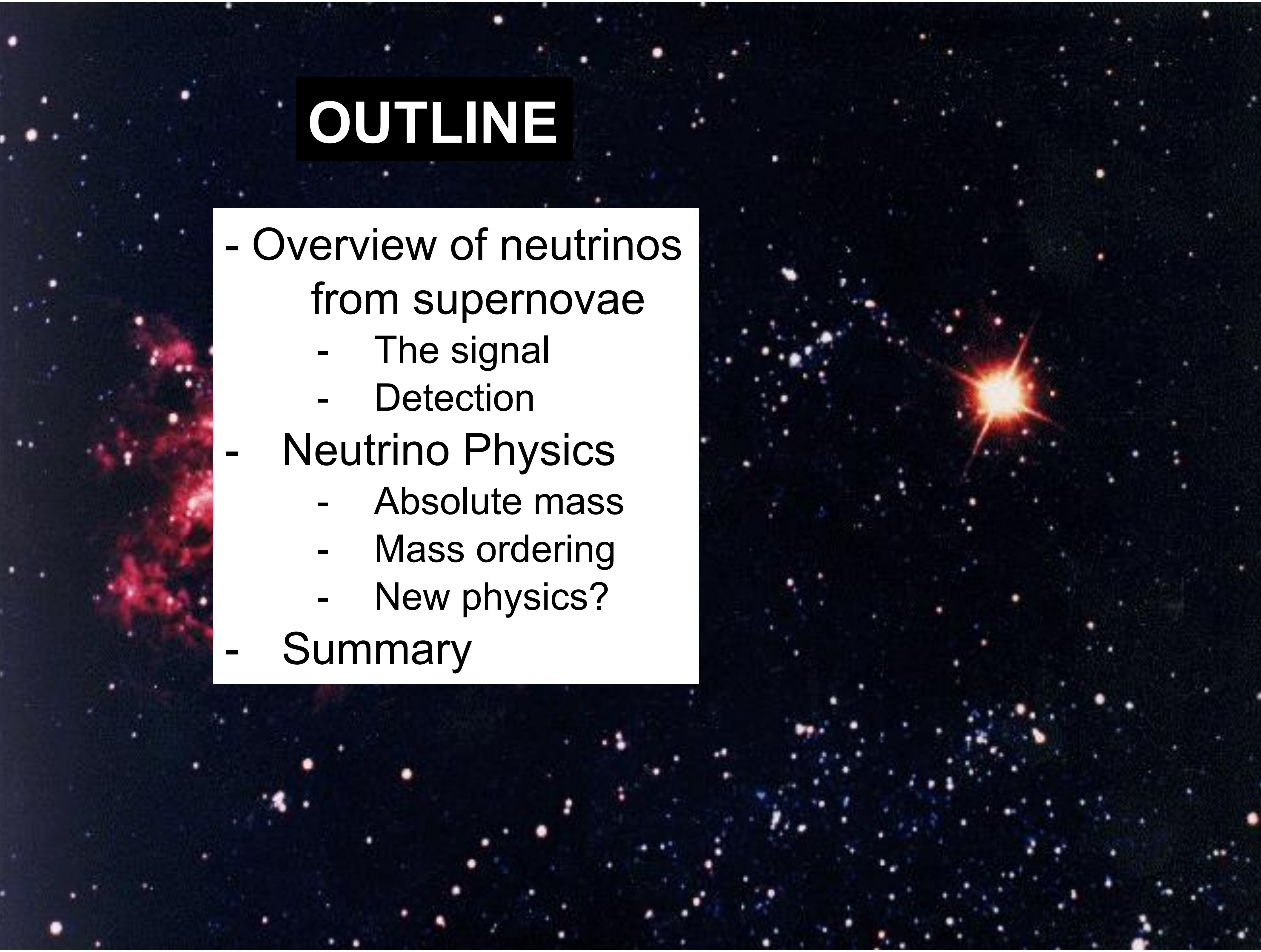
Determining Neutrino Properties from Supernova Neutrinos

Supernova Neutrino Detection

Kate Scholberg, Duke University
Solvay Workshop, Brussels, November 2017

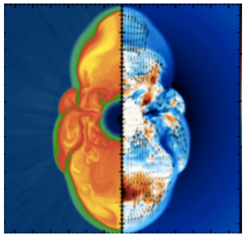


OUTLINE

- 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?

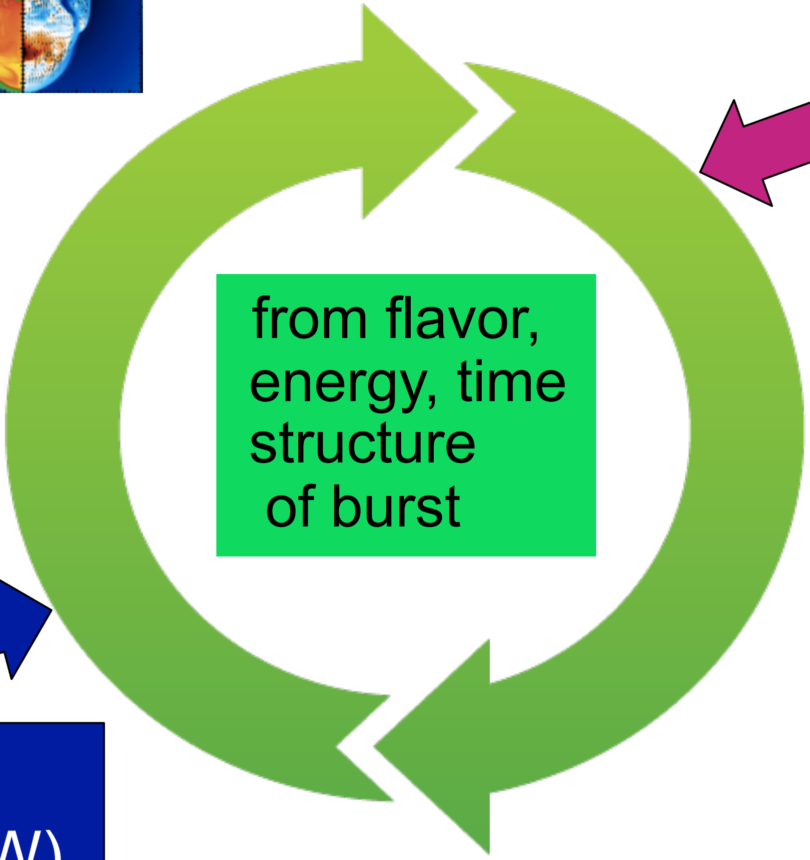
CORE COLLAPSE PHYSICS



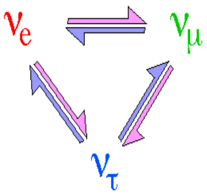
explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from photon (GW) observations

input from neutrino experiments



from flavor, energy, time structure of burst



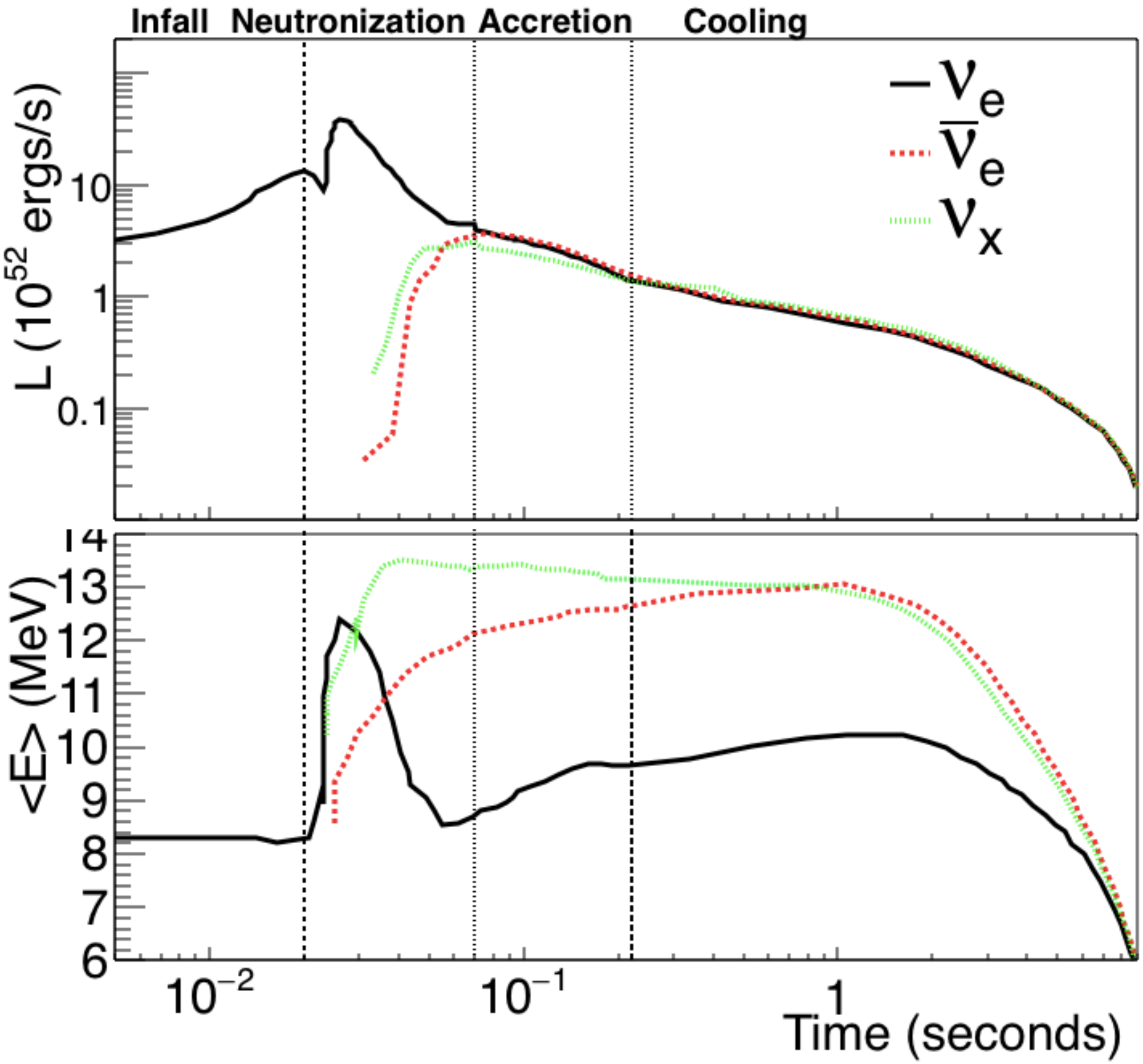
NEUTRINO and OTHER PARTICLE PHYSICS

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, ...

+ EARLY ALERT

Expected neutrino luminosity and average energy vs time

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



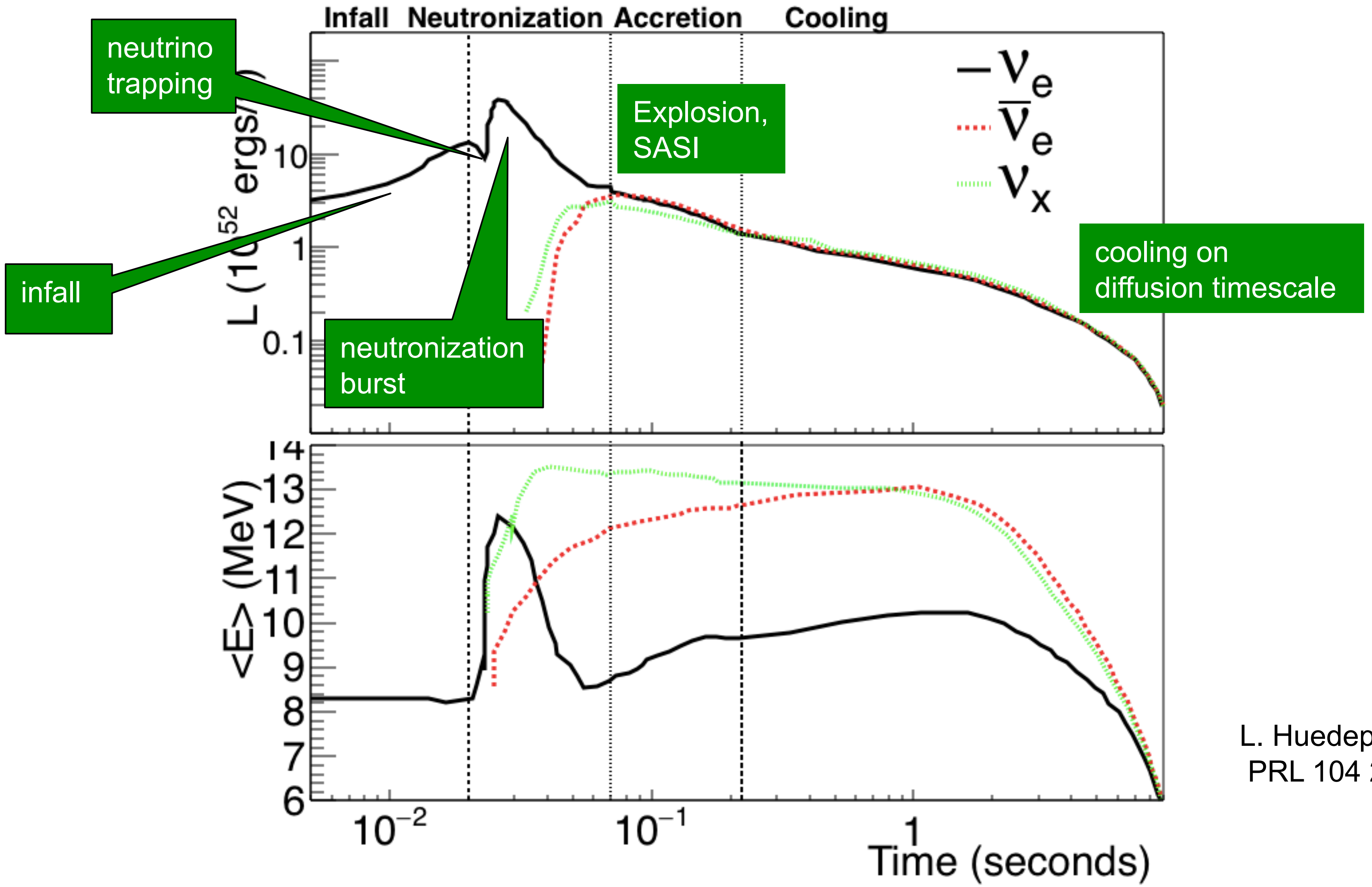
L. Huedepohl et al.,
PRL 104 251101

Generic feature:
(may or may not be robust)

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

Expected neutrino luminosity and average energy vs time

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



neutrino trapping

Explosion, SASI

infall

neutronization burst

cooling on diffusion timescale

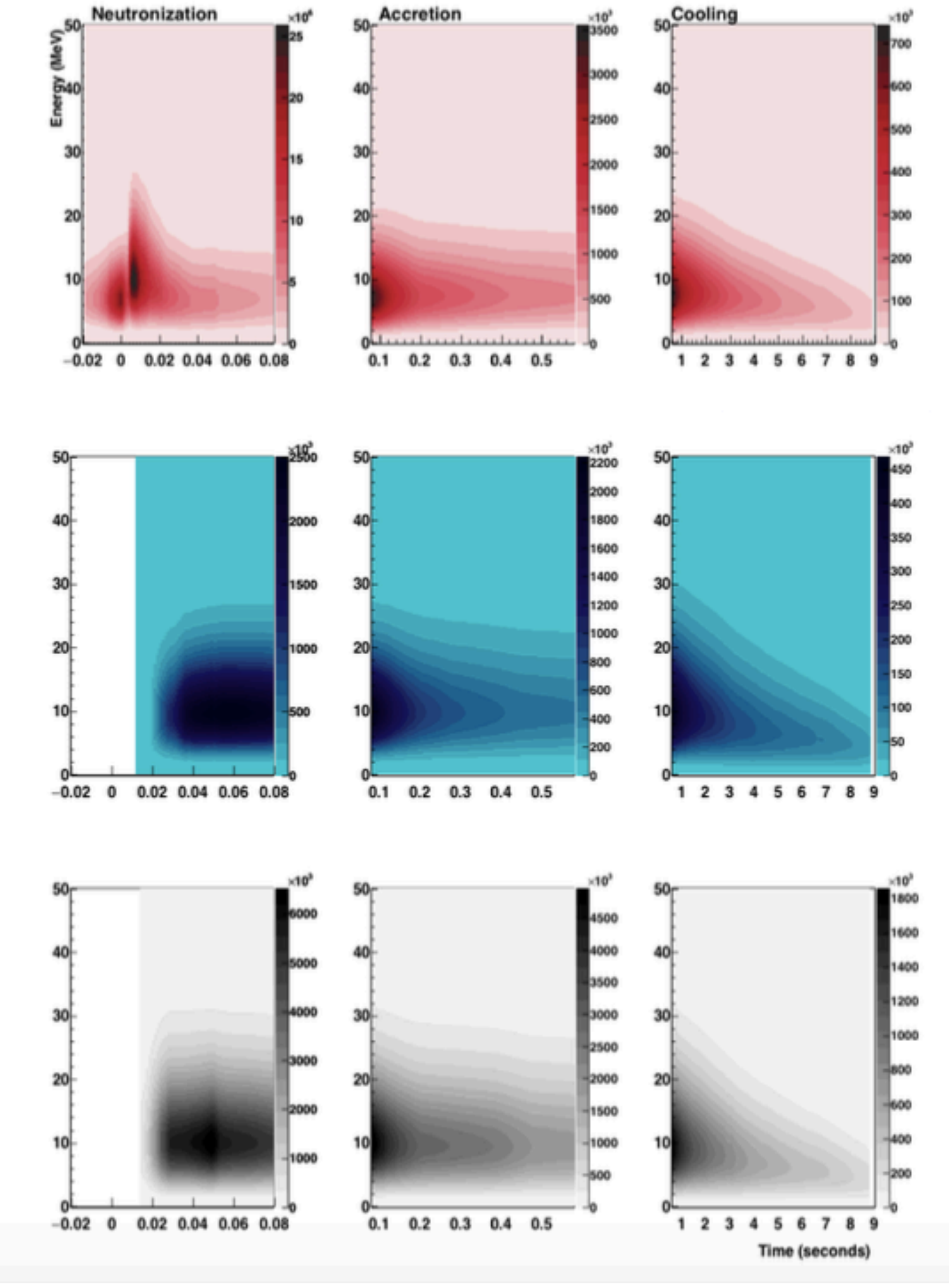
L. Huedepohl et al., PRL 104 251101

Generic feature:

(may or may not be robust)

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

Fluxes as a function of time and energy



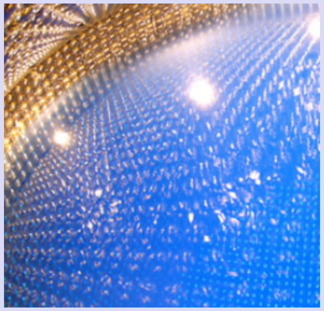
$$\nu_e$$

$$\bar{\nu}_e$$

$$\nu_x$$

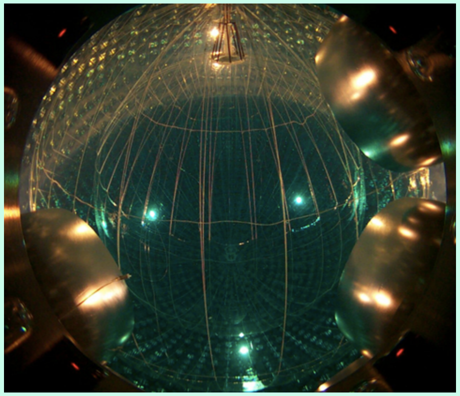
Supernova Neutrino Detectors

Water



$\bar{\nu}_e$

Scintillator



$\bar{\nu}_e$

Argon

ν_e

Lead

ν_e

+ some others (e.g. DM detectors)

Summary of supernova neutrino detectors

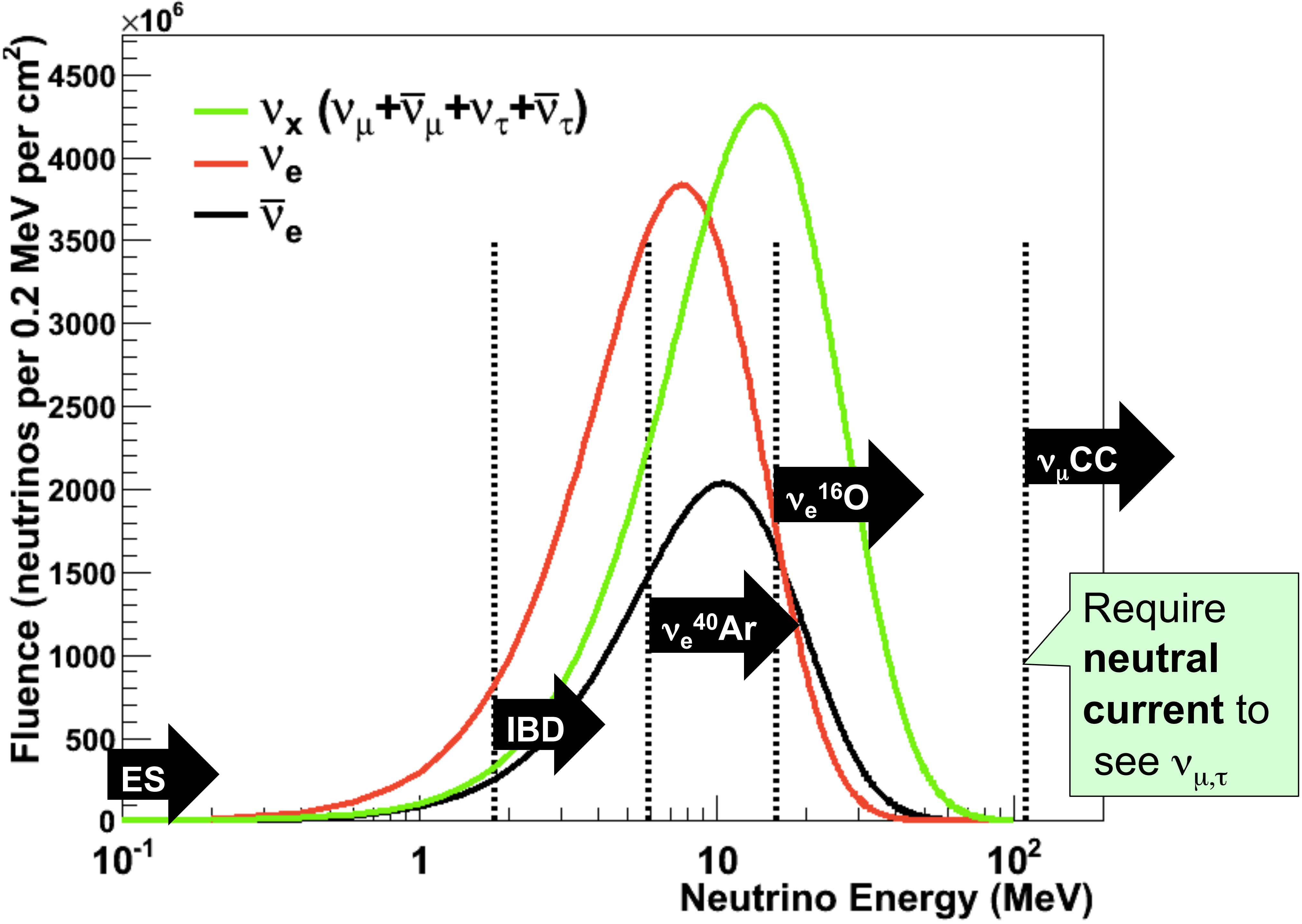
Galactic sensitivity

Extragalactic

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
NOvA	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	Future
PINGU	Long string	South pole	(600)	(10^6)	Future

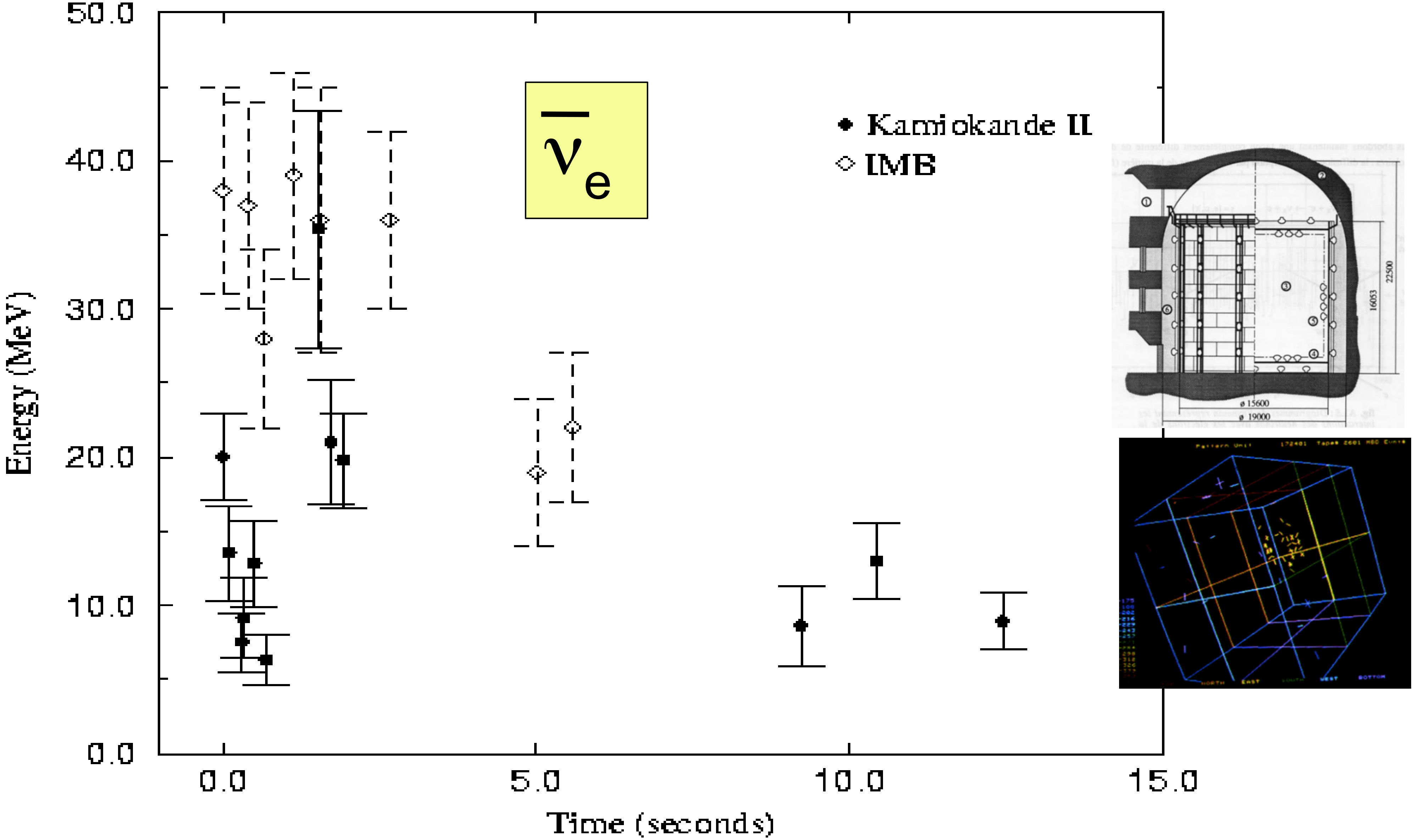
plus reactor experiments, DM experiments...

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...

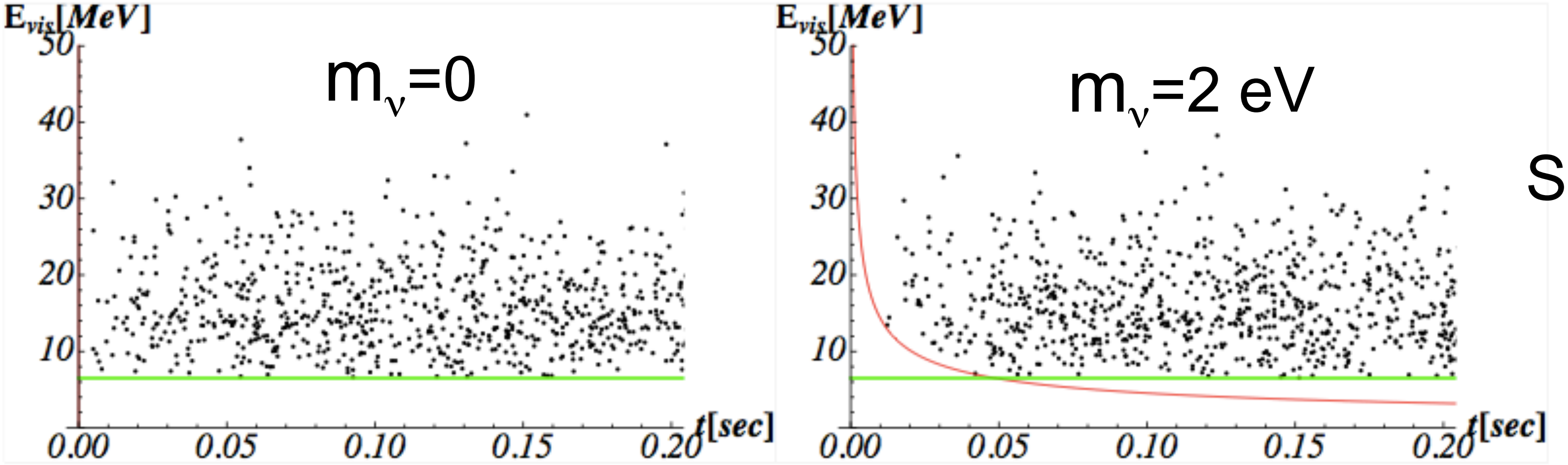
Neutrino Absolute Mass

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



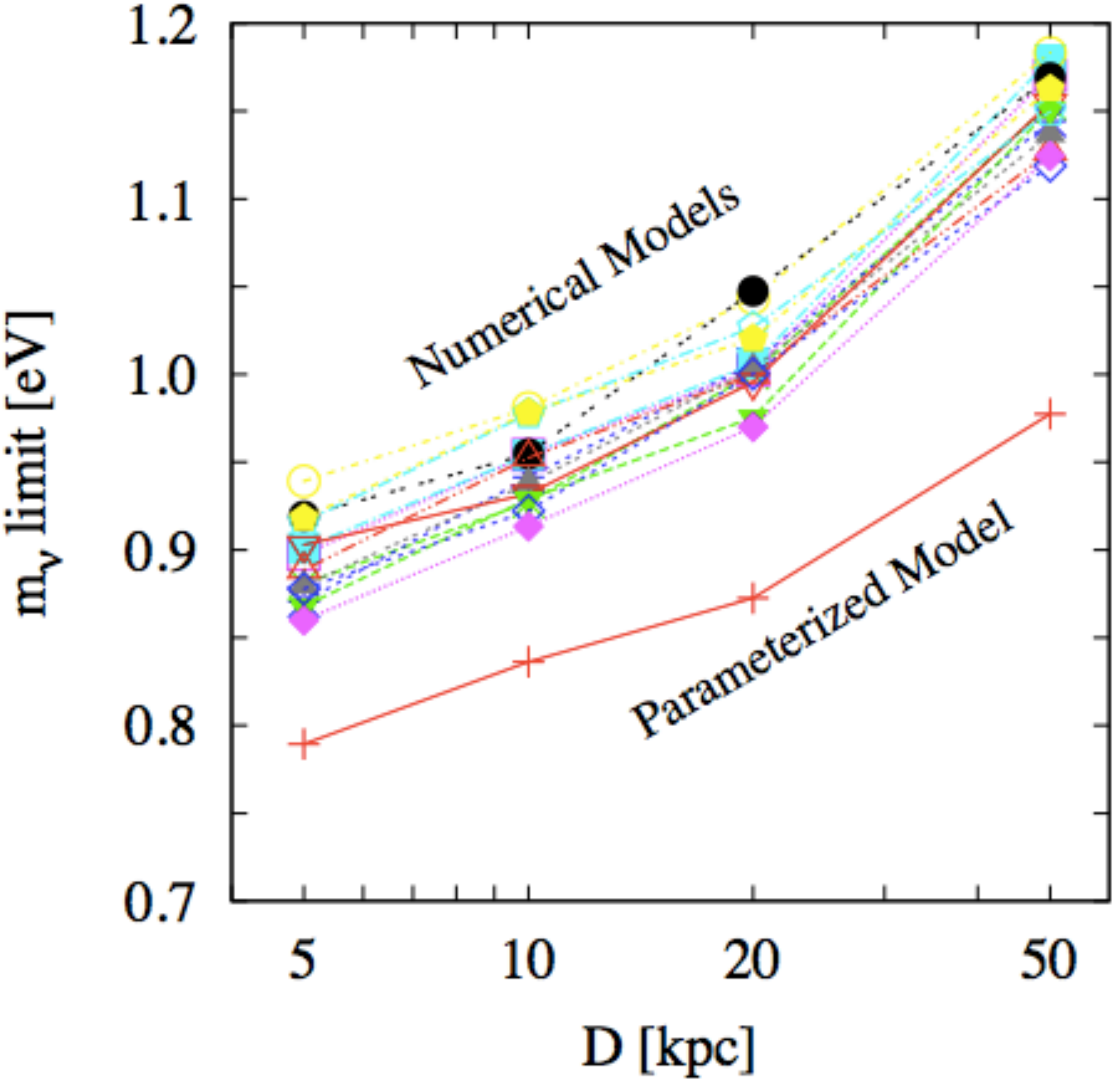
SK@10 kpc

$\bar{\nu}_e$

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

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

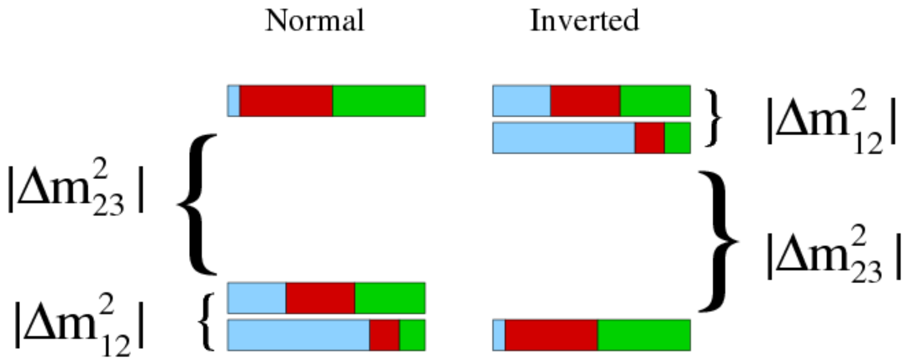
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

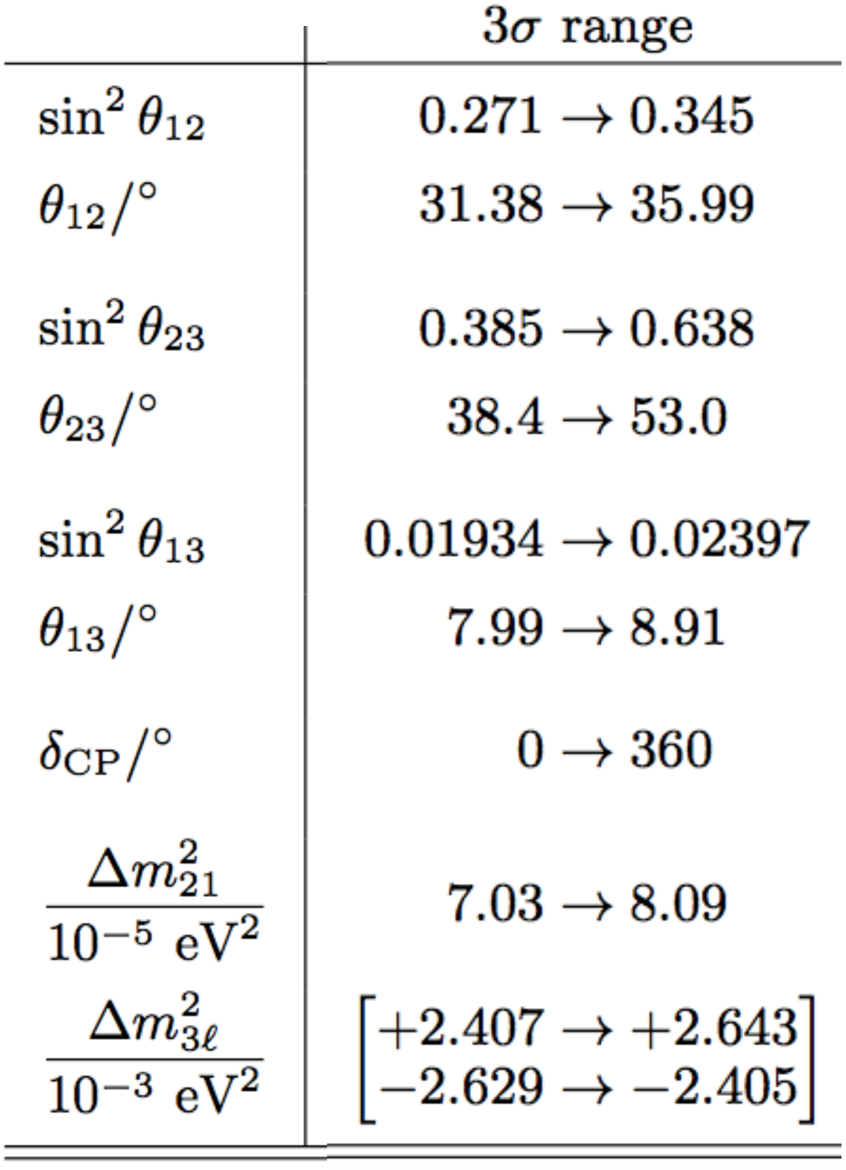
$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$



signs of the
mass differences
matter

The three-flavor picture fits the data well

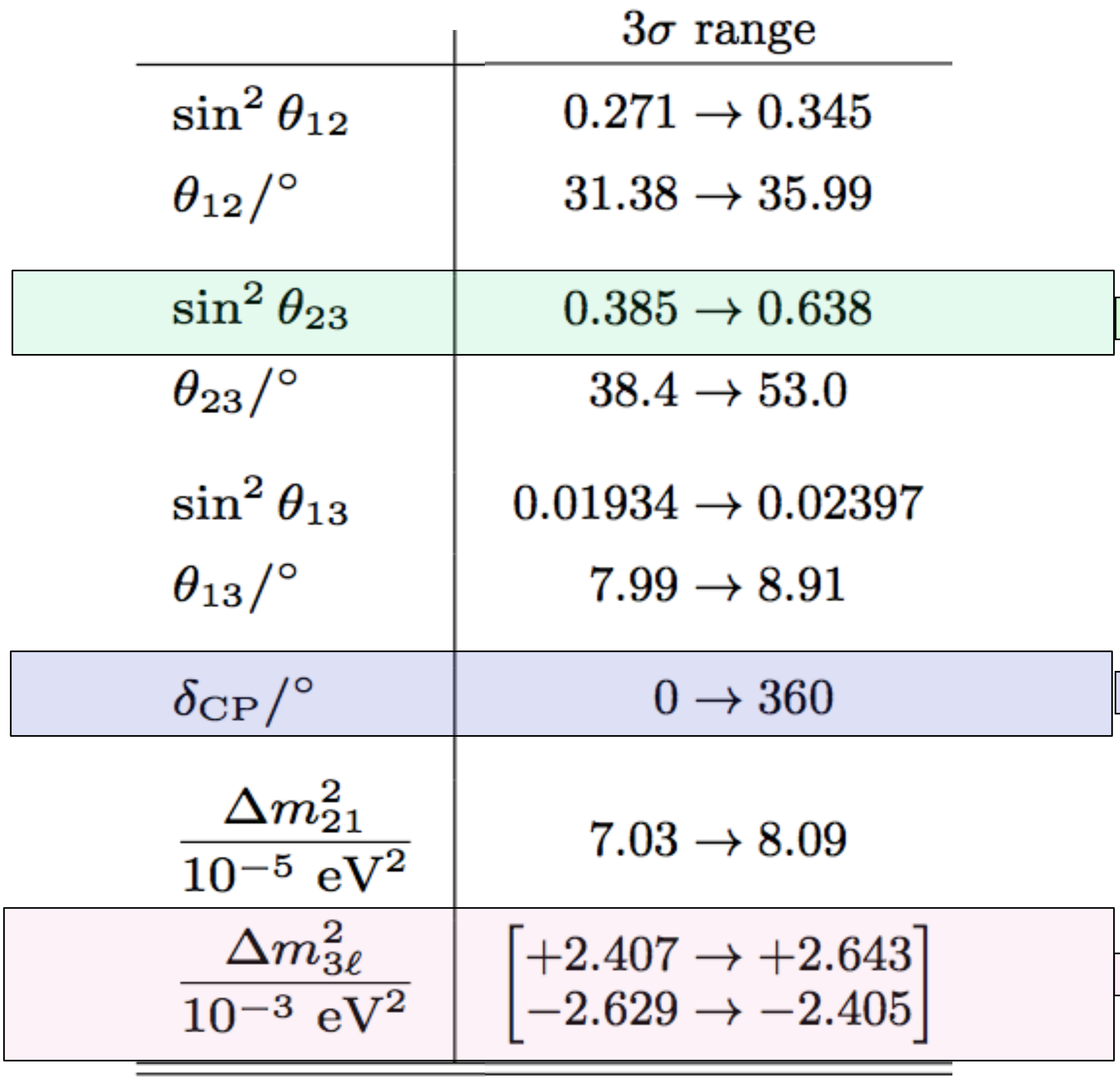
Global three-flavor fits to all data



	3σ range	3σ knowledge
$\sin^2\theta_{12}$	$0.271 \to 0.345$	
$\theta_{12}/^\circ$	$31.38 \to 35.99$	~14%
$\sin^2\theta_{23}$	$0.385 \to 0.638$	
$\theta_{23}/^\circ$	$38.4 \to 53.0$	~32%
$\sin^2\theta_{13}$	$0.01934 \to 0.02397$	
$\theta_{13}/^\circ$	$7.99 \to 8.91$	~11%
$\delta_{\mathrm{CP}}/^\circ$	$0 \to 360$	~no info
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.03 \to 8.09$	~14%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$	~9%

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, T. Schwetz, 1611.01514v2

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



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

basically unknown

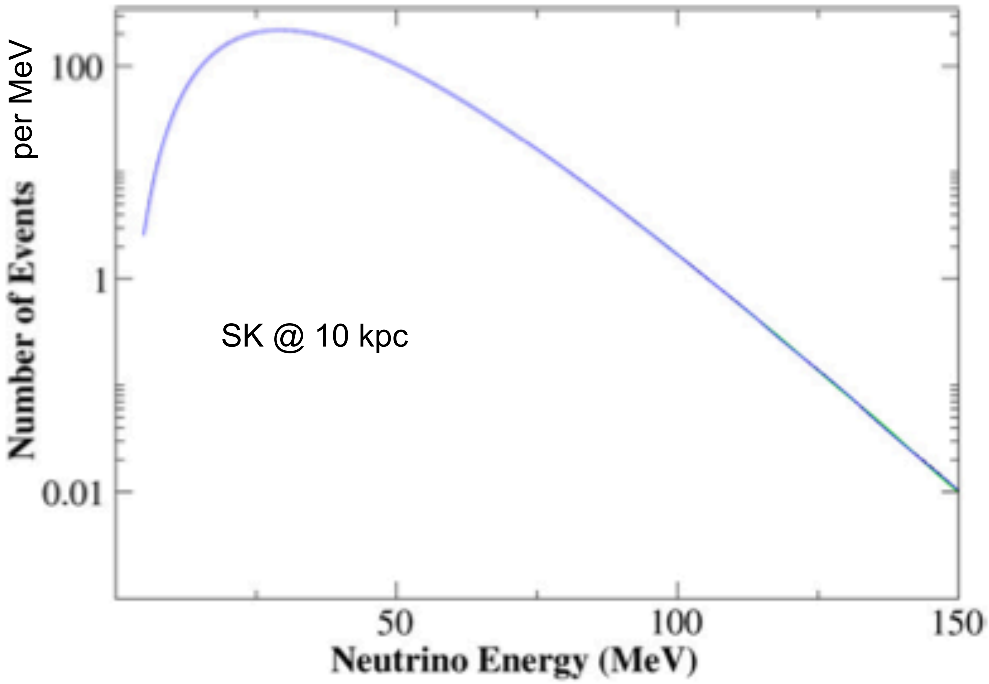
sign of Δm^2 unknown (ordering of masses)

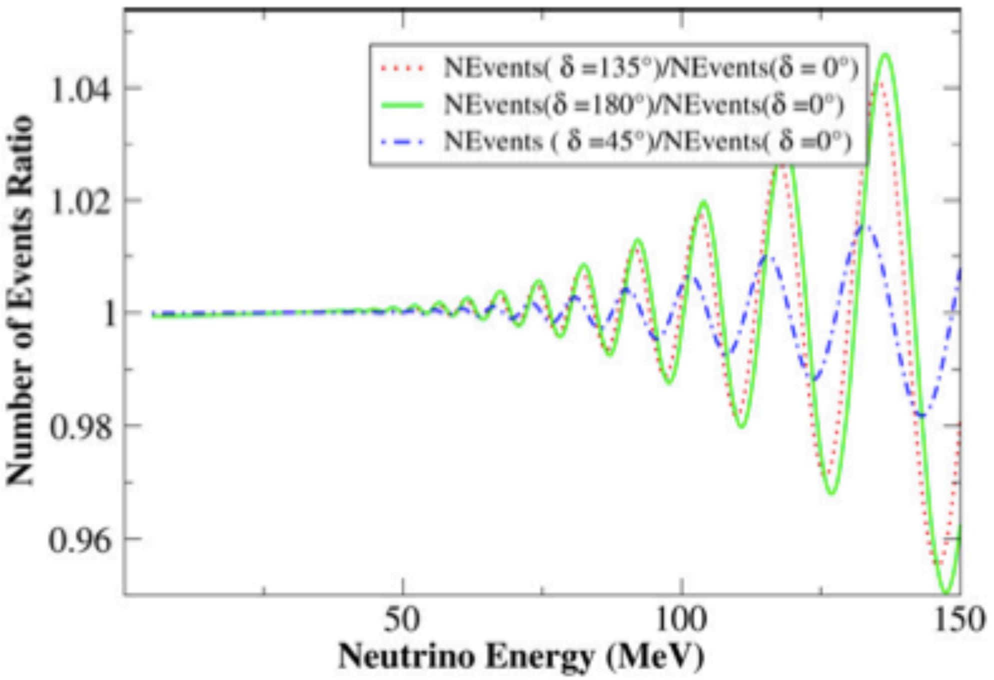
Can we learn about CP violation from a supernova?

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)

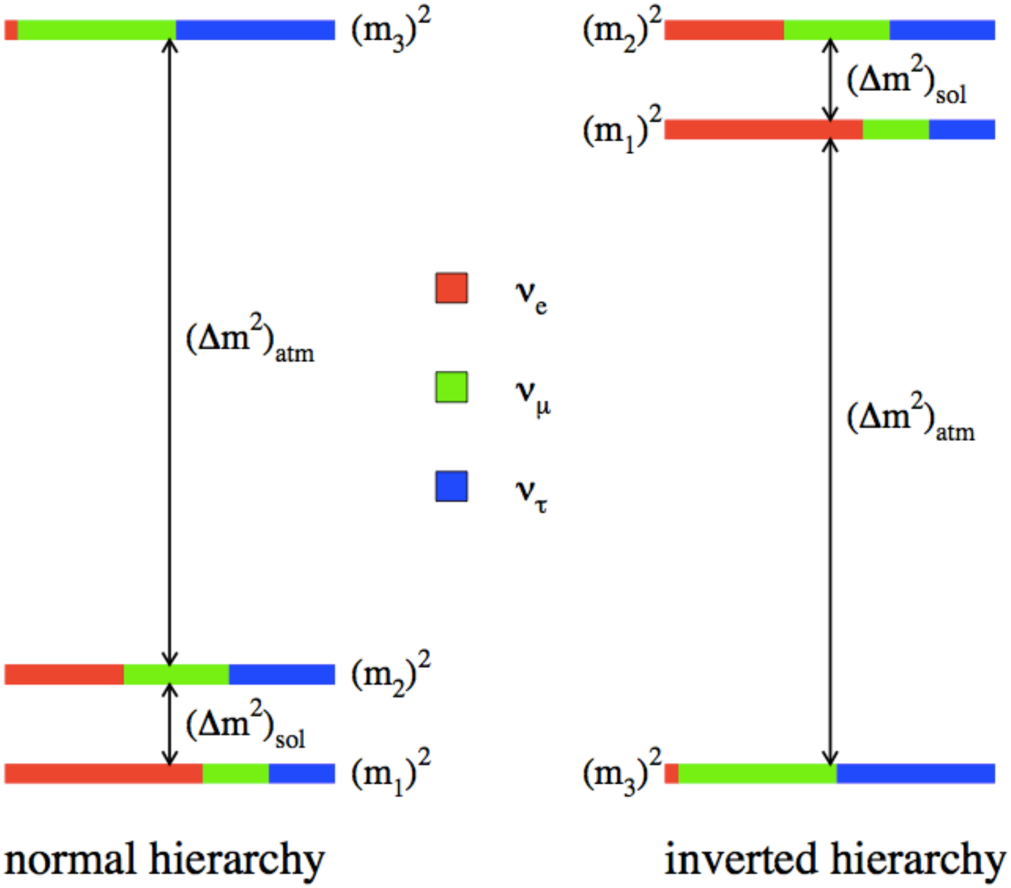




Next on the list to go after experimentally:

mass ordering (hierarchy)

(sign of Δm^2_{32})

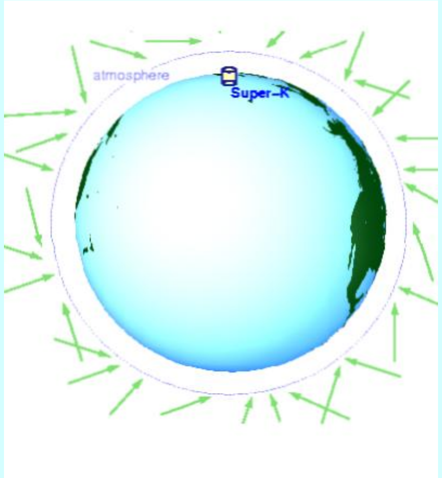


$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

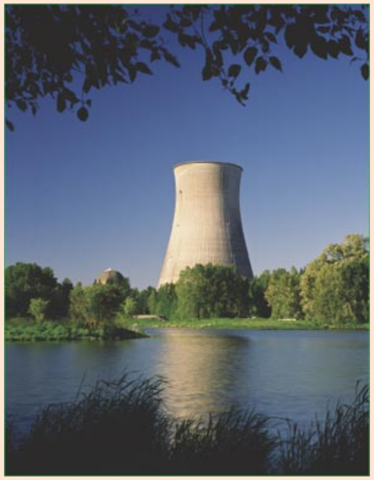
Four of the possible ways to get MO

Long-baseline beams

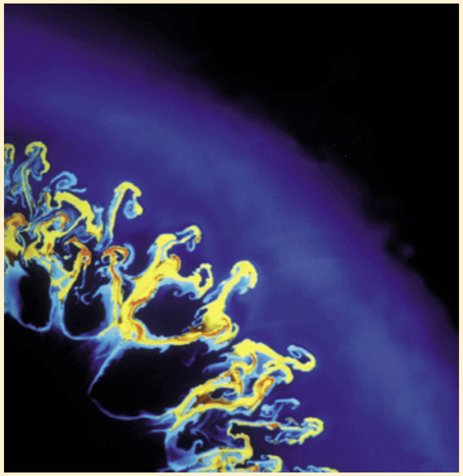
Atmospheric neutrinos



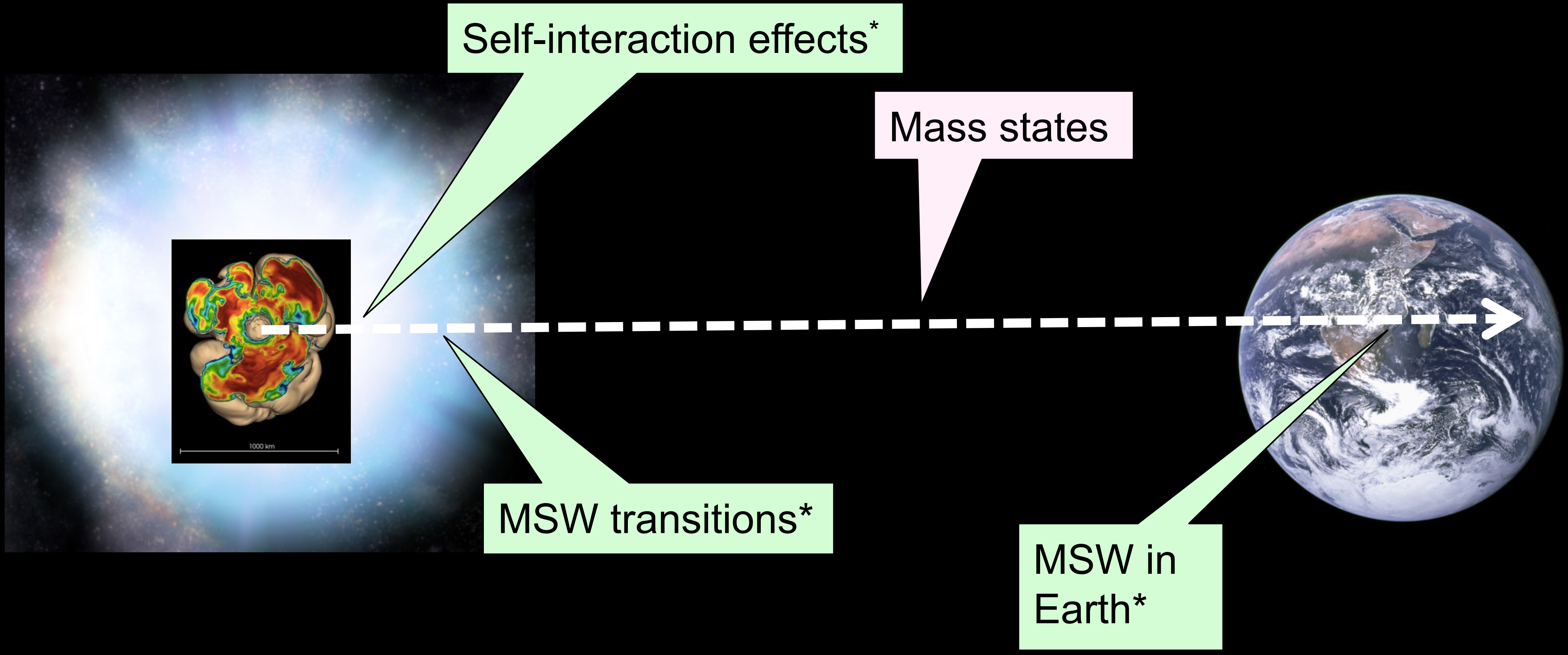
Reactors



Supernovae



Neutrino Mixing for Supernova Neutrinos



Self-interaction effects[*]

Mass states

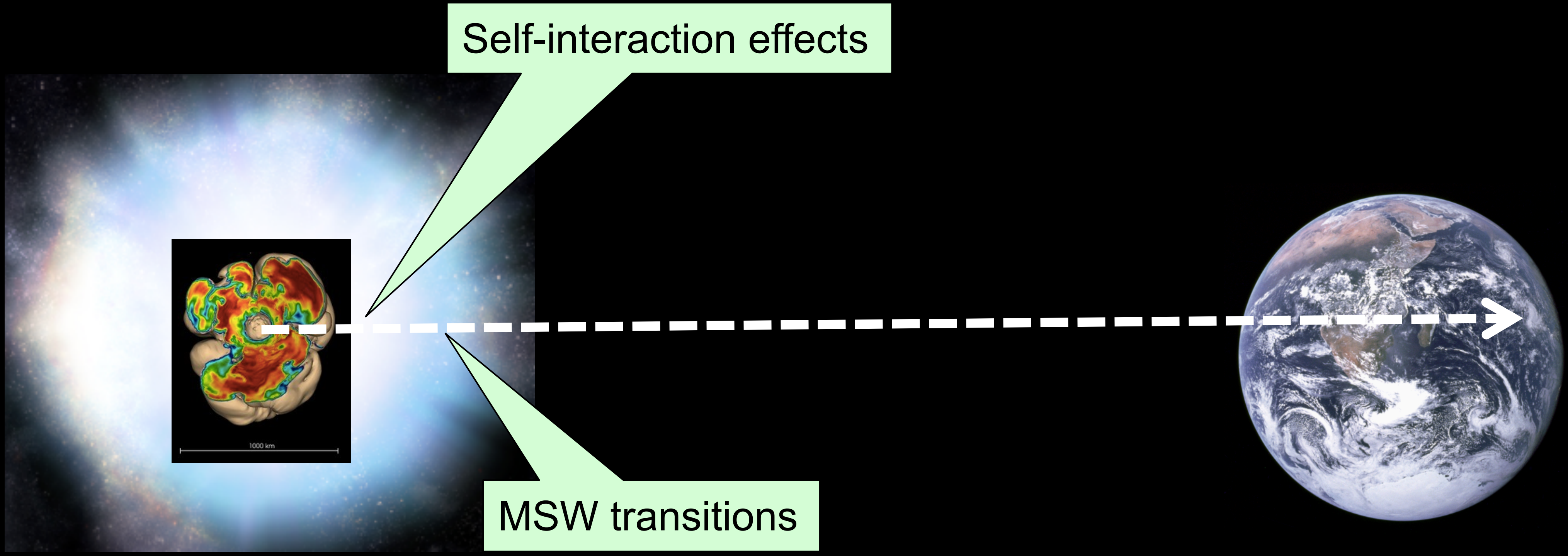
MSW transitions*

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

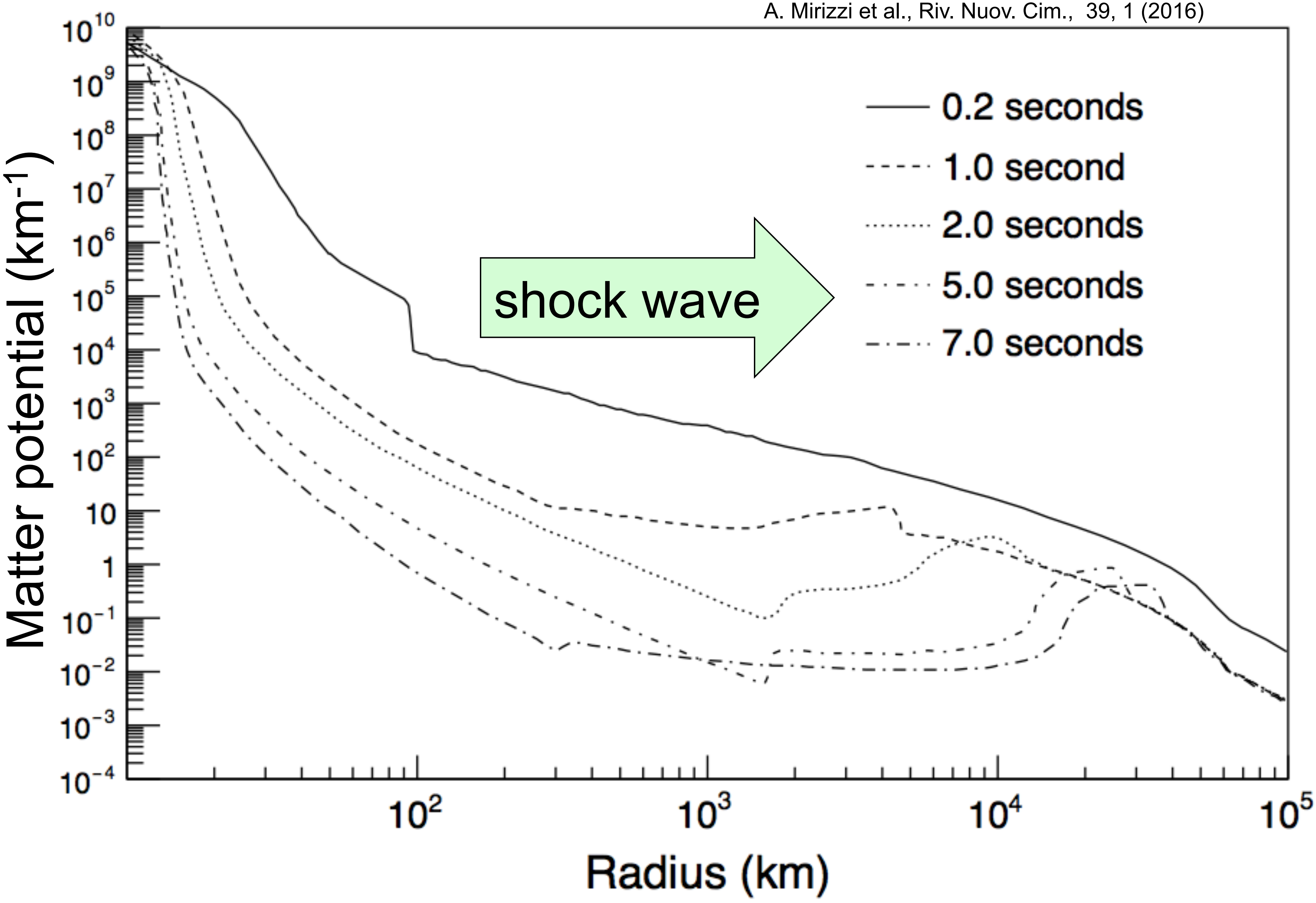


Self-interaction effects

MSW transitions

Matter potential ($\propto$ density) in a supernova vs time

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



Matter potential ($\propto$ density) in a supernova vs time

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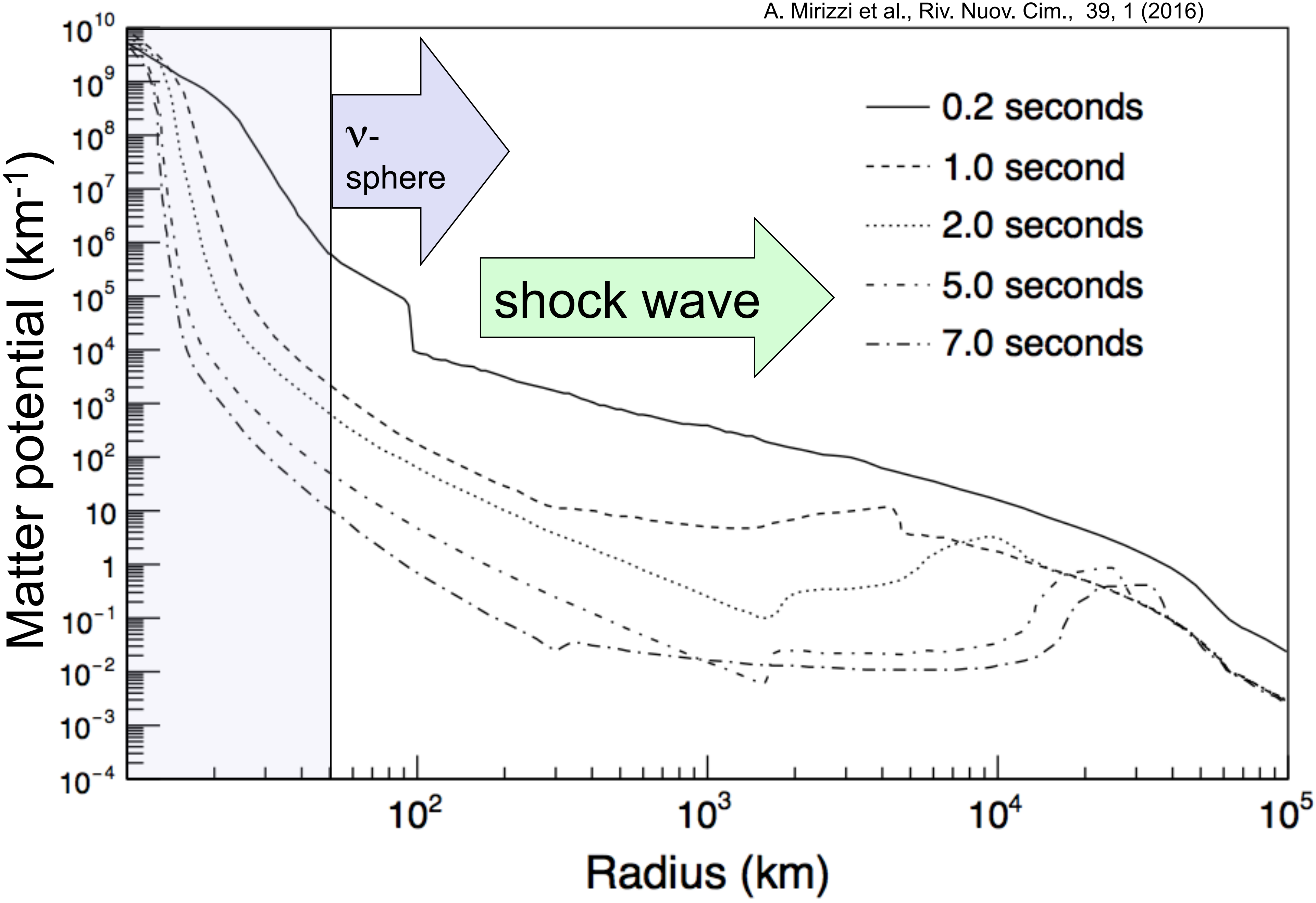
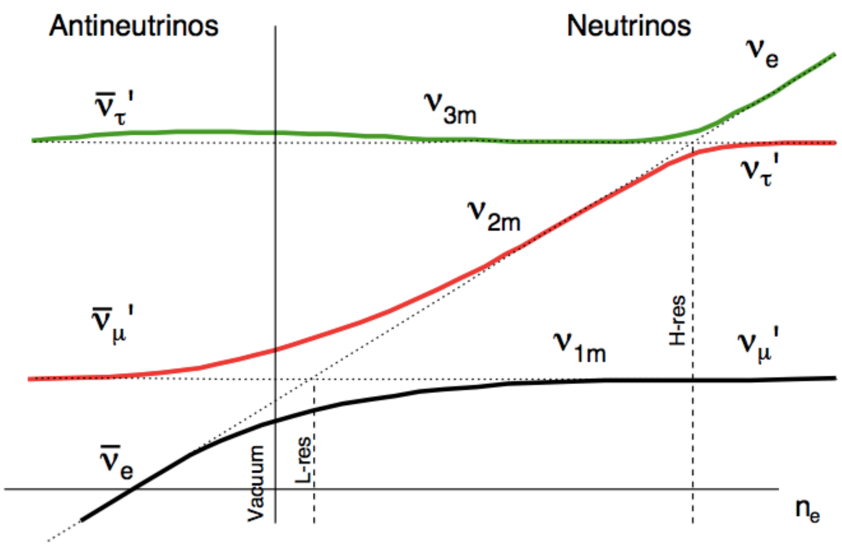
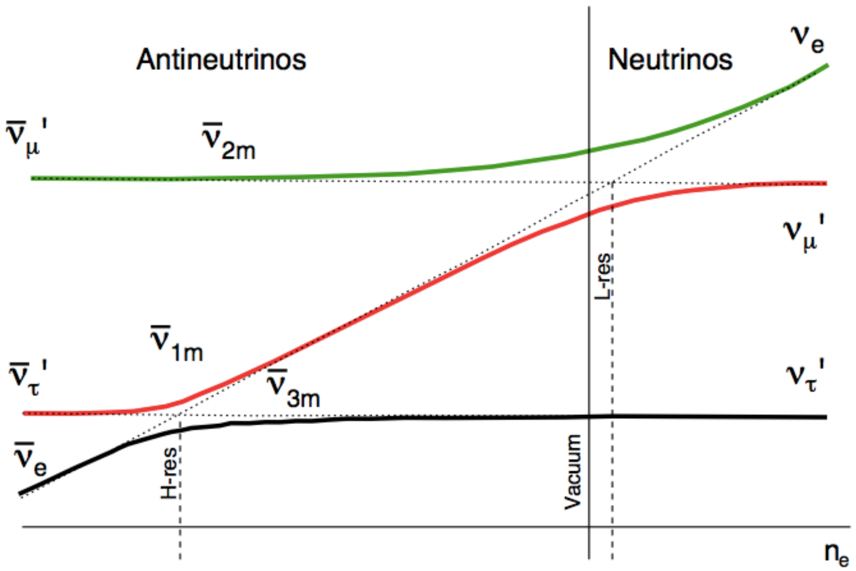


MSW Transitions in Supernova Matter

Normal Ordering



Inverted Ordering

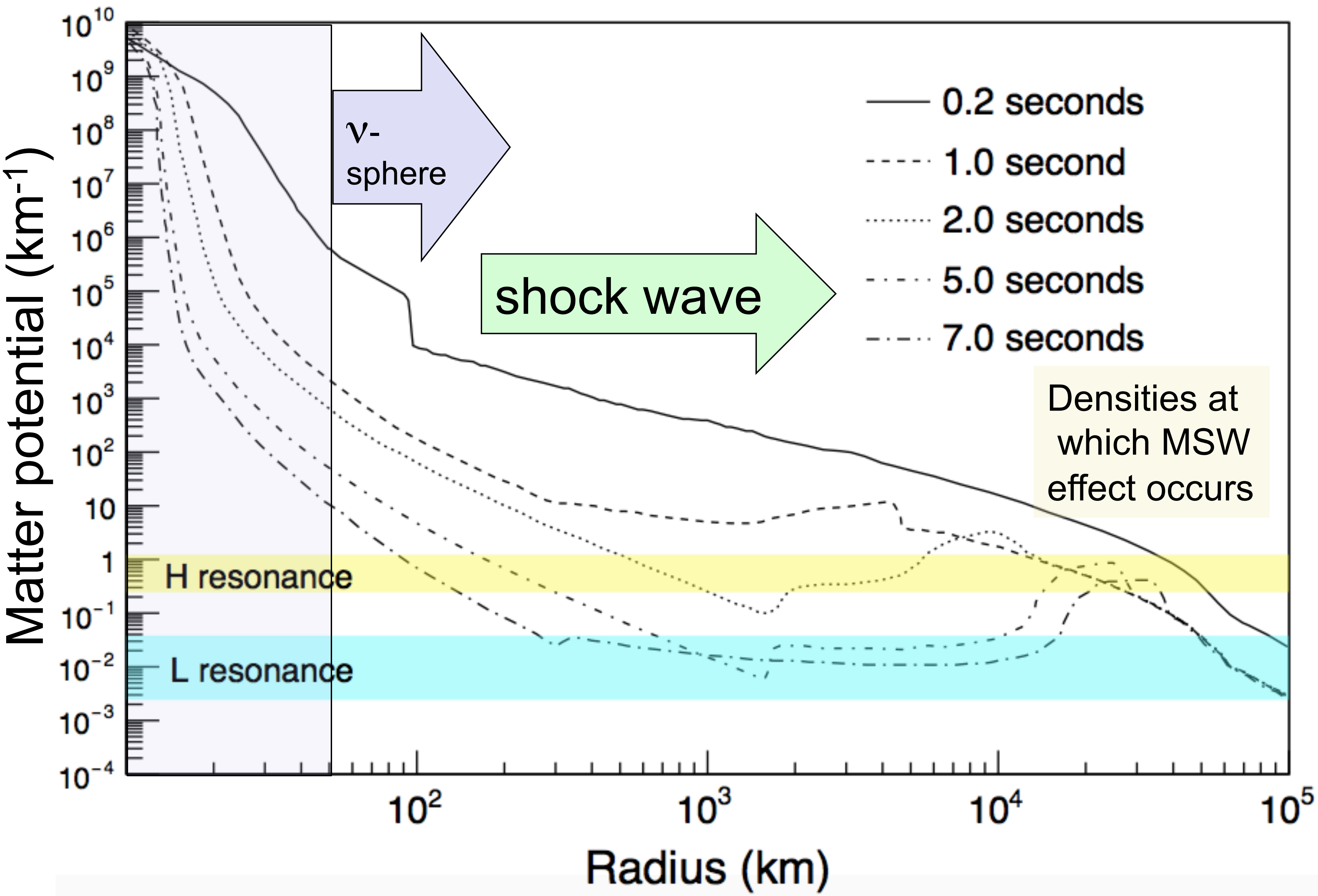


A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016), G. Raffelt, Proc. Int. Sch. Phys. FermI, 182, 61 (2012)

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

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

Matter potential ($\propto$ density) in a supernova vs time



MSW effects *may turn on and off* as the shock propagates

And another effect: “self-interaction effects”

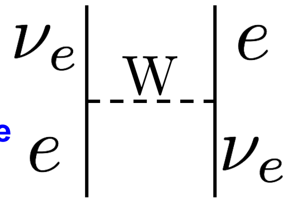
In the proto-neutron star the neutrino density is so high that ***neutrino-neutrino*** *interactions* matter

From G. Fuller

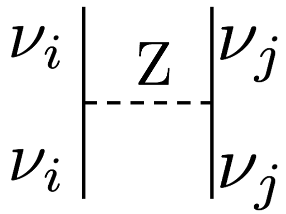
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

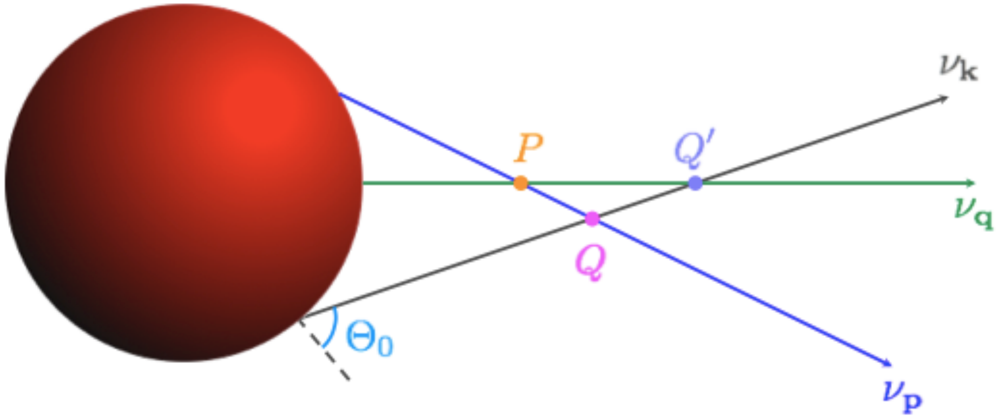
$$i\,\frac{\partial}{\partial t}\,\psi_{\nu,i} \;=\; \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering





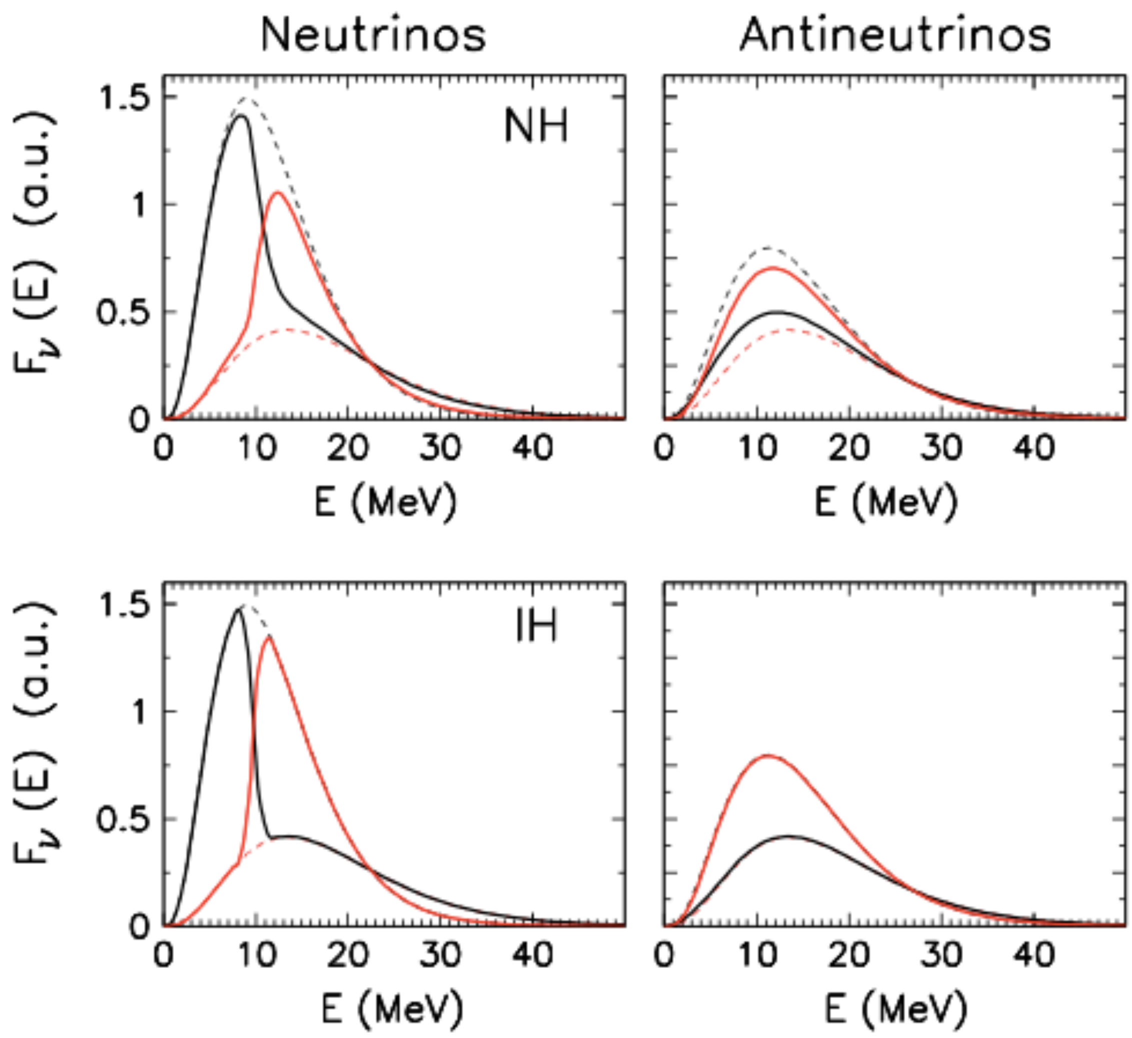
Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories:

“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

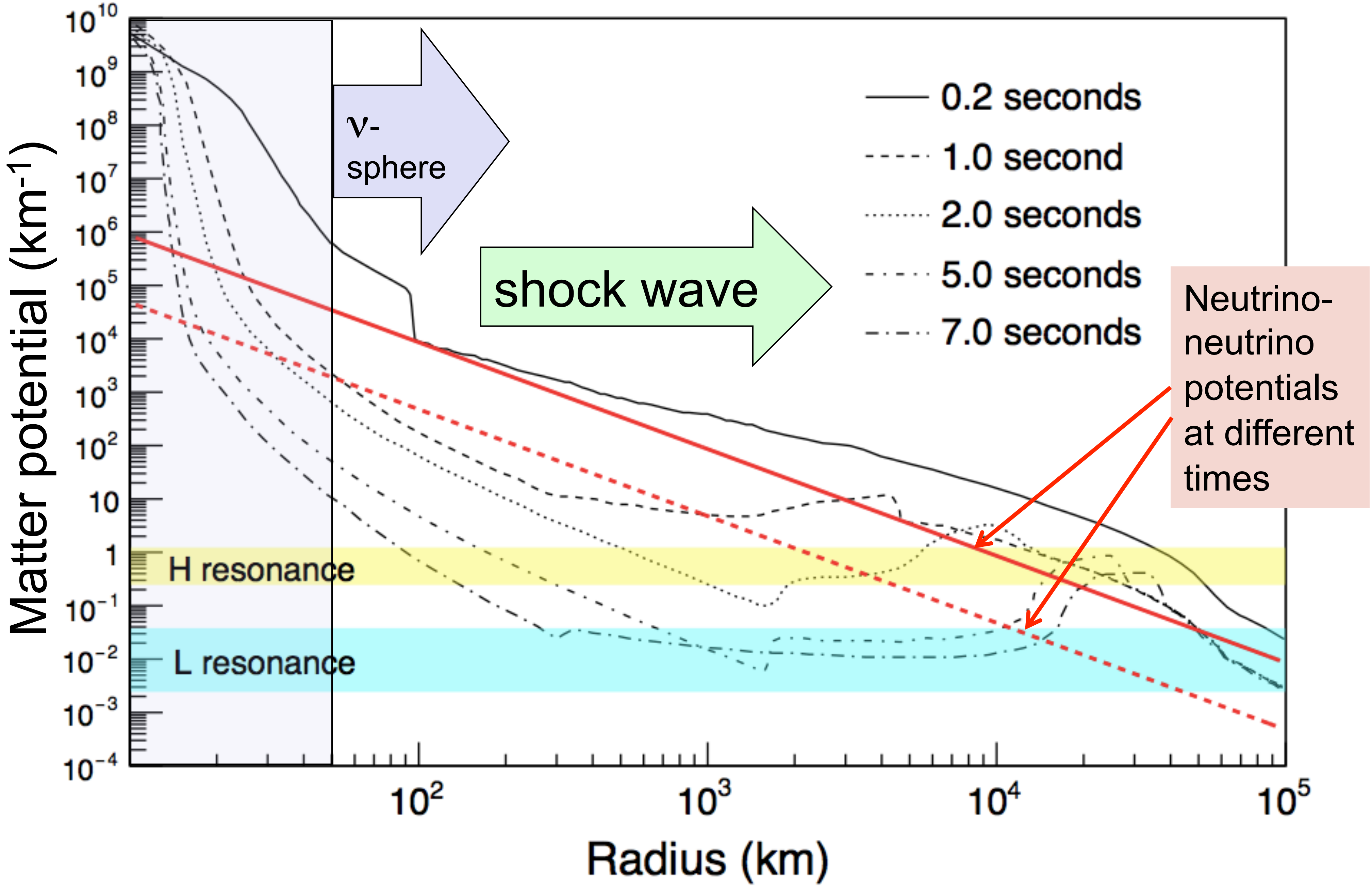
Can get spectral flavor conversion above or below specific energy thresholds

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

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

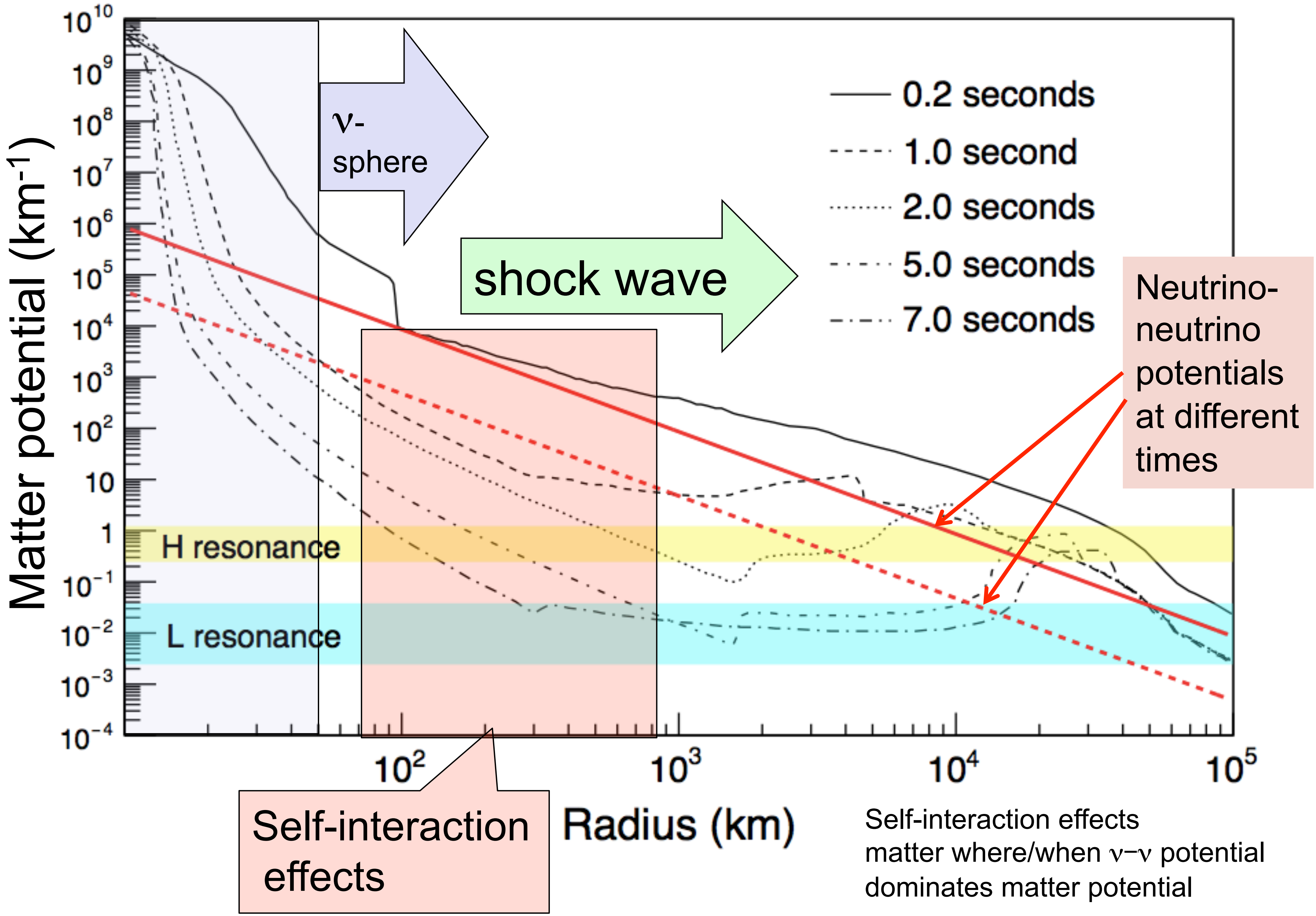
- Depend on flavor flux ratio
- Can be suppressed by matter density
- Time-dependent, also affected by shock propagation

Matter potential (∝ density) in a supernova vs time



Neutrino-neutrino potentials at different times

Matter potential ($\propto$ density) in a supernova vs time



ν-
sphere

shock wave

Neutrino-
neutrino
potentials
at different
times

Self-interaction
effects

Self-interaction effects
matter where/when $\nu-\nu$ potential
dominates matter potential

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 self-interaction effects are
still under study...

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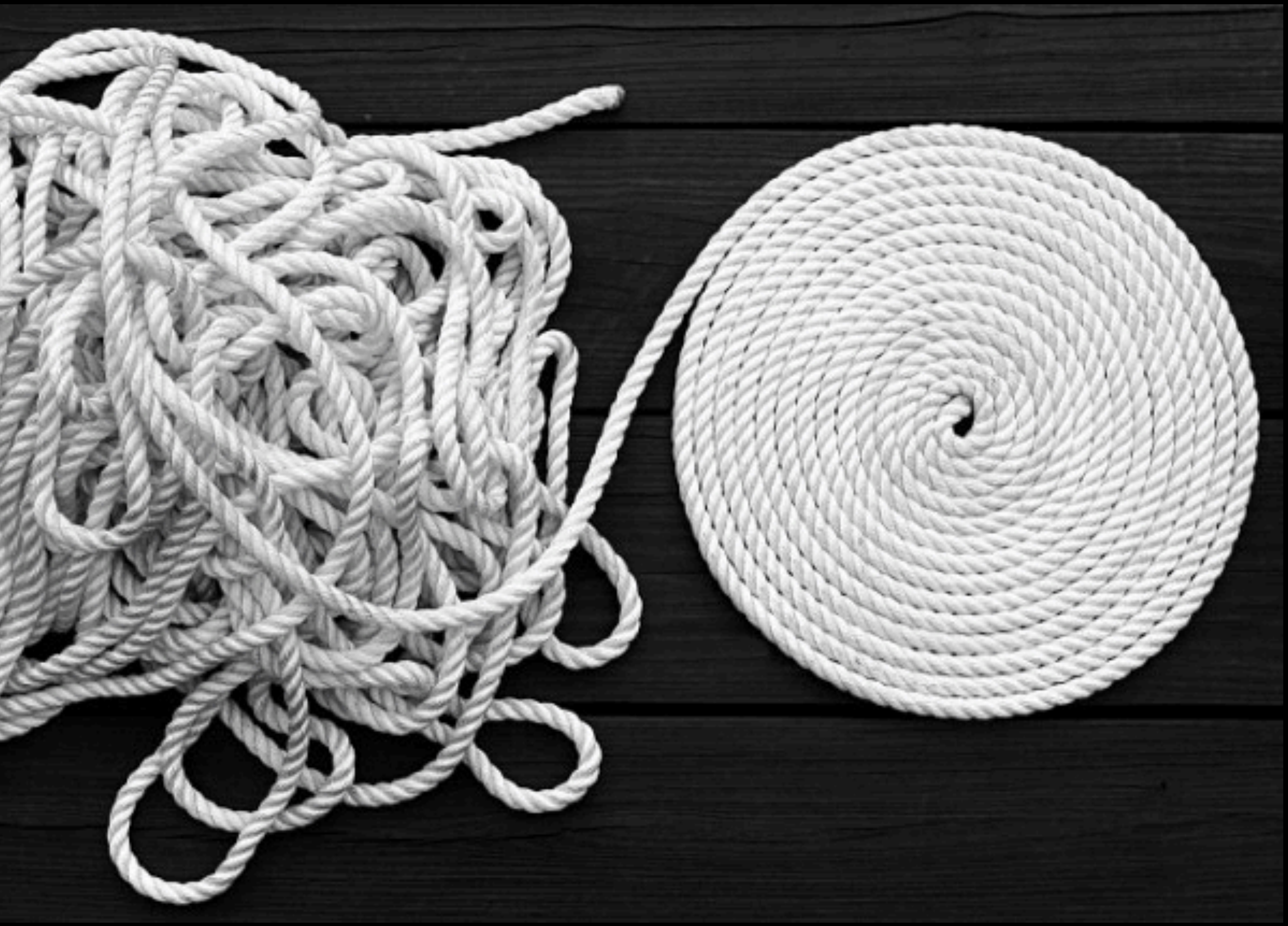
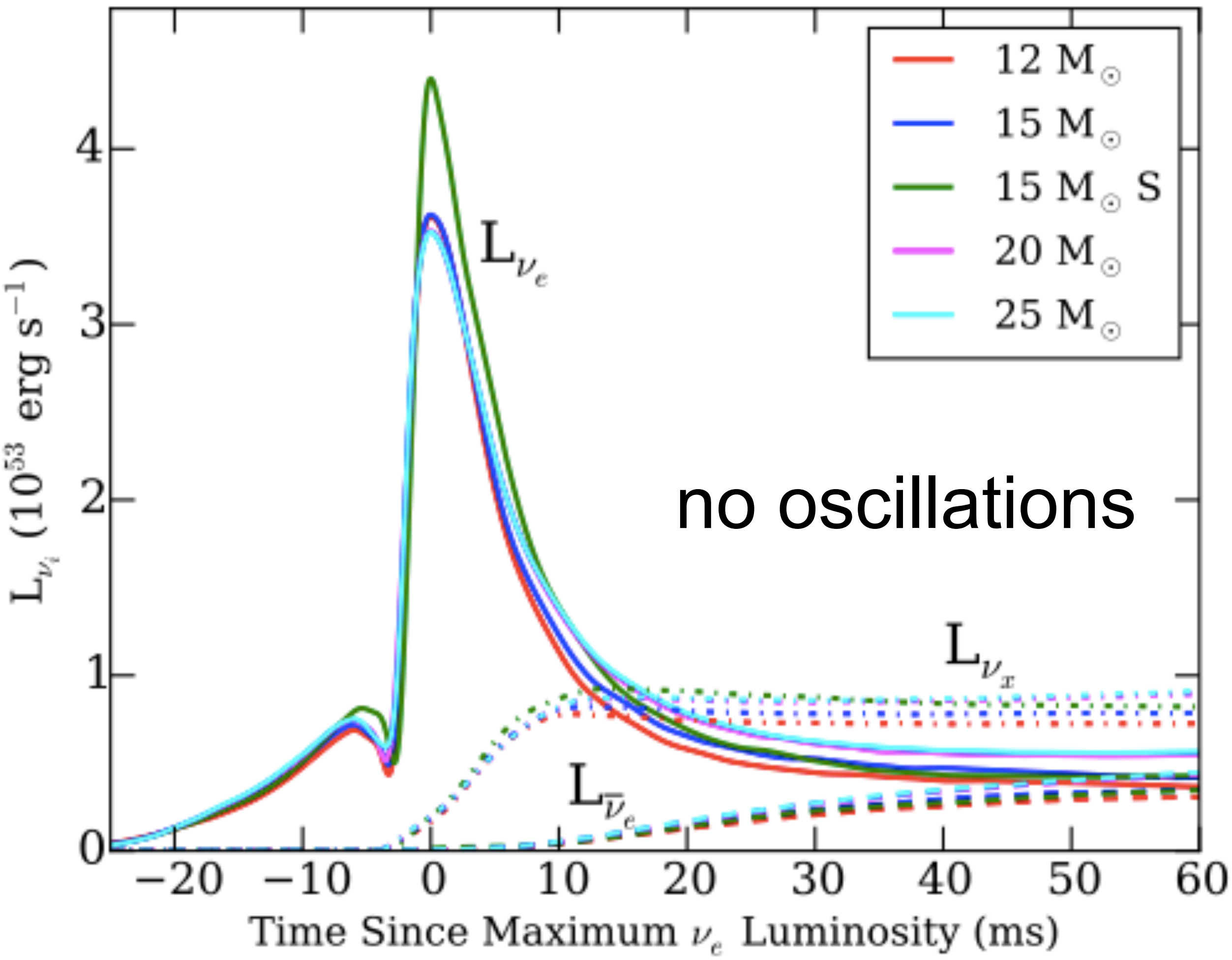


Challenge for theorists is to find **robust, model-independent observables...** challenge for experimentalists is to understand and optimize observability

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 flavor transitions only***

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

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

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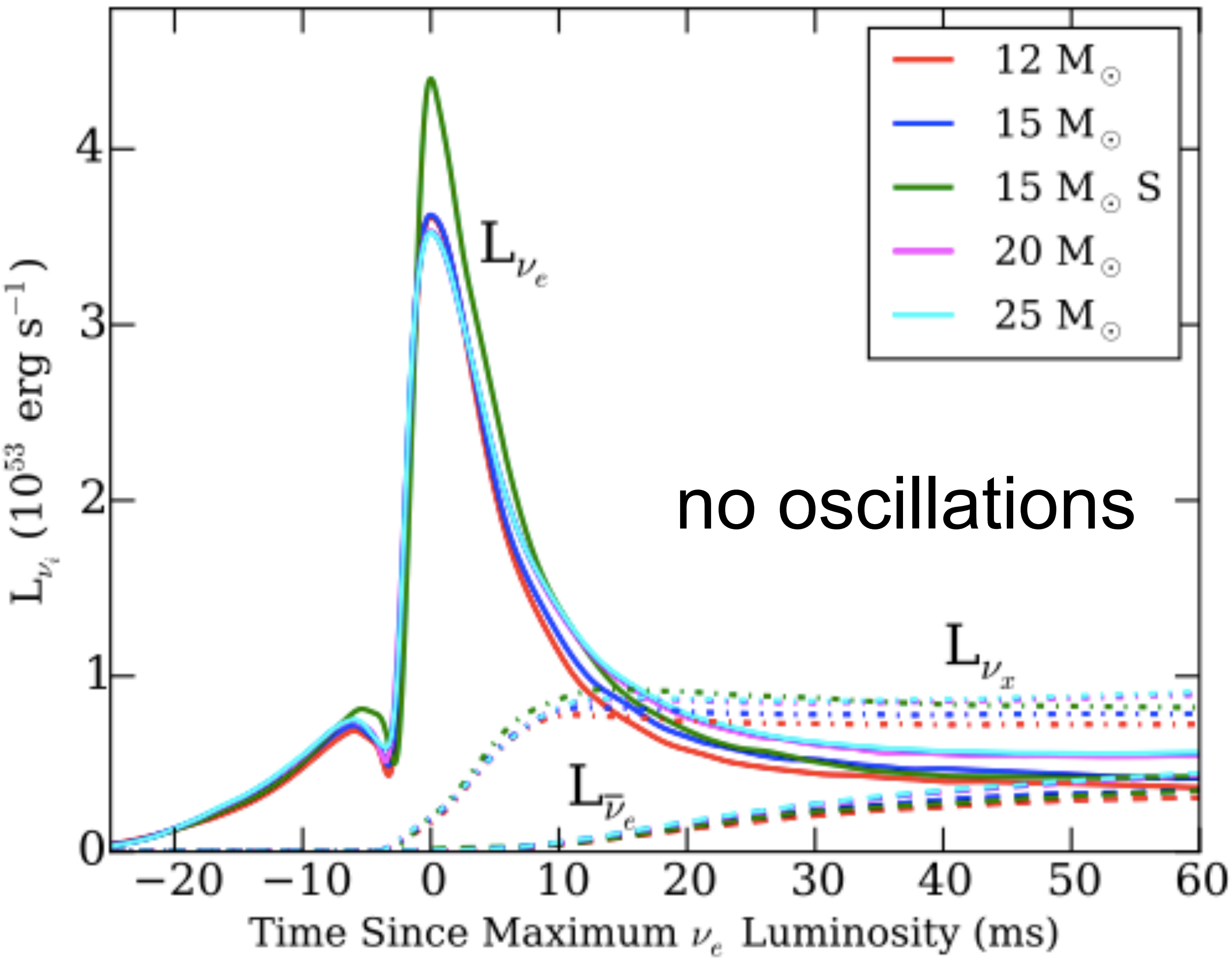


no oscillations

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

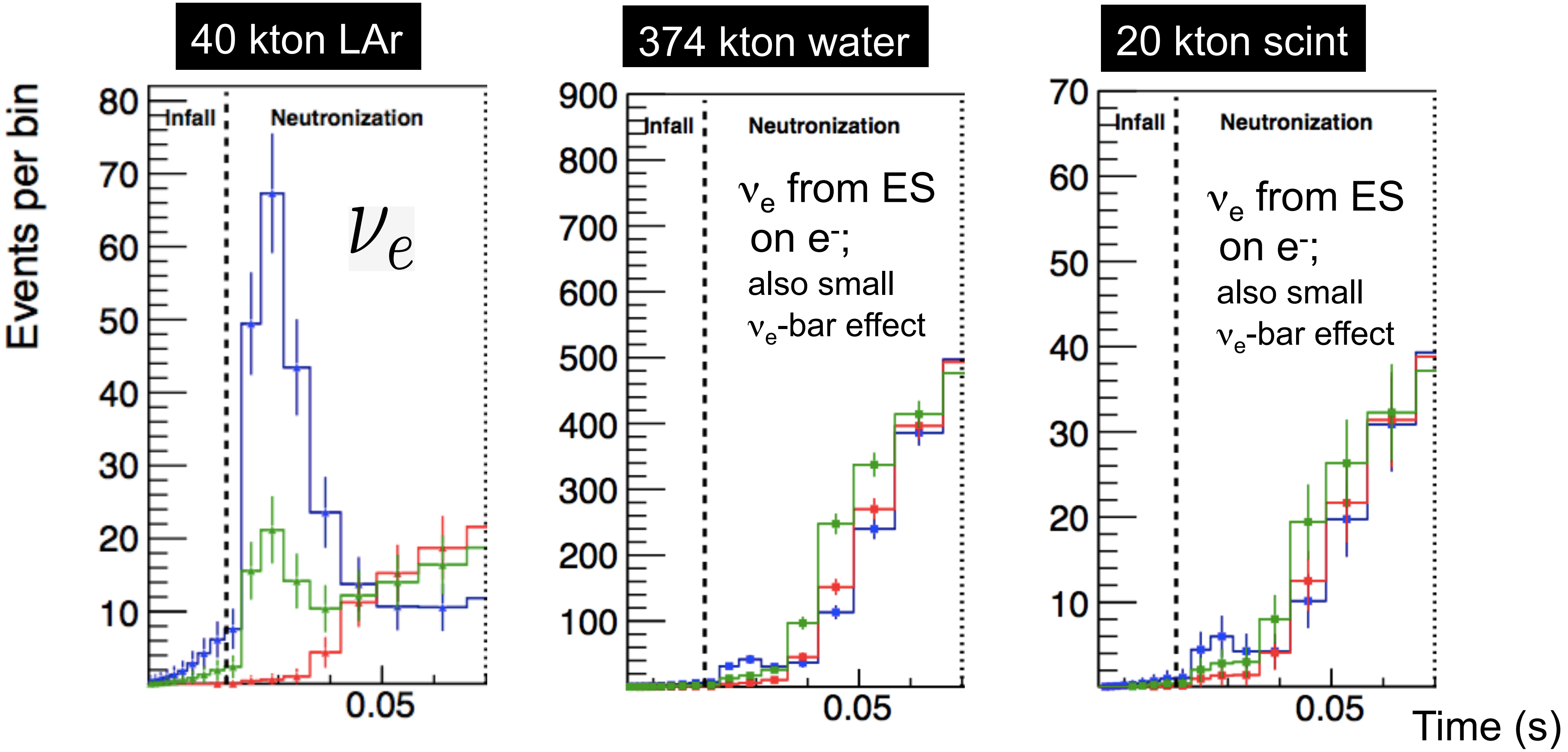
~no collective effects; MSW oscillations only

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**



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

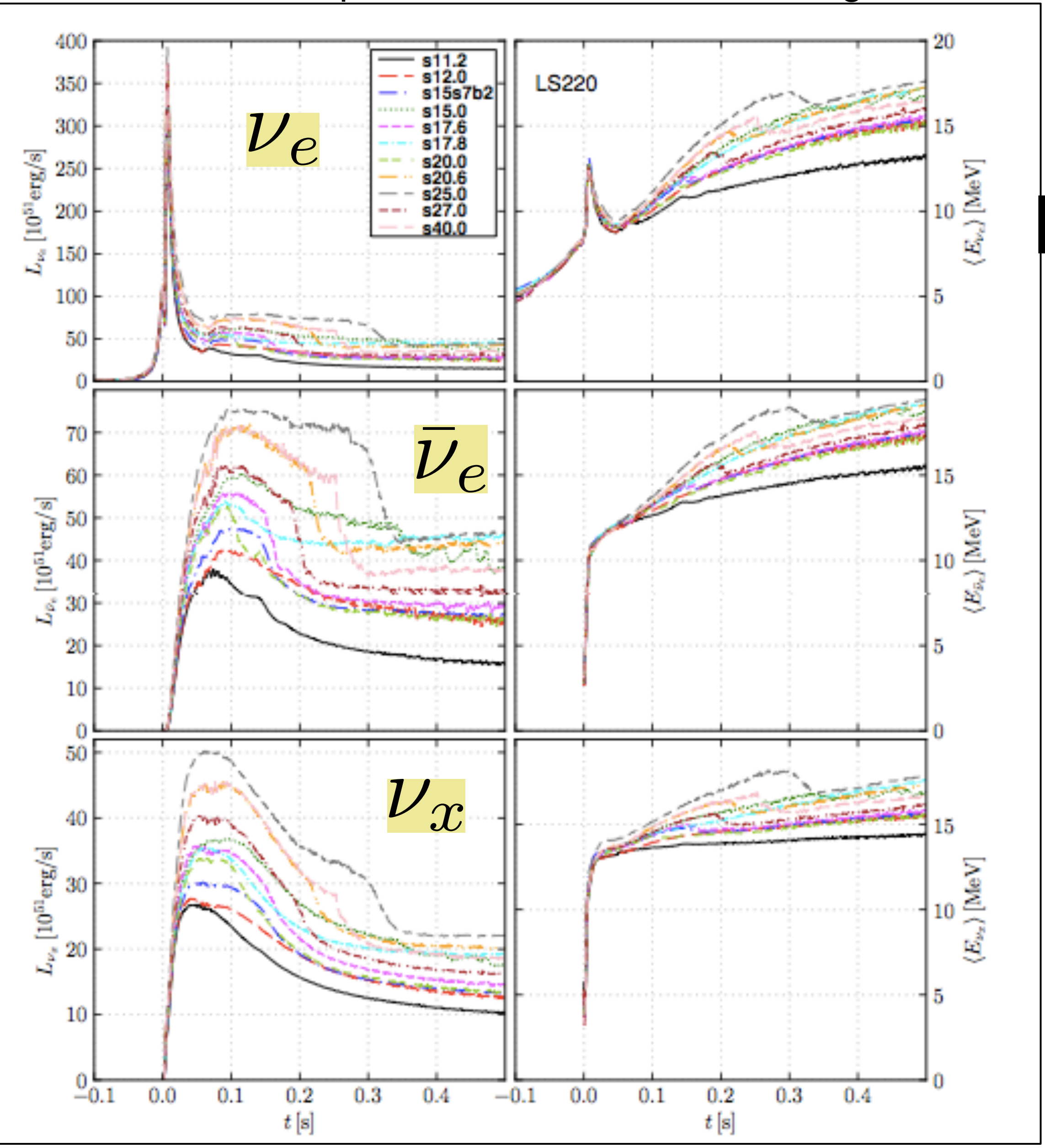
IMO: $F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$

🟦 **No oscillations**
🟥 **Normal ordering**
🟩 **Inverted ordering**

suppression for IMO,
stronger suppression for NMO

Another somewhat robust example: **early time profile**

Different lines represent different 1D “Garching” models



Still MSW-dominated (maybe);
ν_e-bar, ν_x-bar turning on
and fairly consistent
behavior between models

MSW for ν_e-bar :

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

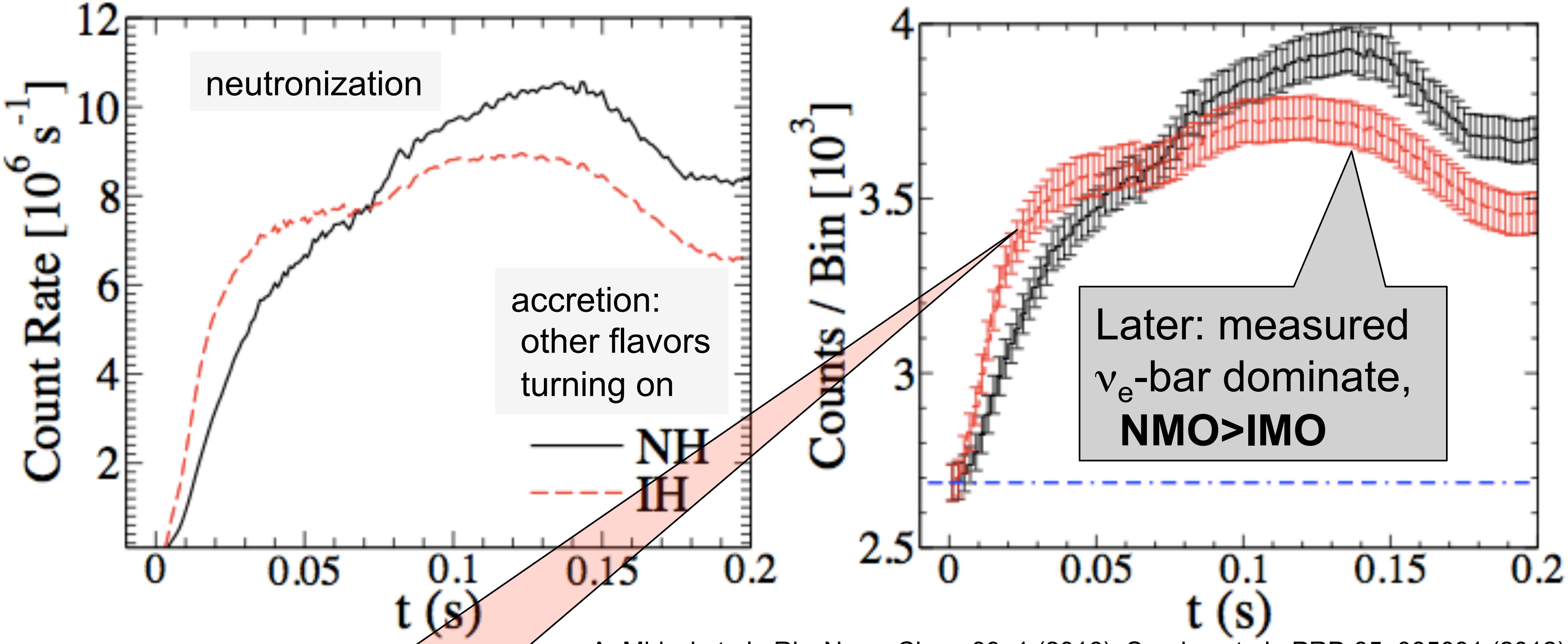
IMO ➔ ν_e -bar represents original ν_x-bar flux, which is lower during accretion, so will be suppressed

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**

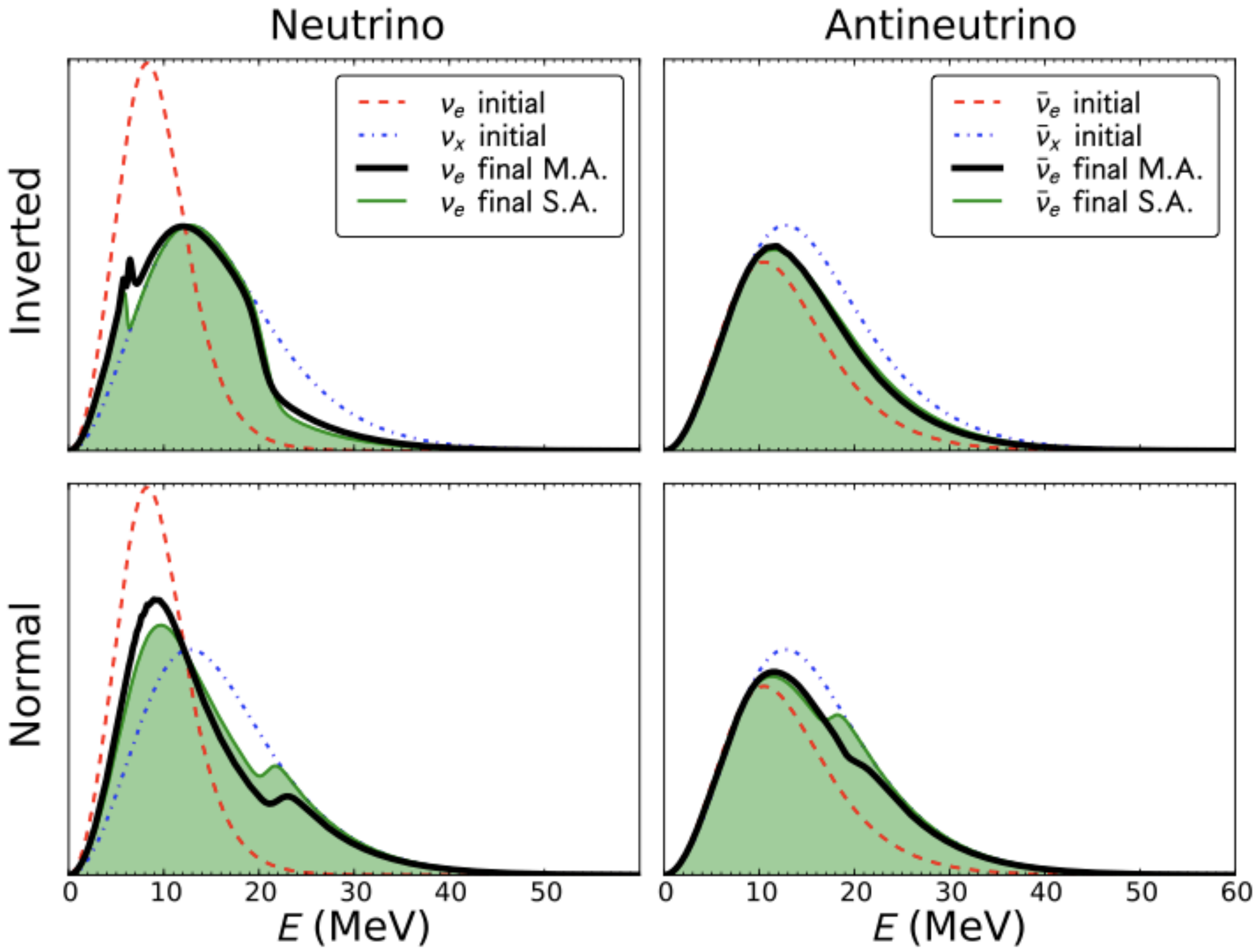
A. Mirizzi et al., Riv. Nuov. Cim., 39, 1 (2016), Serpico et al., PRD 85, 085031 (2012)

Early: measured ν_e dominate, **IMO>NMO**

NMO ➔ ν_e strongly suppressed, since ~no ν_x
IMO ➔ ν_e suppressed by $\sin^2\theta_{12}$~0.3

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

Other examples: **spectral swaps from self-interaction**



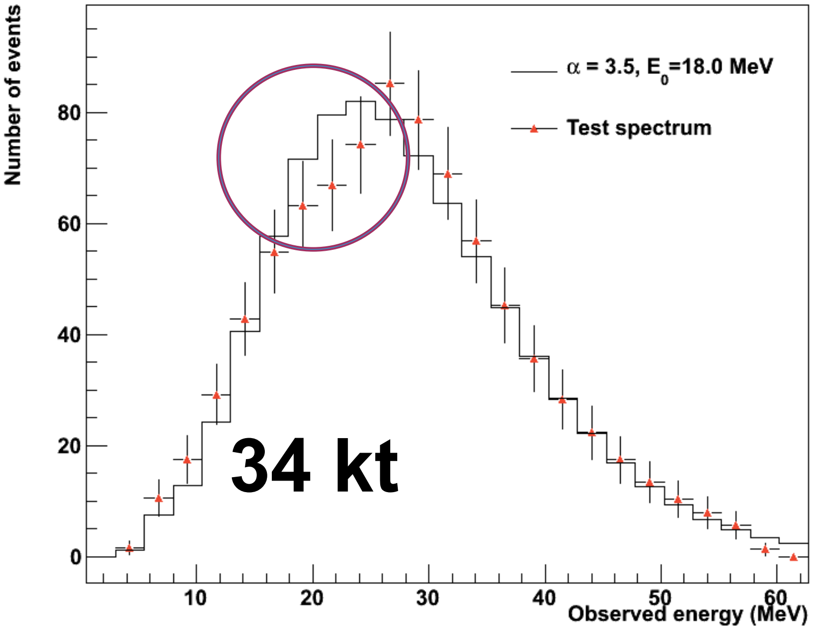
H. Duan & A. Friedland,PRD 106, 091101 (2011)

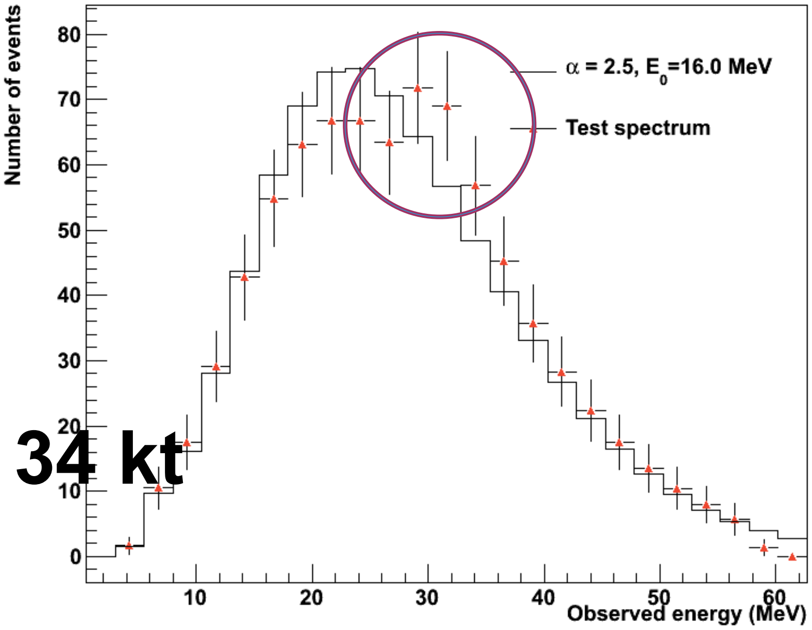
Distinctive spectral swap features depend on neutrino mass hierarchy, for neutrinos vs antineutrinos

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

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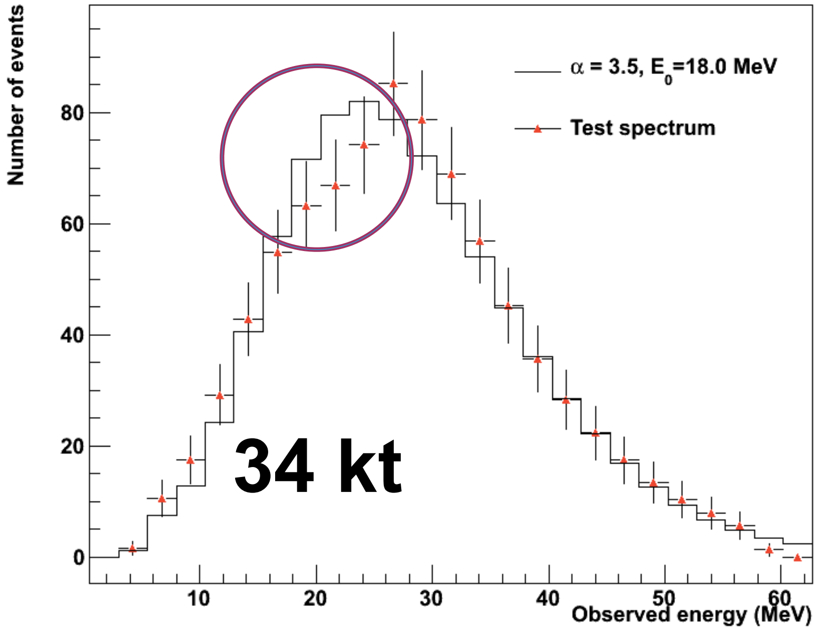

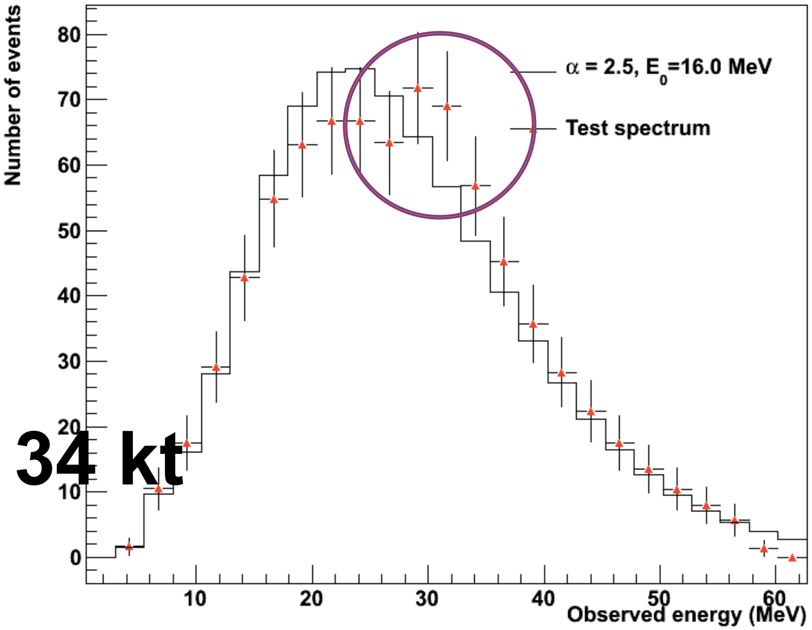

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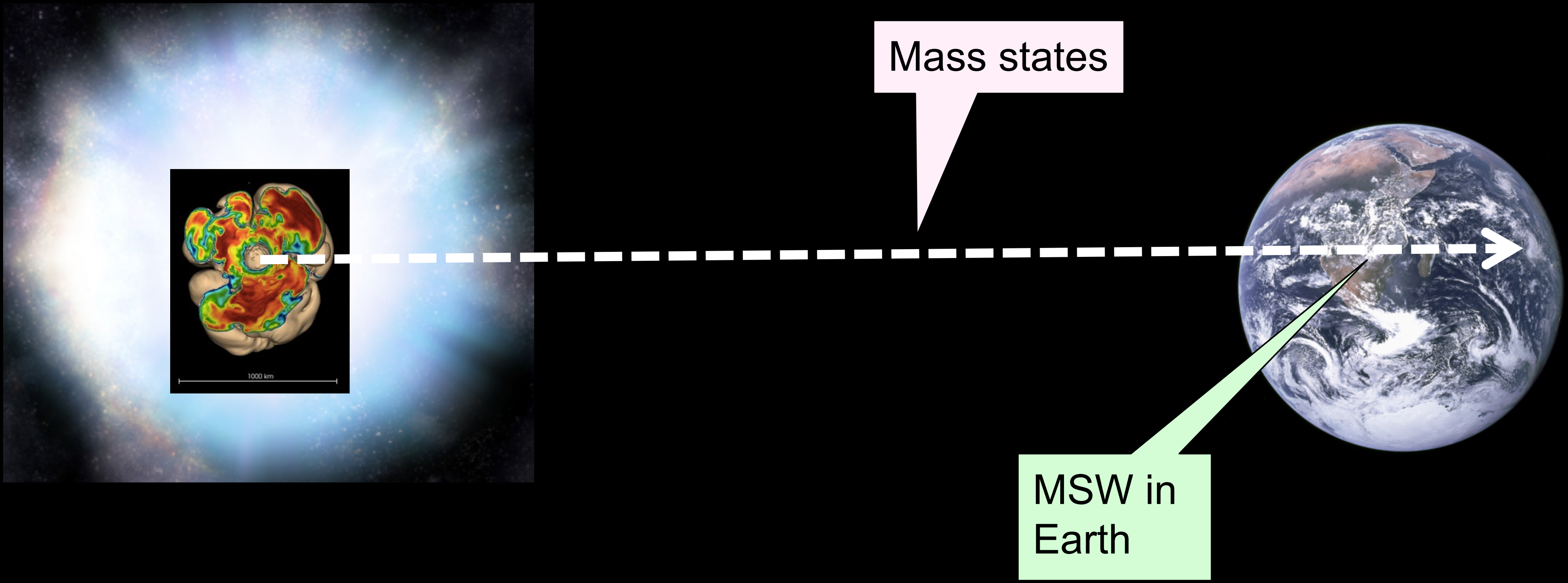
10 kpc spectra from A. Friedland/JJ Cherry/H. Duan
smeared w/ SNOwGLoBES response w/collective effects
Black line: best fit to pinched thermal spectrum

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

Neutrino Mixing in the Earth

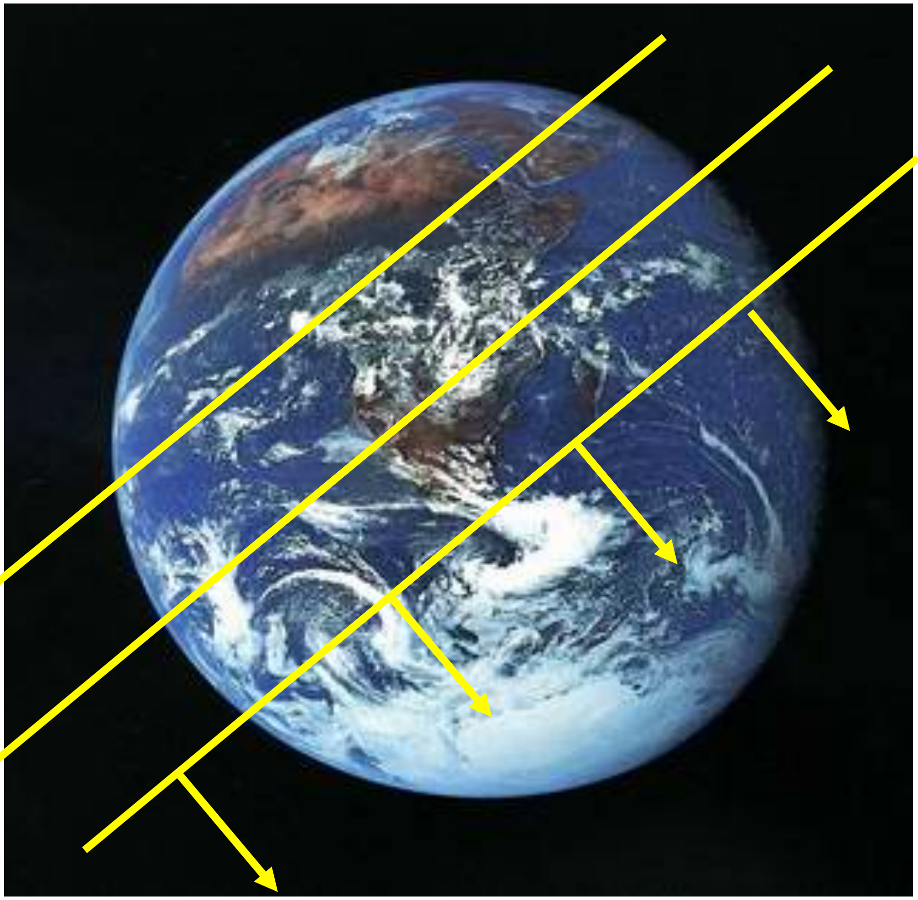


Mass states

MSW in
Earth

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

Matter-induced oscillations in the Earth

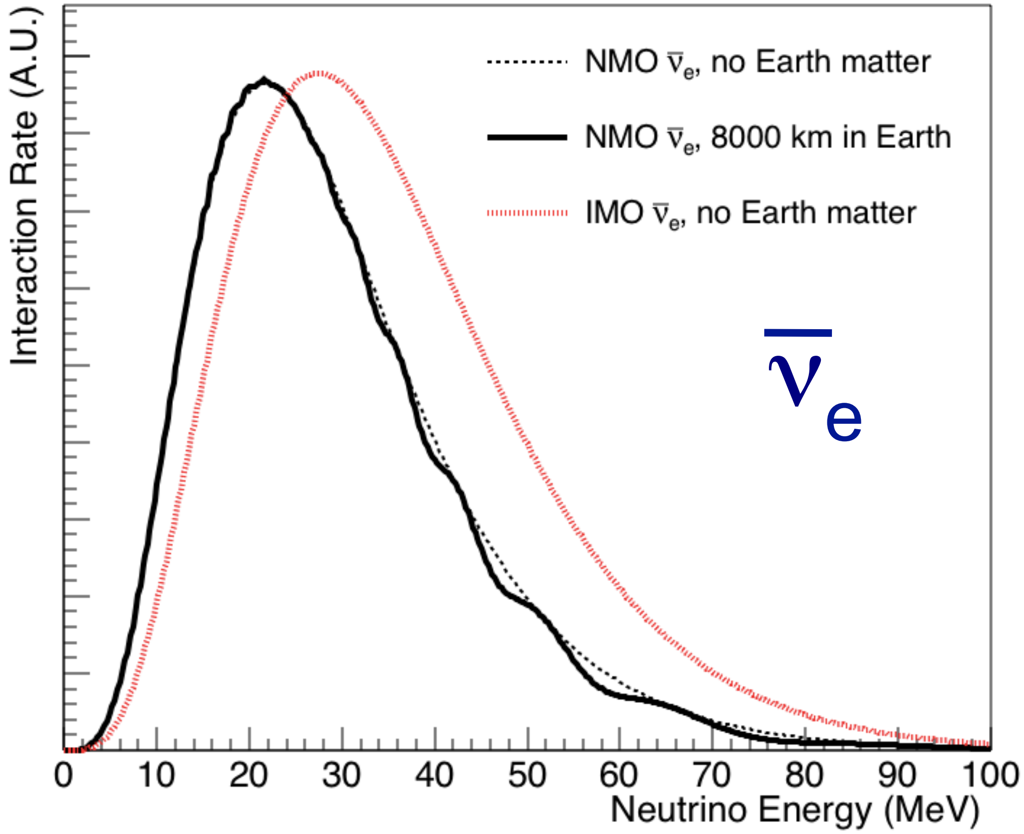


NMO: $F^{\oplus}_{\bar{\nu}_e} = (1-\bar{P}_{2e})F^{0}_{\bar{\nu}_e} + \bar{P}_{2e}F^{0}_{\bar{\nu}_x}$ and $F^{\oplus}_{\nu_e} = F^{0}_{\nu_x}$

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

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

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

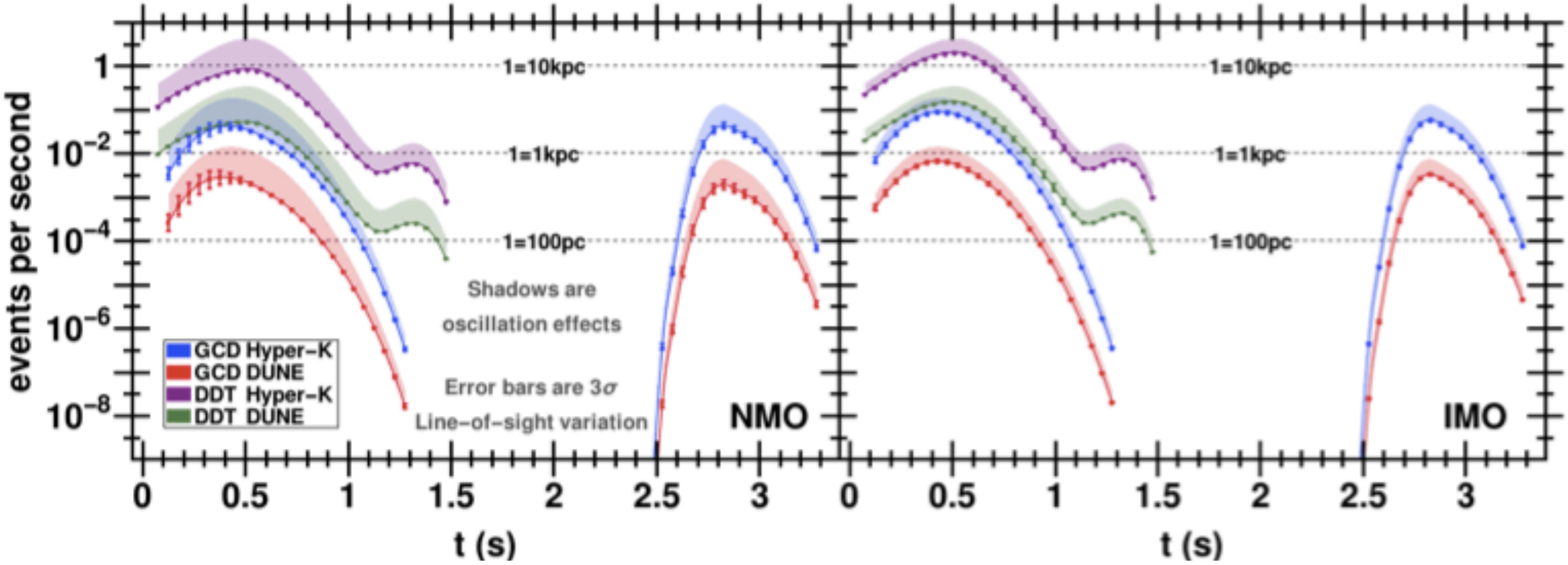


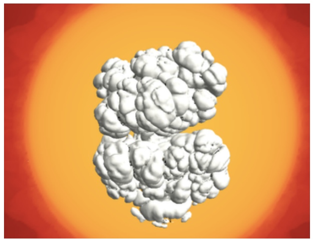
Requires very good energy resolution to resolve wiggles

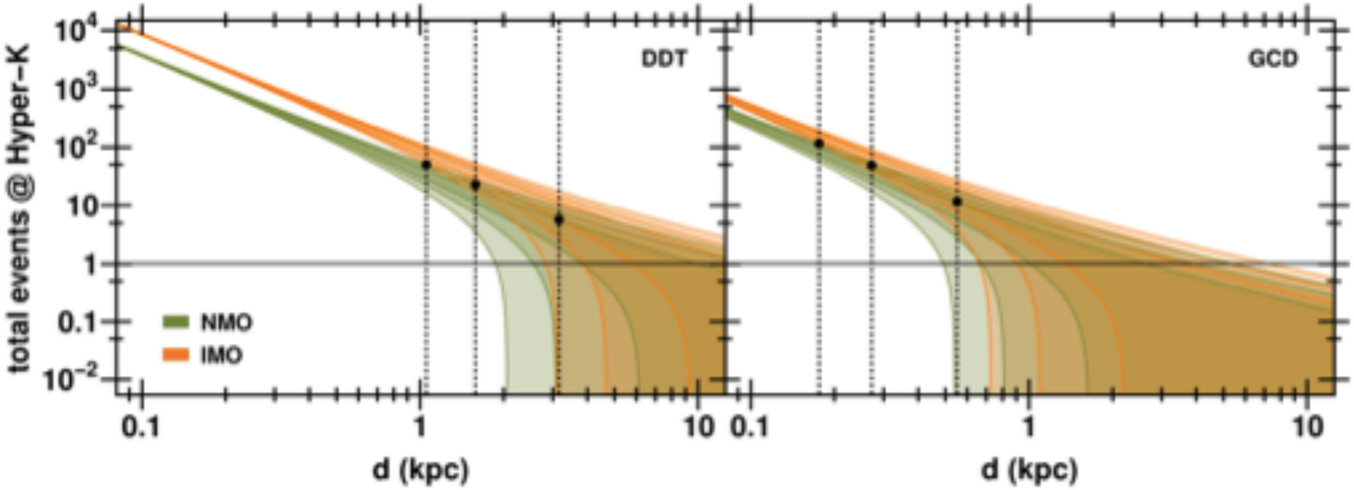
A long shot: Type Ia Supernovae

- 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.,PRD95 043006 (2017), arXiv:1609.07403





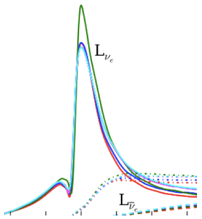


If mechanism is known, w/HK can discriminate MO @ 1σ for d<3.17 kpc for DDT model, d<0.55 kpc for GCD

Need to be lucky!

Summary Table for Supernova MO Signatures

	Normal	**Inverted**	**Robustness**	**Observability**
Neutronization burst	Very suppressed	Suppressed	Excellent	Good, need ν_e (HK, DUNE,...)



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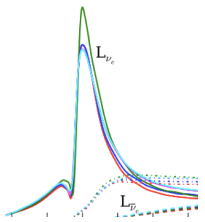

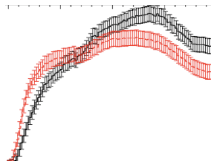

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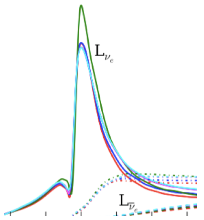

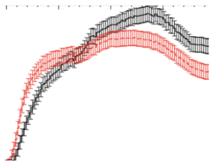

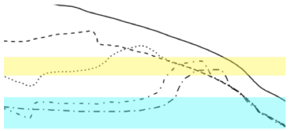

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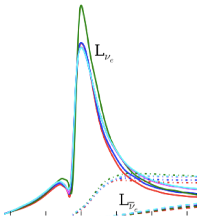

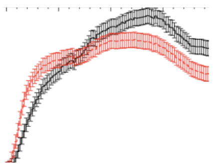

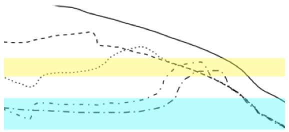

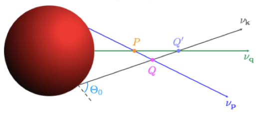

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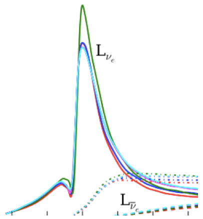
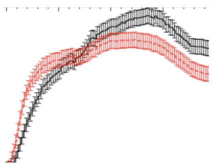
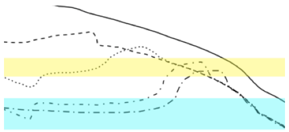
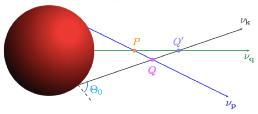
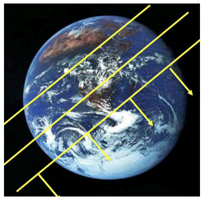
Earth Matter	Wiggles in anti-ν_e	Wiggles in ν_e	Excellent	Hard, need energy resolution, stats (JUNO,...)











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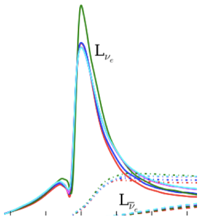
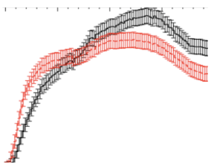
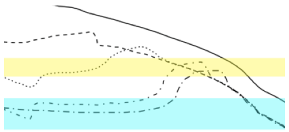
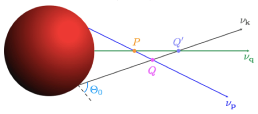
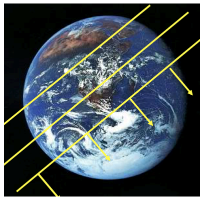
Earth Matter	Wiggles in anti-ν_e	Wiggles in ν_e	Excellent	Hard, need energy resolution, stats (JUNO,...)
Type Ia	Lower flux	Higher flux	Quite	Hard, need stats+luck (HK, DUNE,...)

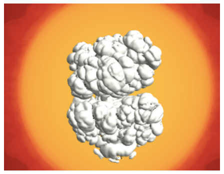








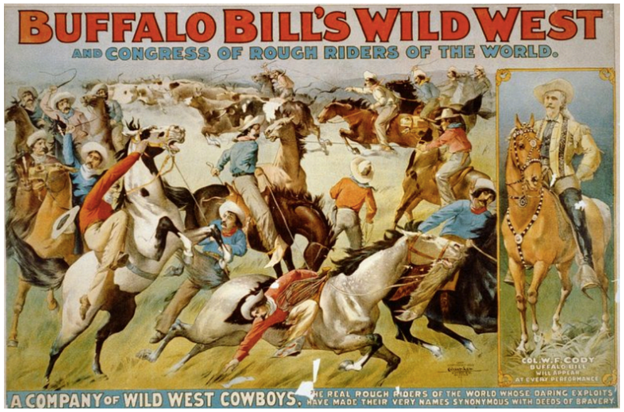




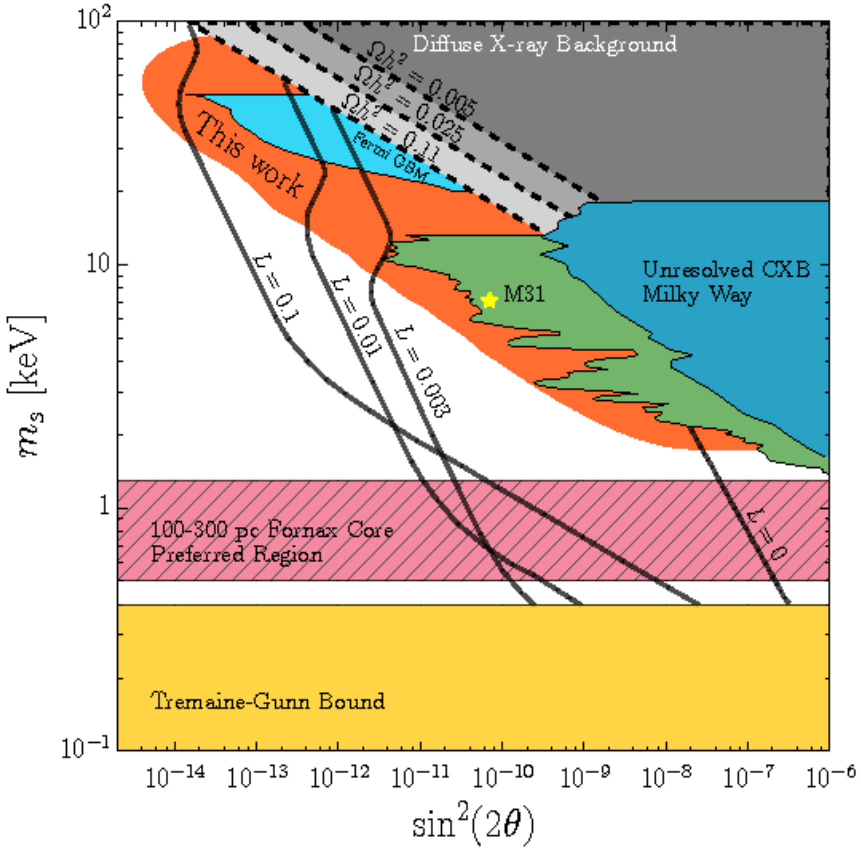
For supernova neutrinos, the more the merrier!

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

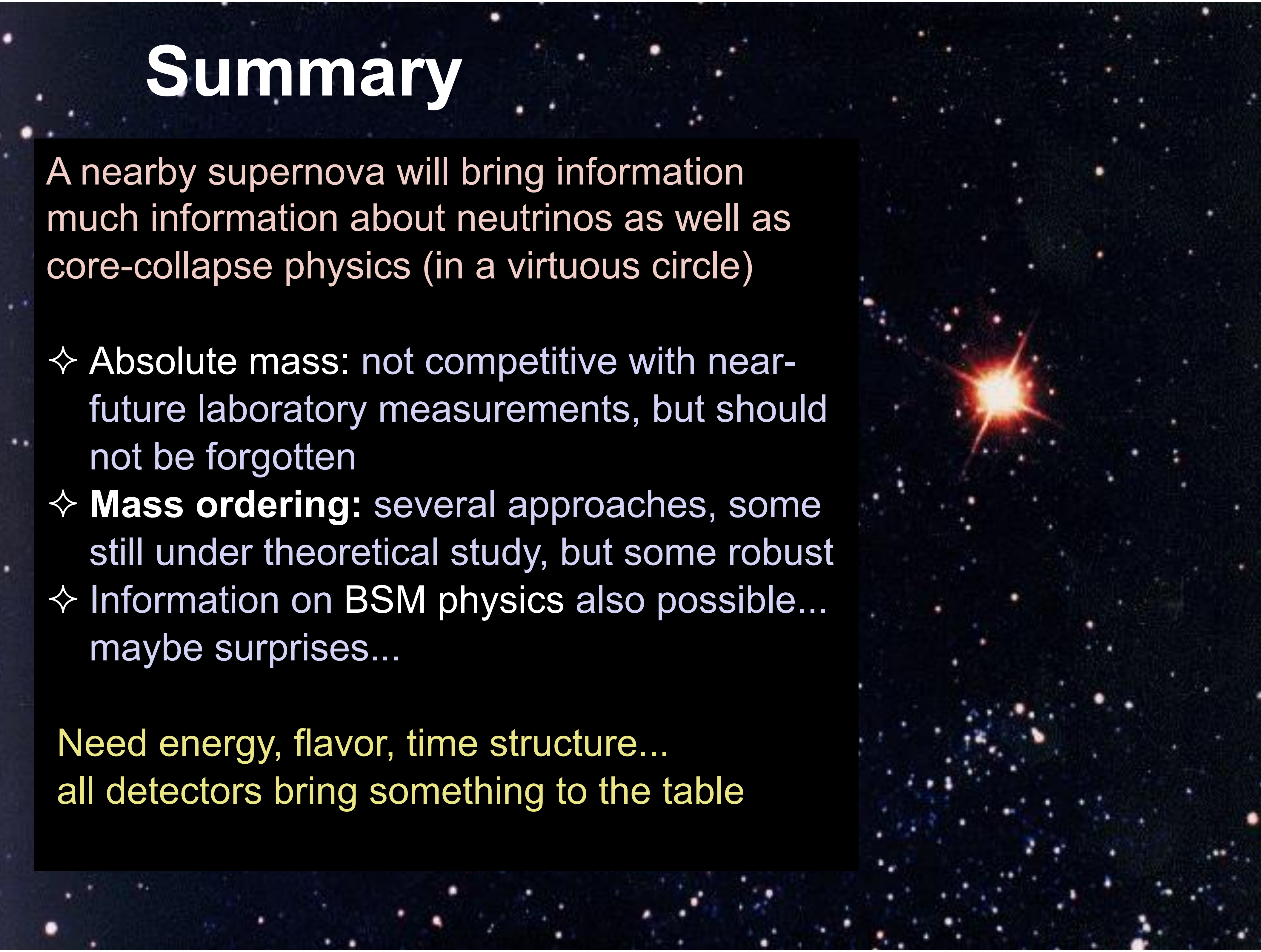


But some robust bounds
from the "energy leakage"
argument

Limits on ~keV sterile neutrinos

C. A. Argüelles, et al. arXiv:1605.00654 [hep-ph]

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

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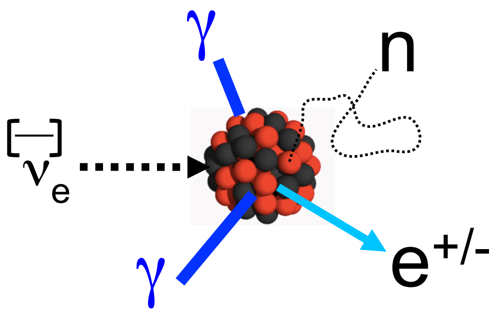
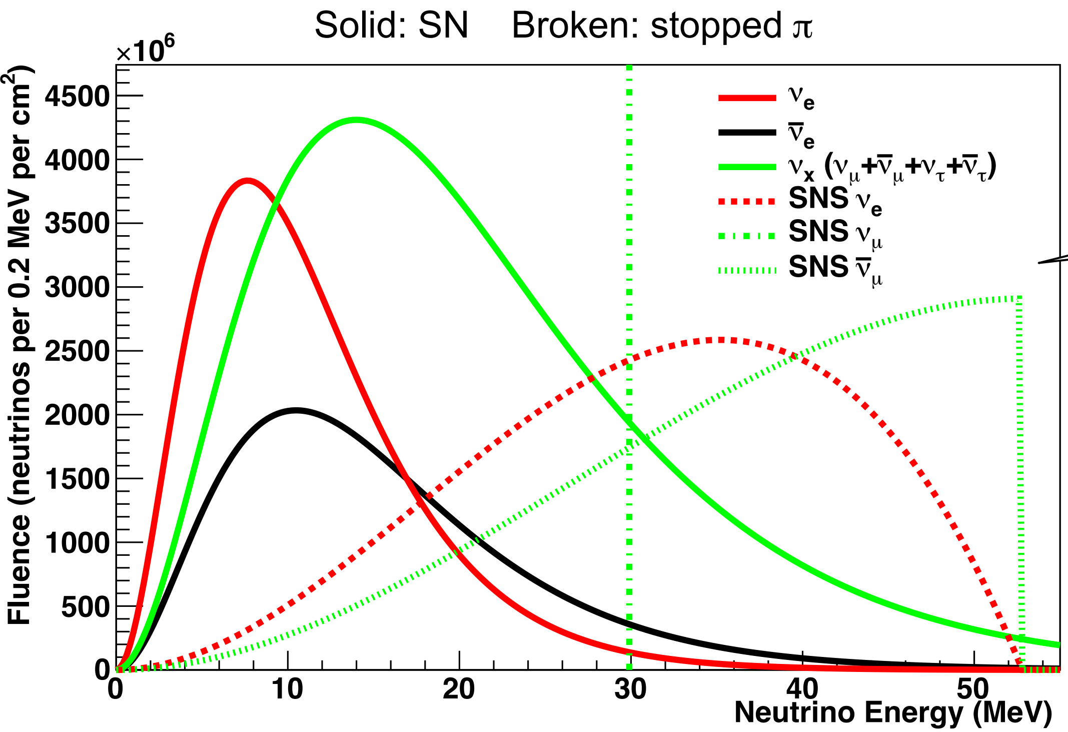


Interactions with nuclei
(cross sections & products)
very poorly understood...
sparse theory & experiment
(*only* measurements at better
than ~50% level are for ^{12}C)

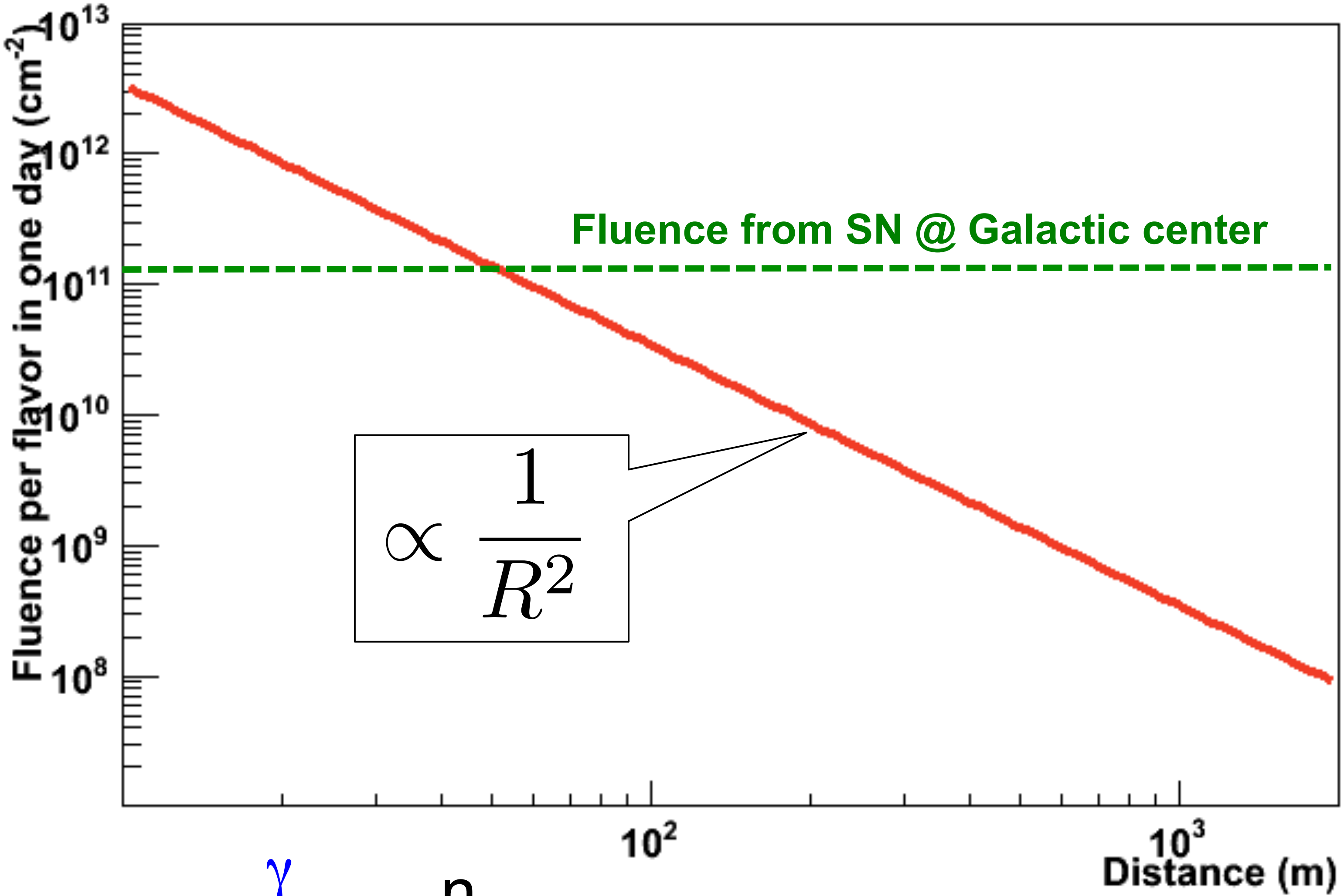


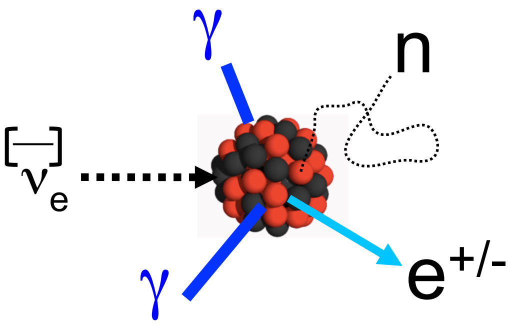
Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source

A. Bolozdynya et al., arXiv:1211.5199

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

(or 0.2 microsupernovae per pulse, 60 Hz of pulses)





This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

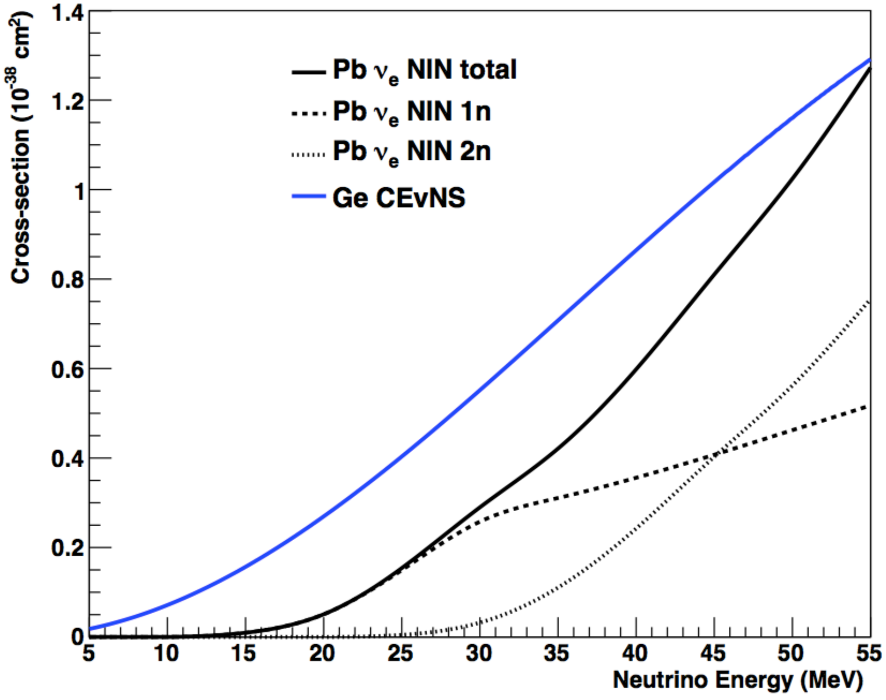
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

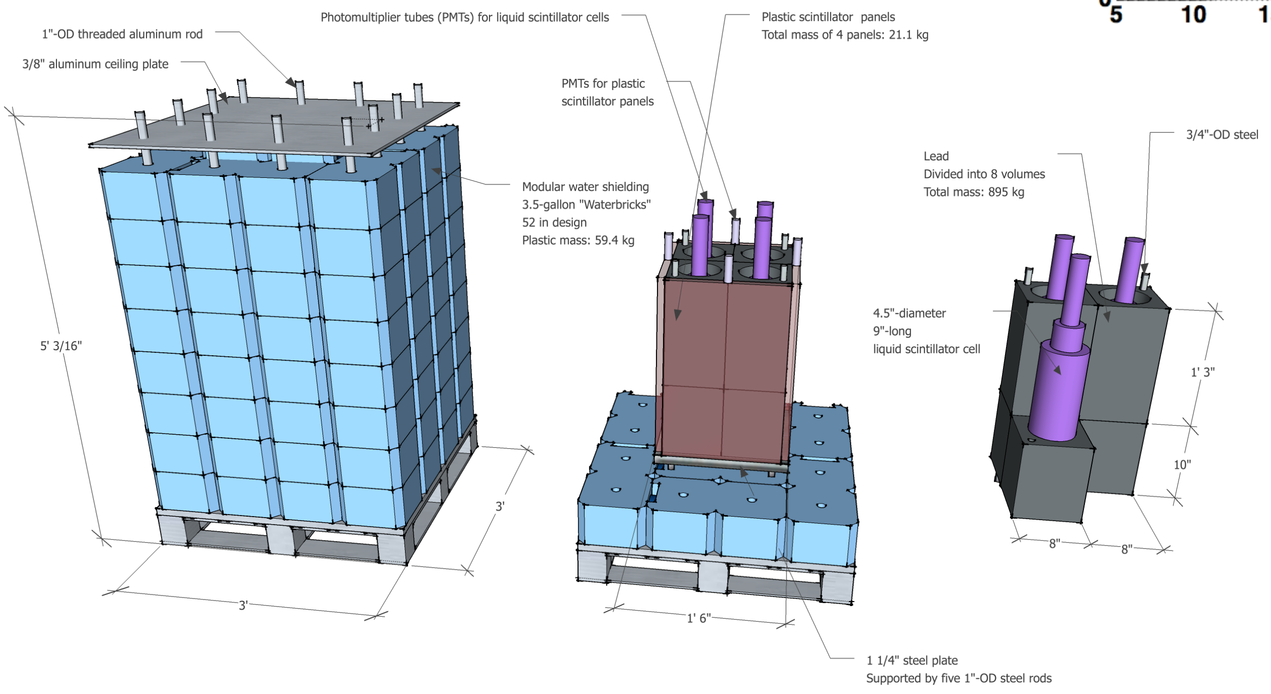
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$ CC

1n, 2n emission

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x$ NC

1n, 2n, γ emission





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