利用太阳中微子研究太阳金属丰度

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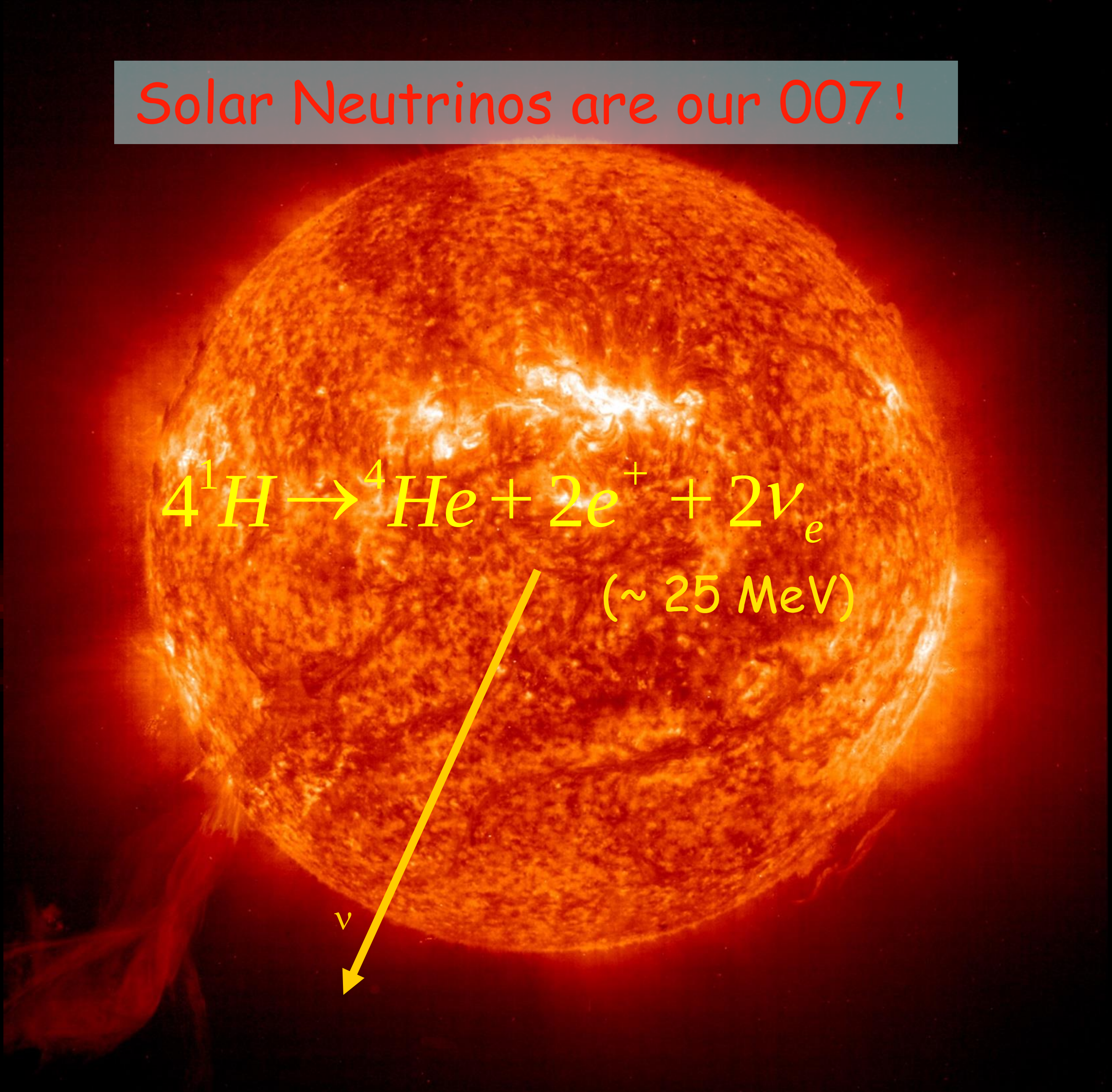
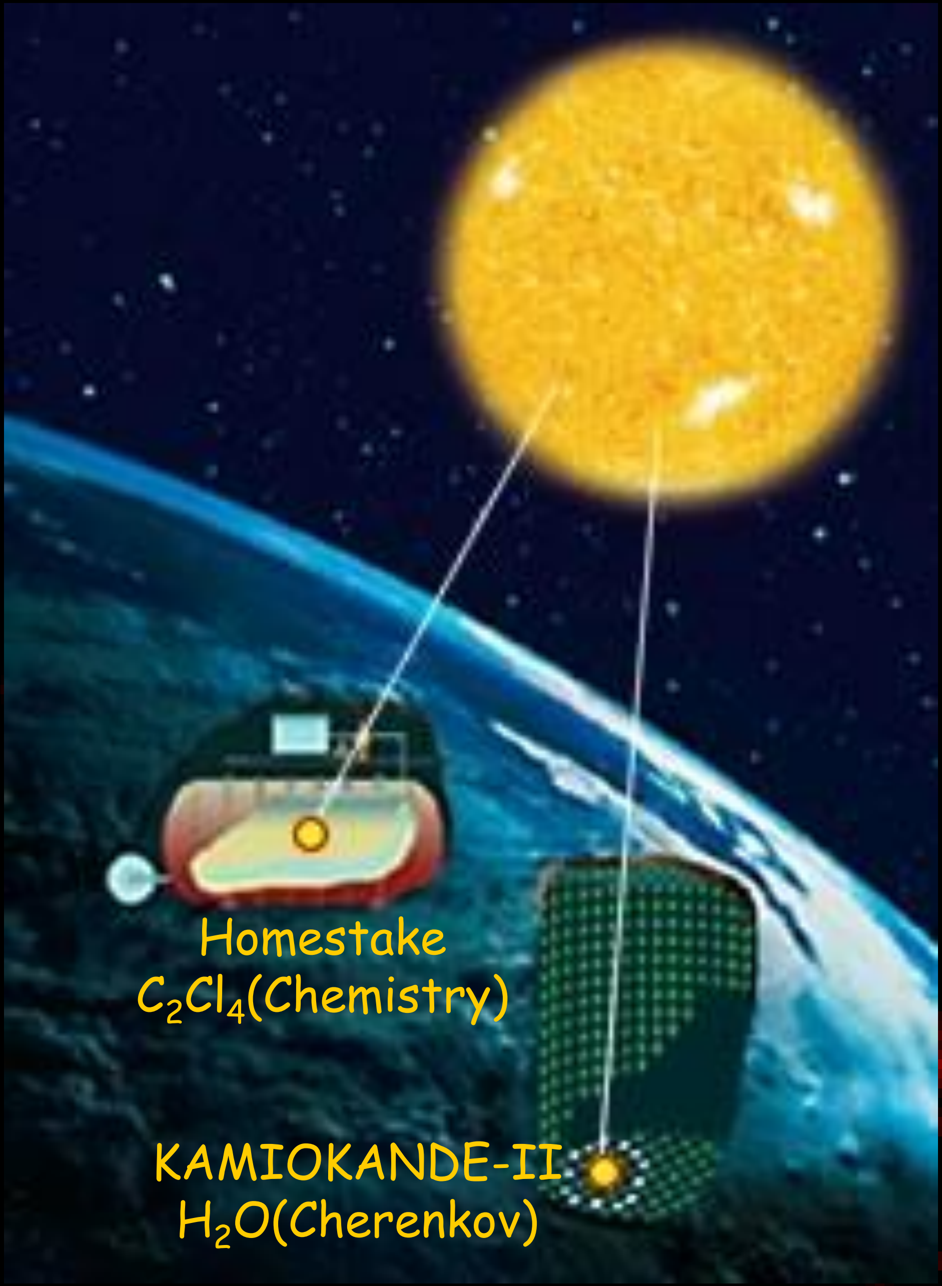
JUNO中微子天文和天体物理学研讨会，7月10-11日，高能所

Outline

- Short history of solar neutrino
- Solar metallicity problem
- Key nuclear physics parameters
- Work done by LUNA at Gran Sasso
- Jinping Underground lab for Nuclear Astrophysics (JUNA) and its possible contributions

Solar Neutrinos are our 007 !

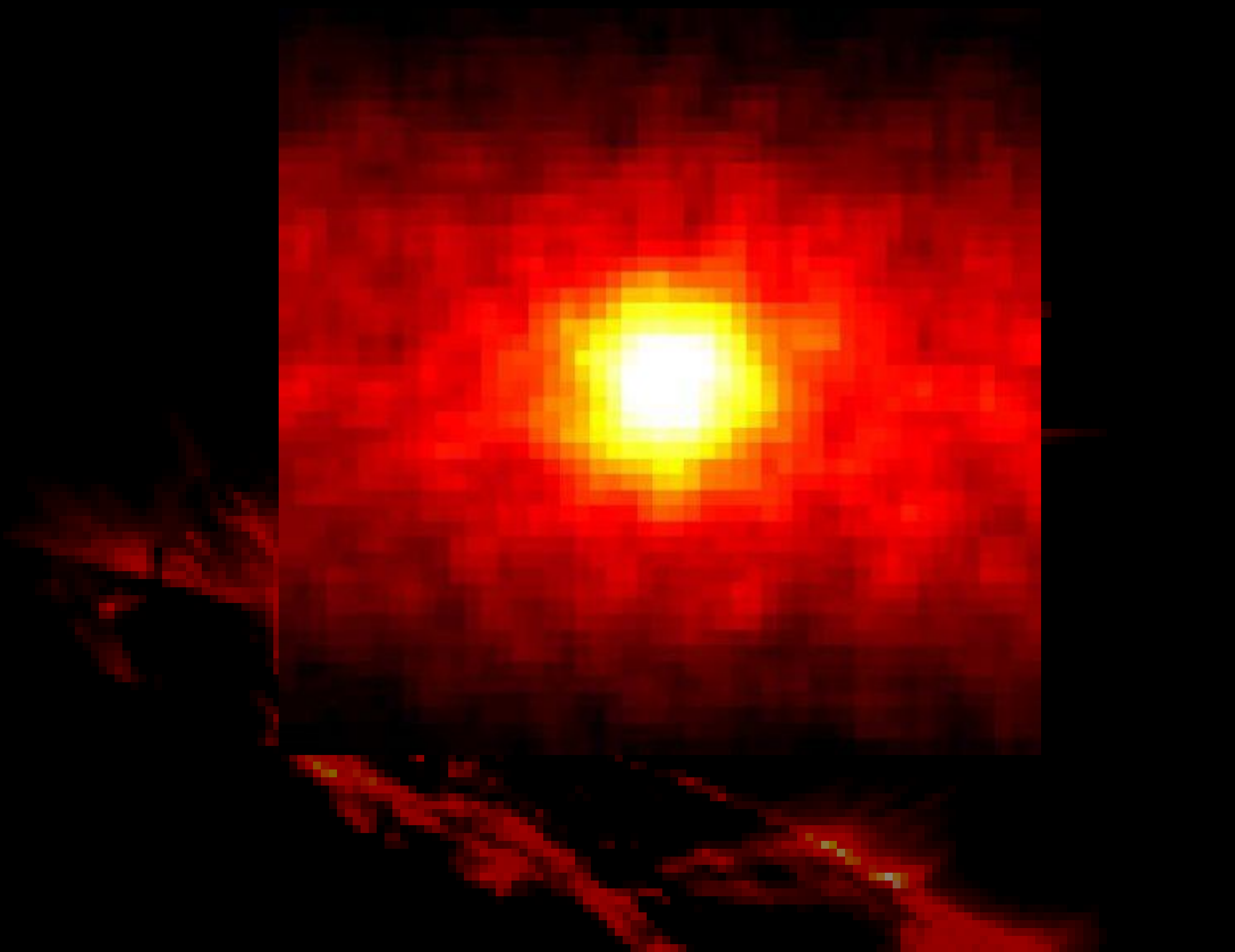




Exp	Target	Data/SSM
Homes-take	^{37}Cl	0.33 ± 0.03
Kamio-kande	water	0.57 ± 0.07

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

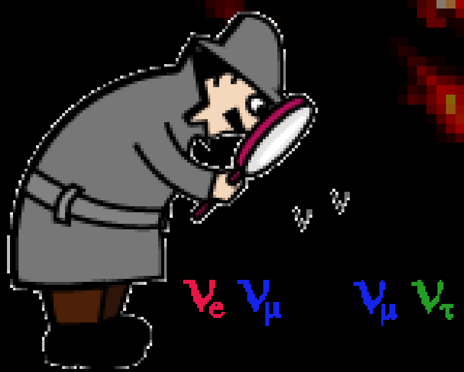


The neutrino image of the Sun with Super-Kamiokande

Credit: R. Svoboda and K. Gordan (LSU)

Solar Neutrino "Problem"

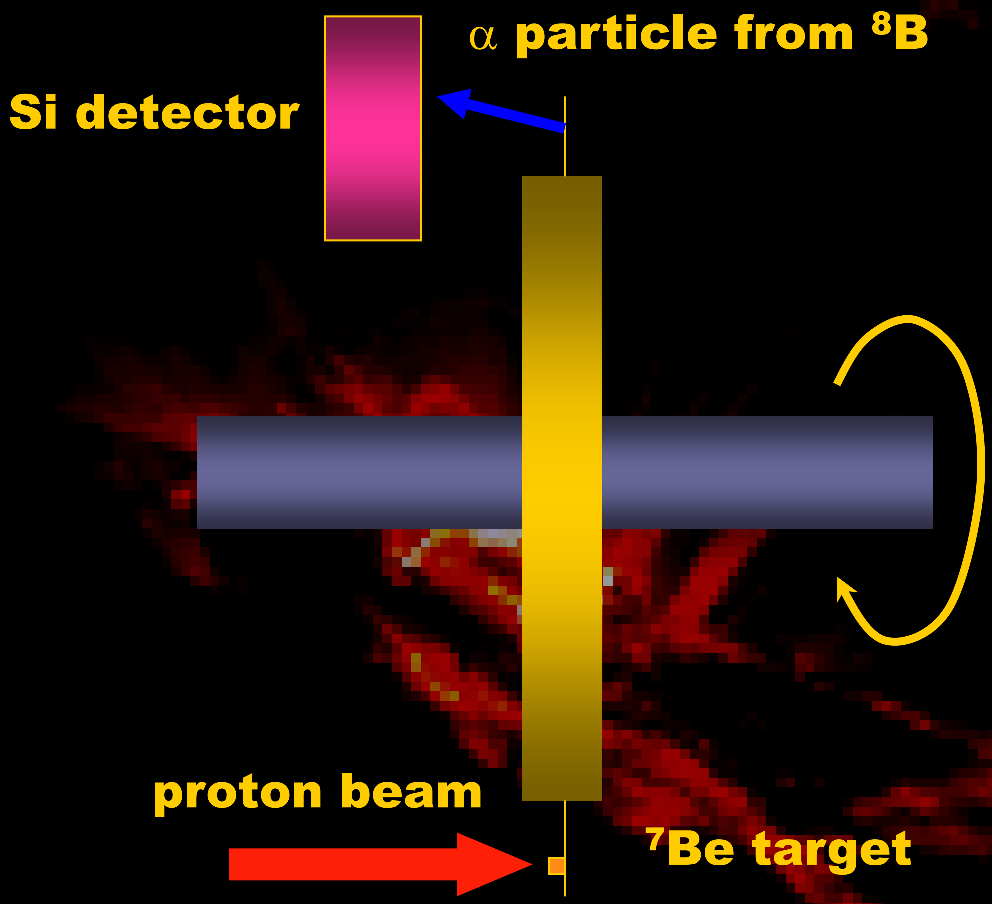
- Solar model
- Important cross sections: $^3He(^3He,2p)^4He$, $^3He(^4He,\gamma)^7Be$, $^7Be(p,\gamma)^8B$
- Unknown neutrino physics-neutrino oscillation???



"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^8B neutrinos to within a factor of 2 or 3..."

Howard Georgi and Michael Luke (1990)

Direct Measurement with ^{7}Be target (1960-)

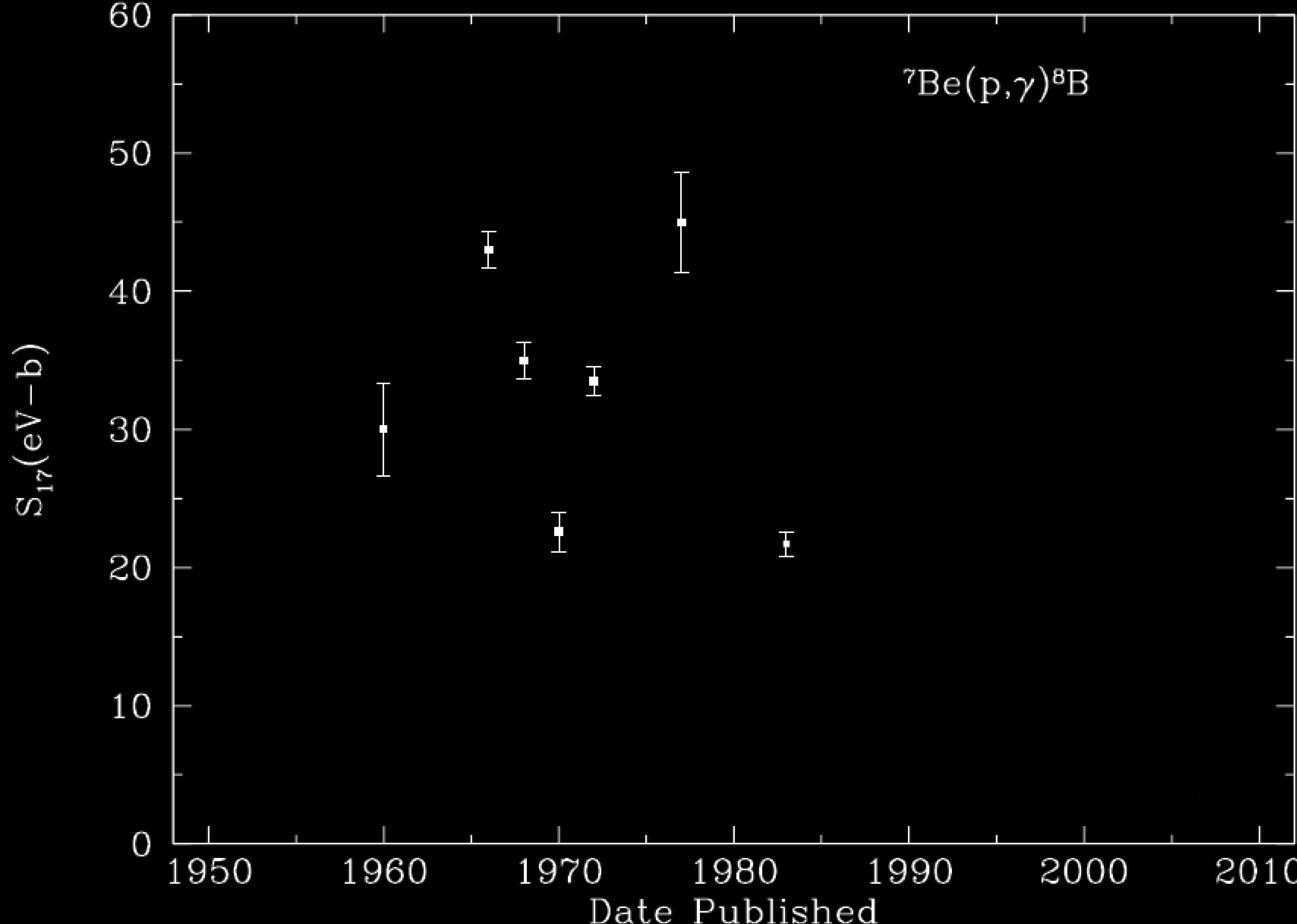


$^{7}Be(p,\gamma)^{8}B$

^{7}Be(53.12 d) ^{8}B(0.77s)

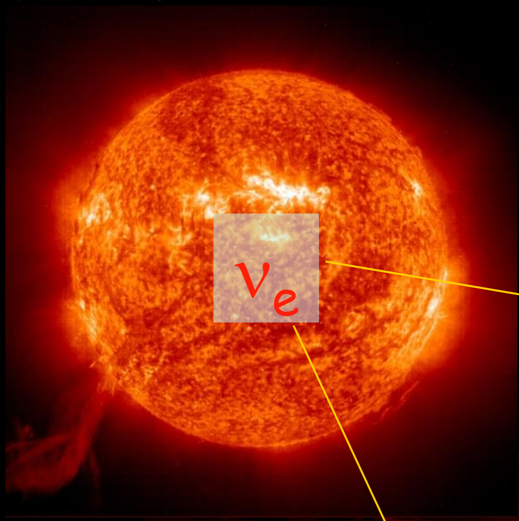
- Radioactive Target (small target size, radiation)
- ^{7}Be target atom number
- Beam-target inhomogeneity
- Solid Angle of Si

A. Junghans et al., PRC **68**, 065803 (2003)



$^7Be(p,\gamma)^8B$
S_{17}(eV−b)
Date Published
60
50
40
30
20
10
0
1950
1960
1970
1980
1990
2000
2010

Neutrino Oscillation



0.57*Solar Model

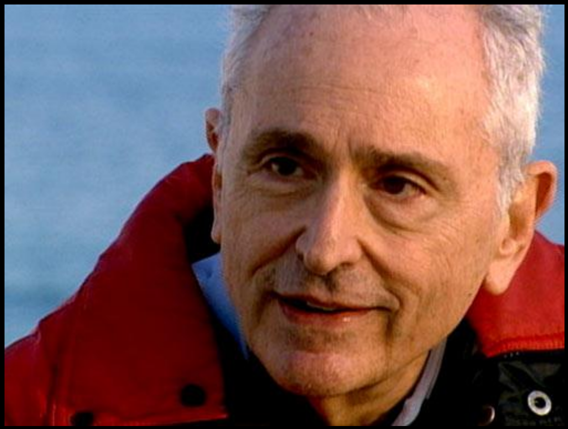
0.32*Solar Model

^{8}B Fluxes at SNO (2001)

(10^6 cm^{-2} s^{-1})

ν_e:	1.75±0.15
$\nu_{\mu\tau}$:	3.69±1.13
ν_{total}:	5.44±0.99
ν_{SSM}:	5.05+1.01/-0.81

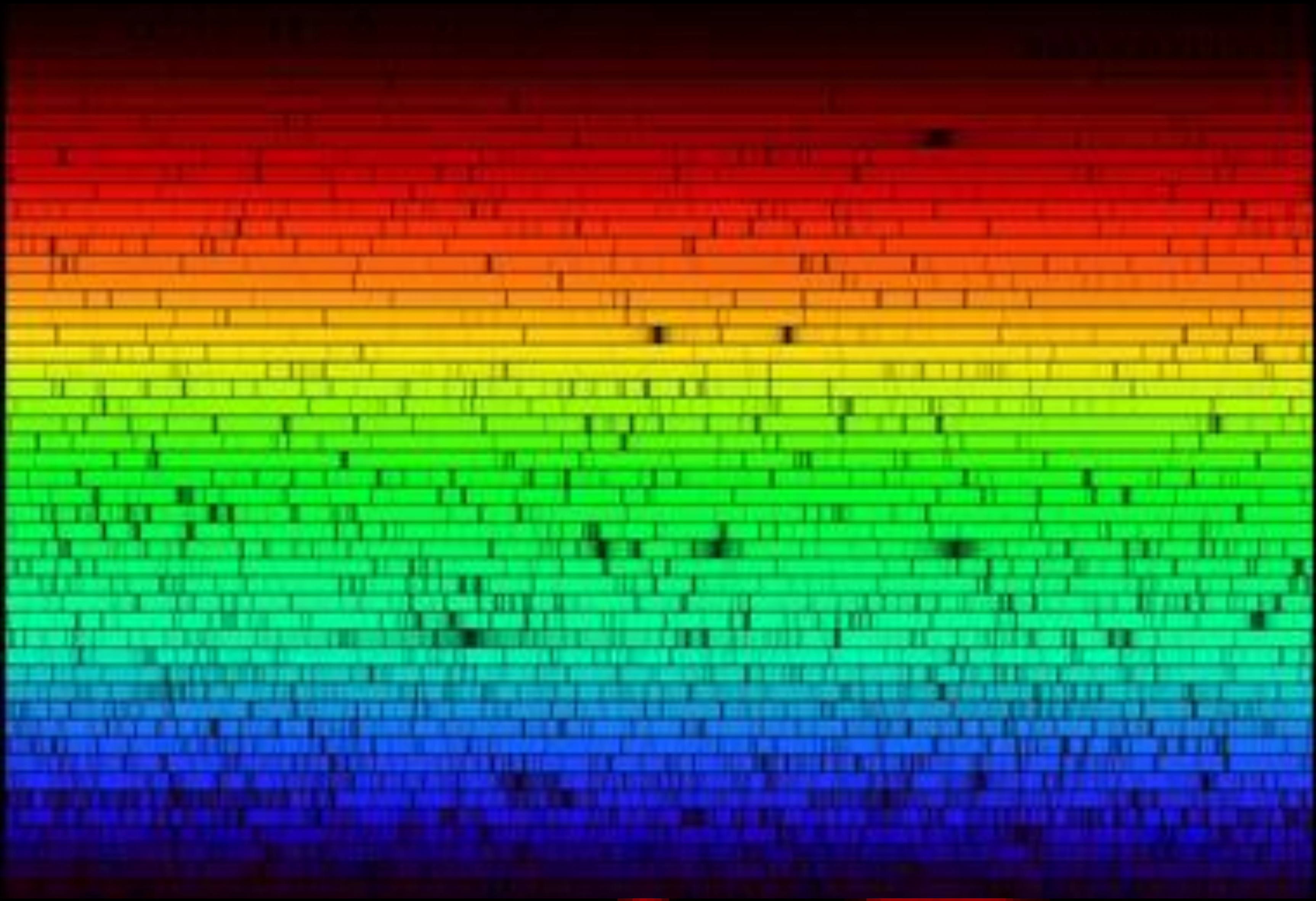
1964



2003

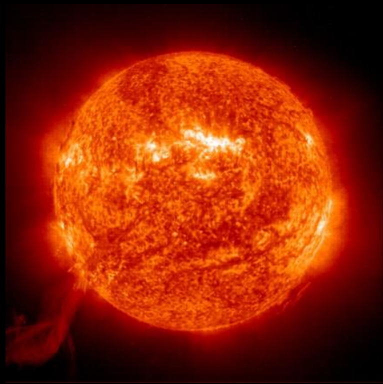
For three decades people had been pointing at this guy and saying this is the guy who wrongly calculated the flux of neutrinos from the sun, and suddenly that wasn't so. It was like a person who had been sentenced for some heinous crime, and then a DNA test is made and it's found that he isn't guilty. That's exactly the way I felt.

John Bahcall (1934-2005), Dancing with neutrinos

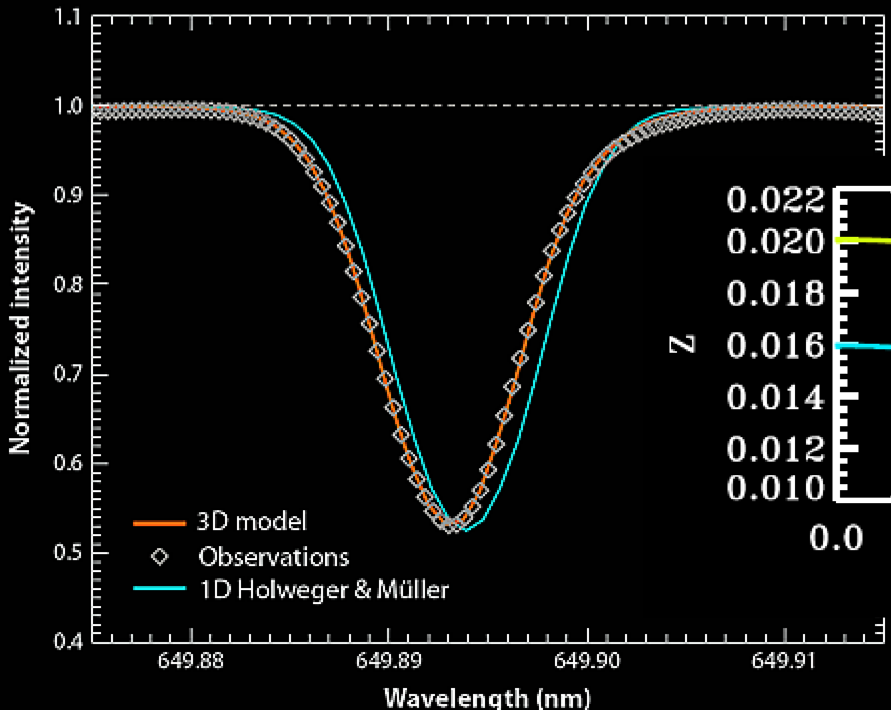


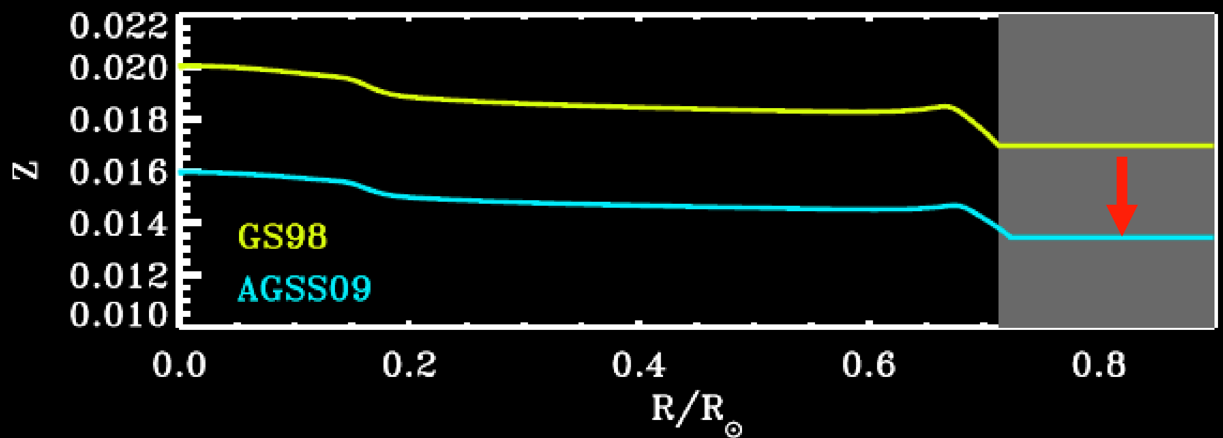
Solar Spectrum by NOAO

solar metallicity puzzle



- New 3D hydrodynamic models of the solar atmosphere
- Parameter free
- significantly improving consistency of line analysis
- Makes sun more consistent with similar stars in local neighborhood

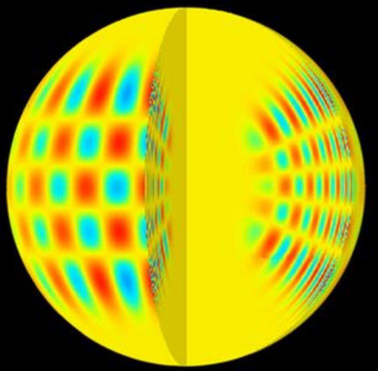


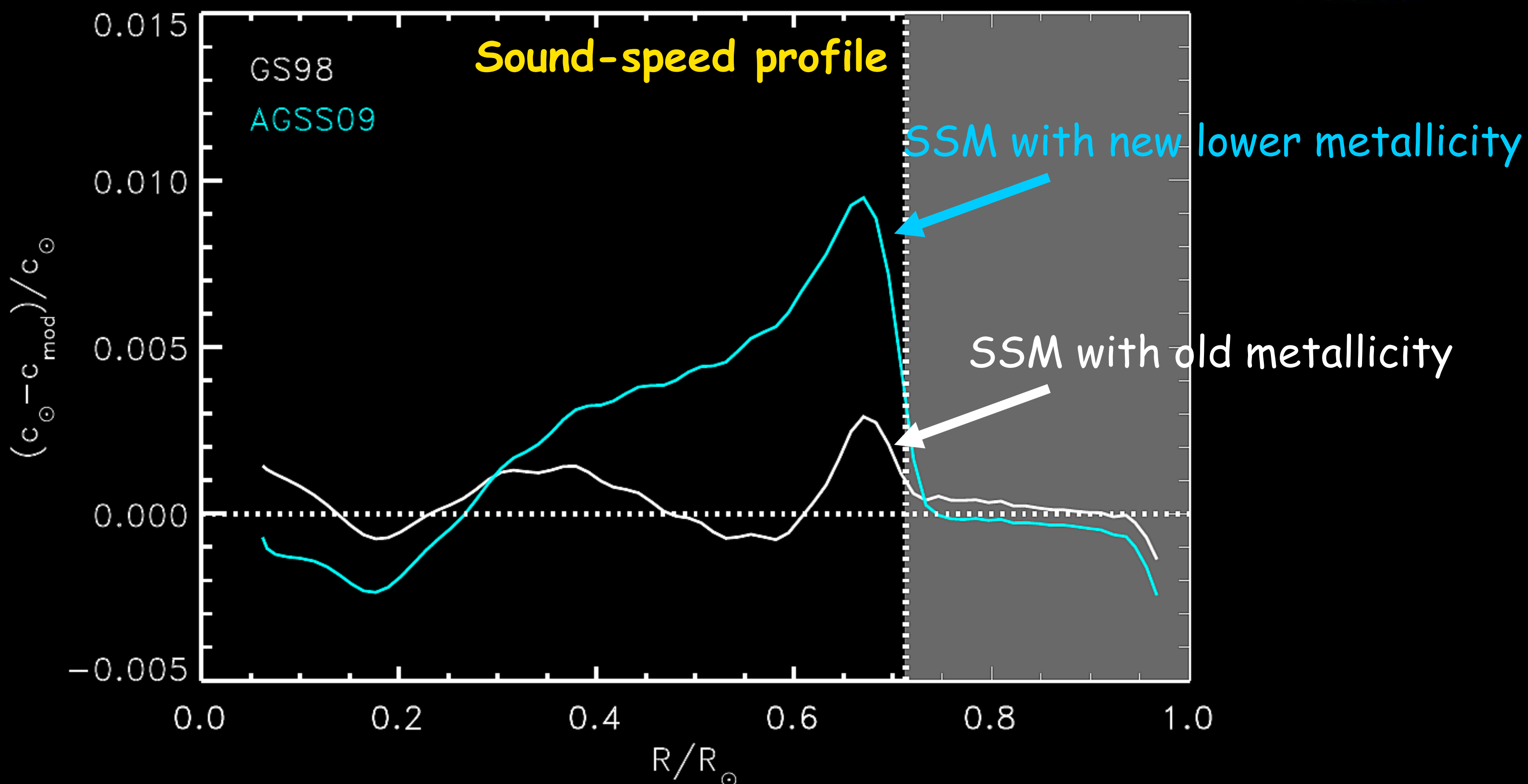


But abundances in the photosphere significantly reduced Z: 0.0169 ⇒ 0.0122

M. Asplund et al., Annu. Rev. Astro. Astrophys. 47 (2009) 481

Better determined metallicity leads to **problems**





Sound speed – Precision 10^{-4}

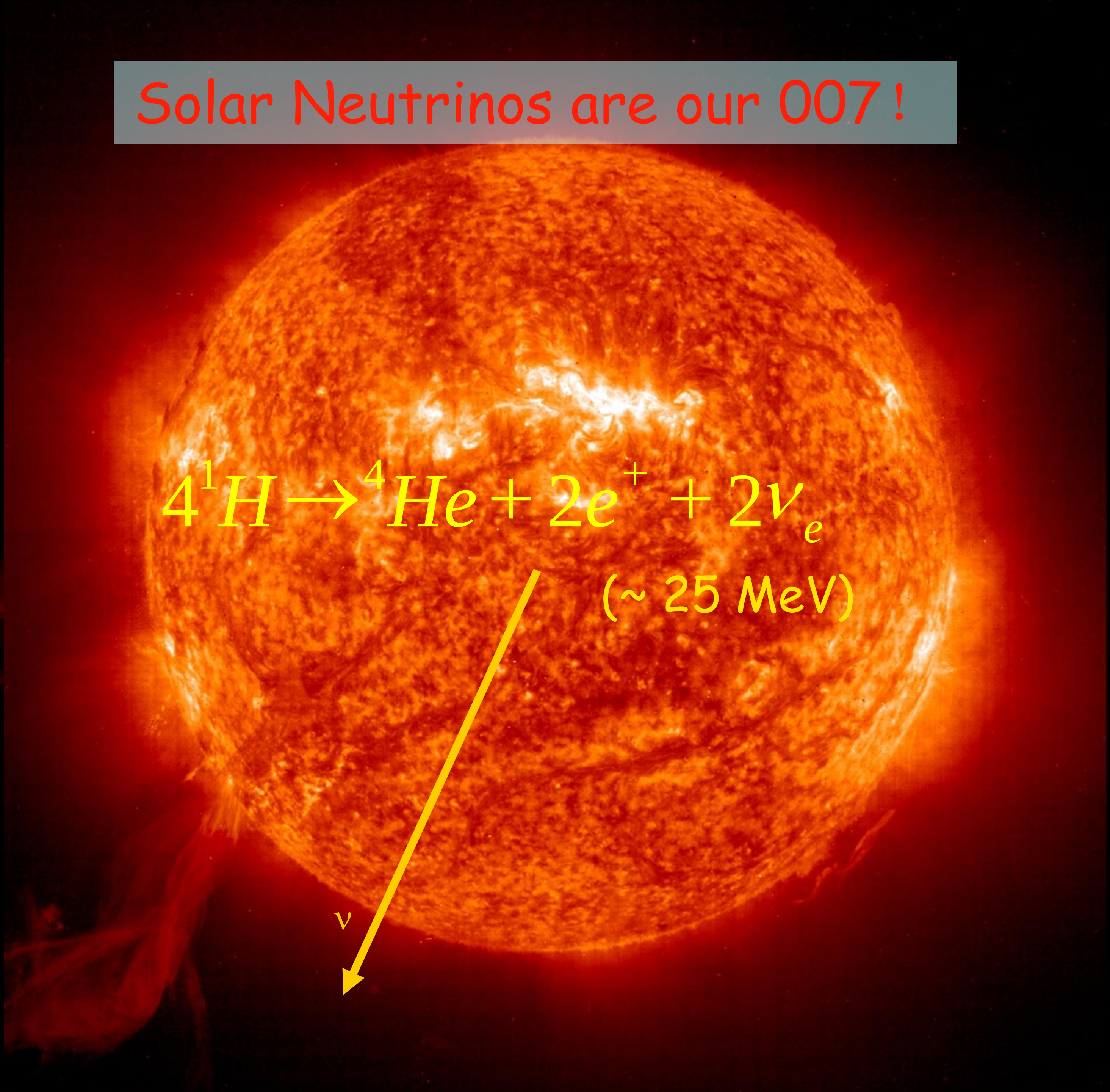
SSM: standard solar model

Serenelli, Haxton, Peñay-Garay (2011)

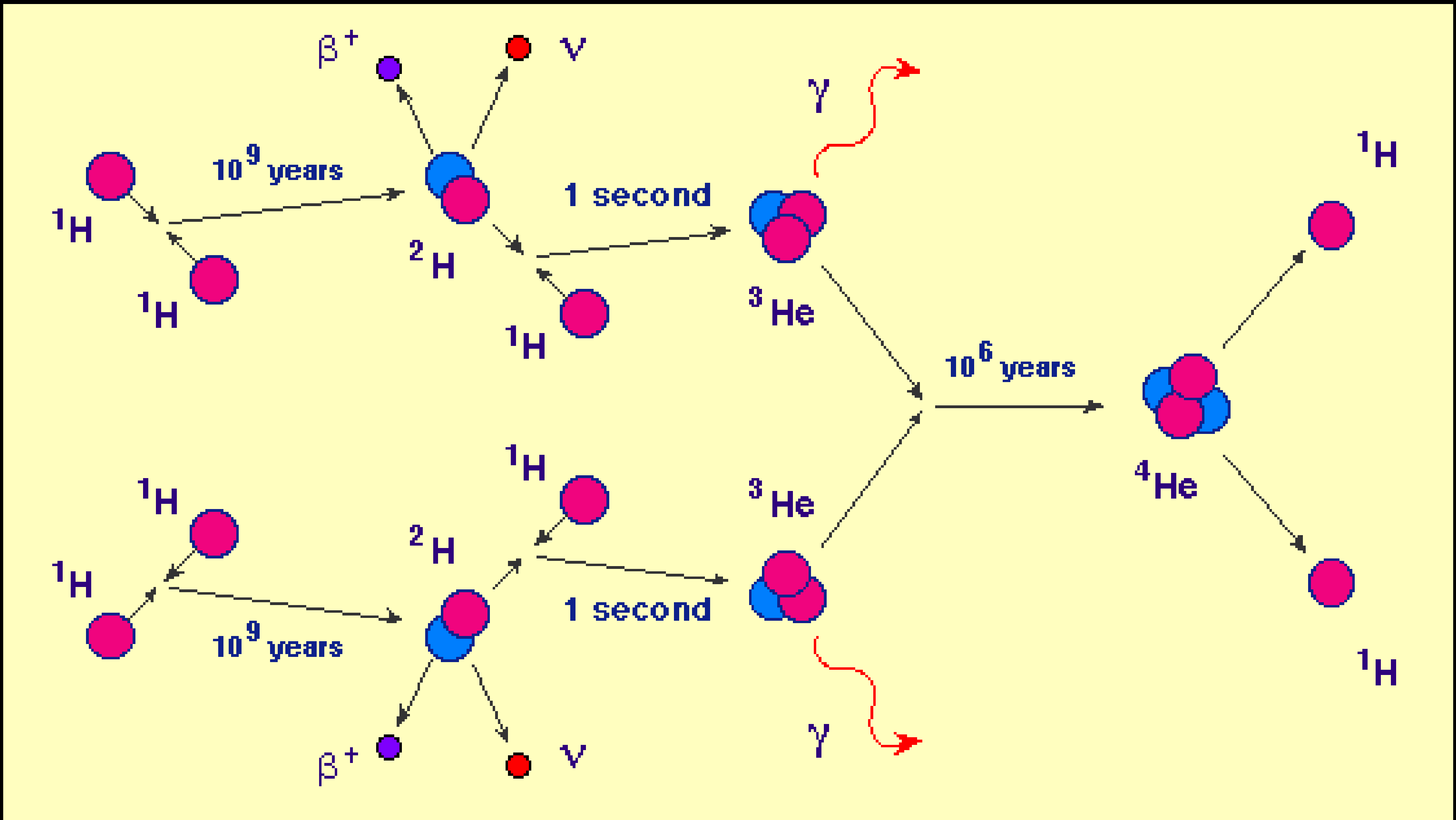
Solar Neutrinos are our 007 !

$$4\,{}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e}$$

(~ 25 MeV)

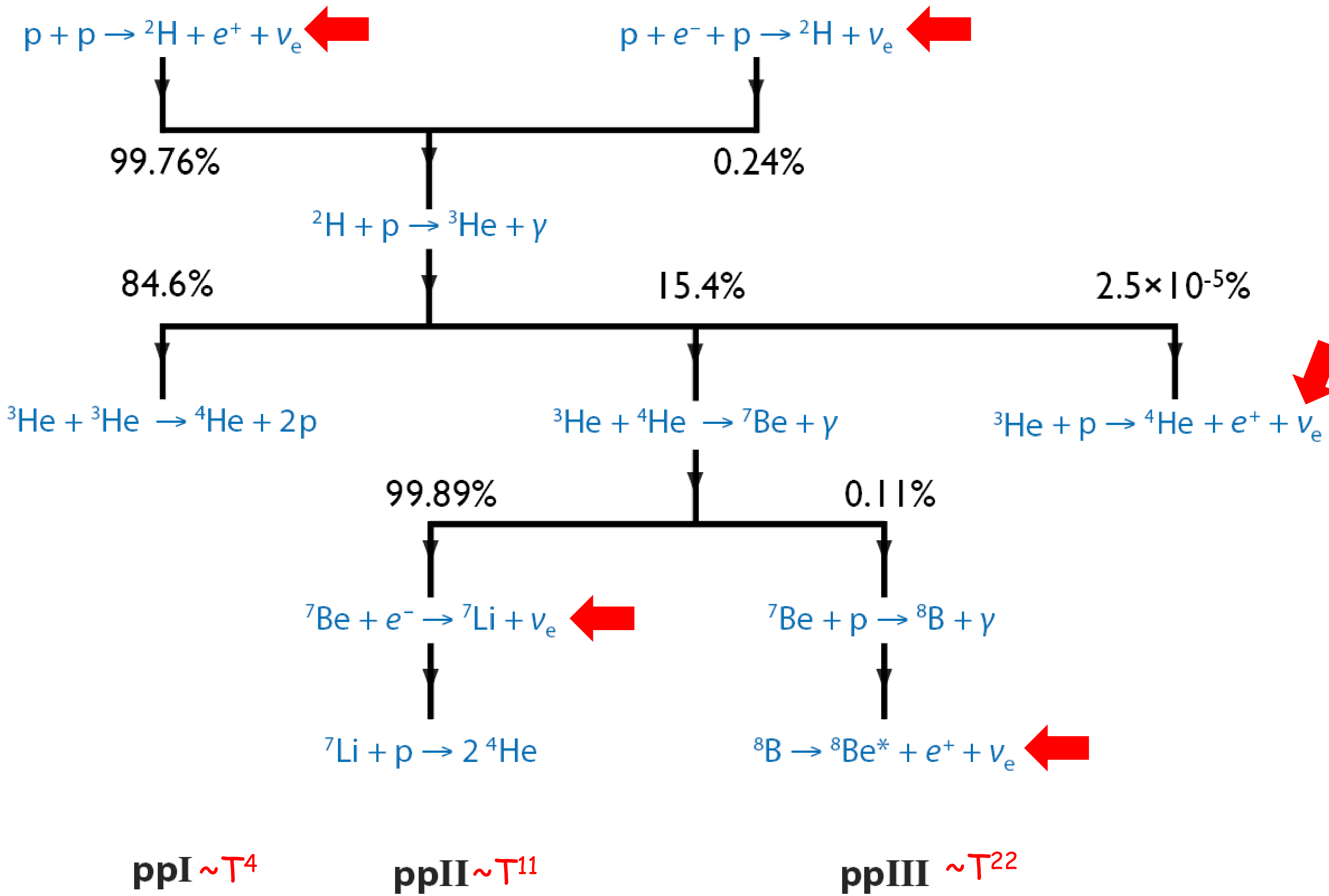


pp-I chain

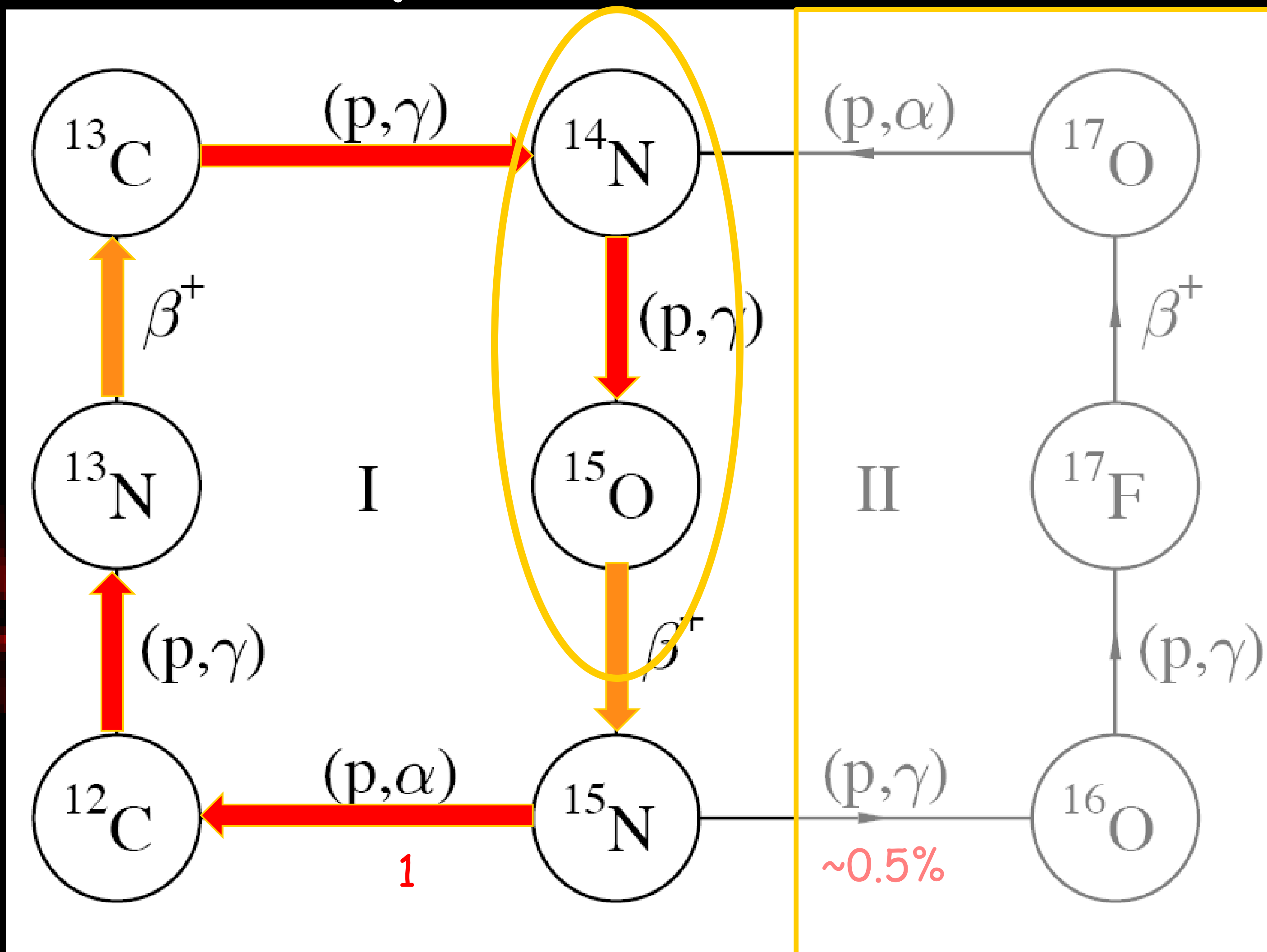


http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html

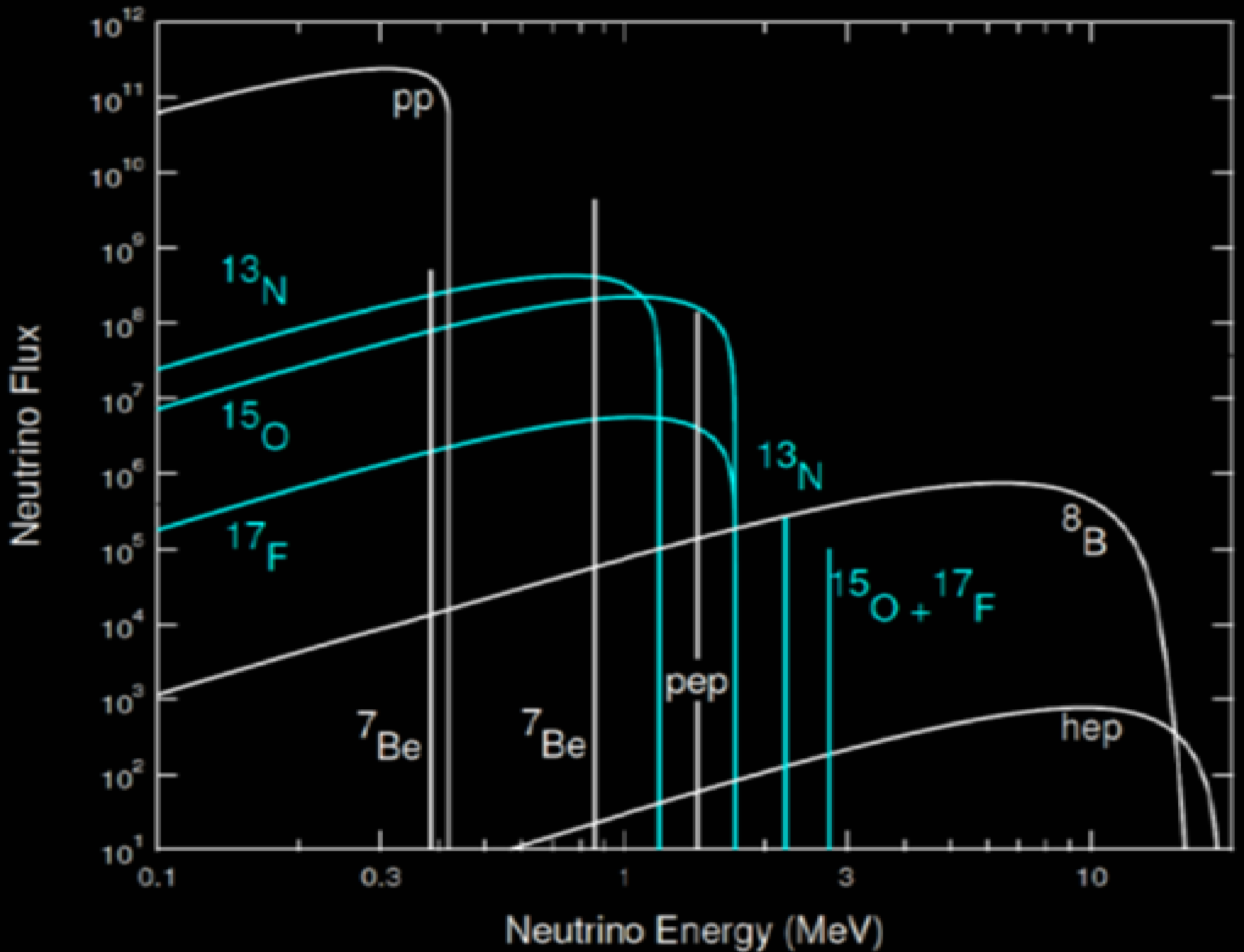
pp Chains within the Sun



CNO bi-cycle



- Making ~1% energy only
- In CNO-I, $^{14}N(p,\gamma)^{15}O$ controls the flow rate



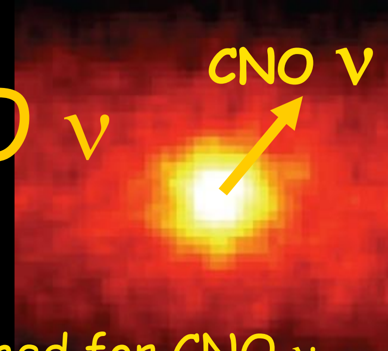
$\Phi(^8B) \sim 10^6\ cm^{-2}s^{-1}$

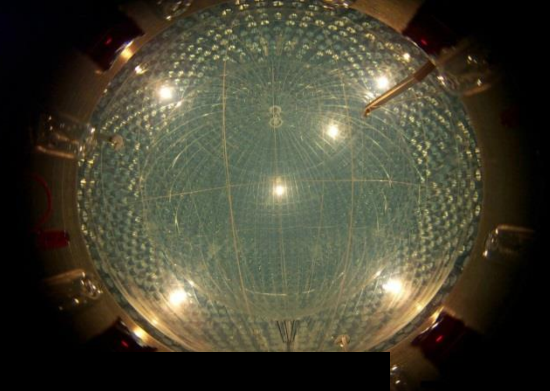
$\Phi(^{13}N) \sim \Phi(^{15}O) \sim 10^8\ cm^{-2}s^{-1}$

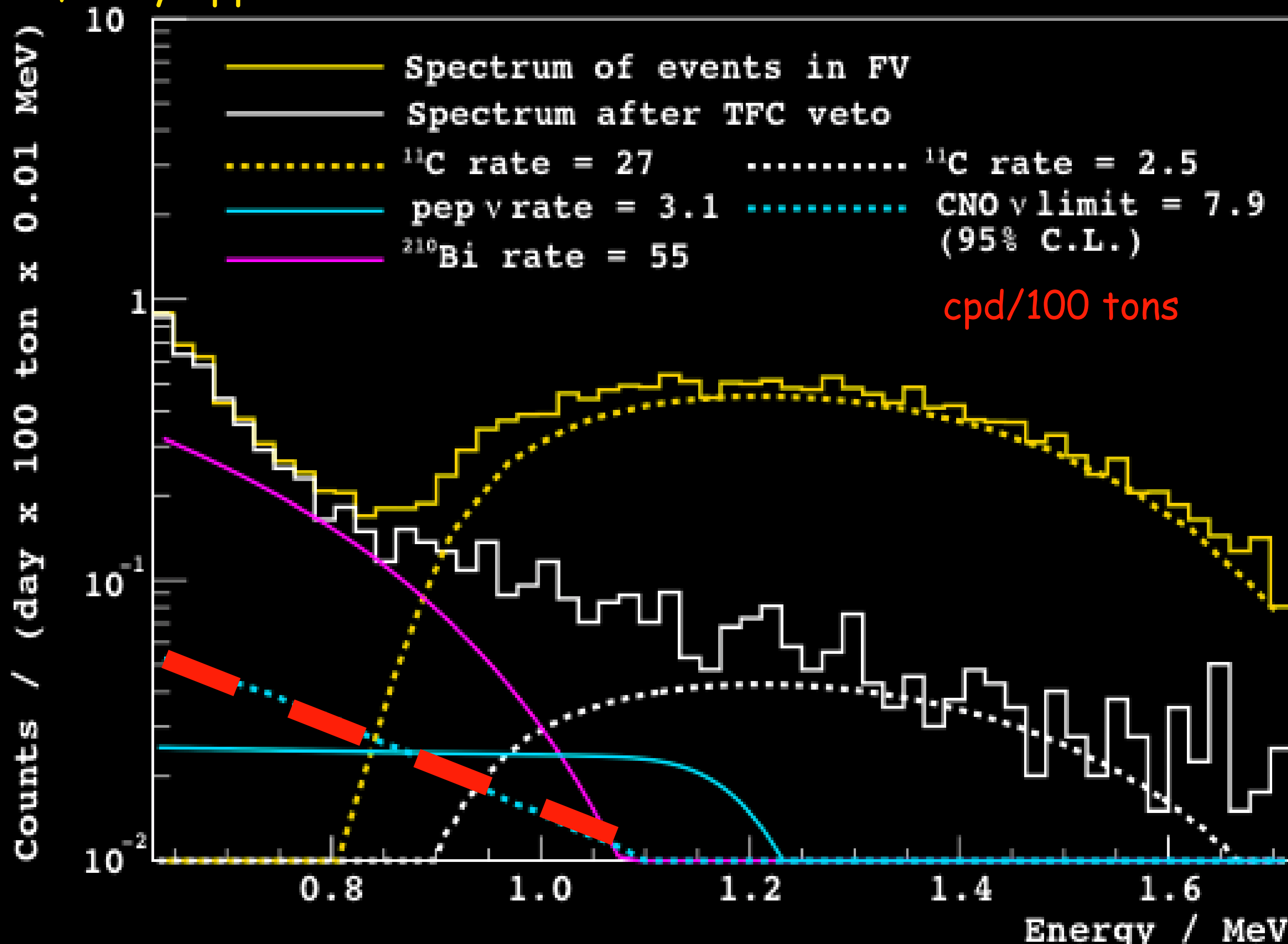
Observation of CNO ν

by Borexino

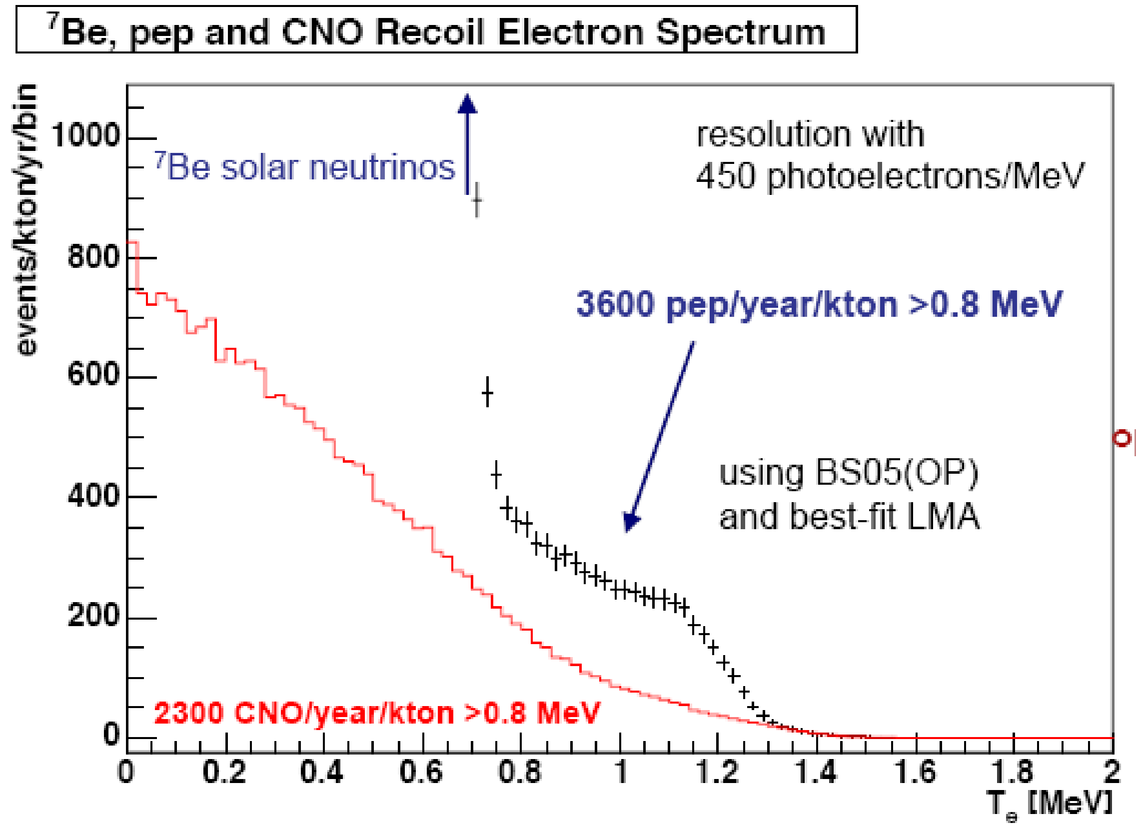
First observation of pep ν.
However, only upper limit was established for CNO ν.







SNO+: Borexino × 3 at SNOLab depts



(from Mark Chen)

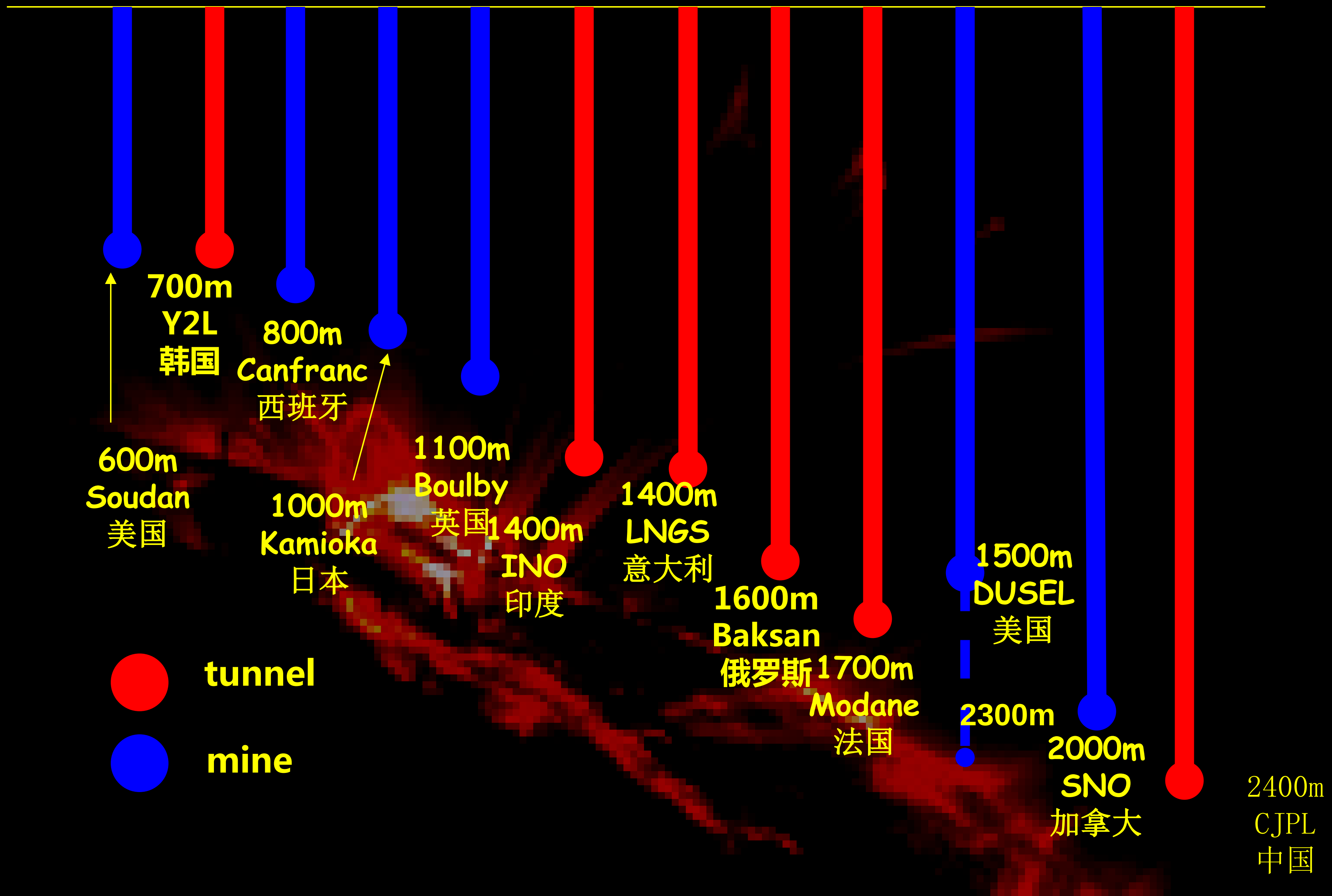
A similar detector -- Borexino -- now operating at Gran Sasso, with exceptional low environmental radioativity rates

Assumes one kt scintillator at SNOLab depth: factor-of-70 reduction in long-lived cosmogenic ^{11}C, to 0.1 c/d/100 tons, relative to Borexino

7% CNO flux measurement predicted, based on BS05(OP) fluxes

Adapted from Haxton's presentation

国际重要地下实验室比较



What need to be measured
Borexino, SNO+,(Jinping?)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

measured to 2% by SuperKamiokande
(the solar thermometer)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

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Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

what we want to know: the primordial core abundance of C + N (in units of SSM best value)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

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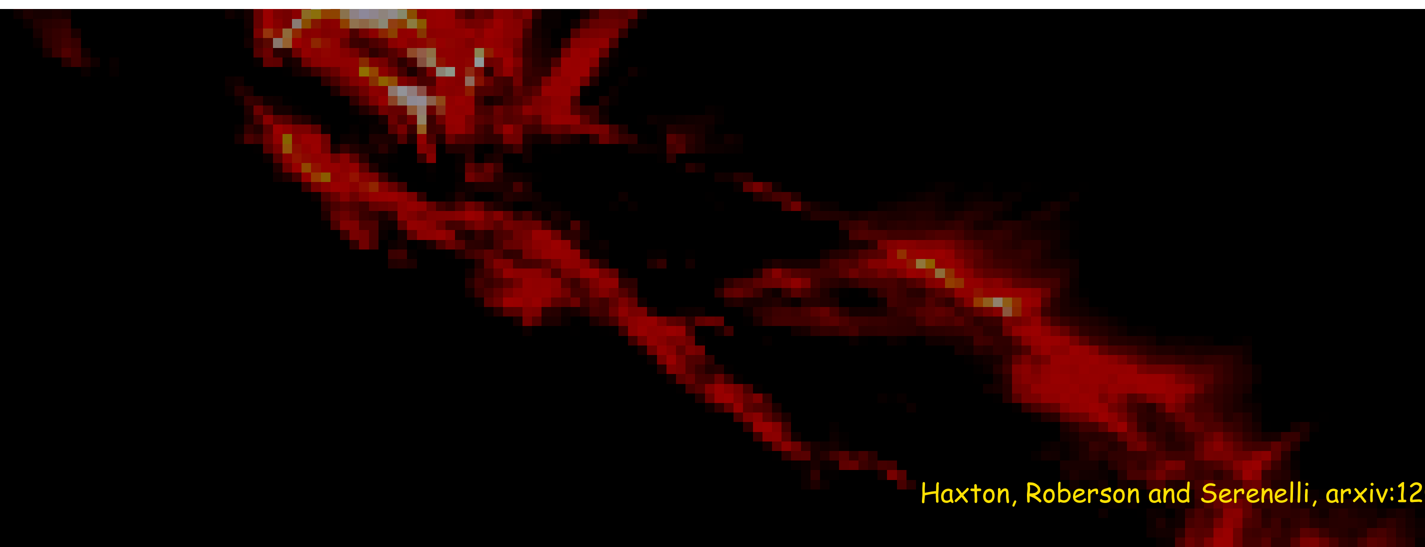

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

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$$\times \left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

the entire solar model dependence:
luminosity, metalicity, solar age, etc.,

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \underline{\pm 0.032(\theta_{12})}]$$

Determined by SNO and KamLAND

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

Nuclear Physics is the iggest uncertainty !

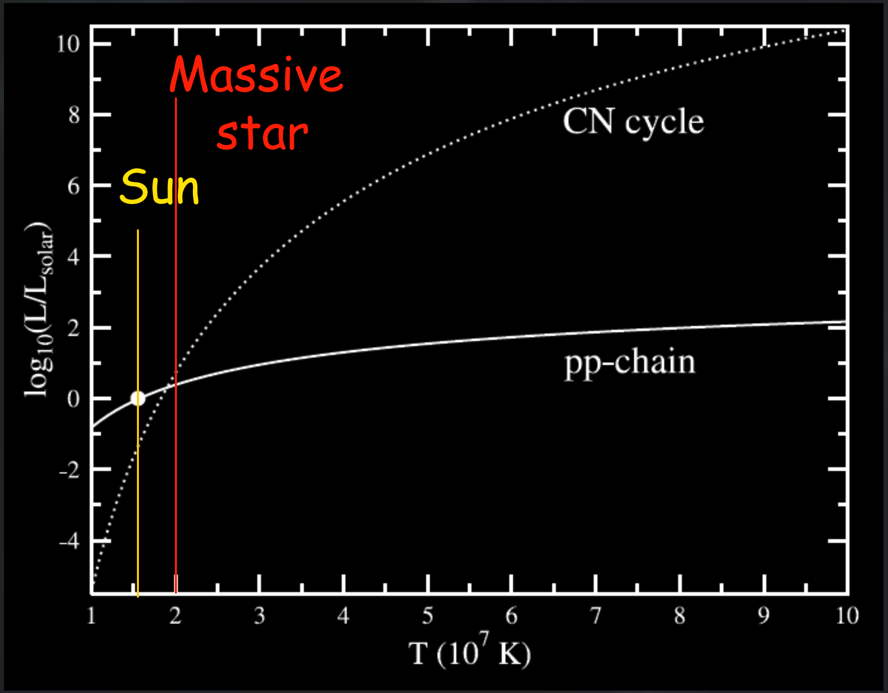
^{7}Be(p,γ)^{8}B (5.5%)

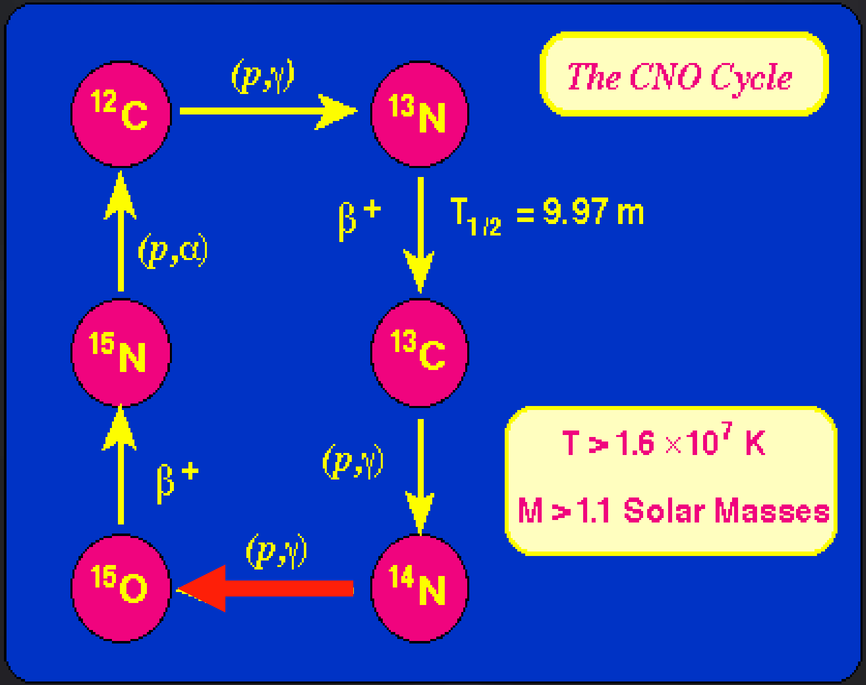
^{14}N(p,γ)^{15}O (7.2%)

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

$^{14}N(p,\gamma)^{15}O$: slowest reaction in the CN cycle

Fuel	Primary Products	Secondary products	Approximate temperature (10^9 K)	Approximate duration
Hydrogen →	^{4}He	^{14}N	0.02	10^7 yr

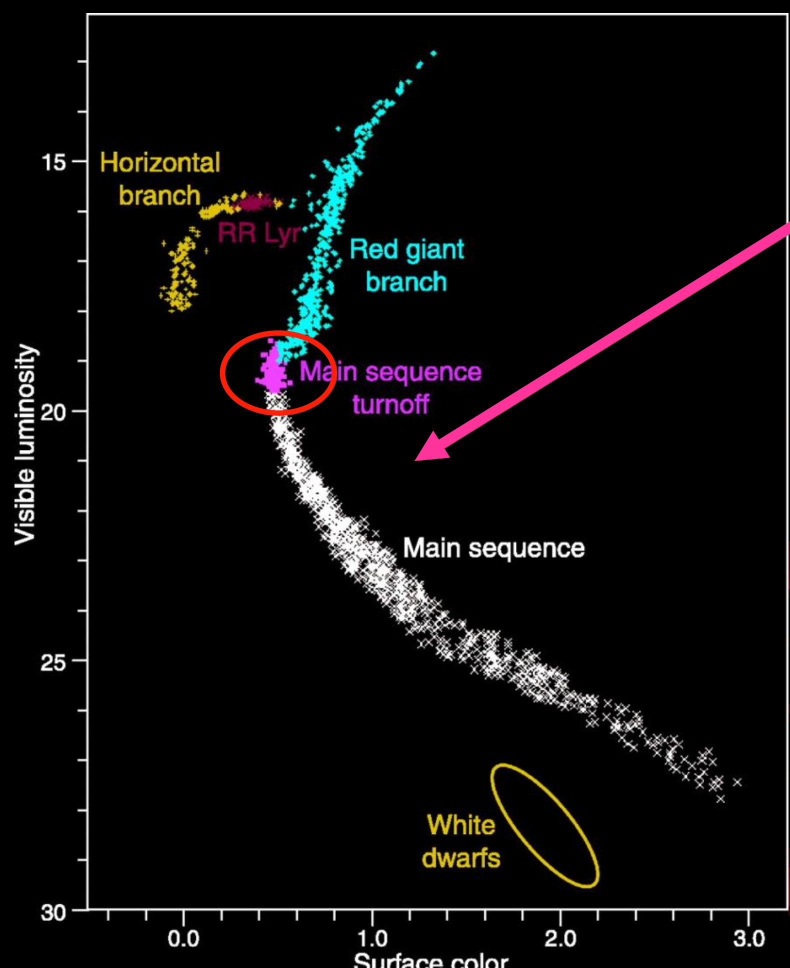


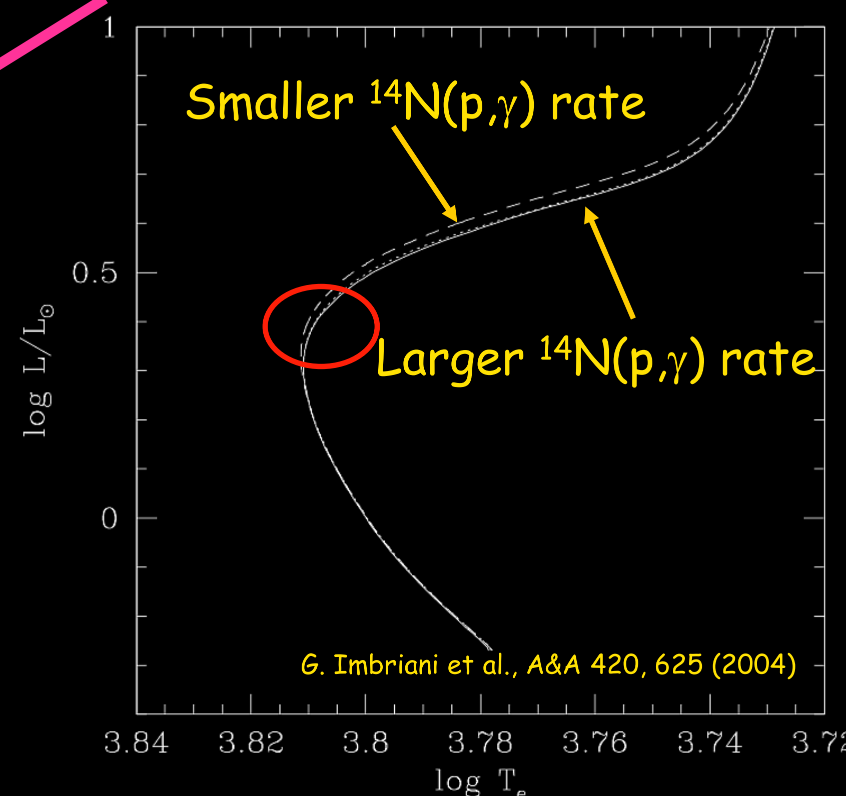


- *Massive MS stars: energy production and their lifetime*

Age Estimates of Globular Clusters in the Milky Way
Constraints on Cosmology

A group of stars with
same initial chemical composition
same age, different masses





Lower limit on the age of the Universe : 11.2 Gy (95% C.L.)

Krauss and Chaboyer, Science 299:65 (2003)

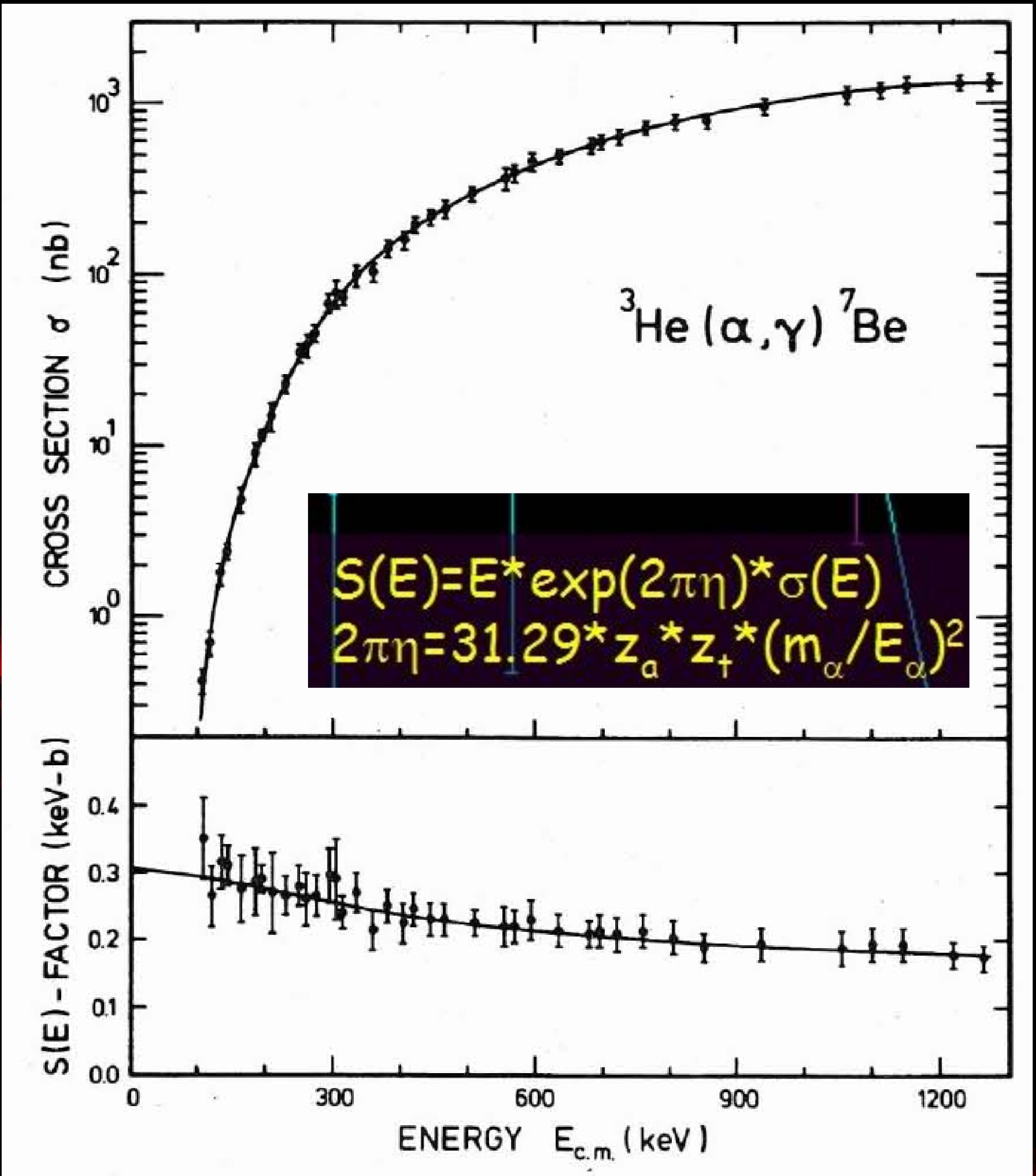
Measurement of CNO neutrino

this measurement is fundamental

- probes the primordial gas from which our solar system formed
- the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions
- could help motivate "standard solar system models" that would link solar ν physics, solar system formation, planetary astrochemistry

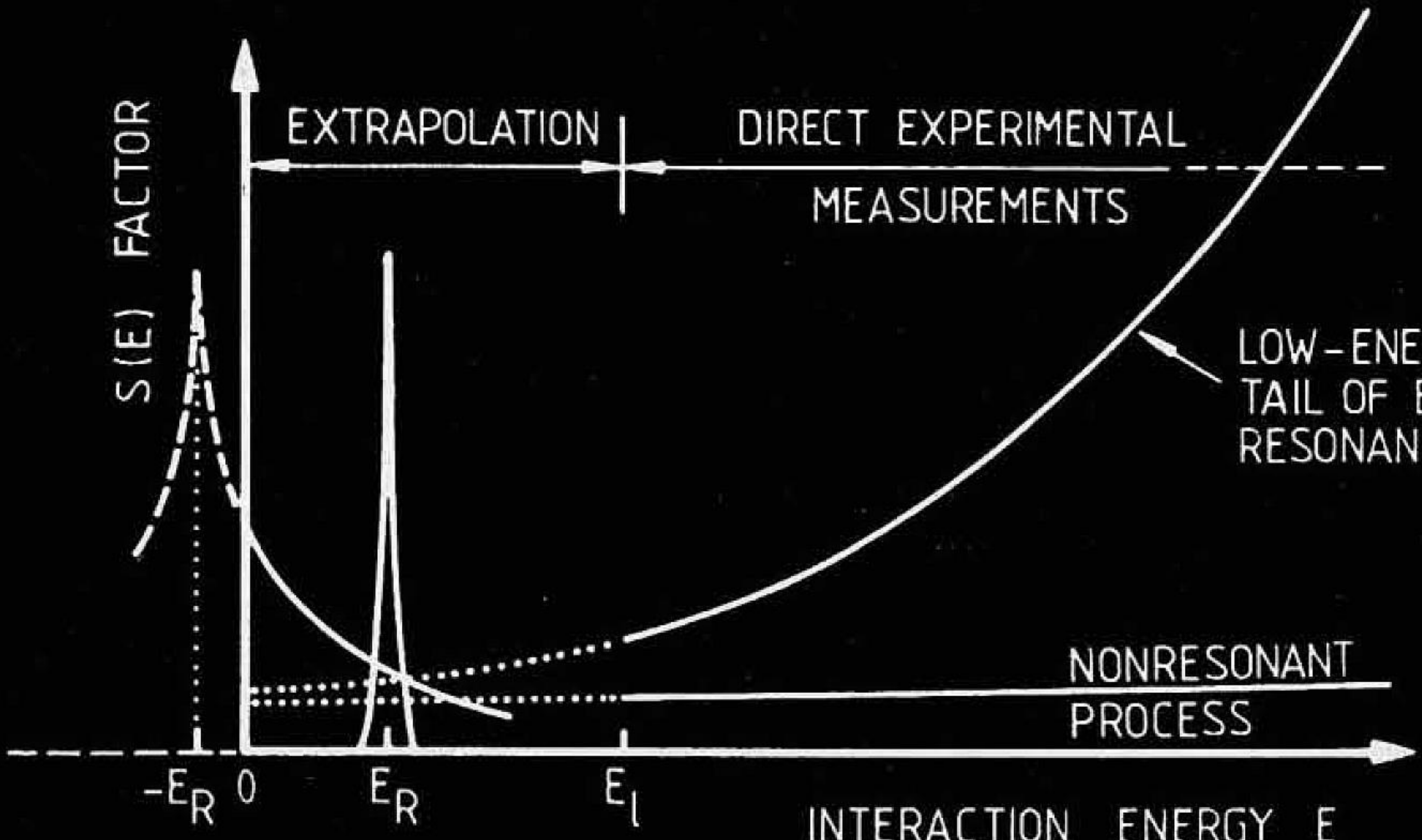
Would test our understanding of hydrogen fusion as it occurs in main sequence stars substantially more massive than the Sun.

adapted from W. Haxton's presentation



$^{3}He(\alpha,\gamma)^{7}Be$
CROSS SECTION σ (nb)
S(E) - FACTOR (keV-b)
ENERGY $E_{c.m.}$ (keV)
$S(E)=E*\exp(2\pi\eta)*\sigma(E)$
$2\pi\eta=31.29*z_a*z_t*(m_\alpha/E_\alpha)^2$

Extrapolation and its risk



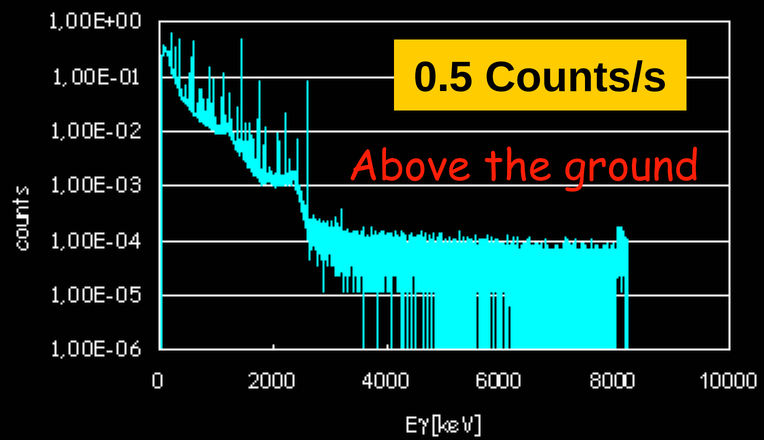
Adopted from "Cauldrons in Cosmos"

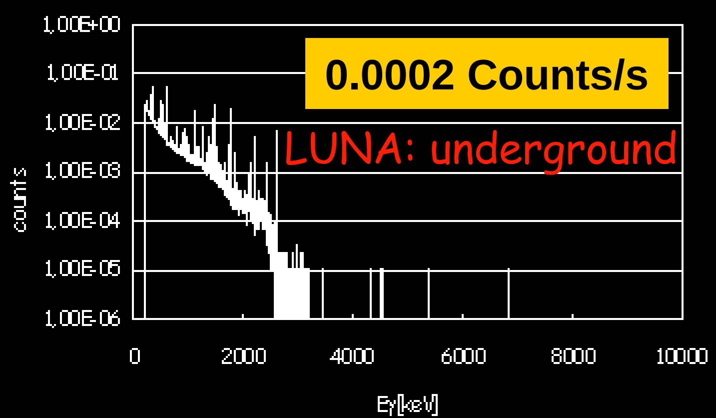
Background reduction in LNGS
(shielding ≡ 4000 m w.e.)

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Photons	10^{-1}

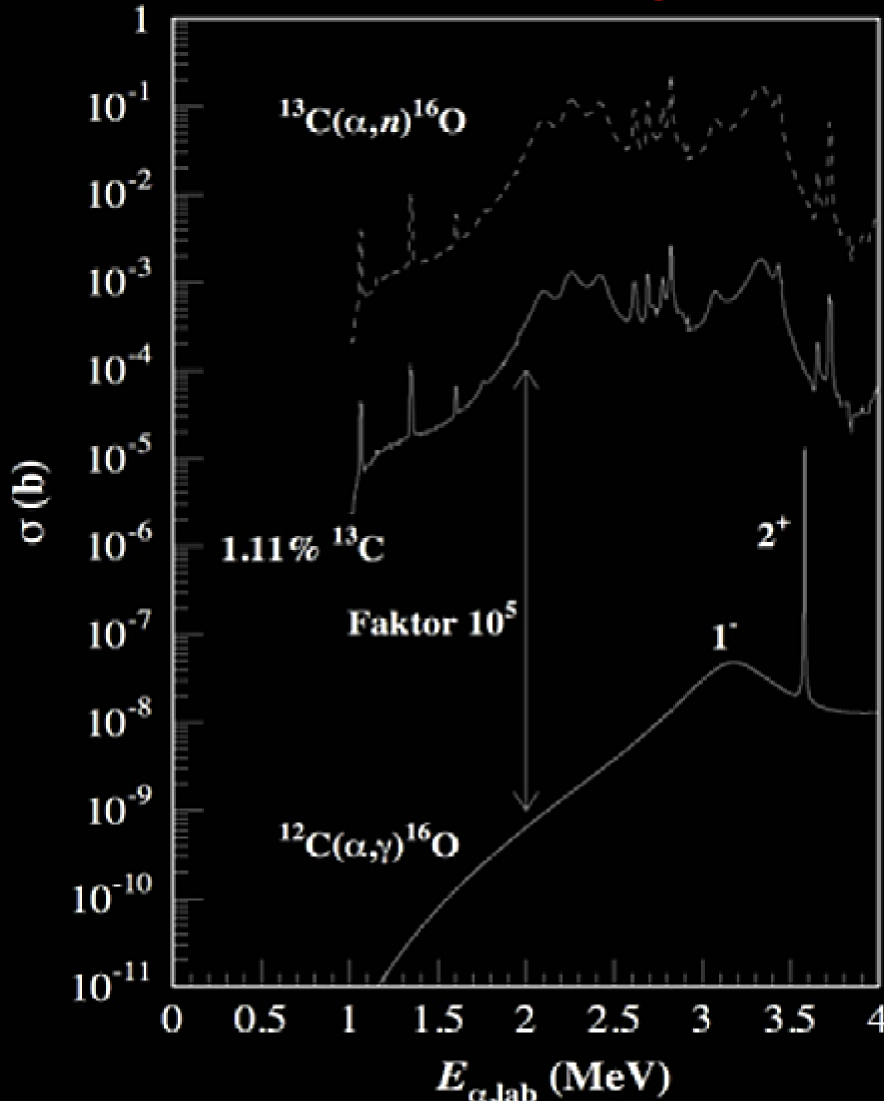
Problems in current direct measurements

Cosmic and Room Background
3 MeV < E_γ < 8 MeV:

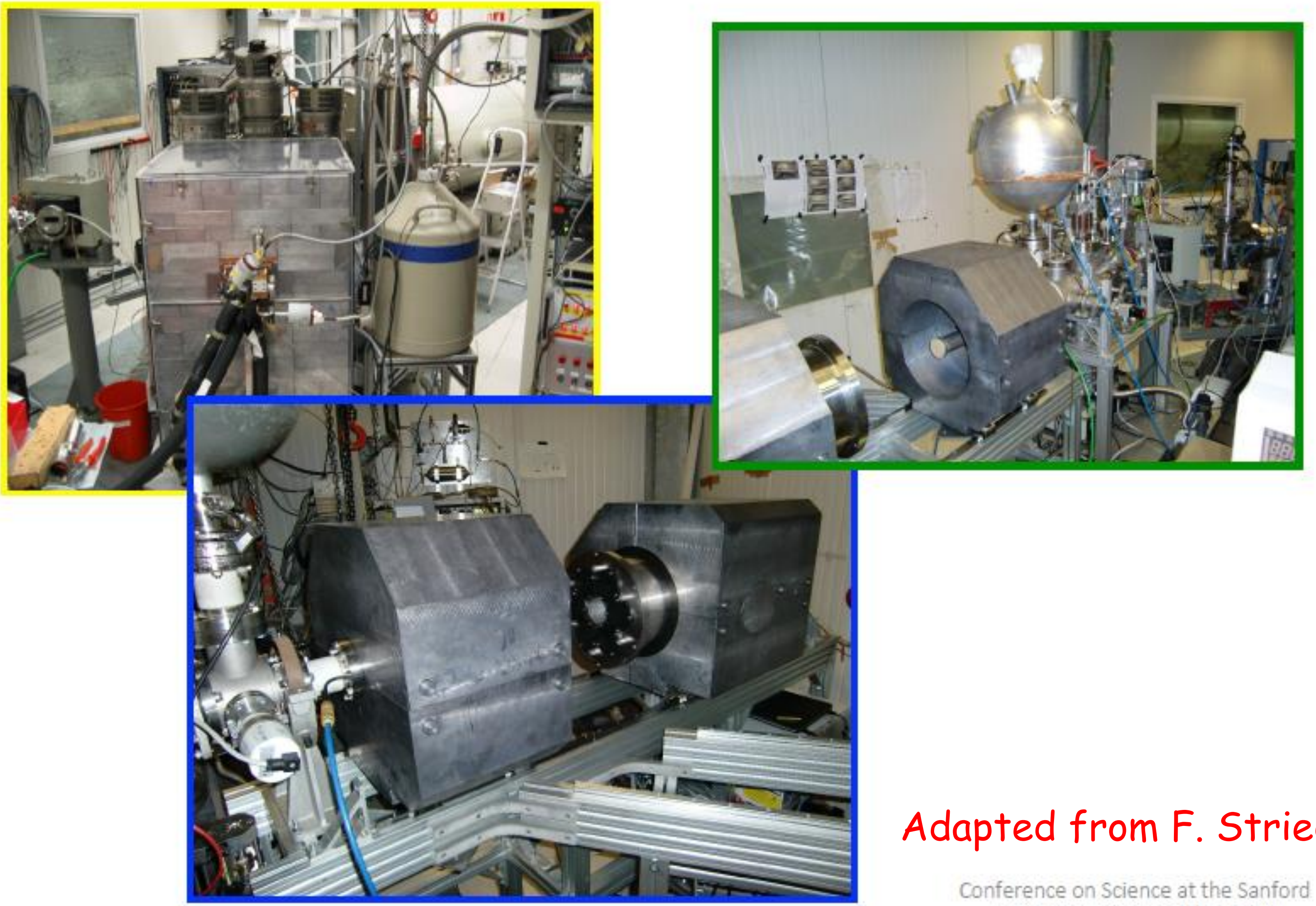




Beam induced background

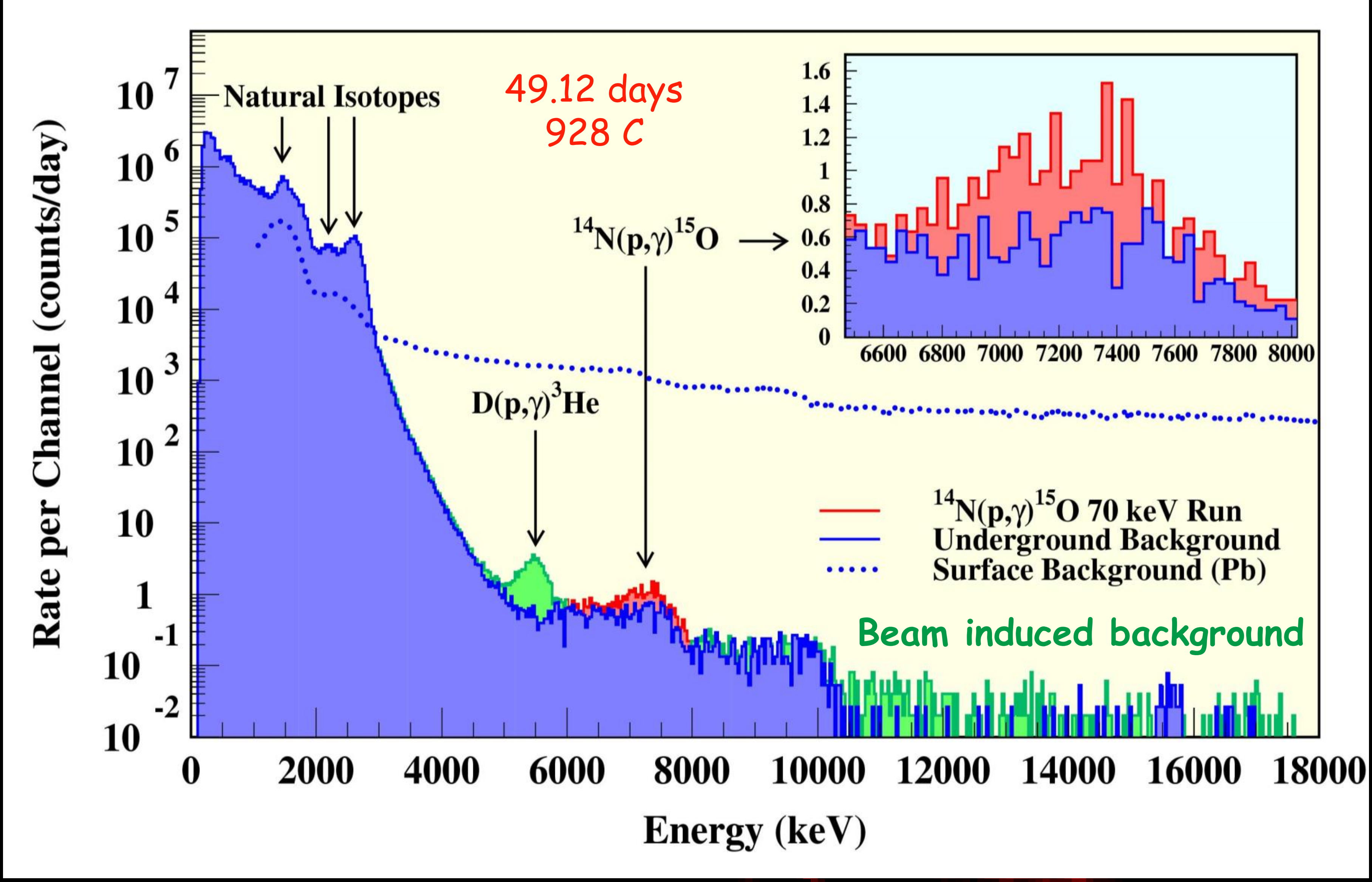


LUNA shielding

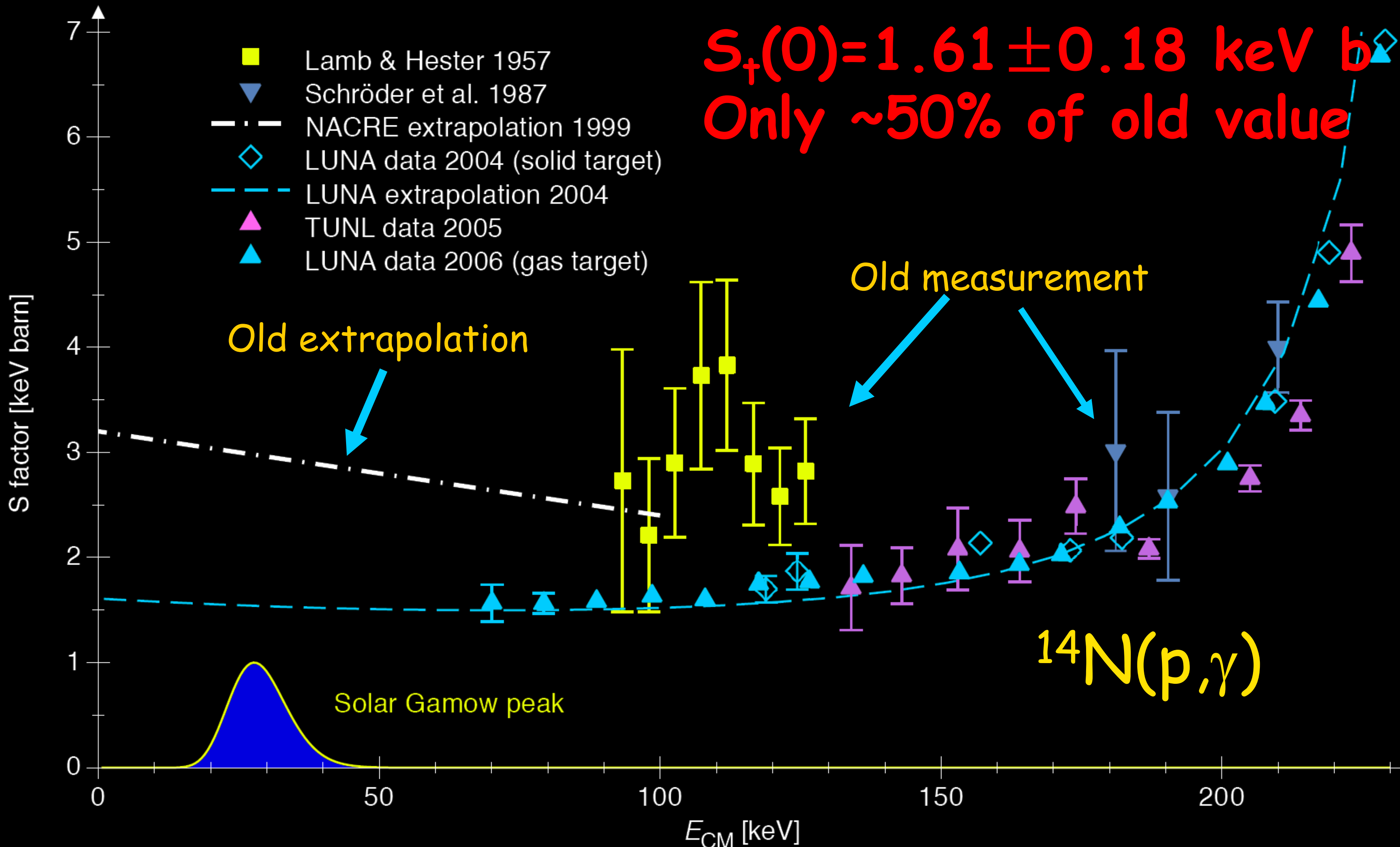


Adapted from F. Strieder's talk

Backgrounds at the lowest energy



LUNA Collaboration / Nuclear Physics A 779 (2006) 297-317

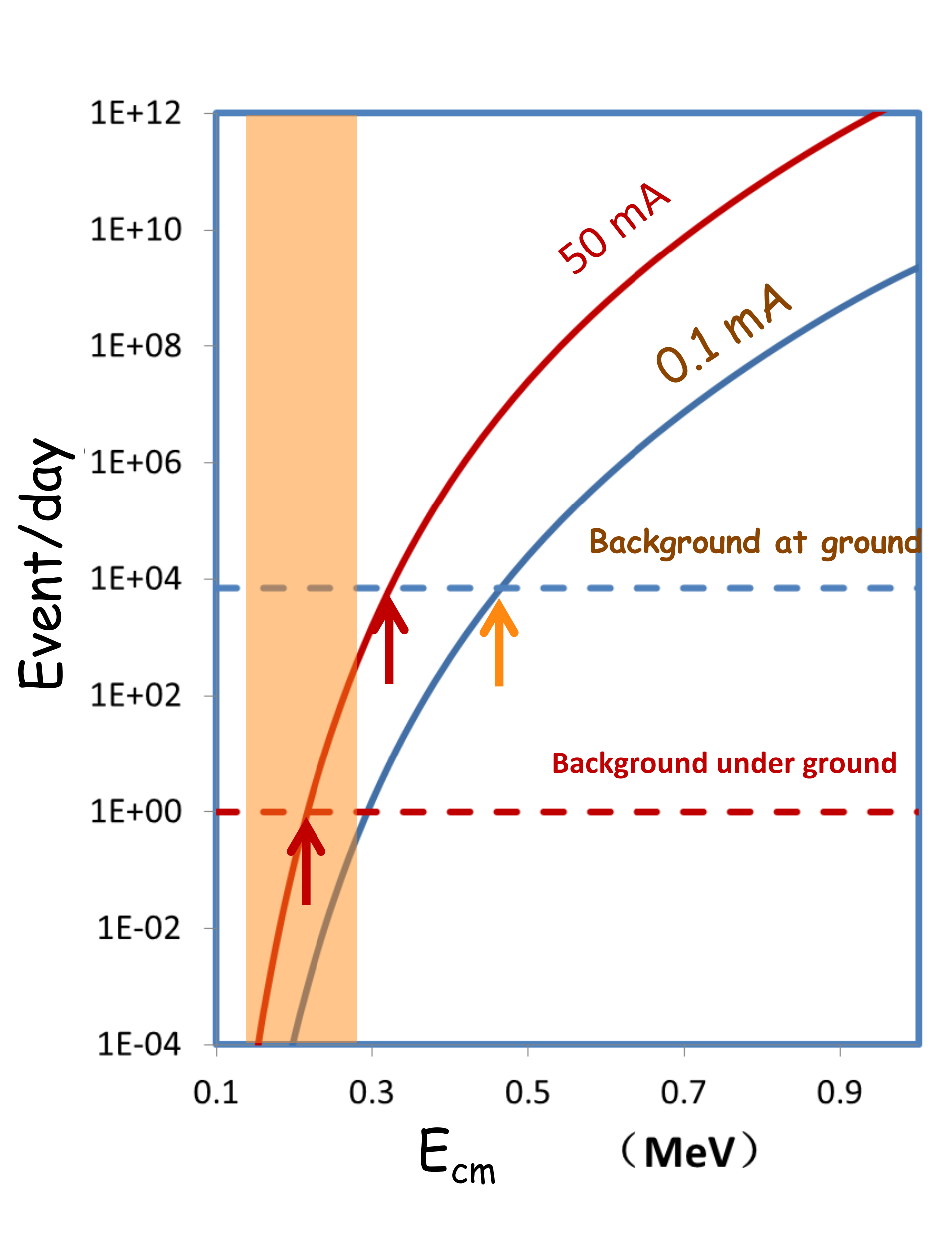


ν_{cno} reduced by ~ 2 with 8% error (precise core metallicity)

Globular cluster age increased by 0.7-1 Gy

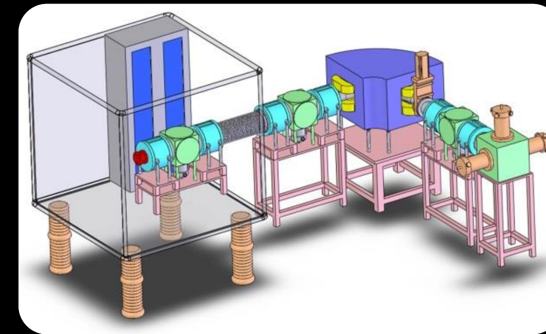
Phys. Lett. B591 (2004) 61-68/ *Nuclear Physics A 779 (2006) 297-317*

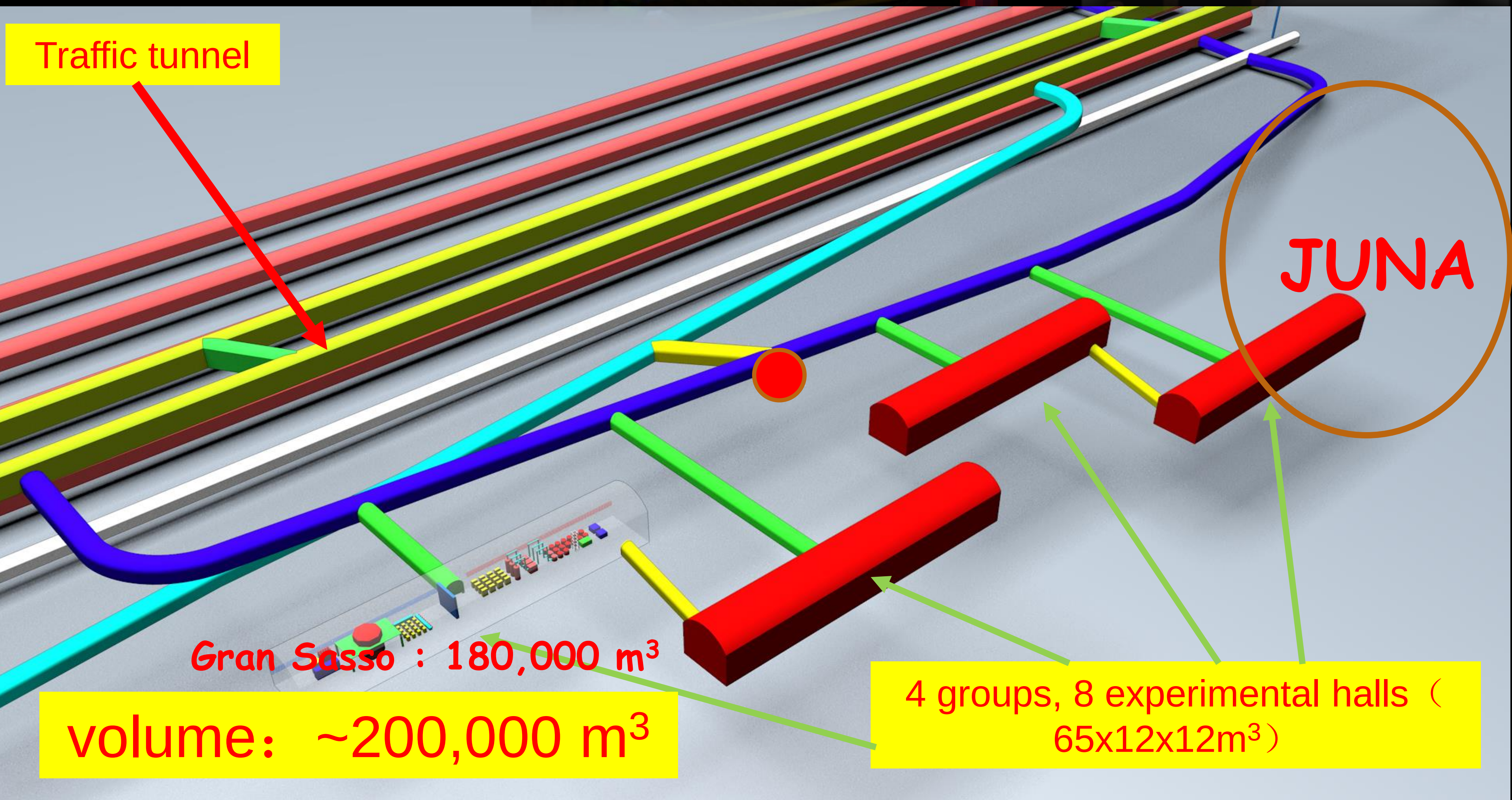
Challenging the tiny cross sections



CJPL-II

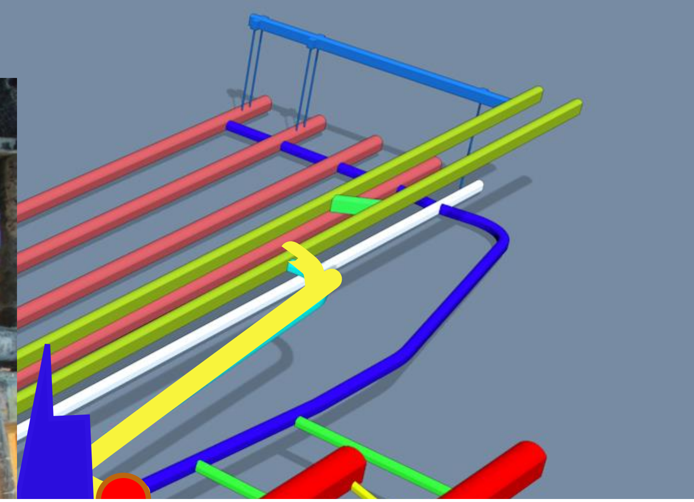
JUNA（Jinping
Underground
laboratory for
Nuclear Astrophysics）





Traffic tunnel
JUNA
Gran Sasso：180,000 m^3
volume：~200,000 m^3
4 groups, 8 experimental halls（
65x12x12m^3）

CJPL-II



PHYSICS

China supersizes its underground physics lab

Planned expansion could pave way for "ultimate dark matter experiment"

By **Dennis Normile**

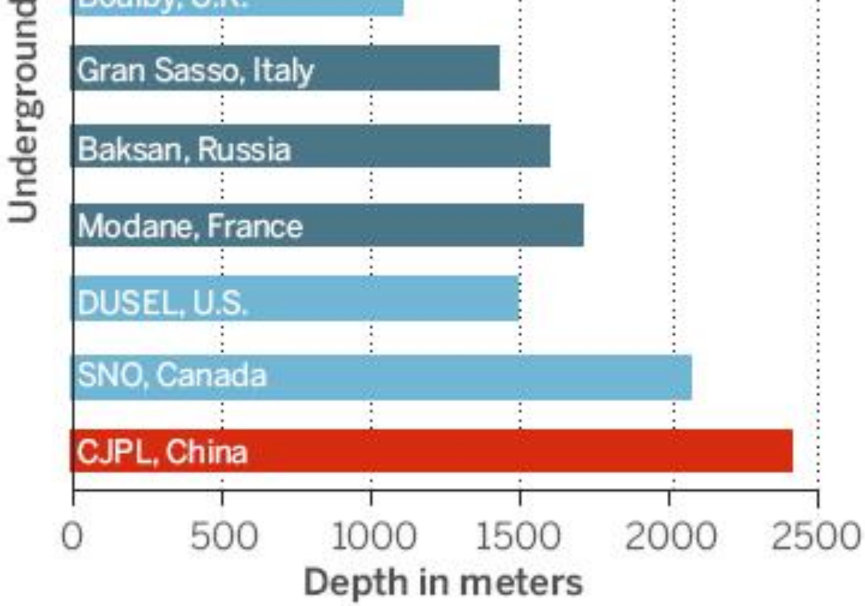
The world's deepest physics laboratory is about to become one of its largest. Early next year, workers will start carving four cavernous experiment halls along a tunnel through Jinping Mountain in China's Sichuan province. Once the science at the China Jinping Underground Laboratory (CJPL) is scaled up as well, "it will be a milestone for Chinese

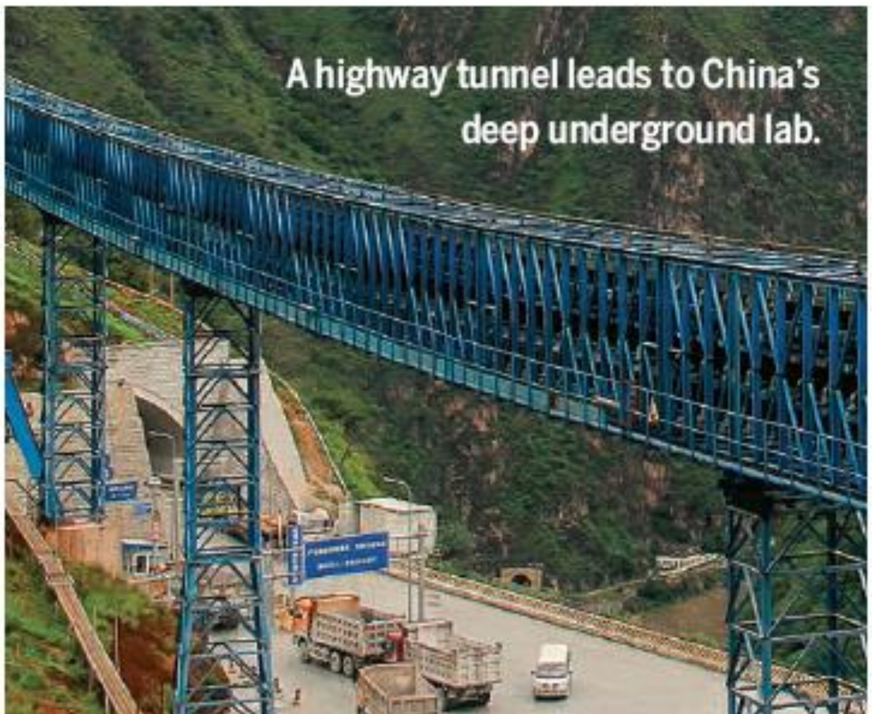
WIMPs exist, they should occasionally travel unmolested through the mountain and collide with a xenon nucleus, producing a flash of light. In the other experimental hall, the China Dark Matter Experiment (CDEX) aims to catch the electrical signal produced if a WIMP bumps into a nucleus within a germanium crystal. "There is complementarity" between the two approaches, […] a physicist at Academia S[…] Physics in Taipei and member of the CDEX

other labs indicating that WIMPs are likely to have very little mass.

For an initial effort, the results are "pretty decent," says Wick Haxton, a theorist at the University of California, Berkeley. To boost its chances of sighting WIMPs and determining their mass, CJPL needs a larger volume of xenon, more germanium crystals, and better […] over the next couple years," Haxton says,

Science, Nov. 30, 2014



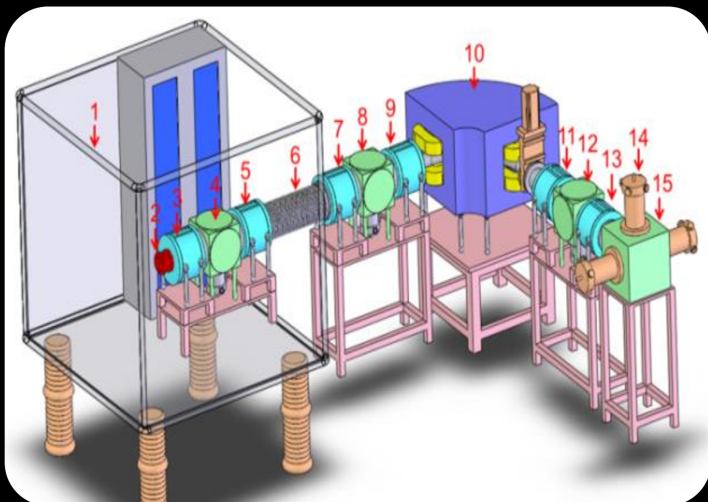


A highway tunnel leads to China's deep underground lab.

20-ton scale liquid xenon experiment," says Xiangdong Ji, a physicist at Shanghai Jiao Tong University and the University of Maryland, College Park. That would be several times larger than existing liquid xenon experiments. Realizing such a mammoth project, says Ji, who leads PandaX, could require teams worldwide to pool resources.

A new experiment planned for the expanded space is the Jinping Underground laboratory for Nuclear Astrophysics (JUNA). Its pièce de résistance would be a particle accelerator used to replicate the nuclear processes generating energy within stars and the synthesis of heavier elements from hydrogen and helium in the primordial universe. The rock shielding would reduce background noise, making it easier for researchers to detect rare and subtle signals. With a more powerful accelerator and a deeper location than other efforts, says project head Weiping Liu, a physicist at the China Institute of Atomic Energy in Beijing, "JUNA has the potential to take a favorable position among underground nuclear astrophysics labs." ■

Jinping Accelerator: **First deep underground accelerator driven by ECR**



400 kV accelerator

- **2014, JUNA formed**
- **2015, NSFC: RMB 20 millions**
  CAS : RMB 5 millions
  CNNC : RMB 3 millions
- **2015-2017: construction of lab and accelerator**
- **2018-2019: 19Fe(p,a), 25Mg(p,g), 13C(a,n) and 12C(a,g)**
- **JUNA core institutes： CIAE， IMP， Tsinghua， Shanghai JiaoTonng， Sichuan；**
- **Other JUNA members： Tanihata, Kubono, Alex Heger, Maria Lugaro, Yongzhong Qian, Wanpeng Tan, Dongmin Mei**

		JJUNA 400 kV	LUNA 400 kV	CASPAR
Ion source		2.45 GHz ECR	RF source	RF source
Intensity	H^+	>10 mA	1 mA	0.1 mA
	He^+	>10 mA	0.5 mA	0.1 mA
	He^{2+}	~2.5 mA	N/A	N/A

JUNA organization

JUNA

Group leader

- CIAE
- IMP
- THU
- SJTU
- SCU
- SDU
- SZU
- …

Weiping Liu
$^{12}C(\alpha,\gamma)^{16}O$

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

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PI

Xiaodong Tang
$^{13}C(\alpha,n)^{16}O$
Ion source

Zhihong Li
$^{25}Mg(p,\gamma)^{26}Al$
↓
$^{14}N(p,\gamma)^{15}O$

Jianjun He
$^{19}F(p,\alpha)^{16}O$

Gang Lian
Accelerator

JUNA international team







Osaka, Isao Tanihata

Monash, Alexander Heger

Notre Dame, Wanpeng Tan

HAS, Maria Lugaro

Minisota, Yongzhong Qian

RIKEN, Shigeru Kubono

South Dakota, Dongming Mei

JUNA IAC

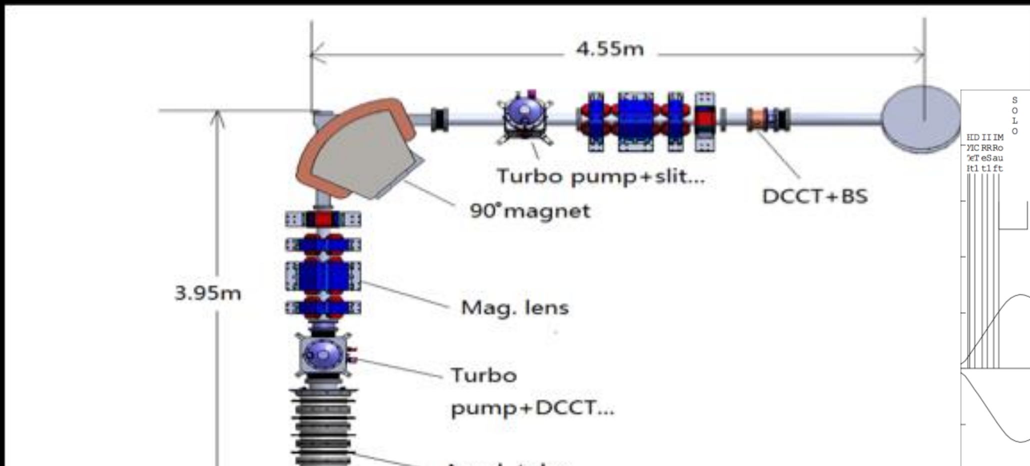


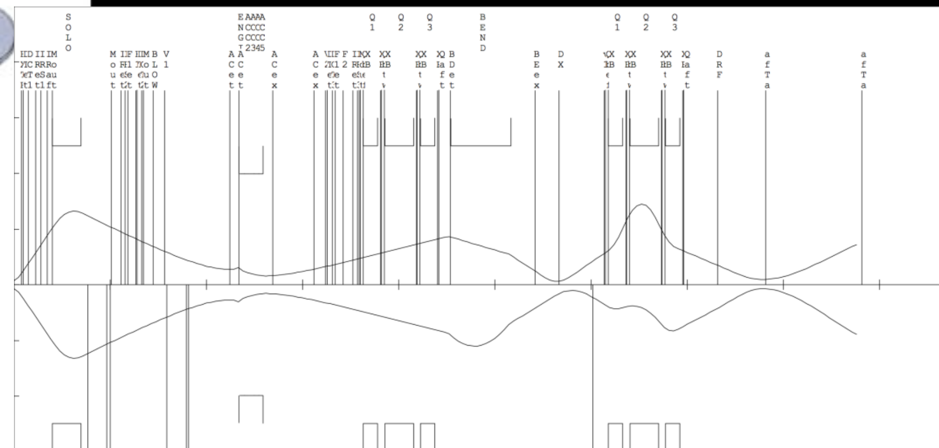


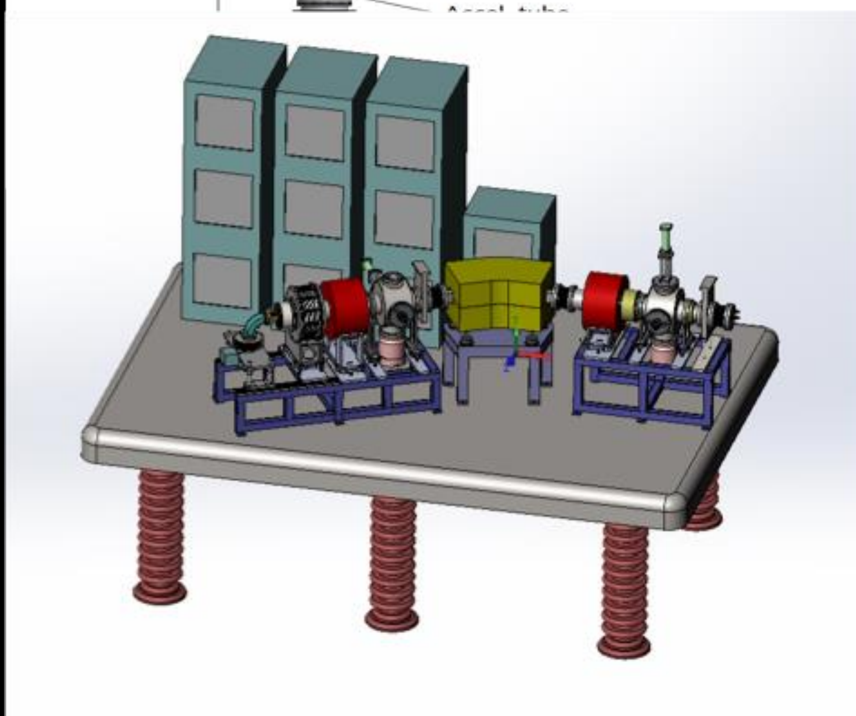


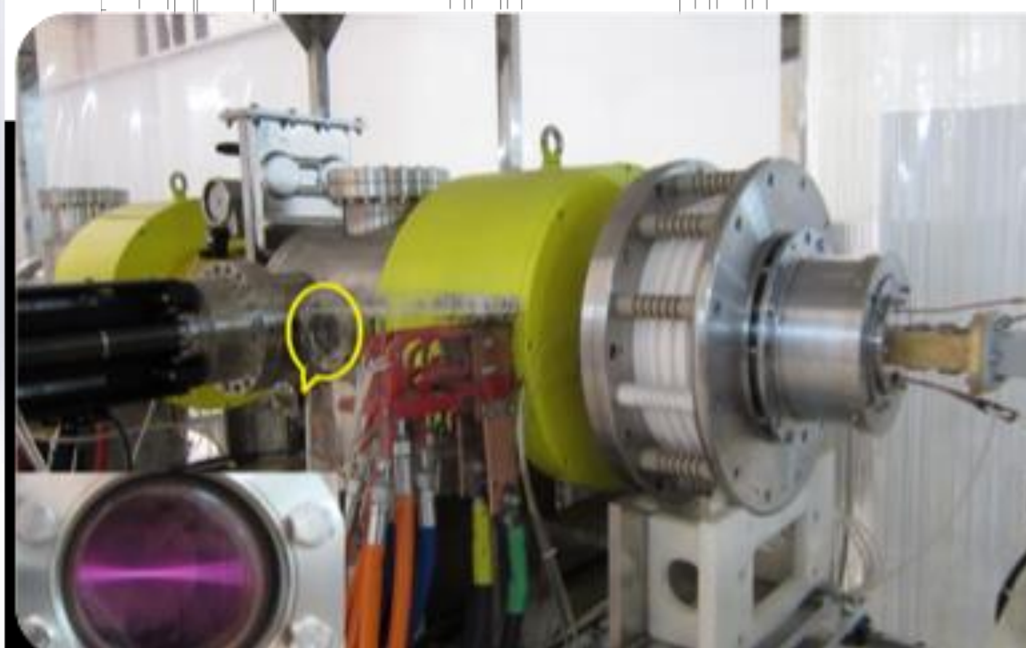

M. Wiescher	Chair	UND
T. Motobayashi	Member	RIKEN
H. Wang	Member	TCAS
C. Brune	Member	Ohio
M. Junker	Member	INFN
D. Robertson	Member	UND
F. Strieder	Member	SDSMT
D. Leitner	Member	LBL
Q. Yue	Member	THU

Accelerator and ion source design





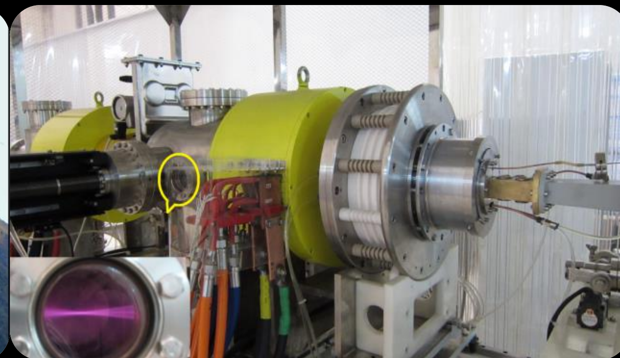




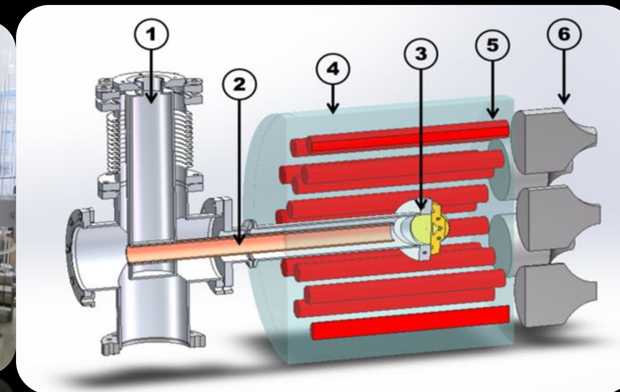
Comparison with other experiments
$^{13}C(\alpha,n)^{16}O$

JUNA

Excellent background



First deep underground accelerator driven by ECR



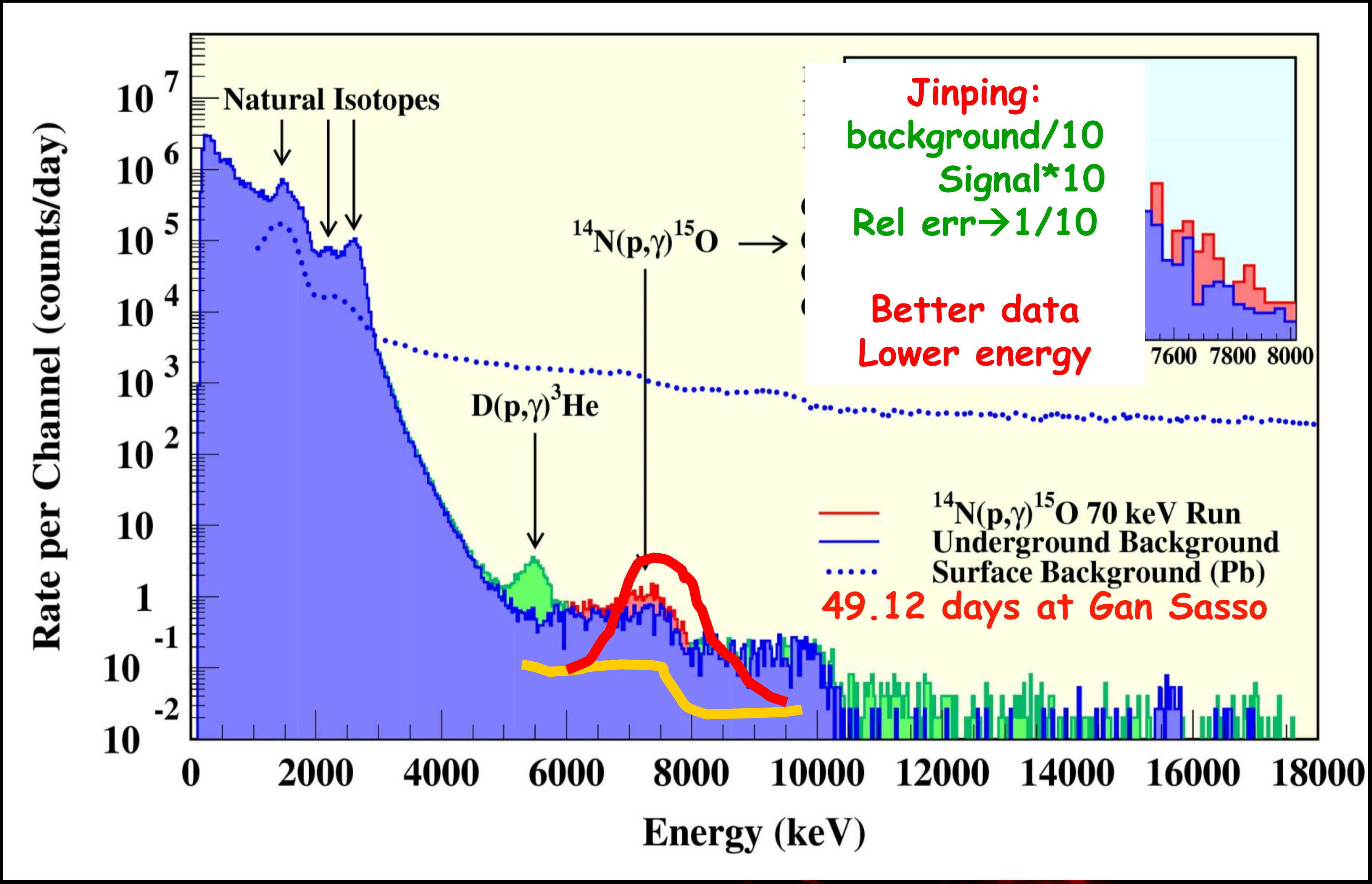
Highly sensitive fast n detector

	Detected bk.（evt/day）	He beam intensity（pmA）	Time for reaching 20% statistical err.（Ecm=0.2 MeV）	signal/bk.
Stuggart	7000	0.1	190,000 yrs	$4.9\times10^6/4.7\times10^{11}$
CASPAR (USA)	1	0.1	28 yrs	$7.4\times10^2/1.0\times10^4$
LUNA (Italy)	1	0.5	1.4 yrs	190/530
JUNA	1	10	8 days	57/8

Reaction Rate=7 evt/day/pmA；10% det. Eff.；

signal=total-background；rel. err. =Sqrt(total+bk)/signal

Better measurement with JUNA



LUNA Collaboration / Nuclear Physics A 779 (2006) 297-317

Better understanding with higher precision
Or New physics

Summary