NEUTRINOS FROM PRE-SUPERNOVA

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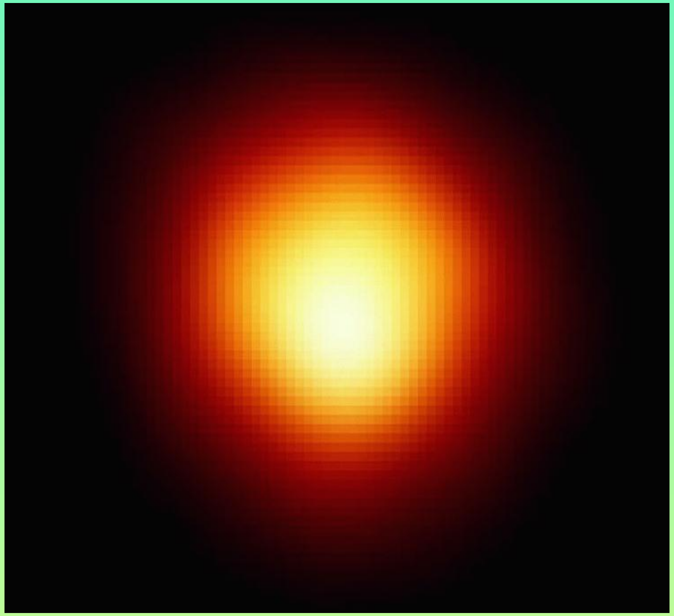
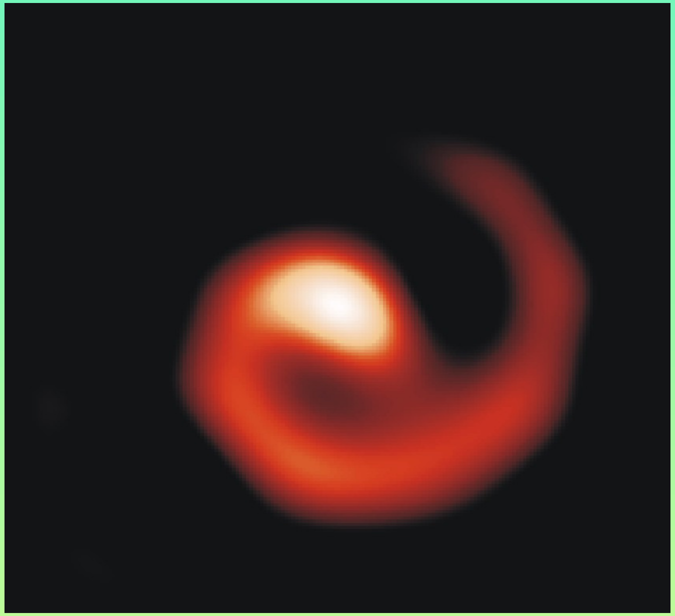
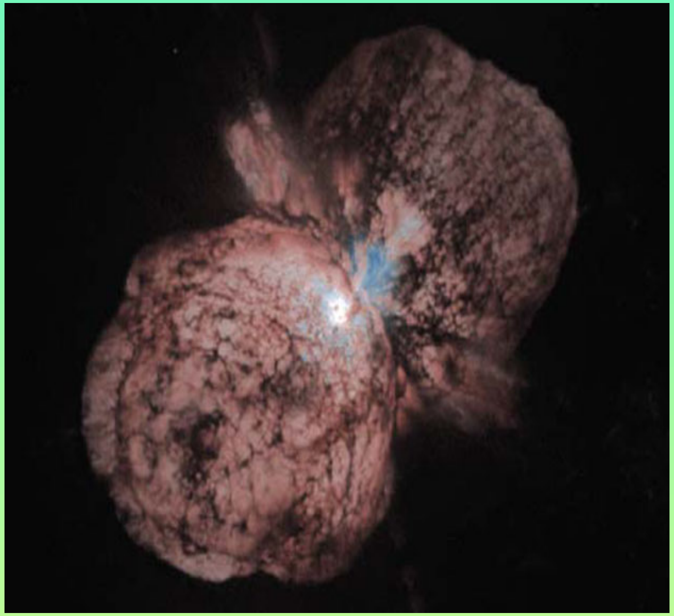
Betelgeuse 130 pc



WR 104 1.5 kpc



Eta Carina 2.7 kpc

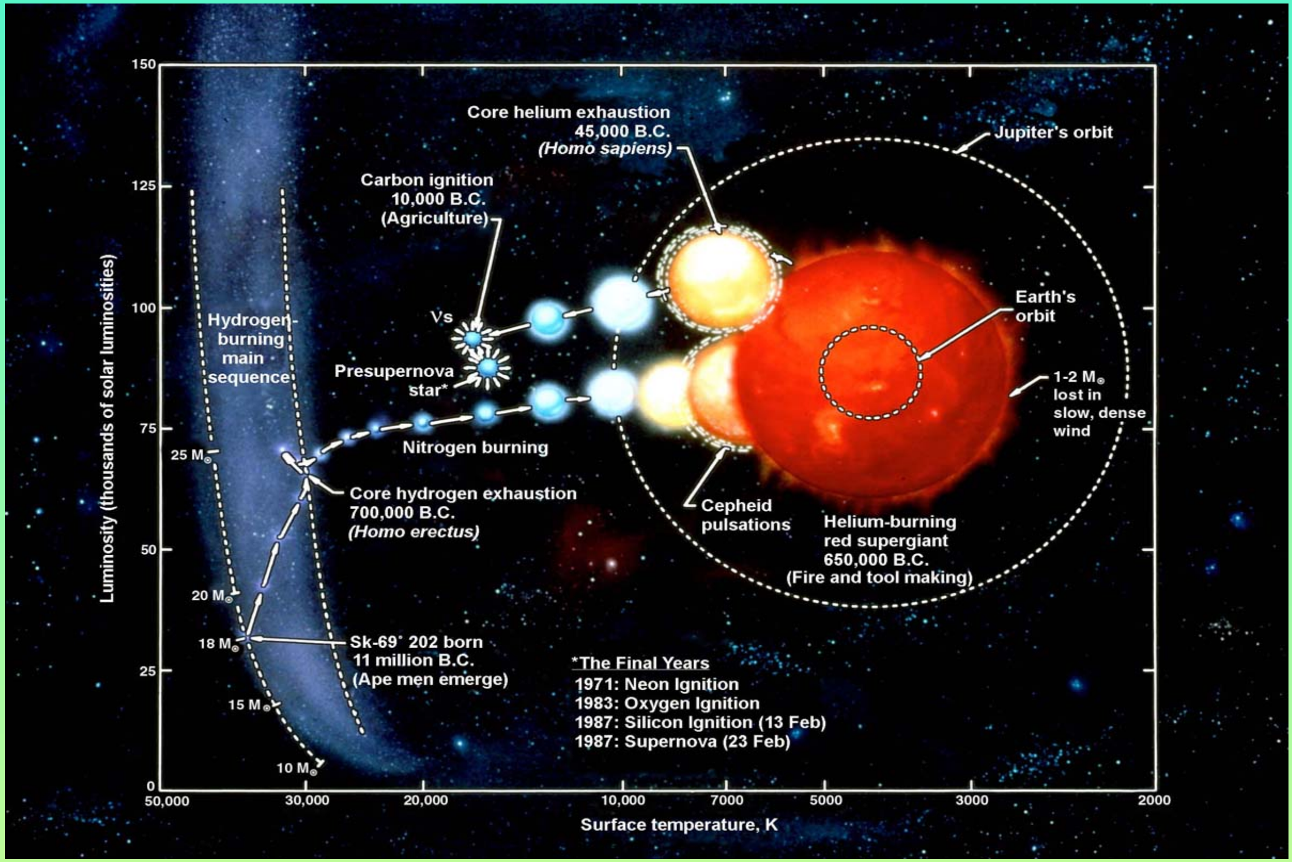


Can we see these stars in neutrinos, accounting for 50 years of progress in theory and experiment?

Massive Star before Supernova

No changes in star appearance hundred years before explosion.

No way to predict supernova!



Source: www.cococubed.com

Confirmed by the analysis of pre-SN1987A supernova photographs back into XIX-th century.

NEUTRINO-COOLED STARS

Massive Star → Neutrino-Cooled Star → Pre-Supernova Star

definition:

↓ Will explode as *core-collapse* **supernova**

↓ **Massive star after carbon burning ignition**

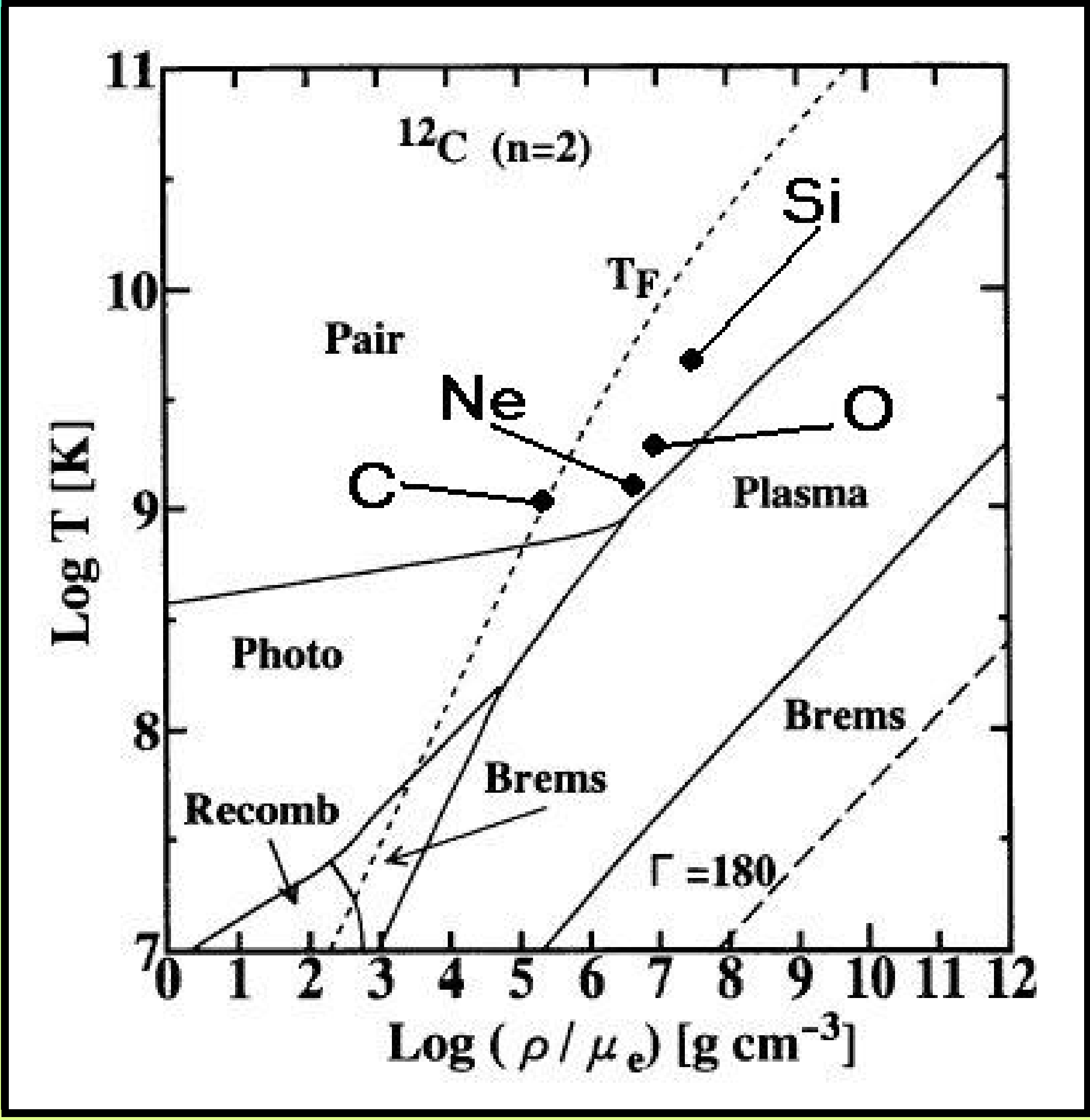
↓ **Star prior to the collapse**

Several hundred years before explosion, however, massive star becomes ***Neutrino-Cooled star***

Burning	$T_c\,[MeV]$	$\rho_c\,[g/cm^3]$	**Duration**	$L/L_\odot$	$L_\nu[erg/s]$
H	3.3×10^{-3}	3.8	5.8 mln yrs	40×10^3	$\sim 0.02L$
He	0.01	200	85 000 yrs	115×10^3	3.9×10^{33}
C	0.05	10^5	280 **years**	165×10^3	3.4×10^{38}
Ne	0.1	2×10^6	300 **days**	185×10^3	6.7×10^{41}
O	0.15	4×10^6	134 **days**	185×10^3	7.9×10^{42}
Si	0.24	3.2×10^7	30 **hours**	185×10^3	3.4×10^{44}
Shell **Si**	0.29	3.2×10^8	5.5 **hours**	185×10^3	–
Collapse	0.14	1.6×10^9	$0.1 \ldots 0.5$ s	185×10^3	$> 10^{54}$

*Position in the HR diagram fixed (**blue**), but neutrino luminosity L_ν evolves rapidly (**red**).*

NEUTRINO COOLING



Thermal neutrinos balance thermonuclear and gravitational energy release.

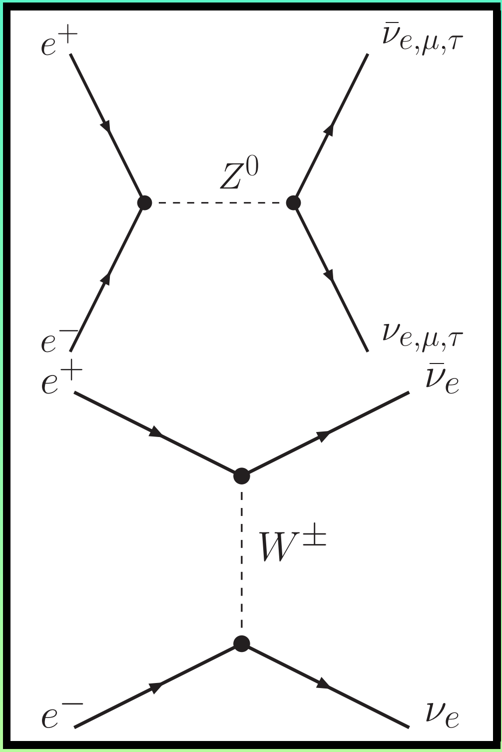
All flavors of the ν-$\bar{\nu}$ pairs are produced

Three competing processes operate:

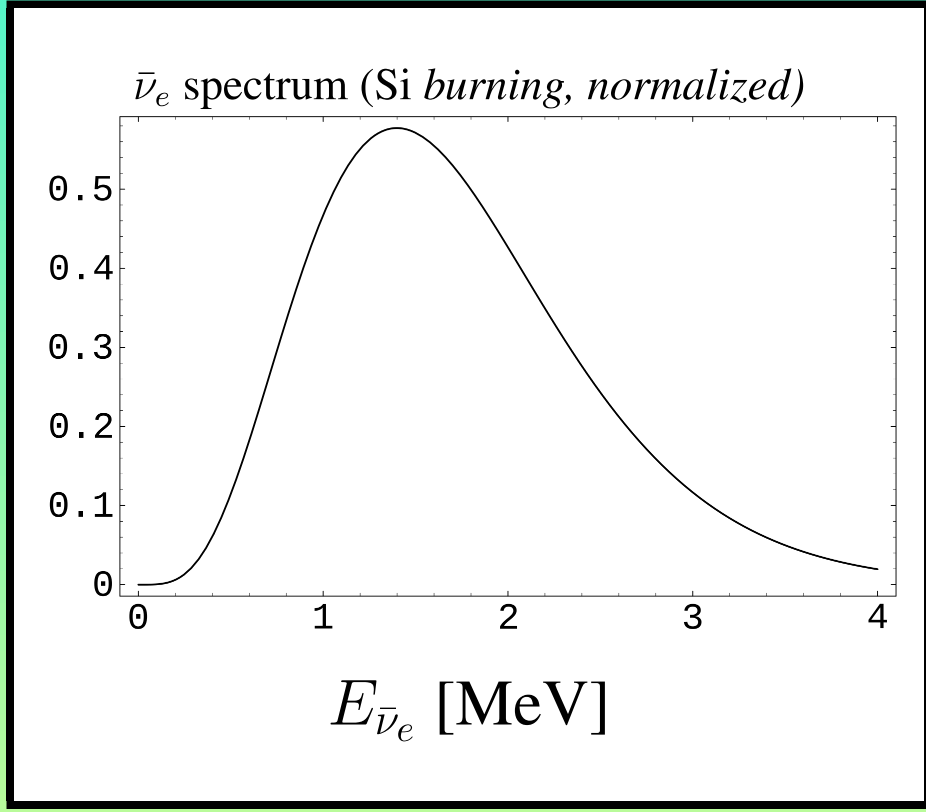
- **pair-annihilation**
- **plasmon decay**
- **photoproduction**

Source: Itoh et.al, ApJSS, **102** (1996) p. 411

PAIR-ANNIHILATION



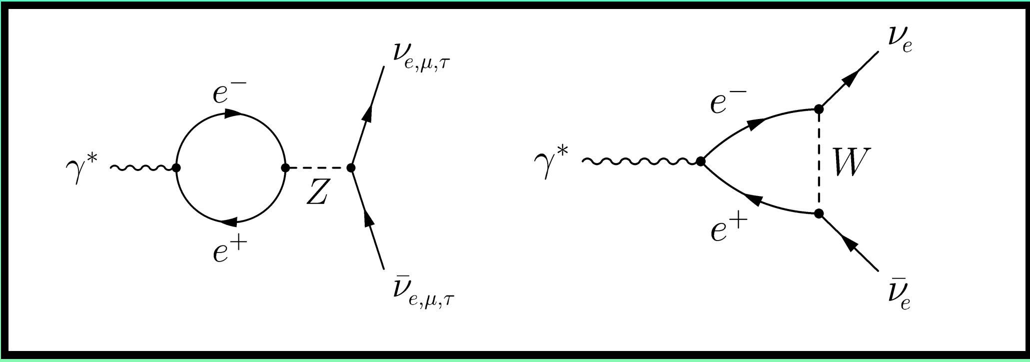
Average antineutrino energy during Si burning:
$E_\nu = 1.71$ MeV



For many astrophysical objects average neutrino energy can be estimated using simple formulae:

$$\langle E_\nu \rangle = \begin{cases} 2/5\,\mu + 2\,kT + m_e/2 & \text{(degenerate)} \\ \frac{2700\,\zeta(5)}{7\,\pi^4}\,kT & \text{(relativistic, non-deg.)} \\ m_e + 3/2\,kT & \text{(non-deg., non-rel.)} \end{cases}$$

PLASMON DECAY

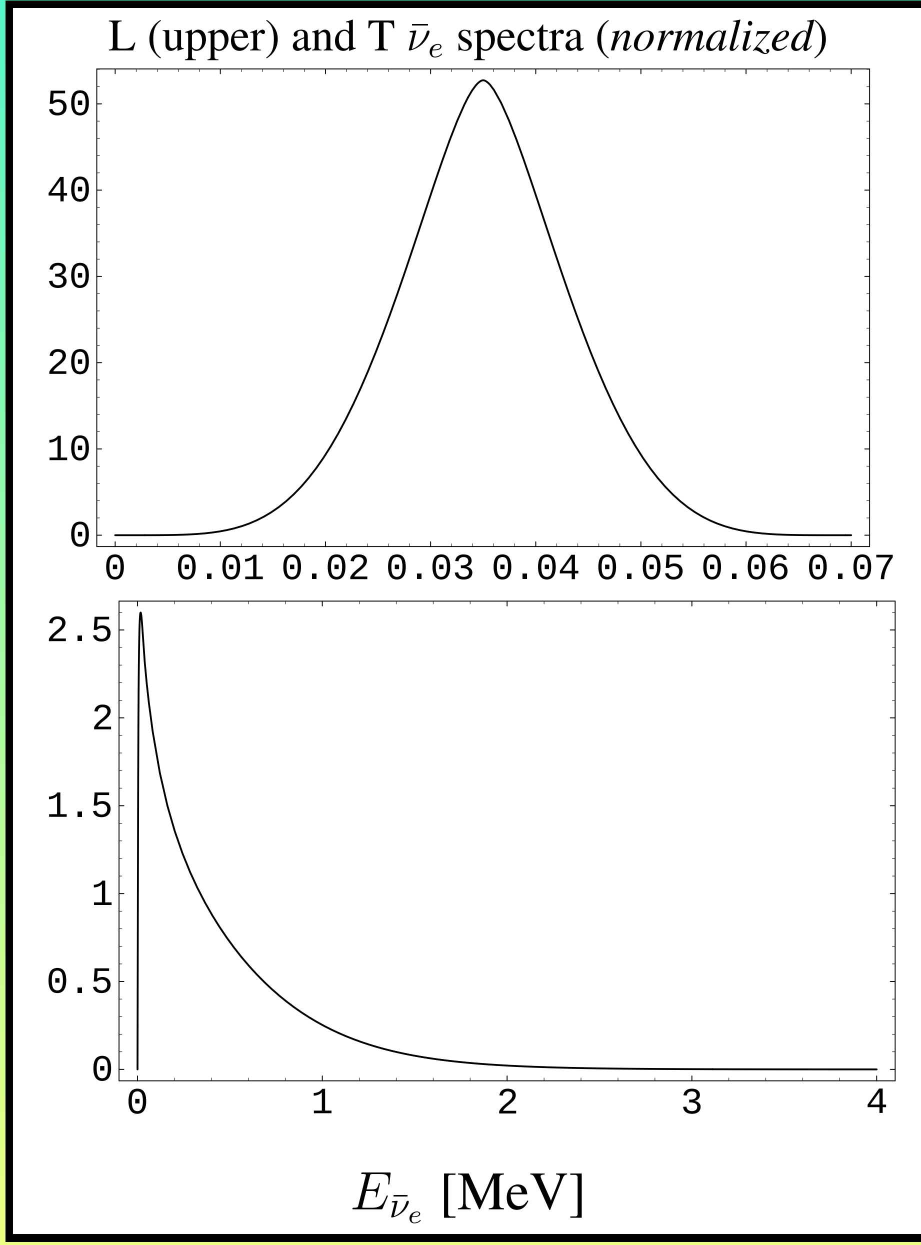


Two modes of collective plasma excitations (γ^*) can decay into ν-$\bar{\nu}$ pairs:

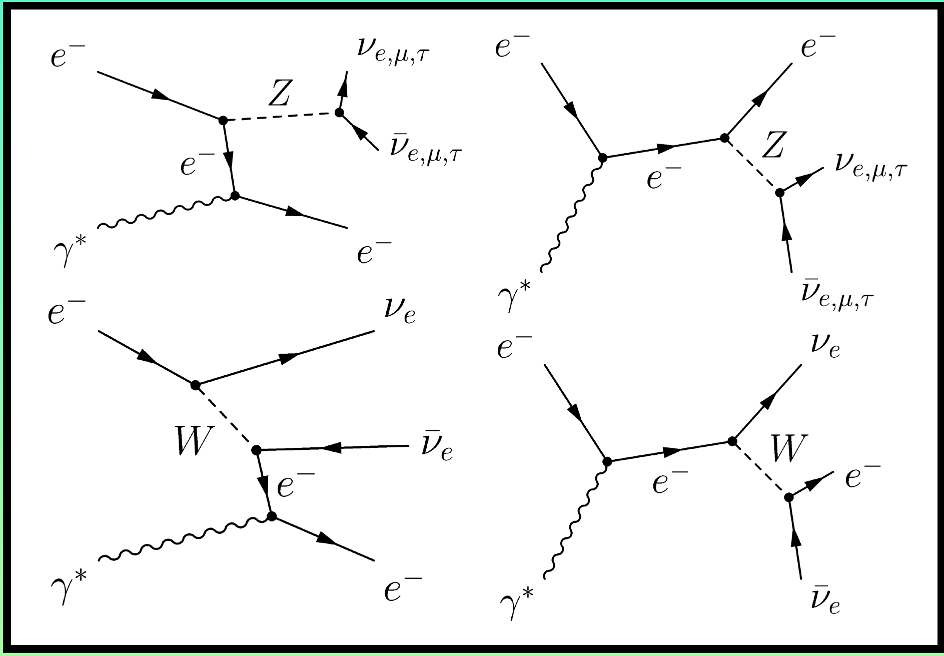
- Massive in-medium photon (T)
- Longitudal plasmon (L)

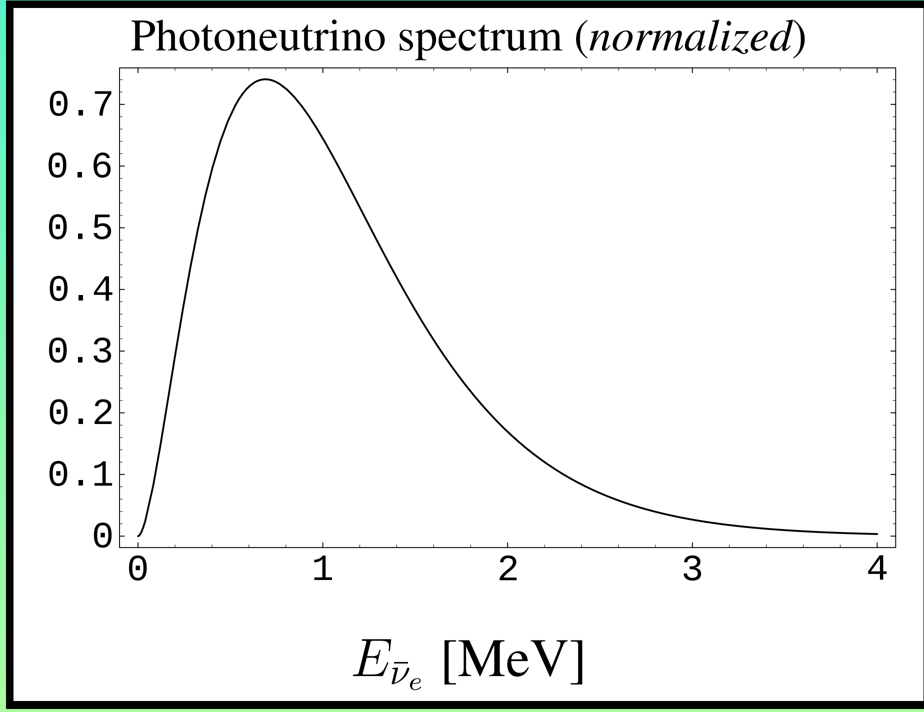
Completely different dispersion relations for these 2 modes lead to the following neutrino energies:

$\langle E_{\bar{\nu}_e} \rangle = 35$ keV (L), $\langle E_{\bar{\nu}_e} \rangle = 440$ keV (T)



PHOTOPRODUCTION





- *Spectrum of the photoneutrinos is computed assuming vacuum dispersion relation for photons.*
- *Spectrum is expressed in the form of 7-dimensional integral and computed using Monte Carlo method*

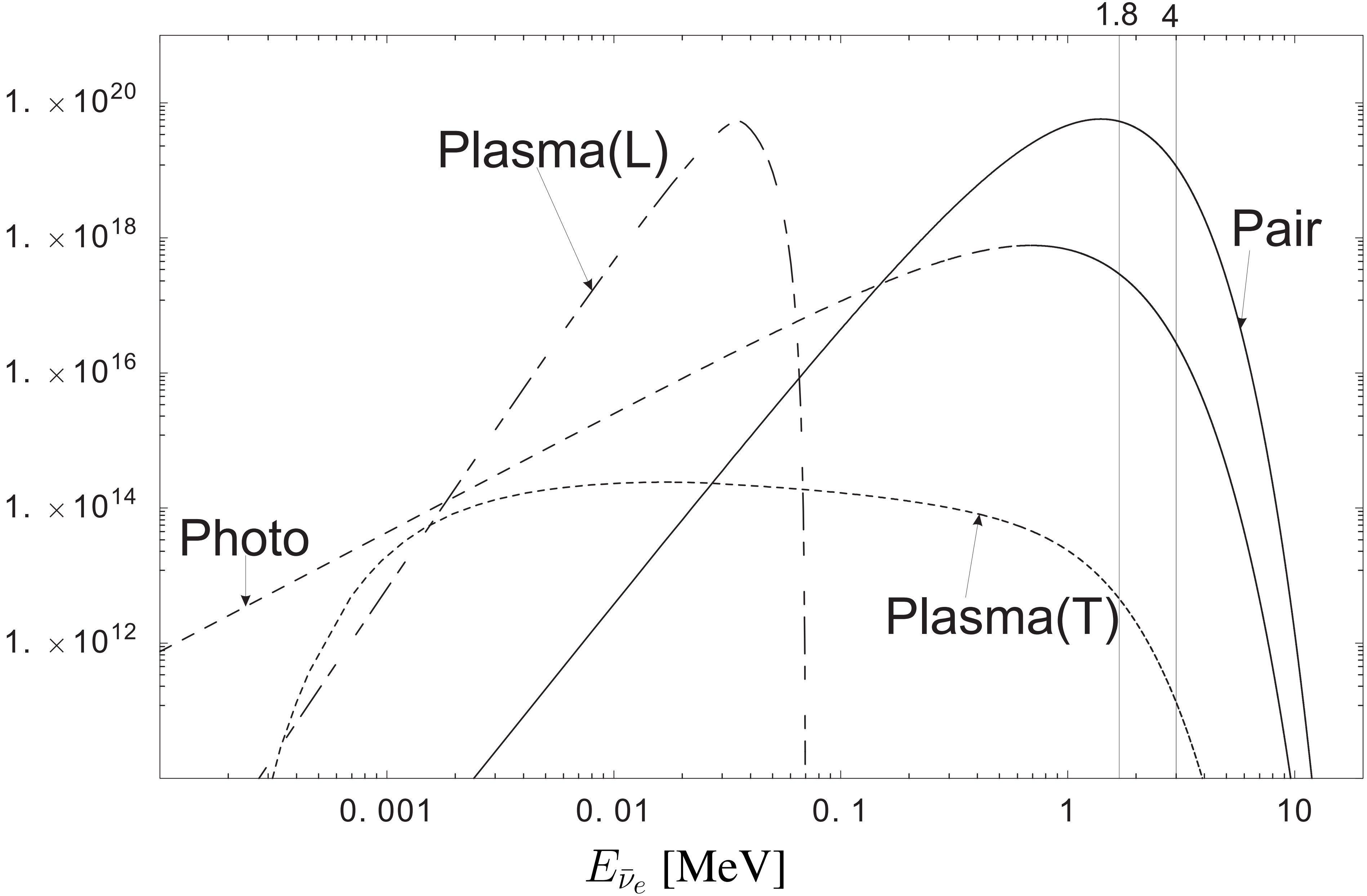
Average antineutrino energy during Si burning $\langle E_{\bar{\nu}_e} \rangle = 1.05$ MeV

ESSENTIAL DATA

- Neutrino luminosity `(`$\sim 10^{12} L_\odot \simeq L_\odot$`@100 light years)`
- Stage duration `(0.7...14 days) for Si burning`
- Distance to pre-supernova `(0.1...30kpc)`
- Avg. time between Galaxy events `(10...200 years)`
- Detector target mass `(1 kiloton ...1 Gigaton)`
- Detector threshold `(1.8...5 MeV)`

The most important: **anti-neutrino spectrum** $\rightarrow$

Combined thermal $\bar{\nu}_e$ spectrum during Si burning



LOW-ENERGY ANTINEUTRINO DETECTION

Inverse β-decay threshold $E_{th} = 1.8$ MeV,
while for water Cherenkov detectors $E_{th} \simeq 4$ MeV.

SOLUTION: (M. Vagins, Neutrino 2004)

Dissolving in pure $\mathrm{H_2O}$ efficient neutron absorber (chloride):
$\boxed{\mathrm{GdCl_3}}$ (NaCl, KCl) cause reaction:

$$\boxed{n + \mathrm{Gd(Cl)} \to \mathrm{Gd^*(Cl^*)} \to \mathrm{Gd(Cl)} + \gamma_i}$$

$$E_{tot} = \sum_i E_{\gamma_i} \simeq 8\,\mathrm{MeV}$$

Gamma-rays scatter off electrons $\Rightarrow$
Electrons emit Cherenkov light $\Rightarrow$
Light detected by photomultipliers

LOW-THRESHOLD ANTINEUTRINO DETECTORS

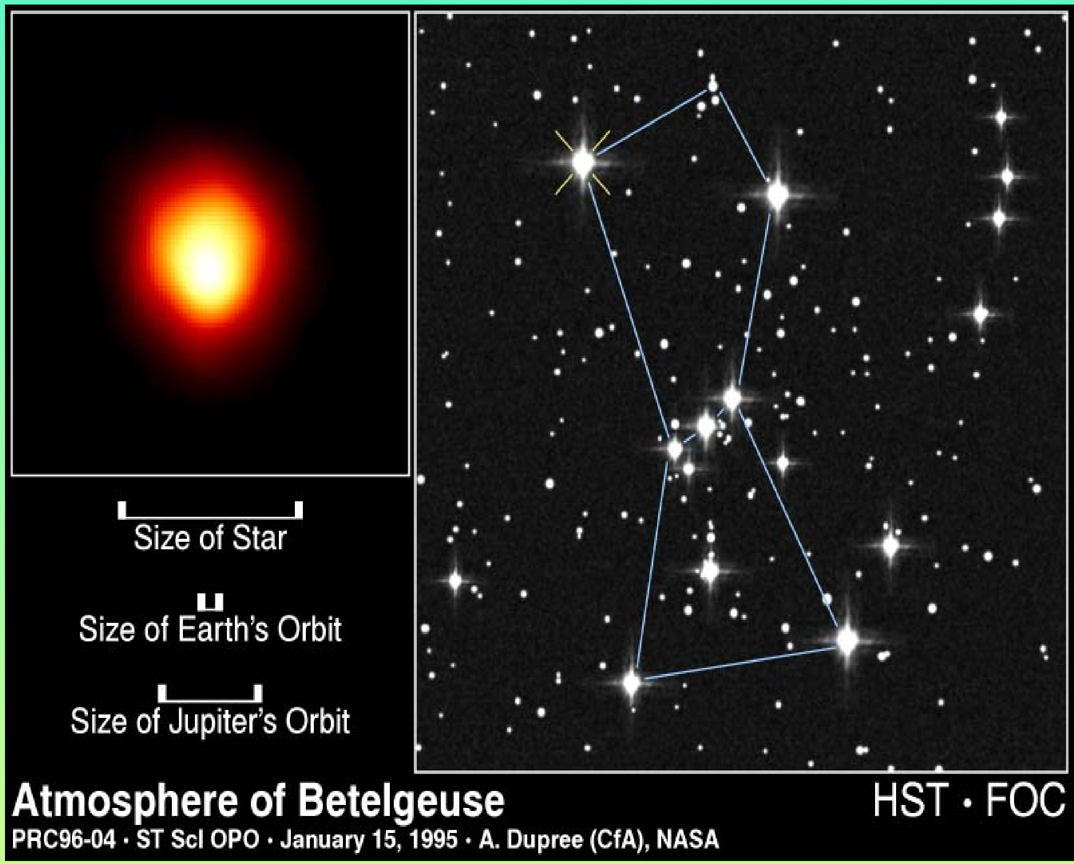
- KAMLAND (1 kt)
- BOREXINO (0.3 kt)
- SNO (1+1.7 kt)
- SUPER KAMIOKANDE (32 kt)
- HYPERK (540 kt)
- UNO (440 kt)
- GADZOOKS! (32 kt)
- *"Gigaton Array"* (10^6 kt)

Utilizing Reines-Cowan reaction (inverse β-decay):

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

$\simeq$1 event/kt H_2O from 1 kpc

If GAZDOOKS! will start in 2008 we could be able to **predict supernova explosion** for few nearby stars: β Ori, α Her, α Sco…

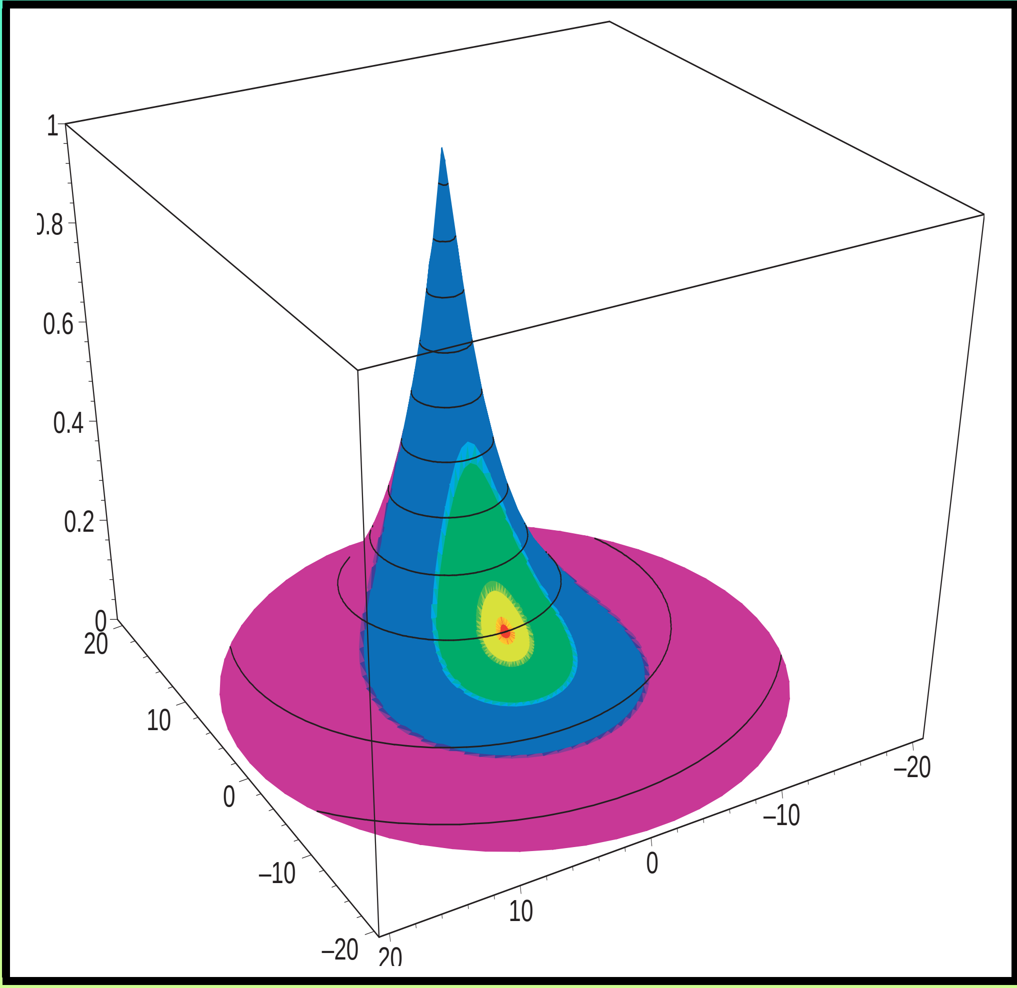


Source: NASA

`Unfortunately,the explosion of the nearby star is` **`highly unlikely:`** $\sim 10^{-4} \times$ *years of* ***continuous monitoring***

Larger** devices are **required!

Galaxy coverage



Number of massive stars available to observations, according to simple Galaxy model

Observation range:

- Red – GADZOOKS! [32 kt]
- Yellow – Hyper-Kamiokande [0.5 Mt]
- Green - 2 Mt detector (`very optimistic`)
- Blue – Single ocean balloon [10 Mt]
- Purple – *Gigaton Array* [1 Gt]

PRE-SUPERNOVA MONITORING

	Detector mass	Maximum observation range	% of the Galactic ***pre-supernovae*** in the range
GADZOOKS!	32 kt	0.5 kpc	0.1%
HYPER-KAMIOKANDE	0.5 Mt	2 kpc	2%
SINGLE DEEP OCEAN BALLOON	10 Mt	10 kpc	50%
GIGATON ARRAY	1 Gt	100 kpc	100%

Number of massive stars available to monitoring increases rapidly as we reach Galactic center

Conclusions & Future plans

- *Pair-annihilation anti-neutrinos are dominant in the thermal neutrino spectrum of the pre-supernova star*
- *Other thermal processes do not produce neutrinos with energy above threshold of existing or planned big detectors*
- *Ability to get supernova warning from Si burning neutrinos will be limited to a few nearby massive stars . . .*

  . . . until new generation of the giant antineutrino detectors

- Computer code computing complete thermal neutrino spectrum
- Neutrino oscillations
- Improved physical input for photo- and plasmaneutrino spectrum (dispersion relations, squared matrix elements)
- Integration with stellar models
- Neutrinos and antineutrinos produced in weak nuclear reactions