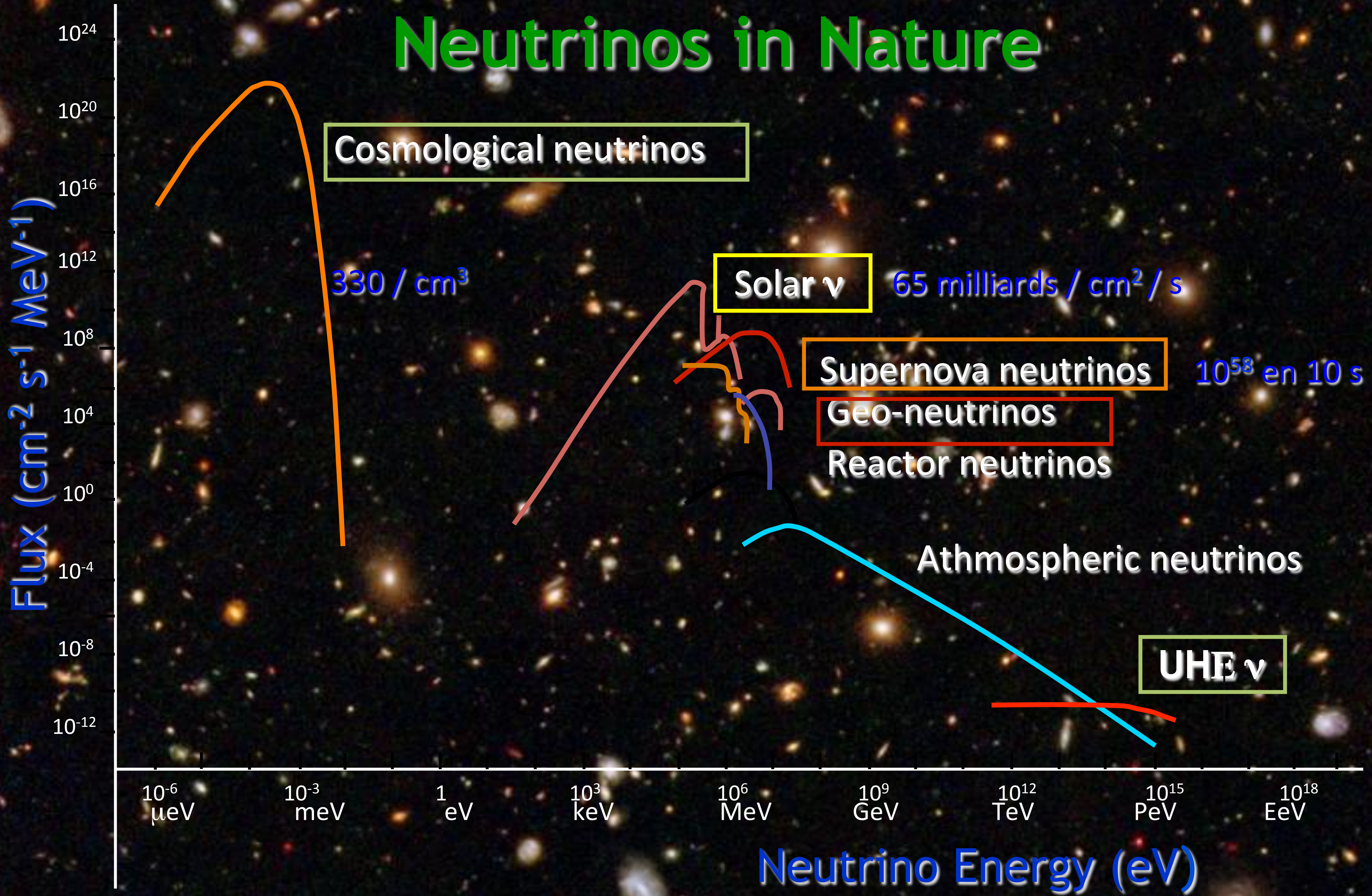
Astrophysique des neutrinos de basse énergie :
avancées et défis

Cristina VOLPE
AstroParticule et Cosmologie (APC), Paris

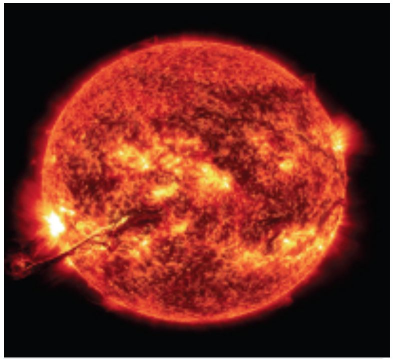
Neutrinos in Nature



Two diffuse neutrino backgrounds never observed :
from the Early Universe and from supernovae

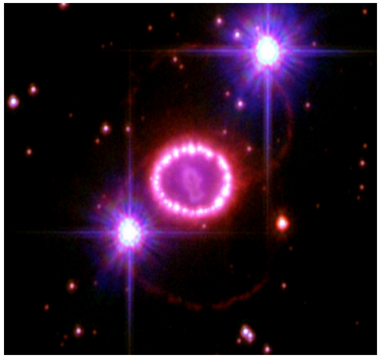
Outline

1 - Solar neutrinos

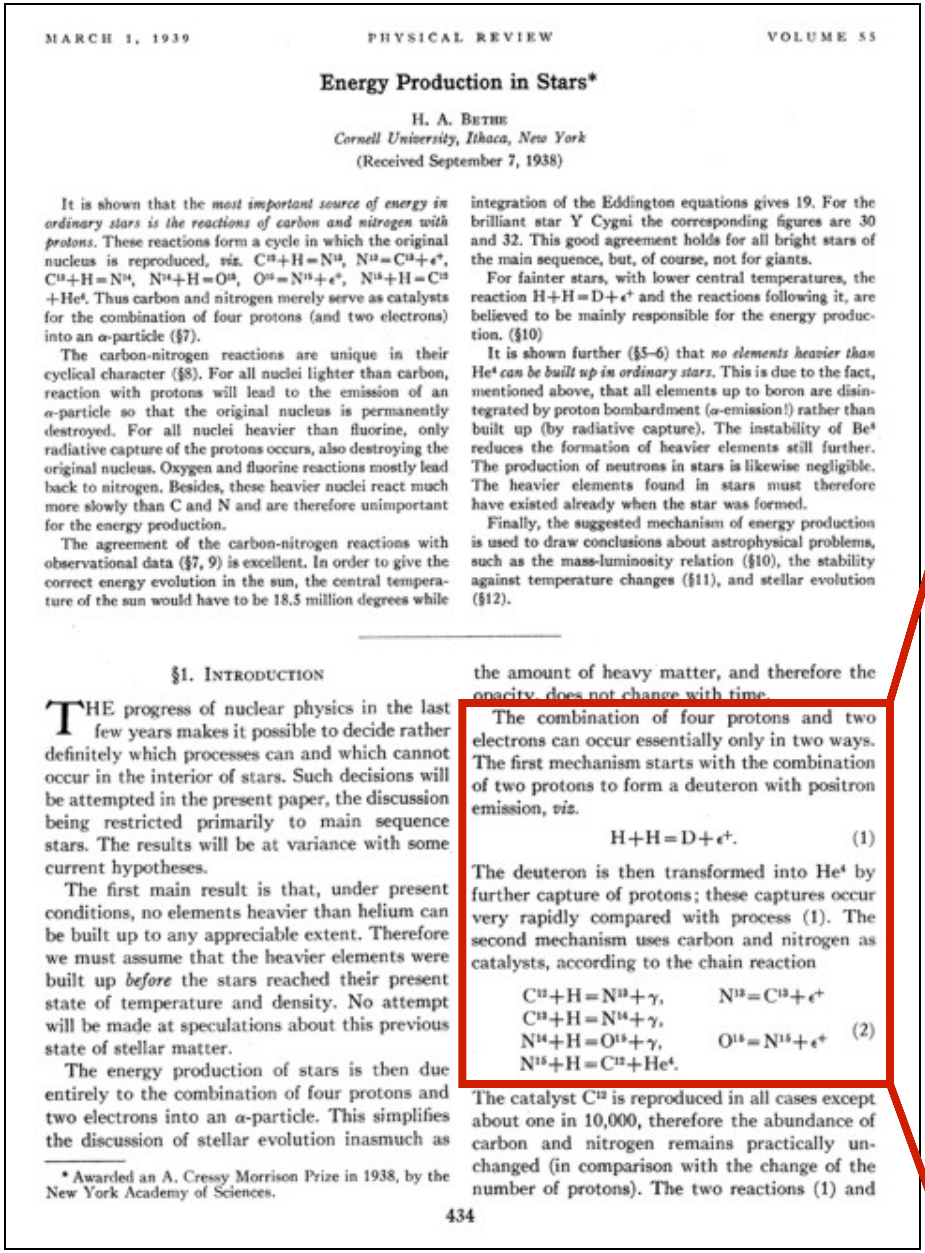


2 – Geoneutrinos

3 – Neutrinos from core-collapse supernovae (SNe) and in accretion disks around compact systems (BNS and BH)



Energy production in stars



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2)$$

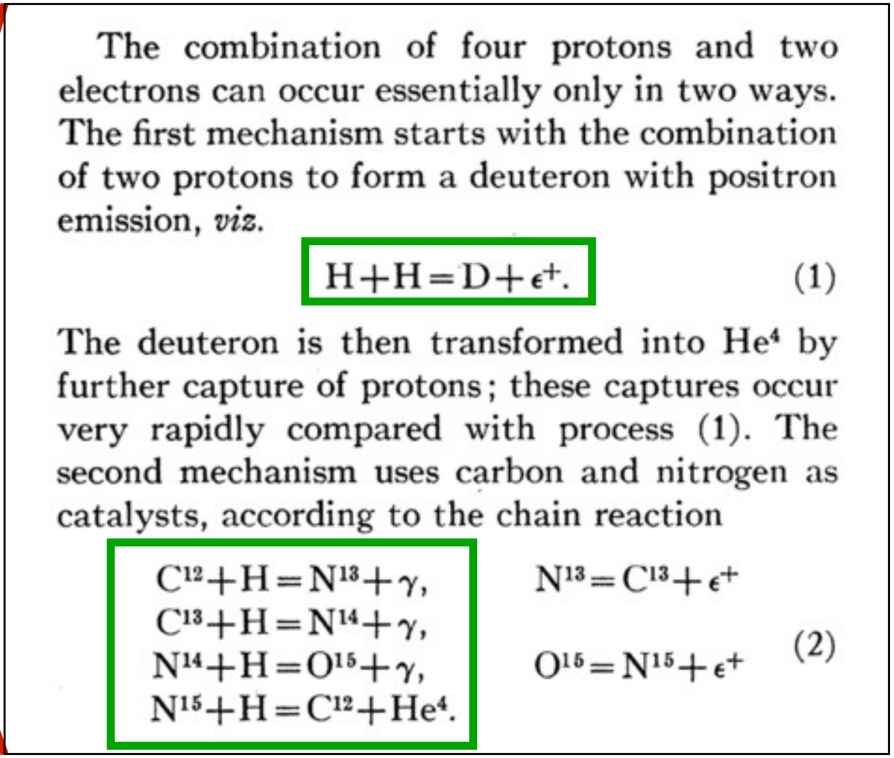
The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

---

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

In 1939 H. Bethe predicts that nuclear reactions are responsible for the energy production in stars.

no neutrinos…



The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

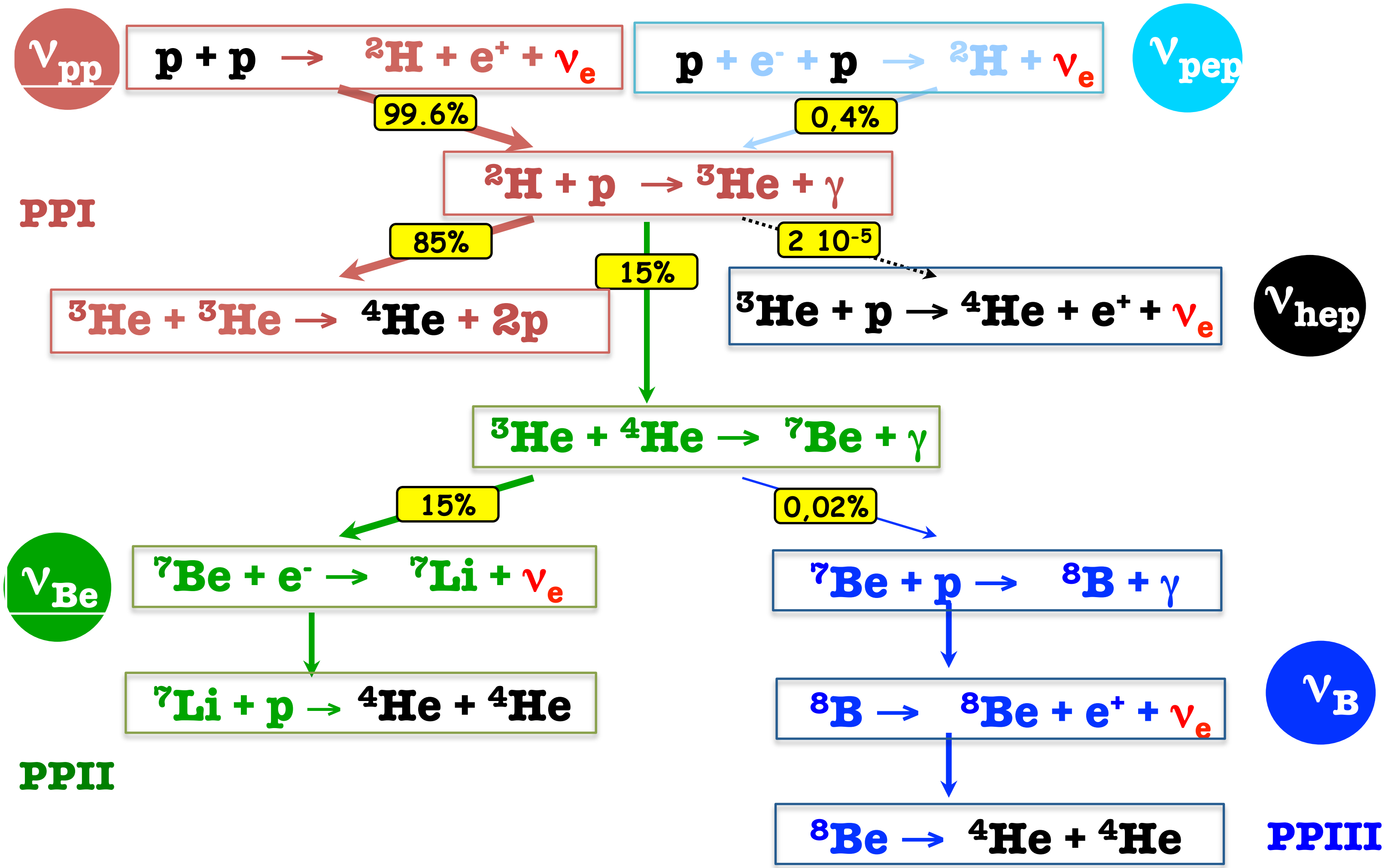
$$\boxed{H+H=D+\epsilon^+.} \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\boxed{\begin{array}{l} C^{12}+H=N^{13}+\gamma, \\ C^{13}+H=N^{14}+\gamma, \\ N^{14}+H=O^{15}+\gamma, \\ N^{15}+H=C^{12}+He^4. \end{array}} \quad \begin{array}{l} N^{13}=C^{13}+\epsilon^+ \\ \\ O^{15}=N^{15}+\epsilon^+ \end{array} \quad (2)$$

Neutrinos from the pp reaction chain

The proton-proton (pp) fusion reaction chain produces 99% of solar energy transforming H into ^{4}He.



ν_{pp} $p + p \rightarrow {}^2H + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2H + \nu_e$ ν_{pep}

99.6%

0,4%

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

PPI

85%

15%

$2\ 10^{-5}$

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

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$ ν_{hep}

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

15%

0,02%

ν_{Be} $^7Be + e^- \rightarrow {}^7Li + \nu_e$

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

$^7Li + p \rightarrow {}^4He + {}^4He$

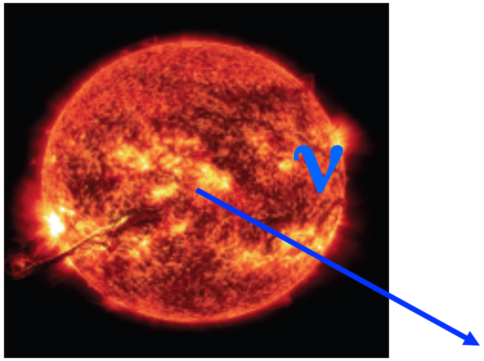
$^8B \rightarrow {}^8Be + e^+ + \nu_e$ ν_B

PPII

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

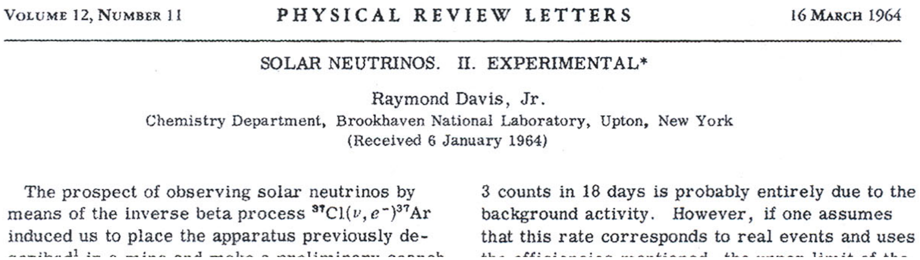
PPIII

First observation of solar neutrinos



Composition : 73% H, 25% He, 2% other
Central temperature : 15 10^6 degrees K

« We observe much less neutrinos than expected. »
Davis, Harmer, Hoffman, PRL20, 1968



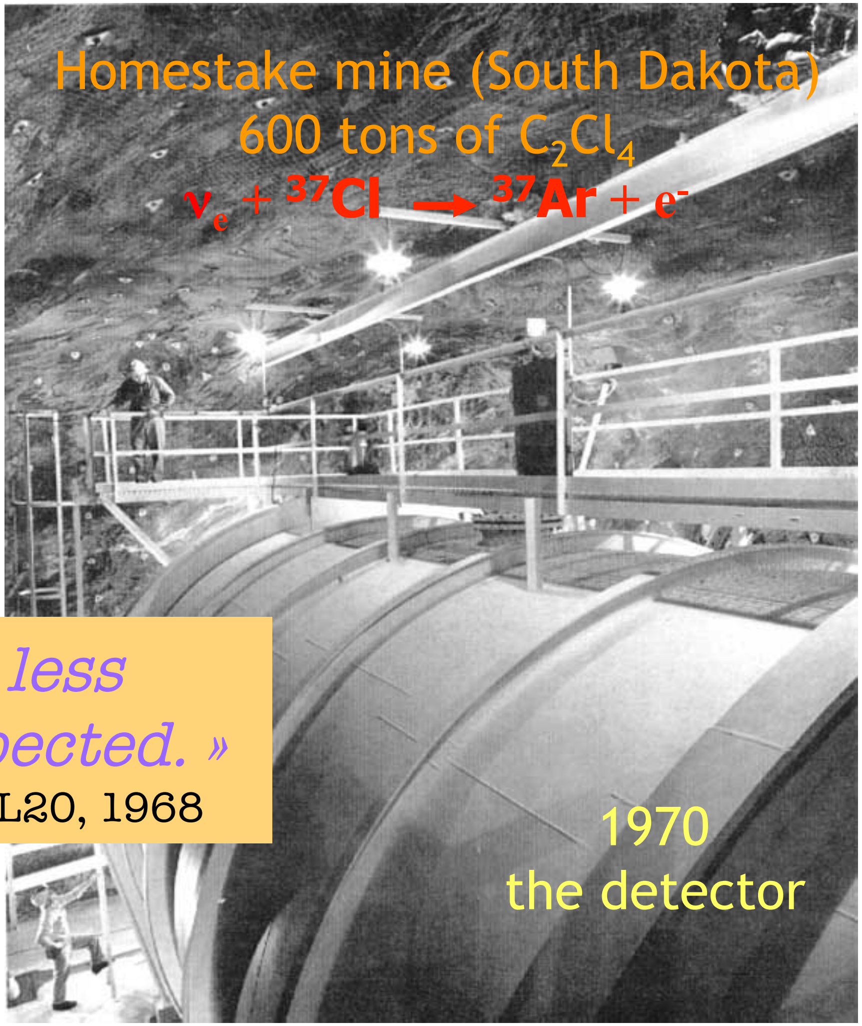
Volume 12, Number 11 PHYSICAL REVIEW LETTERS 16 March 1964

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}\mathrm{Cl}(\nu,e^-)^{37}\mathrm{Ar}$ induced us to place the apparatus previously de-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses



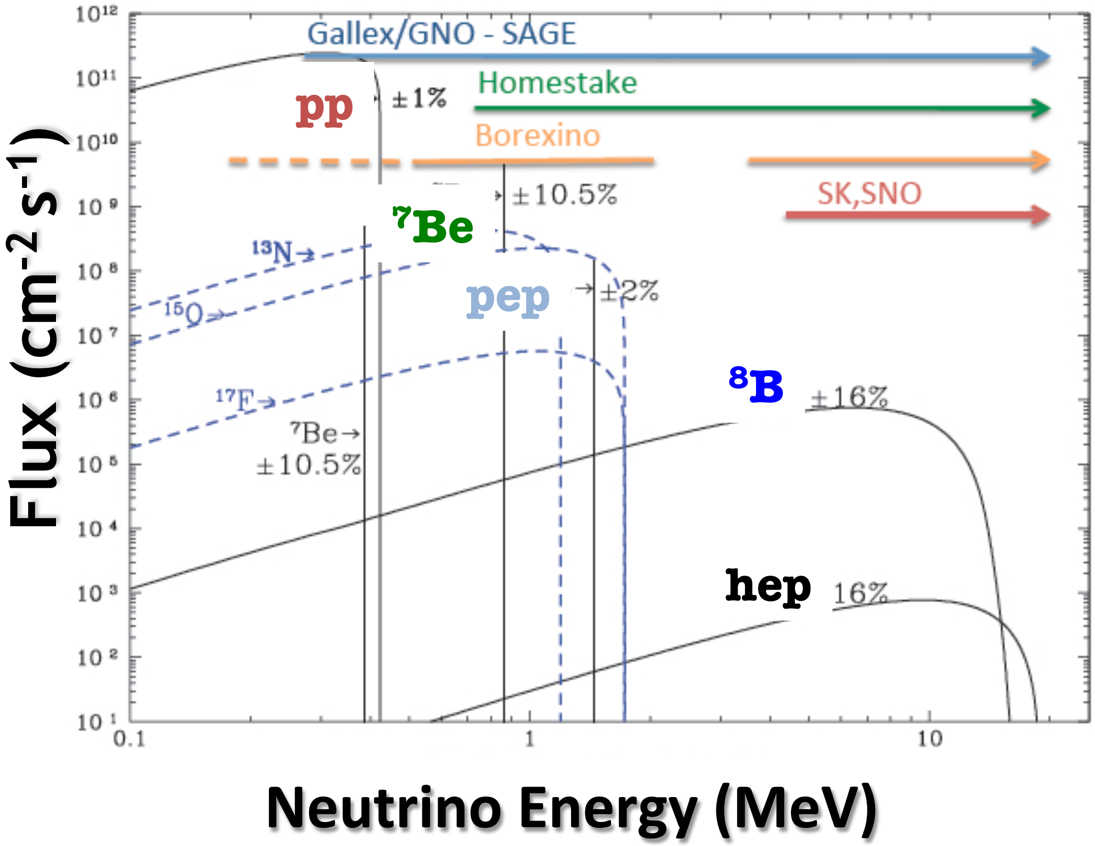
Homestake mine (South Dakota)
600 tons of C_2Cl_4

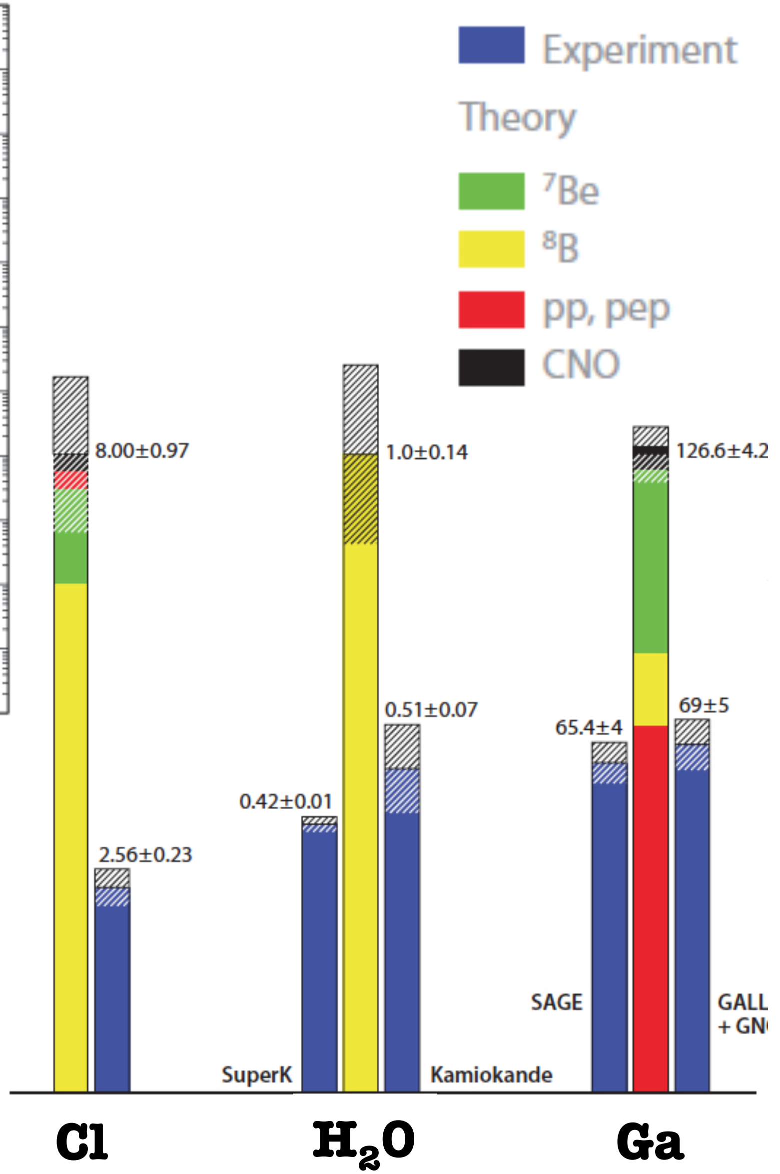
$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$

1970
the detector

2002 Nobel Prize

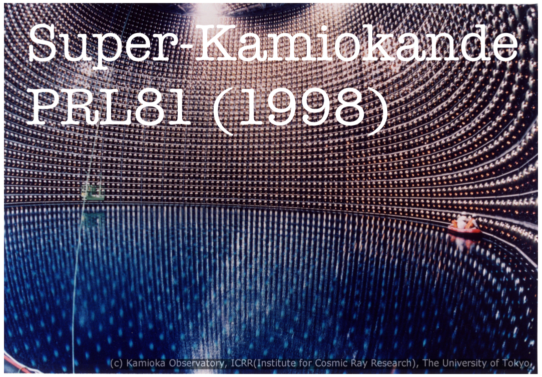
Neutrinos from the pp reaction chain





THE SOLAR NEUTRINO
DEFICIT PROBLEM

Solar ν deficit : the solution



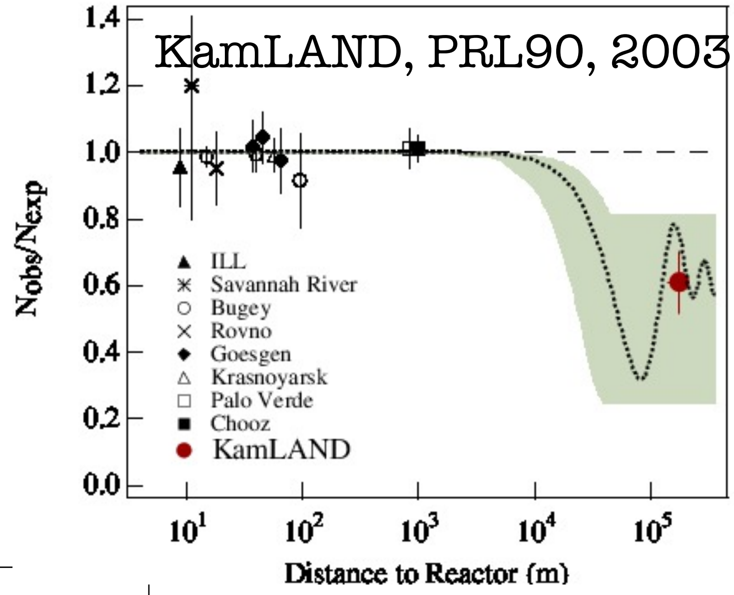
Super-Kamiokande PRL81 (1998)

50 kton, water Cherenkov (Japan)

1) The ν oscillation discovery with atmospheric ν.

3) Kamland identifies the MSW large-mixing-angle (MSW) solution.

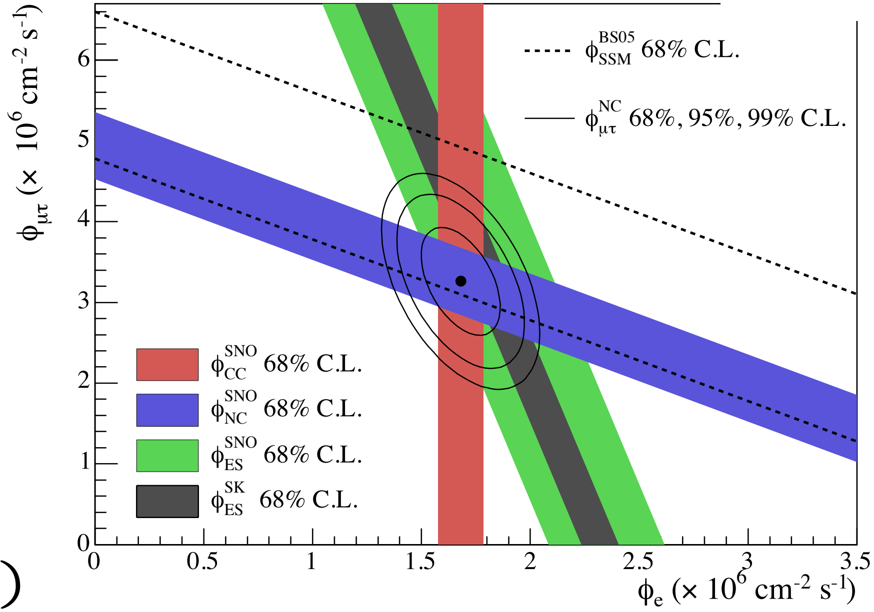
1 kton, scintillator (Japan), reactor $\bar{\nu}_e$



KamLAND, PRL90, 2003

SNO, PRL89, 2002

1 kton, heavy water (Canada)



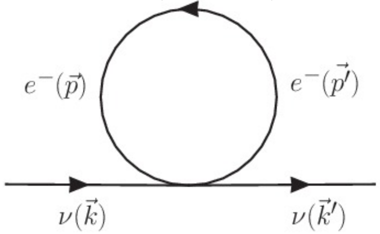
$\nu_e + D \rightarrow p + p + e^-$ (CC)
$\nu_x + D \rightarrow \nu_x + p + n$ (NC)
$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

2) The total solar flux consistent with SSM. Non-zero ν_μ,ν_τ flux (5.3 σ).

2015 Nobel Prize

Mikheev-Smirnov-Wolfenstein (MSW) effect

Wolfenstein PRD (1978)



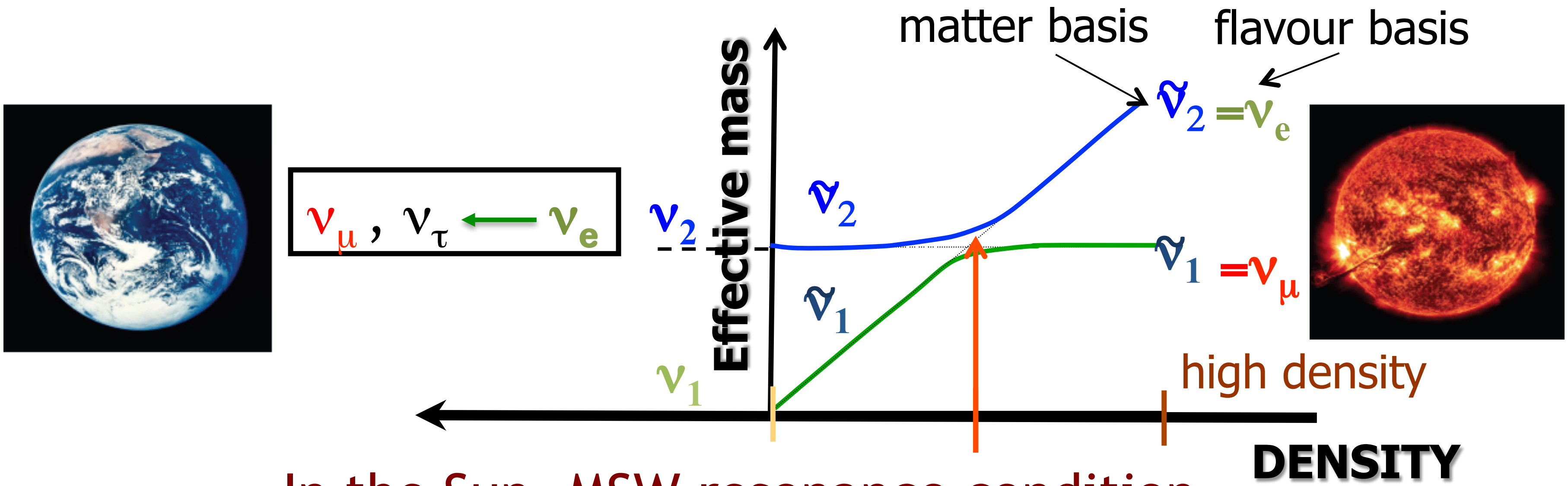
Mikheev, Smirnov(1985)

$$H_{\nu_e}(\rho_e) = \sqrt{2} G_F \rho_e$$

MEAN-FIELD

electron
number density

Resonant flavour conversion due to ν-matter interactions



In the Sun, MSW resonance condition met and evolution adiabatic. It gives the sign of Δm^2.

It occurs in the Sun, in Supernovae, in AD, in Earth and Early Universe (BBN).

Current status of solar ν_e

The low energy pp neutrinos, from the keystone fusion reaction, pep, ^{7}Be measured.

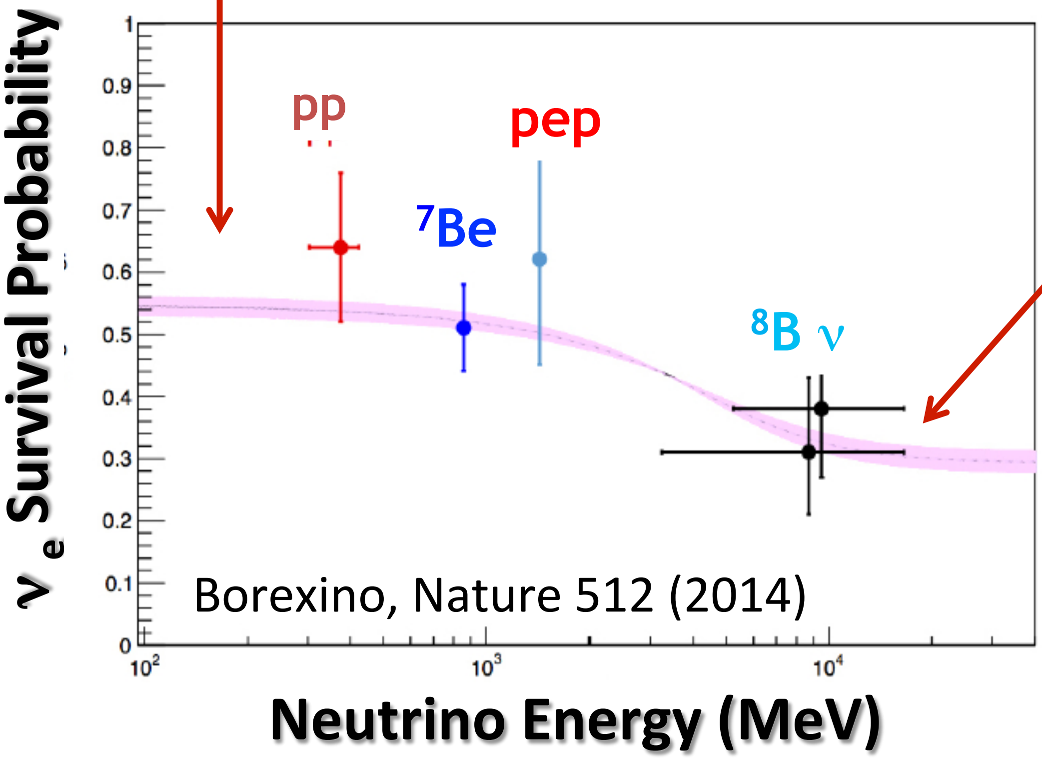

Borexino (Gran Sasso)

280 tons, liquid scintillator

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

Vacuum averaged oscillations

$$P(\nu_e \to \nu_e) \approx 1 - \frac{1}{2}\sin^2 2\theta_{12} \approx 0.57$$



Borexino, Nature 512 (2014)

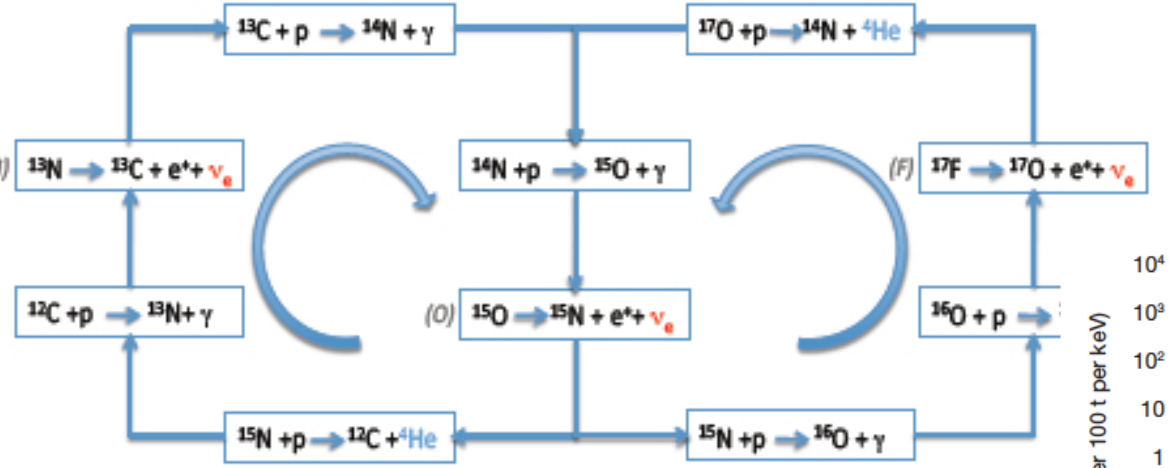
MSW solution

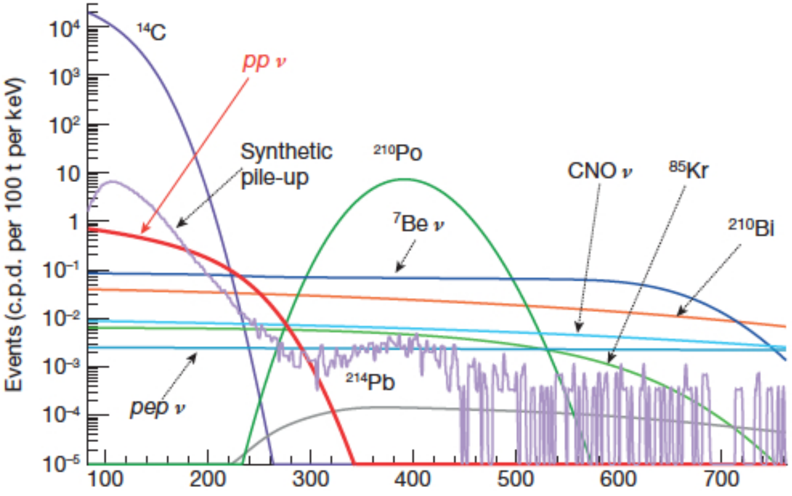
$$P(\nu_e \to \nu_e)^{\text{high density}} \to \sin^2\theta_{12} \approx 0.31$$

Transition from vacuum oscillation to MSW solution can reveal new physics such as non-standard Interactions.

Carbon-Nitrogen-Oxygen (CNO) ν

The CNO cycle : responsible for 1% of the energy production in the Sun. The dominant mode for hydrogen burning in massive main sequence stars.





Neutrino Energy (MeV)

Current limit best limit from Borexino. It will be observed in SNO+ (780 ton) and Borexino (phase II) by achieving Challenging reduced backgrounds.

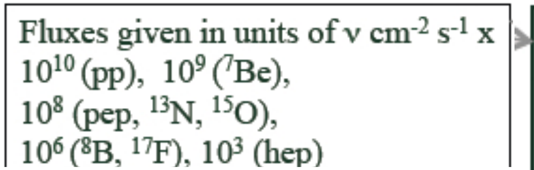
Key CONFIRMATION of evolutionary models.

The metallicity problem

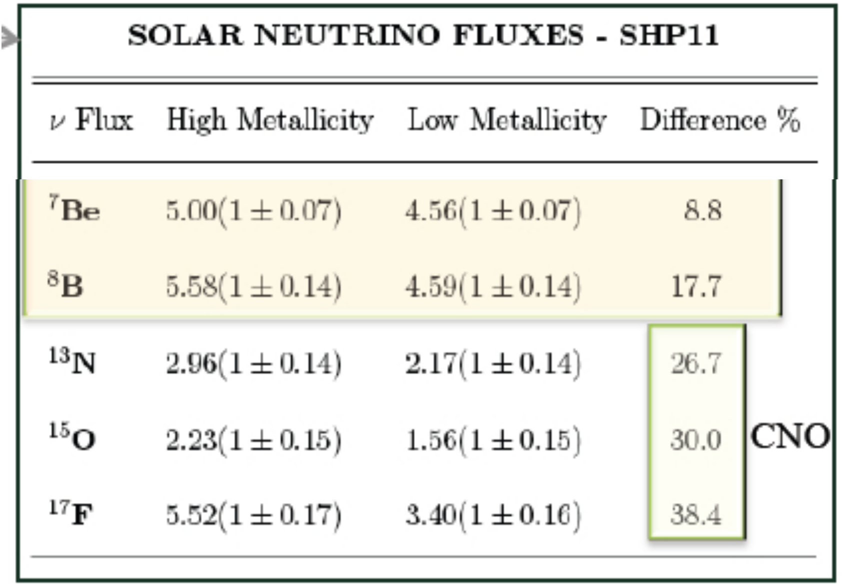
Z/X = surface metals – to –hydrogen ratio

Older Standard Solar Model (SSM) : GS98, Z/X = 0.0229, 1D

New Standard Solar Model : AGSS09, Z/X = 0.0178, 3D, agreement with helioseismology spoiled.



Fluxes given in units of ν cm^{-2} s^{-1} x
10^{10} (pp), 10^{9} (^{7}Be),
10^{8} (pep, ^{13}N, ^{15}O),
10^{6} (^{8}B, ^{17}F), 10^{3} (hep)



SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Low Metallicity	Difference %
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	8.8
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	17.7
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	26.7
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	30.0
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	38.4

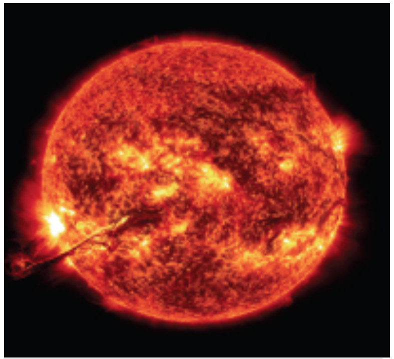
CNO

Serenelli, et al. ApJ 743 (2011)

CNO ν with 12 % precision will solve the metallicity problem.

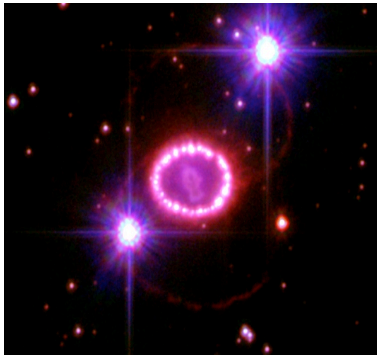
Outline

1 - Solar neutrinos

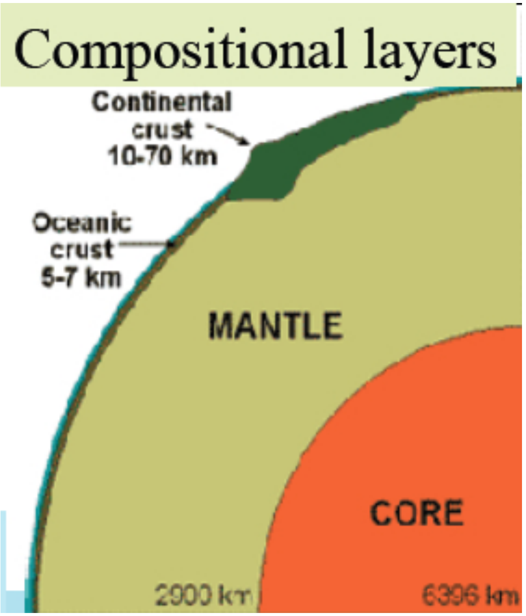


2 – Geoneutrinos

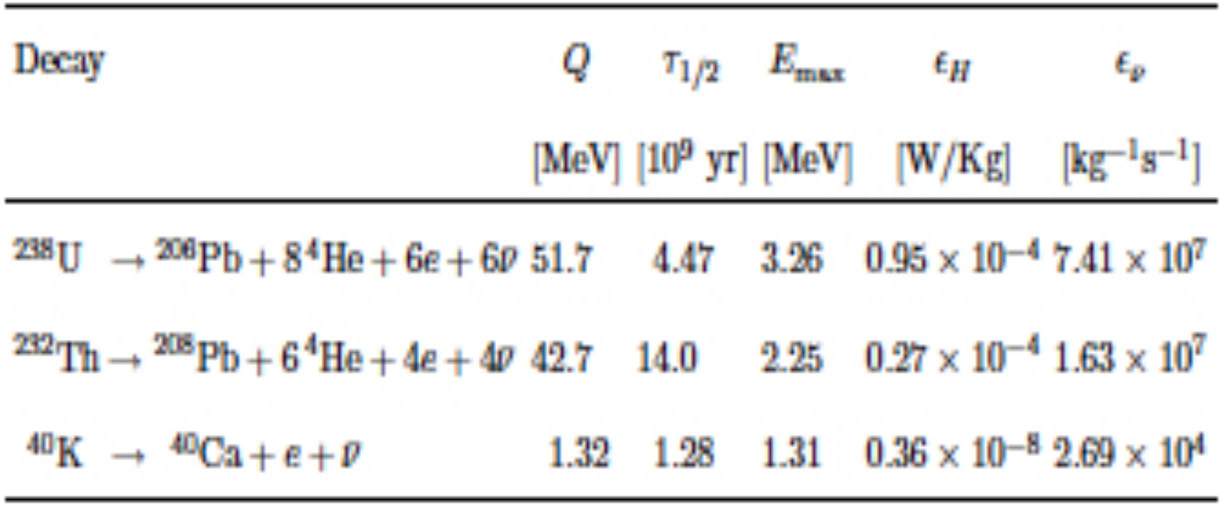
3 – Neutrinos from core-collapse supernovae (SNe) and in accretion disks around compact systems (BNS and BH)



Why geo-neutrinos ?



Geoneutrinos are $\overline{\nu}_e$ produced by long-lived radioactive elements within our planet.



Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	E_{max} [MeV]	ϵ_H [W/Kg]	$\epsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]
$^{238}U \to {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	51.7	4.47	3.26	0.95×10^{-4}	7.41×10^7
$^{232}Th \to {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	42.7	14.0	2.25	0.27×10^{-4}	1.63×10^7
$^{40}K \to {}^{40}Ca + e + \bar{\nu}$	1.32	1.28	1.31	0.36×10^{-8}	2.69×10^4

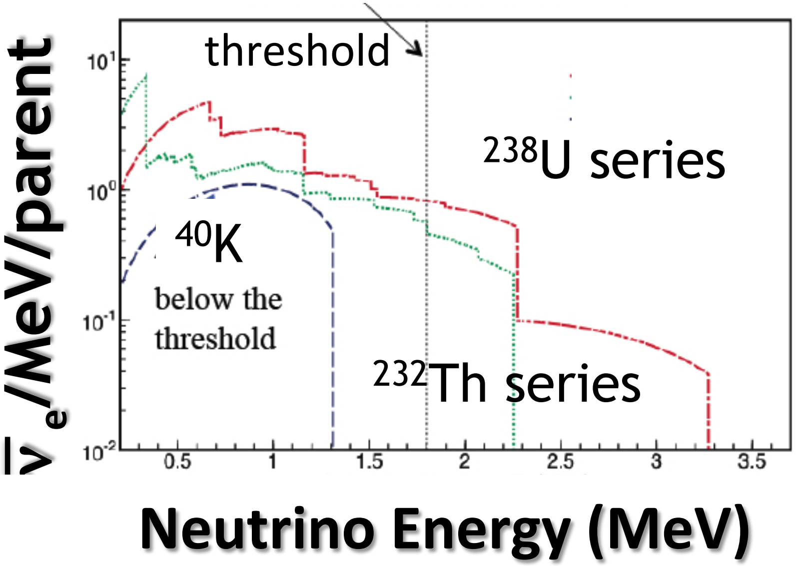
Fiorentini et al. PRD72 (2005)

Global terrestrial power output : 47 pm 2 TW.

Davies and Davies, Solid Earth 1 (2010).

Their measurement of the geoneutrino flux gives information on the amount of U, Th, K in the crust and the mantle, the associated radiogenic heat and furnishes tests of Earth models (BSE).

Geo-neutrino observations

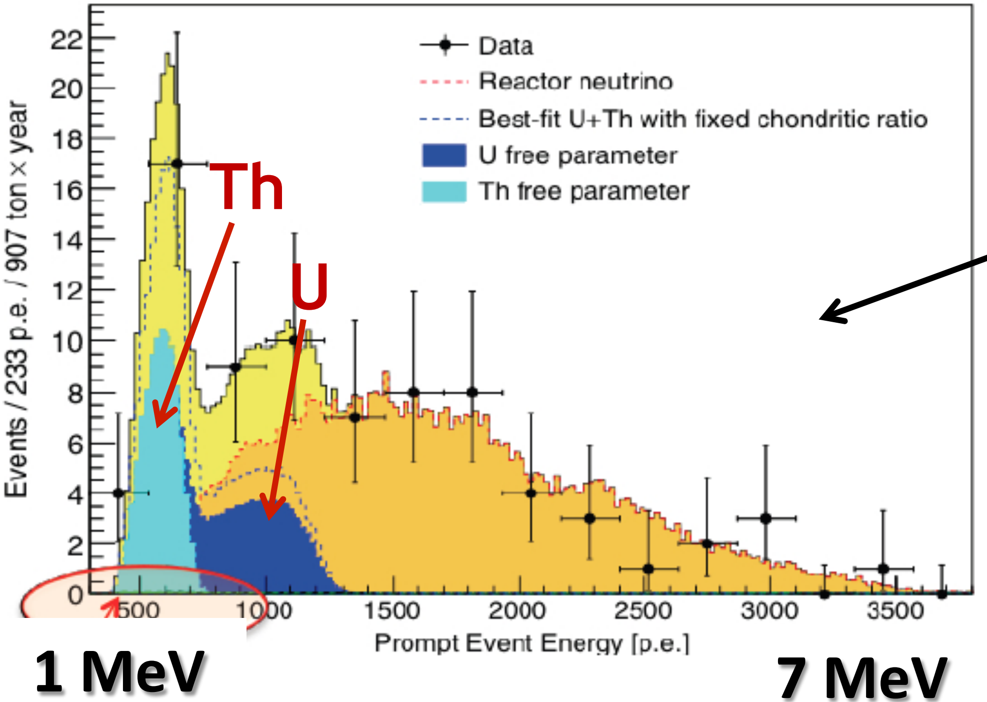


First observed by KamLAND.
Araki et al., Nature 436 (2005).

Detected via inverse beta-decay :

$\bar{\nu}_e + p \rightarrow n + e^+$

prompt signal by γ from $e^- e^+$ annihilation and delayed signal (2.2 MeV γ) from n capture on p.



Geoneutrino events measured :

116^{+28}_{-27} KamLAND, PRD 88 (2013).

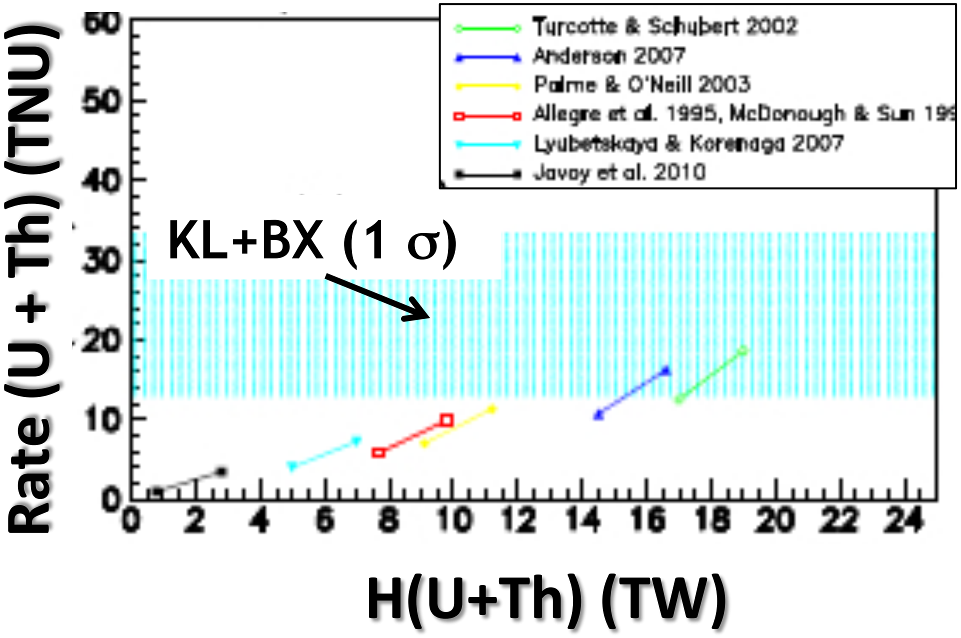
$23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys)

Null hypothesis excluded at 5.9 σ.

Total terrestrial radiogenic power: $P(U+Th+K) = 33^{+28}_{-20}$ TW .

Borexino coll., PRD 92 (2015)

Geo-ν observations and future



Positive signal from the mantle.
It requires a good knowledge of the local crust contribution :
Sgeo(mantle) = Sgeo – Sgeo(crust)

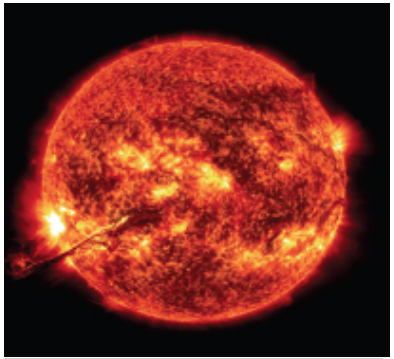
Comparison with different models for the primitive mantle, Th/U ratio and distribution.
Fiorentini et al. PRD86 (2012)

FUTURE

- ☐ Borexino switches to SOX (sterile searches).
- ☐ SNO+ (Canada), starts 2017.
  A good knowledge of local crust contribution needed.
- ☐ JUNO, 20 kton (China), starts 2020.
- ☐ Hano-Hano, 10 kton (Hawaii), transportable, mantle contribution at oceanic crust. Not funded yet.

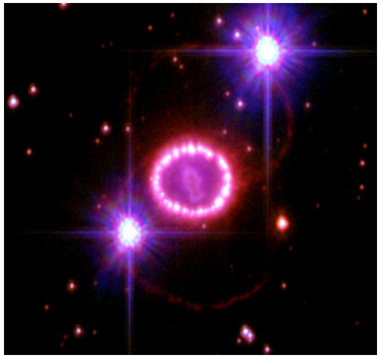
Outline

1 - Solar neutrinos



2 – Geoneutrinos

3 – Neutrinos from core-collapse supernovae (SNe) and in accretion disks around compact systems (BNS and BH)

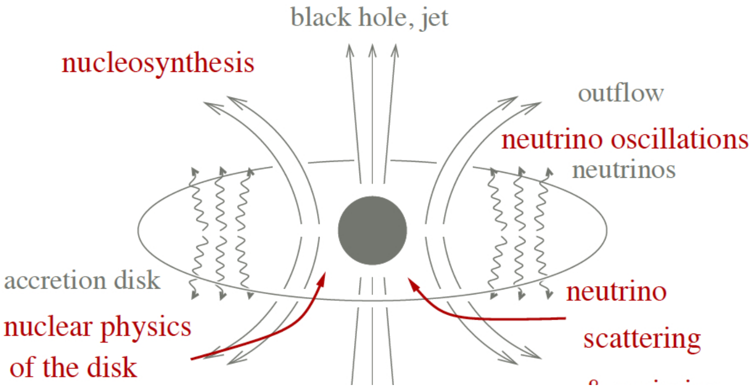


Where are heavy elements made ?

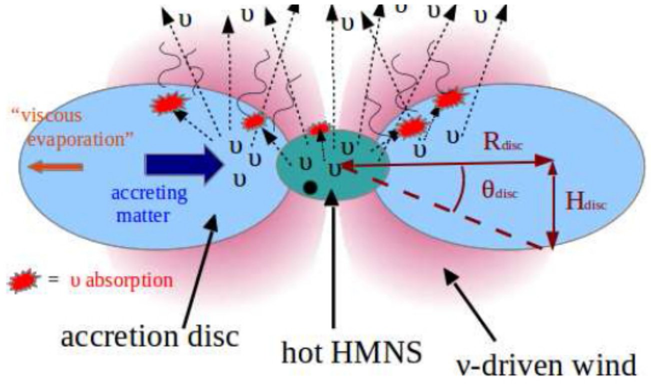
The site(s) where nucleosynthesis produces heavy elements, by rapid neutron capture (r-process), remains unknown. Neutrinos set neutron-to-proton ratio, a key parameter, by

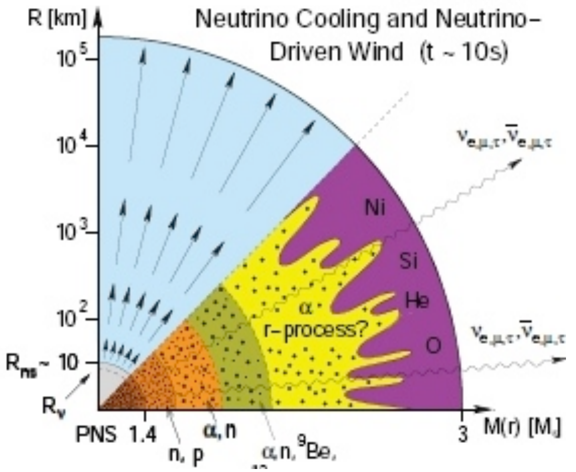
$\nu_e + n \rightarrow p + e^-$ $\bar{\nu}_e + p \rightarrow n + e^+$

accretion disks around black holes

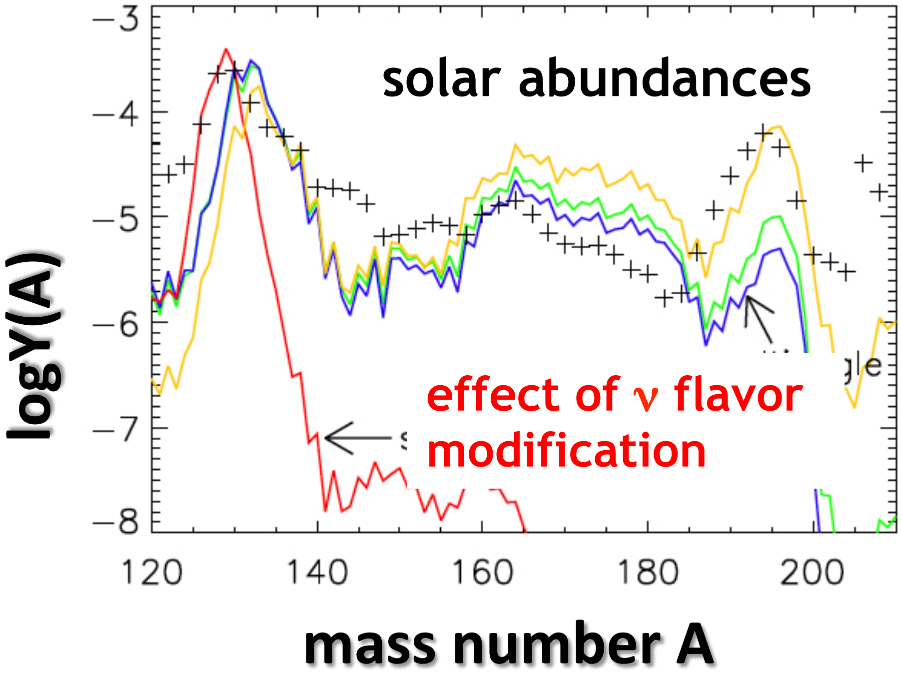


or around neutron star mergers





core-collapse supernovae



solar abundances

effect of ν flavor modification

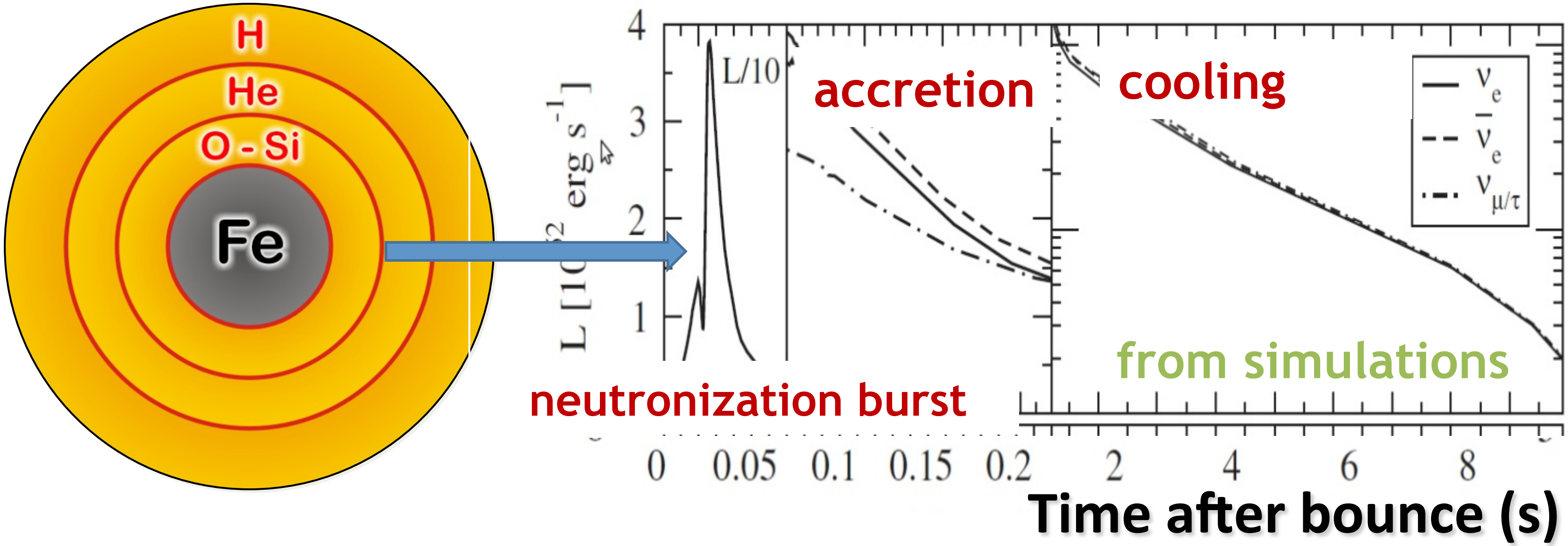
Core-collapse supernova ν

Massive stars ($M > 8\ M_{sun}$) produce 10^{58} ν of about 10 MeV in 10 s from the gravitational collapse of massive stars.

Colgate and White, 1966

Neutrinos deposit energy behind the shock to trigger the explosion - delayed neutrino heating explosion mechanism.

Bethe and Wilson, 1985

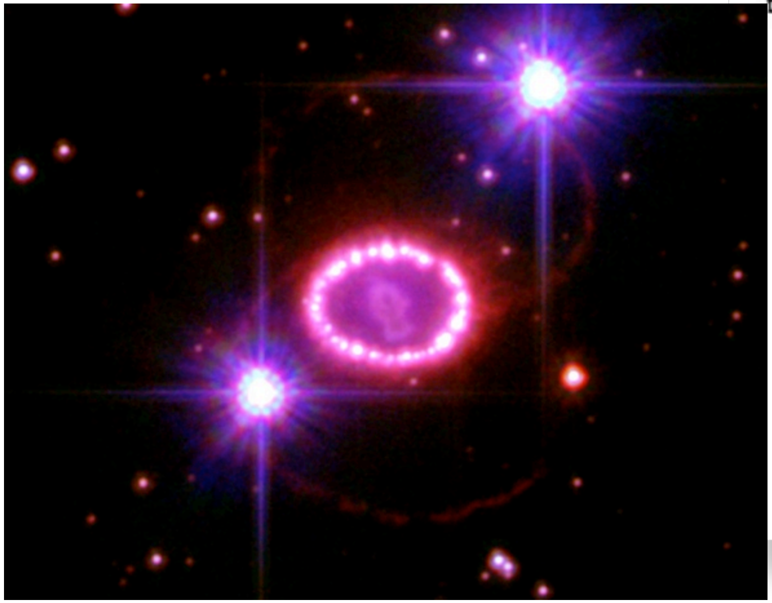


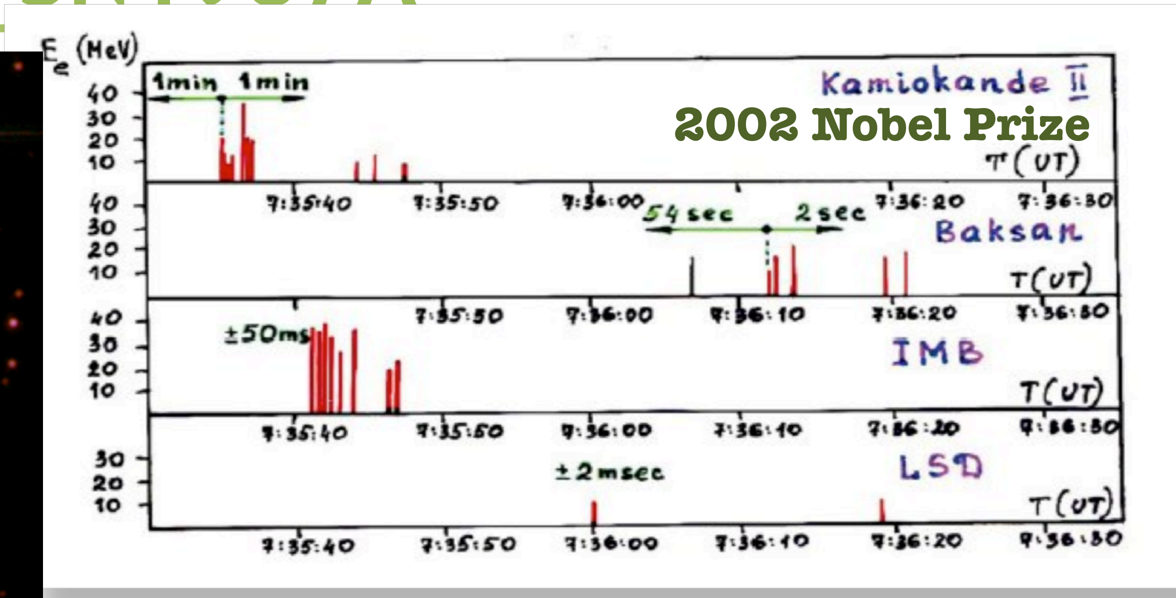
Hüdepohl *et al.* PRL (2010)

Simulations not yet successful

(3D, hydrodynamic instabilities, realistic neutrino transport)

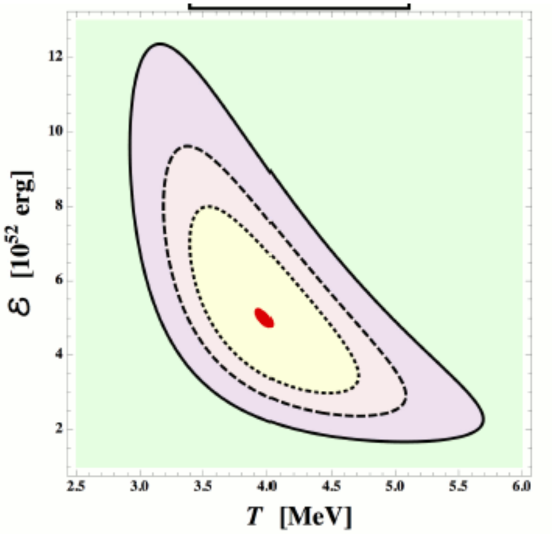
SN1987A





2002 Nobel Prize

Sanduleak 69^{0}202,
a blue super-giant in
Large Magellanic Cloud,
at 50 kpc,
no remnant found so far.



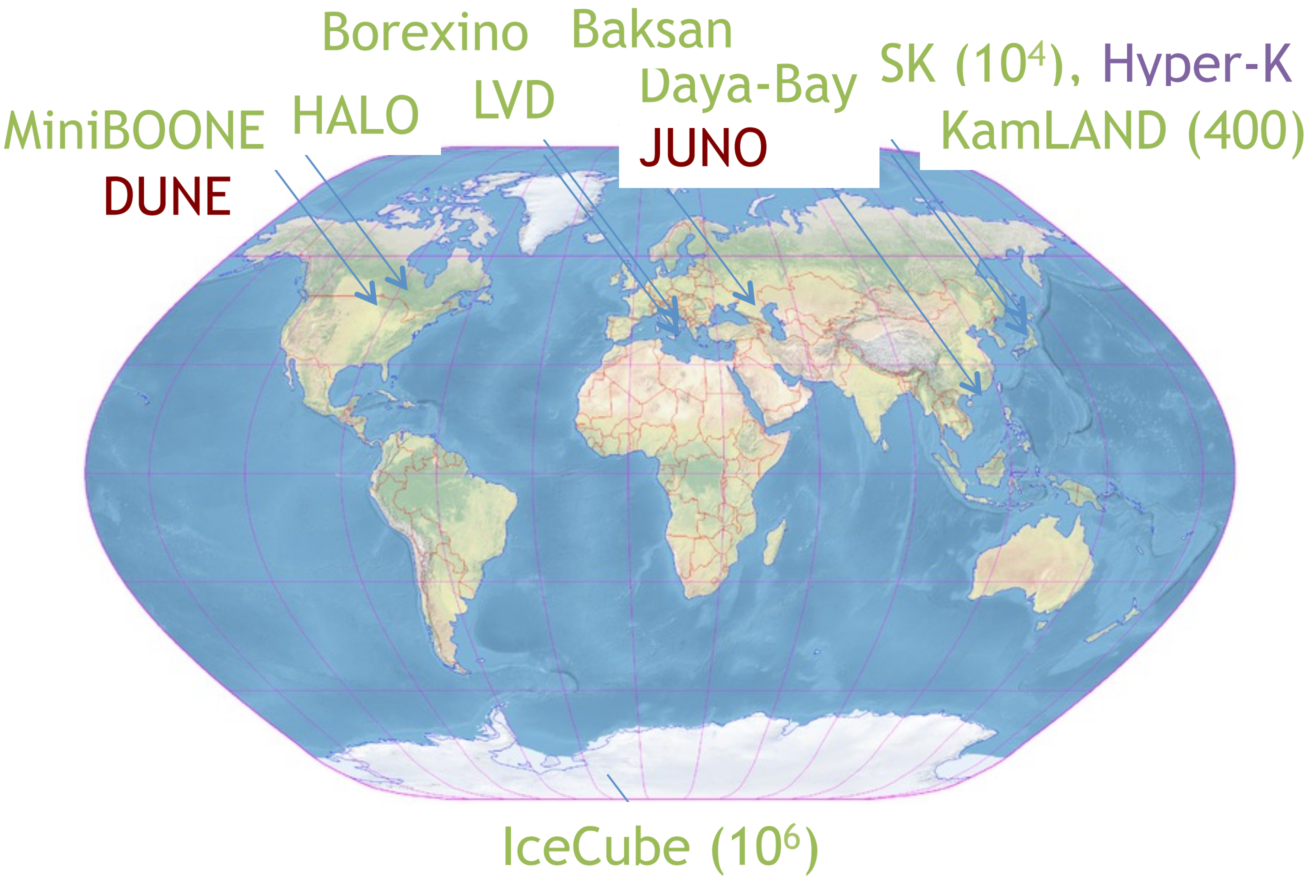
Vissani, JPG (2014)

Time and energy signal
agrees with predictions.

Interesting limits on
neutrino properties
and non-standard physics.

Supernova ν observatories

If a supernova explodes in our galaxy (10 kpc), detectors will collect up to 10^6 events.



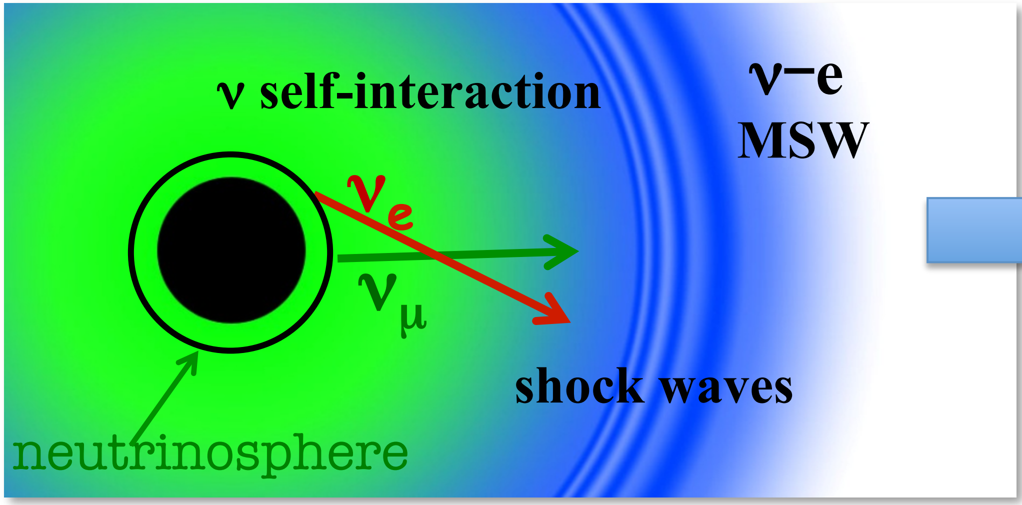
Different detection channels available :
scattering of anti-ν_e with p, ν_e with nuclei, ν_x with e, p

SNEWS – Supernova Early Warning System

Neutrino flavor conversion in media

Flavour conversion phenomena emerge, due to

- ☐ neutrino-matter coupling – MSW effect
- ☐ presence of shock waves or turbulence
- ☐ neutrino-neutrino interaction.



A lot of theoretical work still needed.

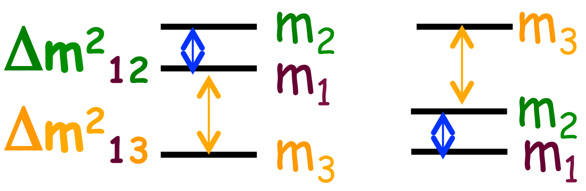
- ➢ impact on nucleosynthesis and supernova dynamics
- ➢ flavor modification phenomena and their effects

Connection to condensed matter and many-body systems (atomic nuclei, clusters).

Volpe et al., PRD 87 (2013).

Signatures of neutrino mass ordering

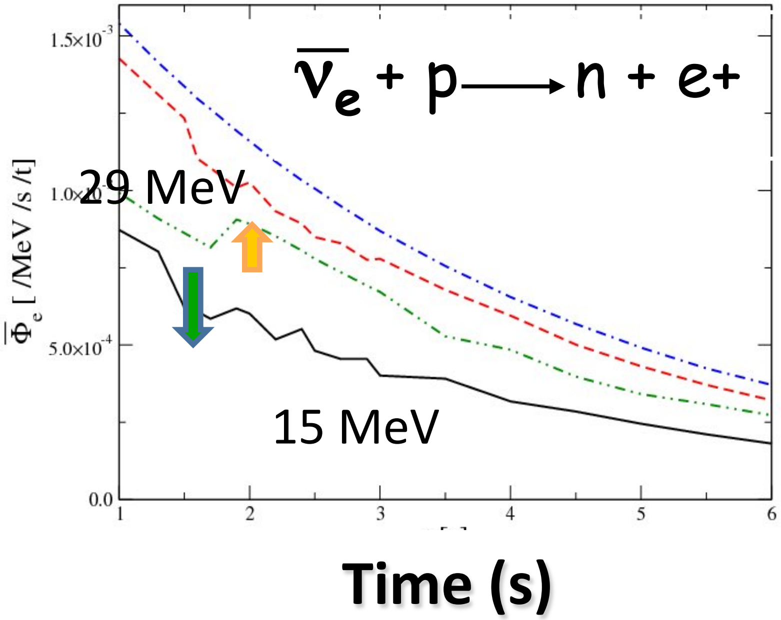
If a supernova (1-3/century) at 10 kpc explodes :



Inverted ($\Delta m^2_{13} < 0$)

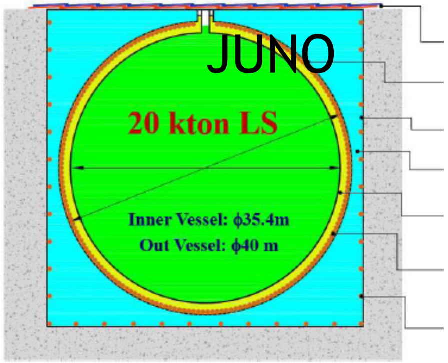
Normal ($\Delta m^2_{13} > 0$)

Shock-wave imprint depending on the mass ordering.



Gava et al, PRL 103 (2009)

Dip (bump) at 3.5 (1) σ in Super-Kamiokande.
JUNO and Hyper-Kamiokande.



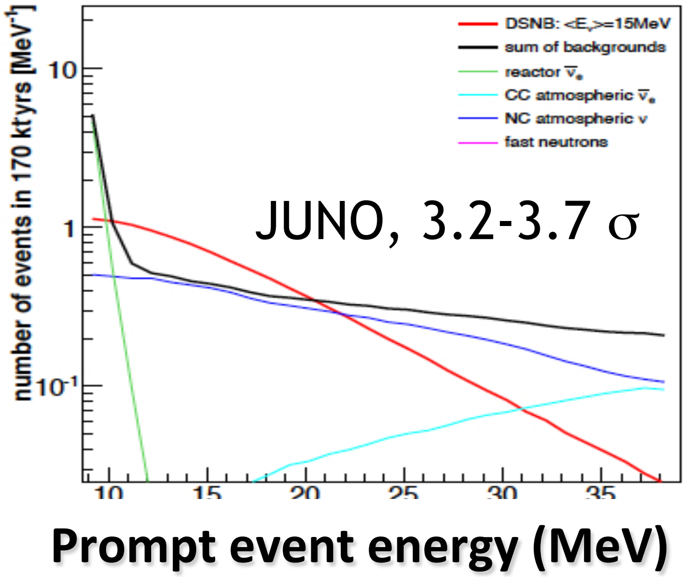
Also in JUNO, Hyper-Kamiokande and ν_e detectors.

SN signals can give Information on unknown ν properties.

The Diffuse Supernova ν Background

The integrated ν neutrino flux from supernovae at different redshifts :

An et al. J. Phys.G (2016)



$$F_\alpha(E_\nu) = \int dz \left|\frac{dt}{dz}\right| (1+z) R_{SN}(z) \frac{dN_\alpha(E'_\nu)}{dE'_\nu},$$

$$E'_\nu = (1+z)E_\nu,$$

✓ Upper limits on DSNB fluxes :
1.4-1.9 anti-ν_e /cm^2/s
73-154 ν_e/cm^2/s

Lunardini and Peres, JCAP (2008)

	Events (10 y)	window	detector	
$\bar{\nu}_e$	90	9-25 MeV	50 kton	scintillator
$\bar{\nu}_e$	300	19-30 MeV	440 kton	Hyper-K
ν_e	30	17-41 MeV	50 kton	liquid argon

Galais et al PRD 81(2010)

EGADS (Super-Kamiokande with Gd.

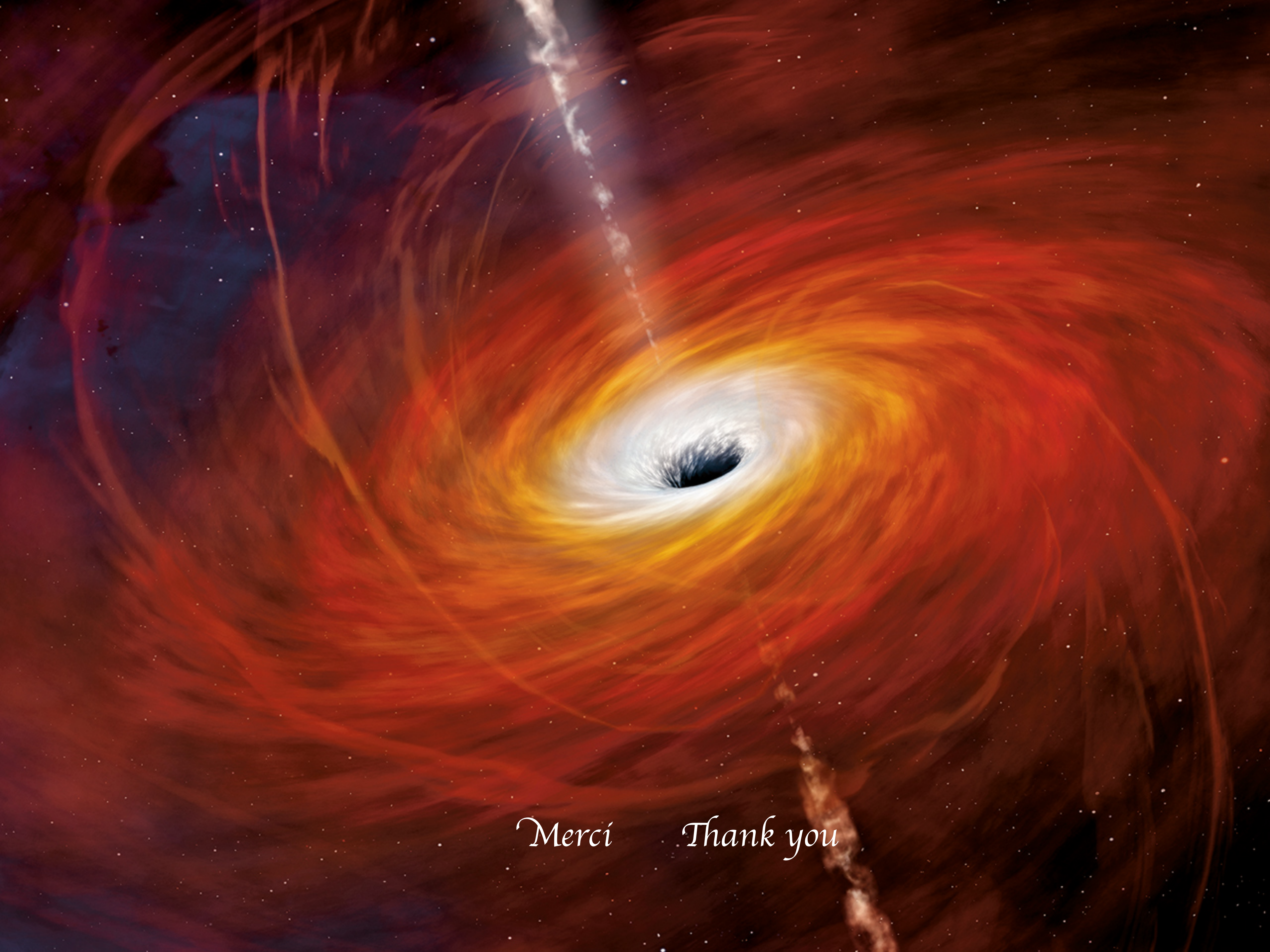
Upcoming projects have the discovery potential.

Conclusions and perspectives

- **Solar neutrinos :** deficit undestood and MSW effect established. We understand how energy is produced in the Sun and low mass stars. Future goals : to study vacuum to MSW transition and discover CNO ν.

- **Geo-neutrinos :** observed. Mantle contribution identified. Future measurements should precisely measure the radiogenic contribution to the Earth power and determine the Th/U ratio.

- **Neutrinos from supernovae and in accretion disks :** discover the diffuse supernova background. Neutrinos from (extra)galactic supernovae will bring key Information on the explosion mechanism.
  Steady theoretical progress on neutrino flavor conversion. Many crucial questions need to be tackled.



Merci Thank you