11th International Neutrino Summer School, Schloss Waldthausen, Mainz
31 May & 1 June 2018

Supernova Neutrinos

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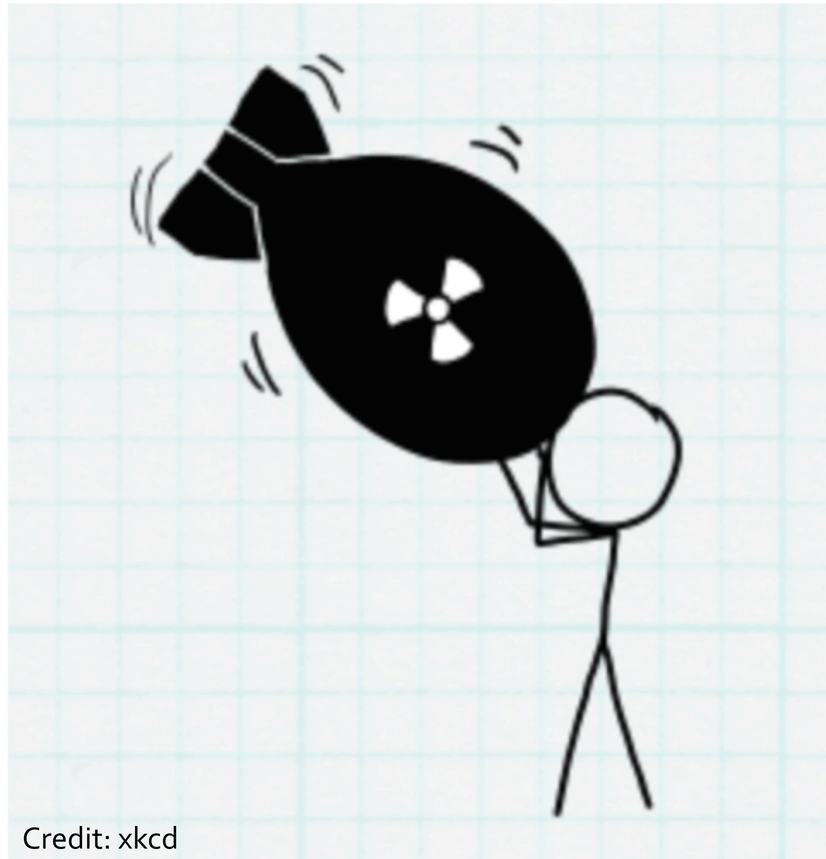
Supernovae are hot!

Which is brighter

- a hydrogen bomb pressed against your eyeball, or
- a supernova at the distance of the Sun?

SN are typically more intense than any source you might think of.



Credit: xkcd

Supernovae are hot!

They are amazing

- Most powerful explosions. Almost as bright as an entire galaxy!

The are important

- Makes heavy elements, e.g., Gold, Silver, and recycles Carbon, Oxygen, etc., as well as black holes!

They are interesting

- Connections to very cool physics leading to several Nobel prizes: Chandrasekhar and Fowler in 1983, Hulse and Taylor in 1993, Koshiba in 2002, Perlmutter, Schmidt, and Riess in 2011, …

Neutrinos are cool!

Which heats better?

- Sunlight falling on a sidewalk on Earth
- Solar neutrinos at the *surface* of the Sun

Neutrinos are typically not very efficient at depositing energy

Neutrinos are cool!

You are here, aren't you? ☺

Supernova Neutrinos

Battle of extremes: Incredible intensity of SN and the supreme shyness of neutrinos!

Nevertheless, in this fight, we all win!

- SN explode because of neutrinos
- Unique tool to study some SN and neutrino properties
- Neutrino signal intensity can be very high
- Neutrino-neutrino interactions are important

Outline

Lecture 1

- Supernovae: What, When, & Why?
- Supernova and the neutrino mechanism
- SN neutrino detection
- Physics with (non-oscillating) SN neutrinos: What can be measured?

Lecture 2

- MSW Physics of SN neutrinos
- Collective oscillations of SN neutrinos
- Physics with SN neutrinos: What can be measured?

Supernovae
What, When, & Why?

Life of a Star

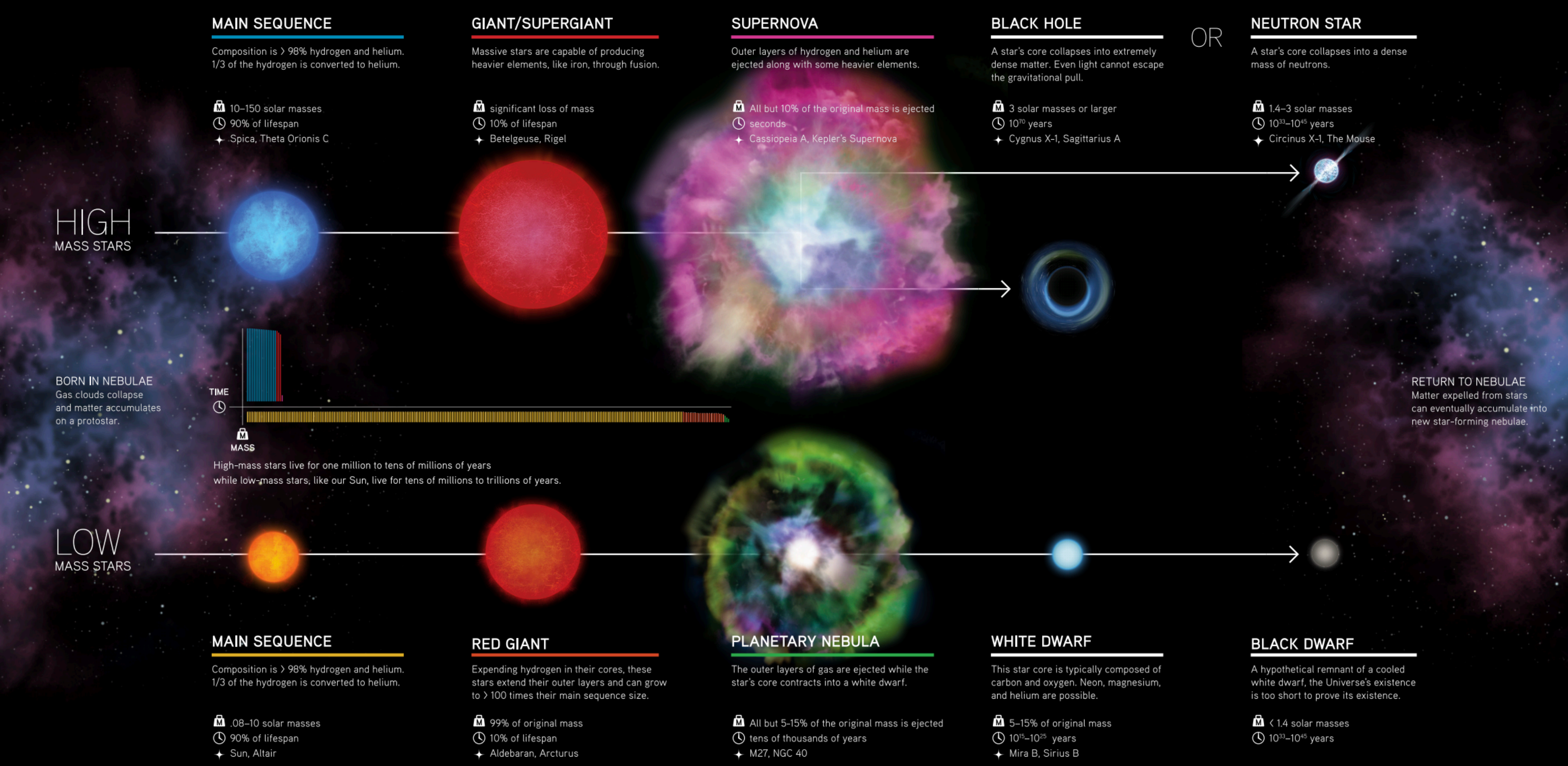


Image credit: Khan Academy

Classification of Supernovae

Type	Ia	Ib	Ic	II
Emission/ Absorption lines	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Light-curve	Standard	Large Diversity		
Mechanism	Nuclear explosion following mass gain	Collapse of the core of a massive star		
Neutrinos	Negligible	Dominant (99% of all SN energy; 1% in light etc.)		
Compact Remnant	None	Neutron star / Black hole		

Thermonuclear SN

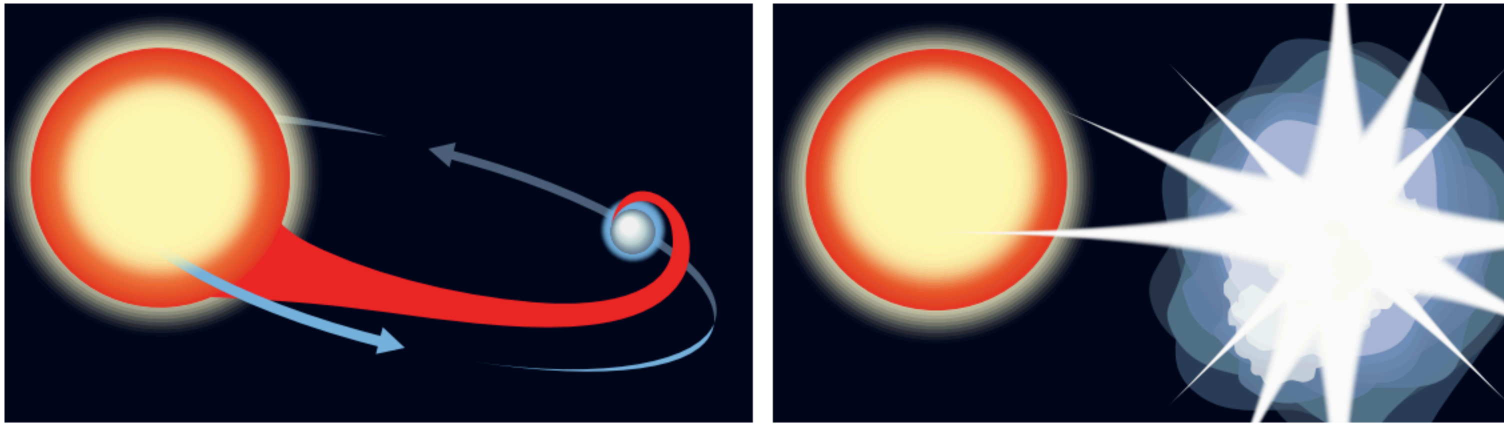
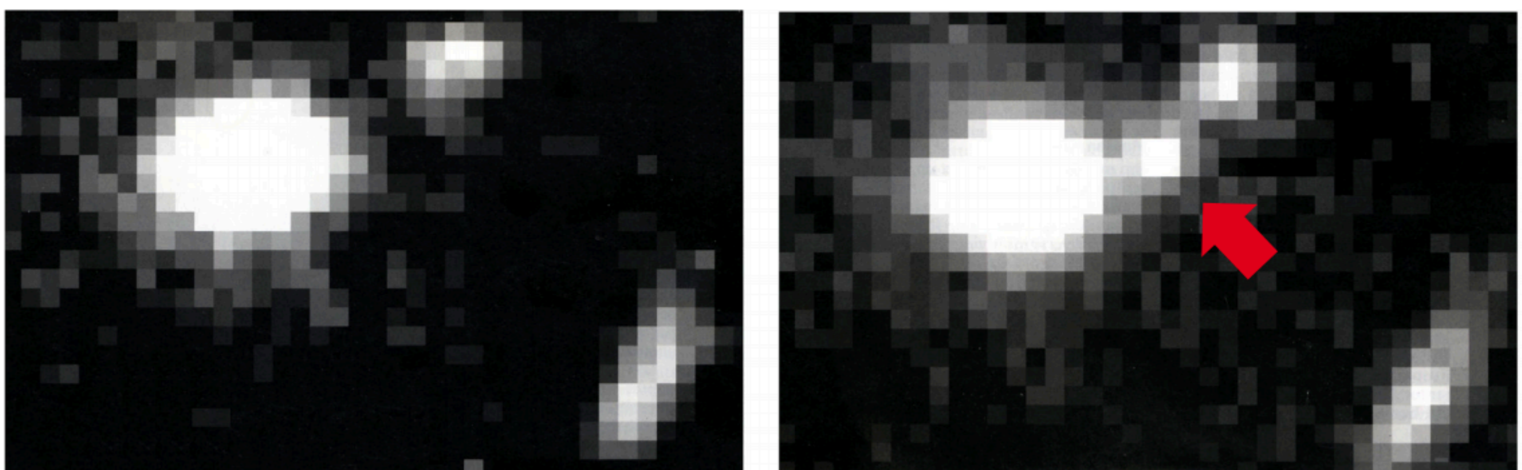
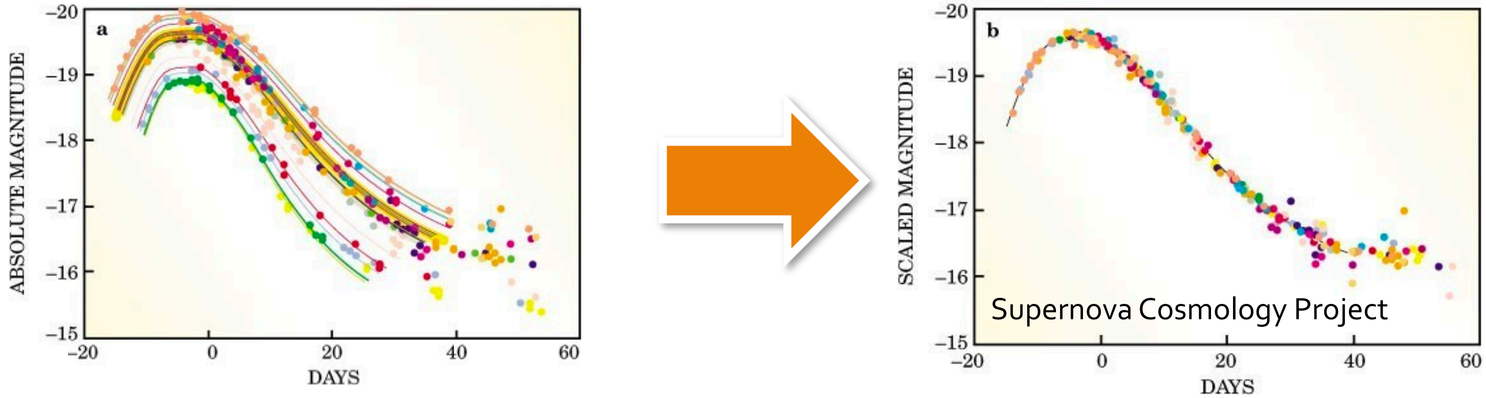


Figure 3. Supernova explosion. A white dwarf steals gas from its neighbour using its gravity.

When the white dwarf has grown to 1.4 solar masses, it explodes as a type Ia supernova.

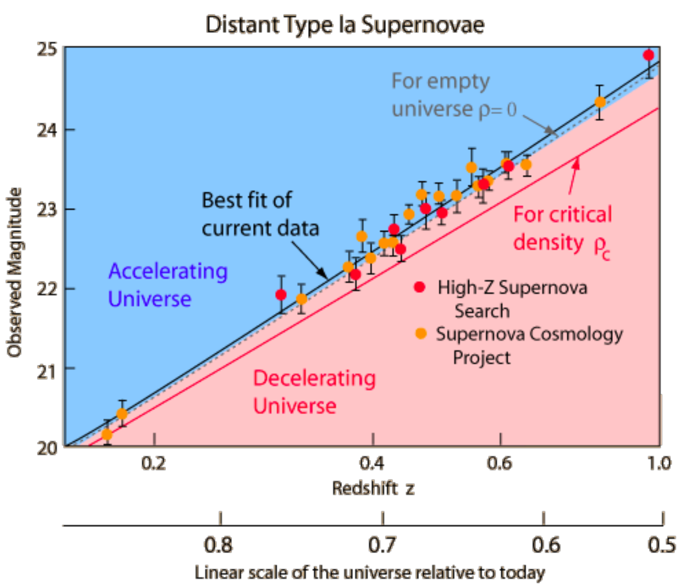


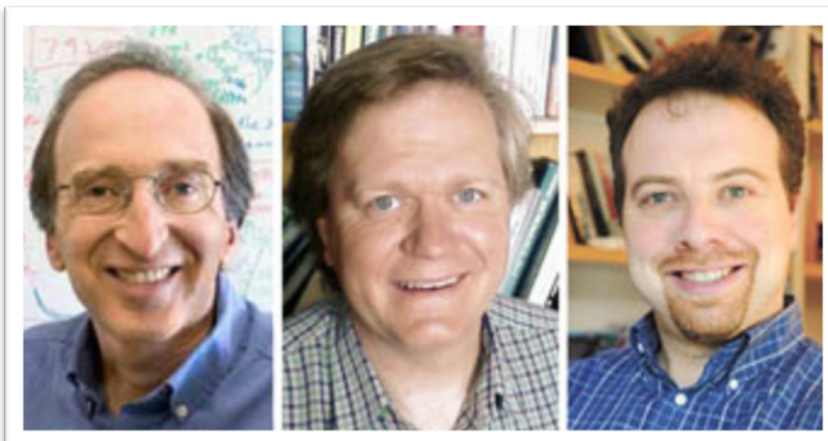
Distance Determination



Empirically Standardizable Sources

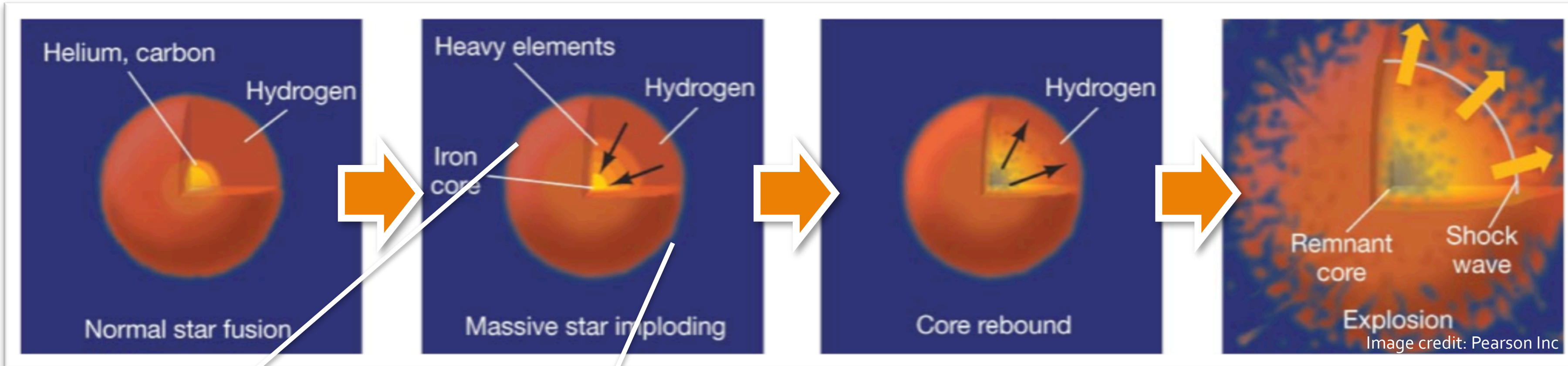
Can use the $1/D^2$ law of dimming and a calibration to determine distances!

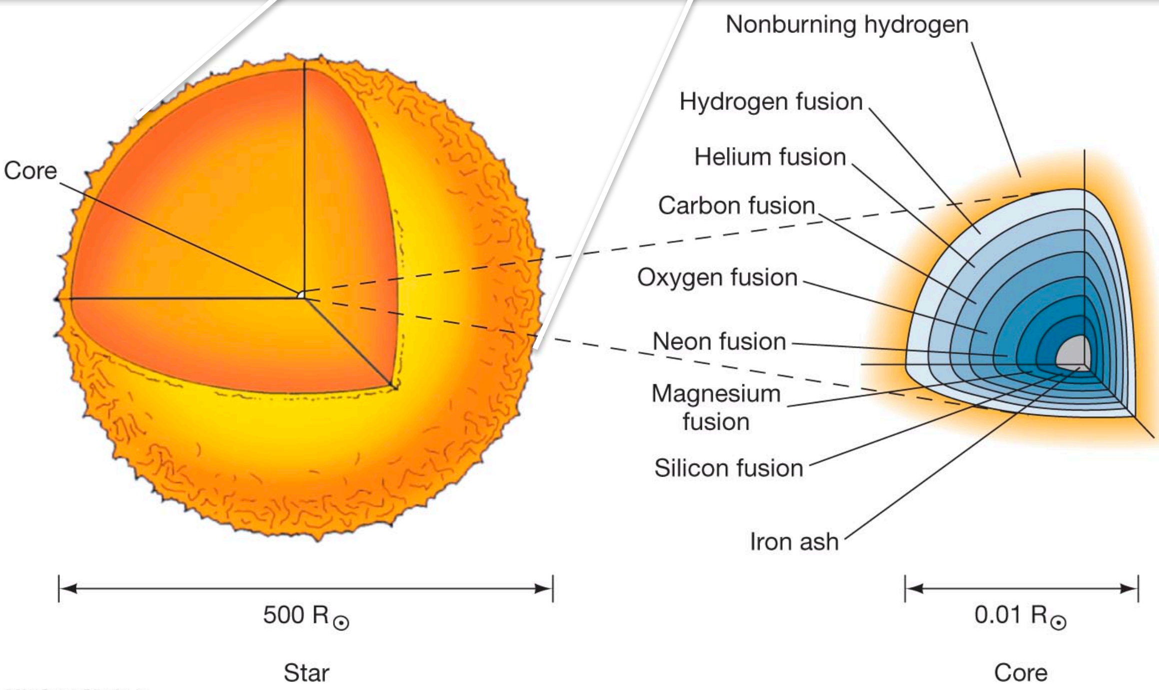




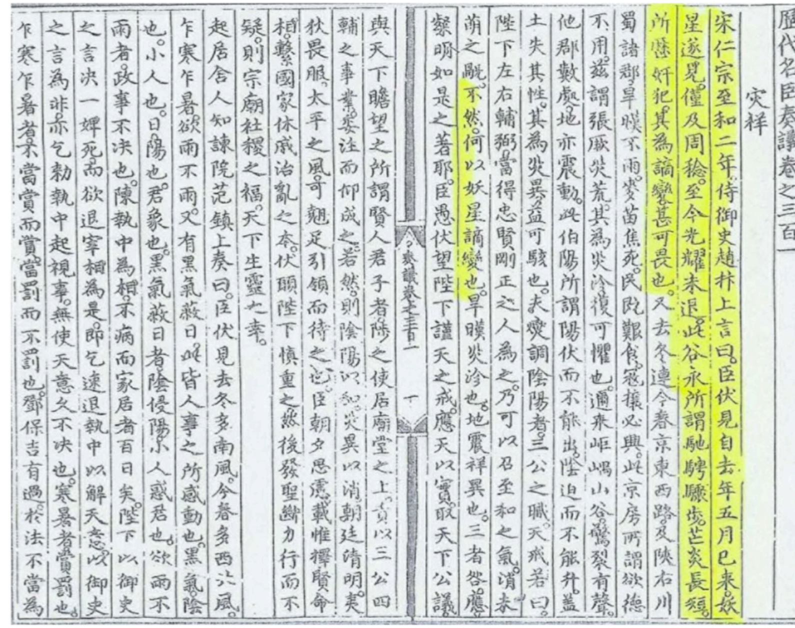
Perlmutter, Schmidt, and Riess

Mechanism of Core-Collapse





Historical Supernovae



歷代名臣奏議卷之三百一

災祥

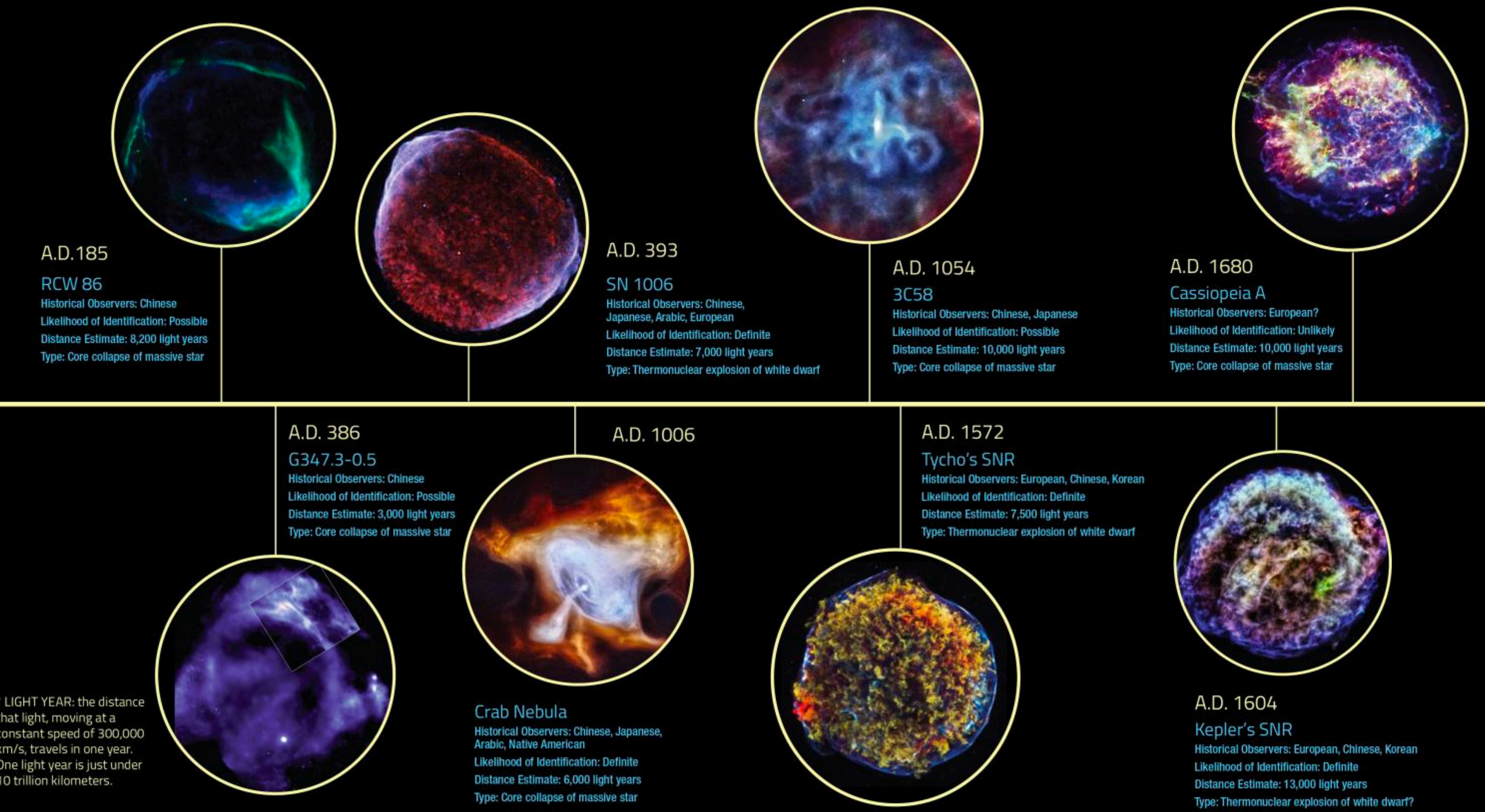
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月巳來妖星遂見偃及周歲至今光耀未退此谷永所謂馳騁驟步芒炎長緩所壓奸犯其為譎變甚可畏也又去冬達今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民阻艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災殄復可懼也邇來岷峨山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消去萌之眺不然何以妖星譎變也旱暵災沴也地震祥異也三者咎應鑿明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議與天下瞻望之所謂賢人君子者俾之使居廟堂之上責以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣狀畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸

起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史之言決一婢死而欲退宰相為是耶乞速退執中以解天意以御史之言為非耶乞勅執中起視事無使天意久不決也寒暑者賞罰也乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

奏議卷之三百一　十

“Guest Star” of 1054, Chinese records

Historical Supernovae



Credit: NASA

Historically observed SNe

Supernova designation (year)	Constellation	Apparent magnitude	Distance (light years)	Type	Galaxy	Comments
SN 185	Centaurus	−4 (?) [1]	8,200	Ia (?)	Milky Way	Surviving description sketchy; modern estimates of maximum apparent magnitude vary from +4 to −8. The remnant is probably RCW 86, some 8200 ly distant,[2] making it comparable to SN 1572. Some researchers have suggested it was a comet, not a supernova.[3][4]
SN 386	Sagittarius	+1.5	14,700	II	Milky Way	The candidate remnant is G11.2-0.3.[5][6]
SN 393	Scorpius	−0	34,000		Milky Way	
SN 1006	Lupus	−7.5[7]	7,200	Ia	Milky Way	Widely observed on Earth; in apparent magnitude, the brightest stellar event in recorded history.[8]
SN 1054	Taurus	−6	6,500	II	Milky Way	Remnant is the Crab Nebula with its pulsar (neutron star)
SN 1181	Cassiopeia	0	8,500		Milky Way	
SN 1572	Cassiopeia	−4.0	8,000	Ia	Milky Way	Tycho's Nova
SN 1604	Ophiuchus	−3	14,000	Ia	Milky Way	Kepler's Star; most recent readily visible supernova within the Milky Way
Cas A, ca. 1680	Cassiopeia	+5	9,000	IIb	Milky Way	Apparently never visually conspicuous, due to interstellar dust; but the remnant, Cas A, is the brightest extrasolar radio source in the sky
SNR G1.9+0.3, ca. 1868	Sagittarius		25,000		Milky Way	"Posthumously" discovered in 1985; age determined in 2008

Source: Wikipedia

Thousands seen every year …

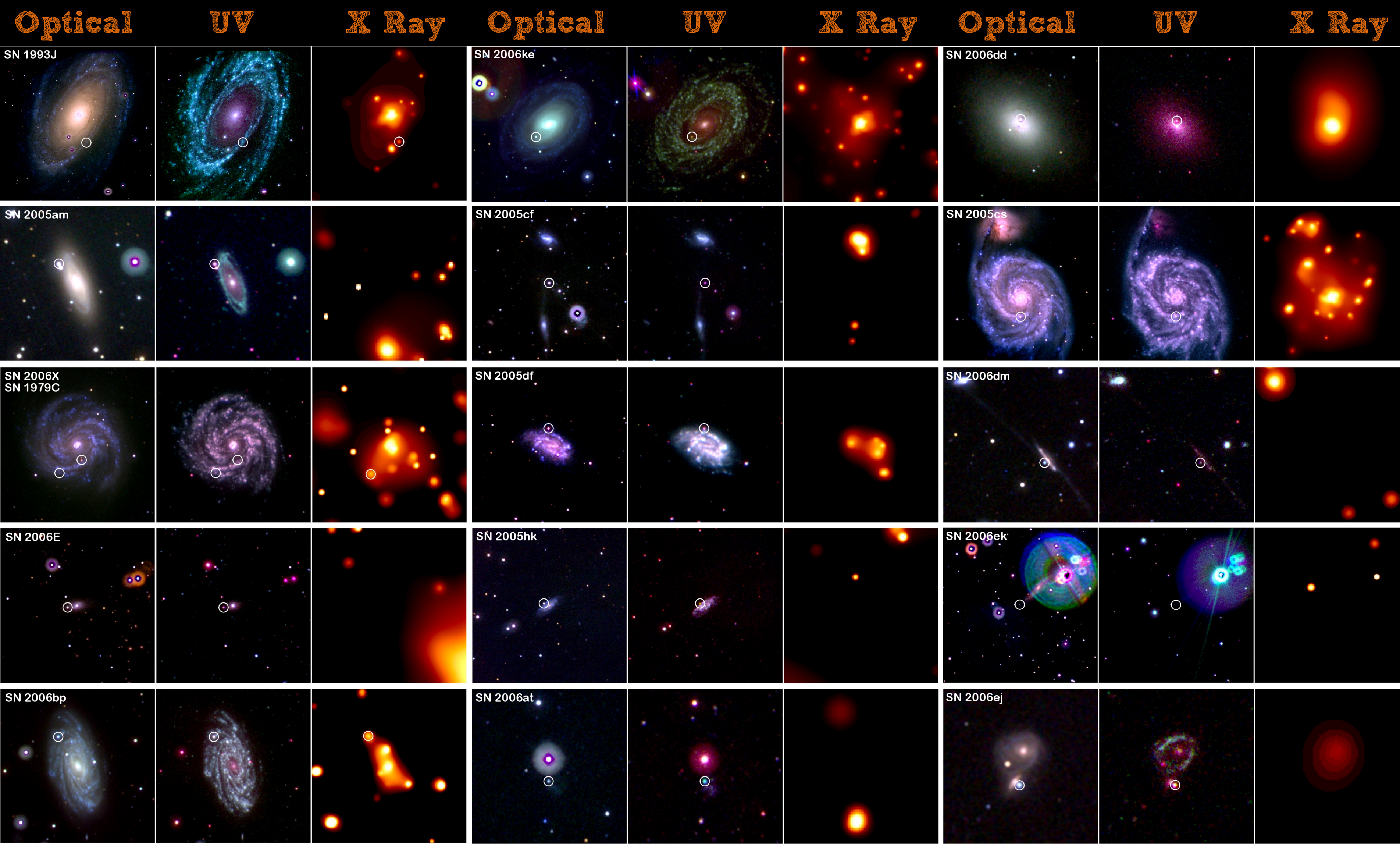
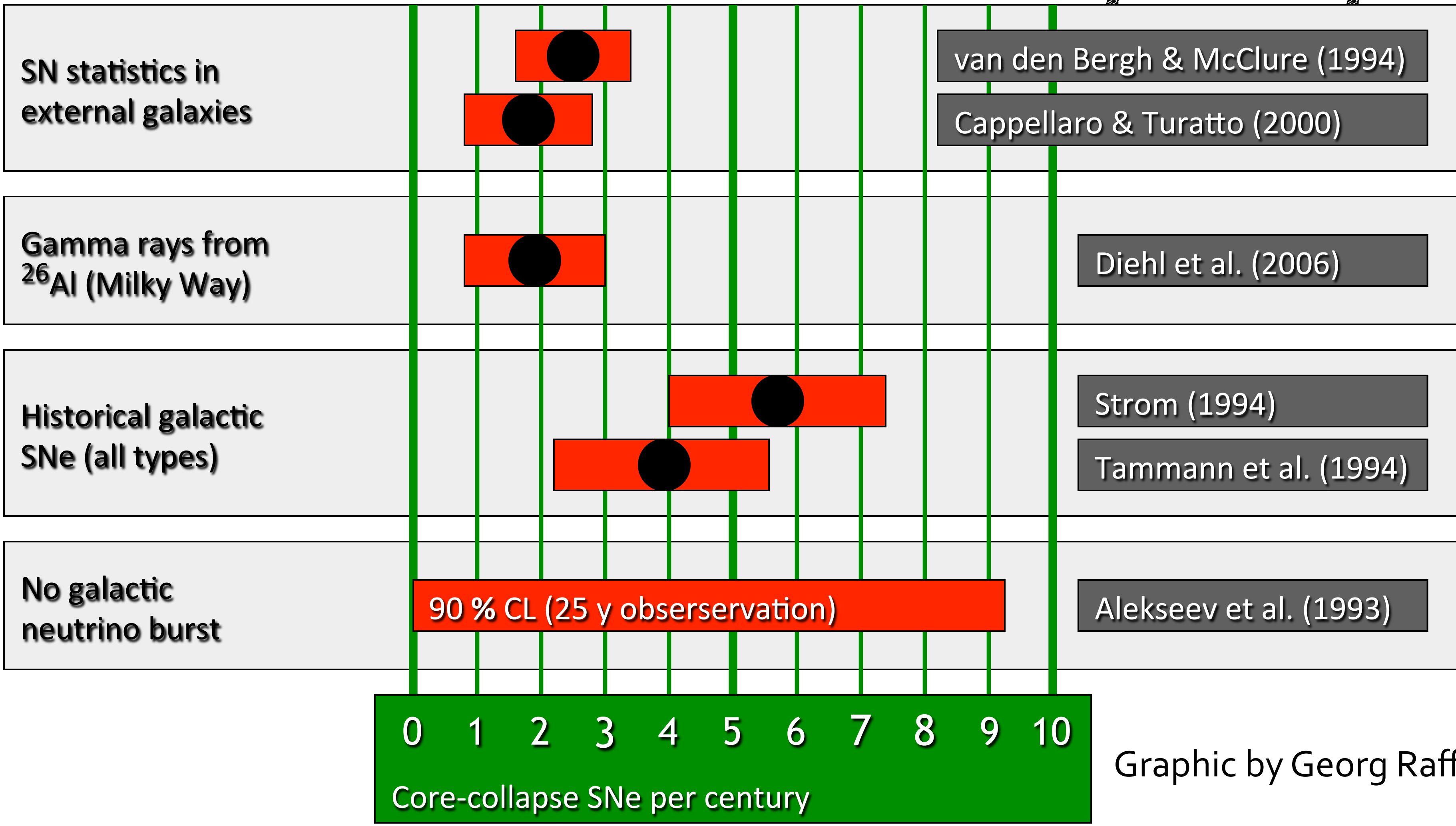


Image: NASA/SWIFT

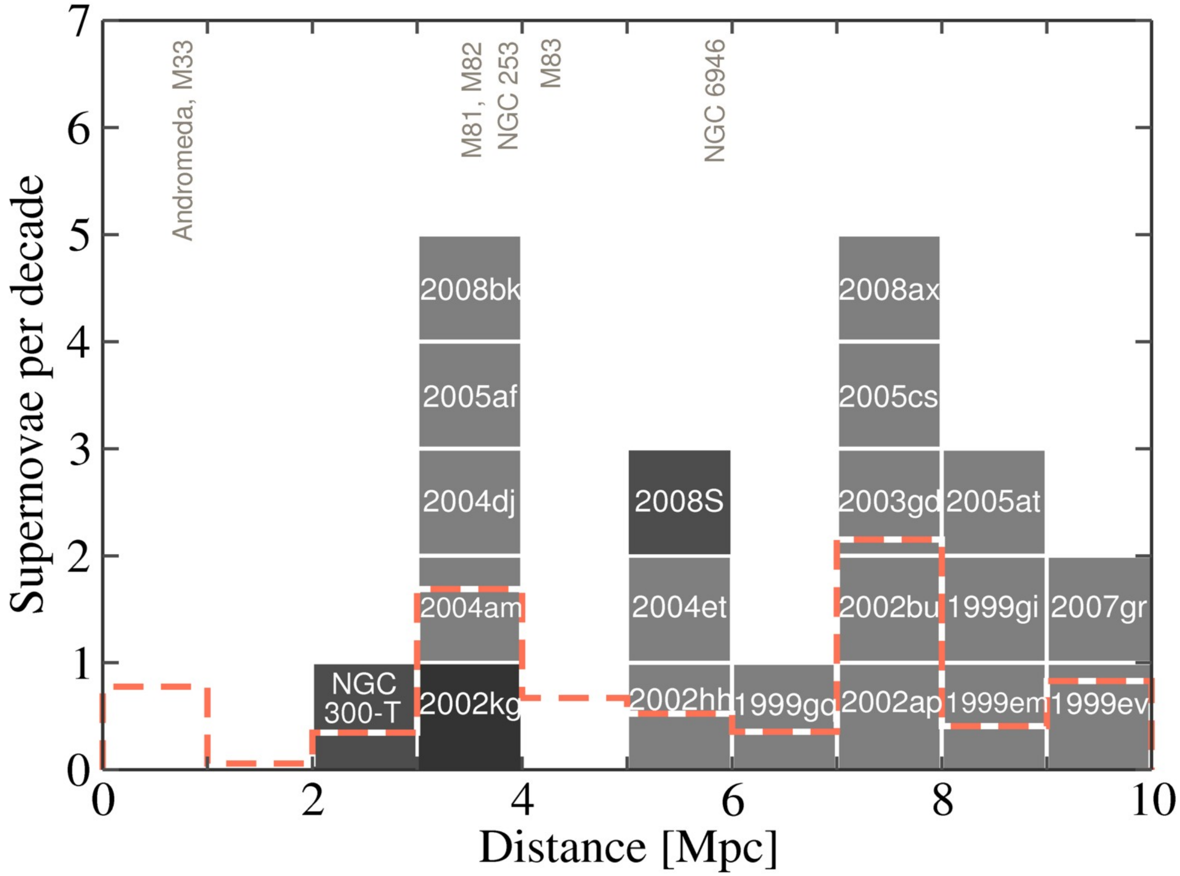
SN Rate in the Milky Way



Graphic by Georg Raffelt

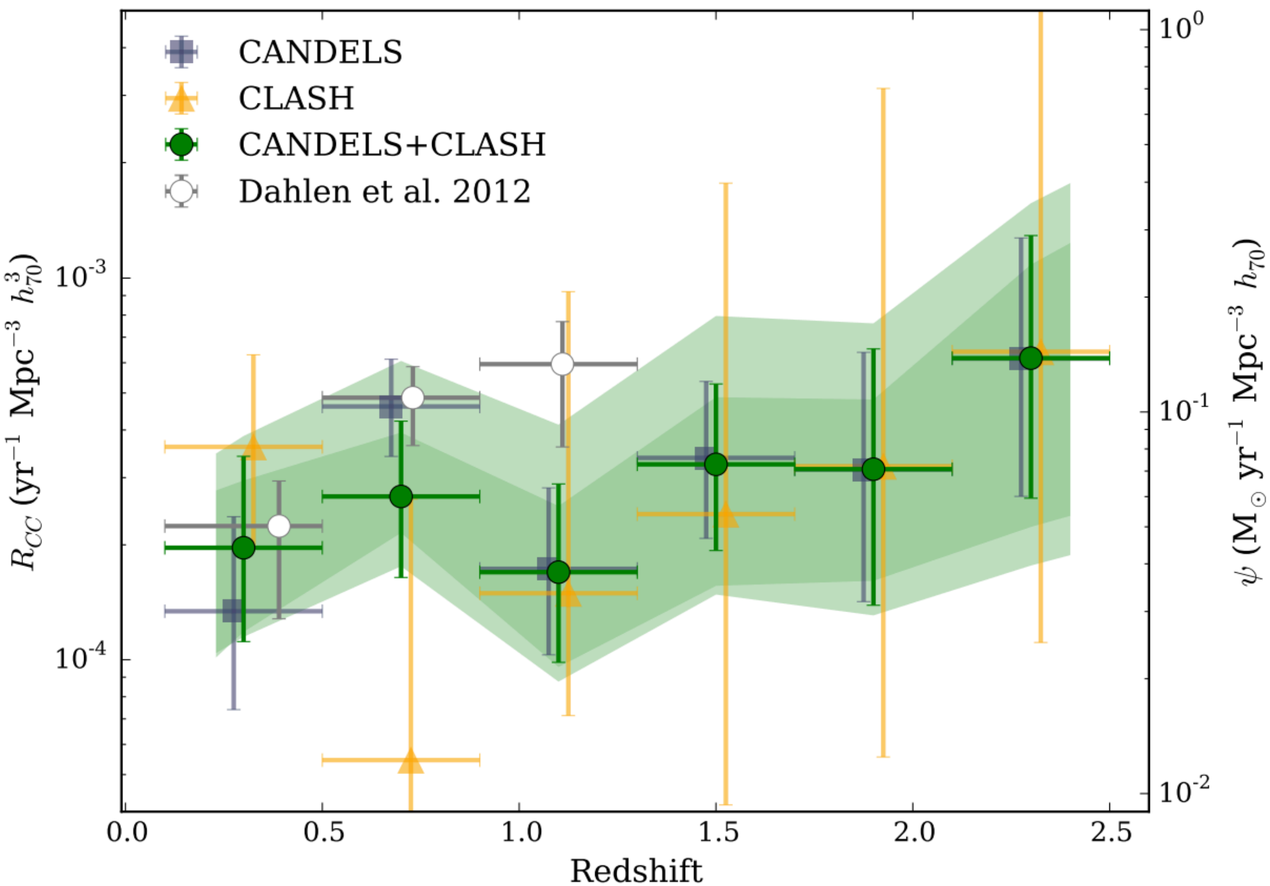
References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekeseev et al., JETP 77 (1993) 339 and Raffelt's updates.

Lots of SN in the 'hood



Kistler et al. (2008)

SN Rate vs z



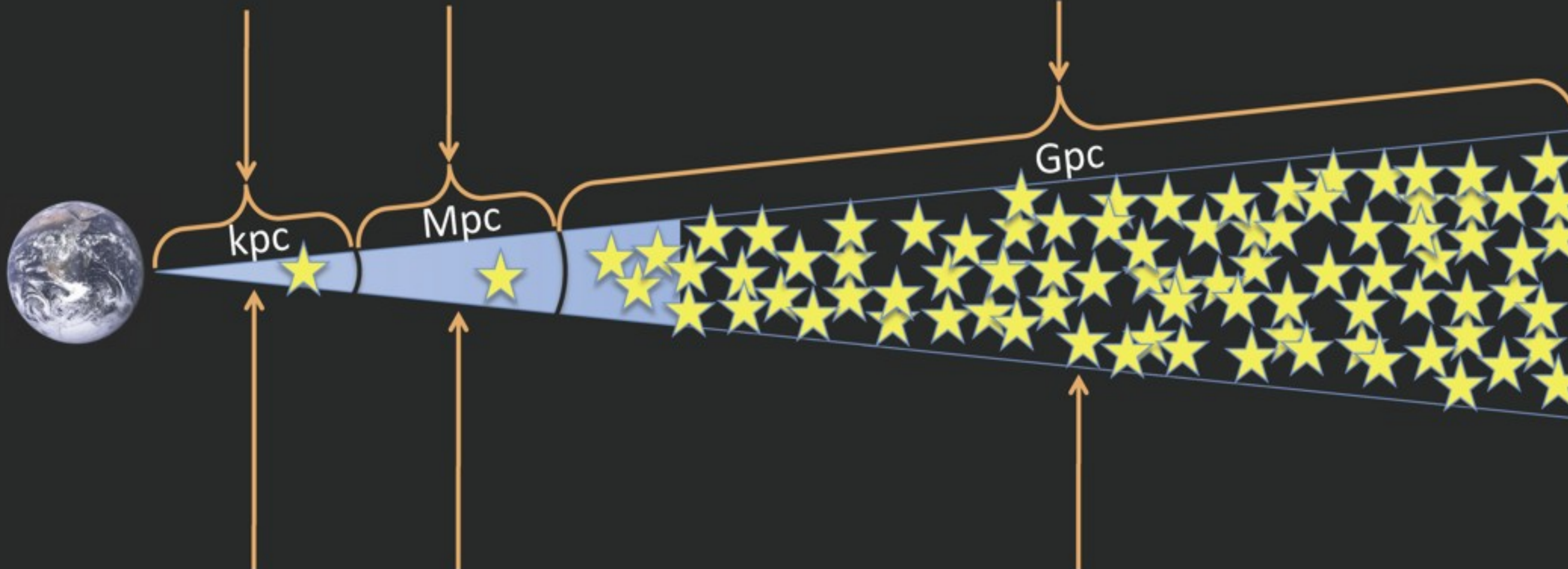
The SN rate is approx 1-3 SN /10^{10} L_{sun} / 100 yr

Cast a wide net

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

high statistics,
all flavors

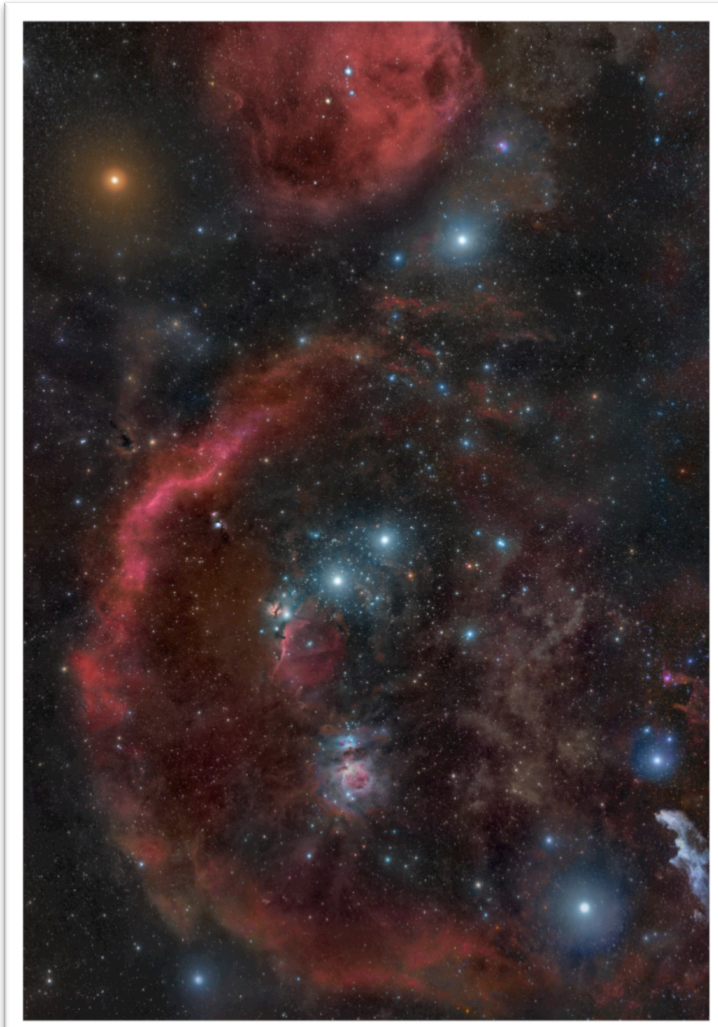
Rate ~ 1/yr

object identity,
burst variety

Rate ~ 10^8/yr

cosmic rate,
average emission

Betelgeuse

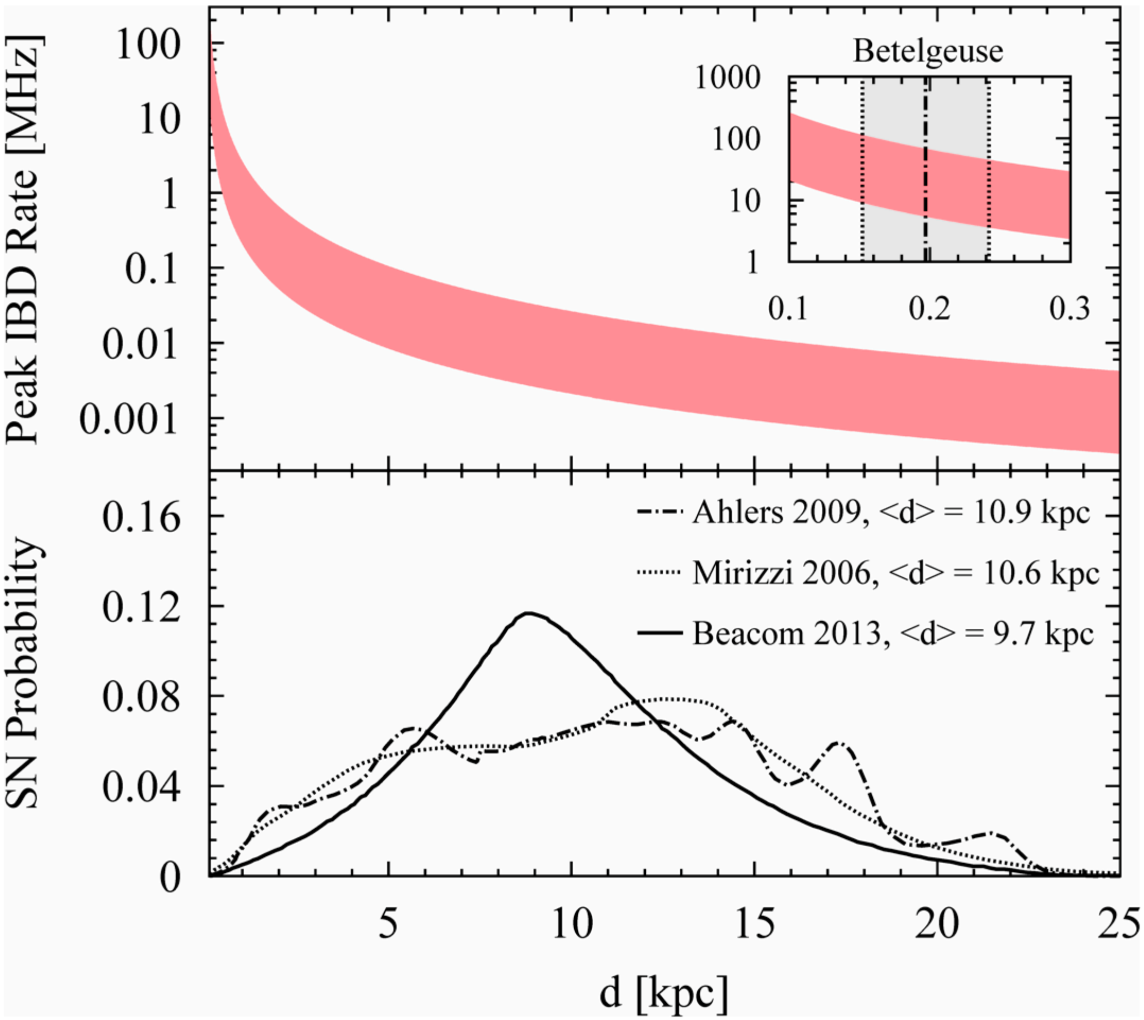


- Red supergiant
- 18 times mass of Sun
- 1180 times larger diameter
- 640 lightyears away

Once it goes supernova …

- Within 10^5 to 10^6 years
- Peak app. Mag. = -12.4
- Brighter than the moon
- Visible during day for 2-3 months

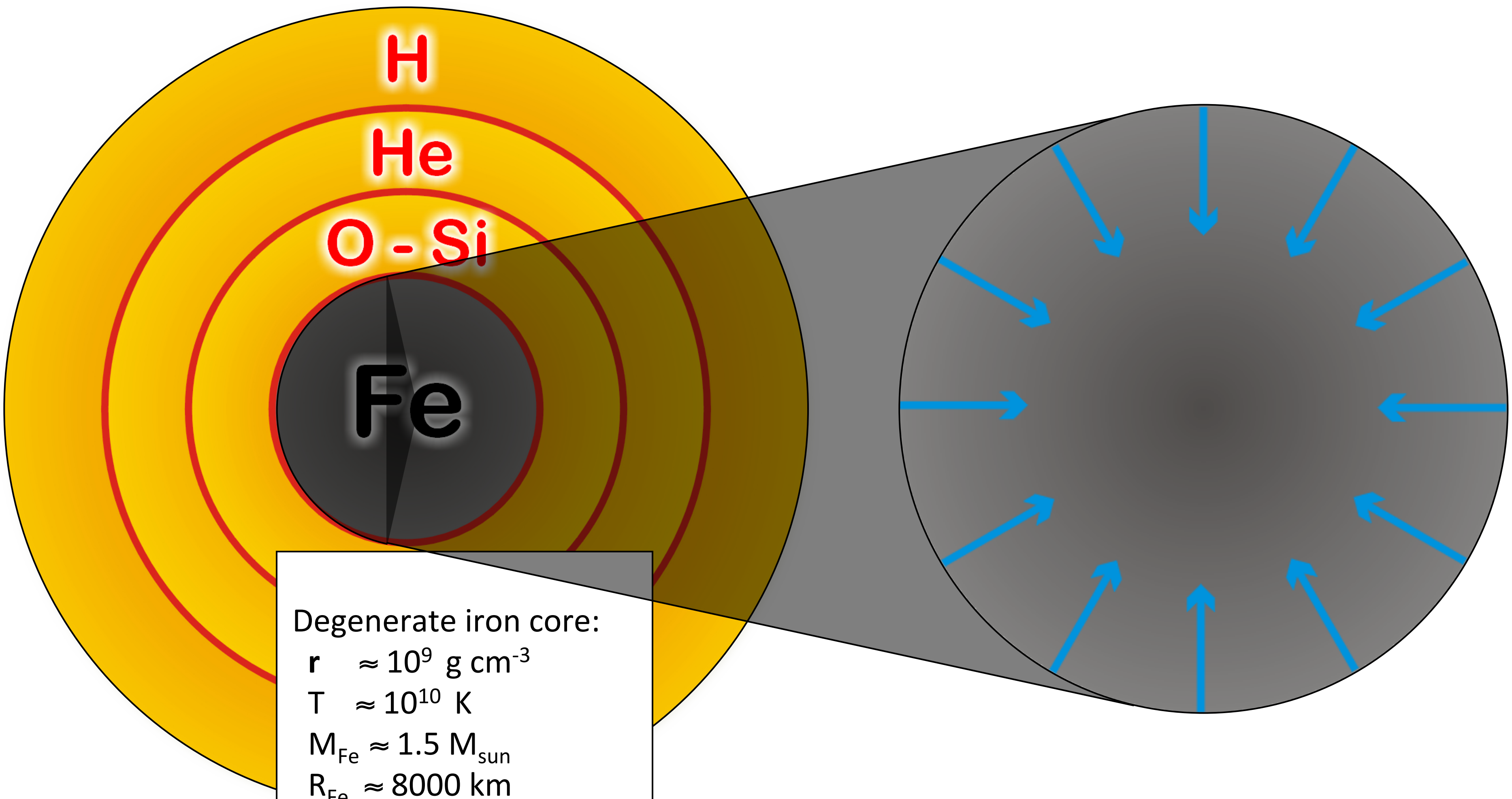
Typical SN Distance



JUNO Yellow Book

Supernova Explosion Mechanism

Onion structure	Collapse (implosion)



Degenerate iron core:

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

T $\approx 10^{10}$ K

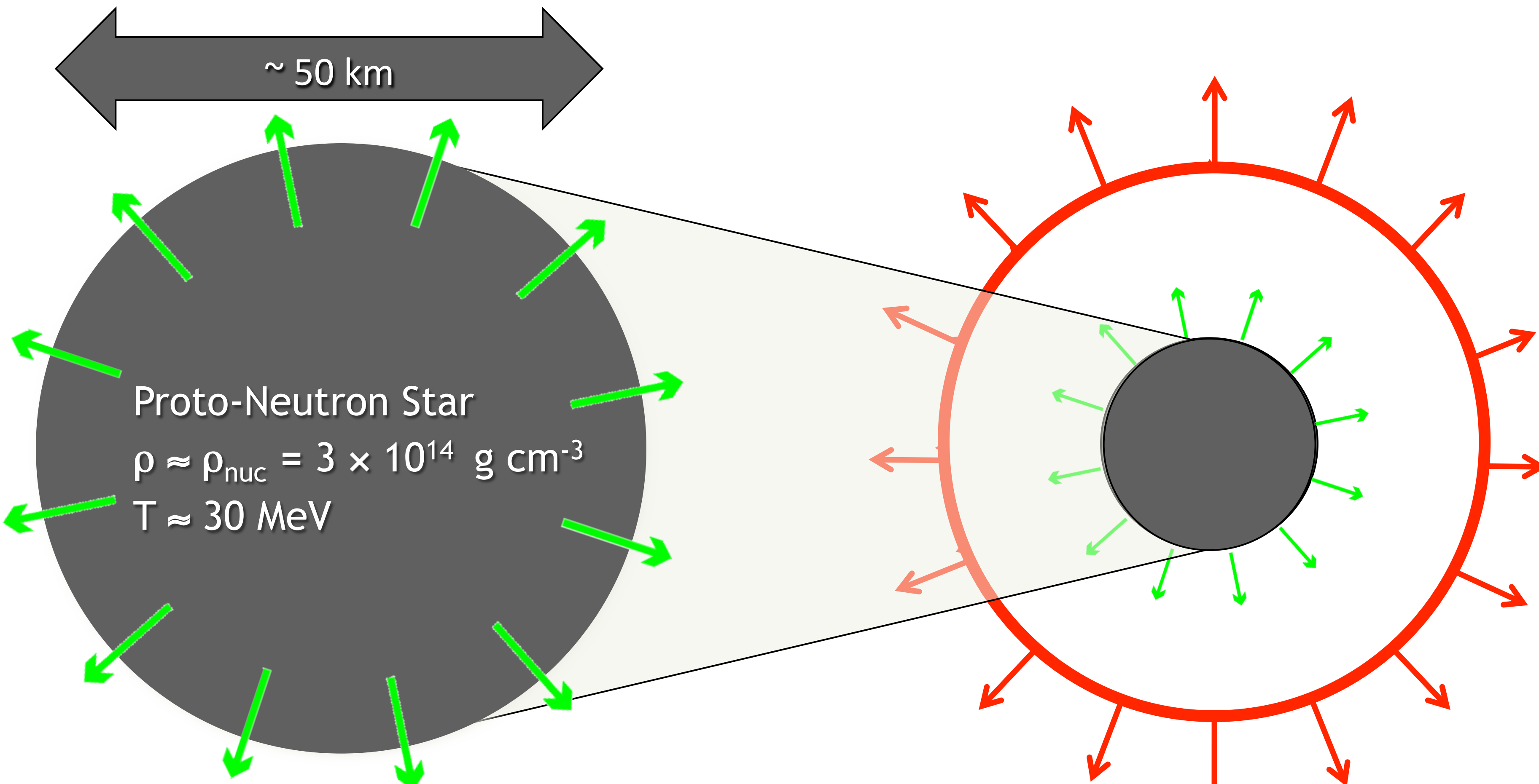
$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Adapted from Georg Raffelt

Supernova Explosion Mechanism

Newborn Neutron Star	Neutrino Driven Explosion



Neutrino Cooling

Adapted from Georg Raffelt

Typical Size of PNS

The protoneutron star is the post-collapse dense core, which will eventually become the neutron star by emitting neutrinos via

$$p + e \to n + \nu_e$$

The core mass is roughly given by the Chandrasekhar limit

$$M_{\rm PNS} = M_{\rm Ch} \approx 1.5 M_\odot = 3 \times 10^{33}\,{\rm g}$$

What is its density? It is supported by nuclear degeneracy, so

$$\rho_{\rm PNS} \approx \rho_{\rm Nuc} \approx 3 \times 10^{14} {\rm g\,cm^{-3}}$$

The radius is therefore approximately

$$\frac{4\pi}{3} R_{\rm PNS}^3 \, \rho_{\rm PNS} = M_{\rm PNS} \implies R_{\rm PNS} \approx 10\,{\rm km}$$

Its Schwarzchild radius is about 4.5 km, so this is not a black hole yet

Typical Energy Output

The gravitational binding energy of the uniform star is

$$E_{\rm grav} = -\frac{3G_{\rm N}M^2}{5R}$$

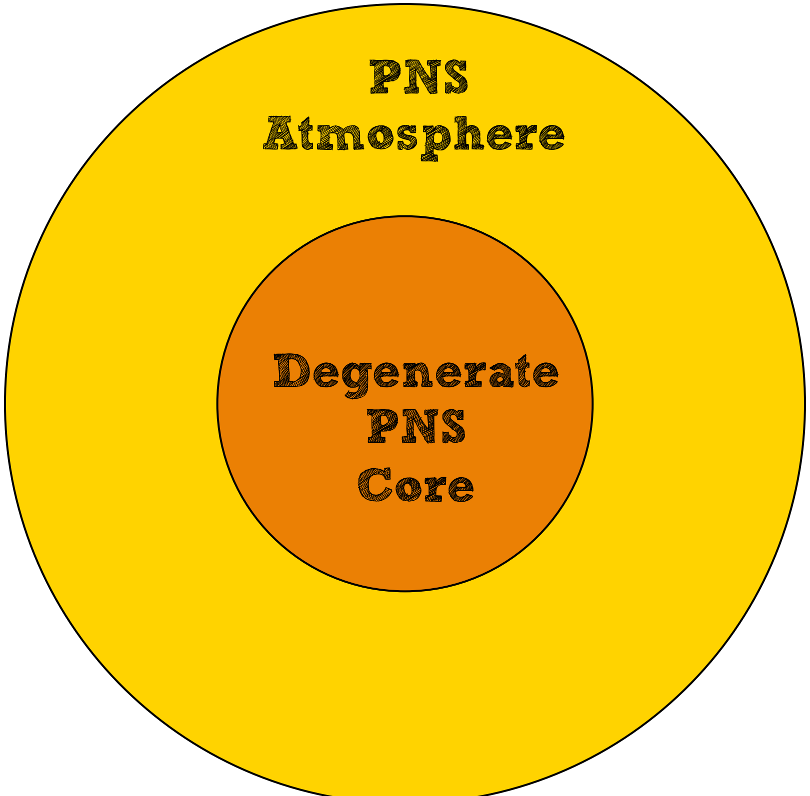
This must be released to become the smaller denser neutron star. Thus the net energy output is

$$E_{\rm bind} = -\frac{3G_{\rm N}M^2}{5}\left(\frac{1}{R} - \frac{1}{R_{\rm PNS}}\right)$$

$$\approx 3 \times 10^{53}\,{\rm erg}$$

This can be in any thing – light, neutrinos, axions, gravitons! But we will see that it is 99% neutrinos!

Typical Neutrino Energy



The neutrinos are emitted by nucleons in the PNS atmosphere virialized with nucleons in the PNS. The gravitational potential energy for a nucleon is

$$V_{\rm grav} = -\frac{G_{\rm N} M_{\rm PNS}\, m_{\rm N}}{R_{\rm PNS}} \approx 30\,{\rm MeV}$$

Now use virial theorem to relate nucleon PE to its KE, which we relate to the neutrino energy

$$E = -\frac{1}{2} V_{\rm grav} = 15\,{\rm MeV}$$

The virial theorem predicts neutrino energies in the 10 MeV range

Typical Timescale

Neutrinos are trapped via weak interactions, so the their scattering cross section goes as

$$\sigma \approx G_{\rm F}^2 E^2 \approx 10^{-44} \left(\frac{E}{\rm MeV}\right)^2 \, {\rm cm}^2$$

Nucleon number density is $n_{\rm B} = \dfrac{\rho_{\rm nuc}}{m_{\rm N}} \approx 10^{38}\,{\rm cm}^{-3}$

Mean free path is $\lambda = \dfrac{1}{n_{\rm B}\sigma} \approx 100\,{\rm cm}\left(\dfrac{10\,{\rm MeV}}{E}\right)^2$

Diffusion time is

$$t_{\rm diff} \approx \frac{R_{\rm PNS}^2}{\lambda} \approx 3\,{\rm sec}\left(\frac{R_{\rm PNS}}{30\,{\rm km}}\right)^2 \left(\frac{E}{10\,{\rm MeV}}\right)^2$$

Why No Prompt Explosion

Shock is formed inside the iron core, and has to get out

In doing so, it breaks Fe nuclei and loses 8.8 MeV/nuc

The total binding energy of the material outside is

$$0.1\frac{M_\odot}{M_N}Q_\mathrm{b} \approx 10^{51}\,\mathrm{erg}$$

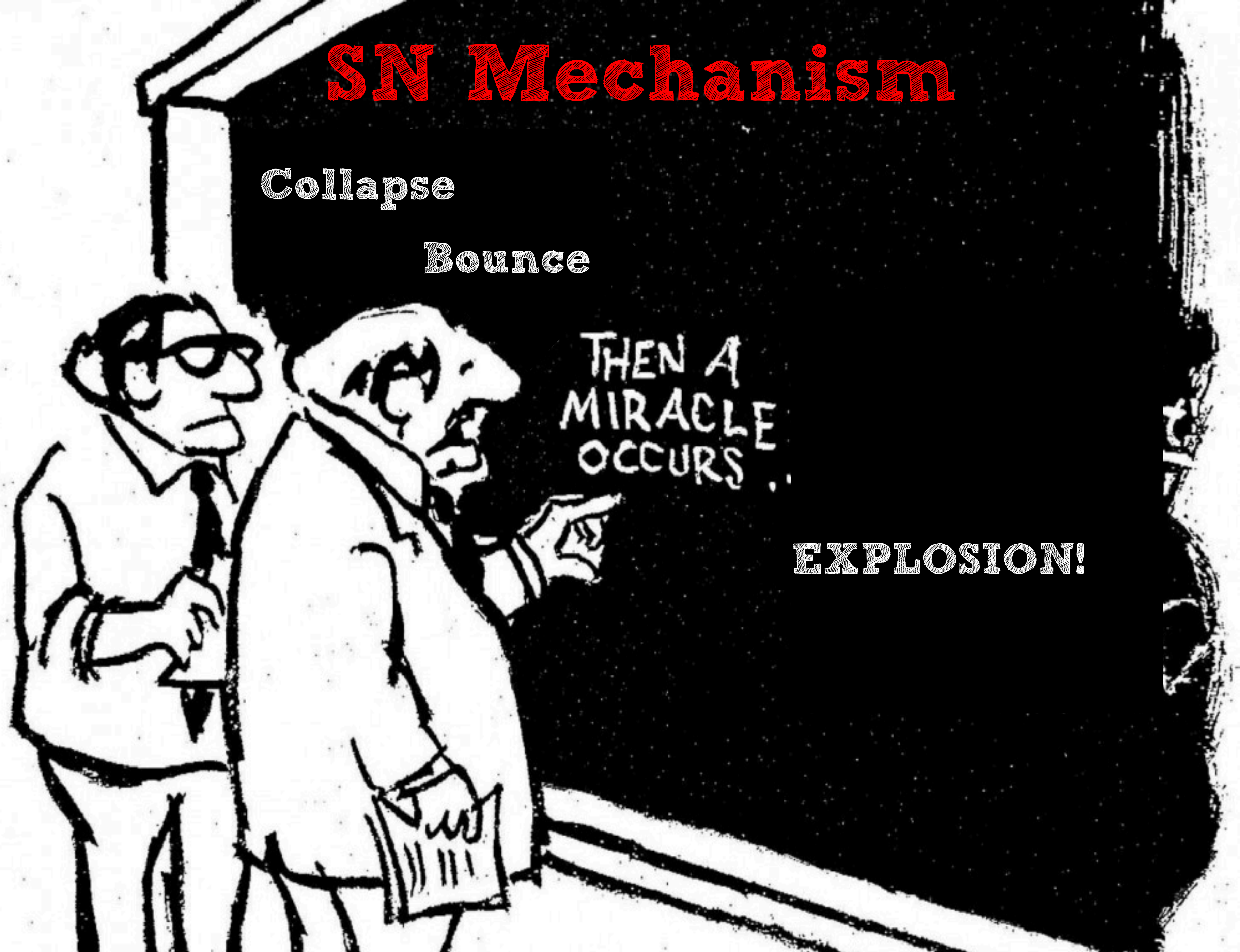
The kinetic energy of the shock wave is comparable

So shock can be launched but does break through

SN Mechanism

Collapse

Bounce



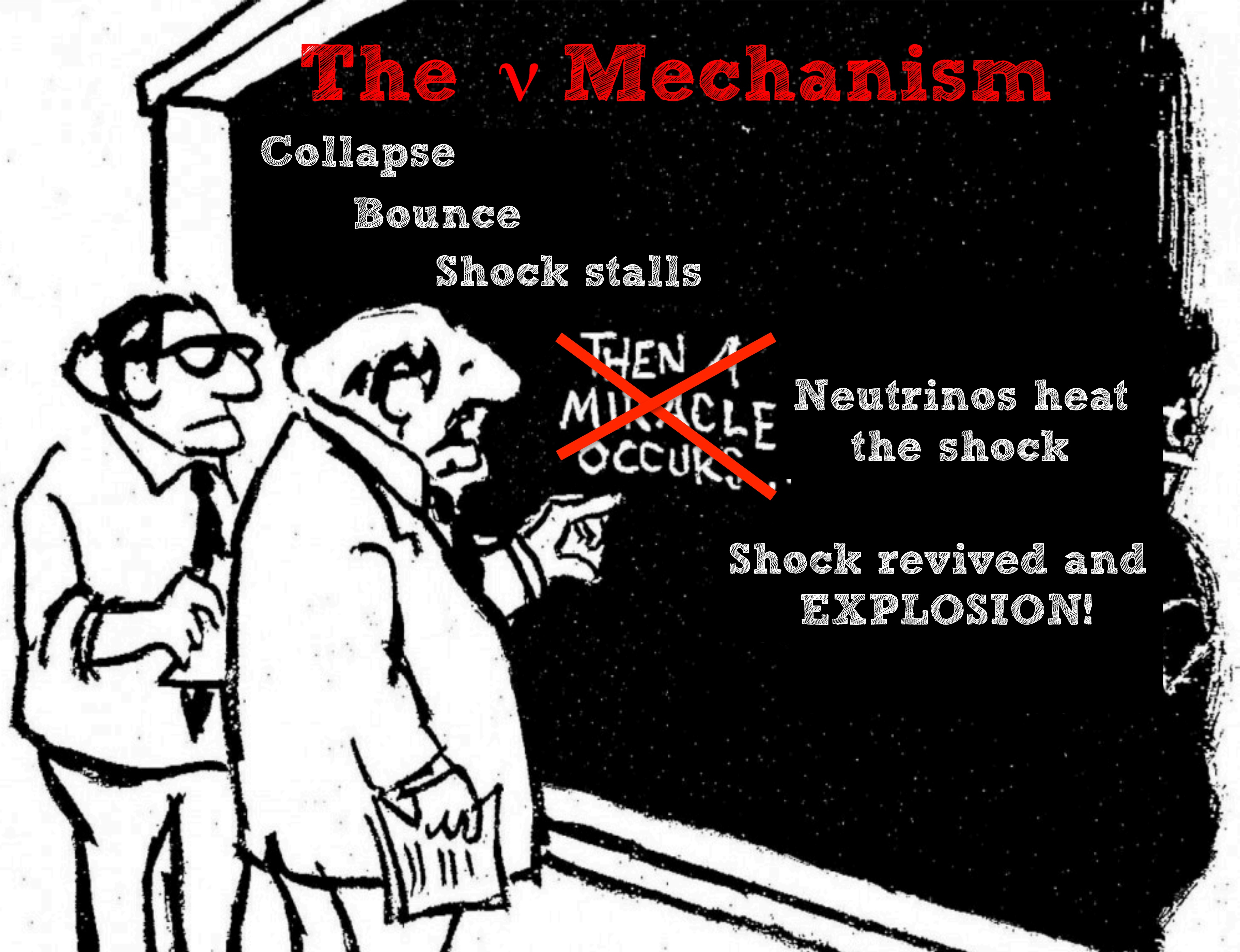
EXPLOSION!

The ν Mechanism

Collapse

Bounce

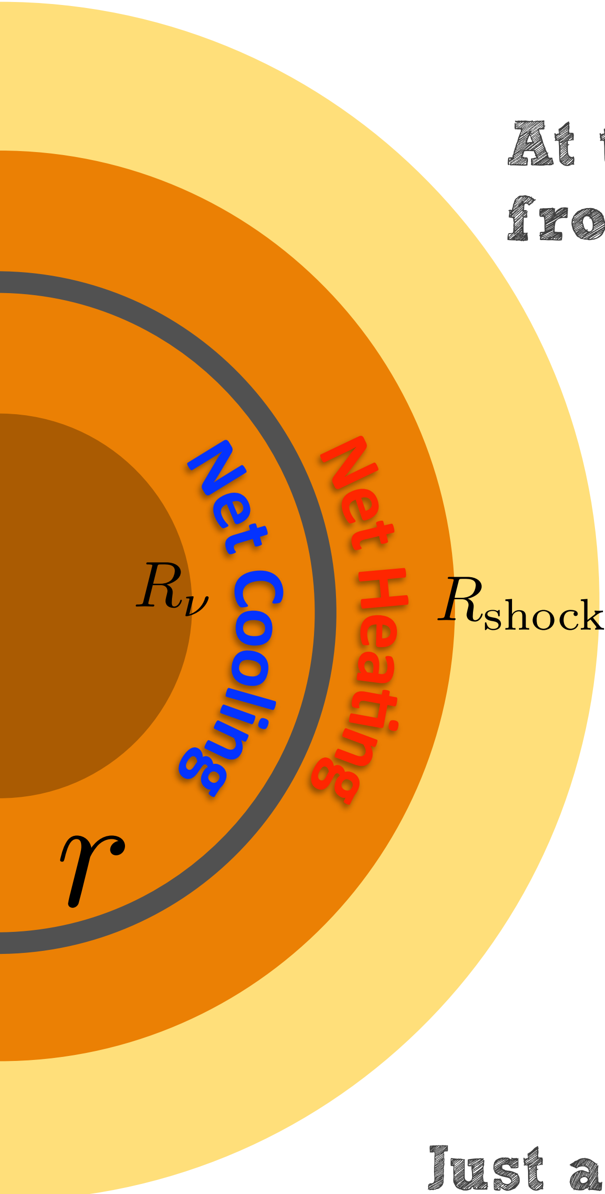
Shock stalls



Neutrinos heat the shock

Shock revived and EXPLOSION!

Heating vs. Cooling



At the shell at radius r, due to neutrinos from below, heating is at a rate

$$Q_+ \sim \frac{L_\nu \sigma}{4\pi r^2}$$

The shell radiates away heat at a rate

$$Q_- \sim a\sigma T^4$$

These are equal at the gain radius

$$r_{\rm gain} = R_{\rm shock}\sqrt{\frac{2R_{\rm shock}}{R_{\rm PNS}}\left(\frac{T_{\rm shock}}{T_{\rm PNS}}\right)^3}$$

Just above the gain radius, there's heating

Flavor Conversion and Explosion

Heating rate depends on electron neutrinos and anti neutrinos

$$Q_+^{\text{before}} \sim \frac{L_{\nu_e}}{4\pi r^2}\sigma_0 \left(\frac{E_{\nu_e}}{E_0}\right)^2$$

But they have the least average energy

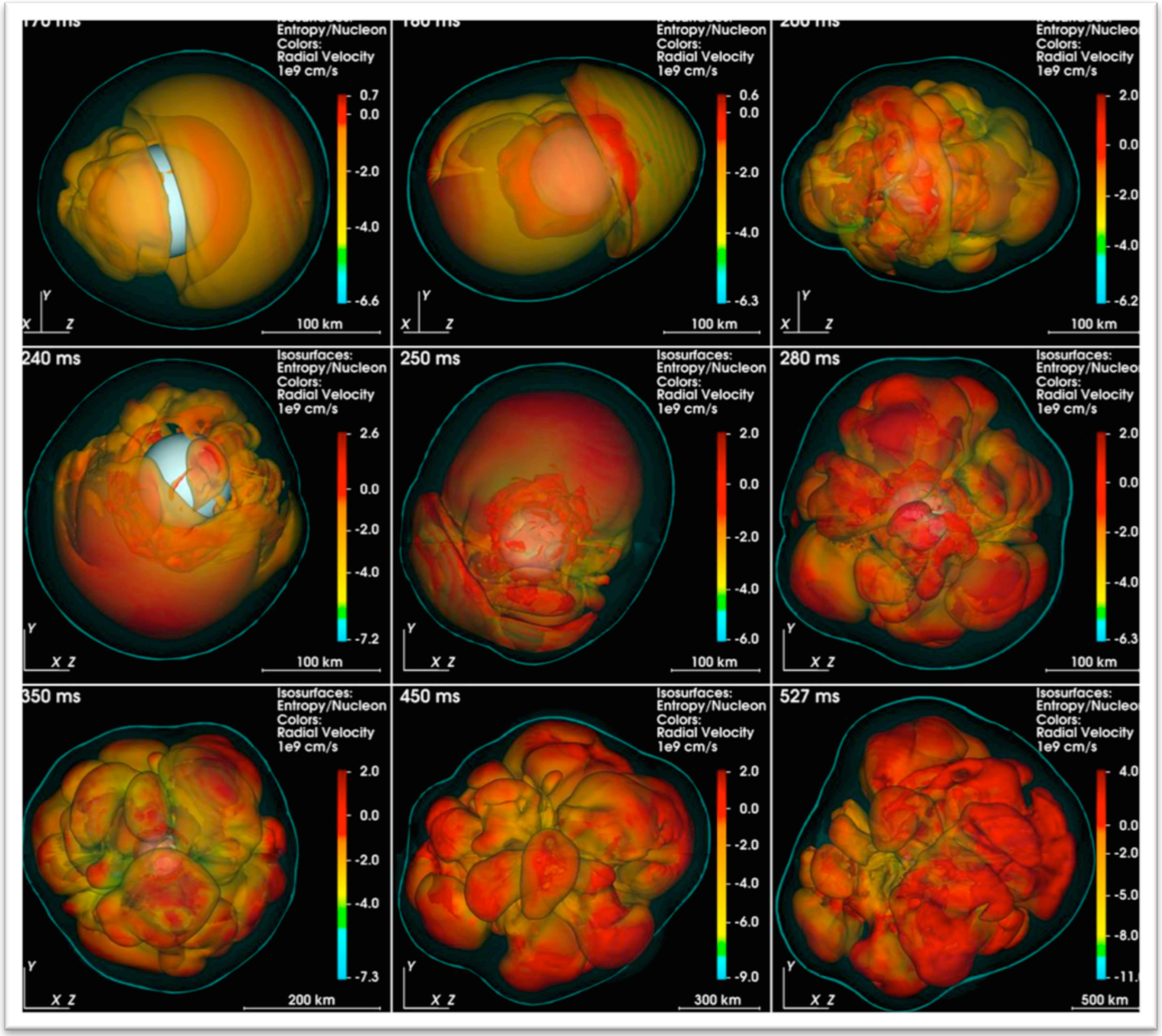
$$\langle E_{\nu_e} \rangle \ll \langle E_{\nu_x} \rangle$$

With a swap of the flavors, i.e., $\nu_e \leftrightarrow \nu_x$

Significant increase in heating rate is possible

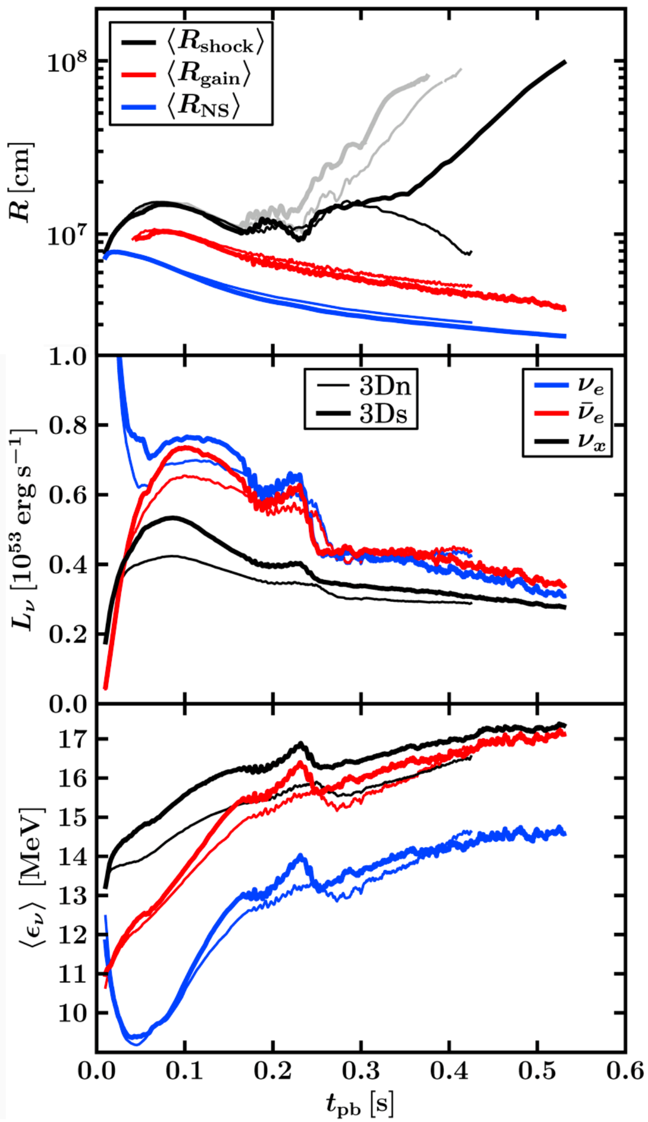
$$Q_+^{\text{after}} \sim \frac{L_{\nu_x}}{4\pi r^2}\sigma_0 \left(\frac{E_{\nu_x}}{E_0}\right)^2 \gg Q_+^{\text{before}}$$

Explosion: 20 Solar Mass



Melson et al. (2015)

Neutrino Signal

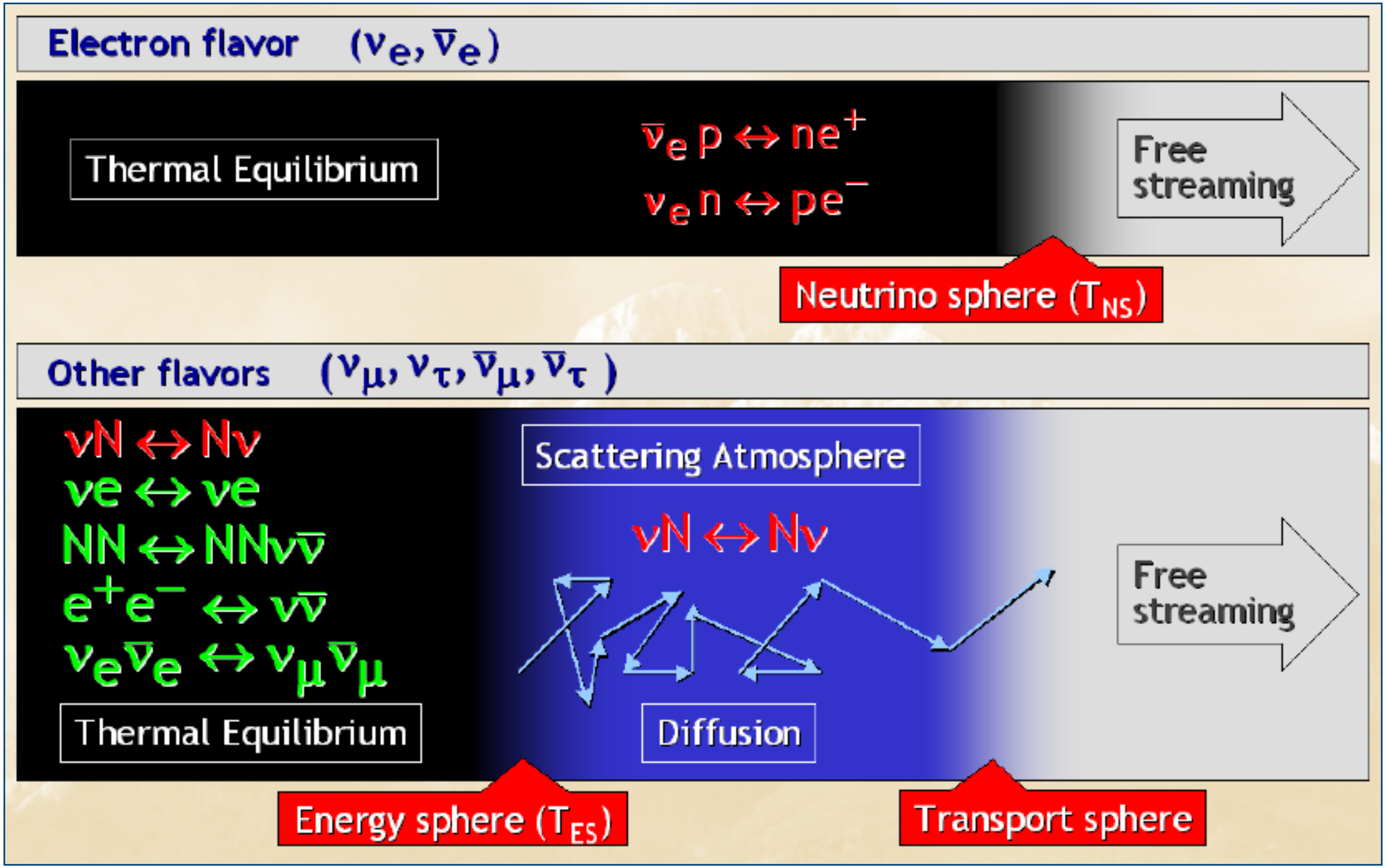


Main features

- Burst phase
  - Mostly nue
- Accretion phase
  - Differences in luminosity
  - Differences in av. Energy
- Cooling phase
  - Luminosity or energy becomes same across all flavors

Melson et al. (2015)

Spectra Formation



Keil, Raffelt, Janka (2002)

Fits to the Energy Spectrum

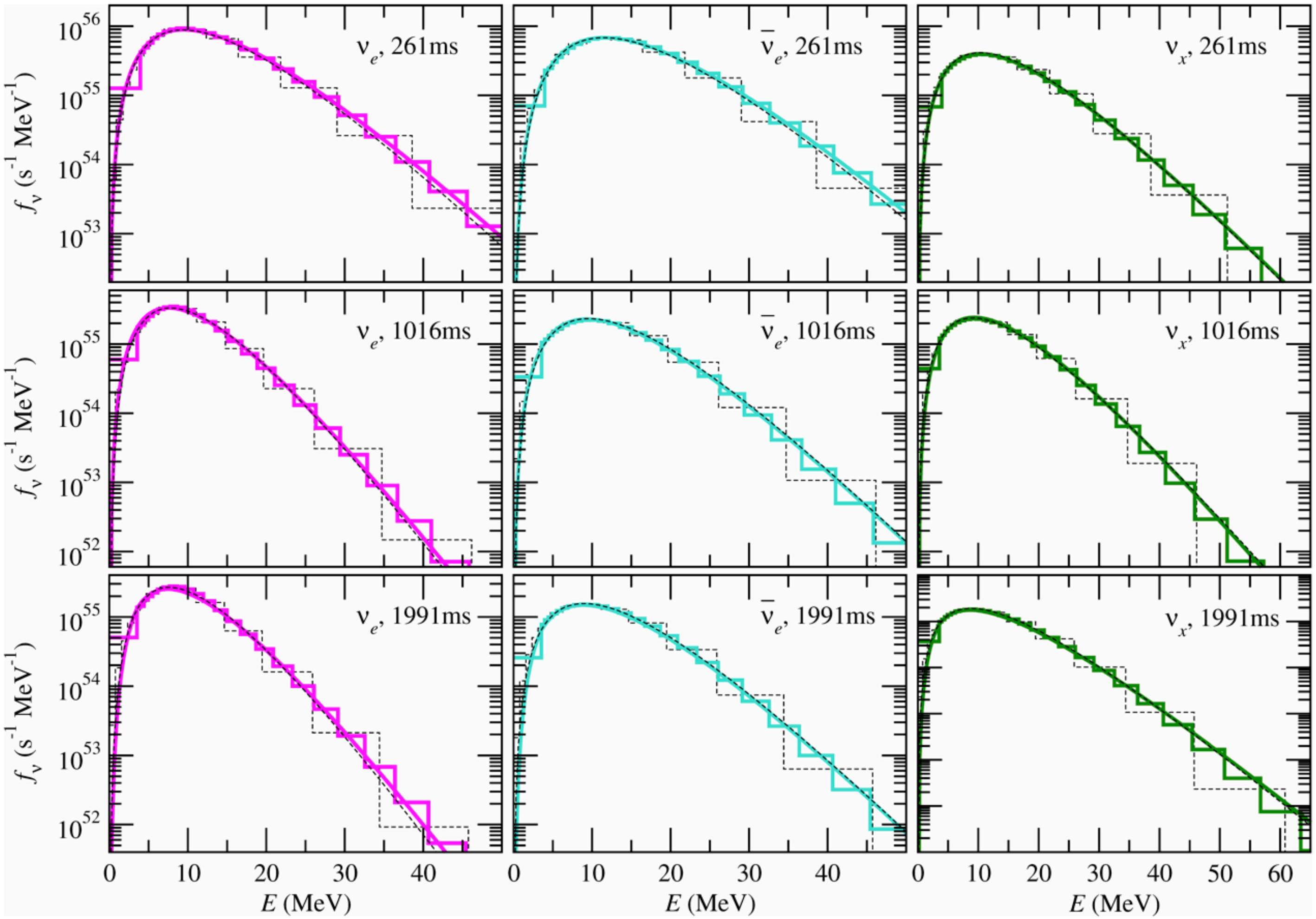
Often neutrino spectra are parametrized using an "alpha-fit" or an "eta-fit". These work quite well for the spectra from simulations. But parameters are flavor and time-dependent.

Alpha Fit	Eta Fit
$f(E) \propto E^\alpha \, e^{-(\alpha+1)\frac{E}{\langle E \rangle}}$	$f(E) \propto \dfrac{E^2}{1+e^{-\eta+\frac{E}{T}}}$
Based on a power-law	**Based on Fermi-Dirac**

Electron flavors have larger alpha say 3-4, vs, 2 for others

Typically pinching decreases with time

Examples of Alpha-fit



Tamborra, Müller, Hüdepohl, Janka & Raffelt, arXiv:1211.3920

Neutrinos from a SN

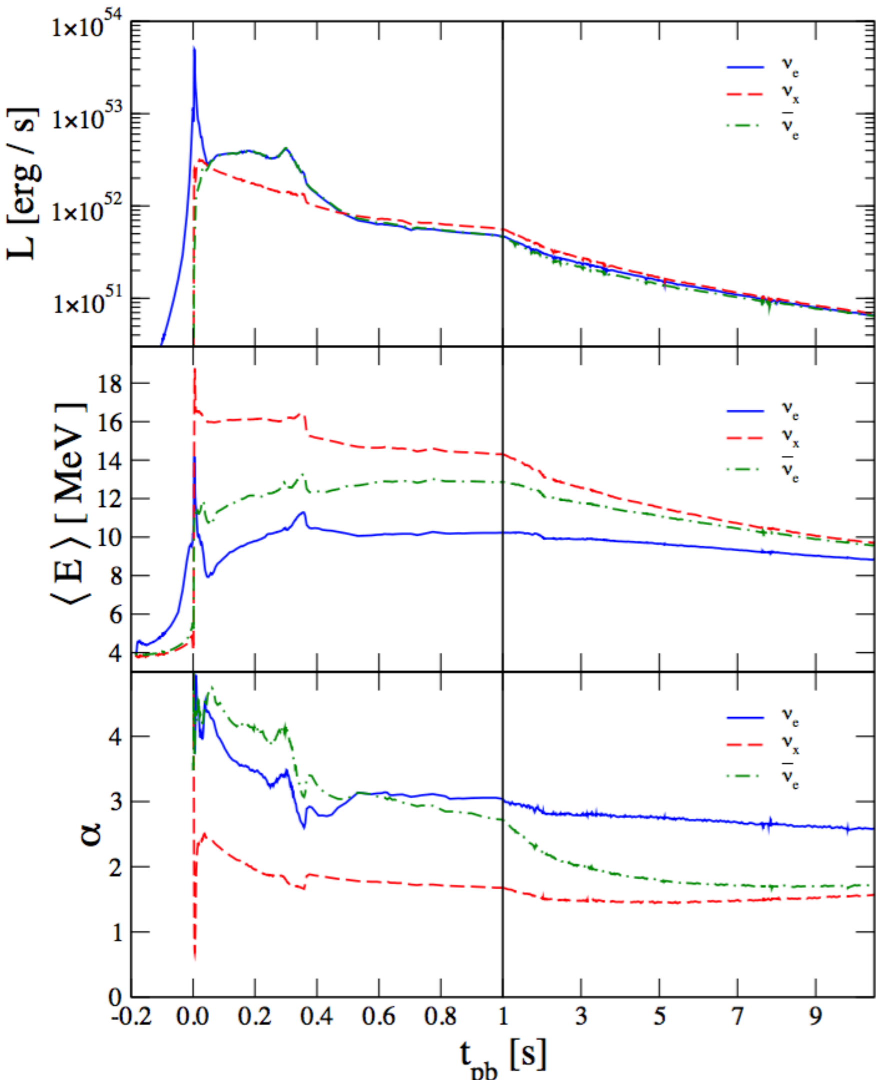


Image: Fischer et al (2010)

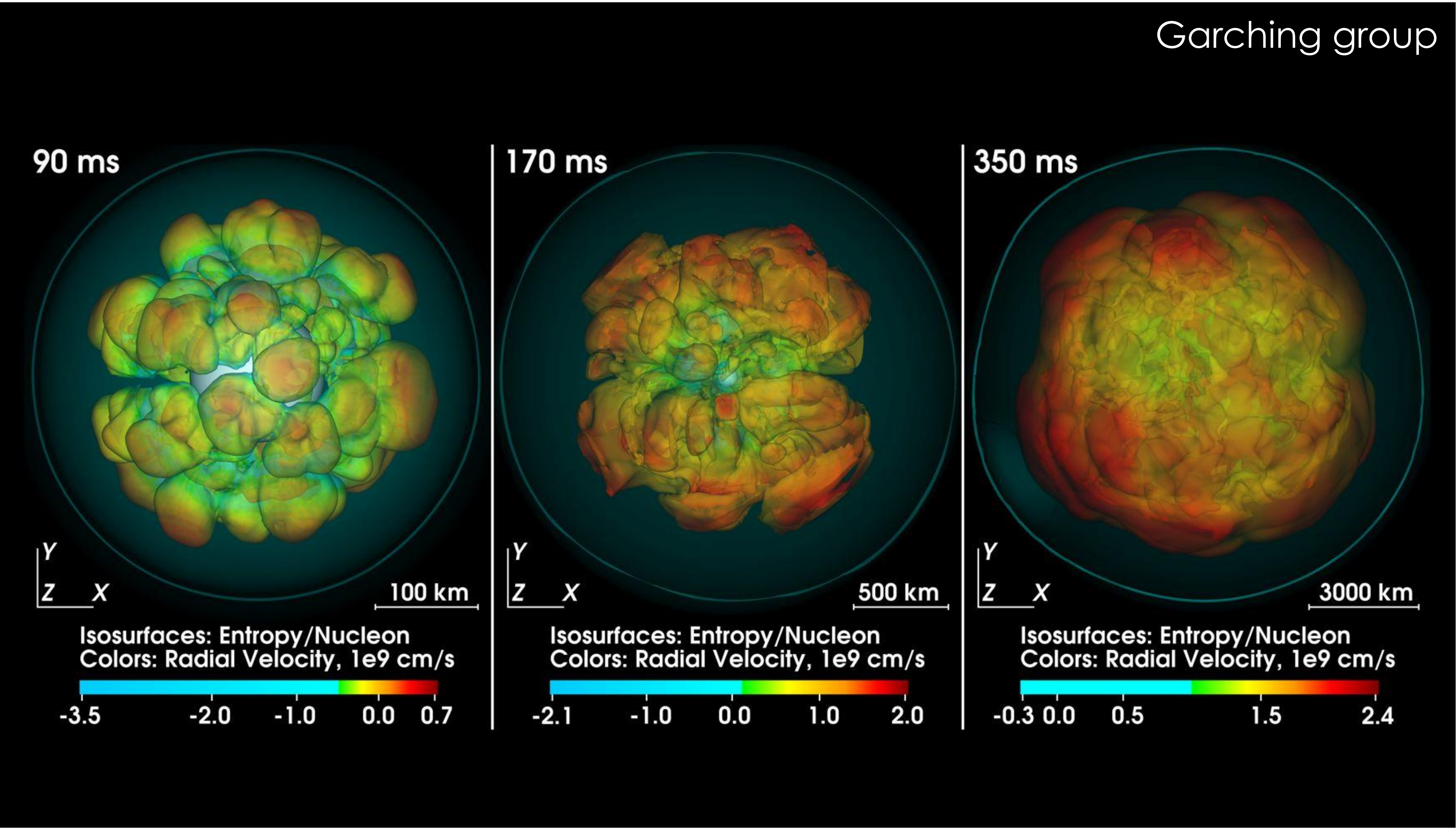
Epoch dependence

- Pre-collapse
- Neutronization burst
- Accretion phase
- Cooling phase

Flavor dependence

- Electron neutrinos
- Electron antineutrinos
- Non-electron neutrinos and antineutrinos

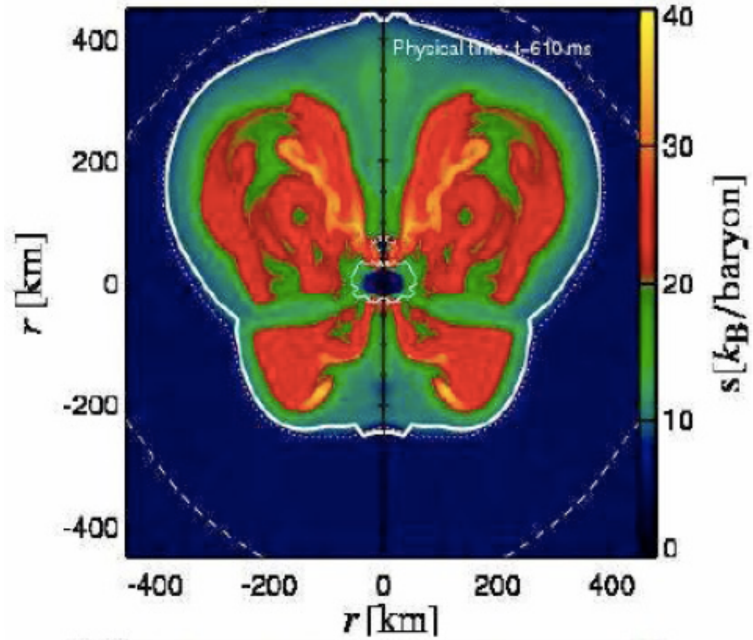
Multidimensional Effects

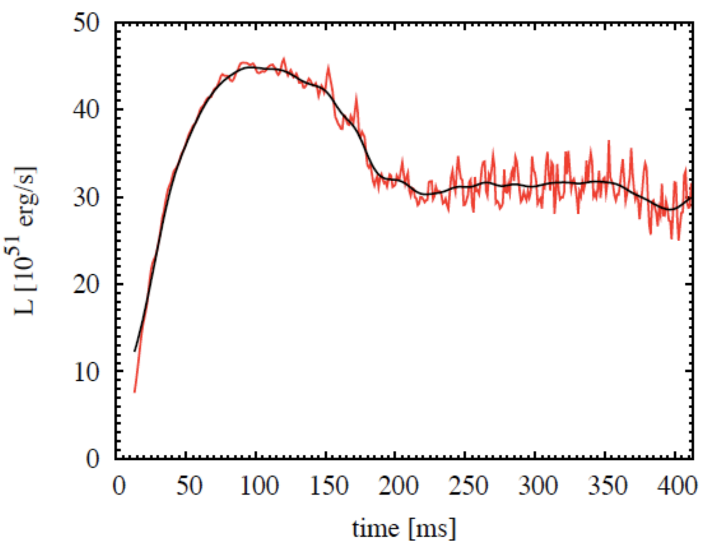


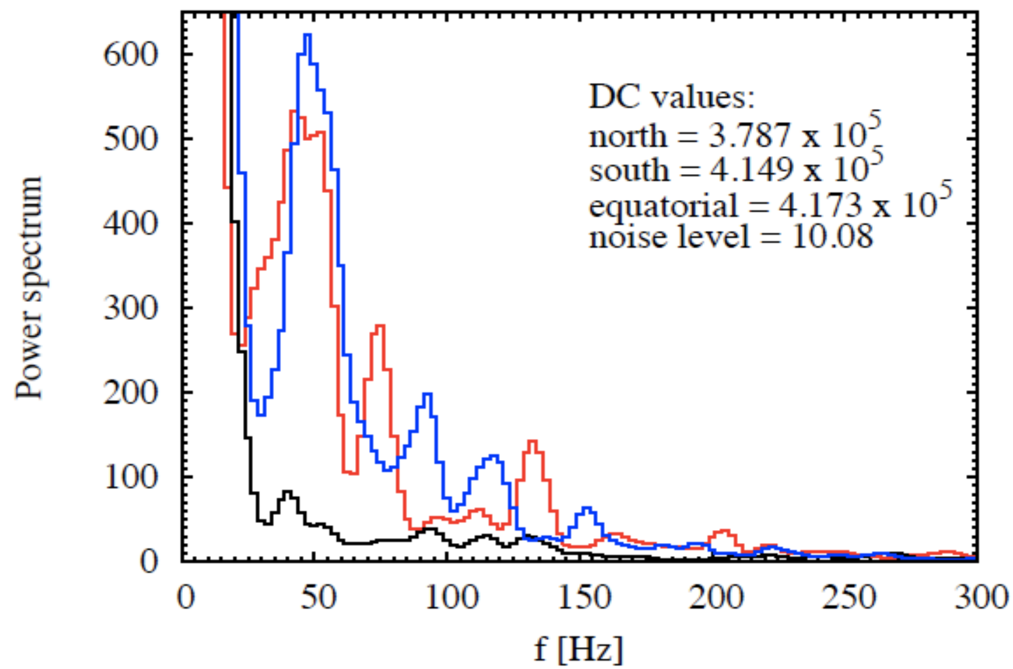
SASI

Standing Accretion Shock Instability

- Large scale motion of the stellar material on a millisecond timescale
- Fluctuations in the neutrino signal, luminosities and energies



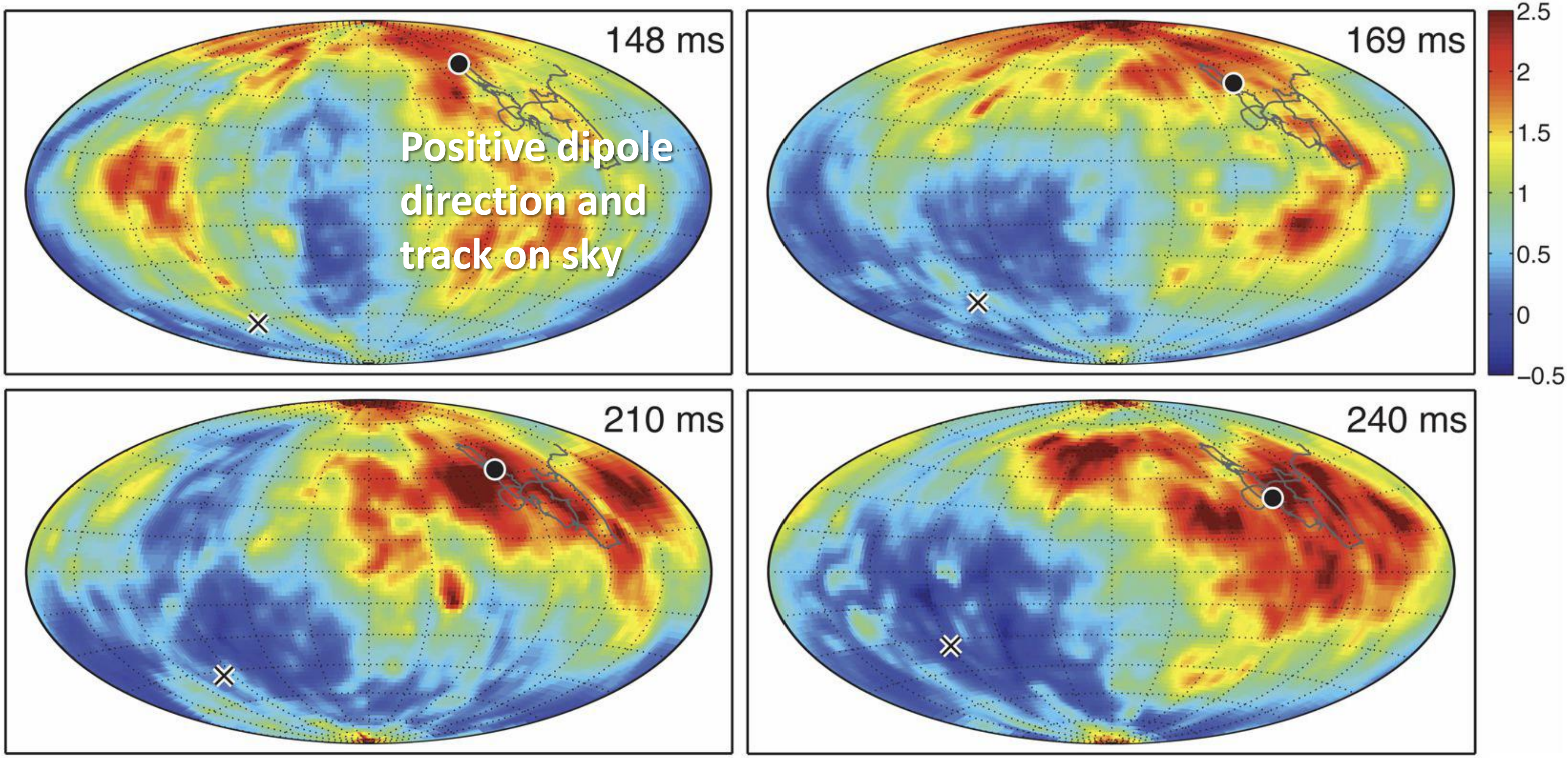




Lund et al. (2010)

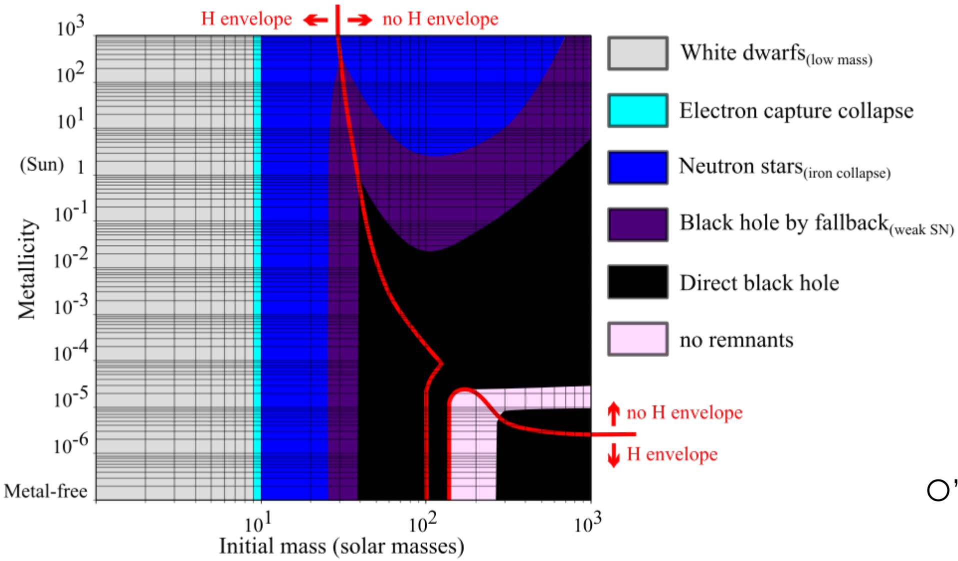
LESA

Lepton-# Emission Self-Sustained Asymmetry

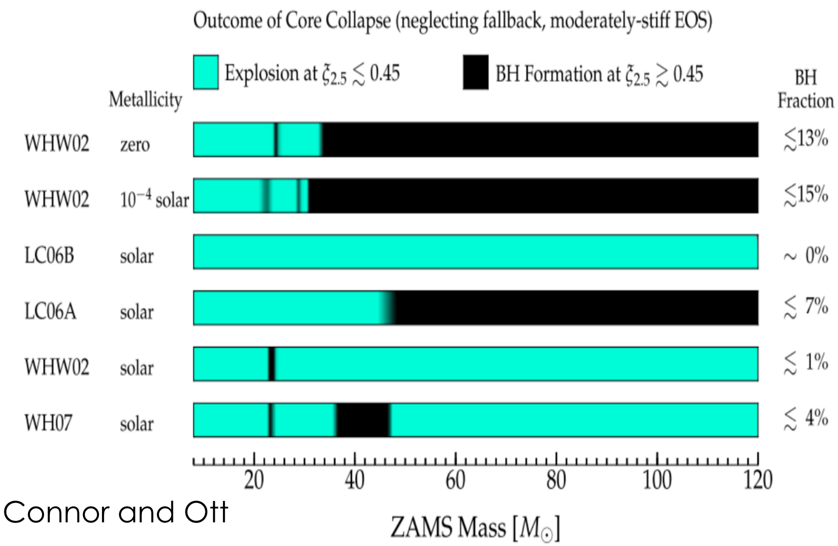


Tamborra et al. (2014)

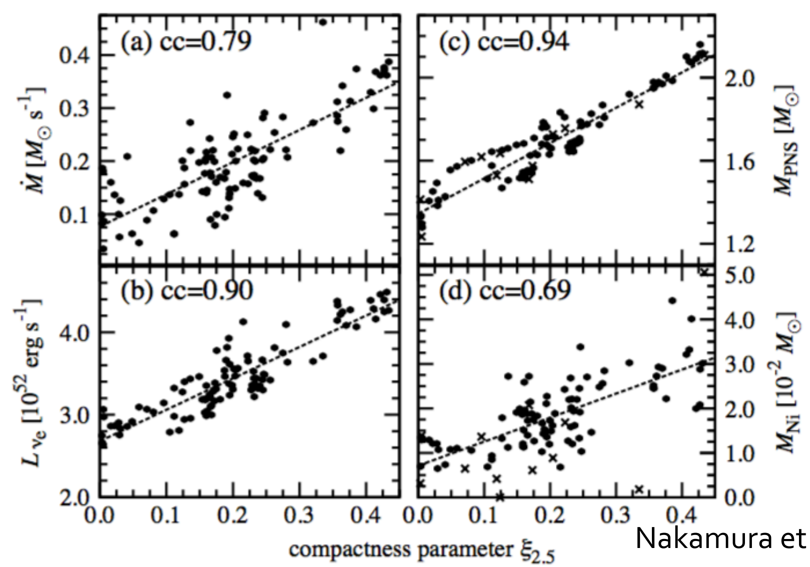
Remnants of Massive Star



Heger et al., ApJ (2003)



O' Connor and Ott

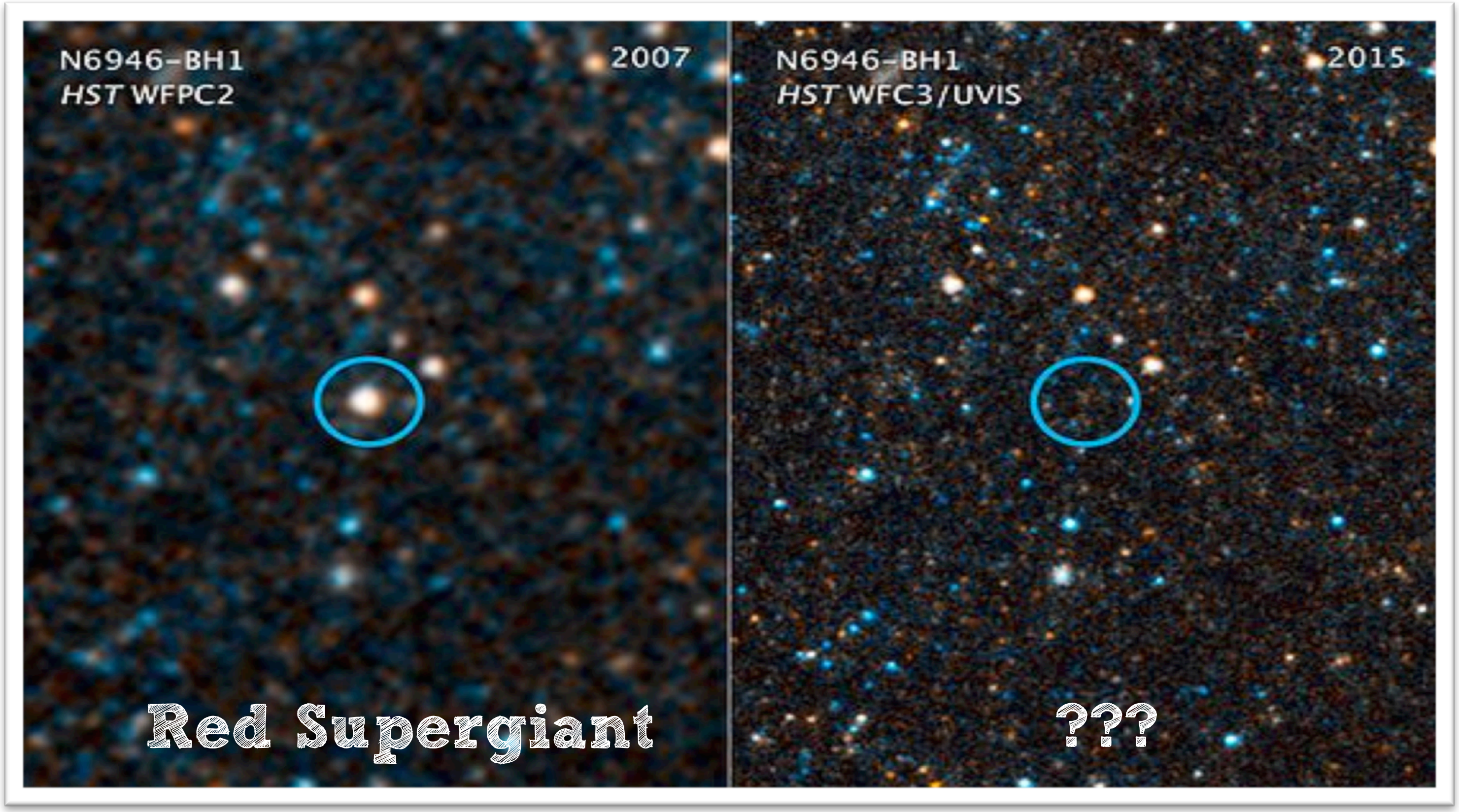


Nakamura et al (2015)

Compactness ~ 1/R enclosing M

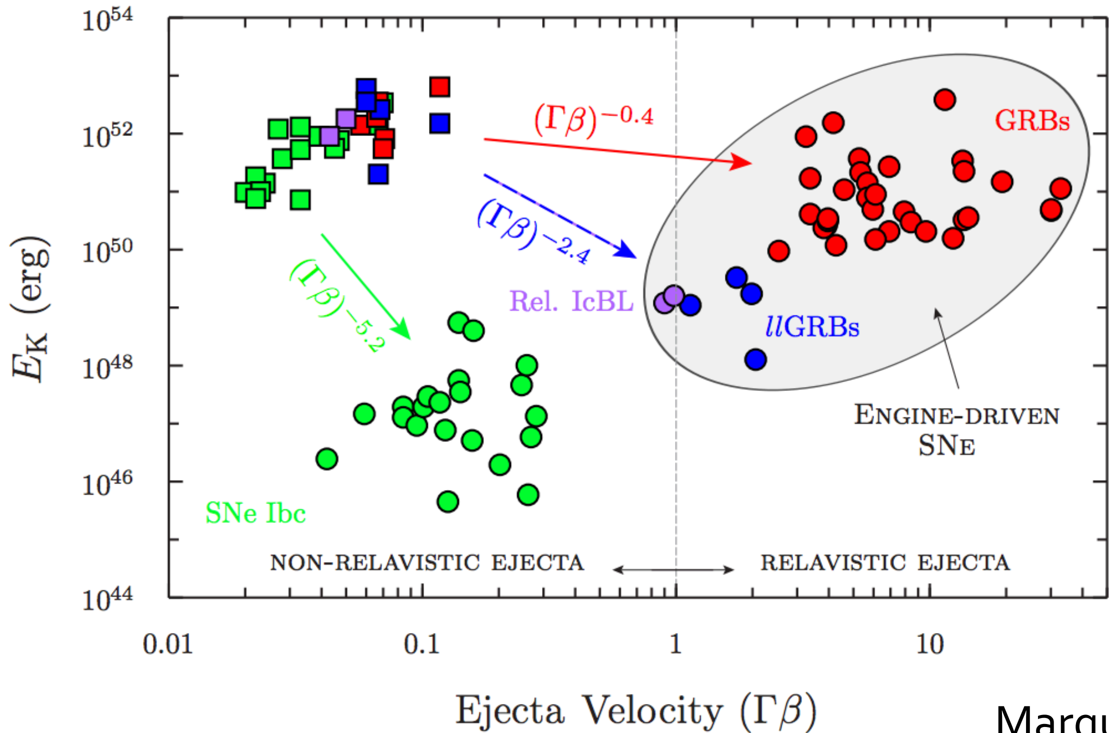
Good predictor of SN properties
O'Connor and Ott (2013)
See also, Sukhbold et al. (2016),
Ertl et al. (2016),..

Failed Supernovae



A Survey about Nothing : Gerke, Kochanek, Stanek (2015)
Adams et al. (2017)

SN-GRB Connection



Margutti et al (2014)

Long duration GRBs are closely related to SN

Reviews: Woosley And Bloom (2006), Hjorth and Bloom (2011) , …, Cano et al. (2016), …

Summary for Lecture 1

Lecture 1

Supernovae:

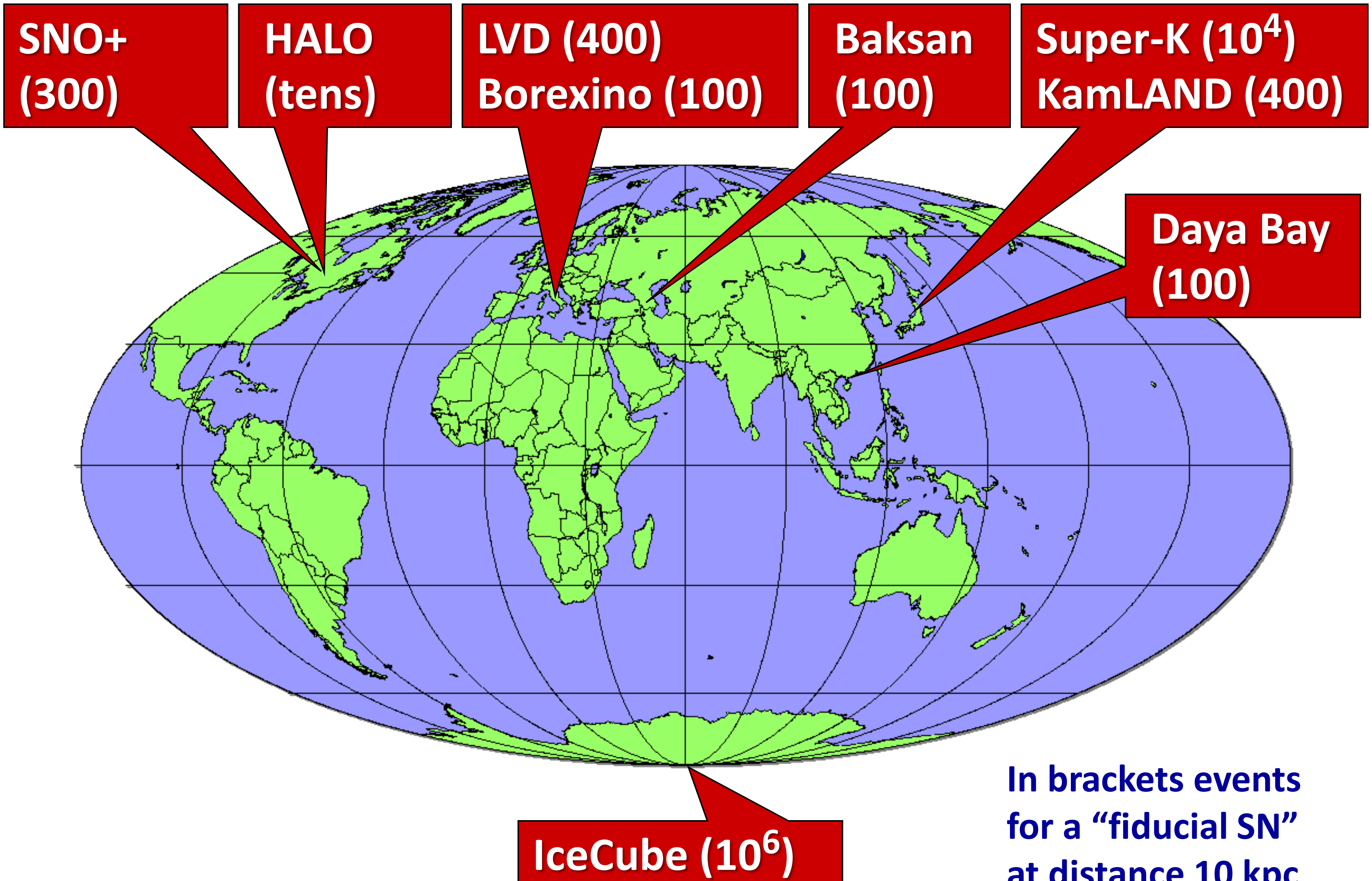
- What: Final stages of > 8-10 solar mass stars
- When: Roughly 1-3 times per century
- Why: Core collapse of massive stars, neutrino aided explosion

Supernova and the neutrino mechanism:

- Rich hydrodynamics:
  - Shock revival,
  - Convection,
  - SASI
  - LESA,
  - Failed SN
- Time dependent neutrino emission in all flavors
  - Energy, Luminosity, Pinching, etc.

How to detect Supernova Neutrinos?

Present Detectors

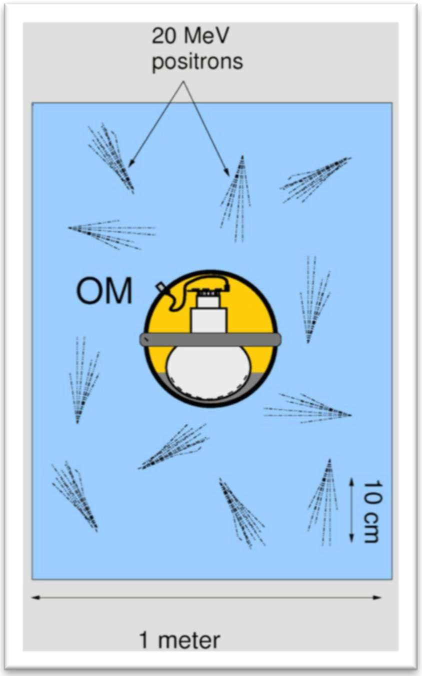


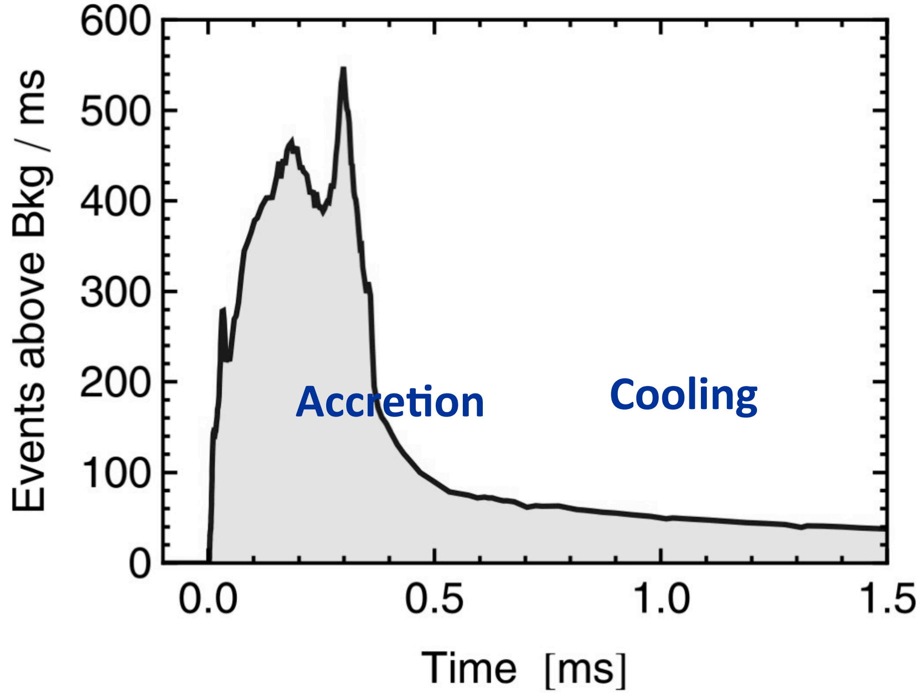
In brackets events for a “fiducial SN” at distance 10 kpc

Future Detectors

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

IceCube





SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

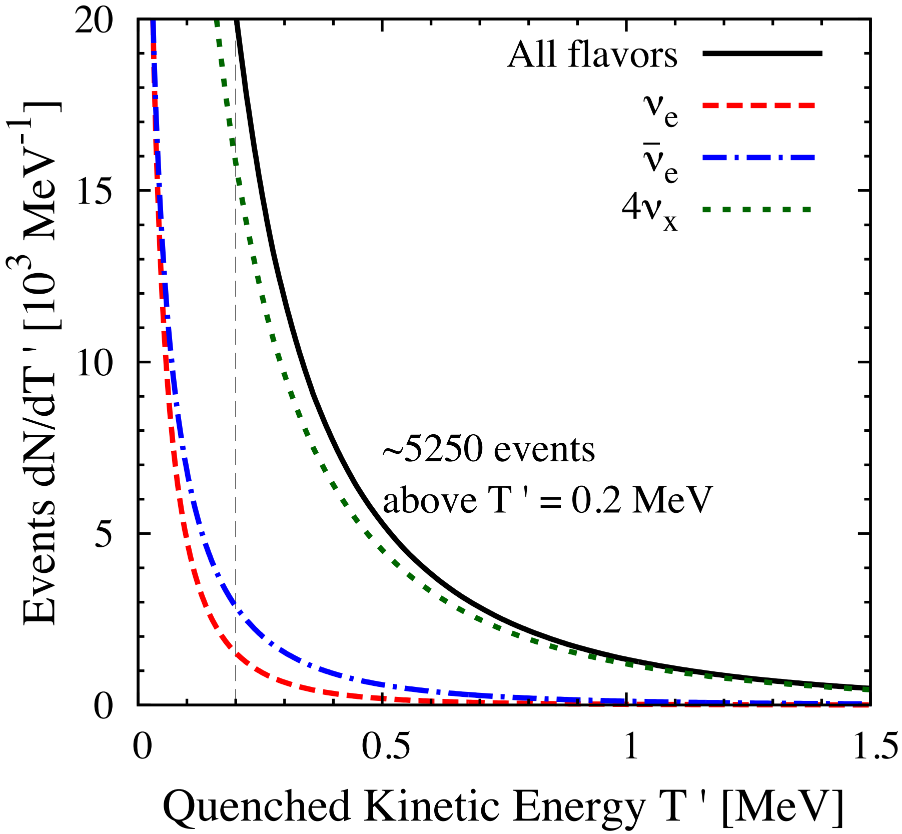
SN neutrinos are not energetic enough to fire multiple DOMs

300 photons in 1 DOM for SN at 10 kpc. Noise < 300 Hz/DOM.

SN signal appears as a correlated increase in noise rate of 5000 optical modules

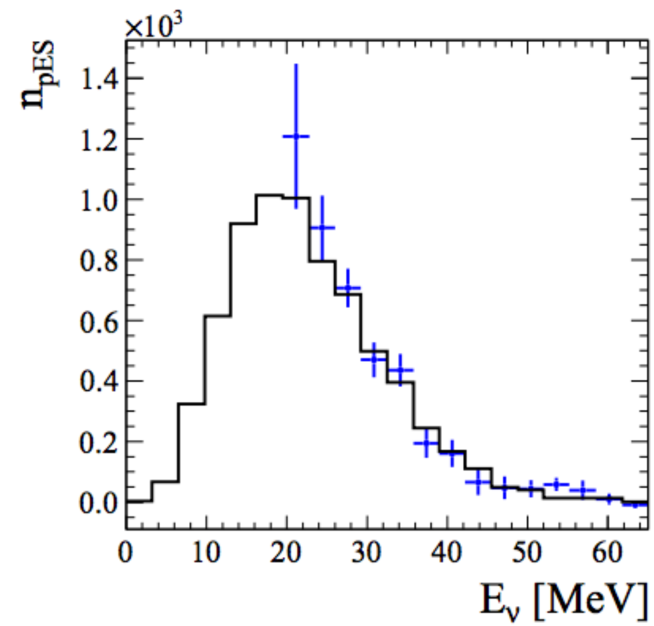
Pryor, Roos & Webster (1988)
Halzen, Jacobsen & Zas (1995)

Oscillation-Immune Data



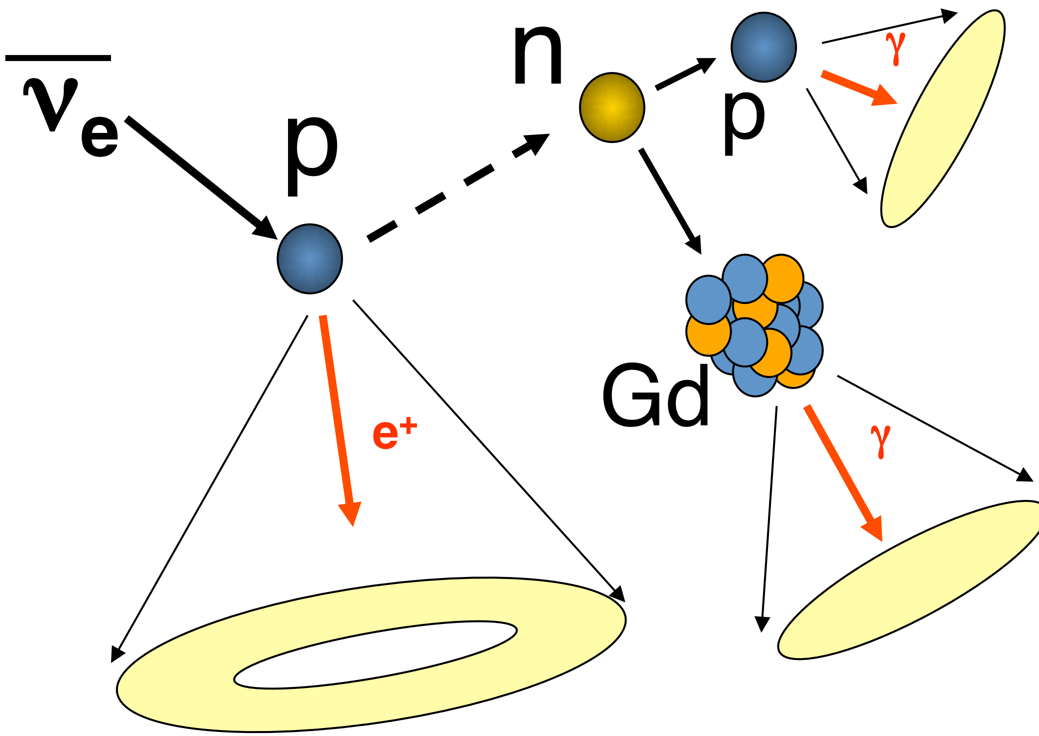
Beacom, Farr, Vogel (2003)
Dasgupta and Beacom (2011)

Neutrino – Proton elastic scattering can give the unoscillated fluxes if measured with enough statistics and reconstructed with precision



Li et al (2018)

Gadzooks



Gadolinium Anti-nu Detector Zealously Outperforming Old Kamiokande. Super!

n+Gd → ~8 MeV γ (90%)

n+p → d + 2.2 MeV γ (10%)

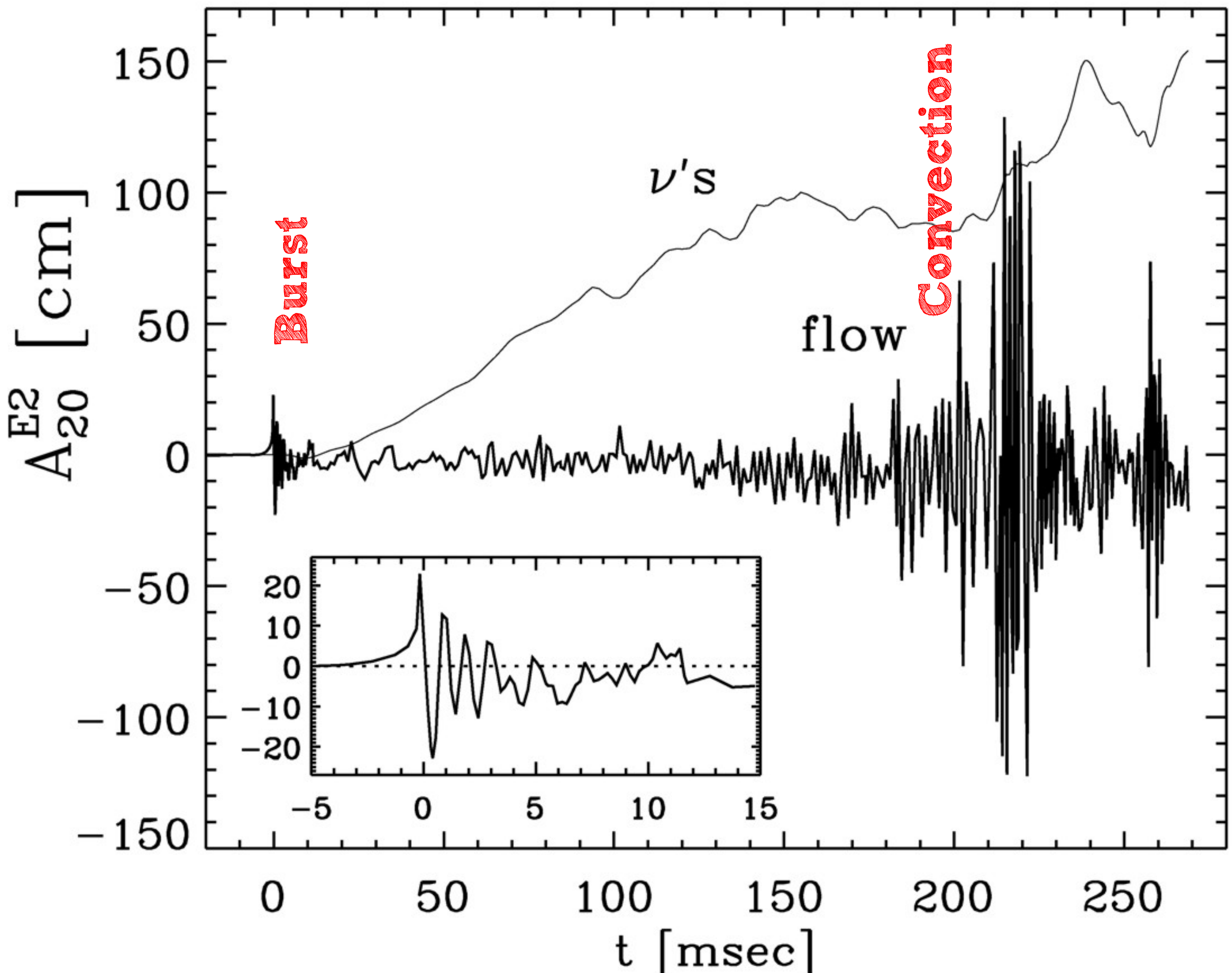
Positron and gamma ray vertices are within 50cm.

Can identify each antineutrino on an event-by-event basis

[reaction schematic by M. Nakahata]

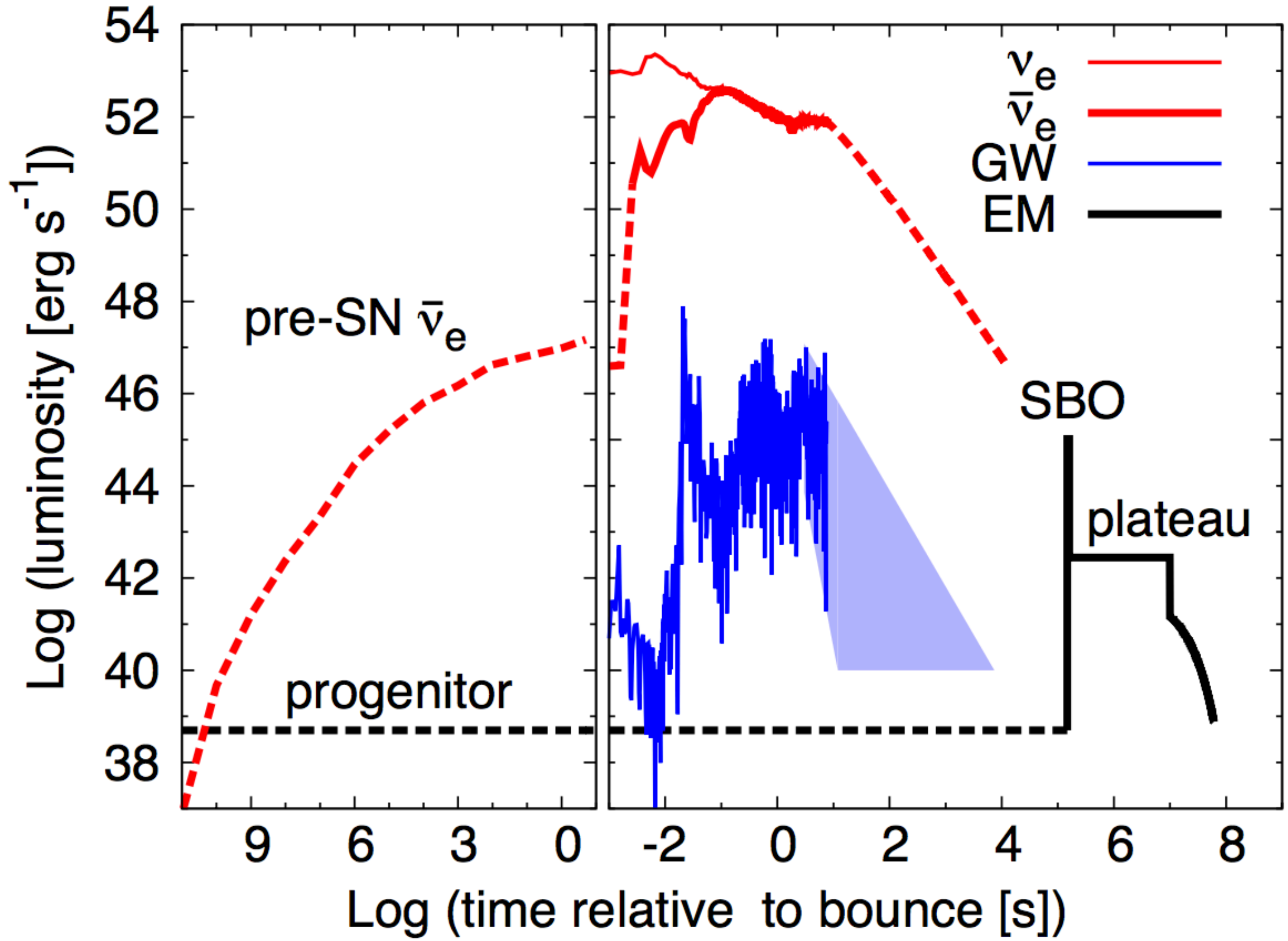
Beacom and Vagins (2003)

Gravitational Waves



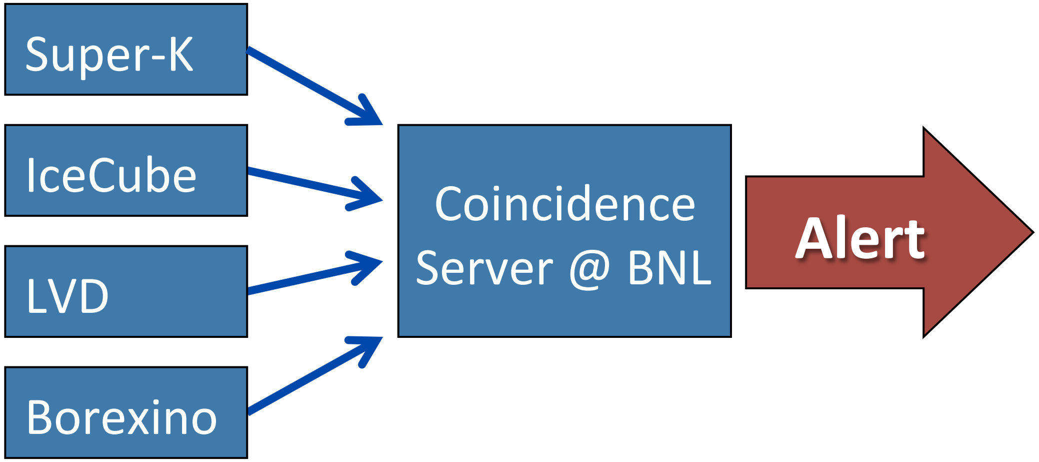
Müller, et al. (2003)

Multimessenger Studies



Nakamura et al (2016)

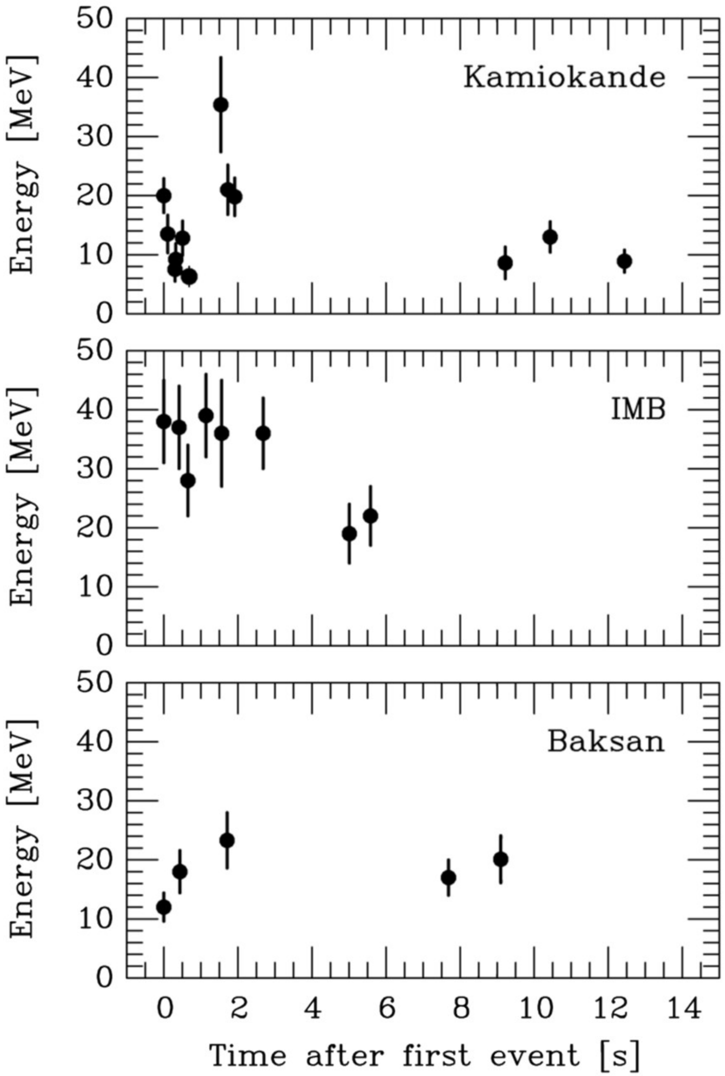
SNEWs

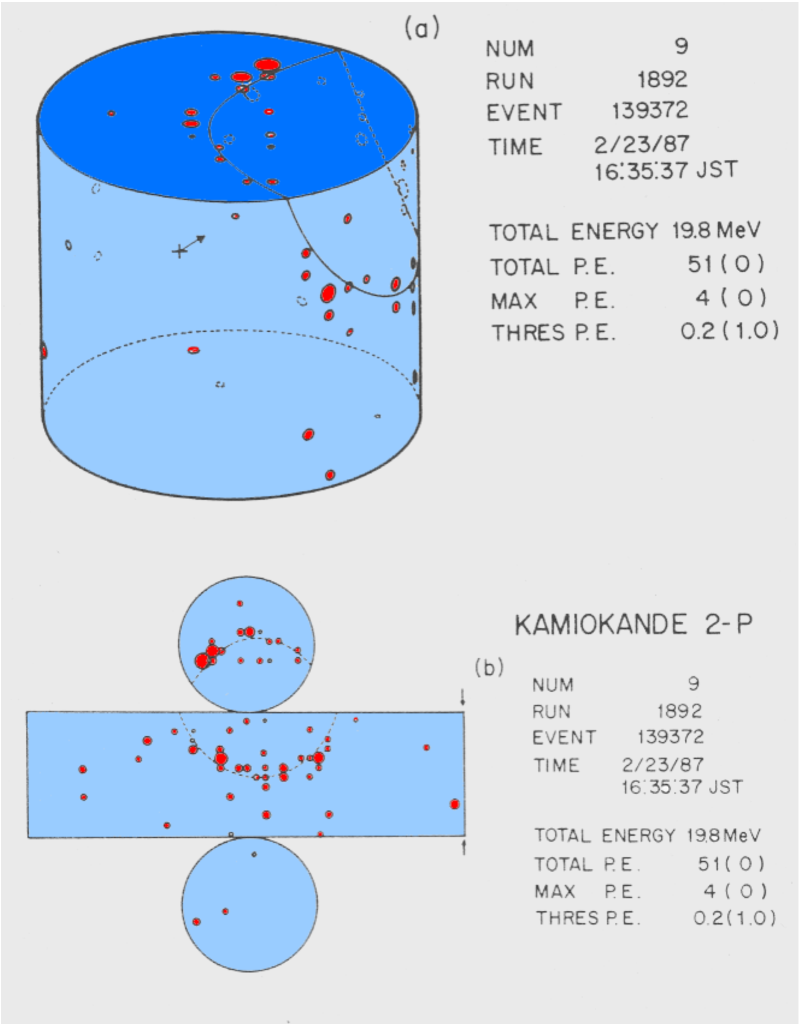


http://snews.bnl.gov

Supernova Early Warning System

SN 1987A in Neutrinos





SN1987A events

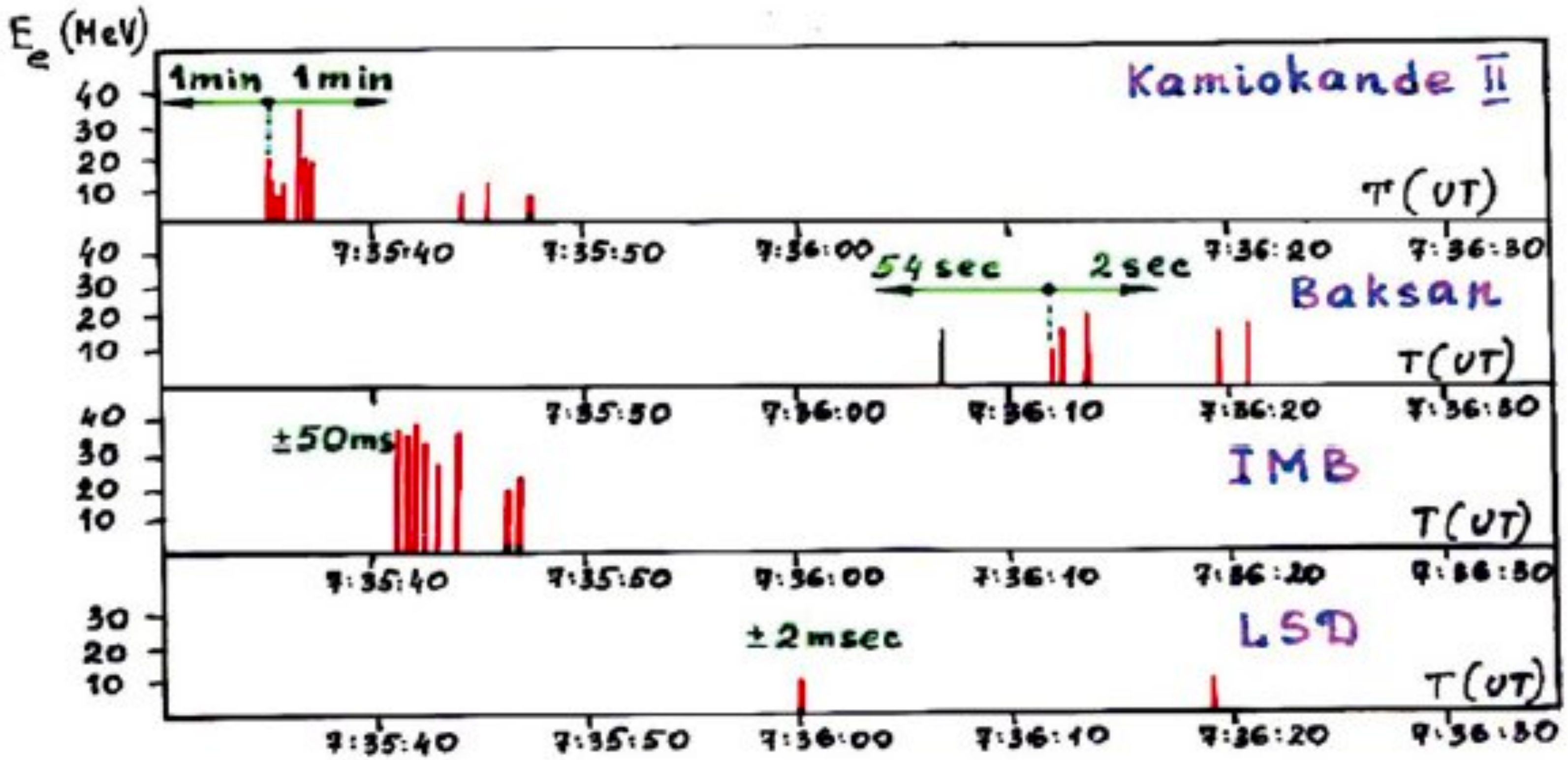
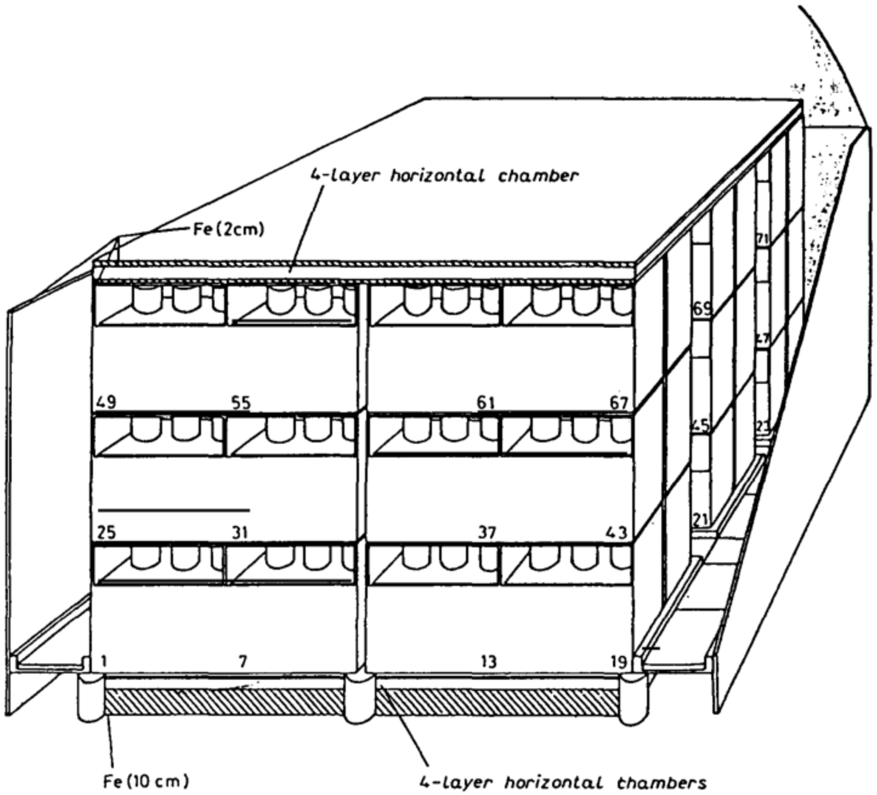


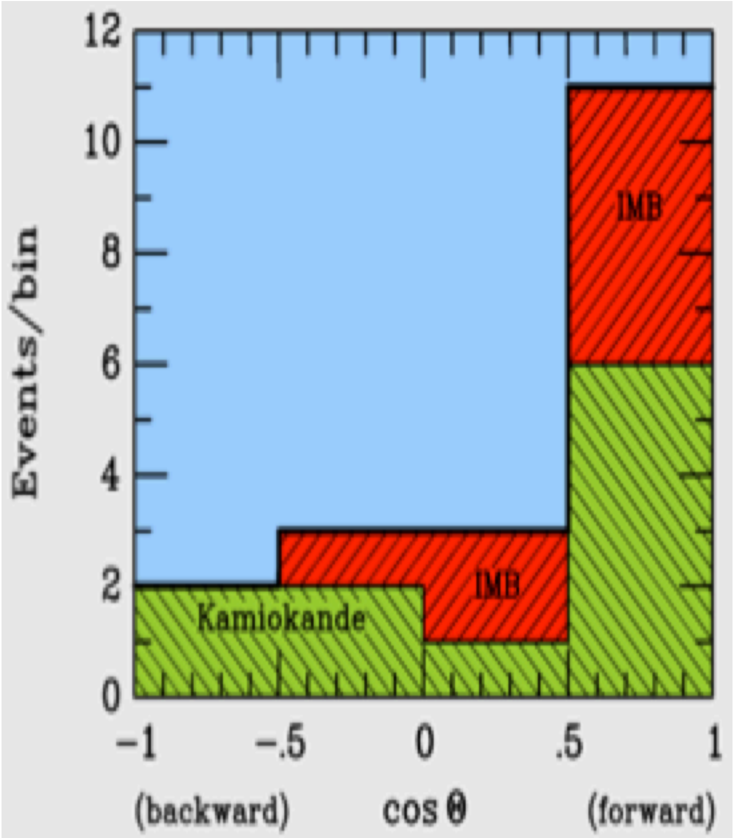
Image credit: Suzuki (2003)

See review by Vissani (2015)

SN1987 problems



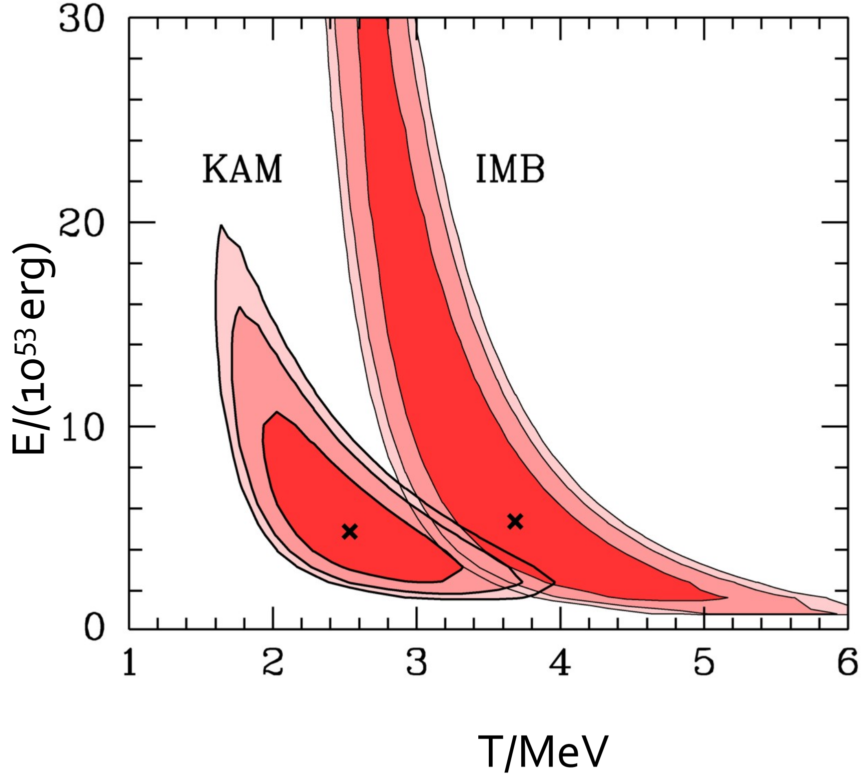
Mont Blanc events

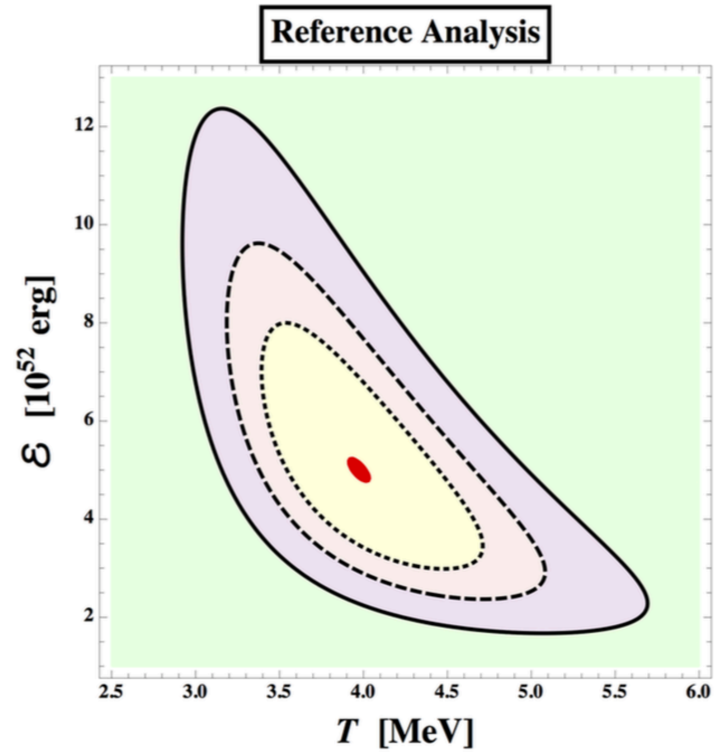


Unexpected angular distribution

See review by Vissani (2015)

SN1987A Lessons





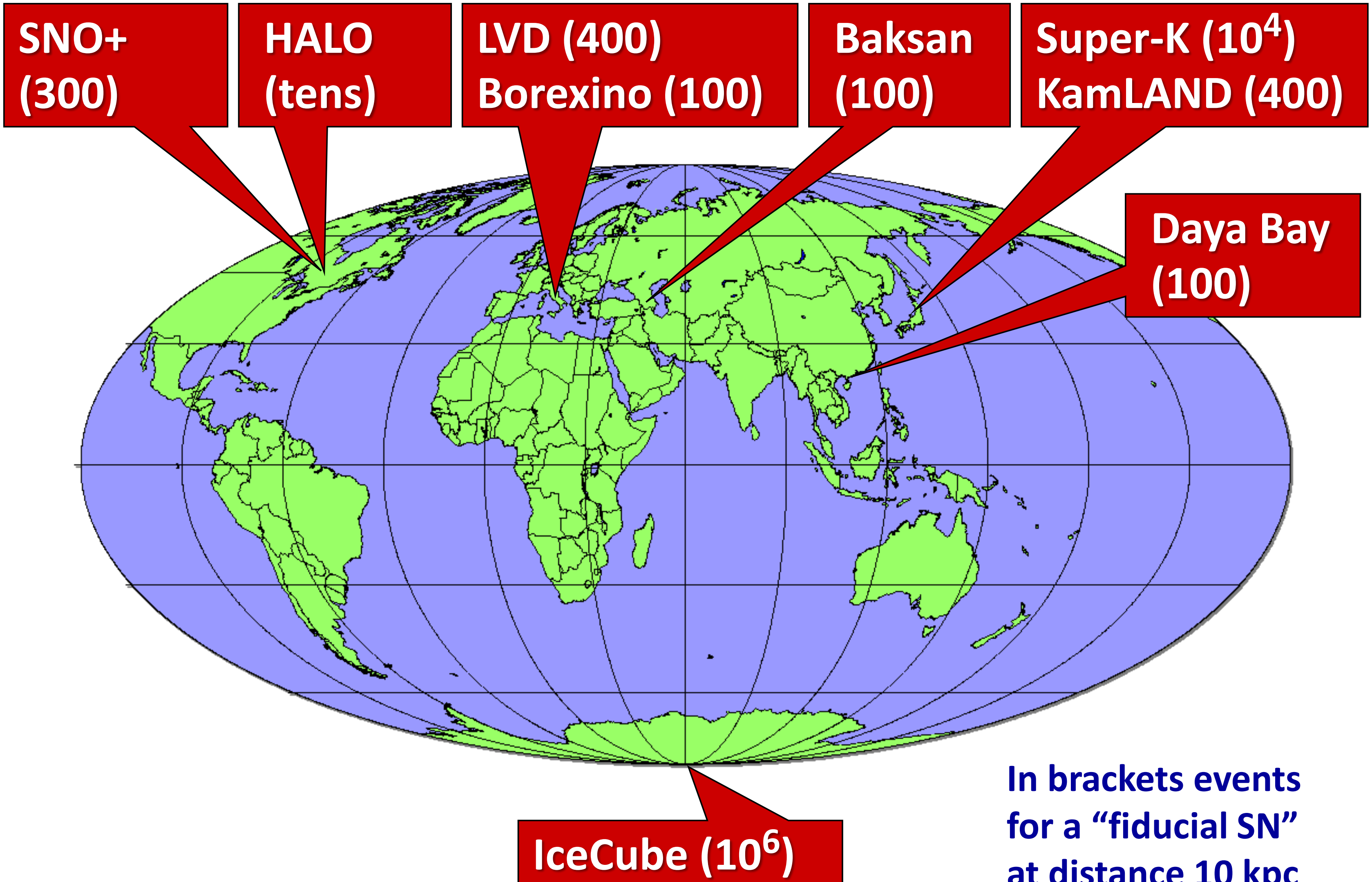
Review by Vissanni (2014)

Rough agreement with SN theory

Jegerlehner, Neubig & Raffelt (1996)

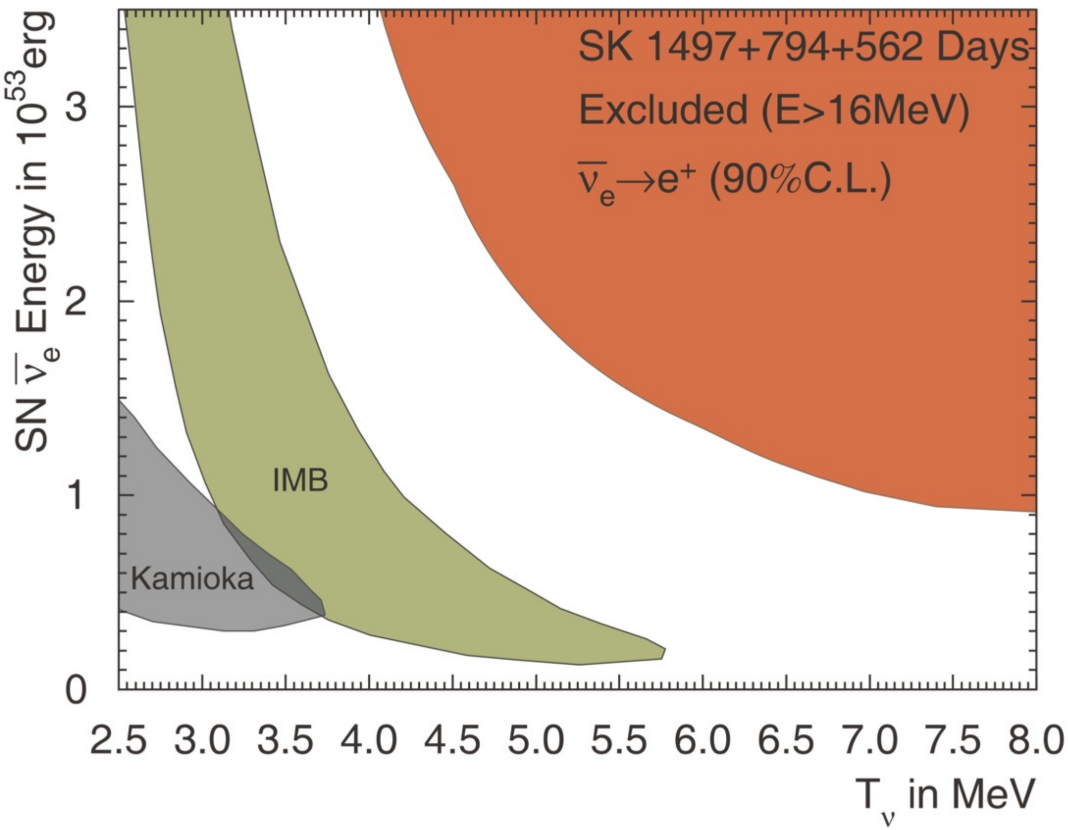
Average Neutrino Energy = 12 MeV
+/- 10%
Total Energy in anti-nue = 5 x 10^{52} erg
+50% - 20%

Next Galactic SN



In brackets events for a "fiducial SN" at distance 10 kpc

DSNB



Kirk Bays et al. (Super-Kamiokande Collaboration) (2011)

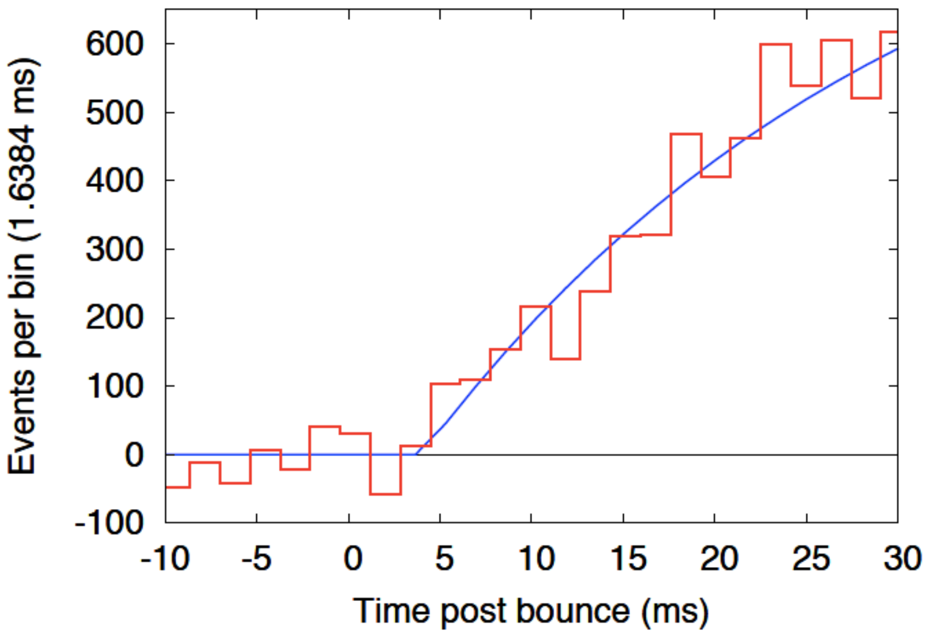
Present-day SN rate of 1 SNu, extrapolated to the entire universe, corresponds to flux of 1 cm^{-2} s^{-1}

We are in the ballpark.

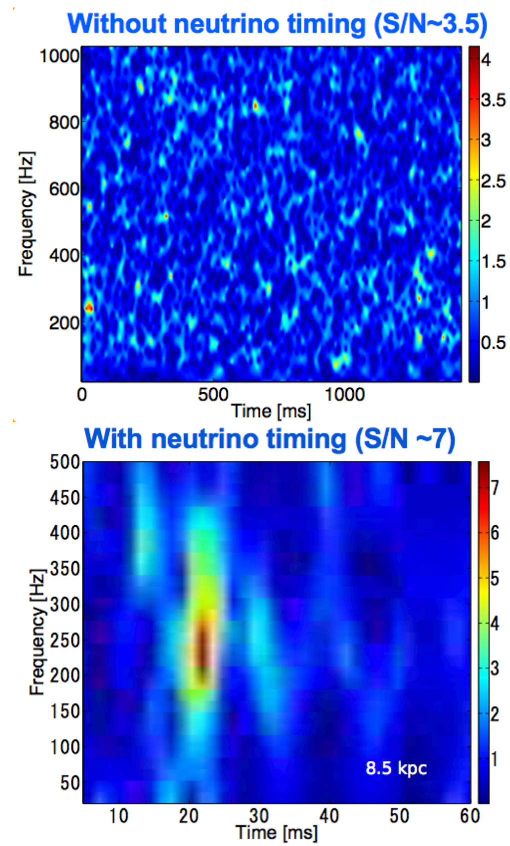
See review by Beacom (2010)

What can we learn?

Timing



Pagliaroni, et al. (2009)
Halzen and Raffelt (2009)



SN neutrino-curve is an excellent probe of the bounce time. This can be used to great advantage for coincidence measurement with gravitational wave detectors

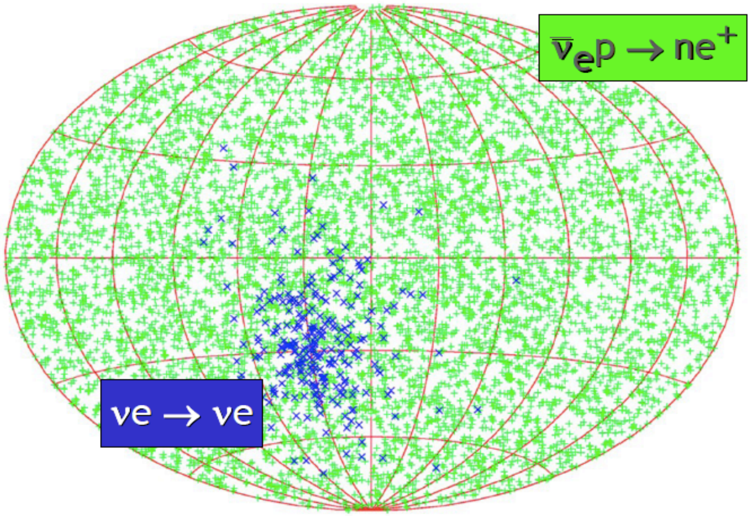
Pointing

Neutrinos reach before the light from SN explosion

SN at 10 kpc may be localized to a cone of 5 degree at SK, factor of 3 better with Gd (90% tagging), and factor of 10 better with a 30 times larger detector than SK

Beacom and Vogel (1998)

Tomas et al. (2003)



This may be crucial for dust-obscured supernovae!

Mini-project: Find the SN

Neutrino Mass Bounds

The SN signal gets stretched out in time if neutrinos are too heavy and all neutrino energies do not travel at the same speed close to speed of light

This is proportional to source distance, and (m/E)²

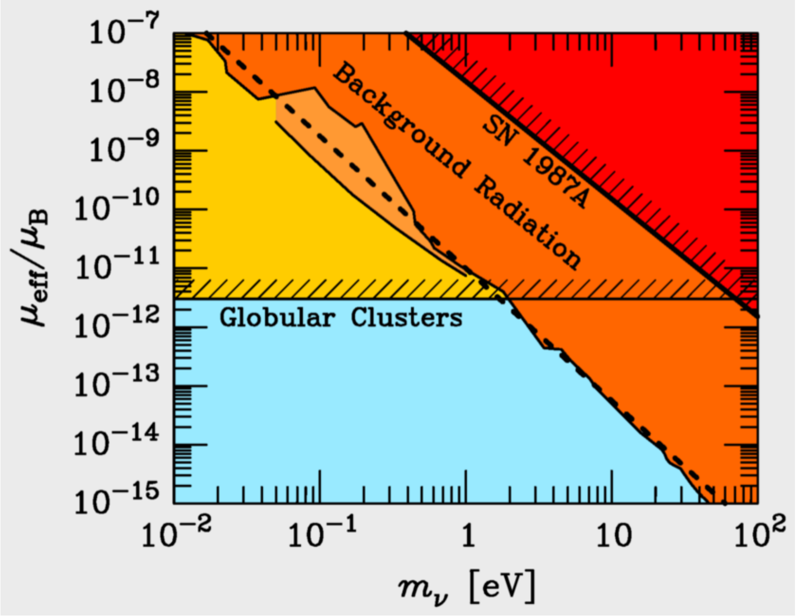
$$\delta t \approx 5\,\mathrm{ms}\left(\frac{D}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E}\right)^2\left(\frac{m}{eV}\right)^2$$

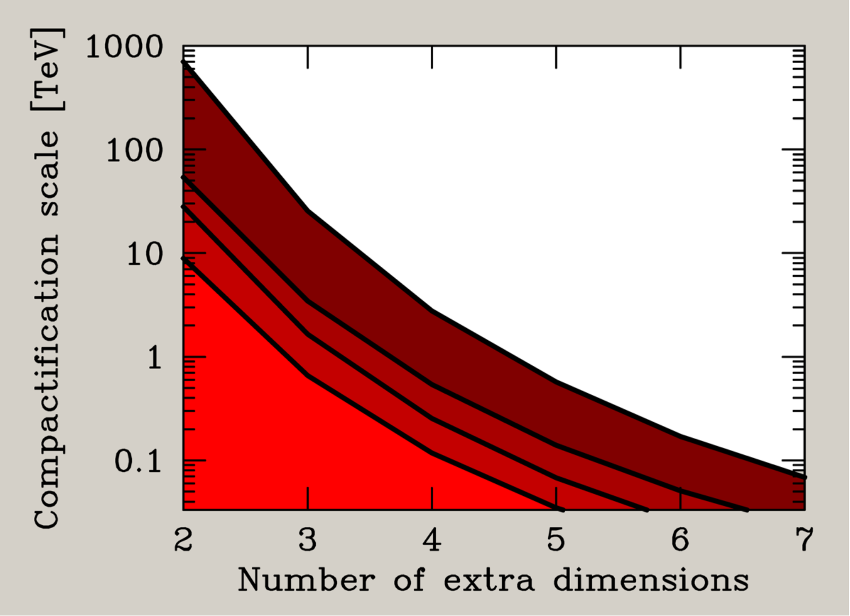
Zatsepin (1968)

Limit improves by a factor of 10 or so with Galactic SN whose time structure can be measured more precisely. E.g., the neutronization burst peak can get stretched or a BH formation cut-off of signal gets smeared.

See "Stars as Laboratories for Fundamental Physics" by Georg Raffelt

Other bounds…





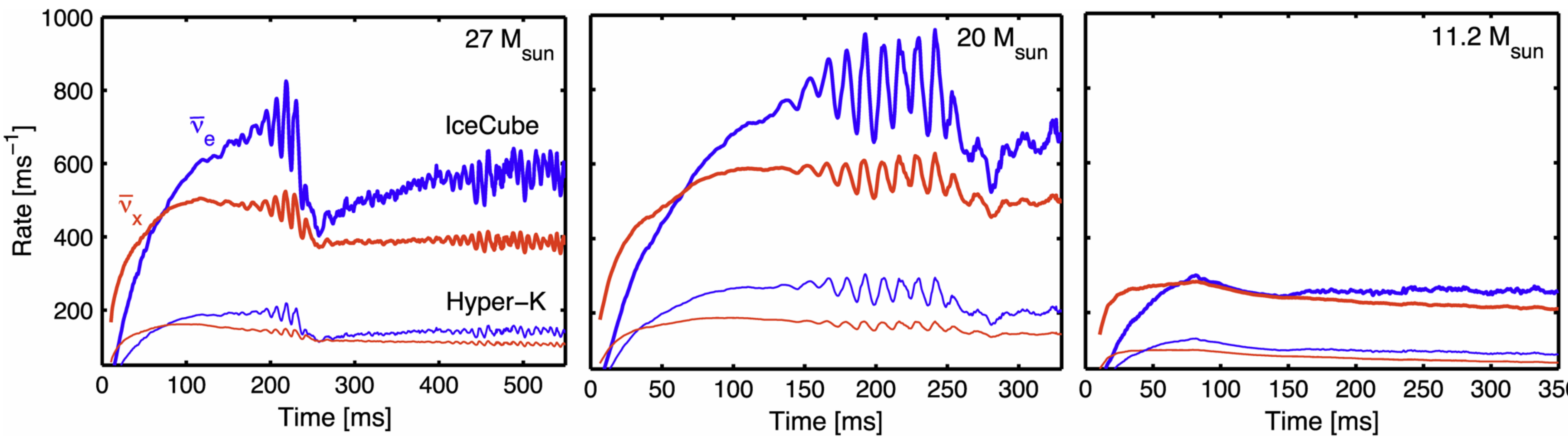
Neutrino magnetic moment, lifetime

Exotic energy losses via
any new particles or interactions of neutrinos

See "Stars as Laboratories for Fundamental Physics" by Georg Raffelt

Convection Physics

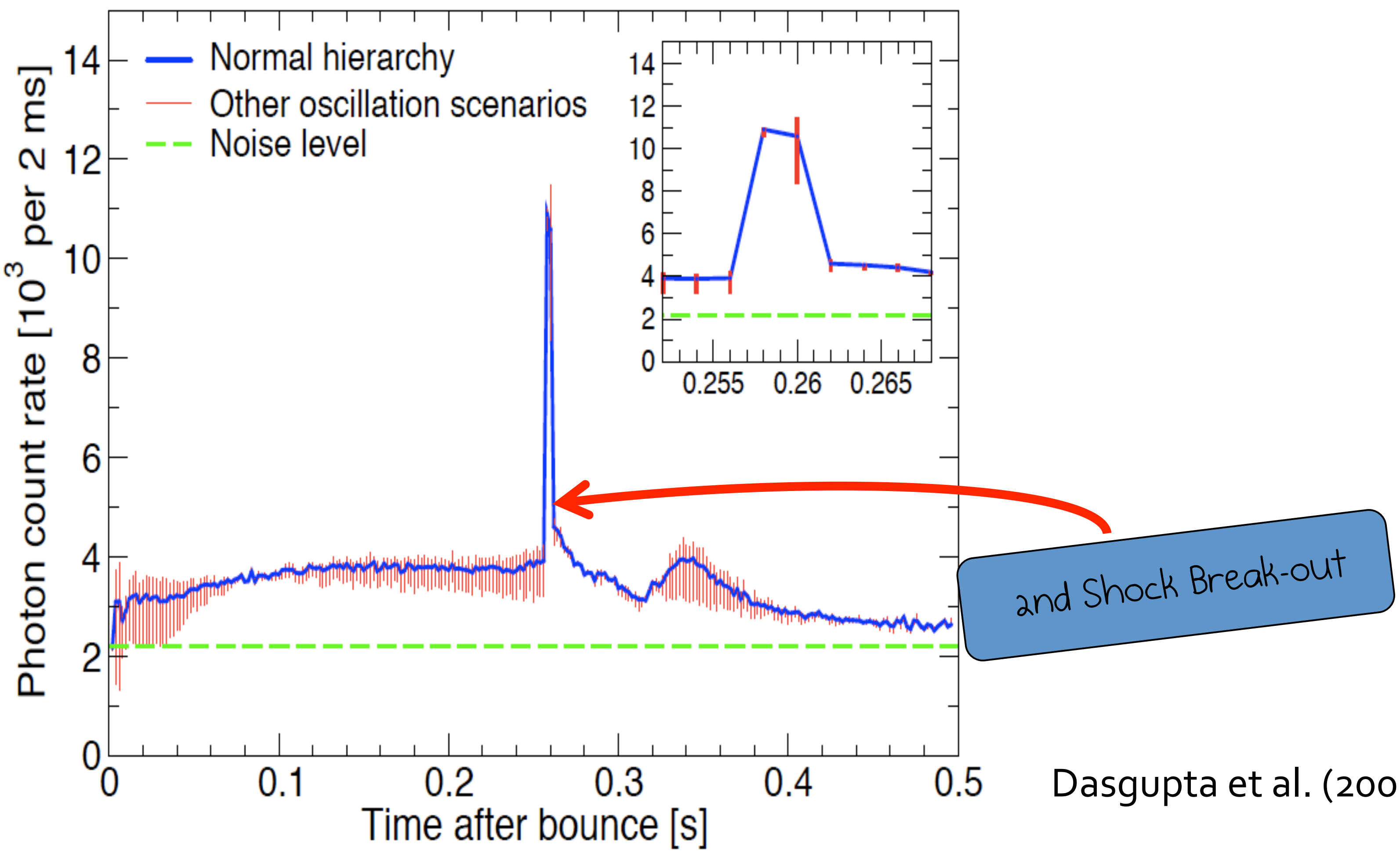
IceCube and Hyper-Kamiokande rates at 10 kpc



Tamborra et al. (2014)

- **Multiple episodes of SASI & convection**
- **Different frequencies**
- **Progenitor dependence**

Exotic Physics within 10s



Dasgupta et al. (2009)

QCD transition in the SN can trigger a second burst which is mostly anti-nue

Oscillation Physics

Neutrino Oscillations

Schroedinger / Wavefunction

$$i\partial_t|\nu\rangle = \hat{H}|\nu\rangle$$

Bloch / Polarization vector

$$\partial_t\vec{\mathbf{P}} = \vec{\mathbf{B}} \times \vec{\mathbf{P}}$$

$$|\nu\rangle\langle\nu| = \hat{\rho}$$

$$\hat{H} \to \sum_{i=0}^{4} B_i\hat{\sigma}_i \qquad \hat{\rho} \to \sum_{i=0}^{4} P_i\hat{\sigma}_i$$

Heisenberg-Boltzmann / Density matrix

$$i\partial_t\hat{\rho} = [\hat{H}, \hat{\rho}] + \ldots$$

Oscillation Hamiltonian

$$i\partial_t \rho_{\vec{p}} = +\left[\frac{M^2}{2p}, \rho_{\vec{p}}\right] + \sqrt{2}G_F[L, \rho_{\vec{p}}] + \sqrt{2}G_F \int \frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{\vec{p}\vec{q}})[(\rho_{\vec{q}} - \bar{\rho}_{\vec{q}}), \rho_{\vec{p}}]$$

Vacuum oscillations
- M is neutrino mass matrix
- Overall minus sign for antineutrinos

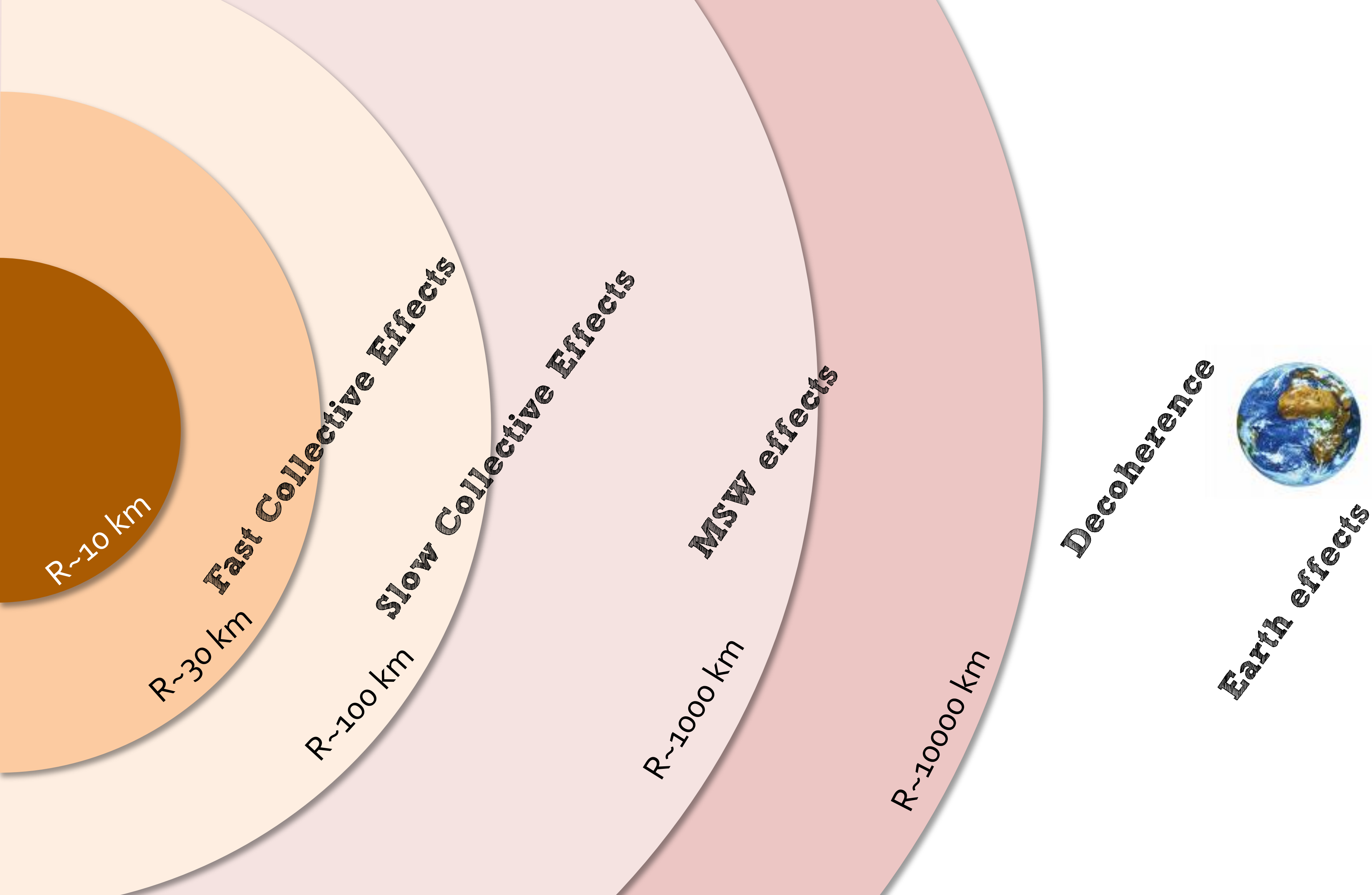
MSW effect depends on ordinary matter density L, i.e. mainly electron density

Nonlinear Effects depends on the neutrino density r

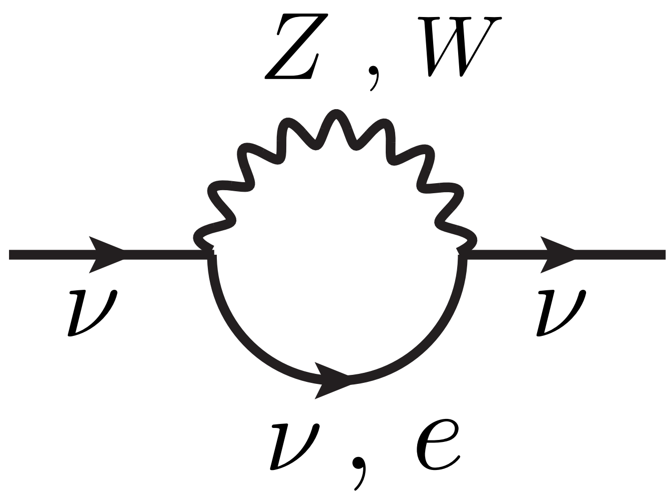
Nonlinear nu-nu effects are important when nu-nu interaction frequency exceeds the typical vacuum oscillation frequency

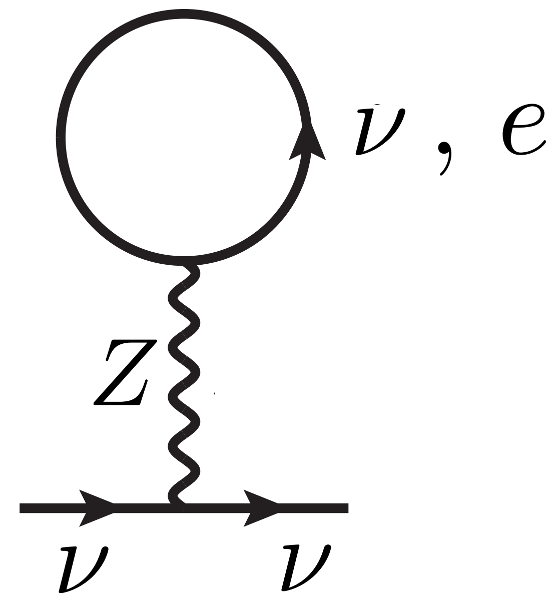
These interactions give rise to "Collective" flavor conversions

Flavor Conversion Zones



Why is there matter effect?





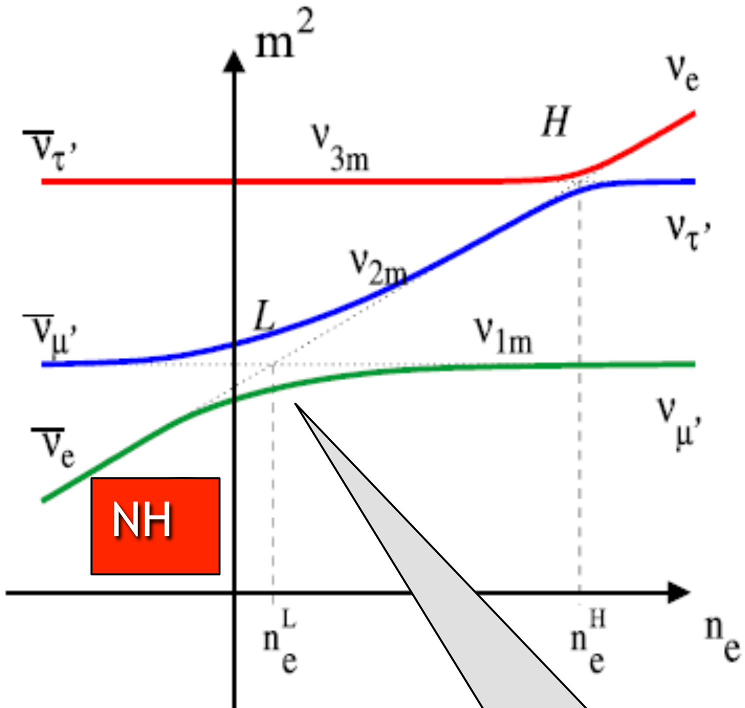
Neutrinos forward-scatter (no momentum exchange) off background fermions

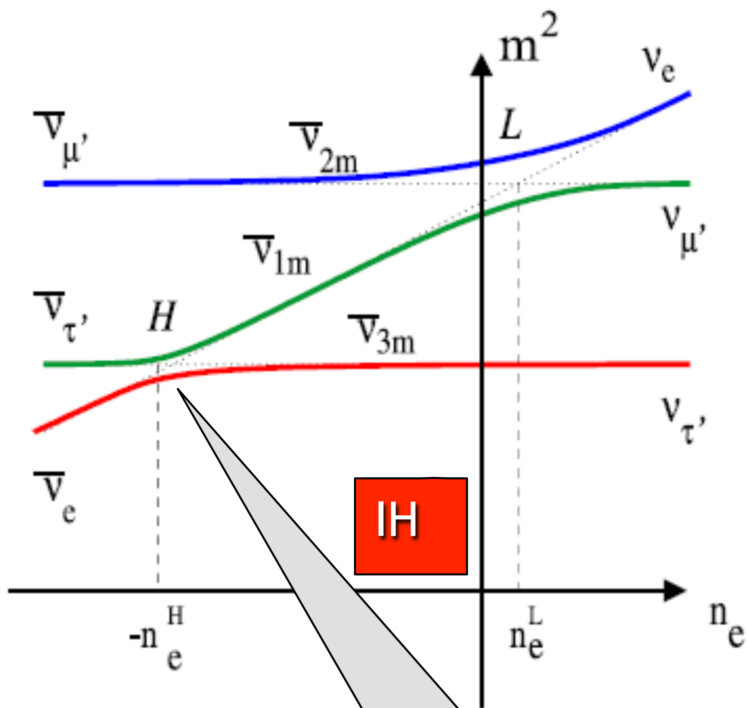
This amplitude must be added to the amplitude for free propagation.

Contributes as interference at order G_F

Diagonal in flavor basis because background is electron flavor

MSW physics of SN Neutrinos





L resonance : $\nu_1 \Leftrightarrow \nu_2$

$(\Delta m_{sol}^2, \theta_{12})$ at 10^1 - 10^2 g/cc

Always in neutrinos.

Always adiabatic.

H resonance : $\nu_1 / \nu_2 \Leftrightarrow \nu_3$

$(\Delta m_{atm}^2, \theta_{13})$ at 10^3 - 10^4 g/cc

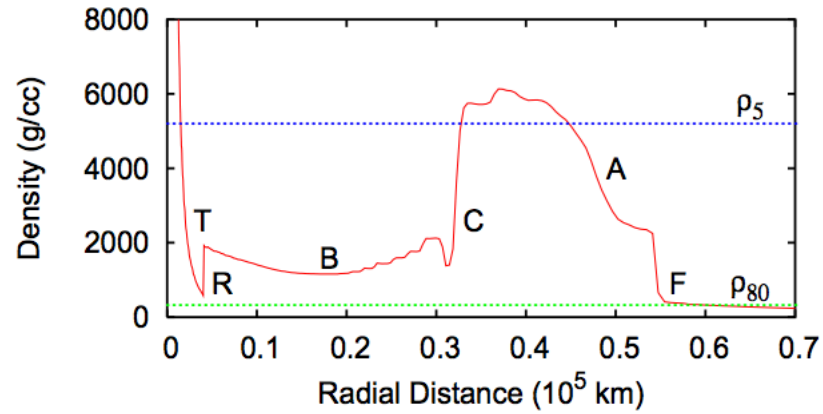
In neutrinos for NH; antinus for IH

Adiabaticity $\approx \sin^2\theta_{13}$

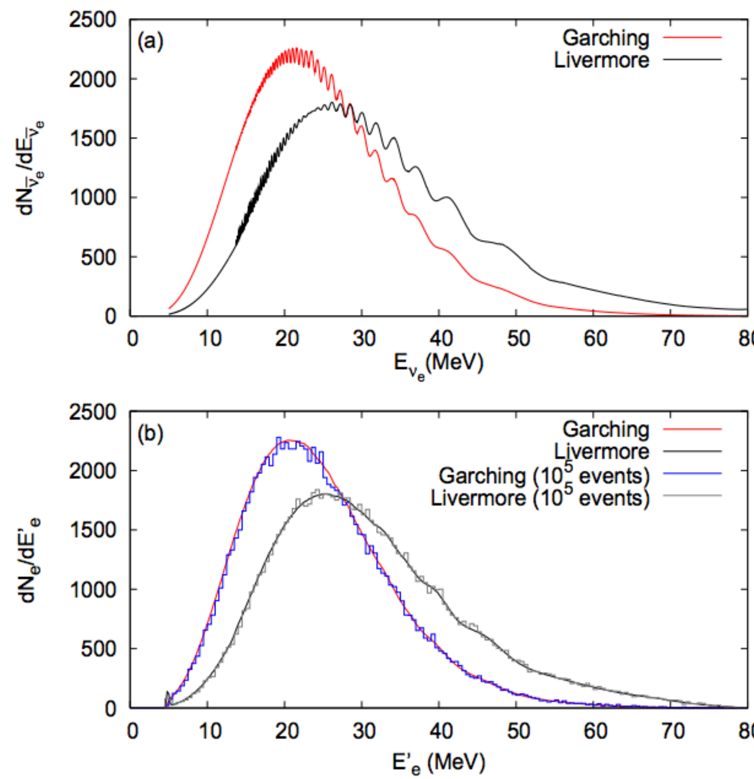
Dighe and Smirnov (1999)

Multiple Resonances

Density along a trajectory is non-monotonic



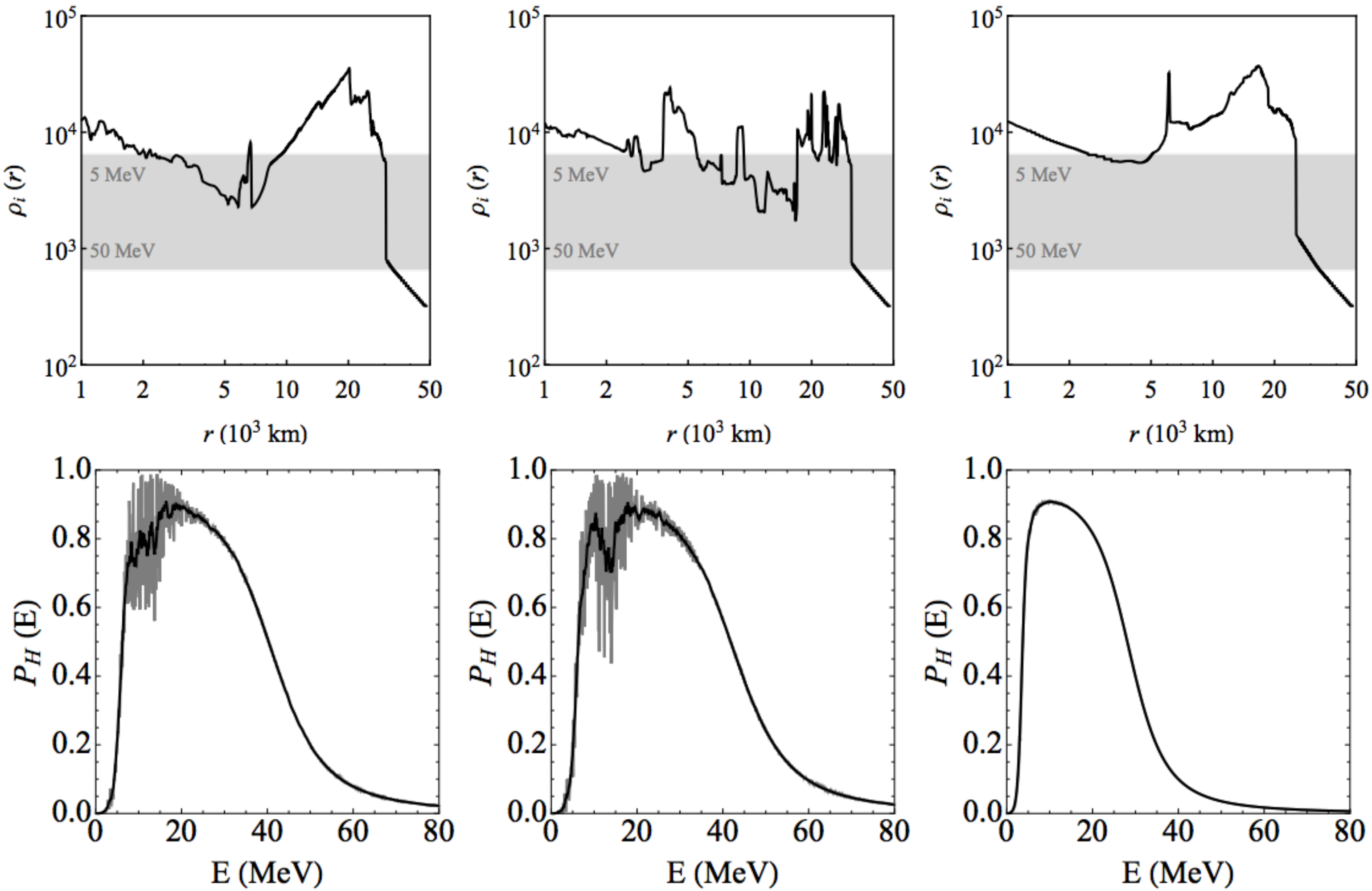
Multiple resonances give interference effects that manifest as oscillations in E, due to optical phase between resonances.



Typically expected to be averaged out by energy resolution of detectors.

Dasgupta and Dighe (2005)

Turbulence



Extreme case of multiple resonances is turbulence

Borriello et al. (2013). See also Friedland and Gruzinov (2006), and papers by Kneller++

Delta CP?

SN is essentially a 2 flavor problem because mu and tau behave identically in a SN

Any dependence on d_CP must be proportional to the breaking of mu-tau symmetry.

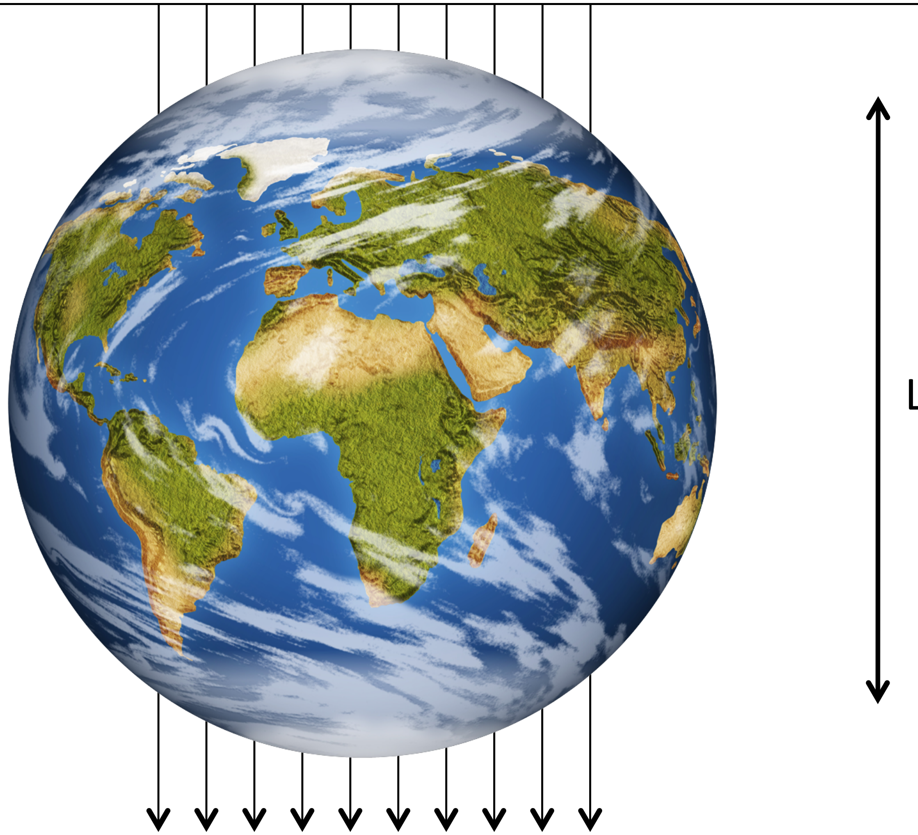
One can show that SN neutrino observations are insensitive to CP violation even if mu and tau neutrino fluxes are unequal initially. This is because only their sum enters the equations.

Akhmedov, Lunardini, Smirnov (2002)

Can some small genuine 3-flavor effect depend on CP?

Earth Matter Effects

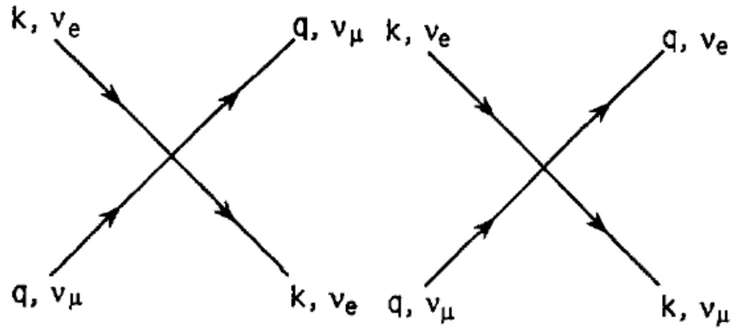
Electron flavor flux = $\cos^2\theta_{12}\,\nu_1 + \sin^2\theta_{12}\,\nu_2$



Detector Location Matters!

Electron flavor: = $(1\text{-}P_{2e})\,\nu_1 + P_{2e}\,\nu_2$
P_{2e} is the probability of ν_2 to ν_e
which depends on Earth density and L

Pantaleone Potential



Two neutrinos forward-scattering off each-other can exchange flavor

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_e(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \end{vmatrix} = V_2 \begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_e(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \end{vmatrix}$$

where

$$V_{2\nu} = \sqrt{2}G_\mathrm{F}\xi\frac{1}{V}\begin{vmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{vmatrix}$$

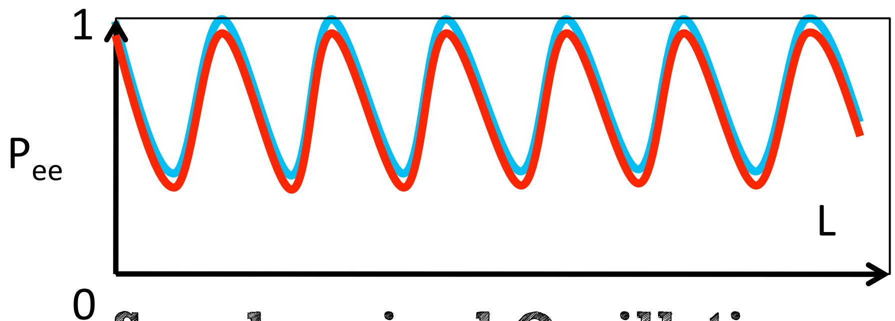
Pantaleone (1992)

Typical Collective Effects

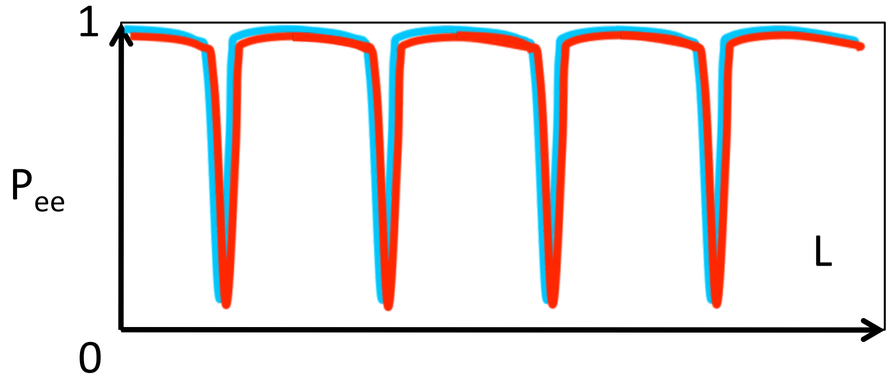
Neutrinos of all energies oscillate together.

Usually if G_F times neutrino density far exceeds vacuum osc. frequency, no large conversions but Sync. Osc.

Once system is dilute, conversions occur via Bipolar oscillations.



Synchronized Oscillations

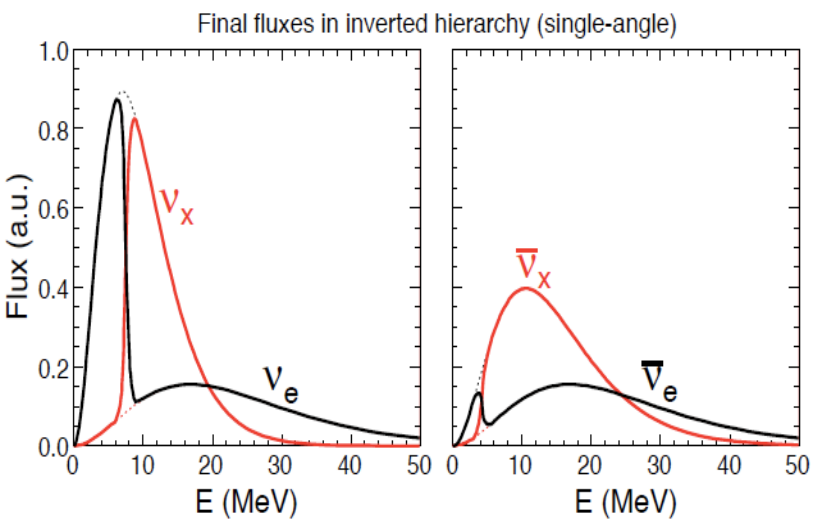


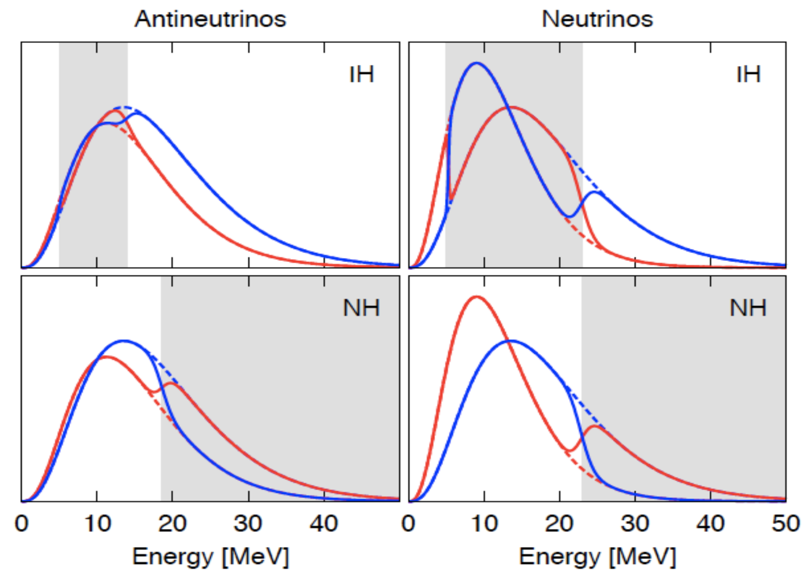
Bipolar Oscillations

Pioneering work by Pantaleone, Kostelecky, Samuel

Seminal papers: Duan, Fuller, Carlson and Qian in 2005, 2006

Swaps





Portions of the energy spectra get exchanged

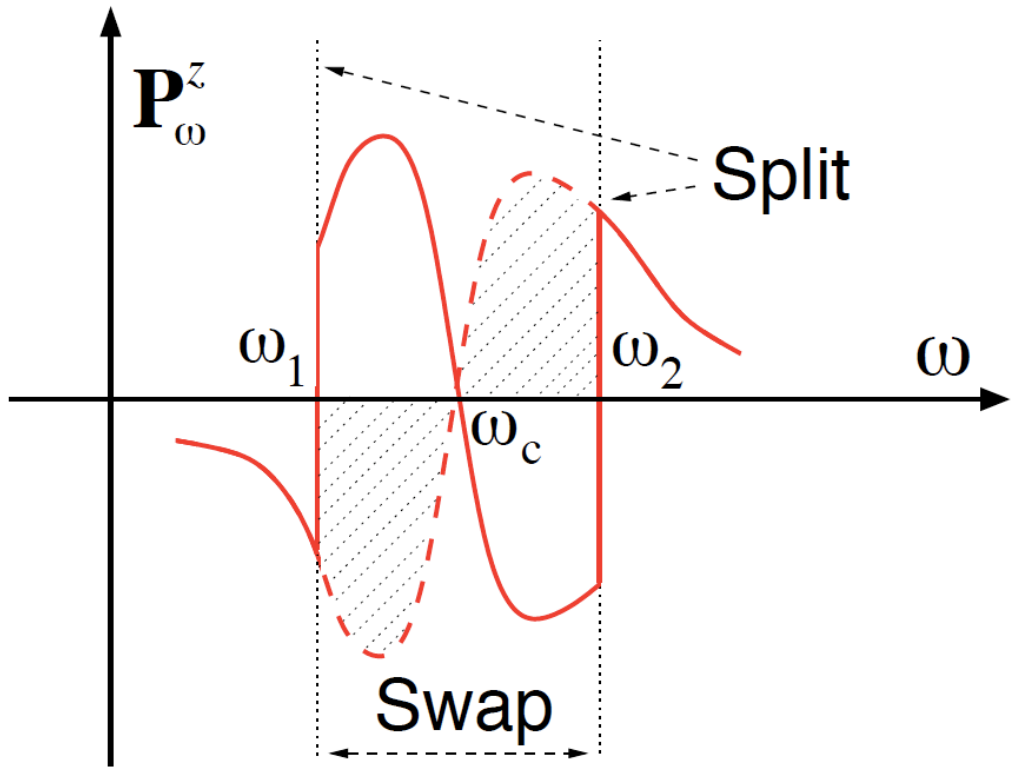
Initially thought to occur for Inverted ordering

Later realized that this occurs for both orderings and there can be multiple spectral splits.

Raffelt and Smirnov (2007)
Plot from Fogli et al. (2007)

Dasgupta et al. (2009)

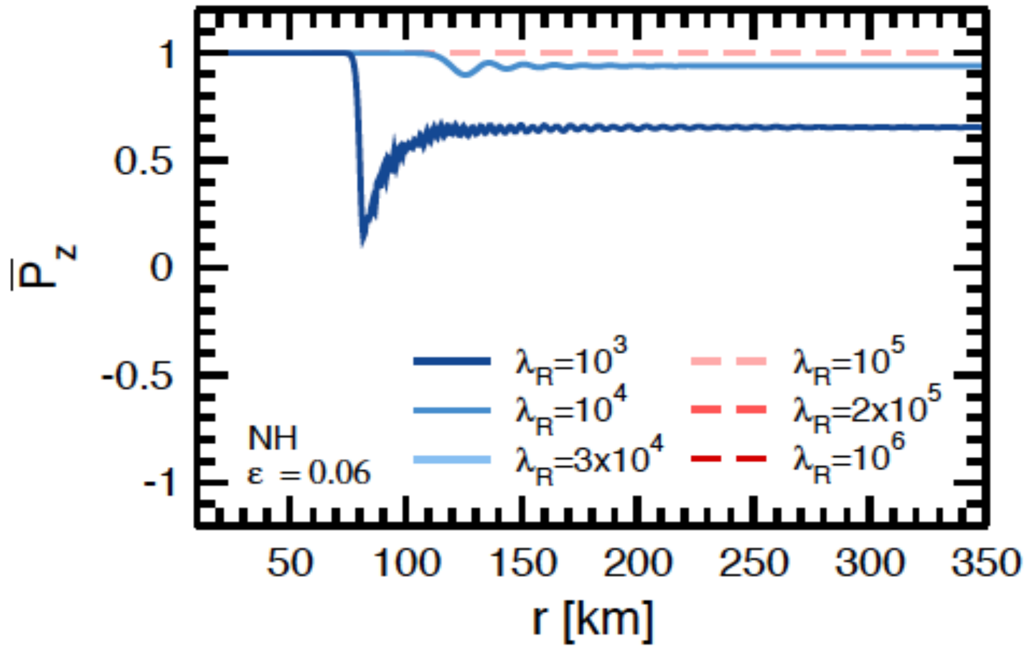
Theory of Splits



The main dynamical quantity turns out to be $F_e - F_{ebar}$
This is often what we refer to as the "spectrum" as a function of energy, or emission angle, etc. It this spectrum has a "crossing" the system tends to unstable and there is flavor conversion.

Dasgupta et al. (2009)

Dense Matter Effect



The electron background is different for the different trajectories, so while most of it drops out as a common phase, the difference is large enough to "block" collective effects. This important result would imply that there are no collective effects if the matter potential exceeds the neutrino potential.

Esteban-Pretel et al. (2010)

Linear Stability Analysis

$$\varrho_{\omega,v_z,\varphi} = \frac{1}{2}\mathrm{Tr}(\varrho_{\omega,v_z,\varphi})\,\mathbb{I} + \Phi_\nu \frac{g_{\omega,v_z,\varphi}}{2}\begin{pmatrix} s_{\omega,v_z,\varphi} & S_{\omega,v_z,\varphi} \\ S^*_{\omega,v_z,\varphi} & -s_{\omega,v_z,\varphi}\end{pmatrix}$$

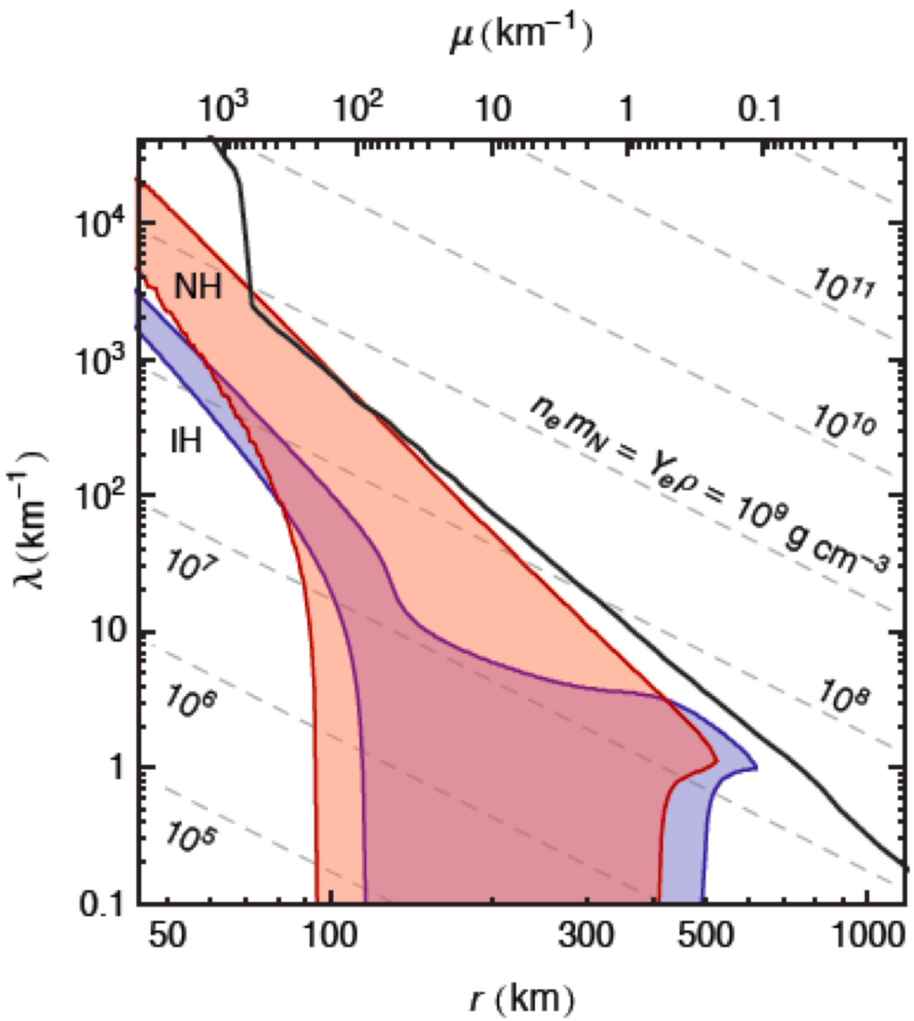
Off-diagonal part of density matrix is nonzero = Not flavor eigenstate

$$\begin{aligned} \mathrm{i}\partial_r S_{\omega,u} &= [\omega + u(\lambda + \epsilon\mu)]S_{\omega,u} \\ &\quad - \mu\int du' d\omega' (u+u') g_{\omega' u'} S_{\omega',u'}. \end{aligned}$$

Look at just the growth of this off-diagonal part

Banerjee, Dighe, Raffelt (2010)

Footprint of Instability



For some values of matter and neutrino density, the system is unstable and flavor conversion occurs. NH seems more unstable!

Remember matter suppression?

Raffelt, Sarikas, Seixas

Symmetry Breaking

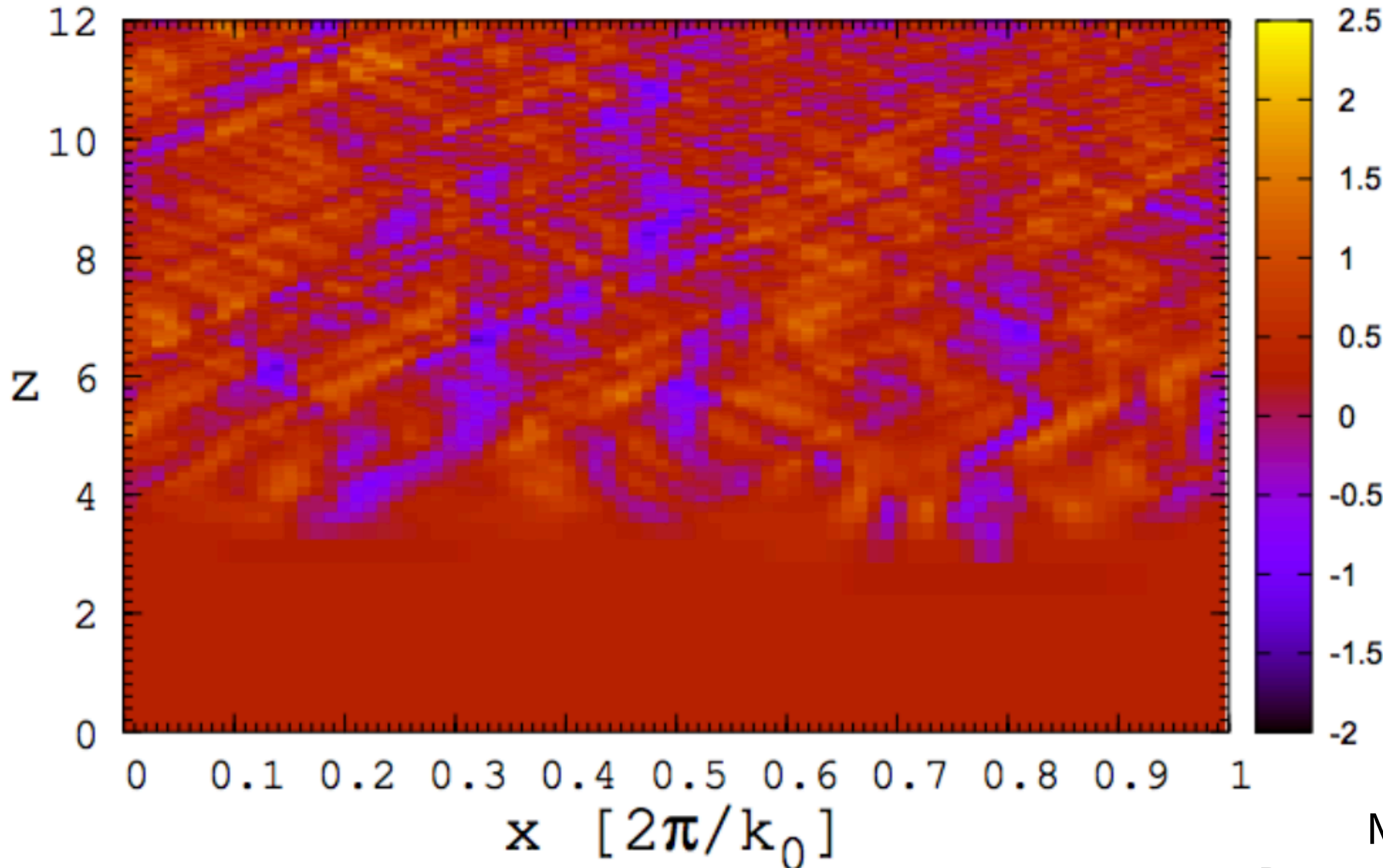
$$i\partial_r \to i(\partial_t + \mathbf{v} \cdot \nabla)$$

- Solution can depend on time
- Solution can depend on angular coordinates even if the source is approximately spherical

Think of the off-diagonal component as a field over x and t

$$S(t,\, \mathbf{x}) \to Q(\omega,\, \mathbf{k})$$

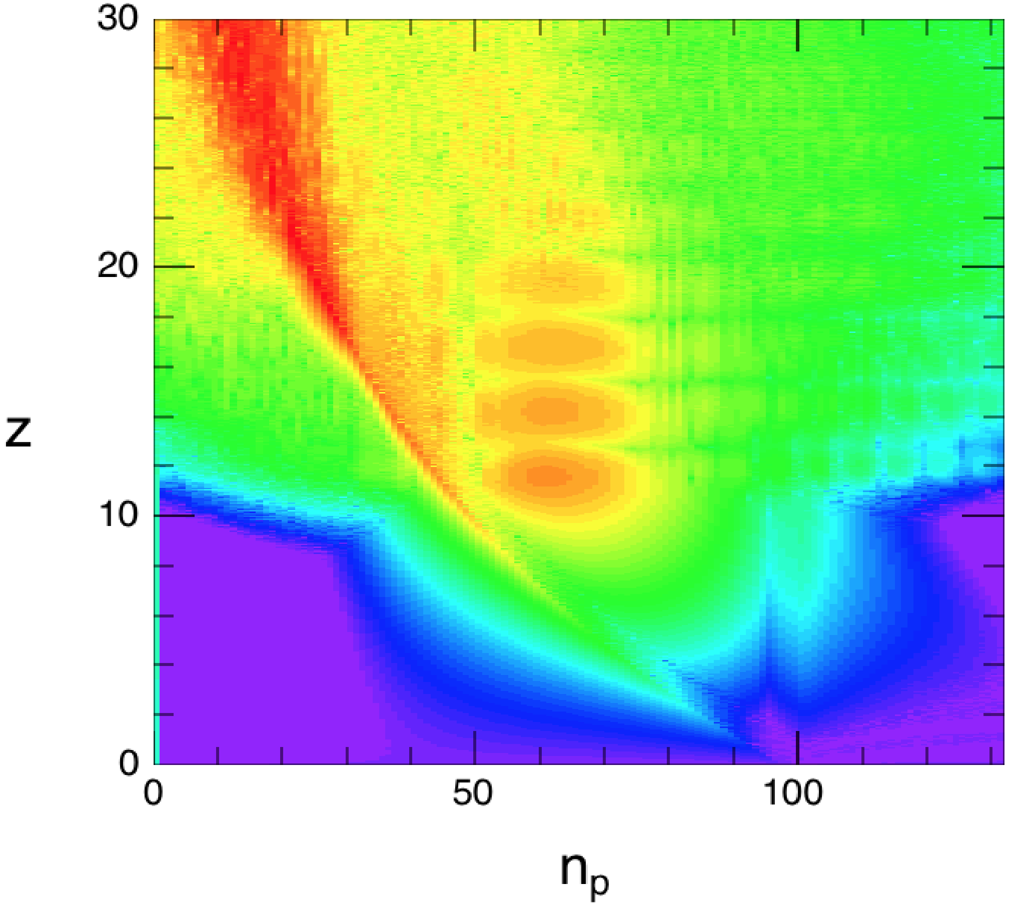
Inhomogeneous Solutions



Mirizzi et al.
Duan and Shalgar

System picks an inhomogeneous solution spontaneously

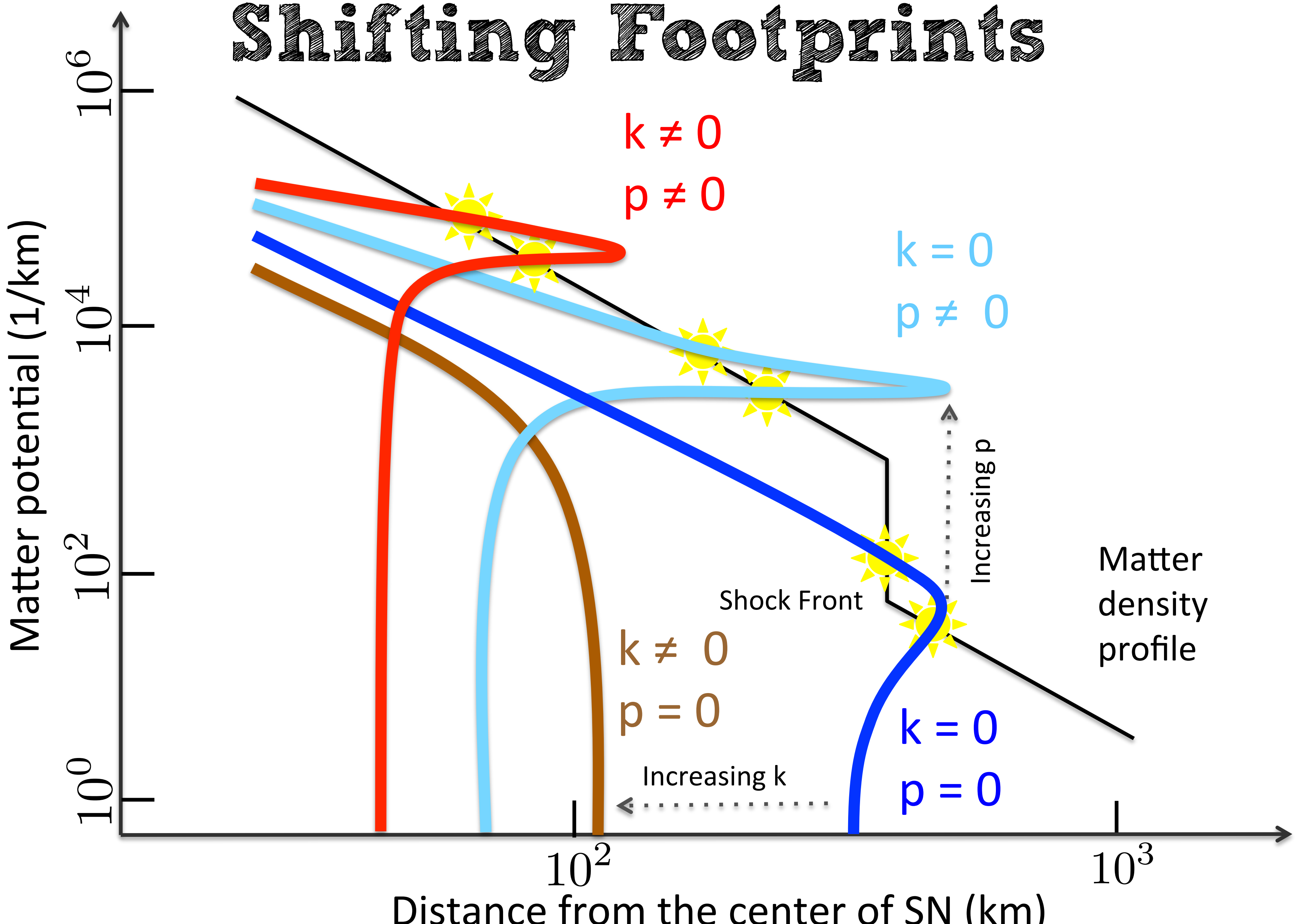
Nonstationary Solutions



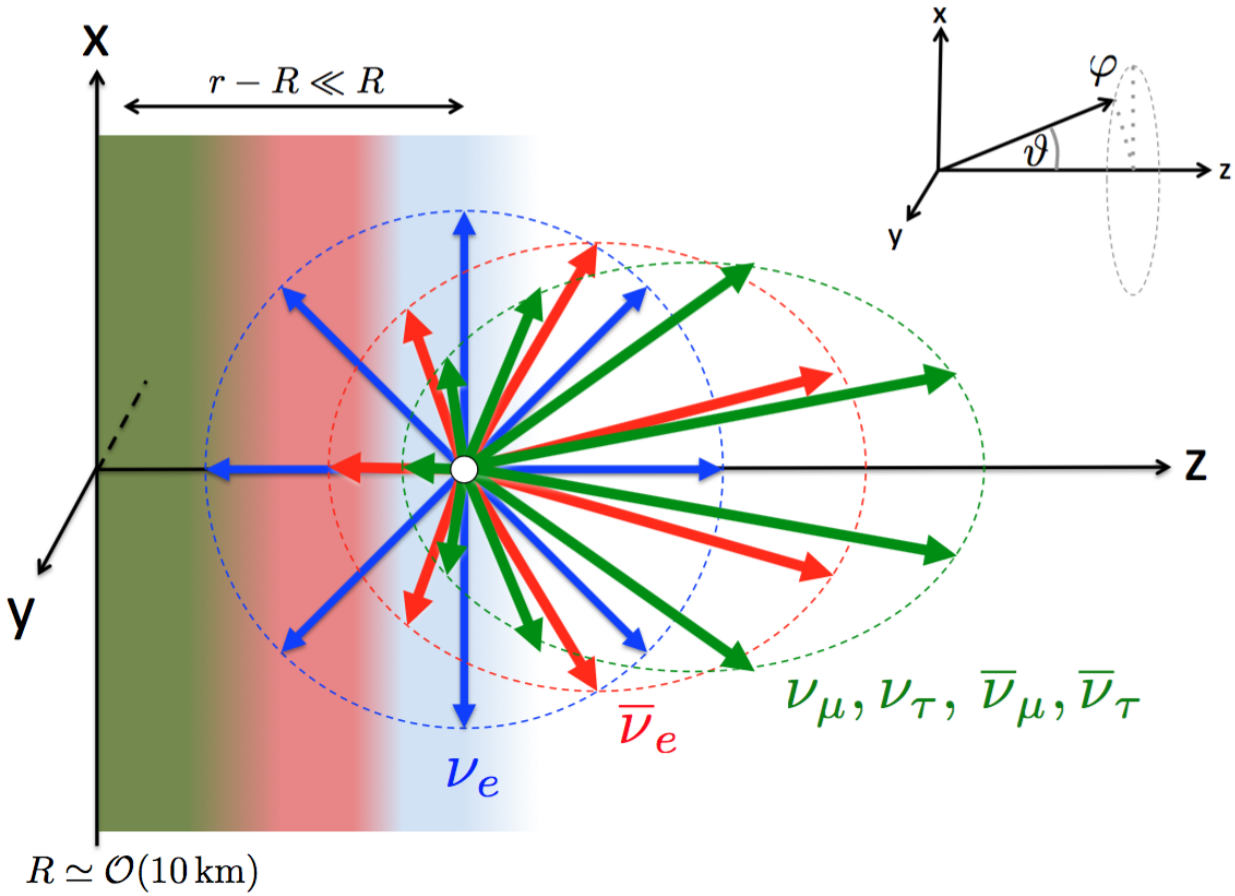
Dasgupta and Mirizzi (2015)
Capozzi, Dasgupta, Mirizzi (2015)

System picks a pulsating instability spontaneously which can cascade to stationary solutions

Shifting Footprints



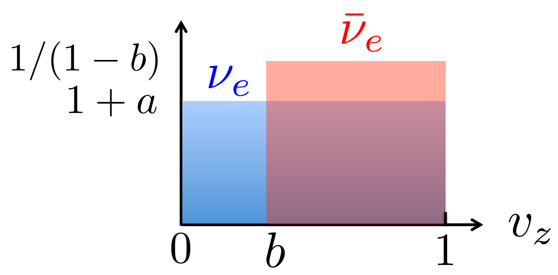
Why Fast Oscillations

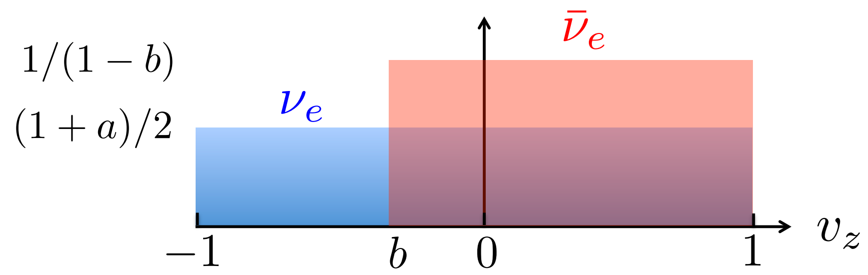


The electron antineutrinos are more forward peaked than the neutrinos. This can leads to a new instability.

Main insight by Ray Sawyer (2005, 2015)

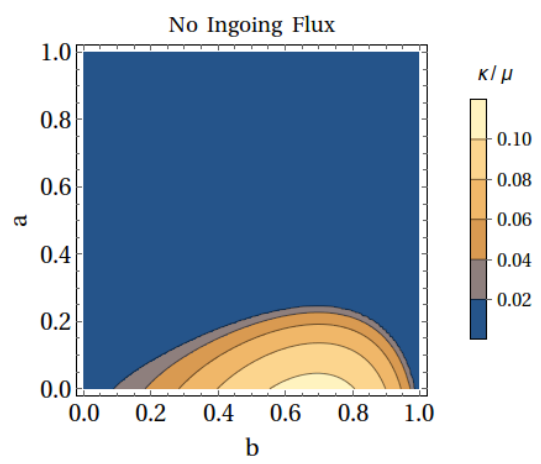
Crossing of Spectra is Key

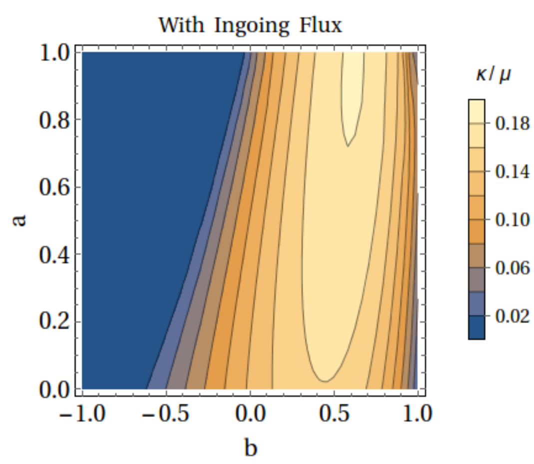




No backward flux

Has backward flux



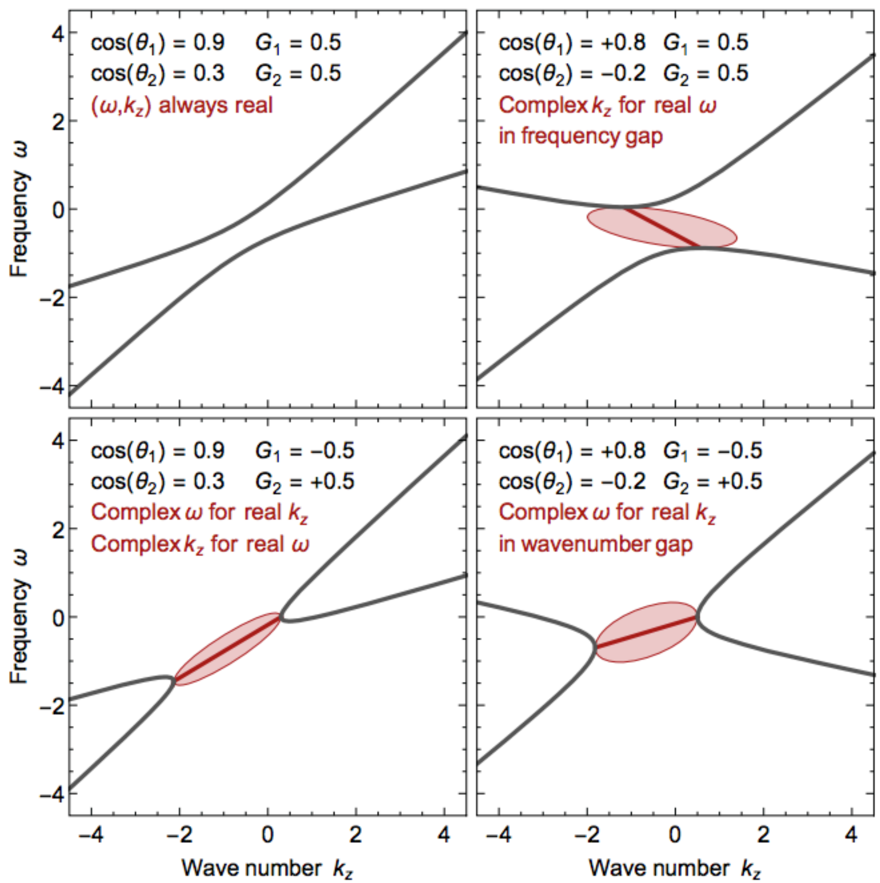


Stronger Instability

Chakraborty, Hansen, Izagguire, Raffelt (2016)

Dasgupta, Mirizzi, Sen (2016)

Dispersion Relations



Some combinations of

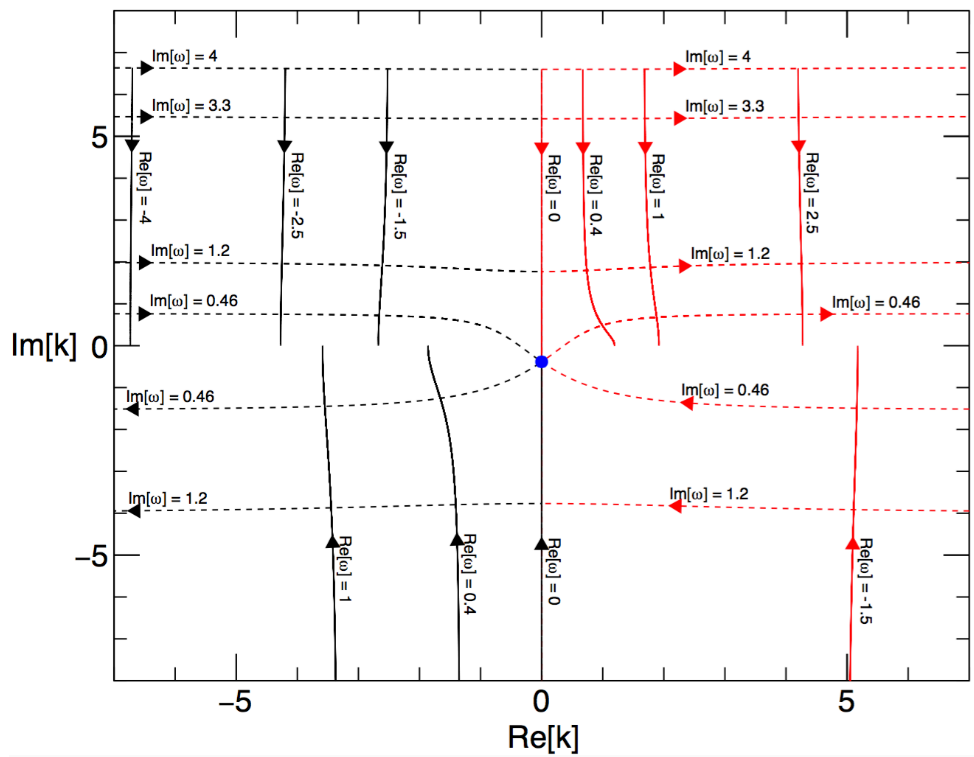
$$(\omega,\, \mathbf{k})$$

not allowed to propagate

Are these all instabilities?

Izagguire, Raffelt, Tambora (2016)

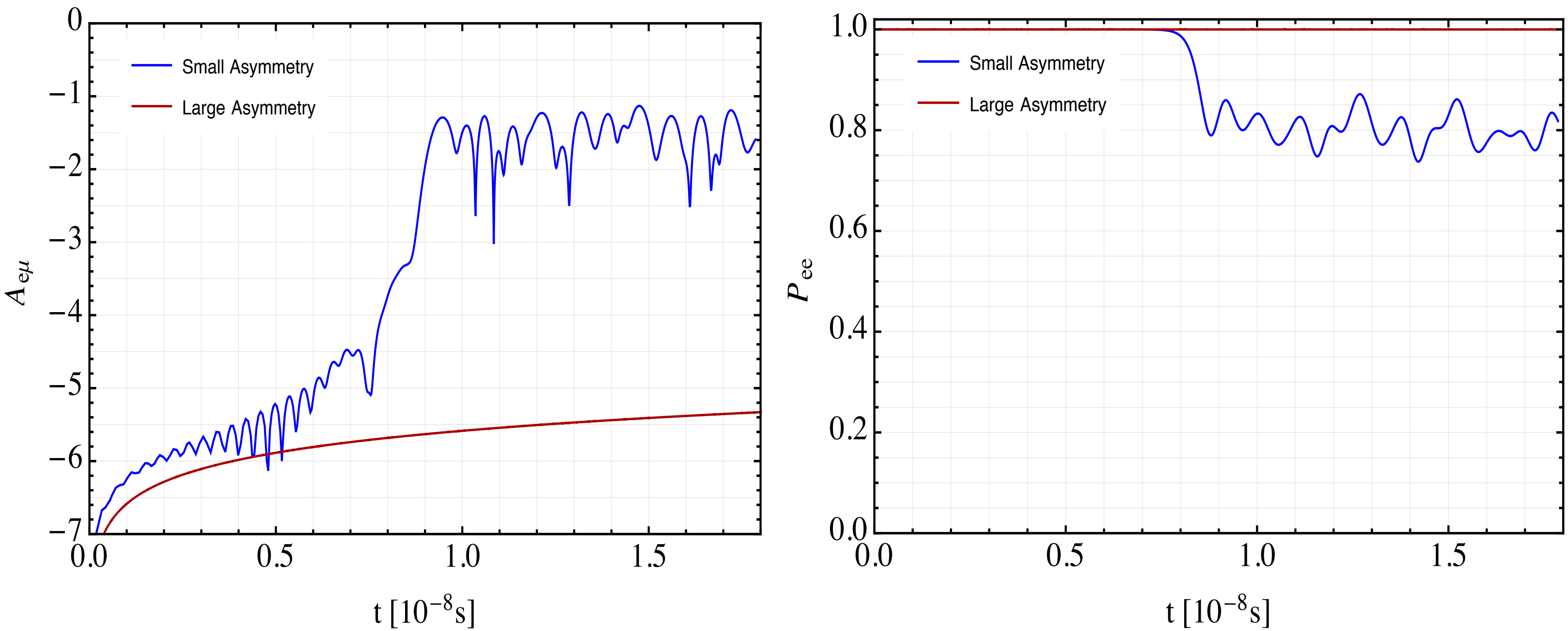
Dispersion Relations



Detailed understanding of the complex analytic structure of poles of the dispersion relation gives the instabilities

Capozzi et al. (2017)

Semi-Realistic Case



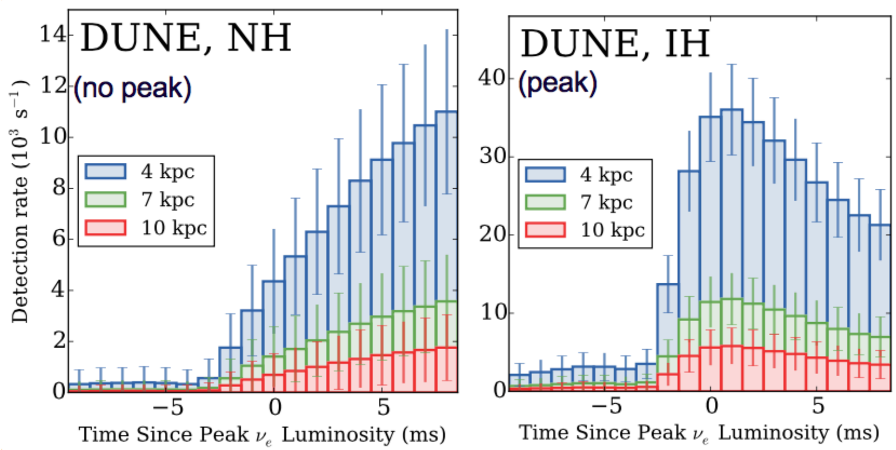
This instability occurs for physically interesting neutrino fluxes

For directions with small lepton asymmetry ~20% flavor con.
Within a few meters and few nanosecs !!!

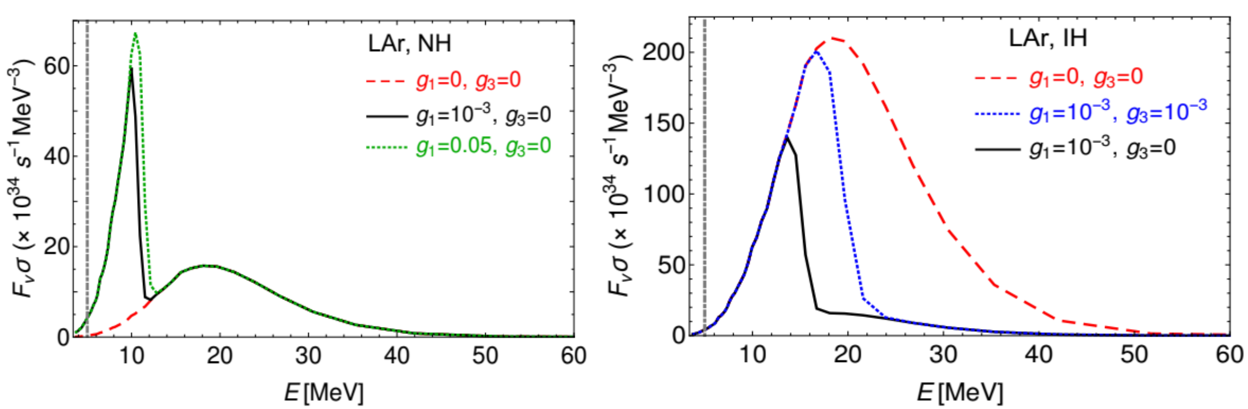
Dasgupta, Mirizzi, Sen (2017)

Flavor Phenomenology

Burst: MSW / NSI Physics



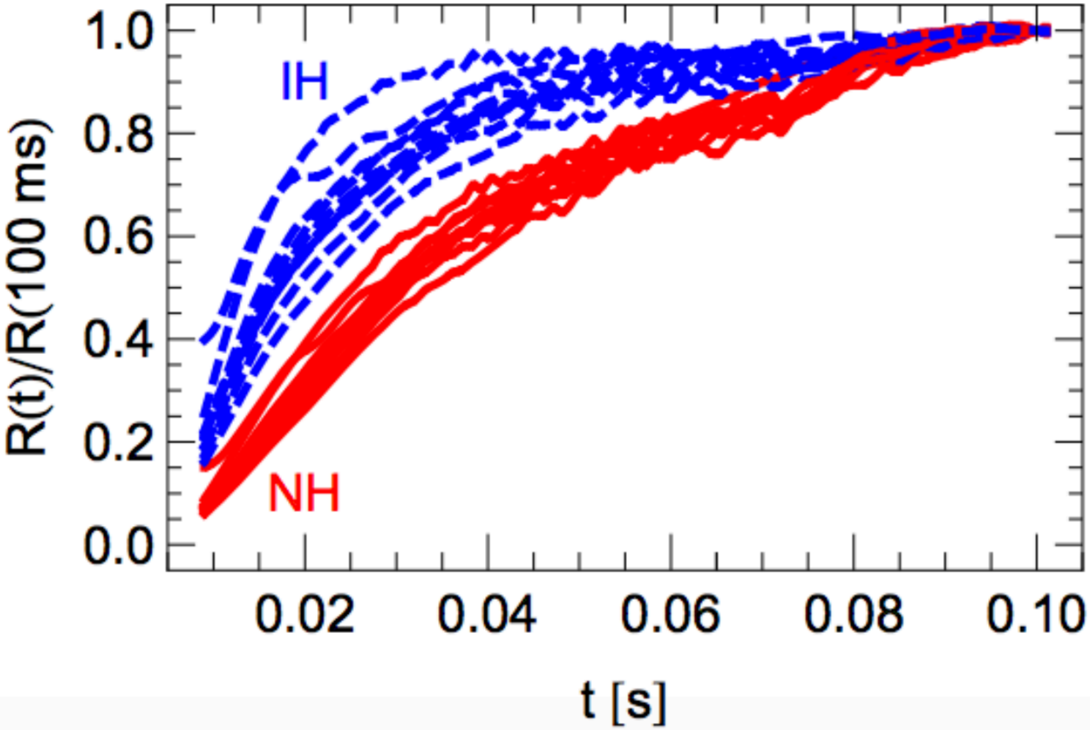
Usually we do not expect collective effects in the burst phase because there is no antinu, and hence no crossing. So only MSW physics. Can have sensitivity to NH/IH.



But flavor changing NSI can create an effective crossing (by a shift in the zero of lepton number)

Das, Dighe, Sen (2016)

Accretion: Mass Hierarchy

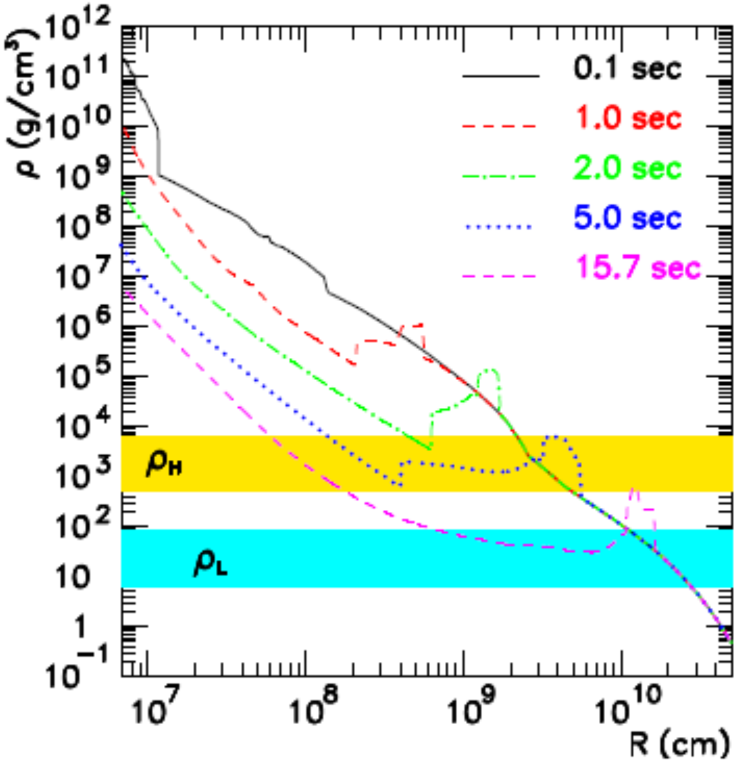


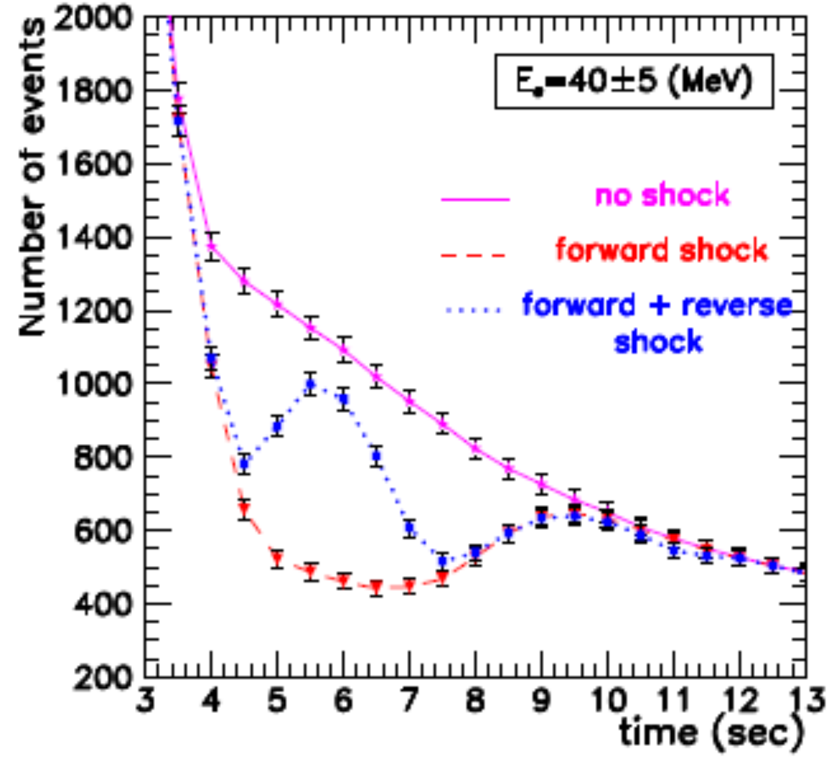
Consider accretion phase, where without fast conversions there are no collective effects (due to matter suppression).

Signal rises faster for Inverted Hierarchy

Serpico et al (2012)

Cooling: Shock tracking

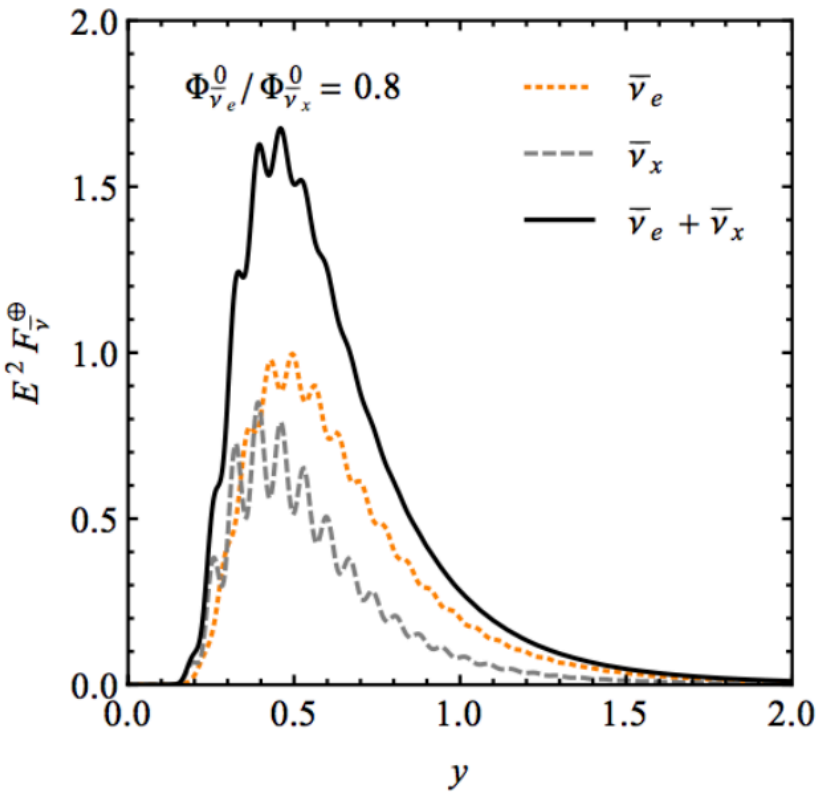


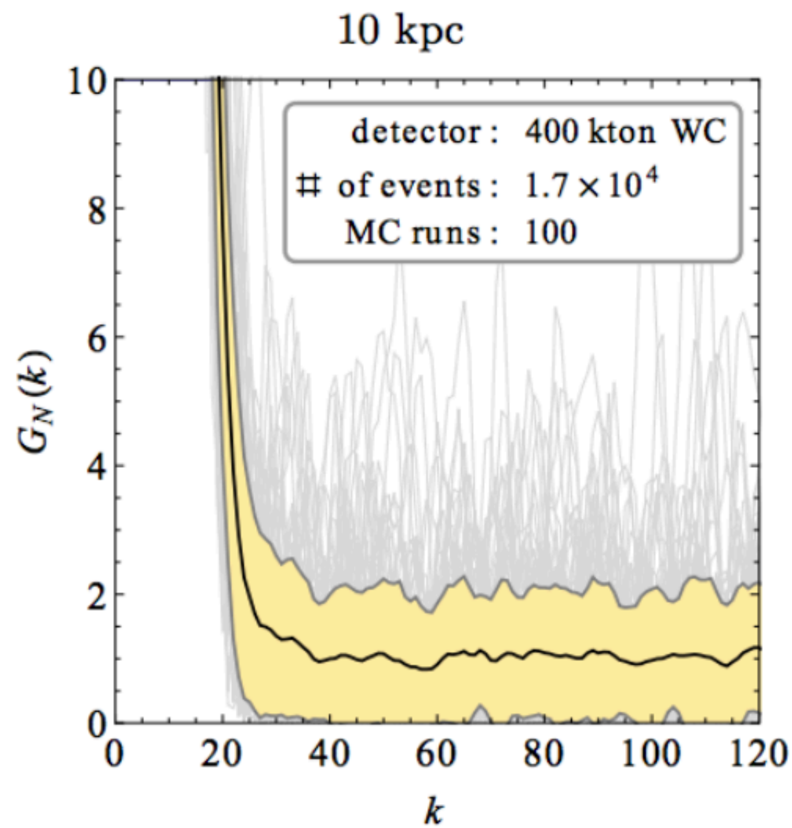


Tomas et al. (2004)

The shockwave creates possibility for the MSW resonance to become non-adiabatic, the E vs, t encodes information about shock radius vs. t. May be... but only if spectra sufficiently different in cooling phase.

Earth Effects





Hard to do... even with SN at 1 kpc

Boriello et al. (2010)

Summary for Lecture 2

SN neutrino detection

Need multiple large detectors with different channels

Gd loading, multimessenger stategies

Physics with (non-oscillating) SN neutrinos: Under Control

Timing, Pointing, Mass, Lifetimes, Energy Loss, SASI LESA, …

IceCube very important for these

Oscillation Physics of SN neutrinos

MSW Same as circa 2000; otherwise a developing subject

Phase effects, Shock, Turbulence etc. harder to see in cooling

Collective oscillations of SN neutrinos

Slow, Symmetry Breaking, Fast, Collisions?

Signatures of SN and neutrinos that use flavor information

Mass Hierarchy, Shock tracking, Decoherence, …

Summary

Lecture 1

Supernovae: What, When, & Why?

Supernova and the neutrino mechanism

SN neutrino detection

Physics with (non-oscillating) SN neutrinos: What can be measured?

Lecture 2

MSW Physics of SN neutrinos

Collective oscillations of SN neutrinos

Physics with SN neutrinos: What can be measured?