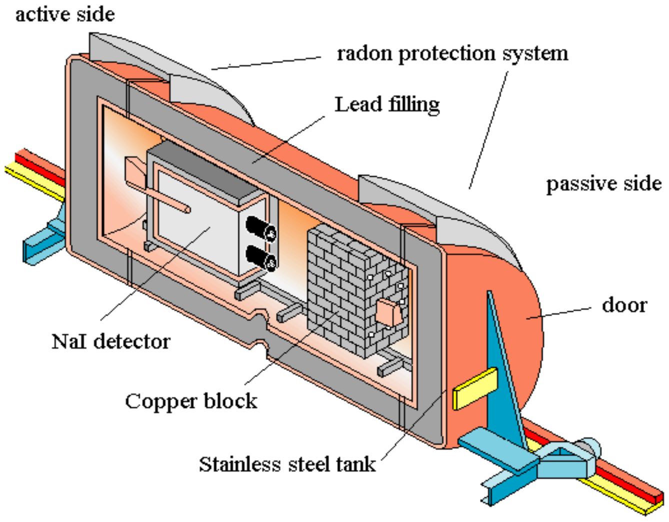
• Neutrino induced ^{71}Ge forms the volatile compound $GeCl_4$

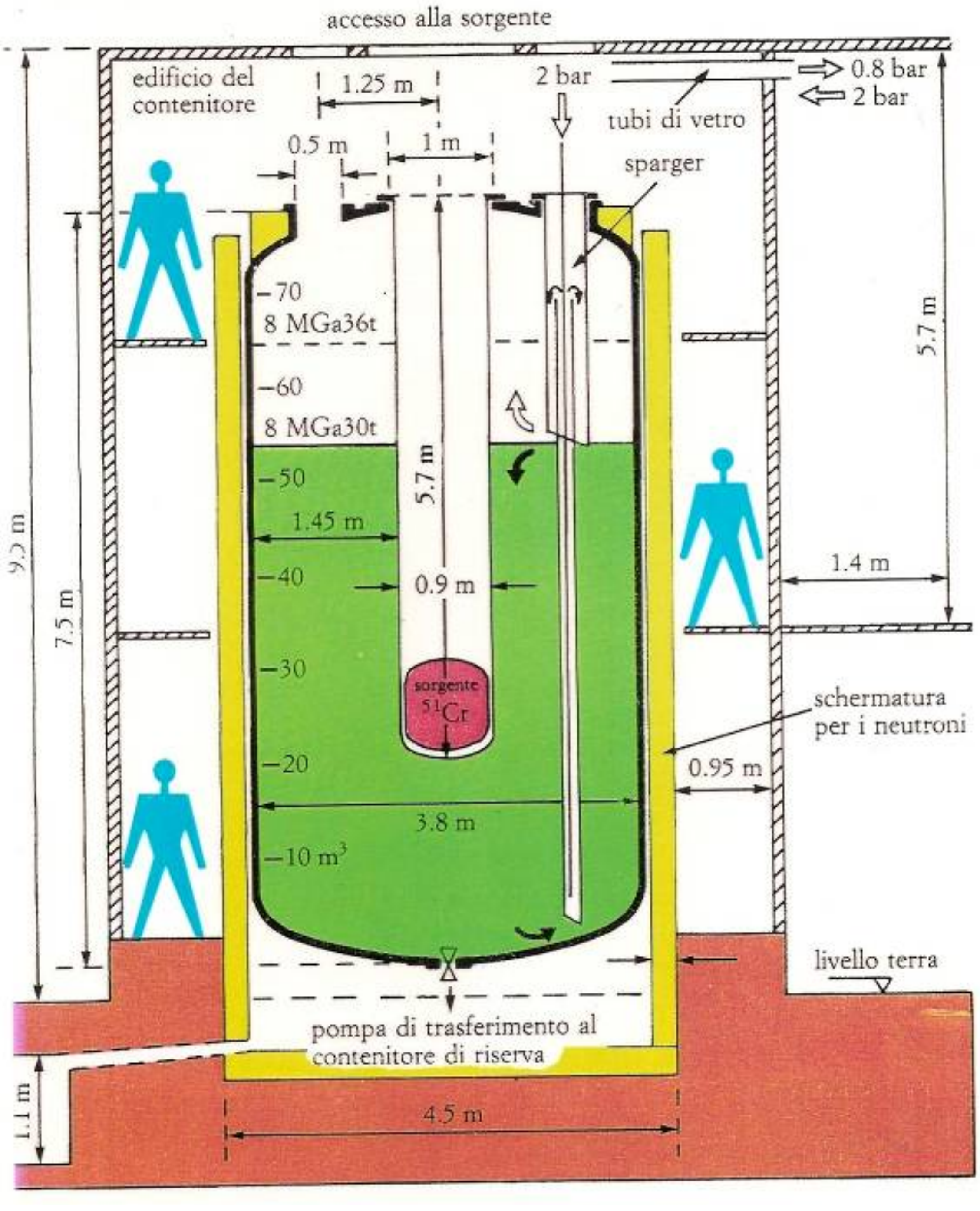
• Nitrogen gas stream sweeps $GeCl_4$ out of solution

• $GeCl_4$ is absorbed in water $GeCl_4 \rightarrow GeH_4$ and introduced into a proportional counter

•Number of ^{71}Ge atoms evaluated by their radioactive decay






accesso alla sorgente
edificio del contenitore
1.25 m
2 bar
0.8 bar
2 bar
tubi di vetro
0.5 m
1 m
sparger
–70
8 MGa36t
–60
8 MGa30t
–50
5.7 m
1.45 m
–40
0.9 m
–30
sorgente
^{51}Cr
–20
3.8 m
–10 m^3
5.7 m
1.4 m
schermatura per i neutroni
0.95 m
7.5 m
livello terra
pompa di trasferimento al contenitore di riserva
1.1 m
4.5 m

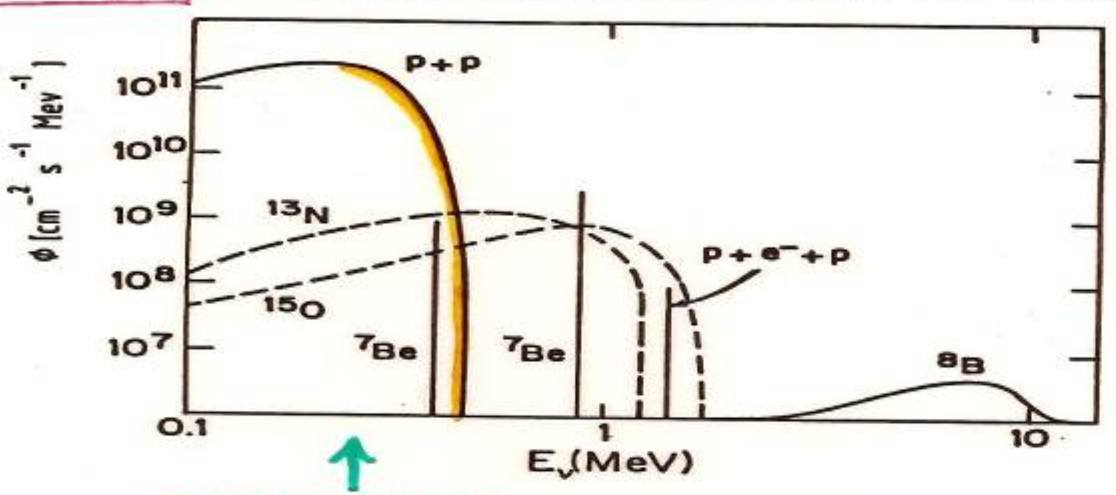
GALLEX

GALLIUM EUROPEAN COLLABORATION

30 TONS OF GALLIUM IN $GaCl_3$ (IN HCl)

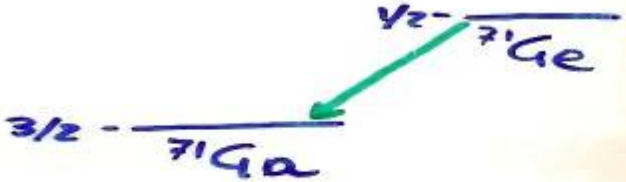
12 Tons ^{71}Ga

NEUTRINO FLUX FROM SUN (BACHALL et al.)



↑ THRESHOLD

E > 233 KeV



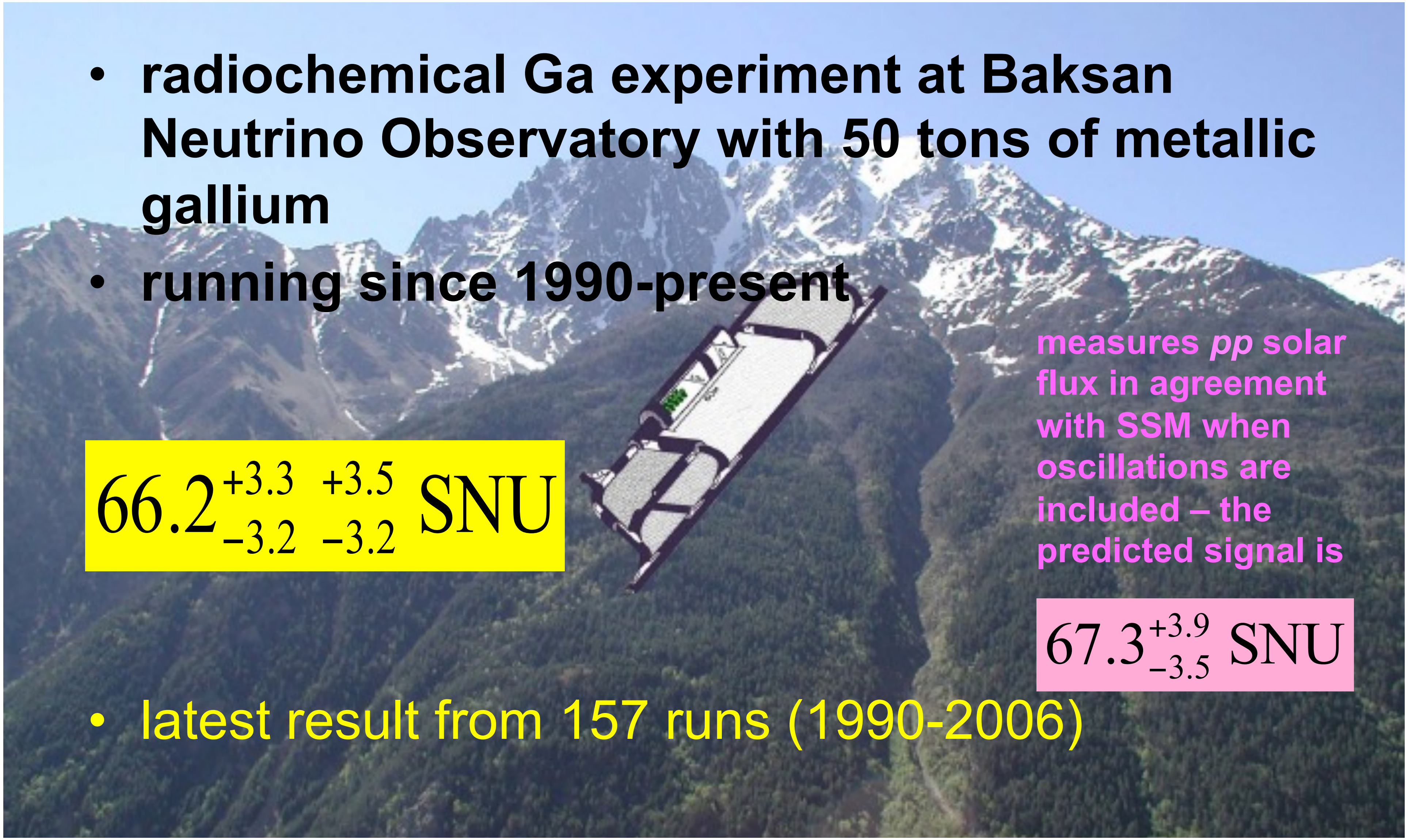
$$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^-$$

LIQUIDO $GaCl_3 \Rightarrow GeCl_4$ GASSOSO

$$T_{1/2} = 11.43\ d$$

$$^{71}Ge \longrightarrow {}^{71}Ga + \gamma \quad \begin{pmatrix} 1.2\ KeV \\ 10.4\ KeV \end{pmatrix}$$

SAGE – Russian American Gallium Experiment



- **radiochemical Ga experiment at Baksan Neutrino Observatory with 50 tons of metallic gallium**
- **running since 1990-present**

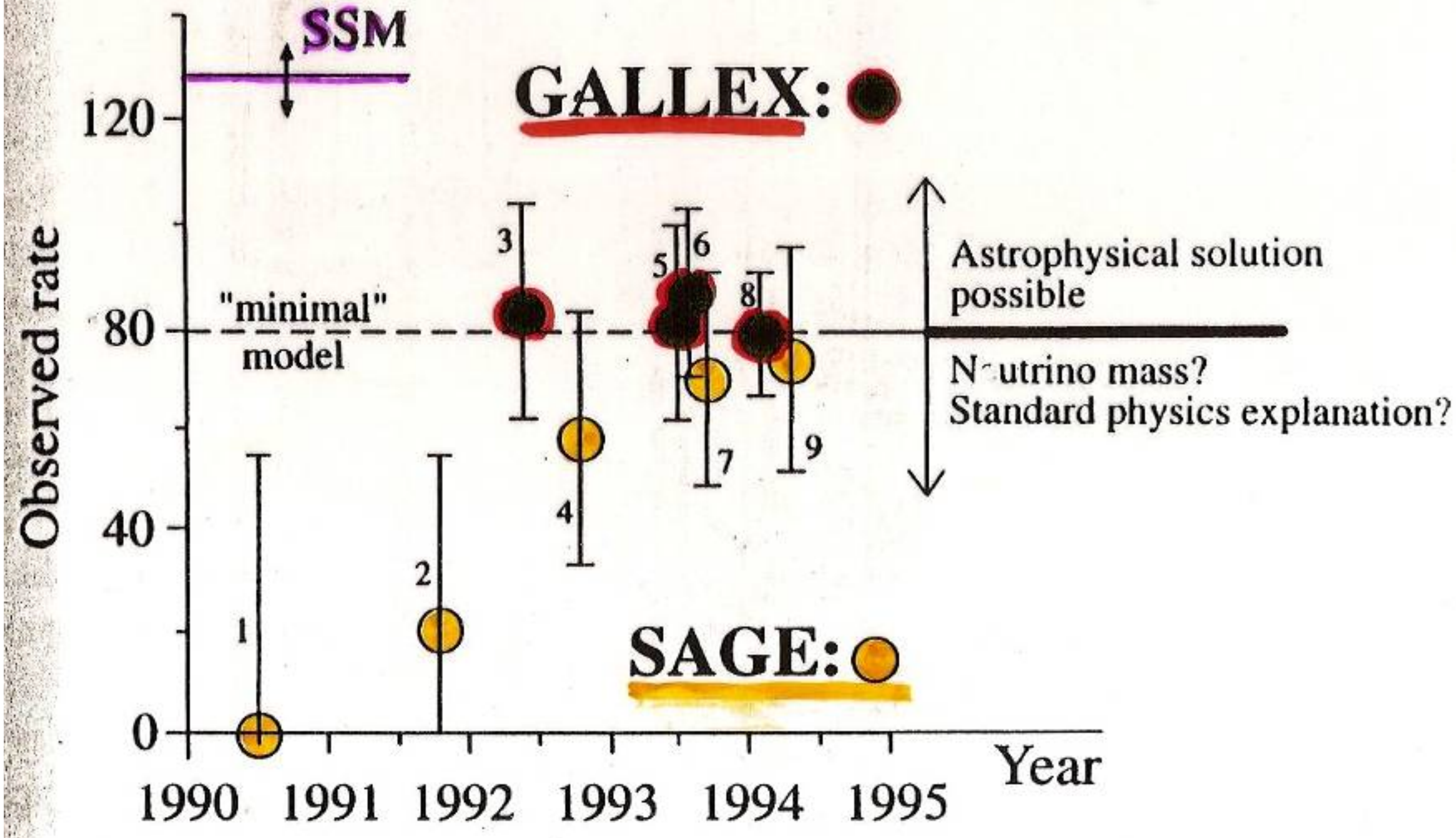
$$66.2^{+3.3}_{-3.2}\ ^{+3.5}_{-3.2}\ \text{SNU}$$

measures *pp* solar flux in agreement with SSM when oscillations are included – the predicted signal is

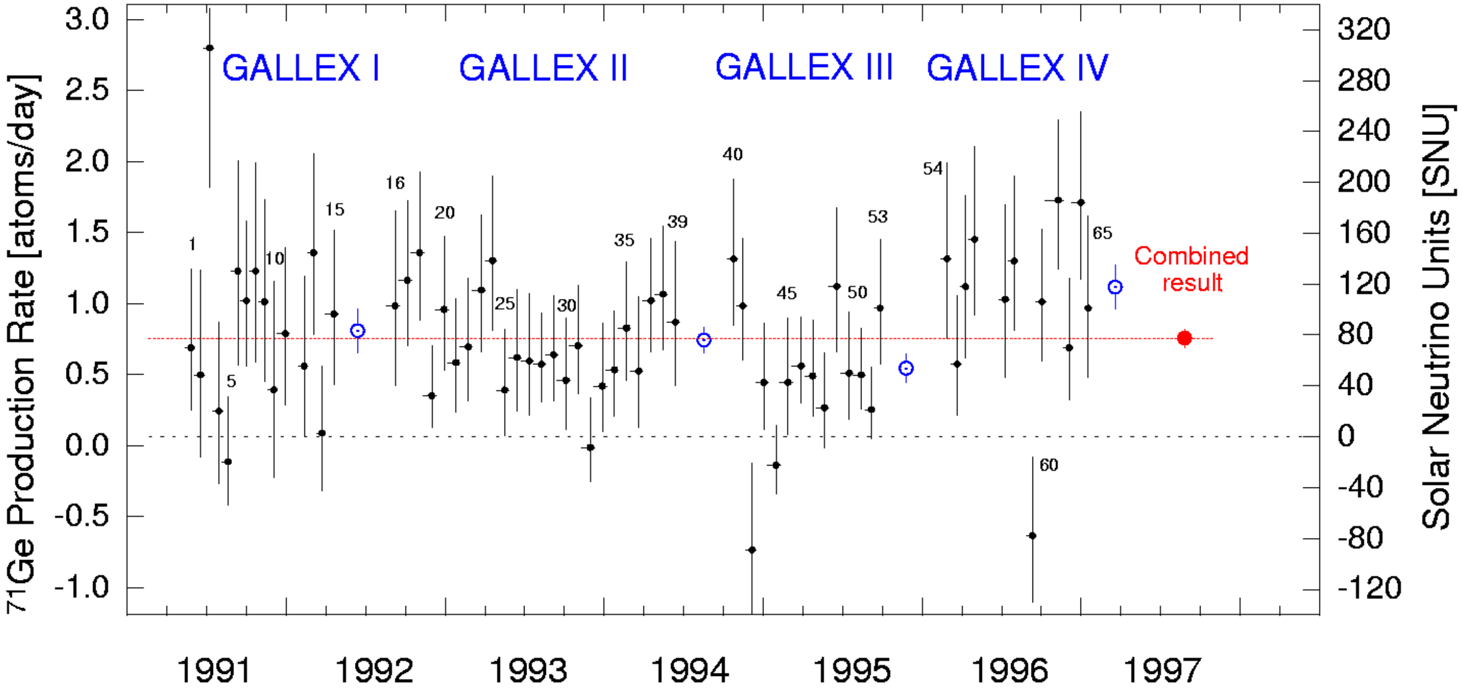
$$67.3^{+3.9}_{-3.5}\ \text{SNU}$$

- latest result from 157 runs (1990-2006)

Figure 12.17. The SAGE experiment in the Baksan underground laboratory in the Caucasus. The 10 so-called reactors can be seen, 8 of which contain a total of 57 tons of metallic gallium (with kind permission of the SAGE collaboration).



GALLEX-SAGE results



	GALLEX+GNO (SNU)	SAGE (SNU)
Measured	71 ± 5	66 ± 5
Expected	128 ± 8	128 ± 8

SNU= 10^{-36} (interactions/s · nucleus)

Solar Neutrino Problem

Experiment	Result	Theory	$\frac{\text{Result}}{\text{Theory}}$
Homestake [38]	$2.56 \pm 0.16 \pm 0.16$ (2.56 ± 0.23)	$7.7\,^{+1.2}_{-1.0}$	$0.33\,^{+0.06}_{-0.05}$
GALLEX [322]	$77.5 \pm 6.2\,^{+4.3}_{-4.7}$ (78 ± 8)	$129\,^{+8}_{-6}$	0.60 ± 0.07
SAGE [323]	$66.6\,^{+6.8}_{-7.1}\,^{+3.8}_{-4.0}$ (67 ± 8)	$129\,^{+8}_{-6}$	0.52 ± 0.07
Kamiokande [41]	$2.80 \pm 0.19 \pm 0.33$ (2.80 ± 0.38)	$5.15\,^{+1.0}_{-0.7}$	0.54 ± 0.07
Super-Kamiokande [48]	$2.44 \pm 0.05\,^{+0.09}_{-0.07}$ $(2.44\,^{+0.10}_{-0.09})$	$5.15\,^{+1.0}_{-0.7}$	$0.47\,^{+0.07}_{-0.09}$

The Solar Neutrino Problem

How can this deficit be explained?

1. The Sun's reaction mechanisms are not fully understood

   NO! new measurements (~1998) of the sun resonant cavity frequencies

2. The experiment is wrong –

   NO! All the fourthcoming new experiments confirmed the deficit!

3. Something happens to the neutrino as it travels from the Sun to the Earth

   YES! Oscillations of electron neutrinos!

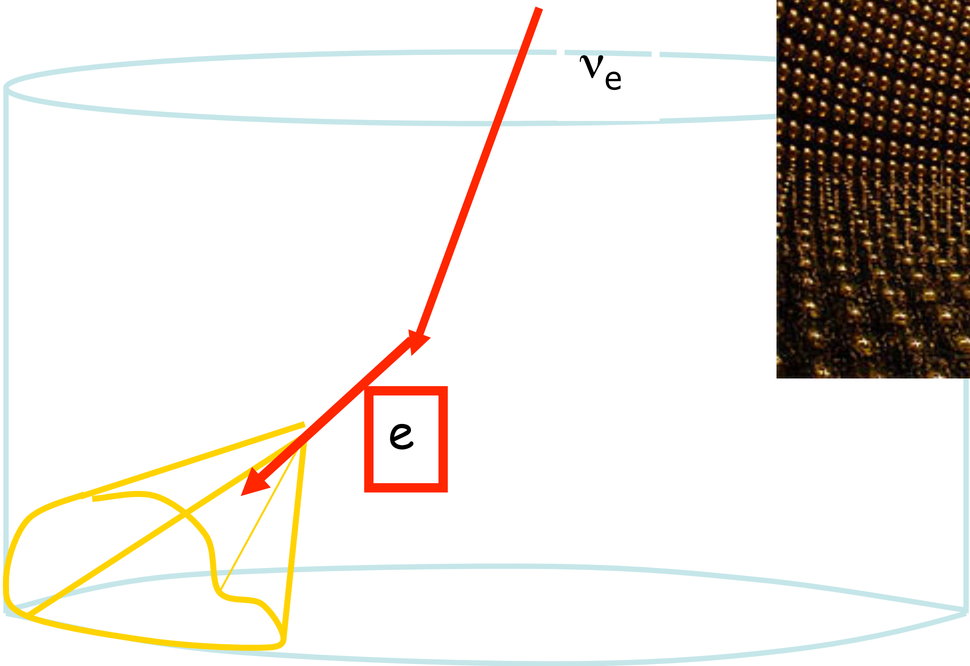
Solar Neutrino Problem

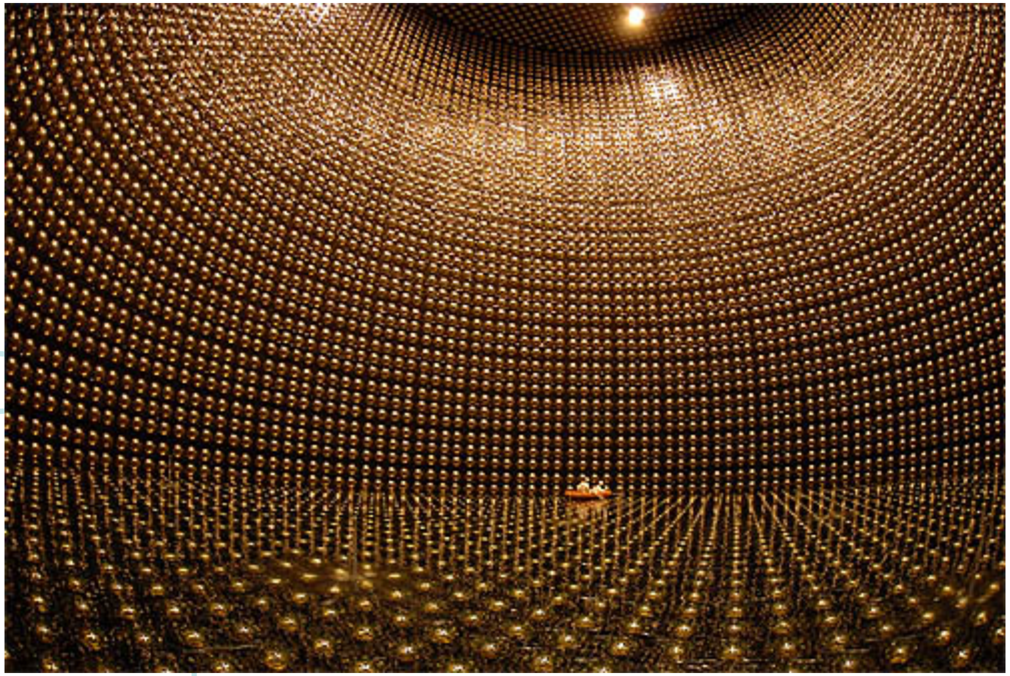
- Astrophysical solutions?:
  - Low metallicity
  - Burnt out core
  - Rapid Rotation
  - High mass loss rate
  - Pure CNO cycle
  - WIMP
  - Central BH

The SK way- The elastic scattering of neutrinos on electrons

- Real-time detector
- Elastic scattering

  $\nu e \rightarrow \nu e$





Neutrino Scattering Experiments

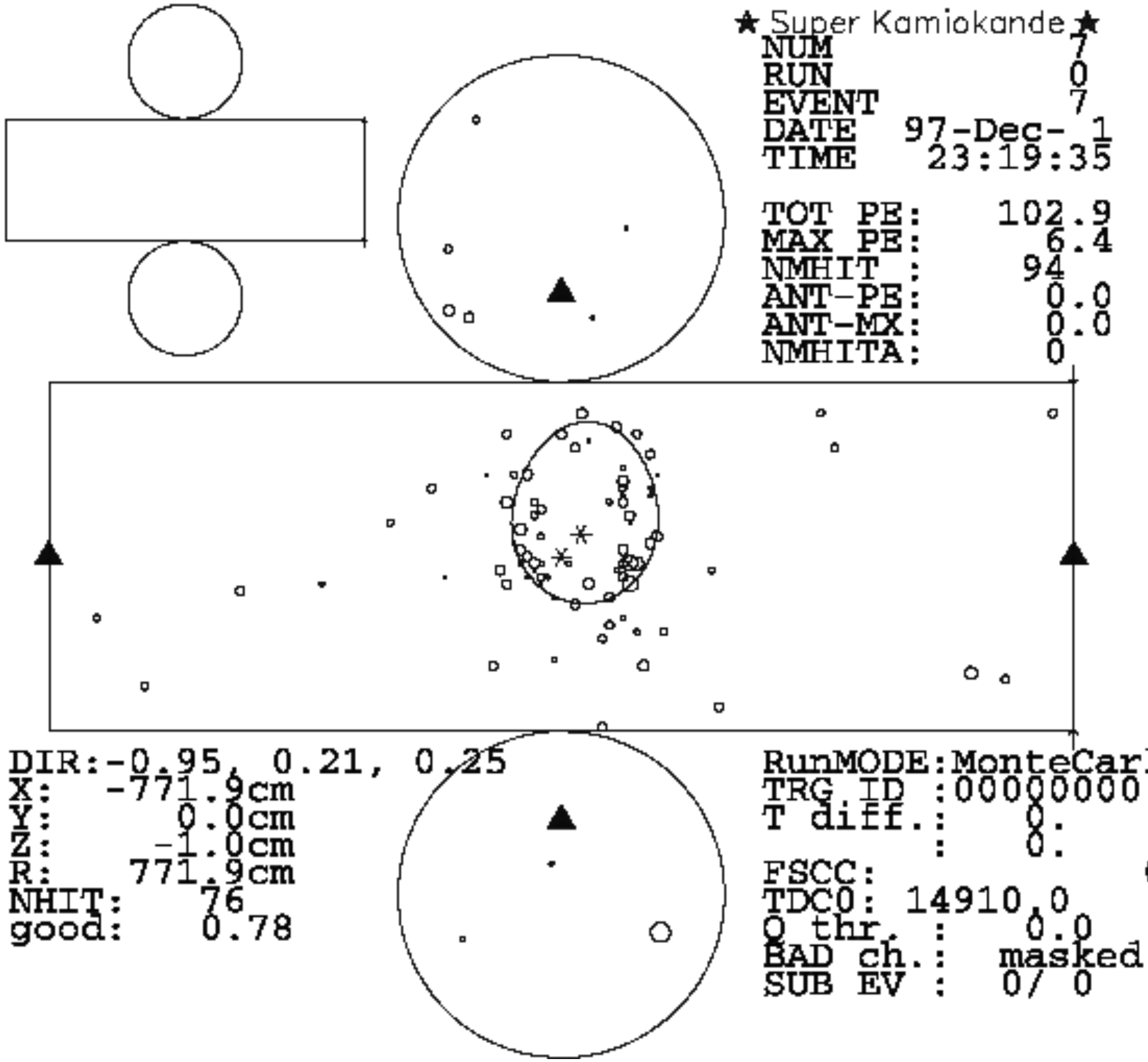
Particle	Cherenkov threshold in total Energy
$e^{\pm}$	0.768(MeV)
$\mu^{\pm}$	158.7
$\pi^{\pm}$	209.7

Cherenkov threshold energies of various particles.

$$\cos\theta = \frac{1}{n\beta'}$$

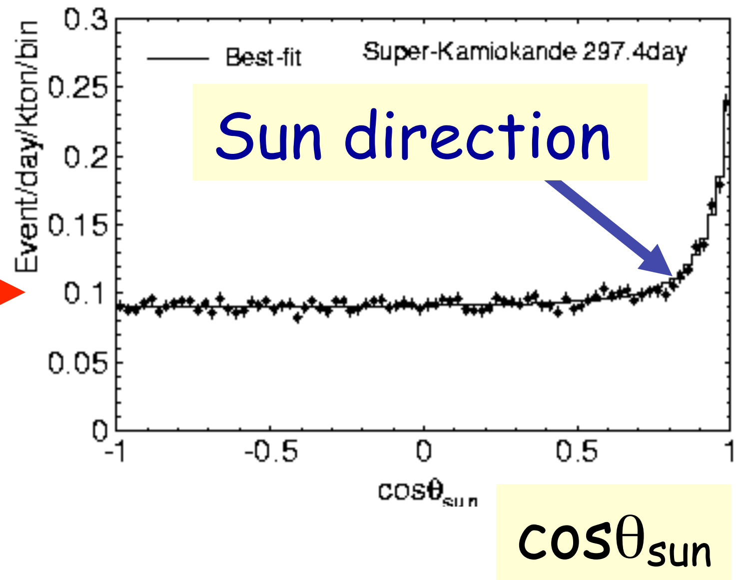
Cherenkov light is emitted in a cone of half angle θ from the direction of the particle track

Neutrino Scattering Experiments

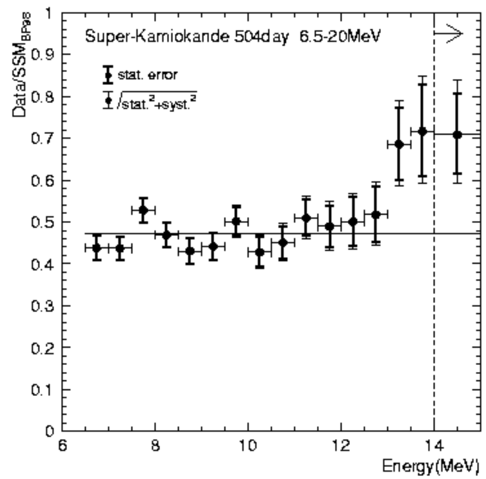


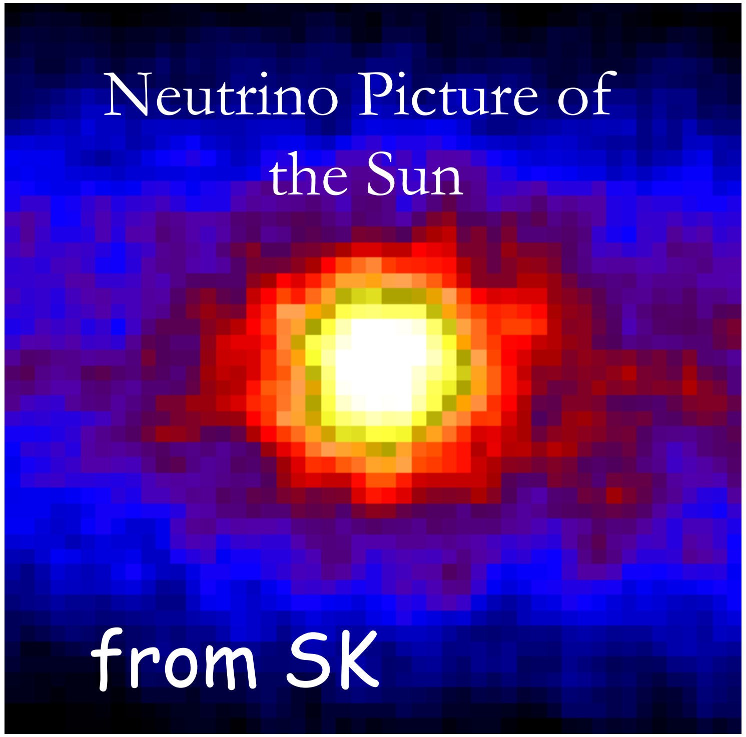
Neutrino Scattering Experiments

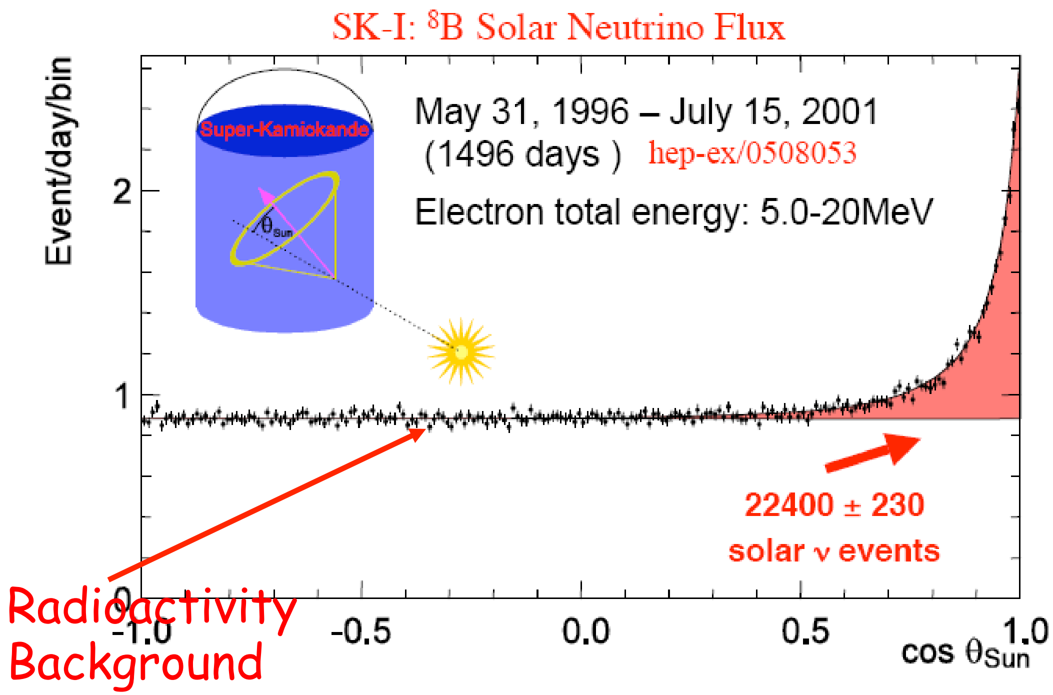
Radioactivity Background



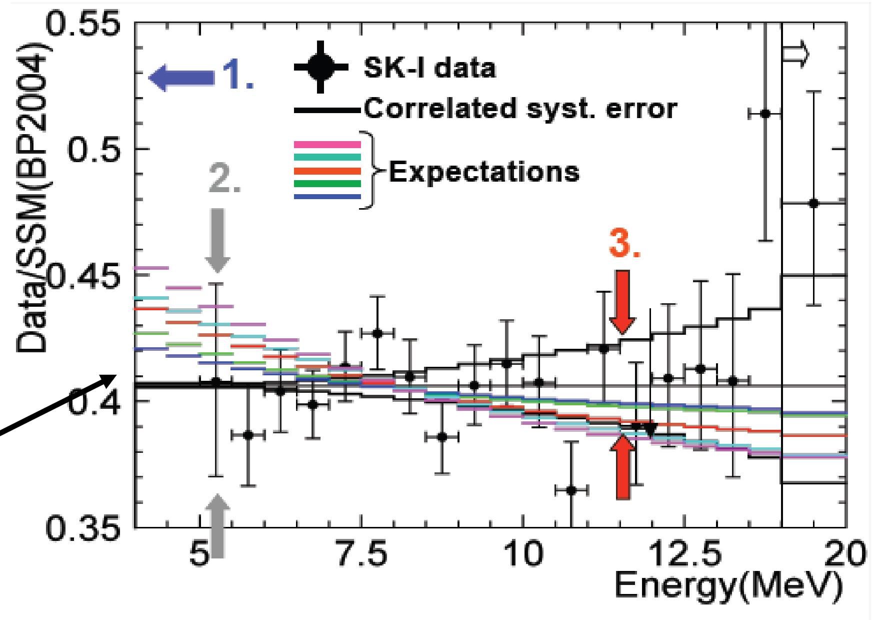
Ratio of observed electron energy spectrum and expectation from SSM







ϕ_{ES} = 2.35 ± 0.02 ± 0.08 [x10^6/cm^2/s]



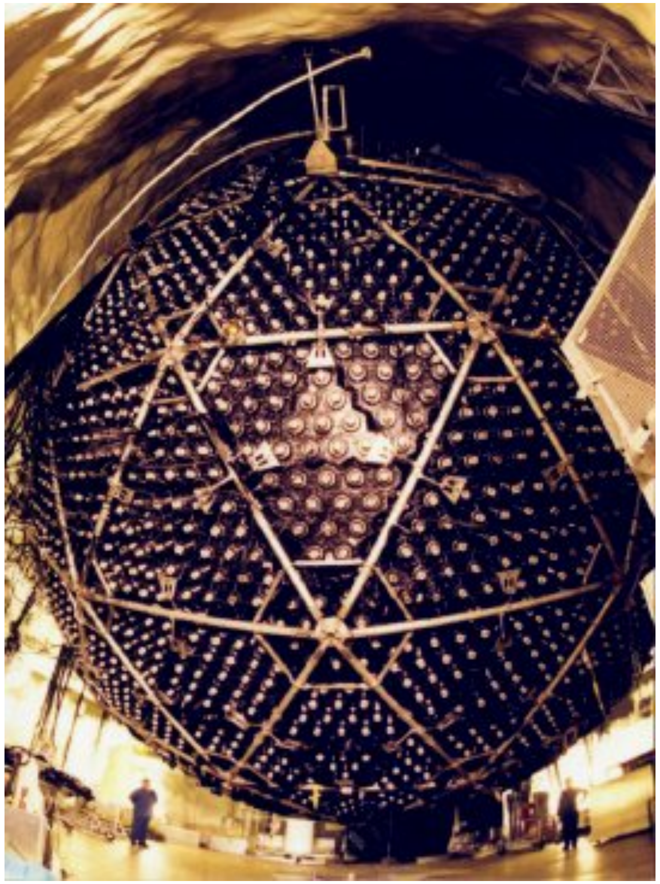
- SK measured a flux of solar neutrinos with energy > 5 MeV (from B^8) about 40% of that predicted by the SSM
- The reduction is almost constant up to 18 MeV

Ratio of observed electron energy spectrum and expectation from SSM

The decisive results: SNO (α: 1999 –Ω:2006)

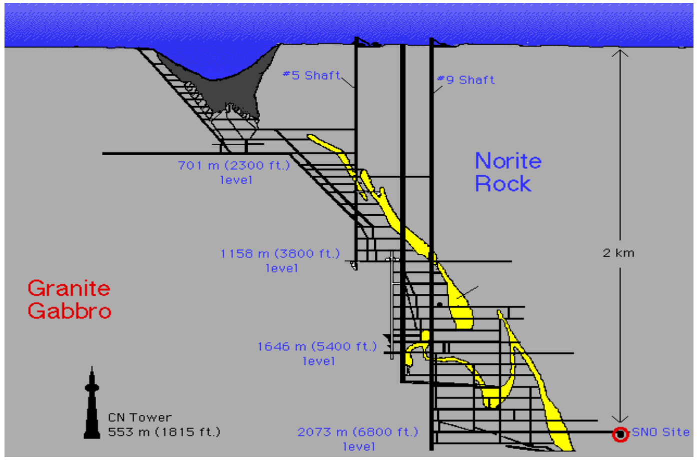
- 18m sphere, situated underground at about 2.5km underground, in Ontario
- 10,000 photomultiplier tubes (PMT)
- Each PMT collect Cherenkov light photons
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- Pure salt is added to increase sensitivity of NC reactions (2002)
- It can measure the flux of all neutrinos '$\Phi(\nu_x)$' and electron neutrinos '$\Phi(\nu_e)$'
- The flux of non-electron neutrinos

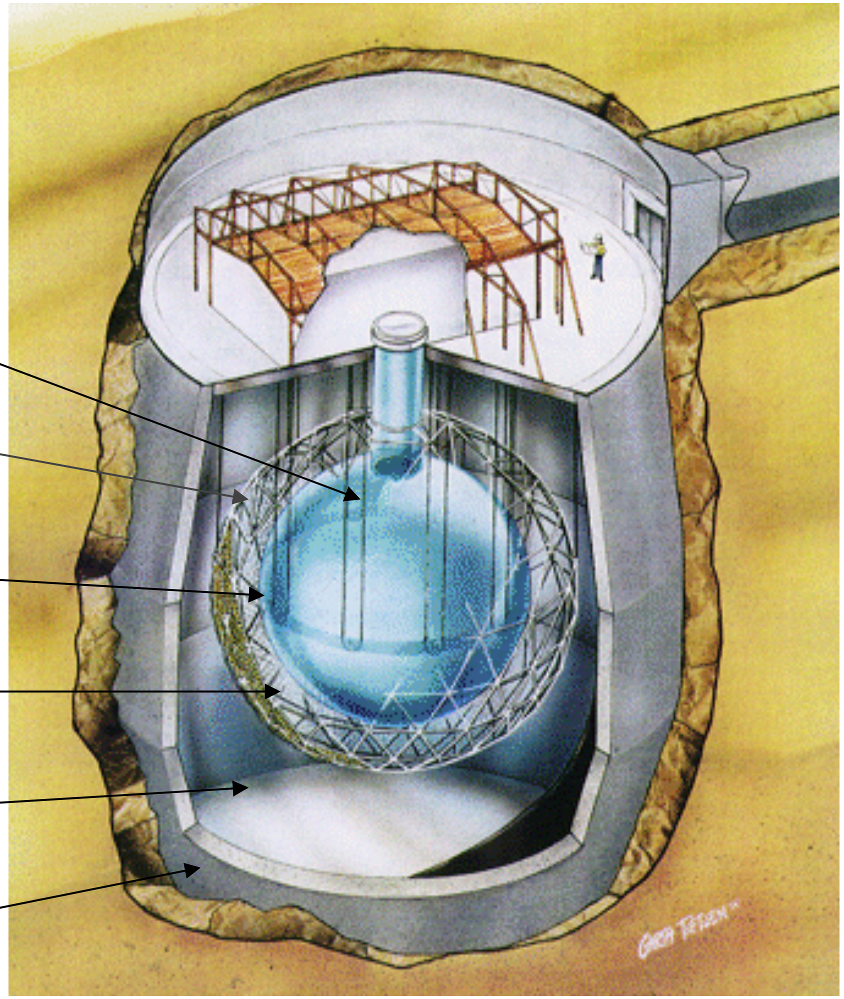
$$\Phi(\nu_\mu,\ \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$



- These fluxes can be measured via the 3 different ways in which neutrinos interact with heavy water

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

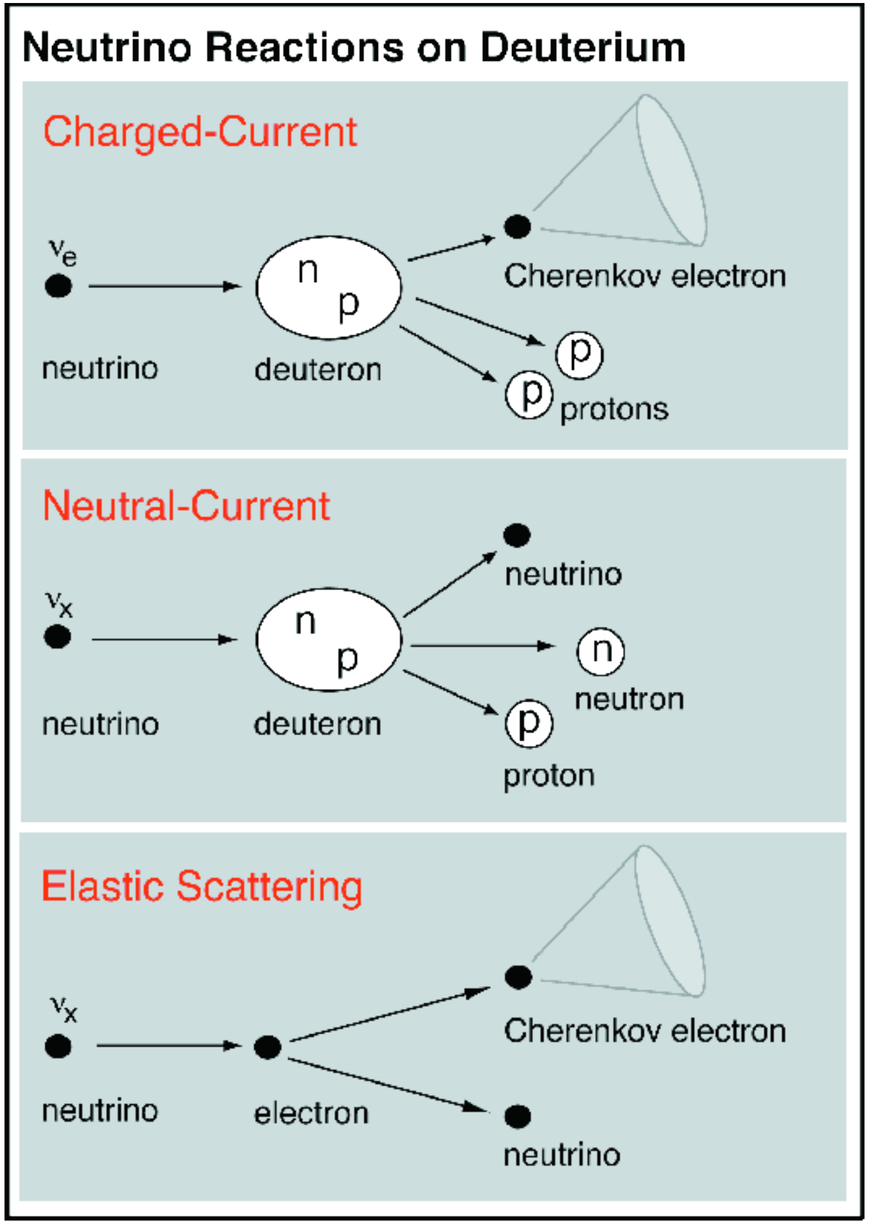
-Gives ν_e energy spectrum well
-Weak direction sensitivity ∝ 1-1/3cos(θ)
- ν_e only.
-SSM: 30 CC events day^{-1}

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types
- SSM: 30/day

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

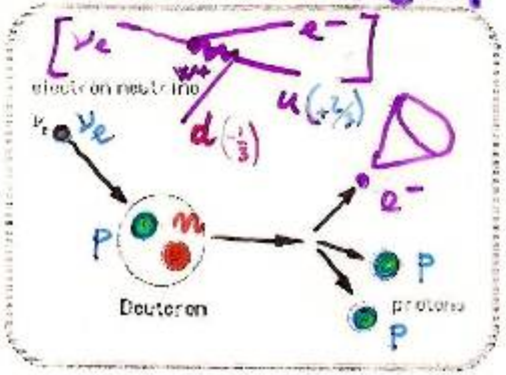
-Low Statistics (3/day)
-Mainly sensitive to ν_e, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



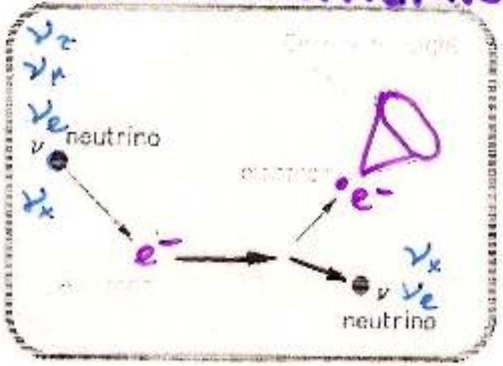
OBSERVABLE REACTIONS IN S.N.O.

Le Reazioni Osservabili in SNO

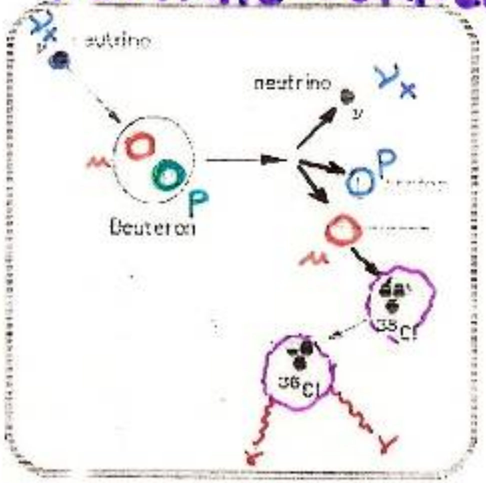
CHARGED CURRENT



ELASTIC SCATTERING



NEUTRAL CURRENT



$\nu_e + d \rightarrow p + p + e^-$ (CC) — Solo neutrini elettronici — ν_e ONLY

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES) — Tutti i neutrini — ν_x = ALL NEUTRINOS

$\nu_x + d \rightarrow n + p + \nu_x$ (NC) — Tutti i neutrini — ν_x = ALL NEUTRINOS

Neutrini prodotti da ^8B (E_ν<15 MeV)

Soglia Rivelatore 6.75 MeV — THRESHOLD @ 6.75 MeV

<u>Può essere separato il contributo dei diversi neutrini</u>

IT IS POSSIBLE TO SEPARATE ν_x CONTRIBUTIONS

⇓

<u>Indipendenza dalle previsioni del modello Solare</u>

INDIPENDENT FROM S. SOLAR MODEL

❑The 2001 results

❑ The ν_e's flux from ^8B decay is measured by the CC (1) reaction: $\phi^{CC}(\nu_e) = (1.75 \pm 0.24) \times 10^6\ cm^{-2}s^{-1}$

❑ Assuming no oscillations, the total ν flux inferred from the ES (3) reaction rate is:

❑$\phi^{ES}(\nu_x) = (2.39 \pm 0.50) \times 10^6\ cm^{-2}s^{-1}$ (SNO)

❑$\phi^{ES}_{SK}(\nu_x) = (2.32 \pm 0.08) \times 10^6\ cm^{-2}s^{-1}$ (SK)

❑The difference between the ^8B flux deduced from the ES and the CC rate at SNO and SK is:

❑$\Phi(\nu_\mu, \nu_\tau) = (0.57 \pm 0.17) \times 10^6\ cm^{-2}s^{-1}$ (3.3 σ)

❑This difference first shows that **there is a non-electron** flavour active neutrino component in the solar flux !

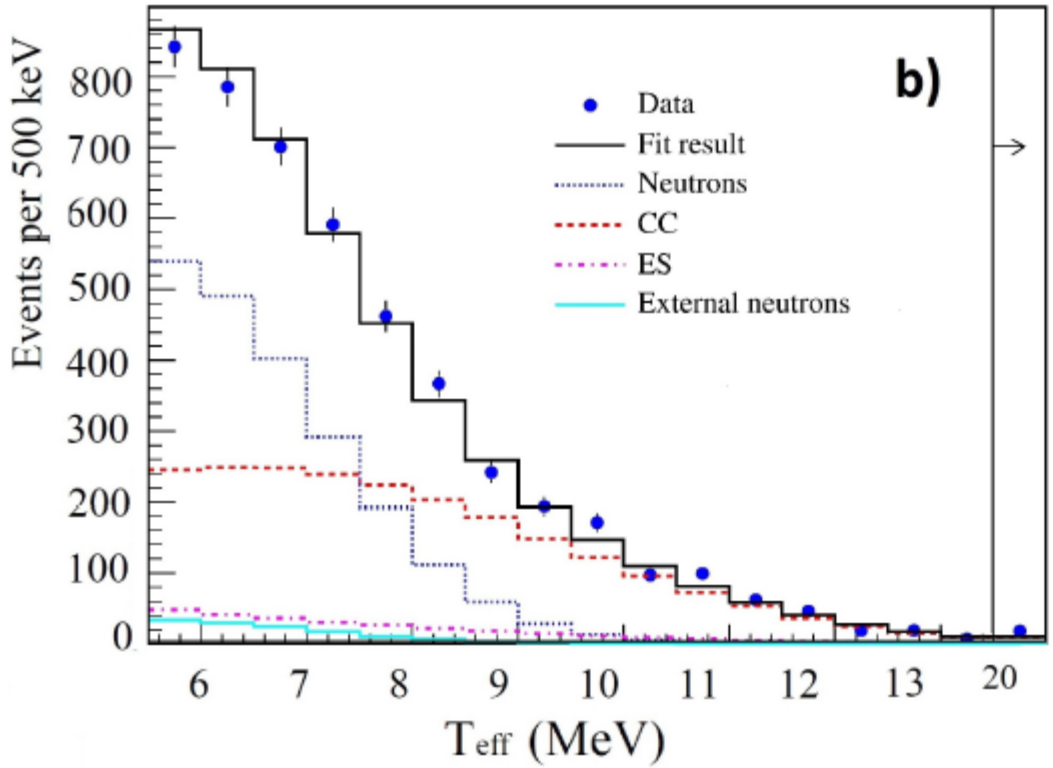
UNITS:
x 10^6 cm^{-2} s^{-1}

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\ (\text{syst})$$

$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\ (\text{stat}) \pm 0.38\ (\text{syst})$$

ATTESO: Bahcall et al. – SSM= **5.05±0.8**



Electron kinetic energy

2003 SNO Energy spectra (Salt data)

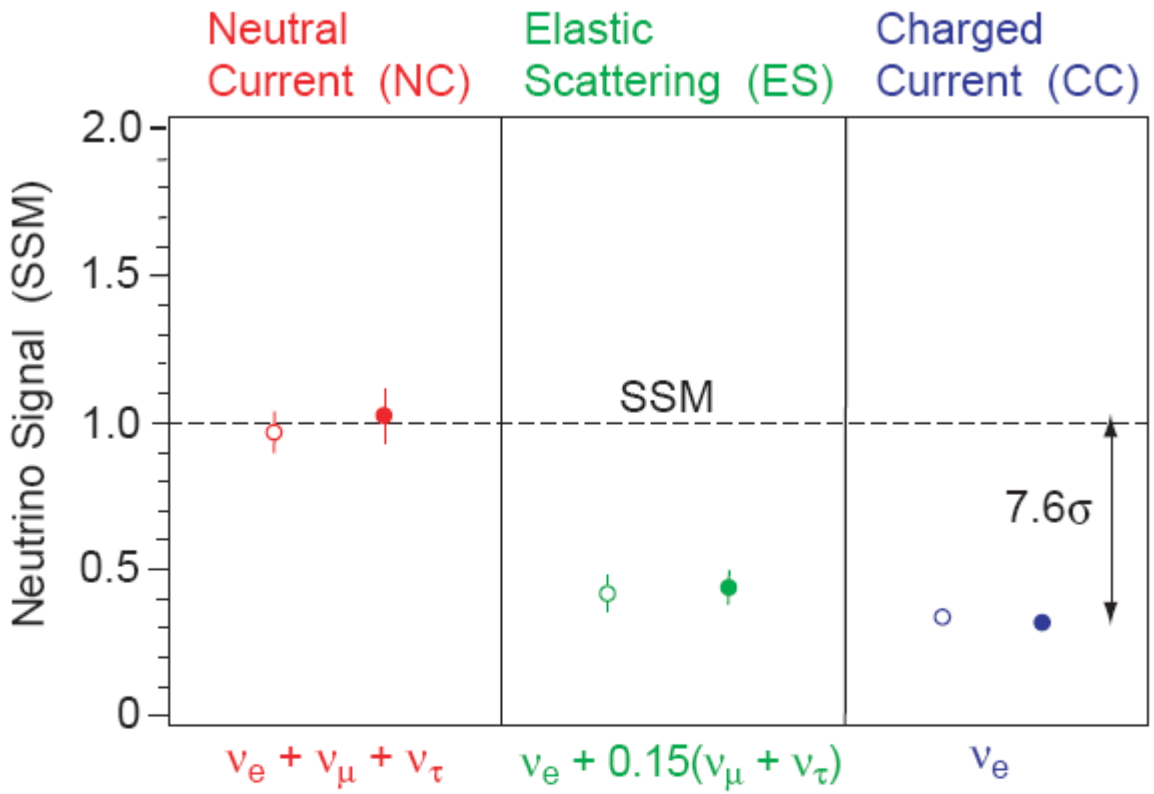
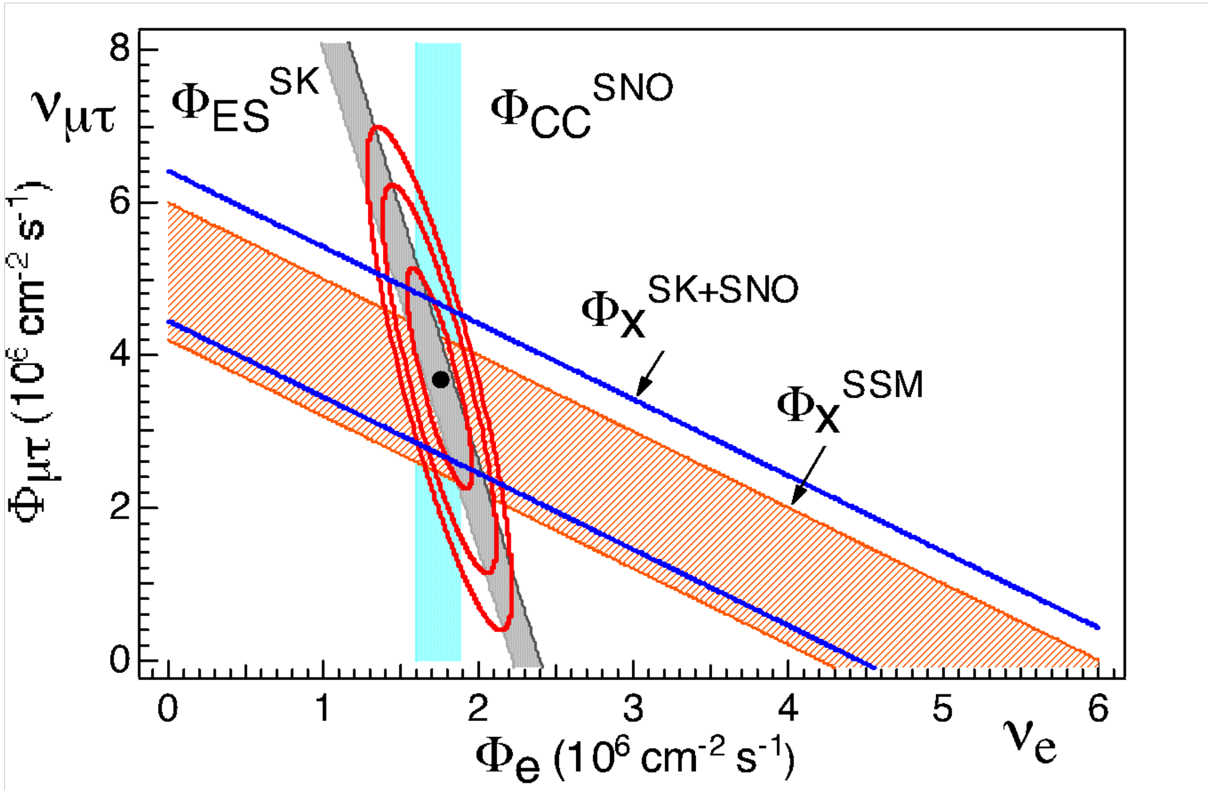


Figure 8: Evidence for neutrino flavor change seen by SNO. The open (filled) circles represent the 2003 SNO flux results, relative to the SSM, under the assumption of an undistorted (unconstrained) ^{8}B neutrino energy spectrum.

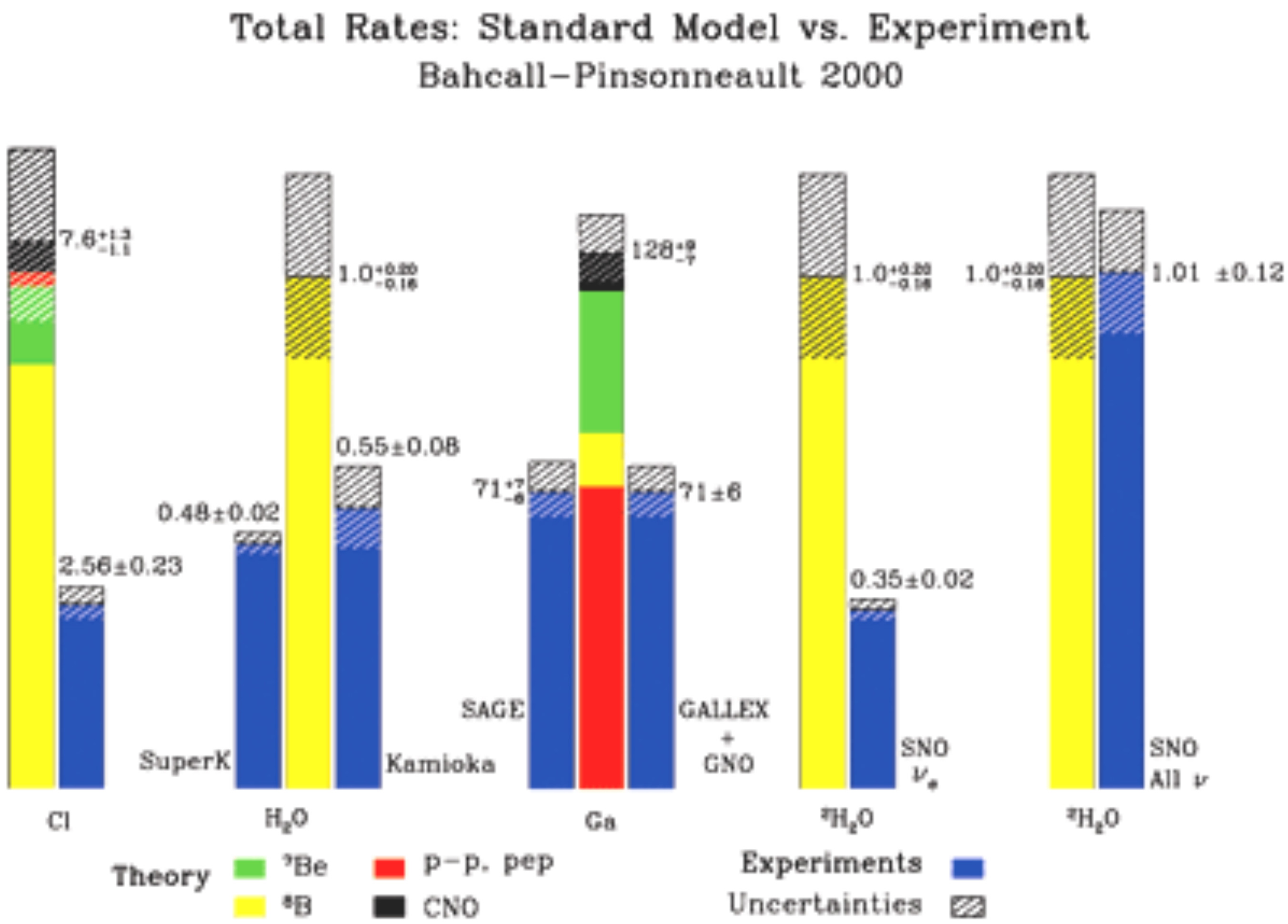
Solar Neutrino Problem



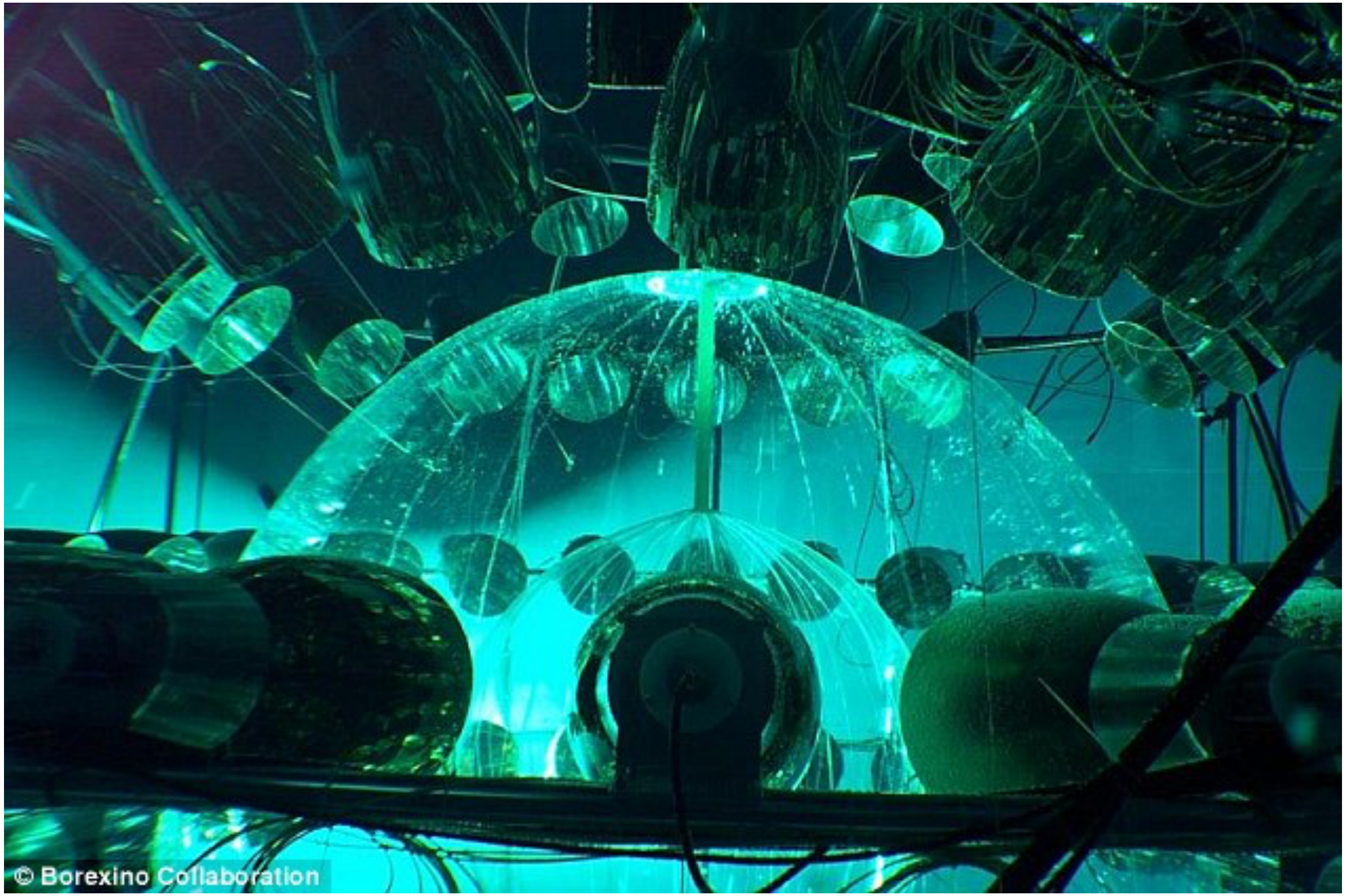
- The total flux of active ^8B neutrinos is:

$(5.44 \pm 0.99) \times 10^6\ cm^{-2}s^{-1}$, in agreement with SSM

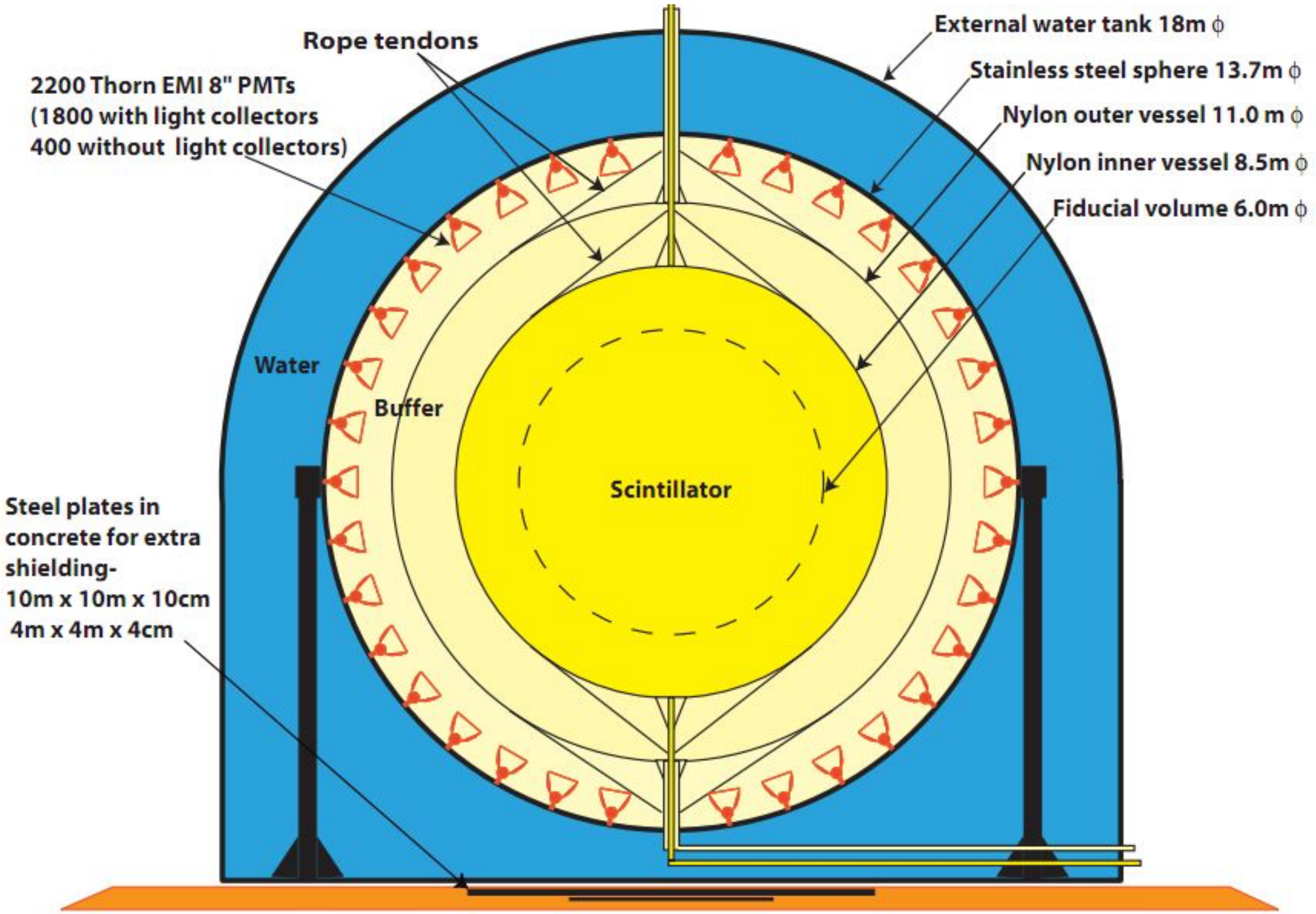
Solar Neutrino Problem



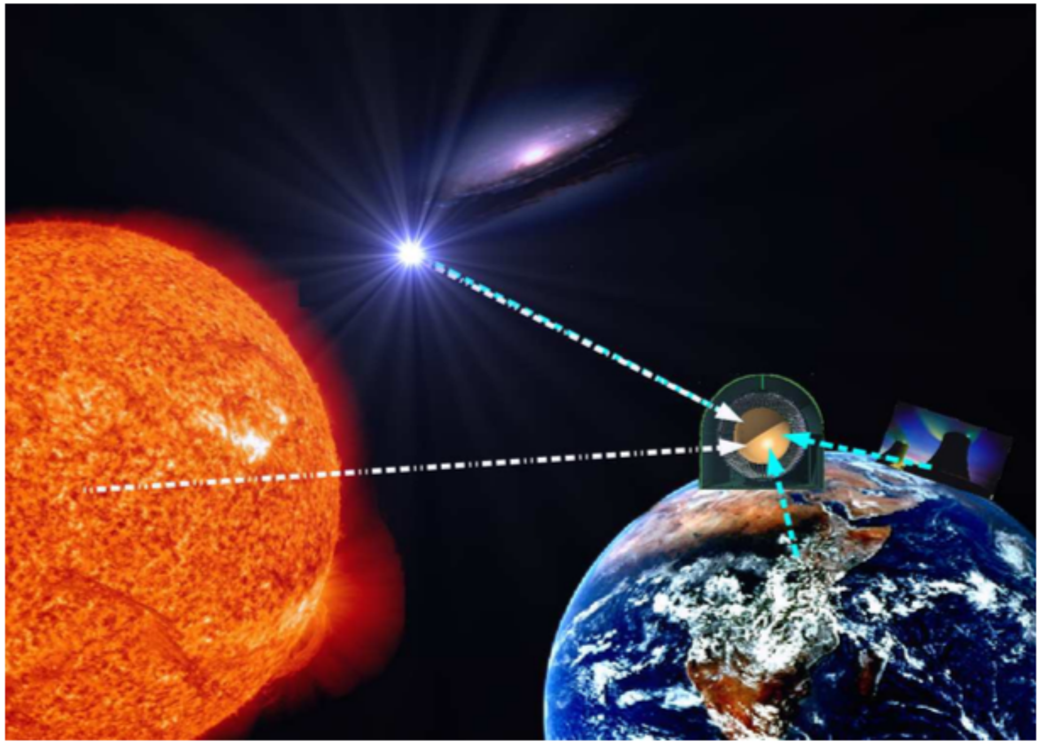
Borexino @LNGS



Borexino @LNGS



BOREXINO
Recent Solar And Terrestrial Neutrino Results



Werner Maneschg
on behalf of the Borexino Collaboration

Borexino: detector properties & design, and physics goals

Main properties:

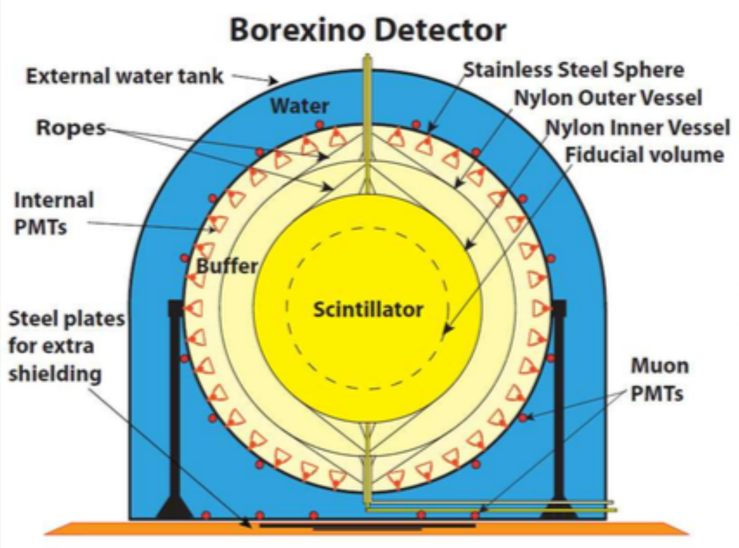
- Large volume organic liquid scintillator detector:
  - at LNGS (1.4 km overburden)
  - operational since May 2007
- Ultra low background (radiopurest environment ever measured)
- Real-time detection (time stamp and pulse shape for every event)
- Spectroscopy at low energies, typically between 0.1-15 MeV
- 3D position reconstruction

Main physics goals:

- Neutrinos from Sun
- Antineutrinos from Earth & reactors
- Sterile neutrinos (TH 23-07-15:13.5)
- SN-(anti)neutrinos & other exotic particles and processes

Nut shell profile:

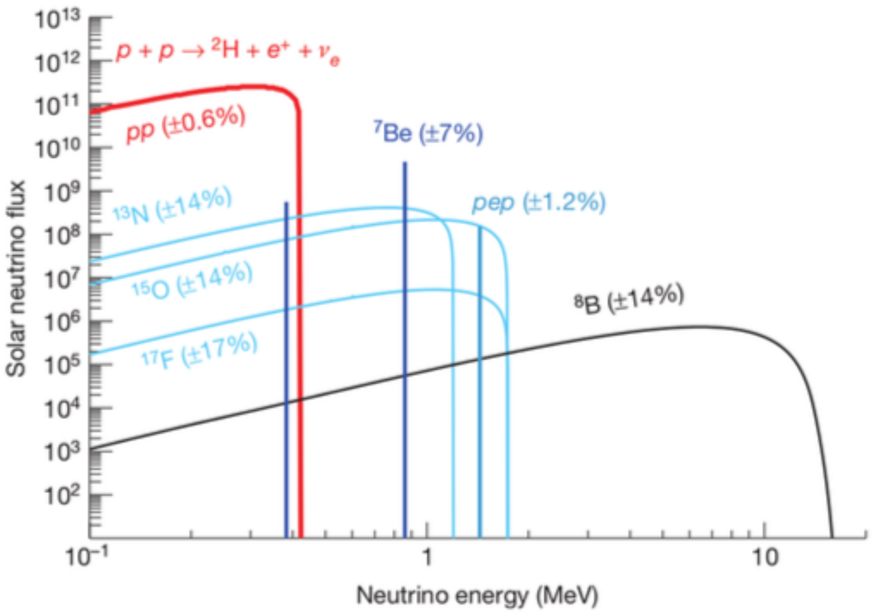
1. Water tank (2100 m^3):
   - Absorption of environmental γ rays and neutrons
   - μ Cherenkov detector (208 PMTs)
2. Stainless Steel Sphere:
   - 2212 PMTs, 1350 m^3, R=6.85 m
3. 2 buffer layers: PC+DMP
   - Outer R_2=5.50 m, Inner R_1=4.25 m
   - Shielding from external γ rays
4. Scintillator: 270 tons of PC+PPO



Solar neutrino fluxes (according to Standard Solar Model predictions)

Neutrino fluxes at 1 AU:

from simulations by A. Serenelli et al., Astrophys. J. 743, 24 (2011)



Units: [$cm^{-2}s^{-1}MeV^{-1}$] for continuum neutrino sources, [$cm^{-2}s^{-1}$] for mono-energetic neutrino sources.

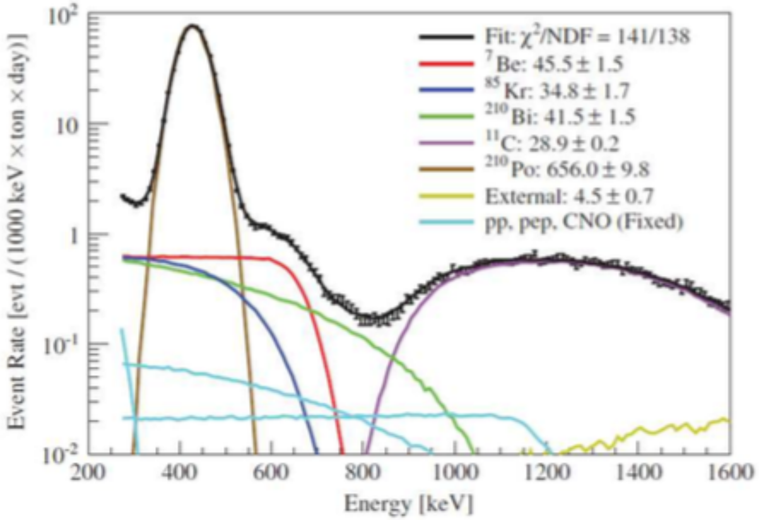
ν flux	GS98	AGSS09
pp	5.98(1±0.006)	6.03(1±0.006)
^{7}Be	5.00(1±0.07)	4.56(1±0.07)
pep	1.44(1±0.012)	1.47(1±0.012)
^{13}N	2.96(1±0.14)	2.17(1±0.14)
^{15}O	2.23(1±0.15)	1.56(1±0.15)
^{17}F	5.52(1±0.17)	3.40(1±0.16)
^{8}B	5.58(1±0.14)	4.59(1±0.14)

Factors: 10^{10} (pp), 10^{9} (^{7}Be), 10^{8} (pep, ^{13}N, ^{15}O), 10^{6} (^{8}B, ^{17}F); **Units**: $cm^{-2}s^{-1}$.

Solar neutrino measurements:
different obstacles: diff. background, detector response, energy threshold
sensitivity for different phenomena: neutrino osc. (incl. matter effects (MSW)), SSM metallicity scenarios

Solar ^{7}Be neutrino rate measurement

Averaged ^{7}Be-ν rate fitted with MC (ROI: 0.2-0.7 MeV)

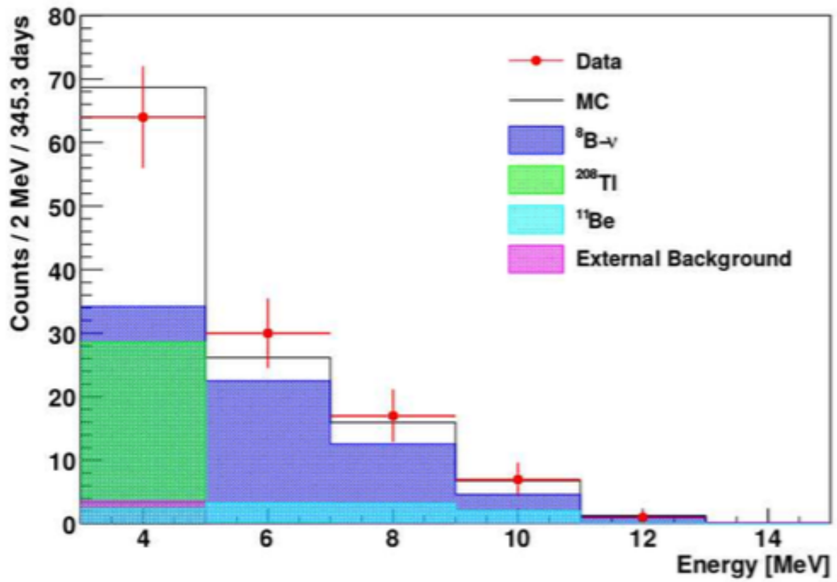


Results and remarks:

- Averaged rate: $R=(46 \pm 1.5(stat)^{+1.5}_{-1.6}(sys))$ c/d/100 ton (uncertainty $\pm 5\%$)
  Comparison to SSM predictions:
  - Without osc.: (74 ± 5) c/d/100 ton (5σ exclusion)
  - With osc.: 44 (High-met.) and 48 (Low-met.) c/d/100 ton
- Day-Night asymmetry: $(N-D)/((N+D)/2) = 0.001 \pm 0.012(stat) \pm 0.007(sys)$ ($8.5\,\sigma$ exclusion of LOW osc. solution)
- 7% Annual modulation: according to rate-vs-time analysis: $T=(1.01 \pm 0.07)$ yr; $\epsilon=0.0398 \pm 0.0102 \rightarrow$ expected value within $2\,\sigma$

Solar ^{8}B neutrino rate measurement

Data vs. MC of ^{8}B recoil energy spectrum (ROI: 3-15 MeV)

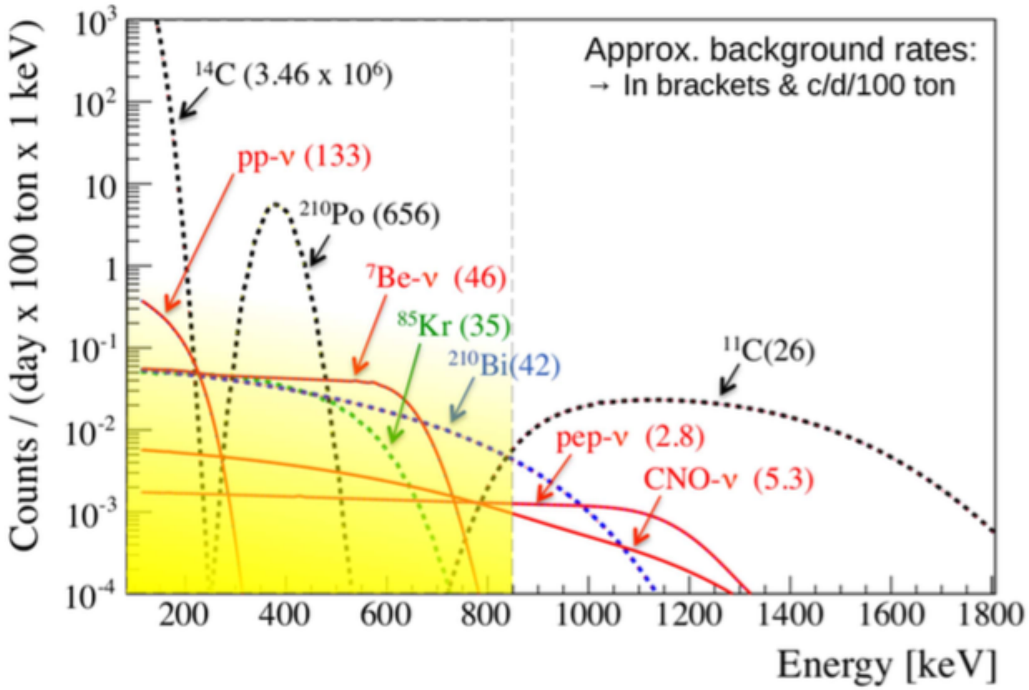


Results and remarks:

- Challenging: low neutrino rate, many small background components
- Rate above 3 MeV: 0.217±0.038(stat)±0.008(syst) c/d/100ton
- Flux at 1 AU: $(2.7 \pm 0.4 \pm 0.1) \times 10^6$ cm^{-2} s^{-1}
  → good agreement with SuperKamiokaNDE and SNO
  → confirmation of MSW-LMA solution for oscillation in vacuum/matter
- Data set: used 488 d; new analysis with multiple statistics ongoing

Towards the detection of solar pp neutrinos

pp recoil energy spectrum (ROI: 0.05-0.27 MeV)



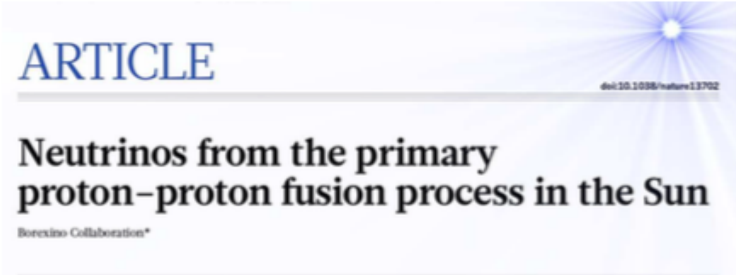
pp neutrinos:

Endpoint energy E_{mx}:
$0 < E_{mx} < 420$ keV
$\rightarrow E_{rec} < 264$ keV
Energy threshold E_{th}:
Borexino: $E_{th} \sim 50$ keV
Radiochem. experiments:
$E_{th} \sim 233$ keV

Main obstacles:

- Above ~240 keV: decays of ^{85}Kr, ^{210}Bi (^{210}Pb daughter)
- Below ~240 keV: decays of ^{14}C, ^{14}C pile-ups

Solar pp neutrino rate measurement (August 2014)


ARTICLE

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

Nature, Vol. 512, August 28, 2014

Results and remarks:

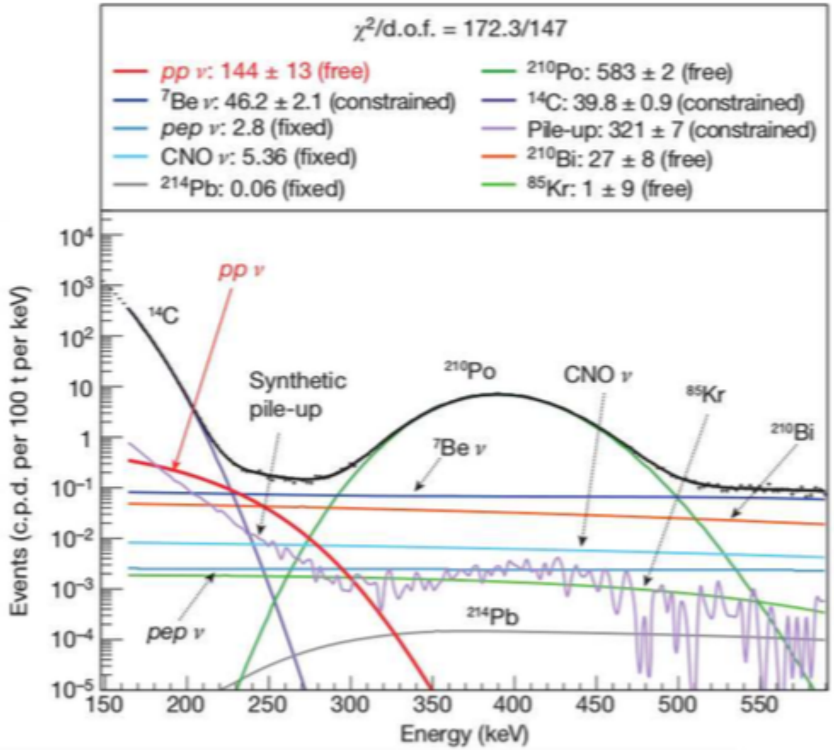
- **Rate:**
  144±13(stat)±10(sys) c/d/100 ton
  (10σ exclusion of pp ν absence)
- **Robustness of analysis:**

Parameter	Systematics:
energy estimator fit energy range data selection pile-up evaluation	±7%
fiducial mass	±2%

- **Check** of residual background

Measured recoil energy spectrum

Fit in (165-590) keV



Rates in [c/d/100 ton], except for ^{14}C [c/s/100 ton]

Astrofisica Nucleare e Subnucleare

Neutrino Oscillations

Scoperta graduale

1964. Homestake + Modello Solare di J. Bahcall

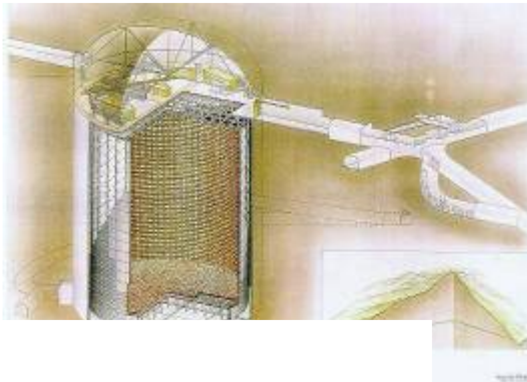
flusso di ν_e dal sole ≈1/3 dell'aspettato ha colpa il sole, la fisica nucleare, il neutrino?

1997. GALLEX + LUNA

il colpevole è il neutrino

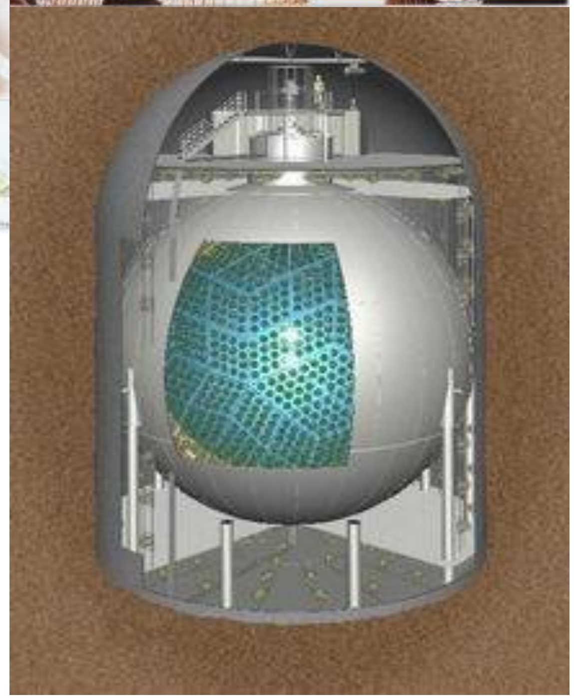
1998. SuperKAMIOKANDE

scoperta oscillazioni: scomparsa nei ν_μ da atmosfera



2002. SNO

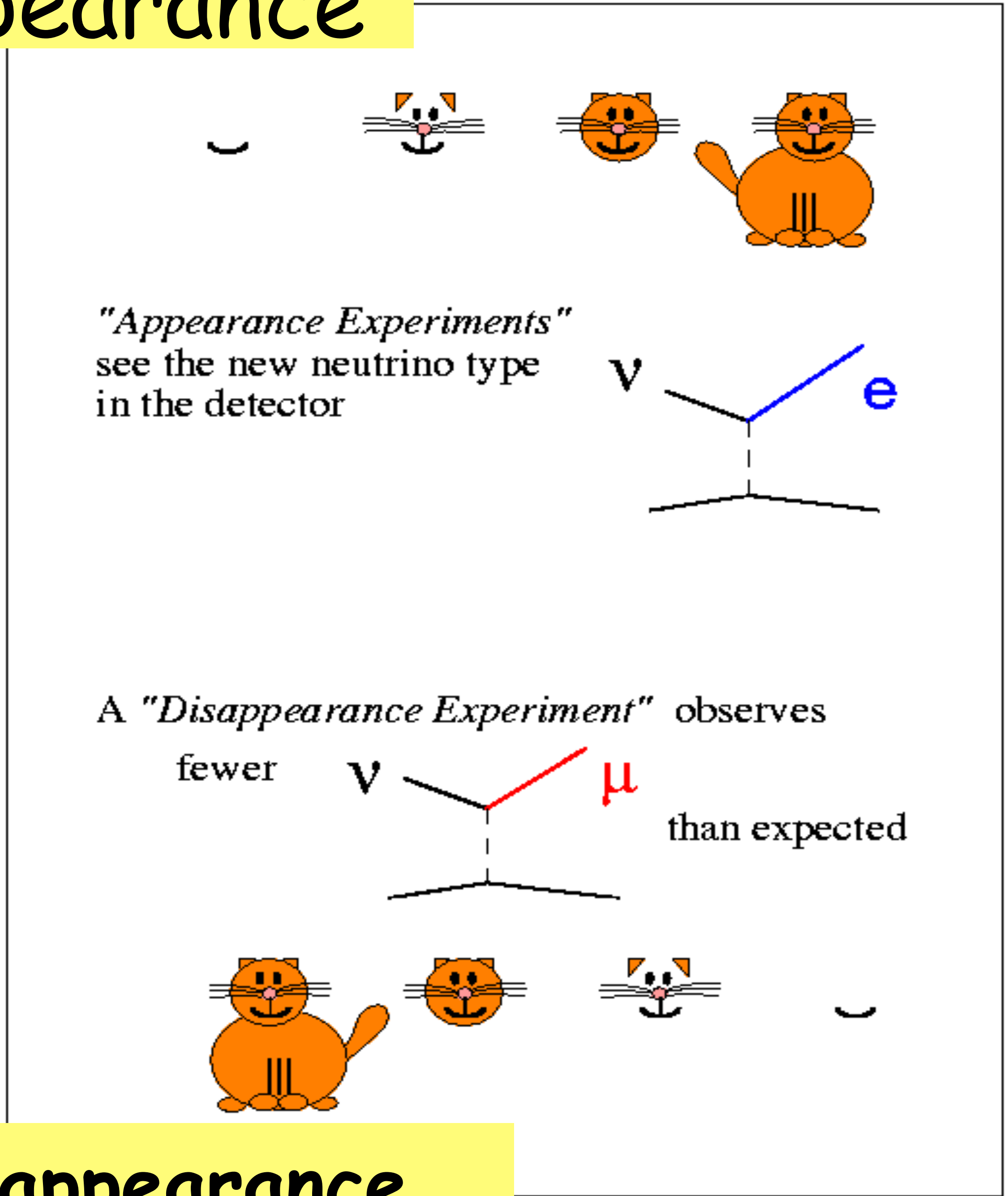
osservazione di comparsa di ν_μ e ν_τ dal sole, tanti quanti sono i ν_e scomparsi



2002. KamLAND

osservazione dell'oscillazione "solare" su ≠ ν_e nel vuoto

Comparsa/Appearance



Scomparsa/Desappearance

Oscillazioni dei Neutrini

- Idea della massa dei neutrini suggerita per la prima volta da Bruno Pontecorvo

I Neutrini Interagiscono (Produzione o Rivelazione) come Autostati dell'Interazione Debole

$|\nu_e>$, $|\nu_\mu>$, $|\nu_\tau>$ =Autostati dell' Interazione Debole

$|\nu_1>$, $|\nu_2>$, $|\nu_3>$ =Autostati di Massa (H → Evoluzione t)

- I Neutrini si propagano (evolvono) come sovrapposizione di autostati di **massa**: ***MESCOLAMENTO***

Mescolamento tra neutrini: p.es. due famiglie

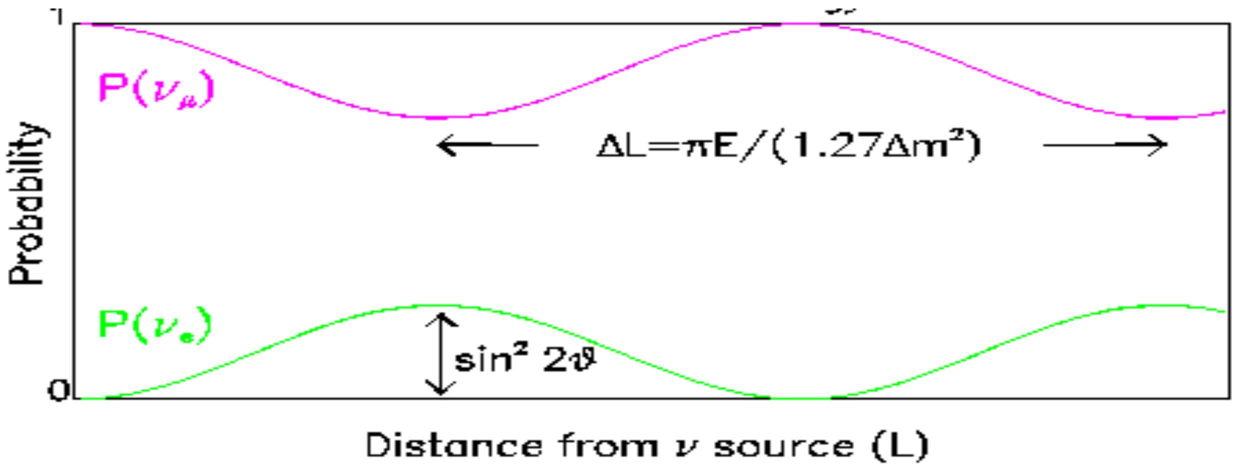
$|\nu_e\rangle = \cos\theta\, |\nu_1\rangle + \sin\theta\, |\nu_2\rangle$

$|\nu_\mu\rangle = -\sin\theta\, |\nu_1\rangle + \cos\theta\, |\nu_2\rangle$

θ = mixing angle
Angolo di mescolamento

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

- **Distanza percorsa** L=ct (Km)
- **Differenza di massa quadra** $\Delta m^2 = m_2^2 - m_1^2$ (eV^2)
- **Energia del neutrino** Eν (GeV)



Vacuum flavor oscillations: mass and weak eigenstates

flavor states	$\vert\nu_e>$	$\leftrightarrow$	$\vert\nu_L>$	m_L	mass states
	$\vert\nu_\mu>$		$\vert\nu_H>$	m_H	

Noncoincident bases $\Rightarrow$ oscillations down stream:

$$\begin{aligned} |v_e> &= \cos\theta|\nu_L> + \sin\theta|\nu_H> \\ |v_\mu> &= -\sin\theta|\nu_L> + \cos\theta|\nu_H> \end{aligned}$$

vacuum mixing angle

$$\begin{aligned} |\nu_e^k> &= |\nu^k(x=0,t=0)> \qquad E^2 = k^2 + m_i^2 \\ |\nu^k(x\sim ct,t)> &= e^{ikx}\left[e^{-iE_Lt}\cos\theta|\nu_L> + e^{-iE_Ht}\sin\theta|\nu_H>\right] \\ |<\nu_\mu|\nu^k(t)>|^2 &= \sin^2 2\theta \sin^2\left(\frac{\delta m^2}{4E}t\right), \qquad \delta m^2 = m_H^2 - m_L^2 \end{aligned}$$

ν_μ appearance downstream $\Leftrightarrow$ vacuum oscillations

Can slightly generalize this

$$|\nu(0)\rangle \;\rightarrow\; a_e(0)|\nu_e\rangle + a_\mu(0)|\nu_\mu\rangle$$

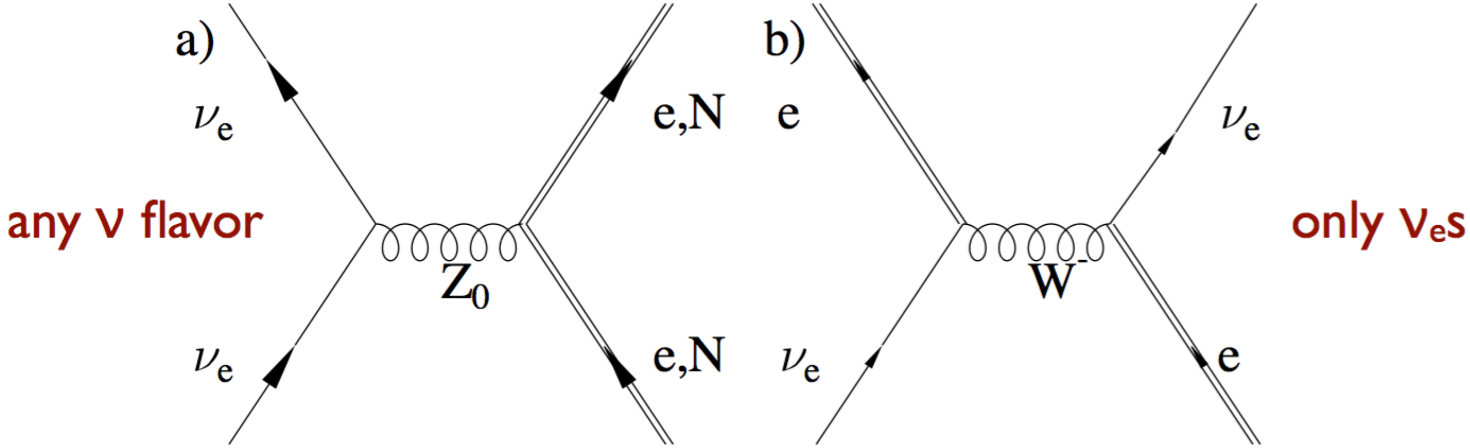
with the subsequent evolution downstream governed by

$$i\frac{d}{dx}\begin{pmatrix} a_e(x) \\ a_\mu(x) \end{pmatrix} = \frac{1}{4E}\begin{pmatrix} -\delta m^2 \cos 2\theta & \delta m^2 \sin 2\theta \\ \delta m^2 \sin 2\theta & \delta m^2 \cos 2\theta \end{pmatrix}\begin{pmatrix} a_e(x) \\ a_\mu(x) \end{pmatrix}$$

vacuum m_ν^2 matrix

This problem familiar from hadronic physics: the Cabibbo angle and CKM matrix.

solar matter generates a flavor asymmetry



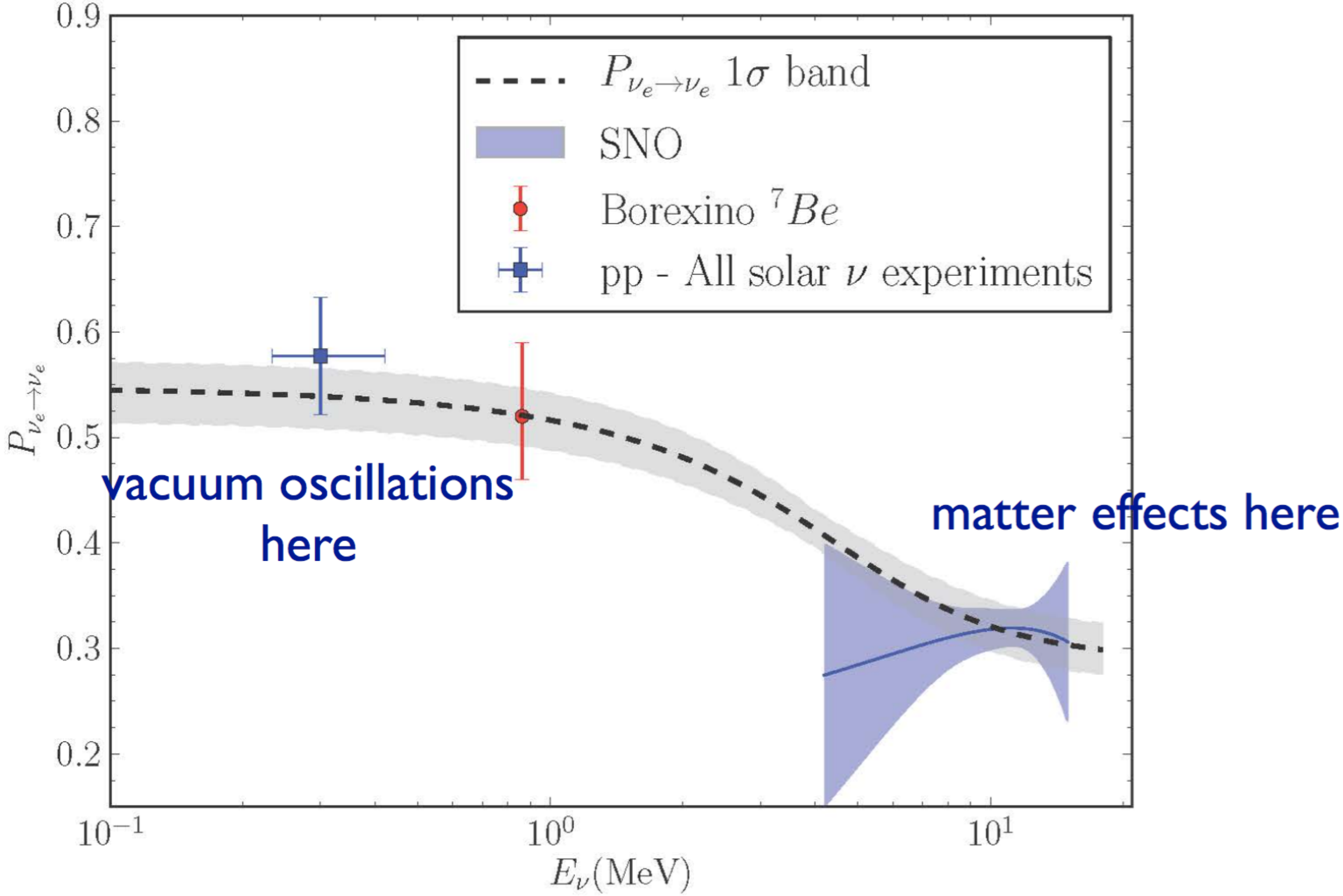
- modifies forward scattering amplitude: flavor-dependent index of refraction

- the affect is proportional to the (changing) solar electron density

- makes the electron neutrino heavier at high density

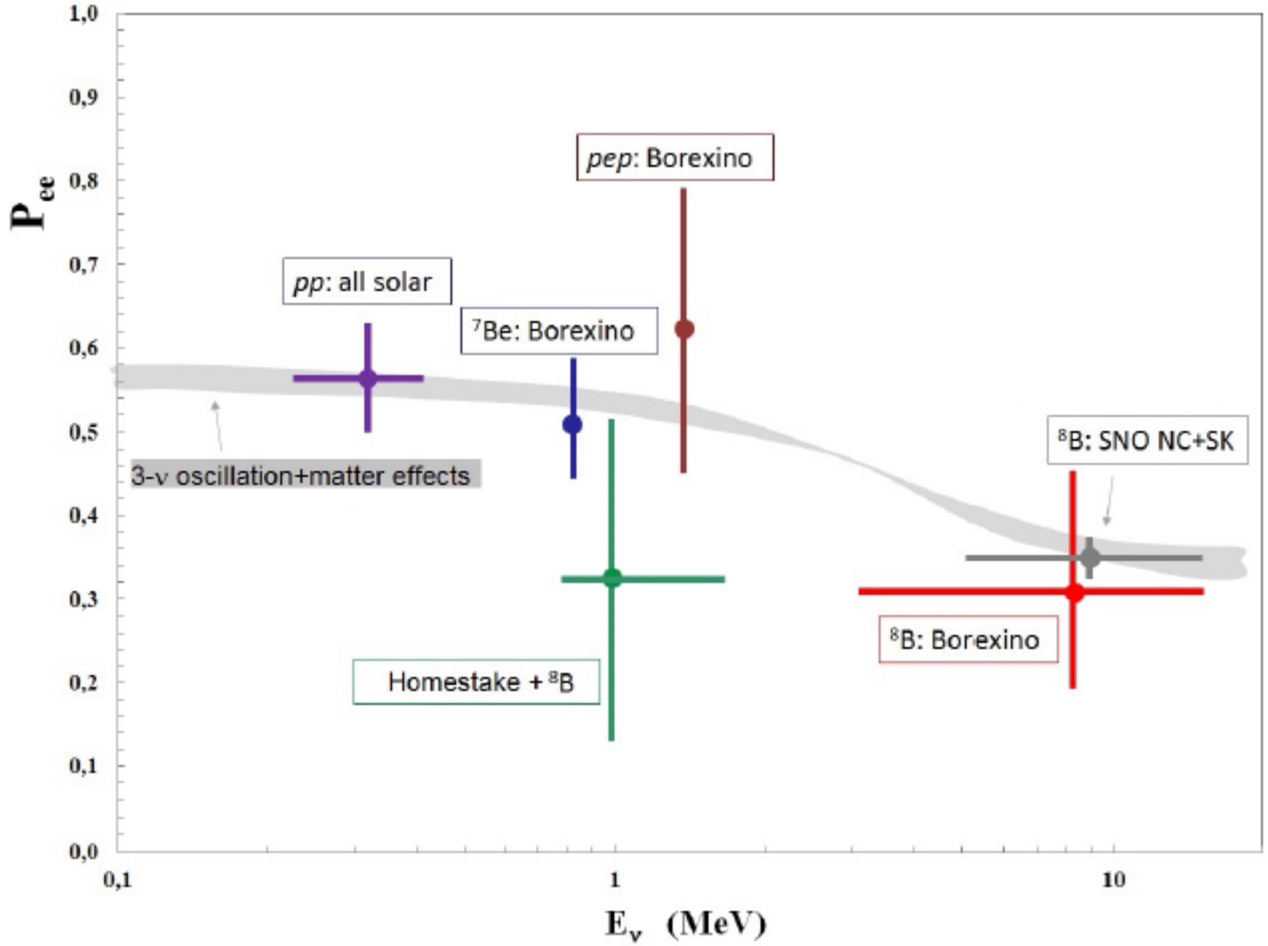
$$m_{\nu_e}^2 = 4E\sqrt{2}G_F \ \rho_e(x)$$

from Art McDonald



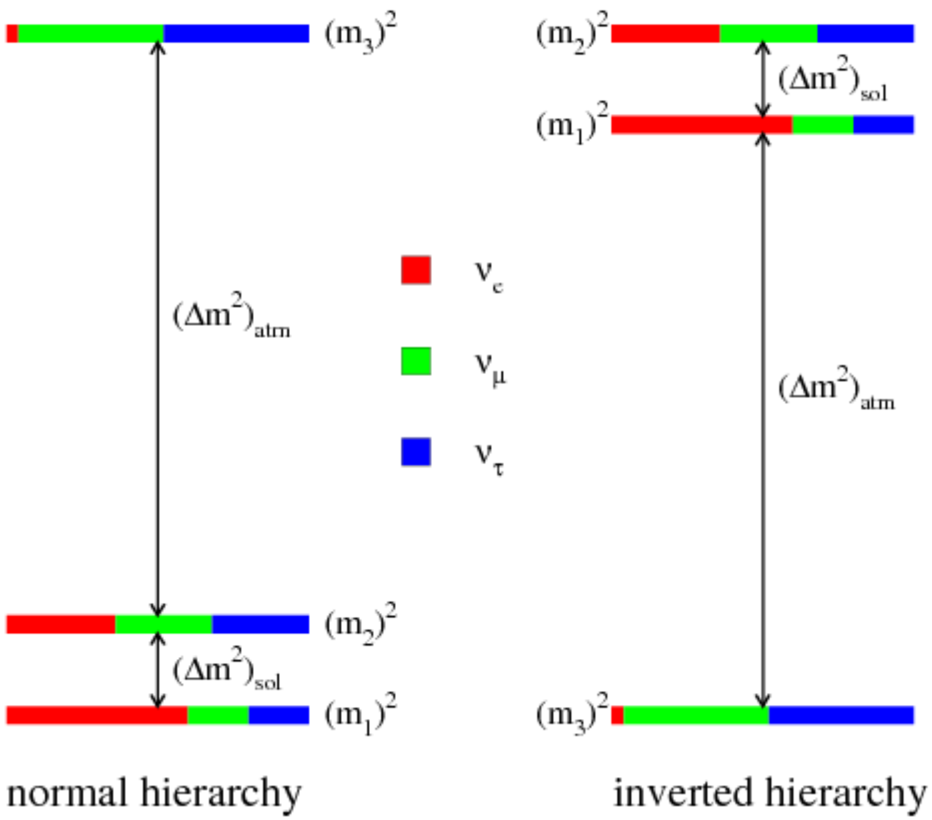
Matter effects produce a characteristic energy-dependence in the ν_e survival probability, in accord with experiments

Neutrino oscillations and the Sun



Neutrino parameters

Parameter	best-fit value ($\pm 1\sigma$)
$\Delta m^2_{\odot}$	$(7.58^{+0.22}_{-0.26}) \times 10^{-5}$ eV^2
Δm^2_{atm}	$(2.35^{+0.12}_{-0.09}) \times 10^{-3}$ eV^2
$\sin^2\theta_{12}$	$0.306^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$	0.0251 ± 0.0034



Astrofisica Nucleare e Subnucleare

The Sun in Gamma-rays

OSSE detector

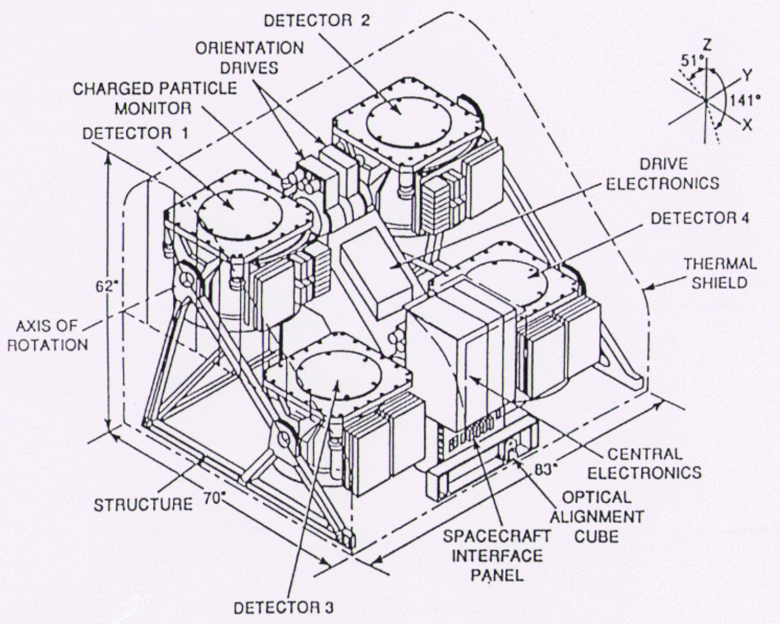
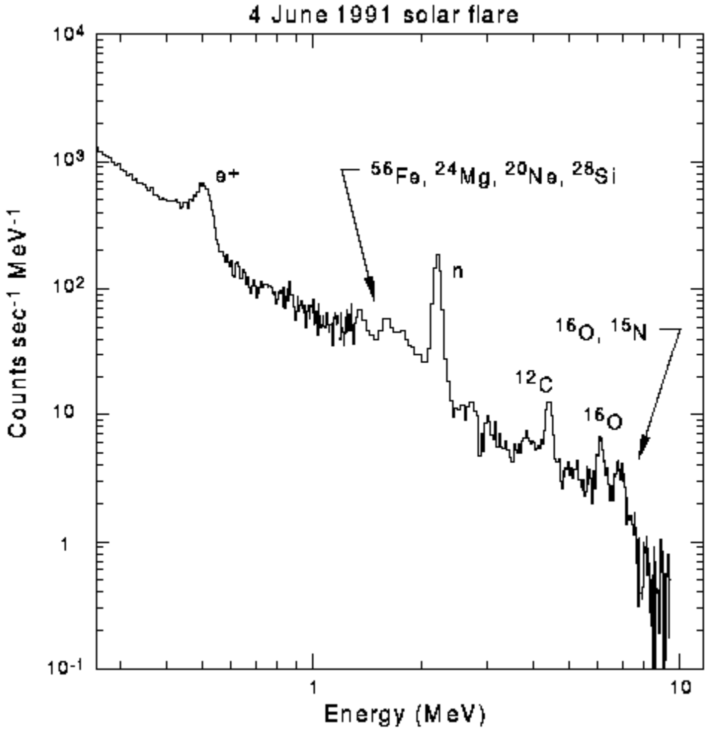


Figure II -1 The Oriented Scintillation Spectrometer Experiment (OSSE)

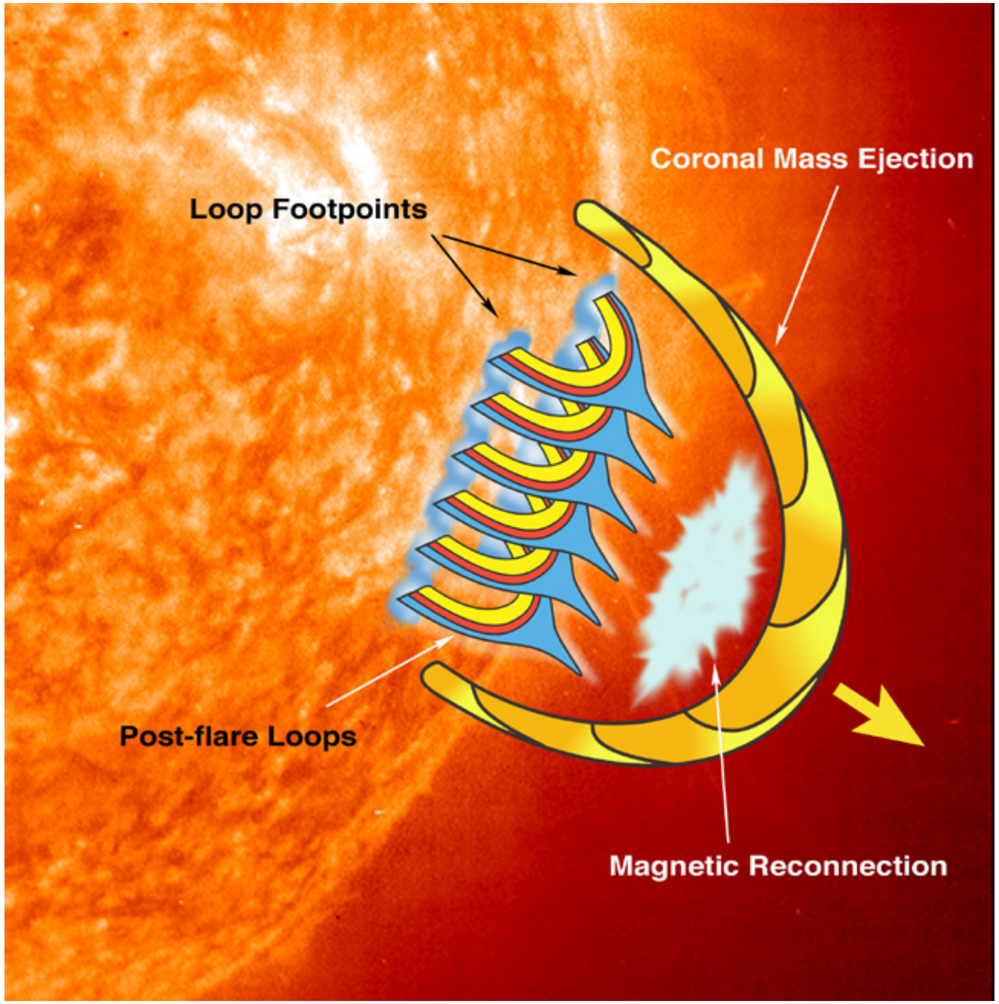
The Oriented Scintillation Spectrometer Experiment (OSSE) measured the distribution of the energy emitted from a number of gamma-ray sources, and as such studied nuclear lines in solar flares, radioactive decay of nuclei in supernova remnants, and matter-antimatter annihilation taking place near the center of our galaxy.
OSSE consisted of four NaI scintillation crystals, and was sensitive to gamma rays with energies ranging from 50 keV to 10 Mev. Each of the detectors could be pointed individually. For most instances, observations of a gamma ray source were alternated with observations of nearby blank sky so as to be able to determine the background gamma ray emission.

The Compton Gamma Ray Observatory



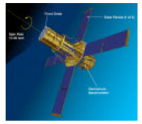
On June 4, 1991, the OSSE instrument observed a bright high-energy flare from an intensely active region of the sun. The energy spectrum of the flare shown in this slide indicates that solar flares accelerate particles to extremely high energies causing interactions which produce nuclear emission lines from excited atomic nuclei of Fe, Mg, Ne, Si, C, O, and N, along with emission lines from the formation of deuterium by neutron capture (labeled "n" in the slide) and electron-positron annihilation (labeled "e+").

Solar Flares

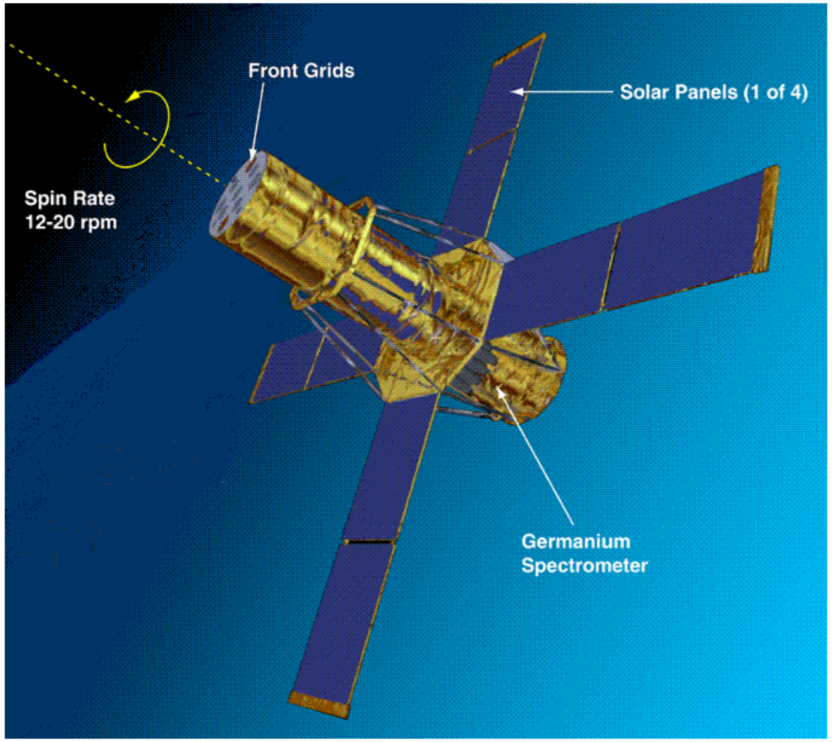


Solar Flares in Gamma-rays

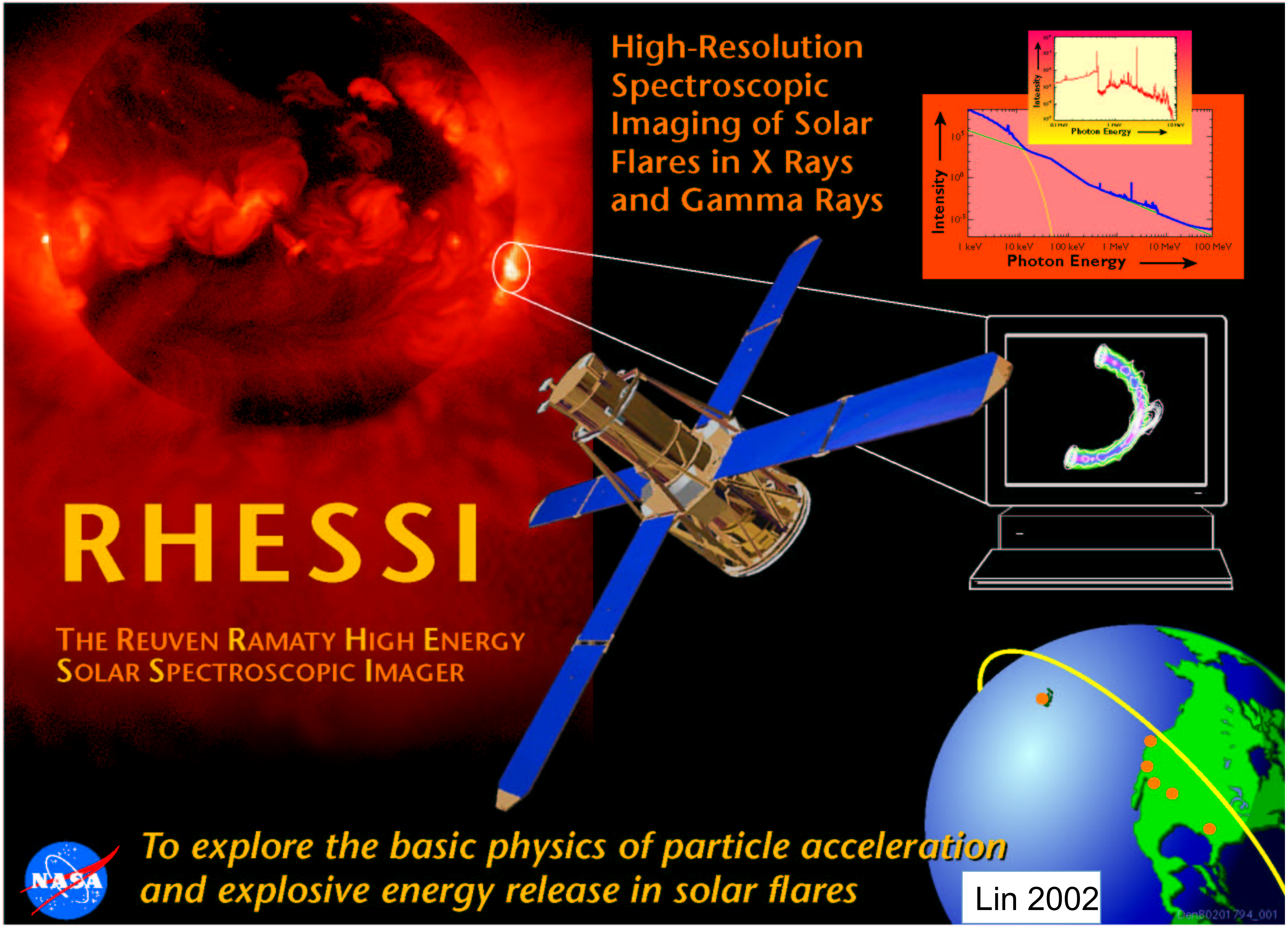
Solar γ-Ray Physics Comes of Age



The High Energy Solar Spectroscopic Imager



Share 2001



High-Resolution Spectroscopic Imaging of Solar Flares in X Rays and Gamma Rays
Intensity
Photon Energy
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
RHESSI
THE REUVEN RAMATY HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER
To explore the basic physics of particle acceleration and explosive energy release in solar flares
NASA
Lin 2002

HESSI Science Objective

To explore the basic physics of particle acceleration and explosive energy release in solar flares

- Impulsive Energy Release in the Corona
- Acceleration of Electrons, Protons, and Ions
- Plasma Heating to Tens of Millions of degrees
- Energy and Particle Transport and Dissipation

Lin 2002

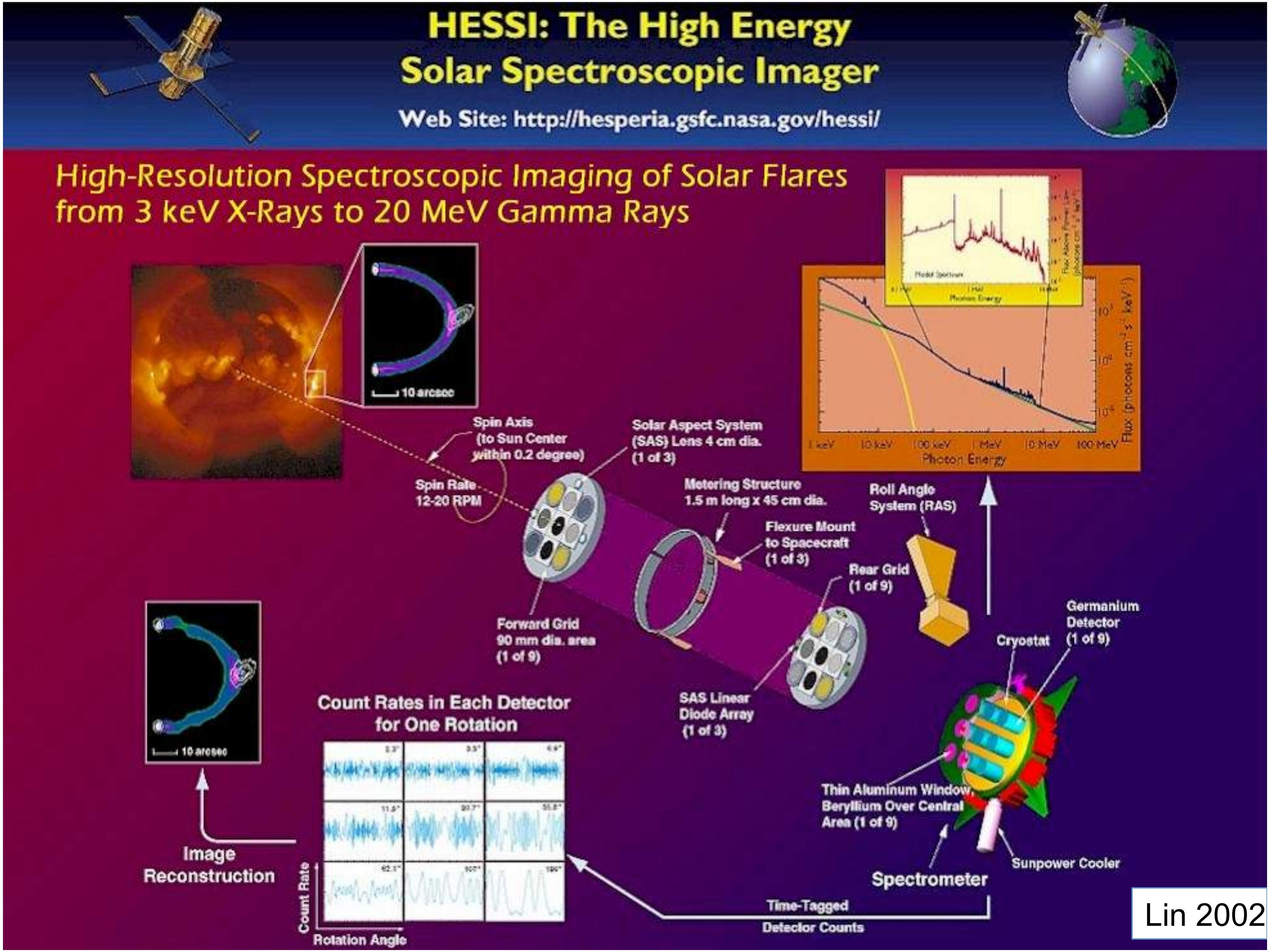
A1309.03

HESSI Primary Observations

- Hard X-ray Images
  - Angular resolution as fine as 2 arcseconds
  - Temporal resolution as fine as 10 ms
  - Energy resolution of <1 keV to ~3 keV (FWHM)
- High Resolution X-ray and Gamma-ray Spectra
  - ~keV energy resolution
  - To energies as high as 15 MeV

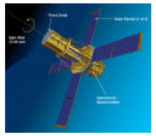
Lin 2002

A1309.05

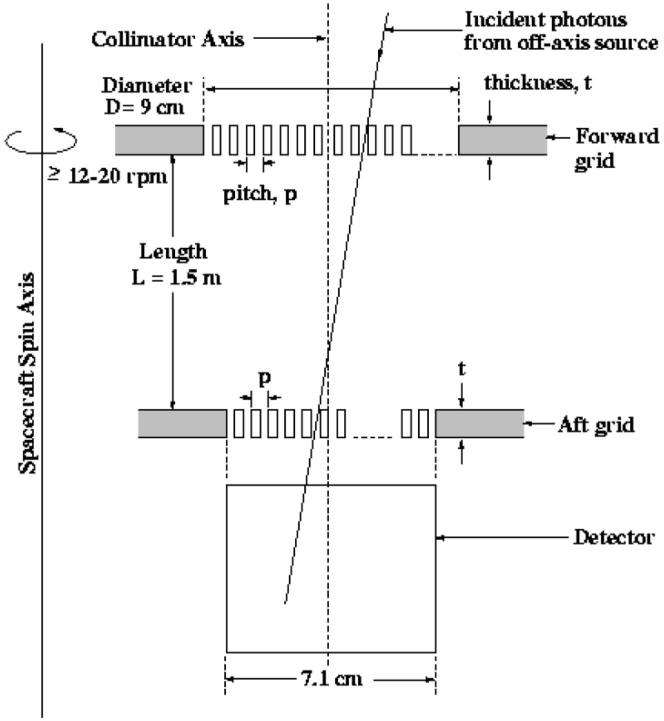

HESSI: The High Energy
Solar Spectroscopic Imager
Web Site: http://hesperia.gsfc.nasa.gov/hessi/
High-Resolution Spectroscopic Imaging of Solar Flares
from 3 keV X-Rays to 20 MeV Gamma Rays
10 arcsec
Spin Axis (to Sun Center within 0.2 degree)
Spin Rate 12-20 RPM
Solar Aspect System (SAS) Lens 4 cm dia. (1 of 3)
Metering Structure 1.5 m long x 45 cm dia.
Flexure Mount to Spacecraft (1 of 3)
Roll Angle System (RAS)
Rear Grid (1 of 9)
Forward Grid 90 mm dia. area (1 of 9)
SAS Linear Diode Array (1 of 3)
Germanium Detector (1 of 9)
Cryostat
Thin Aluminum Window, Beryllium Over Central Area (1 of 9)
Sunpower Cooler
Spectrometer
Time-Tagged Detector Counts
Count Rates in Each Detector for One Rotation
Count Rate
Rotation Angle
Image Reconstruction
10 arcsec
Photon Energy
Flux (photons cm⁻² s⁻¹ keV⁻¹)
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
Lin 2002

Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



HESSI IMAGING SYSTEM



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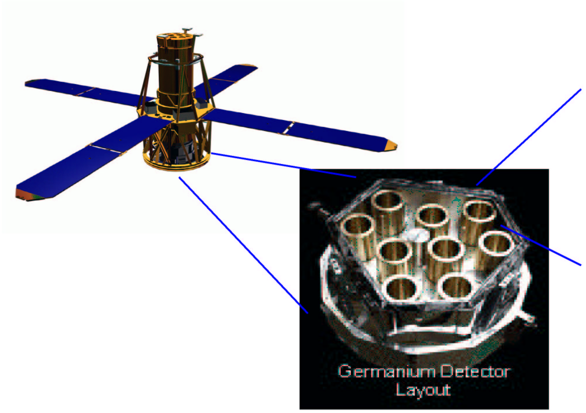
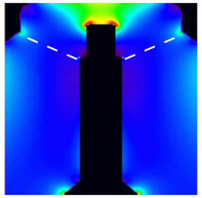
RHESSI

THE RHESSI SPECTROMETER



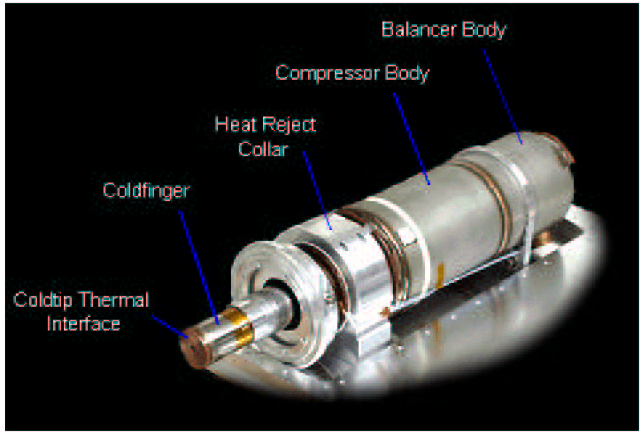


9 segmented coaxial Ge detectors, 7cm x 8.5cm

Energy range:	**Front segments: 3 keV - 2.8 MeV** **Rear segments: 20 keV - 17 MeV**
Resolution:	**Front segments: 1 keV @ 100 keV** **Rear segments: 2.9 keV @ 1 MeV**
Throughput:	**25,000+ counts/segment/second**
Shielding:	**NONE (4mm Al sides, 2cm Al rear)**

Other important subsystems:

Sunpower Stirling-cycle cryocooler, keeps detectors at 75K with 52W of power:



Attenuators: two sets of aluminum disks (thick and thin) that can be manually or automatically moved in front of the detectors to reduce the count rates from large flares.

Lin 2002

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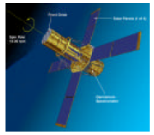
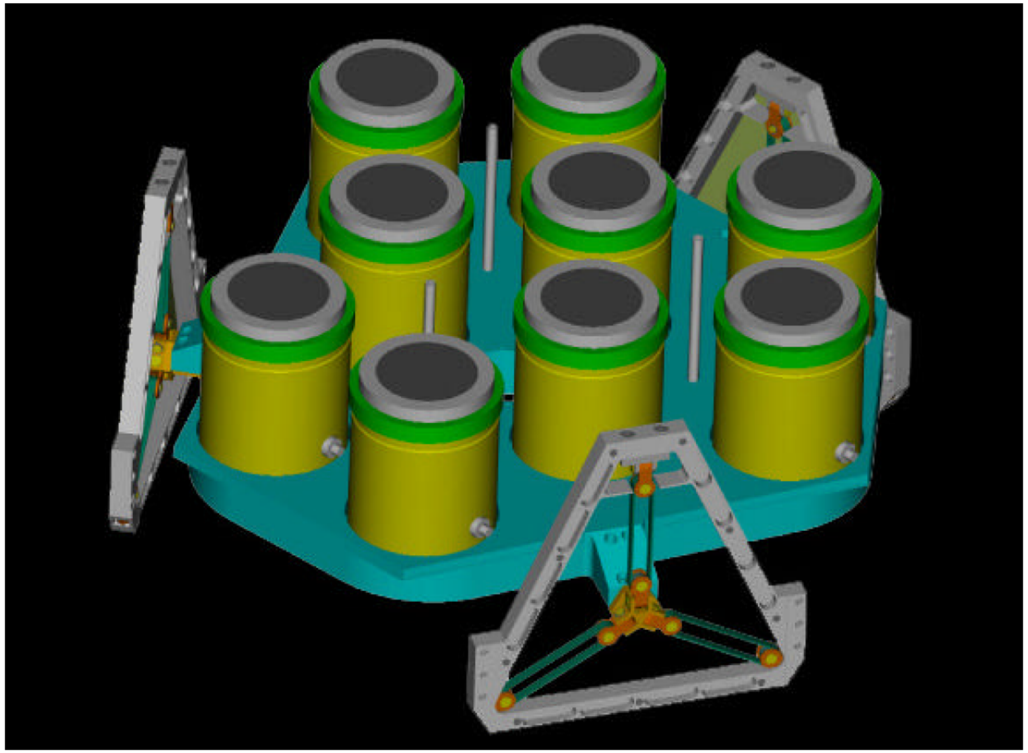


HESSI Germanium Detector Array



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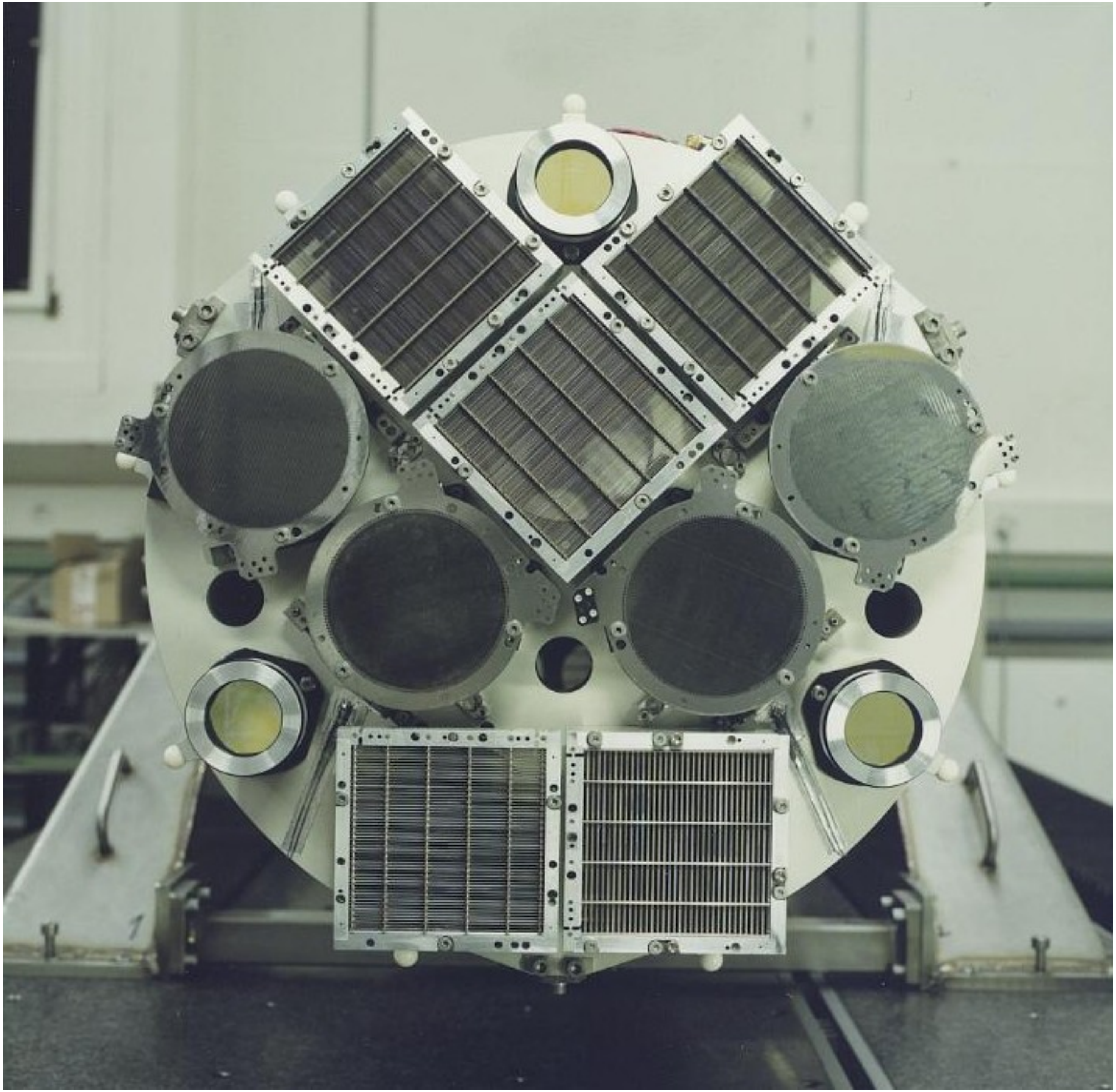

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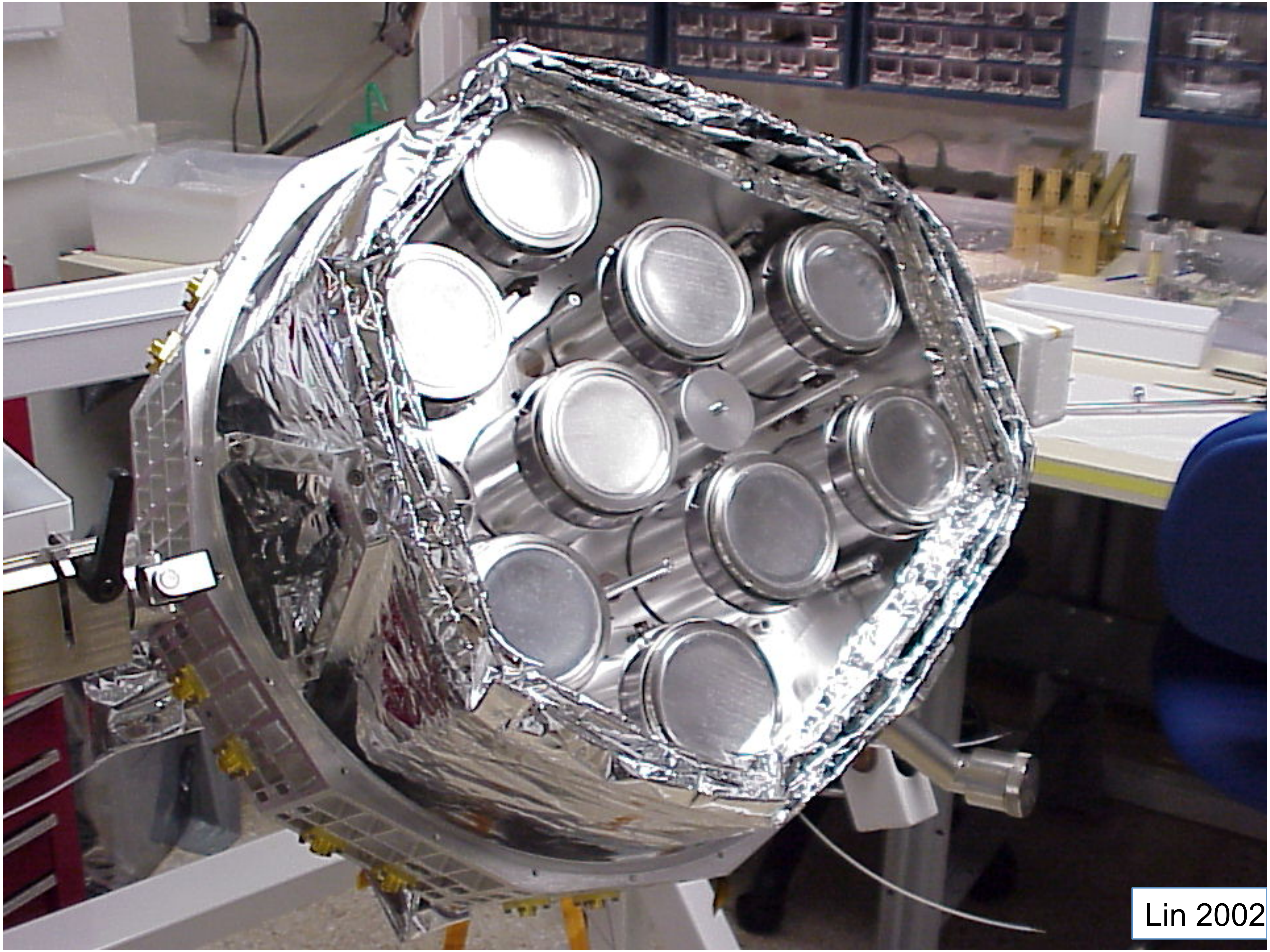

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HESSI Observational Characteristics

• Energy Range	3 keV to 15 MeV
• Energy Resolution (FWHM)	<1 keV FWHM at 3 keV increasing to 5 keV at 15 MeV
• Angular Resolution	2 arcseconds to 100 keV 7 arcseconds to 400 keV 36 arcseconds to 15 MeV
• Temporal Resolution	Tens of ms for basic image 2 s for detailed image
• Field of View	Full Sun
• Effective Area - cm^2 (with attenuators out)	10^{-3} at 3 keV, 50 at 10 keV 60 at 100 keV, 20 at 10 MeV
• Numbers of flares	~1000 imaged to >100 keV. ~100 with spectroscopy to ~10 MeV

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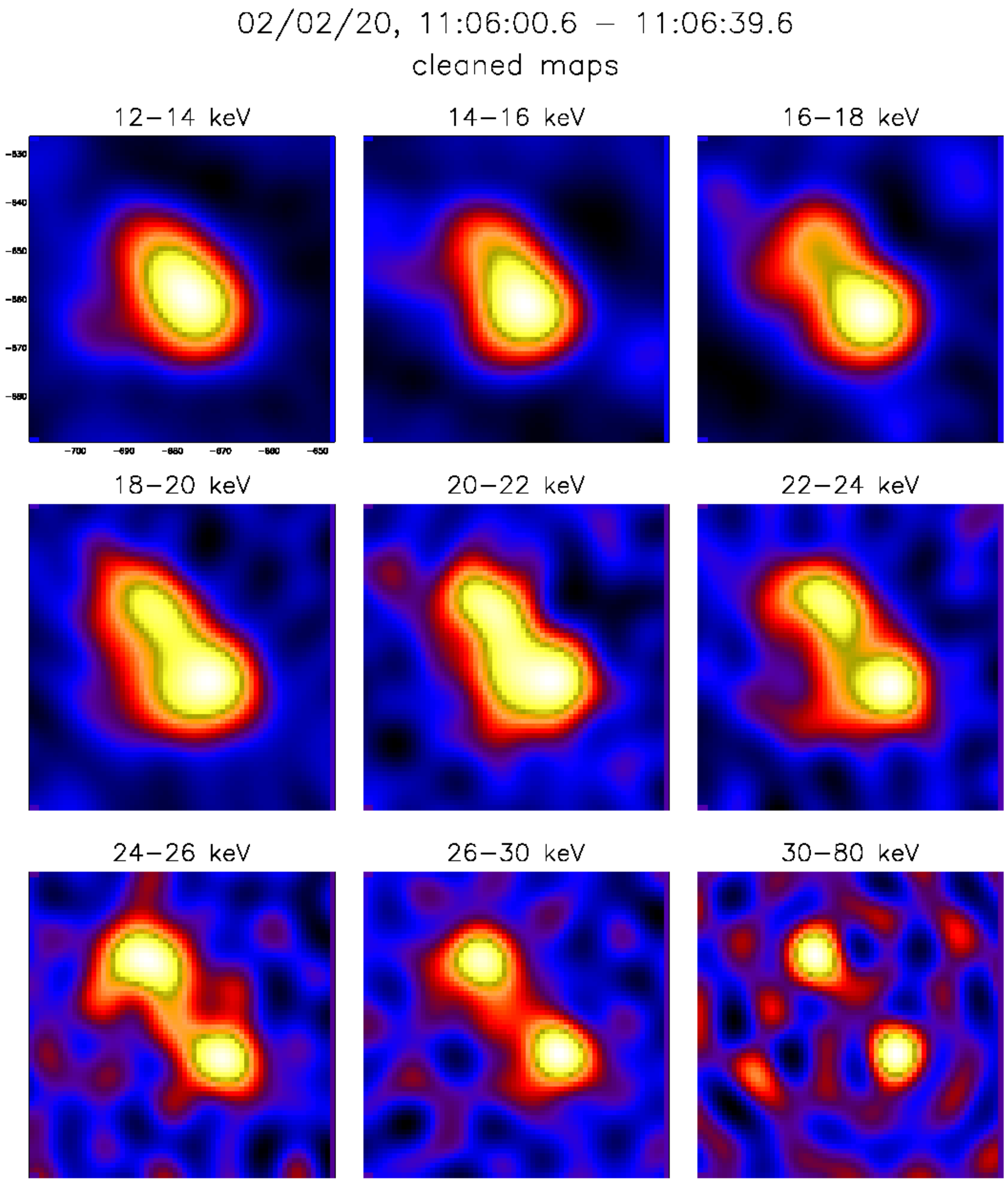

02/02/20, 11:06:00.6 – 11:06:39.6
cleaned maps
12–14 keV
14–16 keV
16–18 keV
18–20 keV
20–22 keV
22–24 keV
24–26 keV
26–30 keV
30–80 keV

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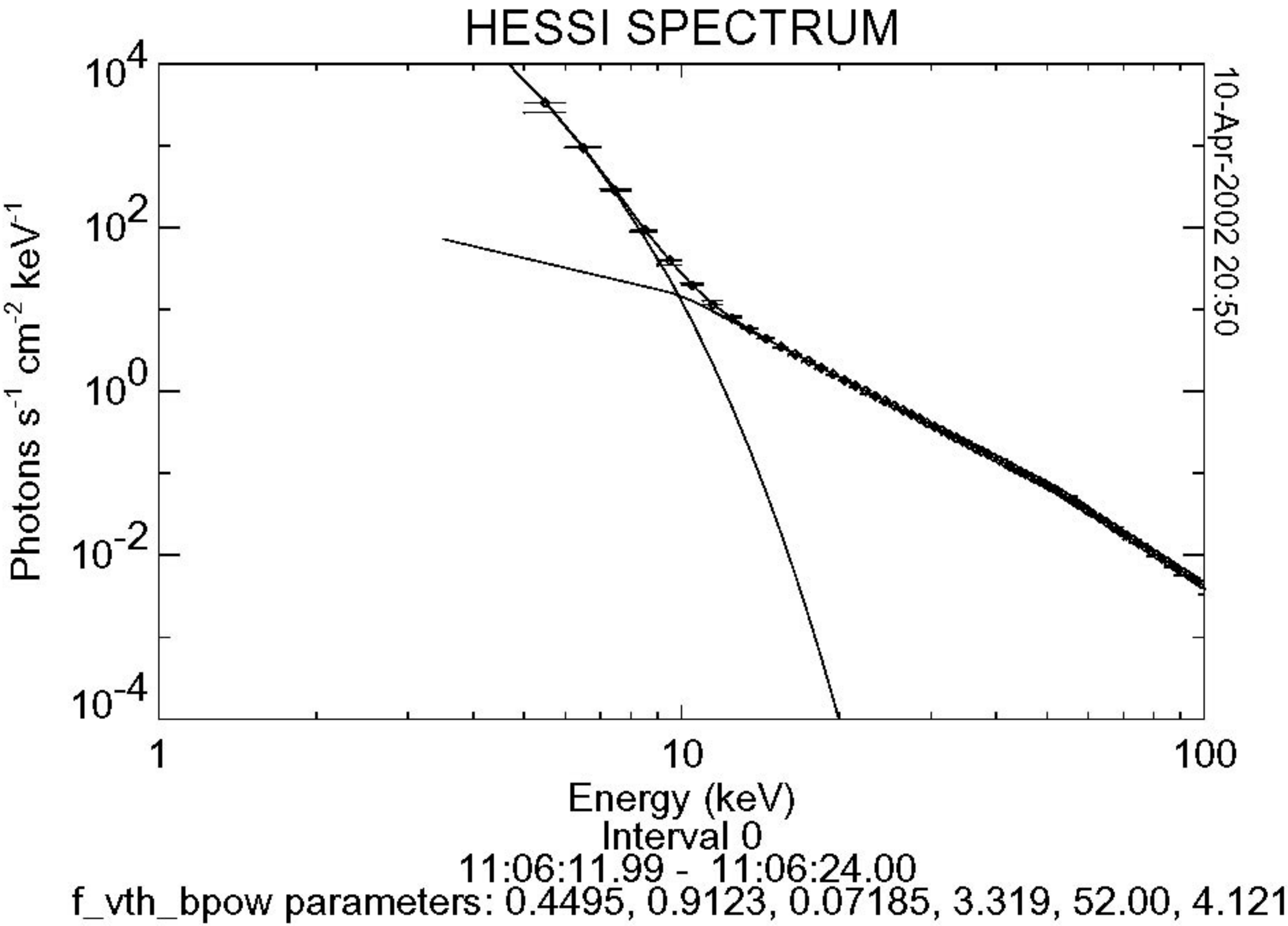

HESSI SPECTRUM
Photons s-1 cm-2 keV-1
10^4
10^2
10^0
10^-2
10^-4
1
10
100
Energy (keV)
10-Apr-2002 20:50
Interval 0
11:06:11.99 - 11:06:24.00
f_vth_bpow parameters: 0.4495, 0.9123, 0.07185, 3.319, 52.00, 4.121

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RHESSI DATA ANALYSIS

Documentation and details at

RHESSI SOFTWARE AND DATA ANALYSIS CENTER

http://hesperia.gsfc.nasa.gov/rhessidatacenter/

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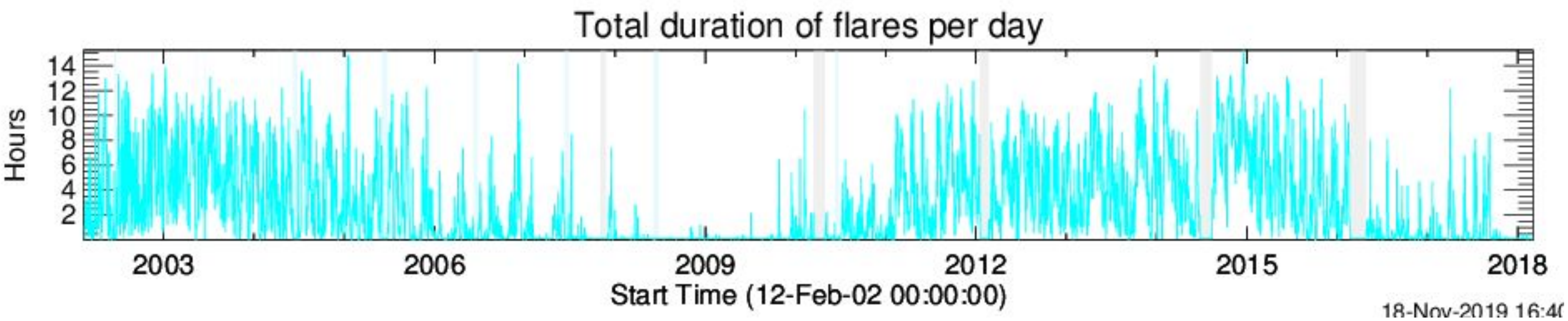
Status of the RHESSI Mission Archive

R. A. Schwartz A. K. Tolbert

Contributing: B Dennis, A Shih, A Inglis, M Fivian, D Smith, M. Abdallaoui



Schartz 2020

Overview of the Archive

- Mission Archive Web Page: https://hesperia.gsfc.nasa.gov/rhessi3/mission-archive/index.html
- Image Archive – so much information
- Energy Spectra – ready for stand-alone spectroscopy
- Ancillary missions – MESSENGER, FERMI, GOES, SMM, AIA

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Flare Image Archive

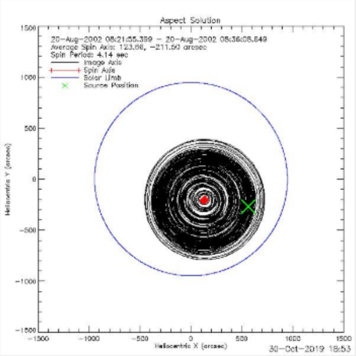
RHESSI Image Archive Strategy   Guide to RHESSI Image Archive

2002   February   Load

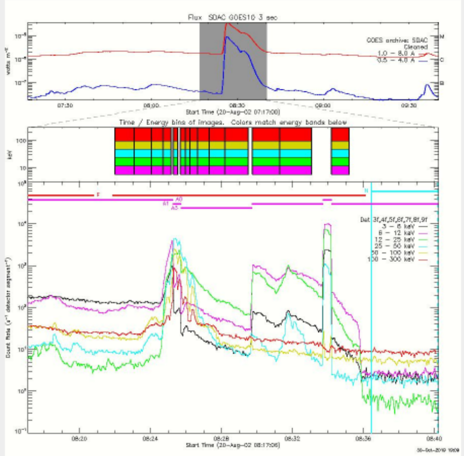
RHESSI Flare Images February 2002

12-Feb-2002 21:30:00 - 21:41:00	6tx2e	Browser	Aspect Plot	Profile Plot	Panels	Image Movies:	-	6-12	12-25	-	-	-
12-Feb-2002 21:44:00 - 21:48:00	-	Browser	Aspect Plot	-	-	-	-	-	-	-	-	-
13-Feb-2002 00:53:00 - 00:57:00	-	Browser	Aspect Plot	-	-	-	-	-	-	-	-	-
13-Feb-2002 04:22:00 - 04:26:00	1tx1e	Browser	Aspect Plot	Profile Plot	Panels	Image Movies:	-	6-12	-	-	-	-
13-Feb-2002 07:03:00 - 07:30:00	18tx2e	Browser	Aspect Plot	Profile Plot	Panels	Image Movies:	-	6-12	12-25	-	-	-

Flare 20820140, 20-Aug-2002 08:21:52 - 08:36:08   Peak: 08:26:22   Duration: 856 s   Peak: 1424 c/s   Total Counts: 2876159
Highest Energy: 100-300 keV Flare Position: 569,-264 asec AR: 69



Movie of Aspect Solution in Image Time Bins



BACK_PROJECTION Images
CLEAN Images
CLEAN_59 Images
MEM_GE Images
VIS_CS Images
VIS_FWDFIT Images

RHESSI Browser
~~AIA movies~~
Direct Link to Plot Folder

Download files:

BACK_PROJECTION Image Cube FITS
CLEAN Image Cube FITS
CLEAN_59 Image Cube FITS
MEM_GE Image Cube FITS
VIS_CS Image Cube FITS
VIS_FWDFIT Image Cube FITS

Visibility FITS
Eventlist FITS

Image Creation Scripts:

BACK_PROJECTION non-default params all params
CLEAN non-default params all params
CLEAN_59 non-default params all params
MEM_GE non-default params all params
VIS_CS non-default params all params
VIS_FWDFIT non-default params all params

Schartz 2020