BOREXINO and the Sun

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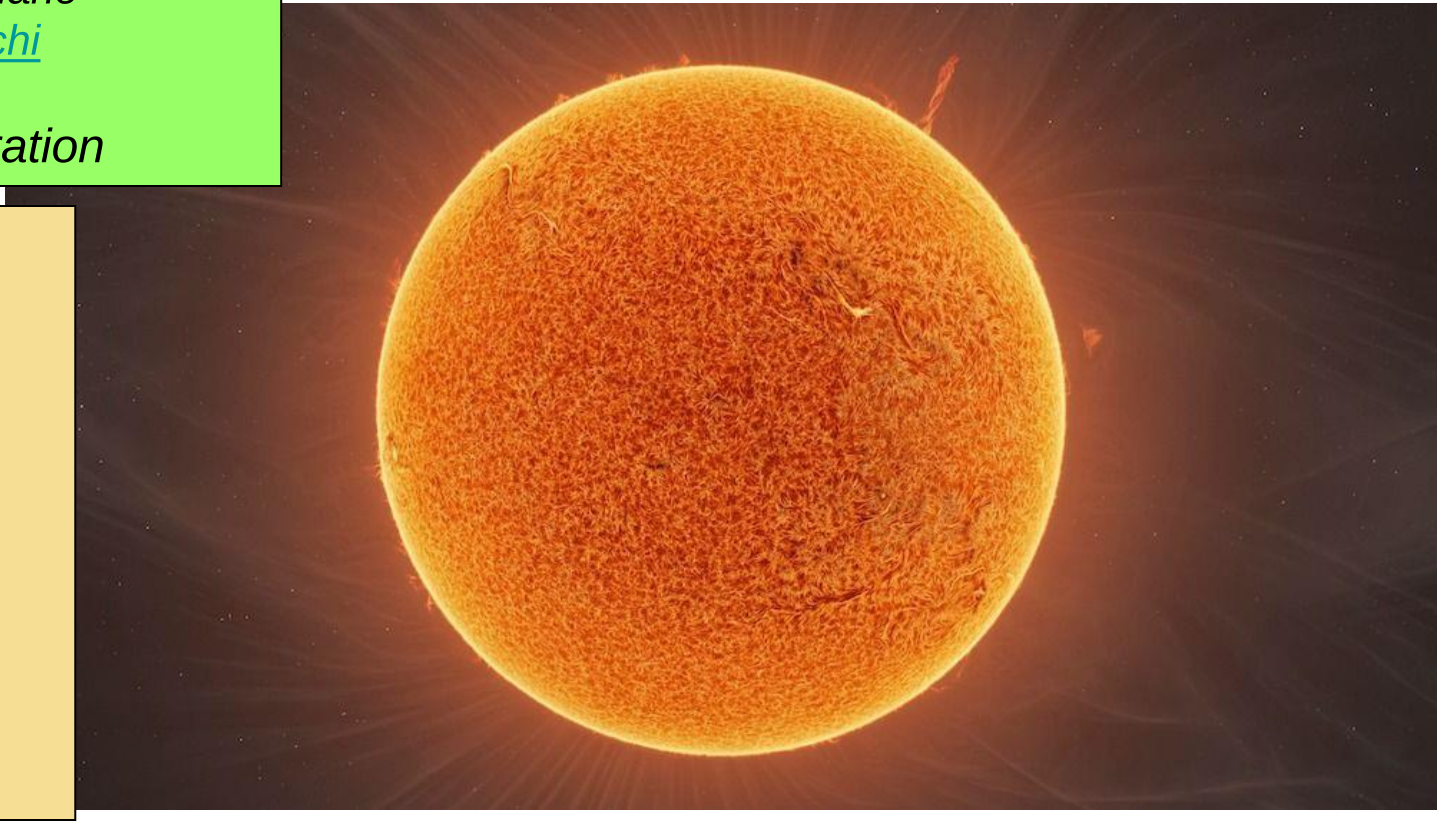
On behalf of the BOREXINO Collaboration

1 Sun and Solar Models

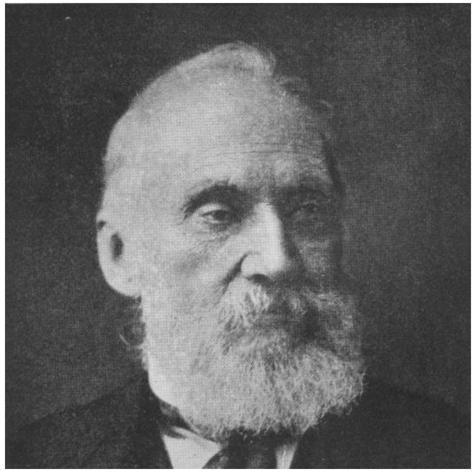
2 BOREXINO (in a nutshell)

3 BOREXINO Solar Physics results

4 Implications for other stars



Sun and Solar Models



William Thomson
(Lord Kelvin)

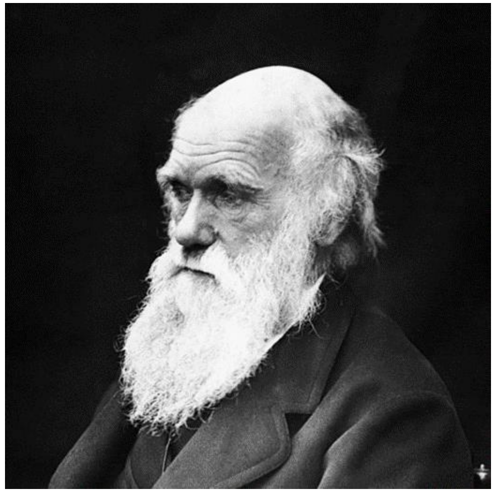
Energy from Gravity

Age of the Sun
less than 20.000.000 years

A longstanding debate (19th c.)

What is the energy source of the Sun and of the stars in general?

Unknown source of energy

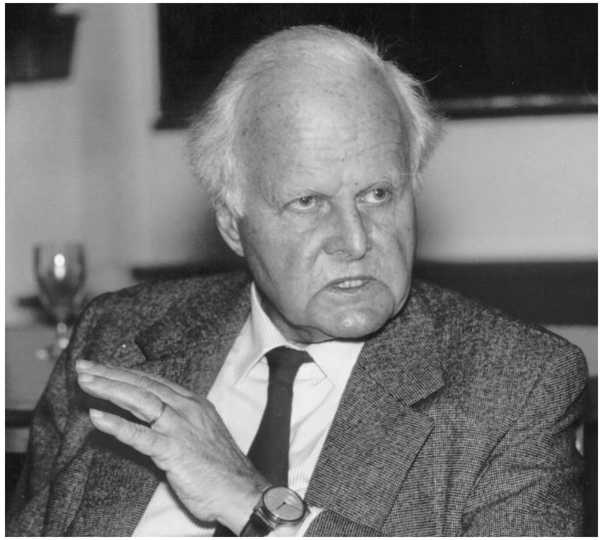


Charles Darwin

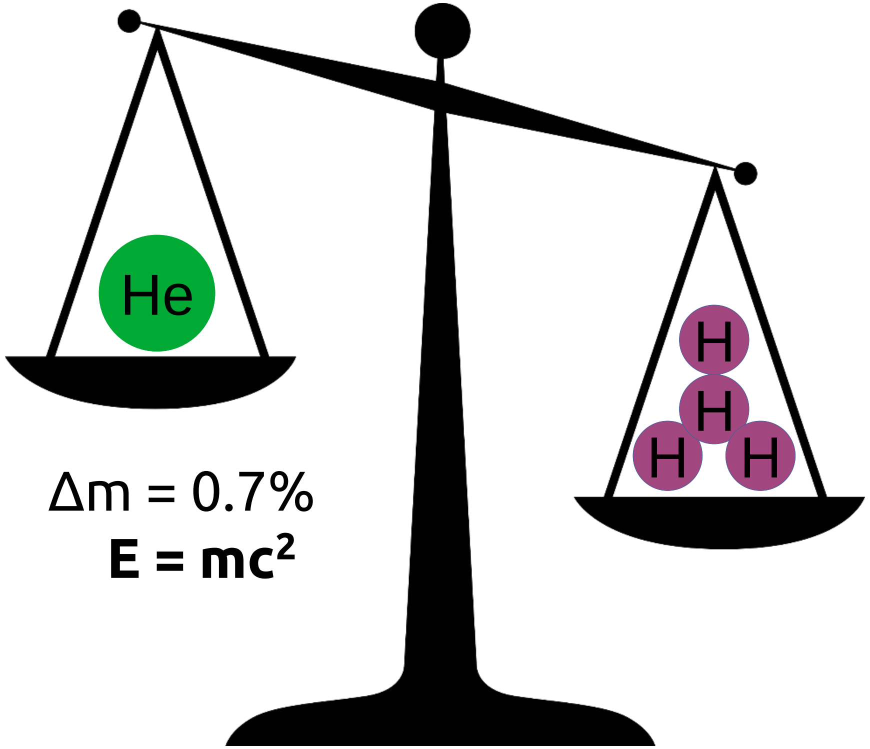
Geology and Biology

Earth is older than
300.000.000 years

Nuclear Physics for the Sun (1938)



Carl F. von Weizsäcker



$\Delta m = 0.7\%$

$\mathbf{E = mc^2}$

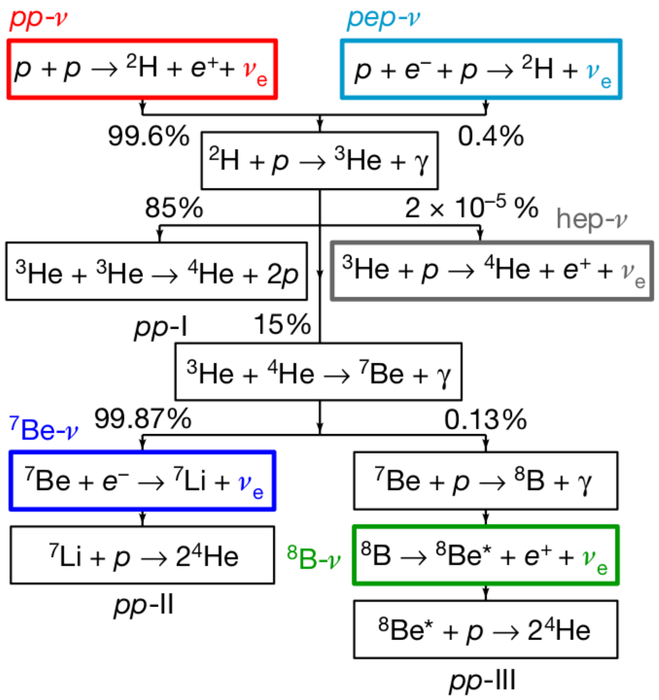
Hans Bethe

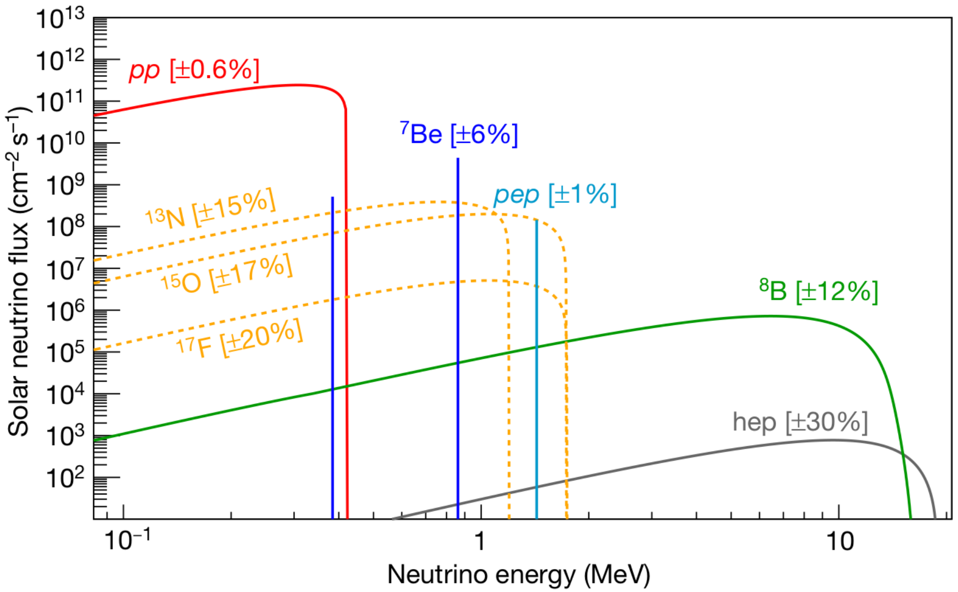
Energy from nuclear reactions: hydrogen burning through **pp chain** and **CNO cycle**

… the Sun is 5.000.000.000 years old!

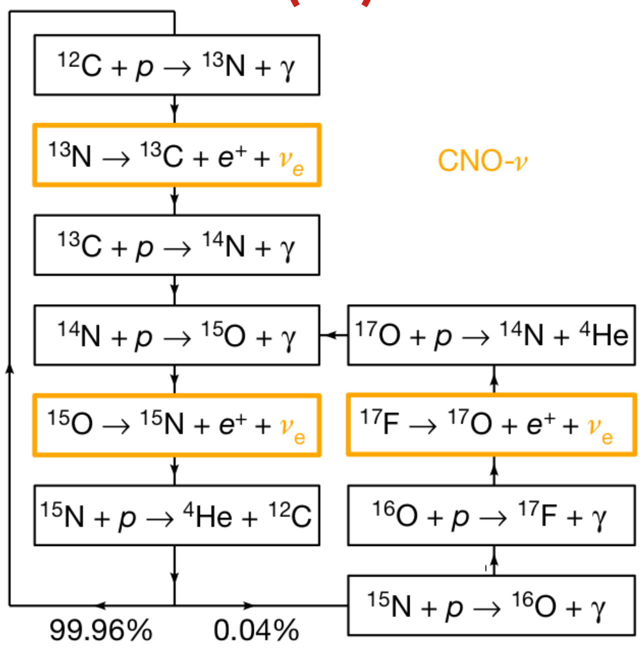
Solar Neutrinos

pp chain (99%)





CNO cycle (1%)



Dominant in the sun

$T_{core} \sim 15 \times 10^6$ K

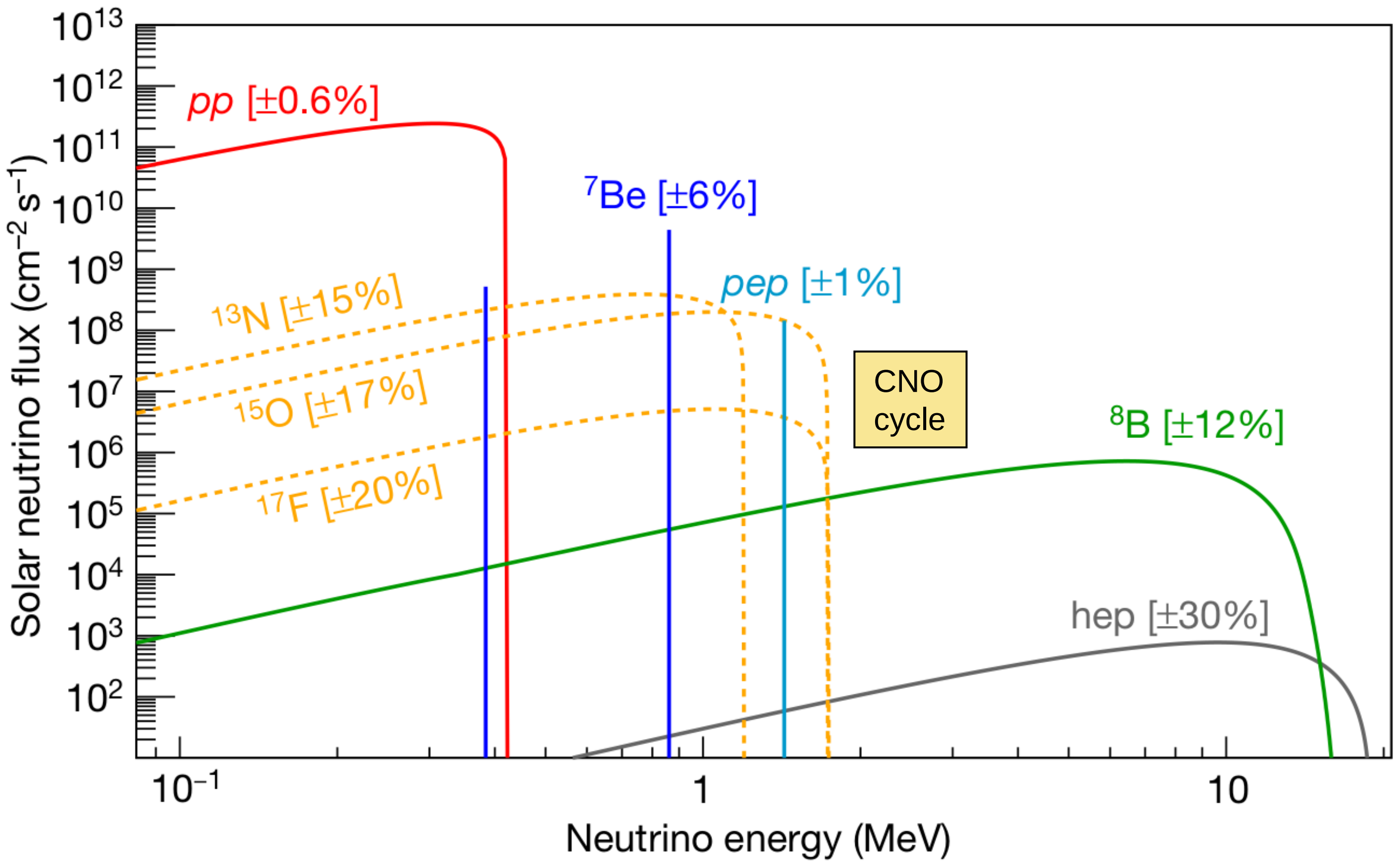
$$4p \rightarrow {}^4\text{He} + 2e^- + 2\nu_e + 26MeV$$

- Dominant in heavier stars (>1.3 Sun mass)

Detection of neutrinos to confirm the working principles of the Sun (R. Davis experiment)

Solar Neutrino Spectrum: experiment and predictions

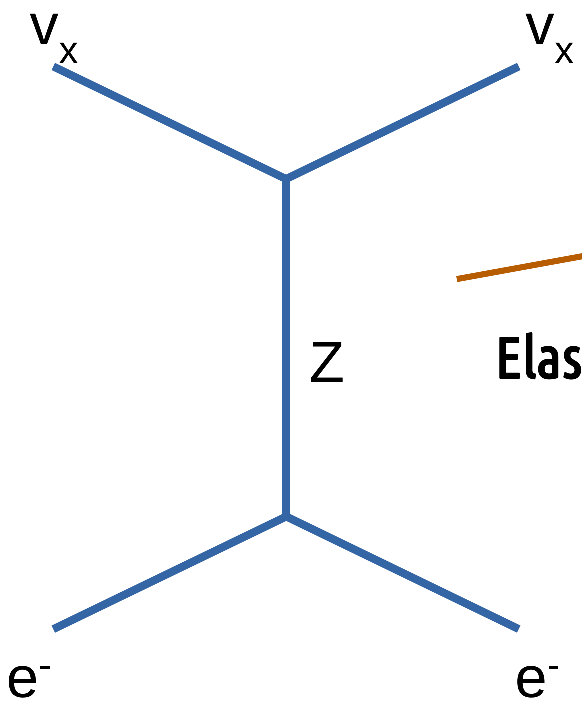
- Davis experiment
- Solar Models (J. Bahcall)
- Discrepancy between the Davis experiment and the Model (Solar Neutrino Problem)
- Astrophysics/Neutrino physics possible solutions
- Neutrino Oscillations! (2002)

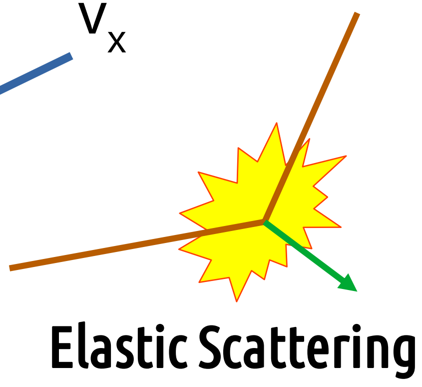


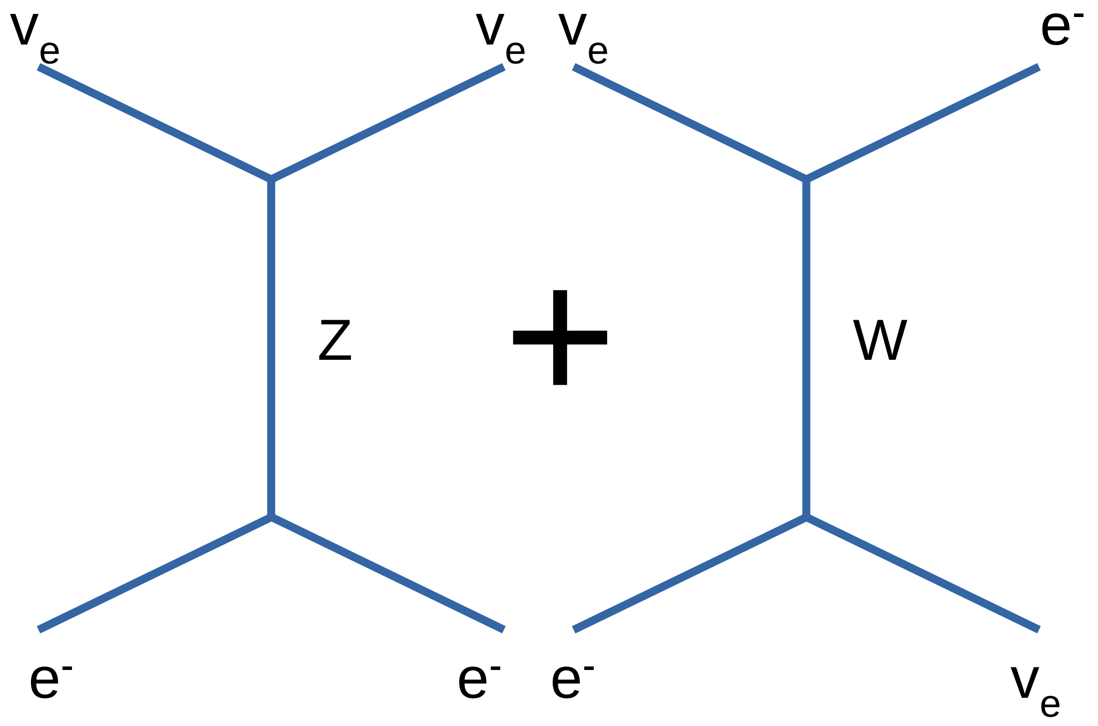
Predicted Neutrino Spectrum from the Sun, according to the Standard Solar Model

BOREXINO

Detection reaction: neutrino-electron elastic scattering







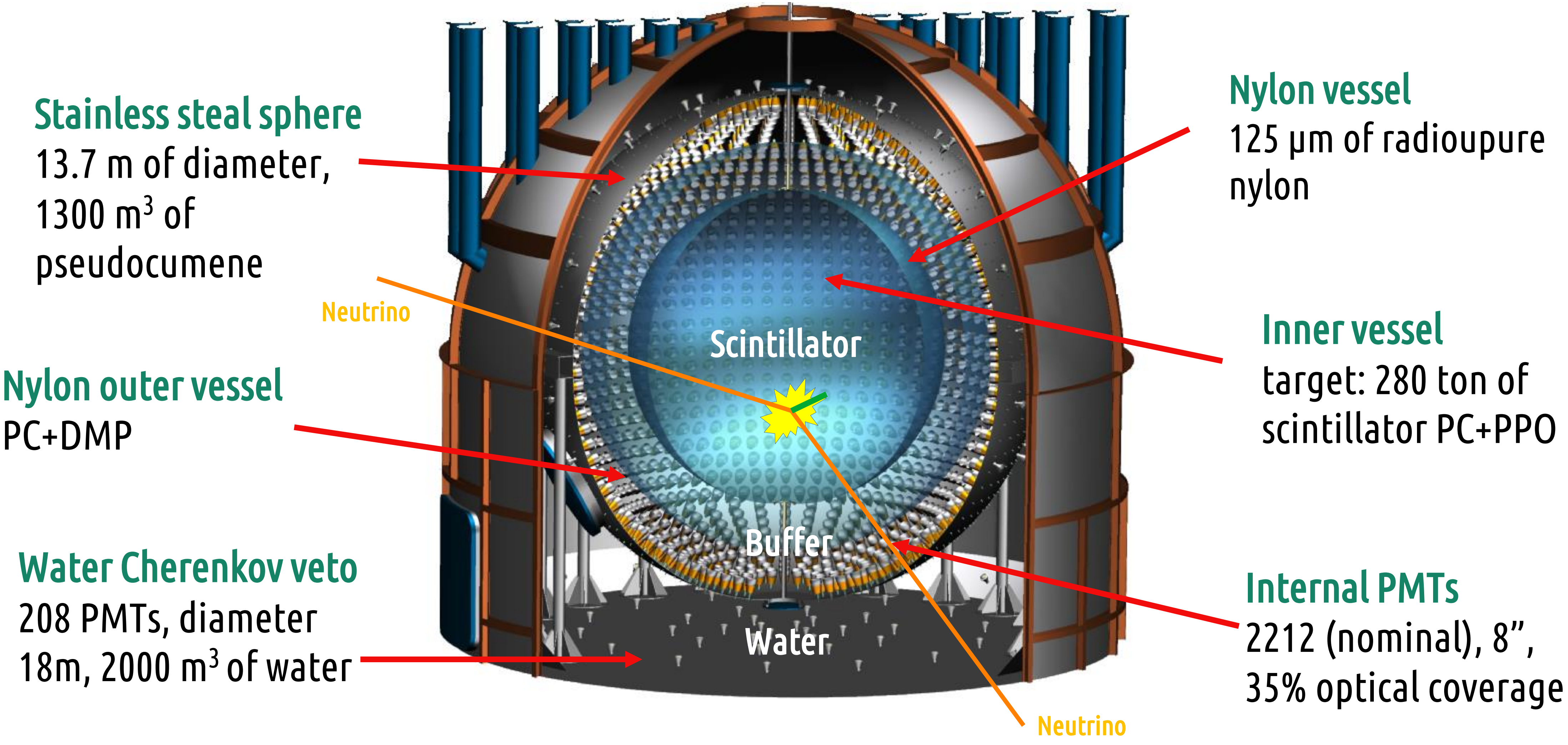
All types (NC)

$\nu_x + e^- \rightarrow \nu_x + e^-$

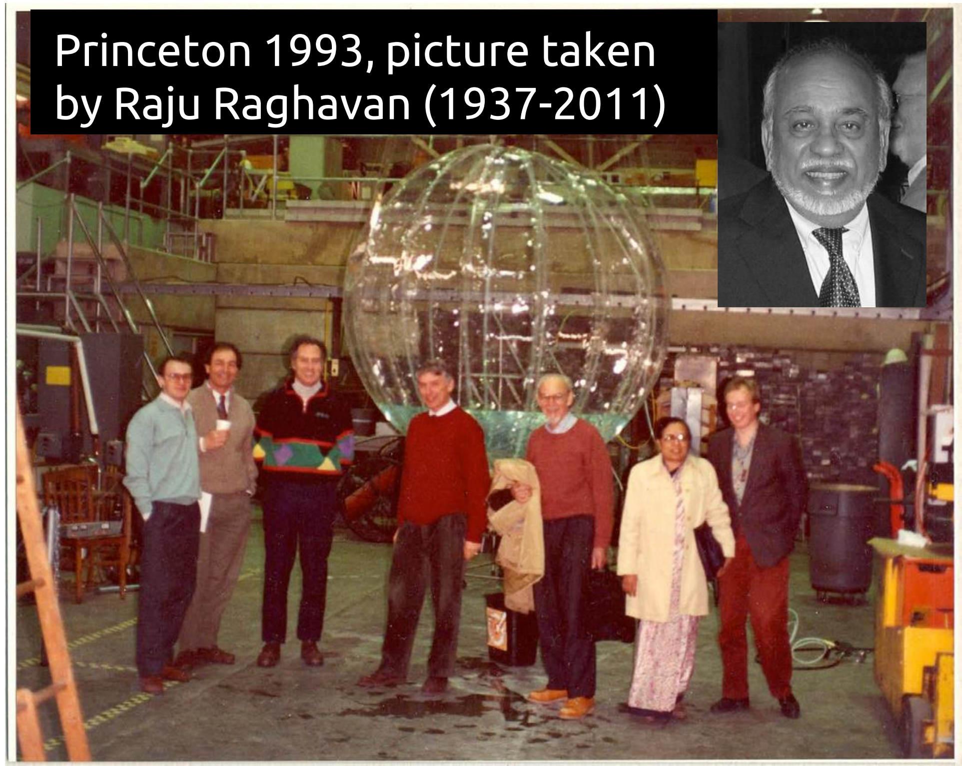
Electron neutrinos (NC, CC)

$\nu_e + e^- \rightarrow \nu_e + e^-$

The BOREXINO detector



The BOREXINO saga



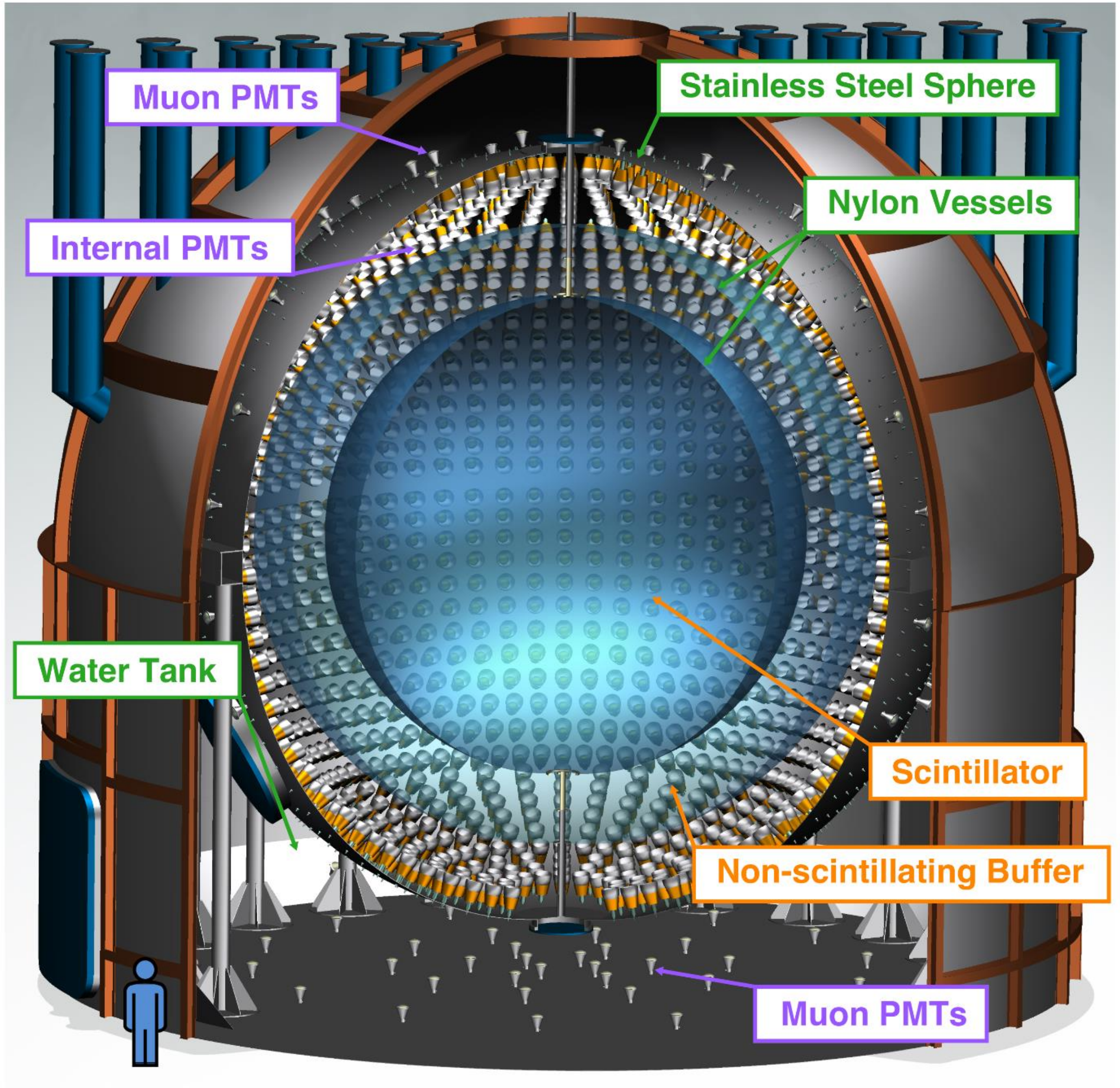
1990: idea of a sub-Mev solar neutrino detector
A real time neutrino detection

1995: CTF testing the record radiopurity
^{238}U, $^{232}Th < 10^{-16}$ g/g & $^{14}C/^{12}C < 10^{-18}$

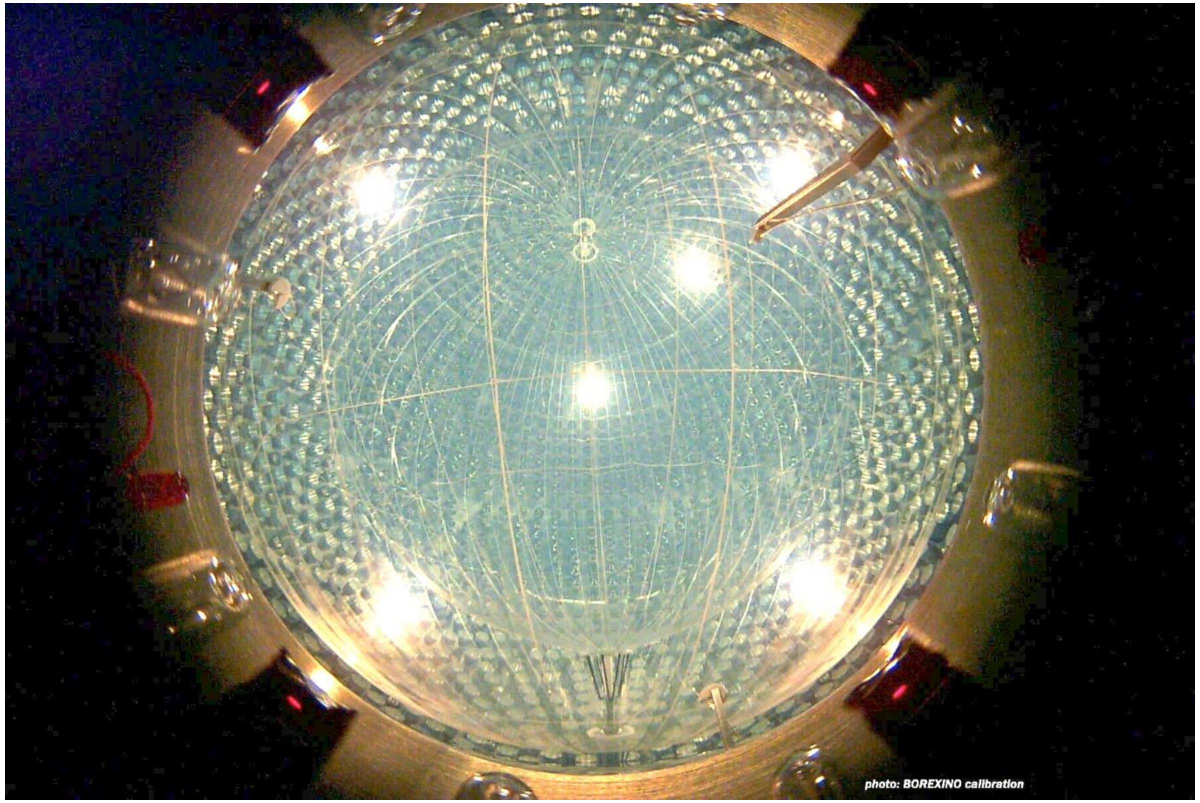
1996-1997: Approval of the experiment

Mid-2007: Beginning of the data taking

Radiopure materials (structure and scintillator)
Purification: distillation, N_2 stripping, water extraction.

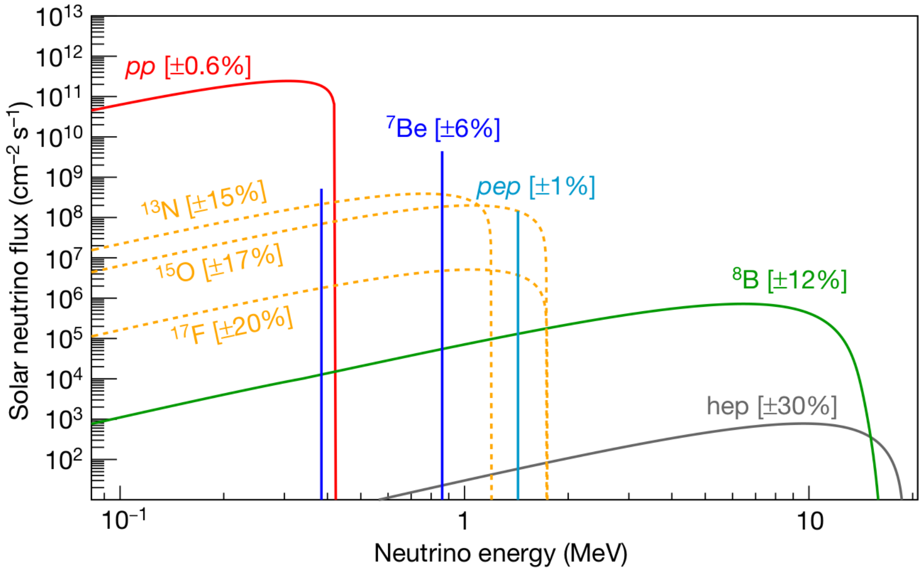


BOREXINO at the Laboratori Nazionali del Gran Sasso

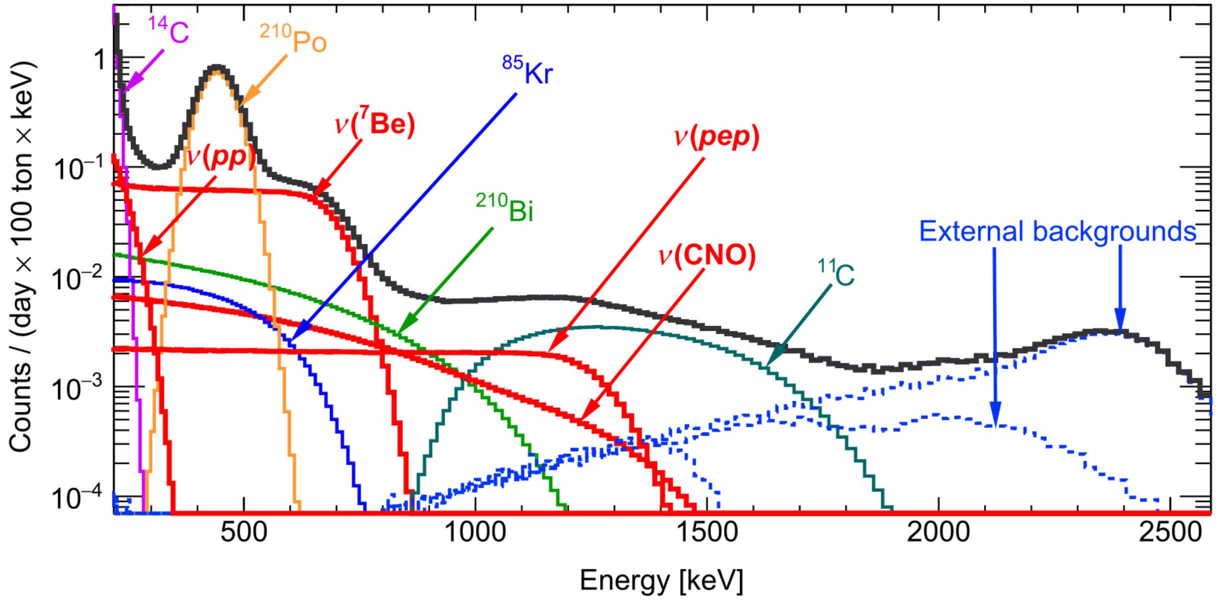


Solar Physics Results

Solar Neutrino Spectrum



Reconstructed electron recoil spectrum and backgrounds in BOREXINO



- Reconstruction of ~all components and backgrounds in the scintillator fiducial volume
  see e.g. M. Agostini et al. *Comprehensive measurement of pp-chain solar neutrinos* Nature 562 (2018) 505

- Identification and measurement of the **pp** main component (first observation made in real-time)
- Identification and measurement of the **CNO** neutrino contribution (first time)

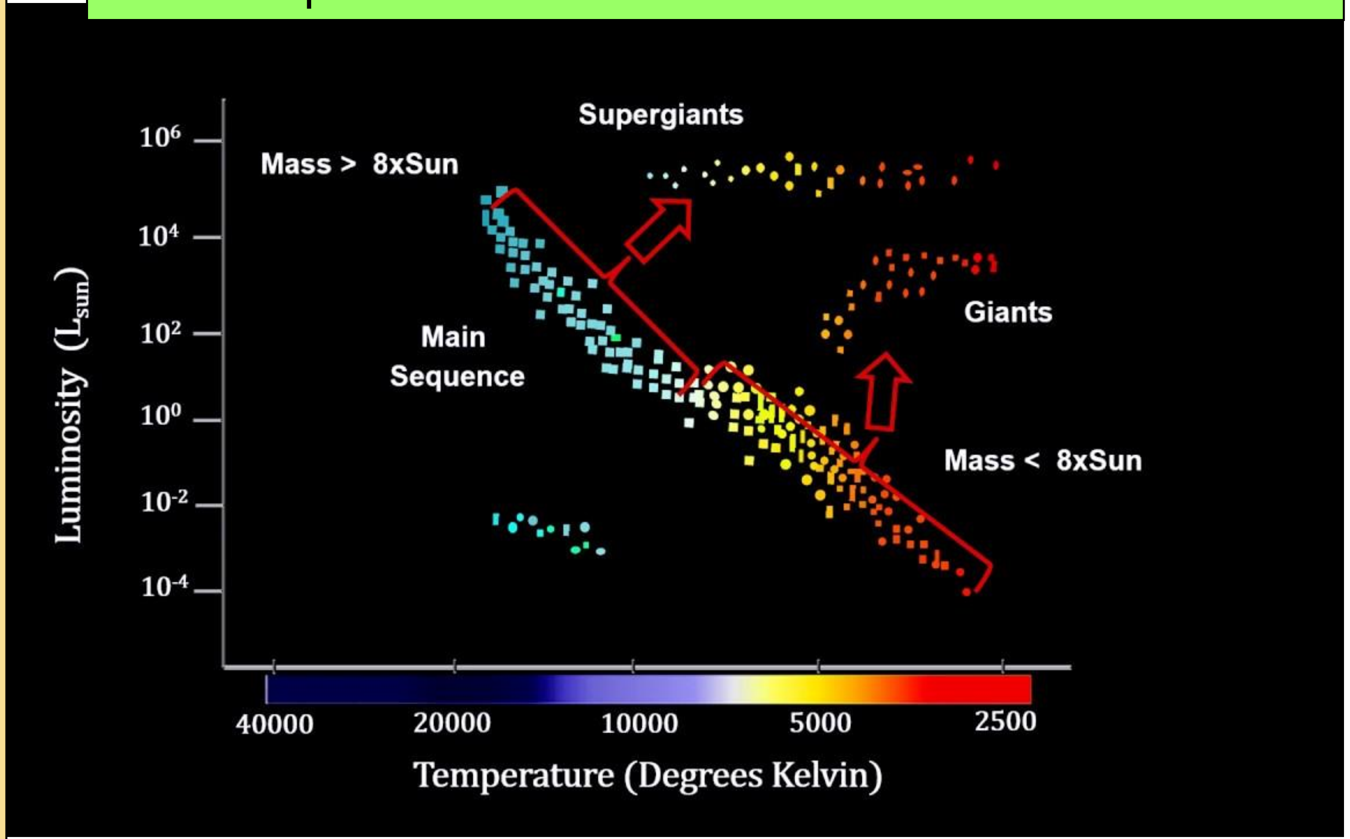
Summary of the BOREXINO Solar results (see also talk by M. Chen)

Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)_{-10}^{+6}$	$(6.1\pm0.5)_{-0.5}^{+0.3}x10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)_{0.7}^{+0.4}$	$(4.99\pm0.11)_{-0.08}^{+0.06}x10^{9}$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ]	$(1.27\pm0.19)_{-0.12}^{+0.08}x10^{8}$[HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}x10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	<1.8x10^{5} (90% CL)
CNO	Nature 2020	$6.7_{-0.8}^{+2.0}$	$6.6_{-0.9}^{+2.0}$x10^{8}

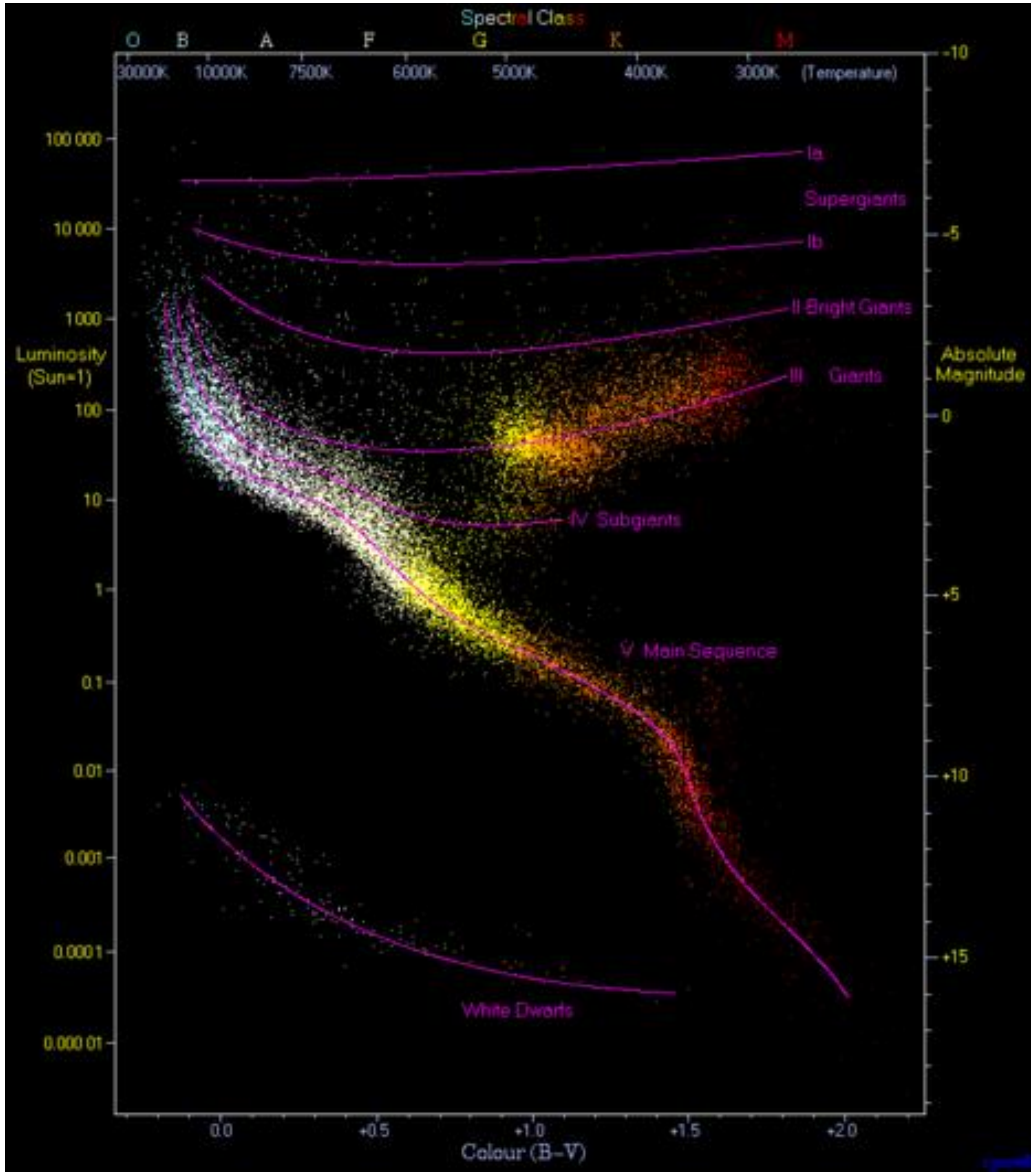
Implications for Main Sequence Stars

- Fuse Hydrogen to form Helium in their cores
- They are about 90% of the Stars
- Masses from ~ 0.2 $M_\odot$ (nuclear fusion limit) to ~ 200 $M_\odot$ (Eddington limit)
- Surface temperatures of
  50,000 K for 100 $M_\odot$
  30,000 K for 18 $M_\odot$
  5,800 K for 1 $M_\odot$
  3,600 K for 0.5 $M_\odot$
- Lifetime of 90×10^9 y for 0.5 $M_\odot$
  10×10^9 y for 1 $M_\odot$
  20×10^6 y for 10 $M_\odot$
- Mass-Luminosity relations

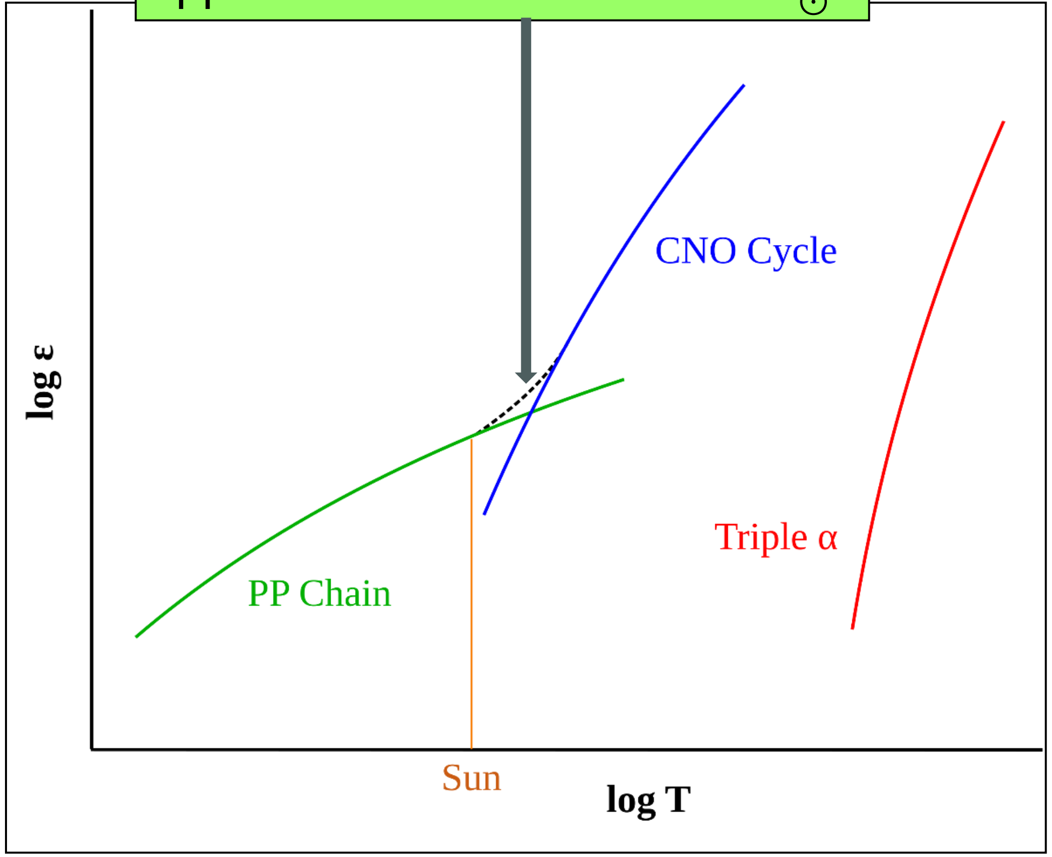
Main Sequence: the most abundant stars in the Universe



All Main Sequence stars call for the same Physics!



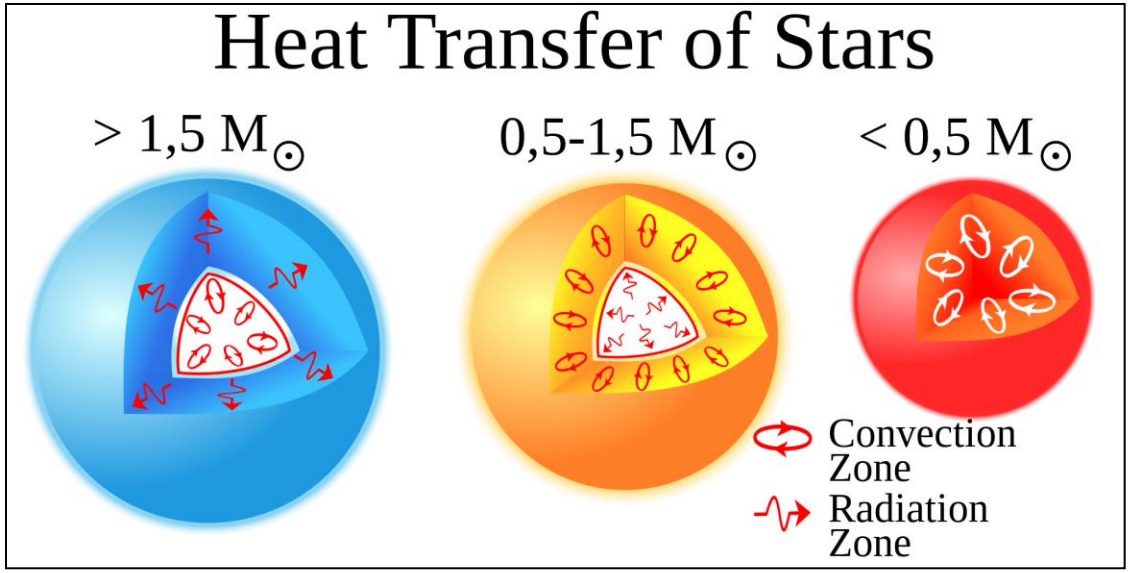
pp – CNO crossover at 1.4 $M_\odot$



BOREXINO measurements are relevant to all Main Sequence stars

(22,000 stars in the Hipparchos catalog)

BOREXINO measurements are relevant to all Main Sequence stars



BOREXINO error on the CNO measurement ~30 % (favoring high metallicity)

Error on C,N,O astrophysical reactions ~20 %

And decreasing because of new measurements planned (as in LUNA and other experiments)

Aiming at reaching ~8 %

Different role of heat transport mechanisms, depending on the T gradient
(should not affect the conclusions!)

Fundamental step to the understanding and the experimental demonstration of the working principle of all stars in the Main Sequence

Grazie!

Premio Cocconi 2021 - EPS

Premio Pontecorvo 2015 G. Bellini

Premio Fermi 2017 G. Bellini

physicsworld TOP 10 BREAKTHROUGH 2014

physicsworld TOP 10 BREAKTHROUGH 2020

Ministerstwo Edukacji i Nauki

Award of Polish Science Minister 2022

APS Advancing Physics

Bethe Prize 2023 F. Calaprice

Thank you for your attention

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