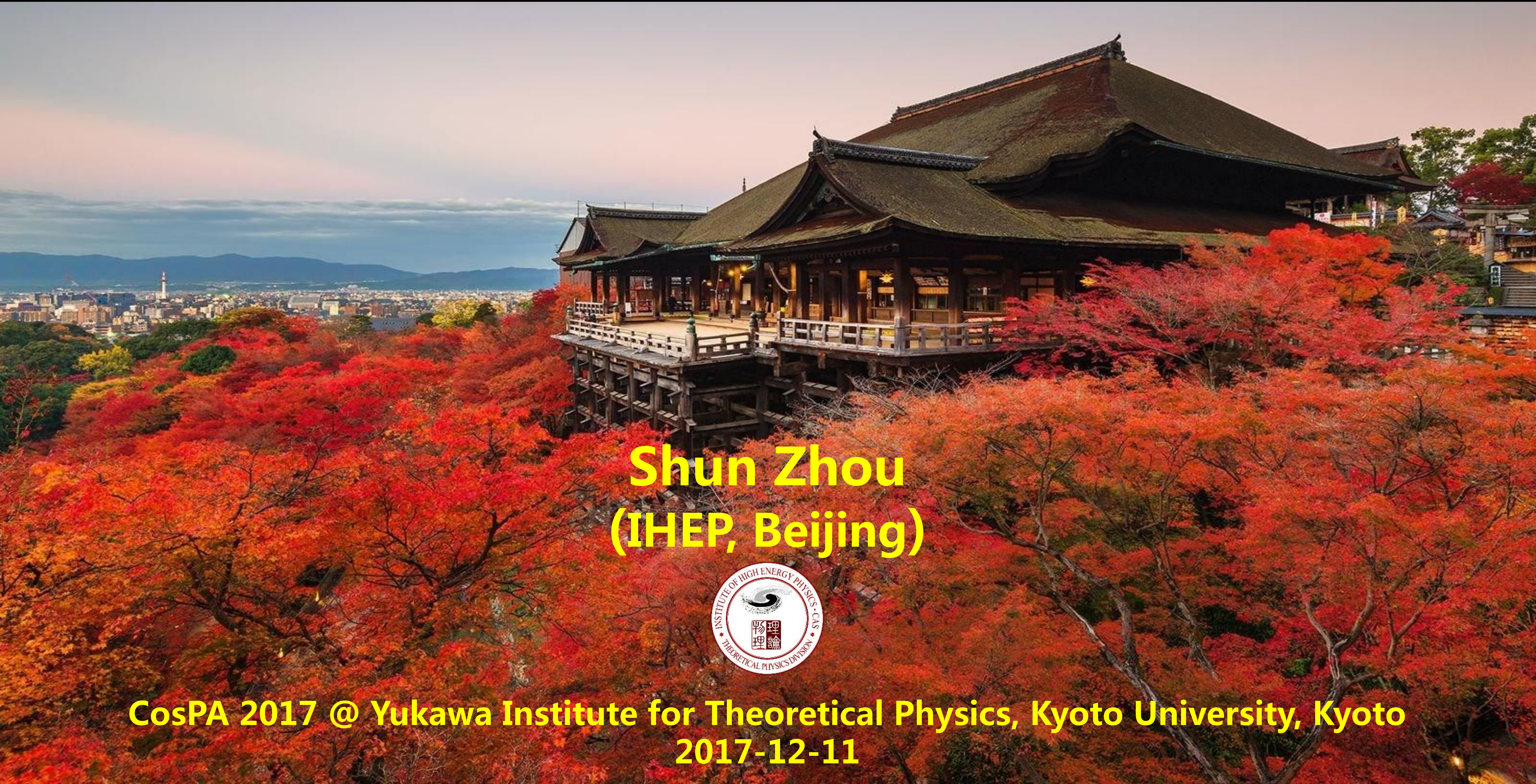
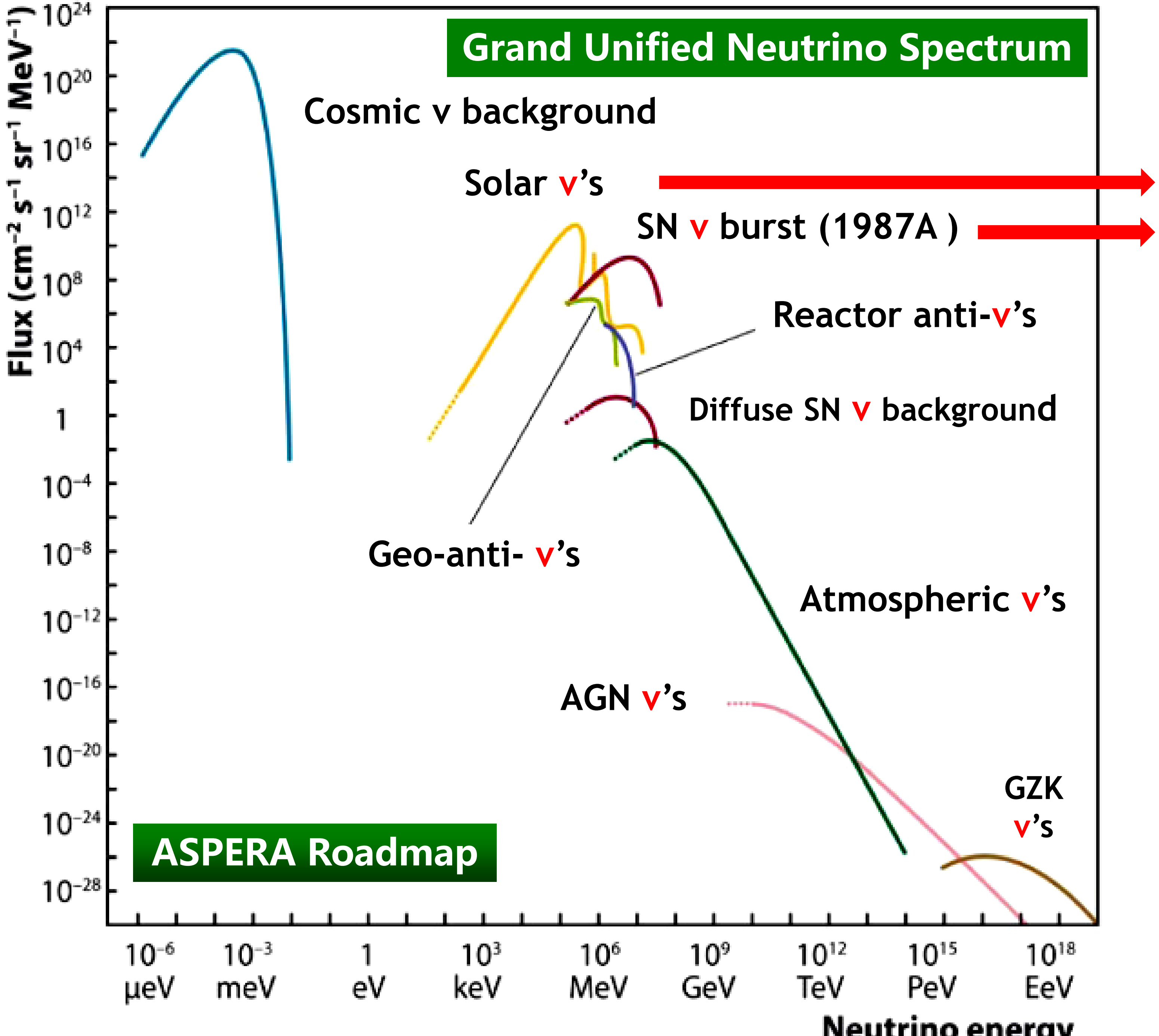
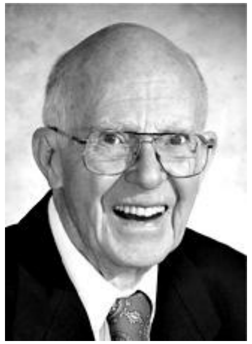
What can we learn from astrophysical neutrinos?



Shun Zhou
(IHEP, Beijing)

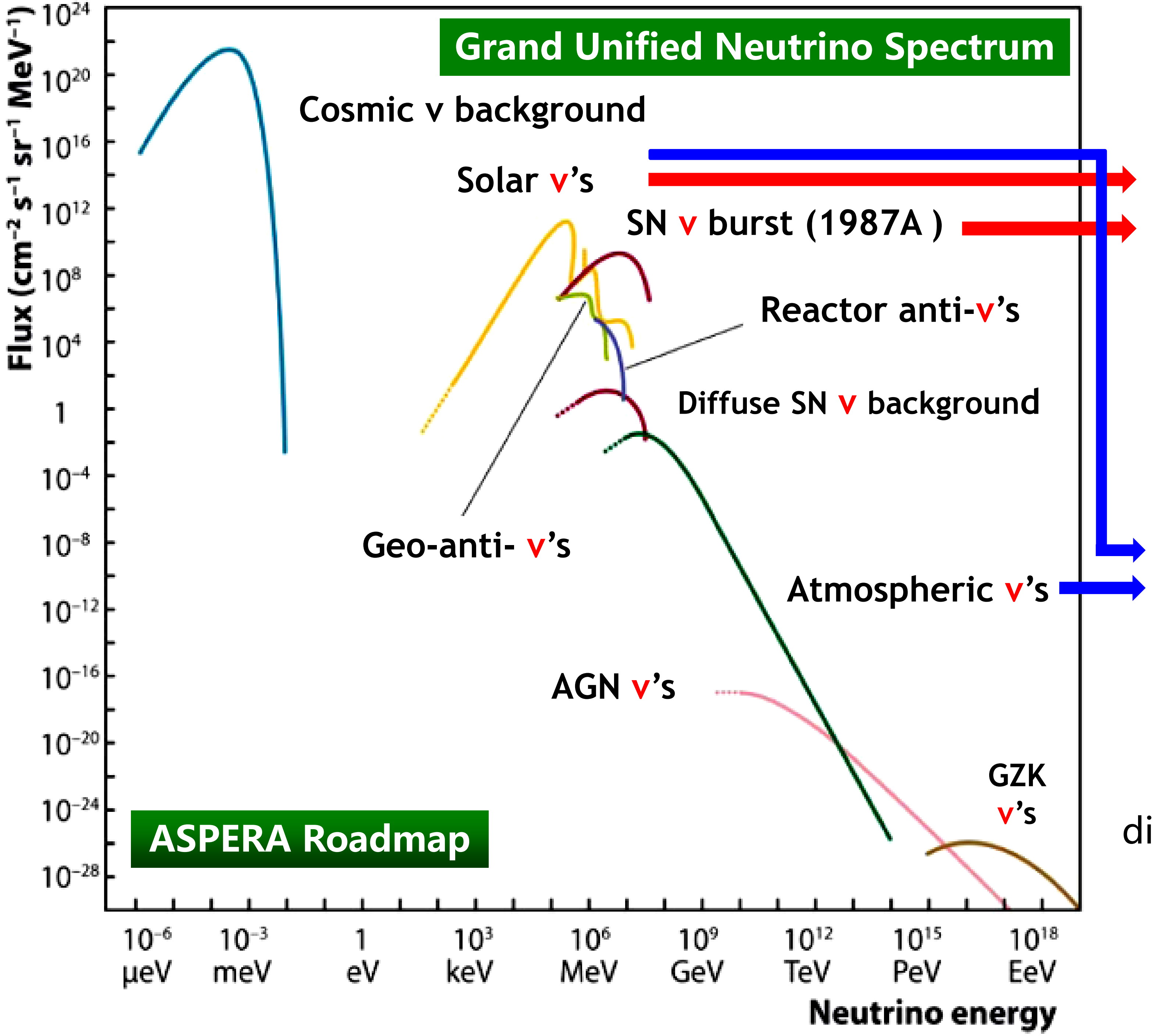
CosPA 2017 @ Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto
2017-12-11

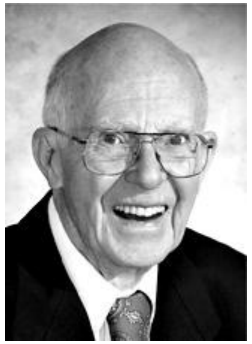




R. Davis Jr. **M. Koshiba**

Nobel Prize in 2002 "for the detection of **cosmic neutrinos**"





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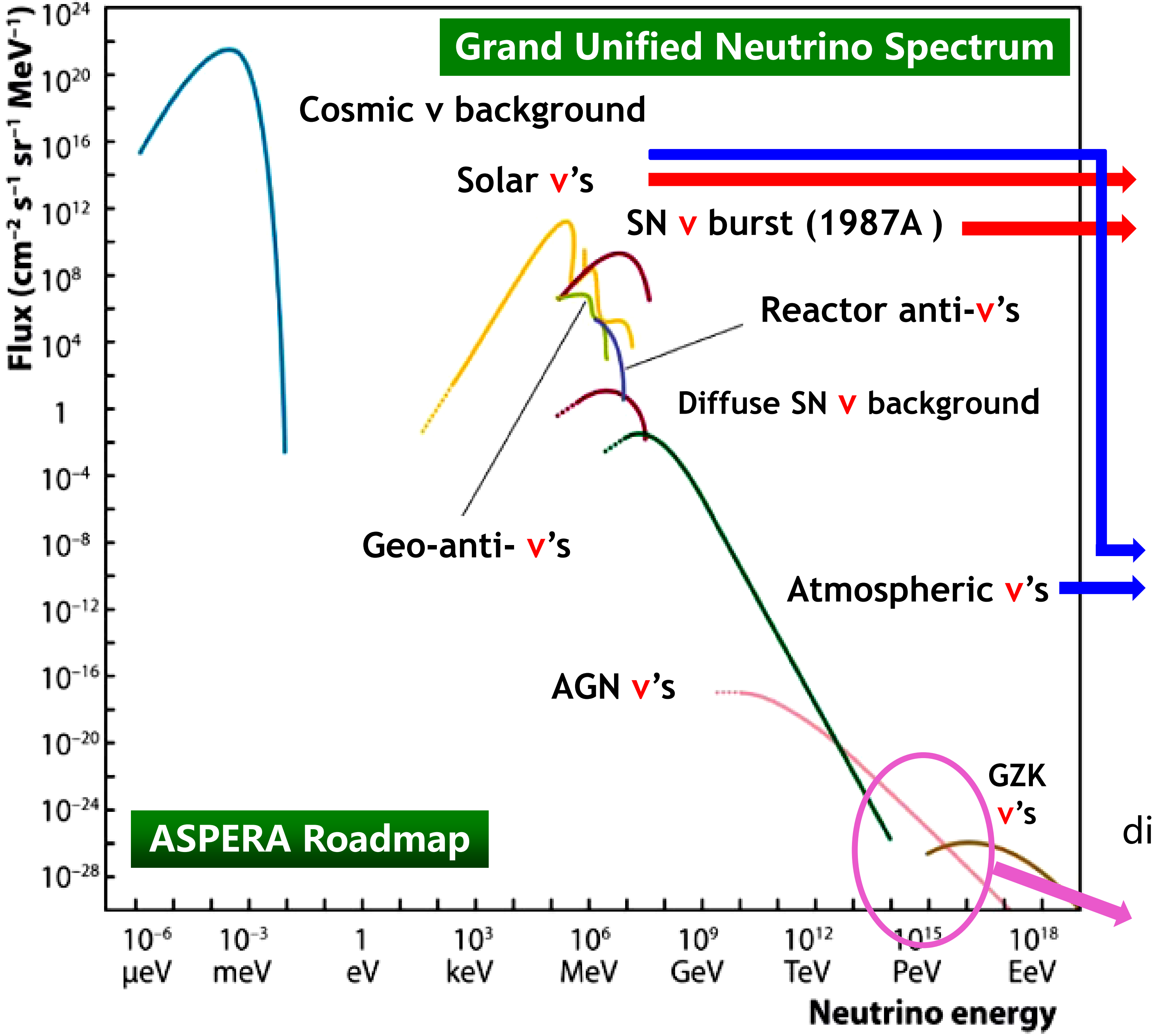

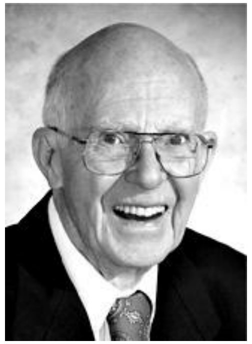

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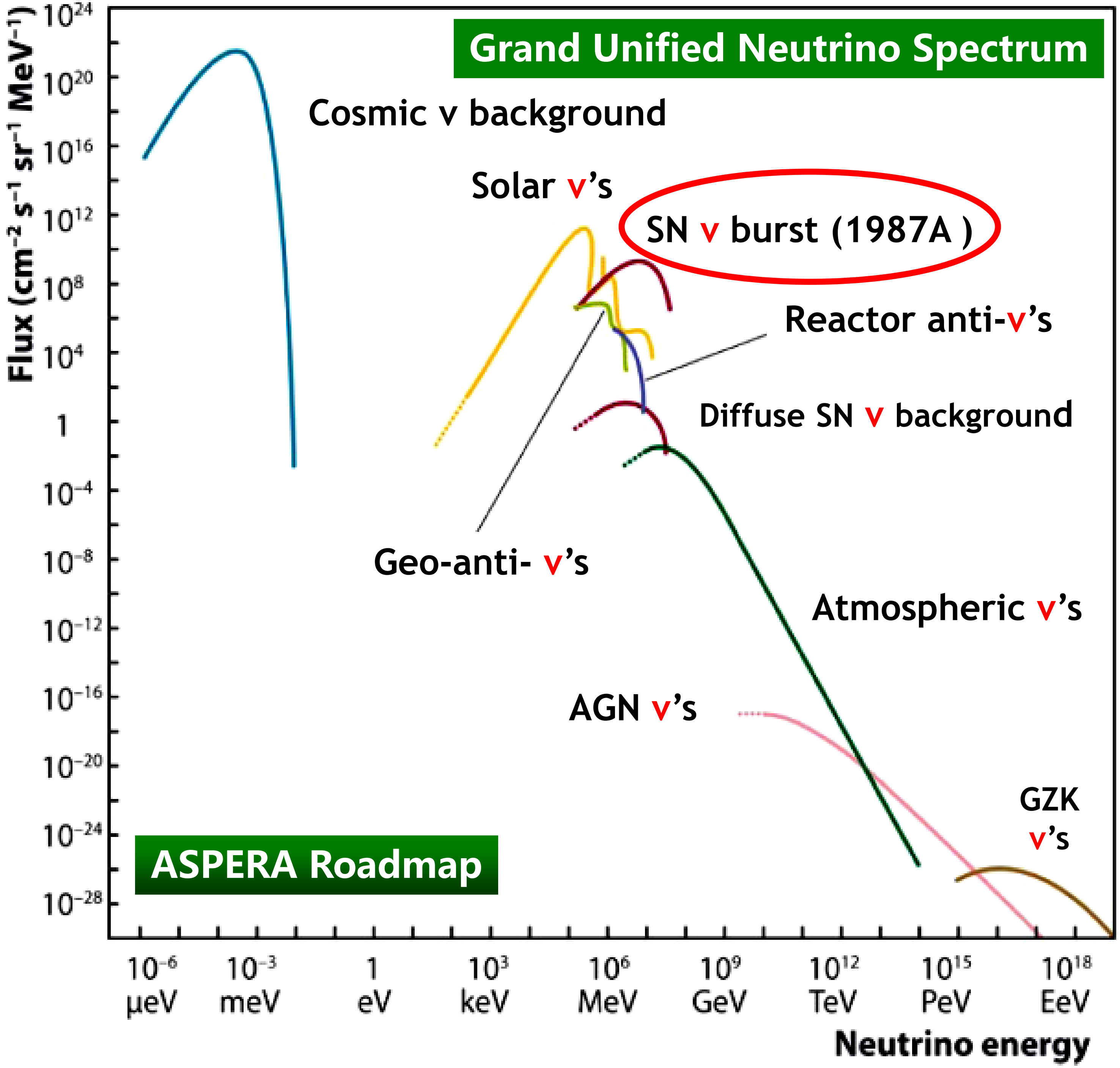
Discovery of **PeV** cosmic neutrinos at **IceCube**

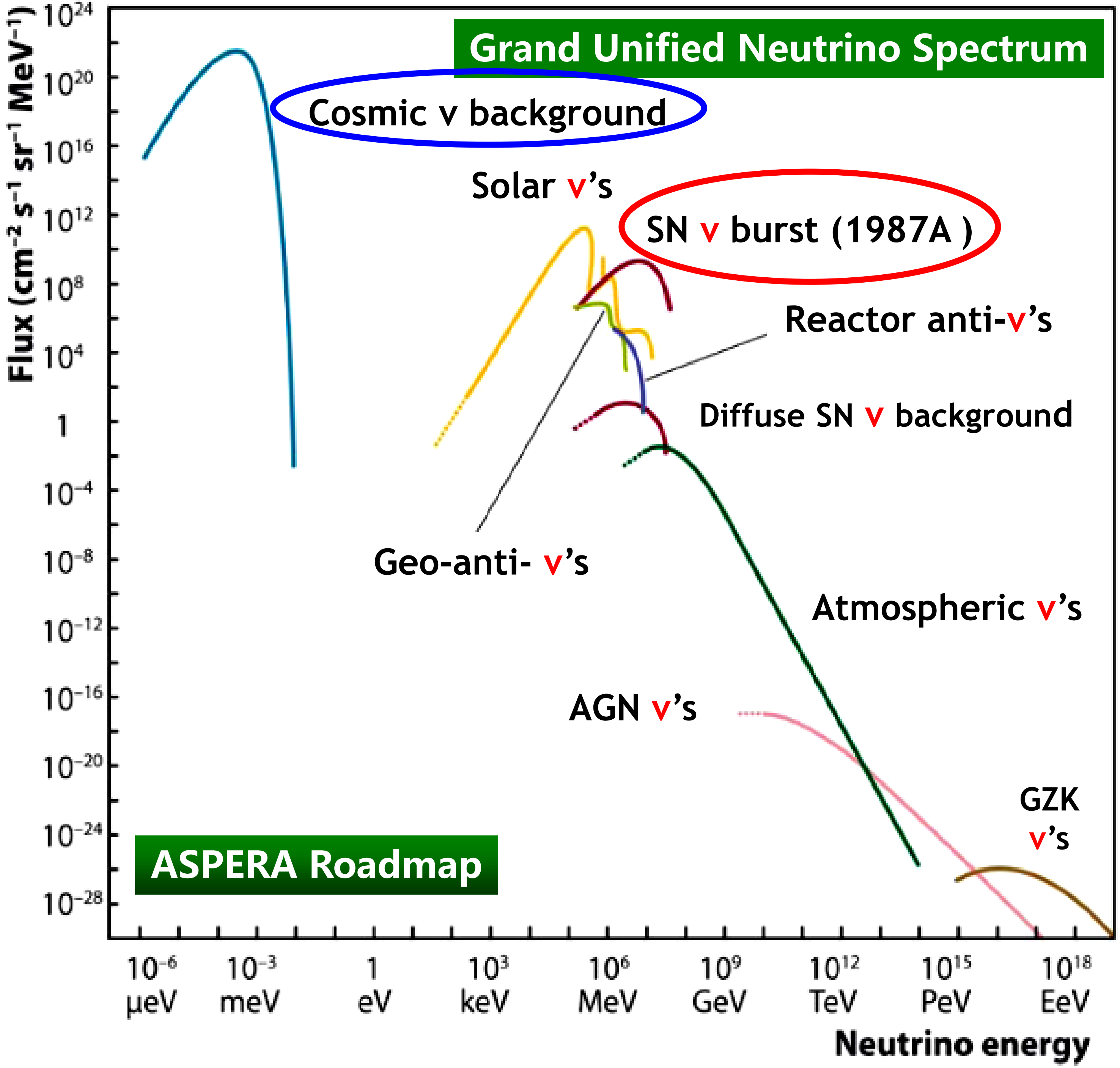
a review by E. Waxman



Outline

from the discovery in 1987 to precision measurements of supernova neutrinos

- Supernova (SN) Neutrinos
- Detection of Galactic SN ν's
- Learn more from SN ν's



Outline

from the **discovery in 1987** to **precision measurements** of supernova neutrinos

- Supernova (SN) Neutrinos
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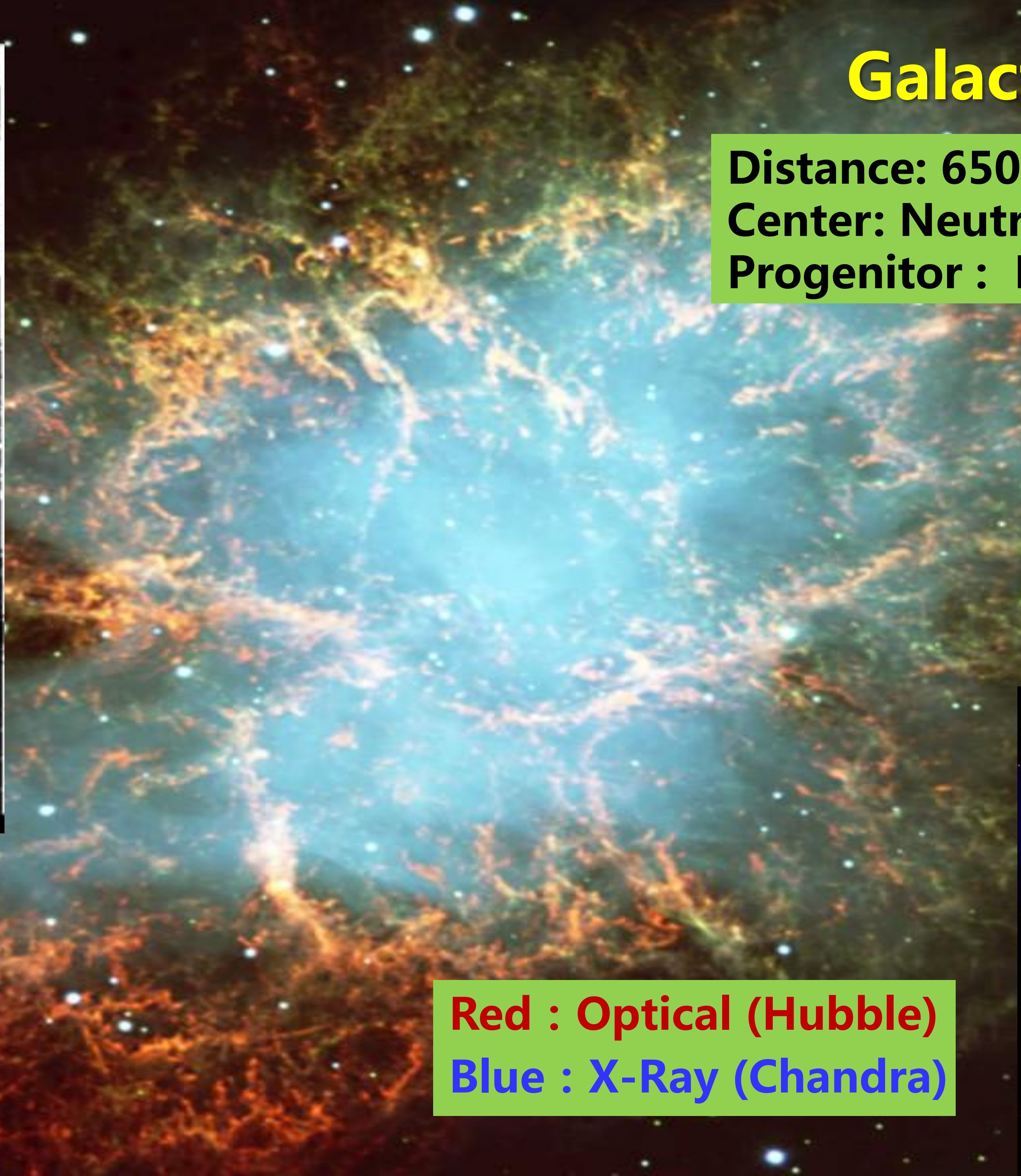
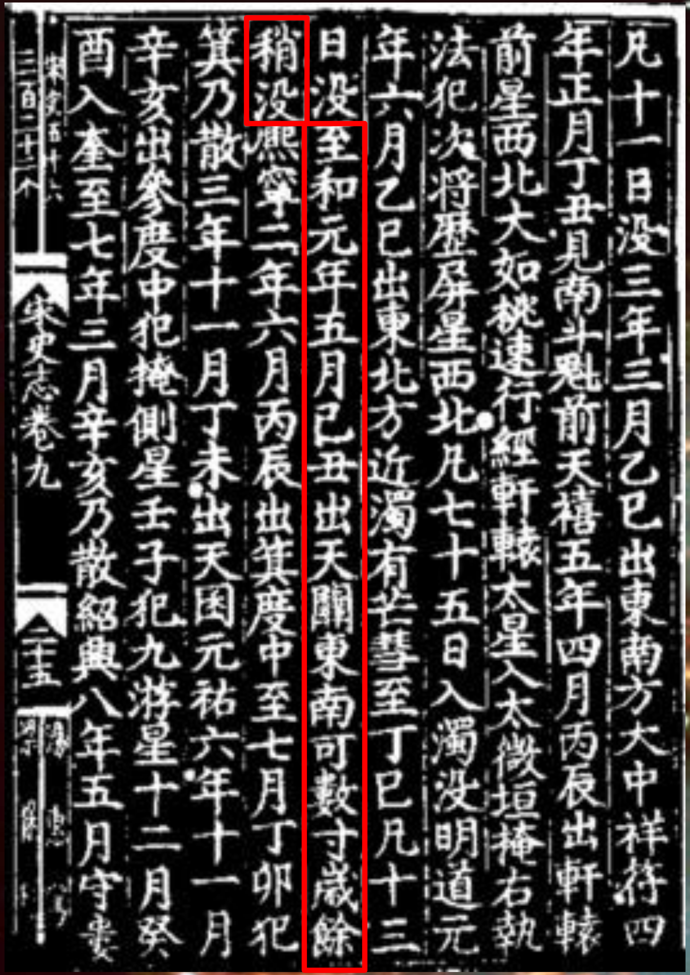
- Learn more from SN ν's

from the **UHE cosmic neutrinos** to **ULE cosmic neutrinos** from Big Bang

- Cosmic ν Background (CνB)
- Detection of CνB@PTOLEMY
- Physics/Cosmology with CνB



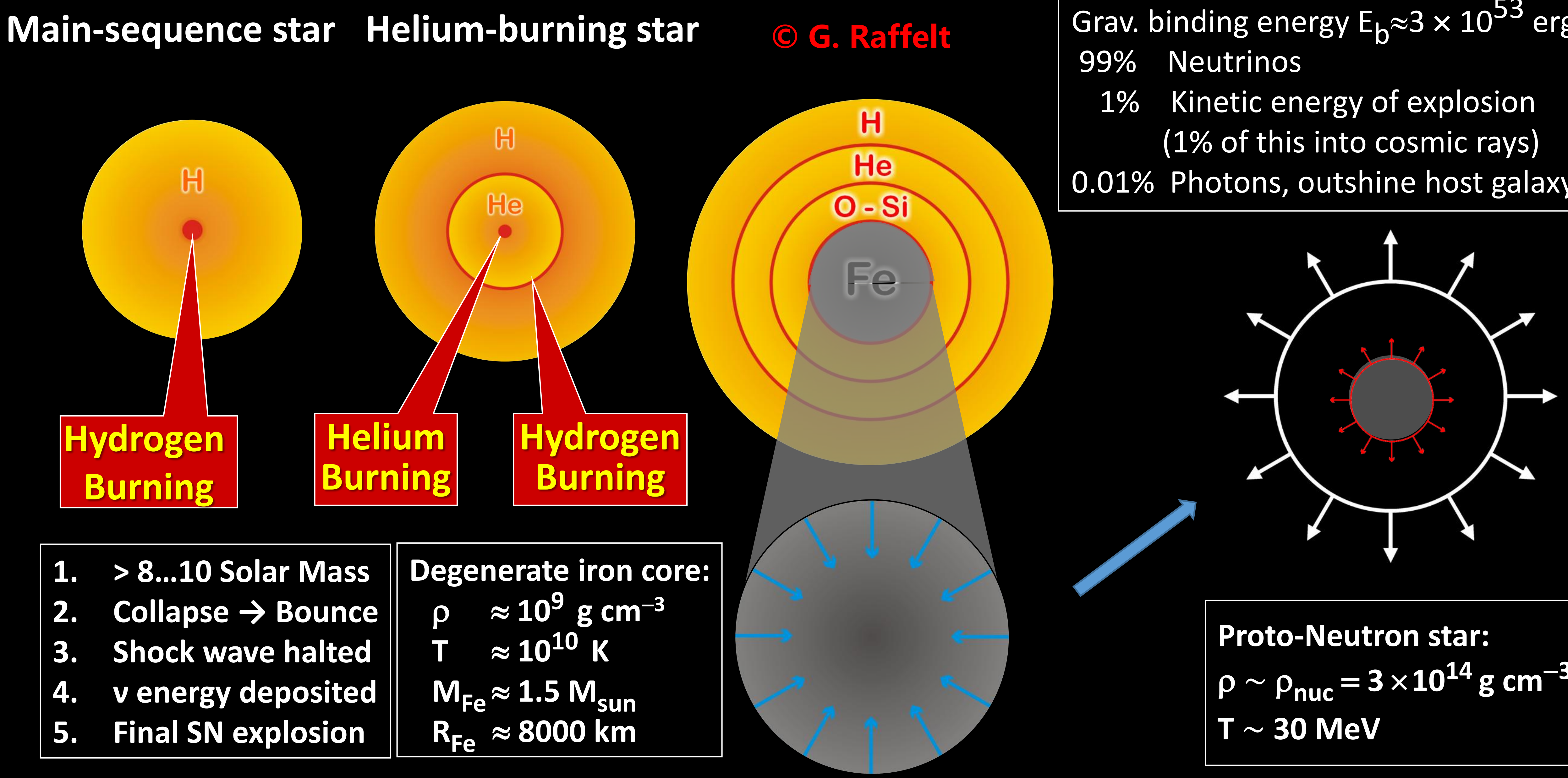


凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

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



1. > 8…10 Solar Mass
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

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

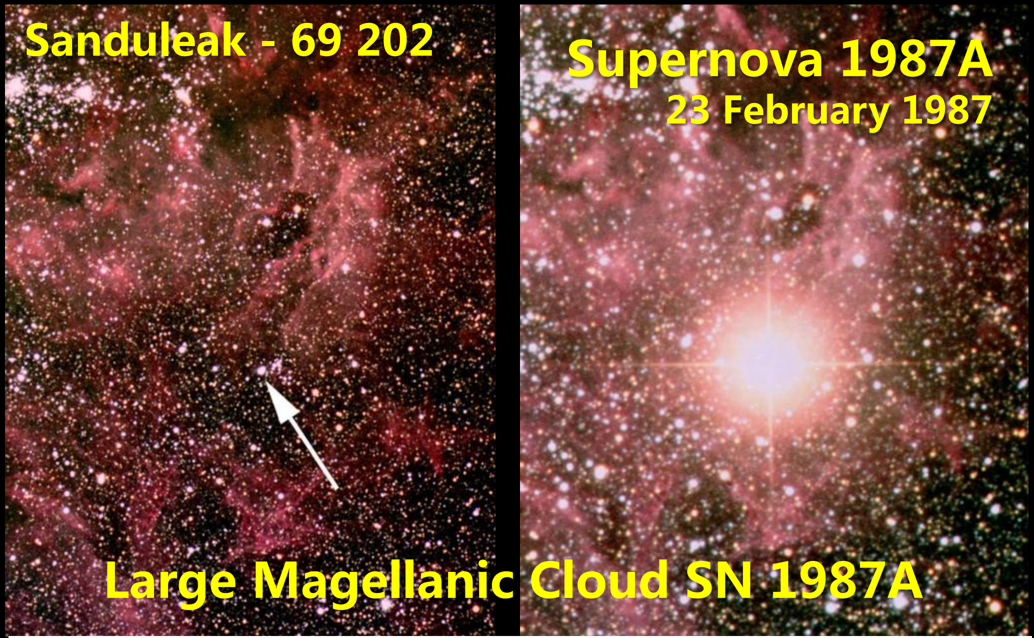
$R_{Fe} \approx 8000$ km

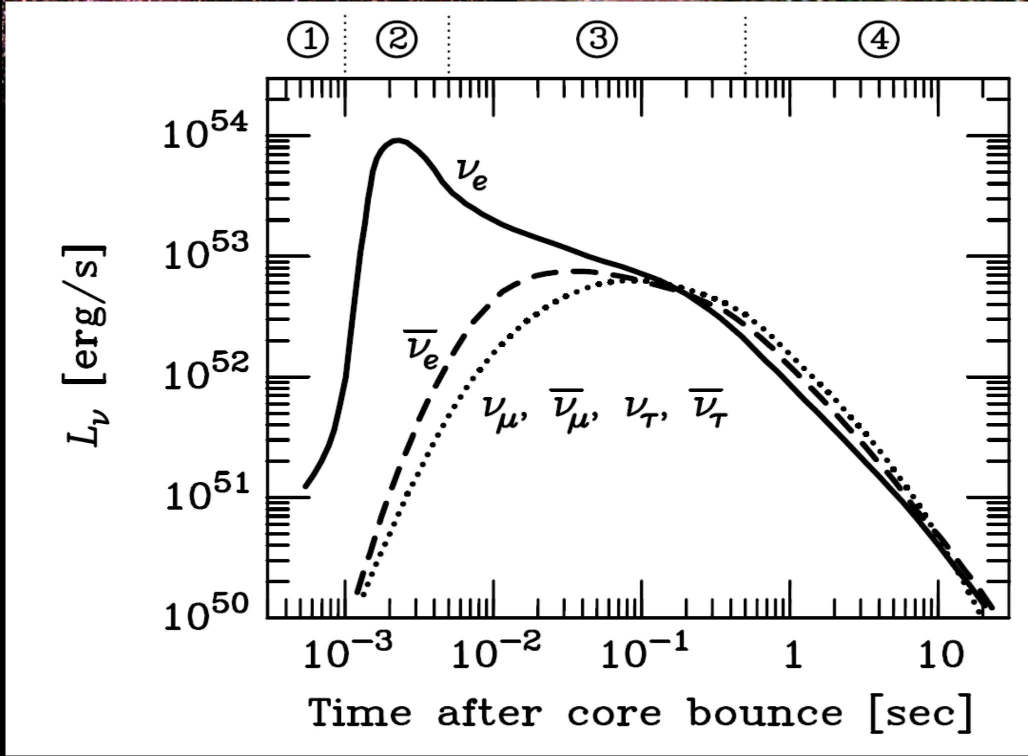
Proto-Neutron star:

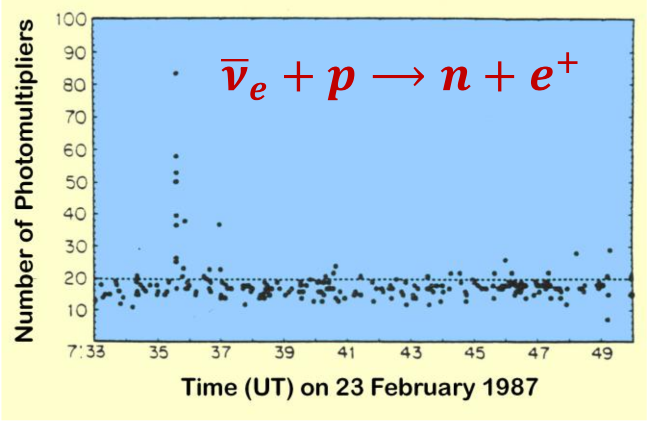
$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

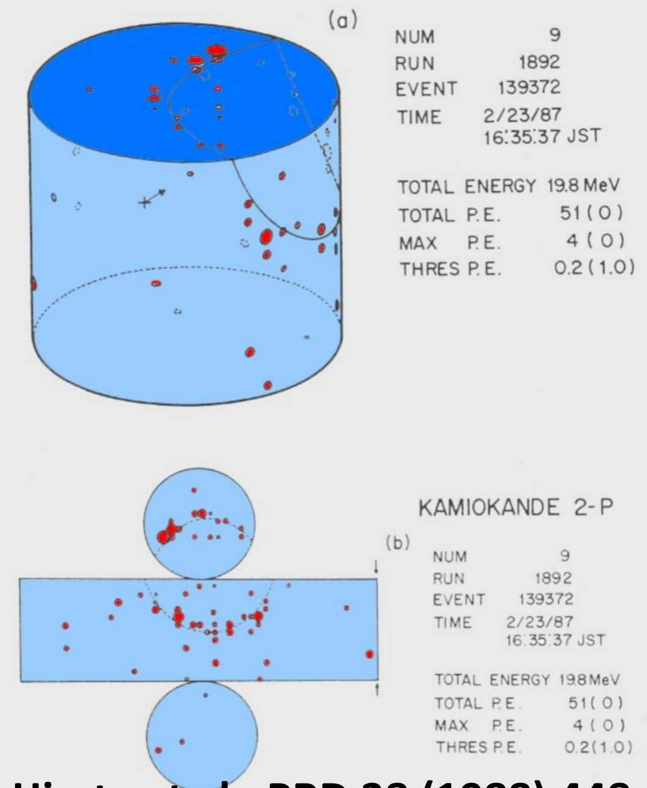
$T \sim 30$ MeV

Neutrinos from SN 1987A

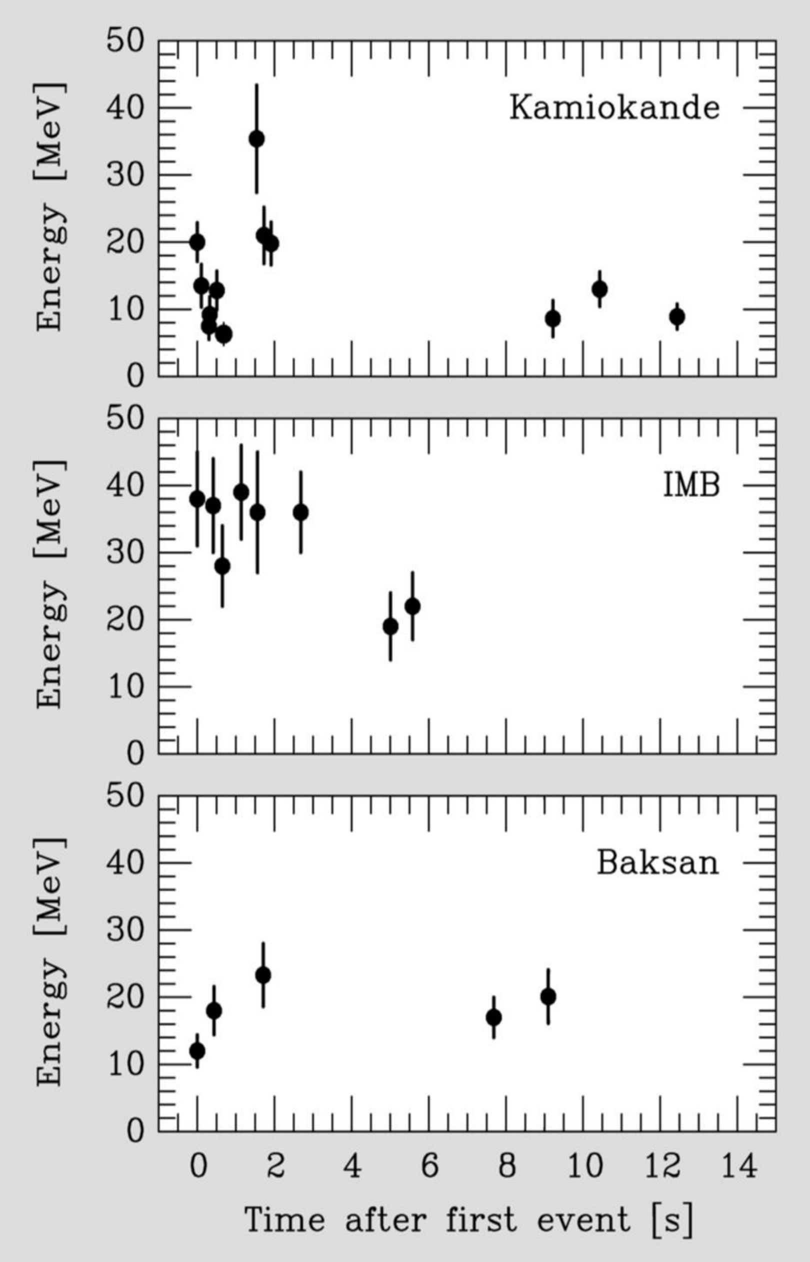








Hirata et al., PRD 38 (1988) 448



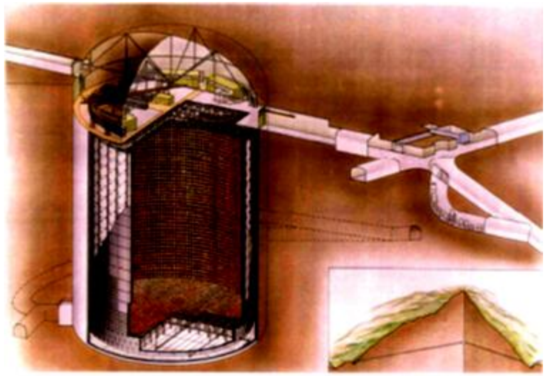
Detection of SN Neutrinos

Supernova-relevant neutrino interactions

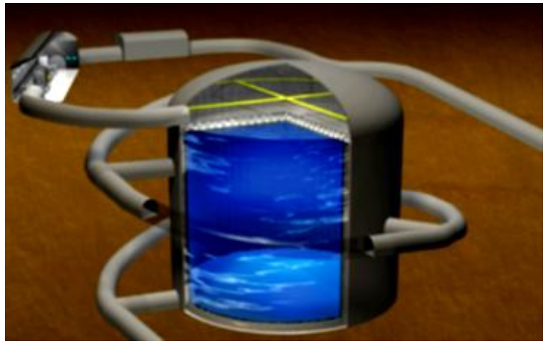
Scholberg, @SNOBS 2017

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$ Various possible ejecta and deexcitation products
Neutral current	Useful for pointing	Elastic scattering very low energy recoils	$\nu + A \rightarrow \nu + A^*$ $\nu + A \rightarrow \nu + A$ Coherent elastic (CEvNS)

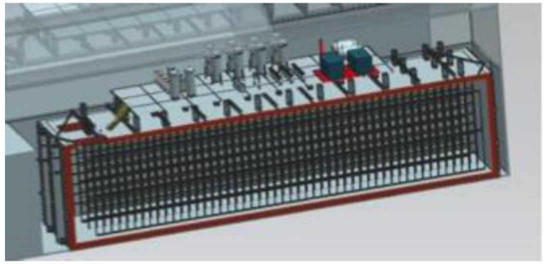
Super-Kamiokande



Hyper-Kamiokande



LAr-TPC DUNE



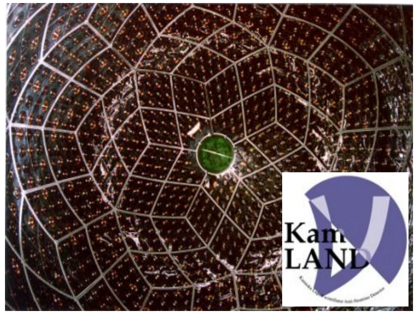
Summary of SN Neutrino Detectors

Scholberg @SNOBS 2017

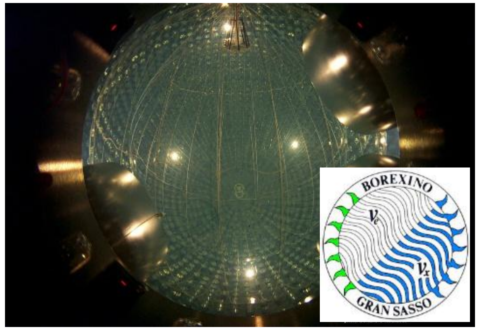
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOνA	Scintillator	USA	15	3000	Running
MicroBooNE	Liquid argon	USA	0.17	17	Running
SNO+	Scintillator	Canada	1	300	Under construction
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Under construction
PINGU/GEN-2	Long string	South pole	(600)	(10^6)	Future

Current & Future Scintillator-based Detectors

LVD, 1 kt

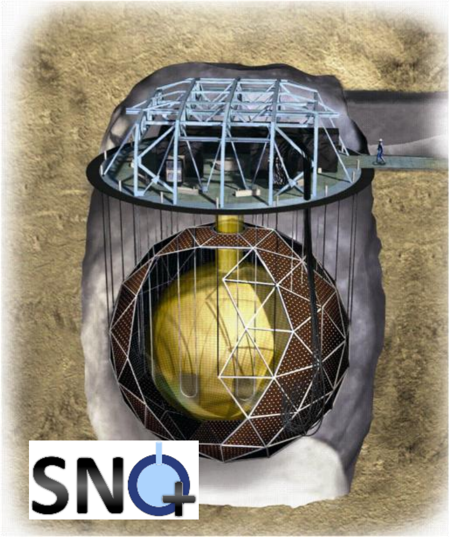


KamLAND, 1 kt

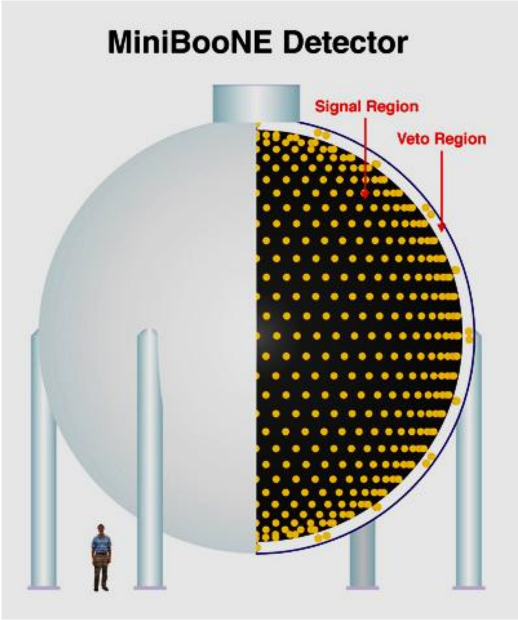


Borexino, 0.3 kt

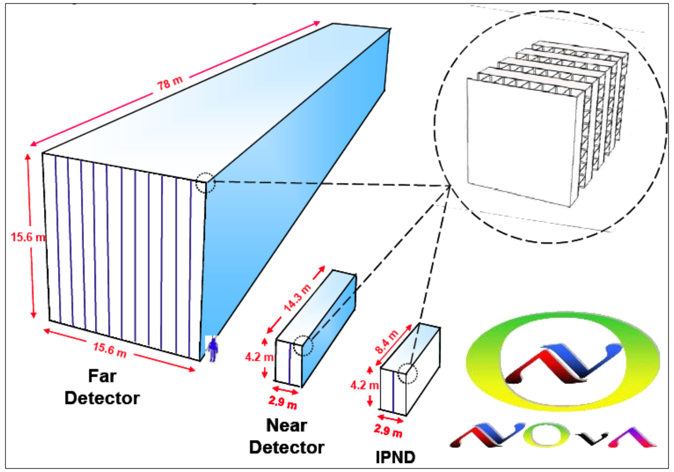
Daya Bay, 0.16 kt



SNO+, 1 kt



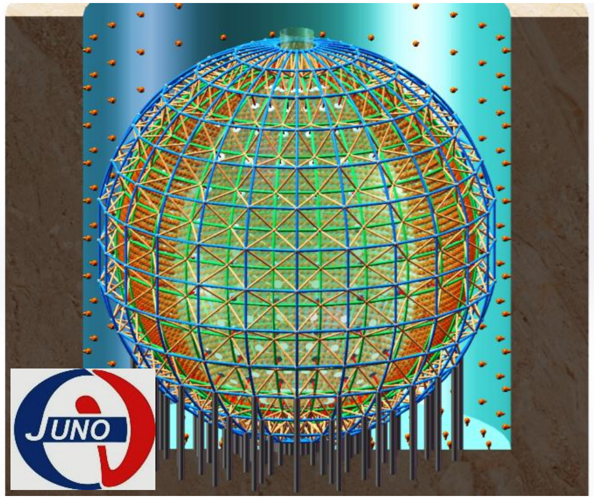
MiniBooNE, 0.7 kt



NOvA, 15 kt

Baksan, 0.33 kt

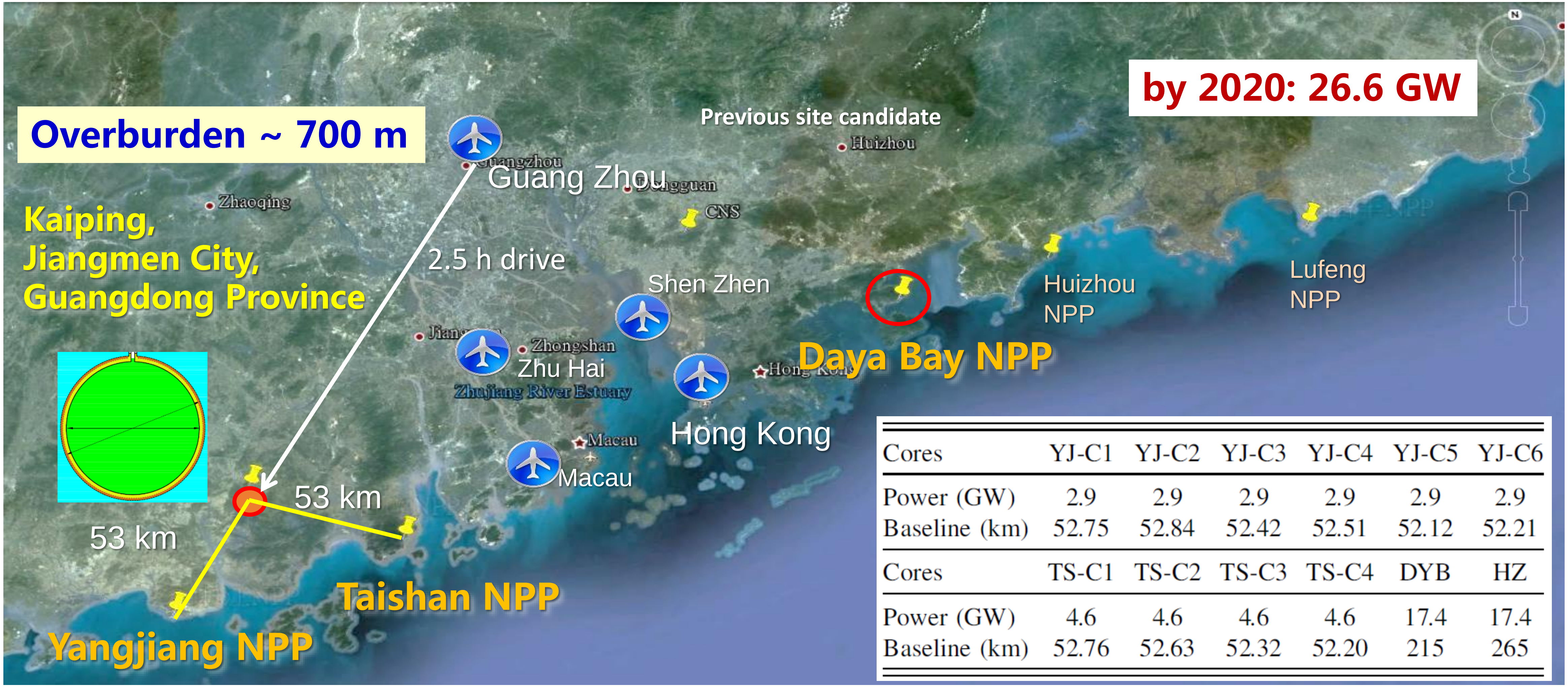
LENA, 50 kt



JUNO, 20 kt

The JUNO Experiment

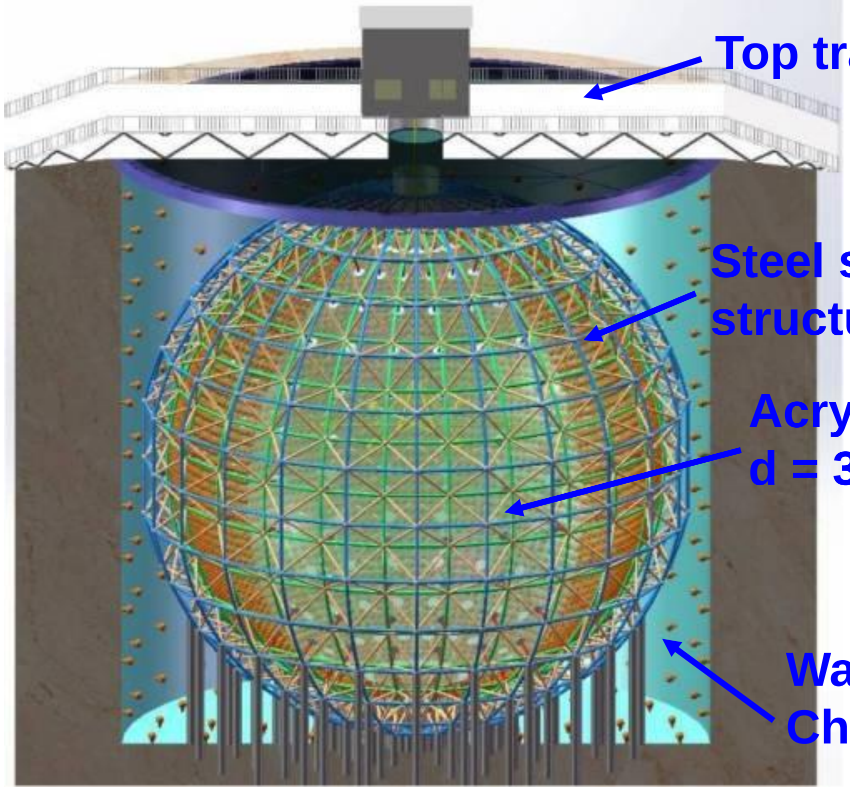
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

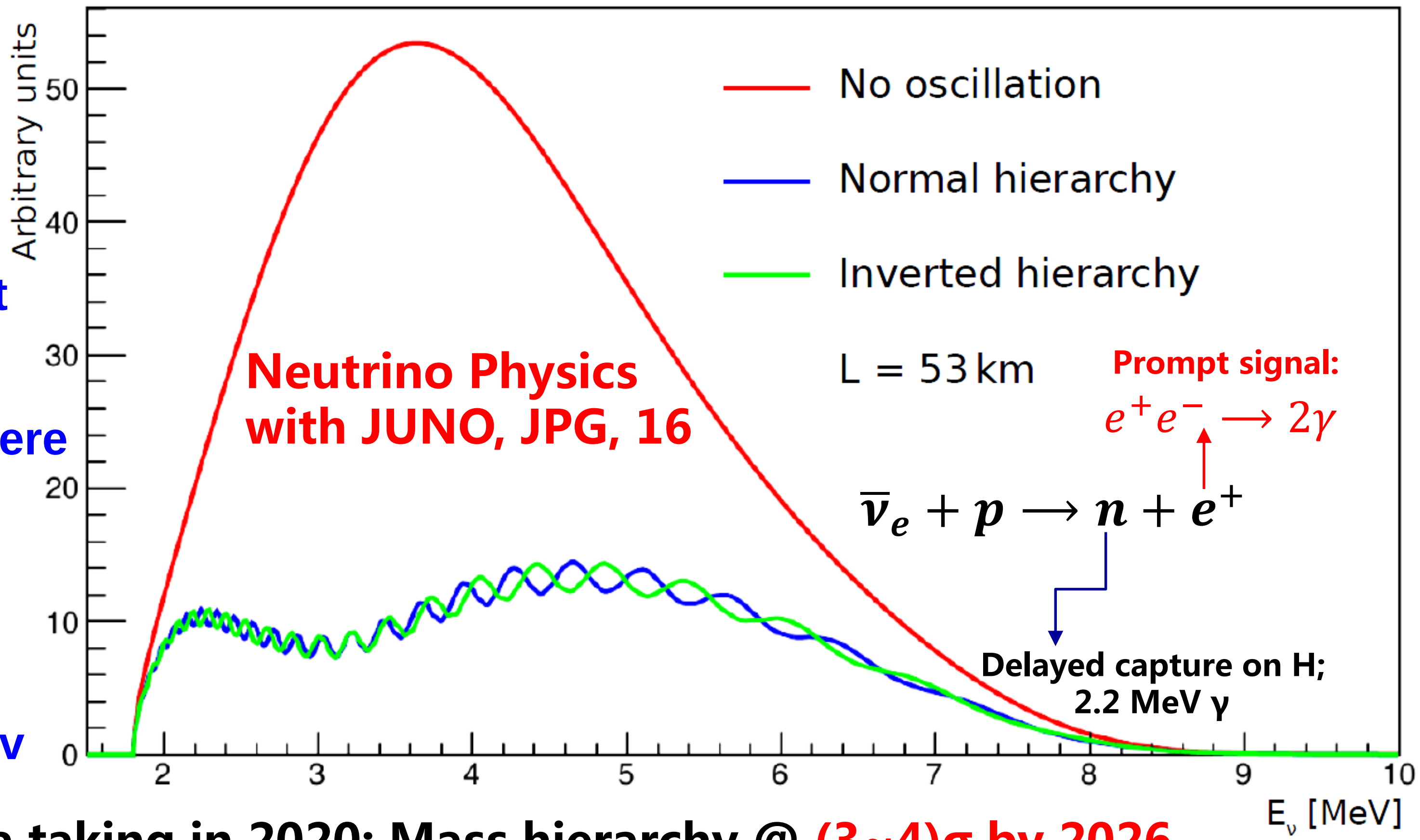


Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

The JUNO Experiment

Jiangmen Underground Neutrino Observatory



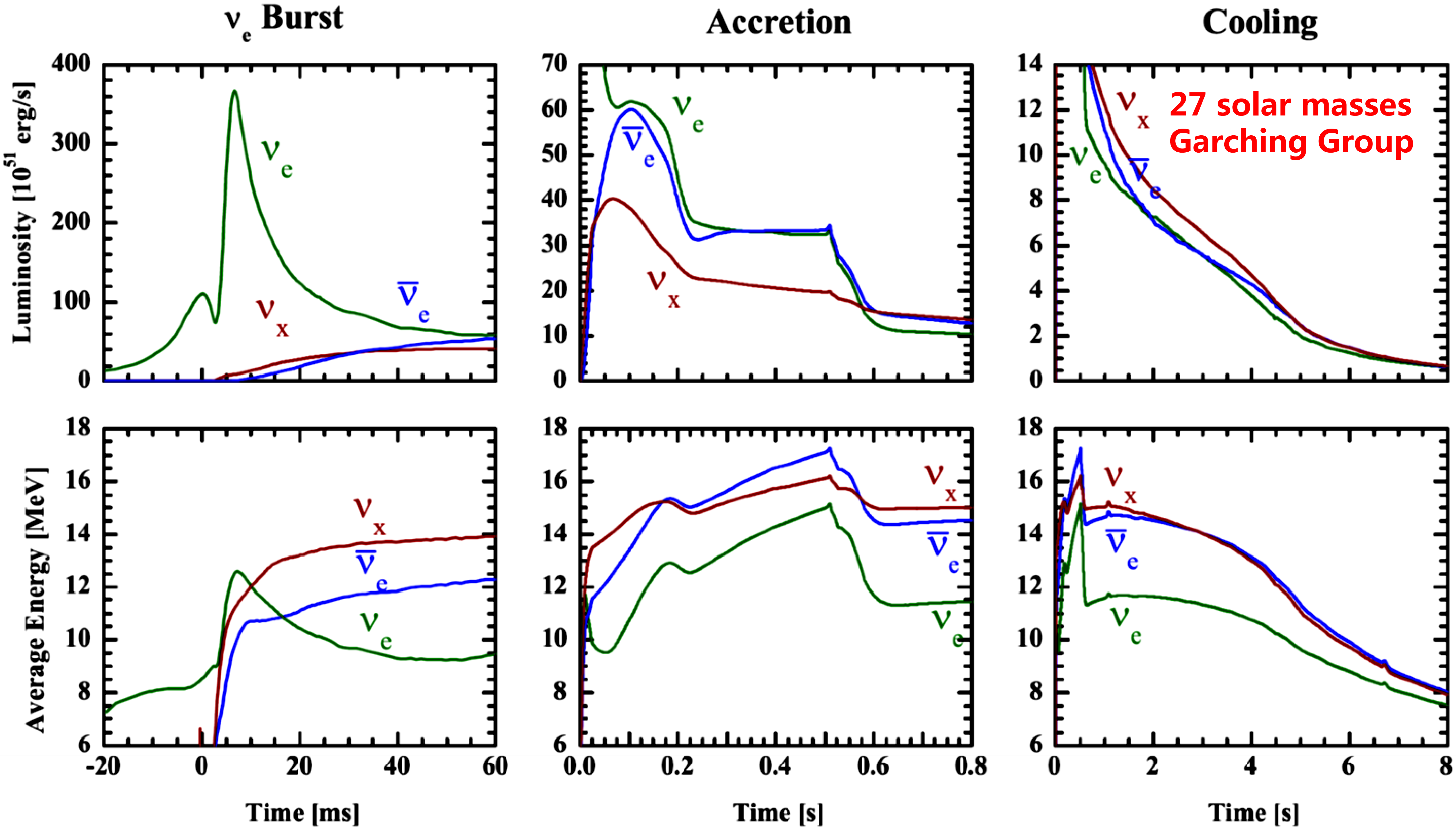


- 20 kiloton LS detector
- 3% energy resolution@ 1 MeV
- 700 m underground
- 18,000 20” +25,000 3” PMTs
- 53 km to the NPPs

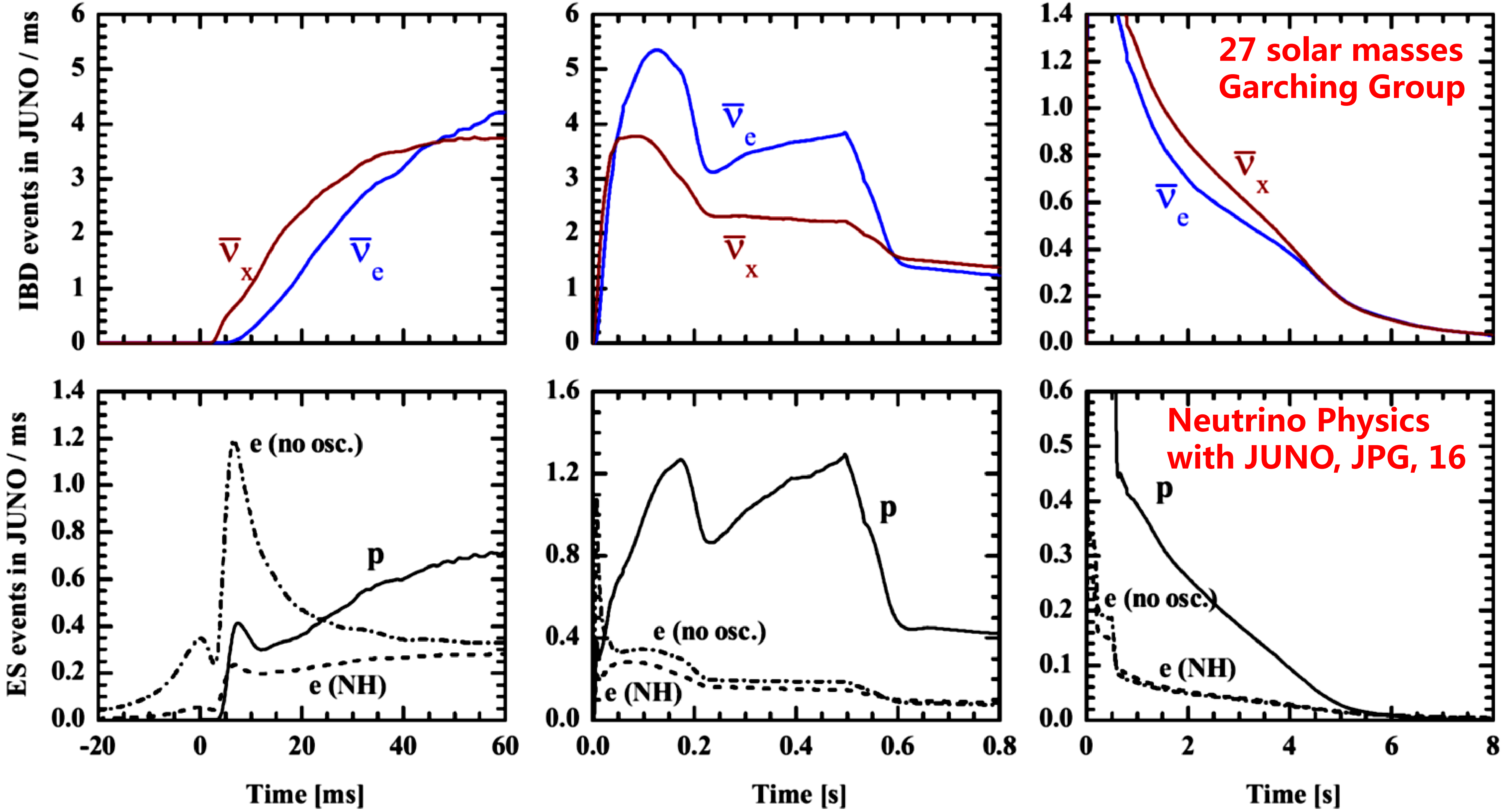
Data taking in 2020; Mass hierarchy @ (3~4)σ by 2026

	KamLAND	Borexino	JUNO
LS mass	1 kt	0.3 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

SN Models & Neutrino Spectra



SN Neutrino Event Rates



SN Neutrinos @ LS Detectors

Reaction channel	Interaction type	Sensitive to
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	$\bar{\nu}_e$
$\nu + p \rightarrow \nu + p$	NC	ν_x
$\nu + e^- \rightarrow \nu + e^-$	CC+NC	ν_e
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$ (14.39 MeV, 20 ms)	CC	$\bar{\nu}_e$
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$ (17.34 MeV, 11 ms)	CC	ν_e
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	ν_x

Natural abundance of ${}^{13}\mathrm{C}$ is about 1.1%

Fukugita *et al.*, PLB, 90; Suzuki *et al.*, PRD, 12

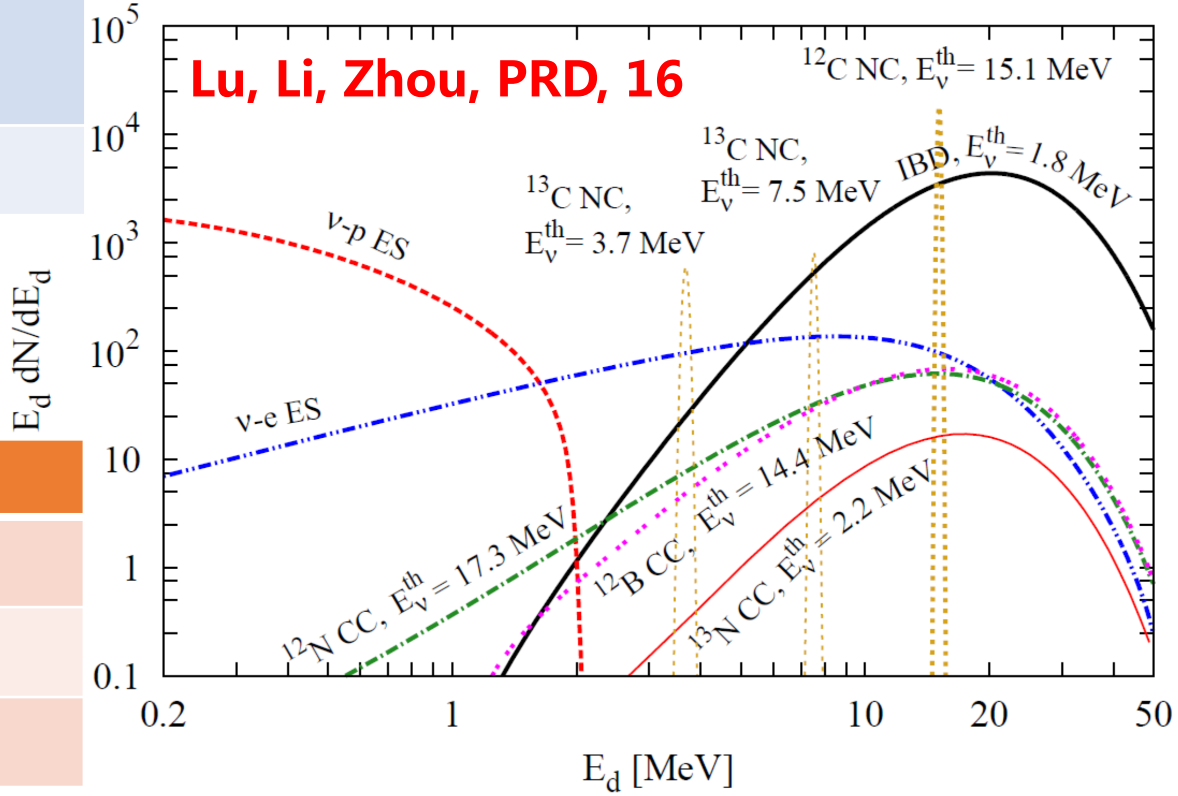
Reaction channel	Interaction type	Sensitive to
$\bar{\nu}_e + {}^{13}\mathrm{C} \rightarrow e^+ + {}^{13}\mathrm{B}$	CC	$\bar{\nu}_e$
$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}$	CC	ν_e
$\nu + {}^{13}\mathrm{C} \rightarrow \nu + {}^{13}\mathrm{C}^*$	NC	ν_x

- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

Beacom, Farr, Vogel, PRD, 02;
Dasgupta, Beacom, PRD, 11

Event Spectra @ JUNO

Average E $(\nu_e, \bar{\nu}_e, \nu_x)$ (12, 14, 16) MeV

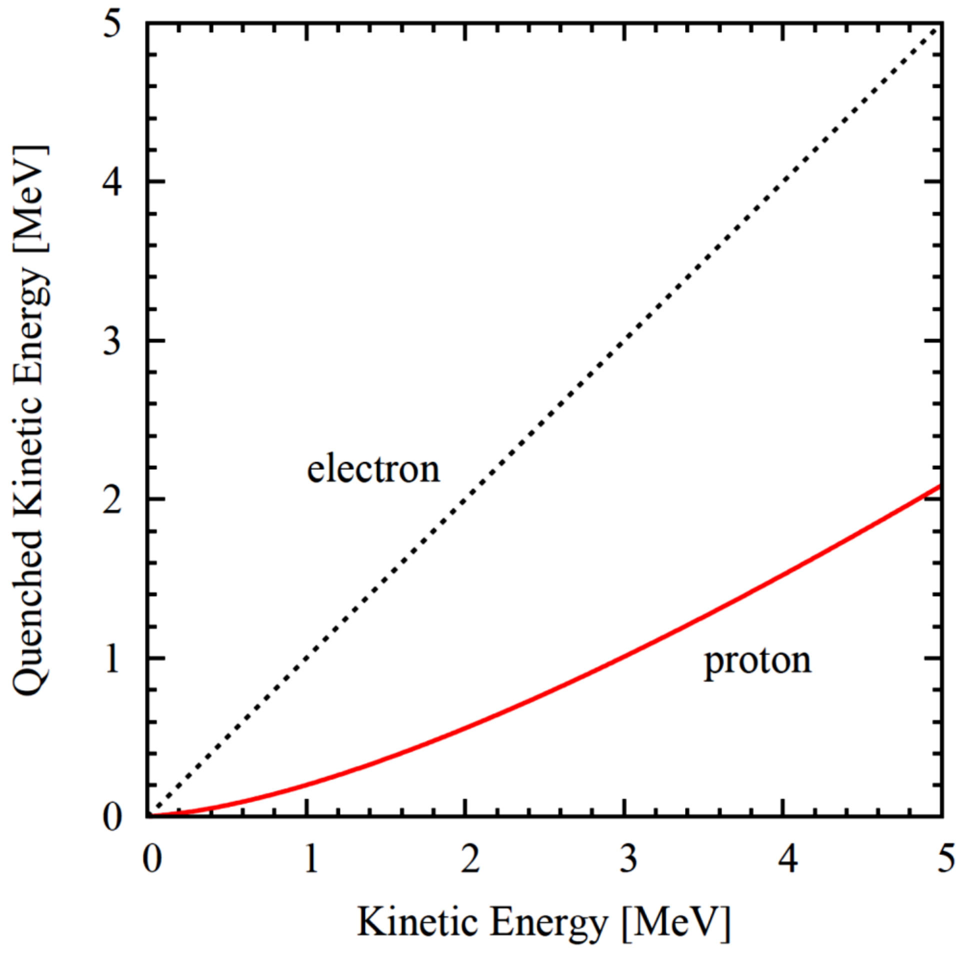


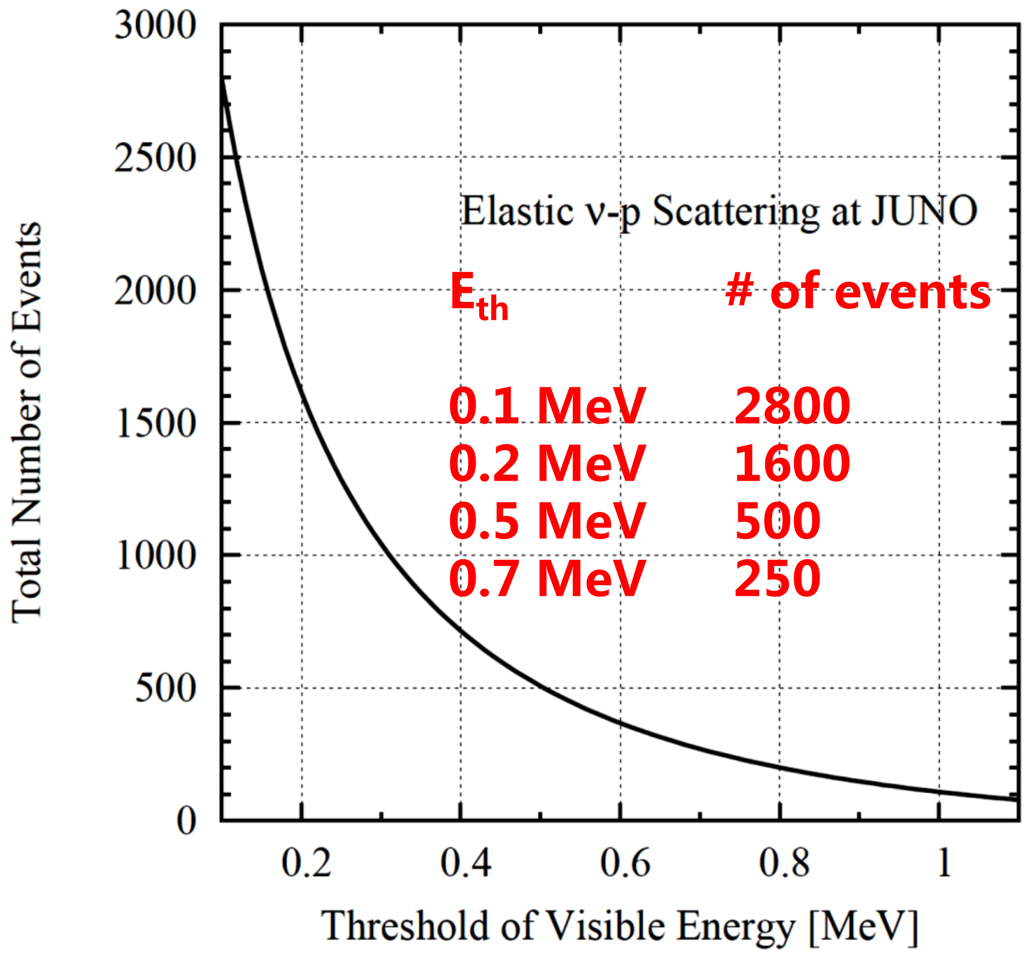
Elastic ν-p Scattering in LS Detectors

Beacom, Farr, Vogel, PRD, 02; Dasgupta, Beacom, PRD, 11; Lu, Li, Zhou, PRD, 16

- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

Quenching effects on the proton recoil energy $T_p \leq 2\,E^2/m_p$





SN Neutrinos @ LS Detectors

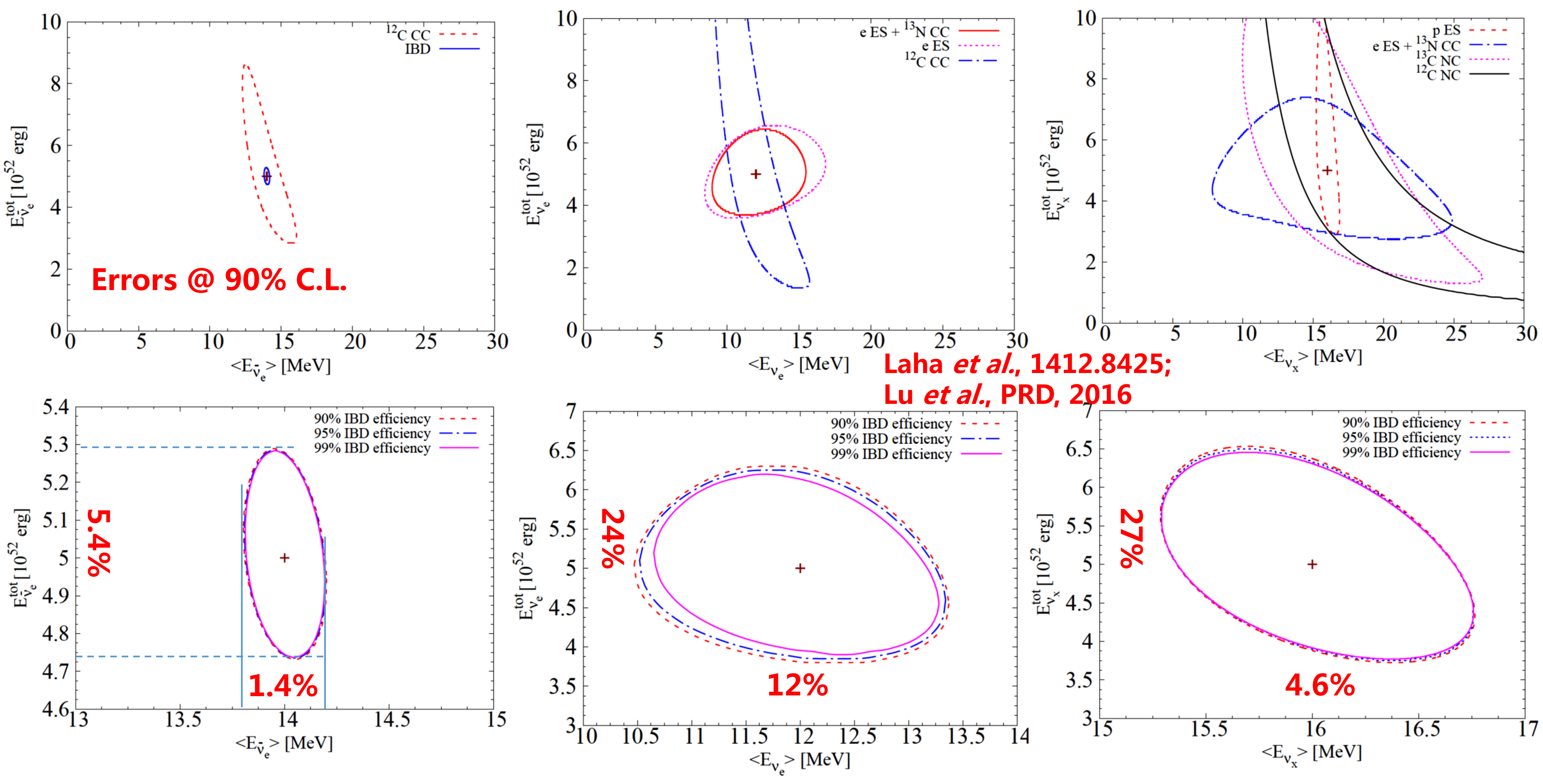
Channel	Type		Number of SN Neutrino Events at JUNO: No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC		43	134	106
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC		86	98	126
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226
$\nu_e + {}^{13}C \to e^- + {}^{13}N$	CC		19	29	26
$\nu + {}^{13}C \to \nu + {}^{13}C^*$	NC	$3/2^-(5/2^-)$	23(15)	23(15)	23(15)
		ν_e	3(1)	4(3)	4(2)
		$\overline{\nu}_e$	3(2)	4(2)	4(3)
		ν_x	17(12)	15(10)	15(10)

Detection channels	ν Flavors	Efficiency	Backgrounds	Systematics	
IBD	$\overline{\nu}_e$	95%	None	Detection	2%
^{12}C-CC	$\overline{\nu}_e$ and ν_e	90%	None	Detection	2%
pES	$\overline{\nu}_e$, ν_e and ν_x	99%	eES	Detection	2%
				Cross section	20%
				k_B	3%
eES	$\overline{\nu}_e$, ν_e and ν_x	99%	^{13}N-CC+IBD+pES	Detection	2%
^{13}N-CC	ν_e	100%	eES+IBD	Detection	2%
				Cross section	20%
^{12}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%
^{13}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%

- **IBD for $\overline{\nu}_e$ + sub-leading effects from ^{12}C CC**
- **Elastic ν-e scattering for ν_e + ^{12}C CC**
- **Elastic ν-p scattering for ν_x + eES**
- **A global analysis of all reaction channels?**

Laha *et al.*, 1412.8425; Lu *et al.*, PRD, 2016

SN Neutrinos @ LS Detectors

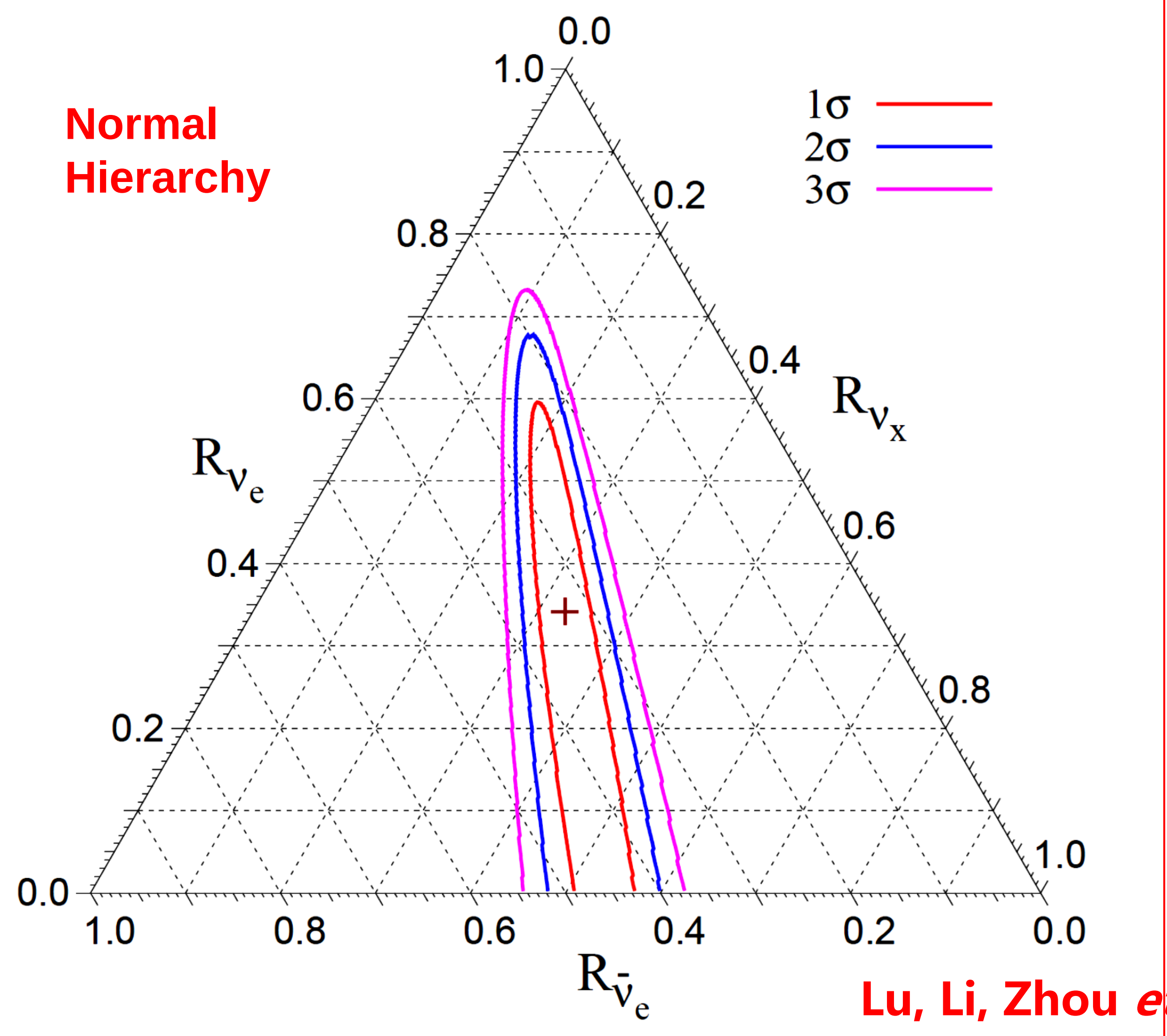


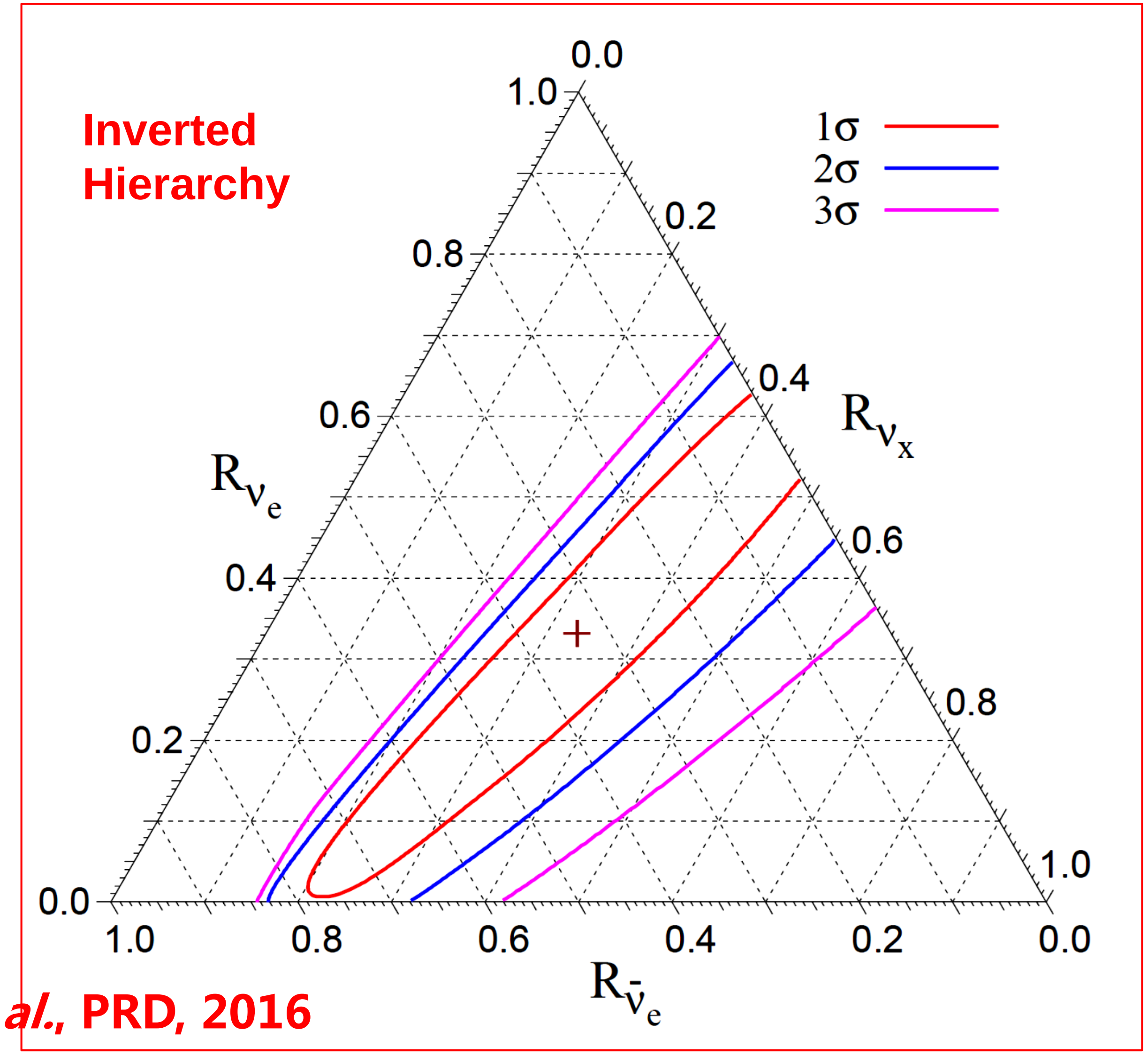
Laha *et al.*, 1412.8425;
Lu *et al.*, PRD, 2016

Test of Energy Equipartition Hypothesis

Including only the MSW matter effects in the SN

For collective flavor conversions, talk by M.R. Wu



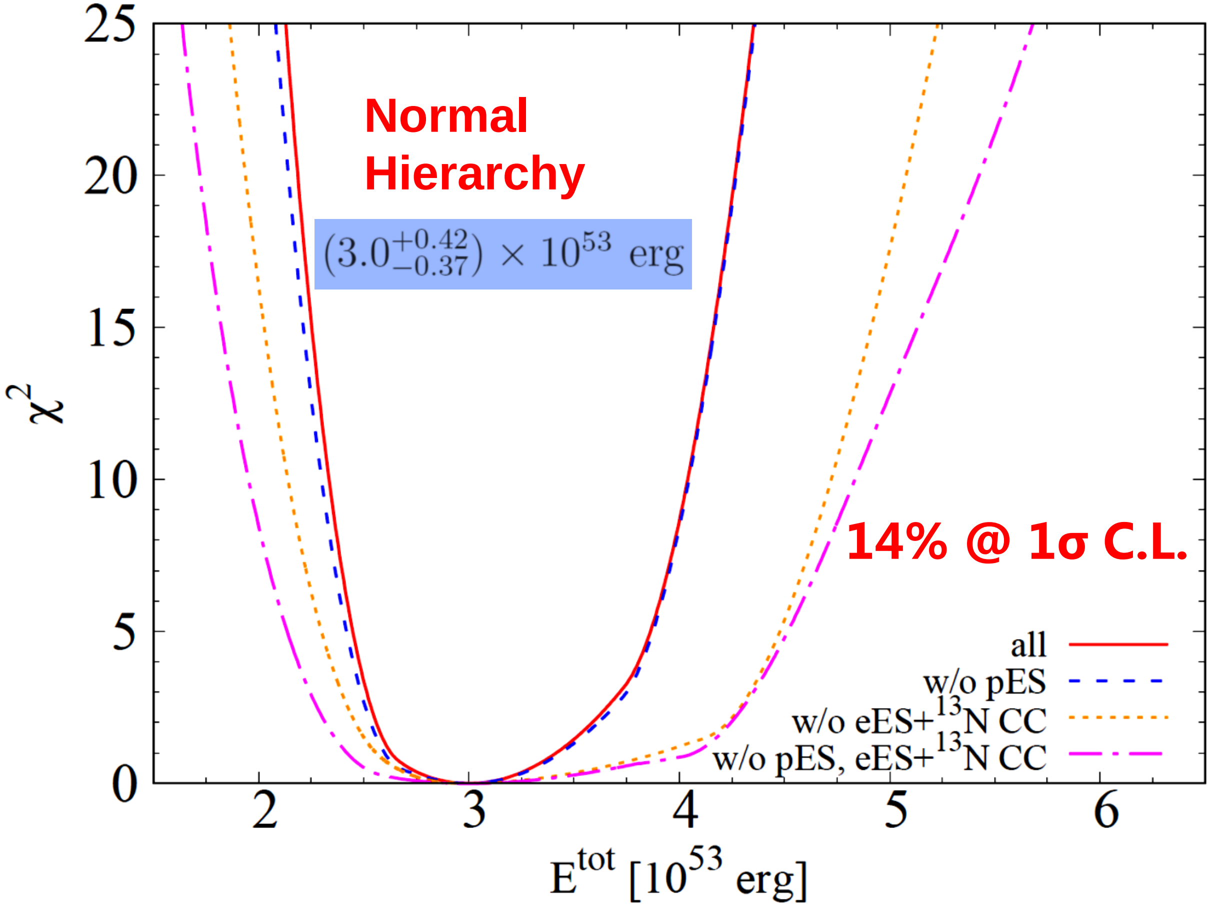


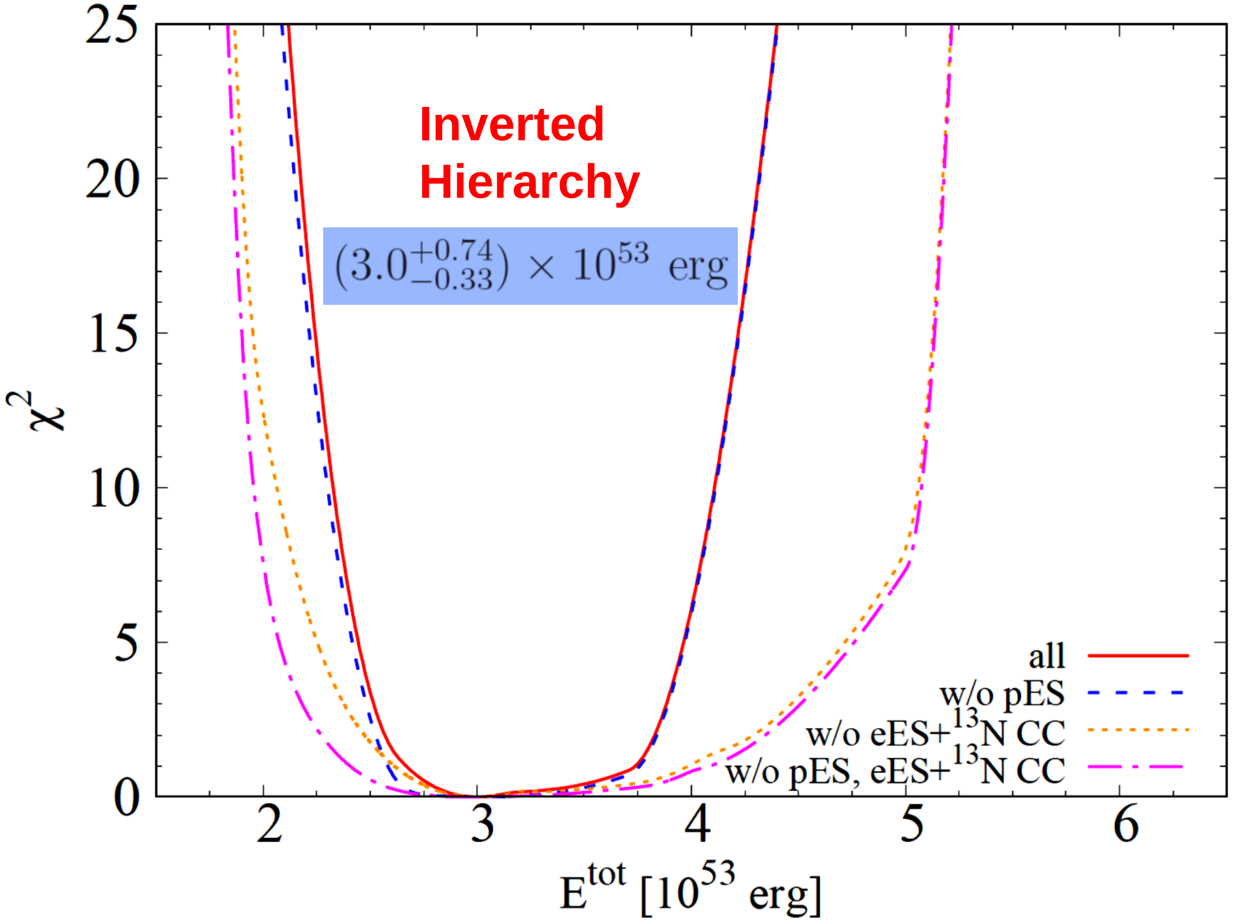
Lu, Li, Zhou *et al.*, PRD, 2016

Total Gravitational Binding Energy

Including only the MSW effects in the SN, and fixing the spectral indices at γ =3

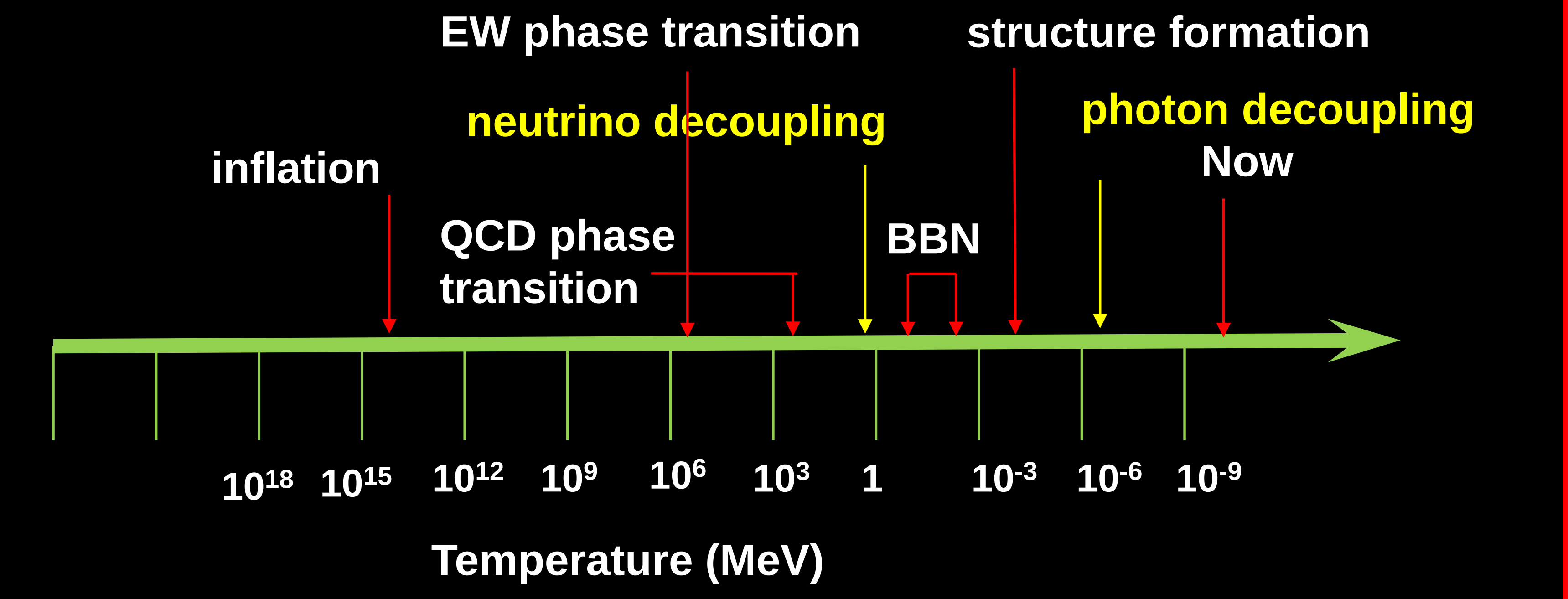
Lu, Li, Zhou *et al.*, PRD, 2016





- **With a high-statistics measurement of a galactic SN: time & energy spectra, all flavors, …**
- **More works need to be done: collective flavor conversions, explosion mechanisms, …**

Formation of Cosmic ν Background

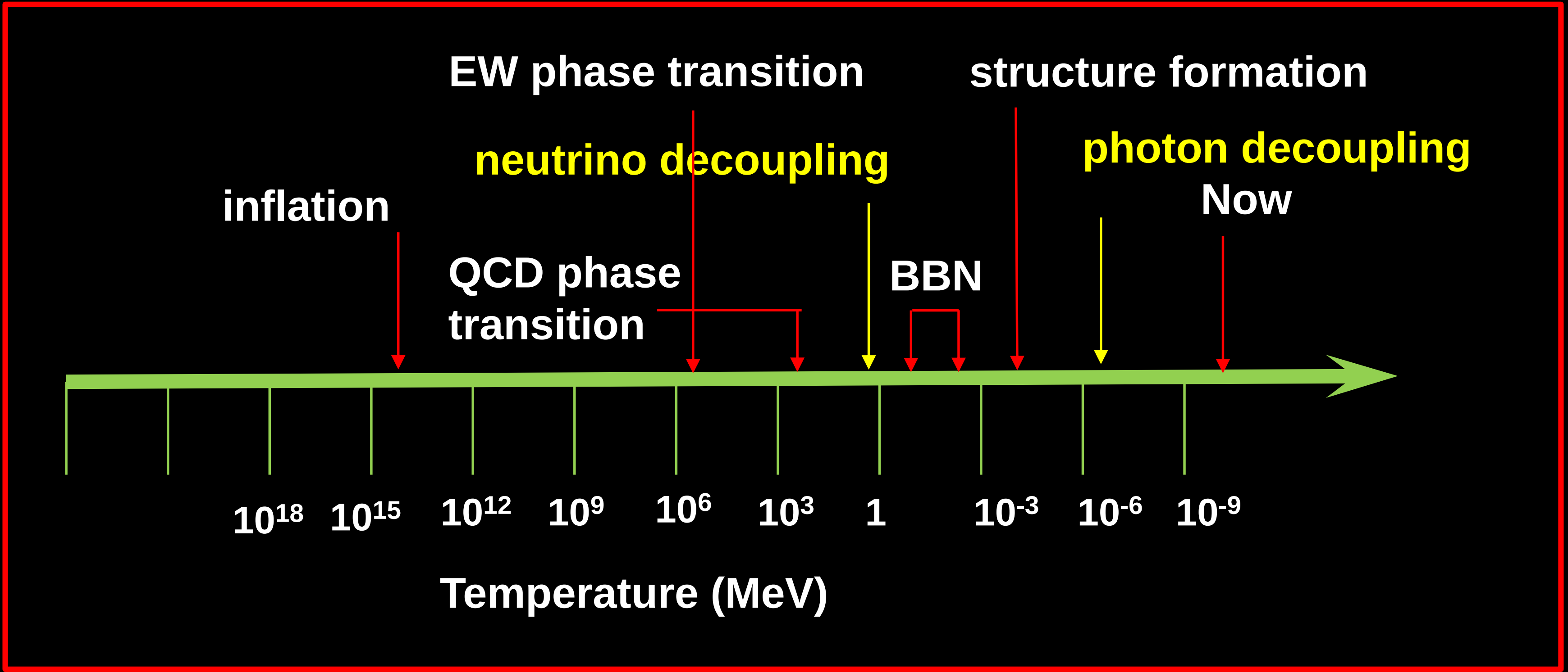


- ν in thermal equilibrium @ high temperature

$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$
$$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$$
$$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$$
$$e^+ e^- \leftrightarrow \gamma\gamma$$

$$T_\nu = T_e = T_\gamma$$

Formation of Cosmic ν Background



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$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$
$$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$$
$$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$$
$$e^+ e^- \leftrightarrow \gamma\gamma$$

$$T_\nu = T_e = T_\gamma$$

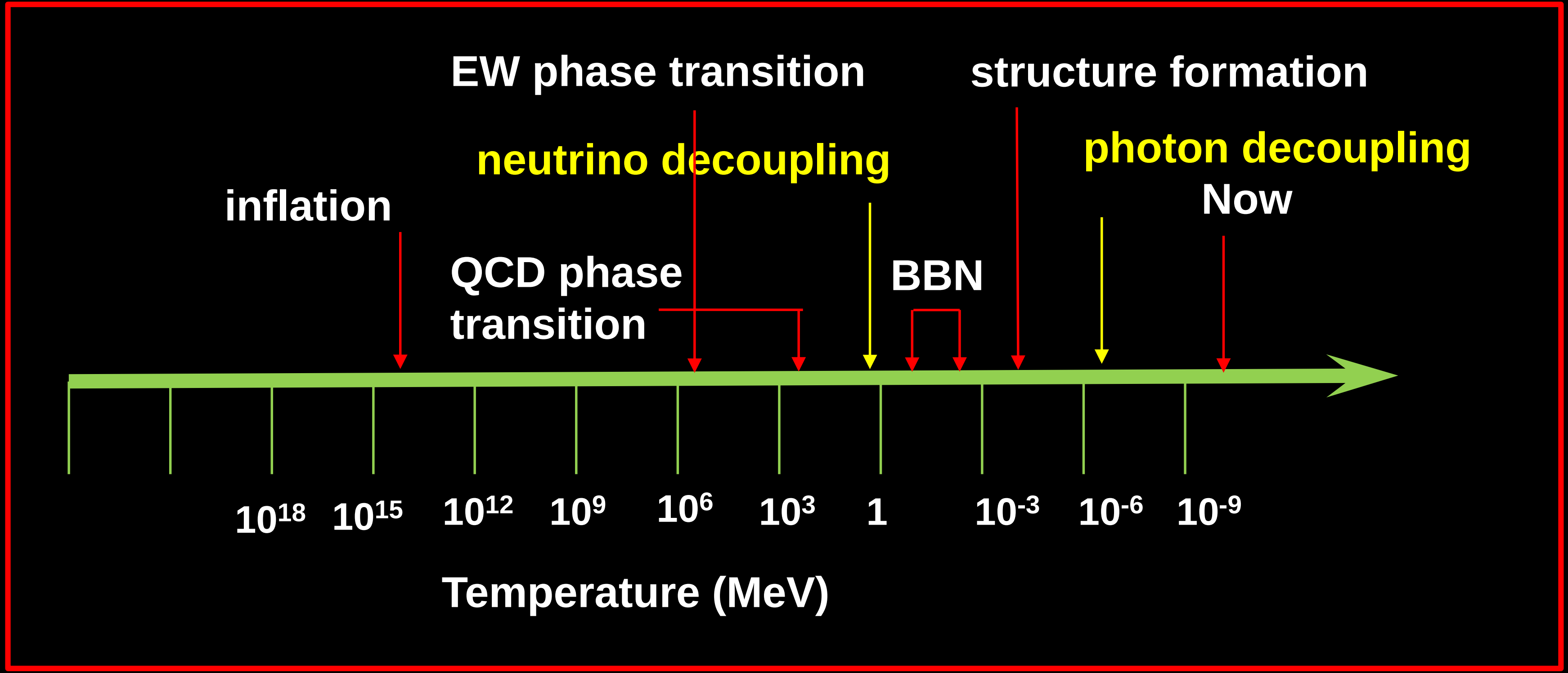
- neutrino decoupling $\Gamma < H$ @ $T \sim 1$ MeV

Weak interactions $\Gamma \approx G_F^2 T^5$

Hubble expansion $H = \frac{\sqrt{g_*} T^2}{M_{pl}}$

Fermi-Dirac spectrum

Formation of Cosmic ν Background



- ν in thermal equilibrium **@ high temperature**

$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$
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Fermi-Dirac spectrum

- photon reheating

$e^+ e^- \leftrightarrow \gamma\gamma$ **@ $T < m_e$** $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$

- Basic properties of **CνB**
  - $T_0 = 1.95$ K and $\langle p \rangle = 3T_0 = $ **5×10^{-4} eV**
  - number density **$n = 56\ \mathrm{cm}^{-3}$** per species

Prospects for CνB Detection

☐ Acceleration in the neutrino wind

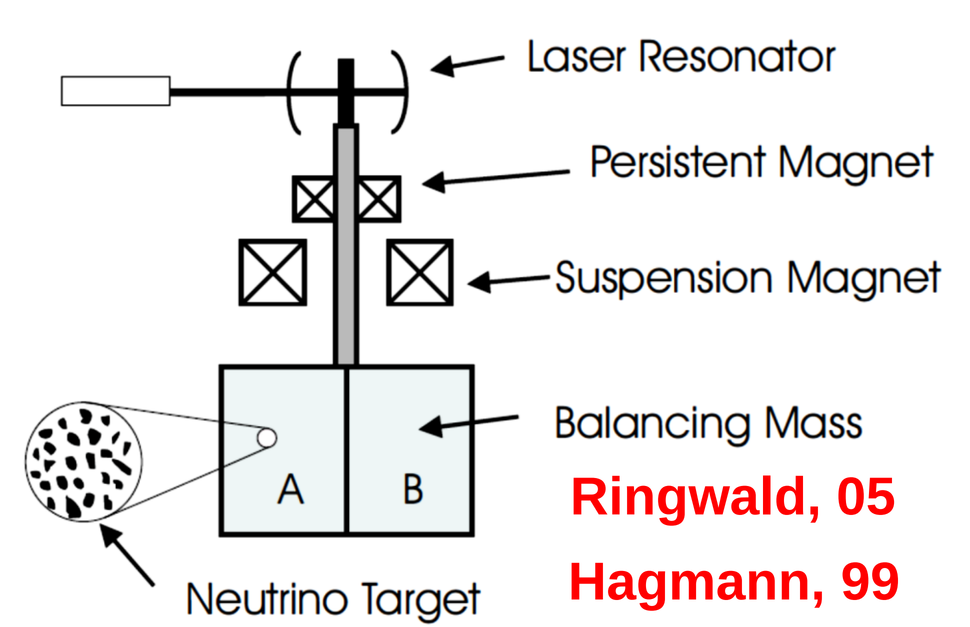
Shvartsman et al., 82; Smith, Lewin, 83; Duda et al., 01

Target mass

$$2 \times 10^{-28} \, \frac{n_\nu}{\bar{n}_\nu} \, \frac{10^{-3}\, c}{v_{\rm rel}} \, \frac{\rho_{\rm t}}{{\rm g/cm^3}} \left(\frac{r_{\rm t}}{\bar{\lambda}}\right)^3 \frac{\rm cm}{\rm s^2}$$

de Broglie wavelength

Current Sensitivity
10^{-13} cm s^{-2}



Ringwald, 05

Hagmann, 99

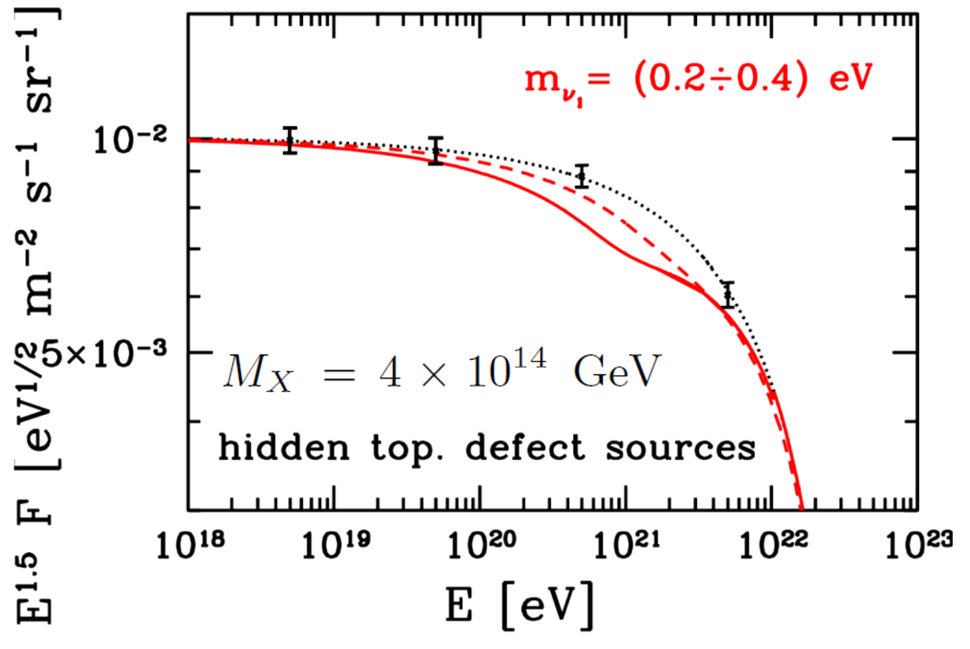
☐ Resonant absorption of EHE neutrinos

Weiler, 82; Eberle et al., 04; Ringwald, 09

$$E_{0,i}^{\rm res} = \frac{m_Z^2}{2 m_{\nu_{0,i}}} = 4.2 \times 10^{12} \left(\frac{\rm eV}{m_{\nu_i}}\right) {\rm GeV}$$

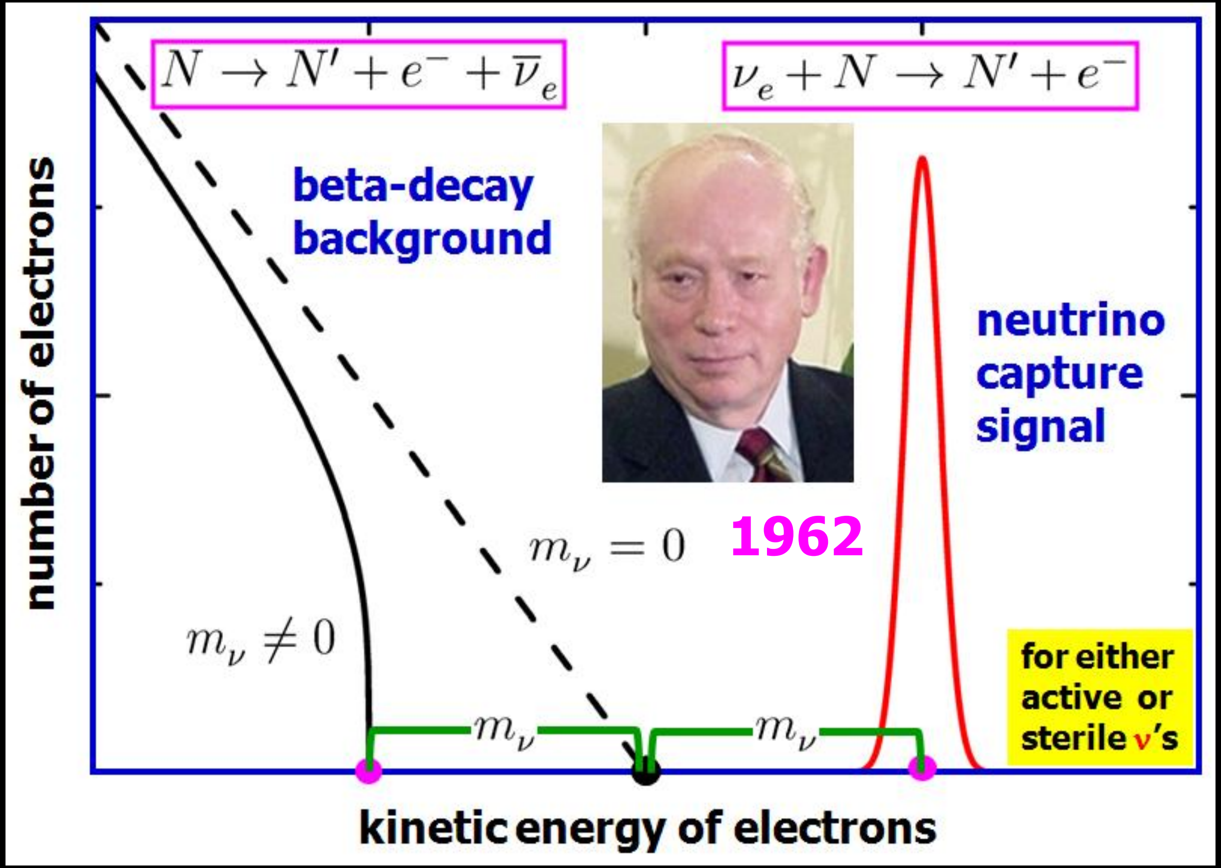
- Sources of EHE neutrinos
- Nearly-degenerate masses
- Z-burst for EHE CR events

Eberle et al., 04



Prospects for CνB Detection

Relic neutrino capture on β-decaying nuclei



no energy threshold on incident ν's mono-energetic outgoing electrons

(Irvine & Humphreys, 83; Cucco et al., 07)

At least 2 ν's cold today NON-relativistic ν's!

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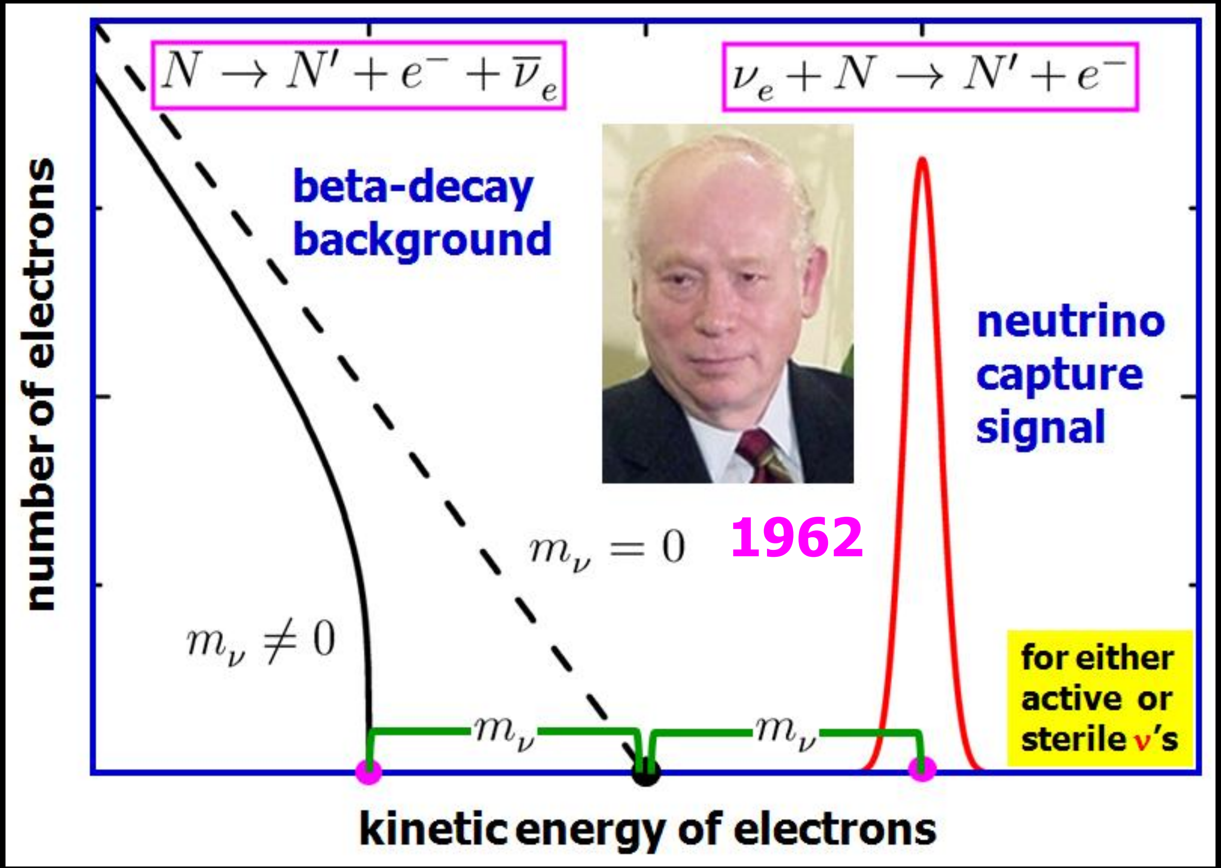

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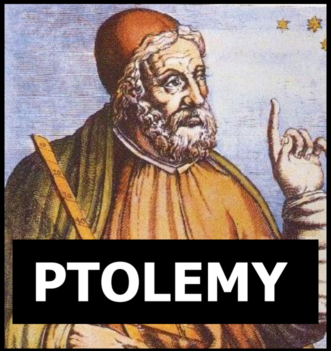

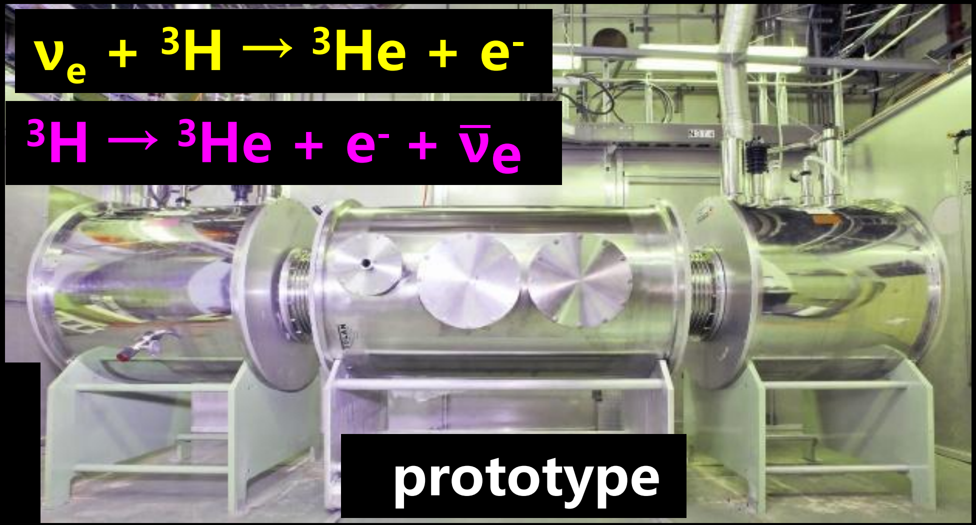

Princeton
Tritium
Observ. for
Light,
Early-Univ.,
Massive-ν
Yield

Betts et al, arXiv:1307.4738

★ CνB capture rate

$$\Gamma^{D}_{C\nu B} \sim 4\ \mathrm{yr}^{-1}$$
$$\Gamma^{M}_{C\nu B} \sim 8\ \mathrm{yr}^{-1}$$

D = Dirac

M = Majorana

- ★ first experiment
- ★ 100 g of tritium
- ★ graphene target
- ★ planned energy resolution 0.15 eV

Prospects for CνB Detection

Capture rate of a polarized neutrino state $\nu_j(s_\nu)$ on a free neutron

$$\sigma_j(s_\nu)v_{\nu_j} = \frac{G_F^2}{2\pi}|V_{ud}|^2|U_{ej}|^2 F(Z,E_e)\frac{m_p}{m_n}E_e p_e A(s_\nu)(f^2+3g^2)$$

$$A(s_\nu) \equiv 1 - 2s_\nu v_{\nu_j} = \begin{cases} 1 - v_{\nu_j}, & s_\nu = +1/2 \quad \text{RH Helicity} \\ 1 + v_{\nu_j}, & s_\nu = -1/2 \quad \text{LH Helicity} \end{cases}$$

In the limit $v_{\nu_j} \longrightarrow 1$, the state of $s_\nu = +1/2$ cannot be captured

In the limit $v_{\nu_j} \longrightarrow 0$, both RH and LH helical states do contribute

Long, Lunardini, Sabancilar, 14; Lisanti, Safdi, Tully, 14

Total Rate

$$\Gamma_{C\nu B} = \sum_j \left[\sigma_j\left(+\frac{1}{2}\right)v_{\nu_j} n_j(\nu_{hR}) + \sigma_j\left(-\frac{1}{2}\right)v_{\nu_j} n_j(\nu_{hL})\right] N_T$$

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Dirac	Majorana
Decoupling	
$n(\nu_L) = n(z)$	$n(\nu_L) = n(z)$
$n(\bar{\nu}_R) = n(z)$	$n(\nu_R) = n(z)$
Nowadays	
$n(\nu_{\rm hL}) = n_0$	$n(\nu_{\rm hL}) = n_0$
$n(\bar{\nu}_{\rm hR}) = n_0$	$n(\nu_{\rm hR}) = n_0$

$\bar{\sigma} \approx 3.8 \times 10^{-45}\ {\rm cm}^2$

$$\Gamma^{\rm D}_{\rm C\nu B} = \bar{\sigma} n_0 N_{\rm T}$$

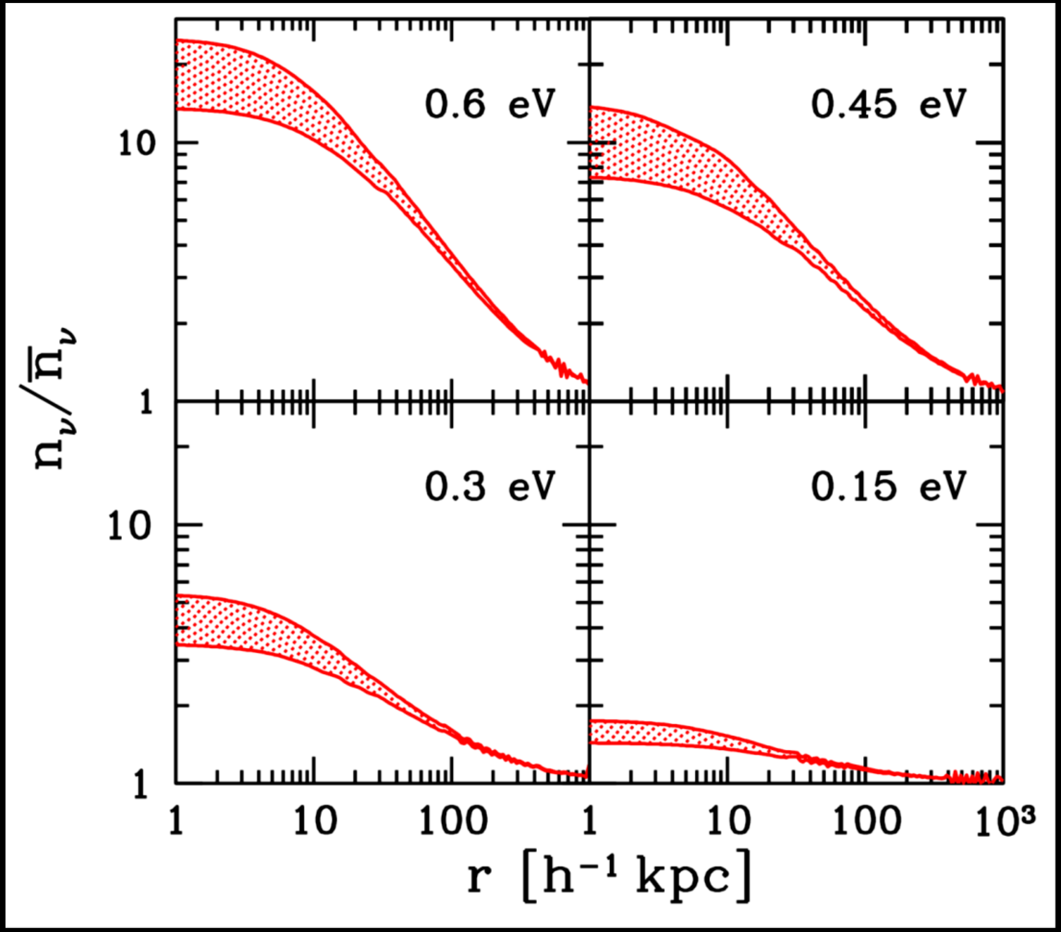
$$\Gamma^{\rm M}_{\rm C\nu B} = 2\bar{\sigma} n_0 N_{\rm T}$$

Prospects for CνB Detection

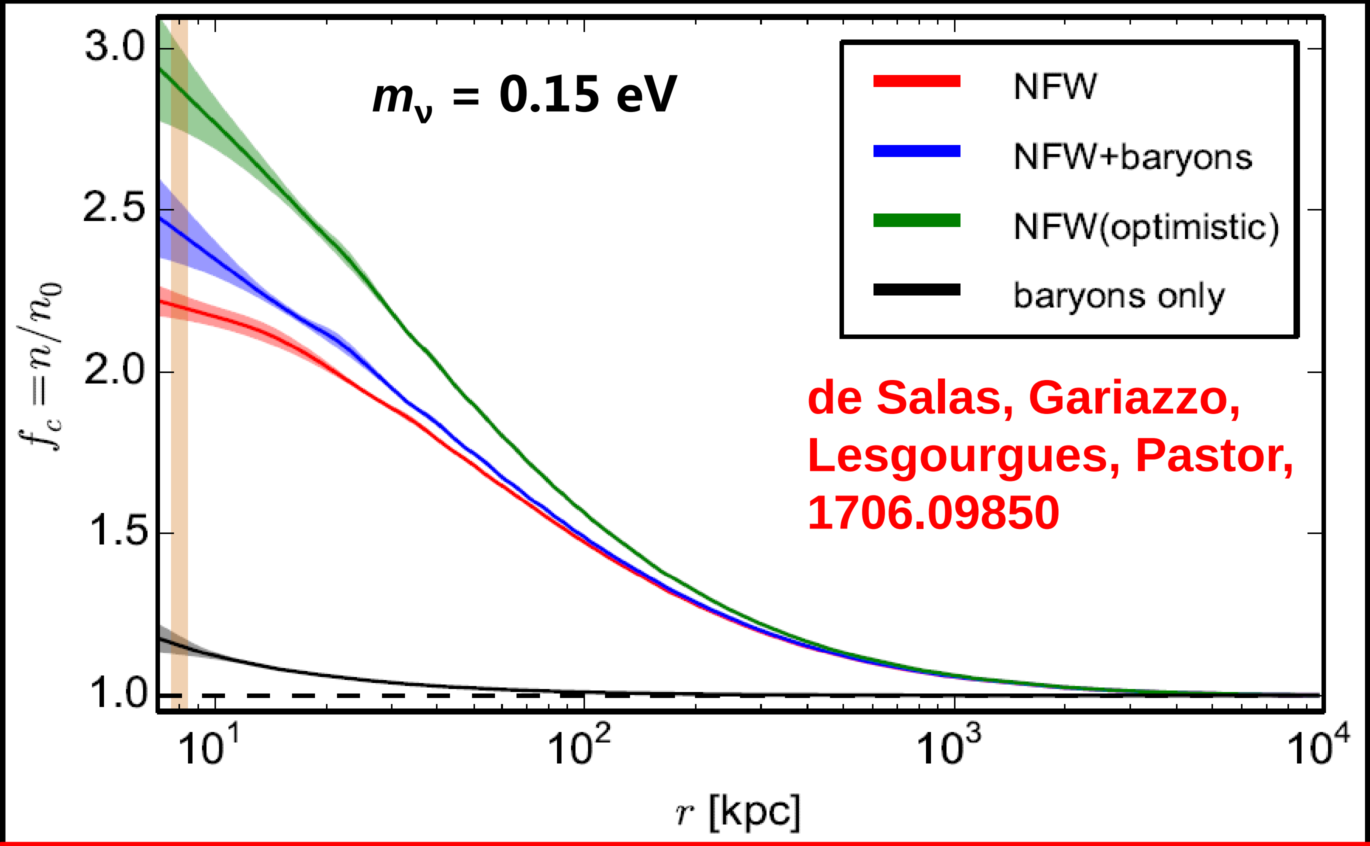
Neutrino Clustering

Ringwald, Wong, 04

Clustering in the Milky Way



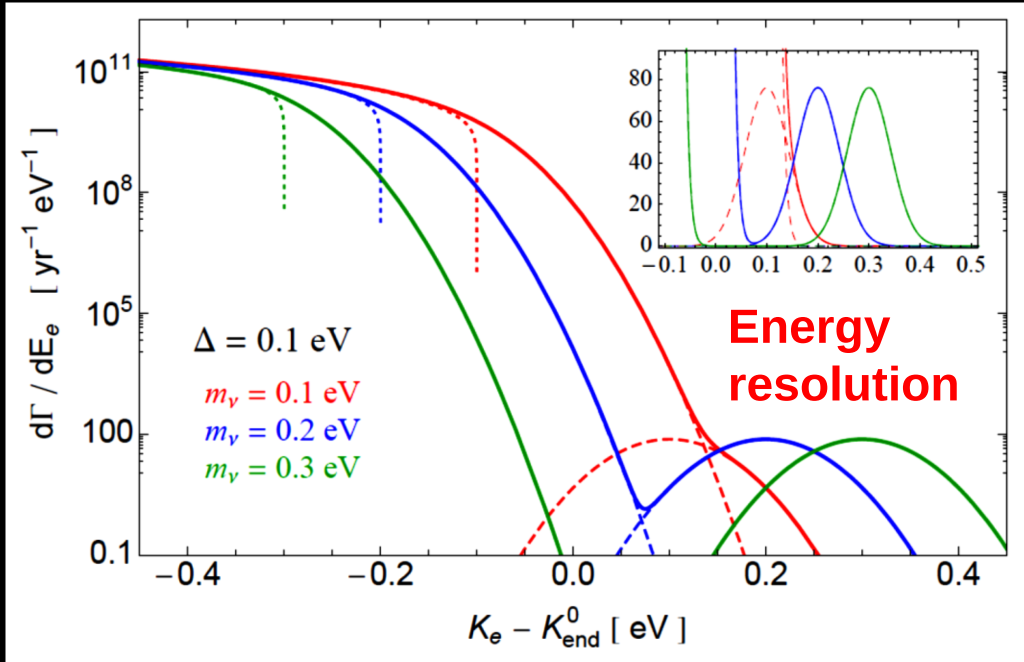
At the Earth, larger by a factor of 1 to 20

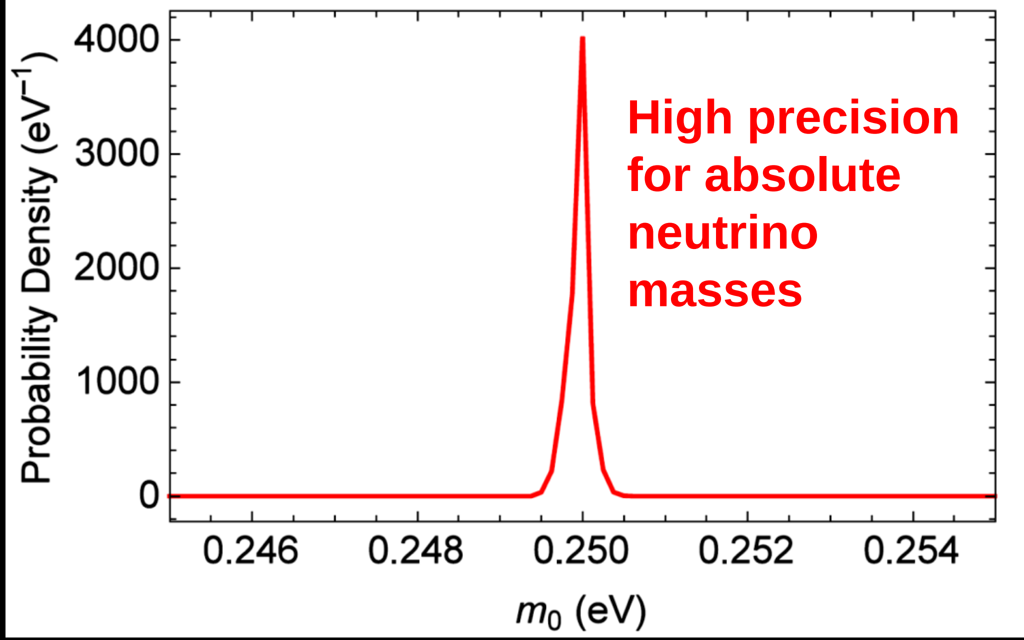


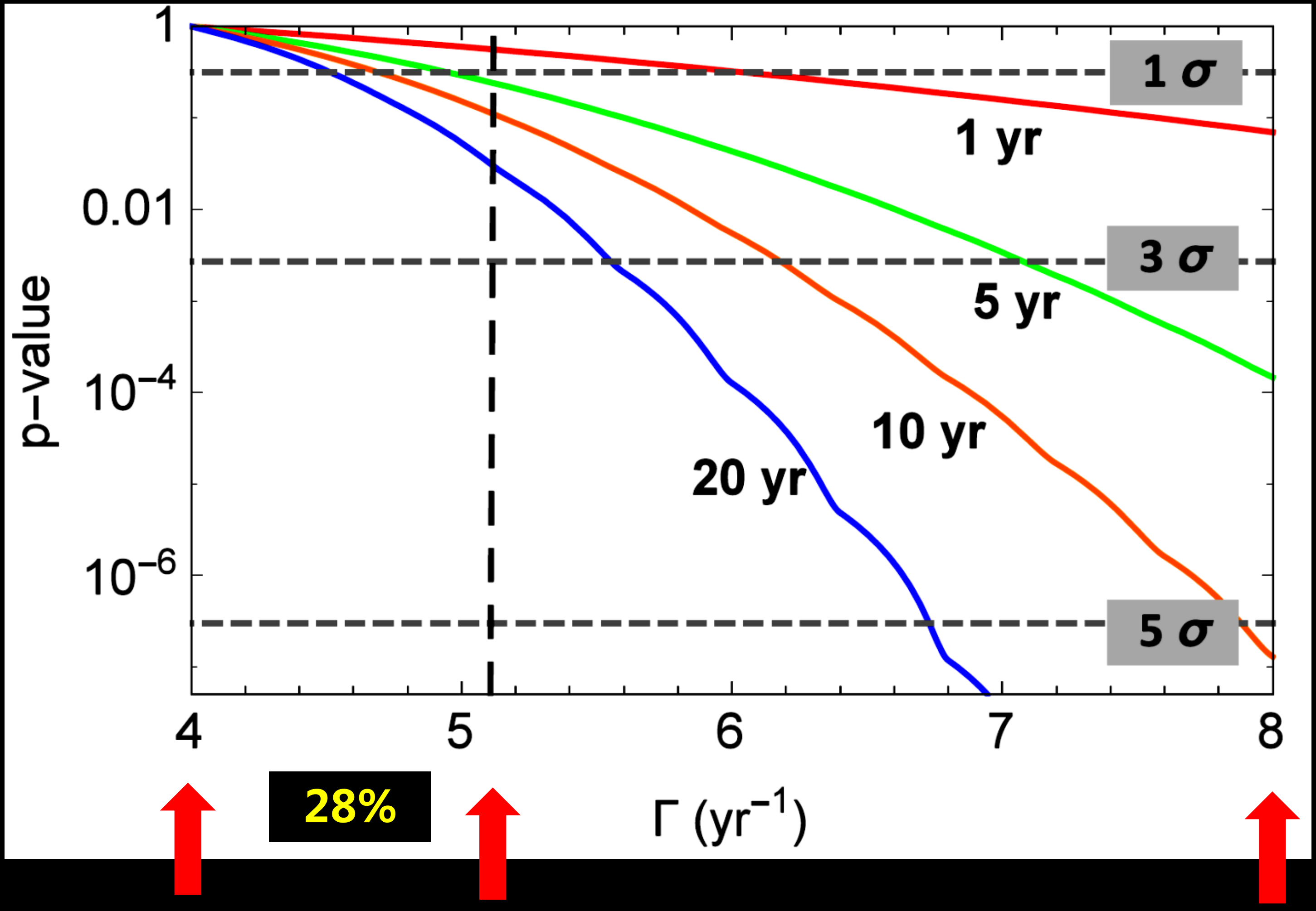
matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	$\Gamma^D_{\rm tot}$ (yr^{-1})	$\Gamma^M_{\rm tot}$ (yr^{-1})
any	no clustering	4.06	8.12
NFW(+bar)	2.18 (2.44)	8.8 (9.9)	17.7 (19.8)
NFW optimistic	2.88	11.7	23.4
EIN(+bar)	1.68 (1.87)	6.8 (7.6)	13.6 (15.1)
EIN optimistic	2.43	9.9	19.7

Particle Physics with CνB

- Nominal setup for PTOLEMY: 100 g ^3H, $\Delta = 0.15$ eV
- Absolute masses, Dirac vs. Majorana, Extra ν's, …







$\Gamma_D = 4\ yr^{-1}$ $\Gamma_R = 5.1\ yr^{-1}$ $\Gamma_M = 8\ yr^{-1}$

Summary and Outlook

- The next galactic core-collapse SN will be measured by a number of neutrino detectors, and a high-statistics real-time measurement is helpful in understanding explosion mechanisms and probing the intrinsic properties of massive neutrinos

- Give the priority to Diffuse SN Neutrino Background, a guaranteed source of SN neutrinos. We have SK with Gd doping, and JUNO (available within 3 years) also has a good chance.

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$2.3\,\sigma$	$2.5\,\sigma$	$2.0\,\sigma$	$2.3\,\sigma$
15 MeV	$3.5\,\sigma$	$3.7\,\sigma$	$3.2\,\sigma$	$3.3\,\sigma$
18 MeV	$4.6\,\sigma$	$4.8\,\sigma$	$4.1\,\sigma$	$4.3\,\sigma$
21 MeV	$5.5\,\sigma$	$5.8\,\sigma$	$4.9\,\sigma$	$5.1\,\sigma$

Neutrino Physics with JUNO, JPG, 16

- Very promising to detect the relic neutrinos from the Big Bang in the PTOLEMY experiment. It is time to have a serious look at theoretical predictions for local number densities, the detection rates and physics potentials for elementary particles and cosmology

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Thanks a lot for your attention!