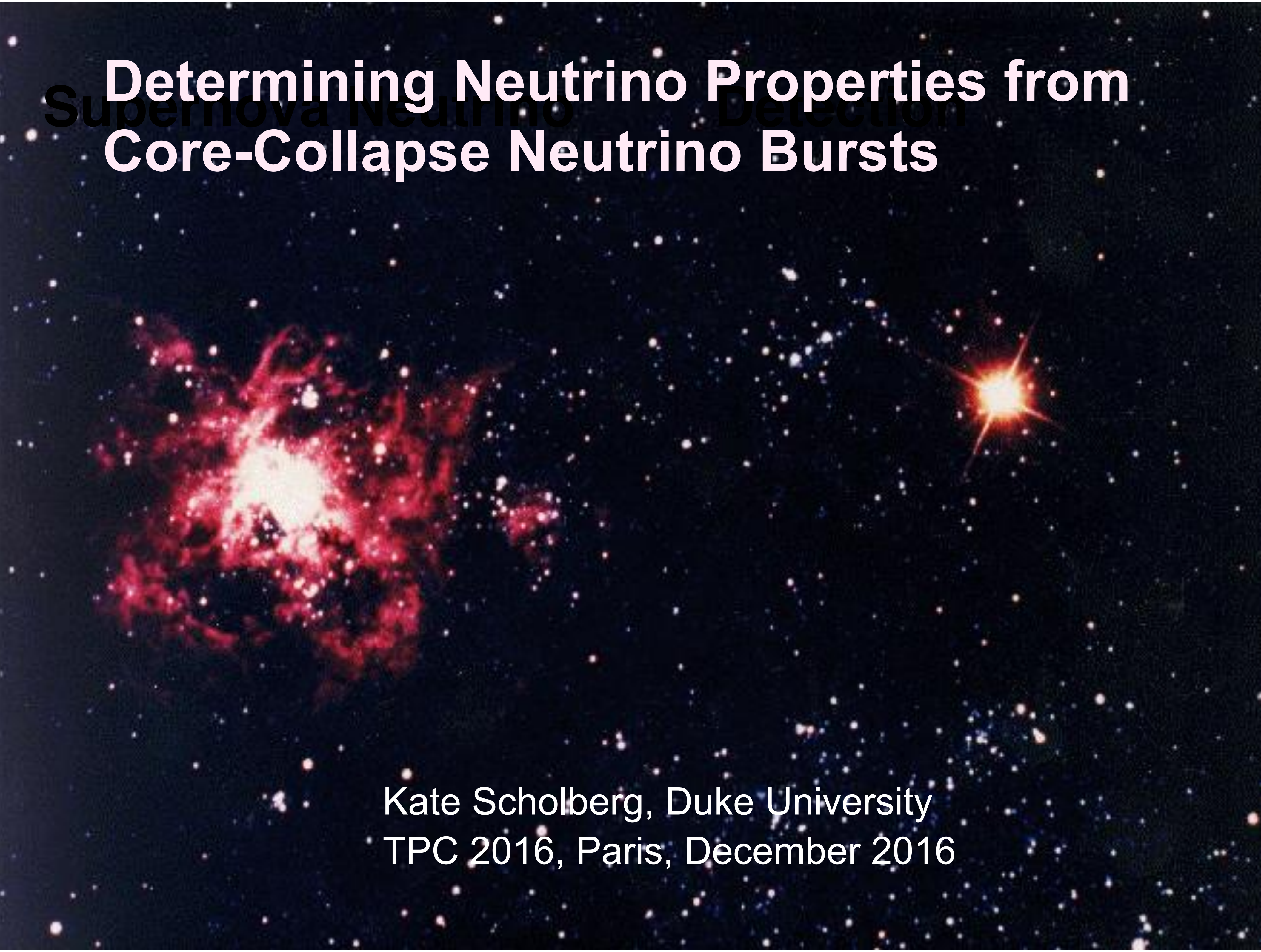
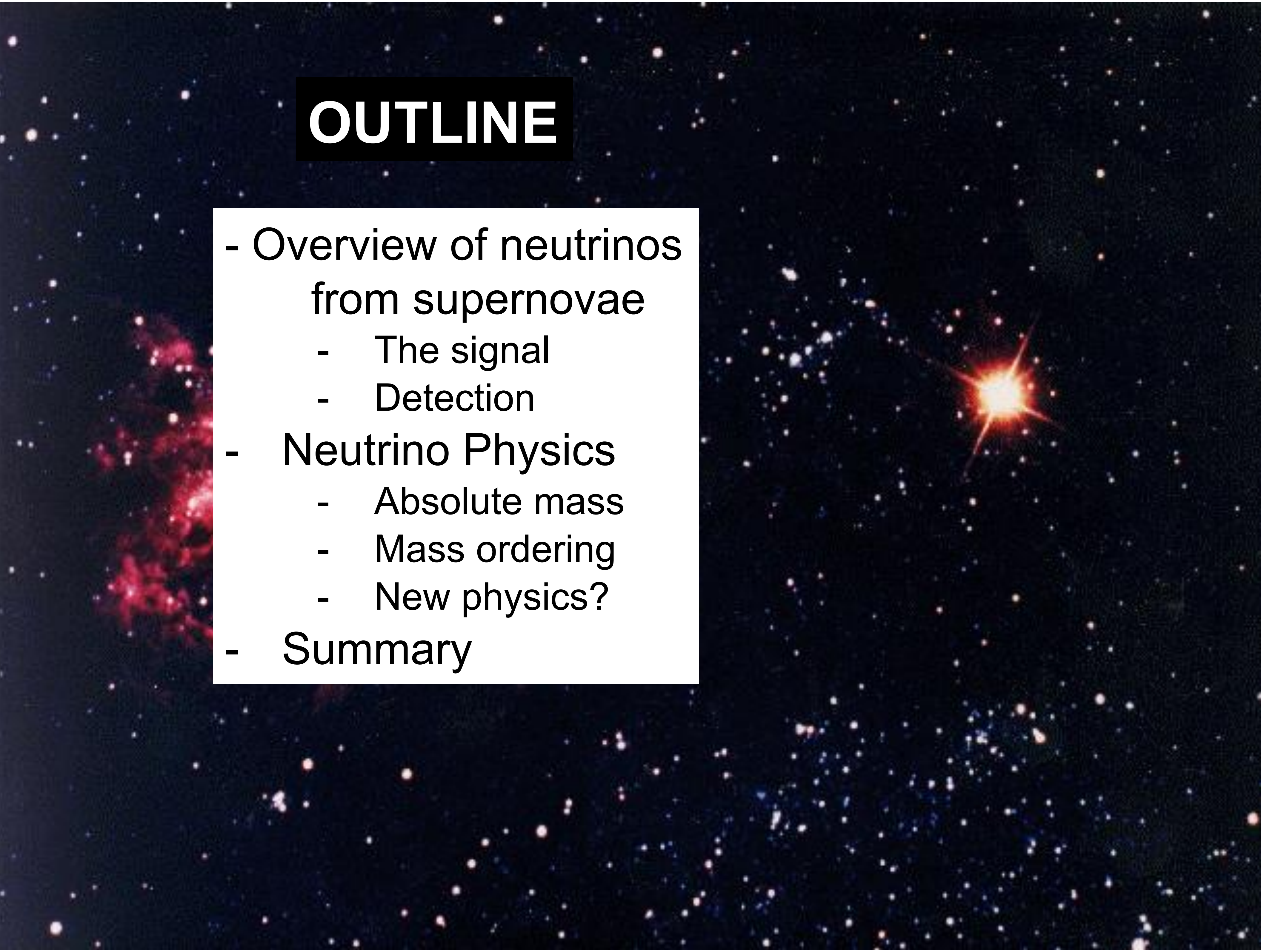


Determining Neutrino Properties from Core-Collapse Neutrino Bursts

Supernova Neutrino Detection

Kate Scholberg, Duke University
TPC 2016, Paris, December 2016

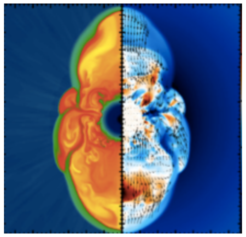


OUTLINE

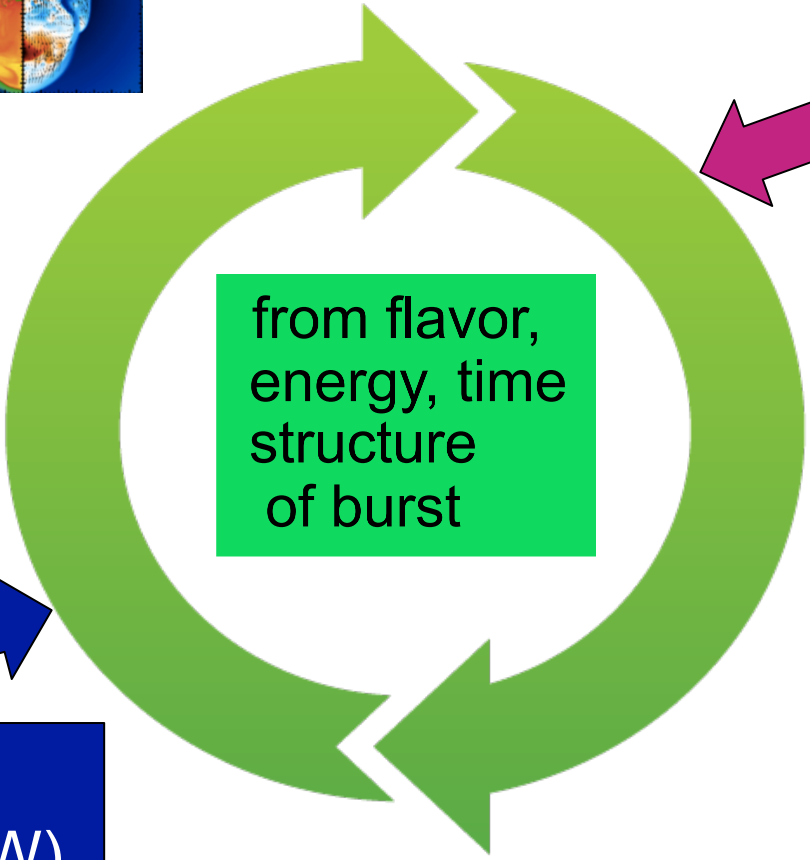
- Overview of neutrinos from supernovae
    - The signal
    - Detection
- Neutrino Physics
    - Absolute mass
    - Mass ordering
    - New physics?
- Summary

What can we learn from the next neutrino burst?

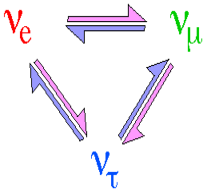
CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....



input from neutrino experiments



NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass ordering)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

input from photon (GW) observations

from flavor, energy, time structure of burst

+ EARLY ALERT

Expected neutrino luminosity and average energy vs time

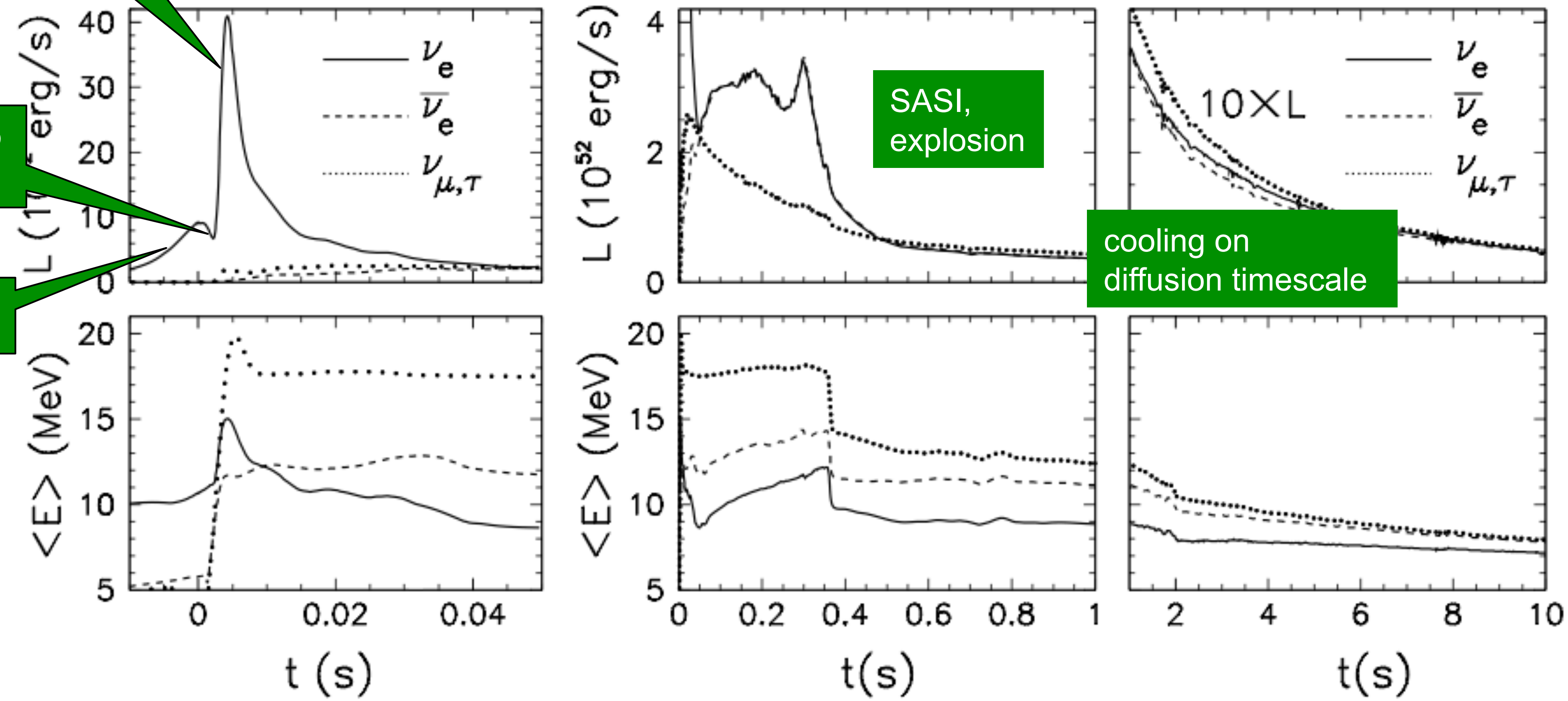
Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: ‘Basel’ model

Early: deleptonization

Mid: accretion

Late: cooling



neutronization burst

neutrino trapping

infall

SASI, explosion

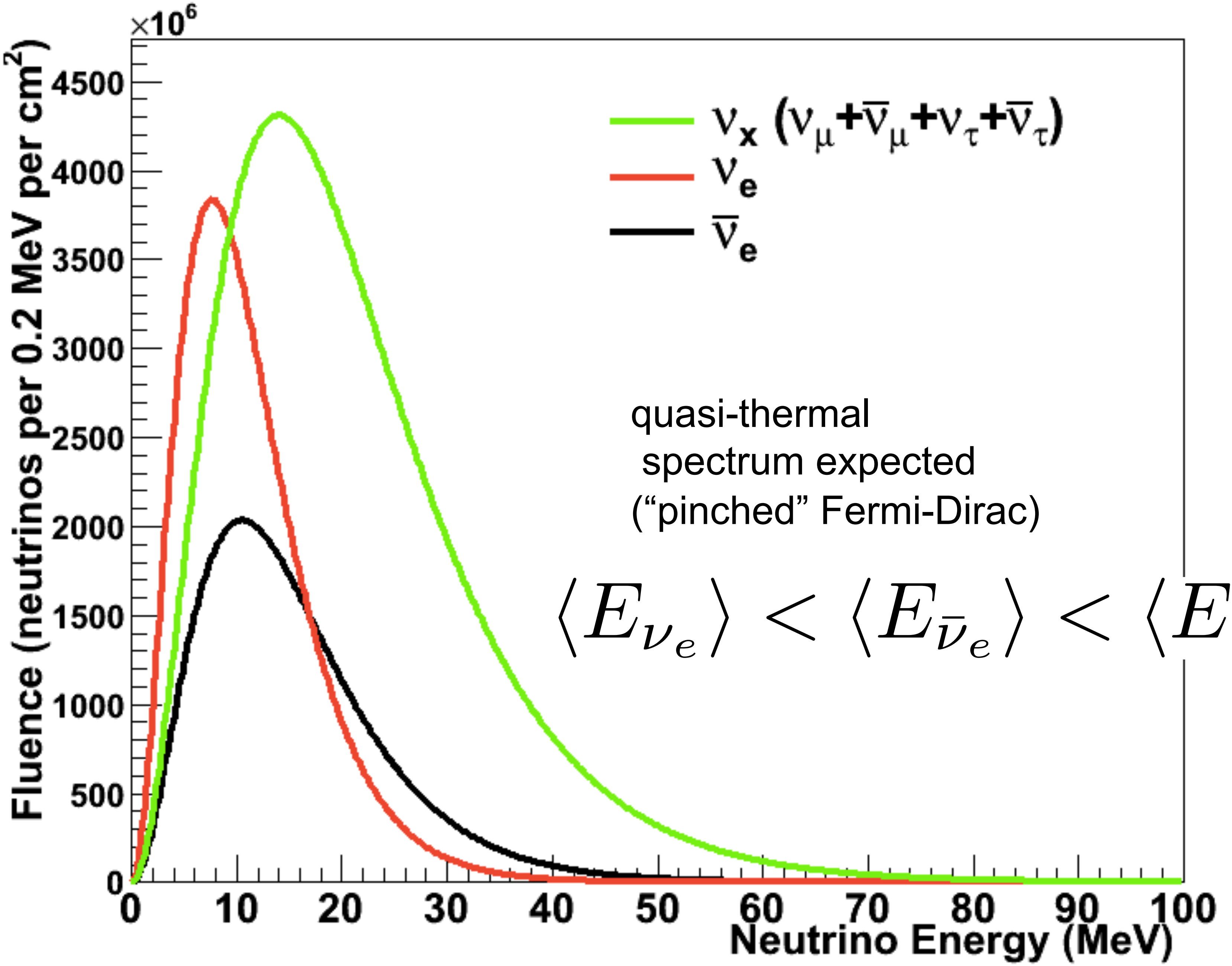
cooling on diffusion timescale

Generic feature:

(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Neutrino spectrum from core collapse



quasi-thermal
spectrum expected
("pinched" Fermi-Dirac)

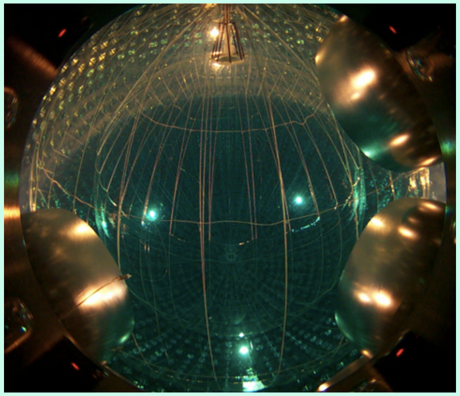
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Supernova Neutrino Detectors

Water

$\bar{\nu}_e$

Scintillator



$\bar{\nu}_e$

Argon

ν_e

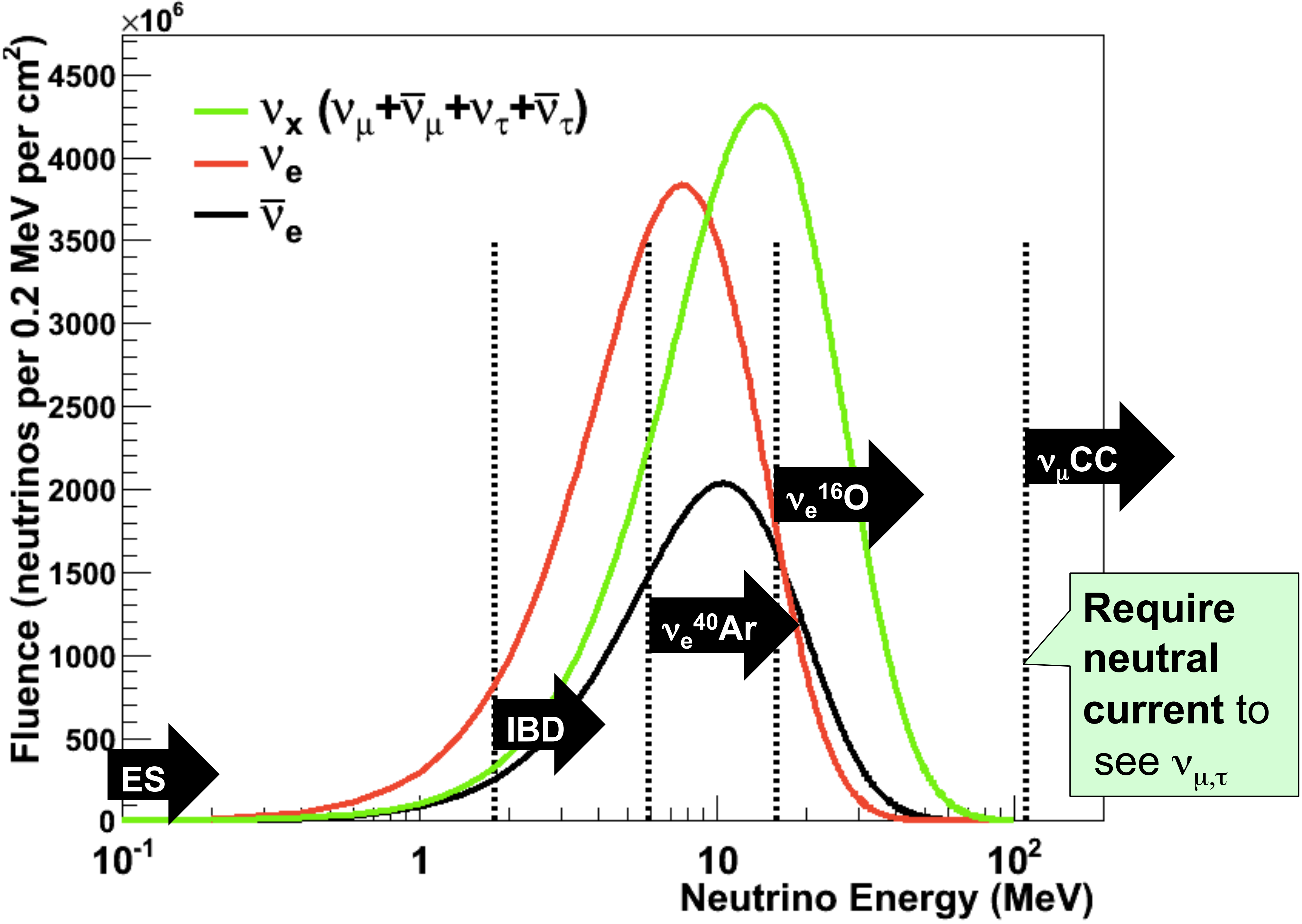
Lead

ν_e

+ some others (e.g. DM detectors)

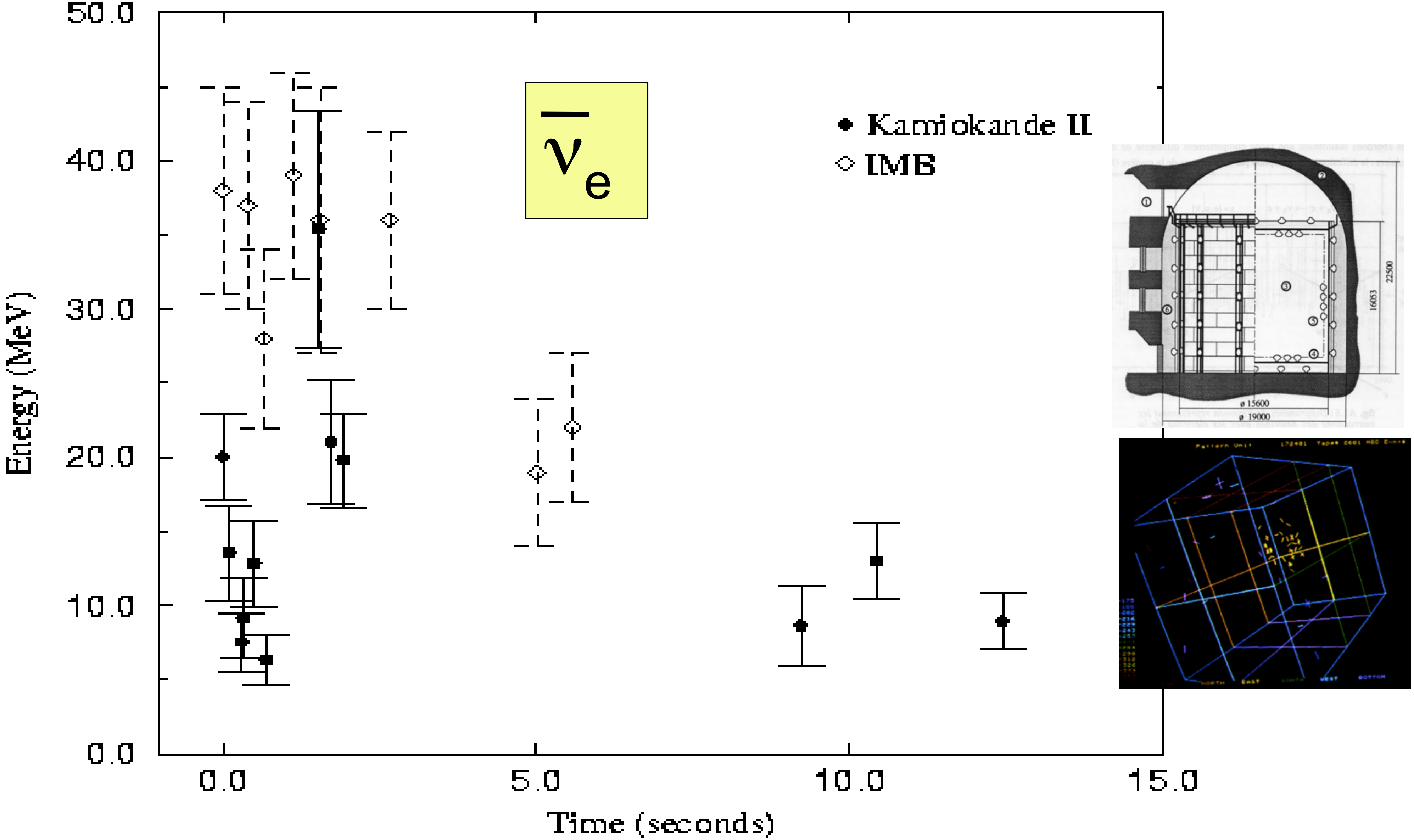
See M. Nakahata talk this afternoon

Neutrino interaction thresholds



Require neutral current to see $\nu_{\mu,\tau}$

SN1987A in LMC



Confirmed baseline model... and limits on ν properties
....but still many questions

Information on Neutrino Properties from Core Collapse

- Absolute Neutrino Mass
- Neutrino Mixing Parameters: Mass Ordering
- New Neutrino States?

A sampler...

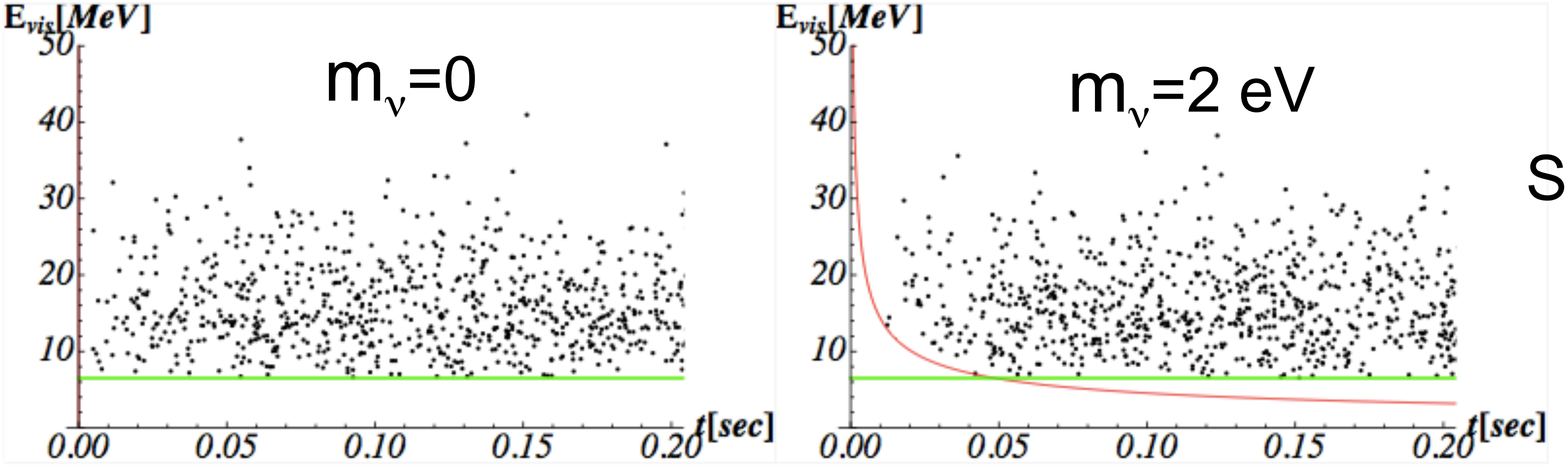
Neutrino Absolute Mass

Expect time of flight delay for massive neutrinos

$$\Delta t(m_\nu, E_\nu) \simeq 5.14\,\mathrm{ms}\ \left(\frac{m_\nu}{\mathrm{eV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2 \frac{D}{10\,\mathrm{kpc}}$$

Look for:

- energy-dependent time spread
- flavor-dependent delay



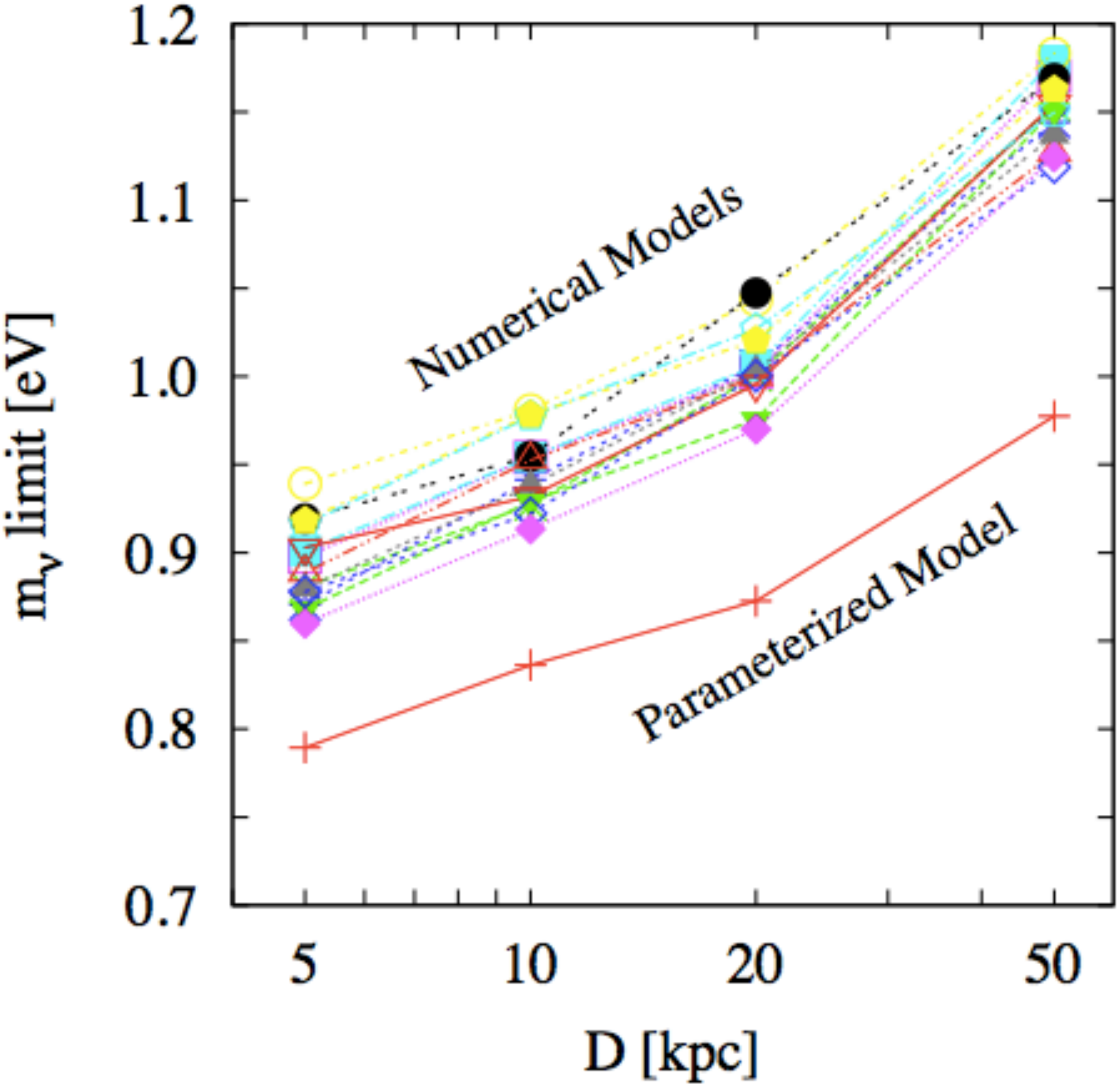
SK@10 kpc

$\bar{\nu}_e$

G. Pagliaroli et al., Astropart. Phys. 33, 287 (2010)

A more recent study example

JUNO mass sensitivity (20 kton scintillator, low energy threshold)



J.-S. Lu et al.,
JCAP 1505, 044 (2015)

Future SN-based ν mass limits ~improvement over current laboratory limits, but not competitive w/next generation

Three-flavor neutrino mixing parameters

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

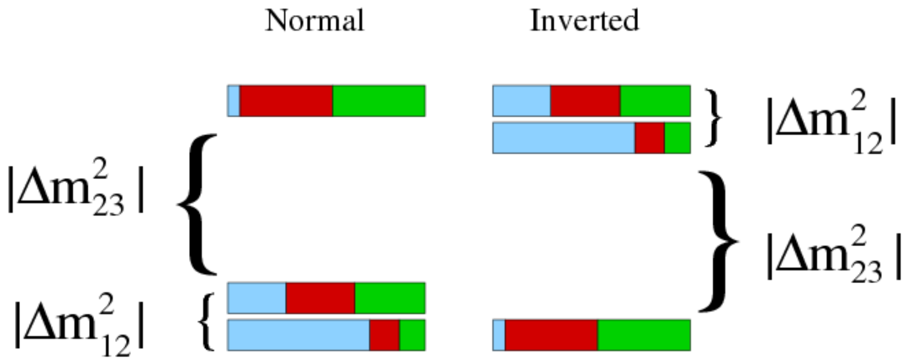
$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Parameters of Nature

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

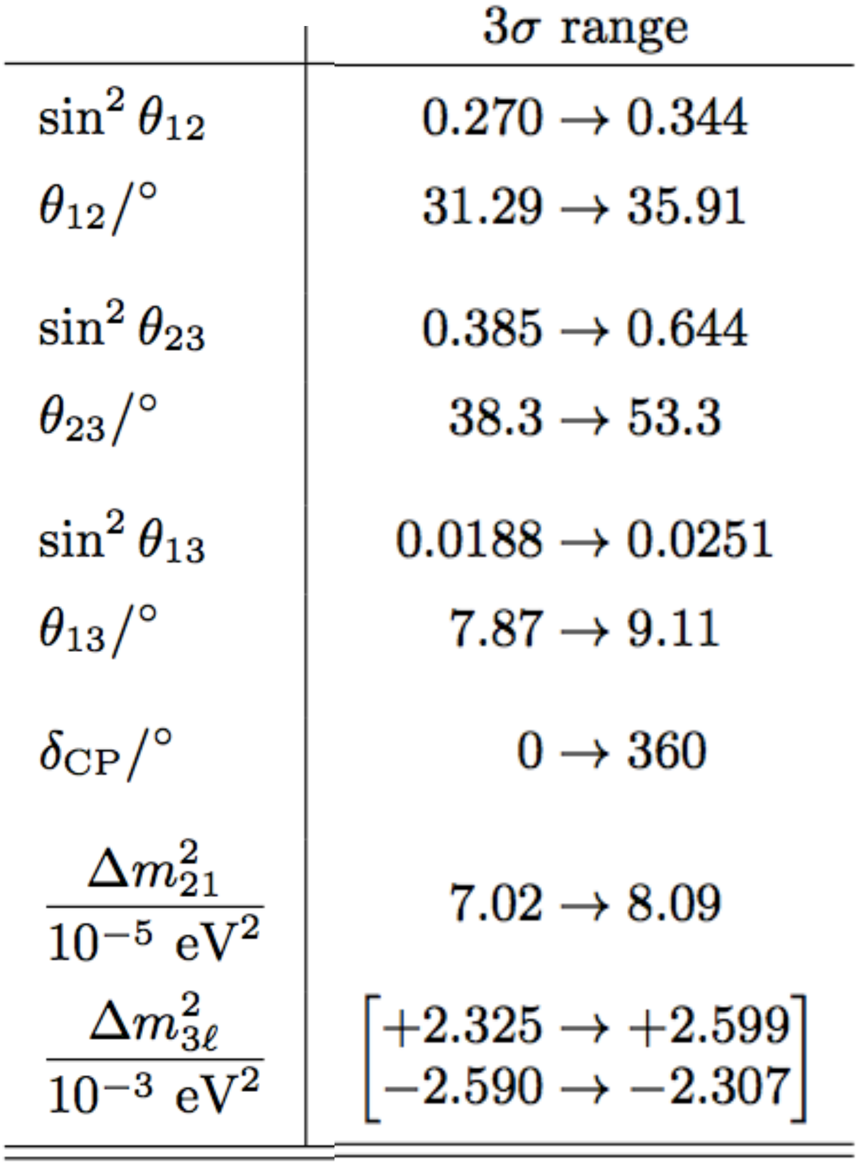
$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

signs of the mass differences matter



The three-flavor picture fits the data well

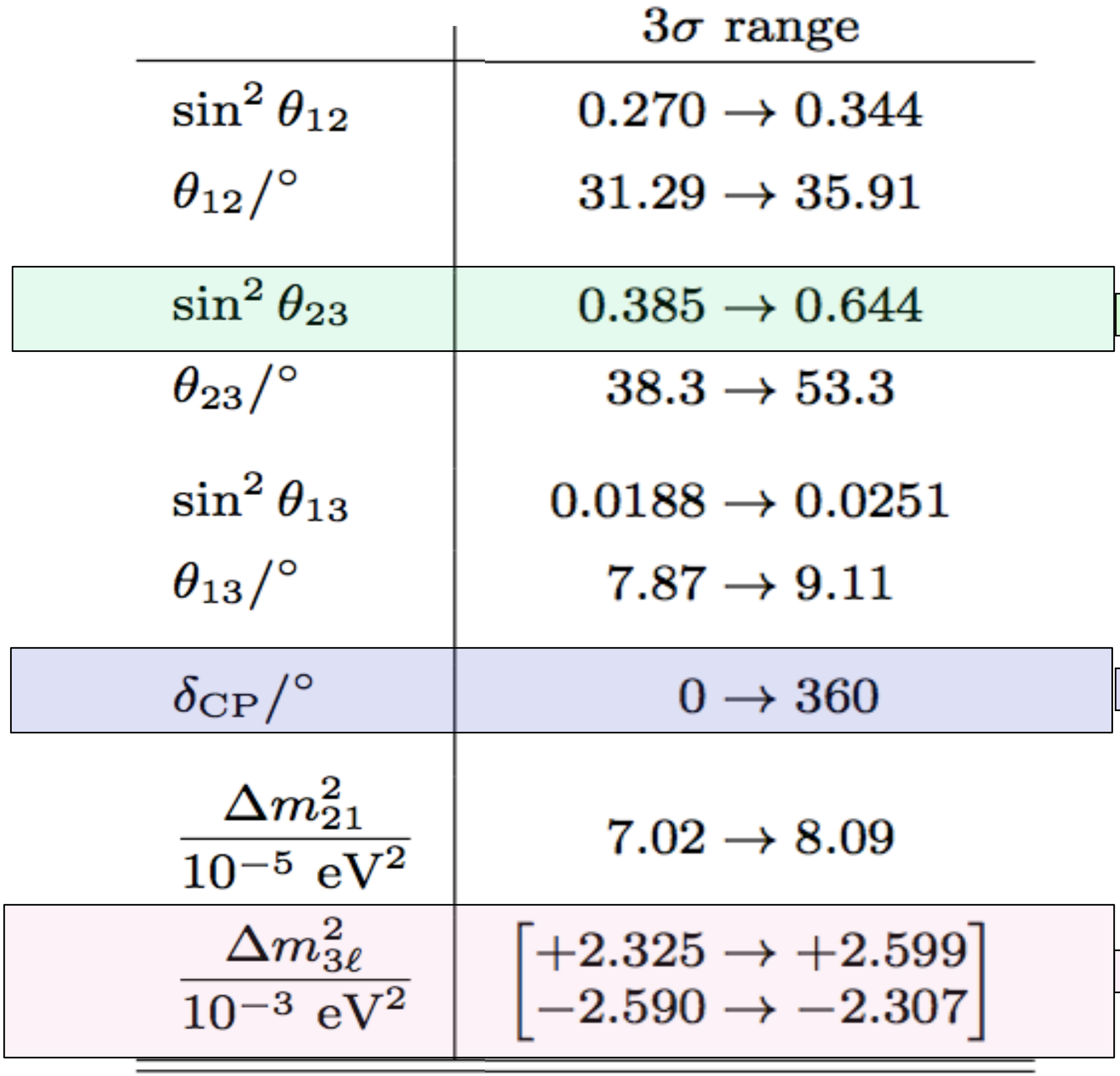
Global three-flavor fits to all data



	3σ range	3σ knowledge
$\sin^2\theta_{12}$	$0.270 \to 0.344$	~14%
$\theta_{12}/^\circ$	$31.29 \to 35.91$	
$\sin^2\theta_{23}$	$0.385 \to 0.644$	~33%
$\theta_{23}/^\circ$	$38.3 \to 53.3$	
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$	~15%
$\theta_{13}/^\circ$	$7.87 \to 9.11$	
$\delta_{\mathrm{CP}}/^\circ$	$0 \to 360$	~no info
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.02 \to 8.09$	~14%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix}+2.325 \to +2.599 \\ -2.590 \to -2.307\end{bmatrix}$	~12%

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 10.1007/JHEP11(2014)052

What do we *not* know about the three-flavor paradigm?



	3σ range
$\sin^2\theta_{12}$	$0.270 \rightarrow 0.344$
$\theta_{12}/^\circ$	$31.29 \rightarrow 35.91$
$\sin^2\theta_{23}$	$0.385 \rightarrow 0.644$
$\theta_{23}/^\circ$	$38.3 \rightarrow 53.3$
$\sin^2\theta_{13}$	$0.0188 \rightarrow 0.0251$
$\theta_{13}/^\circ$	$7.87 \rightarrow 9.11$
$\delta_{\rm CP}/^\circ$	$0 \rightarrow 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.02 \rightarrow 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$\begin{bmatrix} +2.325 \rightarrow +2.599 \\ -2.590 \rightarrow -2.307 \end{bmatrix}$

Is θ_{23} non-negligibly greater or smaller than 45 deg?

basically unknown

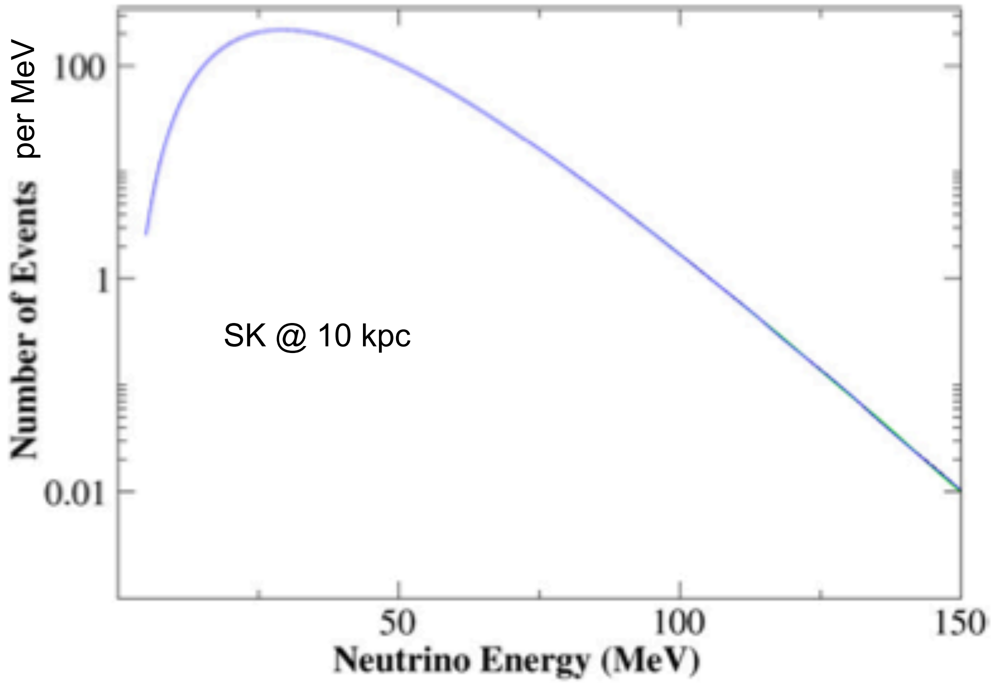
sign of Δm^2 unknown (ordering of masses)

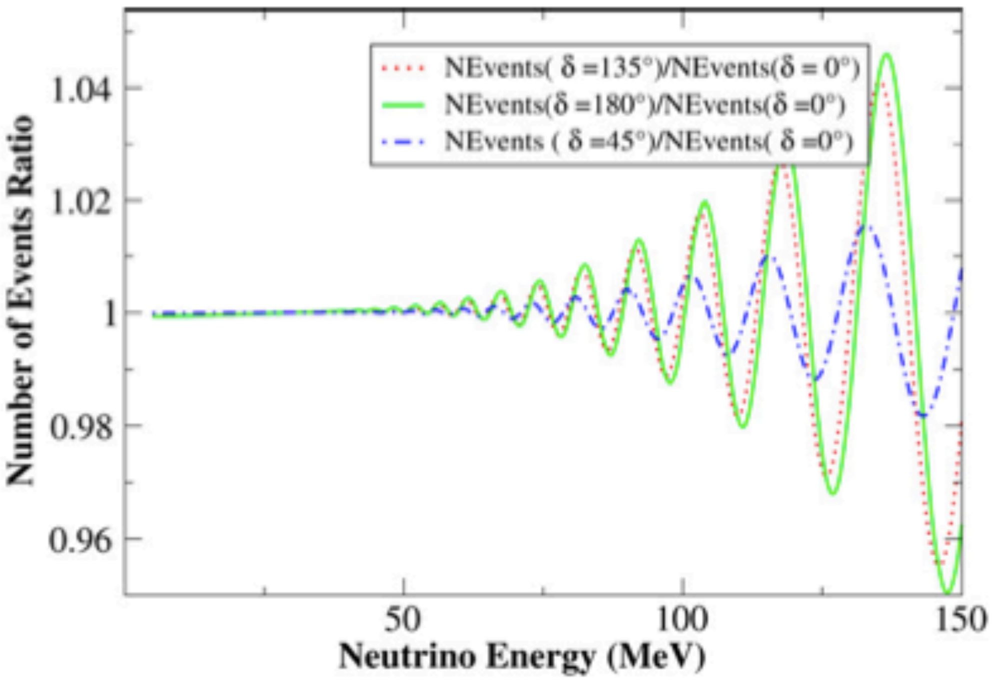
Can we learn about CP violation from a supernova?

Answer: maybe, but very hard...

- Effect of non-zero δ is mainly $\mu\tau$ mixing... unobservable...
- However if ν_μ and ν_τ fluxes differ at neutrinosphere (FCNC?),
  get small effects on electron flavor,
  but in high energy tail where rate is low

A.B. Balantakin, J. Gava and C. Volpe,
Phys. Lett. B 662, 396 (2008)

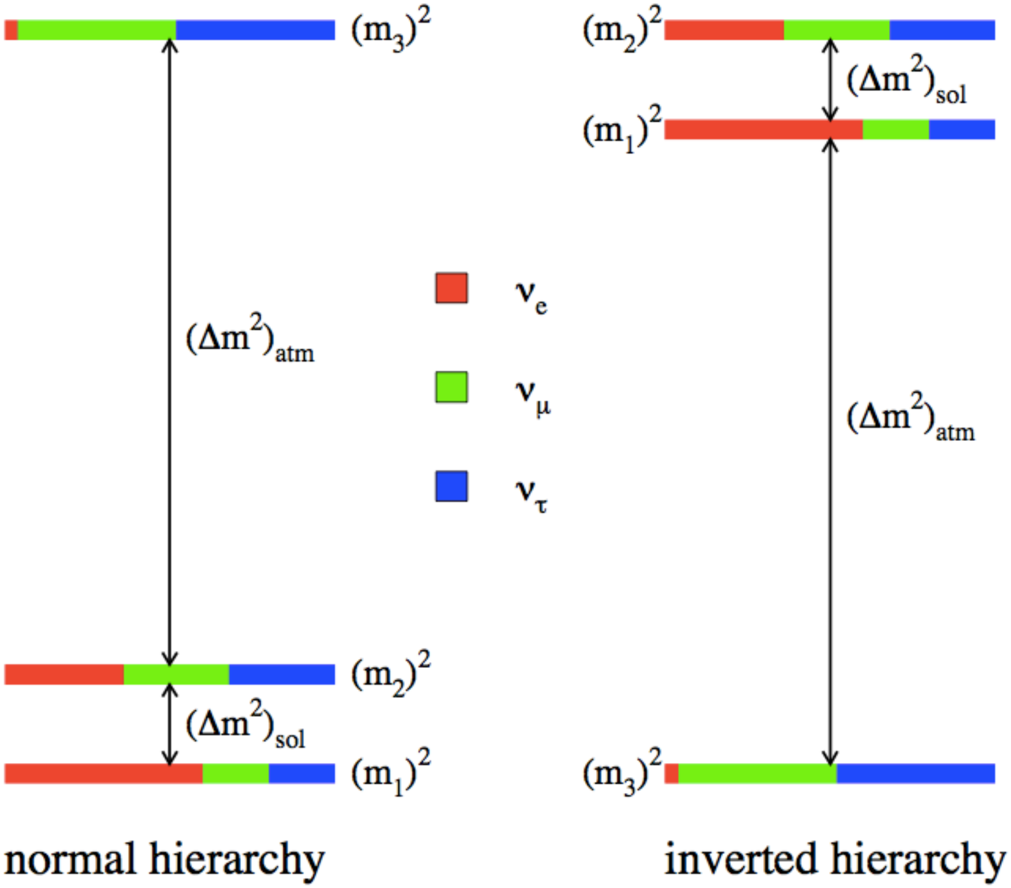




Next on the list to go after experimentally:

mass ordering (hierarchy)

(sign of Δm^2_{32})

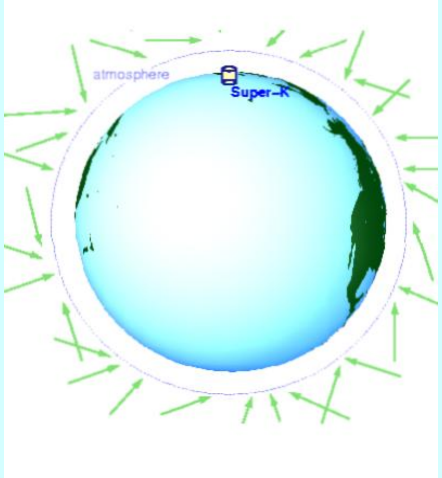


$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

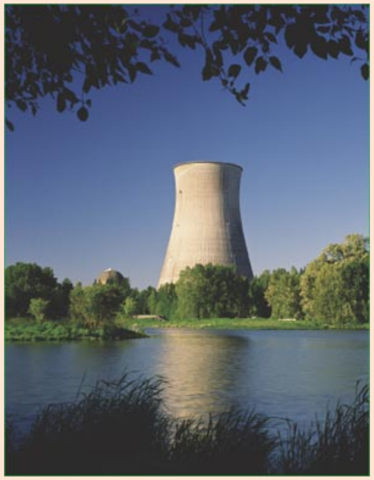
Four of the possible ways to get MO

Long-baseline beams

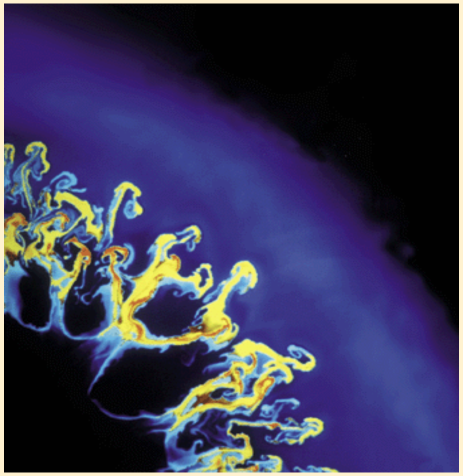
Atmospheric neutrinos



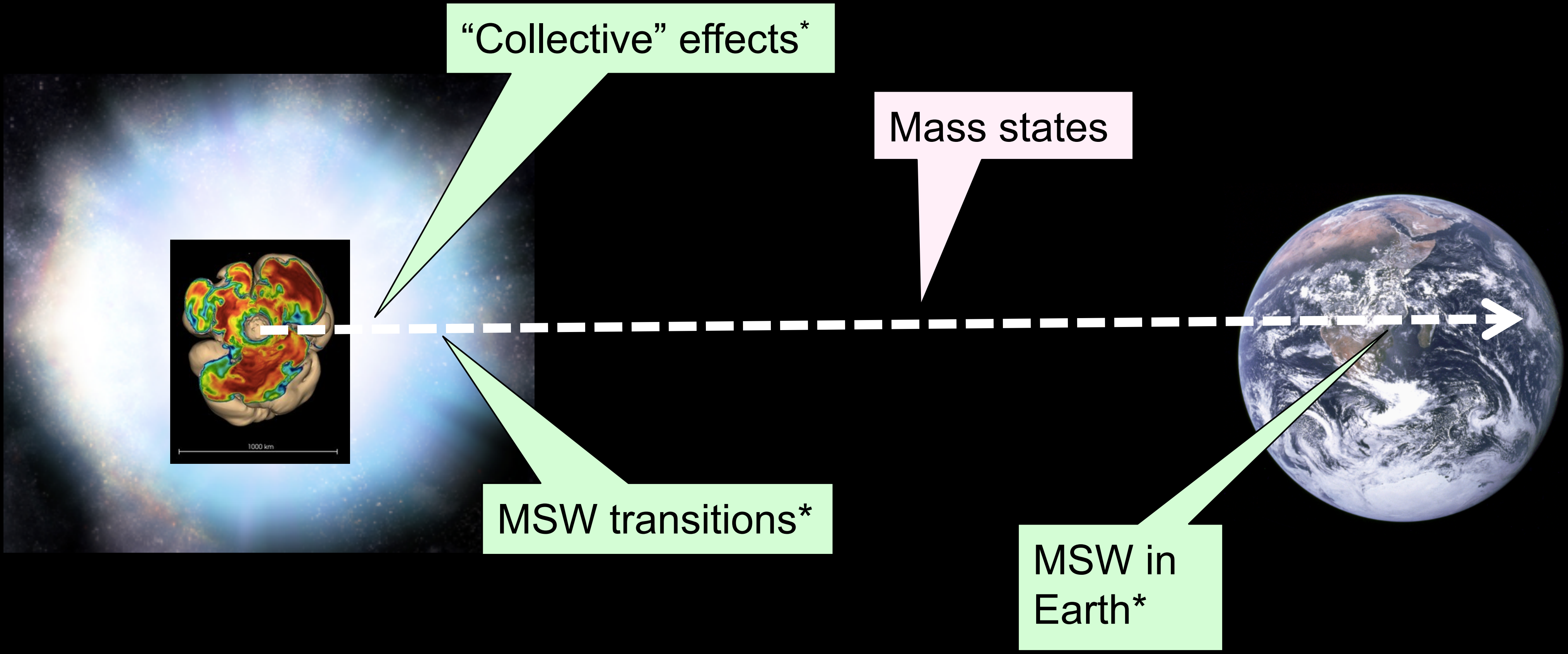
Reactors



Supernovae



Neutrino Mixing for Supernova Neutrinos



"Collective" effects*

Mass states

MSW transitions*

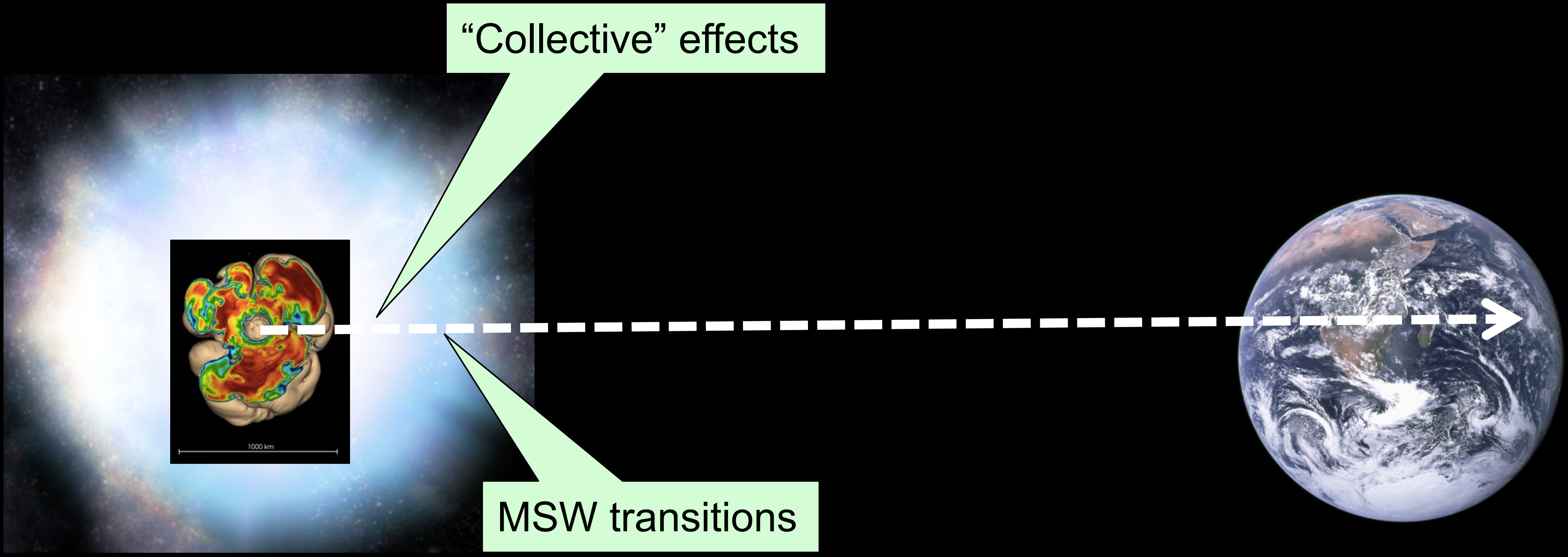
MSW in Earth*

*All of these depend on MO to some extent

... ***multiple signatures*** of MO (although some model-dependence)

Not to scale!

Neutrino Mixing in the Supernova Itself

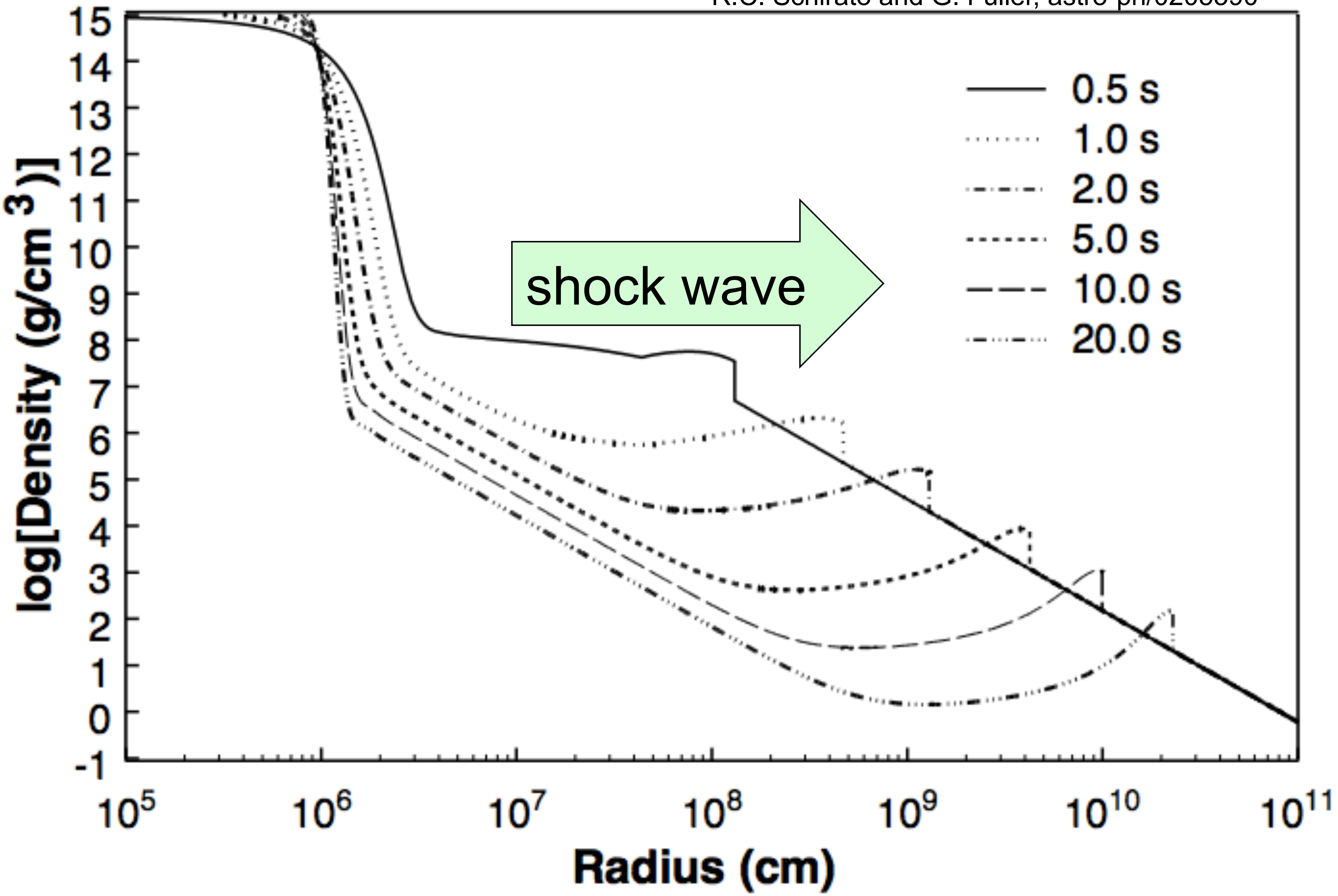


"Collective" effects

MSW transitions

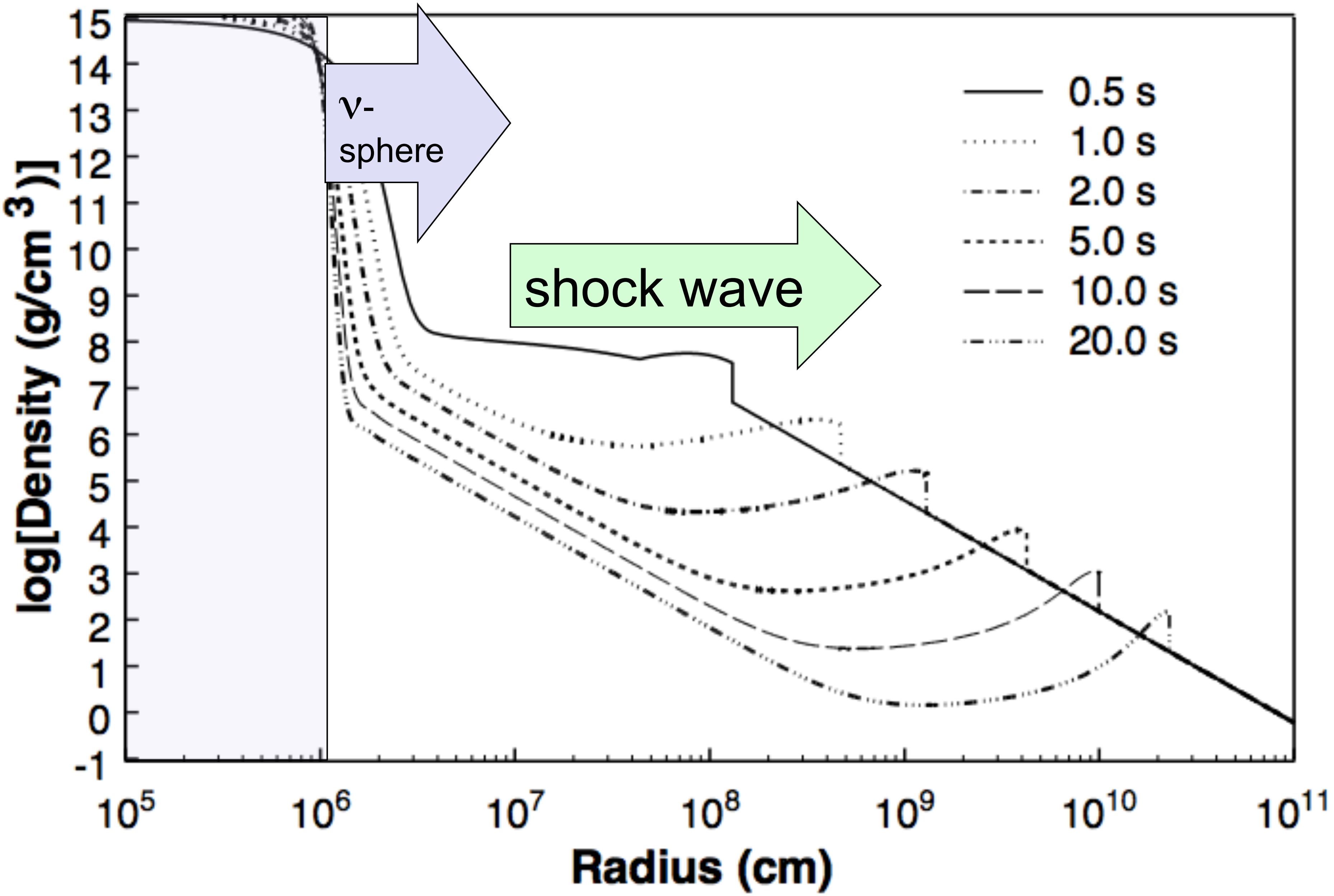
Density of matter in a supernova vs time

R.C. Schirato and G. Fuller, astro-ph/0205390

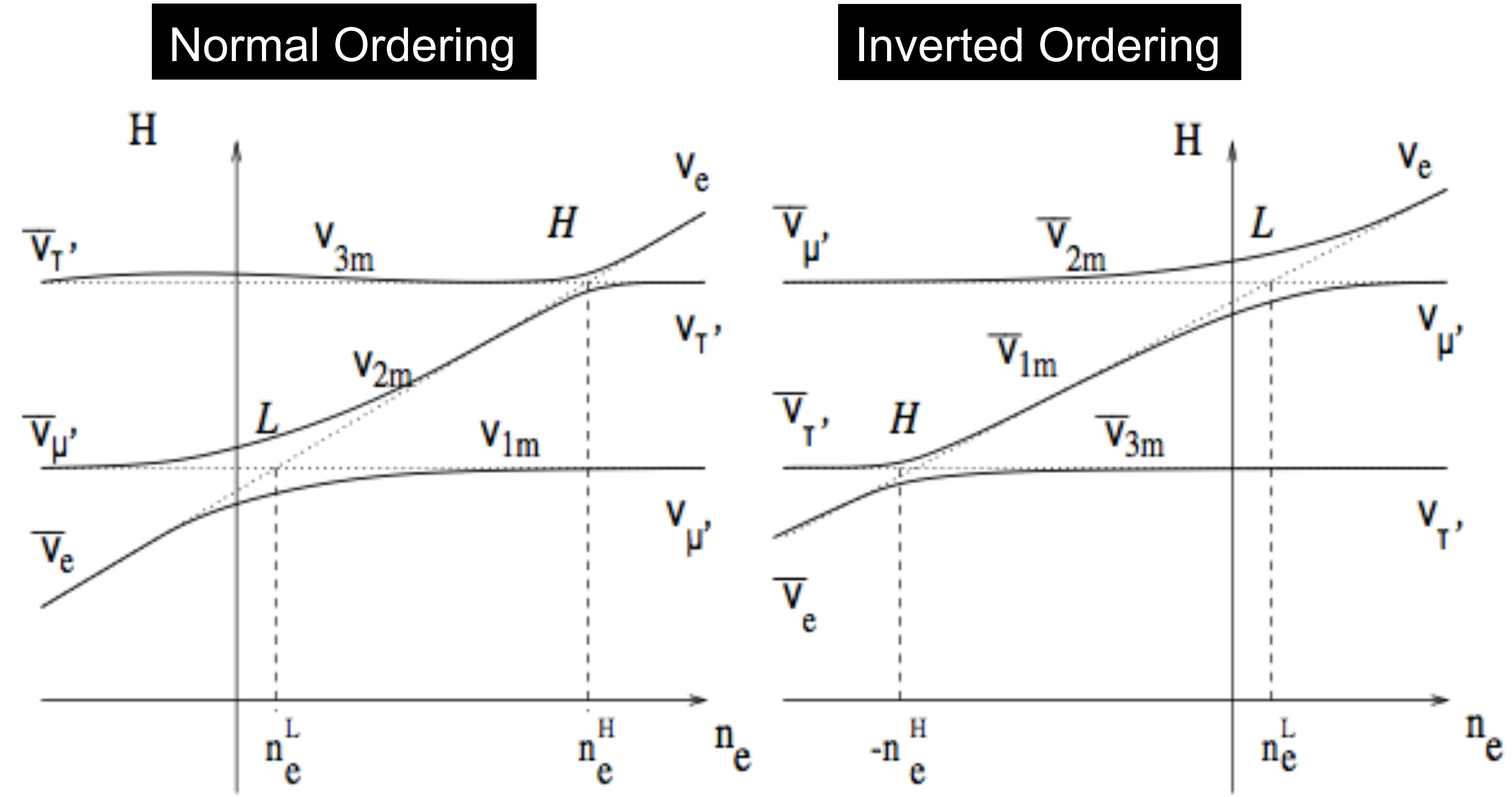


shock wave

Density of matter in a supernova vs time



MSW Transitions in Supernova Matter

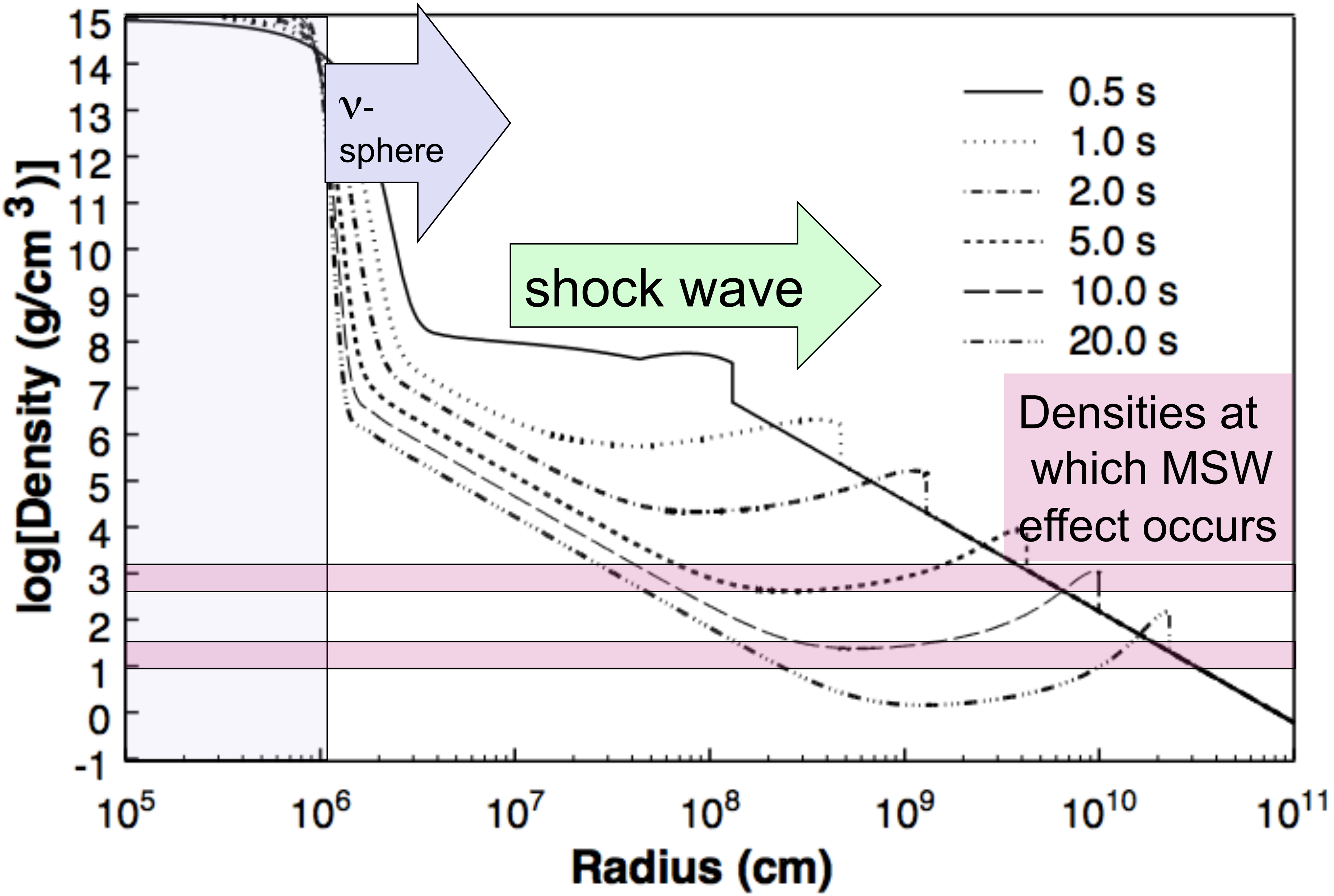


A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016), G. Raffelt, Proc. Int. Sch. Phys. Ferml, 182, 61 (2012)

$$P_{ee} \simeq \begin{cases} \sin^2\theta_{12}\, P_H & (\nu,\ \mathrm{NH}), \\ \cos^2\theta_{12} & (\overline{\nu},\ \mathrm{NH}), \\ \sin^2\theta_{12} & (\nu,\ \mathrm{IH}), \\ \cos^2\theta_{12}\, P_H & (\overline{\nu},\ \mathrm{IH}). \end{cases}$$

- **Mass-ordering-dependent** transition probability for neutrinos and antineutrinos
- Can be adiabatic, or non-adiabatic at a shock front

Density of matter in a supernova vs time



ν-sphere

shock wave

Densities at which MSW effect occurs

MSW effects may turn on and off as the shock propagates

And another effect: “collective effects”

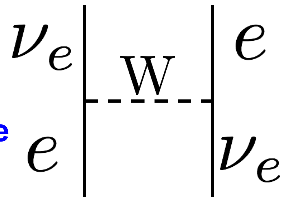
In the proto-neutron star the neutrino density is so high that ***neutrino-neutrino*** *interactions* matter

$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

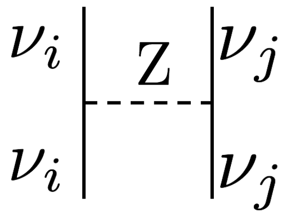
From G. Fuller

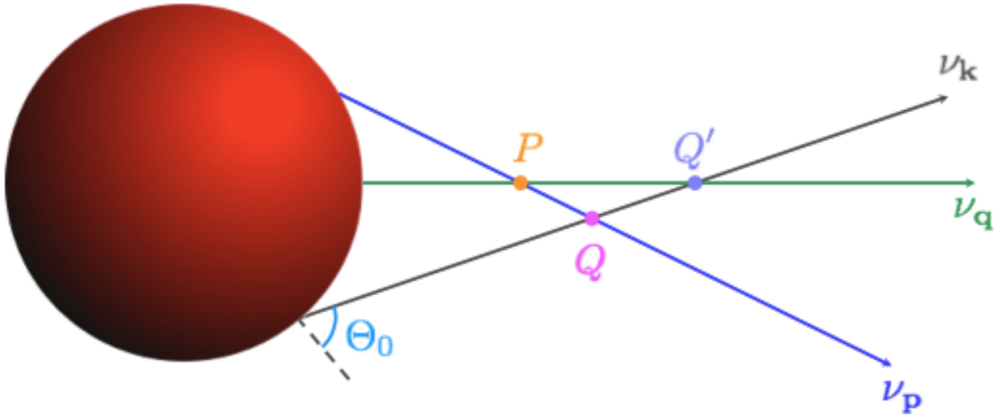
$$i\,\frac{\partial}{\partial t}\,\psi_{\nu,i} \;=\; \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering





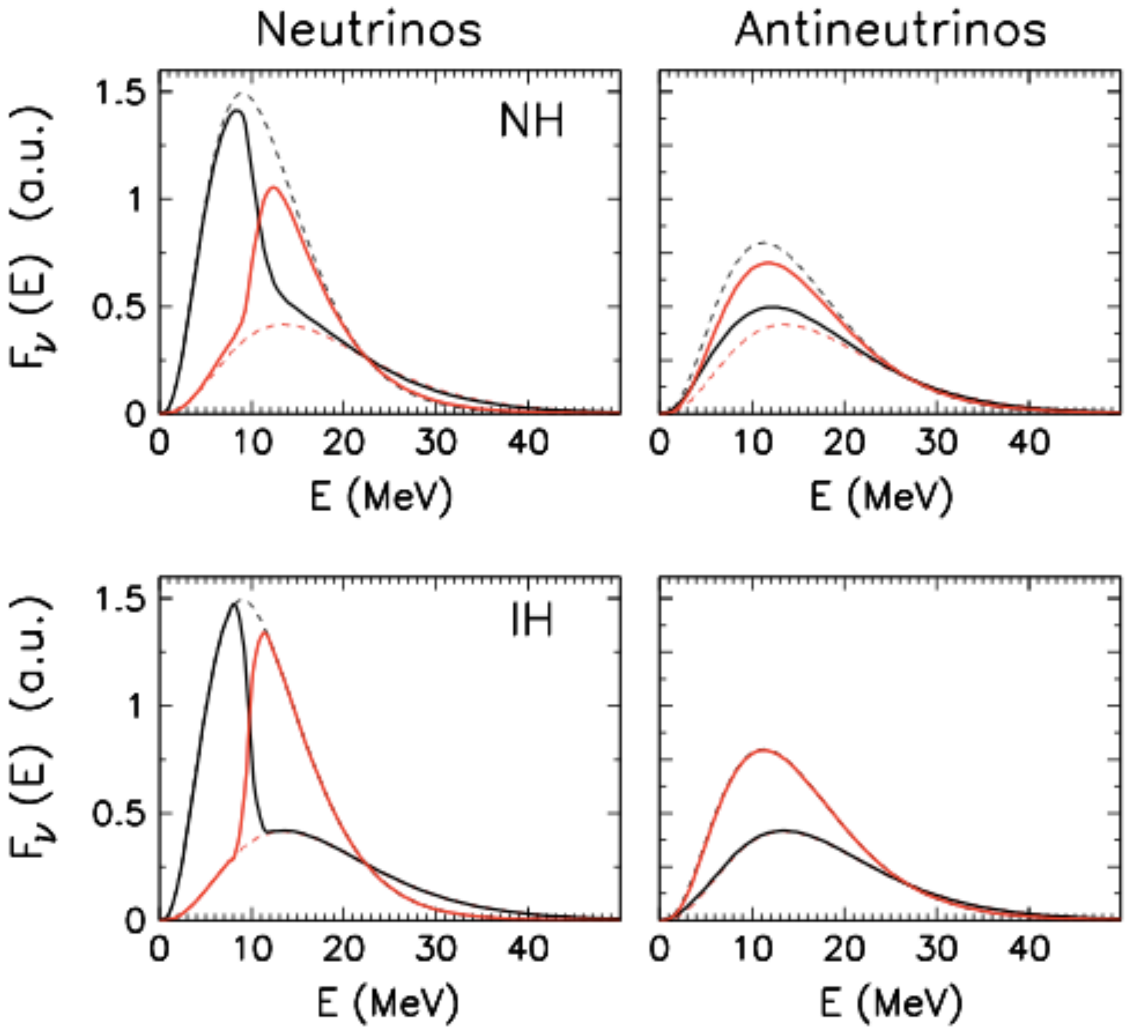
Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories:

“collective effects”

Must solve many *millions* of coupled, nonlinear partial differential equations!!

“The physics is addictive” -- G. Raffelt

A consequence: spectral "swaps" or "splits"



Dashed: no osc

Red: ν_x

Black: ν_e

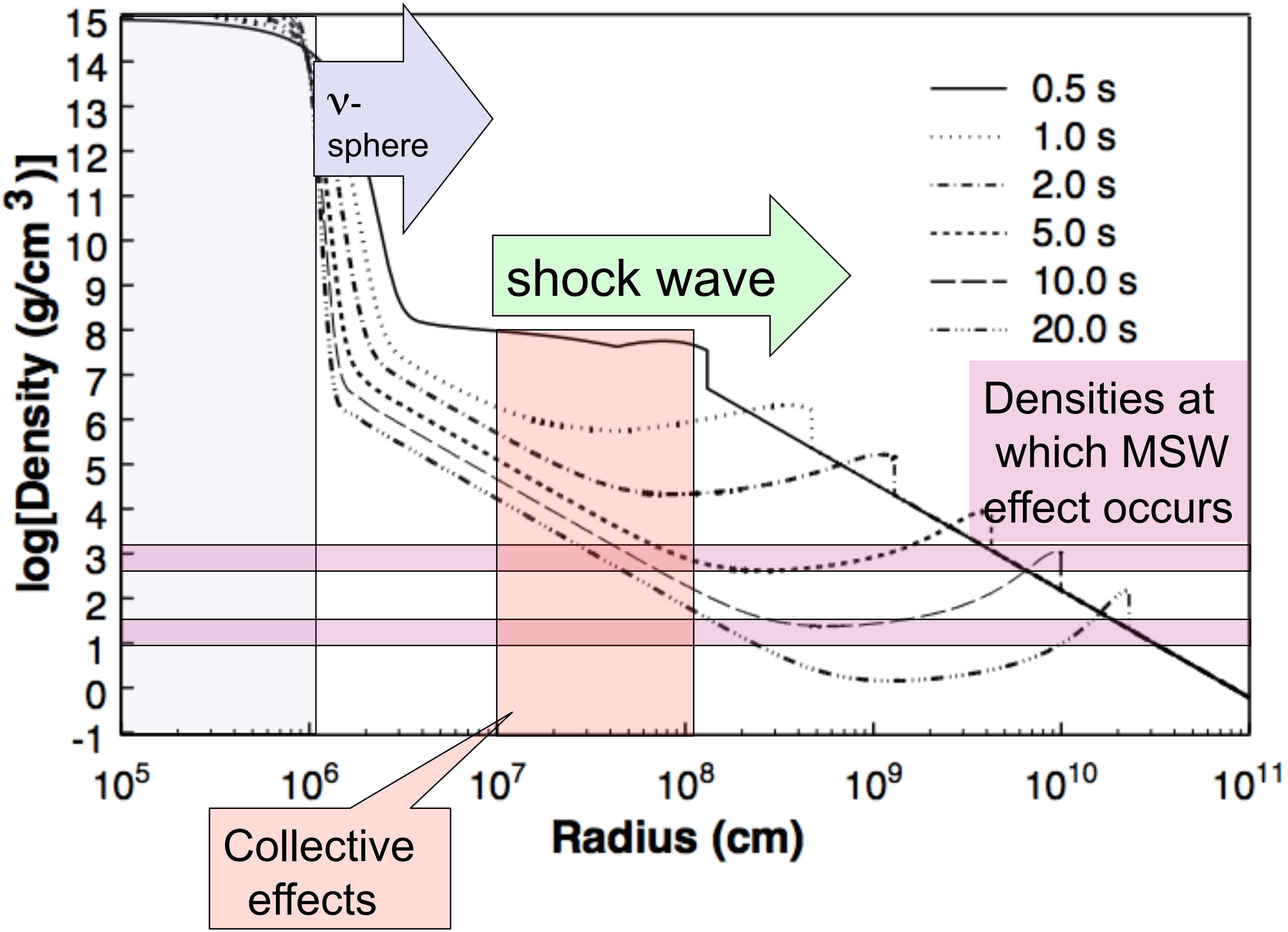
Can get spectral flavor conversion above or below specific energy thresholds

A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016) , S. Chakraborty and A. Mirizzi, PRD 90, 033004 (2014)

Initial fluxes $F^0_{\nu_e} : F^0_{\bar{\nu}_e} : F^0_{\nu_x} = 2.40 : 1.60 : 1.0$

- Depend on flavor flux ratio
- Can be suppressed by matter density
- Time-dependent, also affected by shock propagation

Density of matter in a supernova vs time



ν-sphere

shock wave

Densities at which MSW effect occurs

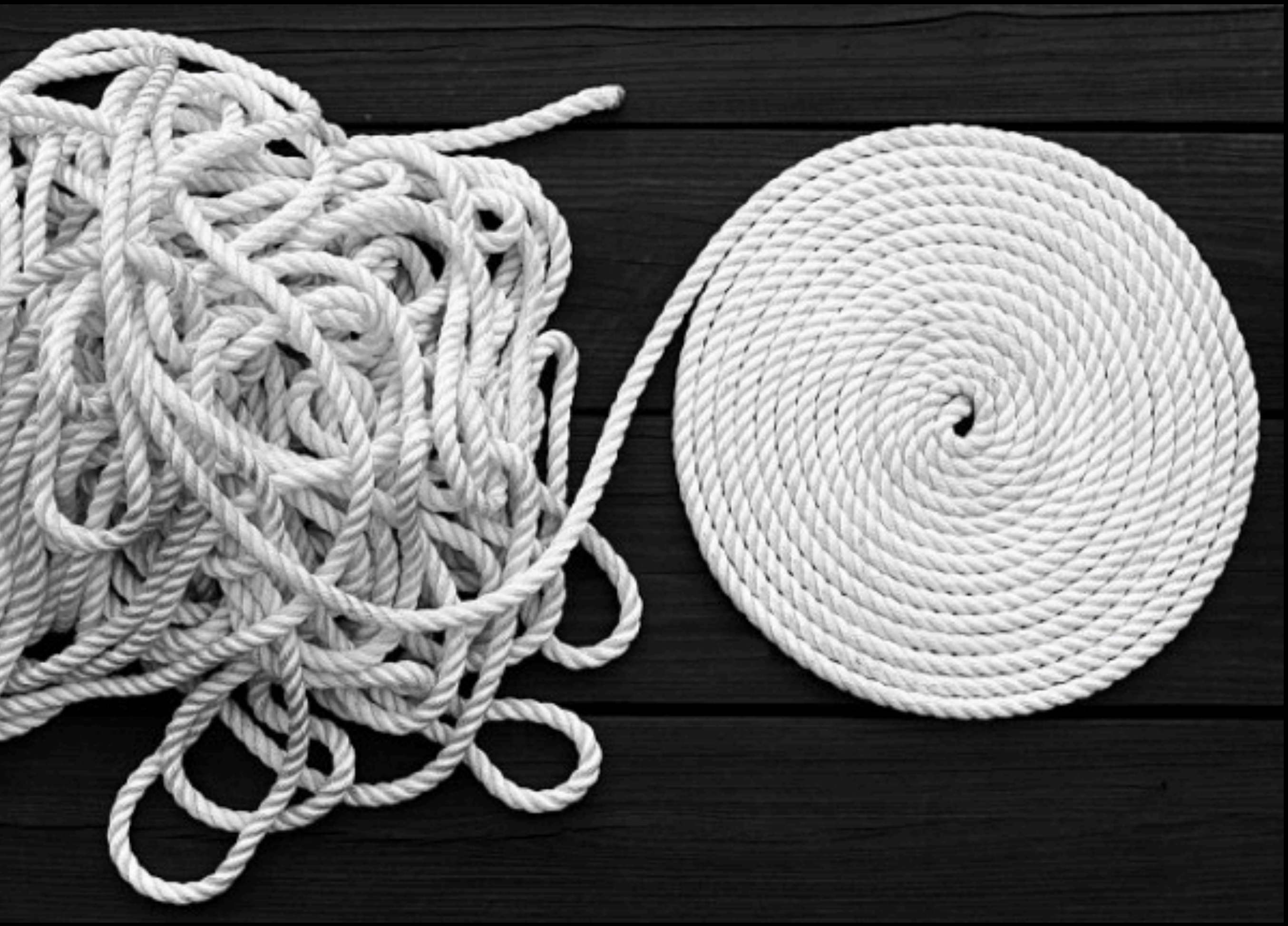
Collective effects

Both MSW and collective effects are complicated... depend on details of the initial fluxes, matter density profile, turbulence, shock wave propagation...

MSW is well understood,
but collective effects are
still under study...

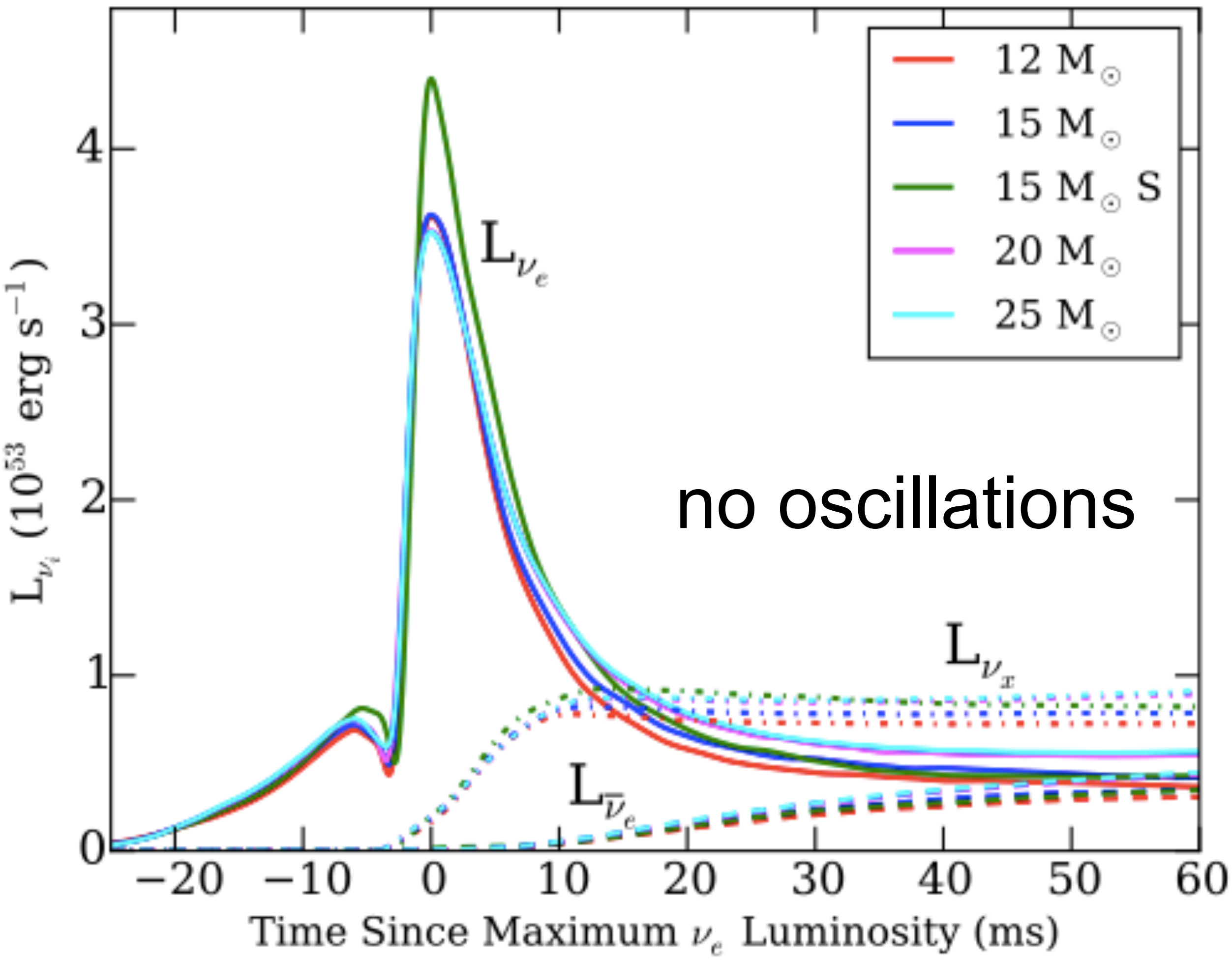
Both MSW and collective effects are complicated... depend on details of the initial fluxes, matter density profile, turbulence, shock wave propagation...

MSW is well understood,
but collective effects are
still under study...



Challenge for theorists is to find **robust, model-independent observables...** challenge for experimentalists is to understand and optimize observability

An example of a robust MO signature: the neutronization burst



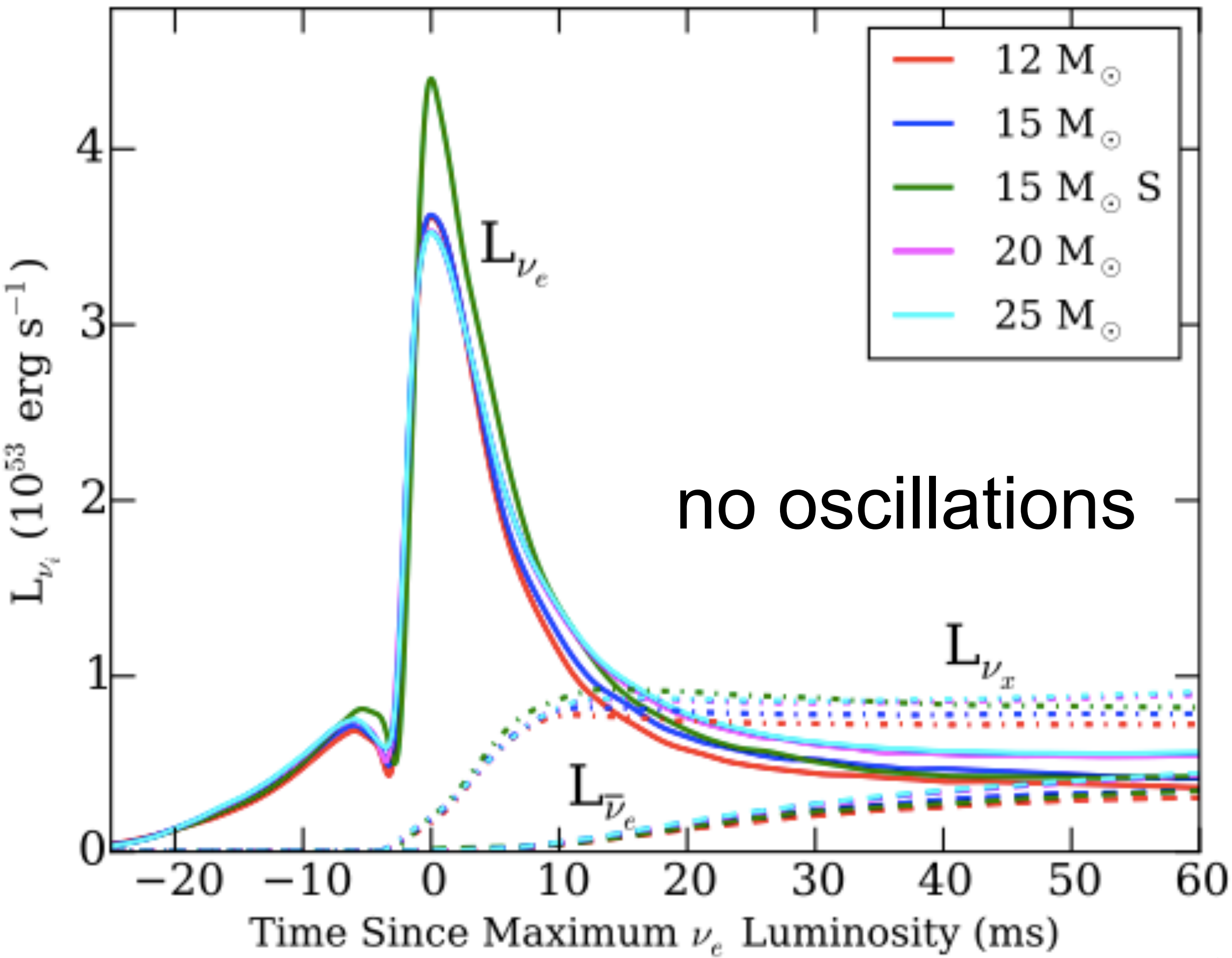
J. Wallace et al., Ap.J., 817, 182 (2016)

- almost a “standard candle”, ~independent of model
- strongly dominated by **electron flavor**
- ~no collective effects; MSW oscillations only

NMO: $F_{\nu_e} = F^0_{\nu_x}$

IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$

An example of a robust MO signature: the neutronization burst



J. Wallace et al., Ap.J., 817, 182 (2016)

- ~no collective effects; MSW oscillations only

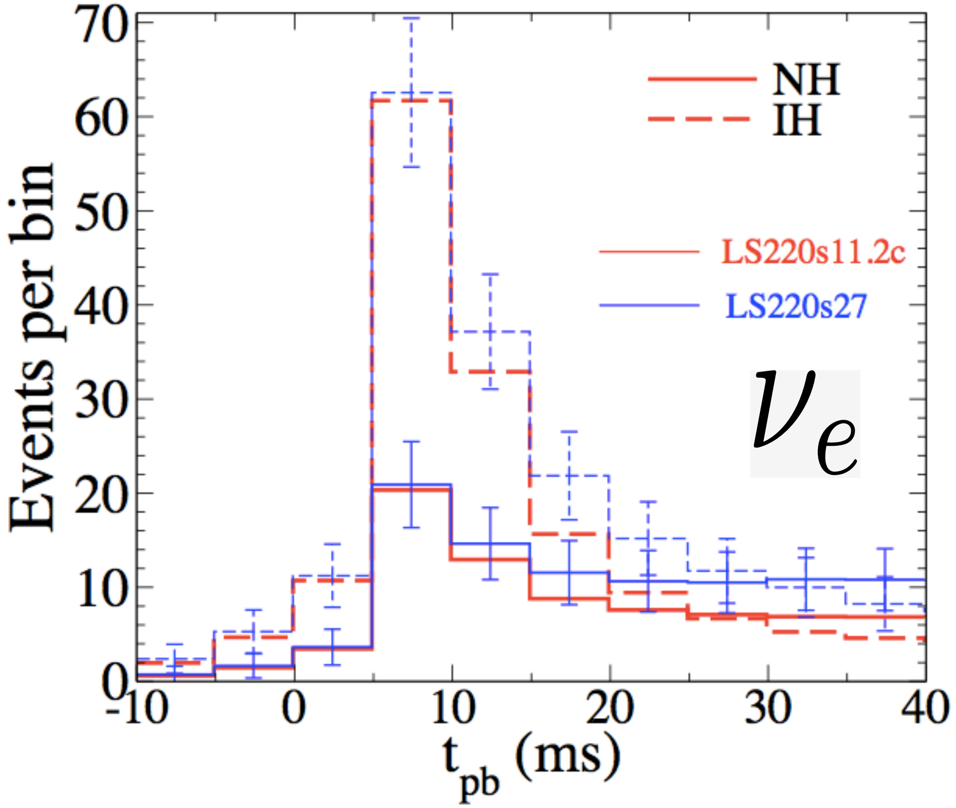
NMO: $F_{\nu_e} = F^0_{\nu_x}$ ➔ ν_e strongly suppressed, since ~no ν_x

IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$ ➔ ν_e suppressed by $\sin^2\theta_{12}$~0.31

➔ suppression for IMO,
stronger suppression for NMO

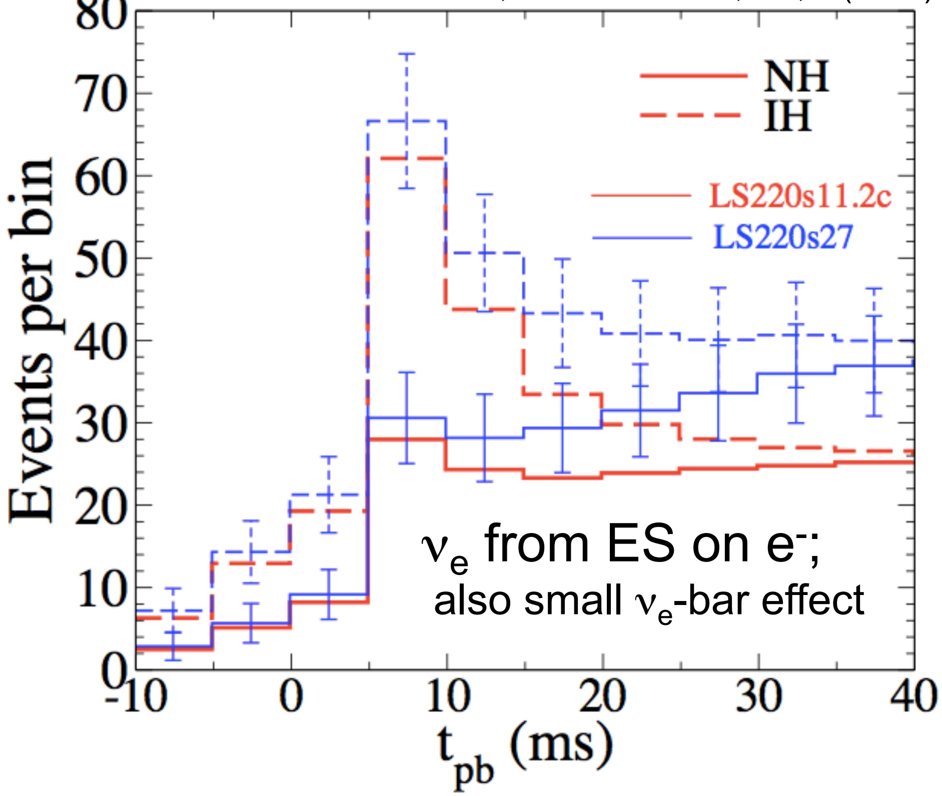
An example of a robust MO signature: the neutronization burst

40 kton LAr



560 kton water

A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016)



ν_e from ES on e^-;
also small ν_e-bar effect

NMO: $F_{\nu_e} = F^0_{\nu_x}$

IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$

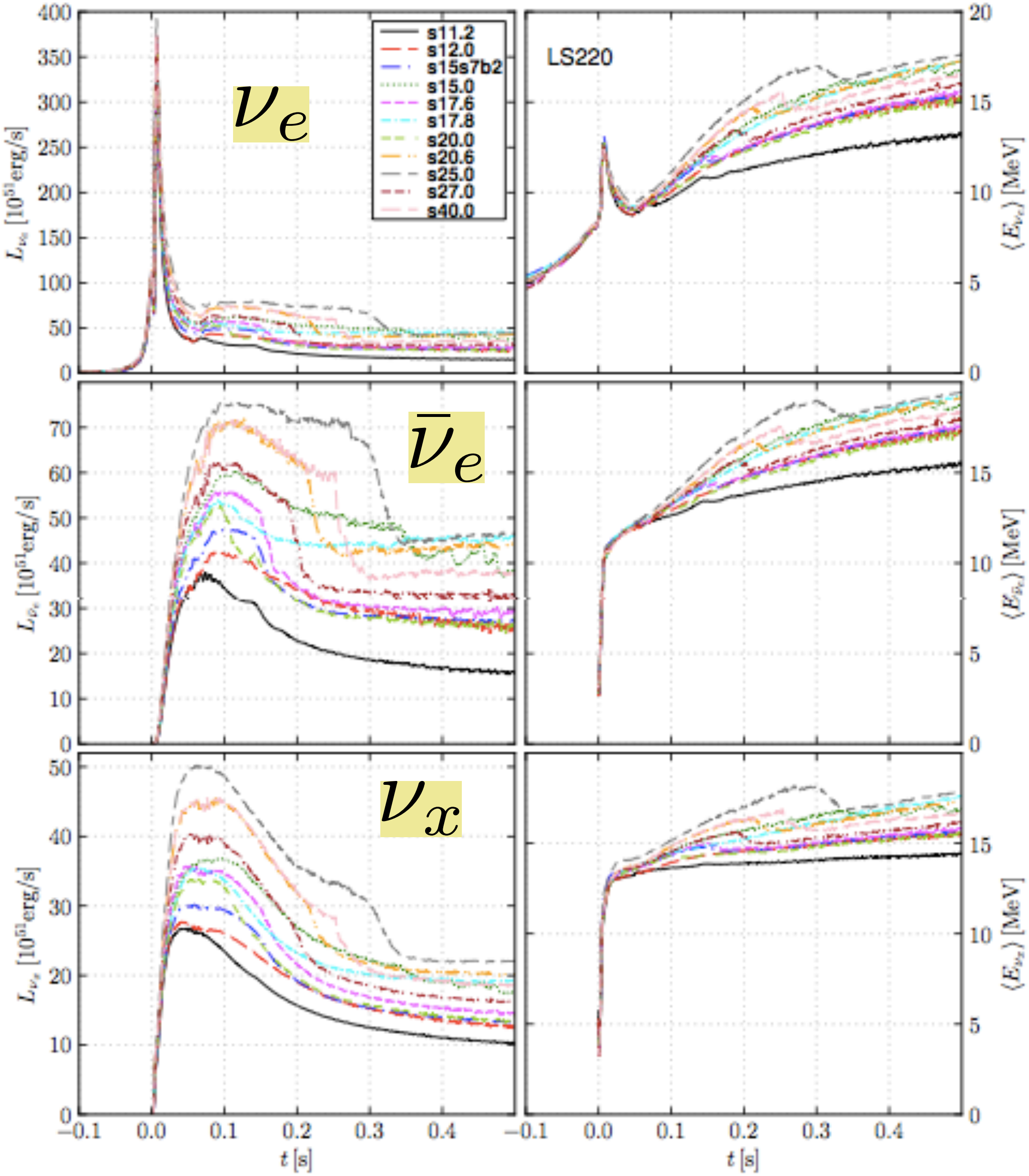
NMO: $F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$

IMO: $F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$

suppression for IMO,
stronger suppression for NMO

Another somewhat robust example: early time profile

Different lines represent different 1D “Garching” models



Still MSW-dominated;
ν_e-bar and ν_x-bar turning on

NMO: $F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$
IMO: $F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$

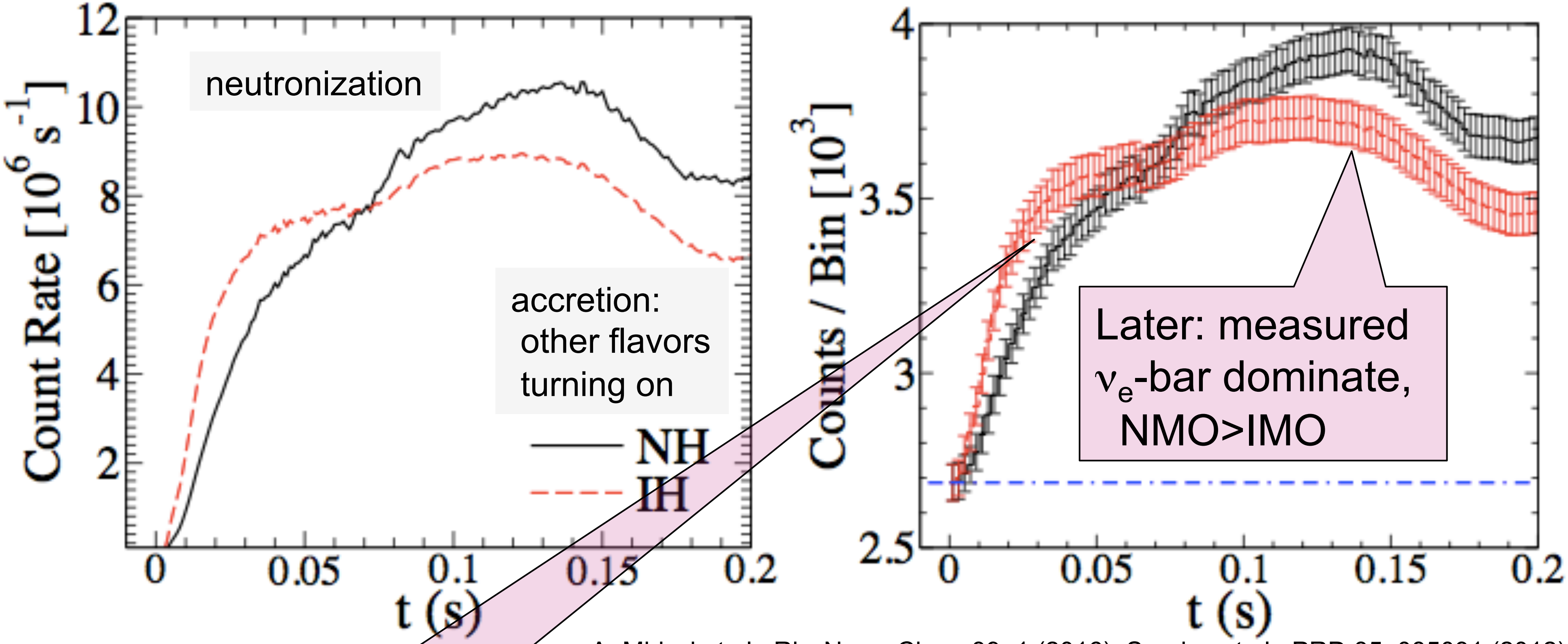
NMO ➔ ν_e-bar mostly non-oscillated
IMO ➔ ν_e-bar represents original ν_x-bar flux, which is lower during accretion, so will be suppressed

A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016),
B. T. Janka et al., PTEP 2012, 01A309

Another somewhat robust example: early time profile

Still MSW-dominated; ν_e-bar and ν_x-bar turning on

IceCube signal: integrated Cherenkov photons



Later: measured ν_e-bar dominate, NMO>IMO

A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016), Serpico et al., PRD 85, 085031 (2012)

Early: measured ν_e dominate, IMO>NMO

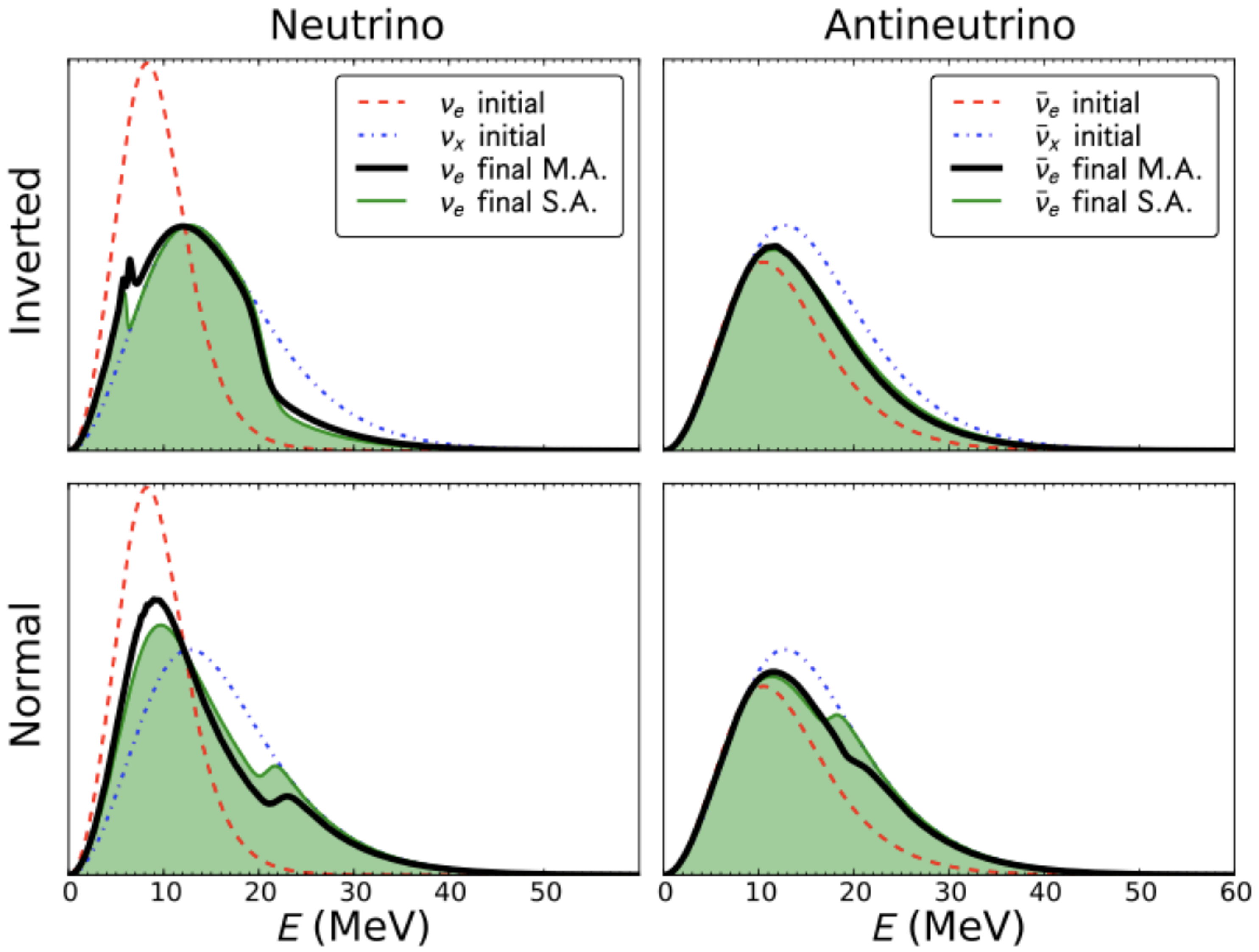
NMO ➔ ν_e-bar mostly non-oscillated

IMO ➔ ν_e -bar represents original ν_x-bar flux, which is lower during accretion

NMO ➔ ν_e strongly suppressed, since ~no ν_x

IMO ➔ ν_e suppressed by $\sin^2\theta_{12}$

Other examples: spectral swaps from collective effects



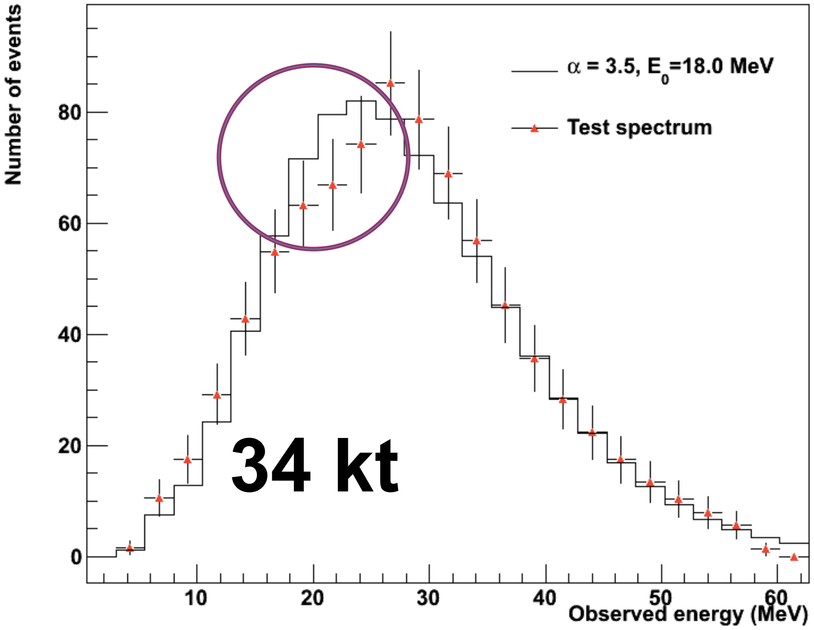
H. Duan & A. Friedland,PRD 106, 091101 (2011)

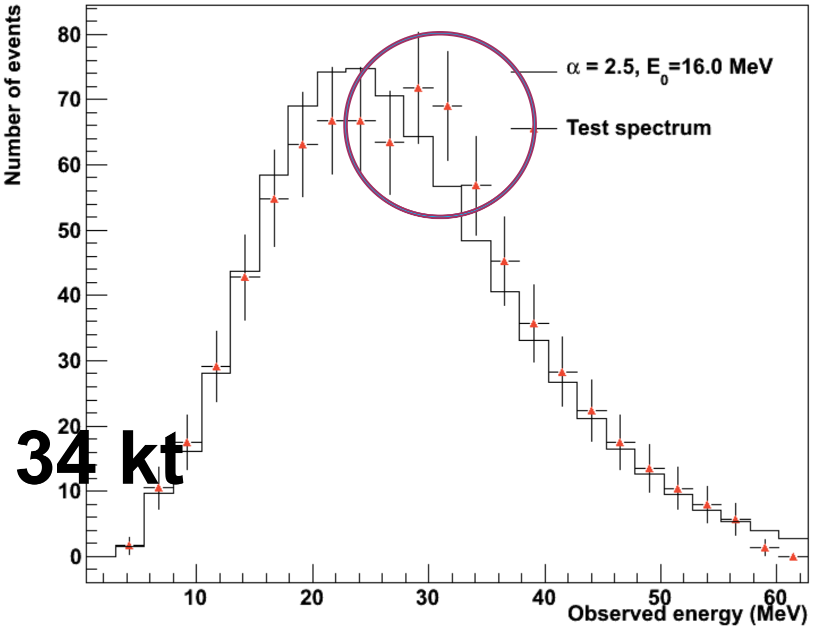
Distinctive spectral swap features depend on neutrino mass hierarchy, for neutrinos vs antineutrinos

Time-dependent shock-wave-induced effects

Snapshots at ~ 1 second intervals (1 s integration), 34-kt argon for cooling phase w/ shock, NMO

Adams et al., arXiv:1307.7335



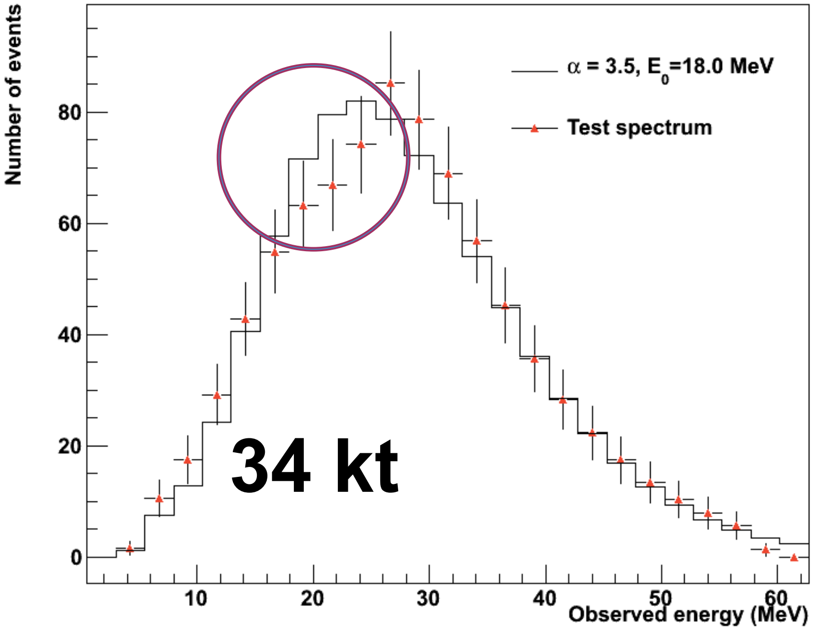


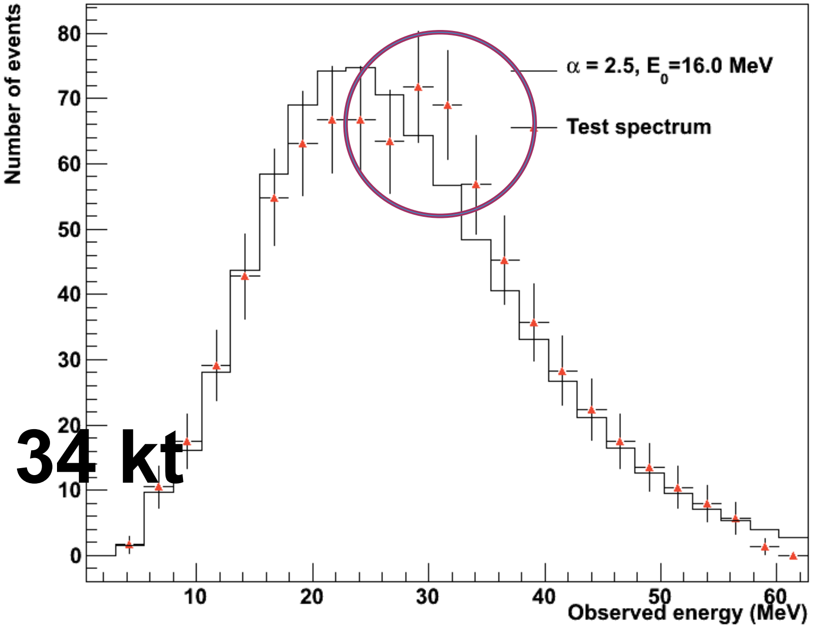
For NMO (*not* for IMO), “non-thermal” features clearly visible, and change as shock moves through the SN

10 kpc spectra from A. Friedland/JJ Cherry/H. Duan
smeared w/ SNOwGLoBES response w/collective effects
Black line: best fit to pinched thermal spectrum

Time-dependent shock-wave-induced effects

Snapshots at ~ 1 second intervals (1 s integration), 34-kt argon for cooling phase w/ shock, NMO



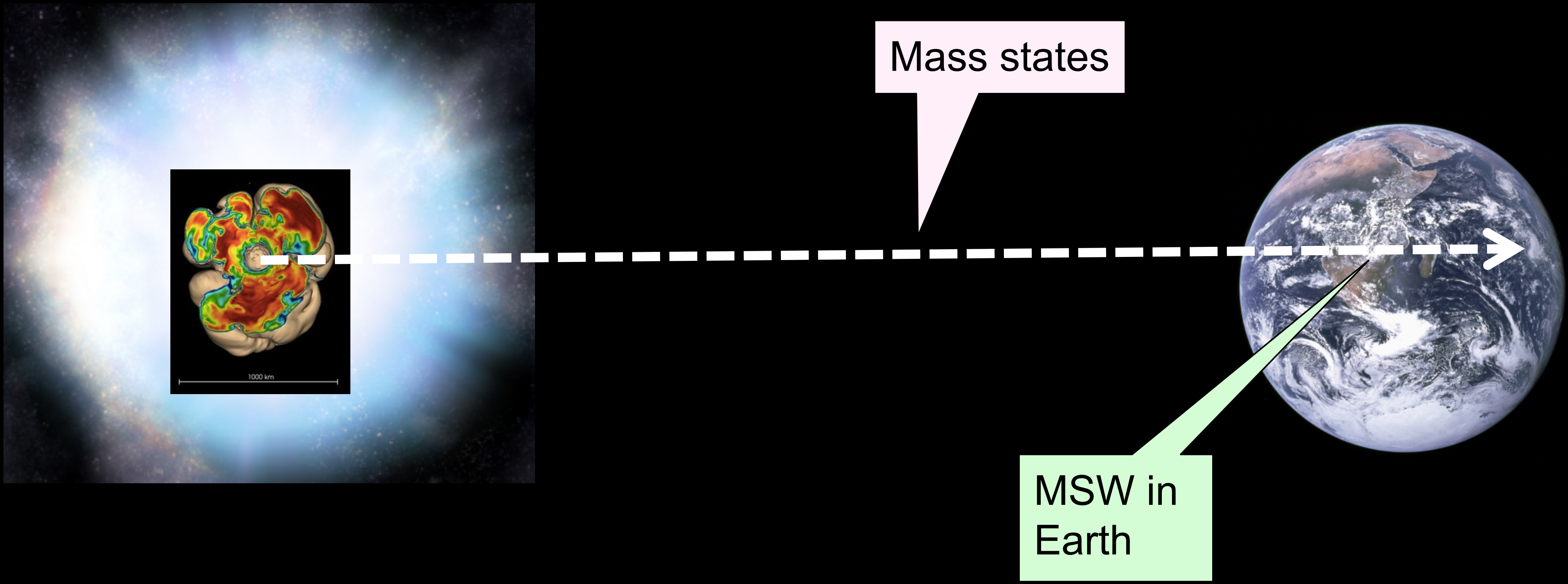


For NMO (*not* for IMO), “non-thermal” features clearly visible, and change as shock moves through the SN

10 kpc spectra from A. Friedland/JJ Cherry/H. Duan
smeared w/ SNOwGLoBES response w/collective effects
Black line: best fit to pinched thermal spectrum

Warning: collective effect signatures are still a bit of a Wild West; more theory work in progress

Neutrino Mixing in the Earth

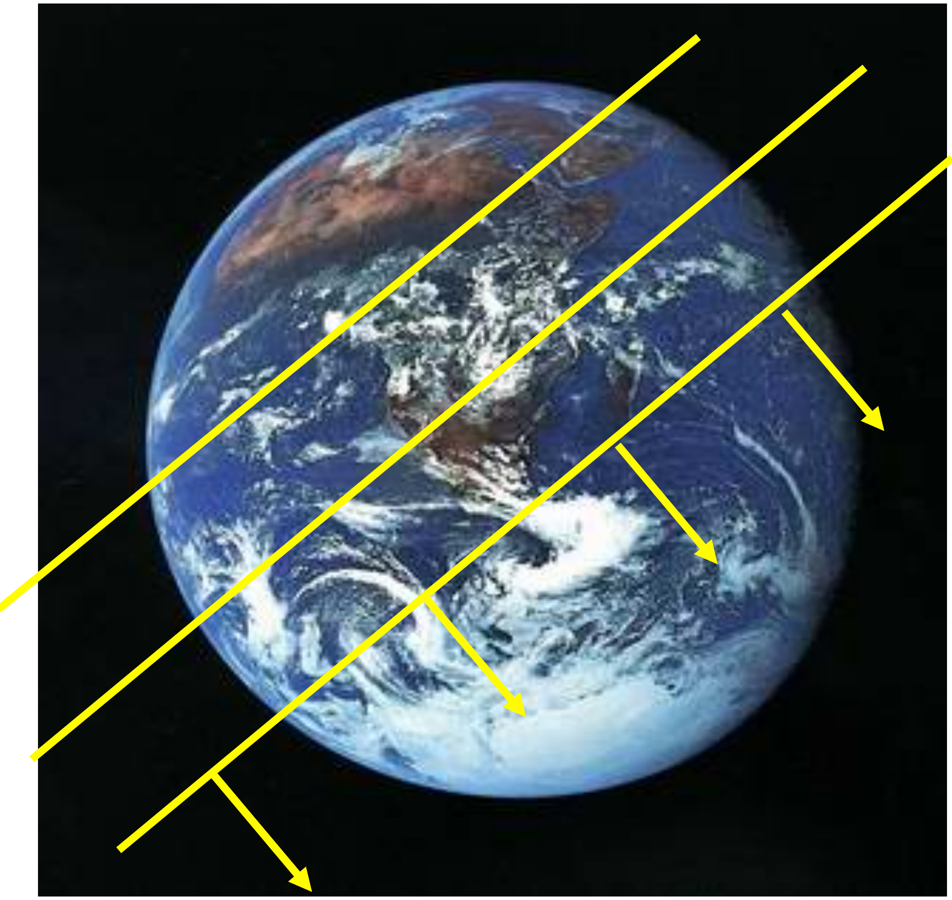


Mass states

MSW in Earth

- Well-understood, and supernova-model-independent!
- Alas, a small effect...
- Requires Earth shadowing

Matter-induced oscillations in the Earth



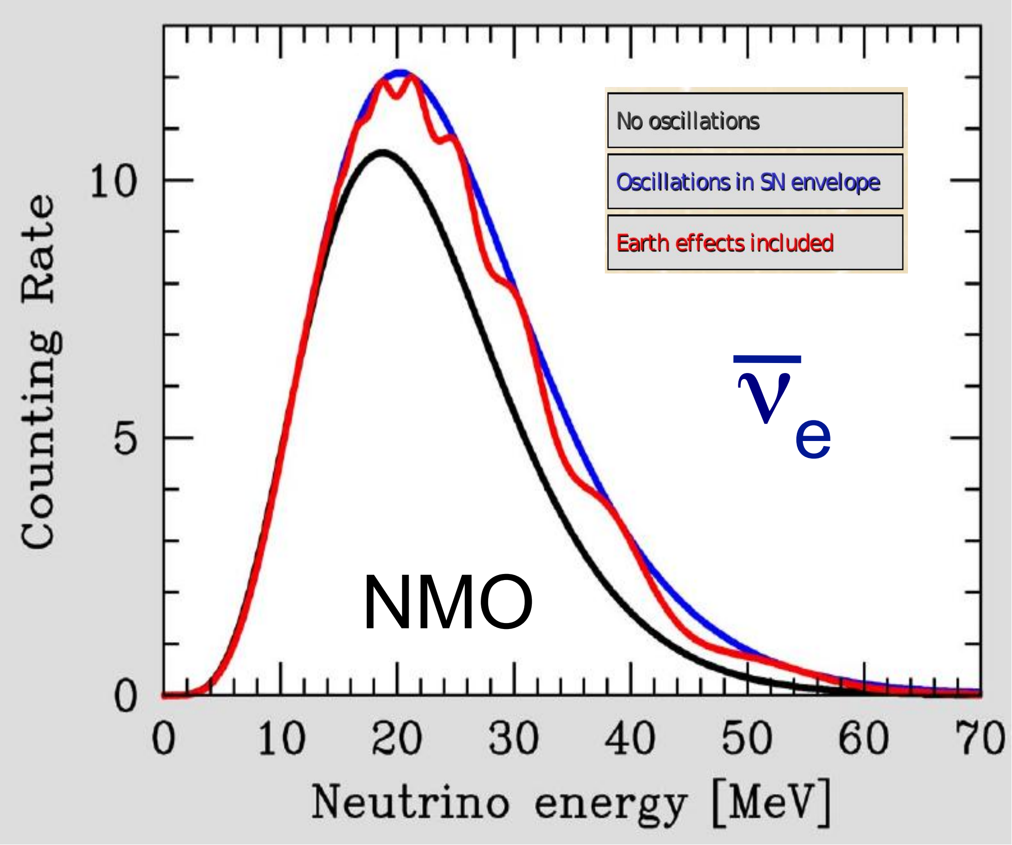
NMO: $F^{\oplus}_{\bar{\nu}_e} = (1-\bar{P}_{2e})F^0_{\bar{\nu}_e} + \bar{P}_{2e}F^0_{\bar{\nu}_x}$ and $F^{\oplus}_{\nu_e} = F^0_{\nu_x}$

IMO: $F^{\oplus}_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$ and $F^{\oplus}_{\nu_e} = (1-P_{2e})F^0_{\nu_e} + P_{2e}F^0_{\nu_x}$

$$P_{2e} = \sin^2\theta_{12} + \sin 2\theta^m_{12}\,\sin(2\theta^m_{12} - 2\theta_{12})\,\sin^2\left(\frac{\delta m^2 \sin 2\theta_{12}}{4E\,\sin 2\theta^m_{12}}\,L\right)$$

$$\bar{P}_{2e} = \sin^2\theta_{12} + \sin 2\bar{\theta}^m_{12}\,\sin(2\bar{\theta}^m_{12} - 2\theta_{12})\,\sin^2\left(\frac{\delta m^2 \sin 2\theta_{12}}{4E\,\sin 2\bar{\theta}^m_{12}}\,L\right)$$

G.Raffelt

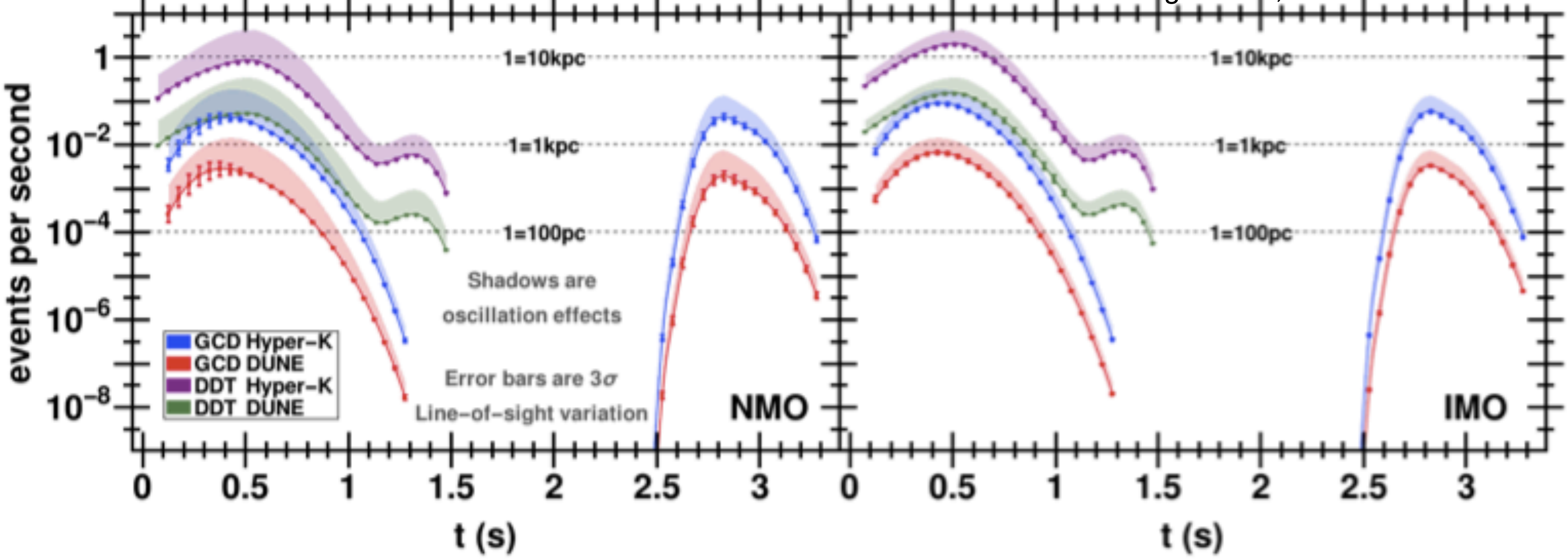


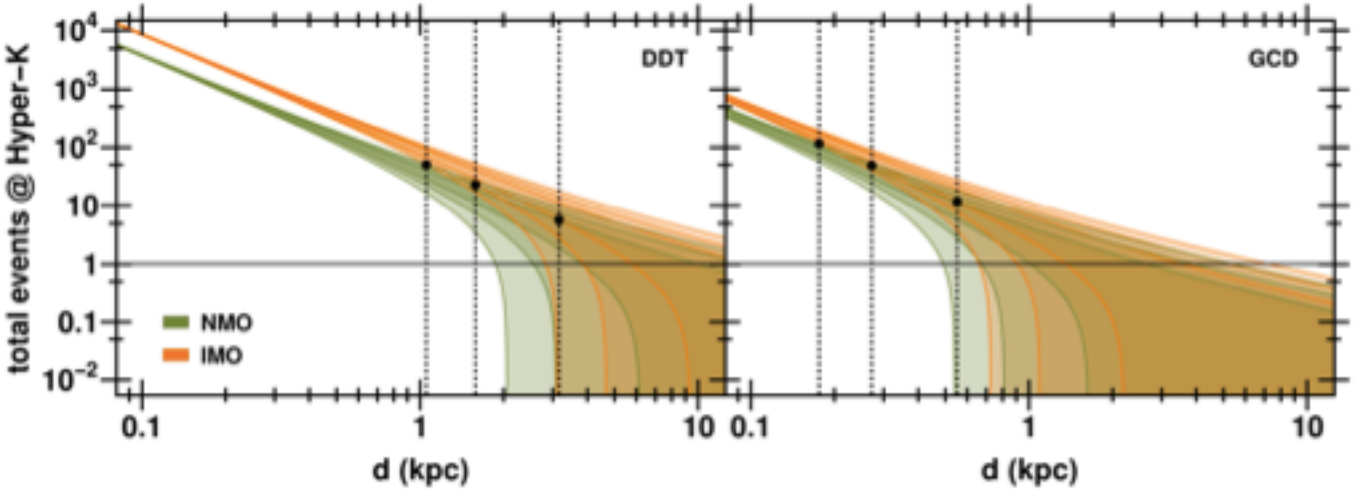
Requires very good energy resolution to resolve wiggles

A long shot: Type Ia Supernovae

- Thermonuclear mechanism (specific mechanism unknown)
- MSW oscillations only (ν density too low for collective)
- Very low flux, but observable within ~1 kpc for next-generation expts

W. Wright et al.,arXiv:1609.07403





If mechanism is known, w/HK can discriminate MO @ 1σ for d<3.17 kpc for DDT model, d<0.55 kpc for GCD

Need to be lucky!

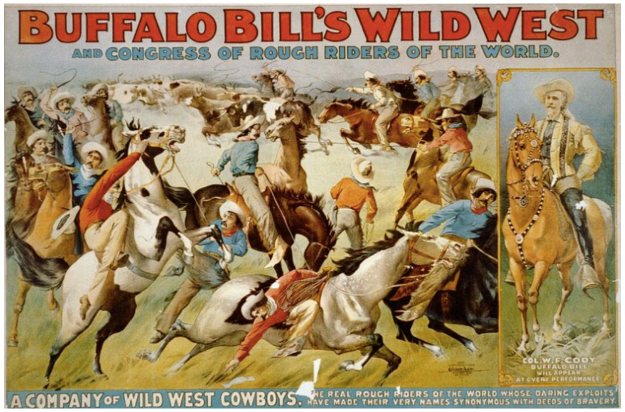
Summary Table for MO Signatures

	Normal	Inverted	Robustness	Observability
Neutronization burst	Very suppressed	Suppressed	Quite	Good, need ν_e (HK, DUNE,...)
Early time profile	Low then high	Flatter	Somewhat	Good, need stats (IceCube...)
Collective effects	Multiple time- and energy-dependent signatures		Yee-haw	Good, want multiple (all...)
Earth Matter	Wiggles in anti-ν_e	Wiggles in ν_e	Excellent	Hard, need energy resolution, stats (JUNO,...)
Type I	Higher flux	Lower flux	Quite	Hard, need stats +luck (HK, DUNE,...)

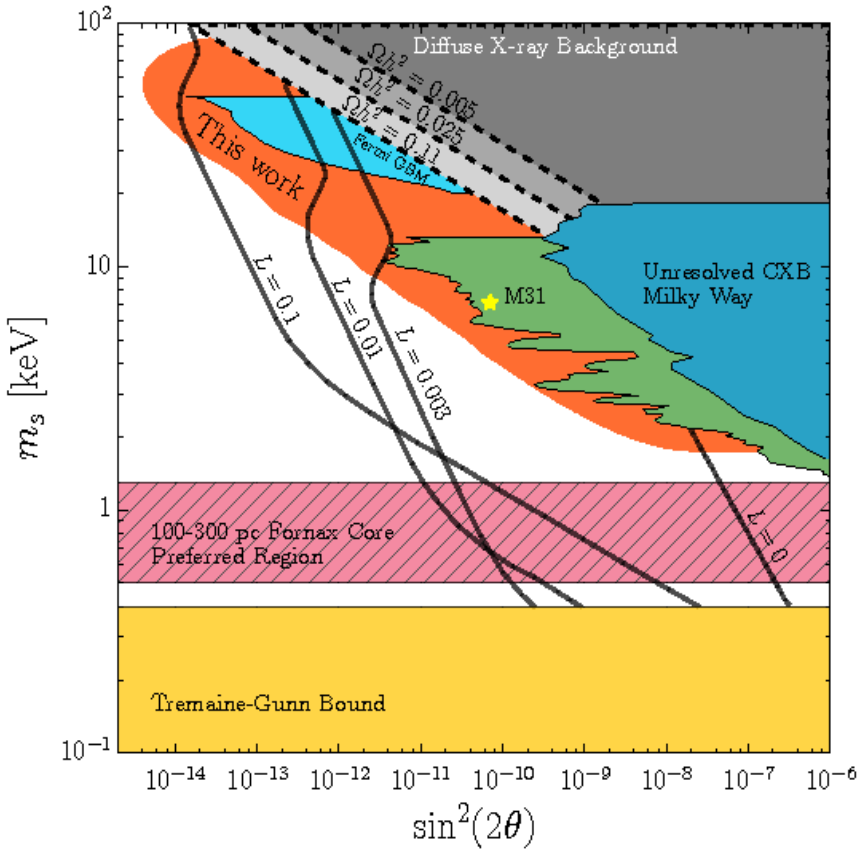
For supernova neutrinos, the more the merrier!

New Neutrino States or Interactions?

Sterile neutrinos, non-standard ν interactions, other exotica...



An even wilder West...
can have complicated
effects on flavor time-evolution



But some robust bounds
from the "energy leakage"
argument

Limits on ~keV sterile neutrinos

C. A. Argüelles, et al. arXiv:1605.00654 [hep-ph]
See A. Smirnov talk at this workshop

Summary

A nearby supernova will bring information much information about neutrinos as well as core-collapse physics (in a virtuous circle)

✧ Absolute mass: not competitive with near-future laboratory measurements, but should not be forgotten

✧ **Mass ordering:** several approaches, some still under theoretical study, but some robust

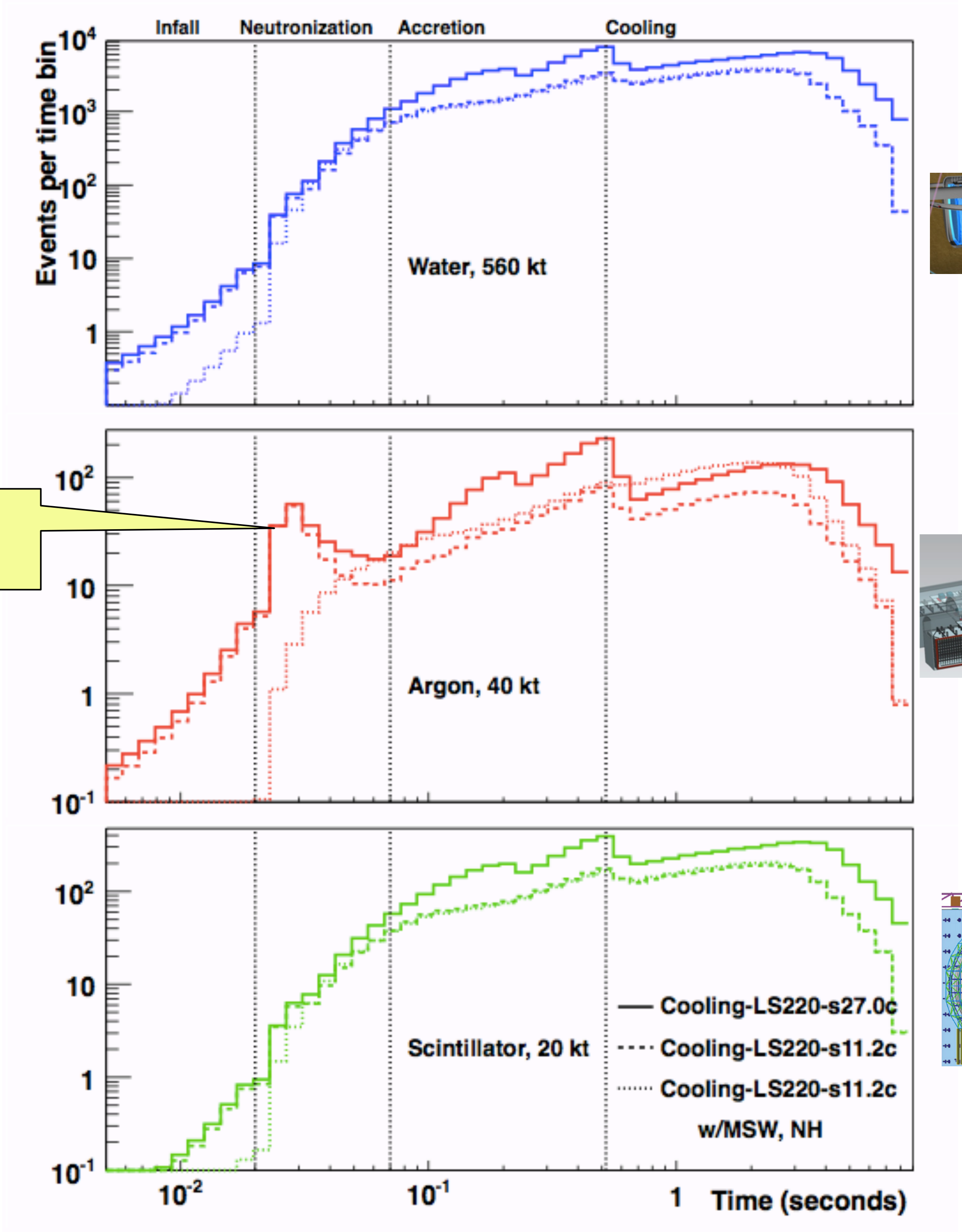
✧ Information on BSM physics also possible... maybe surprises...

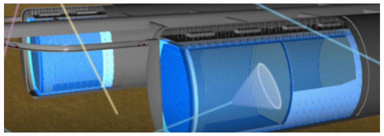
Need energy, flavor, time structure...
all detectors bring something to the table

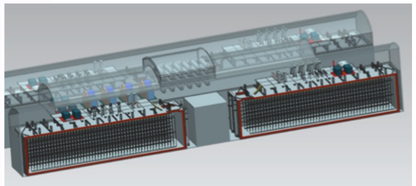
Extras/backups

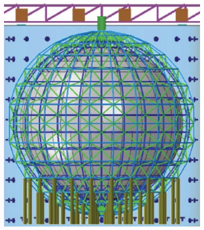
Example signals in future detectors

Neutronization burst in argon









(note logarithmic time bins)