Nuclear astrophysics

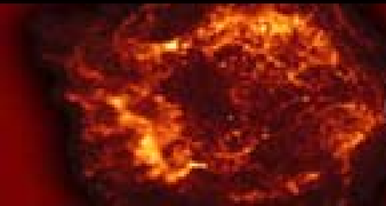
A survey in 6 parts

Jeff Blackmon, Physics Division, ORNL

Nuclear physics plays an important role in astrophysics:

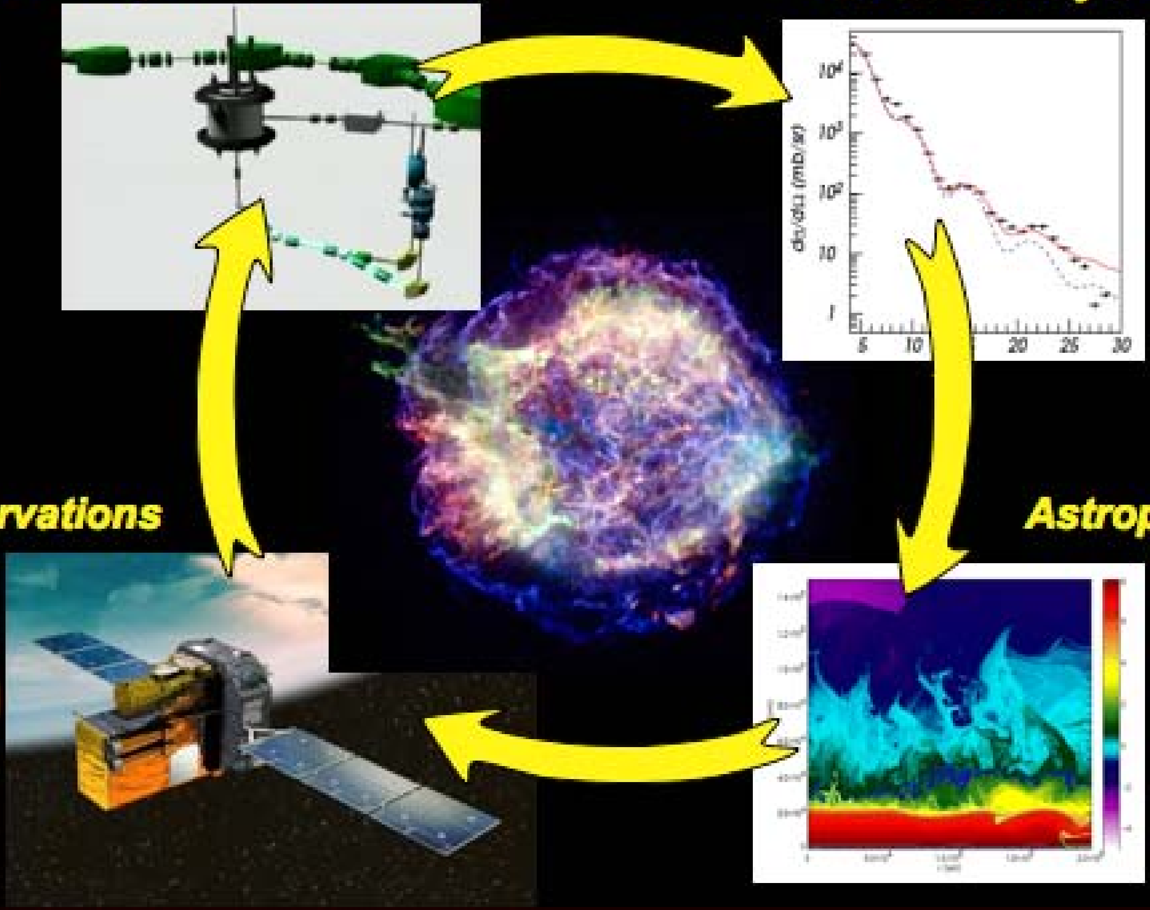
Energy generation
Synthesis of elements
} astronomical observables

1. Introduction
2. Big Bang
3. Stellar structure & solar neutrinos
4. Stellar evolution & s process
5. Supernovae & r process
6. Binary systems: Type Ia, novae, x-ray bursts



Interdisciplinary research

A variety of new tools in many areas are driving progress



Laboratory measurements

New beams & experimental techniques

Nuclear theory and data

Improved shell model, reaction theory, rates, libraries & dissemination via the web

Astrophysics

Advancing computing power →more realistic simulations

Observations

New orbiting instruments, increased optical power, presolar grains

Solar system abundances

One of the most fundamental and important observables

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

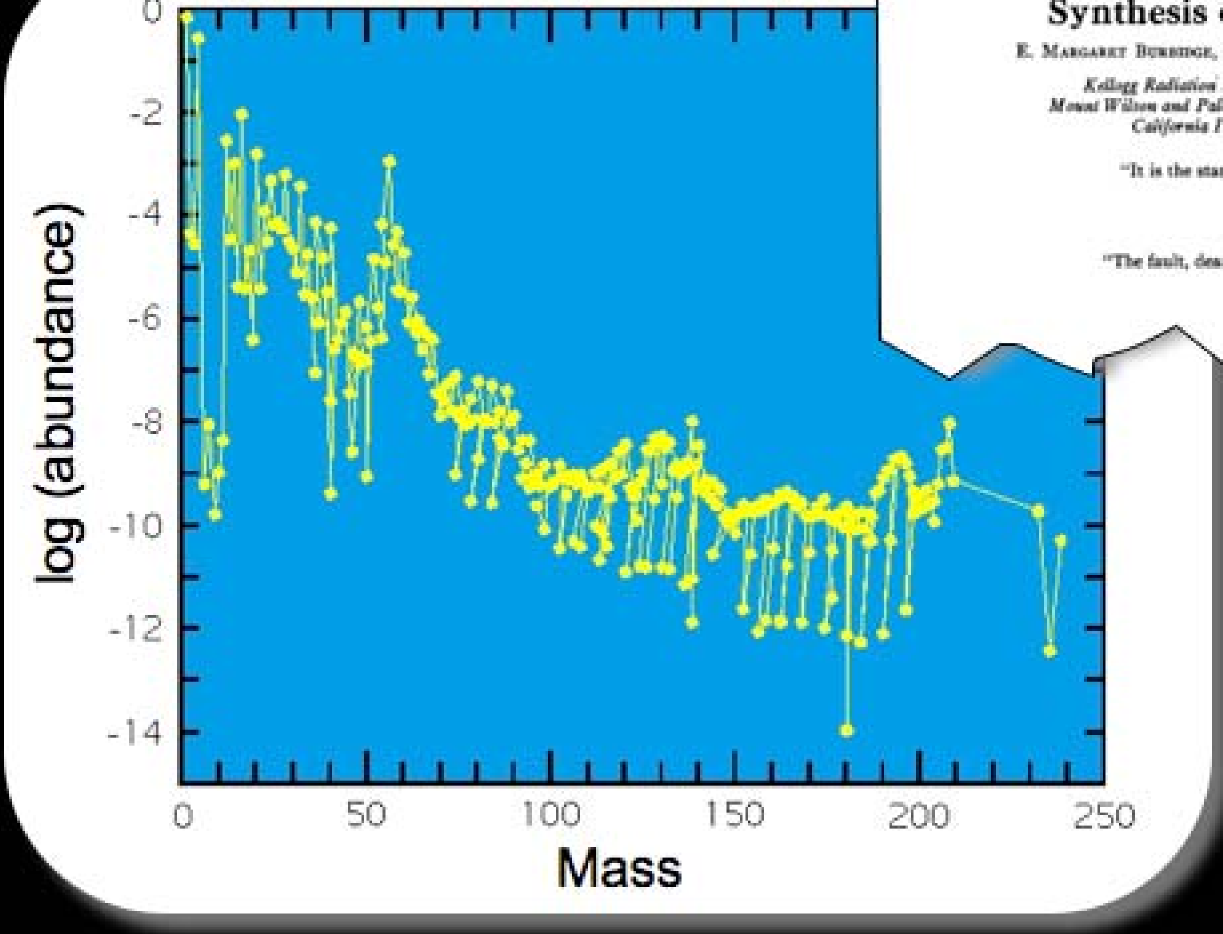
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

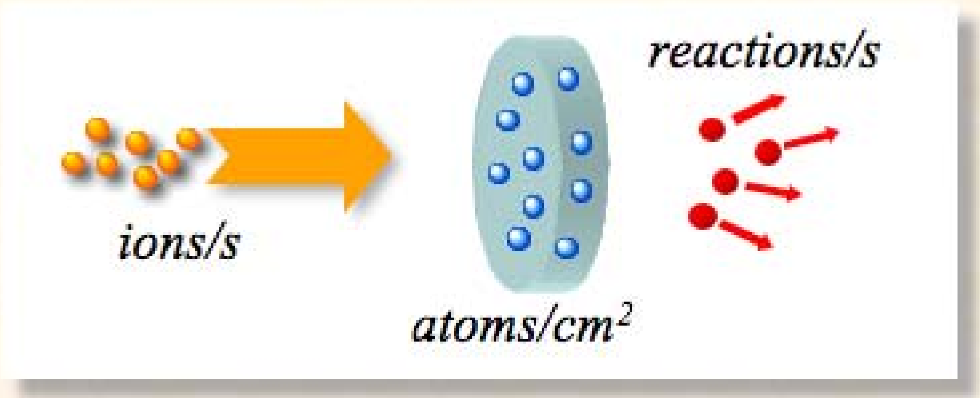
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)



This year marks the 50th anniversary of "B^{2}FH"

Nuclear reactions in the lab & in space

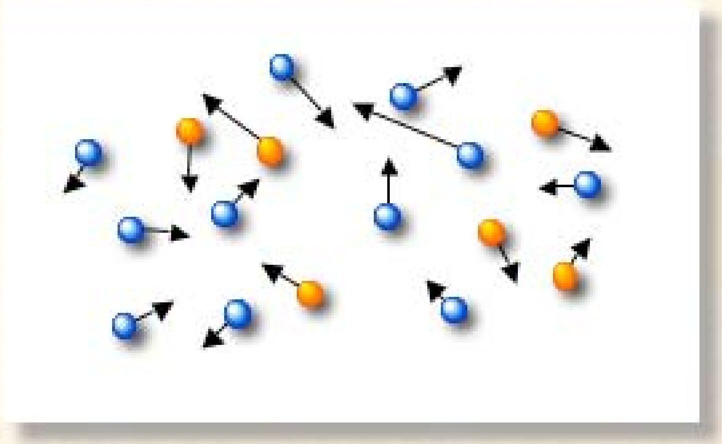
What you are used to in the lab:



cross section

$$\frac{reactions}{s} = \frac{ions}{s}\frac{atoms}{cm^2}\sigma$$

In astrophysical events:



reaction rate

$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\frac{n_y}{cm^3} v\sigma(v)\phi(v)dv$$

$$\phi(v) = 4\pi v^2\left(\frac{\mu}{2\pi kT}\right)^{3/2}\exp\left(-\frac{\mu v^2}{2kT}\right)$$

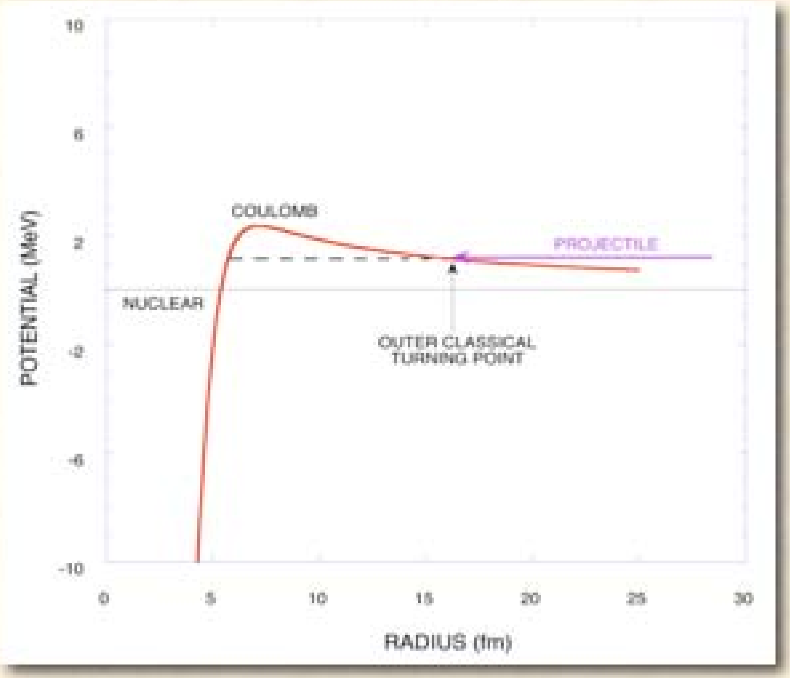
$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\frac{n_y}{cm^3}\langle\sigma v\rangle$$

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)}dE$$

The Coulomb barrier

Energy of particles in astrophysical environments is much lower than the Coulomb barrier

$$V_c = \frac{1.44 Z_a Z_b}{r}\ MeV \cdot fm$$



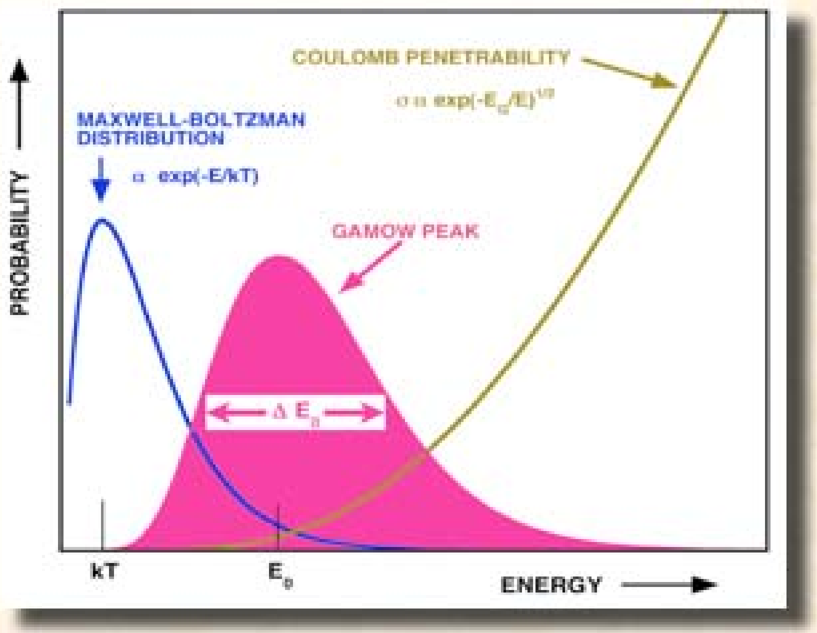
Reaction	*site*	*T (10^6 K)*	*kT (keV)*	*r_{tum} (fm)*	*r (fm)*
p+p	sun	15	1.3	1100	2.5
p+^{14}N	CNO	30	2.6	3900	4.3
α+^{12}C	red giant	190	16	1060	4.8
p+^{17}F	nova	300	26	500	4.5
α+^{30}S	x-ray burst	1000	86	500	5.9
^{3}He+^{4}He	big bang	2000	170	33	3.8

The Gamow window

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}} \qquad E_G \equiv \frac{2\mu}{\hbar^2}\left(\pi Z_1 Z_2 e^2\right)^2$$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty S e^{-\sqrt{E_G/E}} e^{-E/(kT)} dE$$

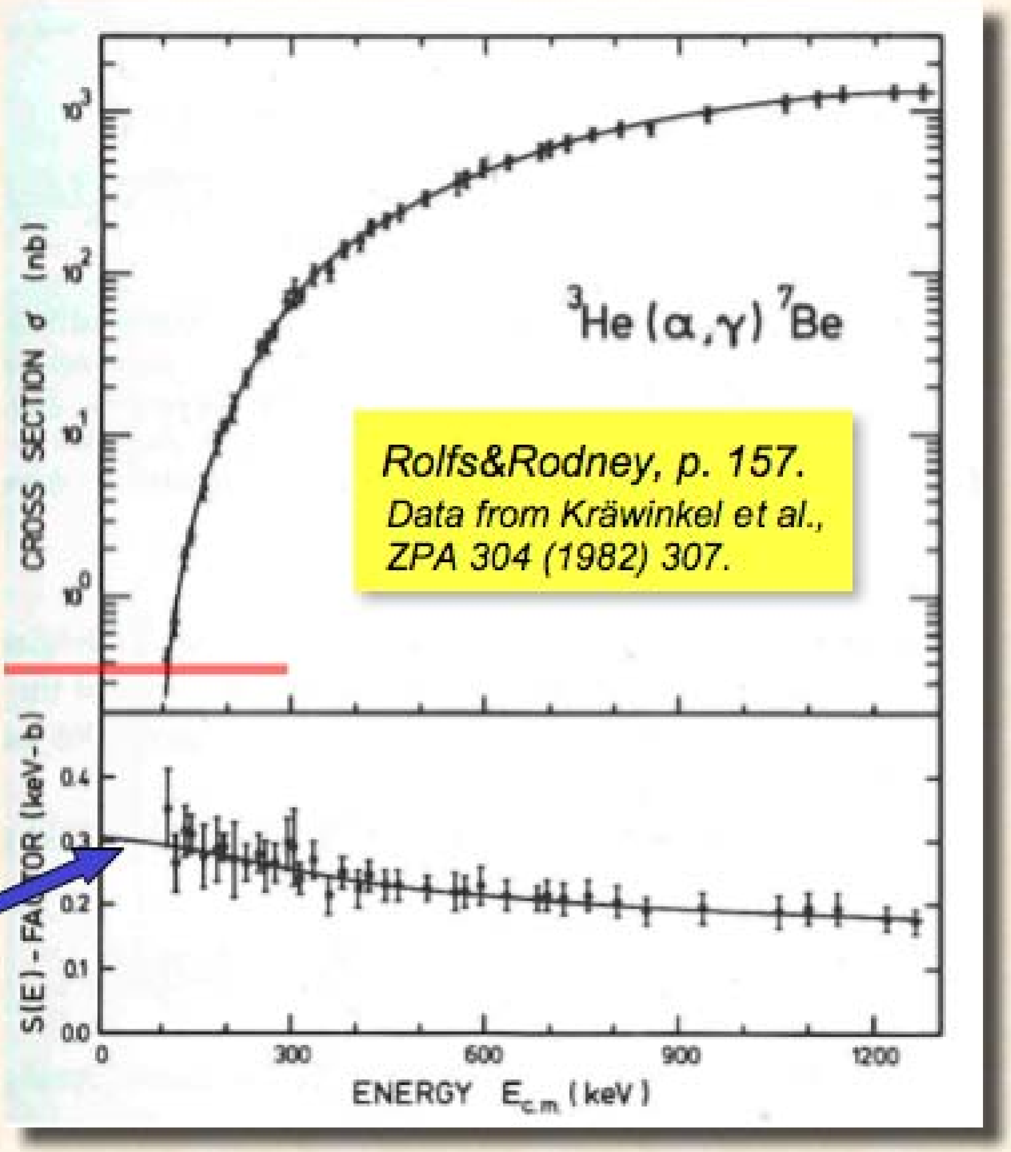


Reaction	site	T (10^6 K)	kT (keV)	r_{tum} (fm)	r (fm)	E_0 (keV)
p+p	sun	15	1.3	1100	2.5	6
p+^{14}N	CNO	30	2.6	3900	4.3	42
α+^{12}C	red giant	190	16	1060	4.8	300
p+^{17}F	nova	300	26	500	4.5	230
α+^{30}S	x-ray burst	1000	86	500	5.9	1800
^{3}He+^{4}He	big bang	2000	170	33	3.8	580

Why the S-factor is useful

Example: $^3He(\alpha,\gamma)^7Be$

Important for:
- The sun (ν production)
- Big Bang (Li production)



Rolfs&Rodney, p. 157.
Data from Kräwinkel et al., ZPA 304 (1982) 307.

Limit of experiments

Need σ here for sun

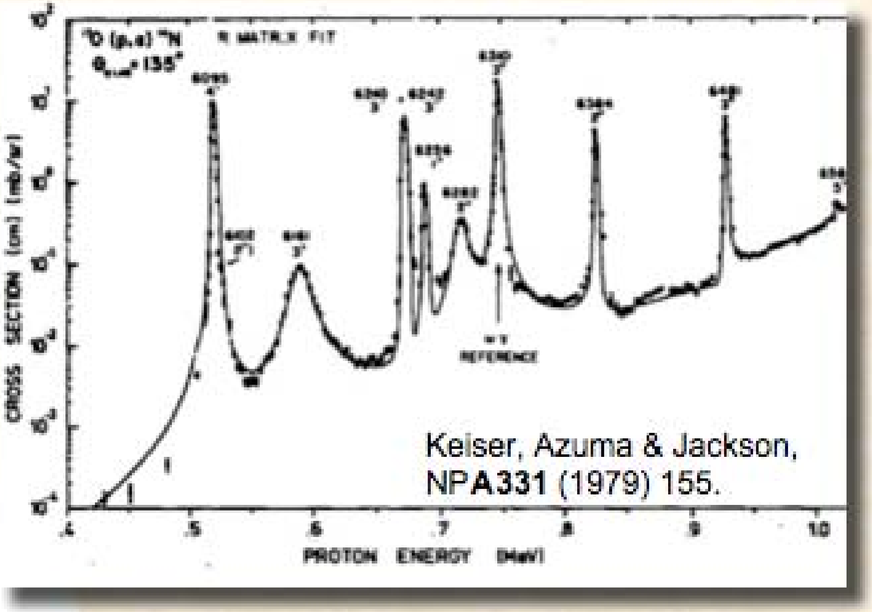
But be careful…

Identifying resonances is crucial

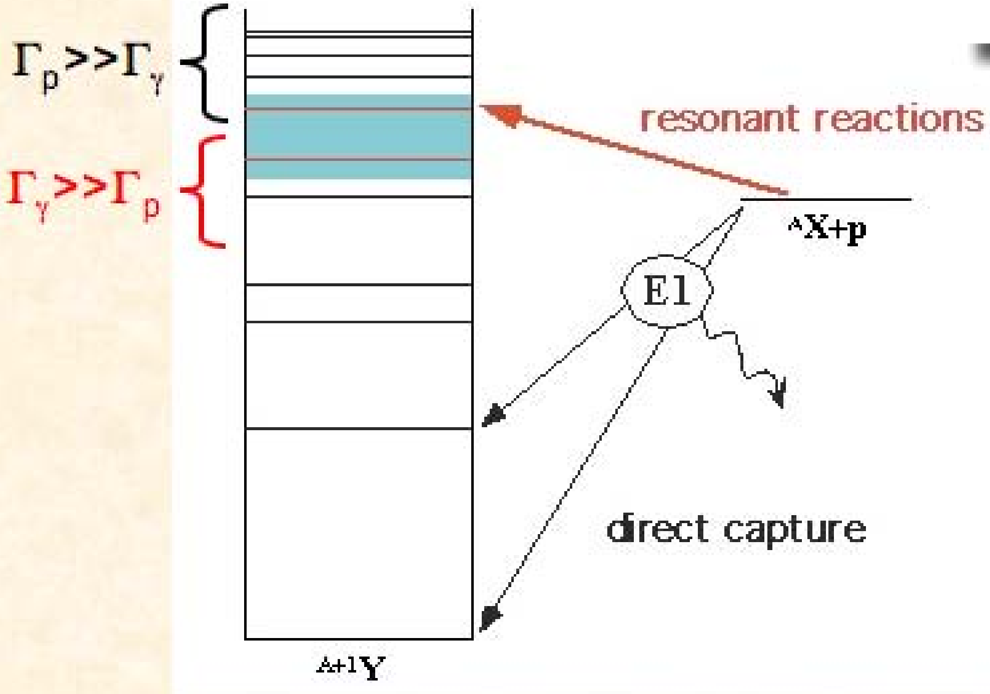
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)}dE$$

$$\sigma(E) = \pi\lambda\!\!\!^-{}^2 \frac{2J+1}{(2J_x+1)(2J_y+1)}\frac{\Gamma_x\Gamma_y}{(E-E_r)^2+(\Gamma/2)^2}$$

$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda\mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2+G_\ell^2}\right)$$ ➡ Lecture 3



Keiser, Azuma & Jackson, NP**A331** (1979) 155.



If resonance is narrow

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu}kT\right)^{3/2}\hbar^2(\omega\gamma)e^{-E_r/kT}$$

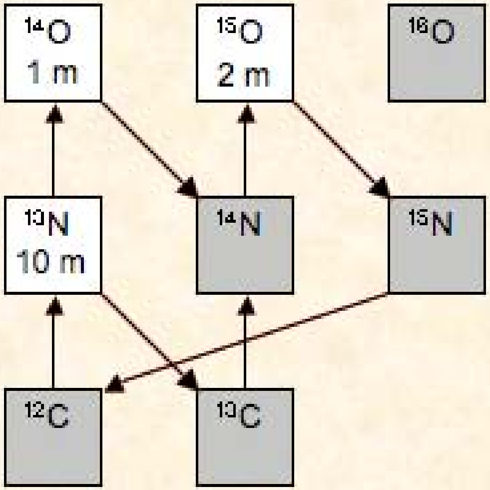
$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)}\frac{\Gamma_x\Gamma_y}{\Gamma}$$

“resonance strength”

Solving a reaction rate network

The CN cycle: hydrogen burning

Identify important reactions



Nuclear physics → reaction rates

Astrophysical model to define the equations of state: ρ, T

Network of many coupled equations

$$\frac{dN_{12C}}{dt} = N_{15N}N_p\langle\sigma v\rangle_{15Np} - N_{12C}N_p\langle\sigma v\rangle_{12Cp}$$

$$\frac{dN_{13N}}{dt} = N_{12C}N_p\langle\sigma v\rangle_{12Cp} - N_{13N}N_p\langle\sigma v\rangle_{13Np} - \lambda_{13N}N_{13N}$$

$$\frac{dN_{13C}}{dt} = \lambda_{13N}N_{13N} - N_{13C}N_p\langle\sigma v\rangle_{13Cp}$$

$$\frac{dN_{14O}}{dt} = N_{13N}N_p\langle\sigma v\rangle_{13Np} - \lambda_{14O}N_{14O}$$

$$\frac{dN_{14N}}{dt} = N_{13C}N_p\langle\sigma v\rangle_{13Cp} + \lambda_{14O}N_{14O} - N_{14N}N_p\langle\sigma v\rangle_{14Np}$$

$$\frac{dN_{15O}}{dt} = N_{14N}N_p\langle\sigma v\rangle_{14Np} - \lambda_{15O}N_{15O}$$

$$\frac{dN_{15N}}{dt} = \lambda_{15O}N_{15O} - N_{15N}N_p\langle\sigma v\rangle_{15Np}$$

➡ Numerically solve for $N_x(t)$

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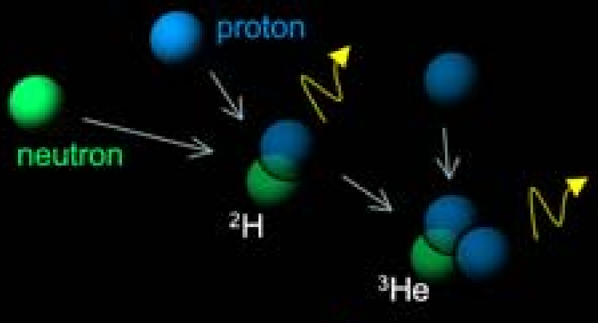
The Early Universe

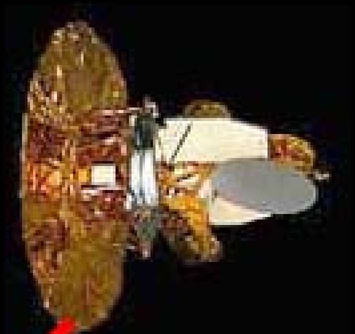
Space, time, matter, & energy began with the Big Bang

Independent observations tell us about different epochs

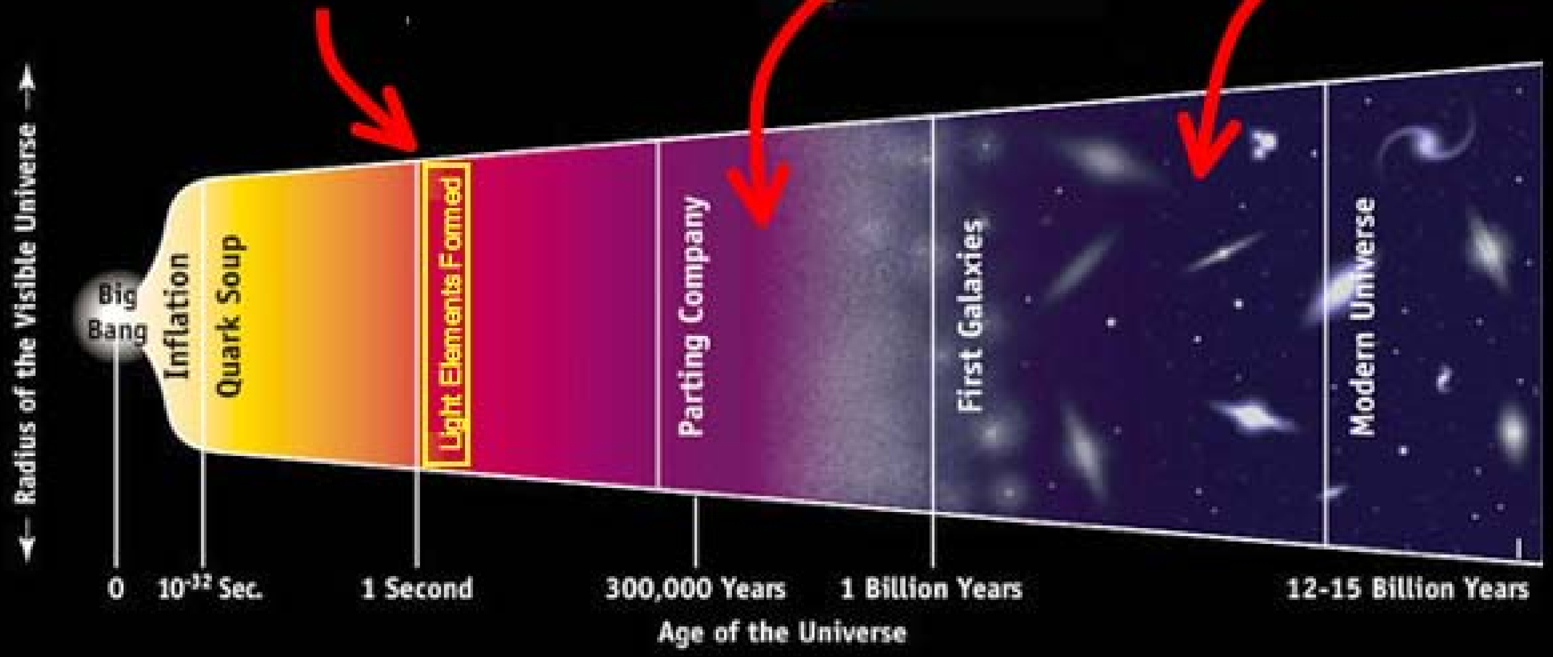
Nucleosynthesis



CMB -The afterglow



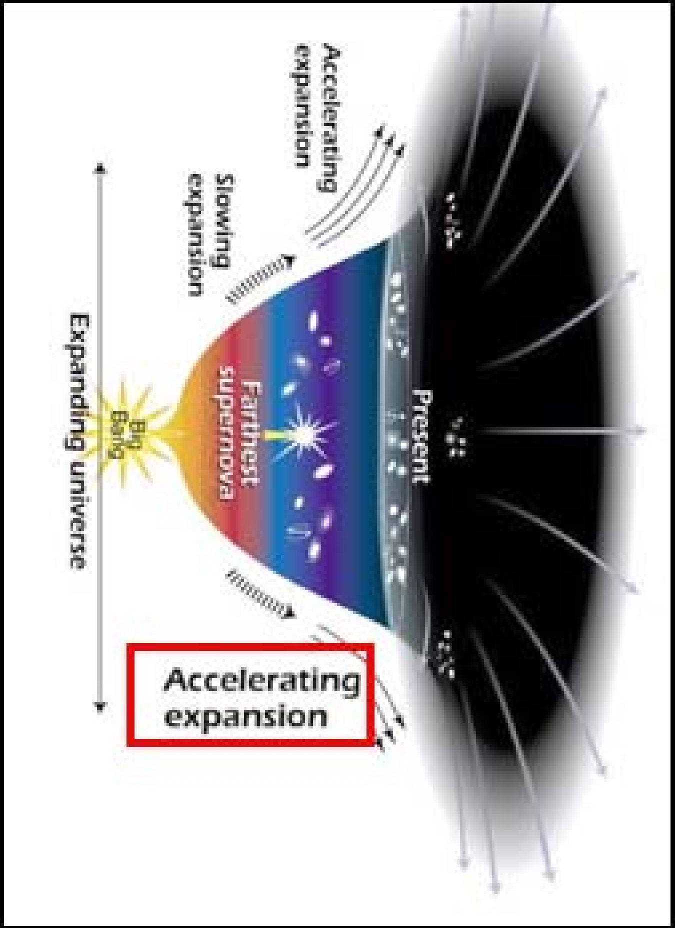
Stellar observations



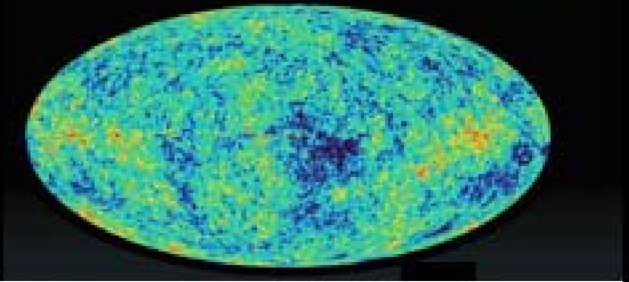
New Cosmological Paradigm

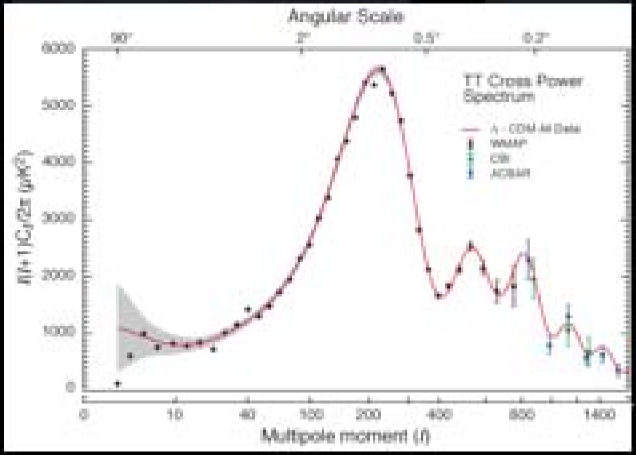
(Lecture 3)

Type 1a supernova redshift vs. distance indicates the expansion rate of the universe is accelerating

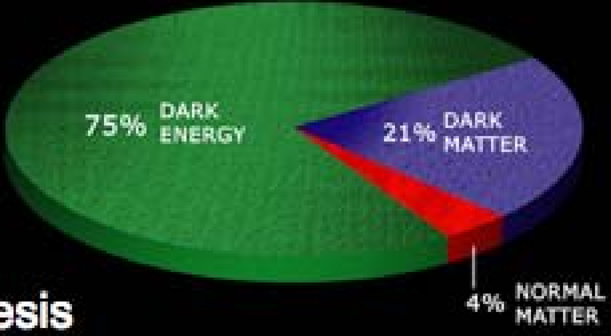


WMAP: CMB Observations



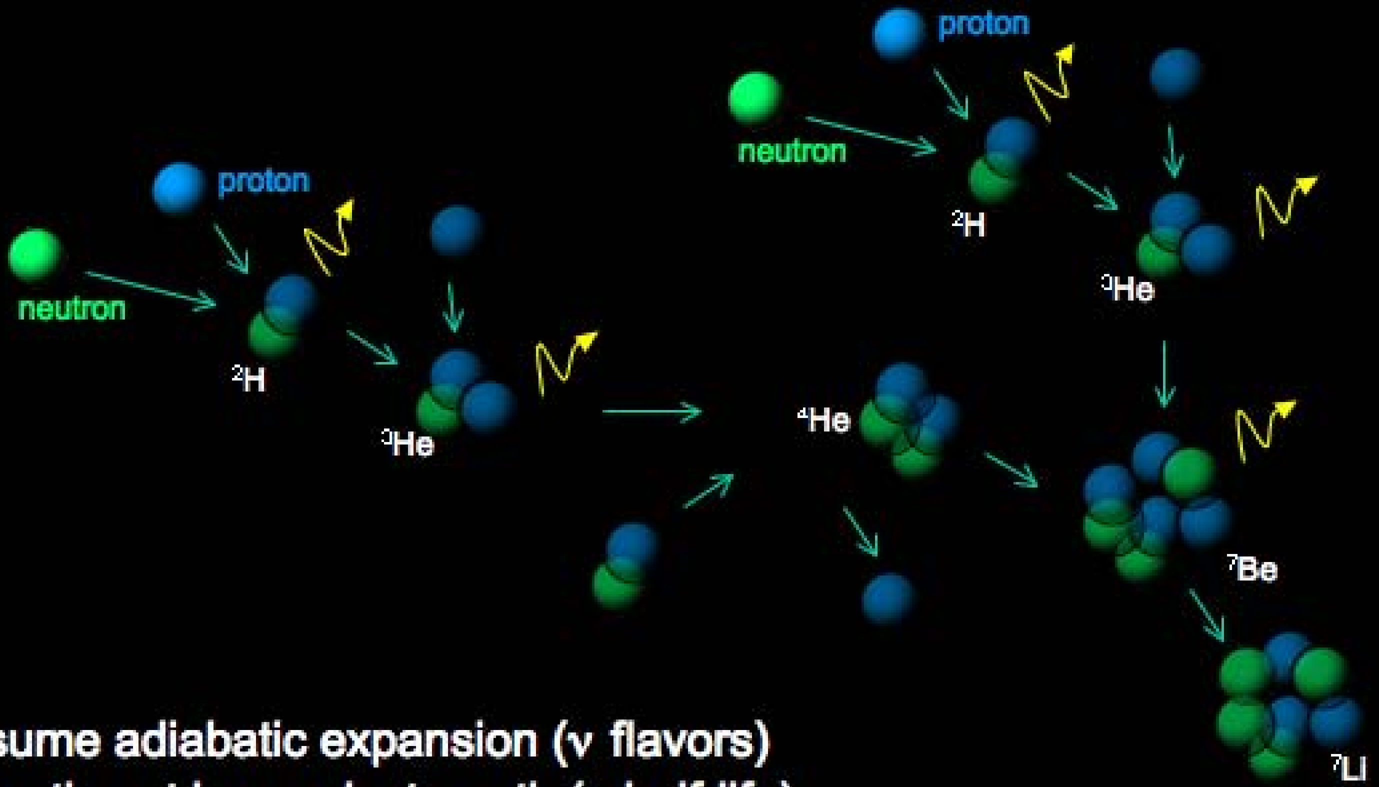


DARK ENERGY (e.g. cosmological constant) exerts a "negative pressure" causing the acceleration



Only 4% of matter is baryonic → test with nucleosynthesis

The Homogeneous BBN Model



Assume adiabatic expansion (ν flavors)
n/p ratio set by weak strength (n half-life)
Only free parameter is baryon/photon ratio

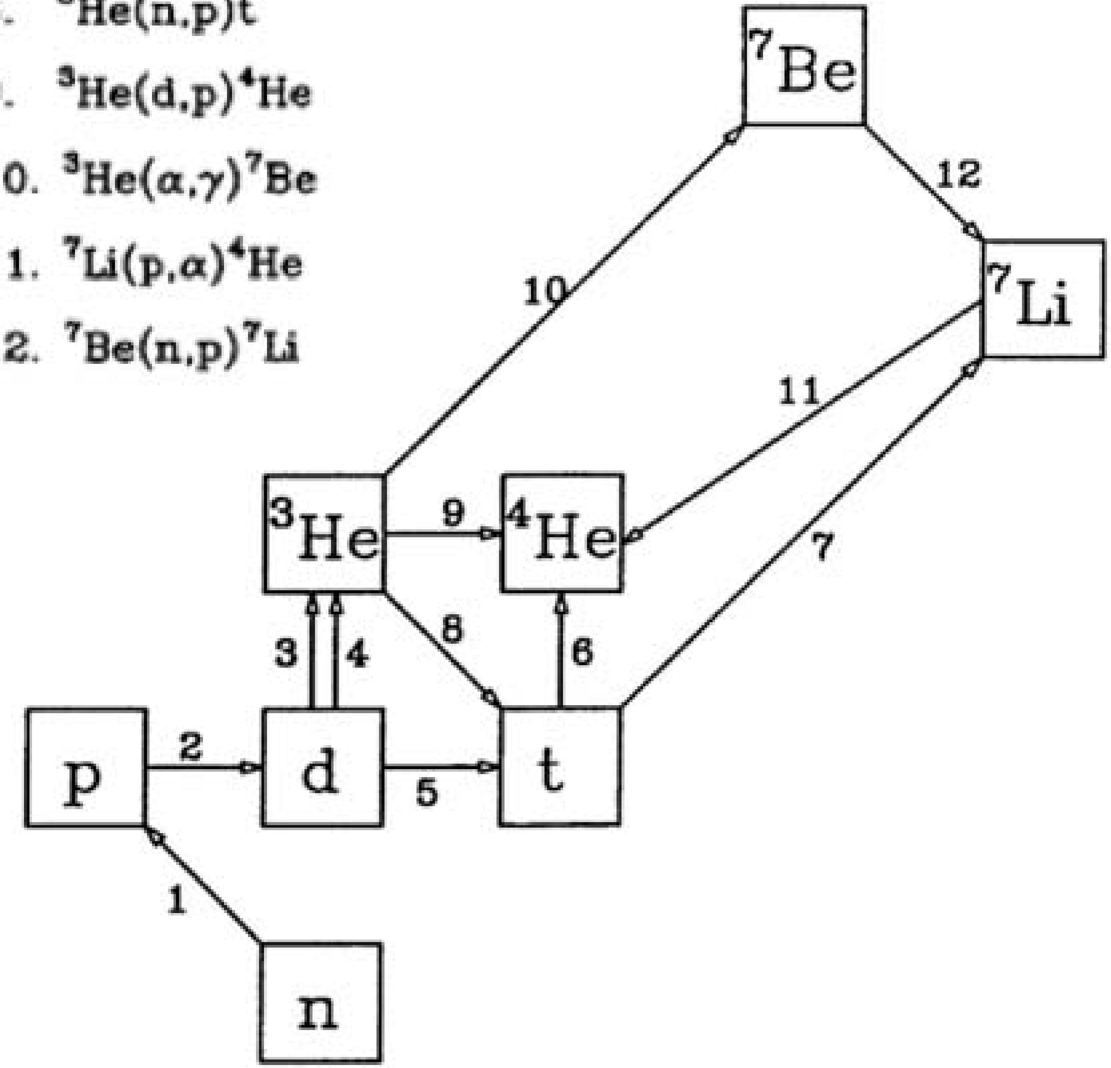
~All free neutrons into ^{4}He
Mass 5 & 8 gaps inhibit formation of heavy elements

⇒

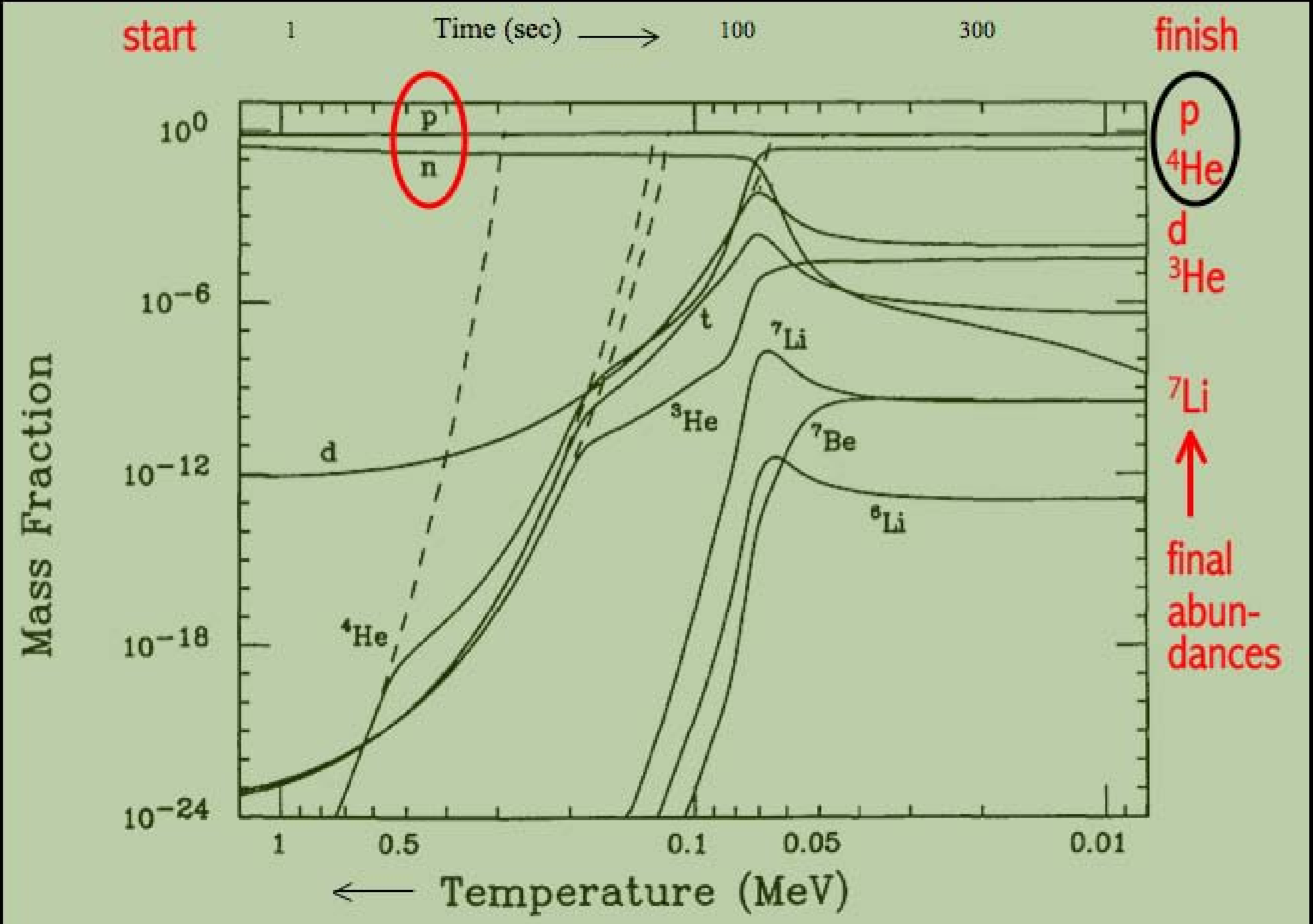
p ~75%
^{4}He ~25%
^{2}H, ^{3}He ~ 10^{-5}
^{7}Li ~ 10^{-10}

A Typical Big Bang Network

1. n <-> p
2. p(n,γ)d
3. d(p,γ)^{3}He
4. d(d,n)^{3}He
5. d(d,p)t
6. t(d,n)^{4}He
7. t(α,γ)^{7}Li
8. ^{3}He(n,p)t
9. ^{3}He(d,p)^{4}He
10. ^{3}He(α,γ)^{7}Be
11. ^{7}Li(p,α)^{4}He
12. ^{7}Be(n,p)^{7}Li



Solve the reaction rate network

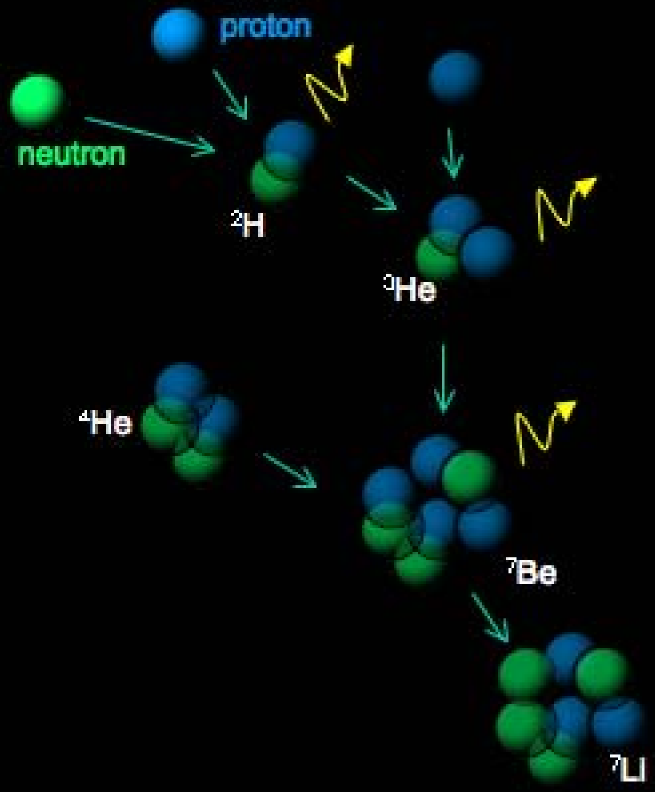


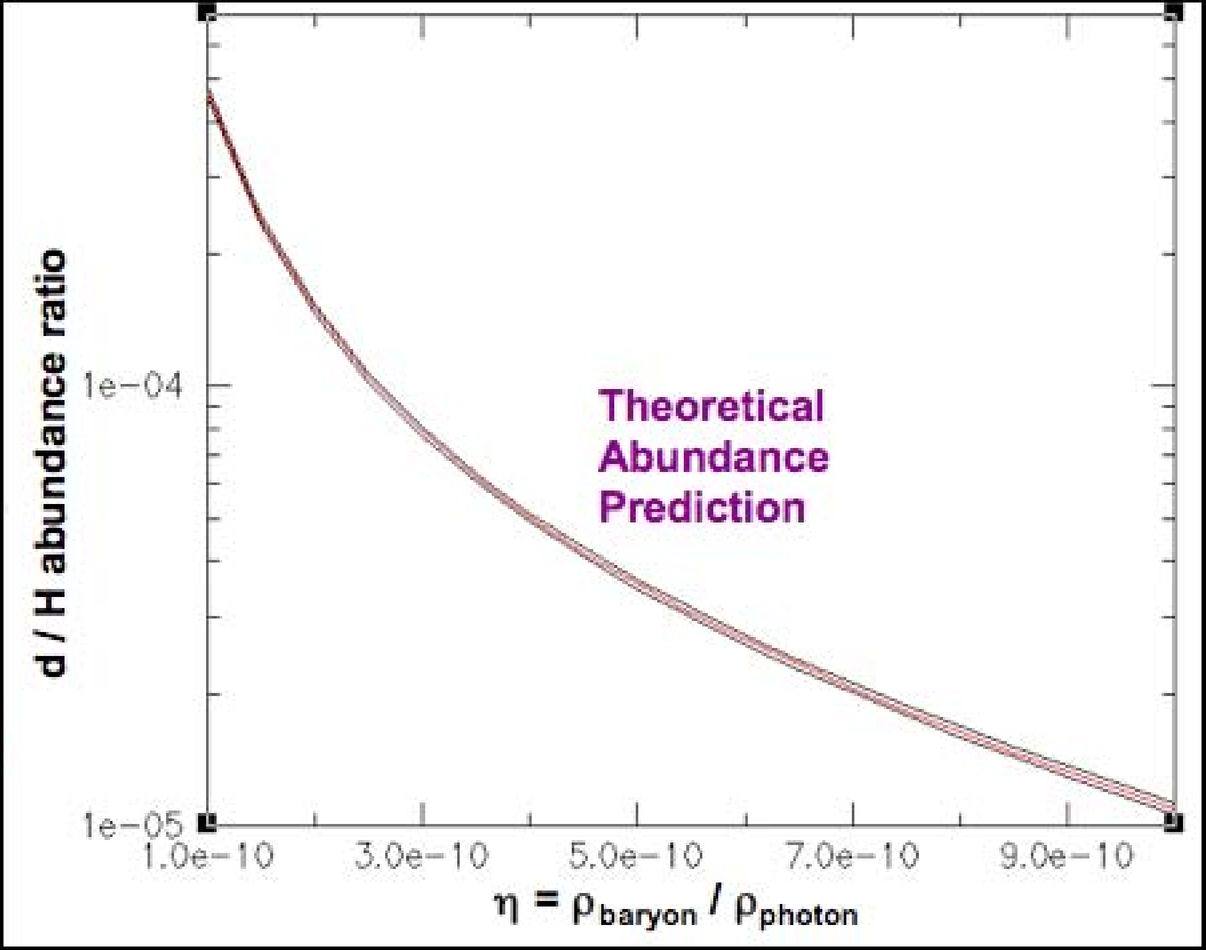
start

finish

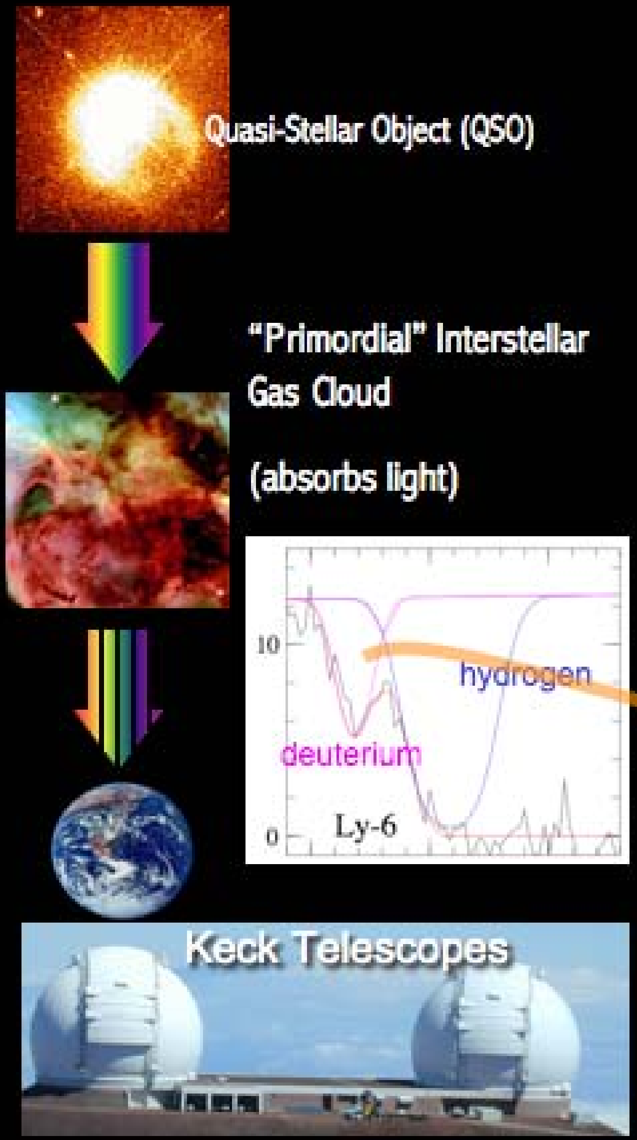
p
⁴He
d
³He
⁷Li

final abundances





Abundance Observations can be used to constrain the “normal” matter density - *the free parameter in the theory* - independent of WMAP

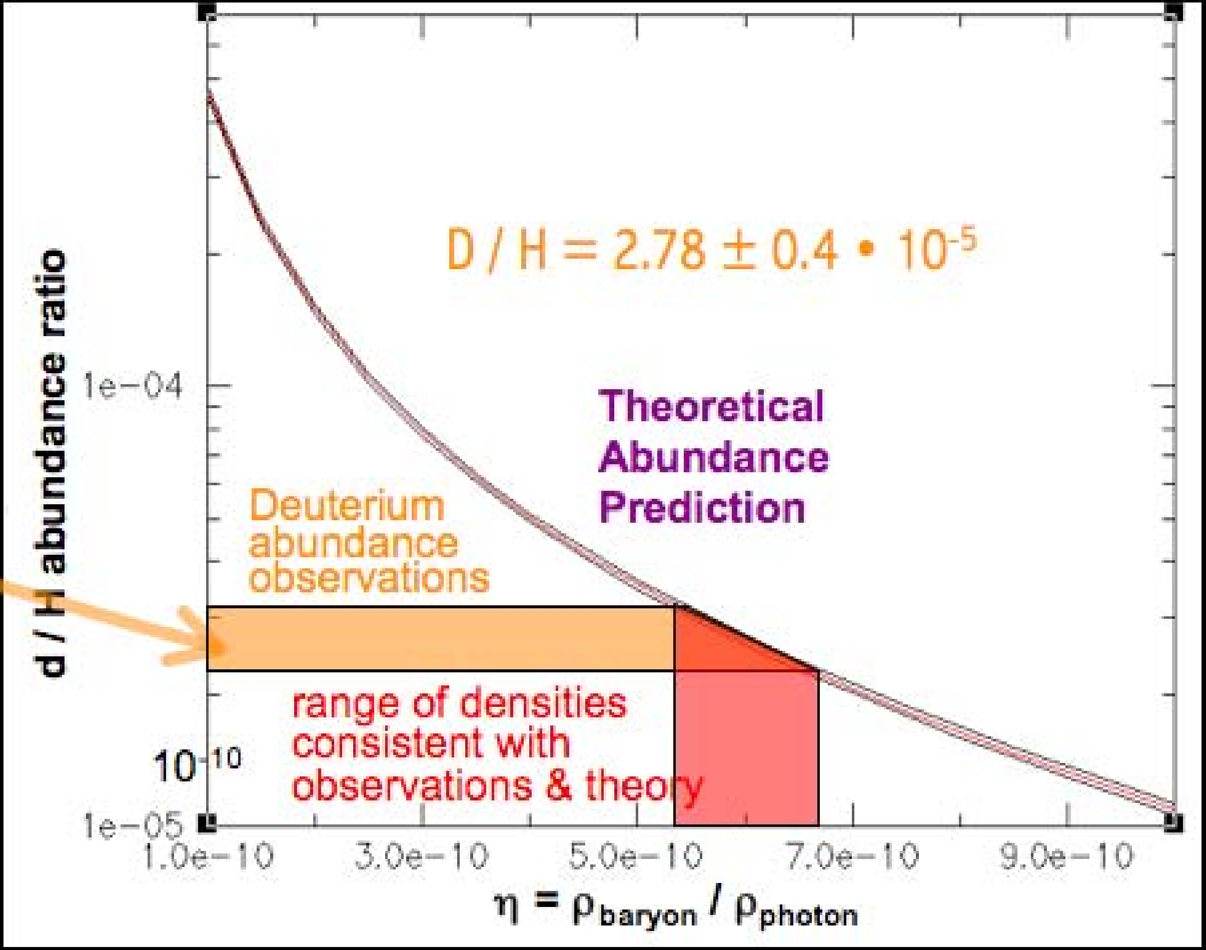


Quasi-Stellar Object (QSO)

"Primordial" Interstellar Gas Cloud

(absorbs light)

Keck Telescopes



$D / H = 2.78 \pm 0.4 \cdot 10^{-5}$

Theoretical Abundance Prediction

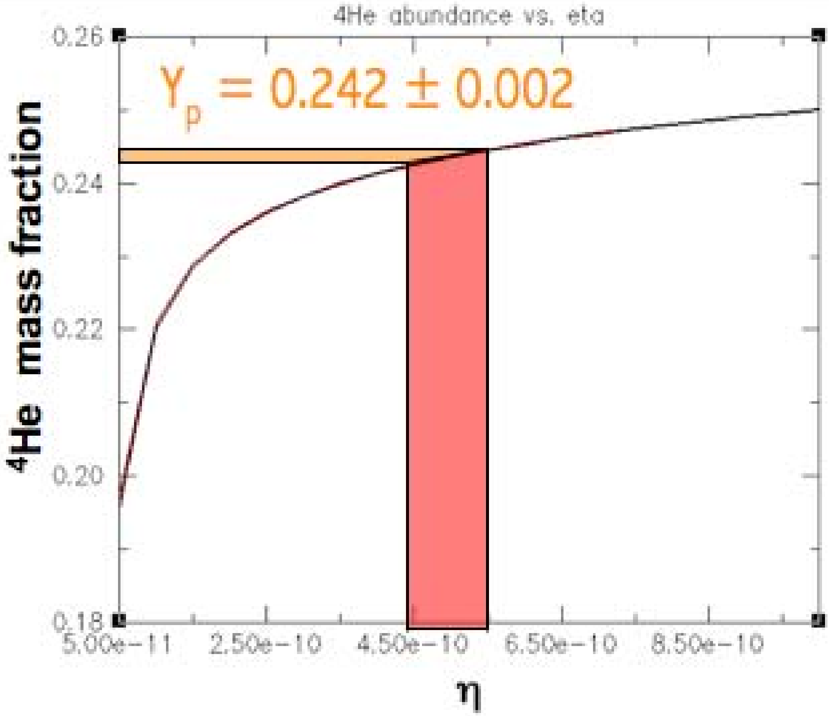
Deuterium abundance observations

range of densities consistent with observations & theory

10^{-10}

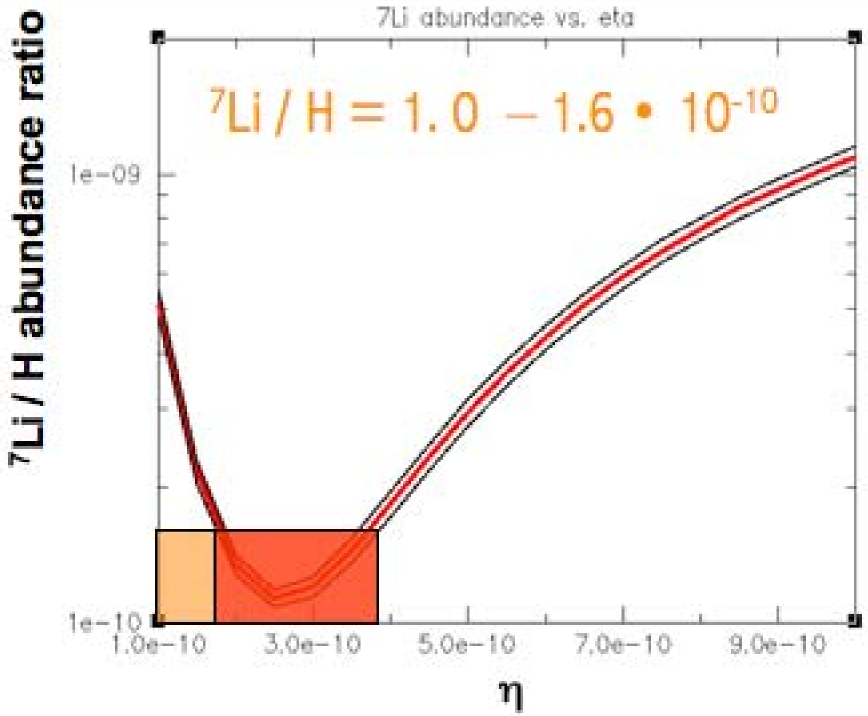
Abundance Observations can be used to constrain the "normal" matter density - *the free parameter in the theory* - independent of WMAP

^{4}He: relatively weak constraint but good observations?



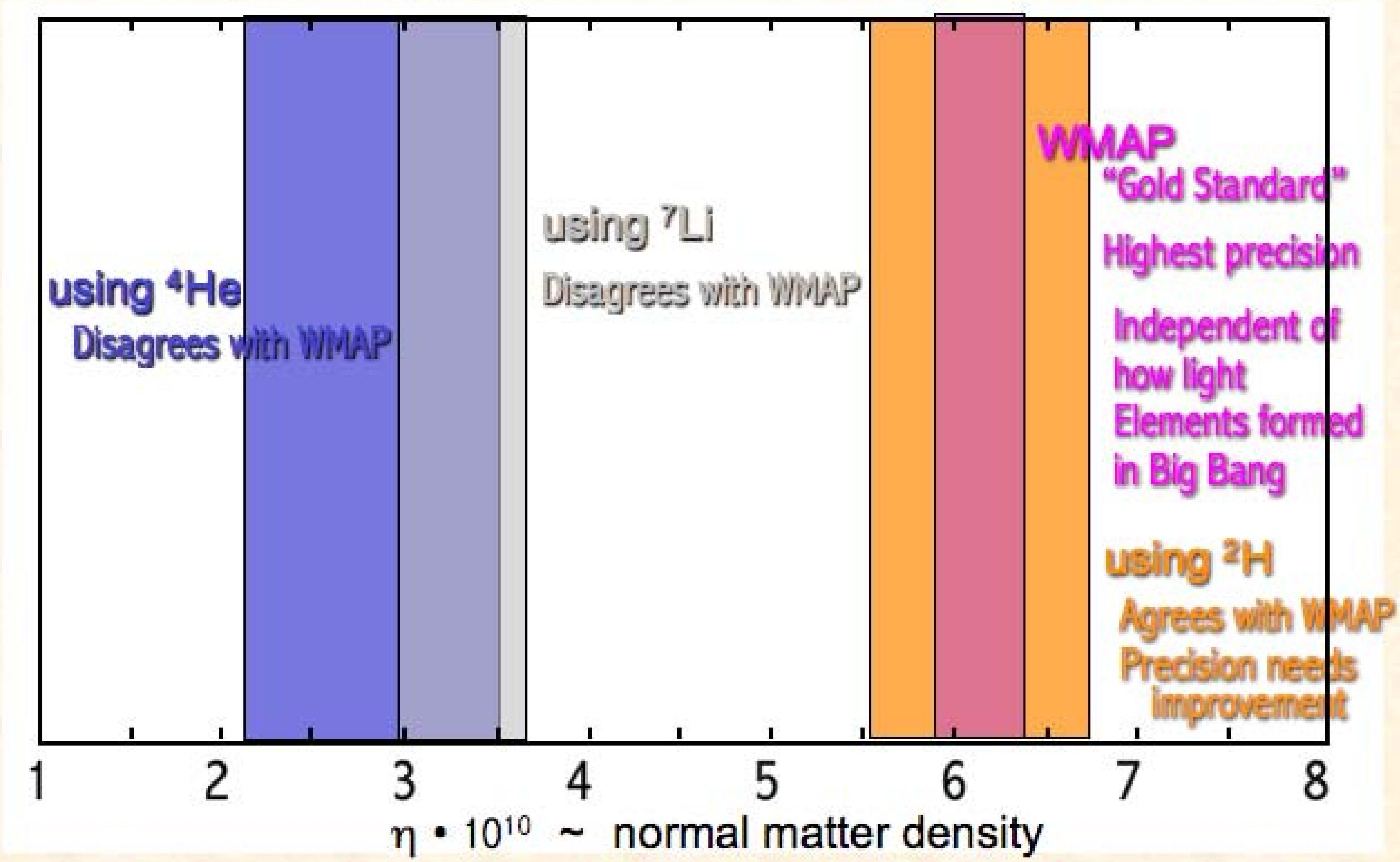
$Y_p = 0.242 \pm 0.002$

7Li: good constraint on baryonic matter density



$^7\text{Li} / \text{H} = 1.0 - 1.6 \cdot 10^{-10}$

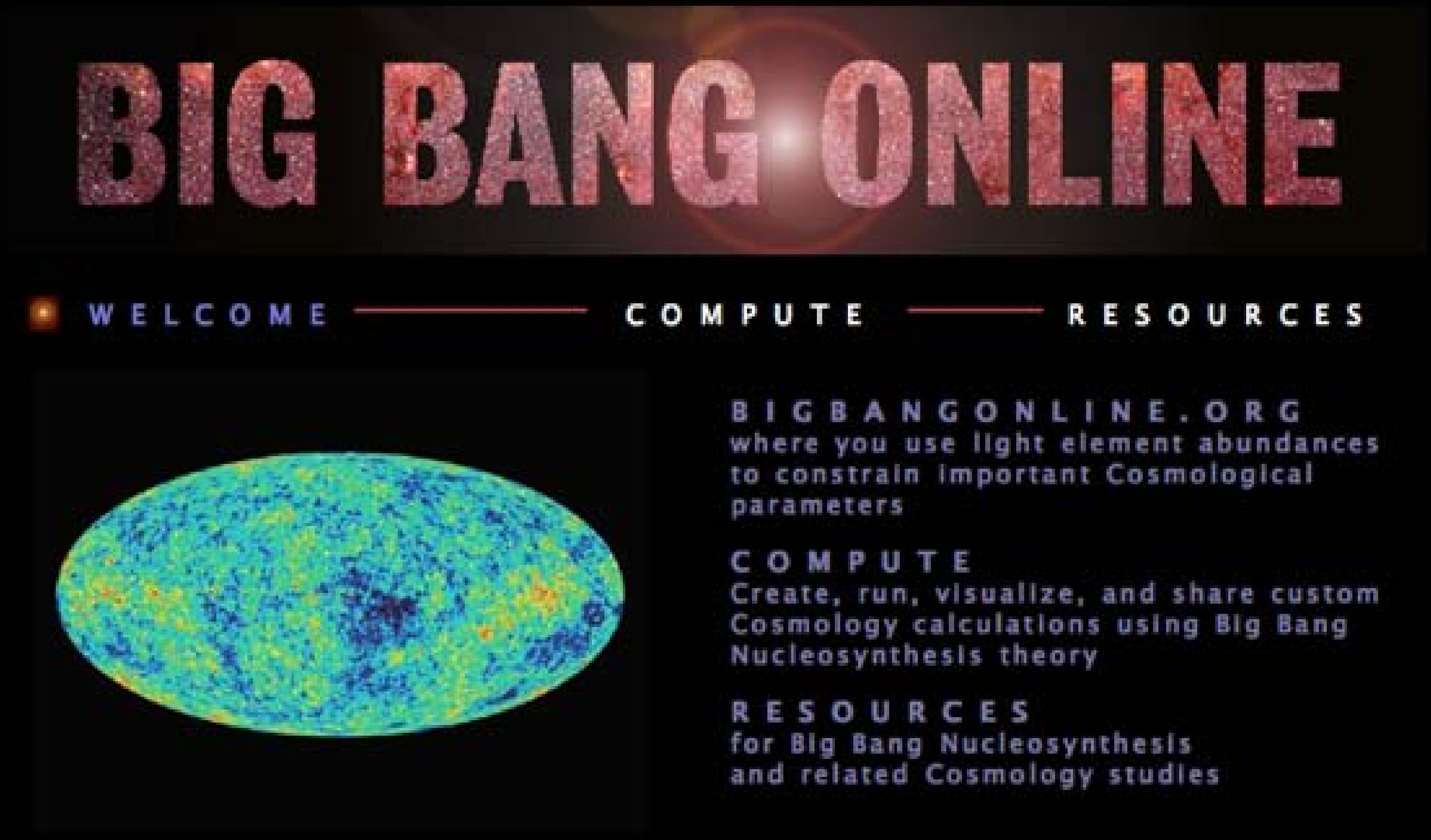
Comparing Matter Density Constraints



Is our understanding of dark energy / dark matter is wrong?

Are our observations / interpretations wrong?

Are there problems with our nuclear reaction network?



BIG BANG ONLINE

BIGBANGONLINE.ORG
where you use light element abundances to constrain important Cosmological parameters

COMPUTE
Create, run, visualize, and share custom Cosmology calculations using Big Bang Nucleosynthesis theory

RESOURCES
for Big Bang Nucleosynthesis and related Cosmology studies

New online suite of cosmology codes under development at **bigbangonline.org**

Enables users to **run** and **visualize** BBN calculations with
- choice of reaction rates
- choice of primordial abundance observations
- choice of standard BBN or some non-standard variants

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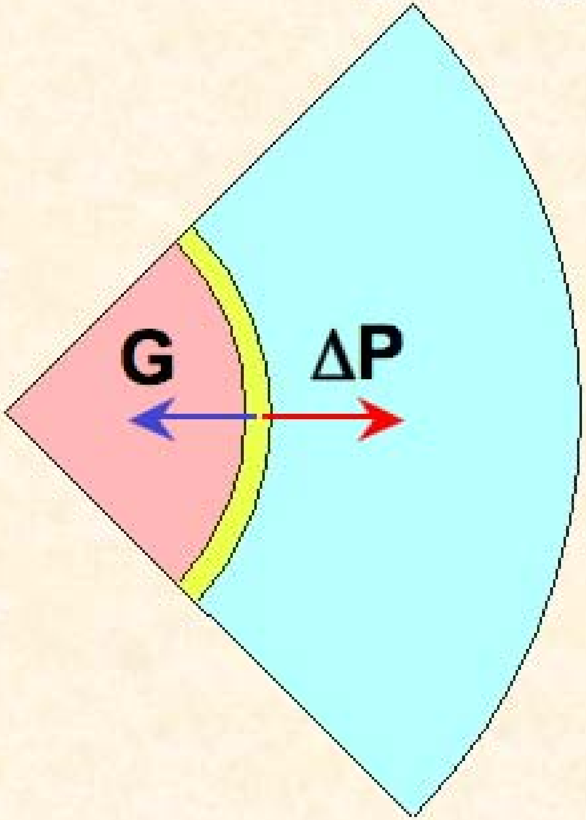
Hydrogen burning in stars



Hydrostatic equilibrium

$$\frac{dP(r)}{dr} = -\frac{GM_{in}(r)\rho(r)}{r^2}$$

Energy conservation

$$\frac{dL(r)}{dr} = \frac{\varepsilon(r)\rho(r)}{4\pi r^2}$$

Pressure

$$P(r) = P_{gas}(r) + P_{rad}(r)$$

For sun (non-degenerate)

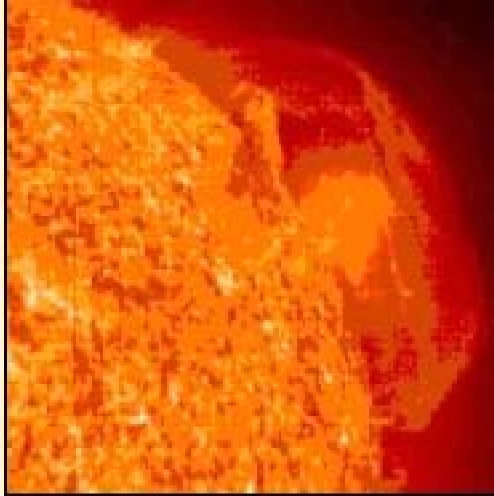
$$P_{gas}(r) = \frac{k}{\langle m \rangle}\rho(r)T(r)$$

$$P_{rad}(r) = \frac{1}{3}aT^4(r) << P_{gas}(r)$$

Large T,P gradient

Opacity: photons absorbed and emitted at shorter λ

Luminosity/opacity/T relationship ➡ $L \propto M^4$



The sun

$M = 2 \times 10^{30}$ kg

$\rho(0) = 150$ g/cm^3

$T(0) = 1.5 \times 10^7$ K

T(surf)=5800 K

$L = 3.8 \times 10^{26}$ W

5×10^4 yr for energy produced in sun's core to be radiated at surface

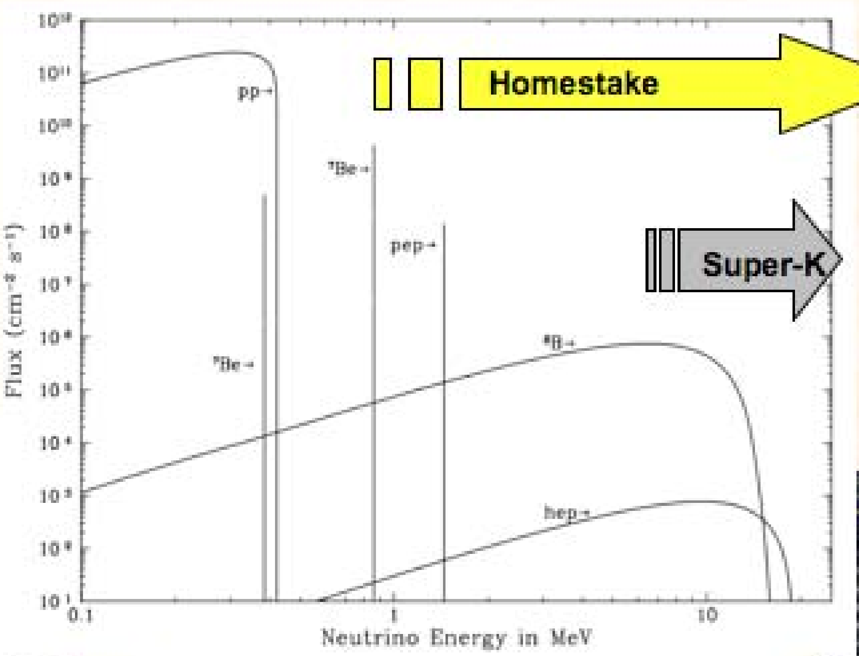
Solar power: The pp-chains

Thanks to substantial efforts in experiment, theory & evaluation

pp-1:	5%	$^1H(p,e^+\nu)^2H$	
	5%	$^2H(p,\gamma)^3He$	
	7%	$^3He(^3He,2p)^4He$	84.7%
pp-2:	7%	$^3He(\alpha,\gamma)^7Be$	13.8%
		$^7Be(e^-,\nu)^7Li$	13.78%
	13%	$^7Li(p,\alpha)^4He$	
pp-3:	5-10%	$^7Be(p,\gamma)^8B$	0.02%
		$^8B(\beta^+\nu)2^4He$	

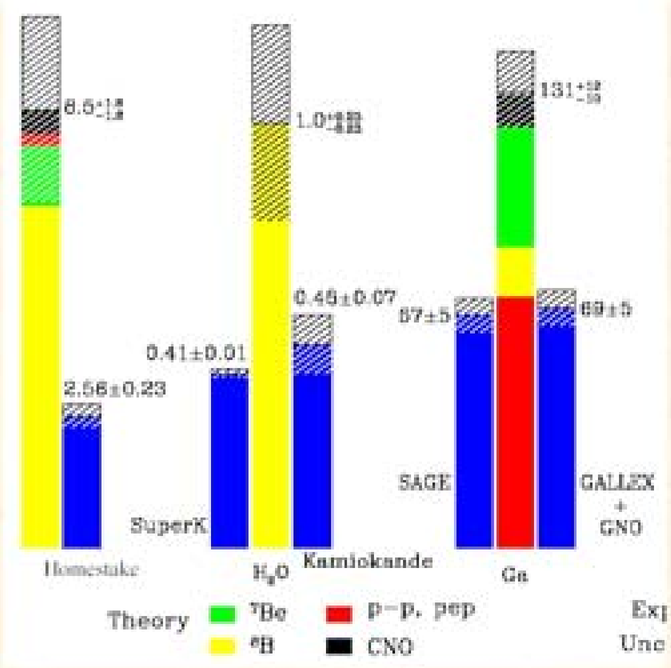
fusion of $4\ ^1H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

$6 \times 10^9\ \nu_e/cm^2/s$
only direct probe
of solar core

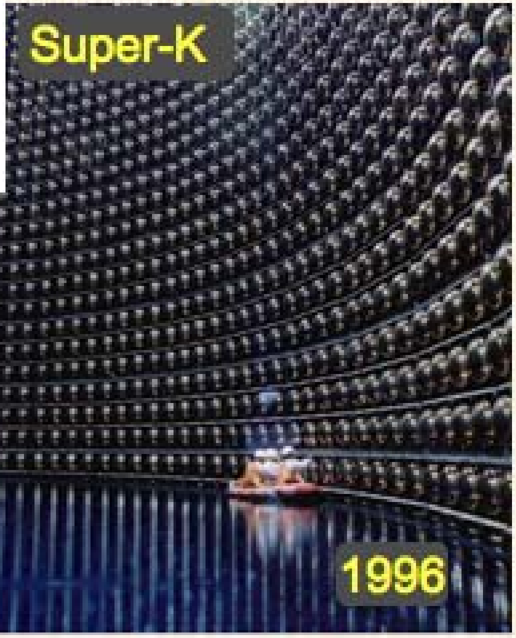


2002 Nobel Prize
Davis & Koshiba

Radiochemical



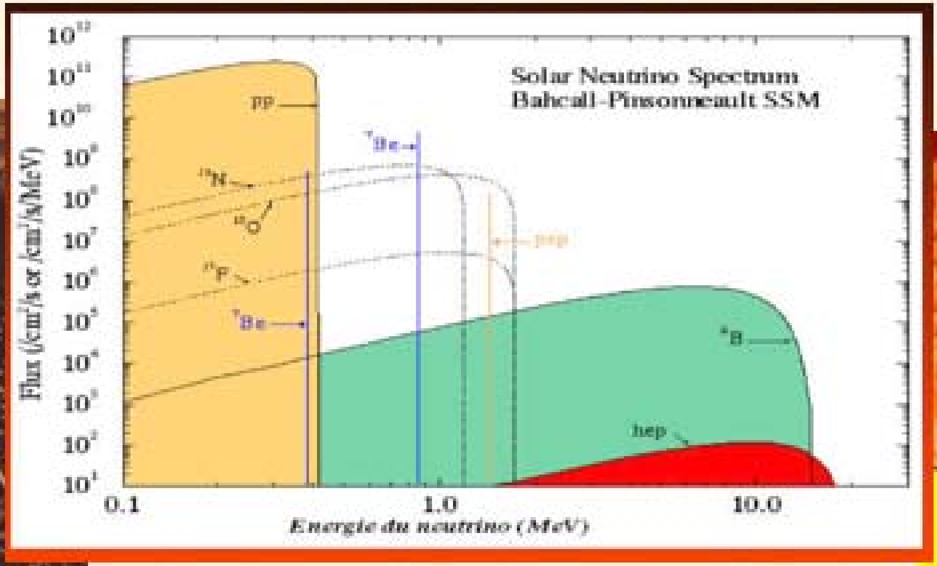
Real-time counting

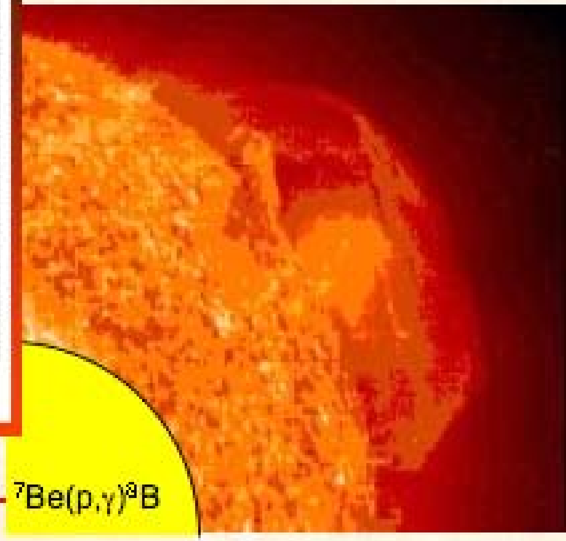


Homestake Gold Mine
600kt perchloroethylene
100 events/yr
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e$
~30% expectations

Mozumi Mine
50,000 kt water
5,000 events/yr
$\nu_e + e^-$ scattering
~40% expectations

SNO & SuperK measure only neutrinos from the decay of ^{8}B





Creighton Nickel Mine
1 kt heavy water
$\nu_x + d \rightarrow p + n$

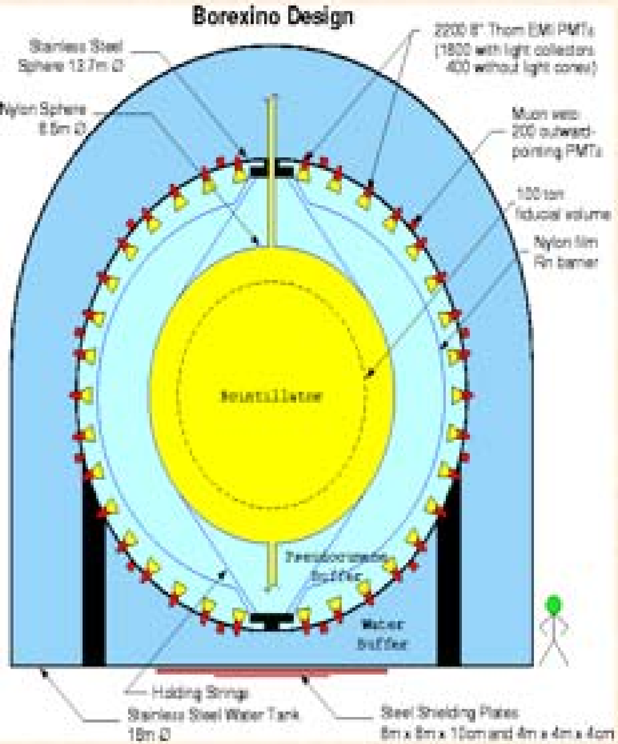
A accurate value for the predicted ^{8}B neutrino flux is need for comparison to the current generation of measurements

SuperK→ $\Phi_{CC} = (2.39 \pm 0.03_{stat} \pm 0.06_{sys}) \times 10^6\ /(cm^2 s)$

SNO→ $\Phi_{NC} = (5.21 \pm 0.27_{stat} \pm 0.38_{sys}) \times 10^6\ /(cm^2 s)$

$\Phi_{SSM} = 5.7 \times 10^6\ /(cm^2 s)$ ± ~15% metallicity
reaction rates

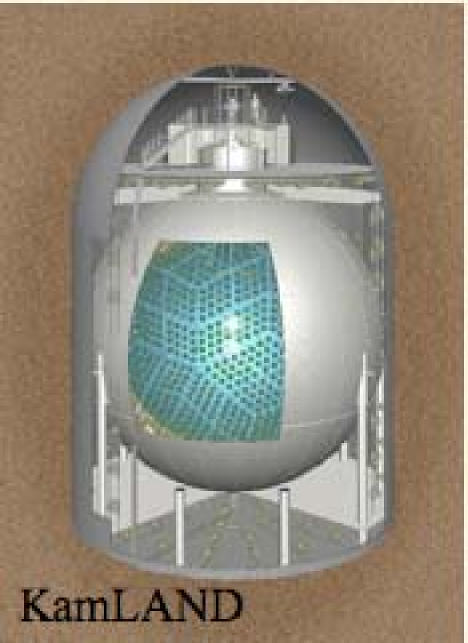
Flavor oscillation



- Neutrino mass eigenstates not the same as flavor eigenstates

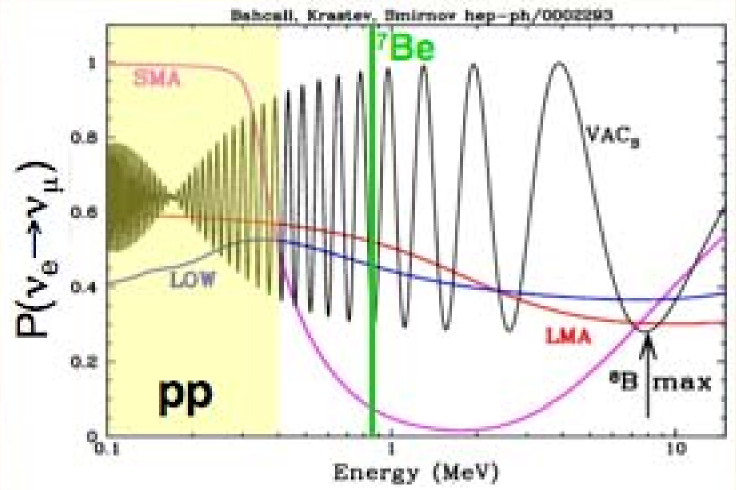
In vacuum $$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

- Strong evidence from observations of atmospheric neutrinos ($\nu_\mu \rightarrow \nu_\tau$)
- Observed in reactor experiments: KamLAND & Chooz
- Oscillations of solar (^{8}B) neutrinos are enhanced by interactions with the high density of electrons in the solar core <u>MSW</u>: Mikheyev & Smirnow, SJNP **42** (85).
  Wolfenstein, PRD **17** (78).

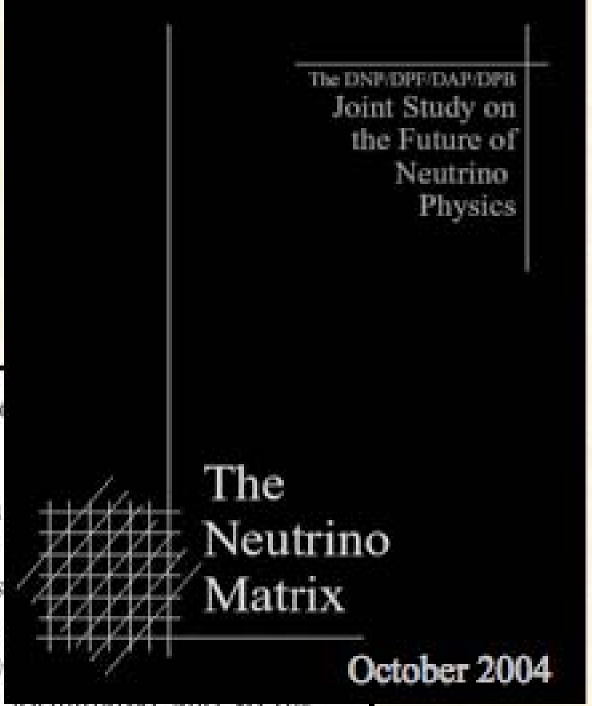


^{7}Be = Focus of current experiments
  KamLAND
  Borexino

pp = Next-generation
  CLEAN
  LENS

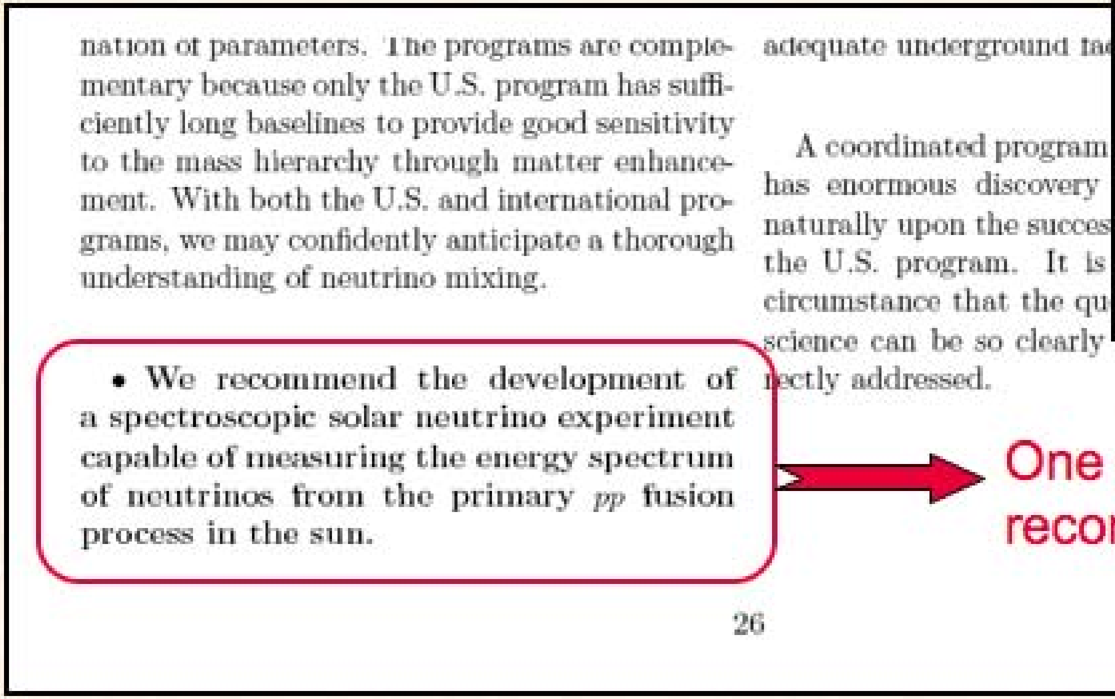


"There are rare moments in science when a clear road to discovery lies ahead and there is broad consensus about the steps to take along that path. This is one such moment."


The DNP/DPF/DAP/DPB
Joint Study on
the Future of
Neutrino
Physics

The
Neutrino
Matrix

October 2004


nation of parameters. The programs are complementary because only the U.S. program has sufficiently long baselines to provide good sensitivity to the mass hierarchy through matter enhancement. With both the U.S. and international programs, we may confidently anticipate a thorough understanding of neutrino mixing.

• We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary *pp* fusion process in the sun.

adequate underground fa

A coordinated program
has enormous discovery
naturally upon the succes
the U.S. program. It is
circumstance that the qu
science can be so clearly
rectly addressed.

26

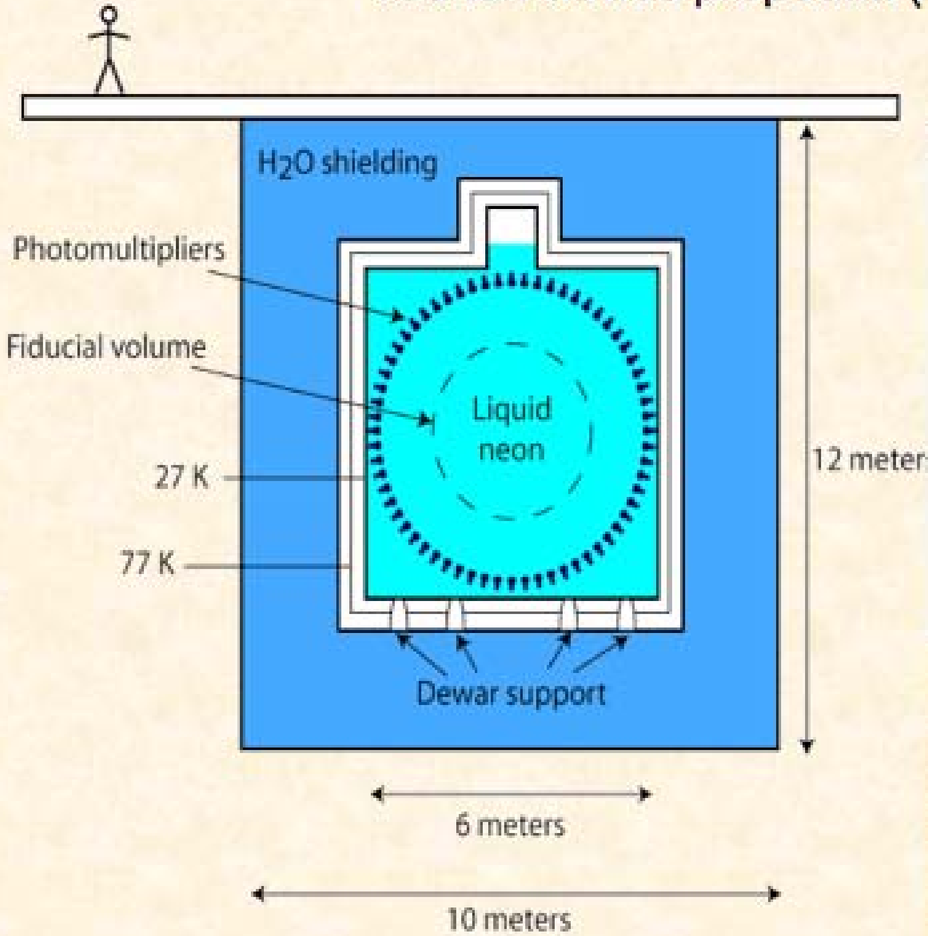
One of the 3 major recommendations

- The pp neutrino flux is accurately predicted by the solar luminosity.
- pp neutrinos oscillate (primarily) by vacuum oscillations not MSW oscillations.
- Would provide a clear test of solar physics, hydrostatic equilibrium, etc.
- Is the sun's energy output now the same as 50,000 years ago?

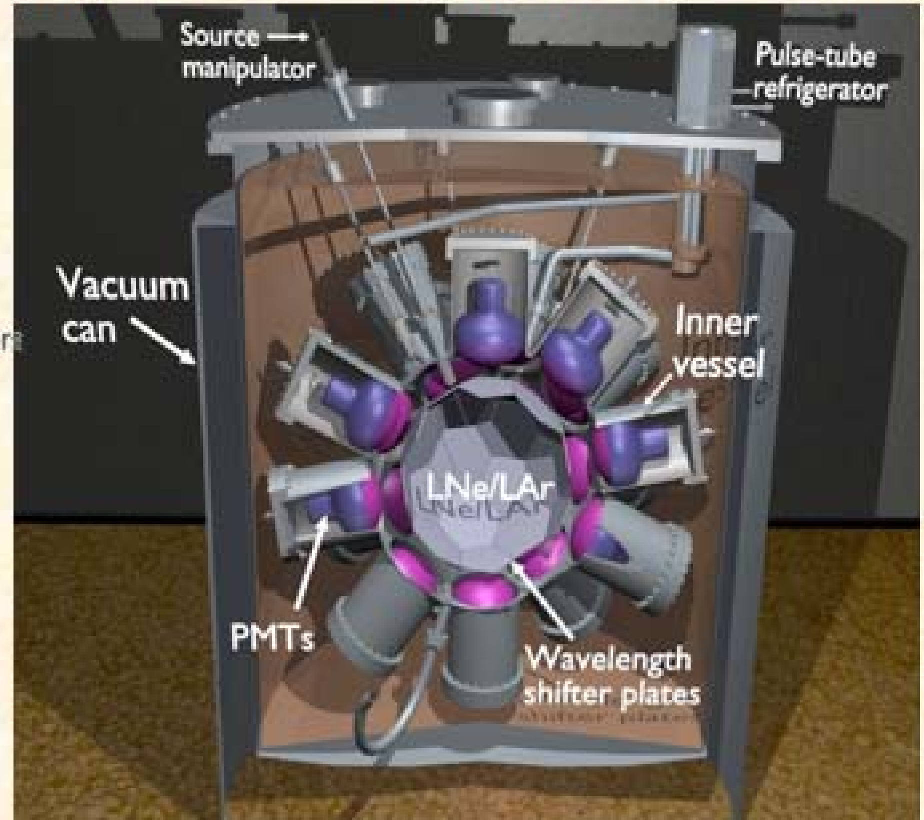
Measuring the pp flux: CLEAN

McKinsey & Coakley, Astroparticle Physics 22 (2005) 355.

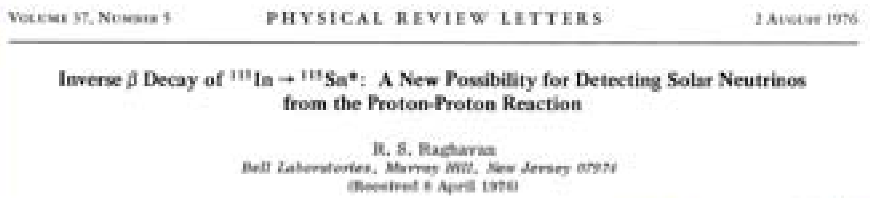
Very high purity liquid Ne or Ar
Thin film of shifting flour in front of PMTs
Good recoil/electron discrimination
Very low threshold (few 10's keV)
130 ton device proposed (either SNO-Lab or DUSEL)



MiniCLEAN now operating 65 liters



LENS: ν_e from pp fusion



VOLUME 37, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1976

Inverse β Decay of $^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}^*$: A New Possibility for Detecting Solar Neutrinos from the Proton-Proton Reaction

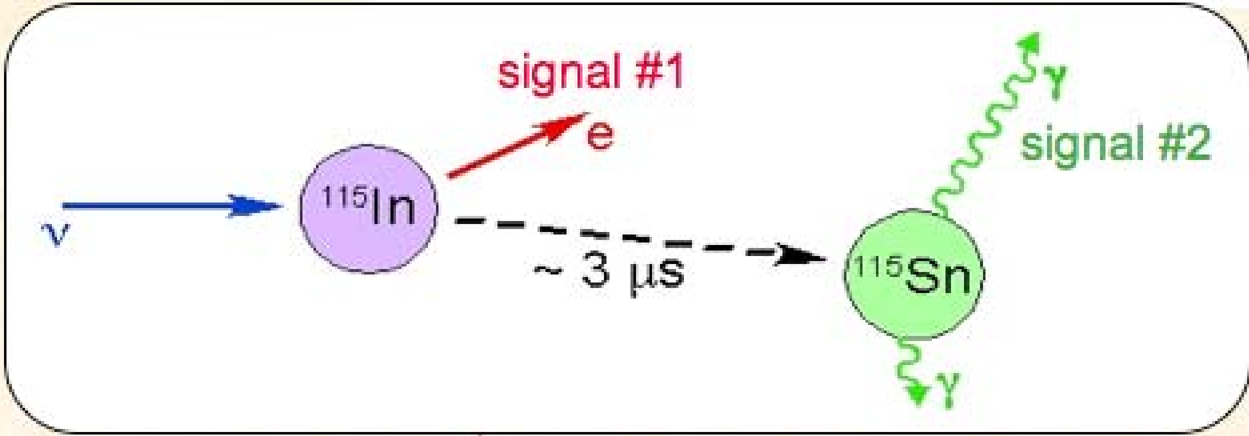
R. S. Raghavan
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 8 April 1976)

#1 prompt electron
→ ν_e energy *(β-like)*

Buffer up to 10μs

Shower
Time/space correlation

➡ **discrimination**

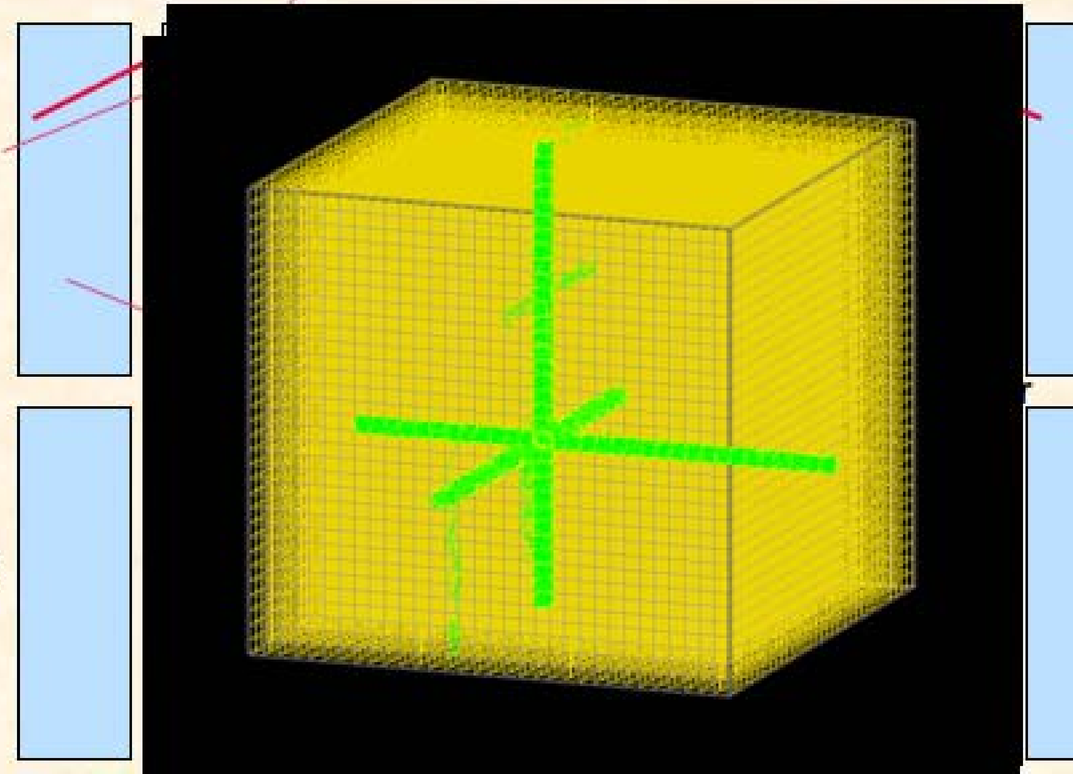


Now: 8% In-loaded scintillator

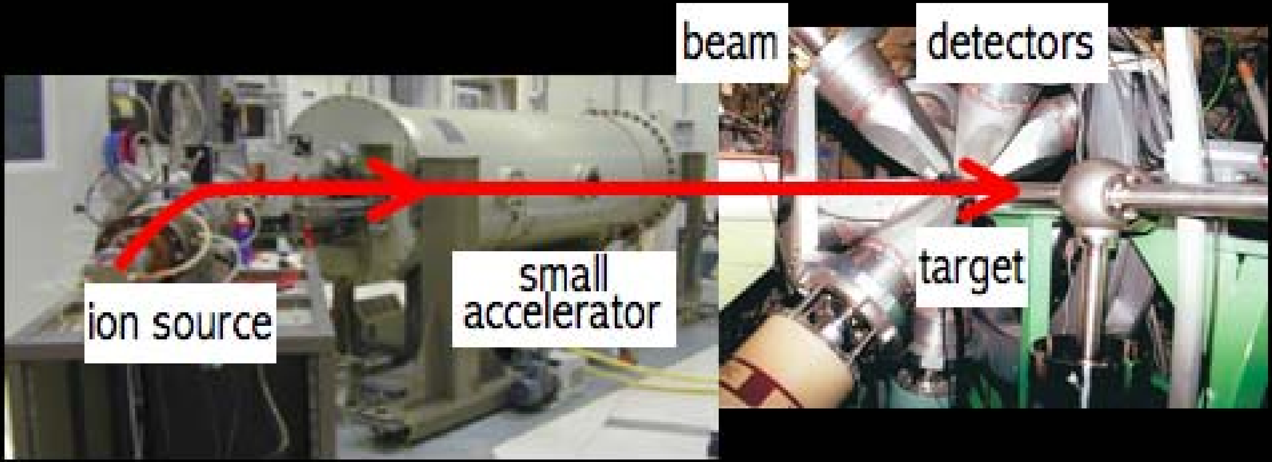
<u>Background</u>
2x ^{115}In decays
1 mimics prompt e
1 mimics γ cascade
→ high segmentation

3D array of transparent cells

(~6 m)^3 fiducial volume = ~15 tons In
~ 500 ν_{pp} events/yr



Nuclear Physics Laboratory Measurements



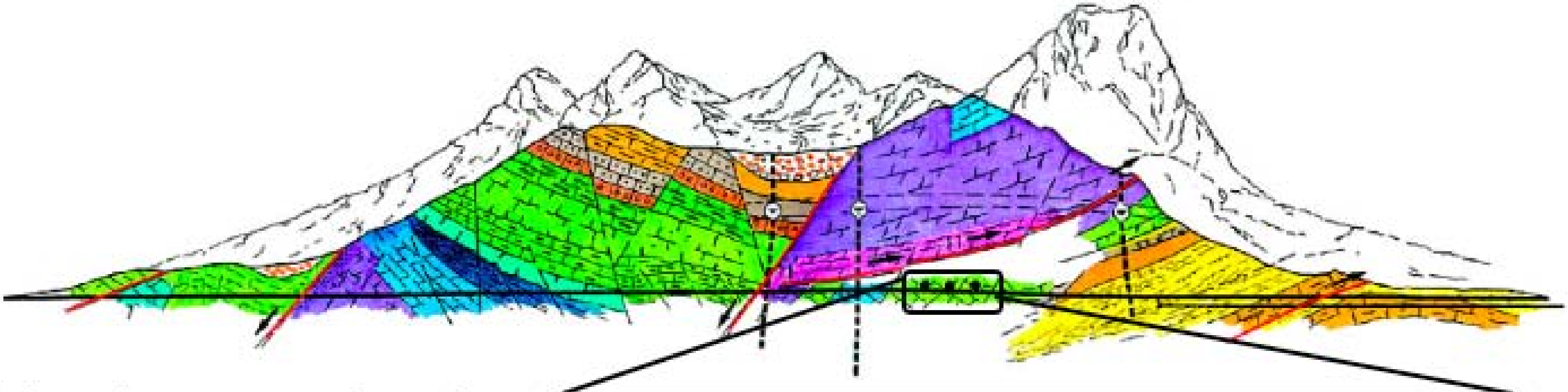
Directly measure cross sections in the lab at the lowest possible energies

Bombarding energy range ~ 10 keV to 3 MeV

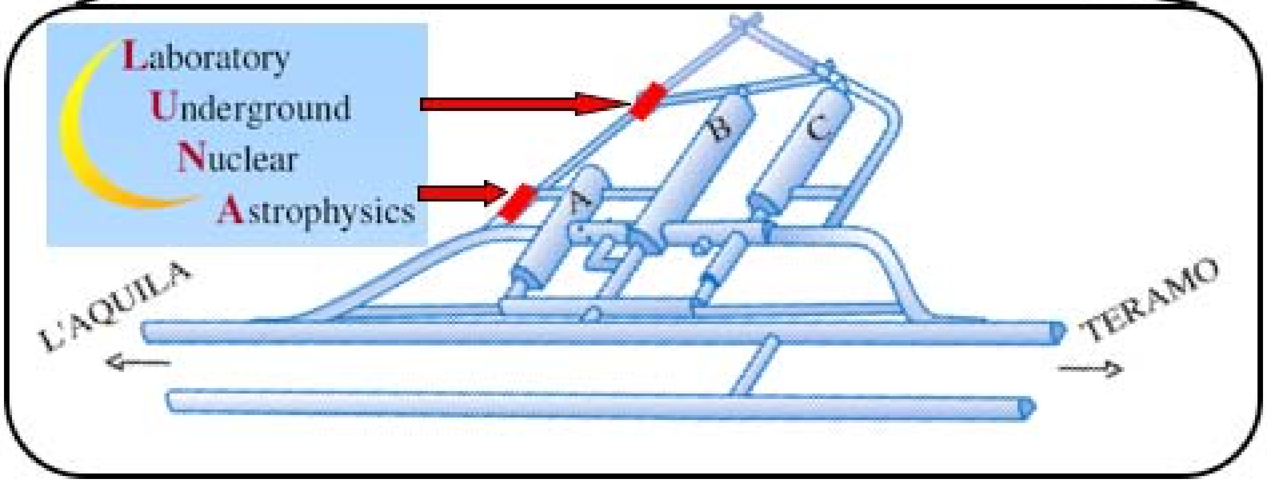
- High currents (~ mA)
- Long run times
- Efficient detectors to obtain high statistics
- Pure, stable targets
- Absolute cross section measurements
  - Good normalization & careful control of systematic uncertainties
- Background suppression crucial

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Gran Sasso



Laboratory space adjacent to highway tunnel



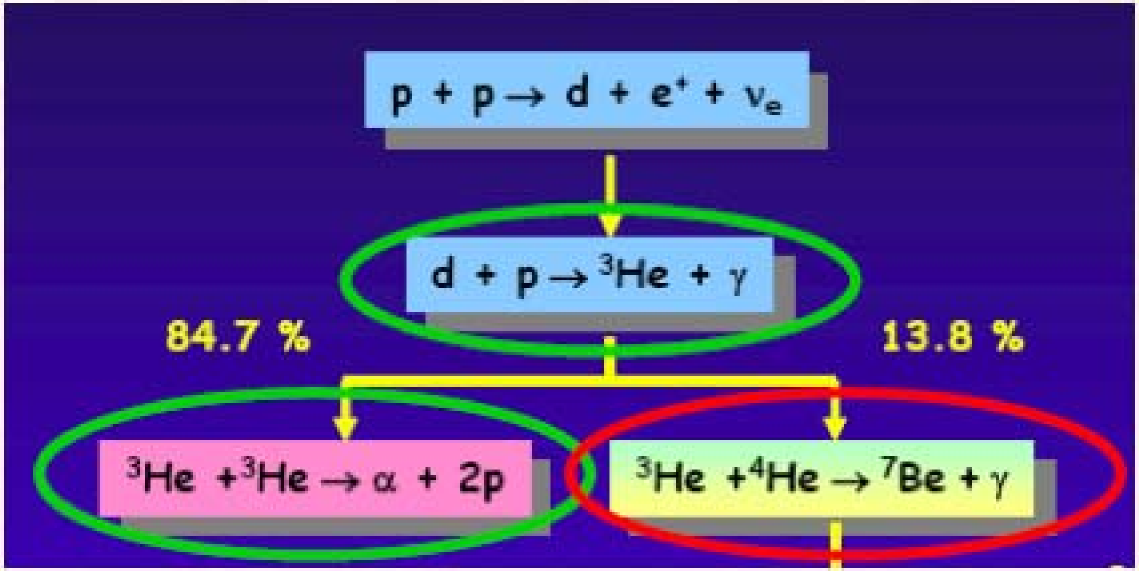
1400 m rock coverage

cosmic μ reduction= 10^{-6}

μ rate ~ 1 (/m^2 h)

Laboratory
Underground
Nuclear
Astrophysics

Low-energy accelerators at LNGS



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

$d + p \rightarrow {}^3He + \gamma$

84.7 %

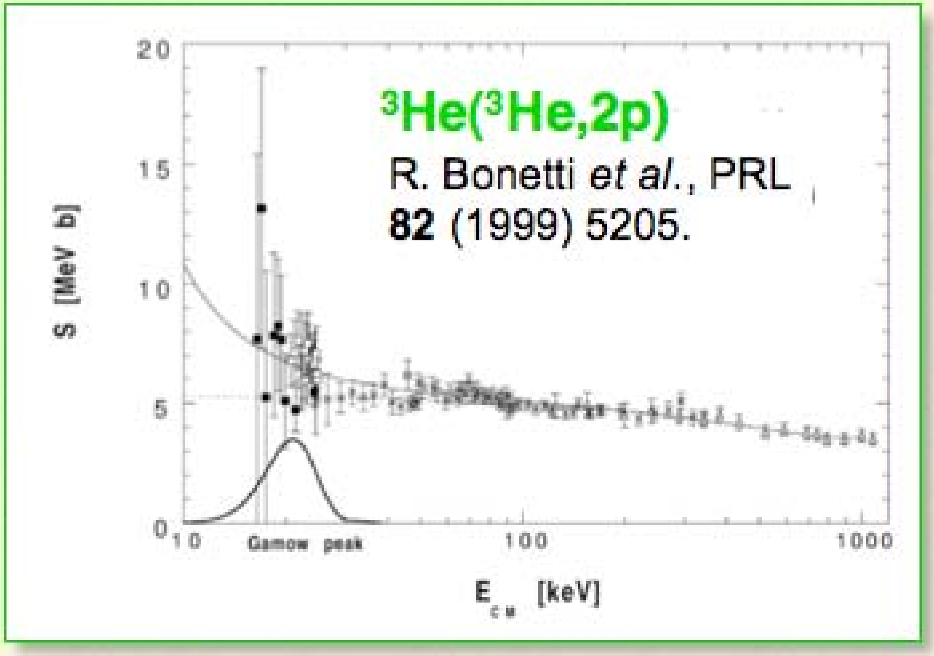
13.8 %

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

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

50 keV accelerator

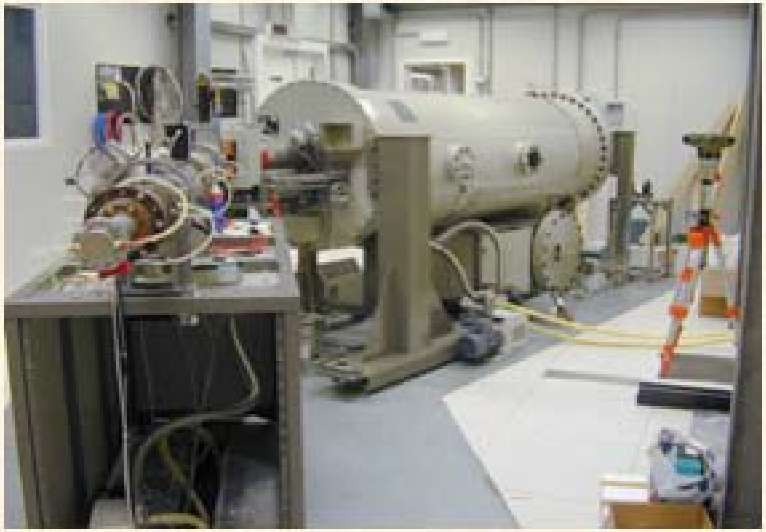
First σ measurements in solar Gamow widow



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

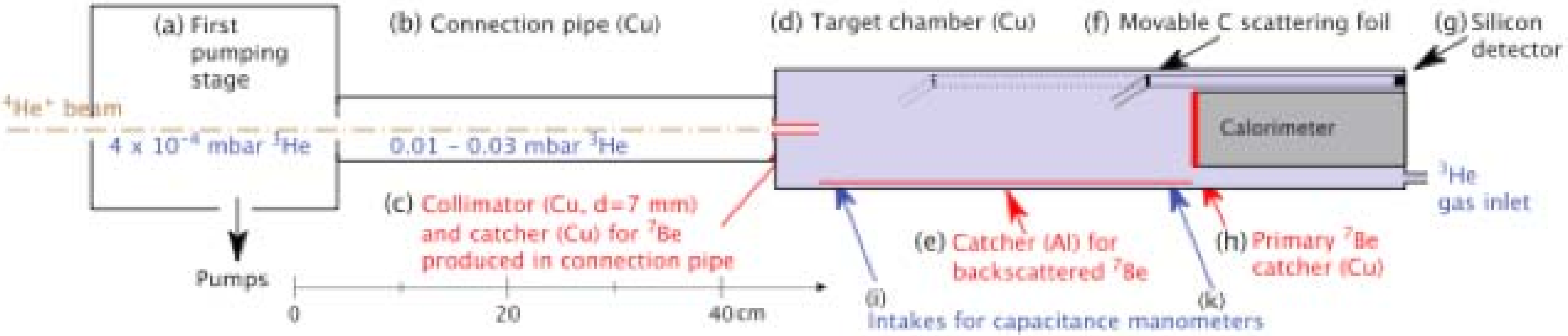
R. Bonetti *et al.*, PRL **82** (1999) 5205.

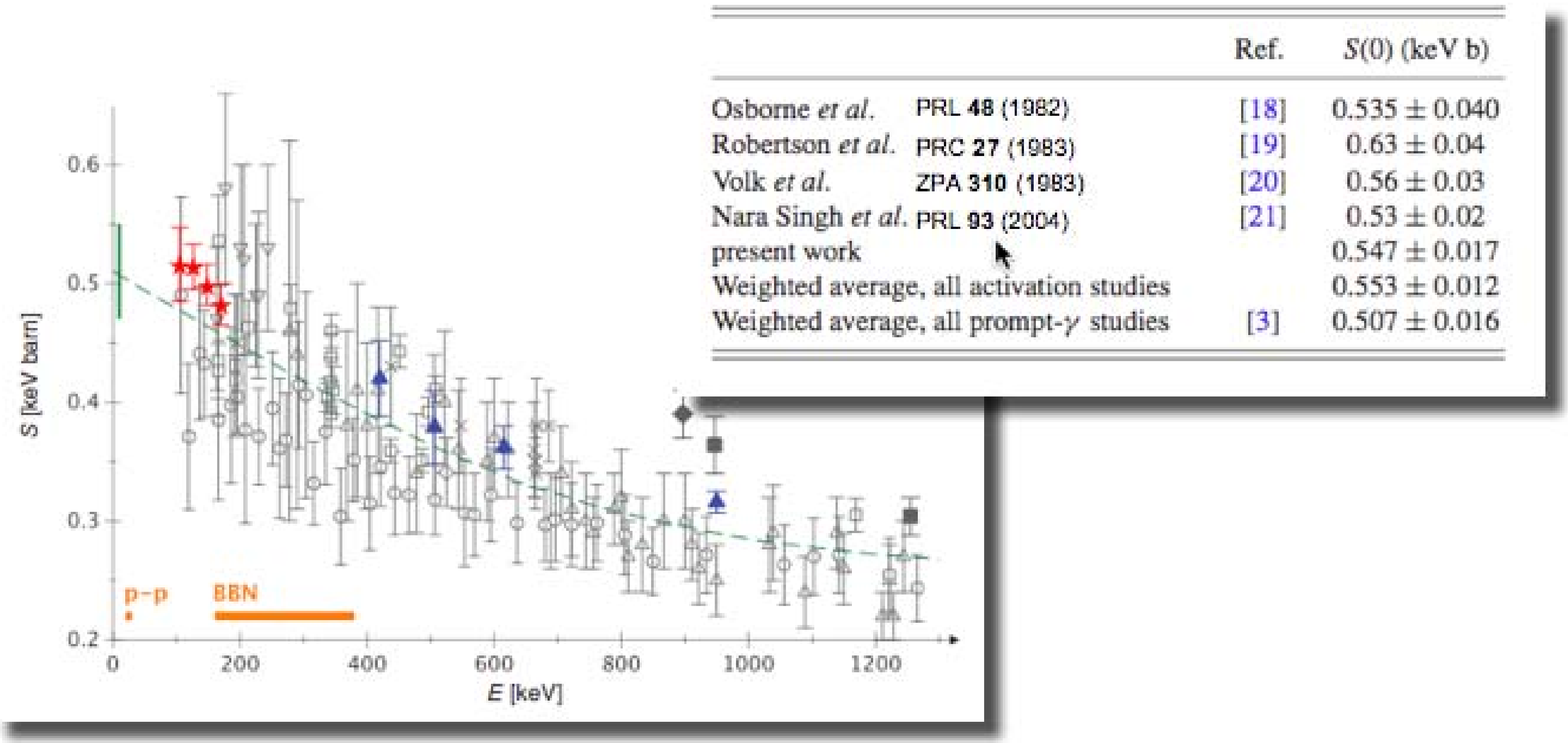
${}^3He(\alpha,\gamma){}^7Be$ with 400 keV accelerator



$^3He(\alpha,\gamma)^7Be$ @ LUNA

Gy. Gyürky, PRC **75** (2007) 035805.

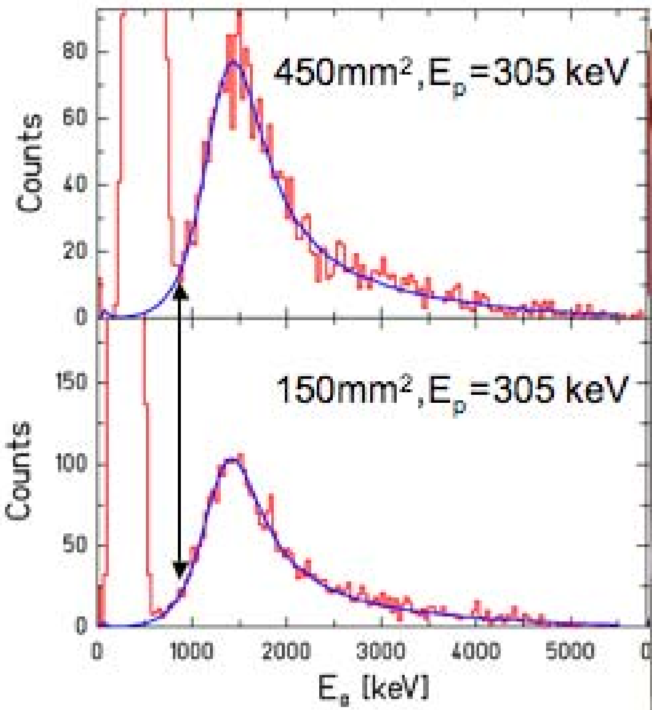




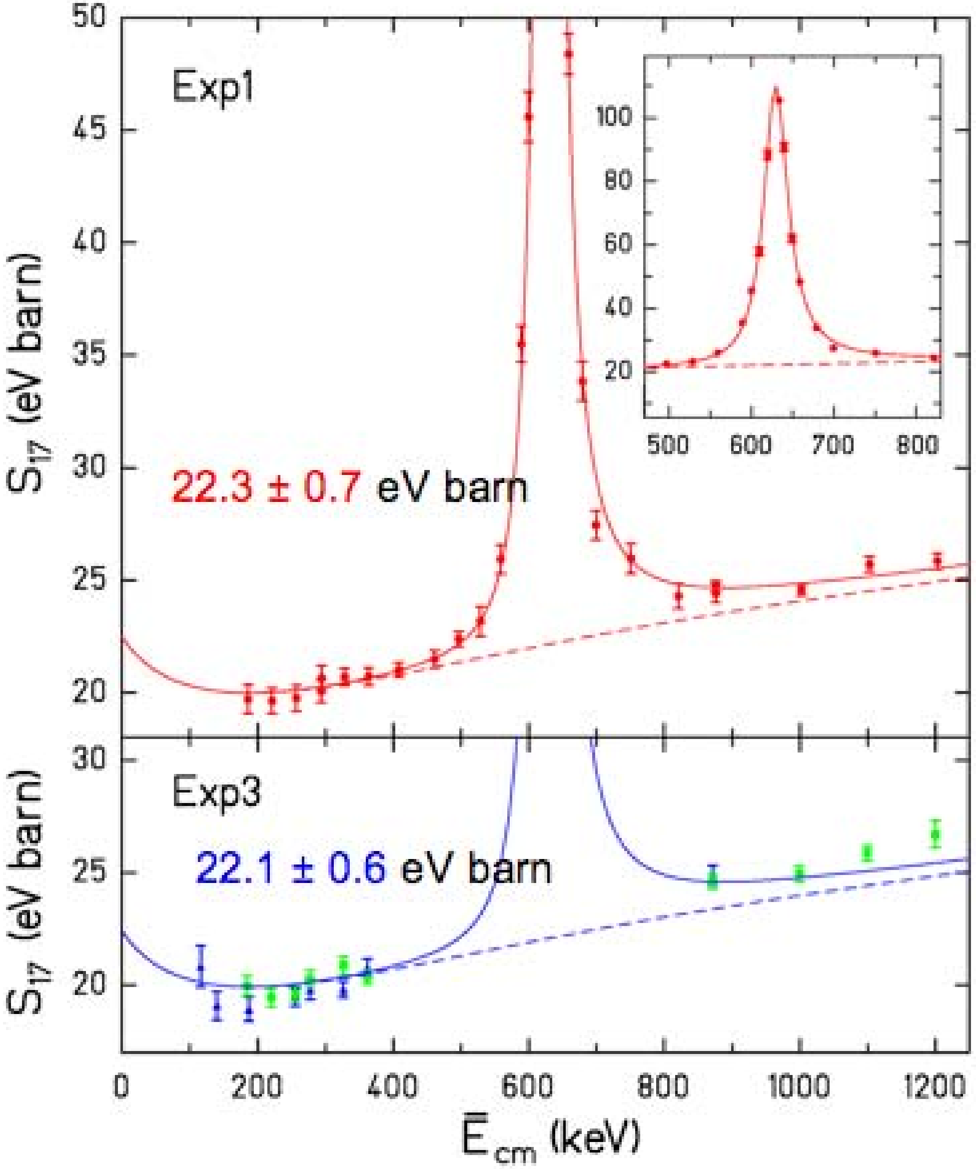
		Ref.	$S(0)$ (keV b)
Osborne *et al.*	PRL **48** (1982)	[18]	0.535 ± 0.040
Robertson *et al.*	PRC **27** (1983)	[19]	0.63 ± 0.04
Volk *et al.*	ZPA **310** (1983)	[20]	0.56 ± 0.03
Nara Singh *et al.*	PRL **93** (2004)	[21]	0.53 ± 0.02
present work			0.547 ± 0.017
Weighted average, all activation studies			0.553 ± 0.012
Weighted average, all prompt-γ studies		[3]	0.507 ± 0.016

$^7Be(p,\gamma)^8B$ at Seattle

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

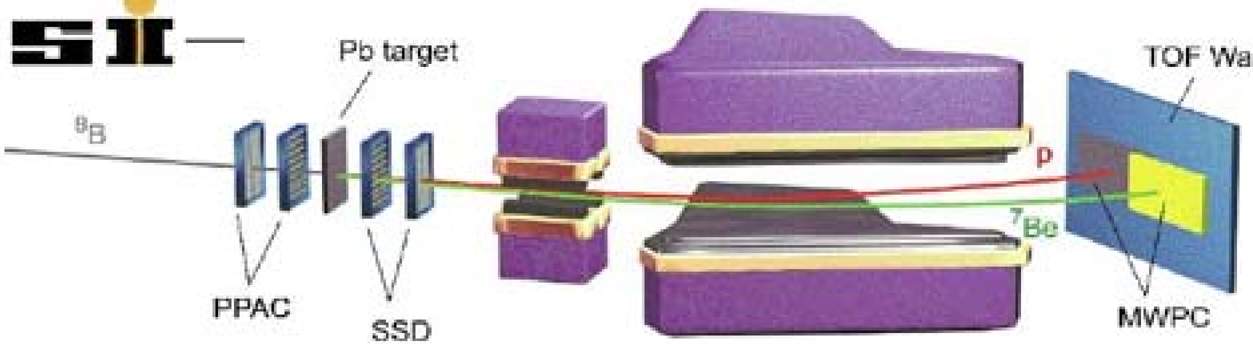


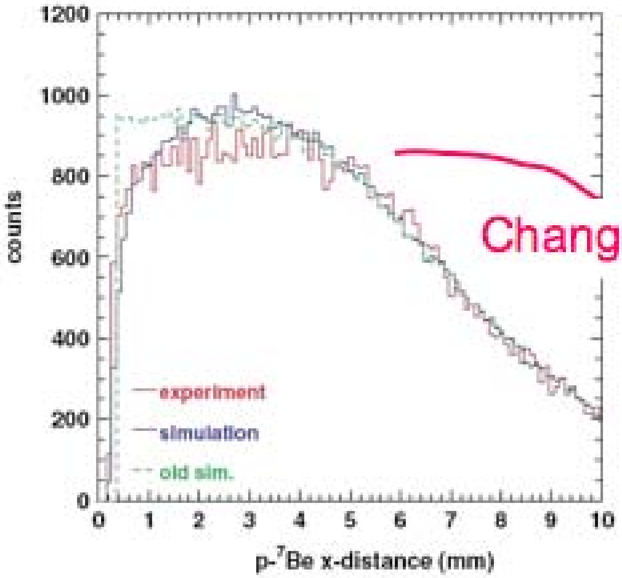
Extraordinary control over systematic uncertainties.

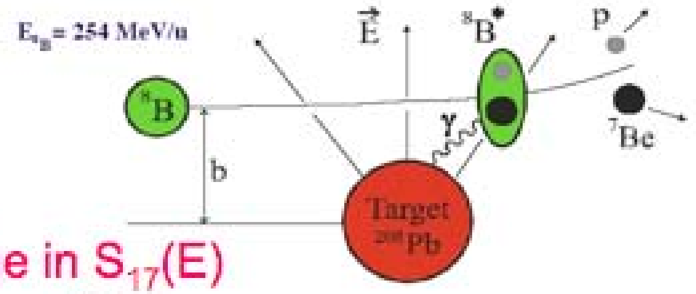


New Coulomb dissociation result

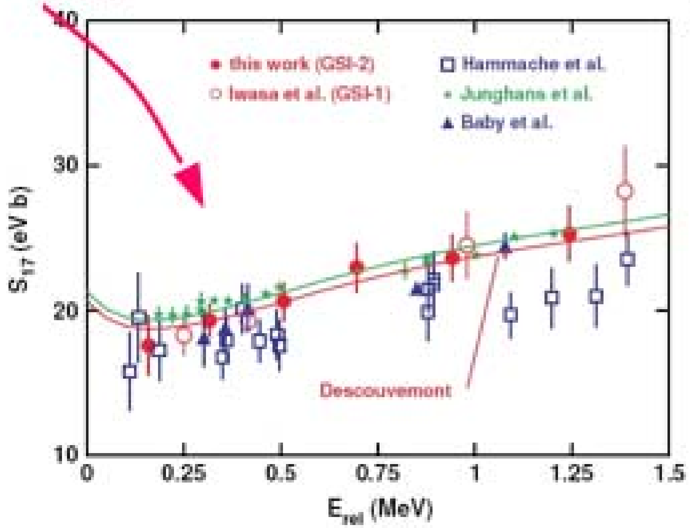
Schumann et al., PRC 73 (2006) 015806.

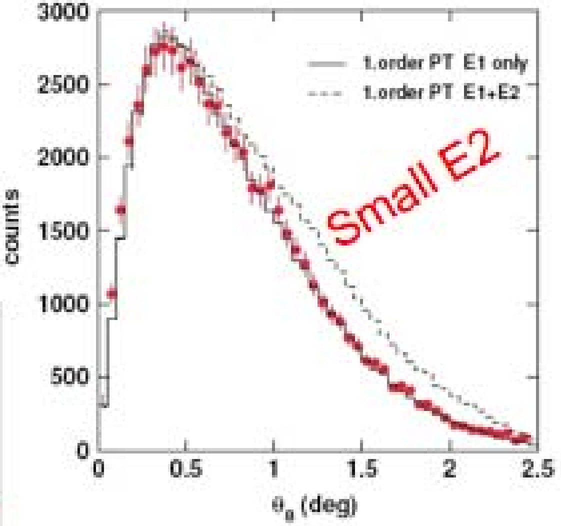






Change in S_{17}(E)

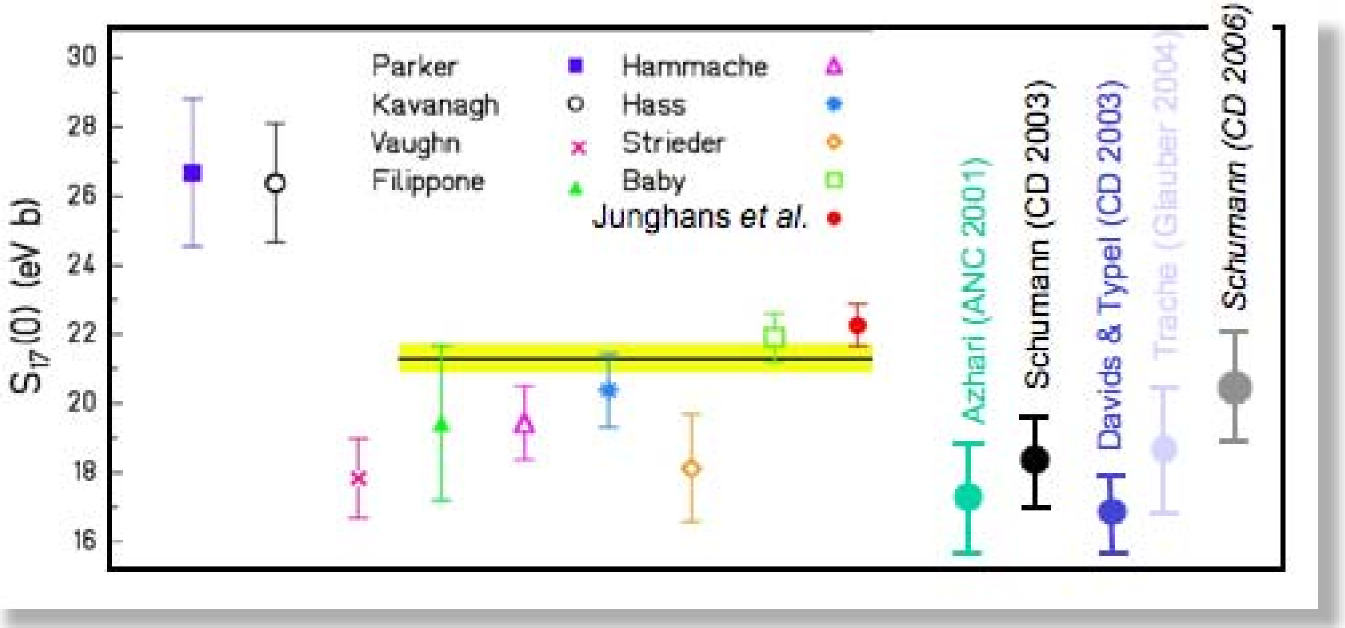




Small E2

20.6±0.8±1.2 eV b

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



	Evaluated S_{17} (eV b)
Junghans PRC **68** (2003) 065803.	21.4±0.5±0.6
Davids & Typel PRC 68 (2003) 045802.	18.6±0.4±1.1
Cyburt *et al.*, PRC 70 (2004) 045801.	19.3 → 21.4 with ~ 6-7% σ

- Precision has been significantly improved.
- Some questions remain.
- Additional high-precision measurement(s) are desired.

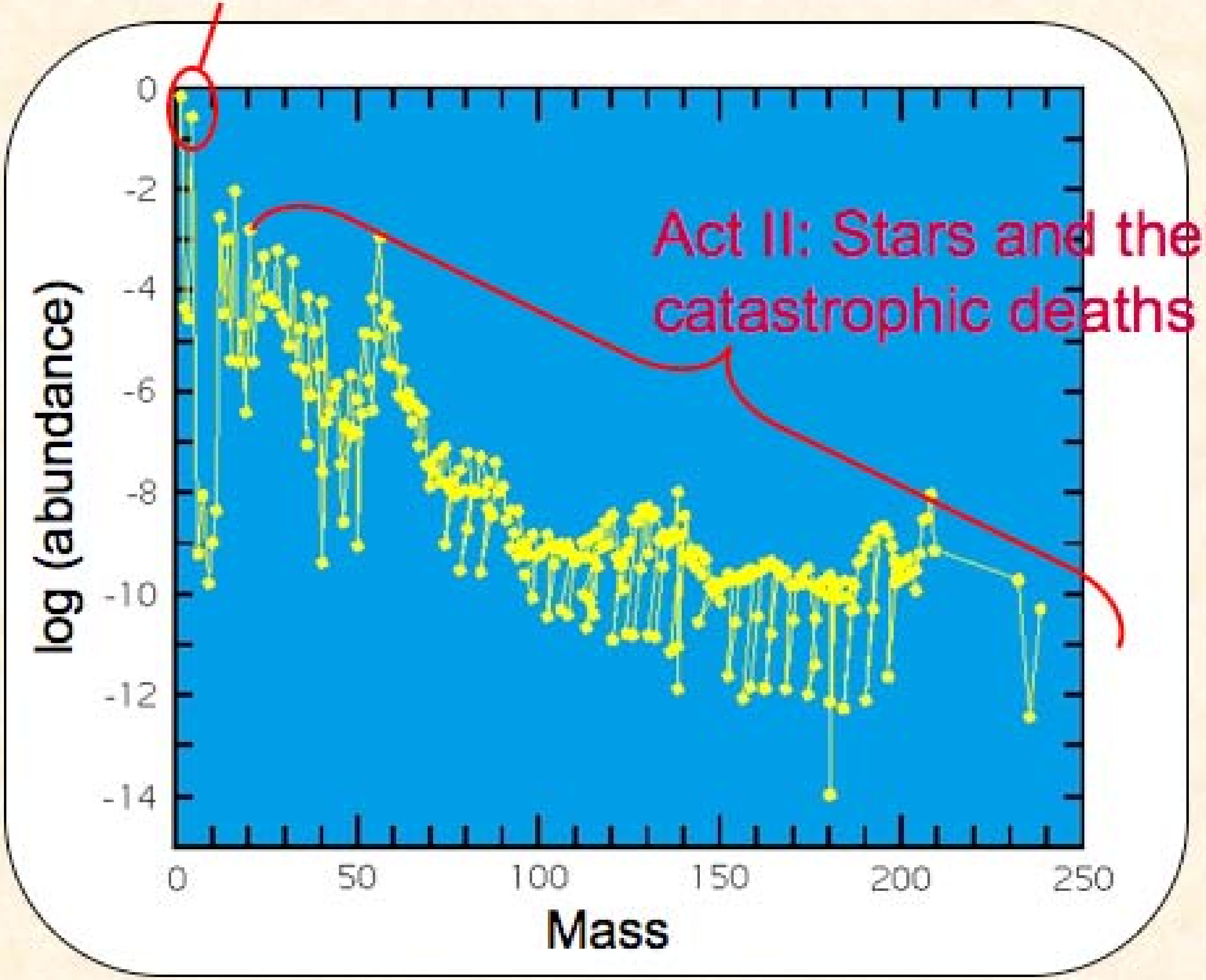
Solar power: The pp-chains

Thanks to substantial efforts in experiment, theory & evaluation

pp-1:	**5%**	$^{1}H(p,e^{+}\nu)^{2}H$	
	5%	$^{2}H(p,\gamma)^{3}He$	
	7%	$^{3}He(^{3}He,2p)^{4}He$	84.7%
pp-2:	**7%**	$^{3}He(\alpha,\gamma)^{7}Be$	13.8%
		$^{7}Be(e^{-},\nu)^{7}Li$	13.78%
	13%	$^{7}Li(p,\alpha)^{4}He$	
pp-3:	**5-10%**	$^{7}Be(p,\gamma)^{8}B$	0.02%
		$^{8}B(\beta^{+}\nu)2^{4}He$	

fusion of $4\ {}^{1}H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

Act I



Act II: Stars and their catastrophic deaths