First EuCAPT Annual Symposium

5 - 7 May 2021

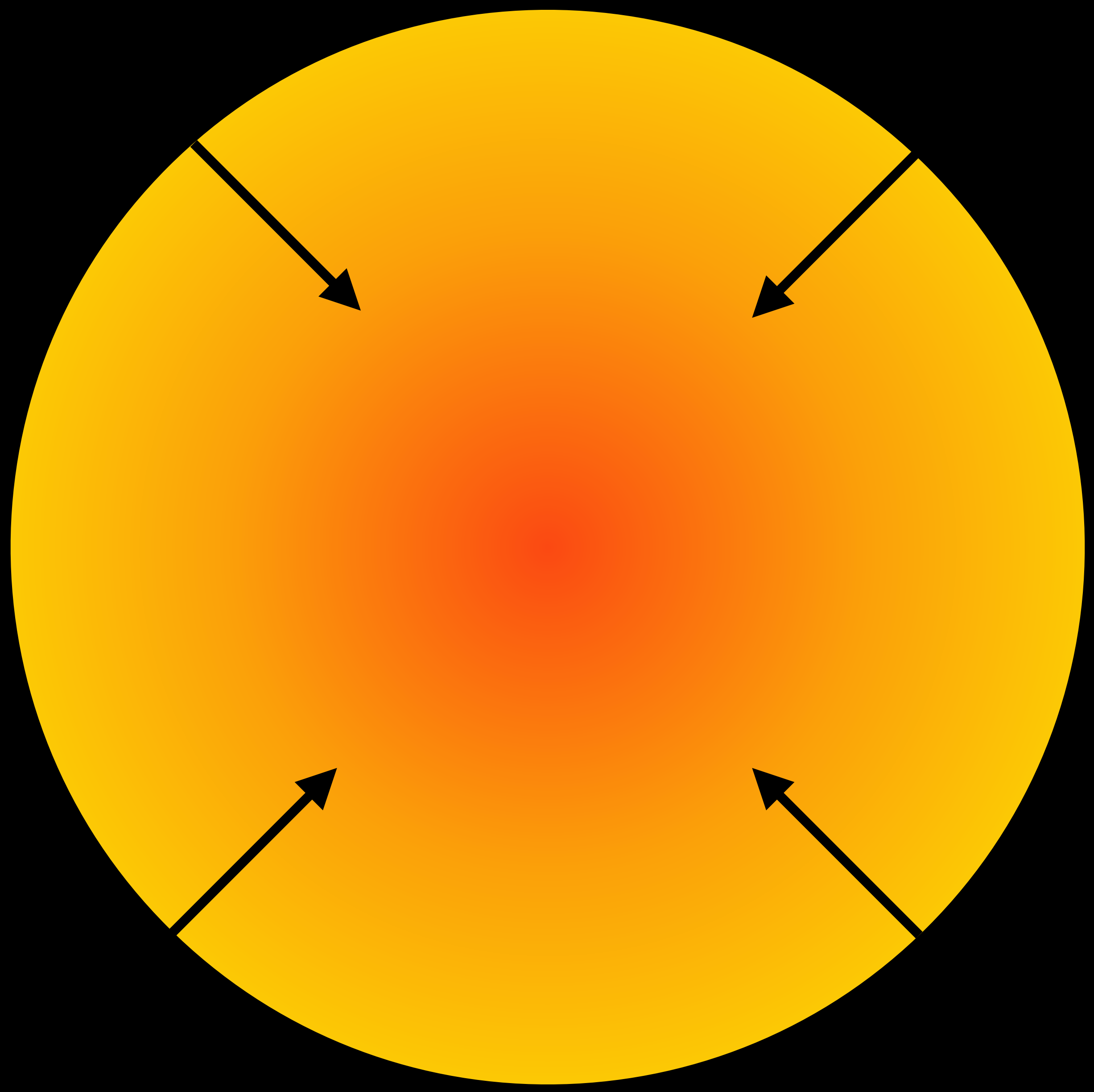
# Supernova Neutrinos in the Standard Model


Francesco Capozzi

VIRGINIA TECH

# What are supernovae?

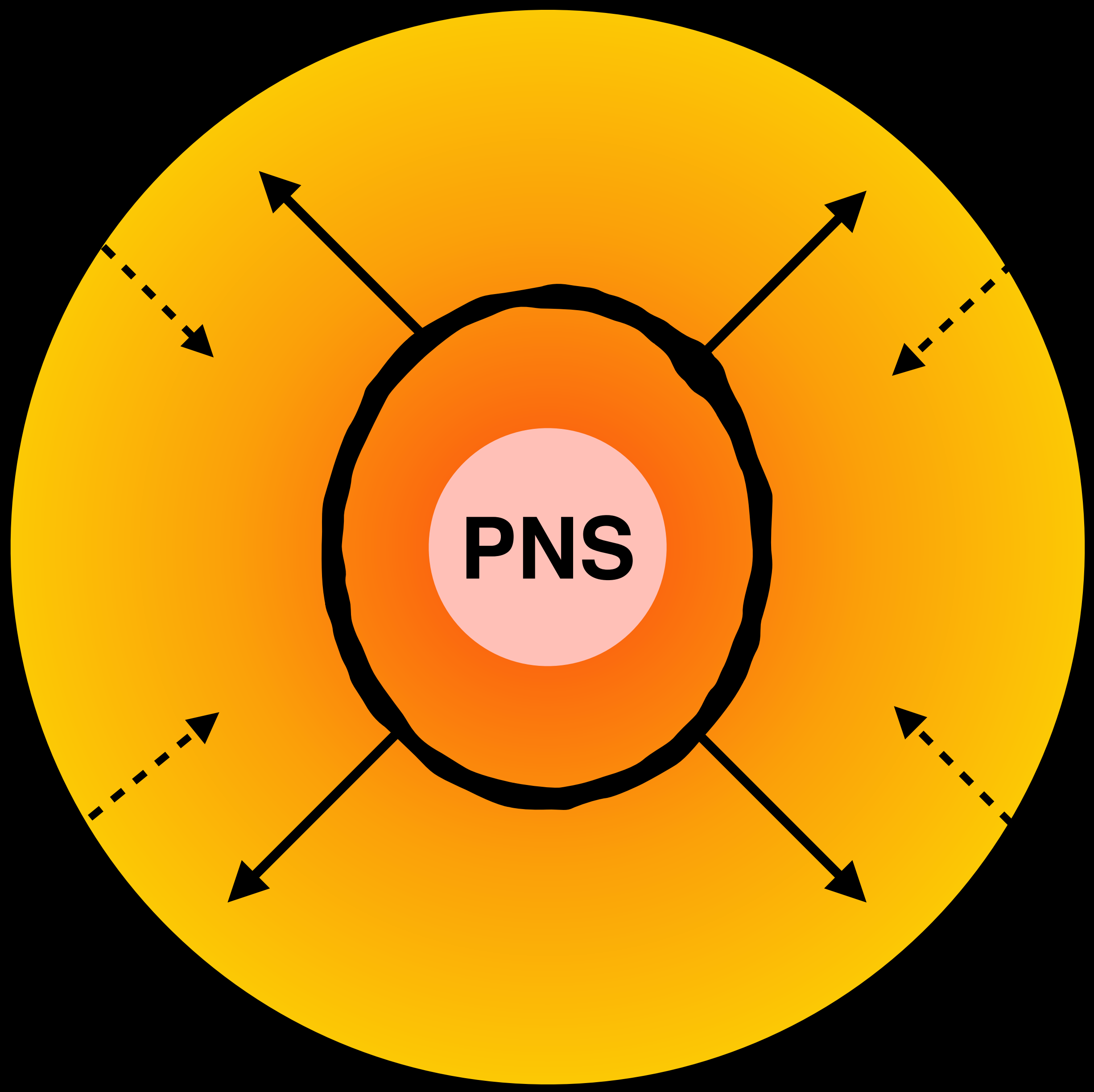
When nuclear fuel ends, massive stars (> 8 $M_\odot$) start collapsing



The density in the core rapidly increases

# What are supernovae?

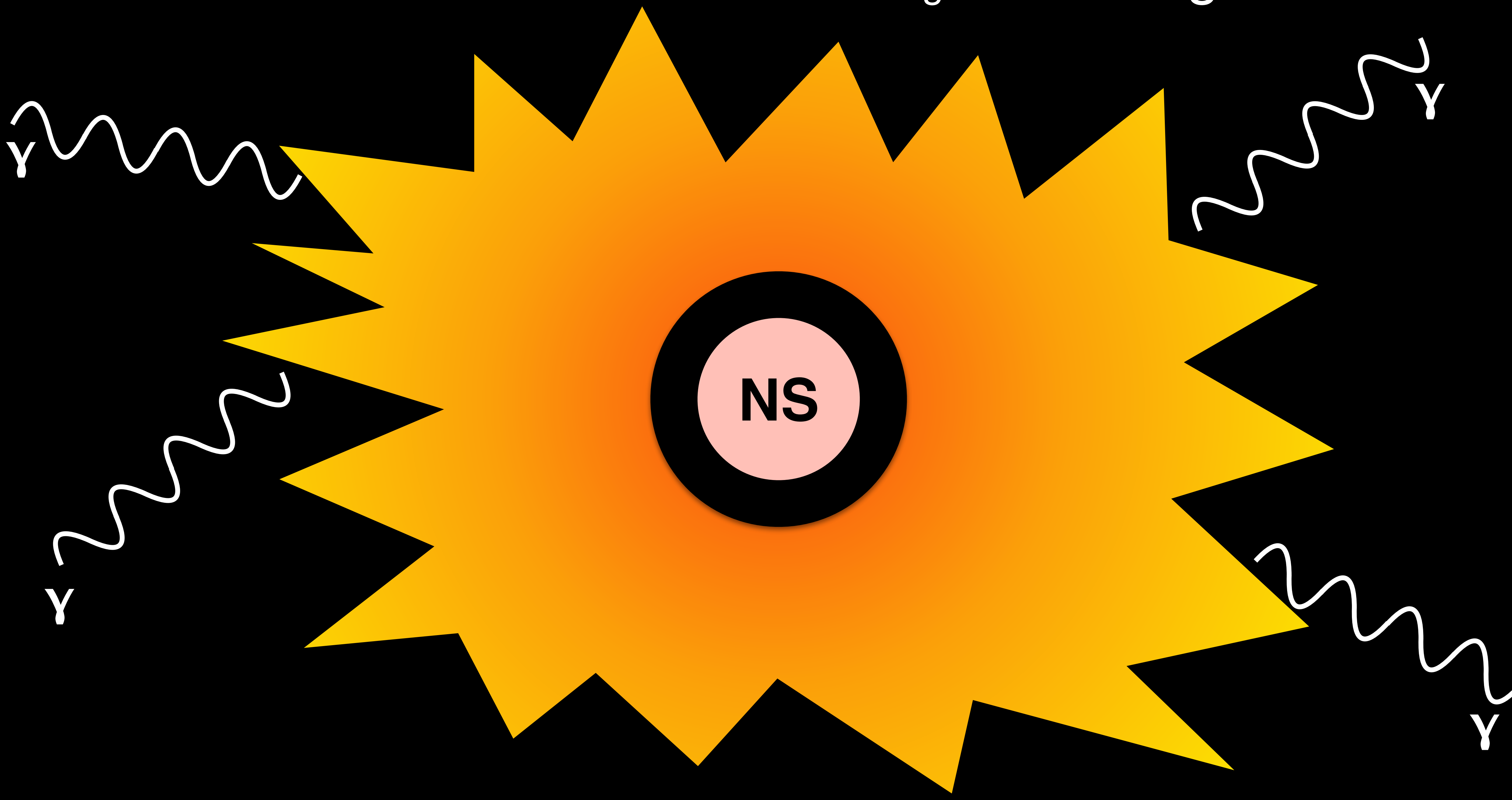
The density reaches nuclear saturation $\rho \sim 10^{14}$ g/cm$^3$




A shock wave is produced blowing up the star (Supernova)

# What are supernovae?

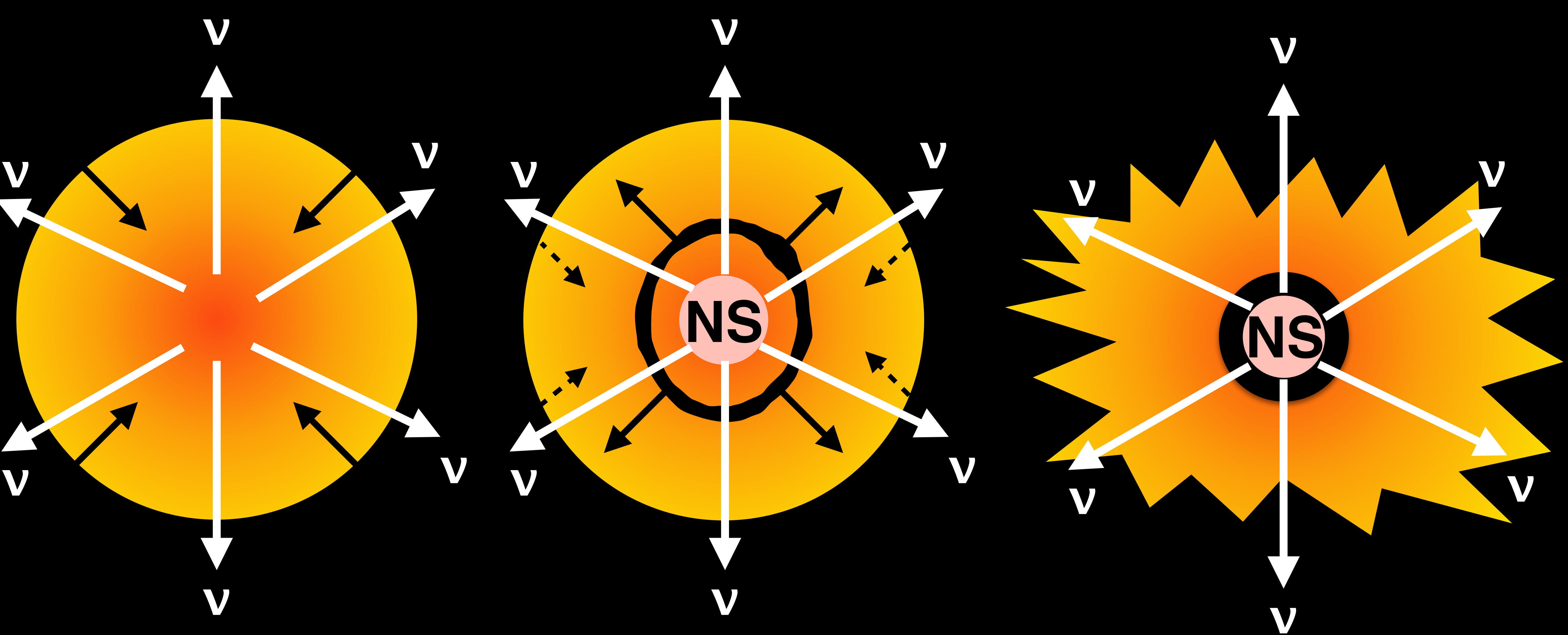
$R_{NS} \sim 10$ km $\quad E_g \sim 10^{53}$ erg




$E_{exp} \sim 1\%\ E_g \quad E_\gamma \sim 0.01\%\ E_g$

# What is the role of neutrinos?

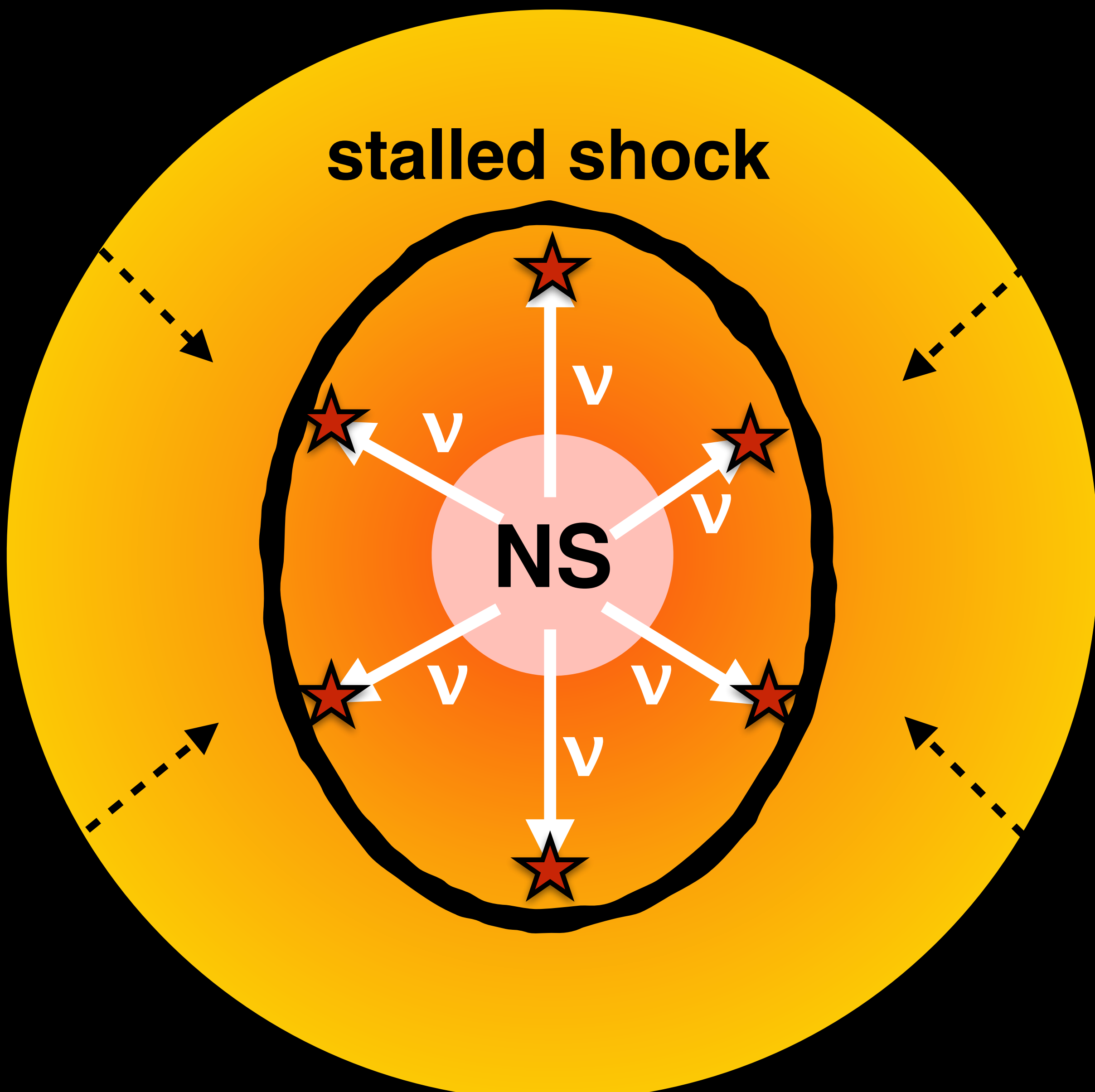
$\nu$ / $\bar{\nu}$ of all flavor carry away 99% of $E_g$ in ~10s seconds




Neutrinos are messengers from the interior of the exploding star

# What is the role of neutrinos?

The shock wave stalls after ~ few 10 ms



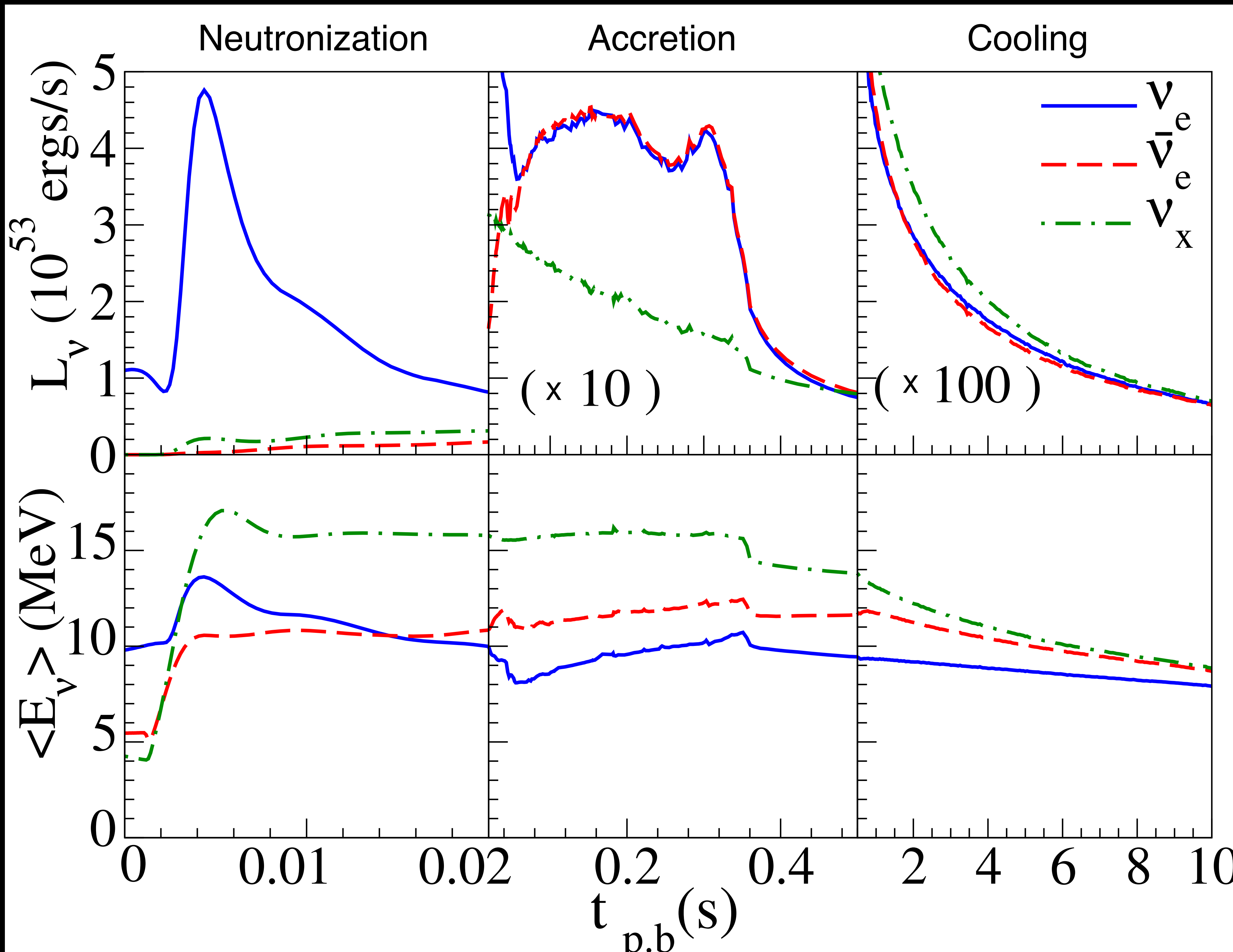

★ $\nu_e + n \longrightarrow e^- + p$

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

**Delayed neutrino heating mechanism** revives the shock

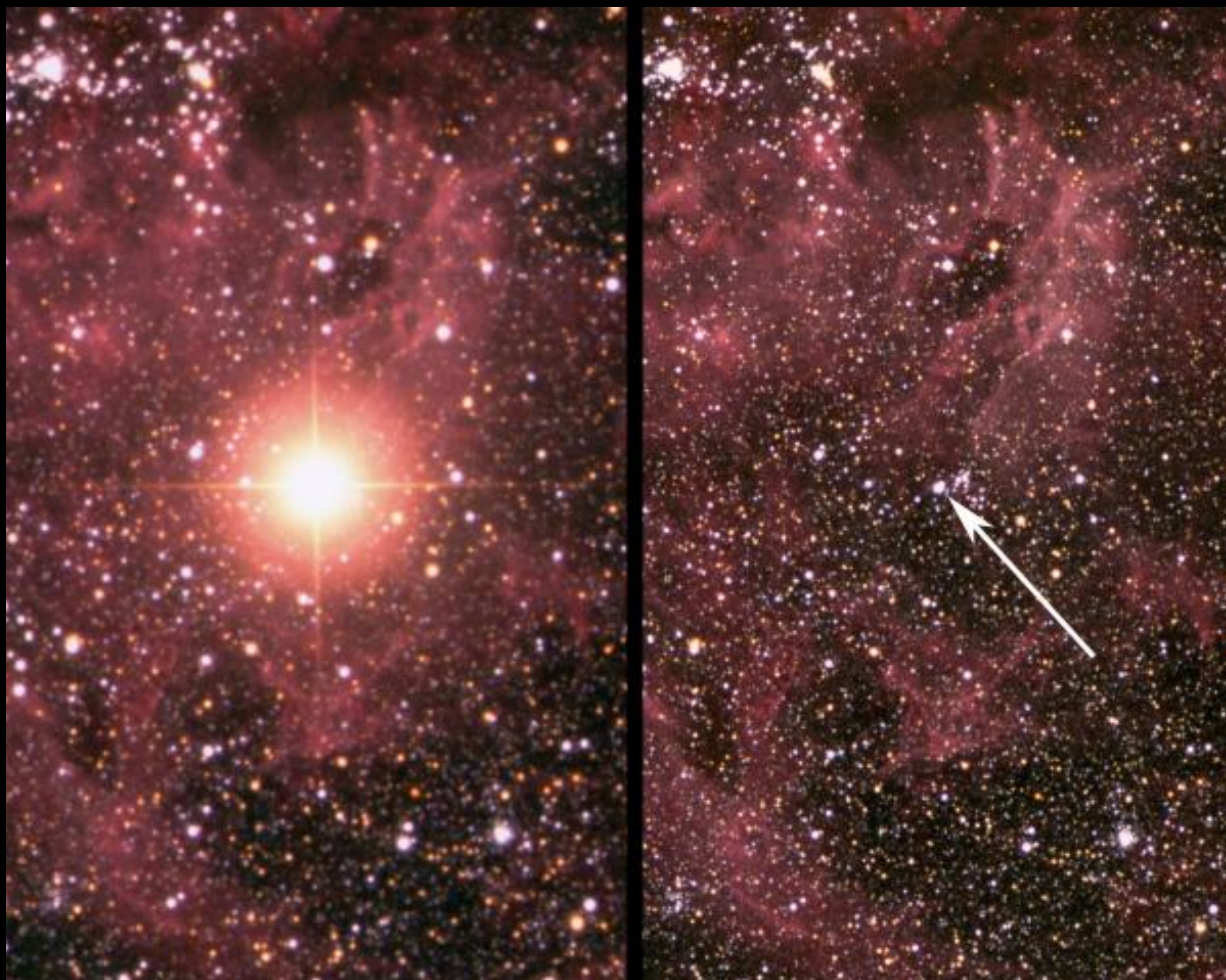
# What is the role of neutrinos?

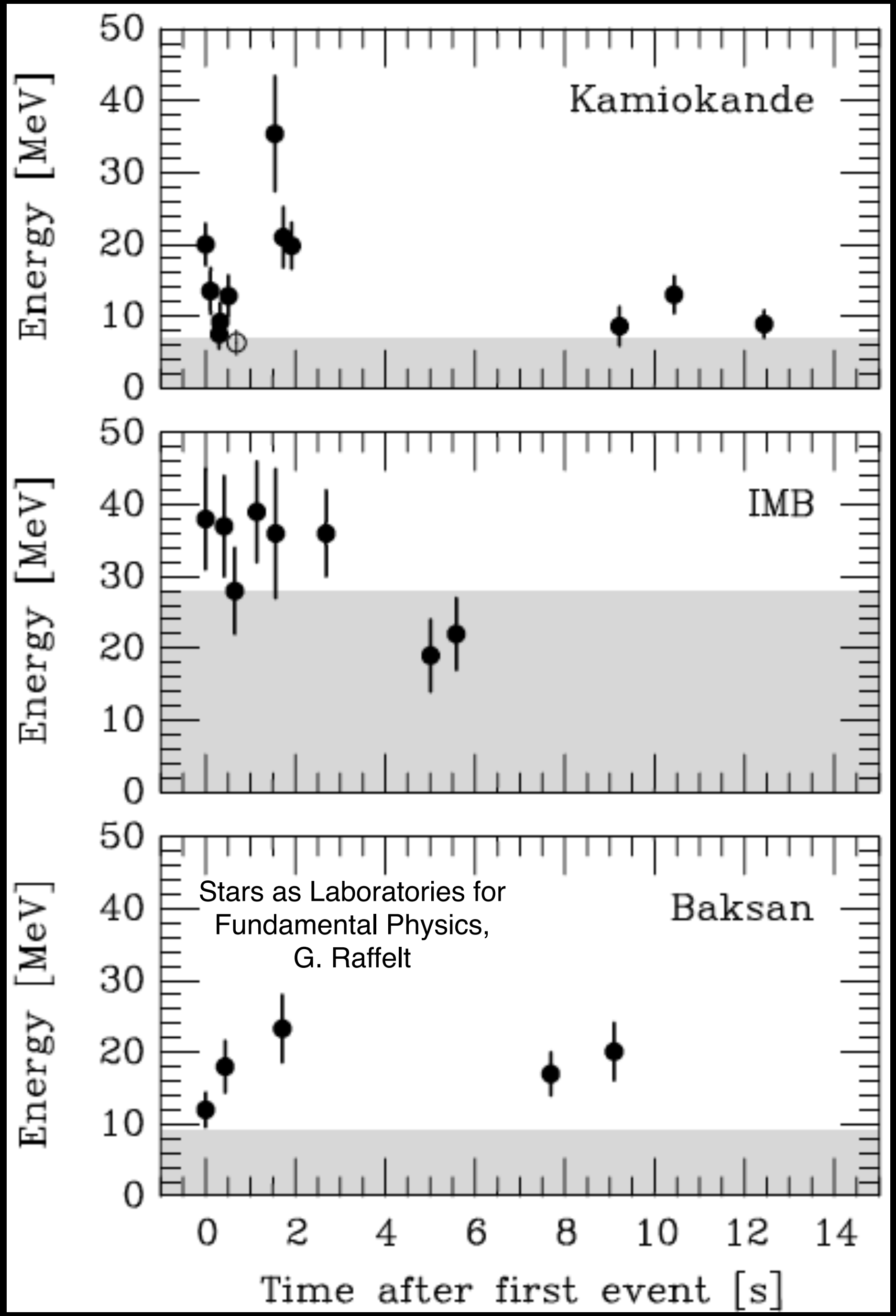
Chakraborty, Bhattacharjee, Kar,  Phys. Rev. D 89 (2014) no.1,  013011, T. Fischer et al,  Astron. Astrophys. 517, A80 (2010)



# What have we learnt so far?

Supernova 1987a





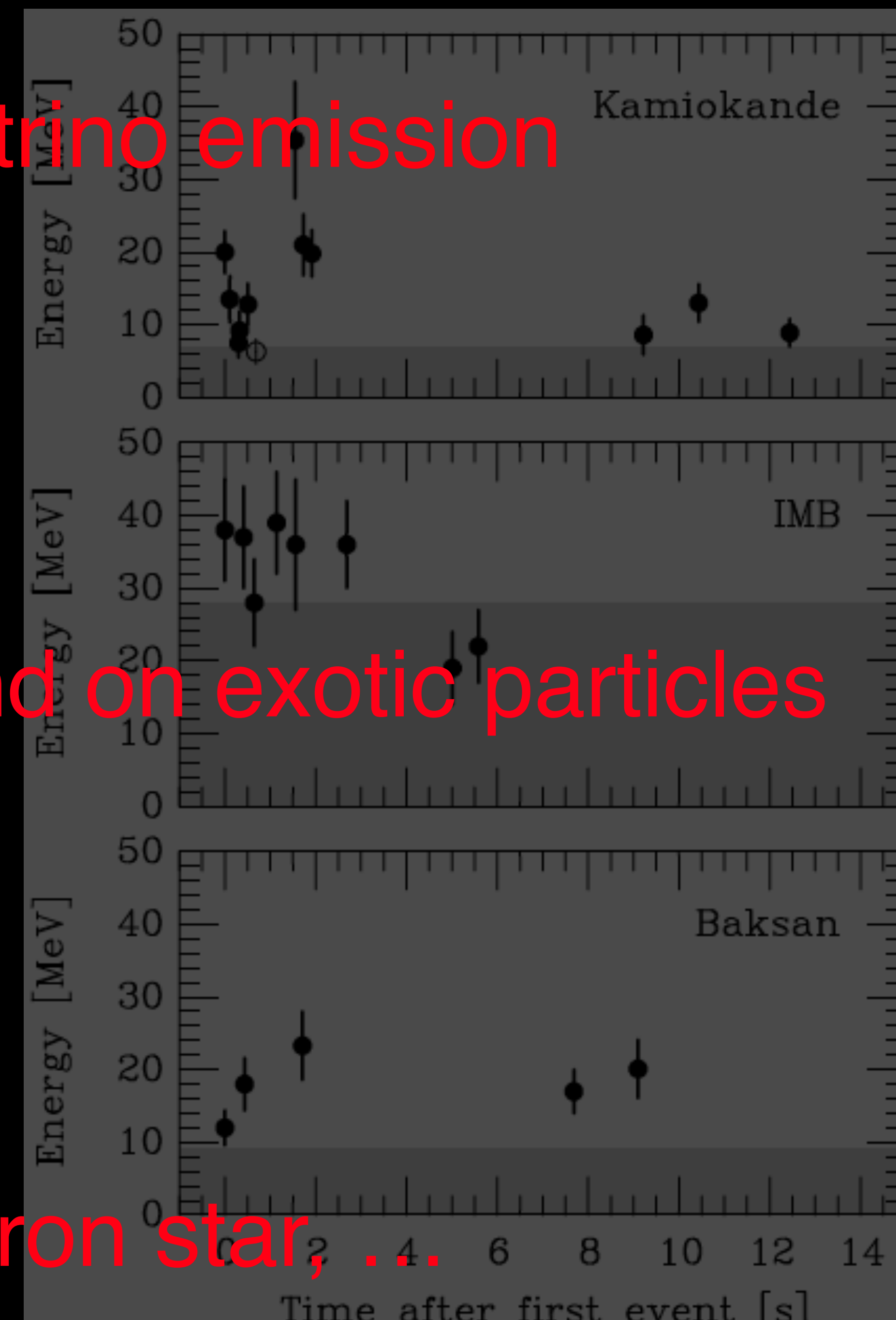

First and only neutrinos observed from a supernova

# What have we learnt so far?

Confirmed expectation for neutrino emission

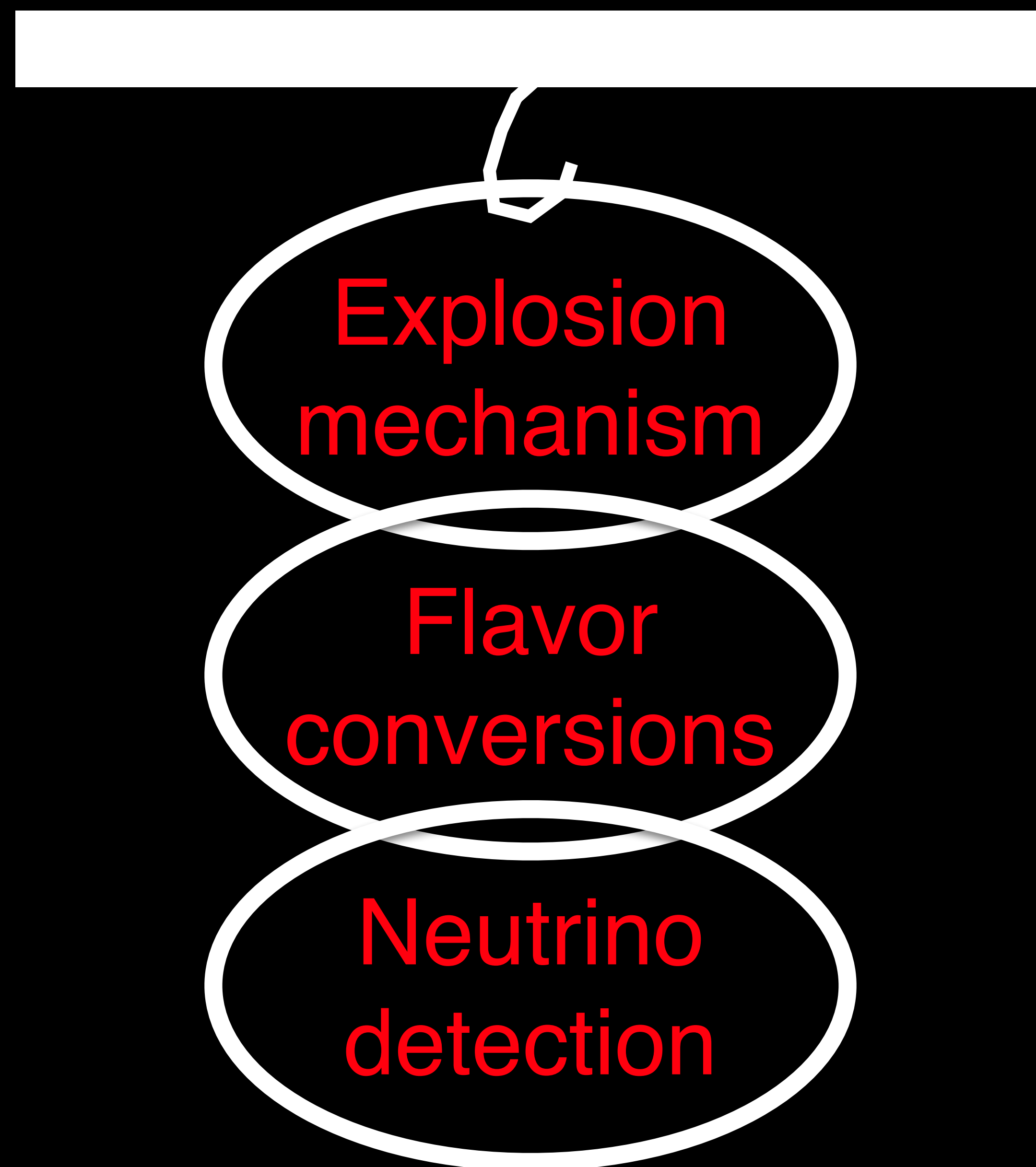
Constraints on neutrino properties and on exotic particles

Asymmetric explosion, neutron star, …

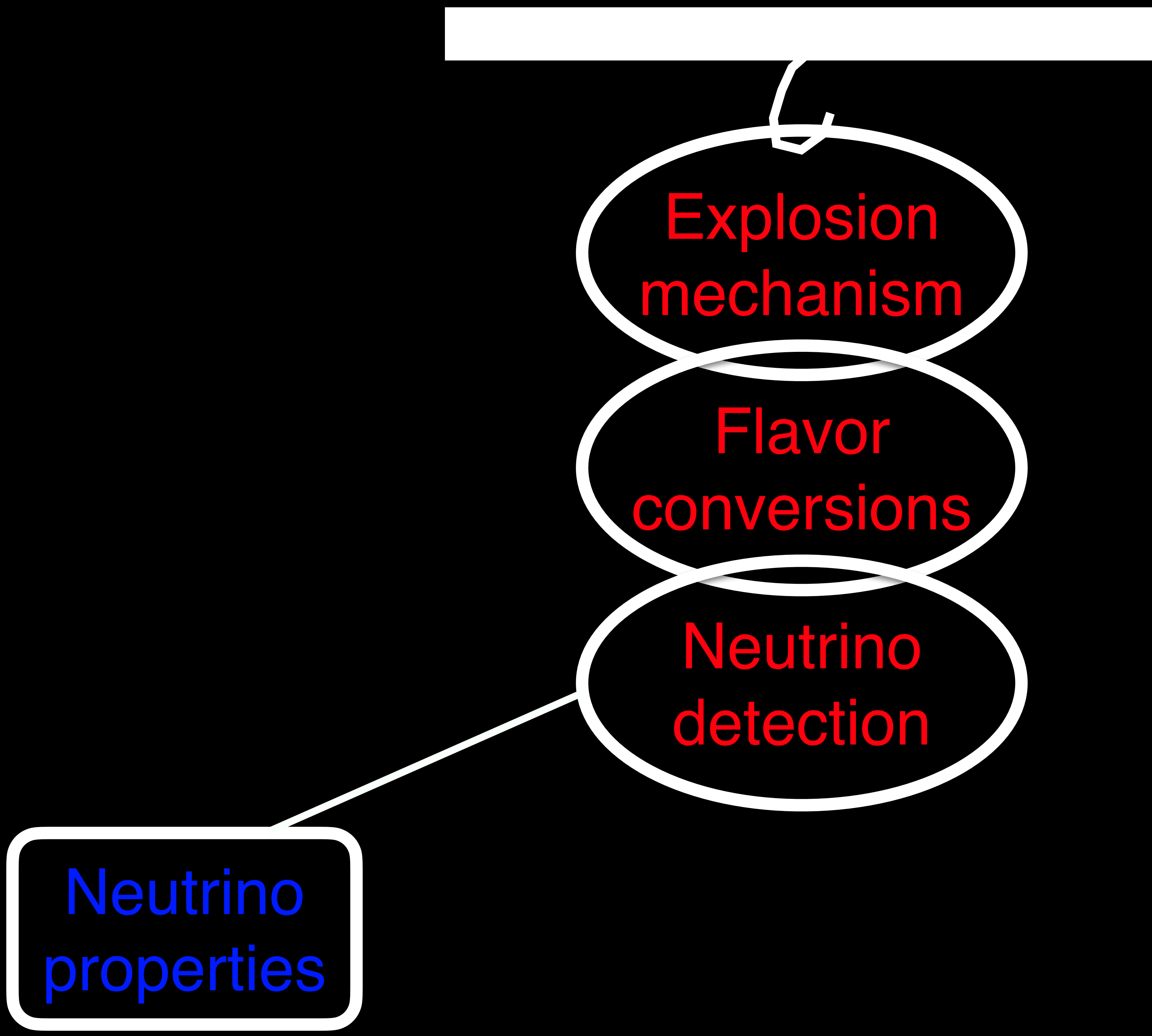
# Are we ready for SN20xy?

The supernova neutrinos chain



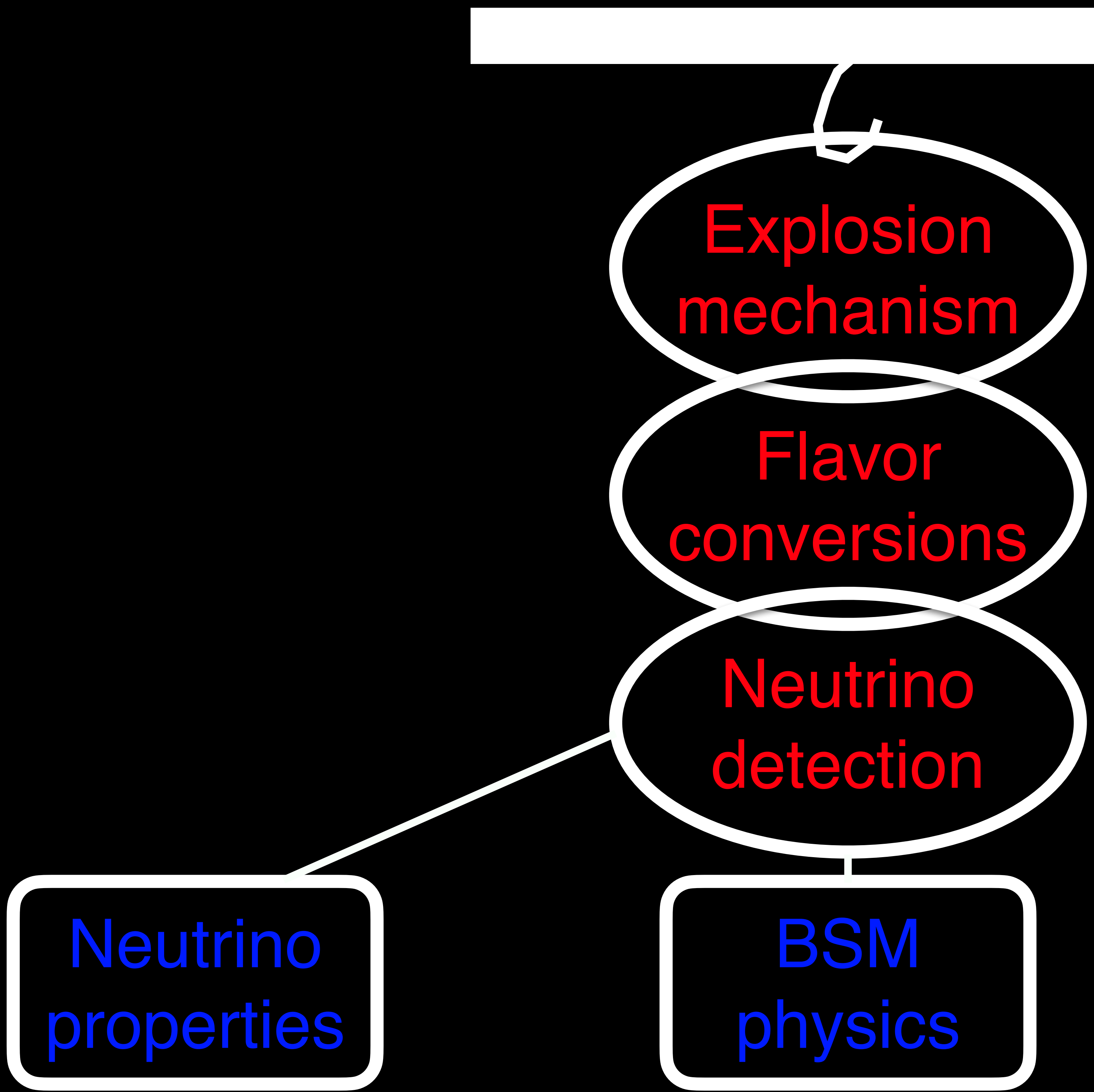
# Are we ready for SN20xy?

The supernova neutrinos chain



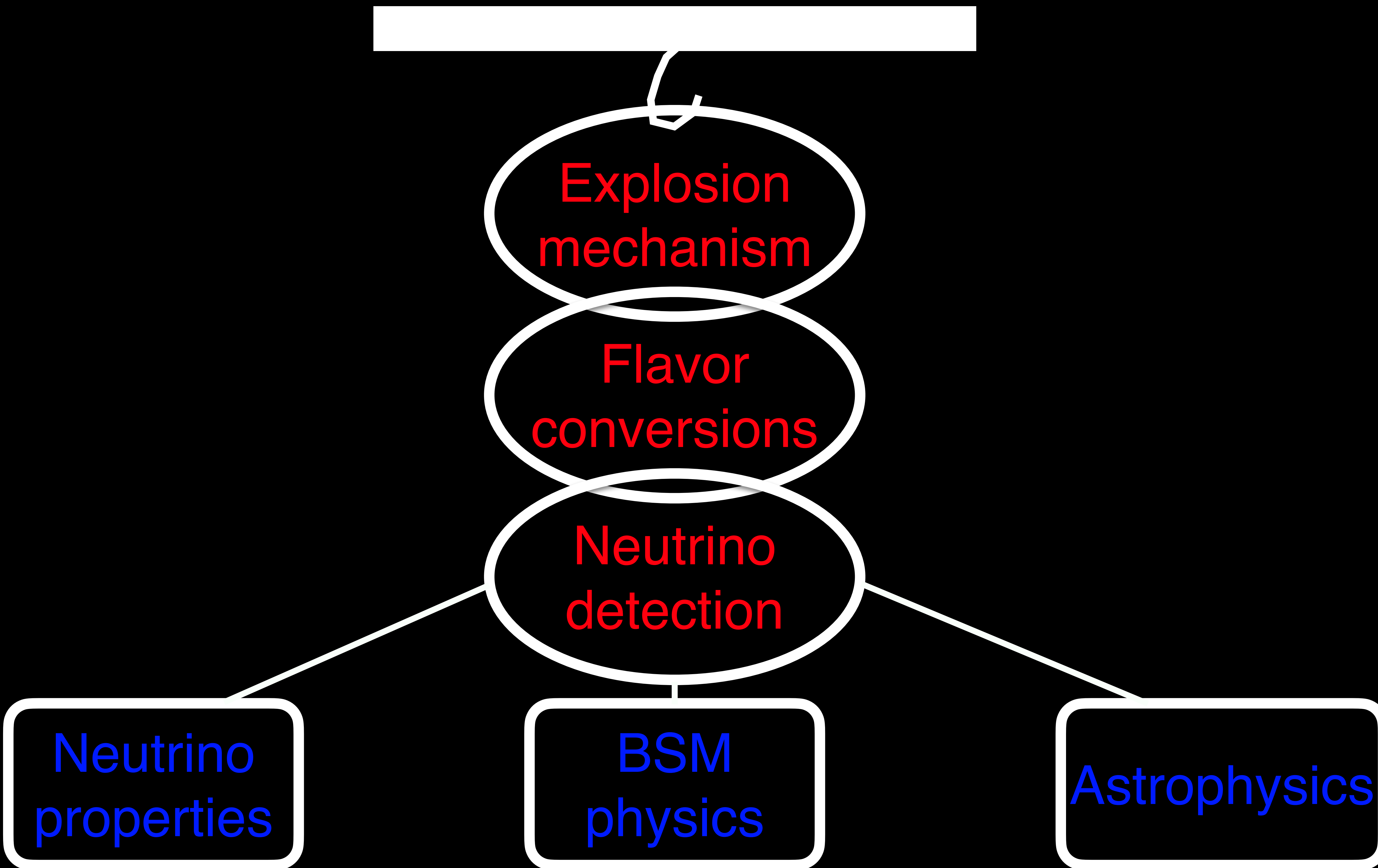
# Are we ready for SN20xy?

The supernova neutrinos chain



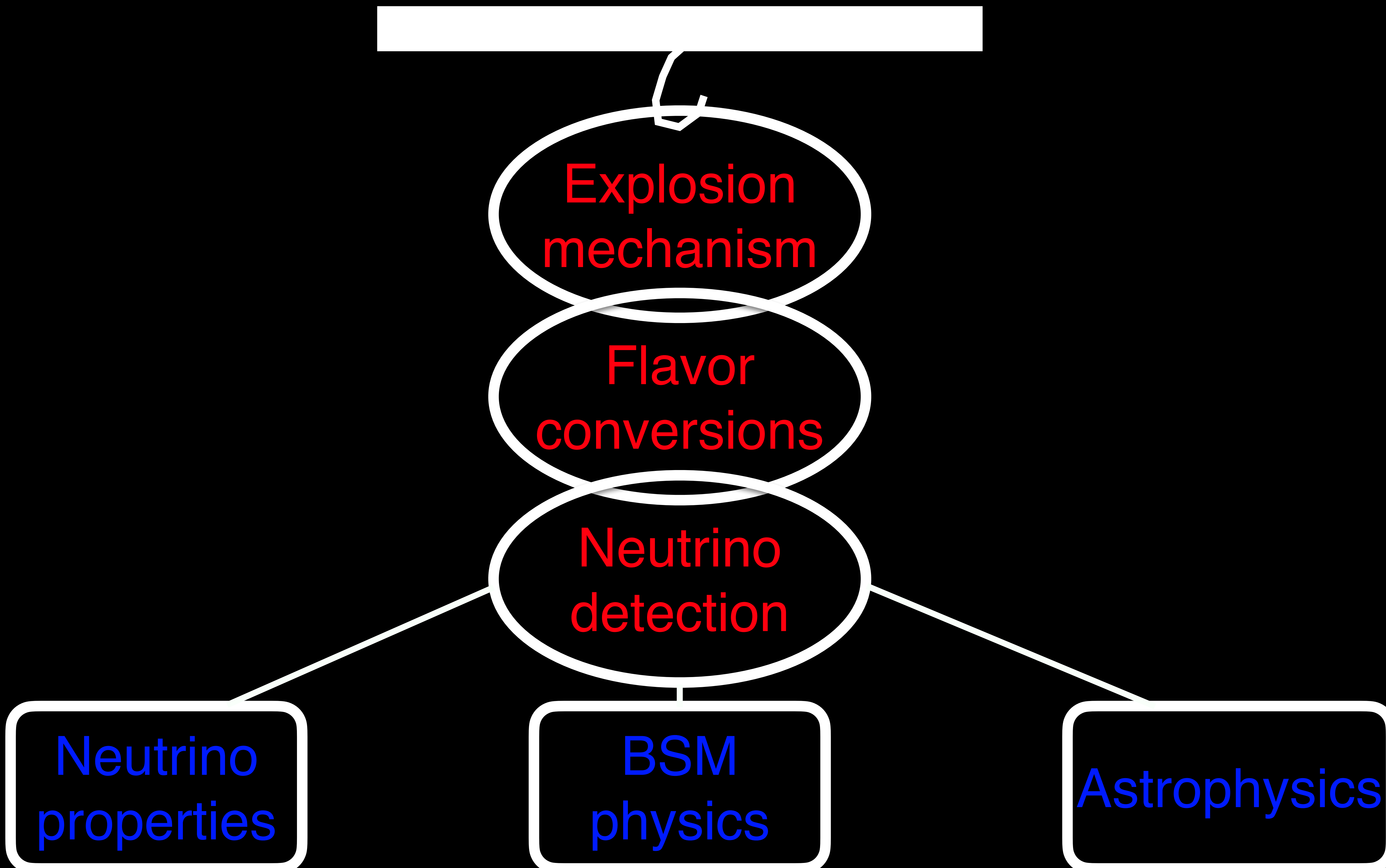
# Are we ready for SN20xy?

The supernova neutrinos chain



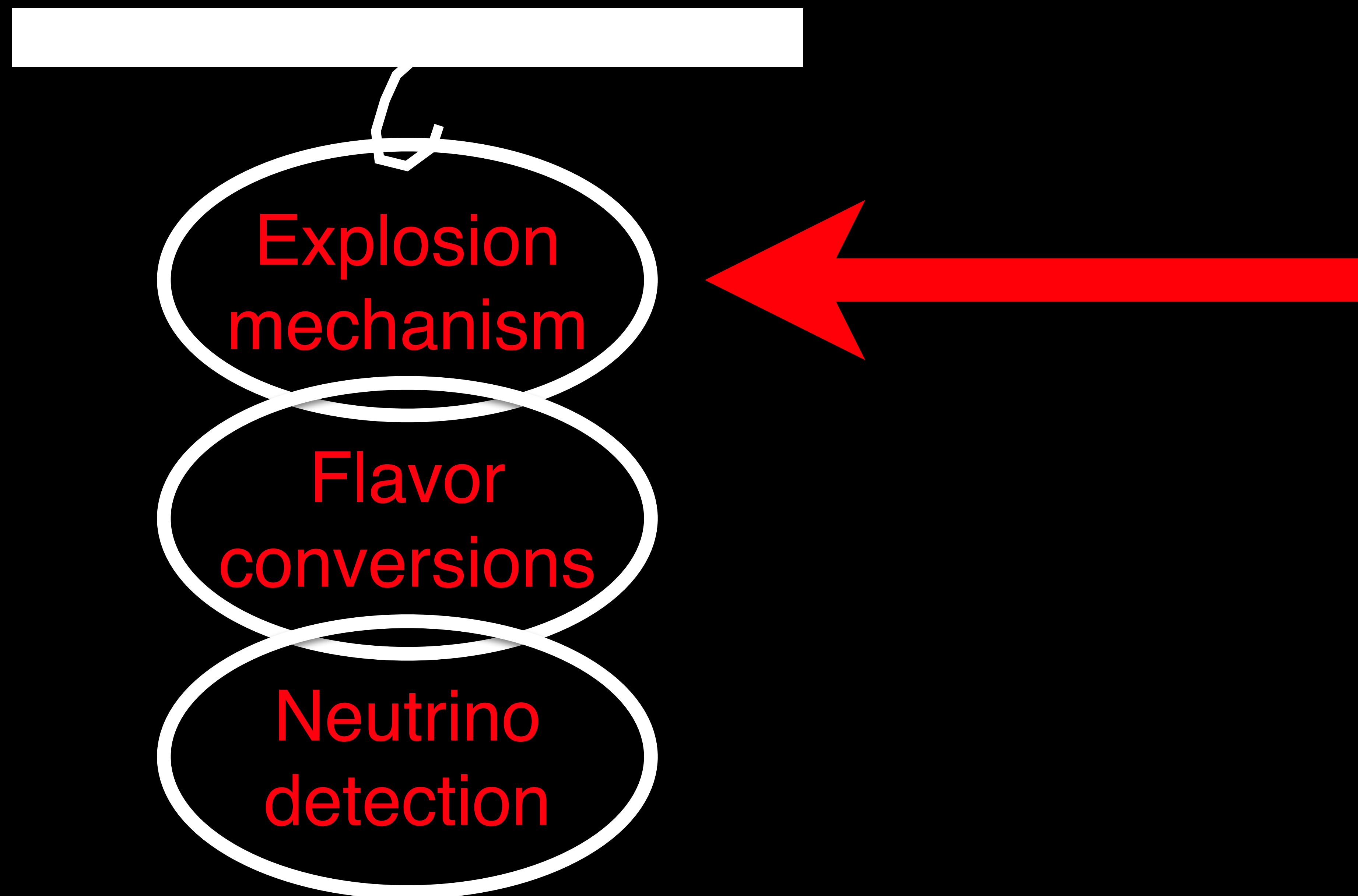
# Are we ready for SN20xy?

Each aspect of the chain to **MUST** be well understood



# Are we ready for SN20xy?

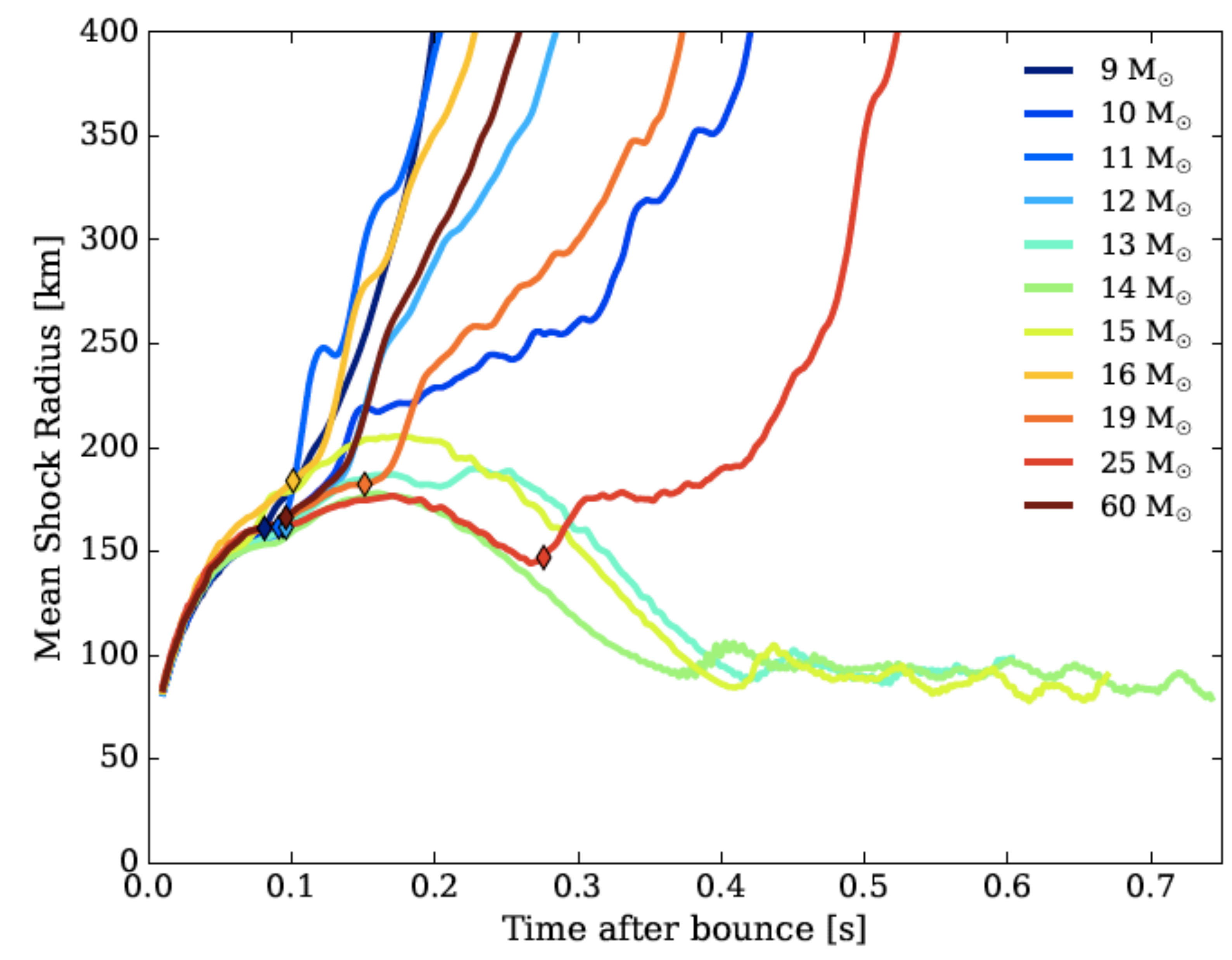
Each aspect of the chain to **MUST** be well understood



# The era of 3D simulations

3D simulations for several progenitor models are available

Vartanyan, Burrows, Radice, Mon. Not. Roy. Astron. Soc. 489 (2019) no.2, 2227-2246

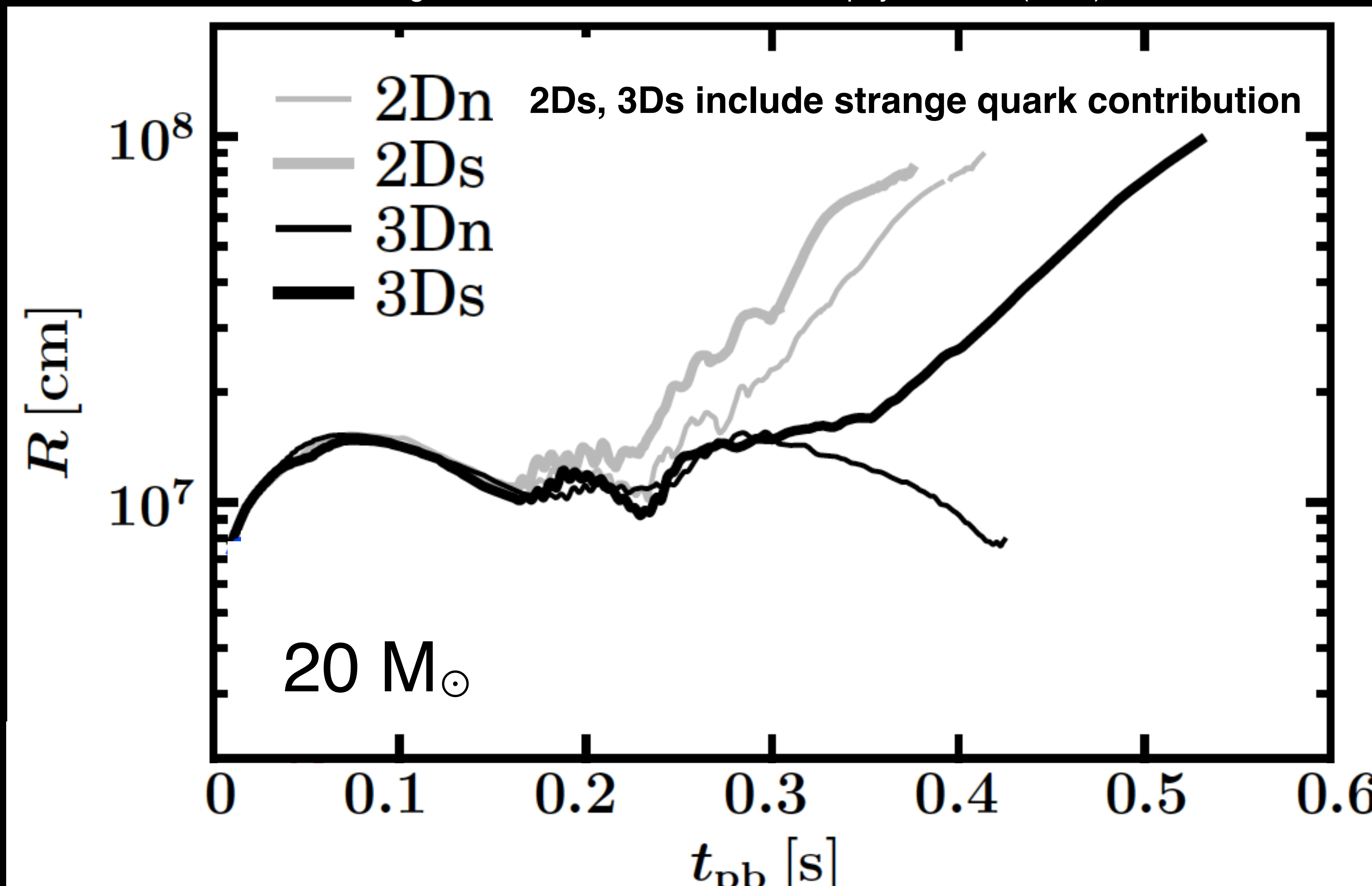



Successful explosions! Consistent picture at low mass…

# The era of 3D simulations

… Less consistent picture for heavy progenitor masses

Melson, Janka, Bollig, Hanke, Marek and Müller, Astrophys. J. 808 (2015) no.2, L42

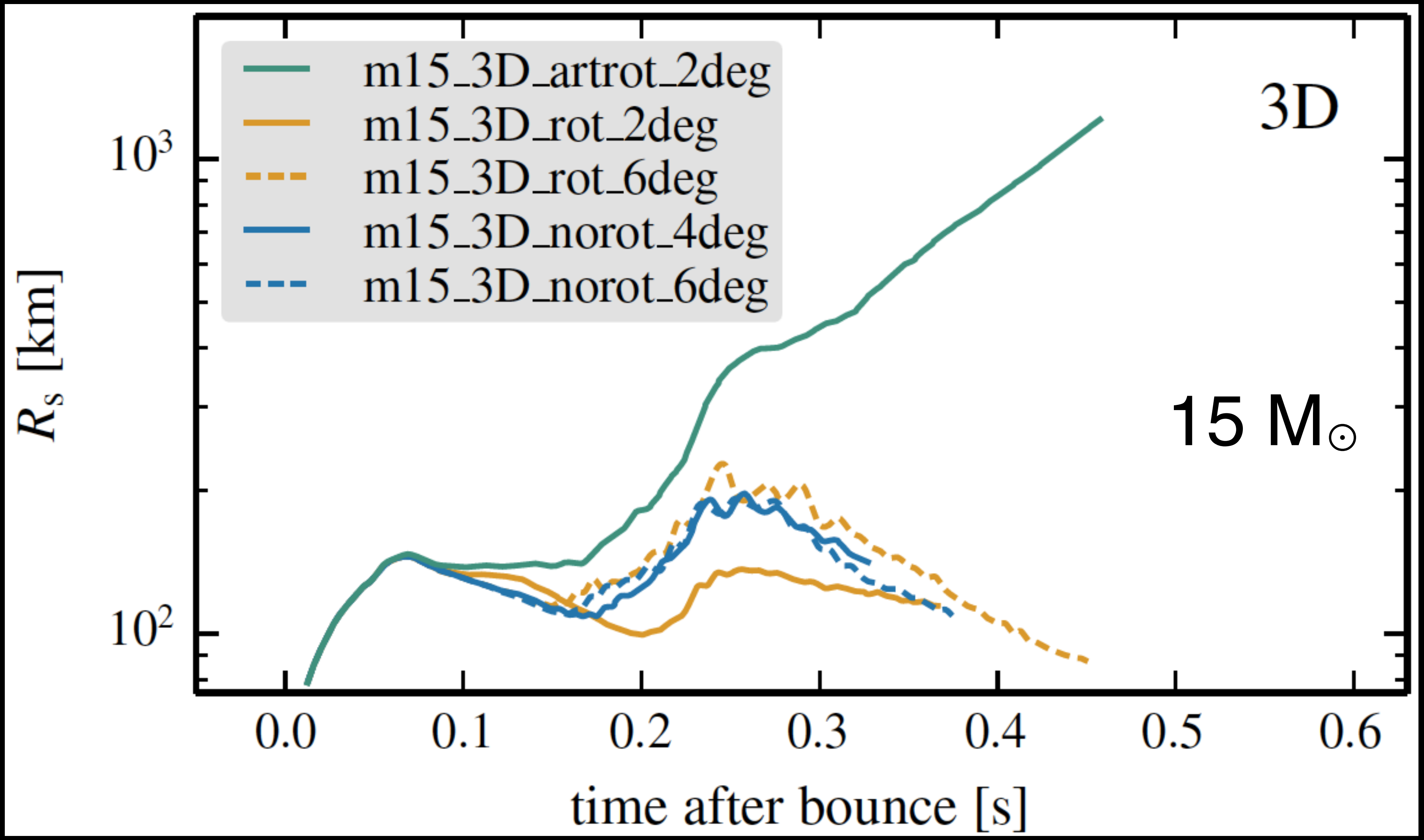



Example: s-quark contribution in ν-n NC creates explosion

# The era of 3D simulations

… Less consistent picture for heavy progenitor masses

Summa, Janka, Melson and Marek, Astrophys. J. 852 (2018) no.1, 28




Example: fast rotation induced explosion

# The era of 3D simulations

Less consistent picture for heavy progenitor masses

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust

# The era of 3D simulations

Less consistent picture for heavy progenitor masses

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust

Hypothesis 2

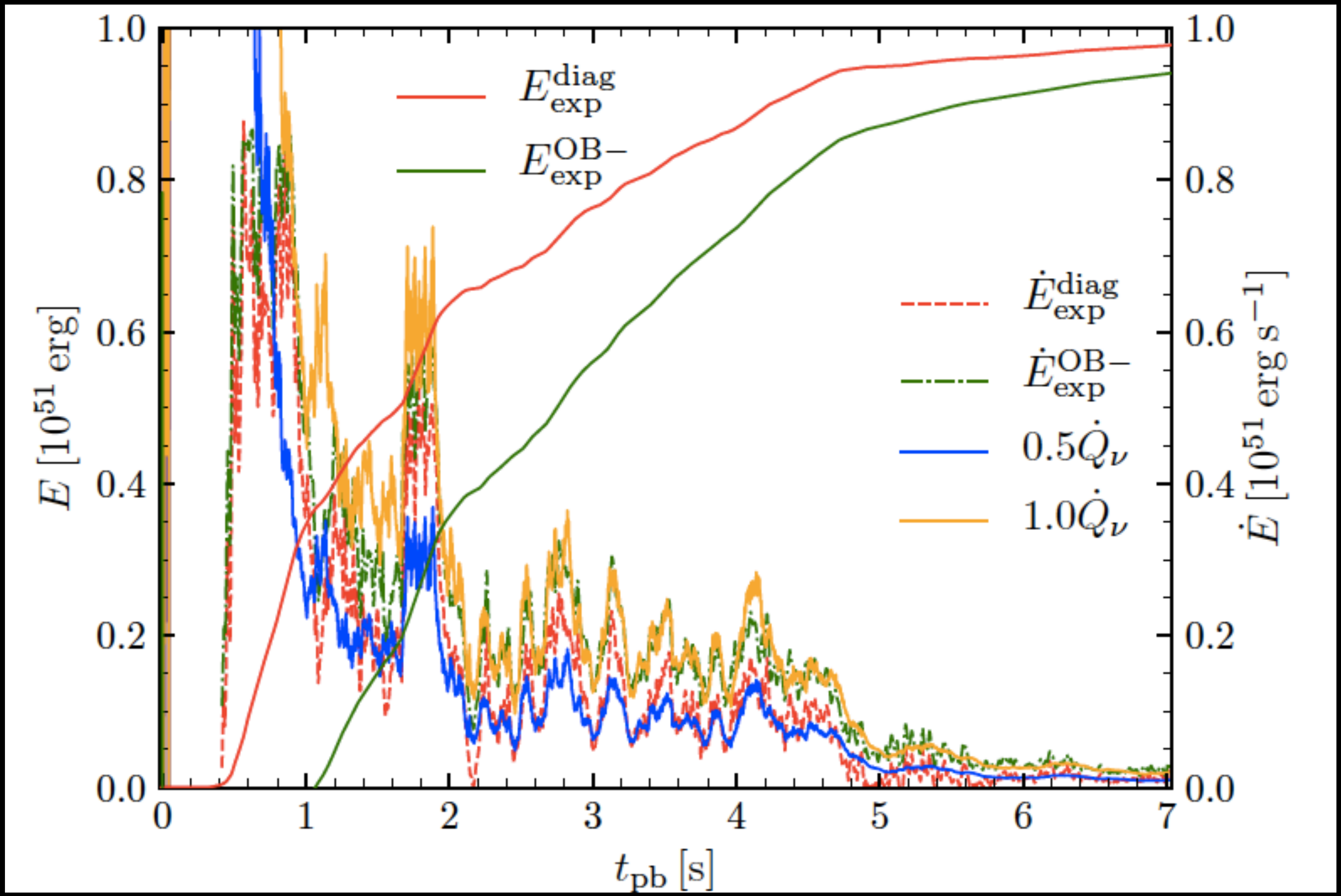
The delayed neutrino mechanism **IS** robust.
Simulations are missing some key ingredients

More refined simulations are needed

# The era of 3D simulations

Long term 3D simulation from -7 mins up to 7 seconds p. b.

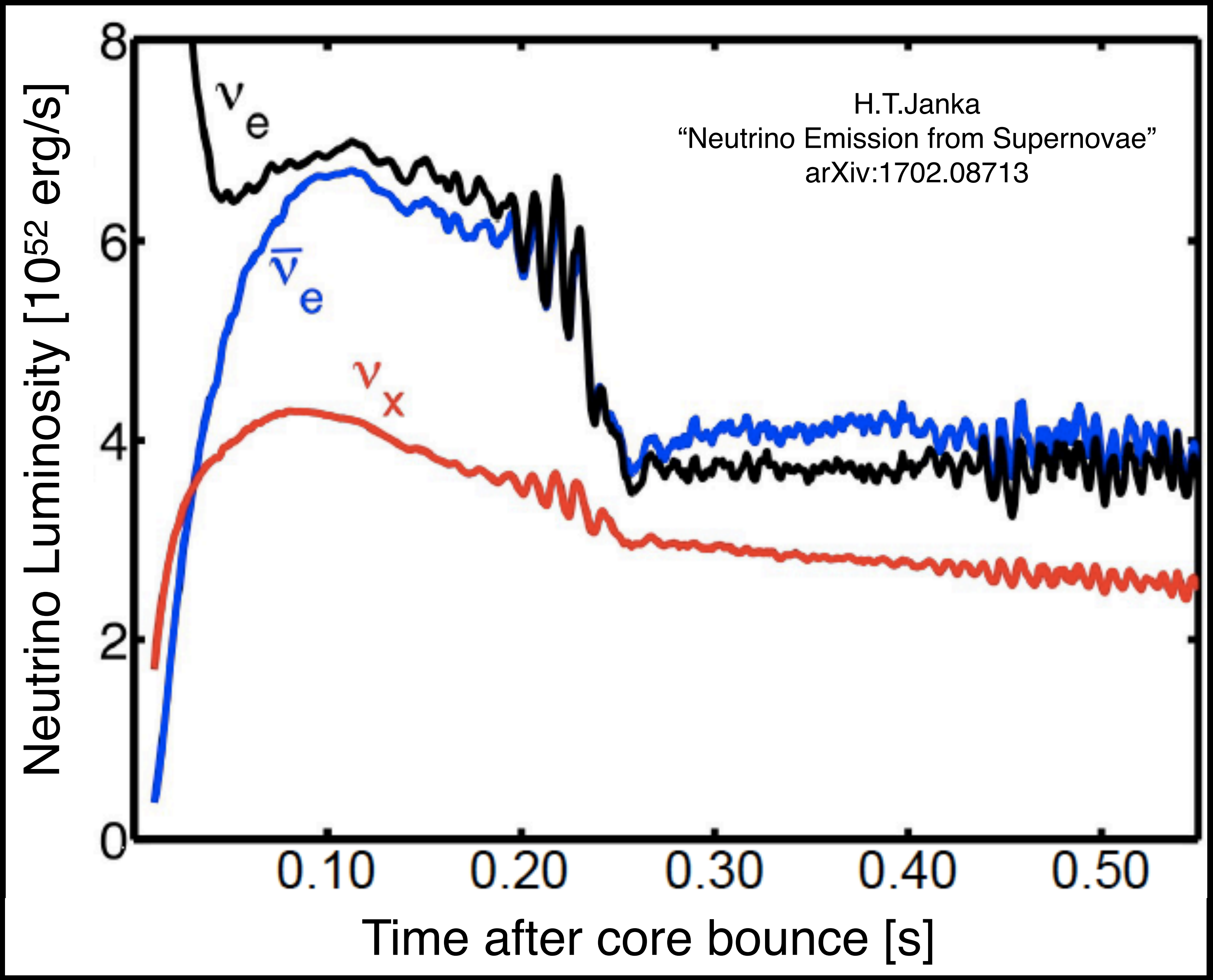
Bollig, Yadav, Kresse, Janka, Mueller and Heger, arXiv:2010.10506




1 Bethe explosions are possible for neutrino-driven SNe of non/slow-rotating < 20 $M_\odot$ progenitors

# Multi-D neutrino signal features

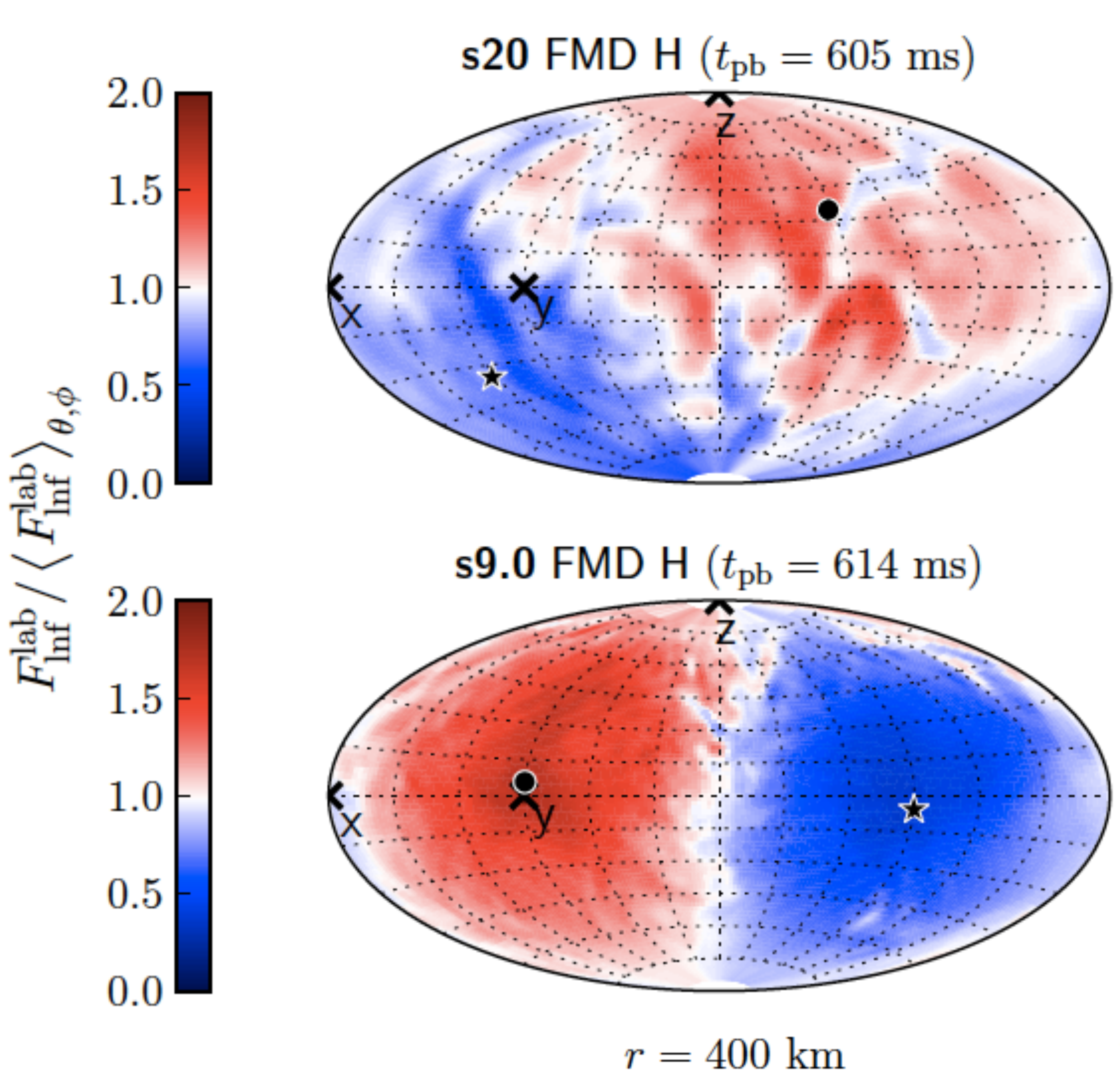
Sloshing/spiraling (SASI) motion of the shock modulates $L_\nu$




Neutrinos are probe of the explosion mechanism

# Multi-D neutrino signal features

Lepton number is emitted asymmetrically (LESA)




Tamborra et al.,
Astrophys. J. 792 (2014) no.2, 96

Glas et al.,
Astrophys.J. 881 (2019) no.1, 36

confirmed by

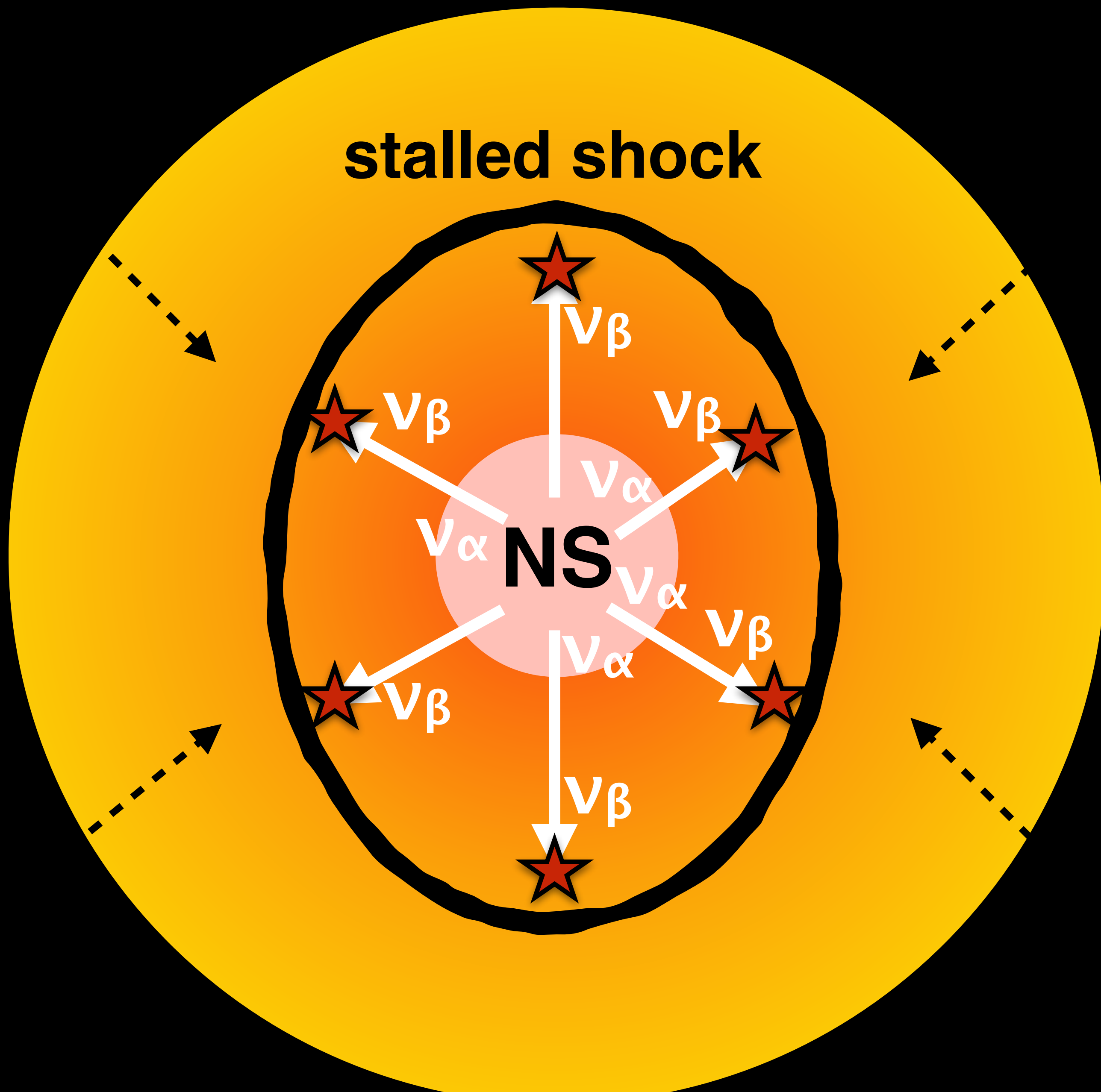
O'Connor and Couch,
Astrophys. J. 865 (2018) no.2, 81

Vartanyan, Burrows and Radice,
MNRAS 489 (2019) 2, 2227

Neutrinos are probe of the explosion mechanism

# Are we forgetting something?

No 2D / 3D simulations include **Flavor Conversions**



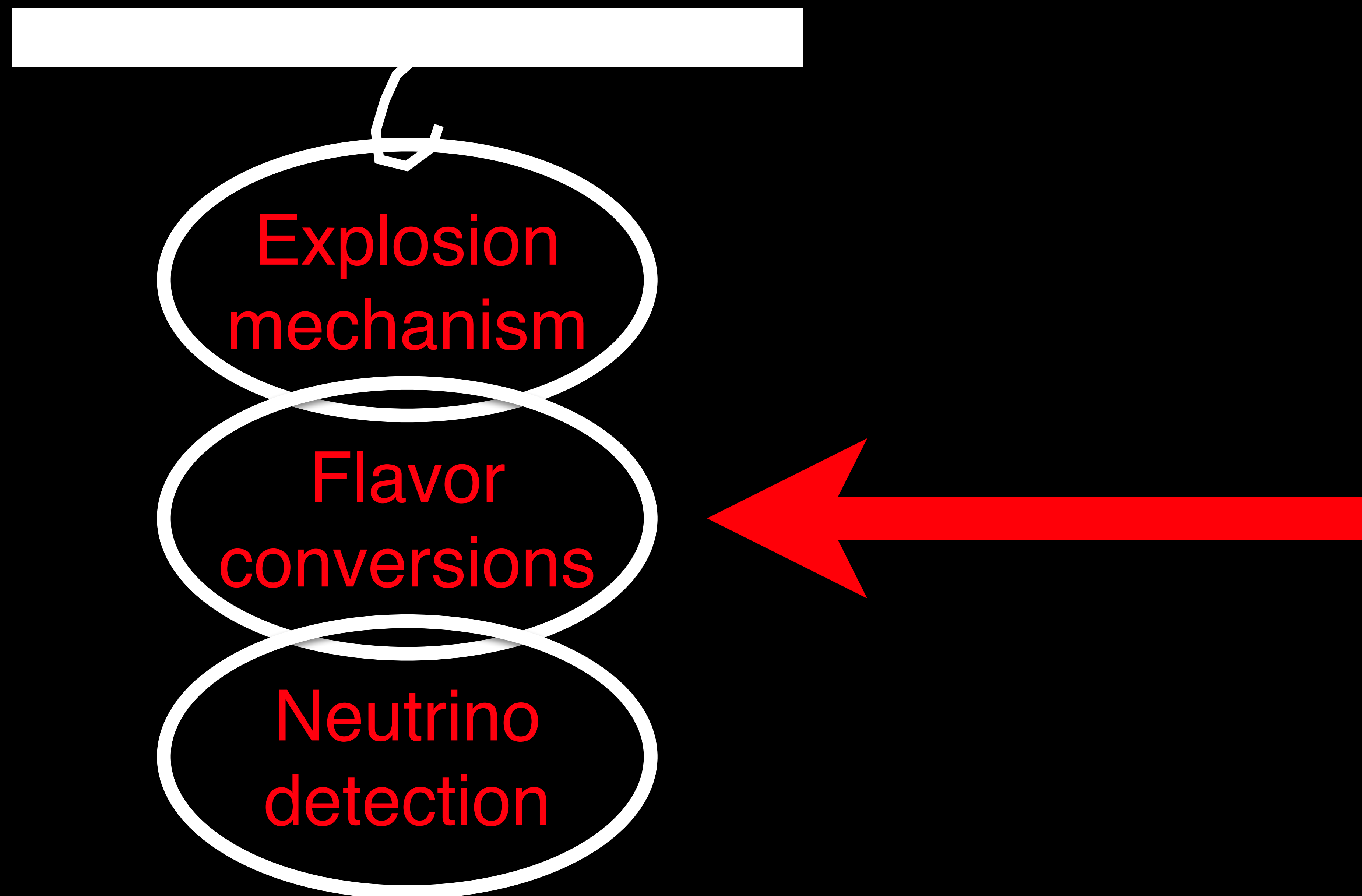

★ $\nu_e + n \longrightarrow e^- + p$

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

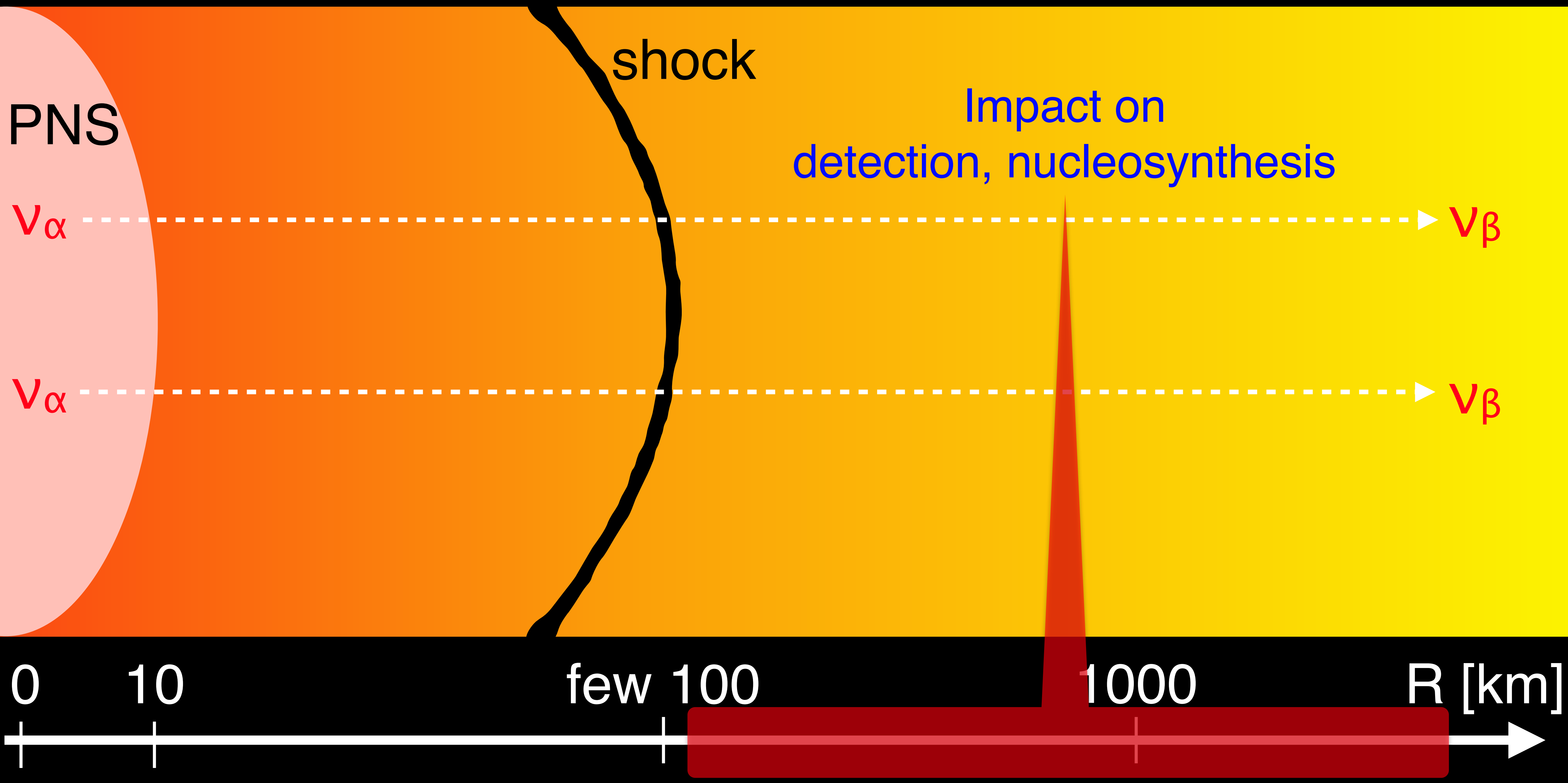
**Neutrino heating is flavor dependent!!!**

# Are we ready for SN20xy?

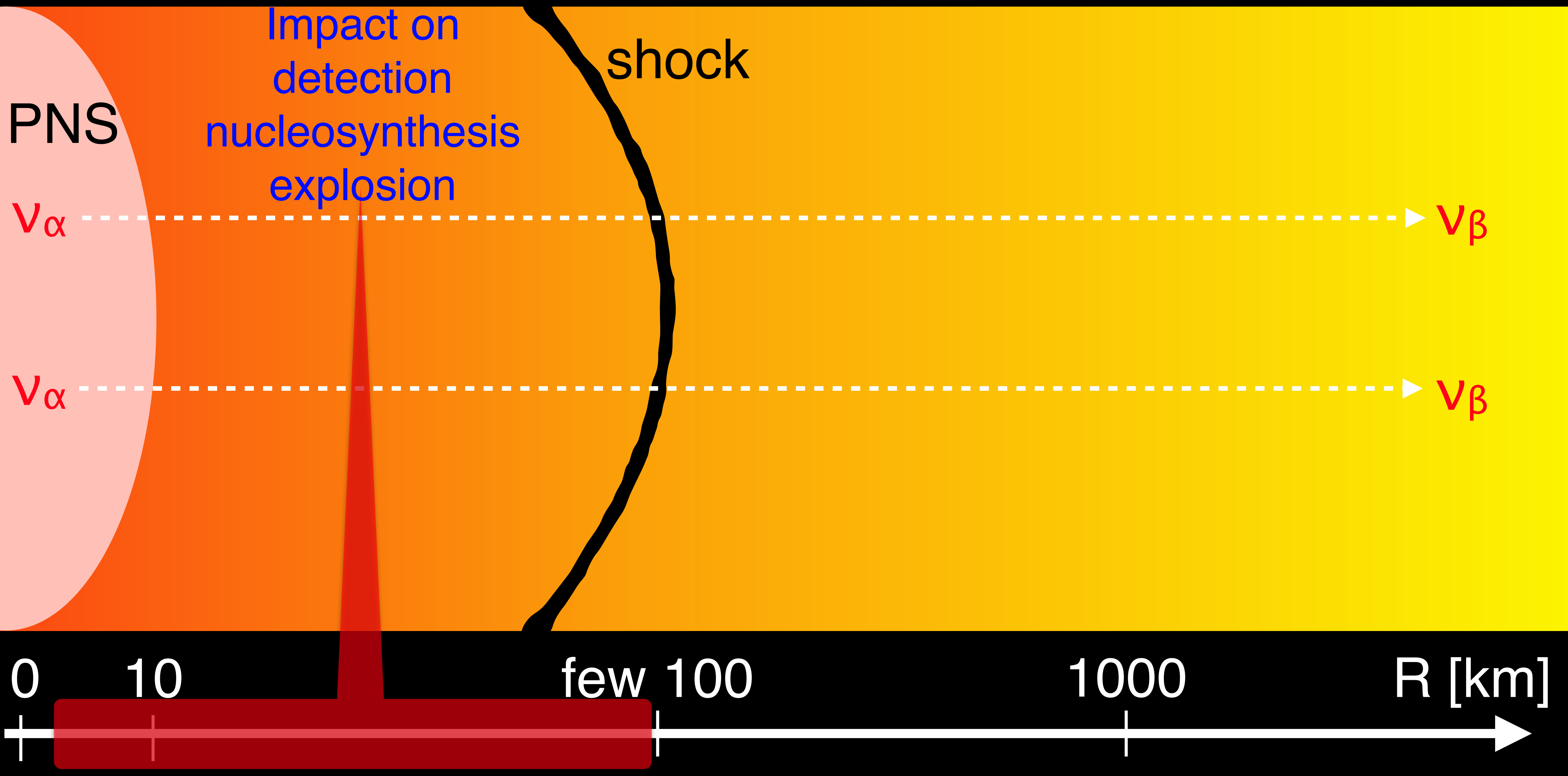
Each aspect of the chain to **MUST** be well understood



# Flavor conversions: overview

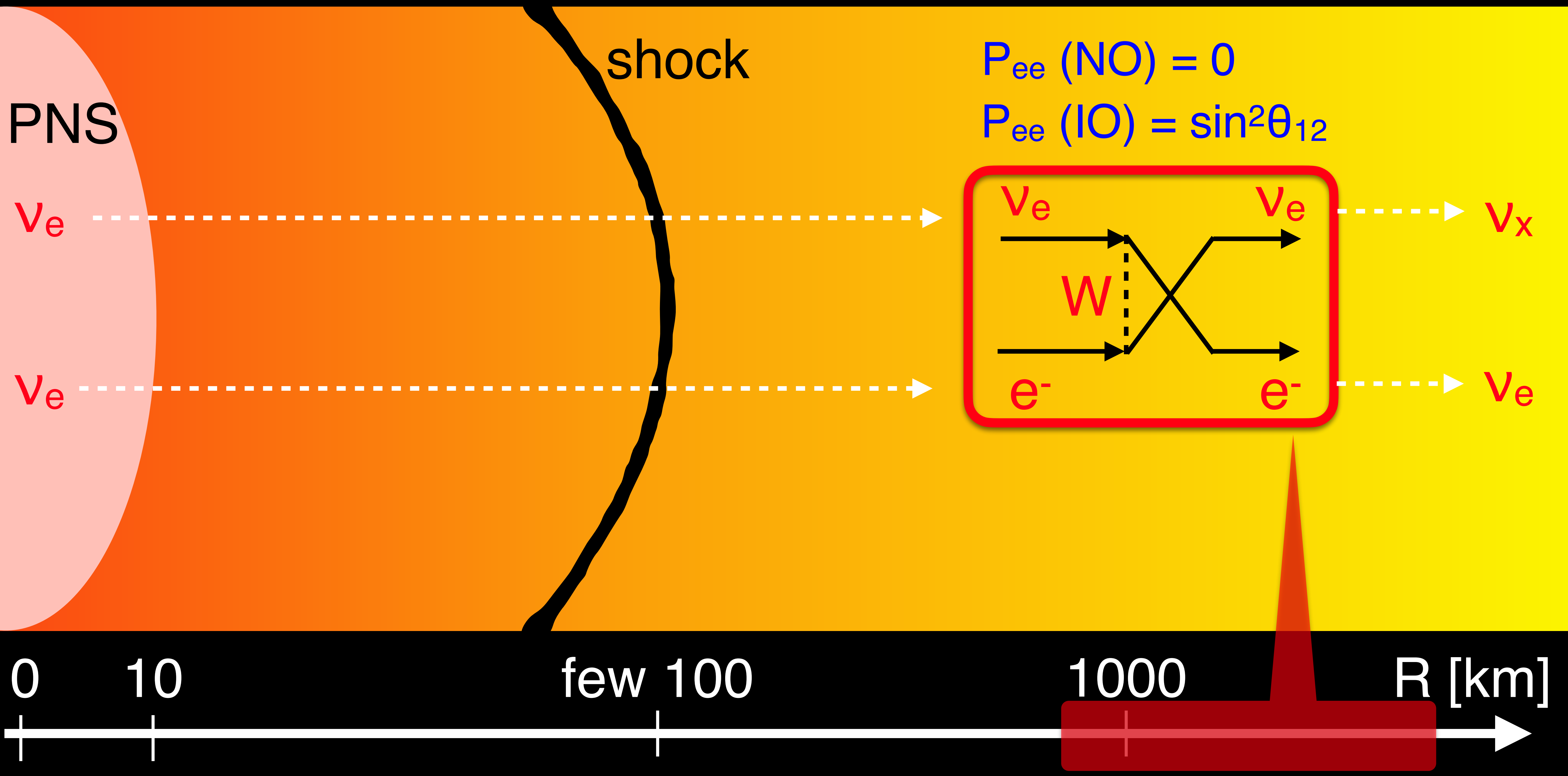


# Flavor conversions: overview



# MSW resonance

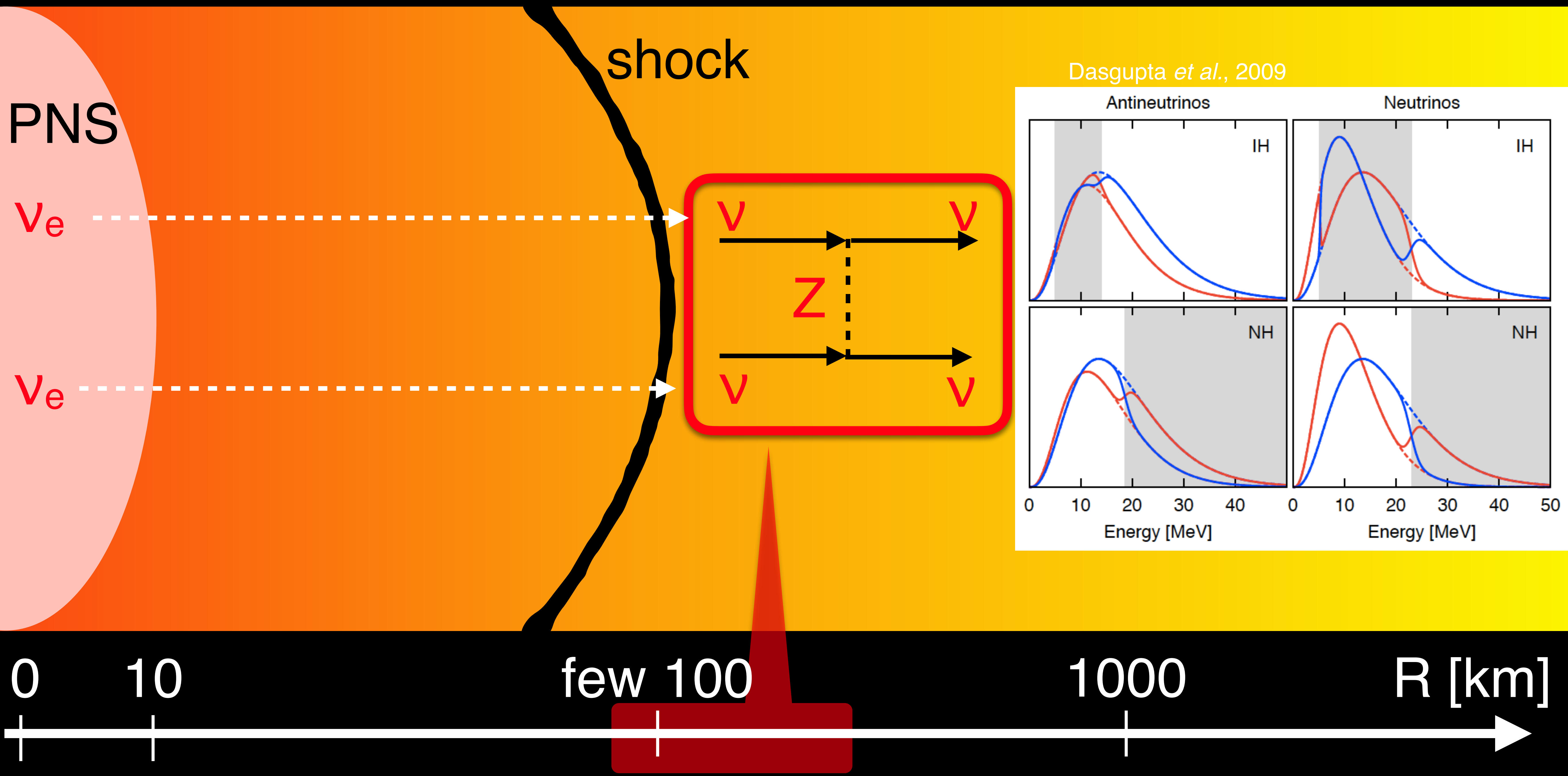
MSW resonances happening in the outer layers




Dighe, Smirnov, 2000, Schirato, Fuller, 2002, Fogli, Lisi, Mirizzi, Montanino, 2002, …

# Self induced flavor conversion

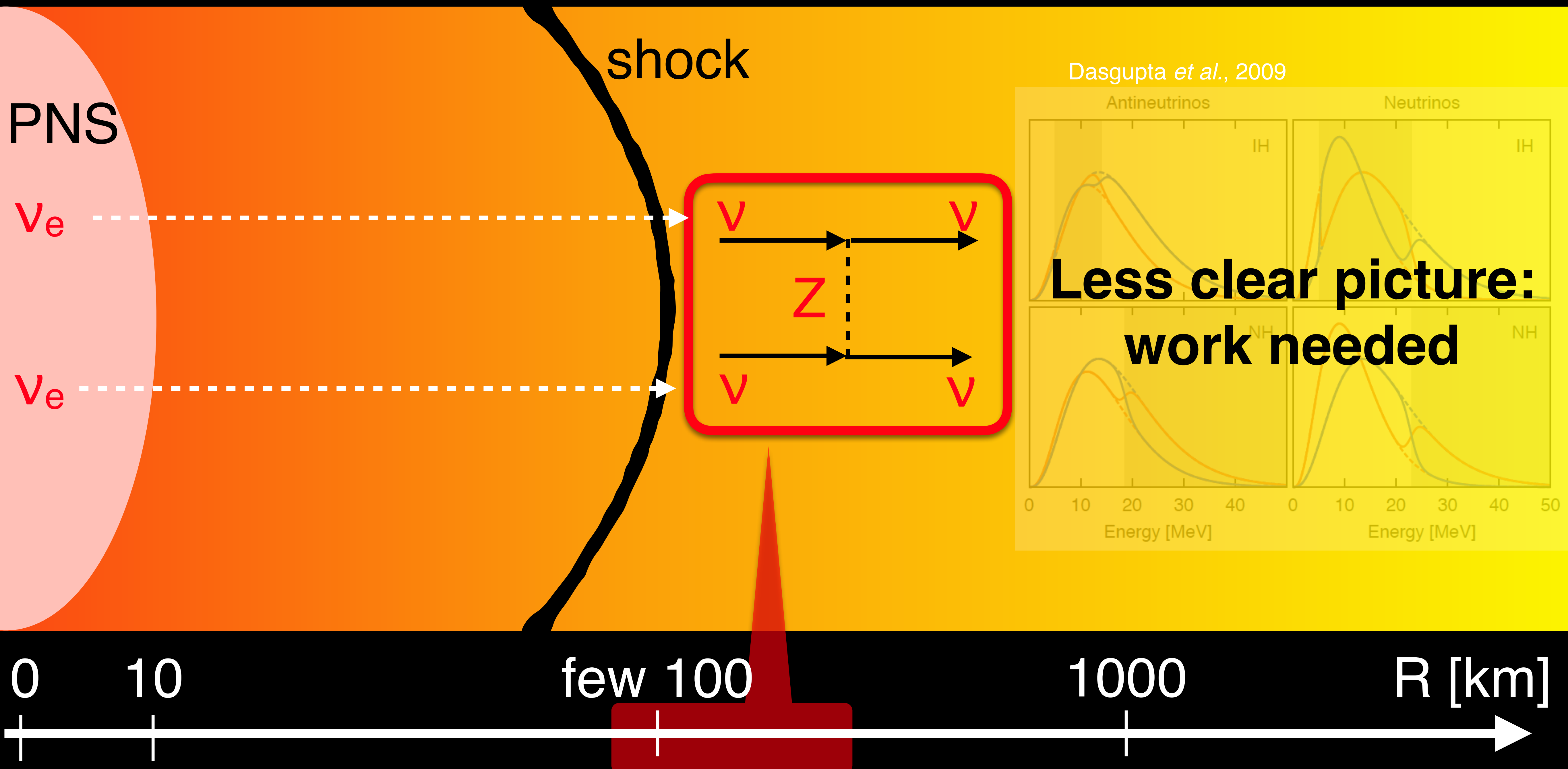
νν interactions are relevant: slow growth rate ~ $\sqrt{\omega\mu}$




Hannestad, Raffelt, Sigl, Wong, 2006, Duan, Fuller, Carlson, Qian, 2006, many others, …

# Self induced flavor conversion

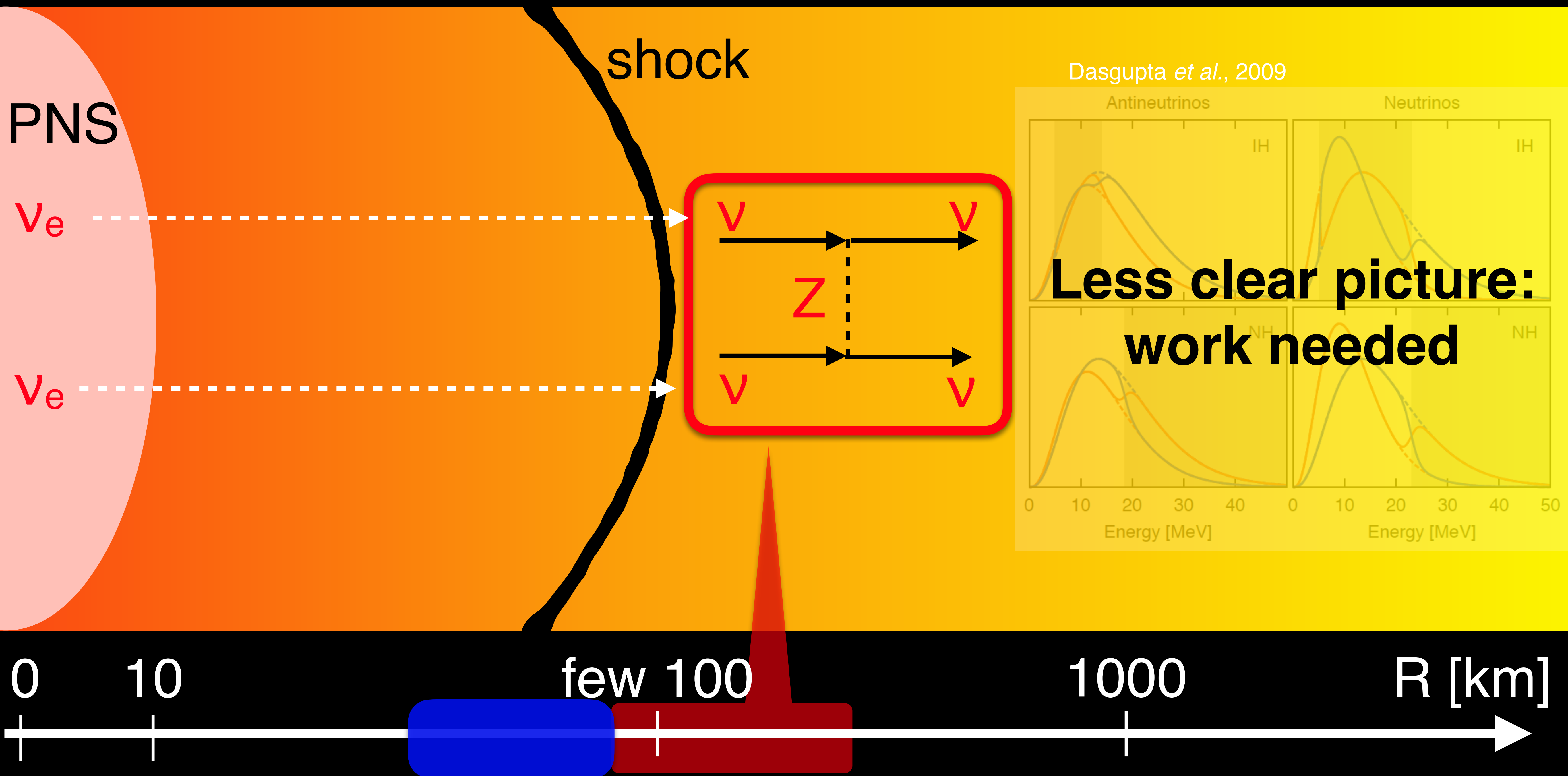
Instability under tiny space inhomogeneities: decoherence?




Raffelt, Sarikas, Seixas 2013, Mangano, Mirizzi, Saviano 2014-2015, Duan, Shalgar 2014, …

# Self induced flavor conversion

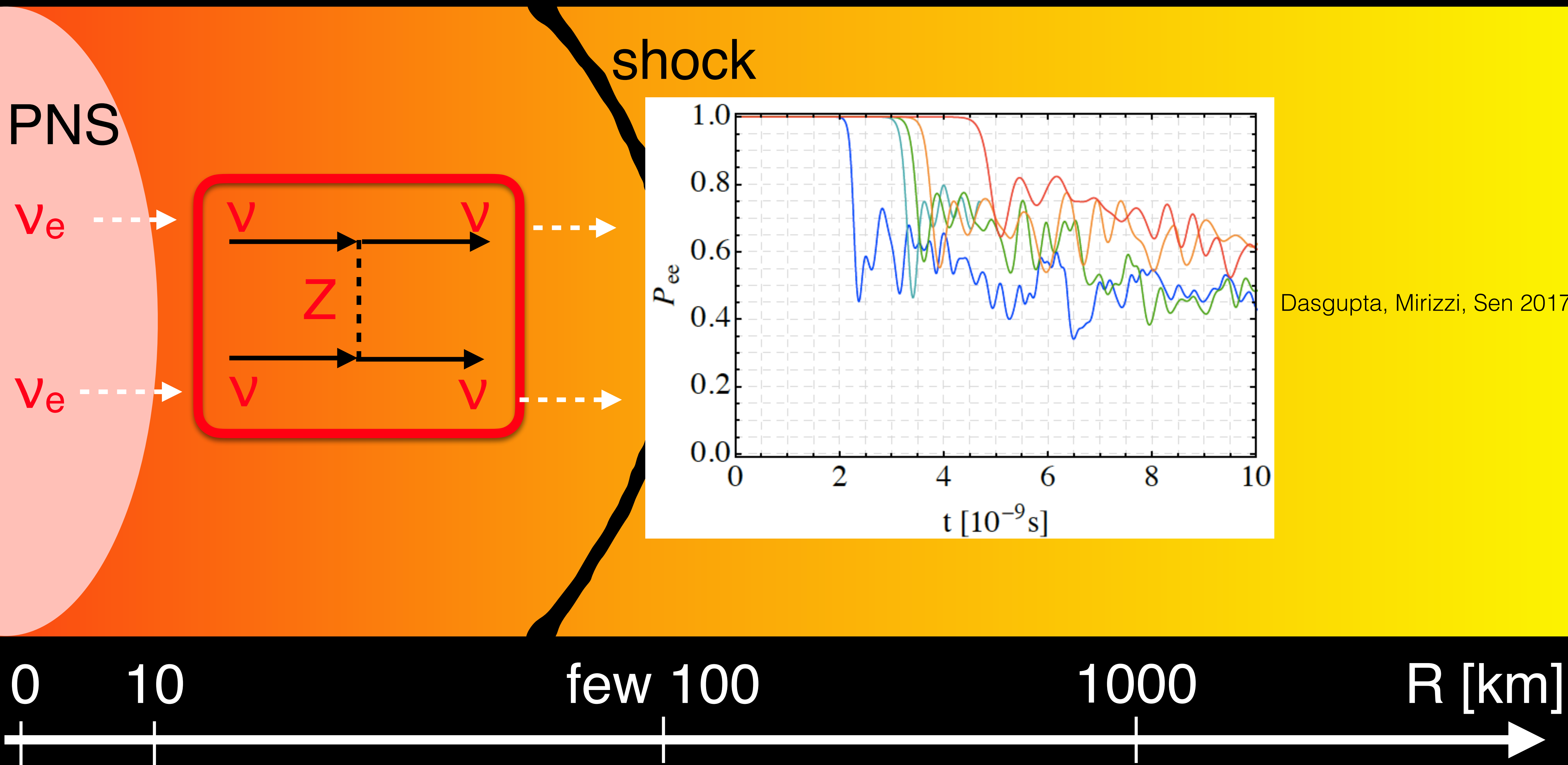
Time instabilities to avoid matter suppression? Turbulence?




Dasgupta, Mirizzi 2015, Duan, Abbar, 2015, Capozzi, Dasgupta, Mirizzi 2016, Abbar 2020…

# Fast self induced flavor conversion

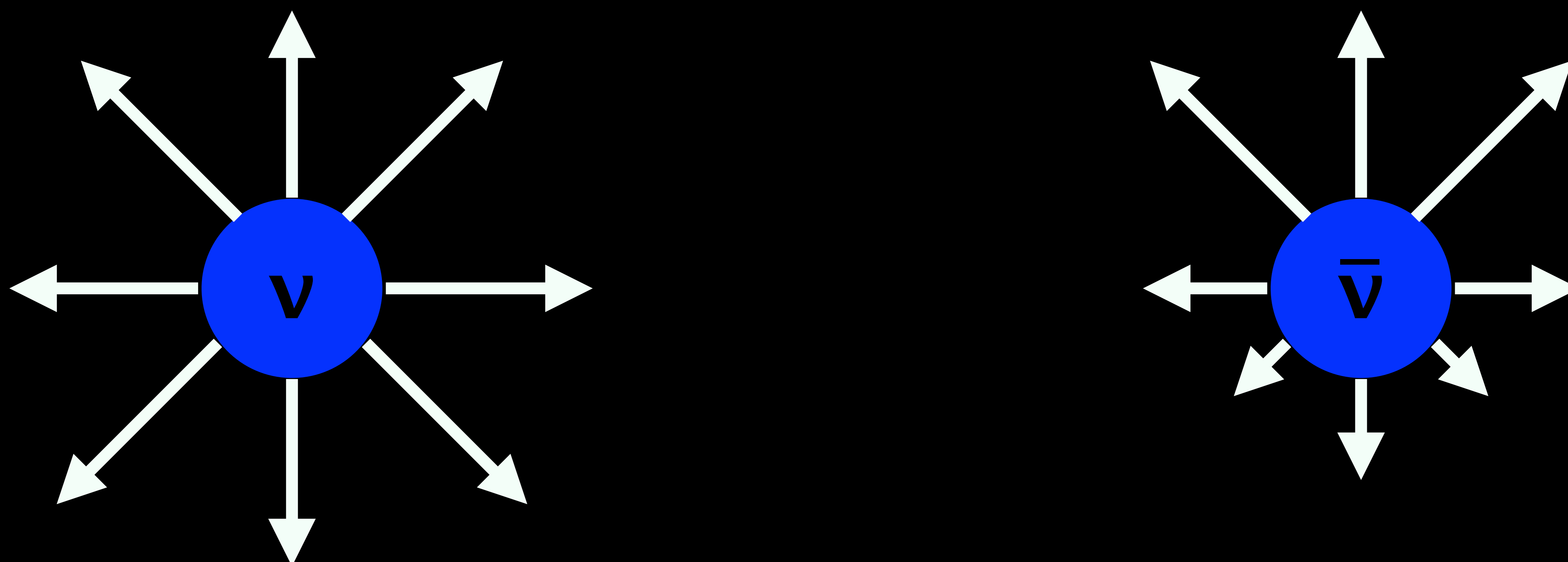
νν interactions are relevant: fast growth rate ~ $\sqrt{\mu}$




Sawyer 2005, 2009, 2015, Chakraborty, Hansen, Izaguirre, Raffelt 2016, Dasgupta, Mirizzi, Sen 2017, …

# Fast conversions

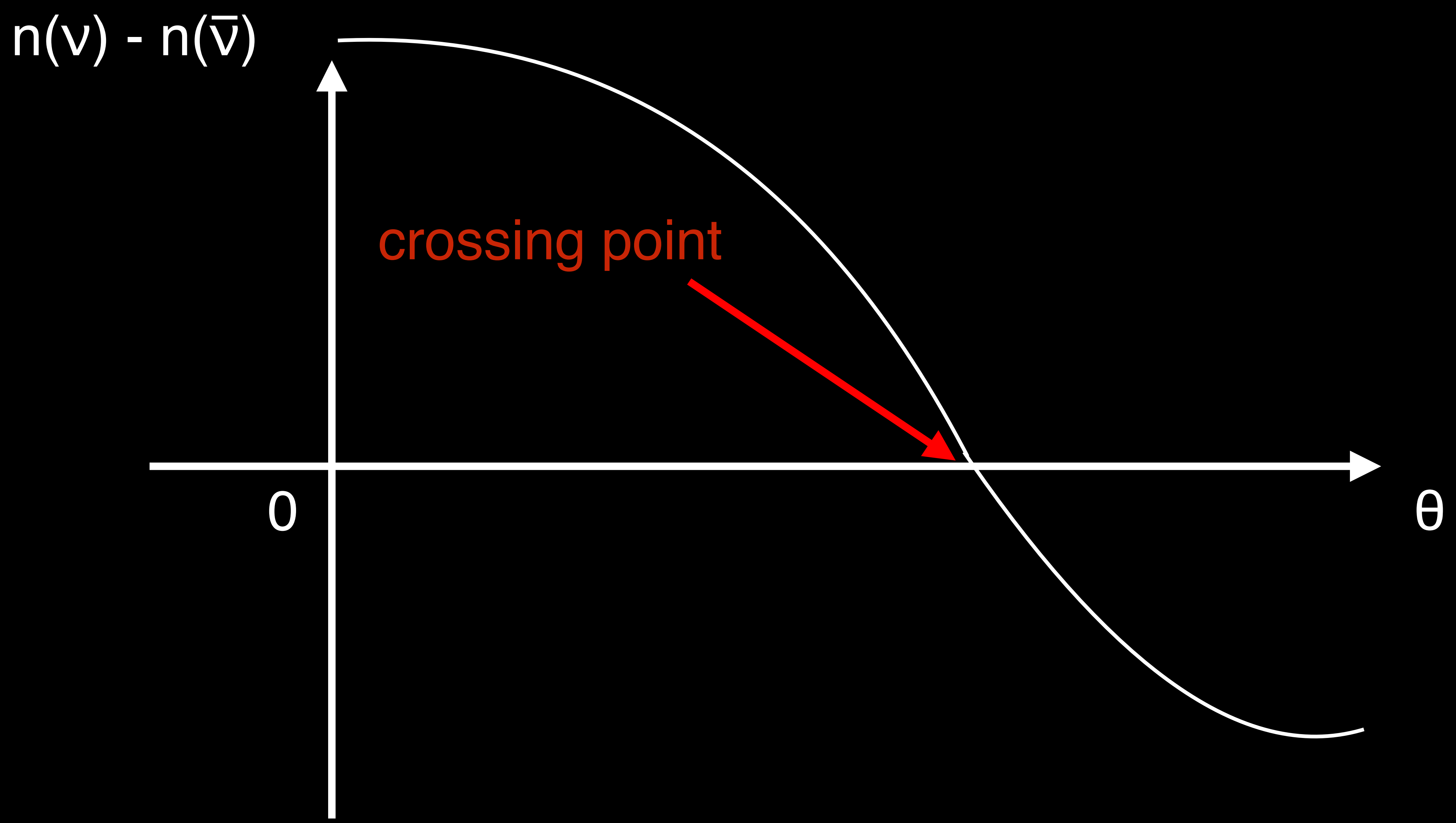
Necessary and sufficient condition for fast conversions: **angular crossing** (Morinaga, arXiv:2103.15267)




Example: ν̄ (ν) dominate in the forward (backward) direction

# Fast conversions

Necessary and sufficient condition for fast conversions: **angular crossing** (Morinaga, arXiv:2103.15267)




Example: ν̄ (ν) dominate in the forward (backward) direction

# Looking at real simulations

Simulations only provide the moments of the distributions

$$N = \int d\Omega \, n_\nu$$

$$\vec{F} = \int d\Omega \, \vec{v} \, n_\nu$$

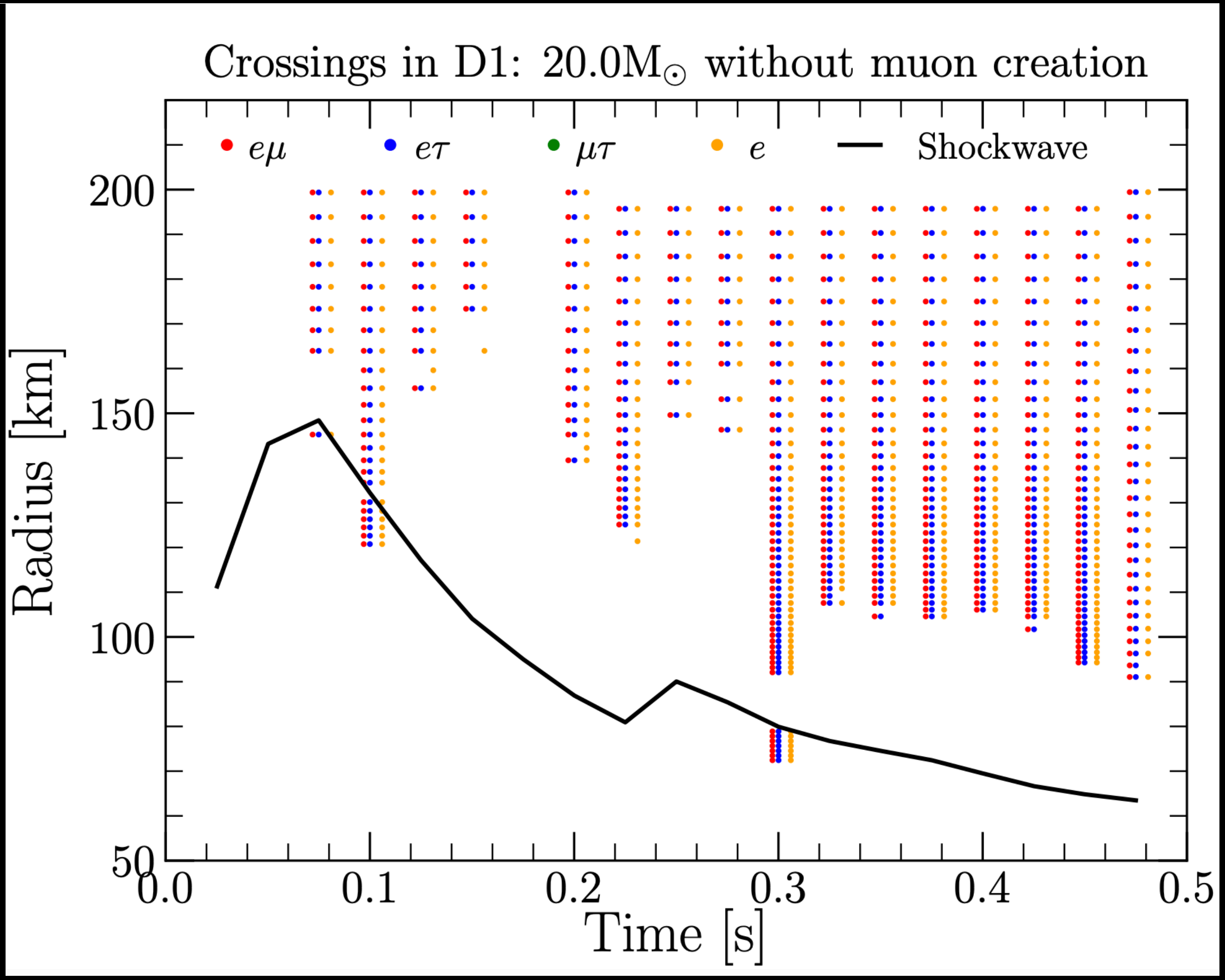
Dasgupta, Mirizzi and Sen, Phys. Rev. D 98 (2018) no.10, 10300
Abbar, JCAP 05 (2020), 027
Johns, Nagakura, Fuller, Burrows, Phys. Rev. D 101 (2020), no. 4 043009
Johns and Nagakura,arXiv:2104.04106
Nagakura and Johns, arXiv:2104.05729

The moments are enough to find some (not all!) crossings

# Looking at real simulations

Are crossing really happening in supernovae?

Capozzi, Abbar, Bollig, Janka, Phys. Rev. D 103 (2021) no.6, 063013




see also

Tamborra, Huedepohl, Raffelt, Janka, 2017; Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018; Morinaga, Nakagura, Kato, Yamada, 2019; Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019; Morinaga, Nagakura, Kato, Yamada 2020; Abbar, Capozzi, Glas, Janka, Tamborra 2021

Crossings possible both below and above the shock wave

# Phenomenology of fast conversions

## What is the impact of fast conversions?

### 1) What is the final outcome of fast conversions?

Abbar, Volpe, Phys. Lett. B 790 (2019), 545-550
Johns, Nagakura, Fuller, Burrows, Phys. Rev. D 102 (2020) no.10, 103017
Bhattacharyya, Dasgupta, Phys. Rev. Lett. 126 (2021) no.6, 061302
Bhattacharyya, Dasgupta, Phys. Rev. D 102 (2020) no.6, 063018
Bhattacharyya, Dasgupta, arXiv:2101.01226

### 2) Is there a dependence on the neutrino energy?

Shalgar, Tamborra, JCAP 01 (2021), 014
Shalgar, Tamborra, arXiv:2103.12743

### 3) How do they develop in space and time?

Shalgar, Padilla-Gay, Tamborra,JCAP 06 (2020), 048
Bhattacharyya, Dasgupta, Phys. Rev. D 102 (2020) no.6, 063018

# Phenomenology of fast conversions

## What is the impact of fast conversions?

### 4) What happens in three flavours?

Chakraborty, Chakraborty, JCAP 01 (2020), 005
Capozzi, Chakraborty, Chakraborty, Sen, Phys. Rev. Lett. 125 (2020), 251801
Shalgar, Tamborra, arXiv:2103.12743

### 5) What is the role of collisions?

Capozzi, Dasgupta, Mirizzi, Sen, Sigl, Phys. Rev. Lett. 122 (2019) no.9, 091101
Martin, Carlson, Cirigliano and Duan, Phys. Rev. D 03 (2021), 063001
Shalgar, Tamborra, Phys. Rev. D 103 (2021), 063002

### 6) What happens with extremely tiny crossings?

Morinaga, Nagakura, Kato, Yamada, Phys. Rev. Res. 2 (2020) no.1, 012046
Zaizen, Morinaga, arXiv:2104.10532

# Phenomenology of fast conversions

**What is the impact of fast conversions?**

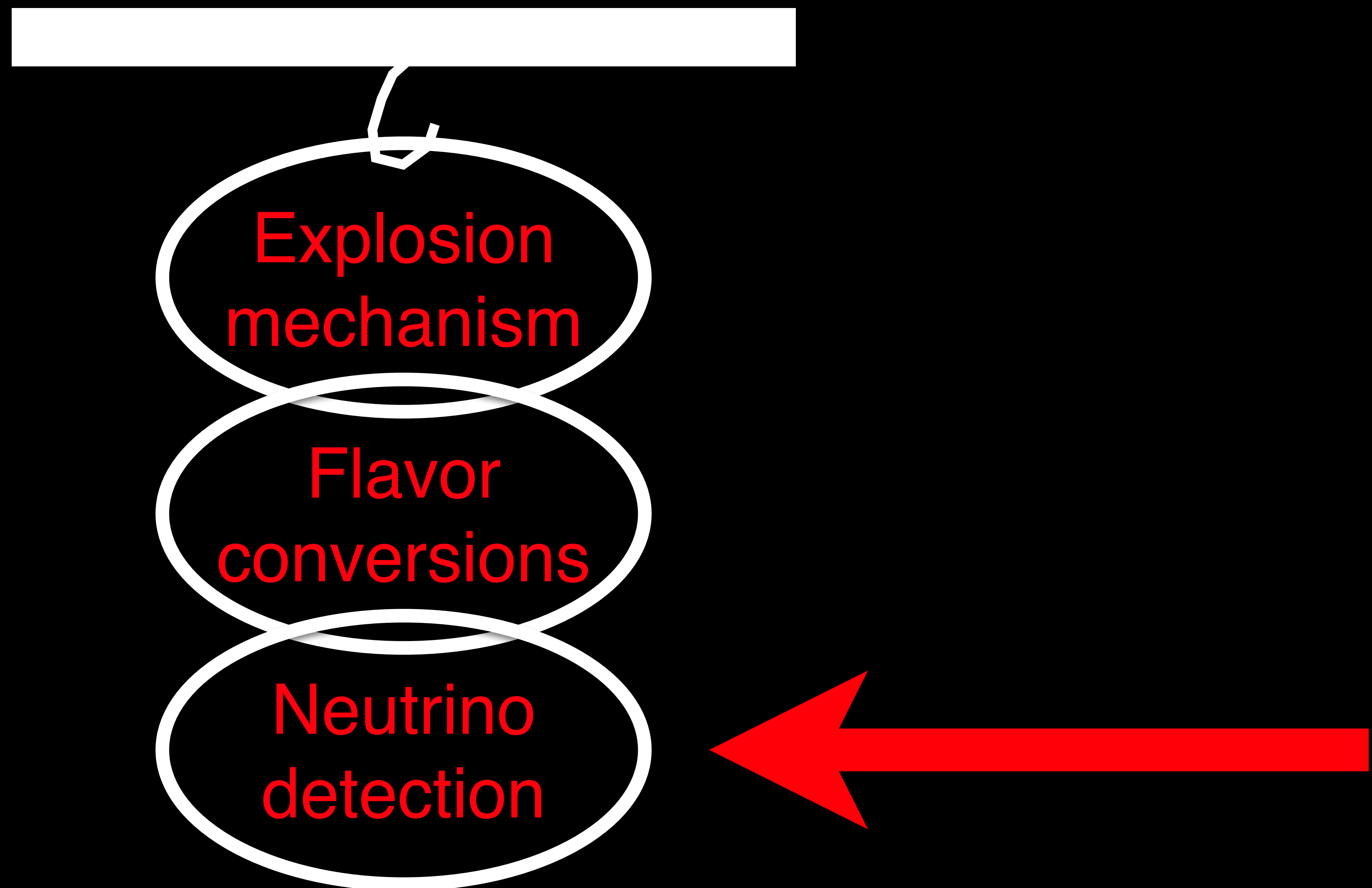
7) Including fast conversions in supernova simulations?

xxxx, et al. Phys. Rev. Lett. nn (20yy) mm, ll

Still a lot of work ahead

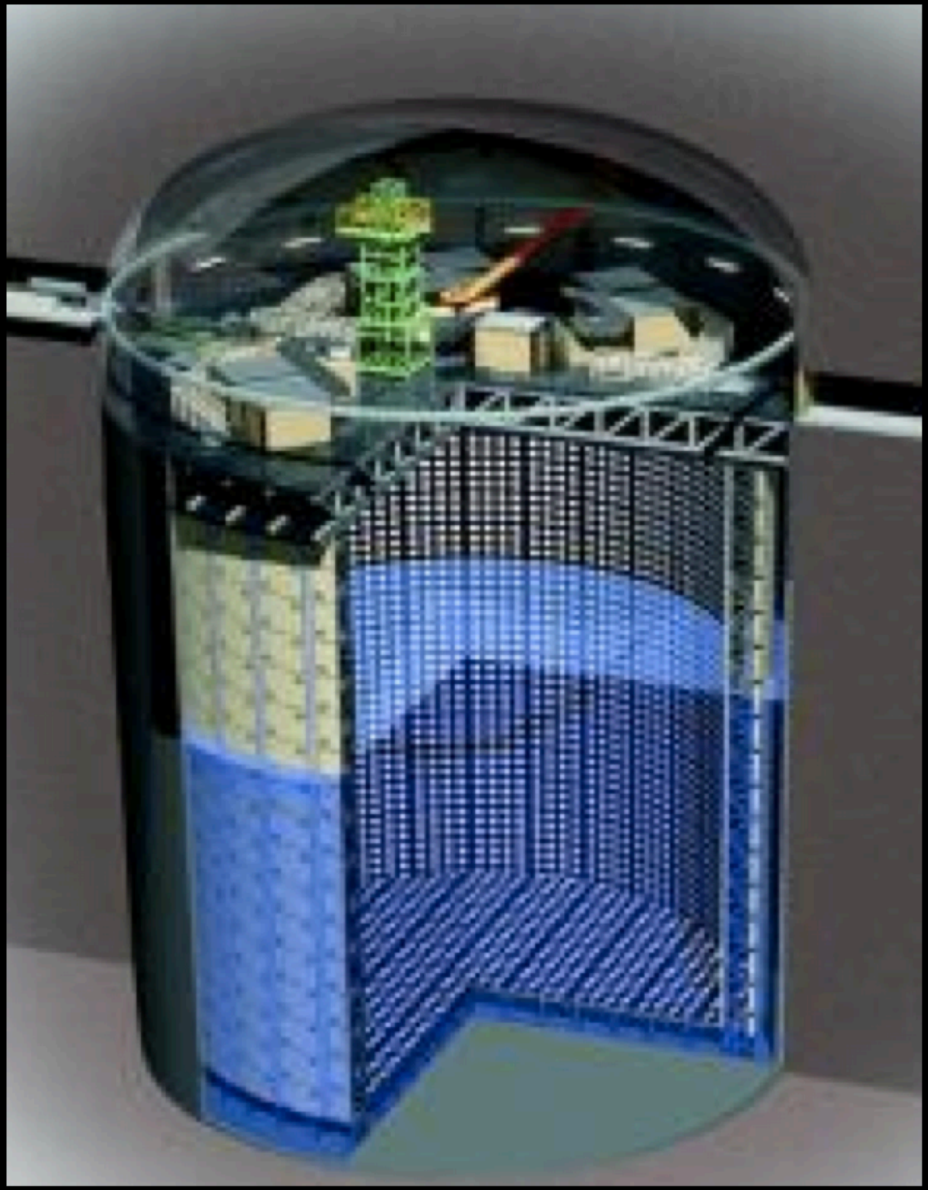
# Are we ready for SN20xy?

Each aspect of the chain to **MUST** be well understood

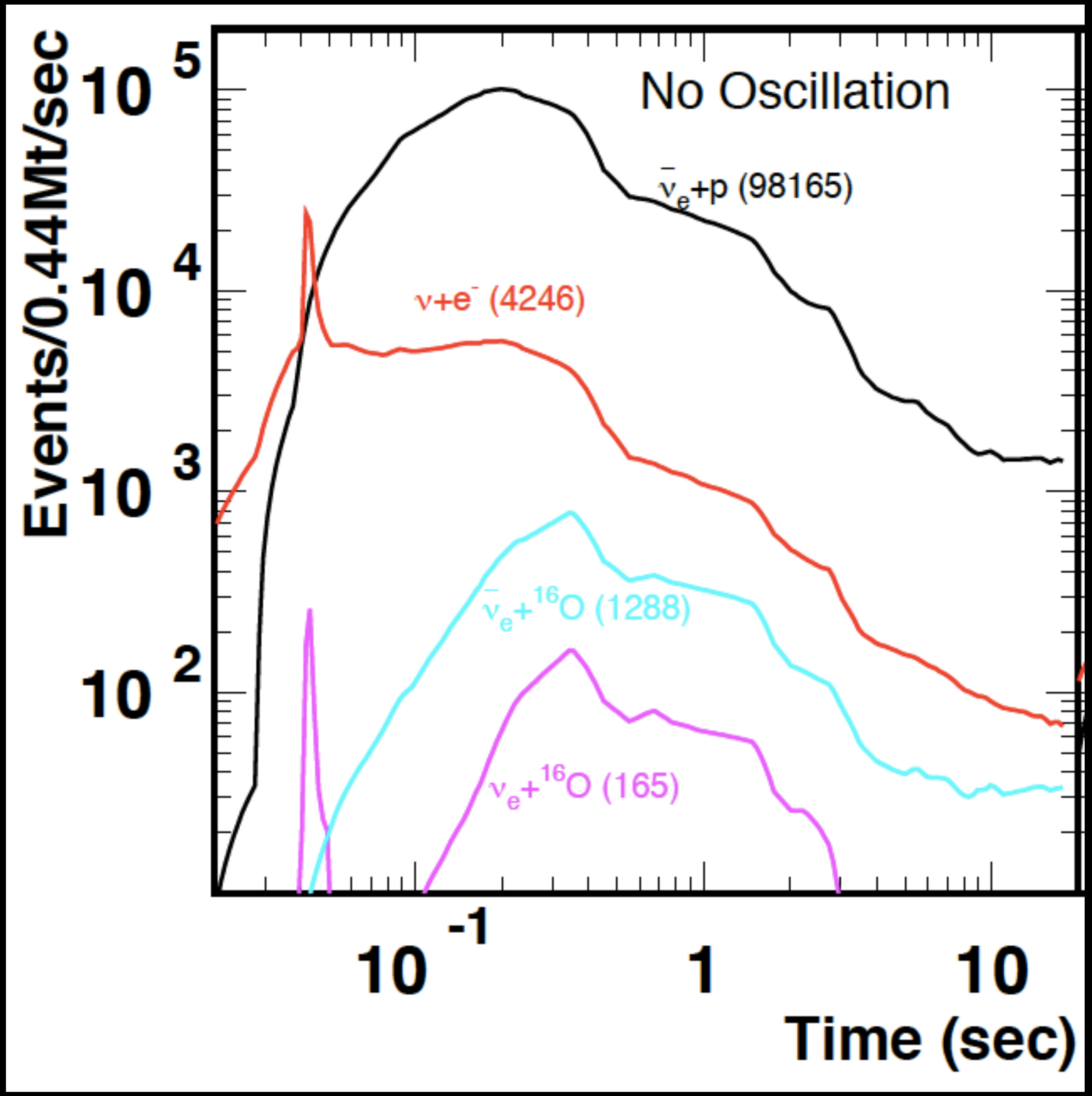


# Water Cherenkov

SuperK or HyperK: main channel inverse β decay



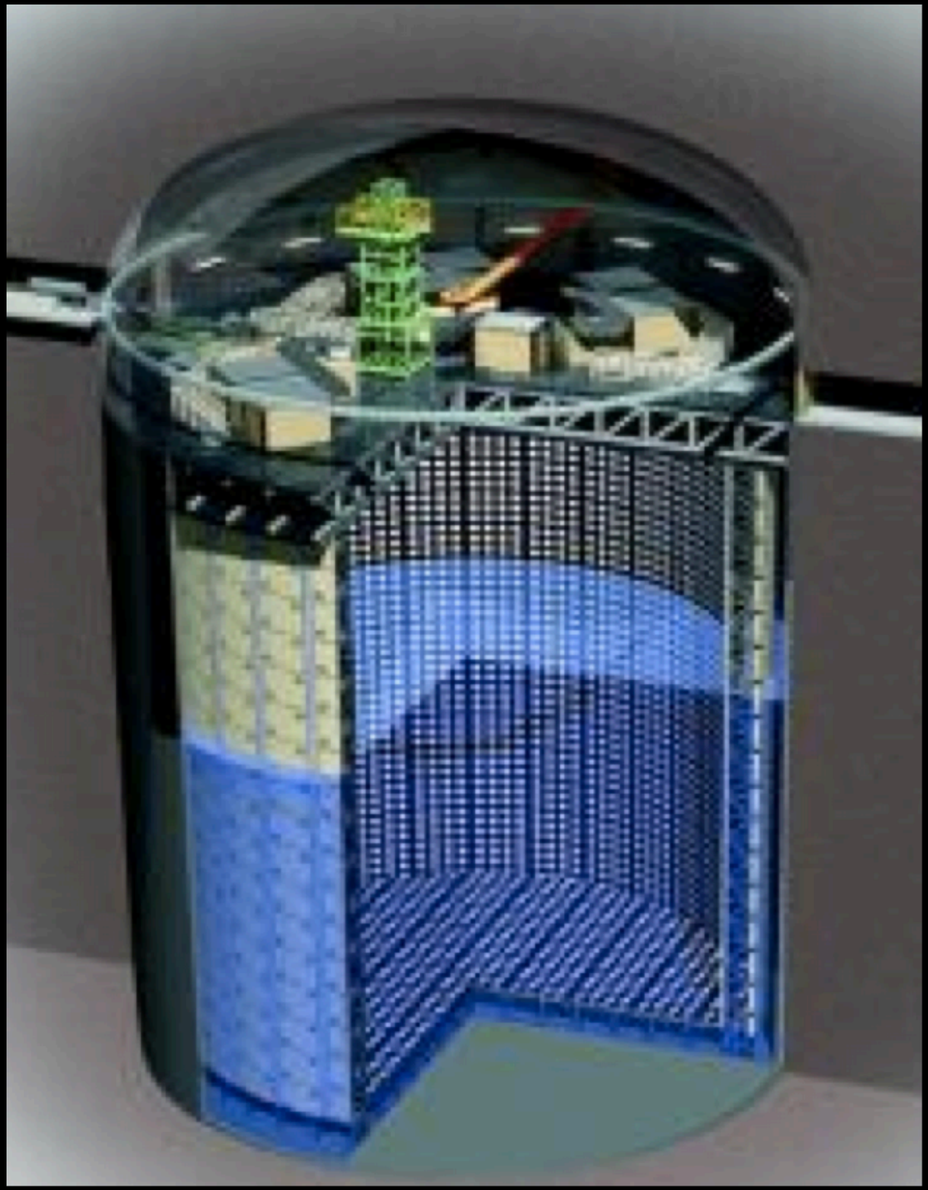
Hyper-Kamiokande Collaboration, ``Hyper-Kamiokande Design Report,"



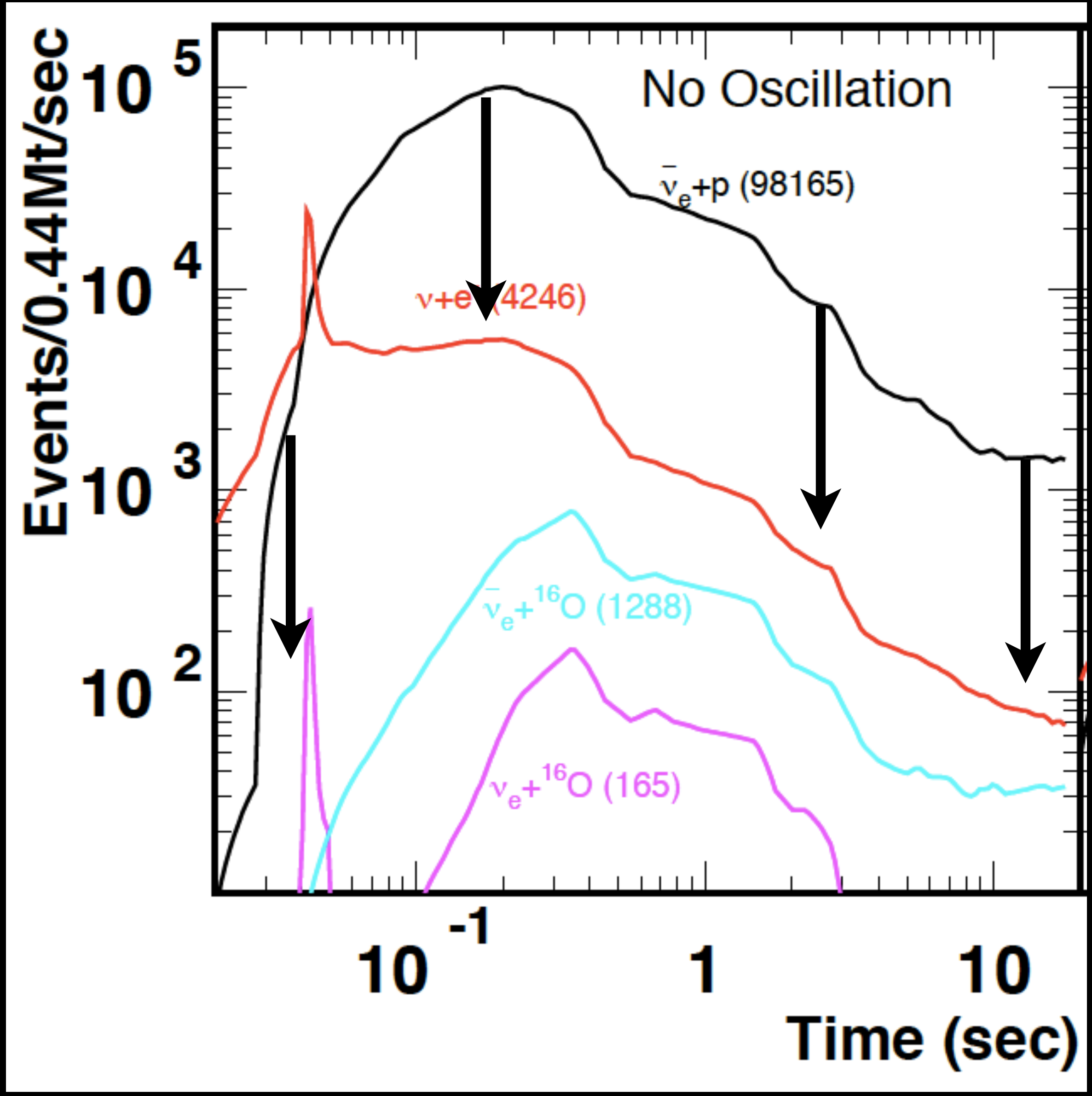

Very precise measurement of $\bar{\nu}_e$, both time and energy

# Water Cherenkov

SuperK / HyperK + Gd: 90% tagging of $\bar{\nu}_e$



Hyper-Kamiokande Collaboration, ``Hyper-Kamiokande Design Report,''

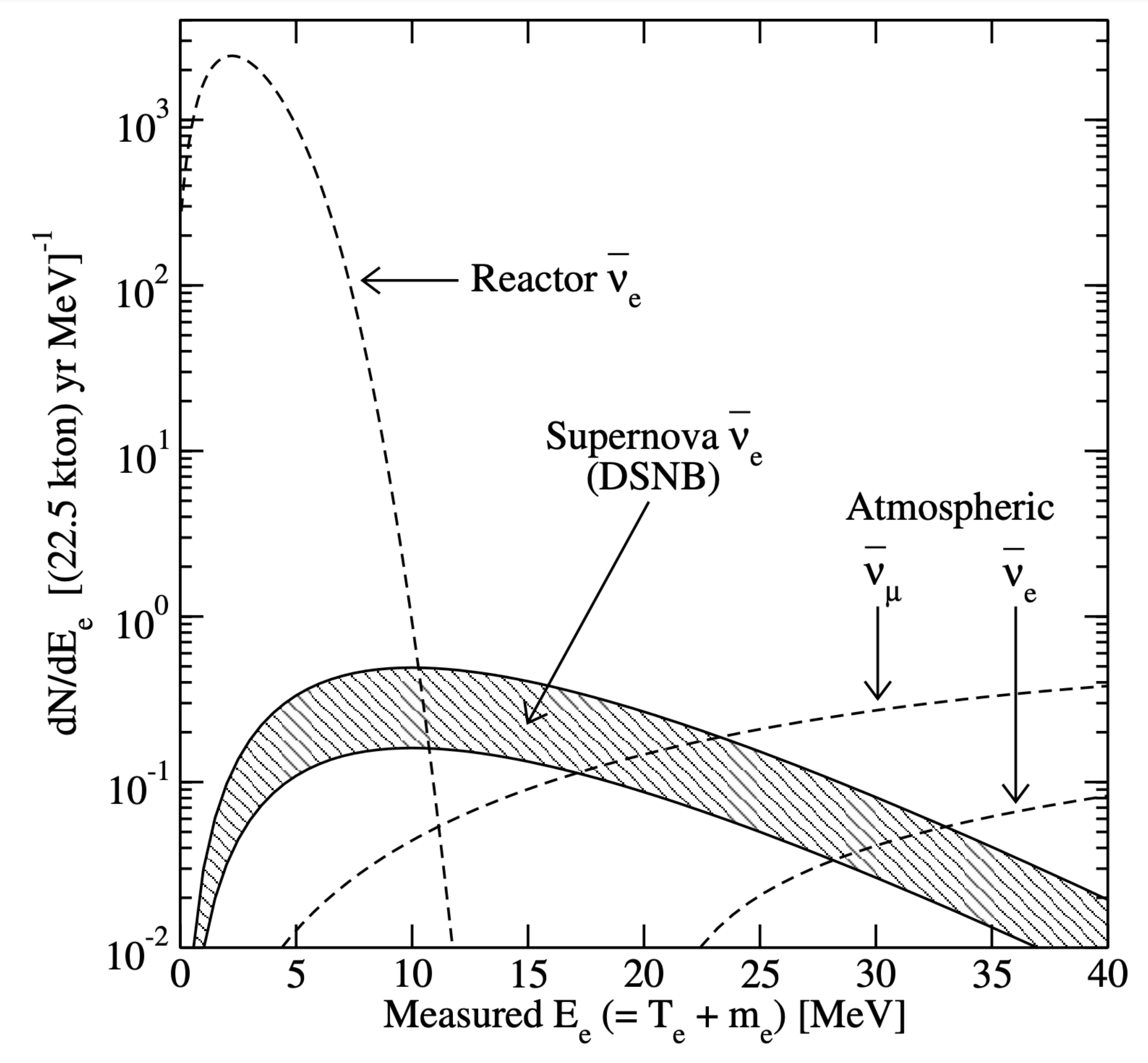



ν + e becomes accessible

# Water Cherenkov

SuperK / HyperK + Gd: 90% tagging of $\overline{\nu}_e$

Beacom, Vagins, Phys. Rev. Lett. 93 (2004), 171101

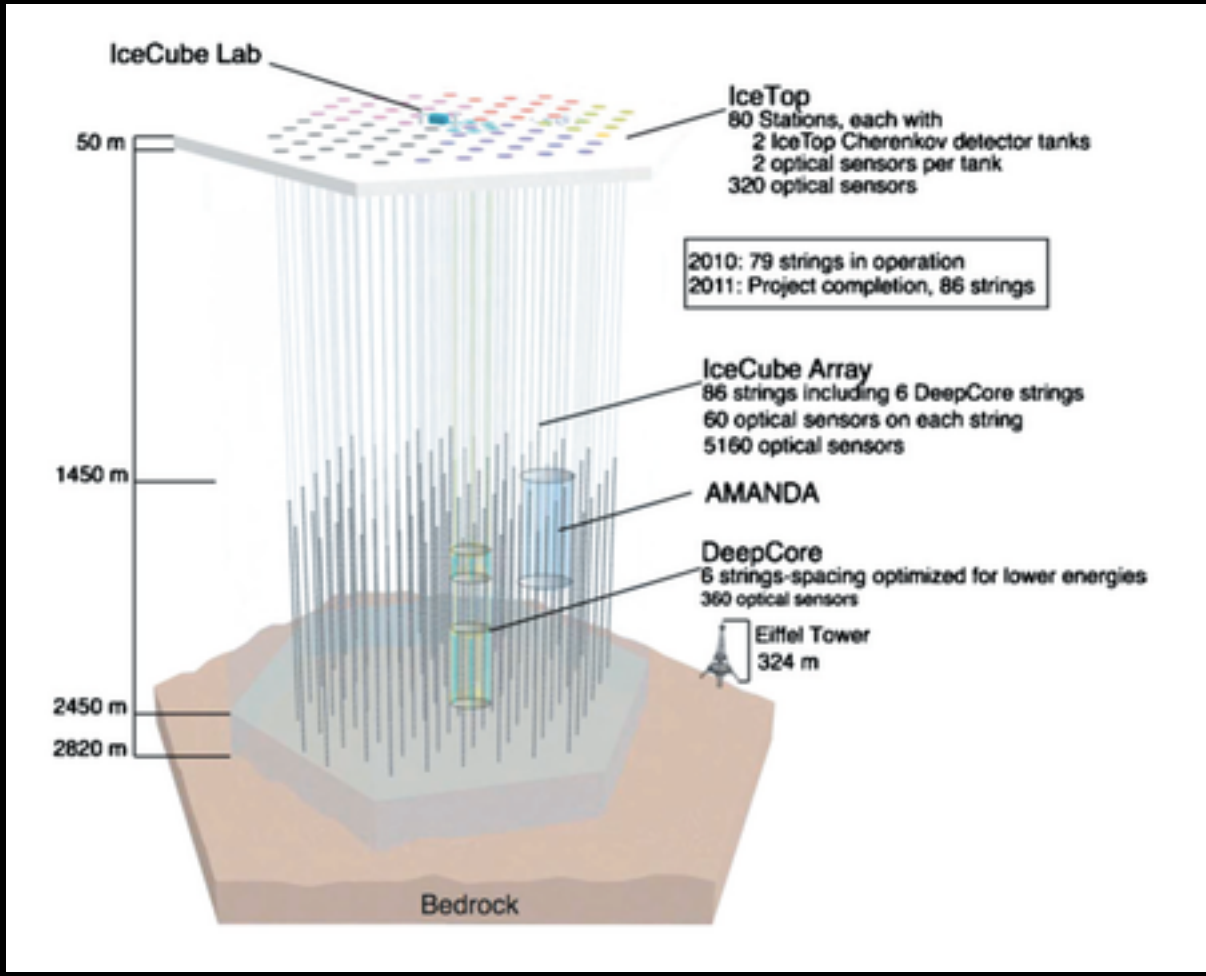


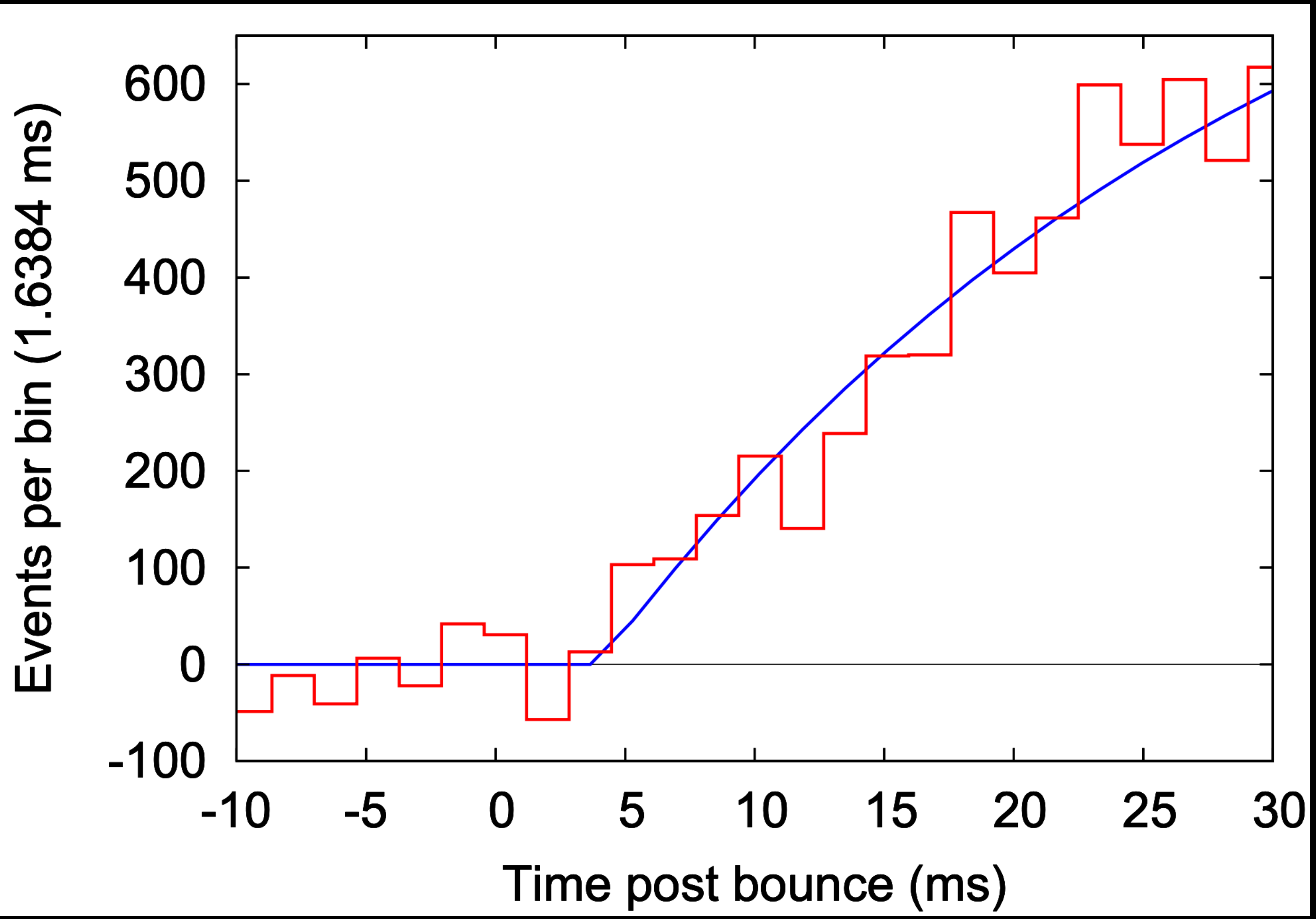

DSNB becomes accessible. Measure supernova rate and fraction of core-collapse and failed SNe

# Water Cherenkov

IceCube sees excess of DOM hits over noise (mostly $\bar{\nu}_e$)

Halzen, Raffelt, Phys. Rev. D 80 (2009), 087301



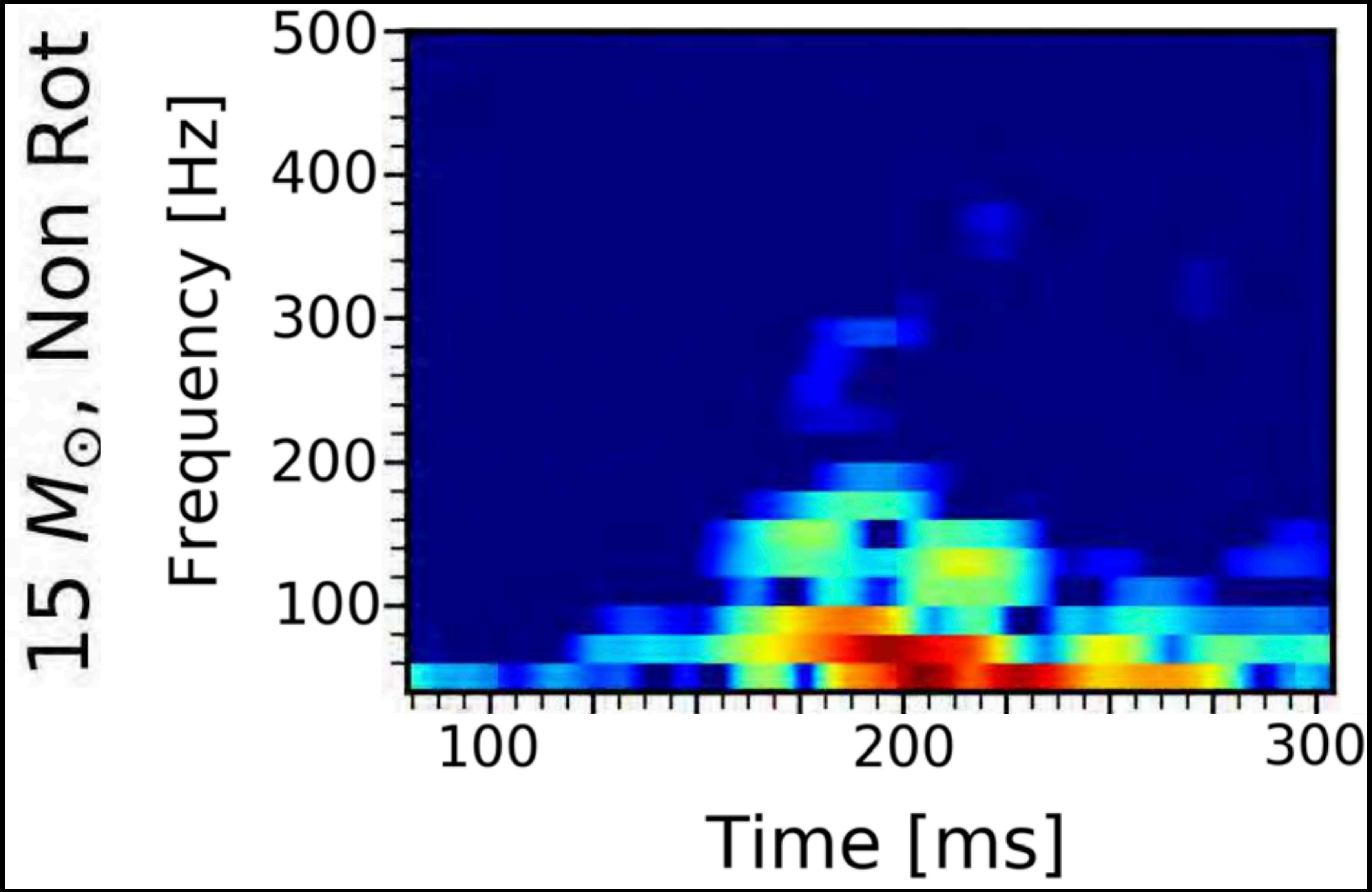




Precise time information

# Water Cherenkov

Water Cherenkov will have high statistics and precise time info

Walk, Tamborra, Janka, Summa, Phys. Rev. D 98 (2018) no.12, 123001

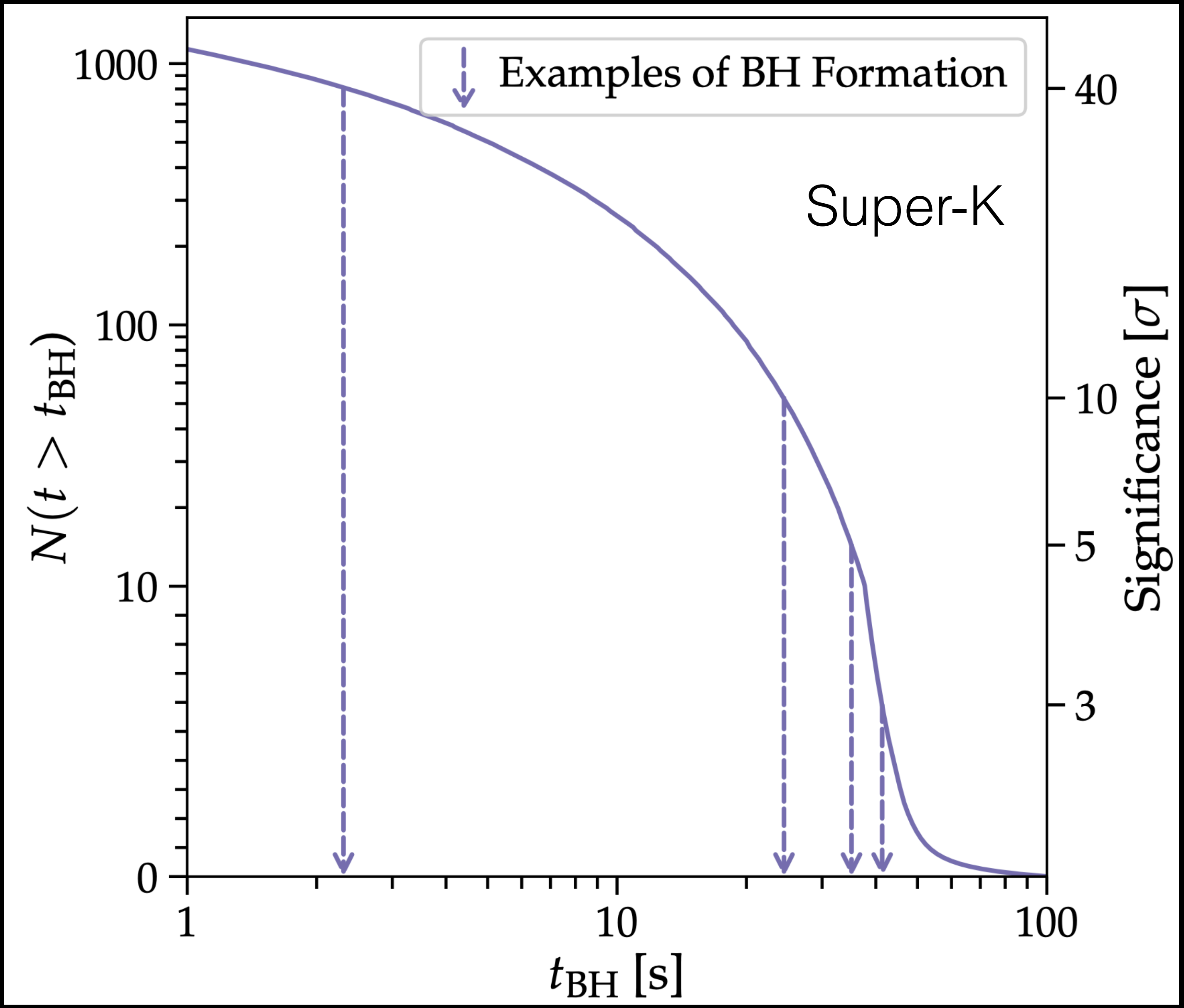



Time variations in the neutrino signal (SASI) can be studied

# Water Cherenkov

Water Cherenkov will have high statistics and precise time info

Li, Beacom, Roberts, Phys. Rev. D 103 (2021) no.2, 023016



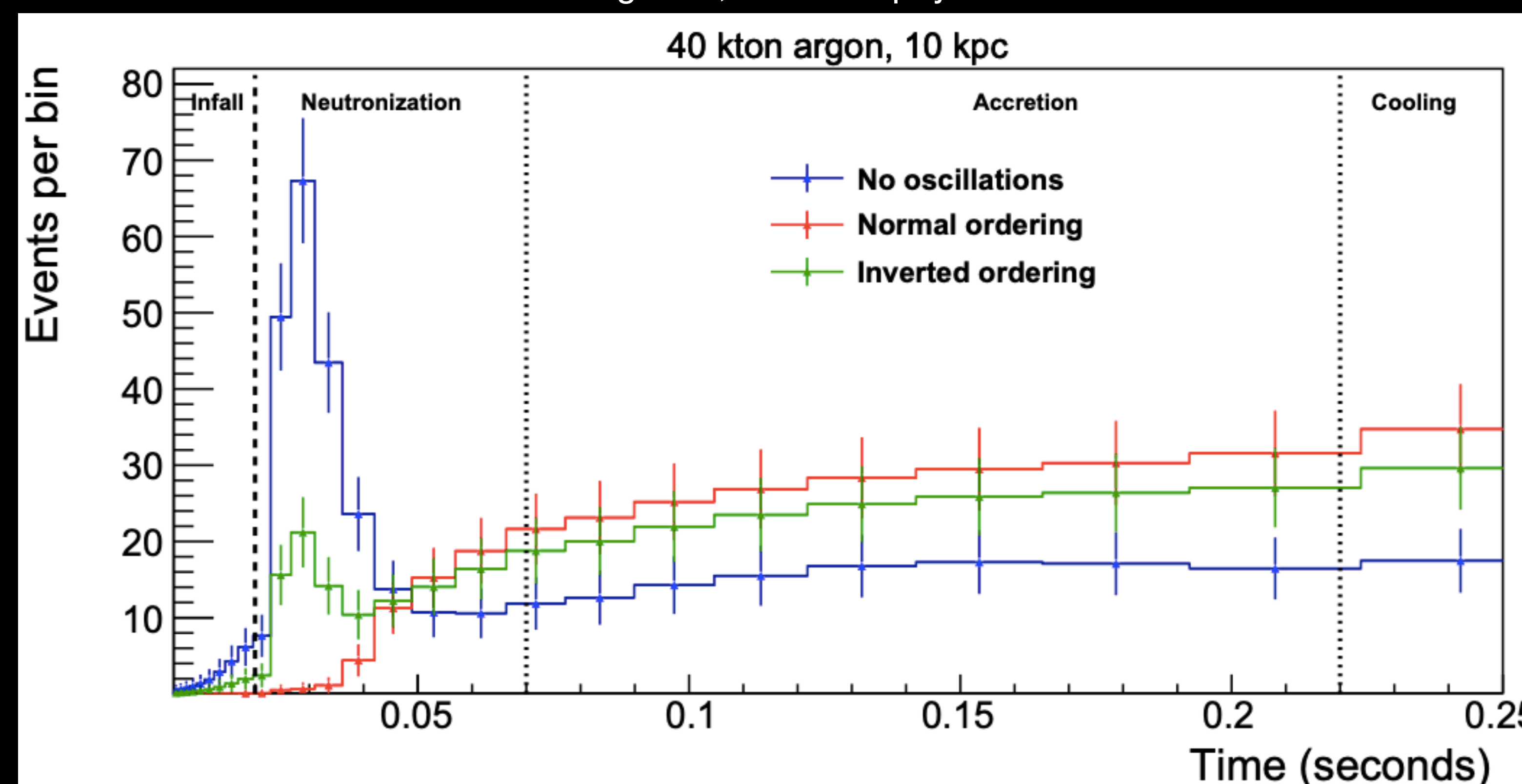

Possible evidence of black hole formation

# Liquid Argon

Direct probe of $\nu_e$: $\nu_e + {}^{40}Ar \longrightarrow e^- + {}^{40}K^*$

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Jost Migenda, talk at Nuphys 2017

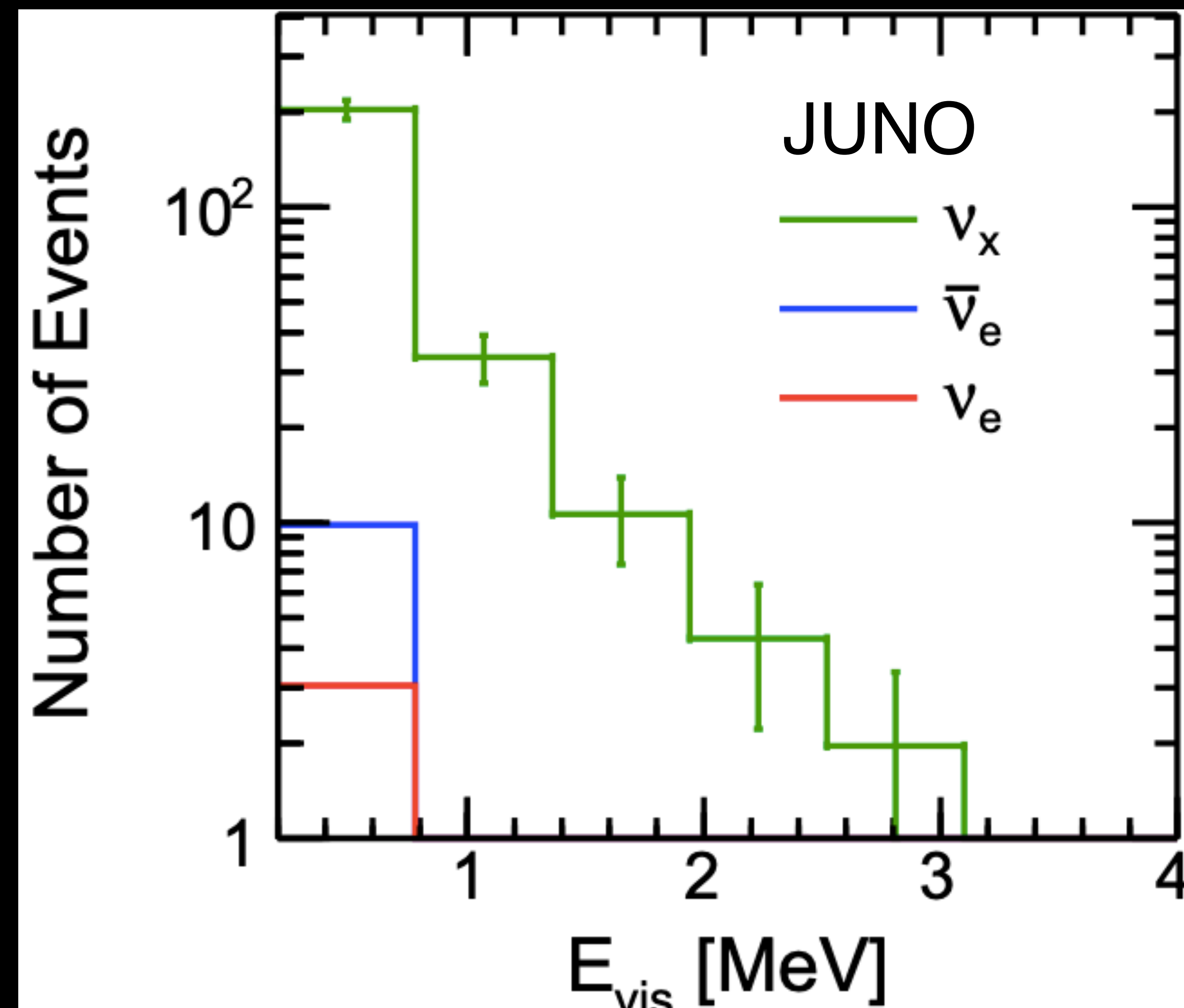



Study the (progenitor independent) neutronization burst. Test oscillation physics. Need improvements on cross section

# Liquid scintillator

## Sensitivity to ν-proton elastic scattering

Beacom, Farr, Vogel 2002, Dasgupta, Beacom 2011, Capozzi, Dasgupta, Mirizzi 2018



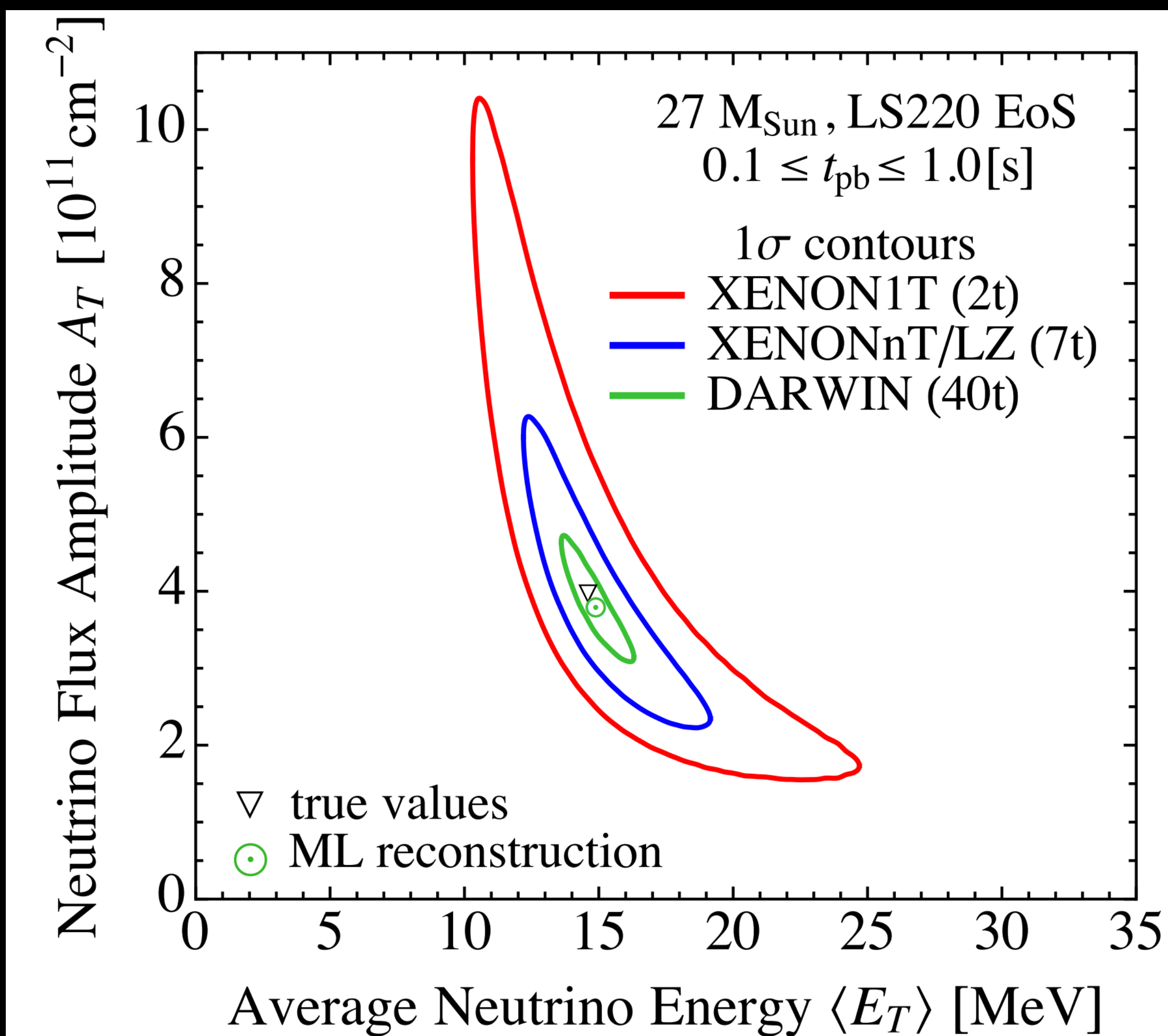

Unique probe for $\nu_x$.

Test oscillation physics. Measure the total energy emitted in νs

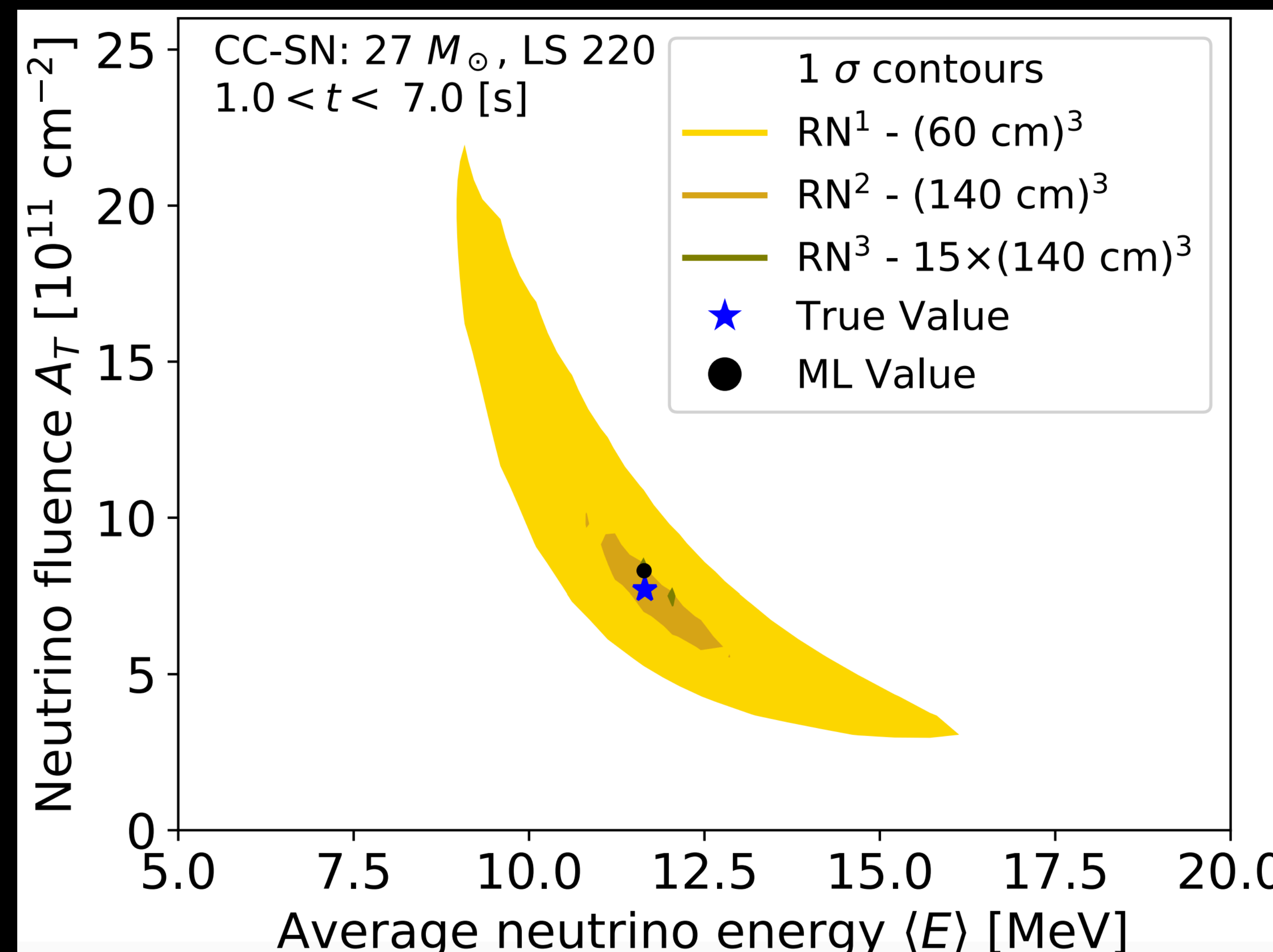
# Other neutral current channels

## CEνNS in dark matter (Xe) and lead detectors

Lang, McCabe, Reichard, Selvi, Tamborra, Phys. Rev. D 94 (2016) no.10, 103009



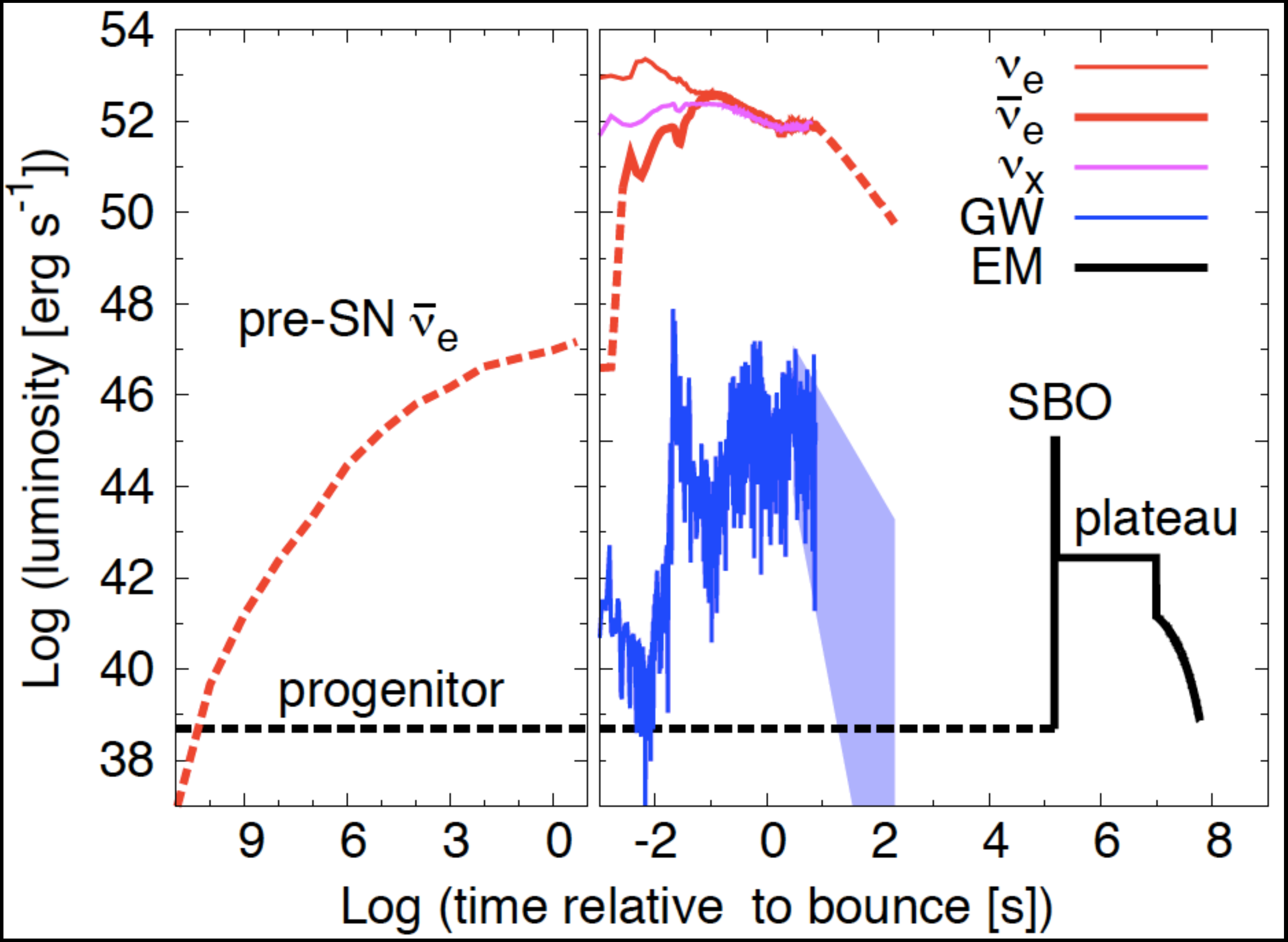

Pattavina, Ferreiro Iachellini, Tamborra, Phys. Rev. D 102 (2020) no.6, 063001




Great potential for $\nu_x$

# Multi-messenger

K. Nakamura, S. Horiuchi, M. Tanaka, K. Hayama, T. Takiwaki and K. Kotake, Mon. Not. Roy. Astron. Soc. 461 (2016) no.3, 3296



# Multi-messenger

Neutrinos produce an alert for other observatories

SNEWS

Water Cherenkov

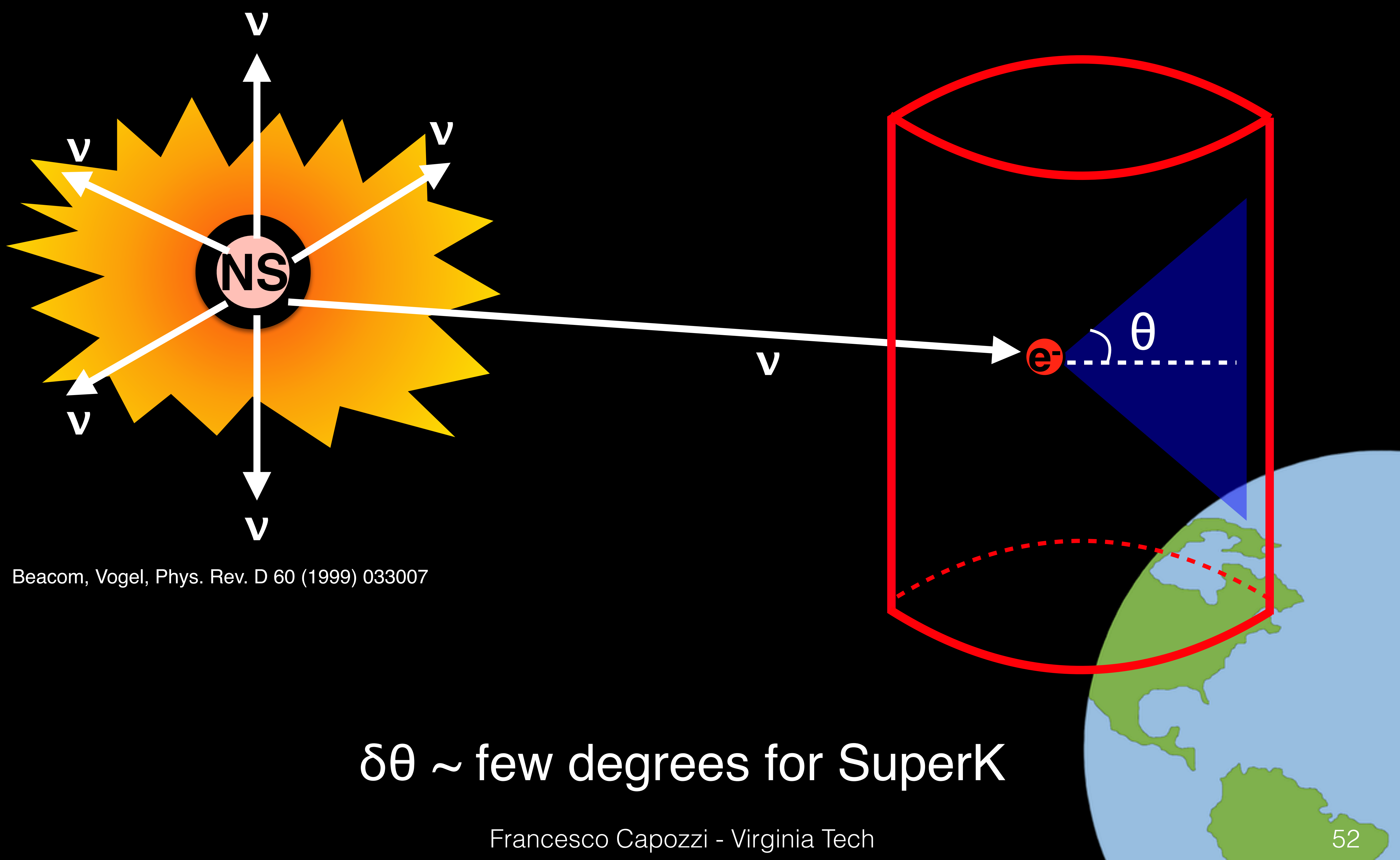
Liquid Scintillator

Liquid Argon

Telescopes LIGO,VIRGO, ...

# Multi-messenger

Neutrino pointing help light collection in telescopes



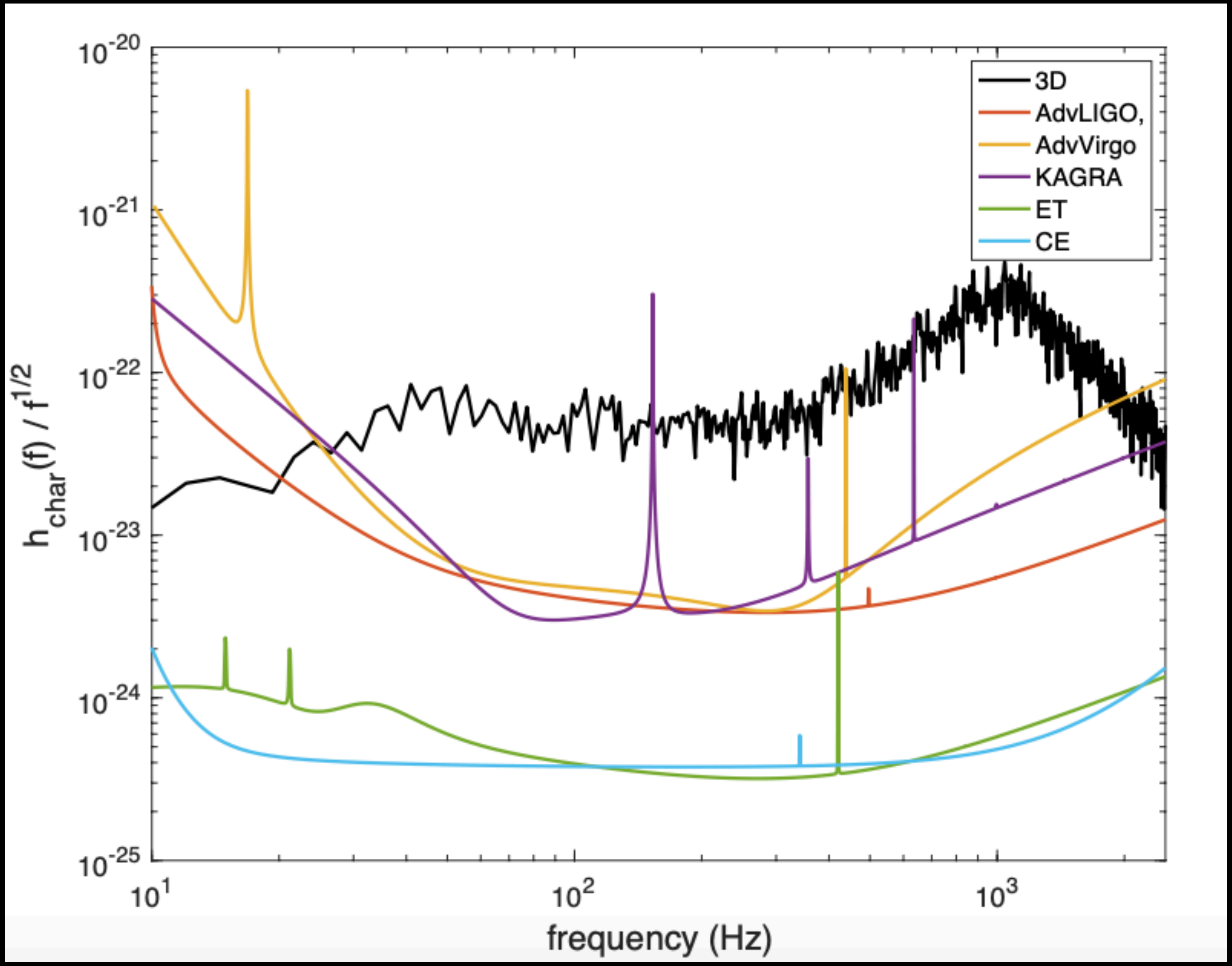

Beacom, Vogel, Phys. Rev. D 60 (1999) 033007

δθ ~ few degrees for SuperK

# Multi-messenger

## Neutrinos and GW carry important information from the PNS

Mezzacappa, et al., Phys. Rev. D 102 (2020) no.2, 023027




see also

Westernacher-Schneider,an,
Phys. Rev. D 100 (2019) no.12, 123009

Vartanyan, Burrows,
Astrophys. J. 901 (2020) no.2, 108

Pan, Liebendorfer, Couch, Thielemann,
arXiv:2010.02453

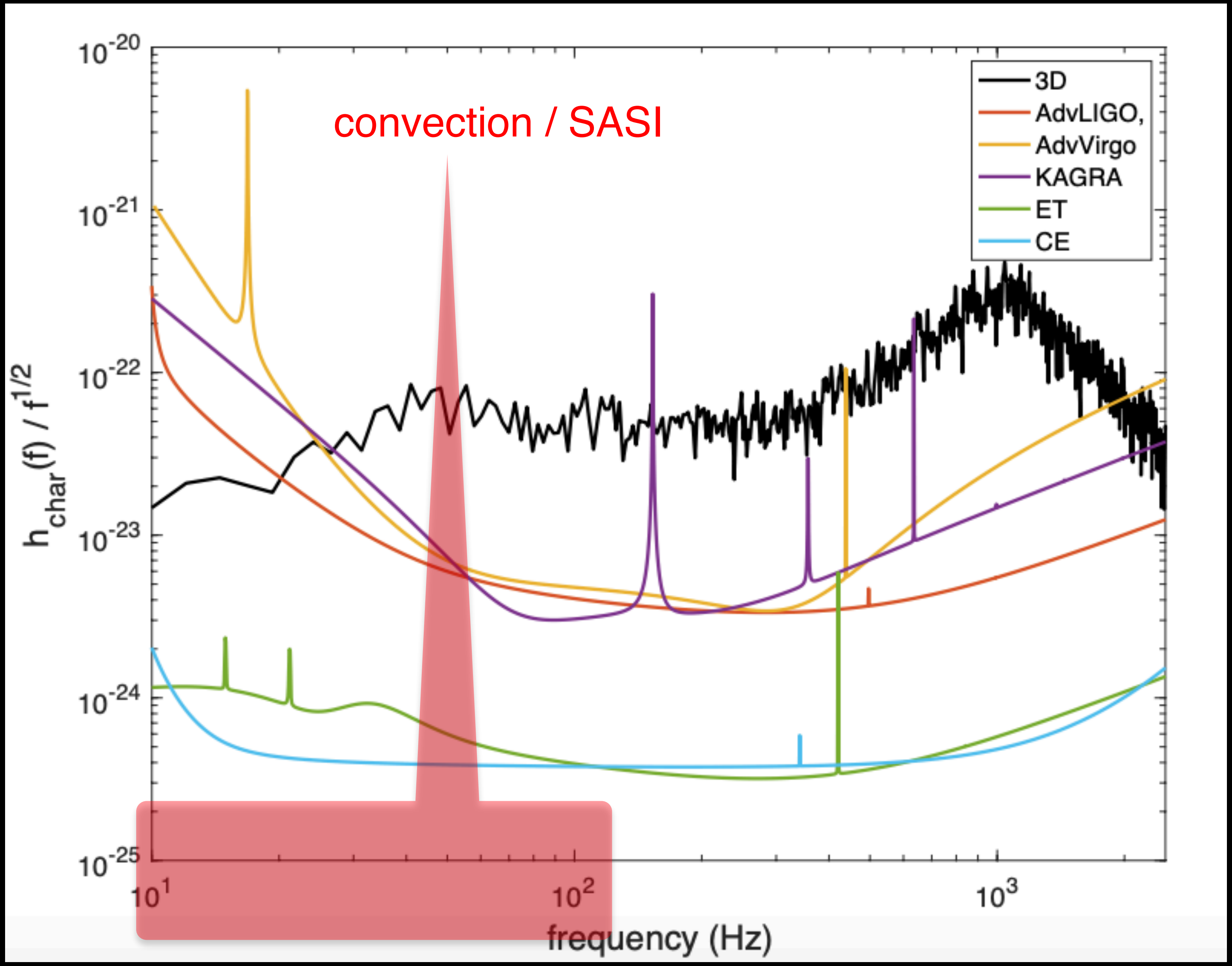
Abdikamalov, Pagliaroli, Radice,
arXiv:2010.04356

....

# Multi-messenger

Neutrinos and GW carry important information from the PNS

Mezzacappa, et al., Phys. Rev. D 102 (2020) no.2, 023027




see also

Westernacher-Schneider,an,
Phys. Rev. D 100 (2019) no.12, 123009

Vartanyan, Burrows,
Astrophys. J. 901 (2020) no.2, 108

Pan, Liebendorfer, Couch, Thielemann,
arXiv:2010.02453

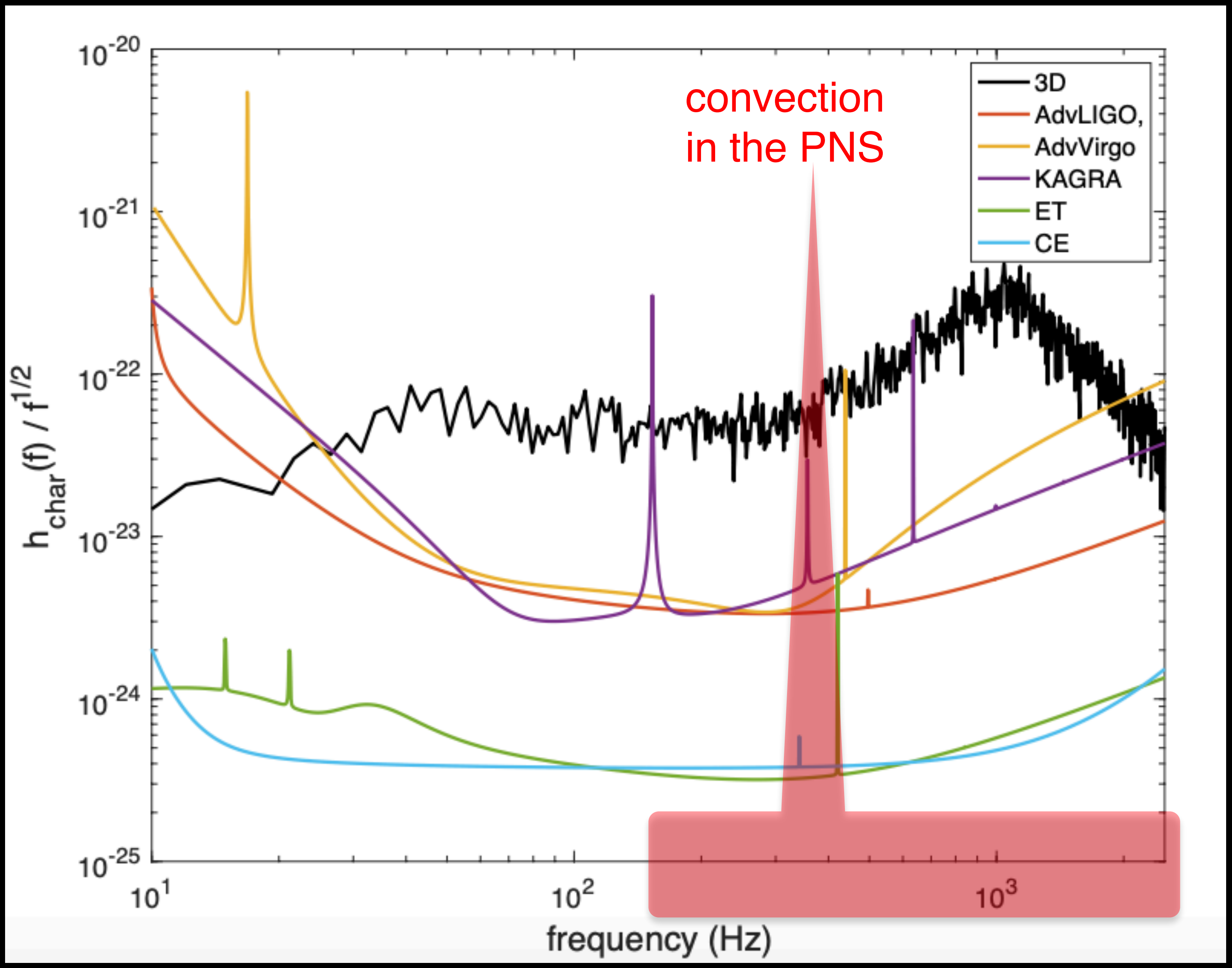
Abdikamalov, Pagliaroli, Radice,
arXiv:2010.04356

….

# Multi-messenger

Neutrinos and GW carry important information from the PNS

Mezzacappa, et al., Phys. Rev. D 102 (2020) no.2, 023027




see also

Westernacher-Schneider,an,
Phys. Rev. D 100 (2019) no.12, 123009

Vartanyan, Burrows,
Astrophys. J. 901 (2020) no.2, 108

Pan, Liebendorfer, Couch, Thielemann,
arXiv:2010.02453

Abdikamalov, Pagliaroli, Radice,
arXiv:2010.04356

….

GW complementary to neutrinos, which are providing time info

# Conclusions

Neutrinos are unique messengers from supernovae

A complete understanding is needed: explosion, flavor, detection

Neutrinos role in the explosion still to be fully assessed, both with and without flavor conversions

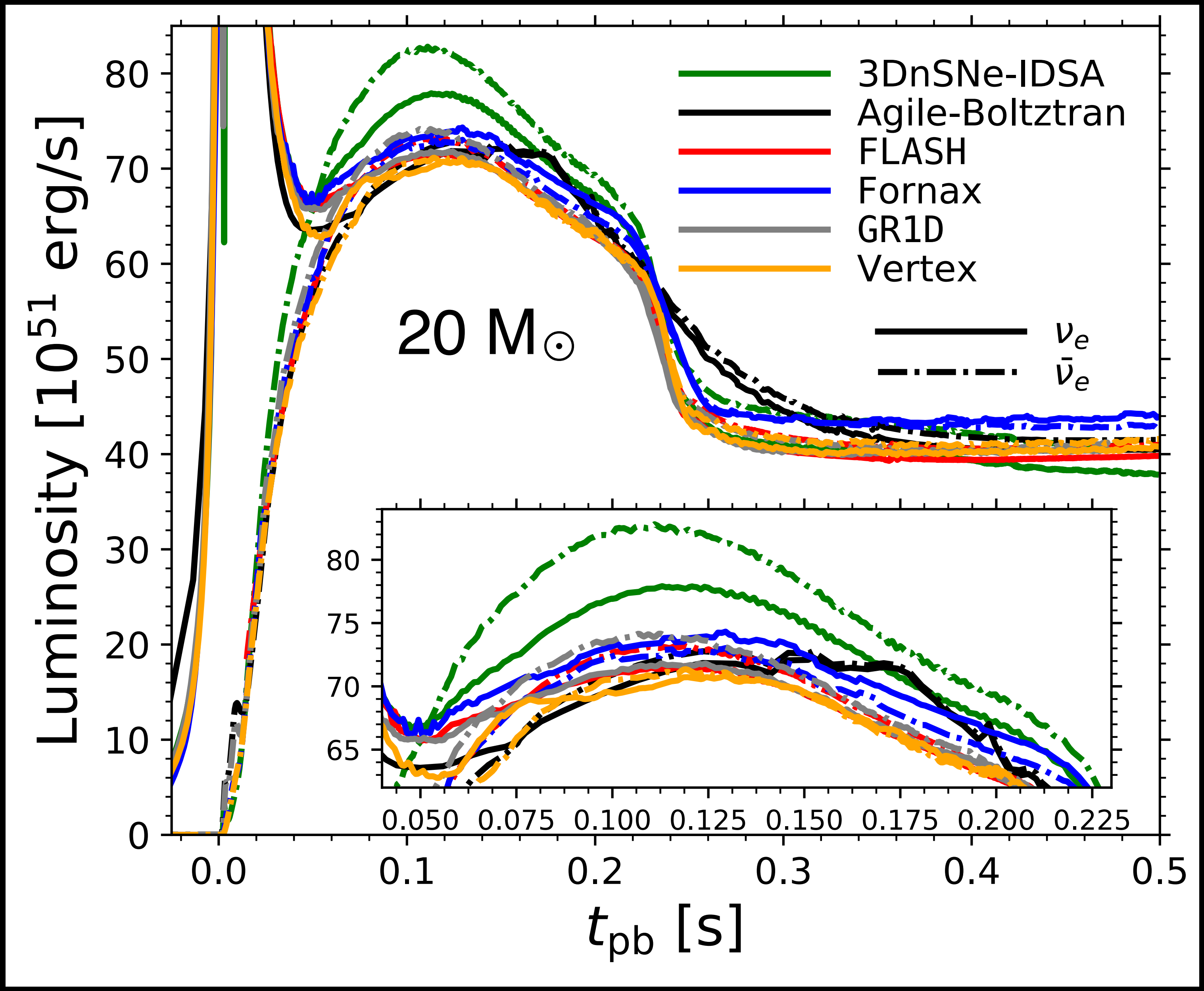
Neutrinos have a key role in the multi-messenger approach


Thank you!

# The era of 3D simulations

Good agreement between 1D simulations

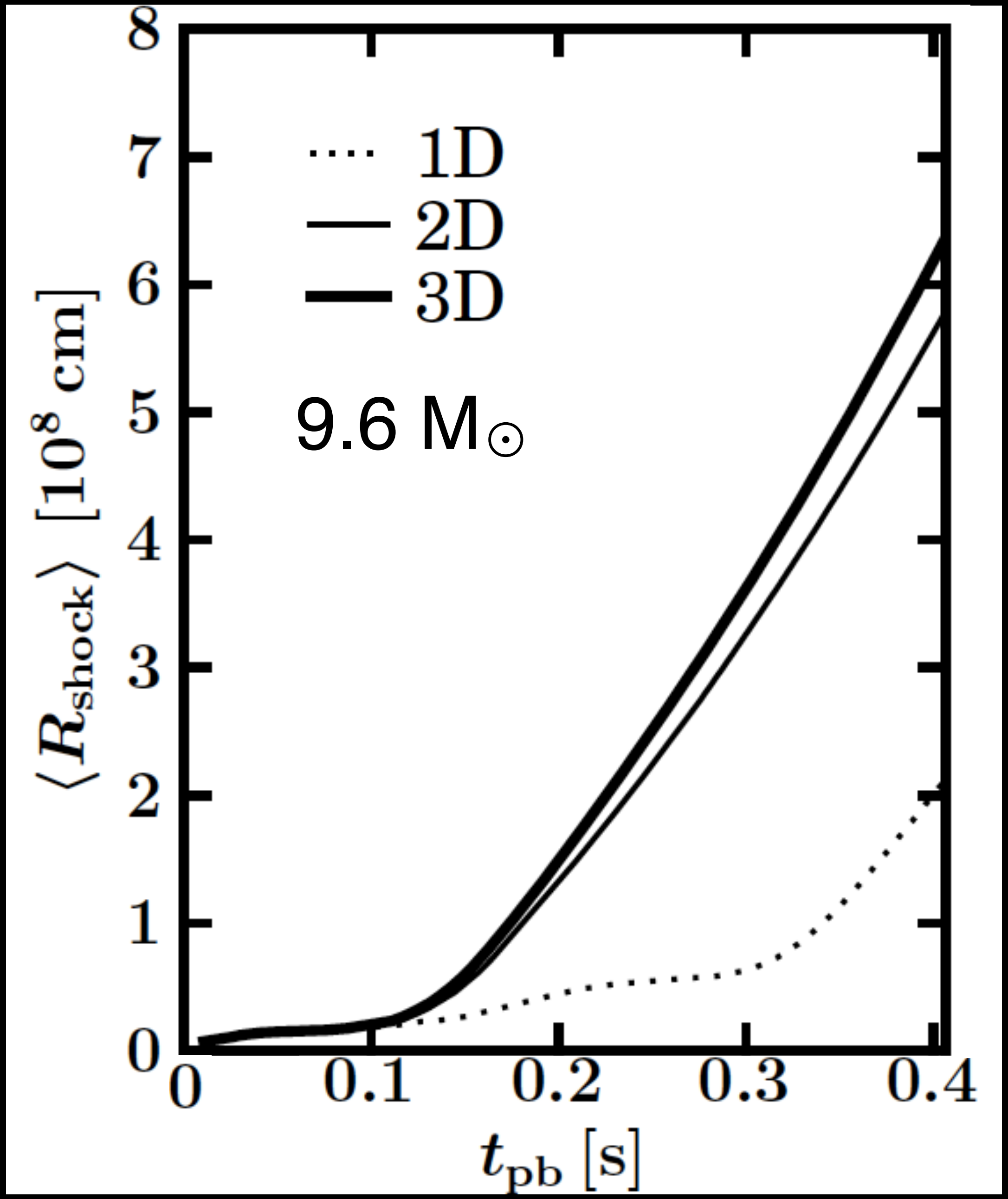
O'Connor, Bollig, Burrows, Couch, Fischer, Janka, Kotake, Lentz, Liebendorfer, Messer, Mezzacappa, Takiwaki, Vartanyan, J. Phys. G 45 (2018) no.10, 104001




Excellent starting point! But we need to move to multi-D

# The era of 3D simulations

Successful explosions are obtained for low mass progenitors




Melson, Janka and Marek, Astrophys. J. 801 (2015) 2, L24

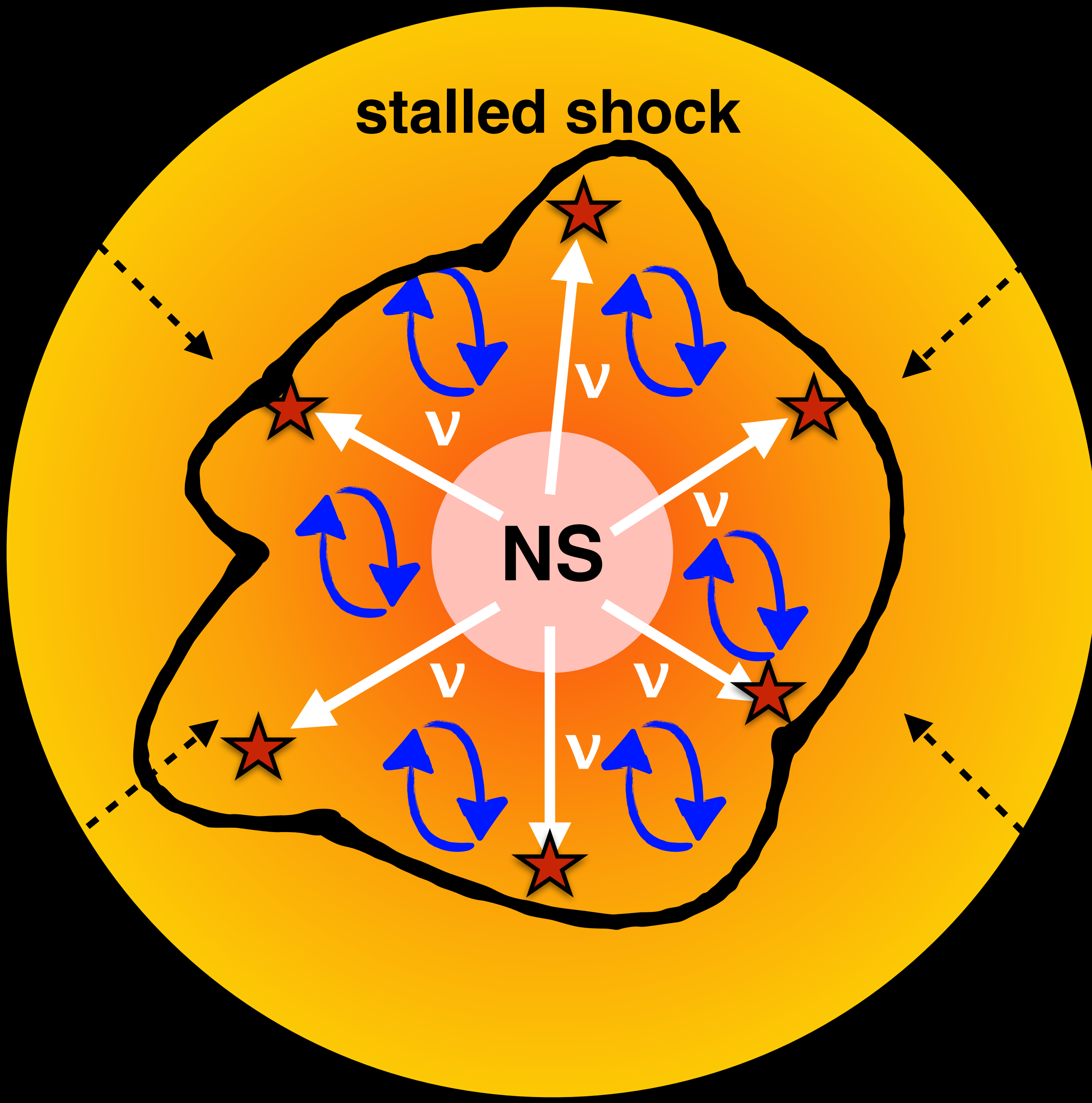
see also

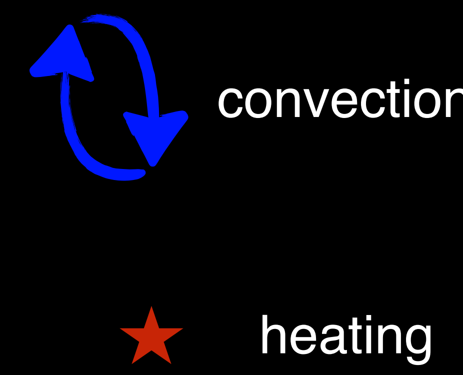
Burrows, Radice and Vartanyan, MNRAS 485 (2019) 3, 3153

Faster explosion in multi-D compared to 1D

# The era of 3D simulations

Multi-D simulations allow for convective / turbulent instabilities



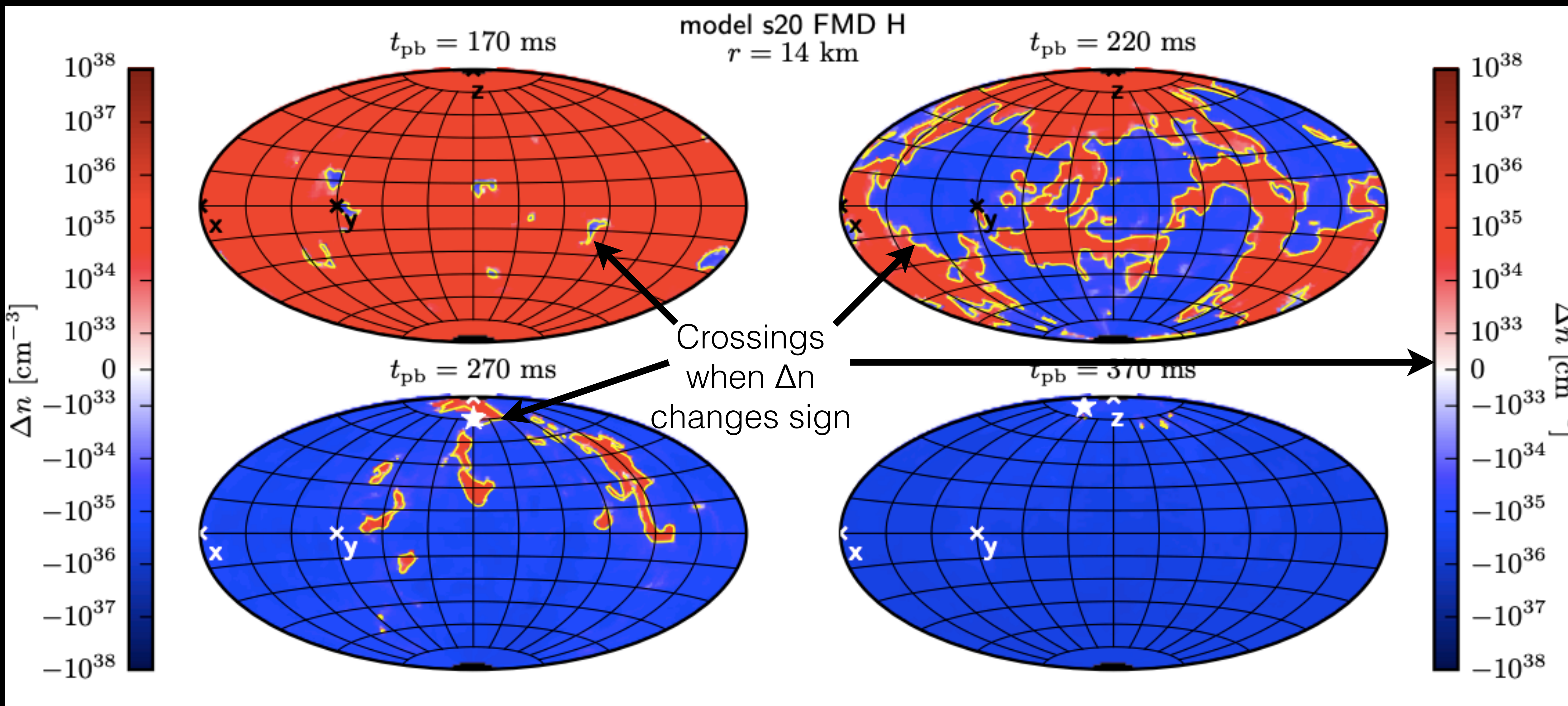

Couch, Ott, Astrophys. J. 799 (2015) no.1, 5
Muller, Janka, Mon. Not. Roy. Astron. Soc. 48 (2015) no.3, 2141-2174
O'Connor, Couch, Astrophys. J. 865 (2018) no.2, 81
Fields, Couch, Astrophys. J. 901 (2020) no.1, 33
Bollig, Yadav, Kresse, Janka, Mueller and Heger, arXiv:2010.10506

Convective instabilities favor neutrino heating and explosion

# Looking at real simulations

## Are crossing really happening in supernovae?

Glas, Janka, Capozzi, Sen, Dasgupta, Mirizzi, Sigl, Phys. Rev. D 101 (2020) no.6, 063001



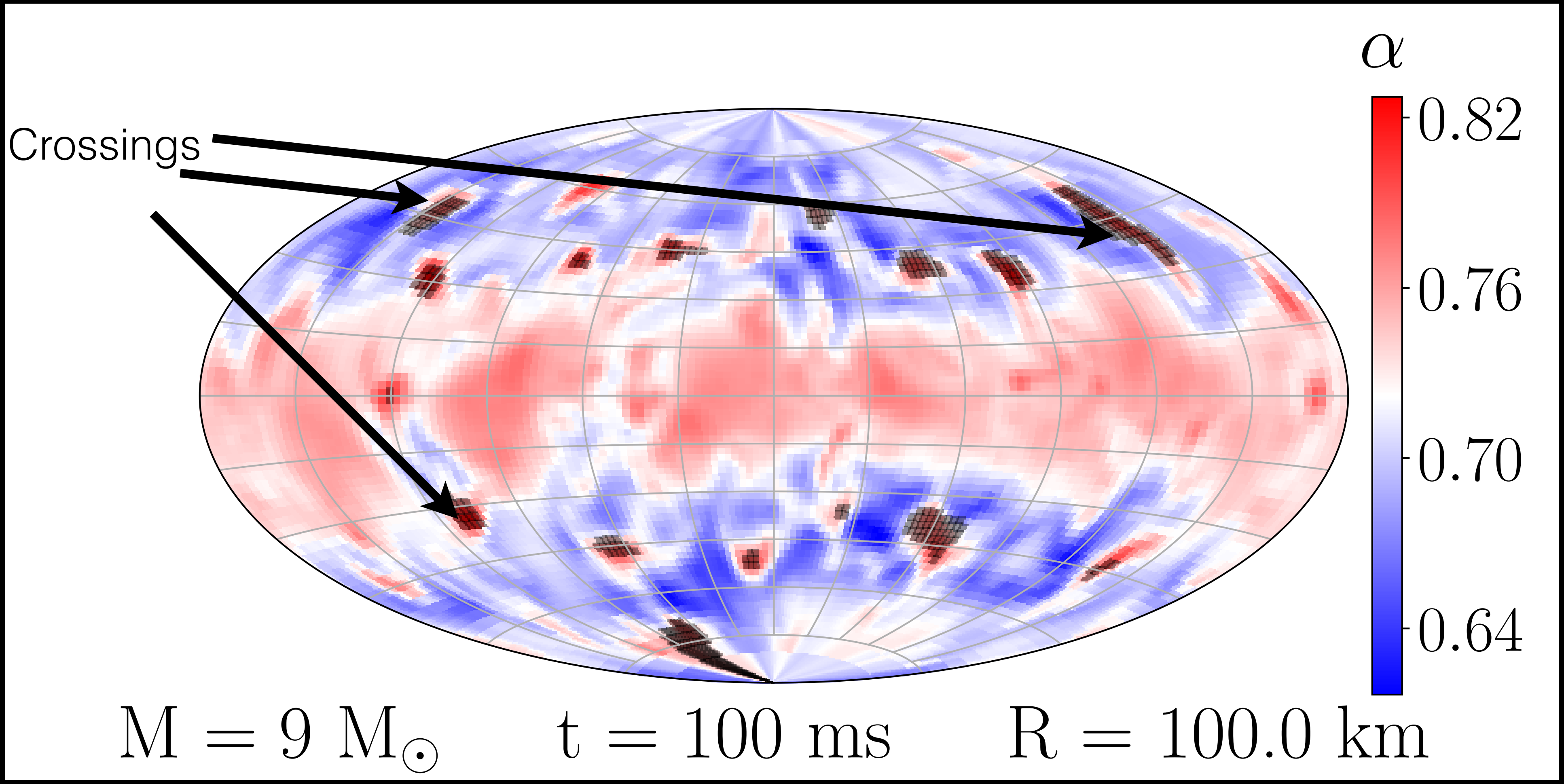

see also
Tamborra, Huedepohl, Raffelt, Janka, 2017; Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018; Morinaga, Nakagura, Kato, Yamada, 2019; Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019; Morinaga, Nagakura, Kato, Yamada 2020

## Crossings possible in the proto neutron star

# Looking at real simulations

## Are crossing really happening in supernovae?

Abbar, Capozzi, Glas, Janka, Tamborra Phys. Rev. D 103 (2021) no.6, 063033




see also Tamborra, Huedepohl, Raffelt, Janka, 2017; Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018; Morinaga, Nakagura, Kato, Yamada, 2019; Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019; Morinaga, Nagakura, Kato, Yamada 2020

Crossings possible below the shock wave