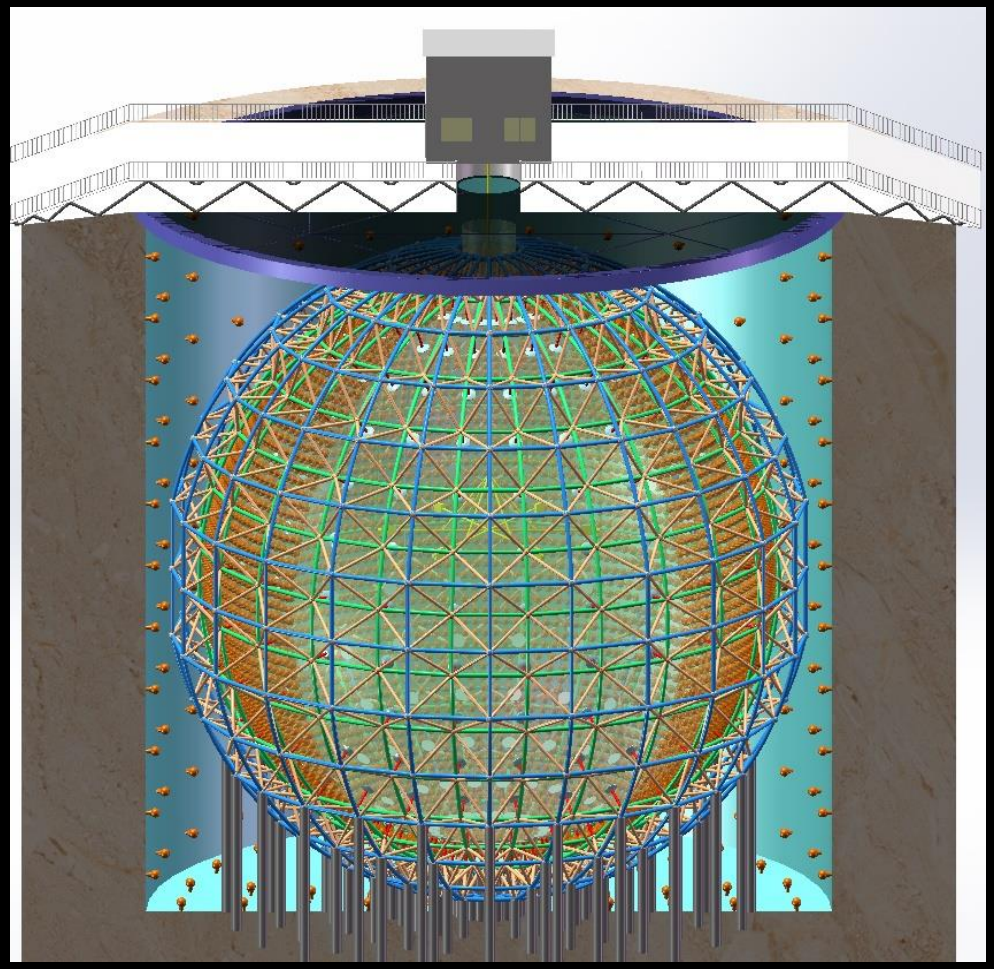
Astrophysics Potential of JUNO

Shun Zhou
IHEP, CAS, Beijing
on behalf of the JUNO Collaboration

The 8th Workshop of France-China Particle Physics Laboratory
USTC, Hefei, April 8 - 10, 2015

The JUNO Experiment

- **Jiangmen Underground Neutrino Observatory (JUNO), a multiple-purpose neutrino experiment, approved in Feb. 2013, ~ 300 M$.**

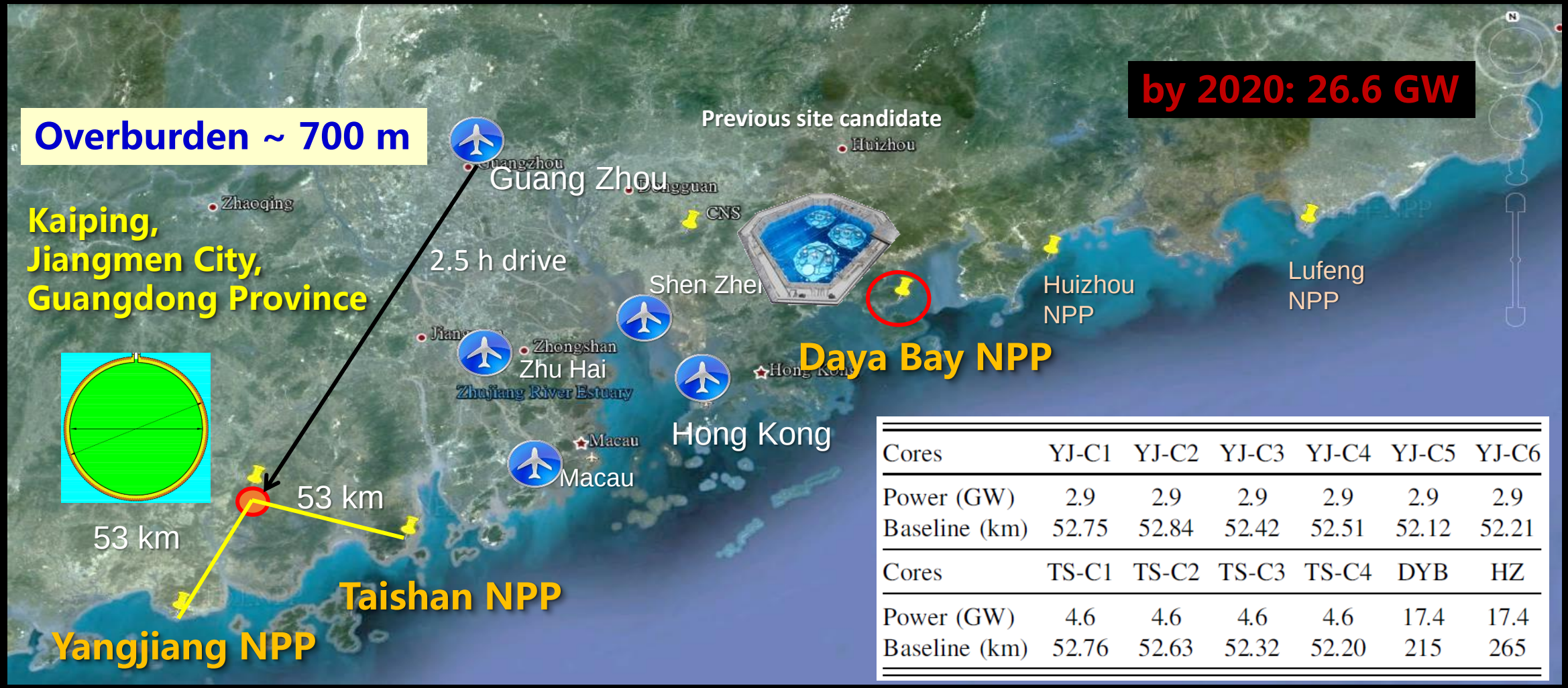


- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich Physics Possibilities**
  - **Reactor Neutrinos for neutrino mass hierarchy & precision measurement of oscillation parameters**
  - ***Supernova Neutrino Burst***
  - ***Diffuse Supernova Neutrino Background***
  - **Geoneutrinos**
  - **Solar Neutrinos**
  - **Atmospheric Neutrinos**
  - **Proton Decays**
  - **Exotic Searches**

Talks by Y.F. Wang at ICFA Seminar 2008, Neutel 2011; by J. Cao at Neutel 2009, NuTurn 2012, NeuTel 2015 ; Papers by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009; Y.F. Li, J. Cao, Y.F. Wang, L. Zhan, PRD 88: 013008, 2013.

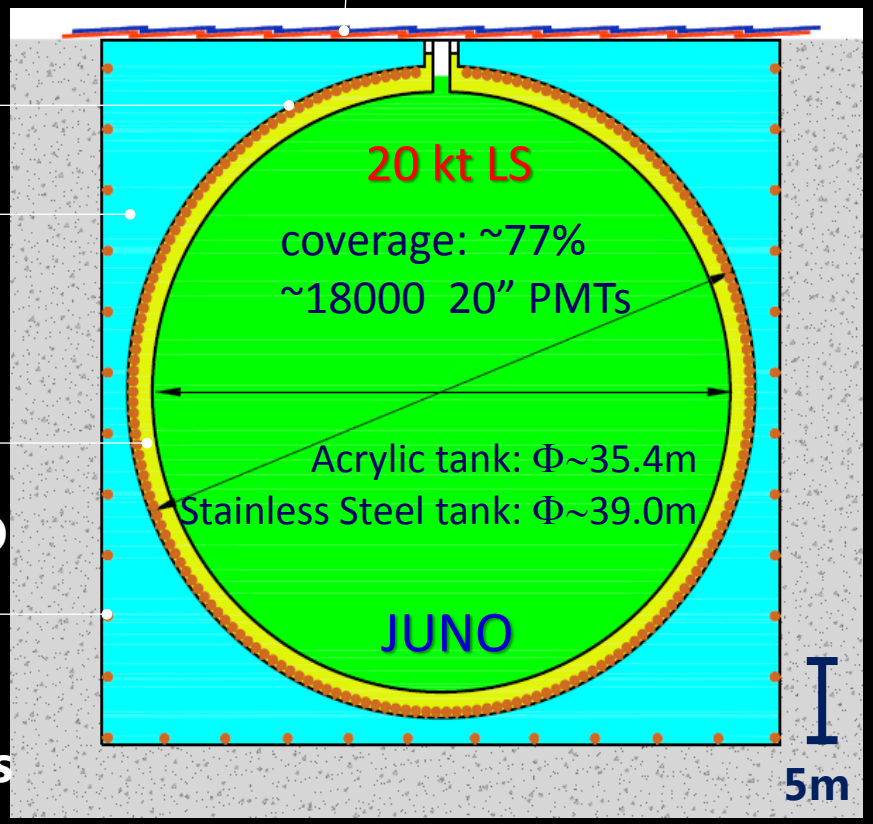
Location of JUNO

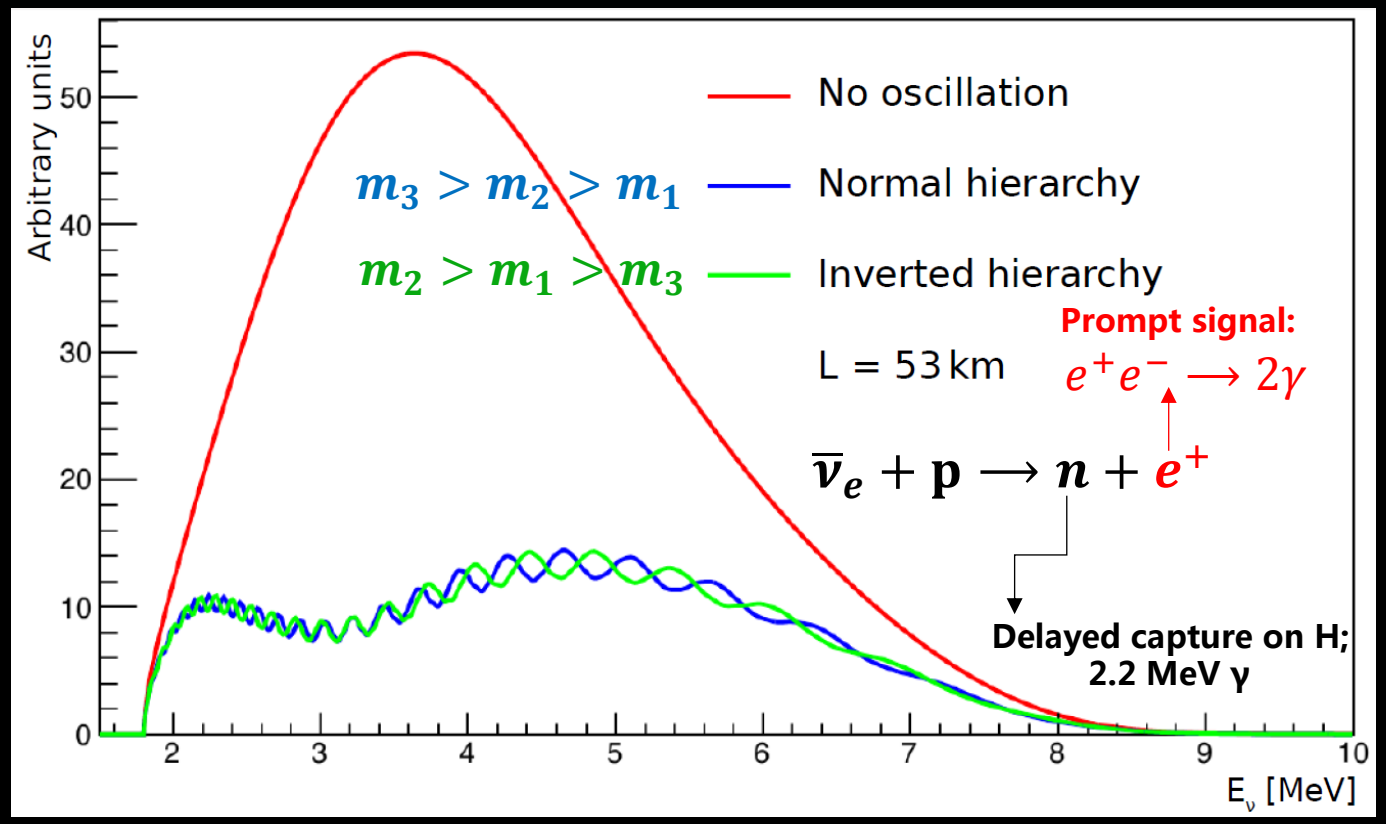
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

High-precision, Giant LS detector

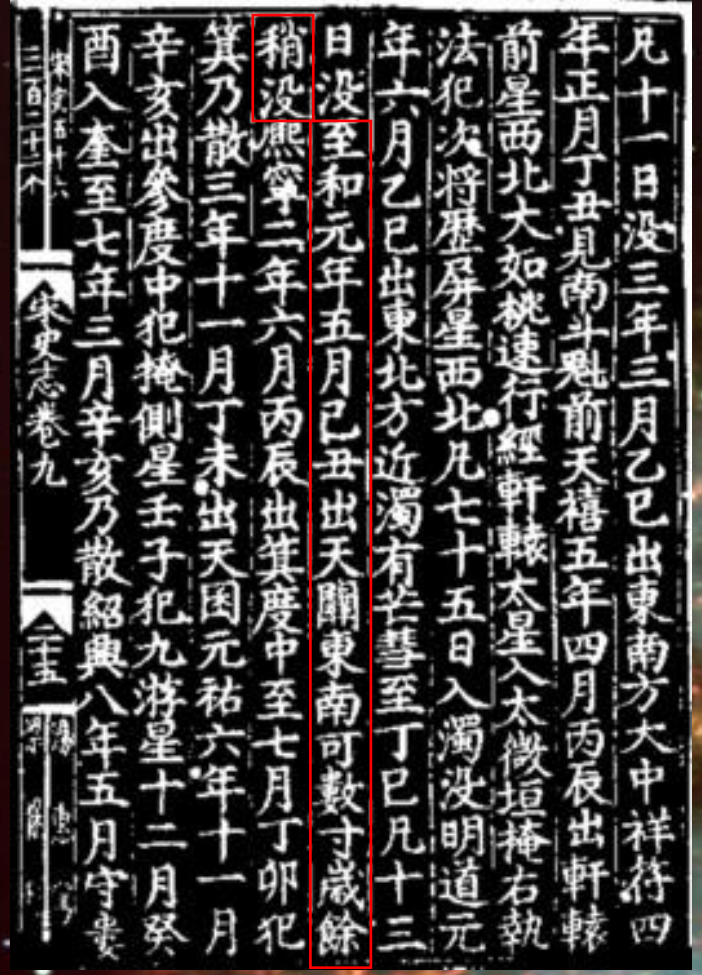




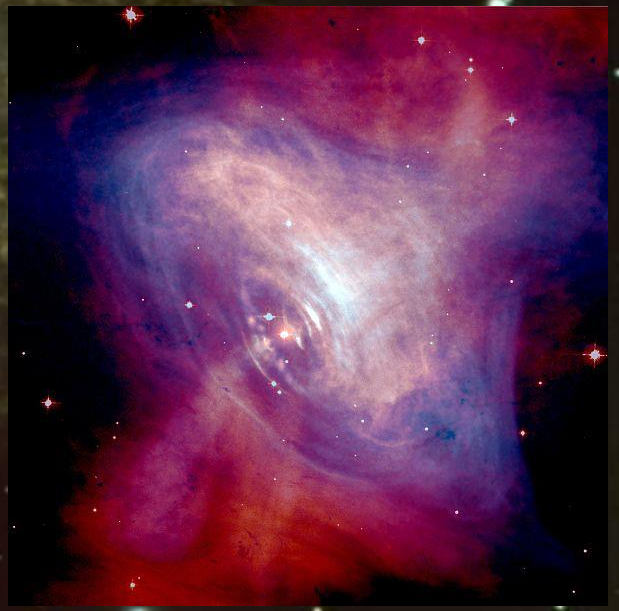
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	6%/$\sqrt{E}$	5%/$\sqrt{E}$	3%/$\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Run for 6 yrs	Relative	Absolute Δm^2
Statistics	4σ	5σ
Realistic	3σ	4σ

Galactic SN 1054


凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧三年六月丙辰出井度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九 三百二十六 三五

Distance: 6500 light years (2 kpc)
Center: Neutron Star (R~30 km)
Progenitor : M ~ 10 solar masses



Red : Optical (Hubble)
Blue : X-Ray (Chandra)

Stellar Collapse and SN Explosion

Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

99% Neutrinos

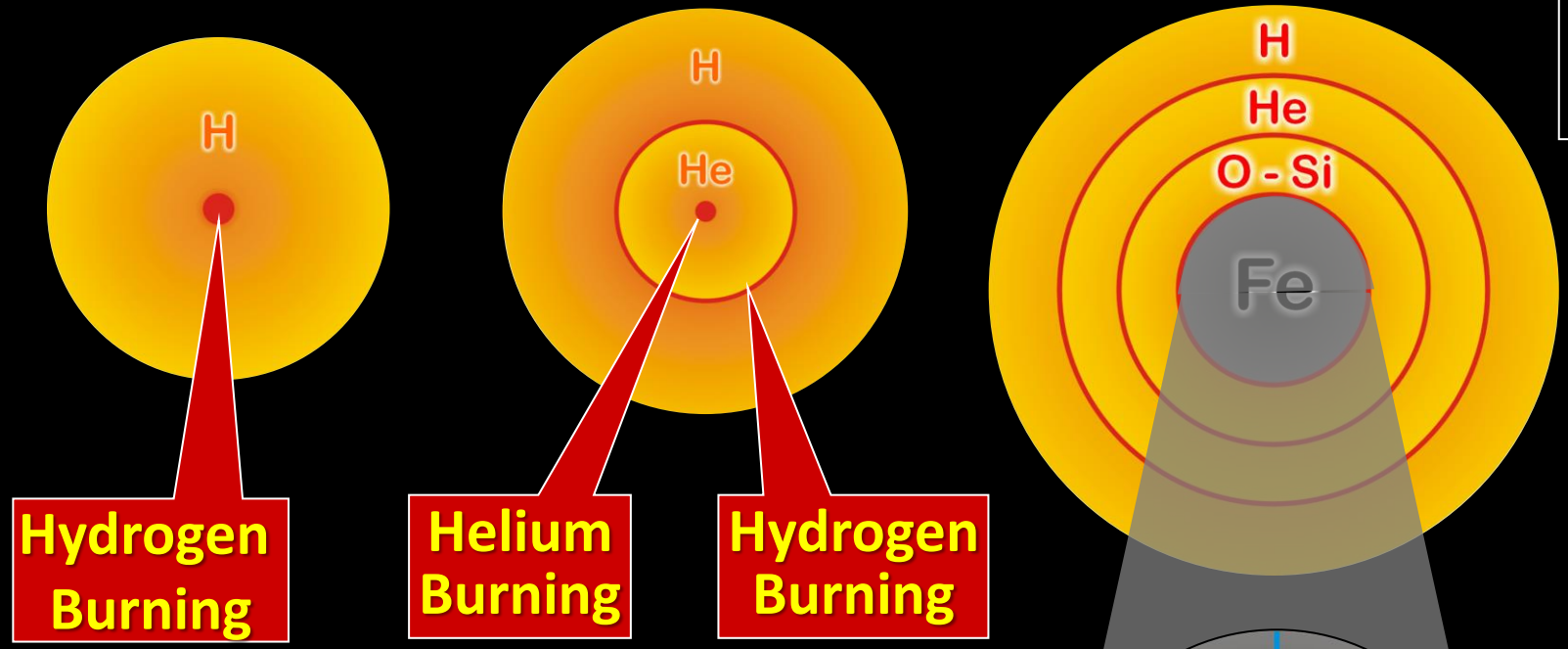
1% Kinetic energy of explosion

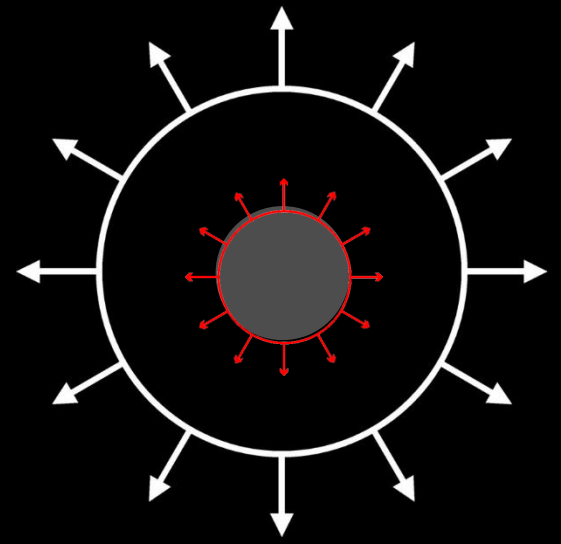
(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

Main-sequence star

Helium-burning star





1. > 8 Solar Masses
2. Collapse→Bounce
3. Shock wave halted
4. ν energy deposited
5. Final SN explosion

Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

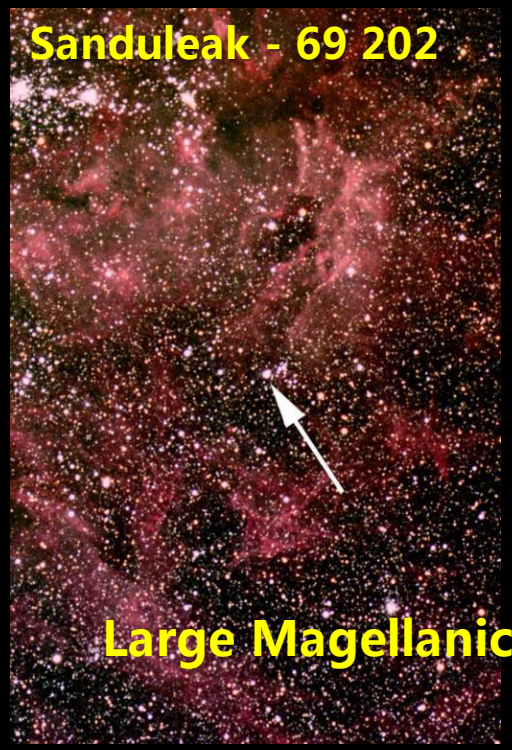
$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Proto-Neutron star:

$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

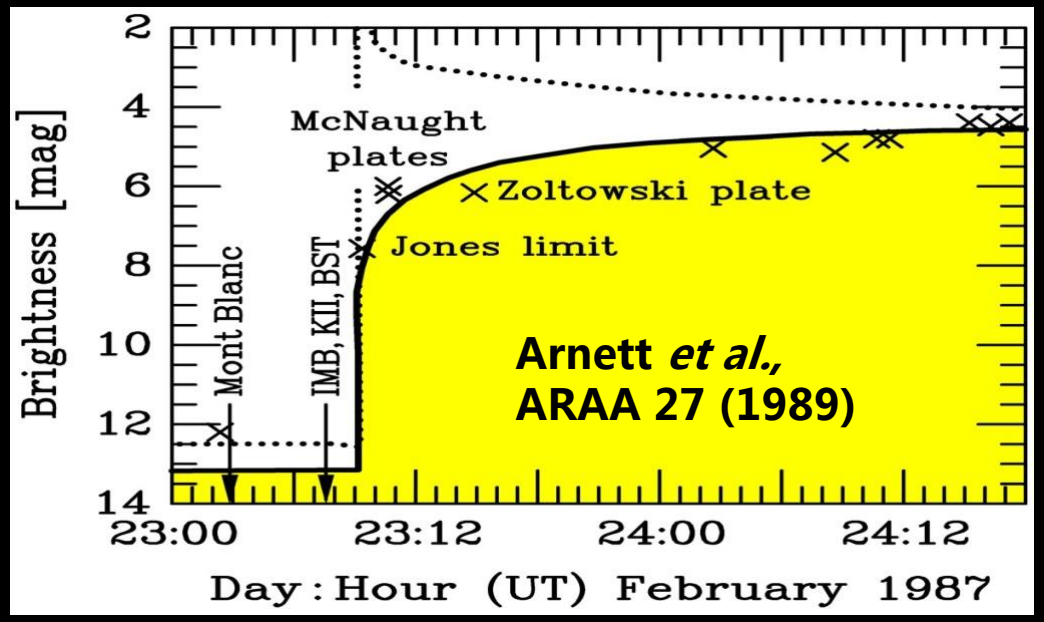
$T \sim 30$ MeV

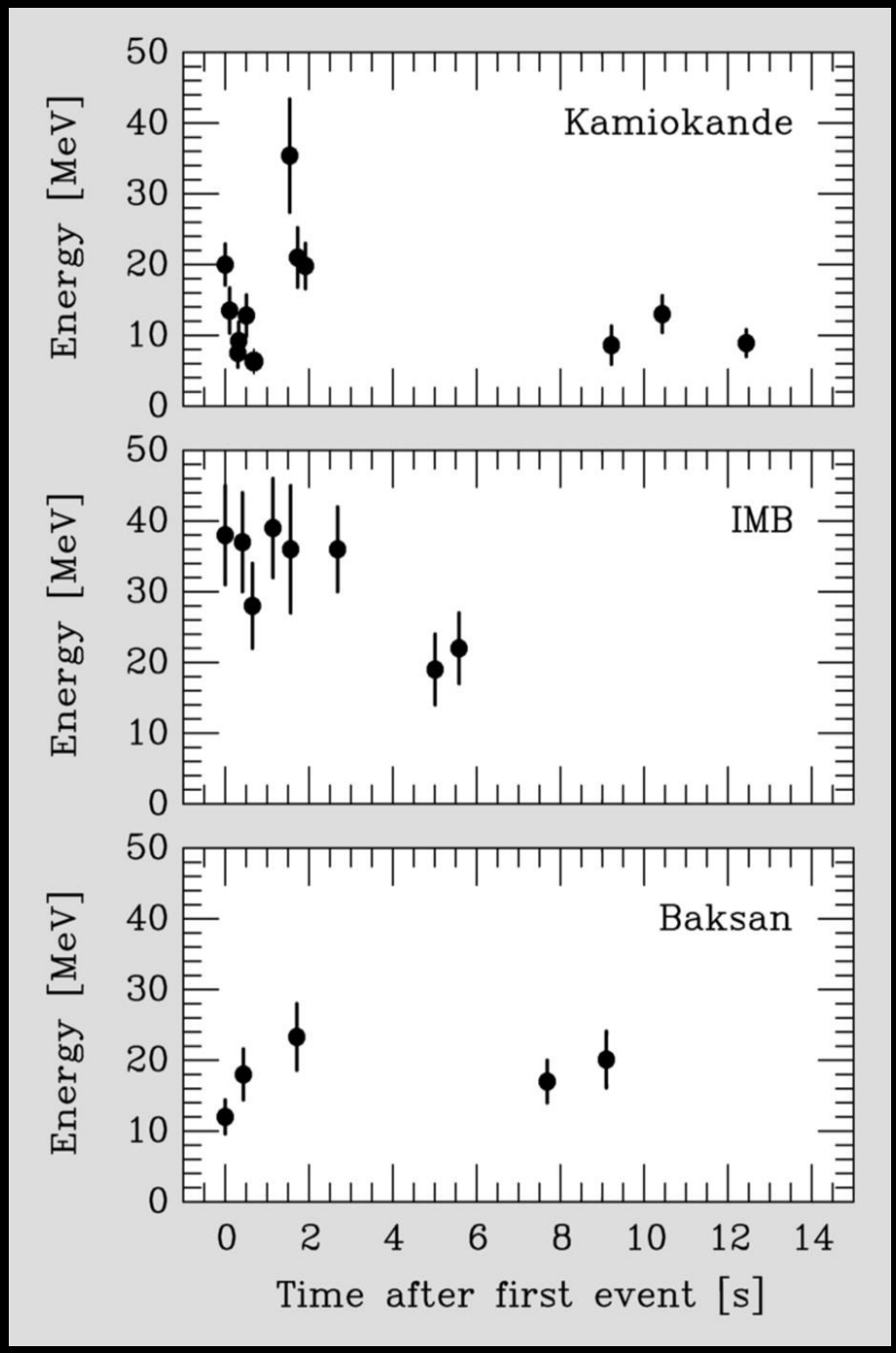


Assumptions:
- ☐ Thermal
- ☐ Equipart.

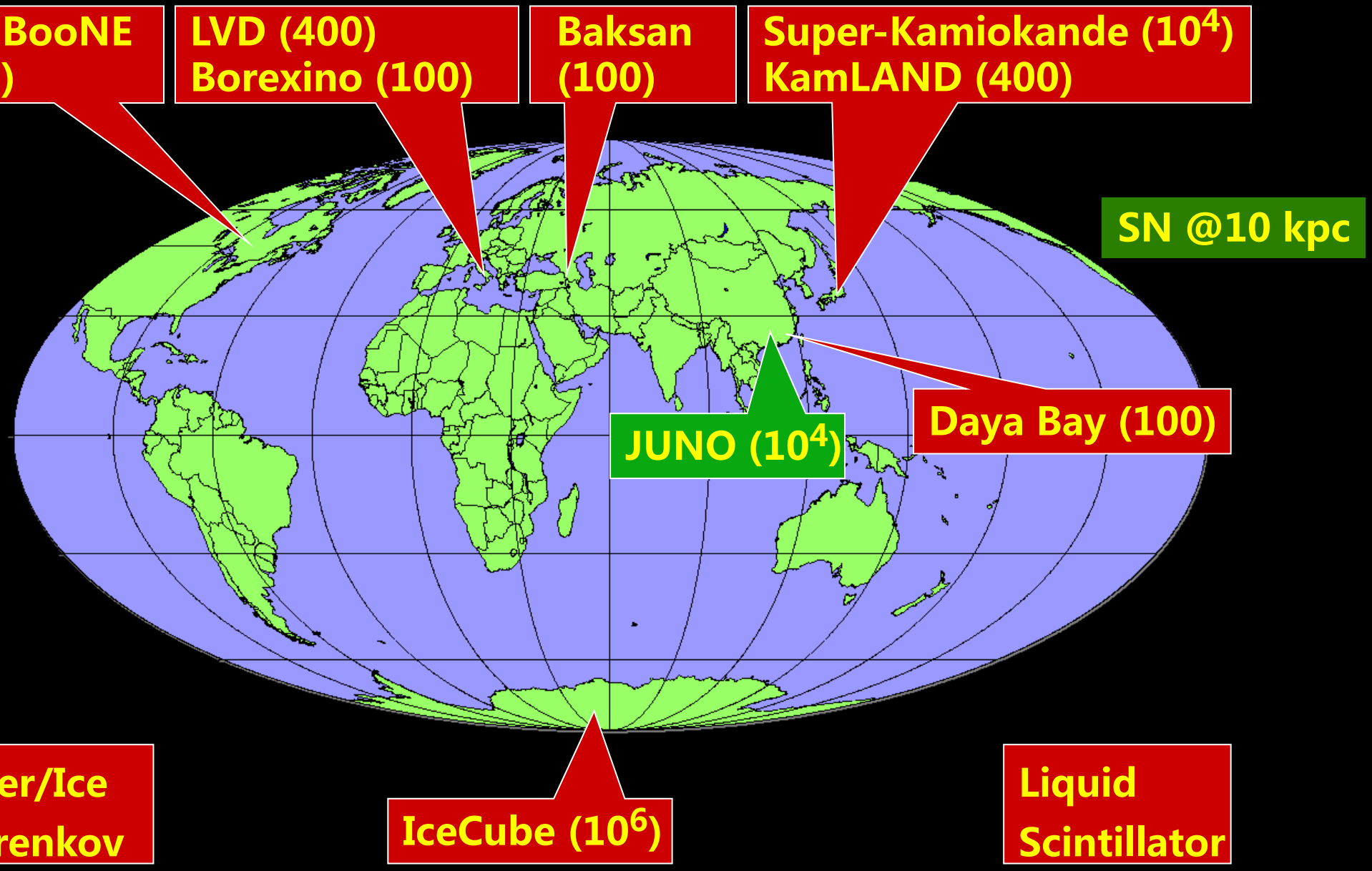
Conclusions:
- ■ Collapse
- ■ Ave.Ener.
- ■ Duration

Problems :
- ☐ 24 events
- ☐ by chance

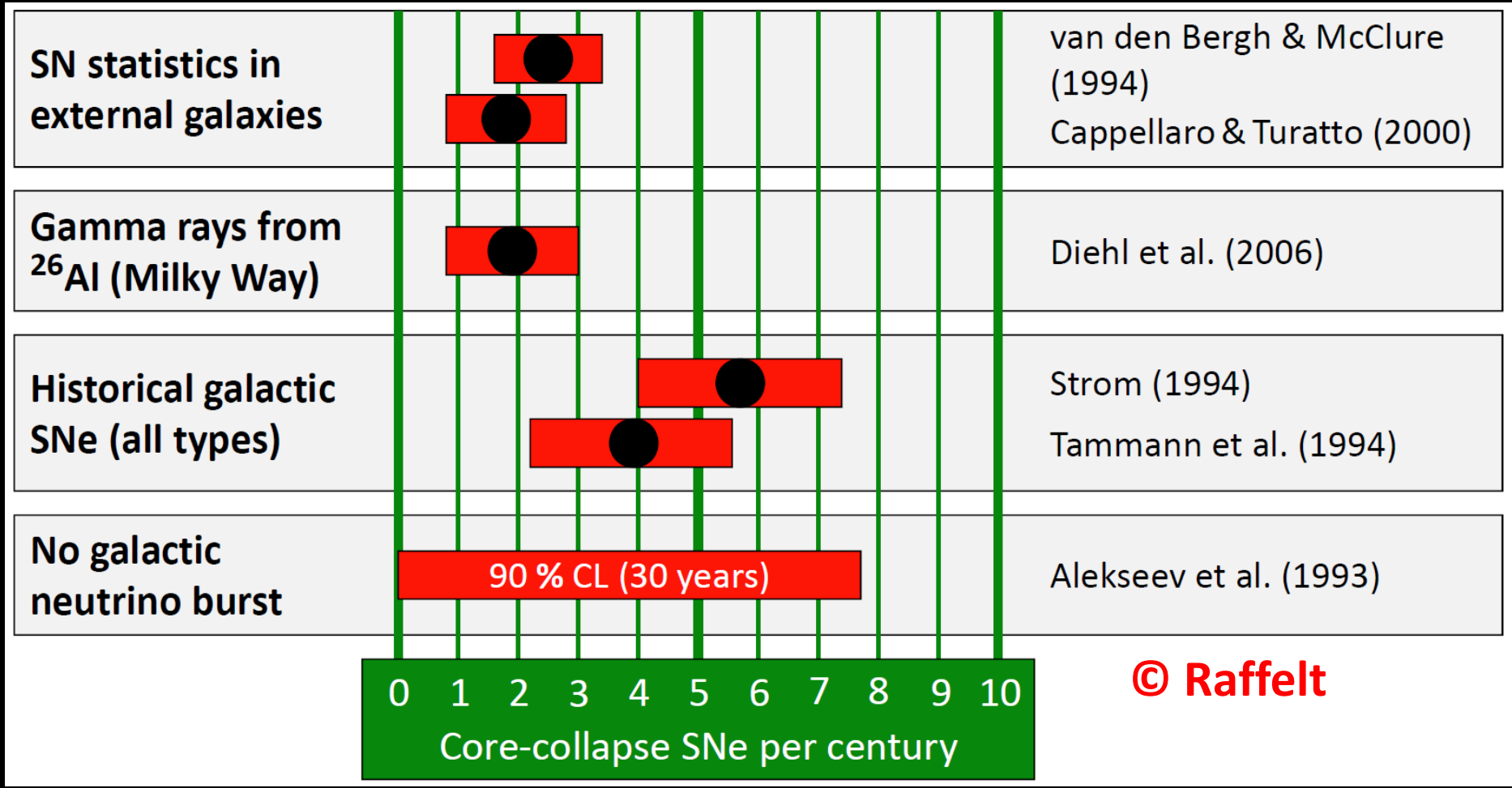




SN ν Detection: present and future experiments



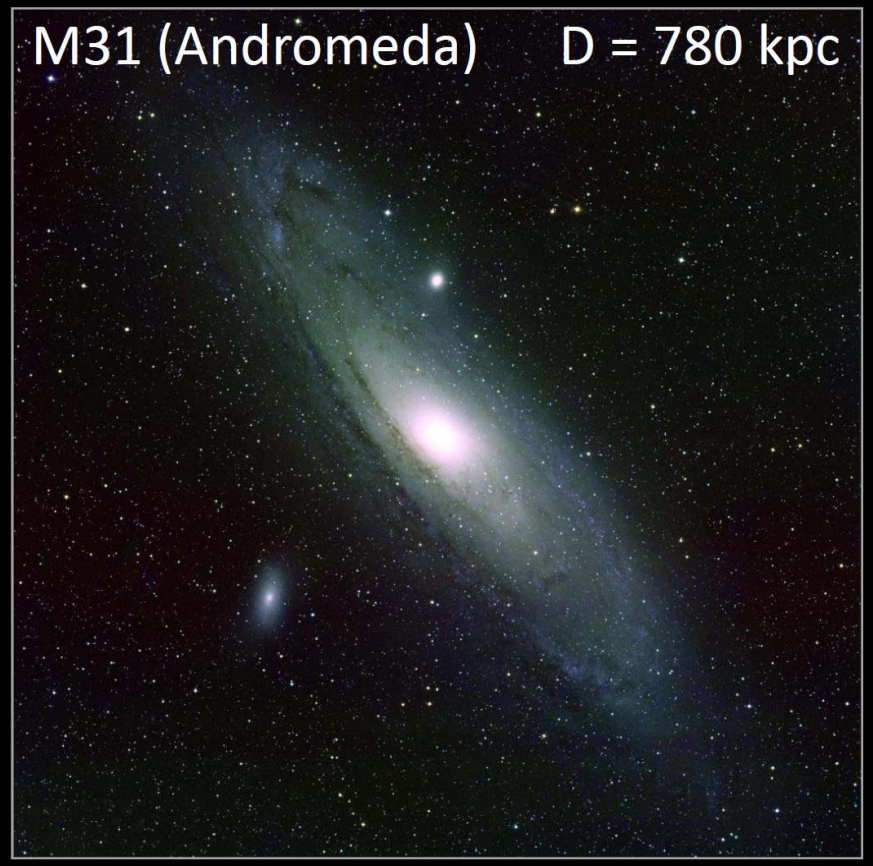
Key Problem: where and when?



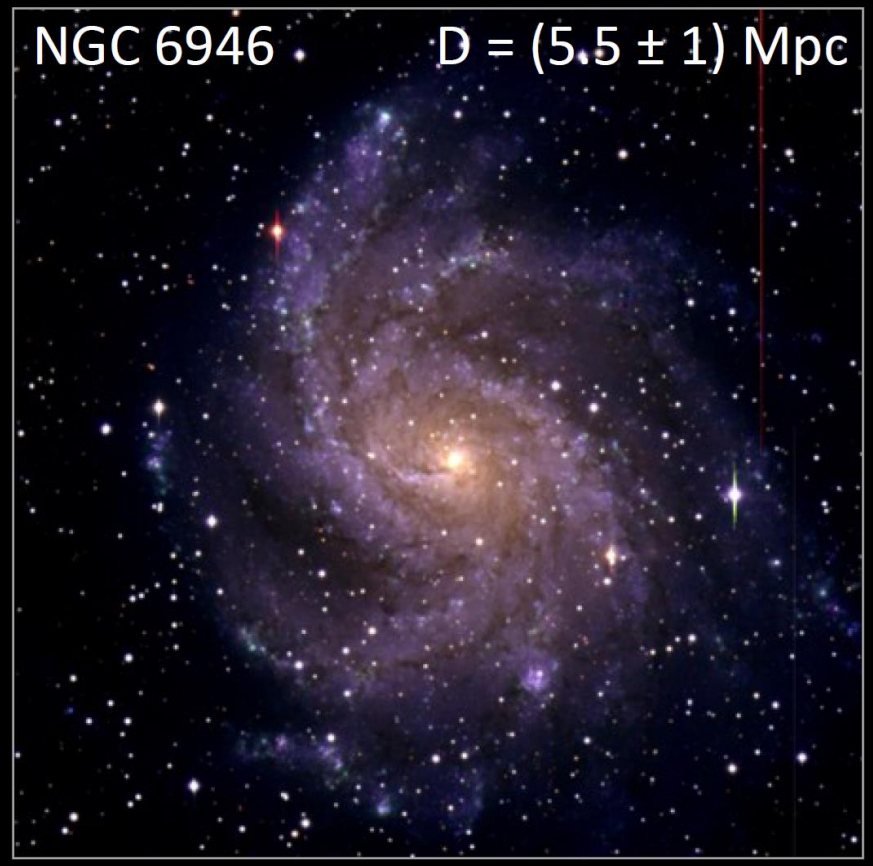
(1) Estimate from SN statistics in other galaxies; (2) Only massive stars produce ^{26}Al (with a half-life 7.2×10^5 years); (3) Historical SNe in the Milky Way; (4) No neutrino bursts observed by Baksan since June 1980

Key Problem: where and when?

High and Low Supernova Rates in Nearby Galaxies

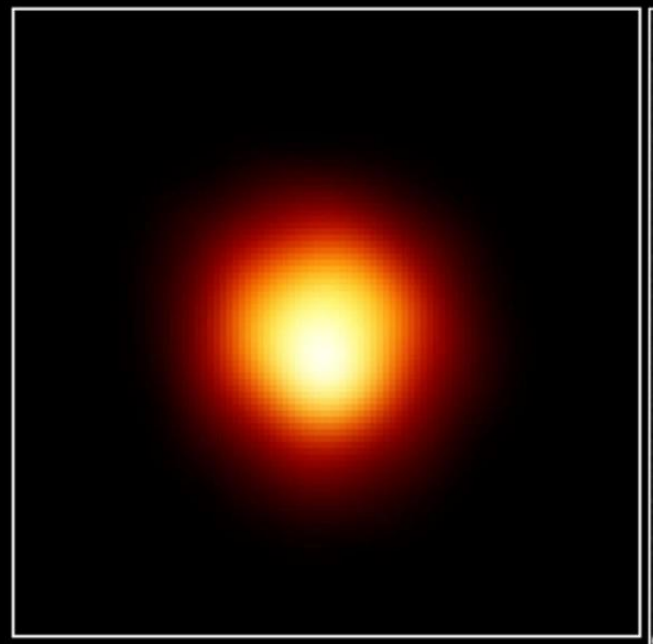


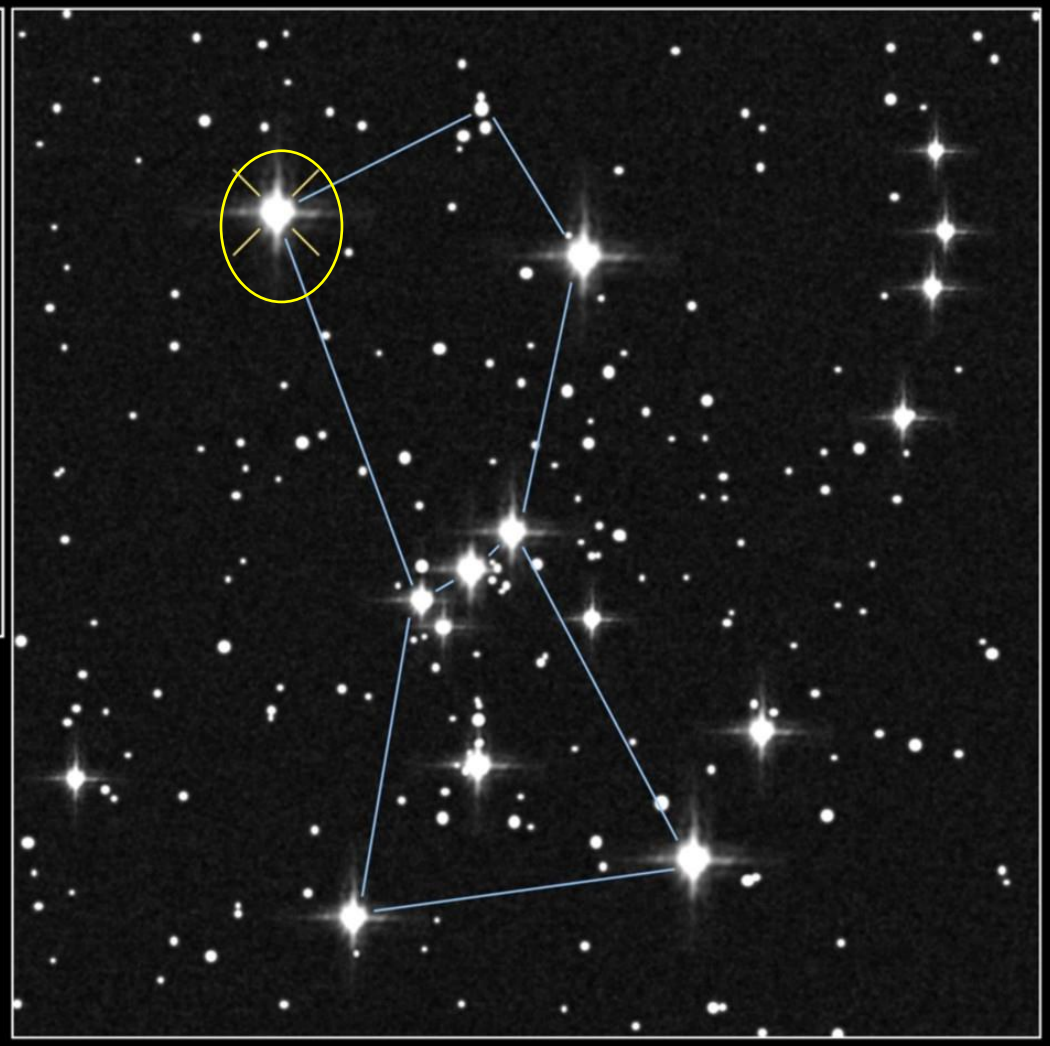
Last observed supernova: 1885A



Observed supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S

SN Candidate: The Red Supergiant Betelgeuse (Alpha Orionis)





Distance: 642 ly (197 pc)
Type： Red Supergiant
Mass： ~ 18 solar masses

Expected to end its life as SN explosion
@ JUNO: 2×10^7 events

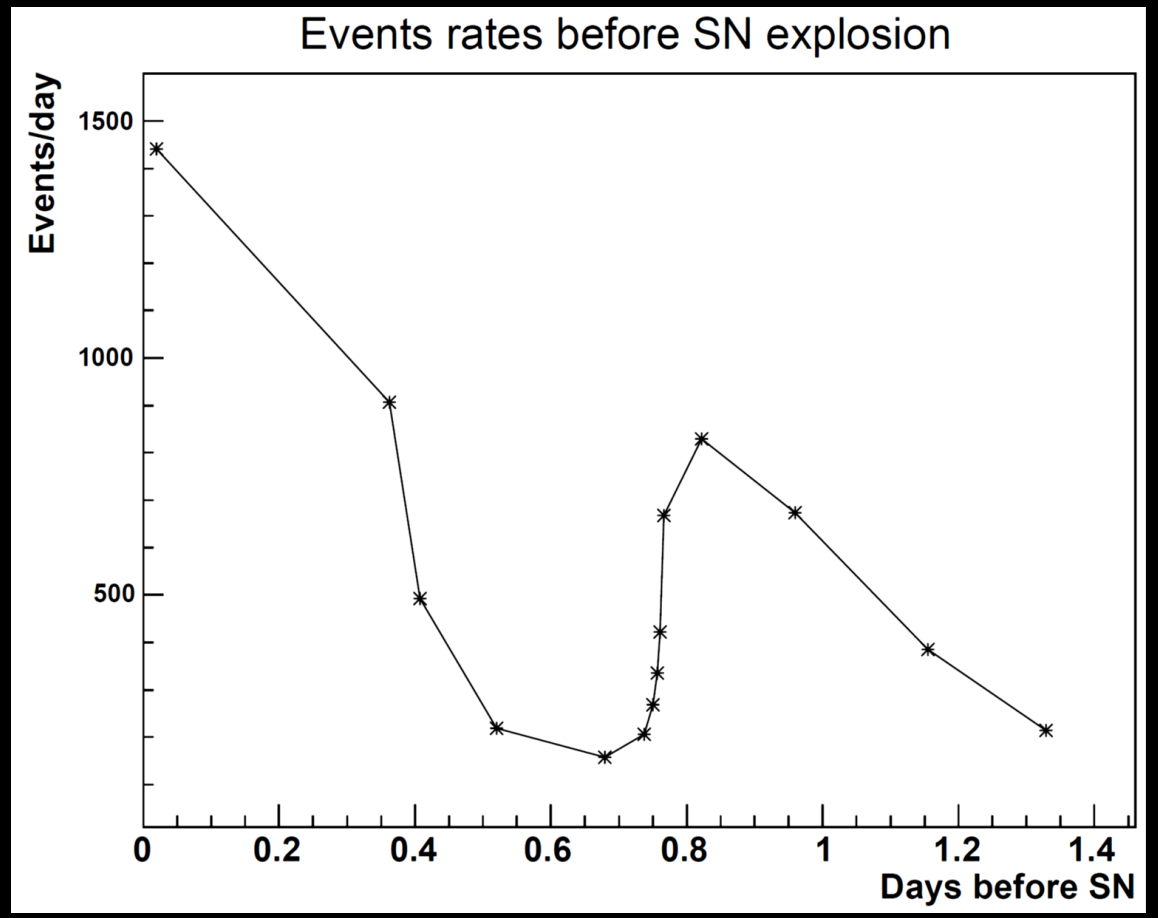
Pre-SN Neutrinos

Burning Phases of a 15 Solar-Mass Star

Burning Phase		T_c [keV]	ρ_c [g/cm^3]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
	Hydrogen	3	5.9	2.1	-	1.2×10^7
	Helium	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
	Carbon	53	1.7×10^5	8.6	1.0	6.3×10^3
	Neon	110	1.6×10^7	9.6	1.8×10^3	7.0
	Oxygen	160	9.7×10^7	9.6	2.1×10^4	1.7
	Silicon	270	2.3×10^8	9.6	9.2×10^5	6 days

Detection of $\overline{\nu}_e$ a massive star before SN explosion

For M = 20 solar masses, D = 0.2 kpc (Betelgeuse), and in the energy range 1 MeV < E_ν < 2.6 MeV

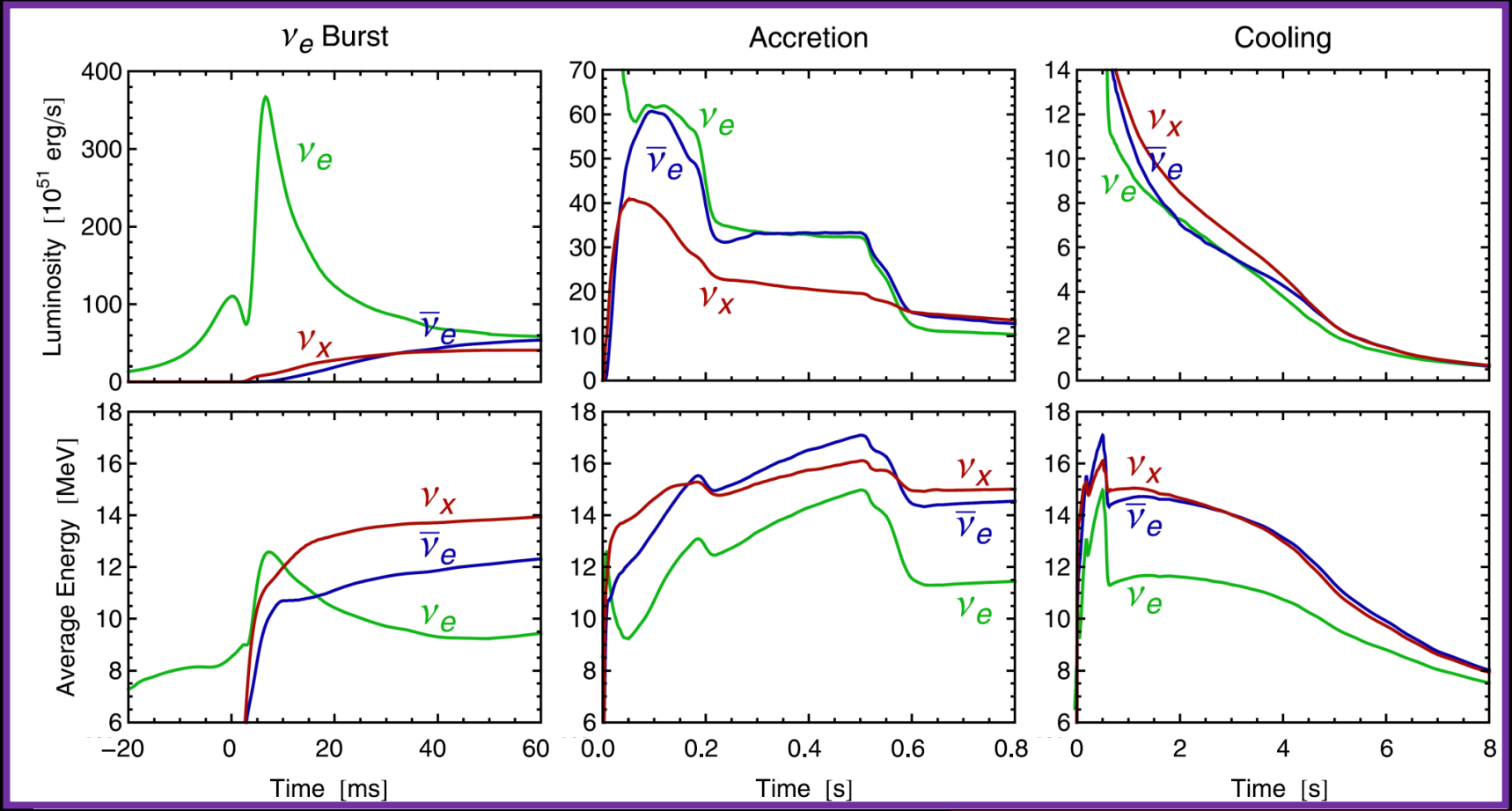


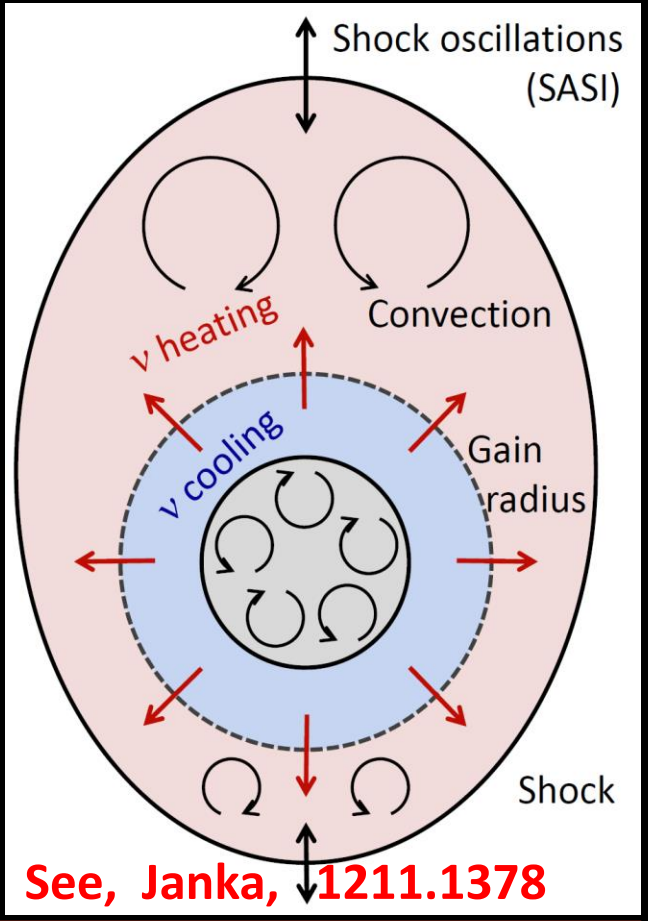
per day	Reactor	Geo.	Pre-SN
# of events	3	0.1	10

JUNO Physics Yellow Book, to be released soon

Burning phase	Average energy [MeV]	Total energy [erg]	Duration [days]
C	0.71	7.0×10^{49}	10^5
Ne	0.99	1.4×10^{50}	140
O	1.13	1.2×10^{51}	180
Si	1.85	5.4×10^{50}	2

Galactic SN Neutrinos





See, Janka, 1211.1378

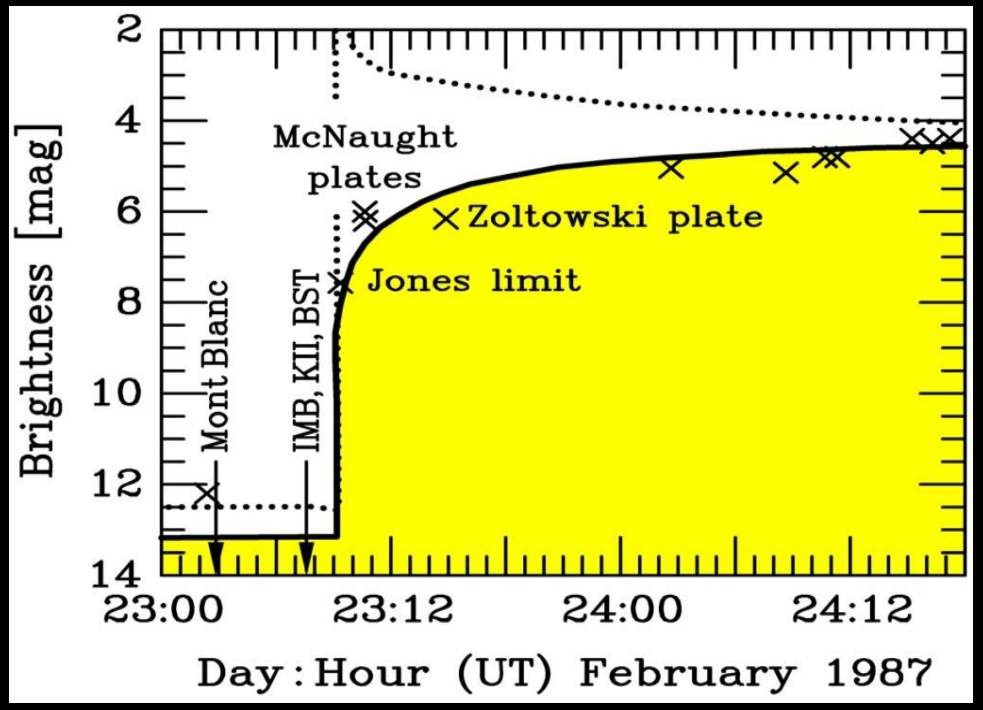
Detect $\bar{\nu}_e, \nu_e, \nu_x$ from a galactic SN @ 10 kpc

- real-time meas. of three-phase ν signals
- distinguish between different ν flavors
- reconstruct ν energies and luminosities
- almost background free due to time info

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Galactic SN Neutrinos

- For Optical Observations: SuperNova Early Warning System (SNEWS)



SNEWS

Daya Bay

Super-K

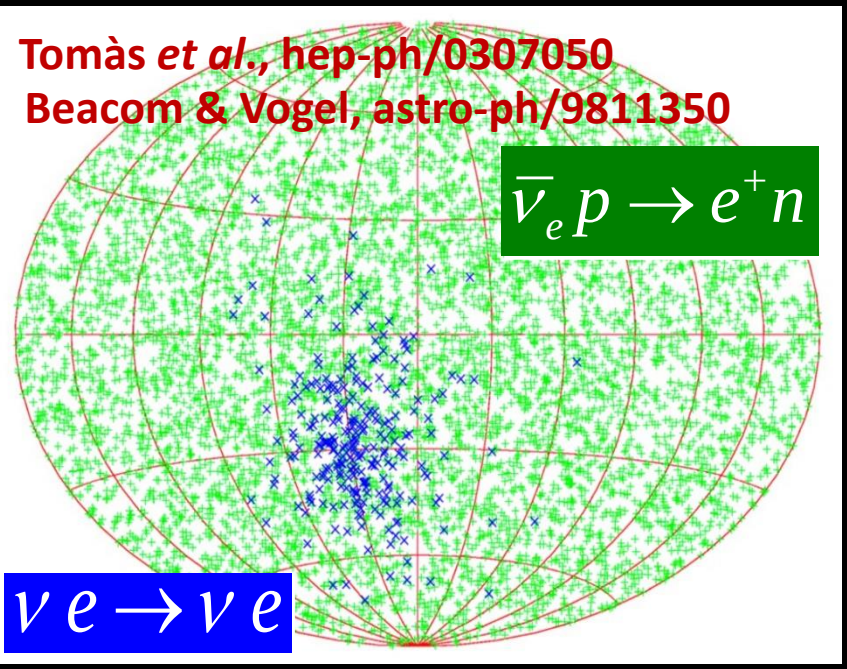
IceCube

LVD

Borexino

Alert @BNL

Tomàs *et al.*, hep-ph/0307050
Beacom & Vogel, astro-ph/9811350



n-tagging efficiency		
None	90 %	
7.8°	3.2°	SK

95% CL half-cone opening angle

Neutrinos arrive several hours before photons; to alert astronomers several hours in advance

Locating a galactic SN @ 10 kpc
Stat. recon. e^+-n correlation: 8.1° @JUNO

Diffuse SN Background (DSNB)

Neutrinos from all the SNe in our Universe

# of SNe per yr per Mpc³(un. SFR, IMF)

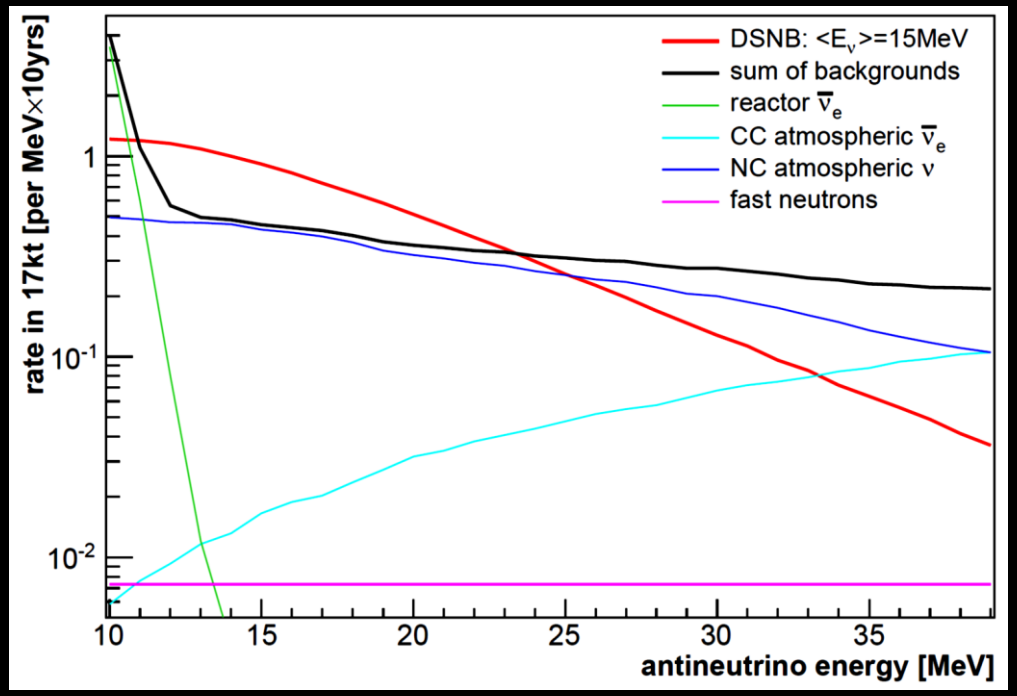
$$\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} dz\, \frac{R_{\rm SN}(z)}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}}\, \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}}$$

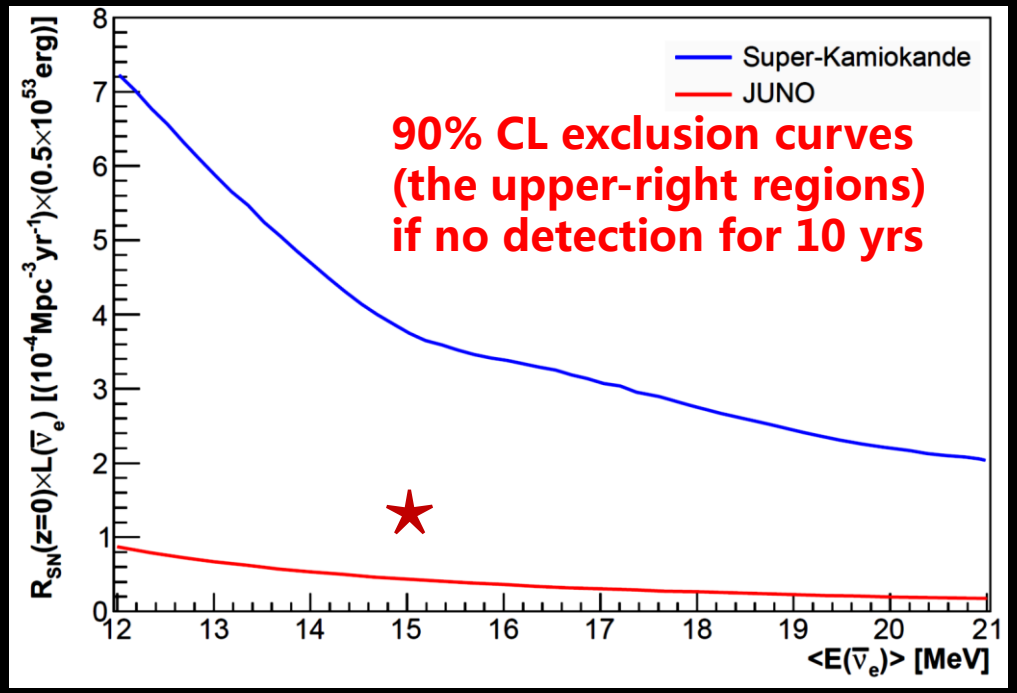
Cosmological evolution

ν spectrum

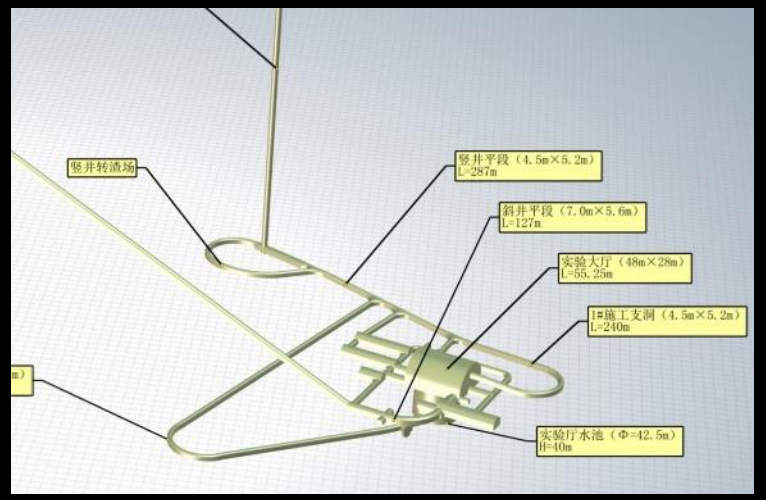
- Obervation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	1.7 σ	1.9 σ	1.5 σ	1.7 σ
15 MeV	3.3 σ	3.5 σ	3.0 σ	3.2 σ
18 MeV	5.1 σ	5.4 σ	4.6 σ	4.7 σ
21 MeV	6.9 σ	7.3 σ	6.2 σ	6.4 σ





JUNO Construction Start-up Meeting on Jan. 10, 2015



600 m vertical shaft
1300-m long tunnel(40% slope)
50-m diameter, 80-m high cavern

Project Plan and Progress

First get-together meeting

Funding(2013-2014) review approved

Geological survey & preliminary civil design

1st 20" MCP-PMT

Collaboration formed

Groundbreaking Ceremony

2013

Kaiping Neutrino Research Center established

2014

Civil/infrastructure construction bidding

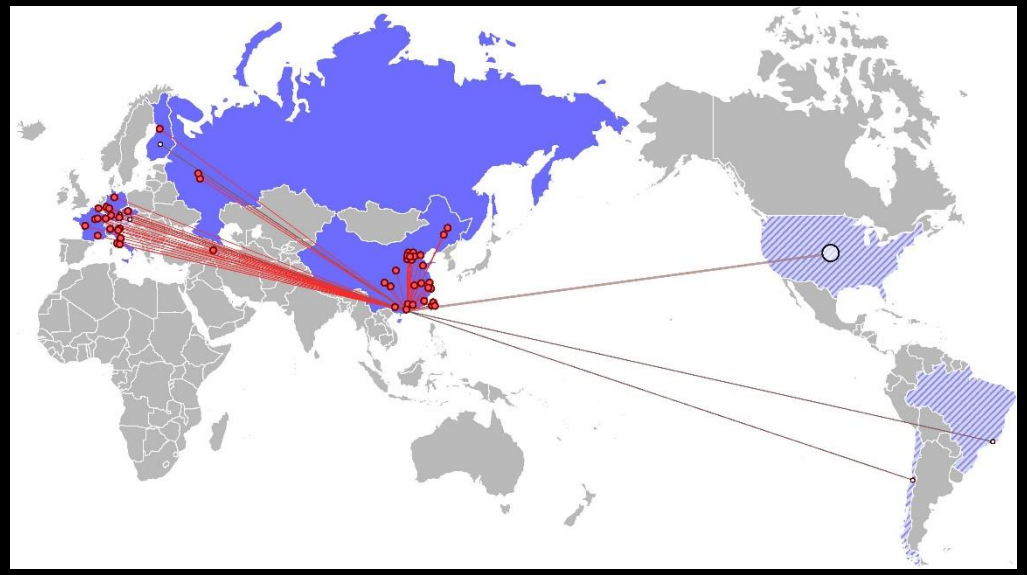
Funding from CAS: "Strategic Leading Science & Technology Program" approved (~CD1)

Yangjiang NPP started to build the last two cores

Civil design approved

- Civil construction : 2015-2017
- Detector component production : 2016-2017
- PMT production : 2016-2019
- Detector assembly & installation : 2018-2019
- Filling & data taking : 2020

JUNO Collaboration



Asia (28)

BNU
CAGS
CQ U
CIAE
DGUT
ECUST
Guangxi U
HIT
IHEP
Jilin U
Nanjing U
Nankai U
Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SYSU
Tsinghua
UCAS
USTC
Wuhan U
Wuyi U
Xiamen U
Xi'an JTU

Observers:
US institutions
HEPHY Vienna
PUC Brazil
PCUC Chile
MPP Munich
Jyvaskyla U.

Europe (23)

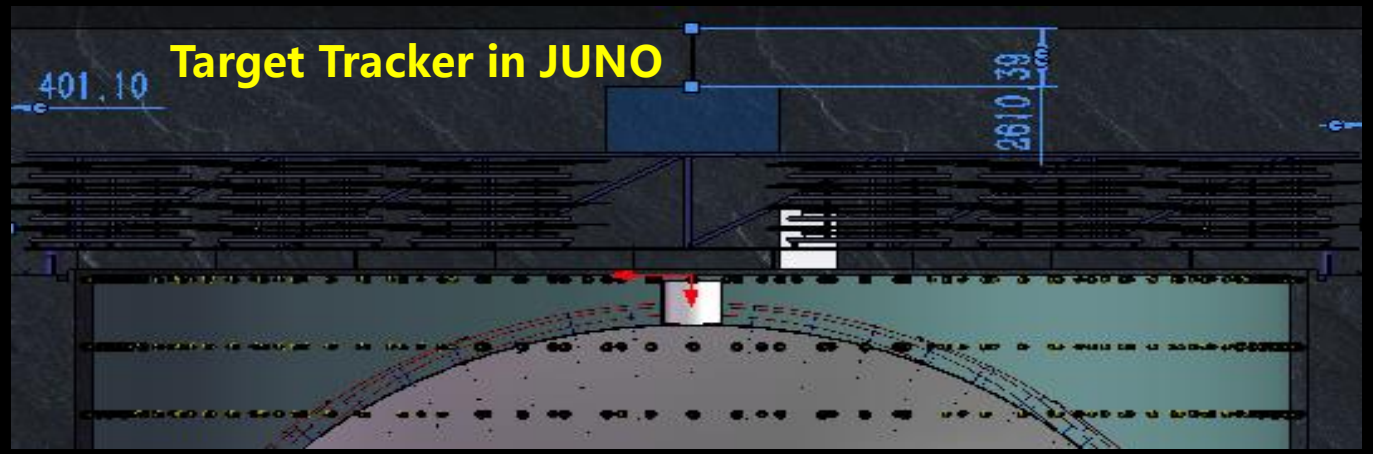
APC Paris
Charles U
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Padova
INFN-Perugia
INFN-Roma 3
IPHC Strasbourg
INR Moscow
JINR
LLR Paris
RWTH Aachen
Subatech Nantes
TUM
U.Hamburg
ULB
U Mainz
U Oulu
U Tuebingen
YPI Armenia

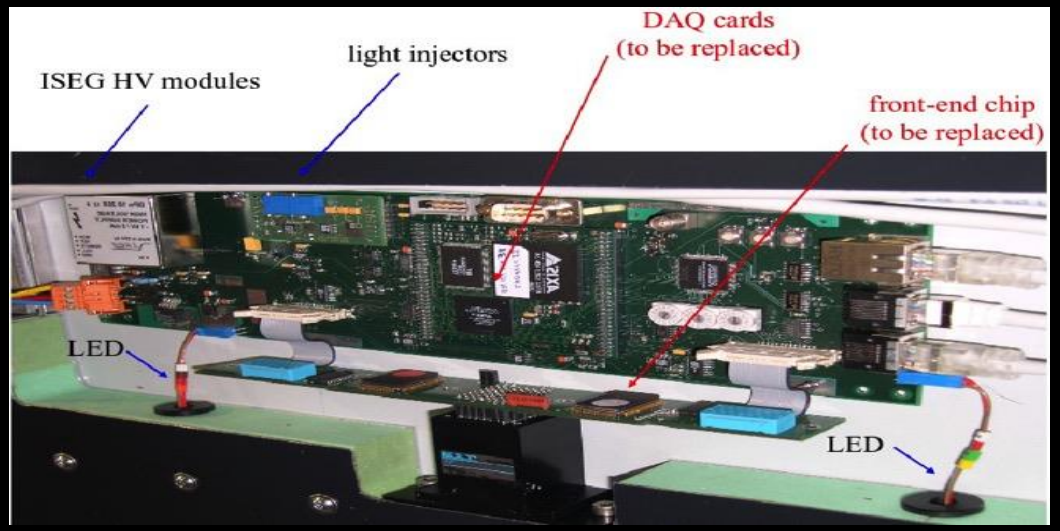
French contributions to JUNO

from Marcos Dracos (IN2P3)

5 French institutes are involved in JUNO: APC, IPHC, LLR, CPPL, SUBATECH

- Veto: installation of the OPERA Target Tracker on top of JUNO detector (IPHC, LLR, JINR, INFN)
- Cosmogenic background study and evaluation.
- DAQ and electronics of the JUNO central detector (APC, CPPM, SUBATECH).
- Radon background (CPPM).
- Data simulation and analysis.





Modification of TT electronics (in collaboration with OMEGA/IN2P3 electronics lab)