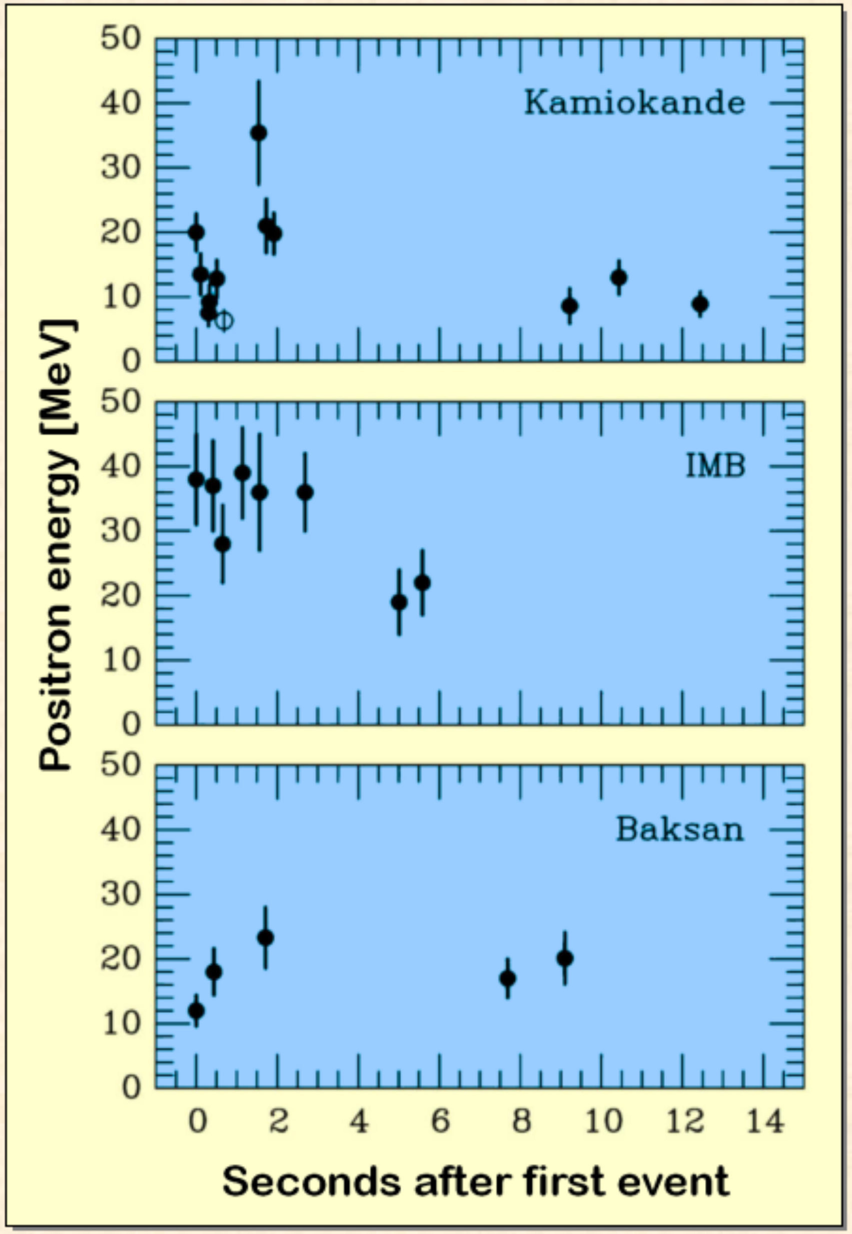
Astrofisica Nucleare e Subnucleare

Neutrino Astrophysics

Astrofisica Nucleare e Subnucleare

Supernovae Neutrinos

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

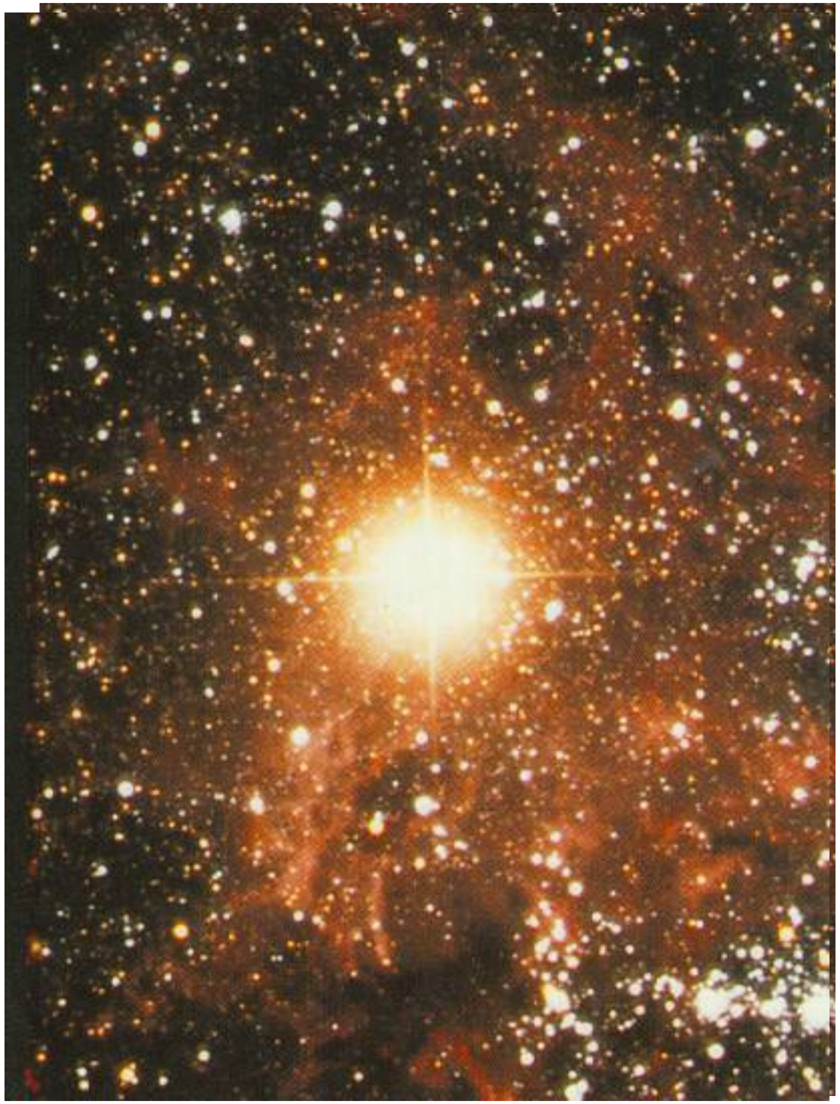
Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Georg Raffelt, Max-Planck-Institut für Physik (München)

Supernovae



Anglo-Australian Telescope

The field of the supernova SN1987A after 23 February 1987.

This picture shows a small area of sky in the **Large Magellanic Cloud**, the nearby dwarf companion galaxy to our own Galaxy.

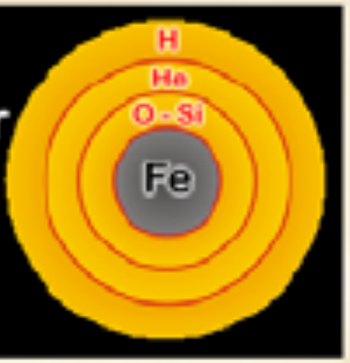
Type Ia vs. Core-Collapse Supernovae

Type Ia

- Carbon-oxygen white dwarf (remnant of low-mass star)
- Accretes matter from companion

Core collapse (Type II, Ib/c)

- Degenerate iron core of evolved massive star
- Accretes matter by nuclear burning at its surface

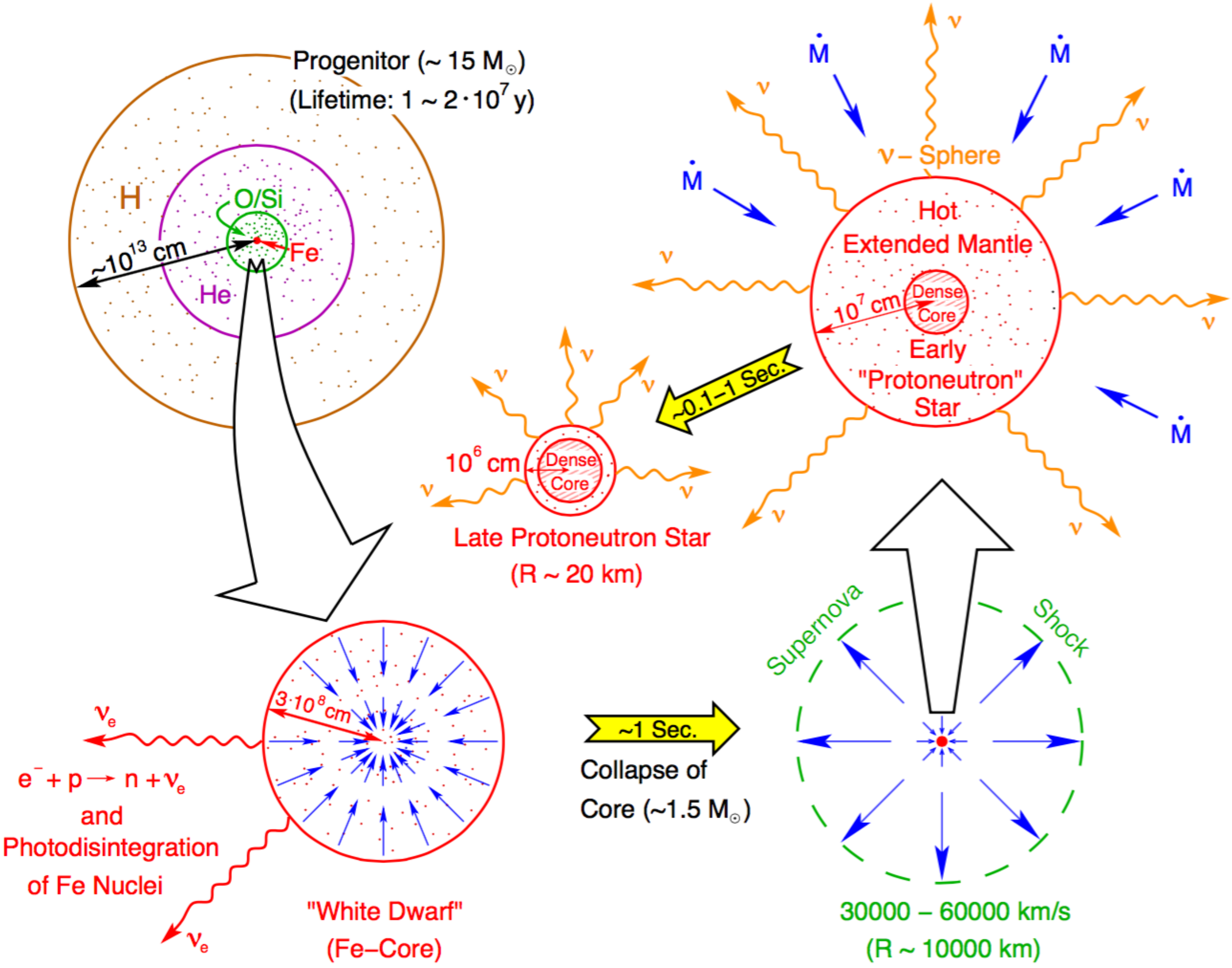


Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

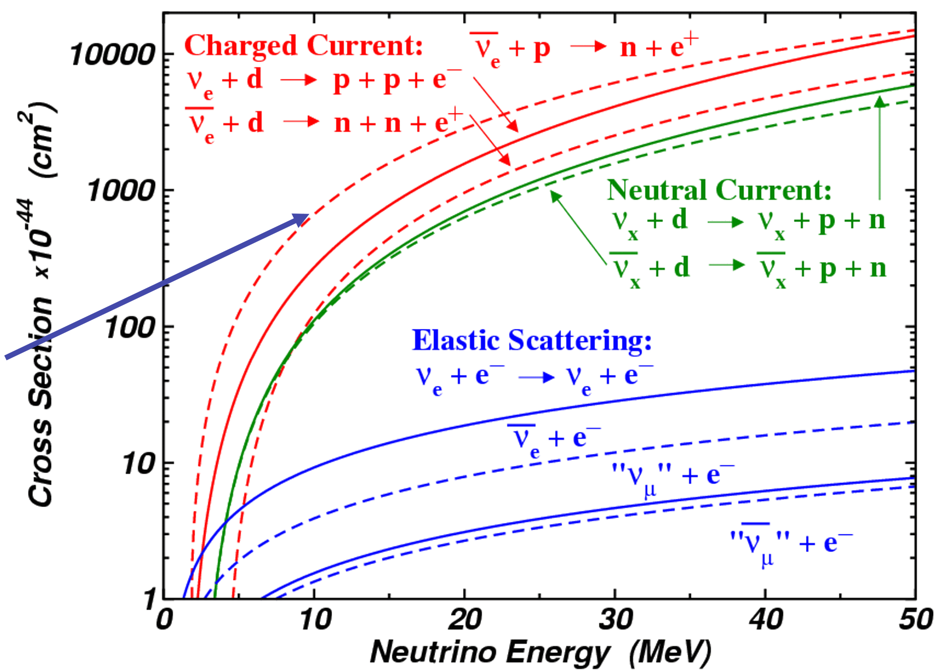
Type Ia	Core collapse (Type II, Ib/c)
Nuclear burning of C and O ignites → Nuclear deflagration (“Fusion bomb” triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Schematical Evolution



8.6 The SN1987A

Neutrino cross sections:

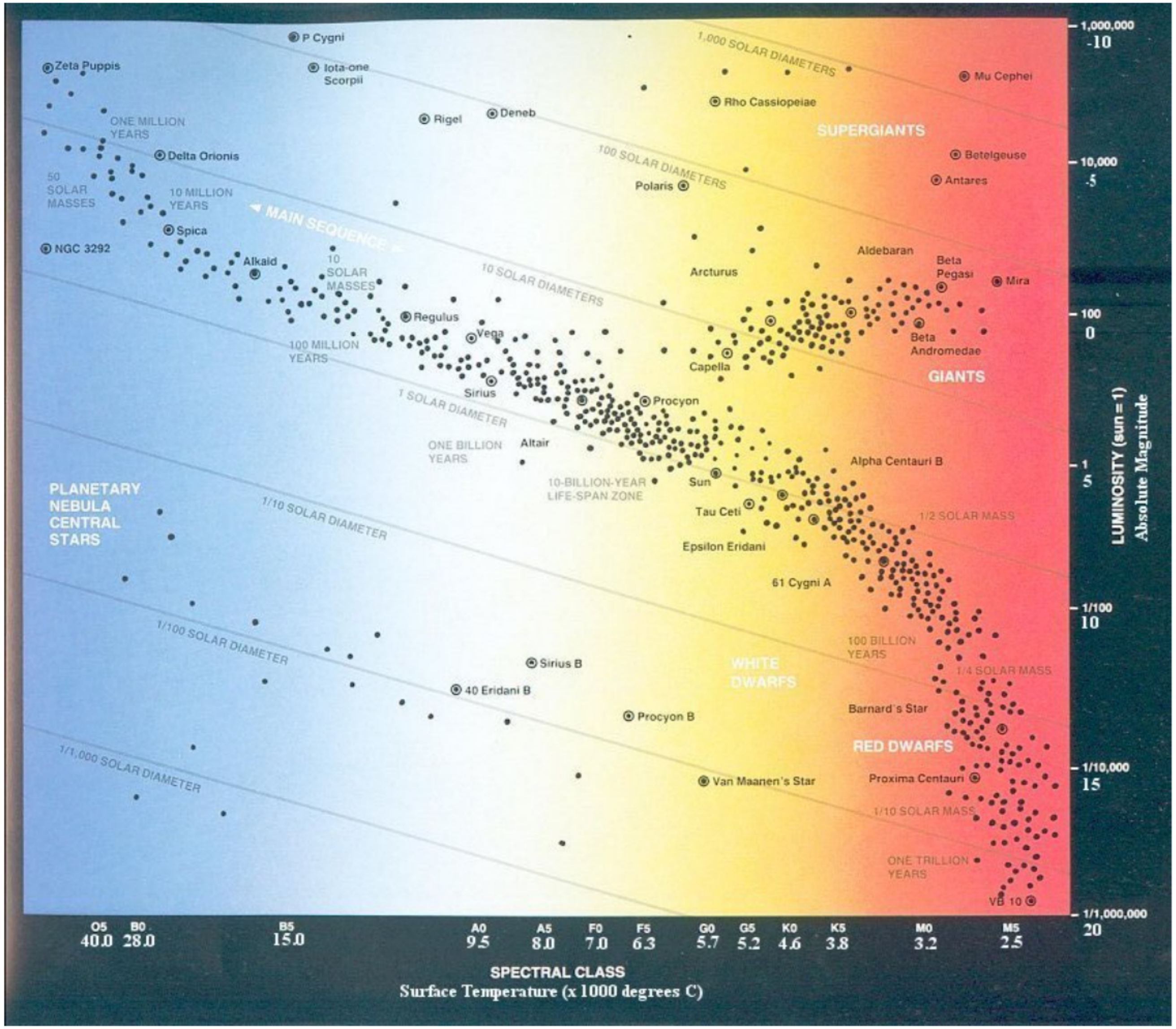


Distance: 52 kpc (LMC)

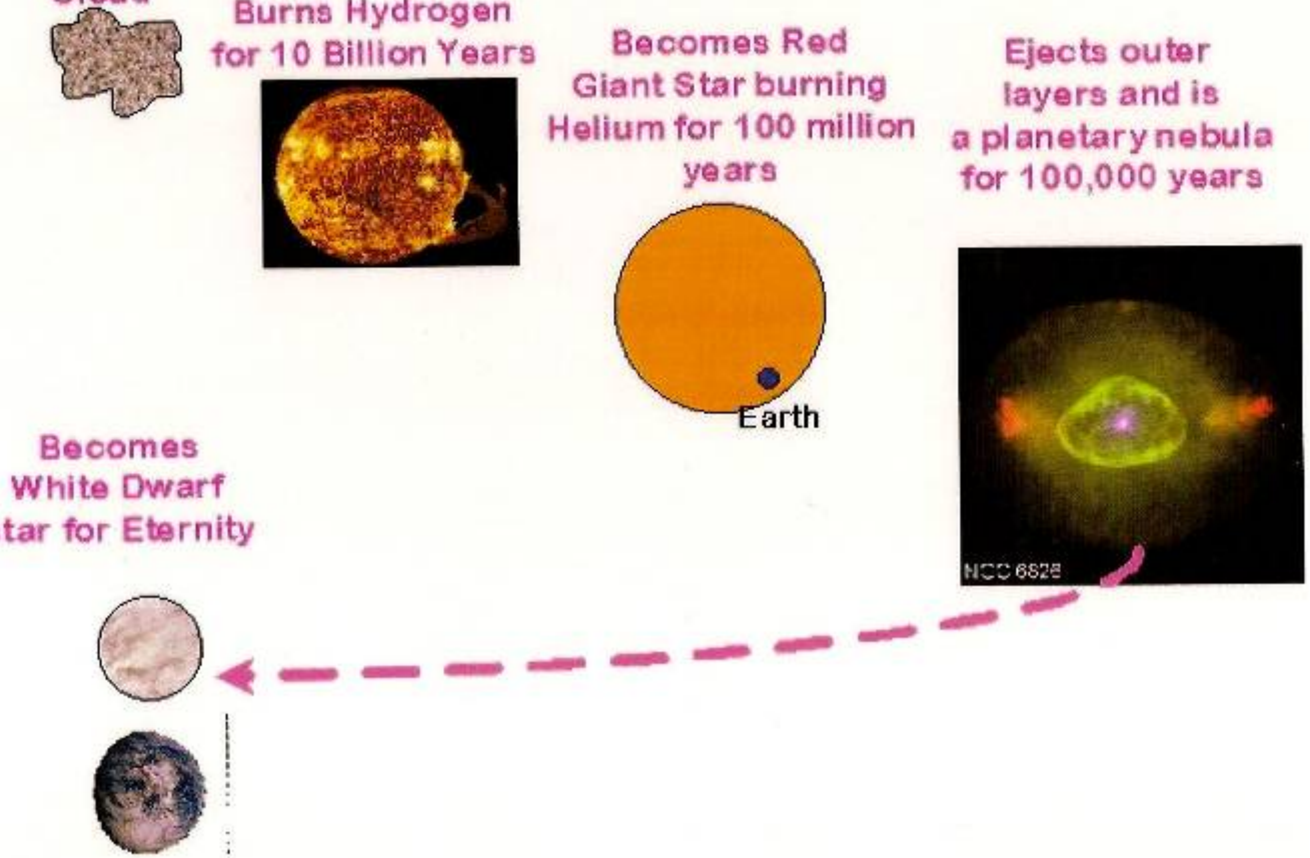
Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics - 1

Hertzspung-Russell diagram



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



Forms in Dust & Gas Cloud

Burns Hydrogen for 10 Billion Years

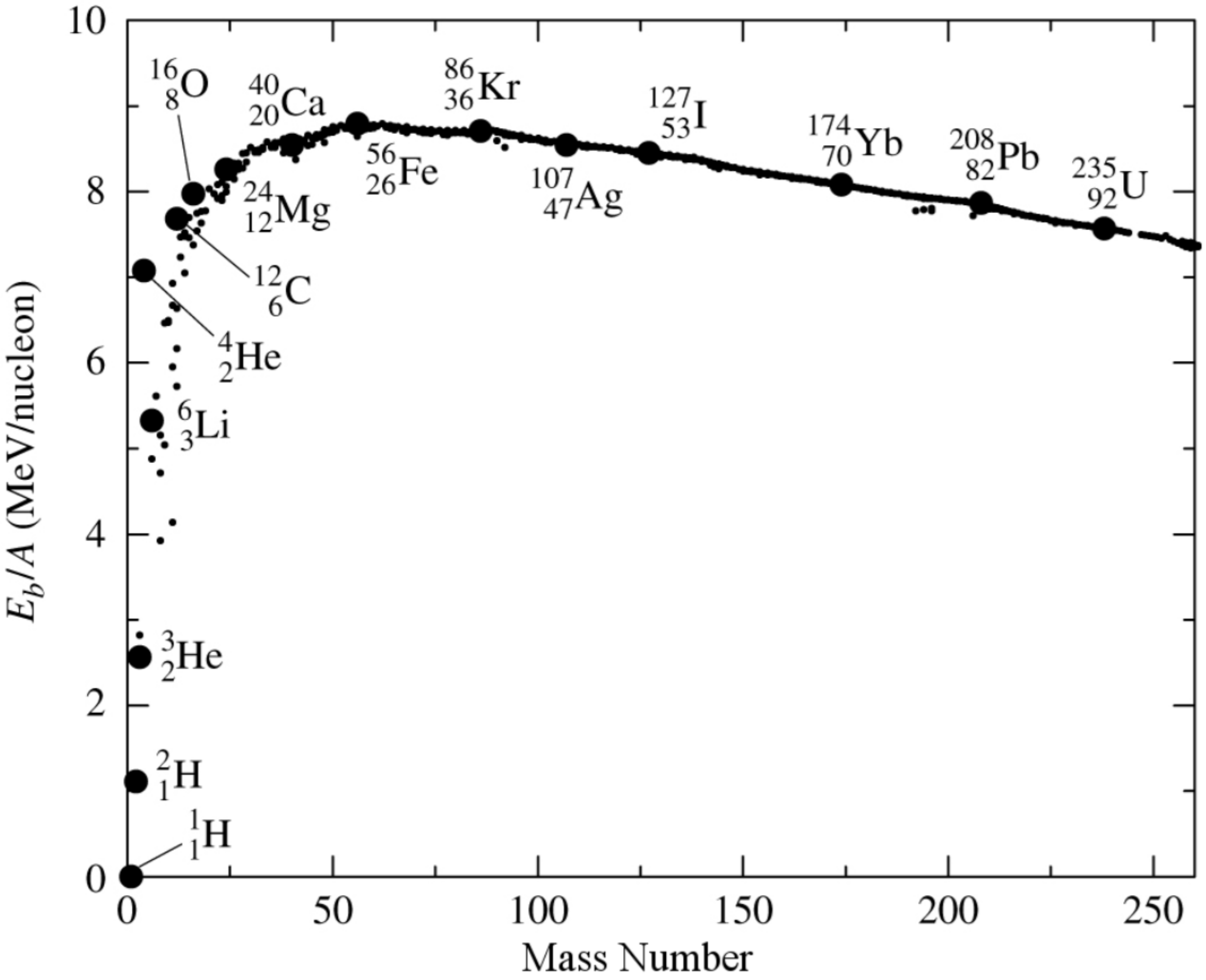
Becomes Red Giant Star burning Helium for 100 million years

Ejects outer layers and is a planetary nebula for 100,000 years

Becomes White Dwarf star for Eternity

Nuclear Binding Energy

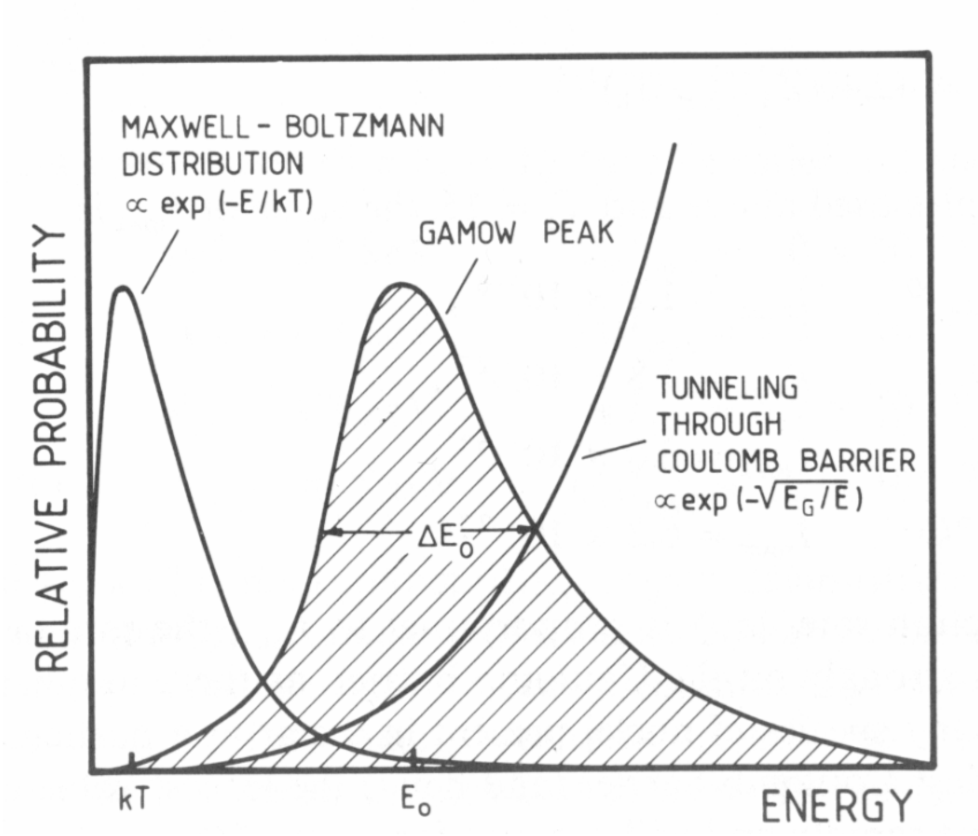
Liberated energy is due to the gain in nuclear binding energy.



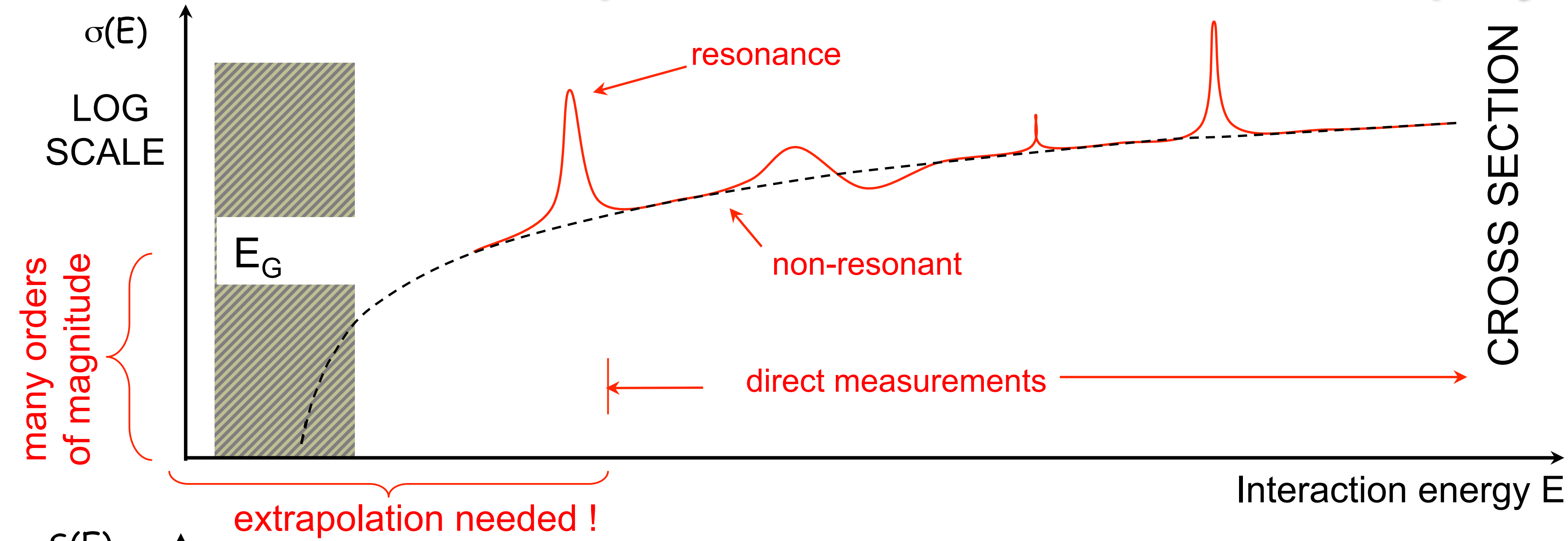
Gamow window

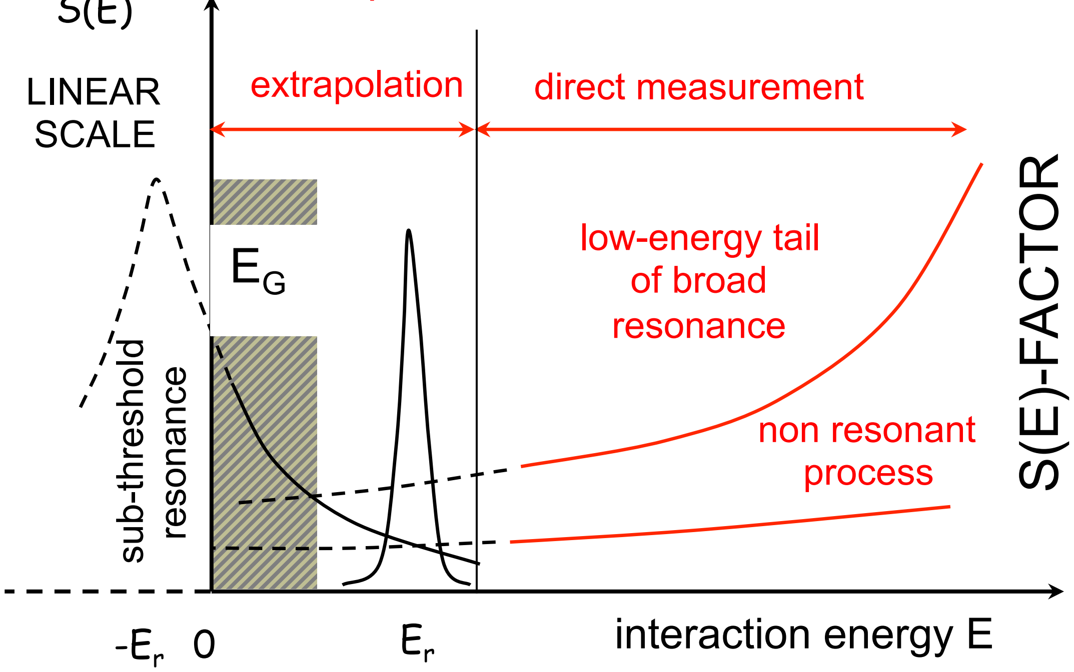
Using definition S factor:

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



Problem of extrapolation in nuclear astrophysi





Most of the reactions of astrophysical interest happen via radiative capture.

$^{14}N(p,\gamma)^{15}O$,
$^{12}C(\alpha,\gamma)^{16}C$...

Hydrogen burning: ppI-chain

Step 1: $p + p \longrightarrow {}^2\mathrm{He}$ (not possible)

$p + p \longrightarrow d + e^+ + \nu_e$

Step 2: $d + p \longrightarrow {}^3\mathrm{He}$

$d + d \longrightarrow {}^4\mathrm{He}$ (d abundance too low)

Step 3: ${}^3\mathrm{He} + p \longrightarrow {}^4\mathrm{Li}$ (^{4}Li is unbound)

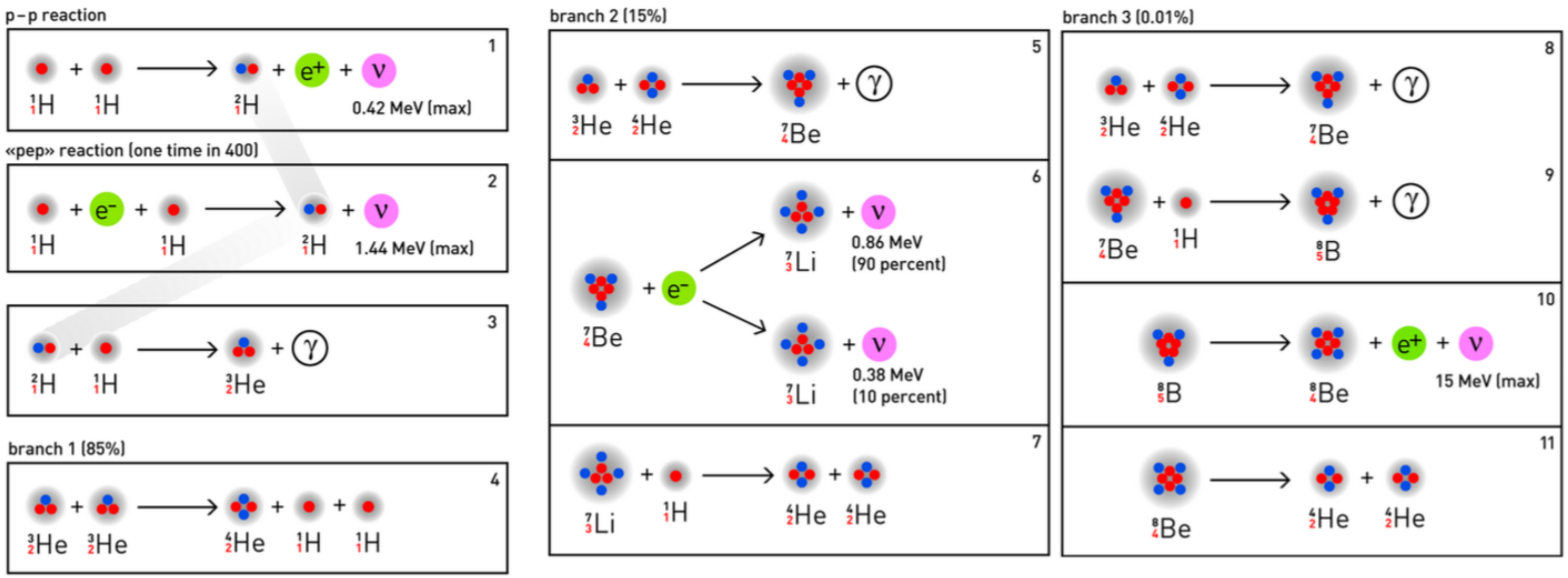
${}^3\mathrm{He} + d \longrightarrow {}^4\mathrm{He} + n$ (d abundance too low)

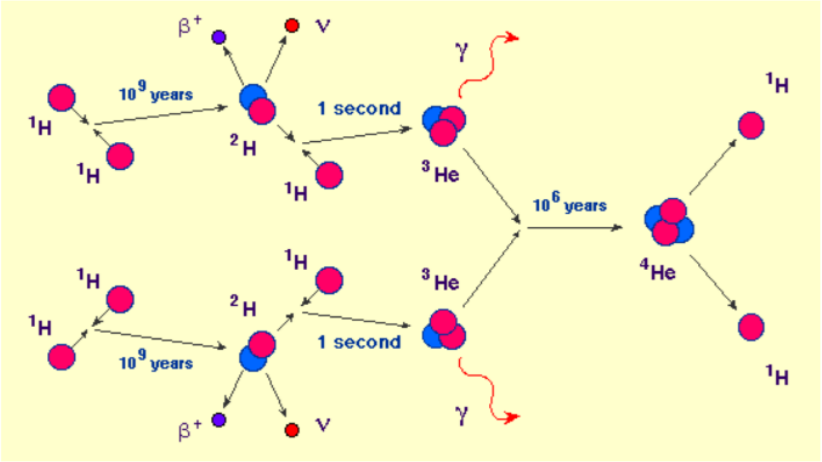
${}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p$

$d + d$ not going because Y_d is small and $d + p$ leads to rapid destruction.
${}^3\mathrm{He} + {}^3\mathrm{He}$ goes because $Y_{3\mathrm{He}}$ gets large as nothing destroys it.

pp chains

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





Reaction Network ppI-chain

$$\frac{dY_p}{dt} = -Y_p^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{pp} - Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd} + Y_3^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

$$\frac{dY_d}{dt} = \frac{Y_p^2}{2} \frac{\rho}{m_u} \langle \sigma v \rangle_{pp} - Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd}$$

$$\frac{dY_3}{dt} = Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd} - Y_3^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

$$\frac{dY_4}{dt} = \frac{Y_3^2}{2} \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

Stiff system of coupled differential equations.

The relevant S-factors

$p(p, e^+\nu_e)d$: $S_{11}(0) = (4.00 \pm 0.05) \times 10^{25}$ MeV b

calculated

$p(d, \gamma)^3$He: $S_{12}(0) = 2.5 \times 10^{-7}$ MeV b

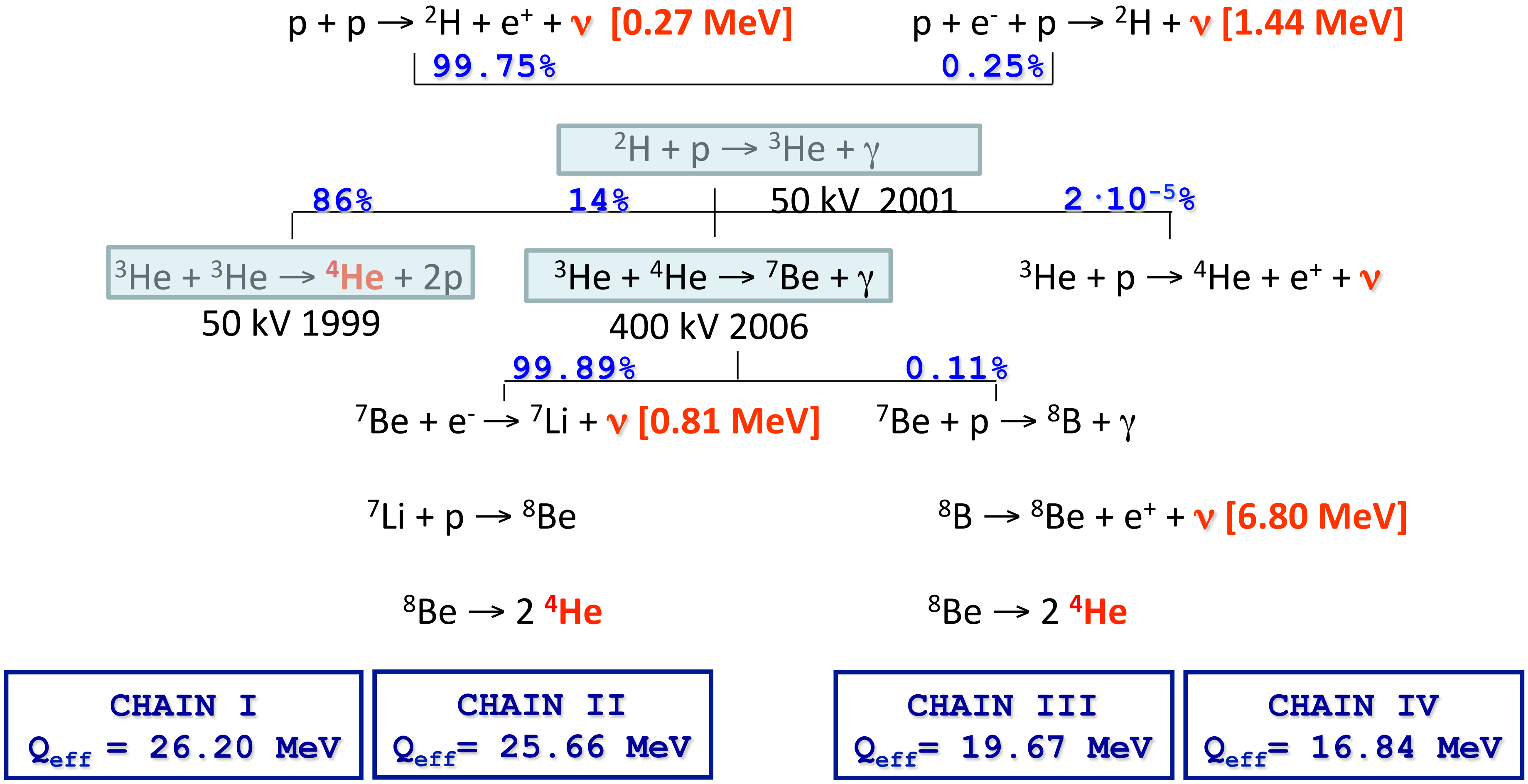
measured at LUNA

^{3}He(^{3}He, $2p$)^{4}He: $S_{33}(0) = 5.4$ MeV b

measured at LUNA

Laboratory Underground for Nuclear Astrophysics (Gran Sasso).

LUNA program: pp chain



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

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

99.75%

0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

50 kV 2001

86%

14%

$2 \cdot 10^{-5}$%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

50 kV 1999

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

400 kV 2006

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

99.89%

0.11%

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

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

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

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

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

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

CHAIN I
$Q_{eff} = 26.20$ MeV

CHAIN II
$Q_{eff} = 25.66$ MeV

CHAIN III
$Q_{eff} = 19.67$ MeV

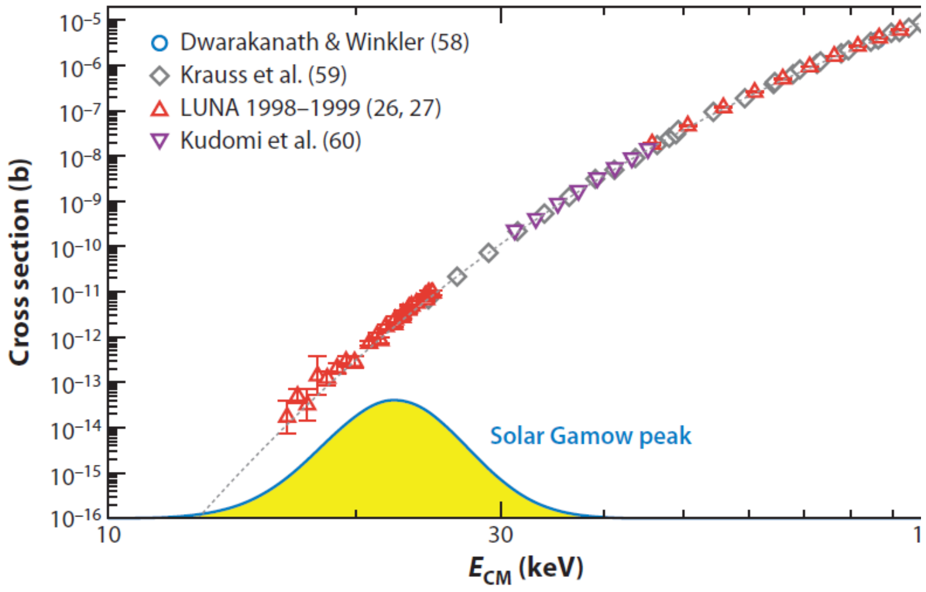
CHAIN IV
$Q_{eff} = 16.84$ MeV

LUNA (**L**aboratory **U**nderground for **N**uclear **A**strophysics)

50 kV accelerator @ Gran Sasso – Italy (1400 m rock -> 10^6 shielding factor)

^{3}He(^{3}He,2p)^{4}He

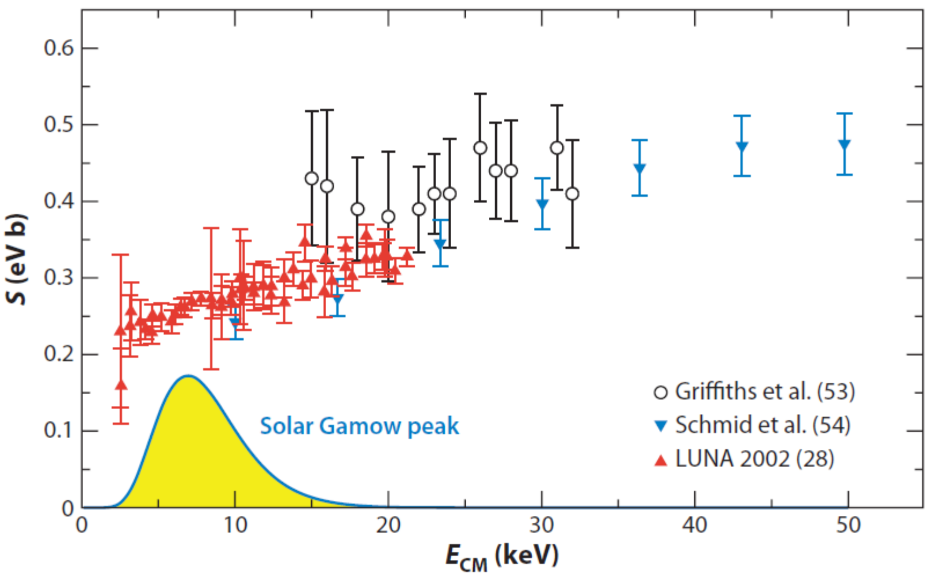
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



At lowest energy: σ ~ 20 fb → 1 event/month

d(p,γ)^{3}He

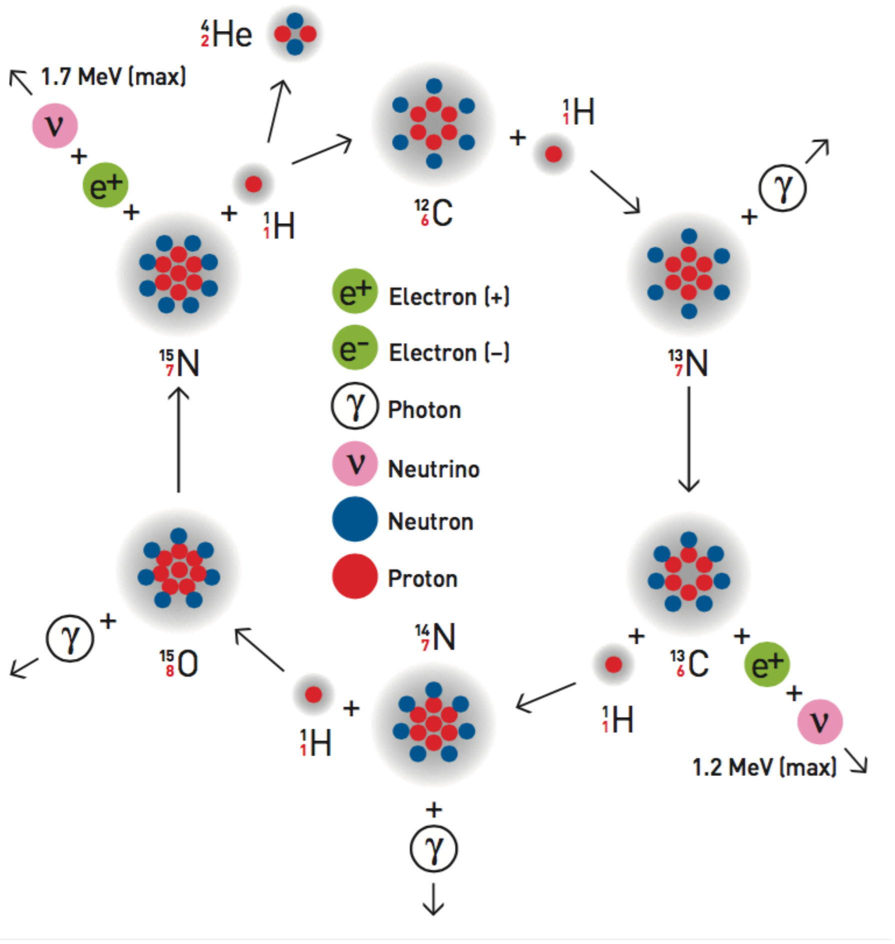
C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



At lowest energy: σ ~ 9 pb → 50 counts/day

No *extrapolation* needed!

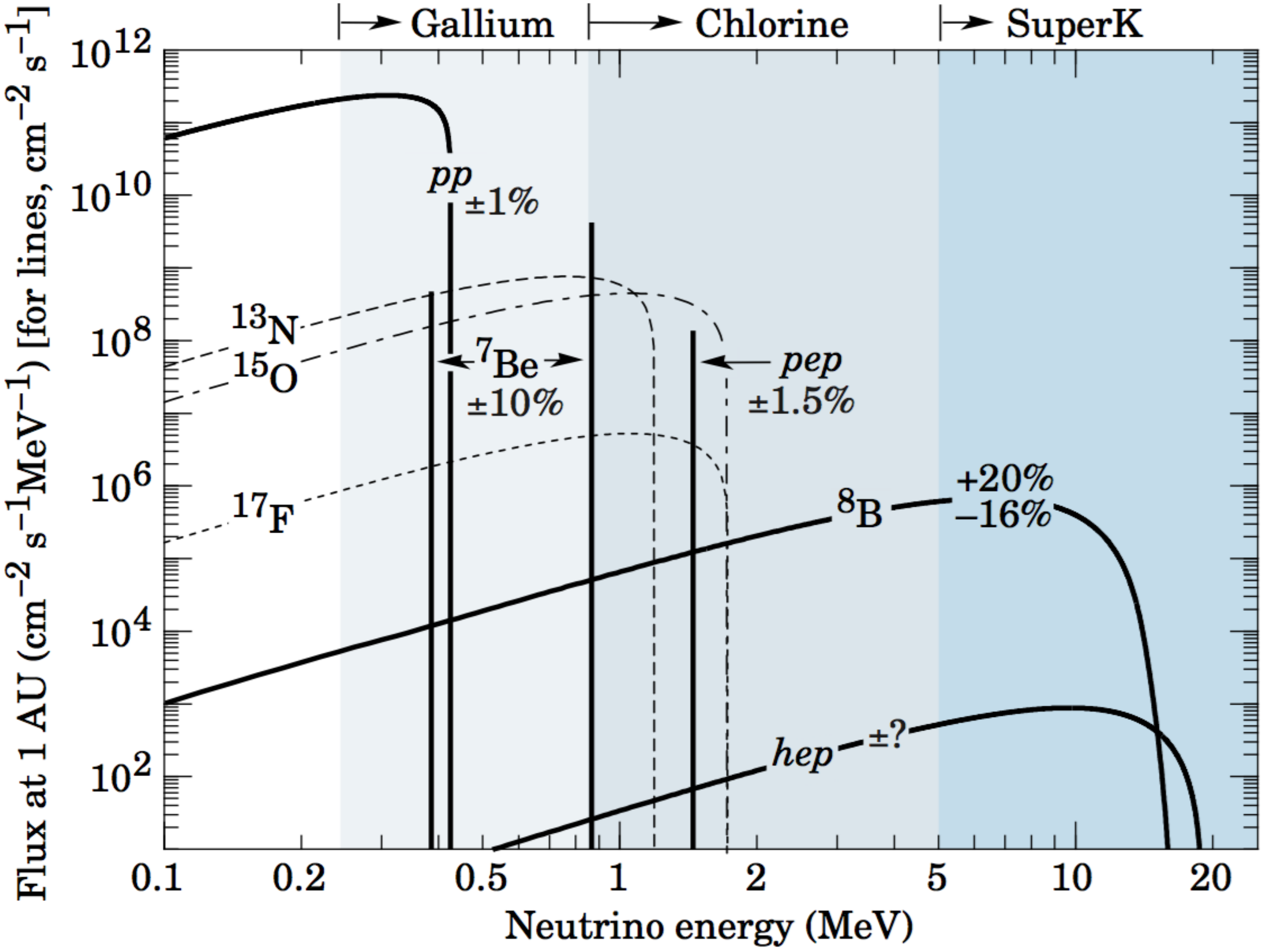
The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst.

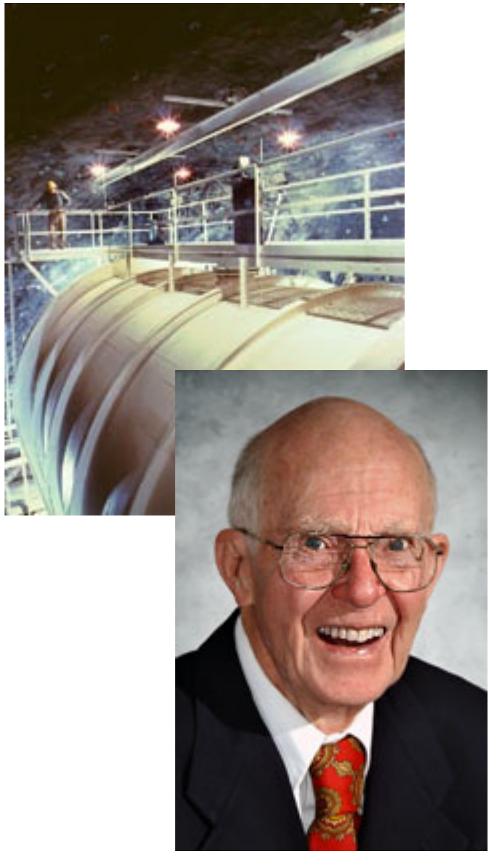
Neutrino spectrum (Sun)

This is the predicted neutrino spectrum

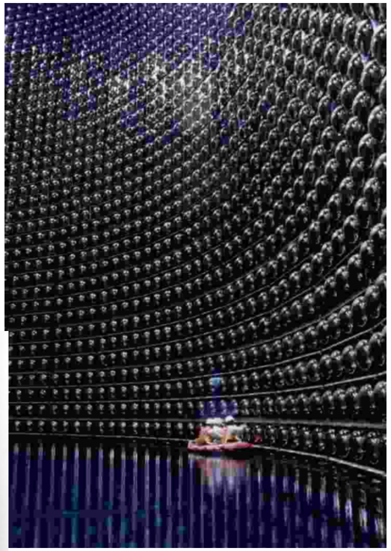


Astrofisica Nucleare e Subnucleare
Solar Neutrinos

The 2002 Nobel Prize for the Solar Neutrino Physics

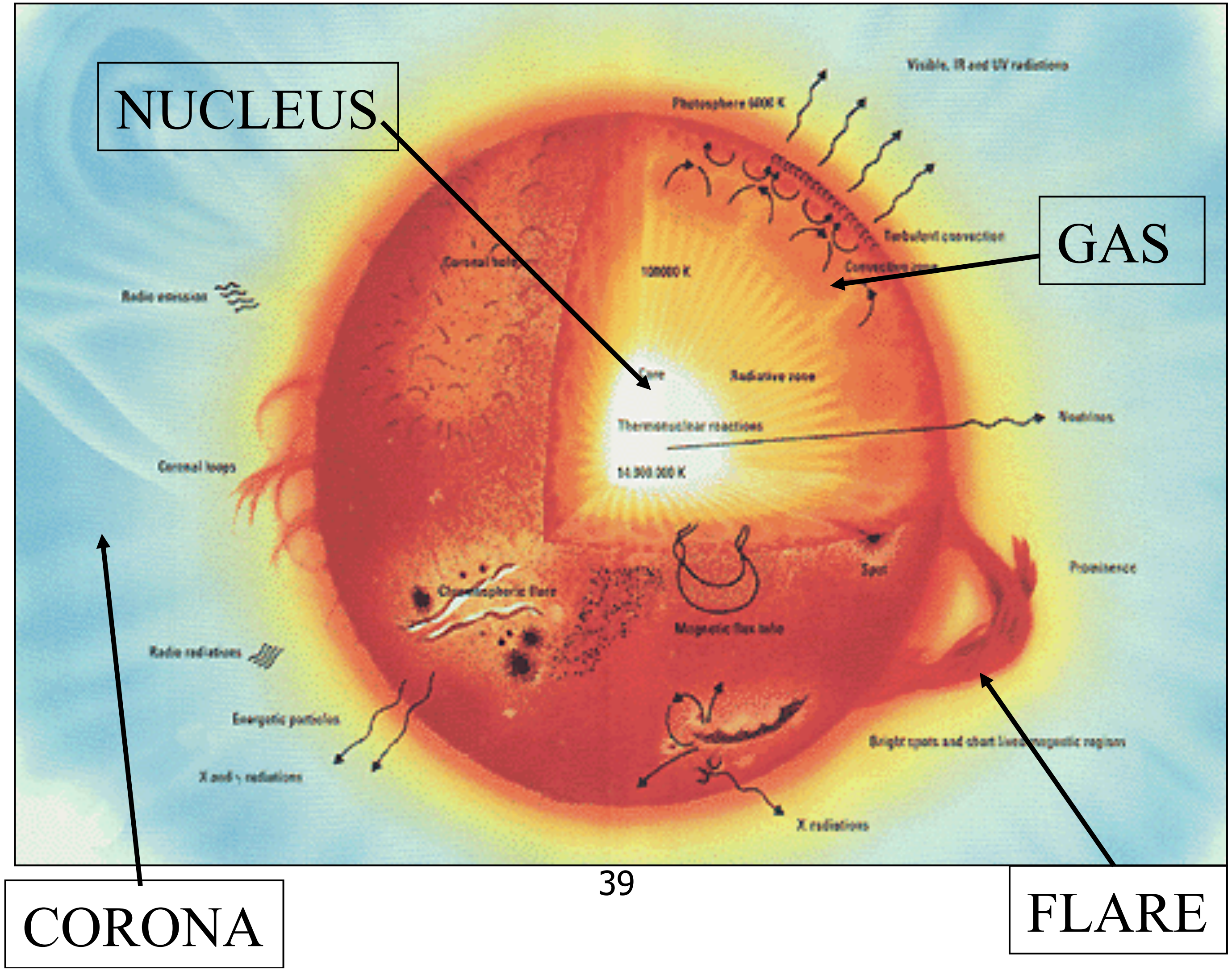


Raymond Davis Jr.
http://nobelprize.org/nobel_prizes/physics/laureates/2002/davis-lecture.pdf



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

The Standard Solar Model



NUCLEUS

GAS

CORONA

FLARE

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

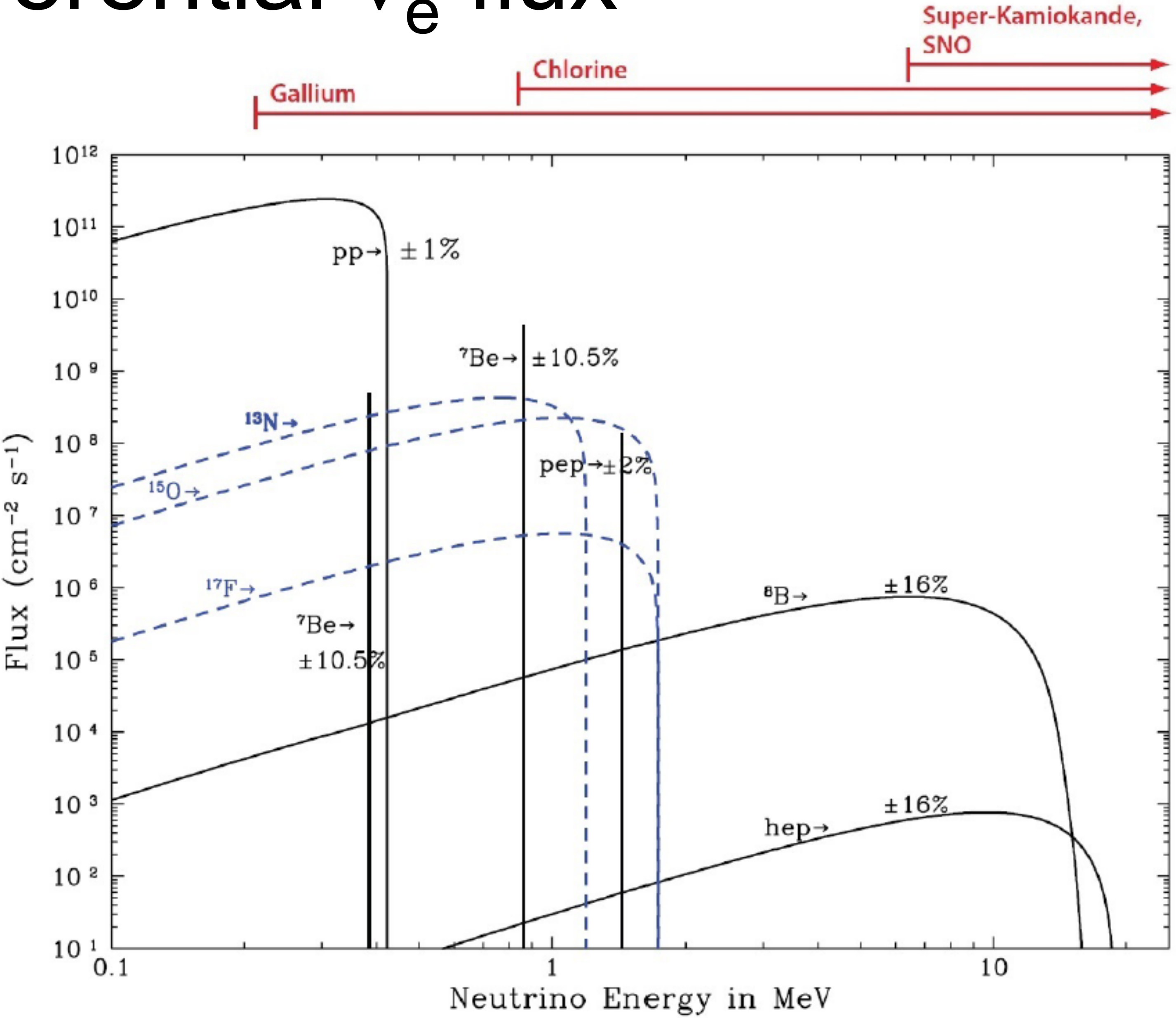
•Fusion ⇒ neutrinos

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.

Differential ν_e flux



Neutrino Emission

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

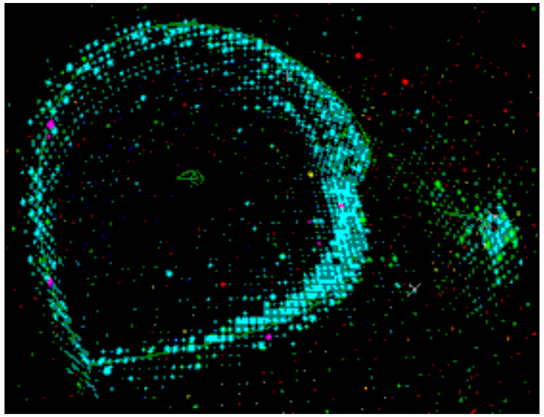
Experimental Techniques

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

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

- 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

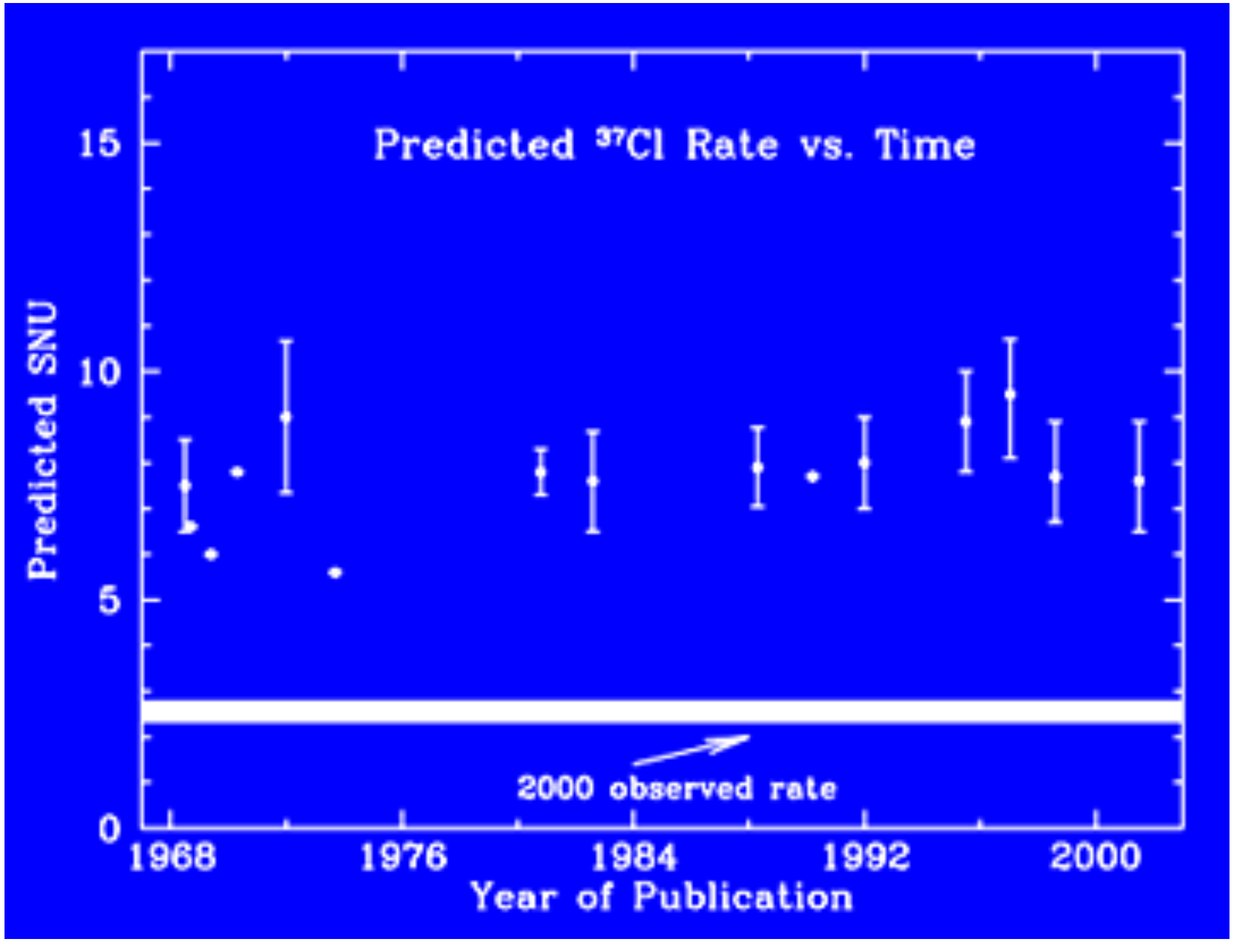
- The Clorine or 'Davis' experiment

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

- 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:

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

- Solar neutrino experiment based on the reaction:

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

- 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

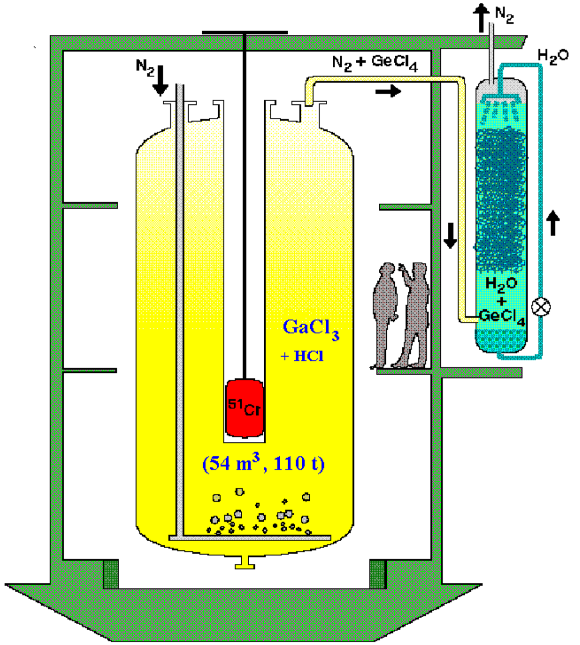
- 30.3 tons of gallium in form of a concentrated $GaCl_3$-HCl solution exposed to solar ν's

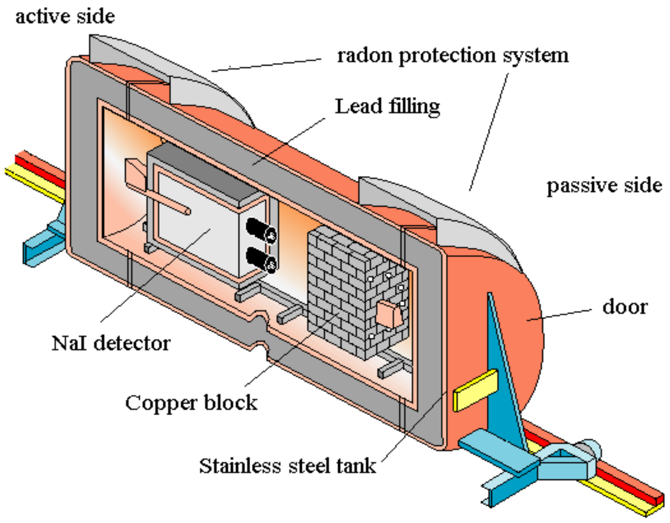
- Neutrino induced ^{71}Ge forms the volatile compound $GeCl_4$

- 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





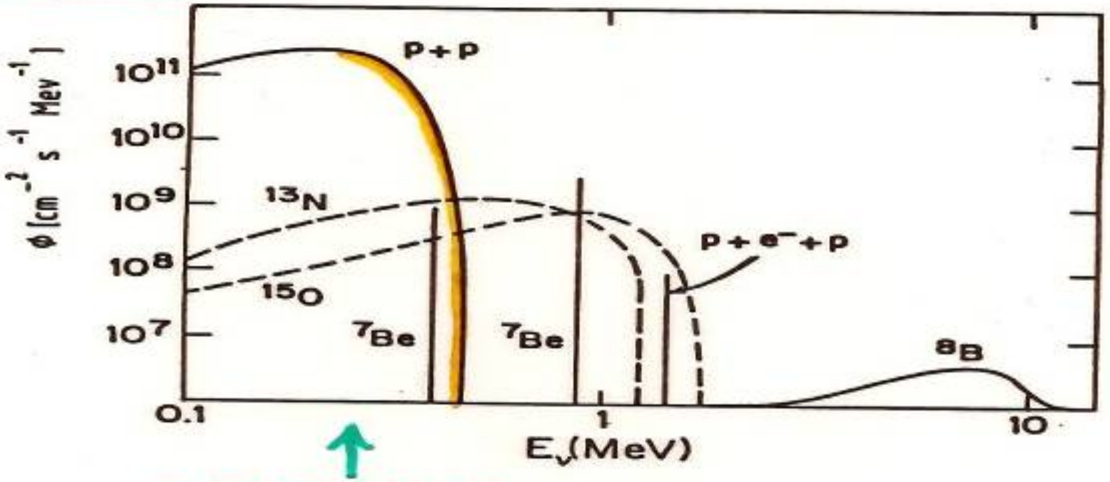
GALLEX

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

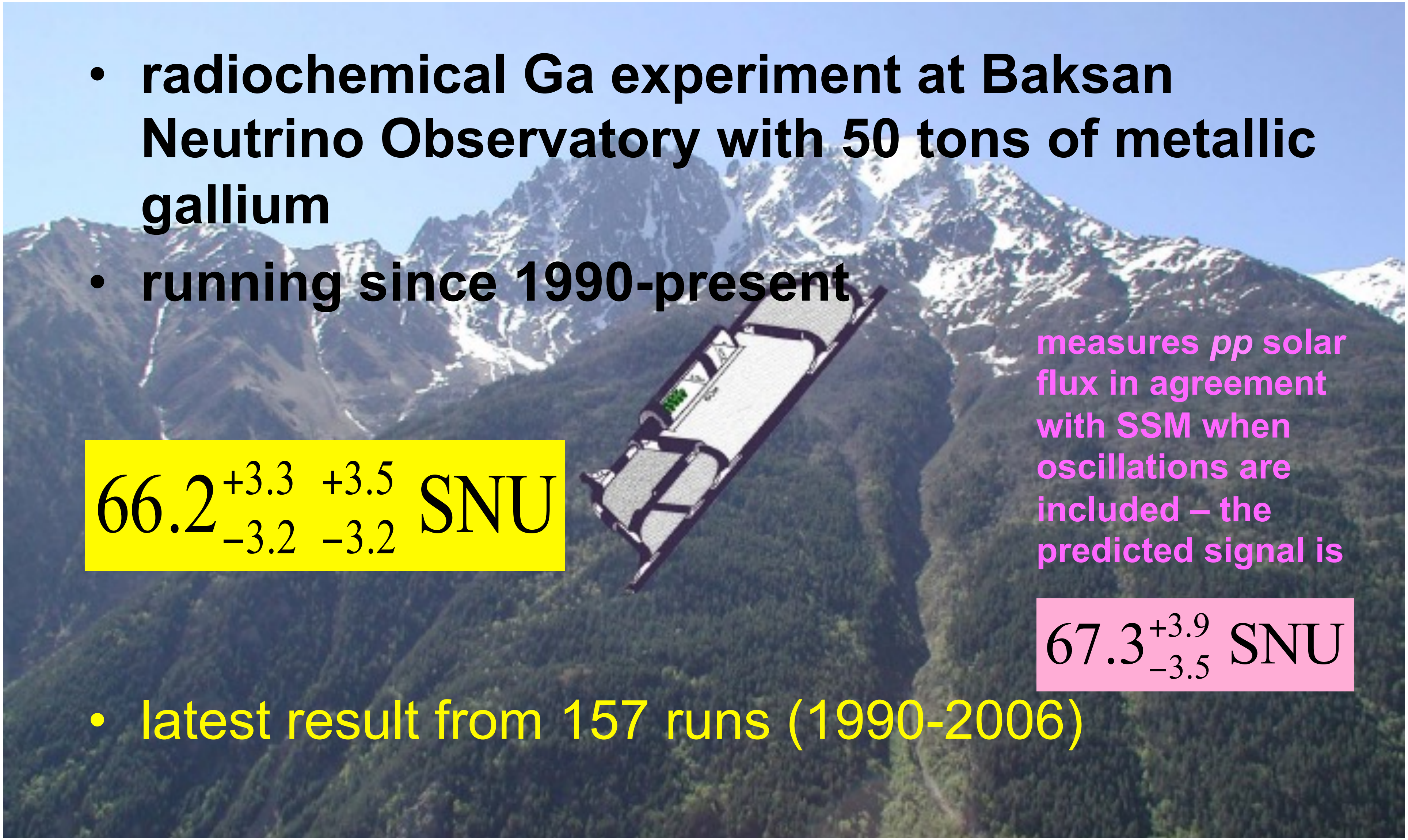
$$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^-$$

LIQUIDO $GaCl_3 \Rightarrow GeCl_4$ GASSOSO

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

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

SAGE – Russian American Gallium Experiment



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

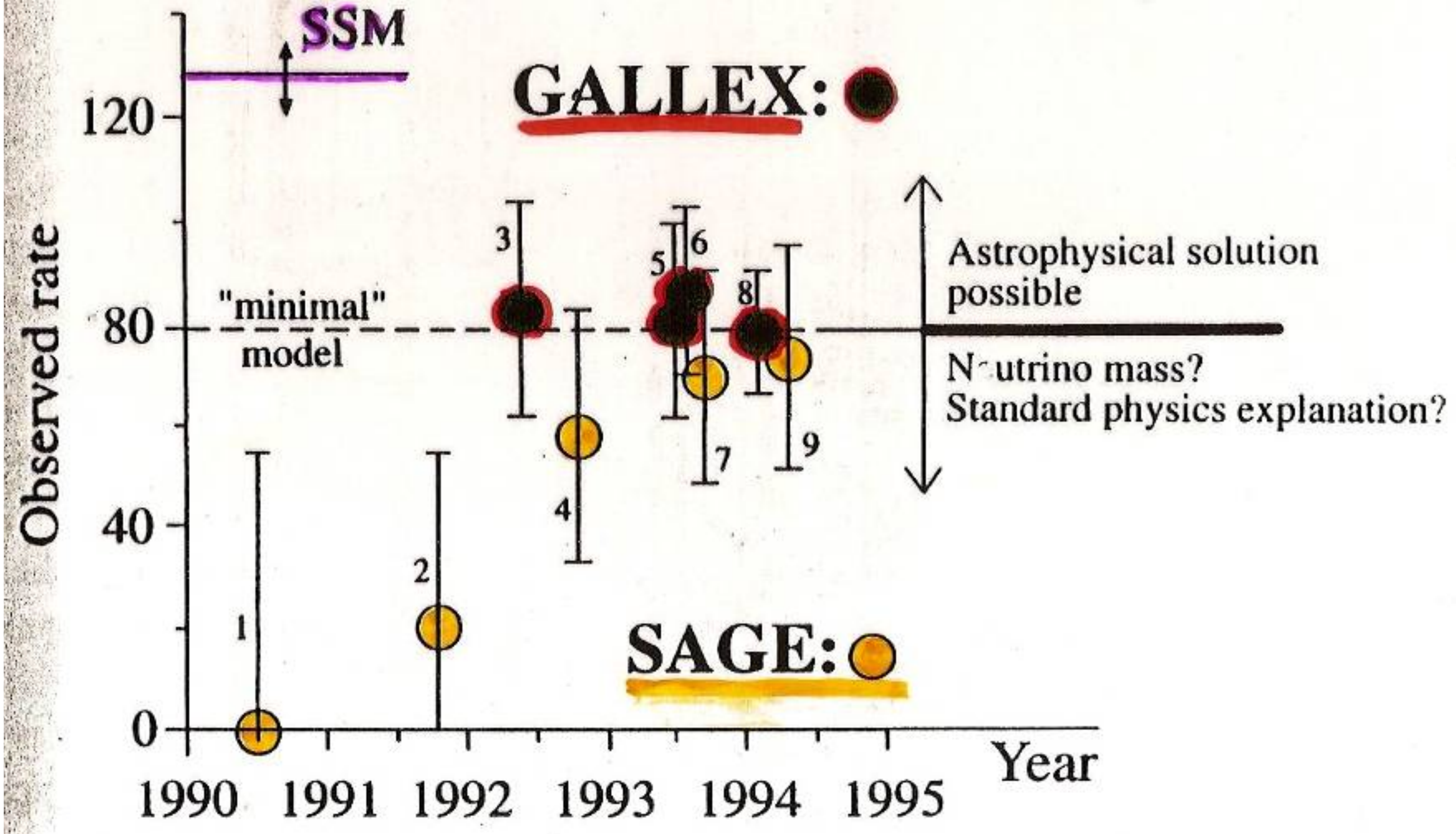
$$66.2^{+3.3}_{-3.2}\ {}^{+3.5}_{-3.2}\ \text{SNU}$$

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

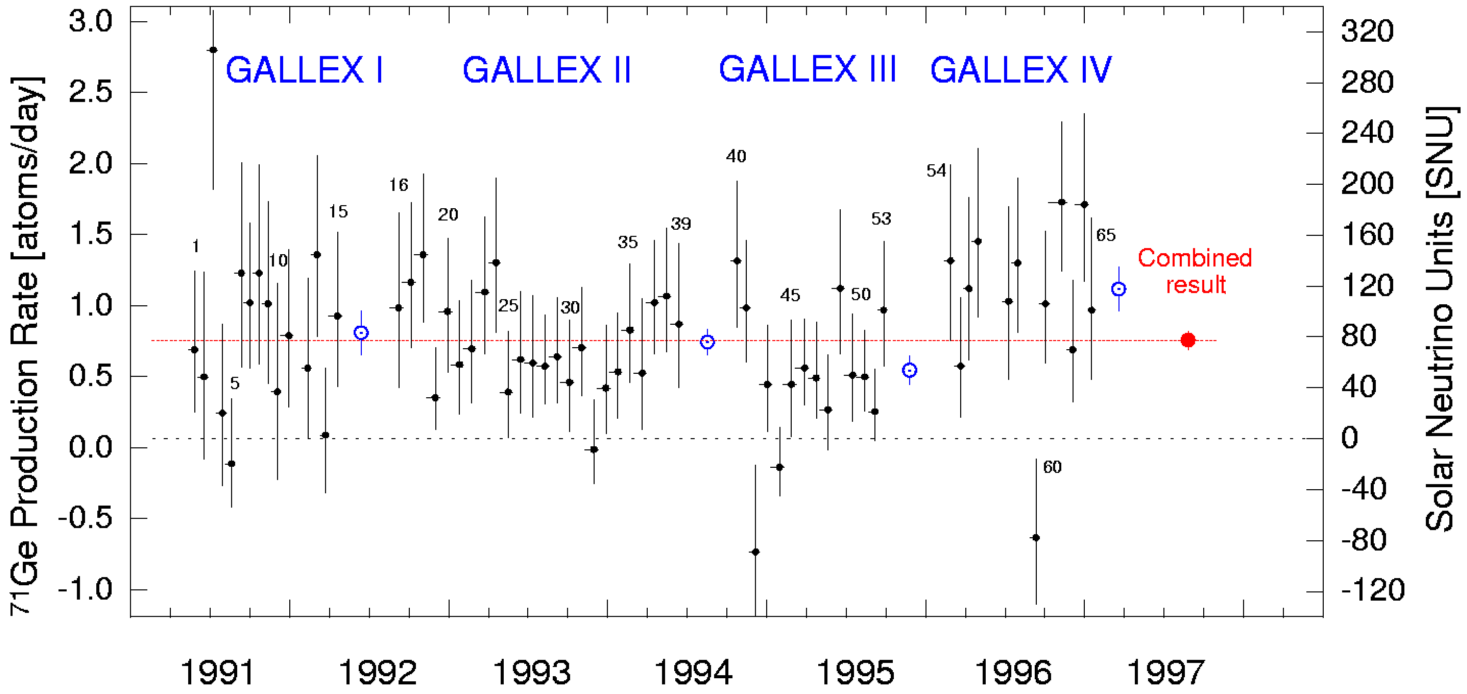
$$67.3^{+3.9}_{-3.5}\ \text{SNU}$$

- 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).



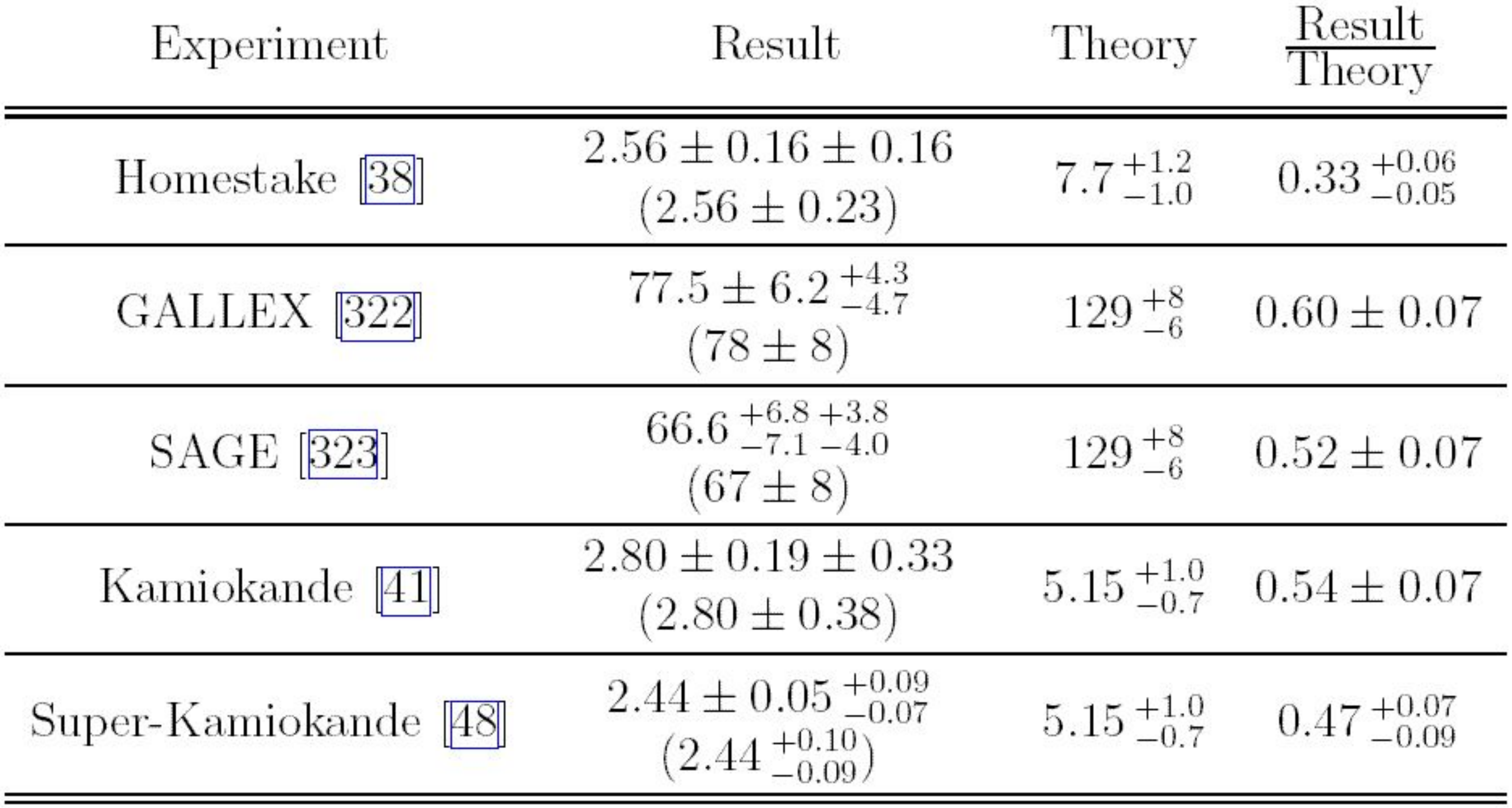
GALLEX-SAGE results



	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!

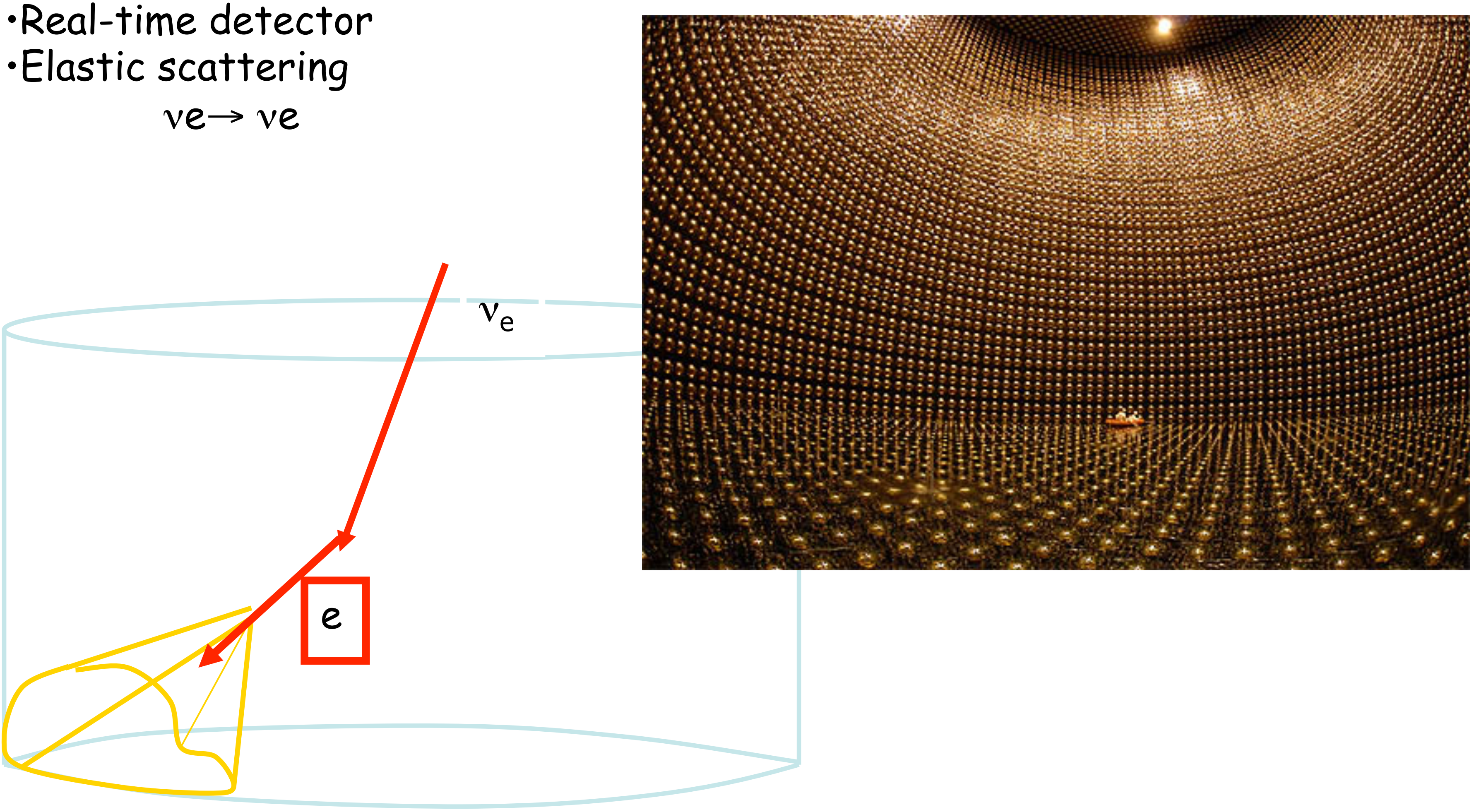
Solar Neutrino Problem

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

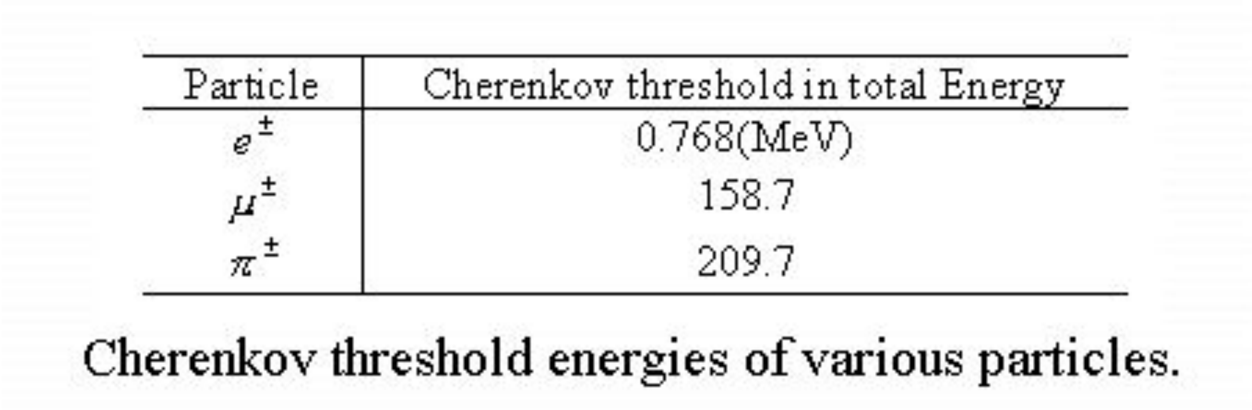
The SK way- The elastic scattering of neutrinos on electrons

- Real-time detector
- Elastic scattering

$\nu e \rightarrow \nu e$



Neutrino Scattering Experiments



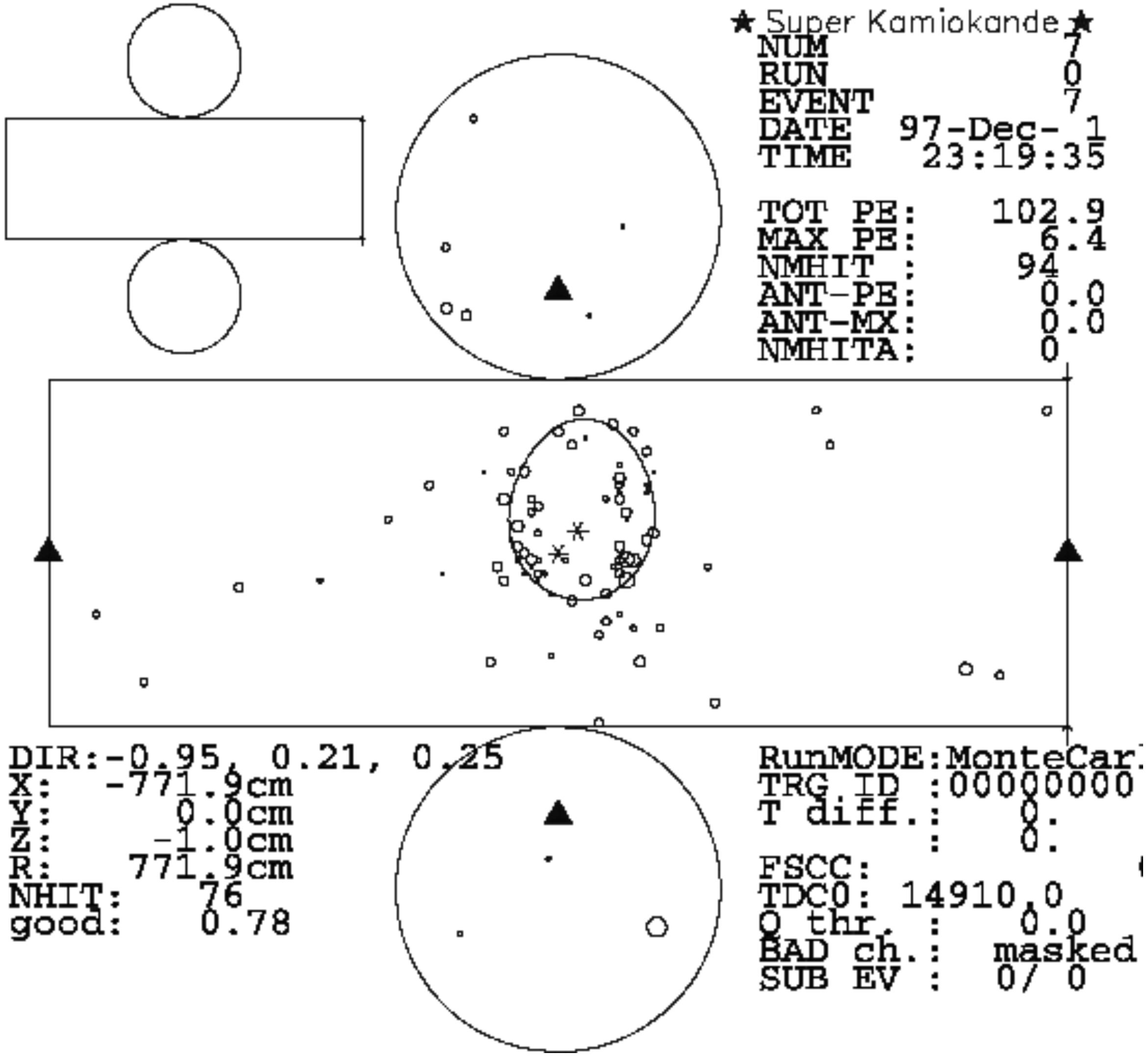
Particle	Cherenkov threshold in total Energy
$e^{\pm}$	0.768(MeV)
$\mu^{\pm}$	158.7
$\pi^{\pm}$	209.7

Cherenkov threshold energies of various particles.

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

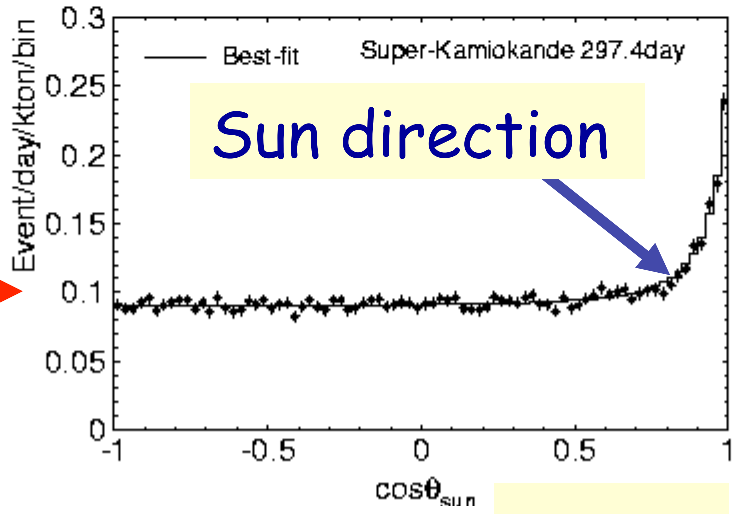
Cherenkov light is emitted in a cone of half angle θ from the direction of the particle track

Neutrino Scattering Experiments



Neutrino Scattering Experiments

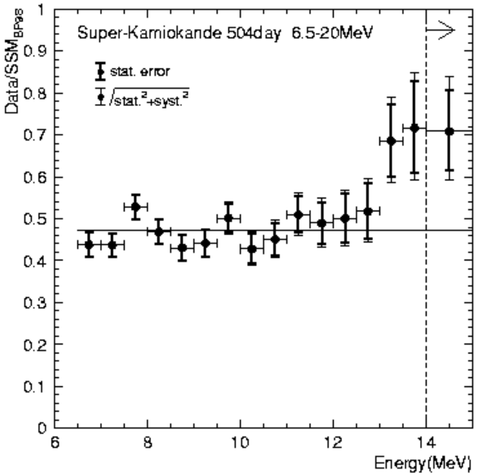
Radioactivity Background

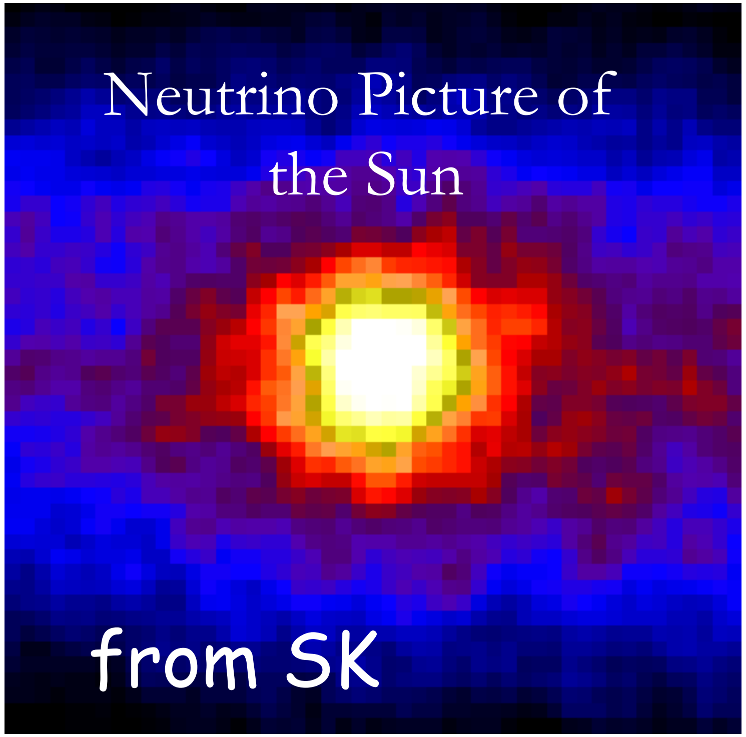


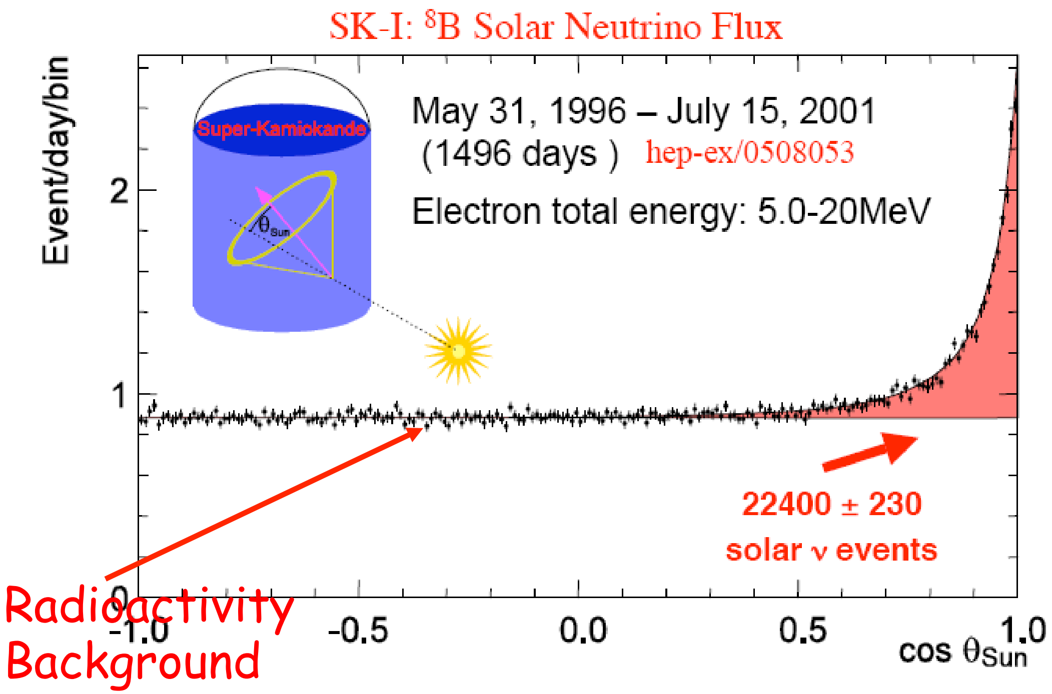
Sun direction

cosθ_{sun}

Ratio of observed electron energy spectrum and expectation from SSM

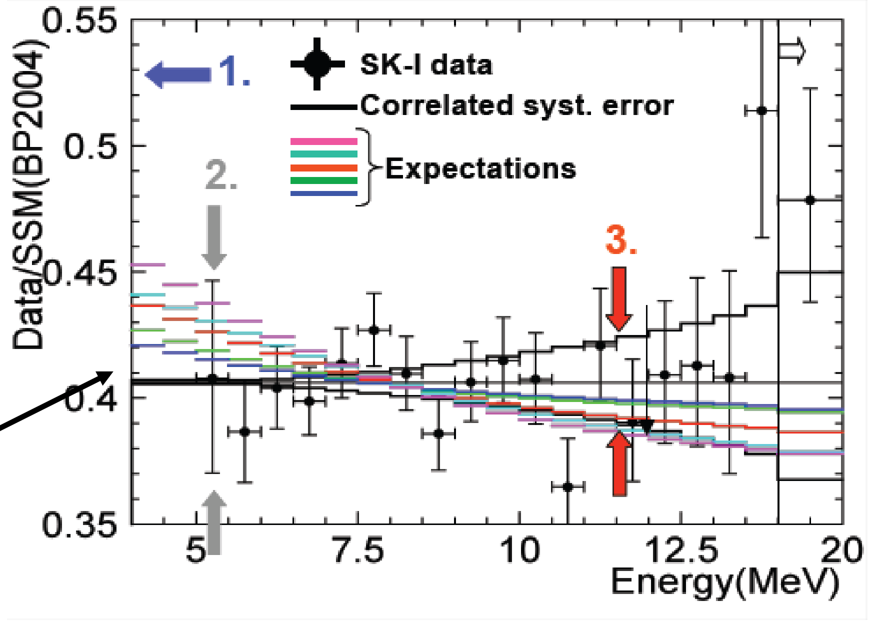






$\phi_{ES} = 2.35 \pm 0.02 \pm 0.08$ [x10^6/cm^2/s]

- 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

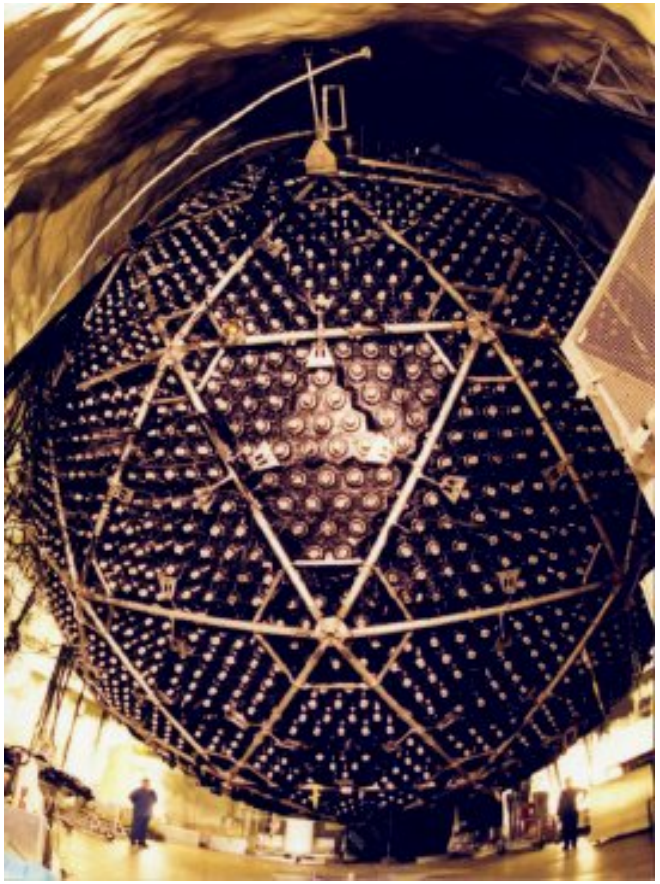


Ratio of observed electron energy spectrum and expectation from SSM

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

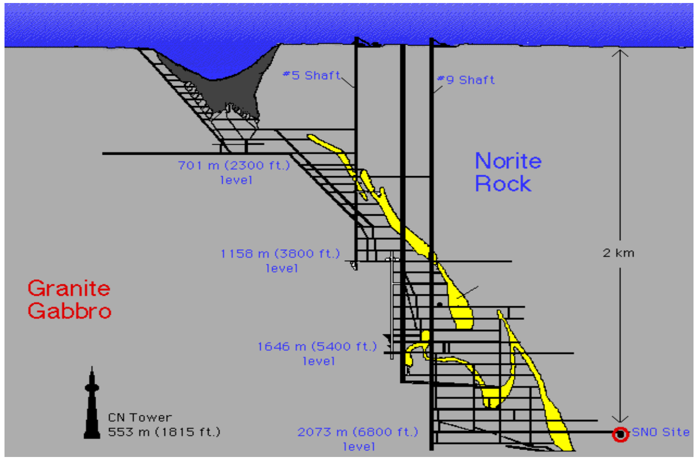
- 18m sphere, situated underground at about 2.5km underground, in Ontario
- 10,000 photomultiplier tubes (PMT)
- Each PMT collect Cherenkov light photons
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- Pure salt is added to increase sensitivity of NC reactions (2002)
- It can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

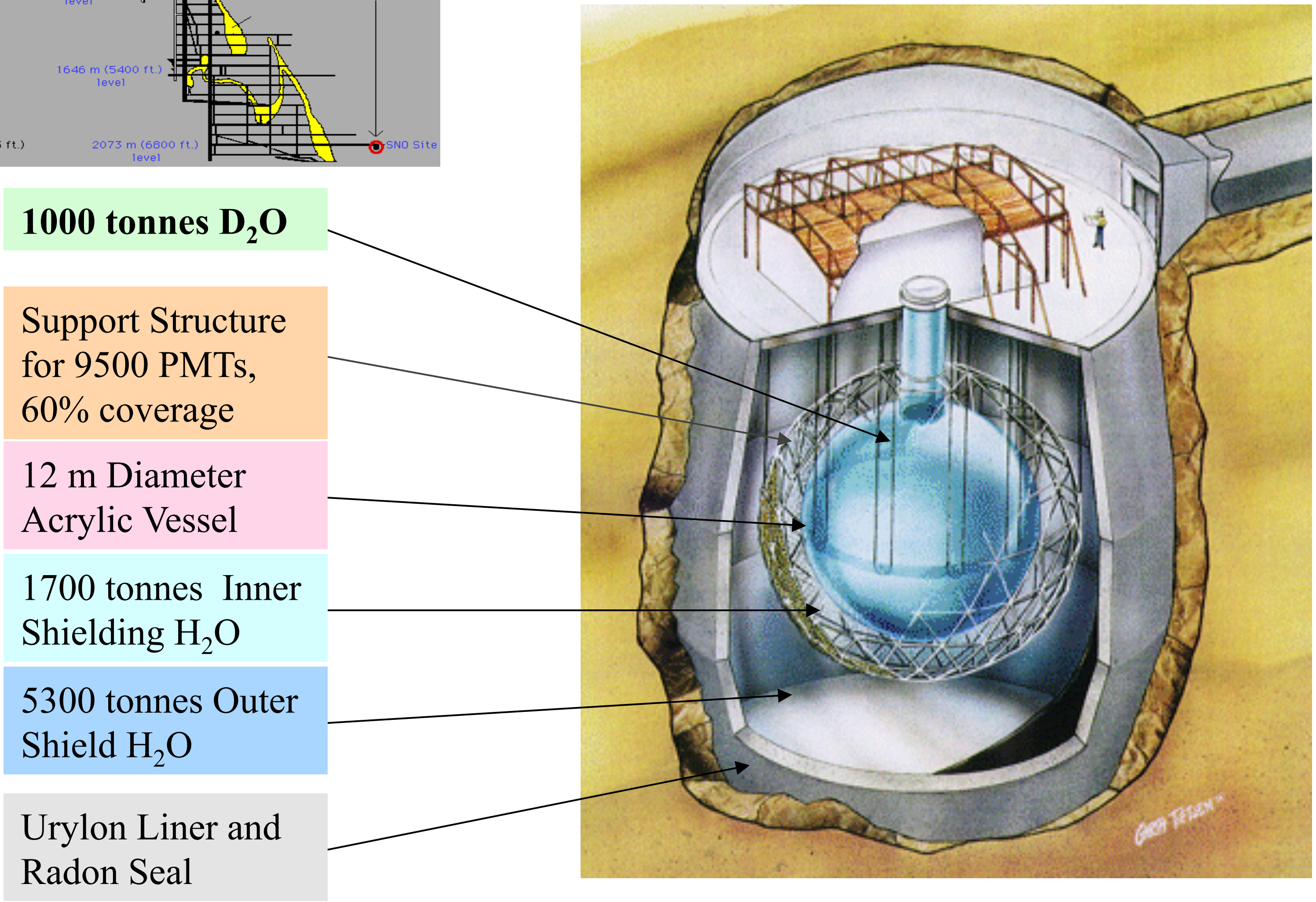
$$\Phi(\nu_\mu,\ \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$



■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 $\nu_e + d \Rightarrow p + p + e^-$

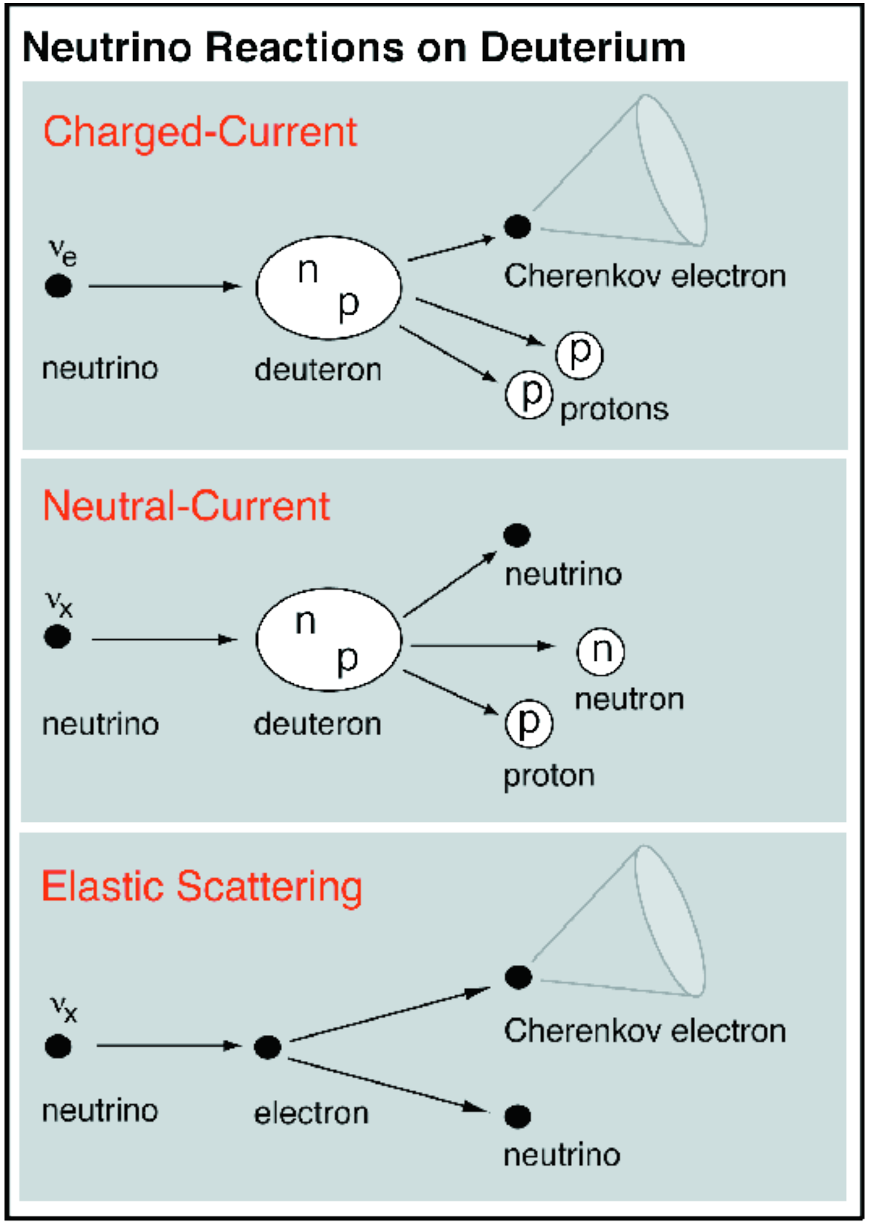
-Gives ν_e energy spectrum well
-Weak direction sensitivity ∝ 1-1/3cos(θ)
- ν_e only.
-SSM: 30 CC events day^{-1}

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

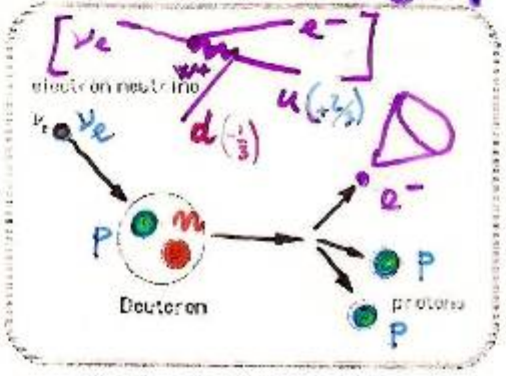
-Low Statistics (3/day)
-Mainly sensitive to ν_e,, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



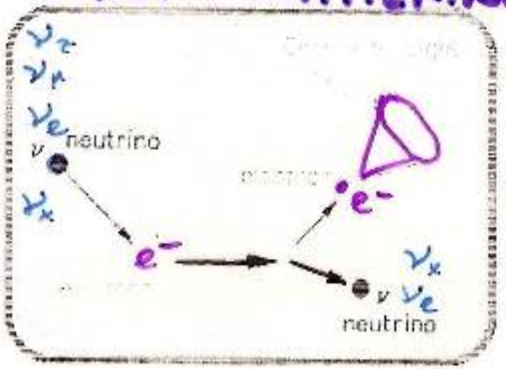
OBSERVABLE REACTIONS IN S.N.O.

Le Reazioni Osservabili in SNO

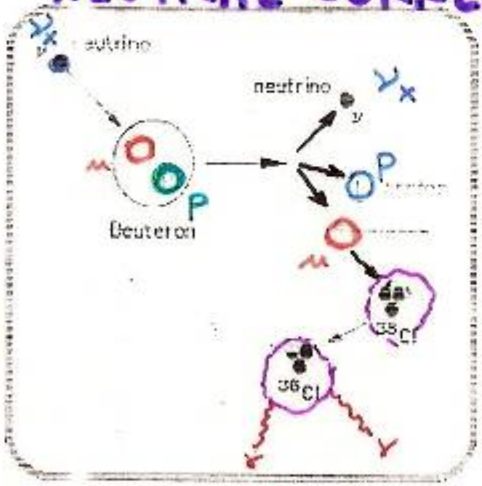
CHARGED CURRENT



ELASTIC SCATTERING



NEUTRAL CURRENT



$\boxed{\nu_e} + d \rightarrow p + p + e^-$ ($\underline{\text{CC}}$) $\boxed{\nu_x} + e^- \rightarrow \nu_x + e^-$ ($\underline{\text{ES}}$) $\boxed{\nu_x} + d \rightarrow n + p + \nu_x$ ($\underline{\text{NC}}$)

Solo neutrini elettronici
ν_e ONLY

Tutti i neutrini
ν_x = ALL NEUTRINOS

Tutti i neutrini
ν_x = ALL NEUTRINOS

Neutrini prodotti da ^{8}B (E_ν<15 MeV)
Soglia Rivelatore 6.75 MeV THRESHOLD @ 6.75 MeV

Può essere separato il contributo dei diversi neutrini

IT IS POSSIBLE TO SEPARATE ν_x CONTRIBUTIONS

⇓

Indipendenza dalle previsioni del modello Solare

INDIPENDENT FROM S. SOLAR MODEL

❑The 2001 results

❑ The ν_e's flux from ^{8}B 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)

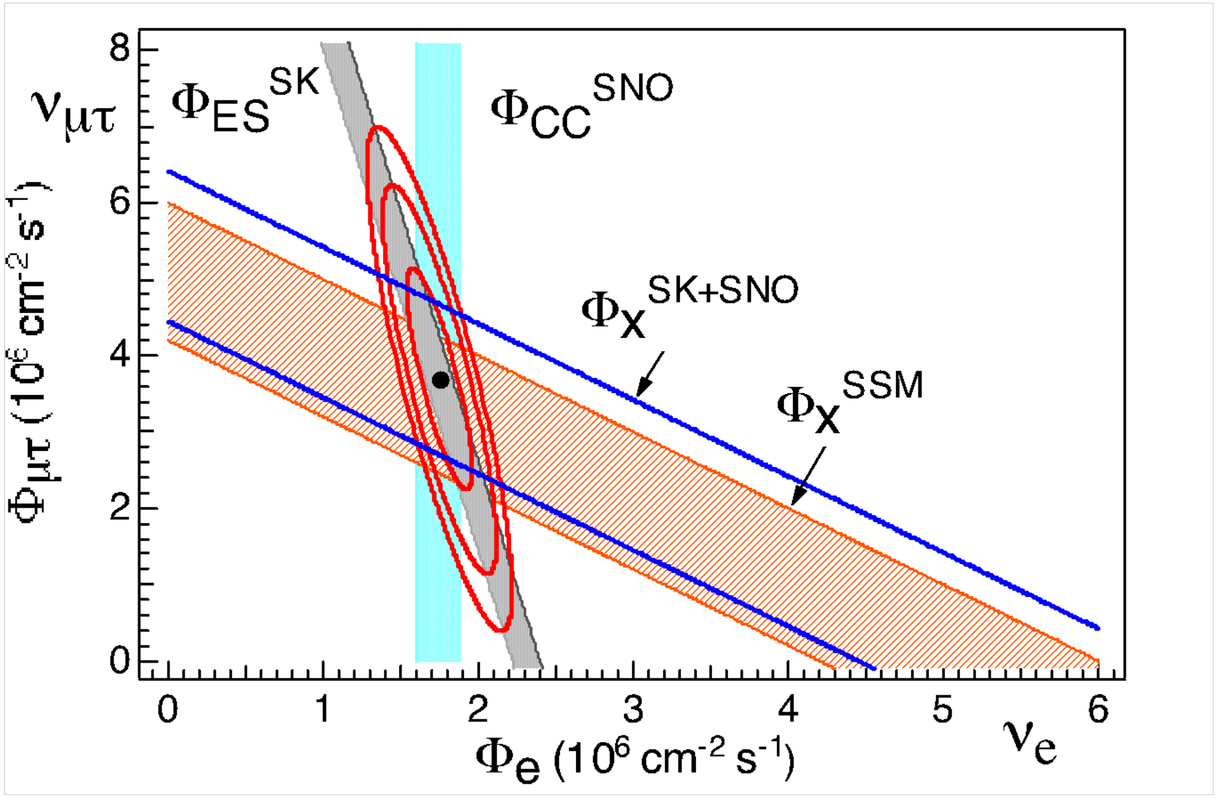
❑$\phi^{ES}_{SK}(\nu_x) = (2.32 \pm 0.08) \times 10^6\ cm^{-2}s^{-1}$ (SK)

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

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

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

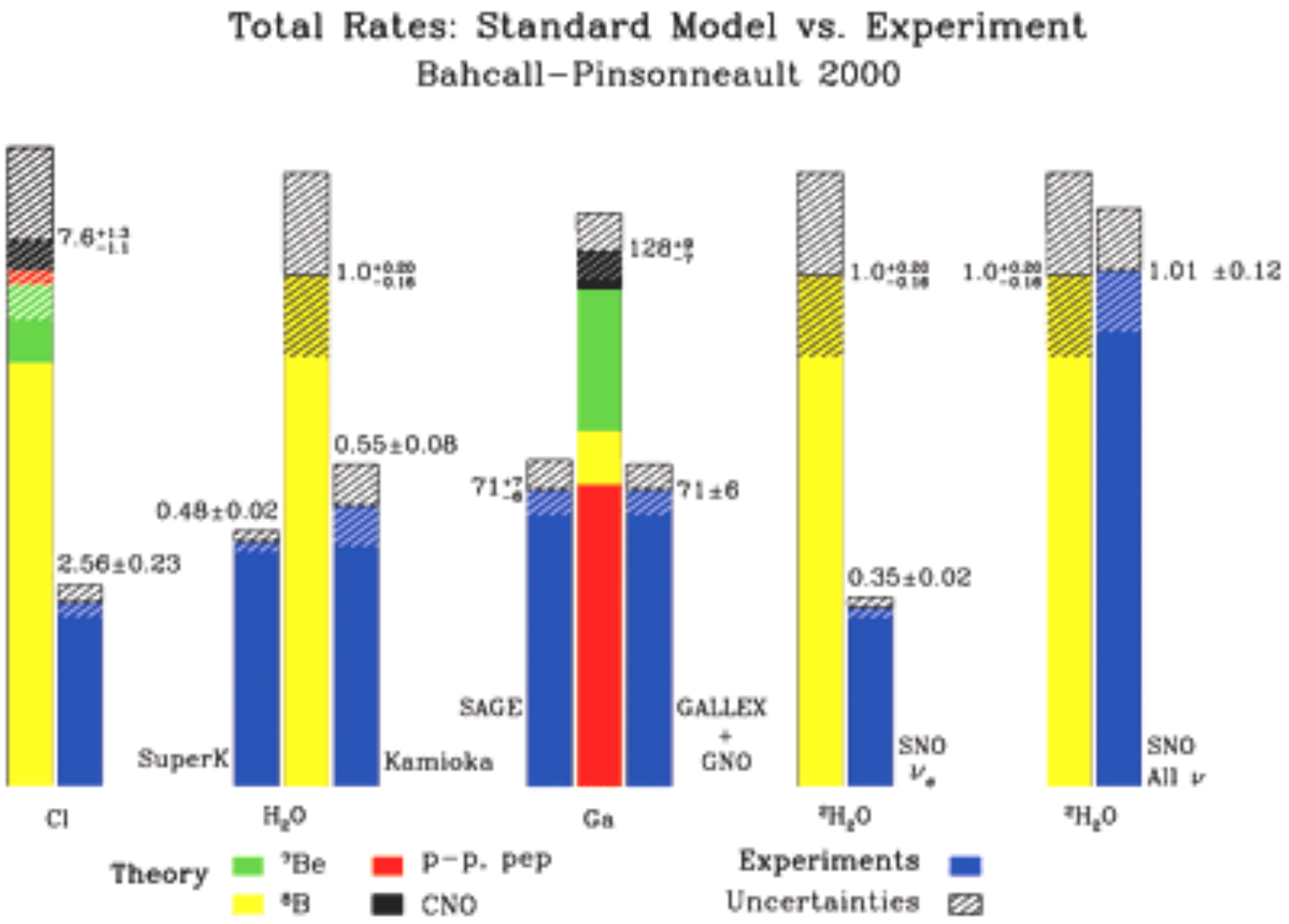
Solar Neutrino Problem



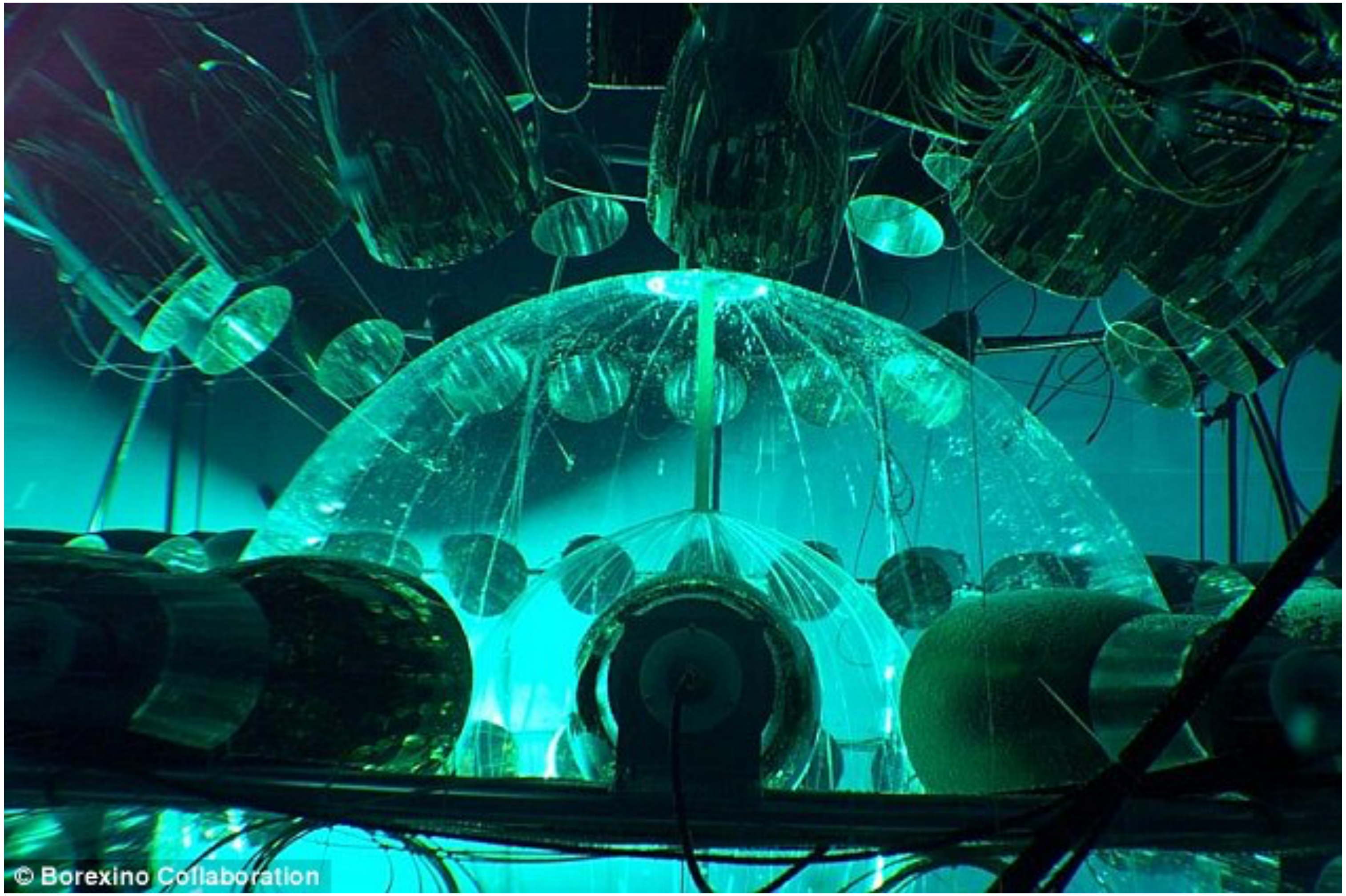
- The total flux of active ^{8}B neutrinos is:

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

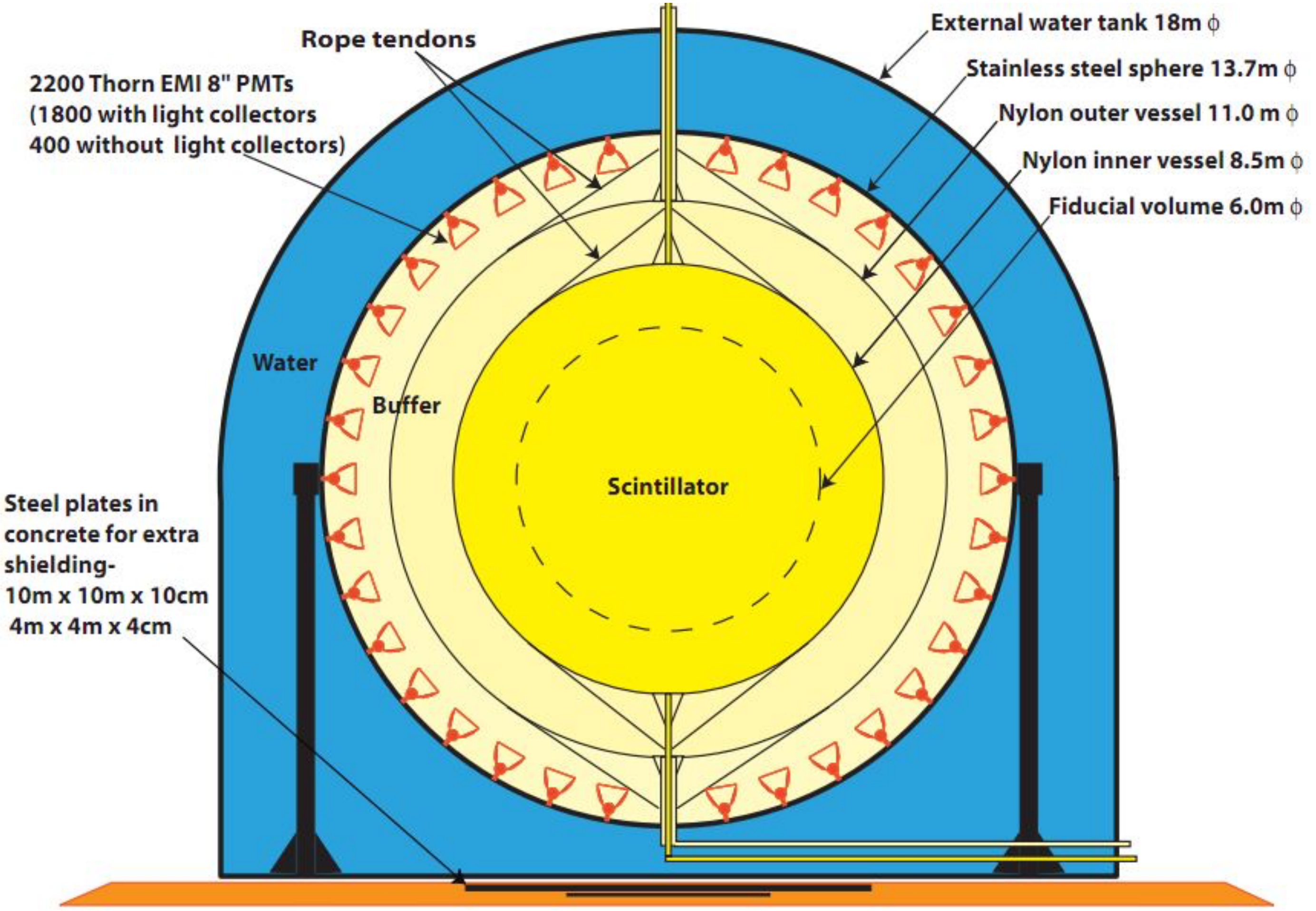
Solar Neutrino Problem



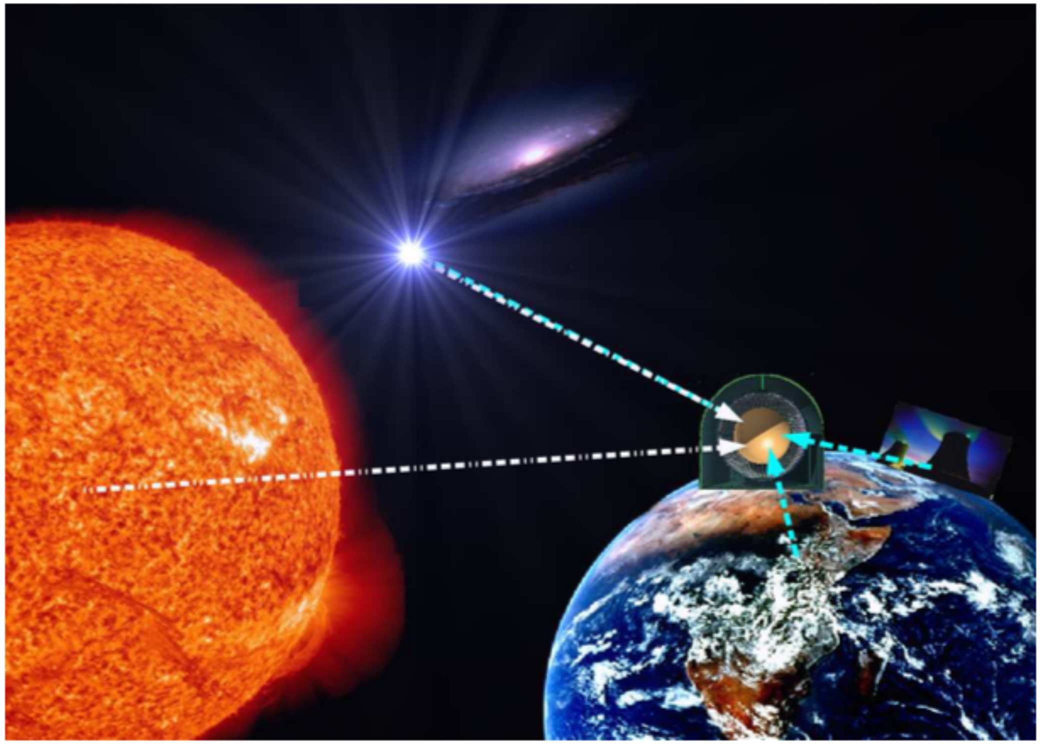
Borexino @LNGS



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

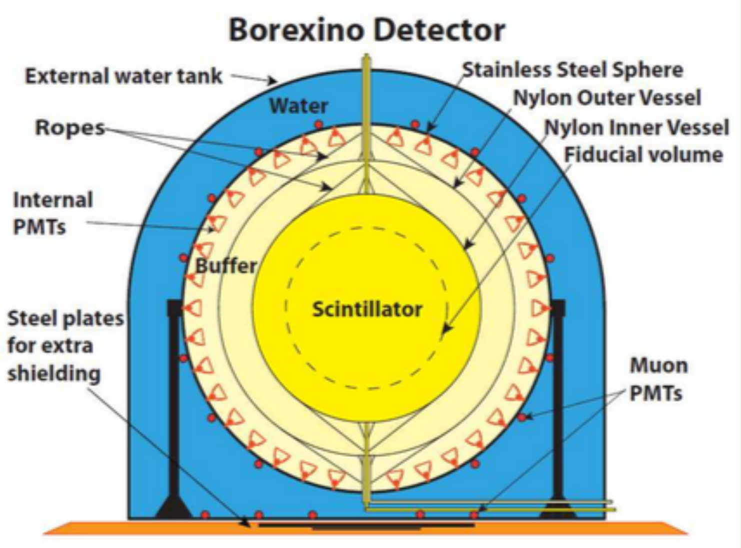
Nut shell profile:

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

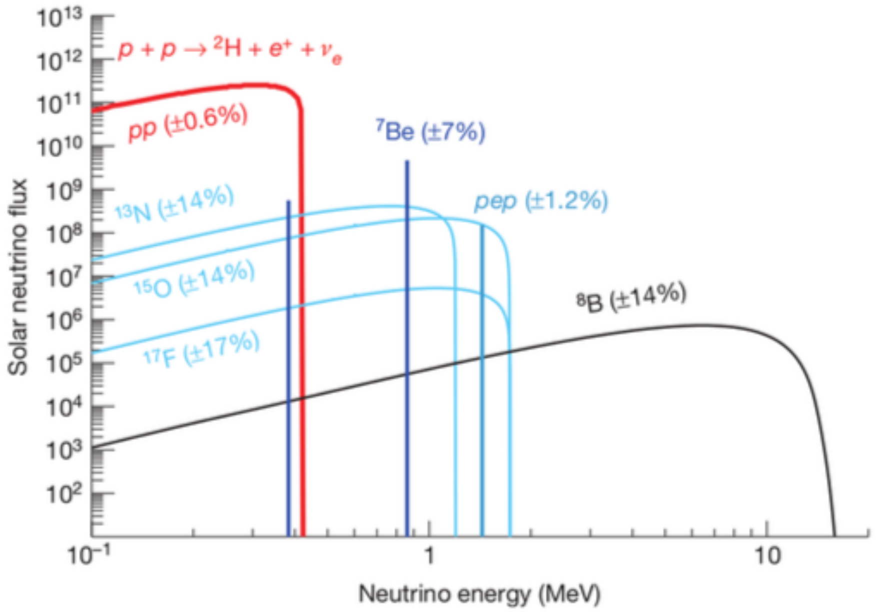
④ Scintillator: 270 tons of PC+PPO



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.

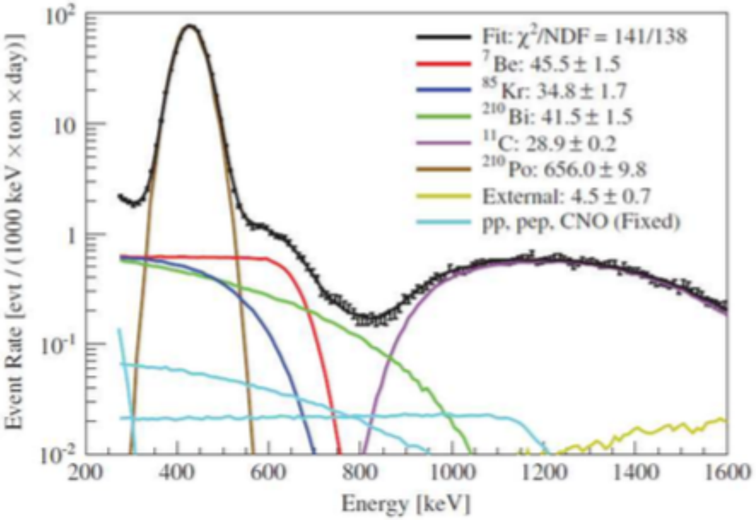
ν flux	GS98	AGSS09
pp	$5.98(1\pm0.006)$	$6.03(1\pm0.006)$
^{7}Be	$5.00(1\pm0.07)$	$4.56(1\pm0.07)$
pep	$1.44(1\pm0.012)$	$1.47(1\pm0.012)$
^{13}N	$2.96(1\pm0.14)$	$2.17(1\pm0.14)$
^{15}O	$2.23(1\pm0.15)$	$1.56(1\pm0.15)$
^{17}F	$5.52(1\pm0.17)$	$3.40(1\pm0.16)$
^{8}B	$5.58(1\pm0.14)$	$4.59(1\pm0.14)$

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)

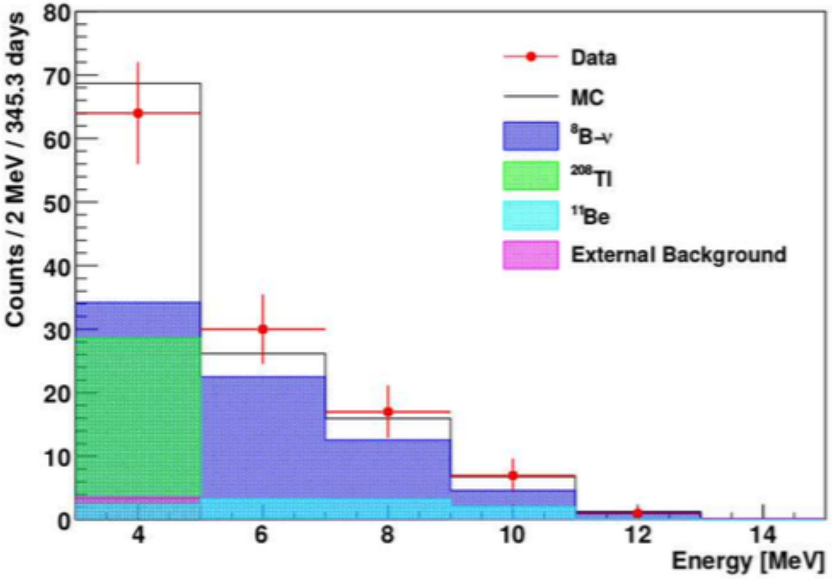


Results and remarks:

- **Averaged rate**: R=(46±1.5(stat)$^{+1.5}_{-1.6}$(sys)) c/d/100 ton (uncertainty ±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±0.012(stat)±0.007(sys) (8.5σ exclusion of LOW osc. solution)
- **7% Annual modulation**: according to rate-vs-time analysis: T=(1.01±0.07) yr; ϵ=0.0398±0.0102 → expected value within 2σ

Solar ^{8}B neutrino rate measurement

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

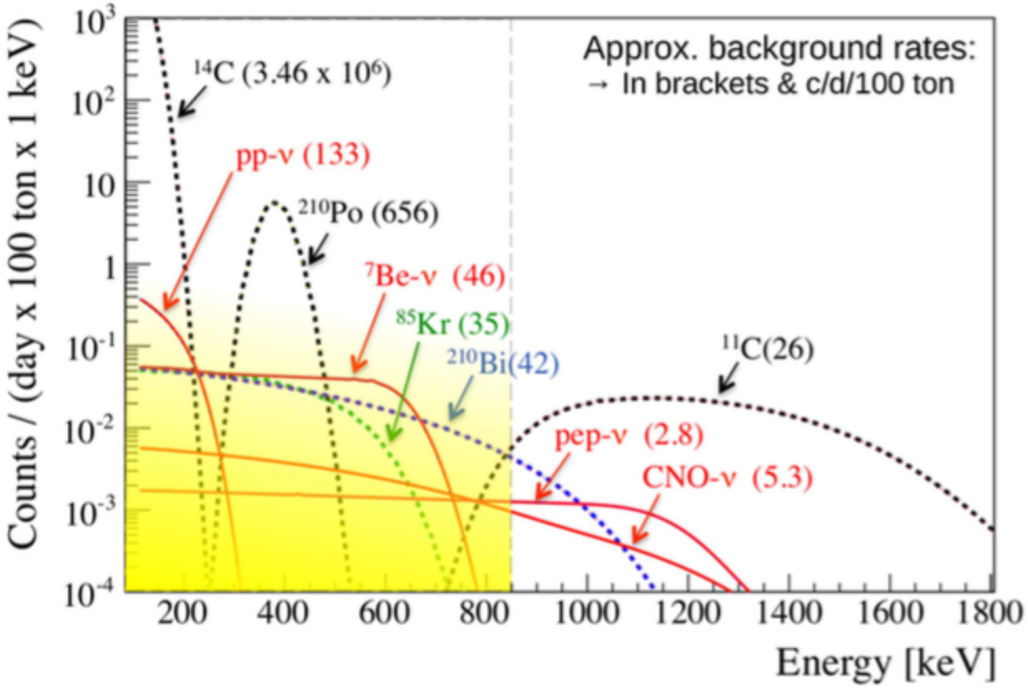


Results and remarks:

- 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)



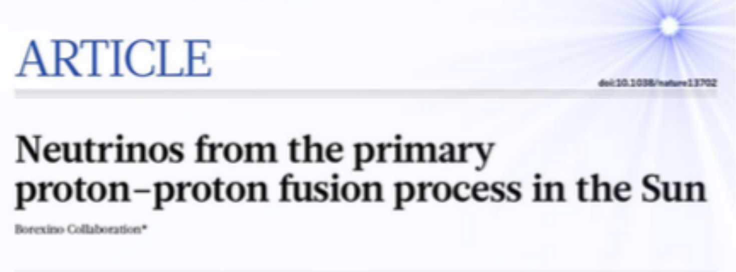
pp neutrinos:

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

doi:10.1038/nature13702

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

Borexino Collaboration*

Nature, Vol. 512, August 28, 2014

Results and remarks:

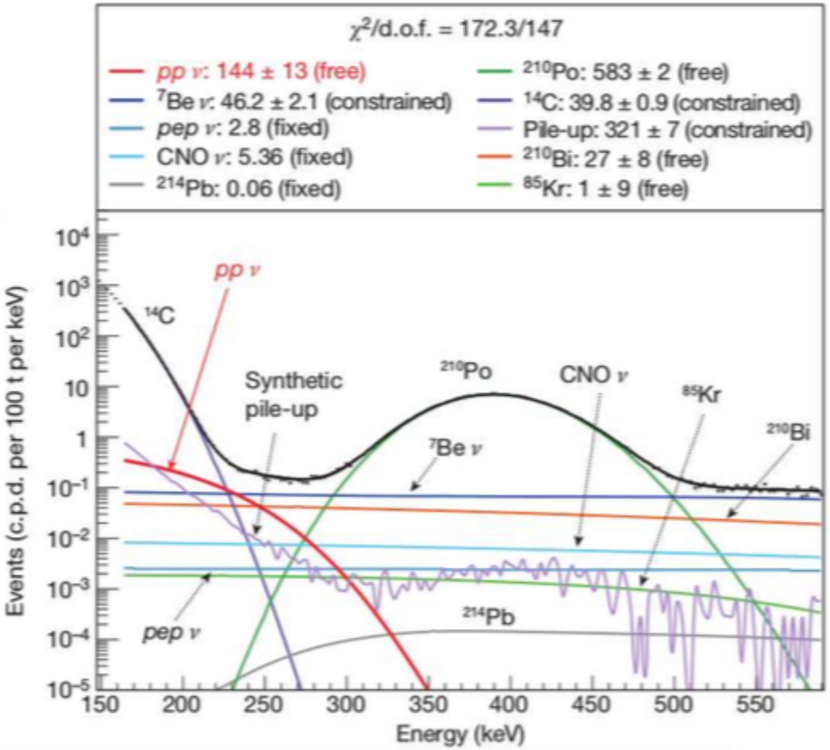
- Rate:
  144±13(stat)±10(sys) c/d/100 ton
  (10σ exclusion of pp ν absence)
- Robustness of analysis:

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

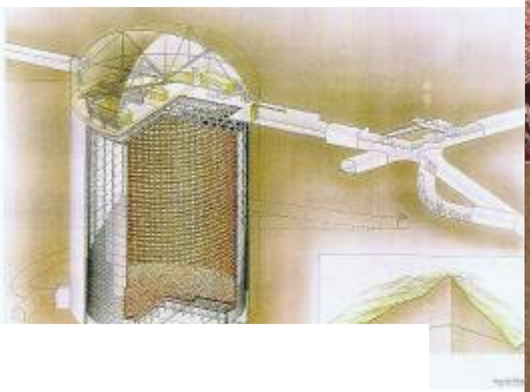
Scoperta graduale

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?

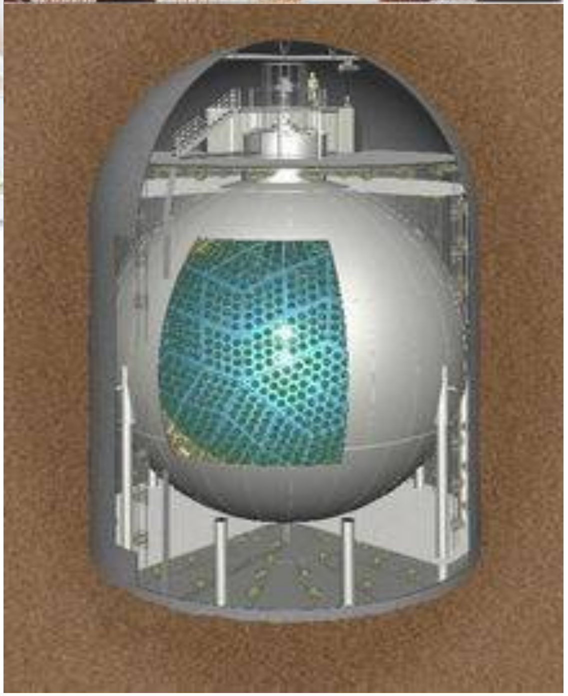
1997. GALLEX + LUNA

il colpevole è il neutrino



1998. SuperKAMIOKANDE

scoperta oscillazioni: scomparsa nei ν_μ da atmosfera



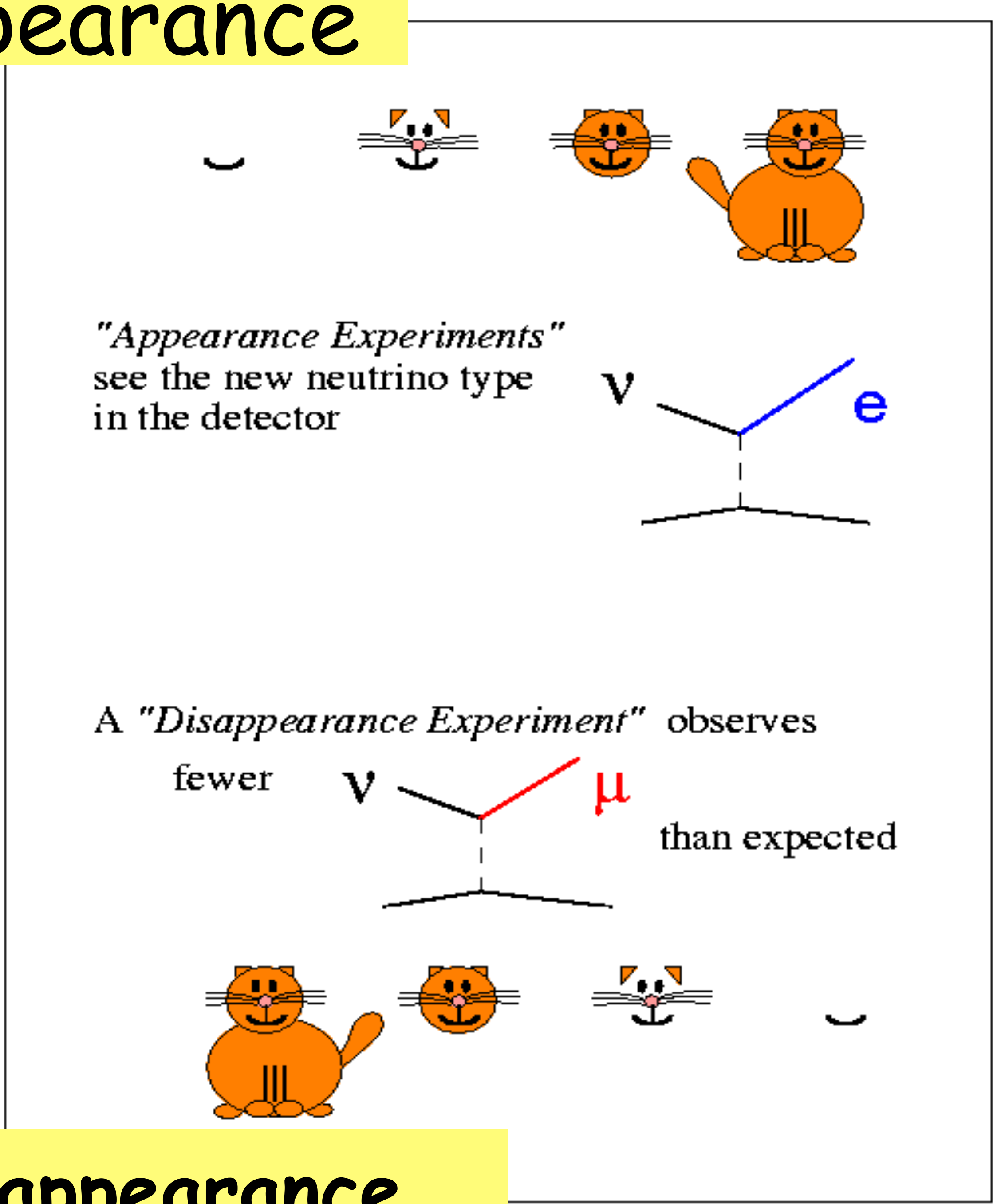
2002. SNO

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



"Appearance Experiments" see the new neutrino type in the detector

A *"Disappearance Experiment"* observes fewer ν μ than expected

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

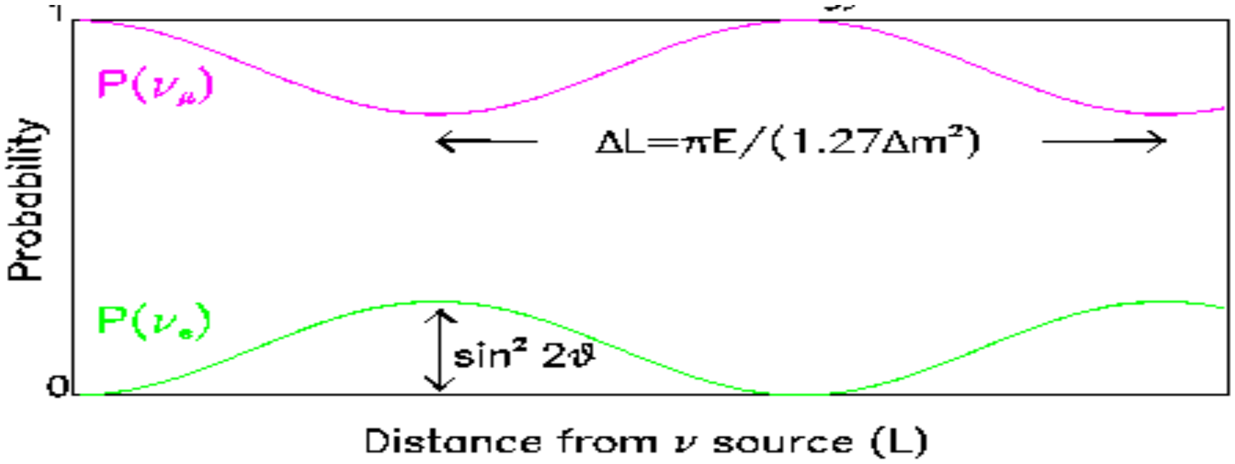
$|\nu_e> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$

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

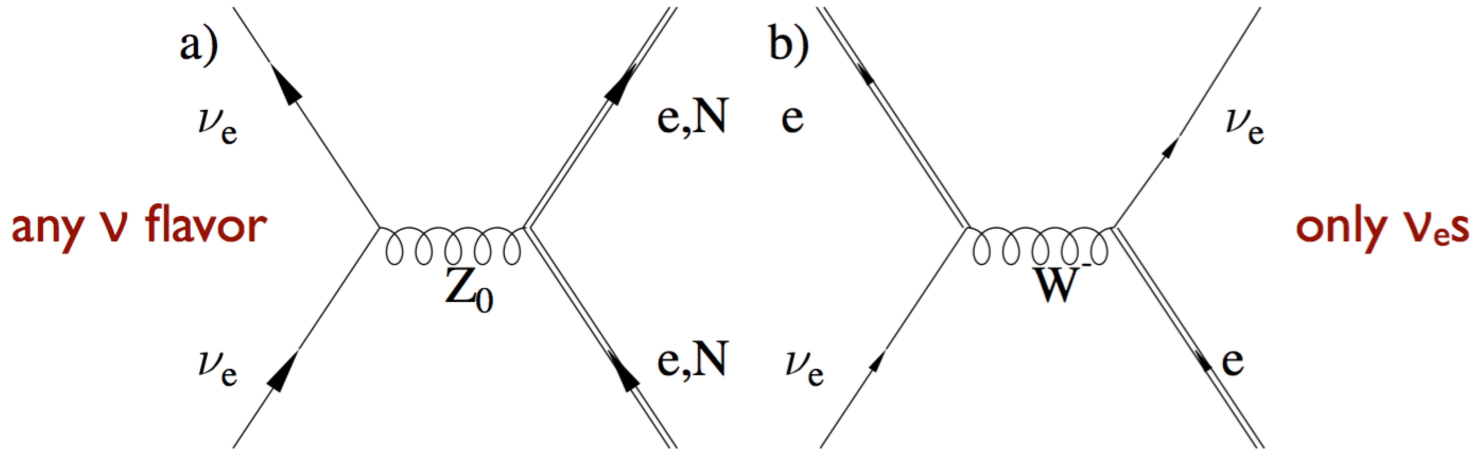
θ = mixing angle
Angolo di mescolamento

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

- 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)**



solar matter generates a flavor asymmetry



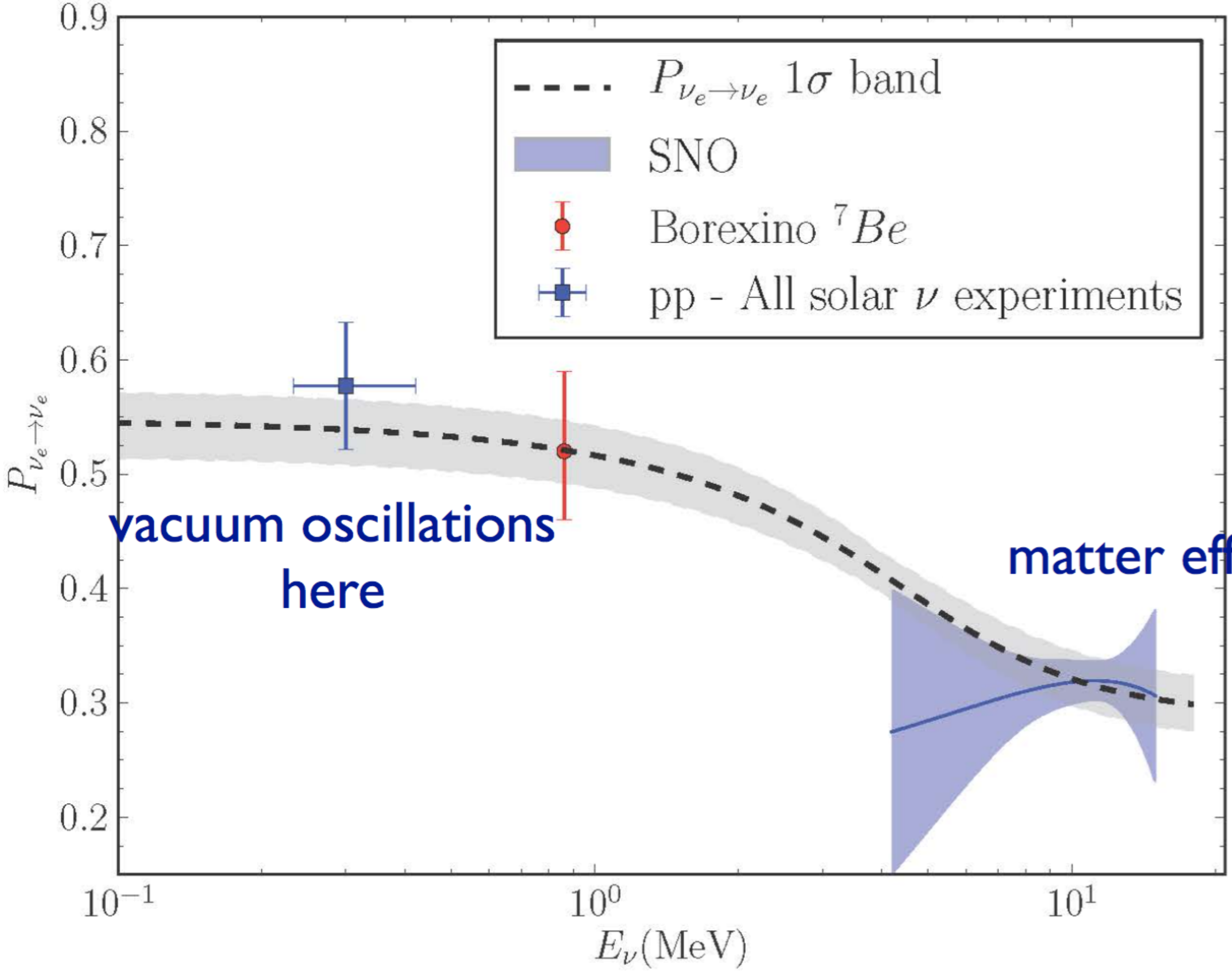
- modifies forward scattering amplitude: flavor-dependent index of refraction

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

- makes the electron neutrino heavier at high density

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

from Art McDonald



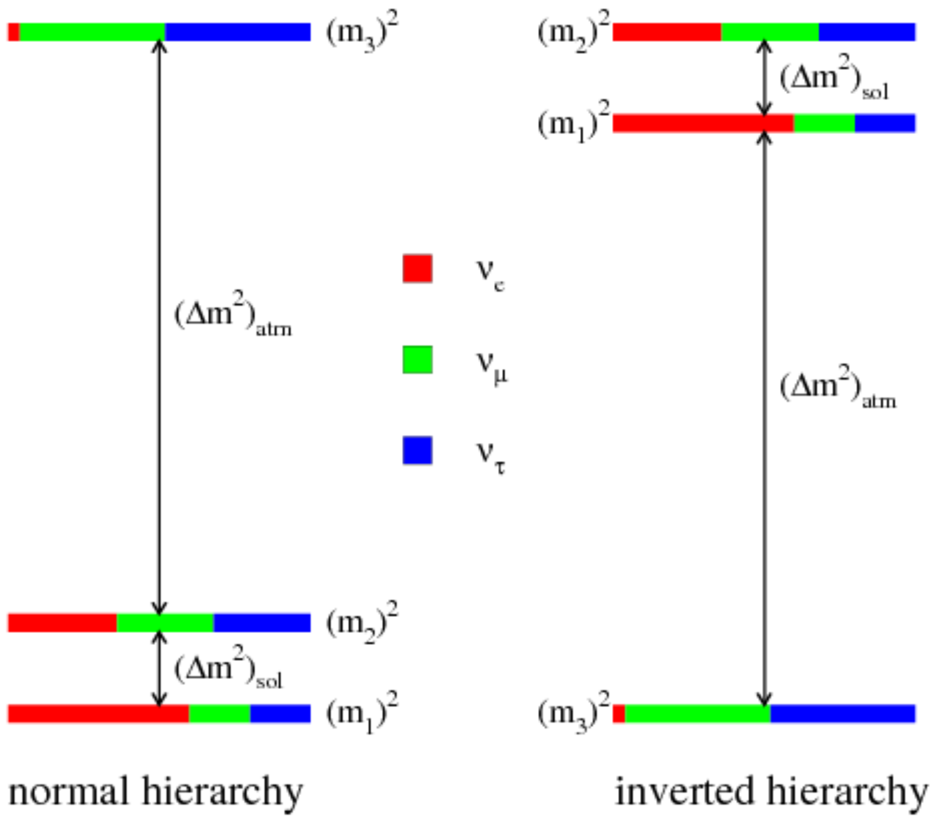
vacuum oscillations here

matter effects here

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

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

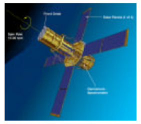


Astrofisica Nucleare e Subnucleare

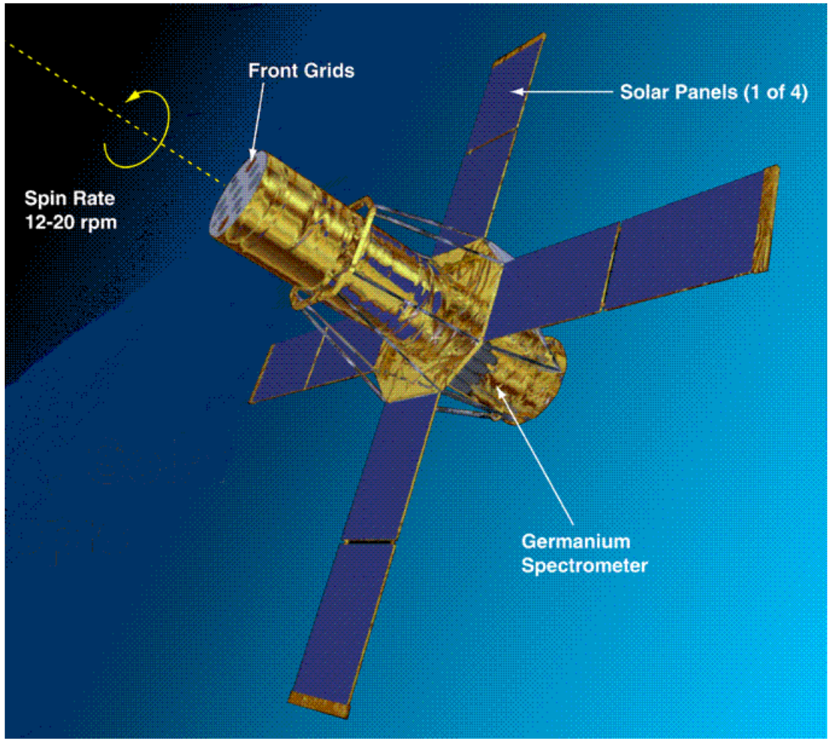
The Sun in Gamma-rays

Solar Flares in Gamma-rays

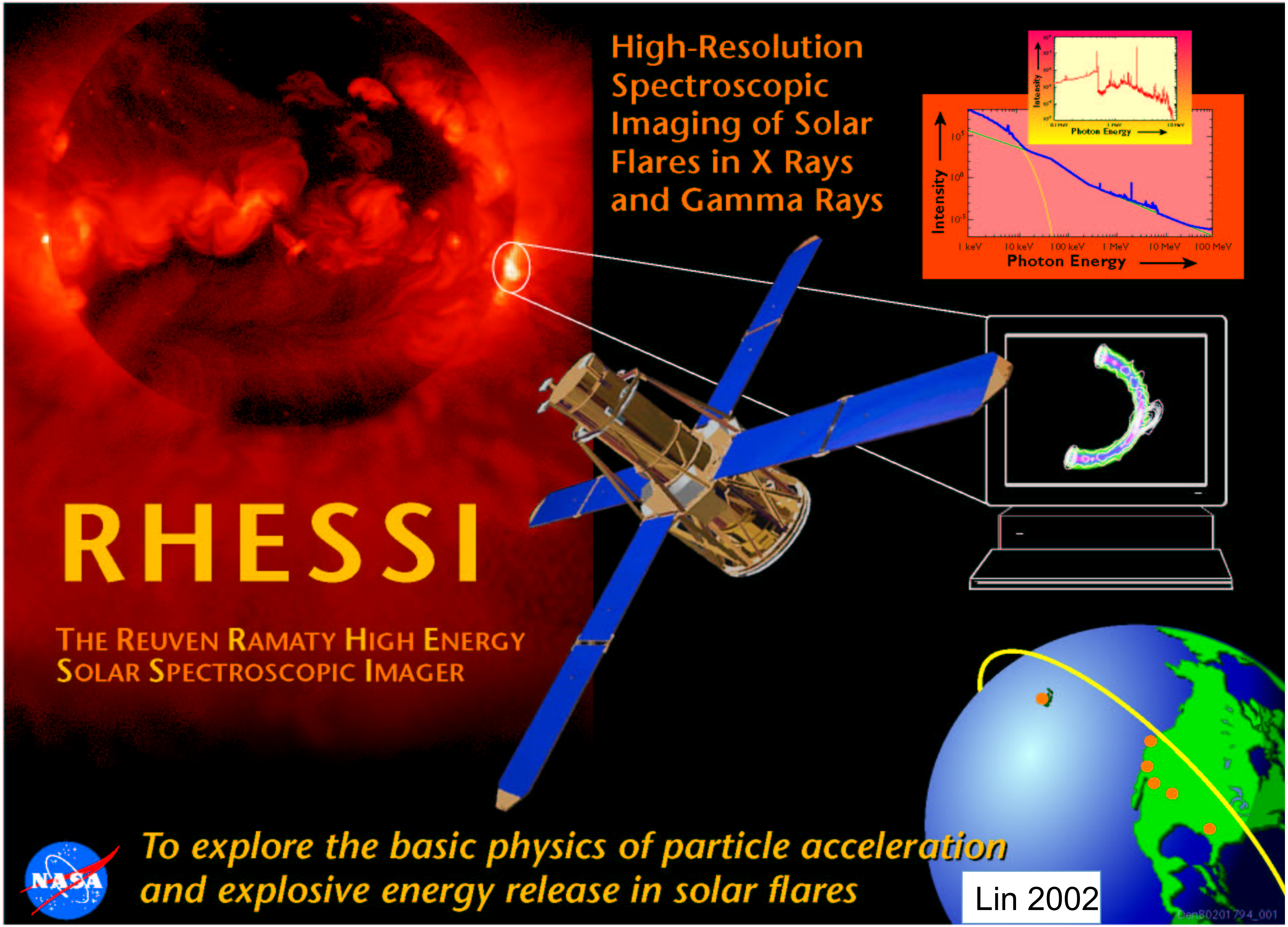
Solar γ-Ray Physics Comes of Age



The High Energy Solar Spectroscopic Imager



Share 2001



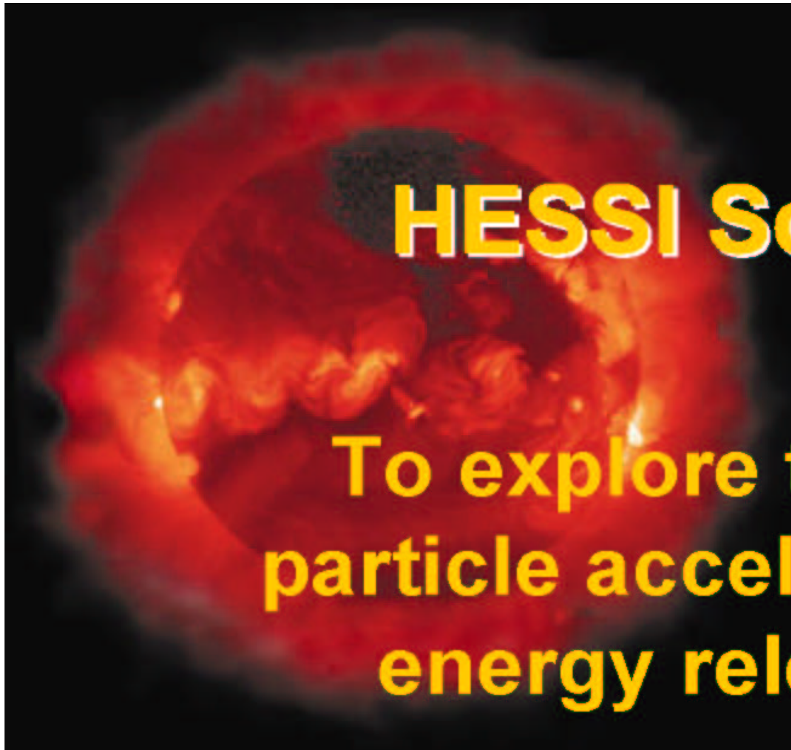
High-Resolution Spectroscopic Imaging of Solar Flares in X Rays and Gamma Rays

RHESSI

THE REUVEN RAMATY HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER

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

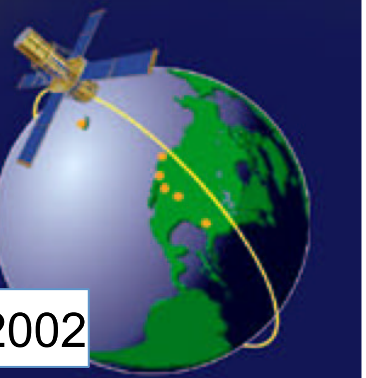
Lin 2002



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

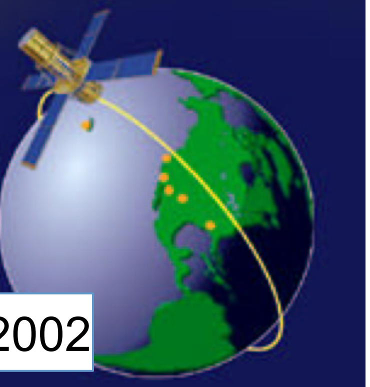


Lin 2002

A1309.03

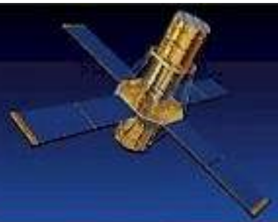
HESSI Primary Observations

- 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

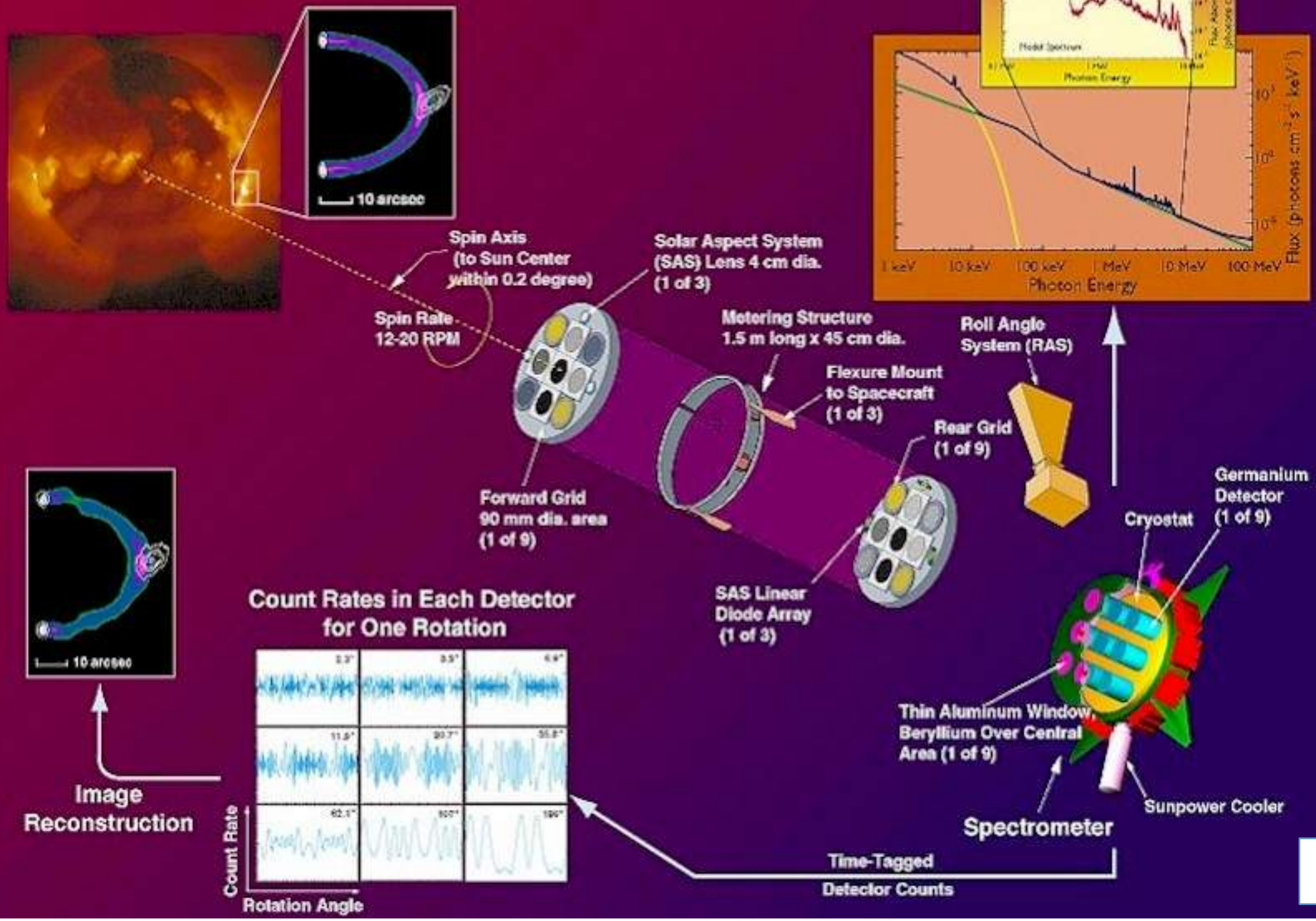
A1309.05



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



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

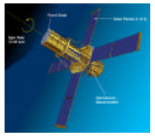
Count Rates in Each Detector
for One Rotation

Image
Reconstruction

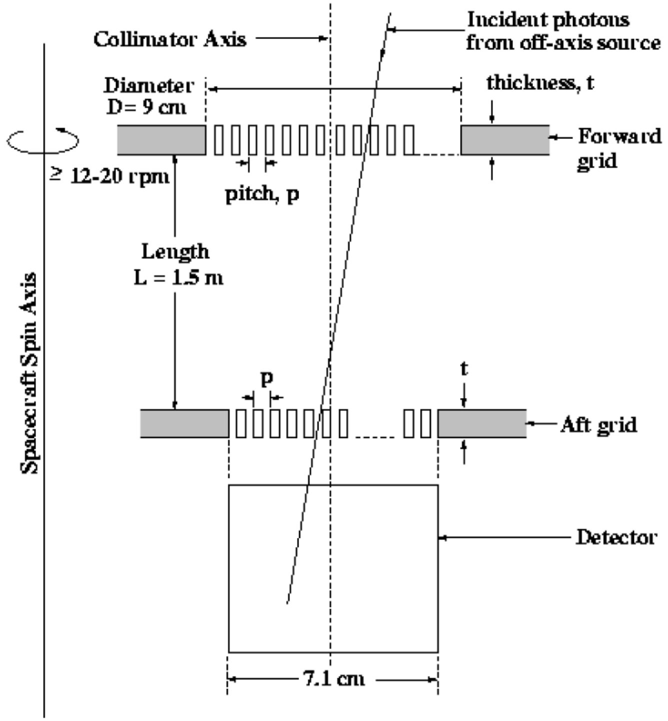
Lin 2002

Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



HESSI IMAGING SYSTEM



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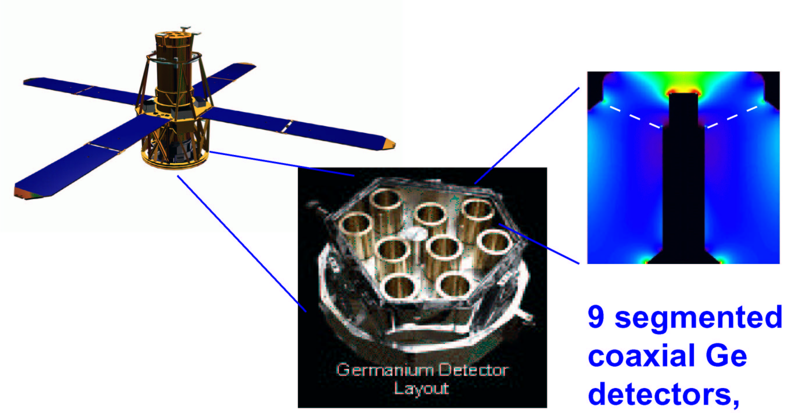
RHESSI

THE RHESSI SPECTROMETER

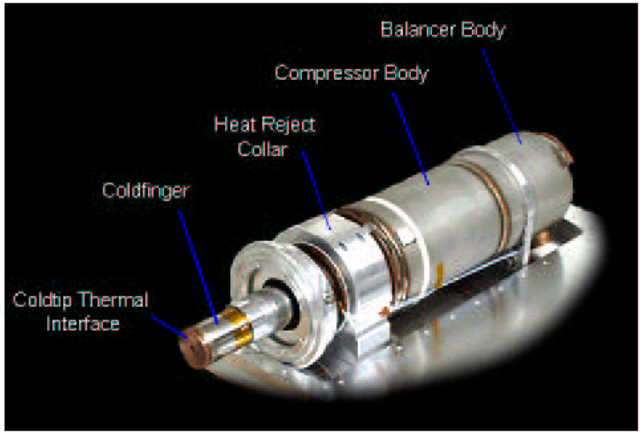


9 segmented coaxial Ge detectors, 7cm x 8.5cm

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:

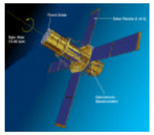


Attenuators: two sets of aluminum disks (thick and thin) that can be manually or automatically moved in front of the detectors to reduce the count rates from large flares.

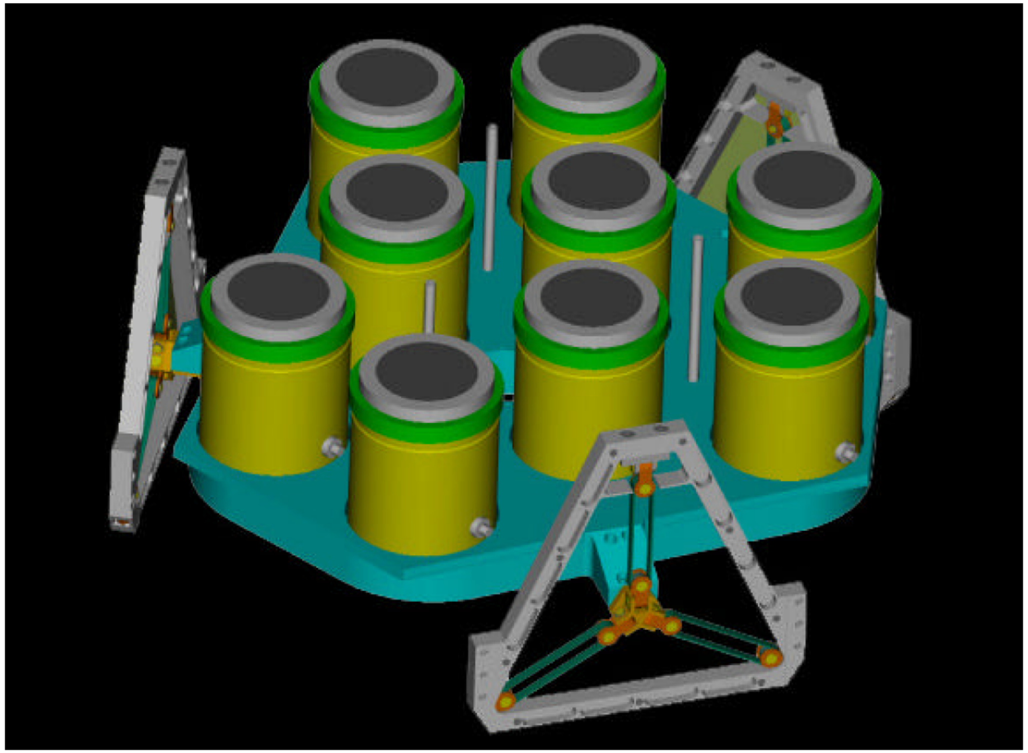
Lin 2002

Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



HESSI Germanium Detector Array



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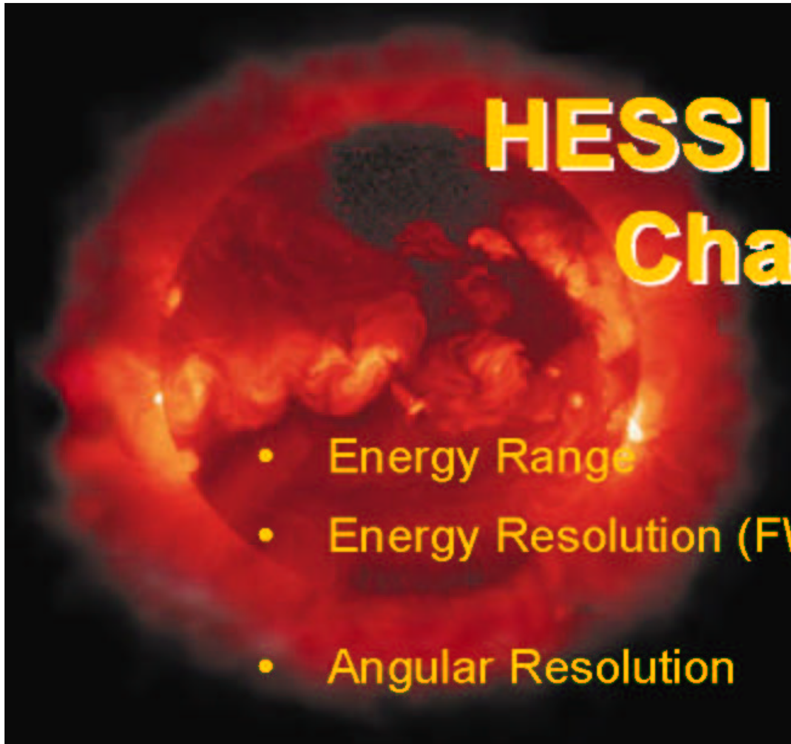
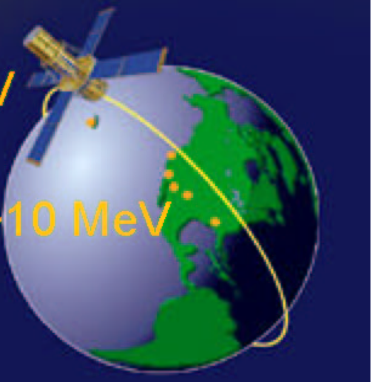
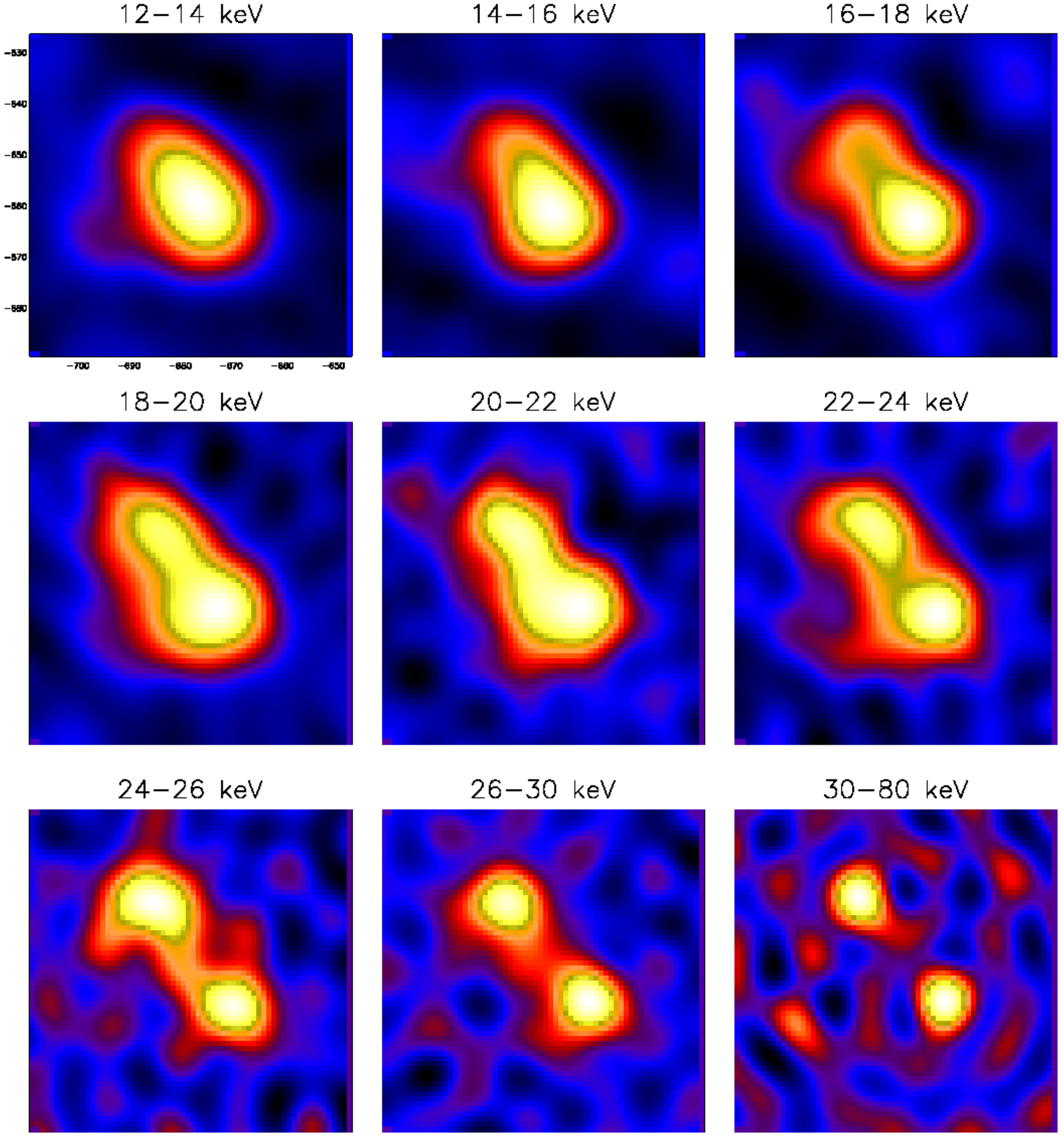
HESSI Observational Characteristics



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

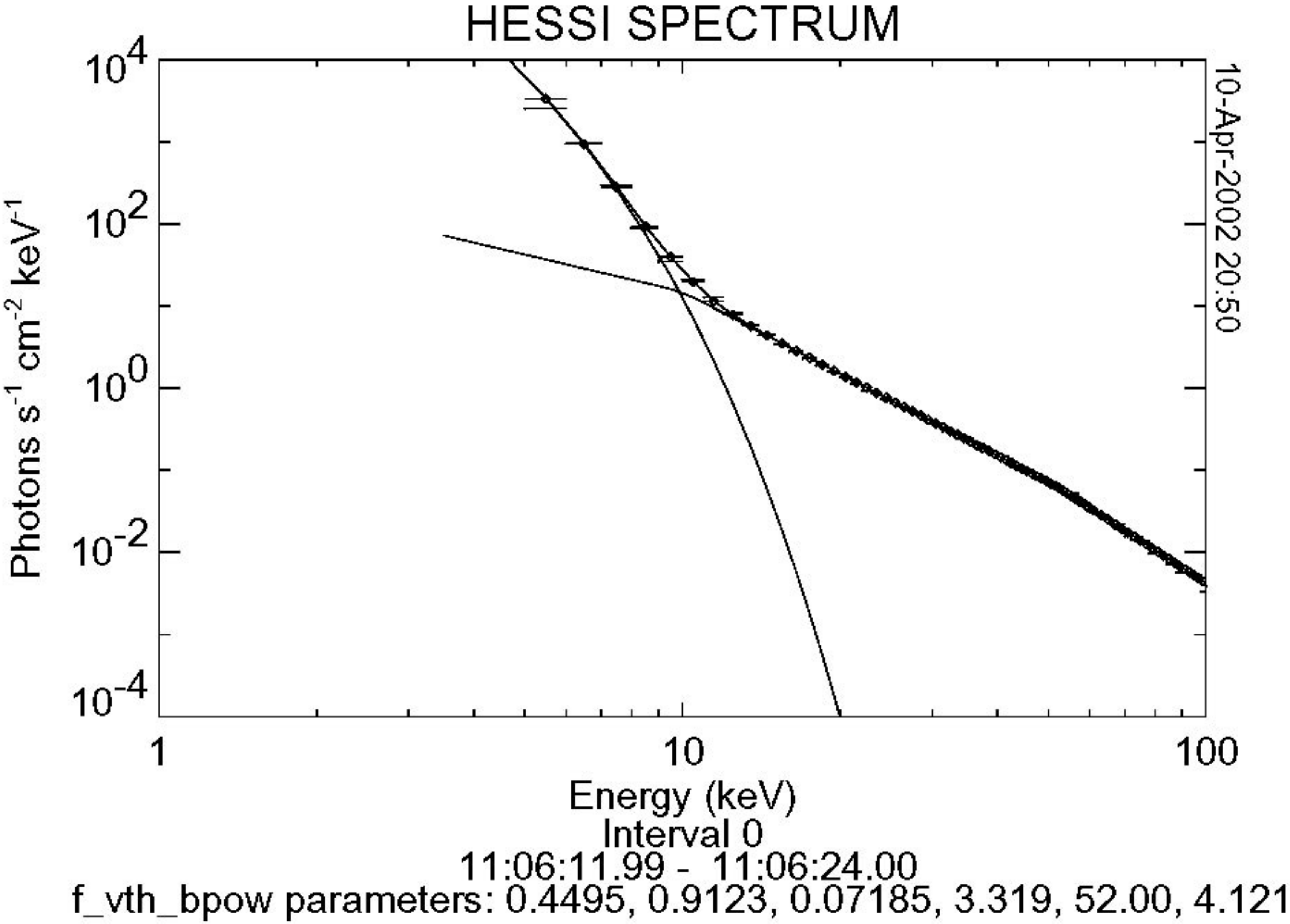


Lin 2002


02/02/20, 11:06:00.6 – 11:06:39.6

cleaned maps

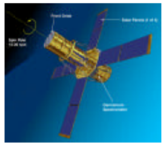
Lin 2002


HESSI SPECTRUM
10-Apr-2002 20:50
Photons s^{-1} cm^{-2} keV^{-1}
10^4
10^2
10^0
10^{-2}
10^{-4}
1
10
100
Energy (keV)
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

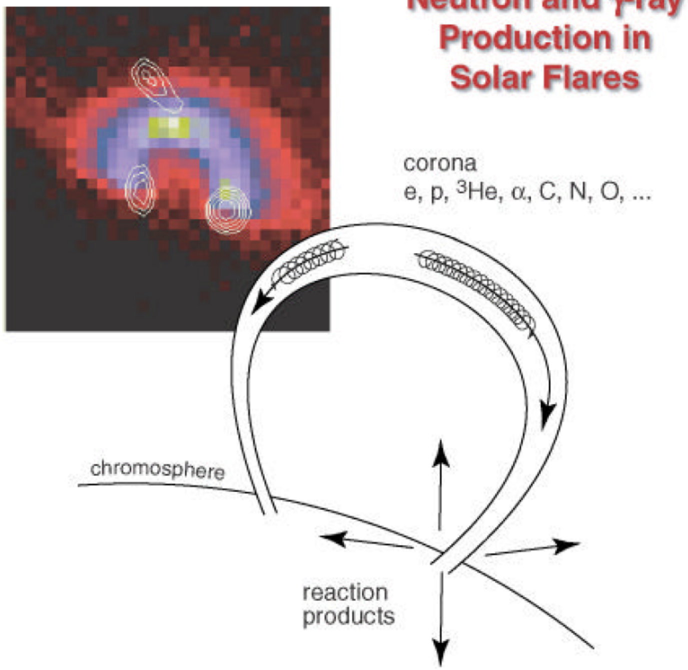
Lin 2002

Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Neutron and γ-ray Production in Solar Flares



electrons:	X- and γ-ray bremsstrahlung
ions:	radioactive nuclei → e^+ → γ_{511} π → γ (decay, $e^\pm$ bremsstrahlung) excited nuclei → γ–ray line radiation neutrons → { escape to space 2.223 MeV capture line

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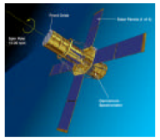
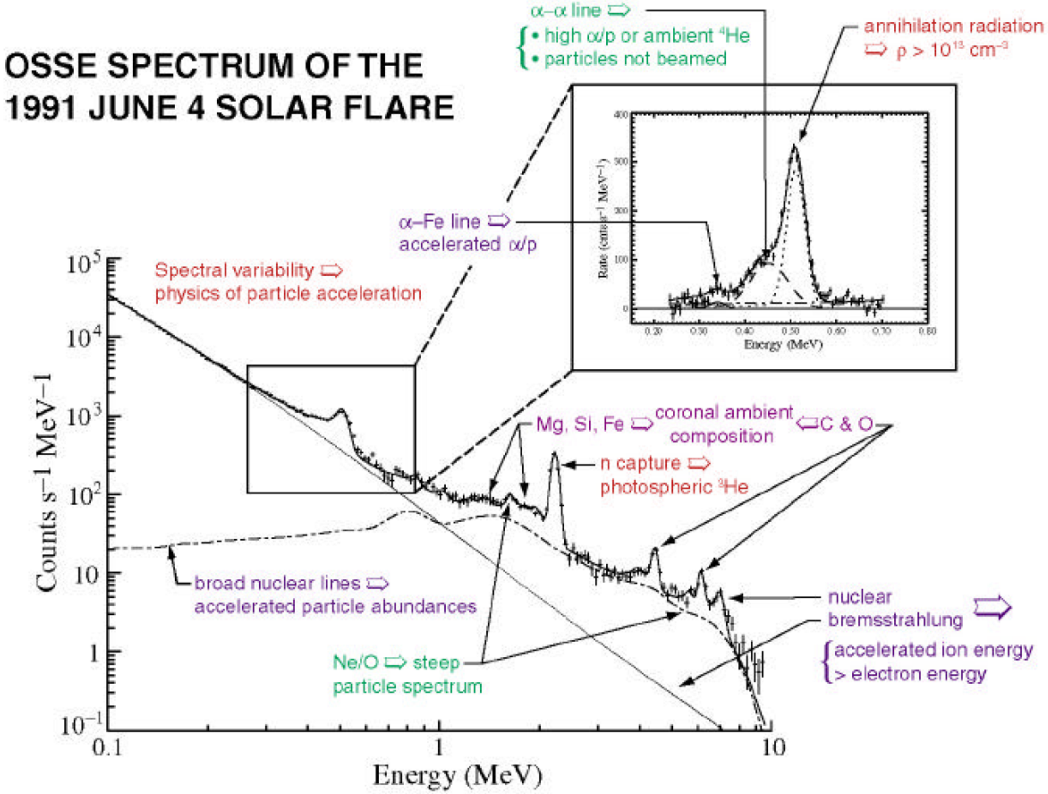
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



The Physics of Flares Revealed by γ-Ray Spectroscopy



OSSE SPECTRUM OF THE 1991 JUNE 4 SOLAR FLARE

α–α line ⇨
- high α/p or ambient ^{4}He
- particles not beamed

annihilation radiation ⇨ $\rho > 10^{13}$ cm^{-3}

α–Fe line ⇨ accelerated α/p

Spectral variability ⇨ physics of particle acceleration

Mg, Si, Fe ⇨ coronal ambient composition ⇦ C & O

n capture ⇨ photospheric ^{3}He

broad nuclear lines ⇨ accelerated particle abundances

Ne/O ⇨ steep particle spectrum

nuclear bremsstrahlung ⇨
- accelerated ion energy
- > electron energy

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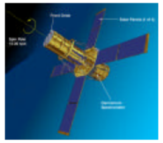
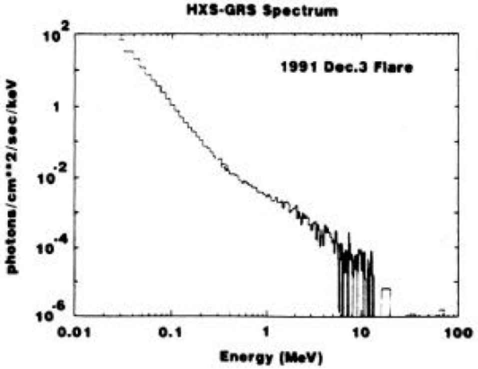
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age

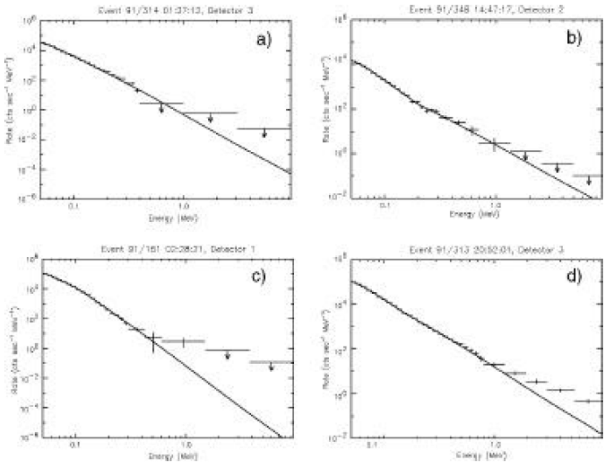


Shape of Bremsstrahlung Continuum >100 keV

Yohkoh



OSSE



Hardening found in spectra >100 keV by combined analysis of *SMM* GRS/HXRBS spectra.

Similar hardening observed in combined spectrum from *Yohkoh* HRS/GRS.

Important for measurements to be made with the same instrument.

Best instruments BATSE, OSSE, and HESSI.

OSSE continuum spectra exhibit: single power laws, broken power laws with hardening and softening between ~100 and 200 keV, and additional hardening above ~1 MeV.

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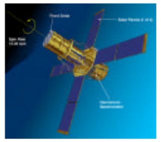
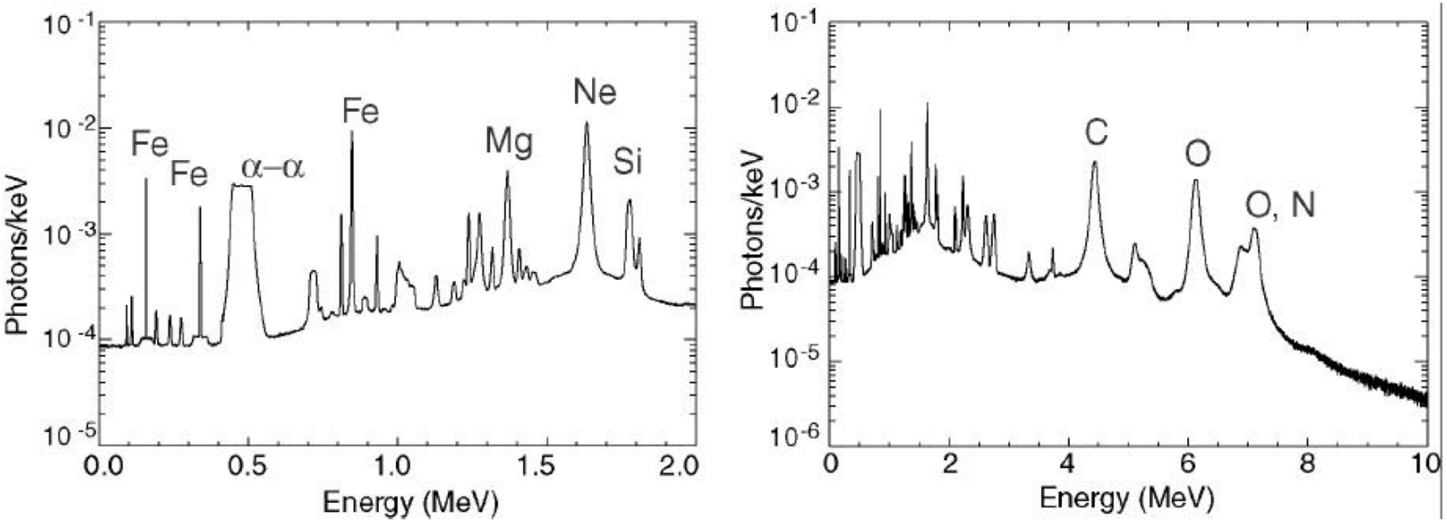
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Theoretical Nuclear Line Spectrum



Ramaty, Kozlovsky, Lingenfelter, and Murphy

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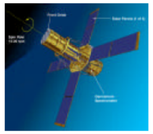
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Narrow γ-Ray Lines Observed in Flare Spectra

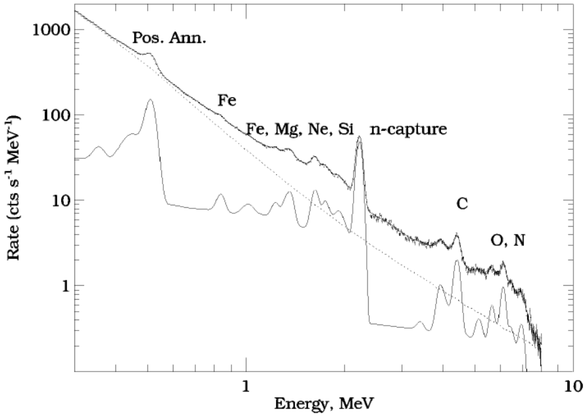
Produced by p and α interactions with ambient material.

At least 30% of flares with emission >0.3 MeV exhibit γ-ray line features. *HESSI* will make more definitive measurement.

At least 19 de-excitation lines have been identified in fits to flare spectra.

Widths of de-excitation lines measured to be ~2-4% in the summed spectrum. This exceeds theory in some cases suggesting presence of blended lines (e.g. ^{14}N near ^{20}Ne) or different Doppler shifts in the flares (see later discussion).

HESSI can resolve these lines and determine intrinsic widths.



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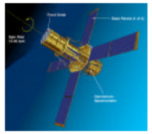
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Narrow γ-Ray Lines in Solar-Flare Spectra

Sum of 19 SMM Flares

Energy, MeV	Width (% FWHM)	Identification
0.357 ± 0.002	3.7 ± 3.1	^{59}Ni (0.339 MeV)
0.454	--	^{7}Be, ^{7}Li (0.429, 0.478 MeV)
0.513 ± 0.001	< 2	e^{+}- e^{-} annihilation (0.511 MeV)
0.841 ± 0.003	--	^{56}Fe (0.847 MeV)
0.937	--	^{18}F (0.937 MeV)
~1.020	--	^{18}F, ^{58}Co, ^{58}Ni, ^{59}Ni (1.00/4/5/8)
1.234	3.3 ± 3.9	^{56}Fe (1.238 MeV)
1.317	--	^{55}Fe (1.317 MeV)
1.366 ± 0.003	3.0 ± 1.1	^{24}Mg (1.369 MeV)
1.631 ± 0.002	2.9 ± 0.6	^{20}Ne (1.633 MeV)
1.785	4.3 ± 1.5	^{28}Si (1.779 MeV)
2.226 ± 0.001	< 1.5	n-capture on H (2.223 MeV)
3.332 ± 0.030	--	^{20}Ne (3.334 MeV)
4.429 ± 0.004	3.3 ± 0.3	^{12}C (4.439 MeV)
5.200	--	^{14}N, ^{15}N, ^{15}O
6.132 ± 0.005	2.6 ± 0.3	^{16}O (6.130 MeV)
6.43	--	^{11}C (6.337, 6.476 MeV)
6.983 ± 0.015	4.0 ± 0.5	^{14}N, ^{16}O (7.028, 6919 MeV)

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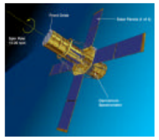
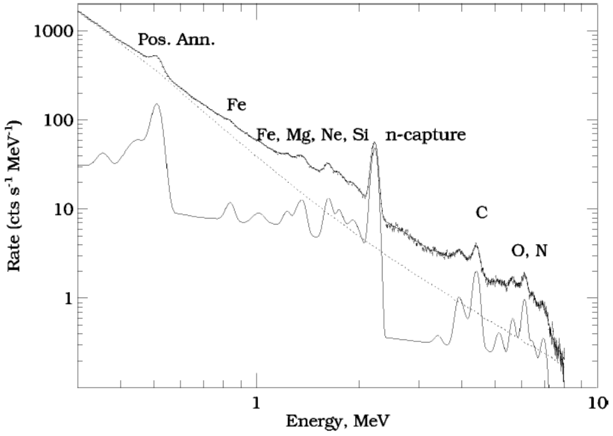
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age

Revealing the Spectrum from Accelerated Heavy Ions





Accelerated heavy ions are excited by interaction with ambient H.

De-excitation lines from these ions are expected to be Doppler broadened by ~25%.

Broad line spectrum is revealed by subtracting best fitting narrow-line and bremsstrahlung components shown for sum of 19 flares observed by the *SMM*/GRS.

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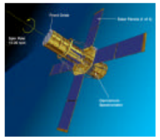
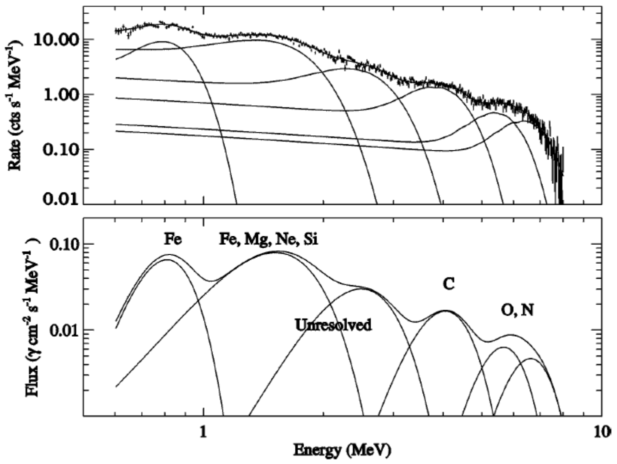
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Gamma-Ray Spectrum from Accelerated Heavy Ions



Residual spectrum after subtracting contributions from bremsstrahlung and narrow lines reveals broadened lines from accelerated ions.

Best fit to spectrum contains six Gaussian features that can be identified with different ions.

Fe and C are resolved. The Fe, Mg, Ne, and Si lines between 1 - 2 MeV cannot be resolved.

Major uncertainty is the shape of the 'unresolved line' component that is expected to peak in the 1 - 3 MeV region.

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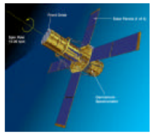
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age



Broadened Lines Identified in γ-Ray Spectra

Energy, MeV	Width, MeV	Identification	Enhancement	
			γ-Rays	SEP's
0.81 ± 0.01	0.25 ± 0.02	^{56}Fe	7.8 ± 1.9	6.7 ± 0.8
1.52 ± 0.02	0.78 ± 0.05	Unresolved, ^{56}Fe, ^{24}Mg, ^{20}Ne, ^{28}Si	2.4 ± 0.4	
		^{24}Mg, ^{20}Ne, ^{28}Si		~2.7
2.49 ± 0.07	1.05 ± 0.17	Unresolved lines		
4.04 ± 0.05	1.26 ± 0.15	^{12}C	1	1
5.67 ± 0.19	1.5	^{16}O	0.9 ±0.2	1.1 ±0.1
6.63 ± 0.16	1.7	^{14}N, ^{16}O	1.3 ± 0.4	

Lines appear to be red-shifted by ~5 - 9 %.

Lines are broadened by ~30%.

Some shift and broadening may be due to summing of 19 spectra.

Enhancement (γ-ray) = $(Fe_{brd}/Fe_{nar})/(C_{brd}/C_{nar}) * Z^2/A$.

O and Fe enhancements in good agreement with SEPs.

Mg, Si, Ne enhancement is upper limit due to unknown contribution from unresolved lines. This suggests higher temperatures than inferred from SEP's.

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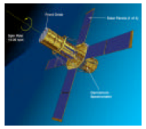
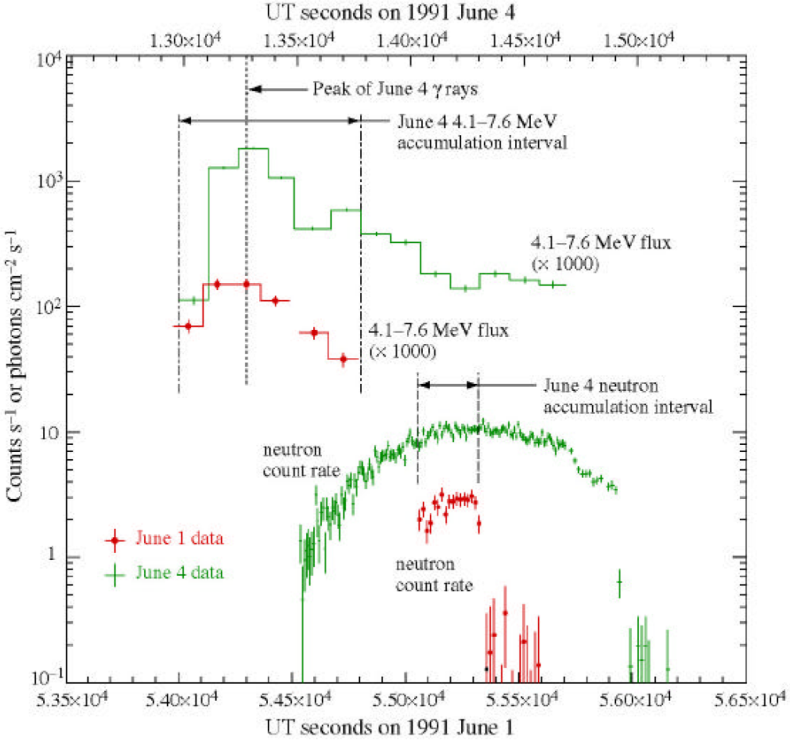
Solar Flares in Gamma-rays

Solar γ-Ray Physics Comes of Age

γ Rays and Neutrons Observed from the 1 & 4 June 1991 Flares





OSSE and GRANAT

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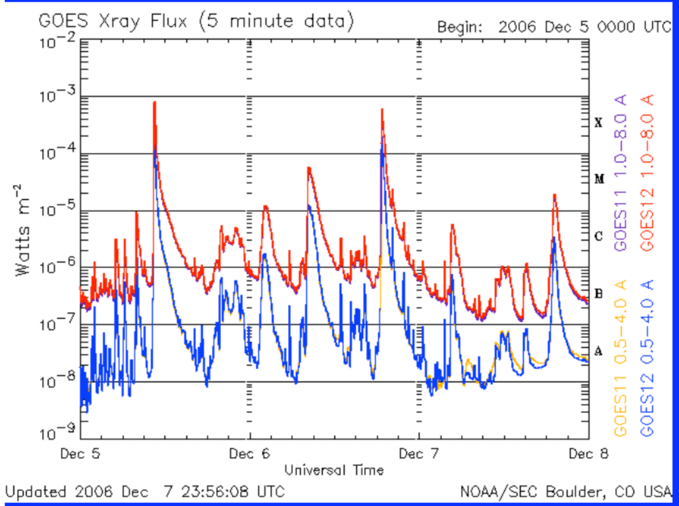
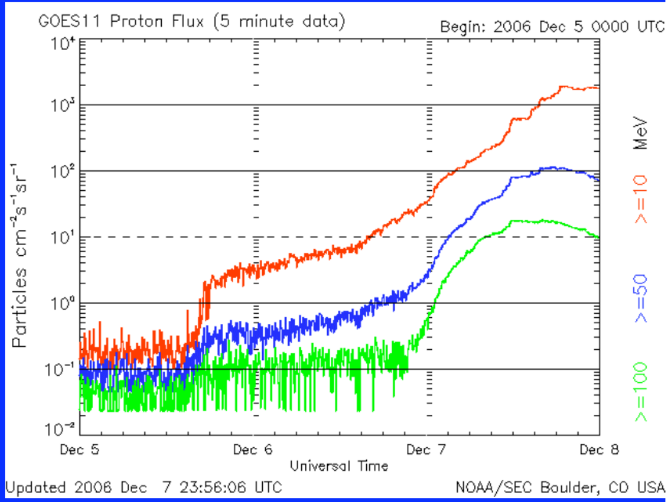
Solar Flares in Gamma-rays

Surprises though!
Active regions in January 2005 and December 2006 produced
intense X-Class Flares





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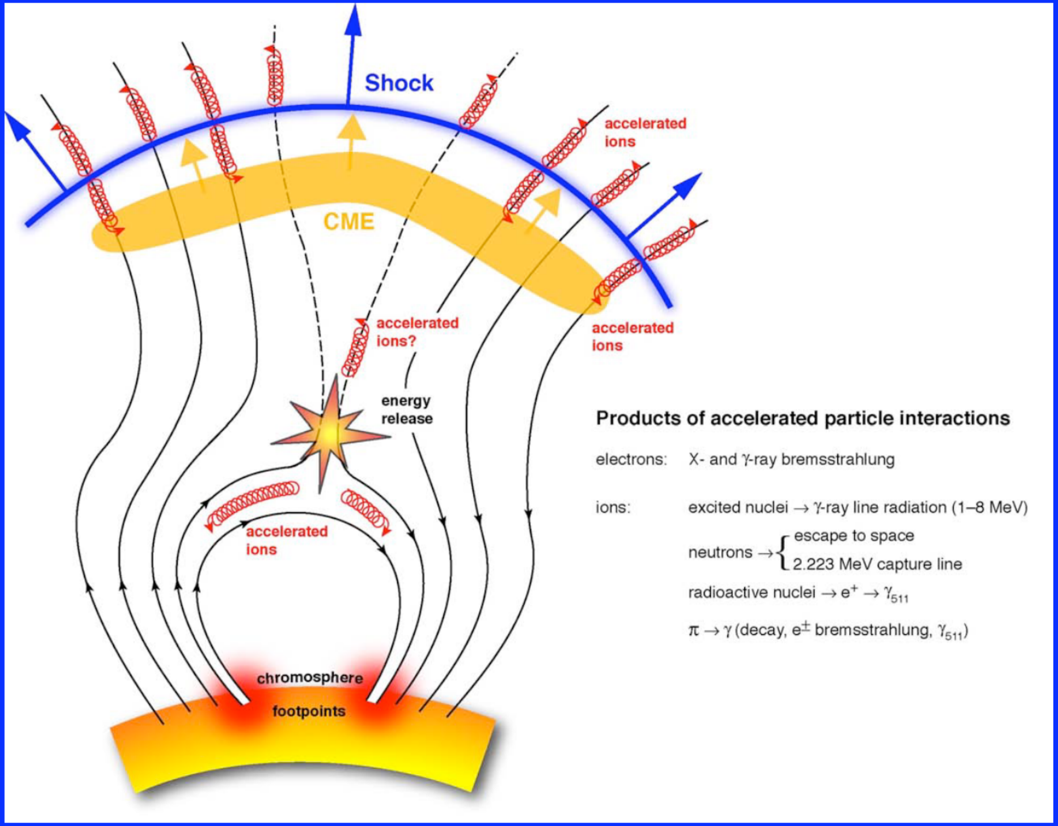
Solar Flares in Gamma-rays



Products of accelerated particle interactions

electrons:	X- and γ-ray bremsstrahlung
ions:	excited nuclei $\rightarrow$ γ-ray line radiation (1–8 MeV)
	neutrons $\rightarrow \begin{cases} \text{escape to space} \\ \text{2.223 MeV capture line} \end{cases}$
	radioactive nuclei $\rightarrow e^+ \rightarrow \gamma_{511}$
	$\pi \rightarrow \gamma$ (decay, $e^\pm$ bremsstrahlung, γ_{511})

Study how particles are accelerated at the Sun and their relationship to Solar Energetic Particles (SEP) and Ground Level Events (GLE).

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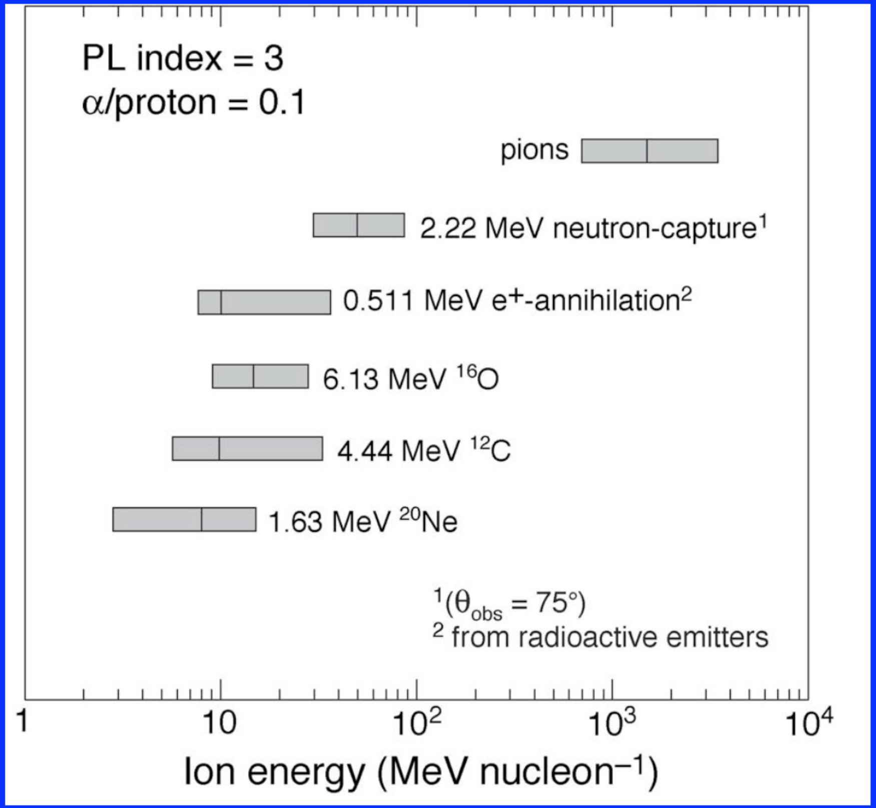
Solar Flares in Gamma-rays

Measure the spectrum of flare-accelerated ions and electrons to energies > 1 GeV/nuc



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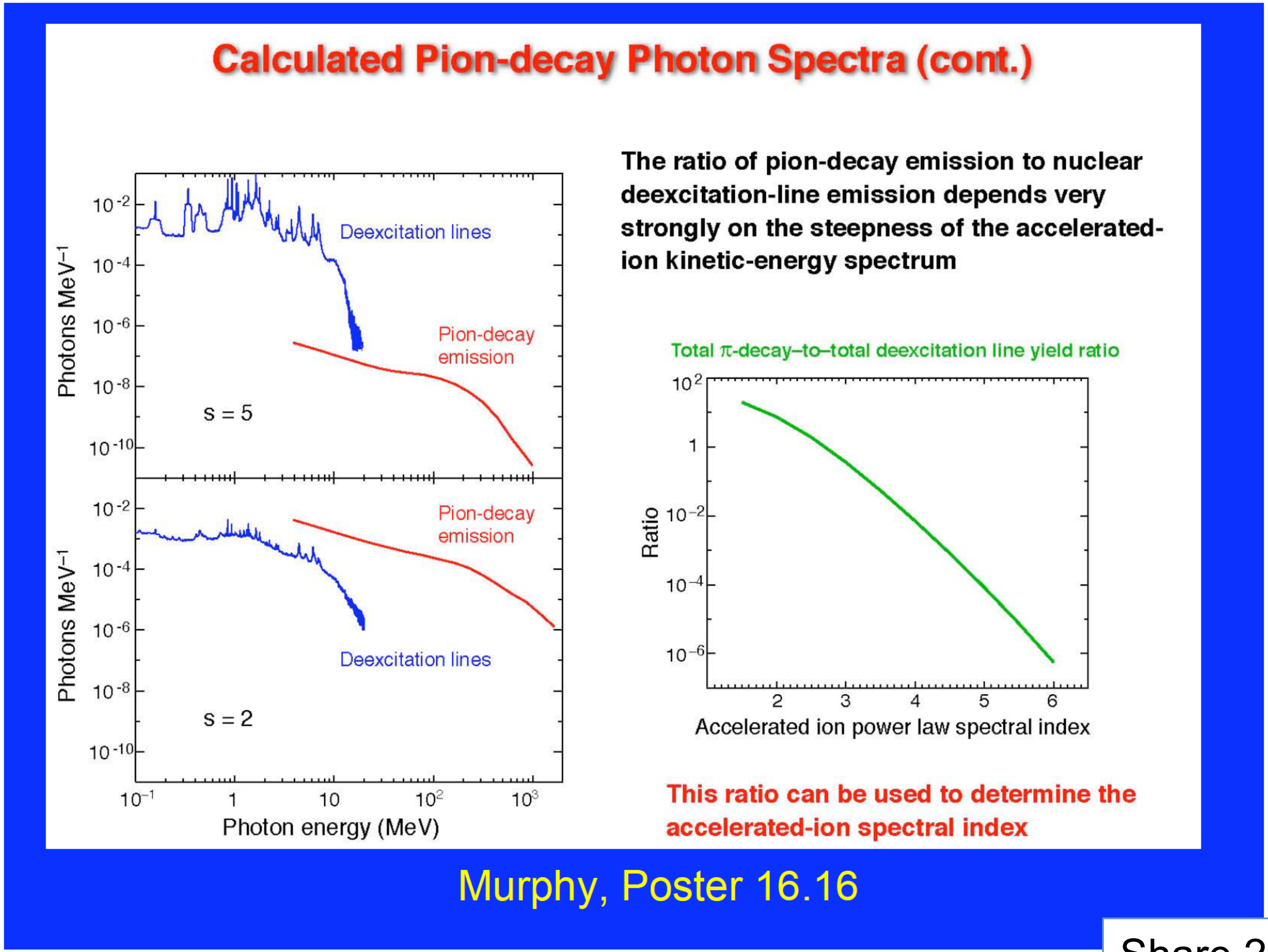
Solar Flares in Gamma-rays



Calculated Pion-decay Photon Spectra (cont.)

The ratio of pion-decay emission to nuclear deexcitation-line emission depends very strongly on the steepness of the accelerated-ion kinetic-energy spectrum

This ratio can be used to determine the accelerated-ion spectral index

Murphy, Poster 16.16

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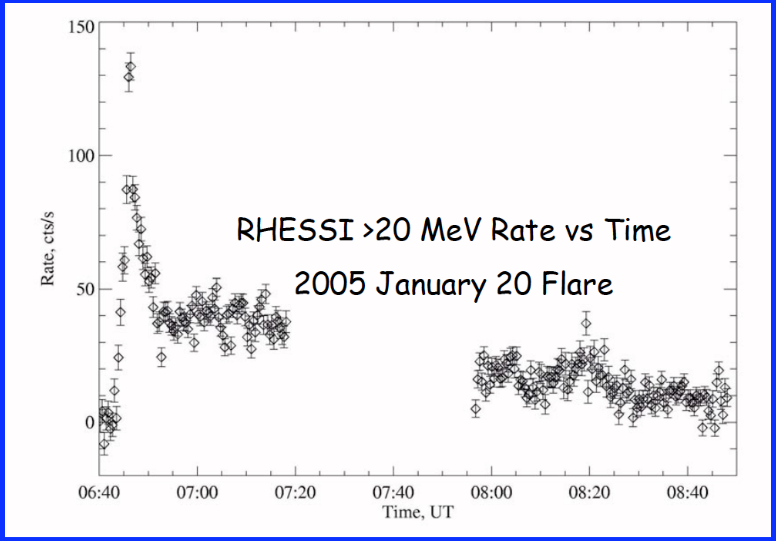
Solar Flares in Gamma-rays

Study particle acceleration and magnetic trapping of high-energy ions from minutes to hours after flares (e.g. EGRET observation on June 11, 1991; Kanbach et al.)


RHESSI >20 MeV Rate vs Time

2005 January 20 Flare

LAT is 10^4 times more sensitive to pion radiation than RHESSI

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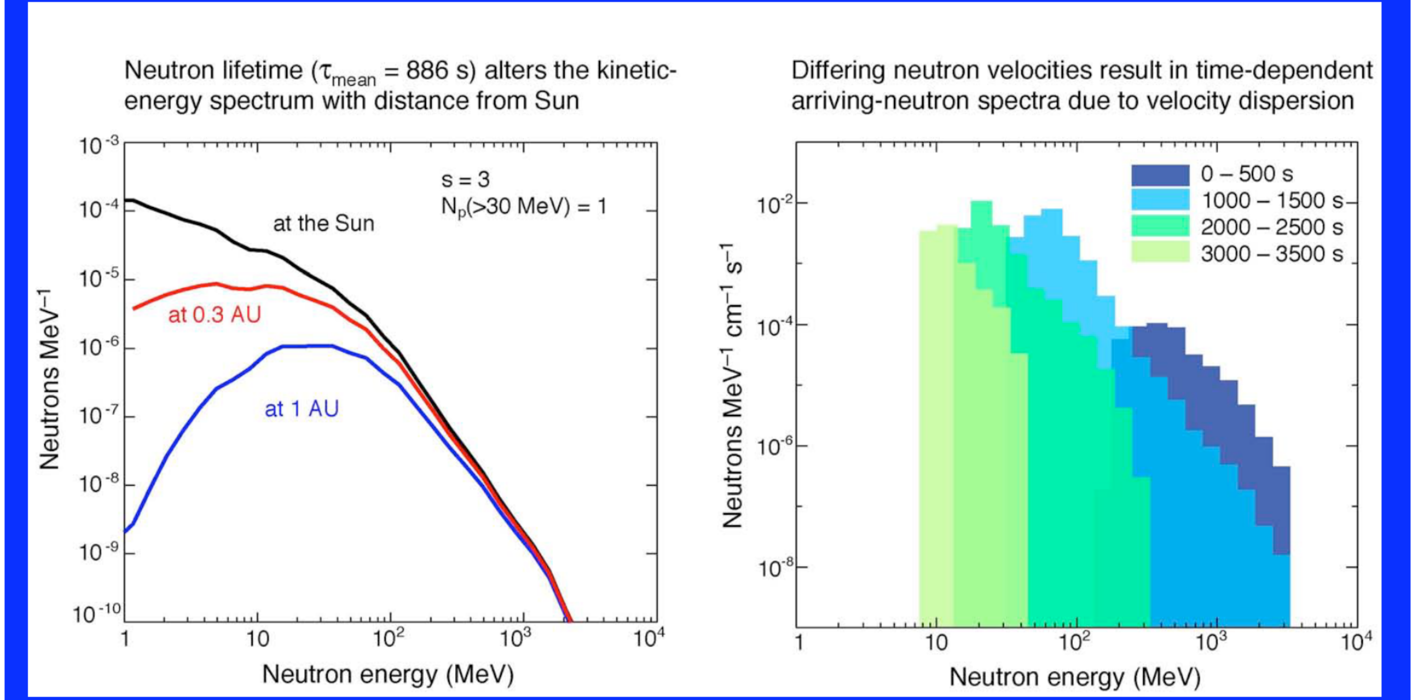
Solar Flares in Gamma-rays



Neutron lifetime (τ_{mean} = 886 s) alters the kinetic-energy spectrum with distance from Sun

Differing neutron velocities result in time-dependent arriving-neutron spectra due to velocity dispersion

Murphy, Poster 16.16

GBM will also detect an increase minutes after the impulsive phase of the flare.

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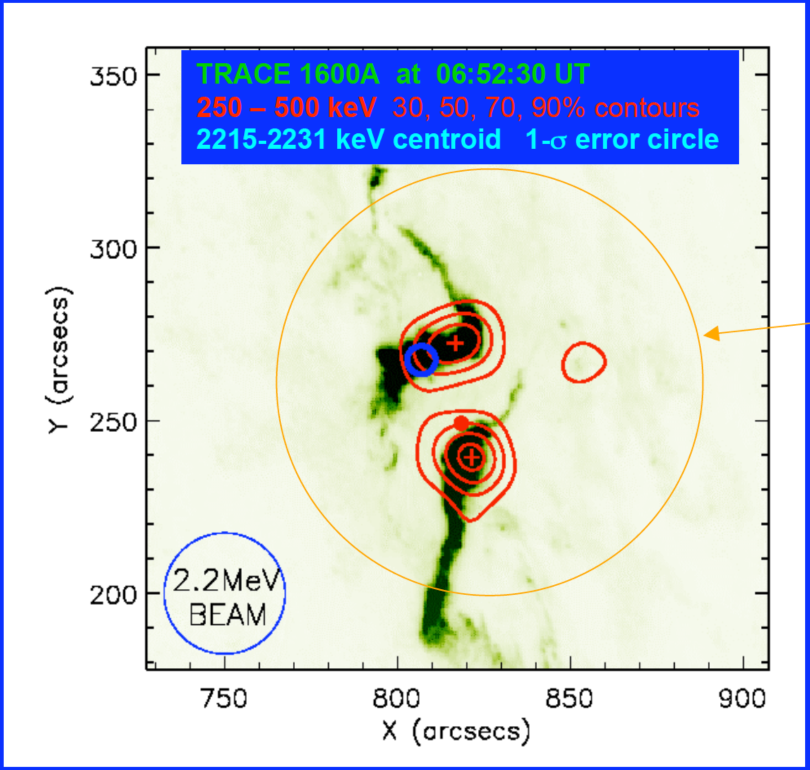
Solar Flares in Gamma-rays

20 January 2005 06:44-06:56

RHESSI, Hurford et al. 2007



GLAST Location

Localize the source of >1 GeV photons to ~30 arc sec

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