Neutrino Platform Week 2019:
Hot Topics in Neutrino Physics

Supernova Neutrinos: Current Challenges

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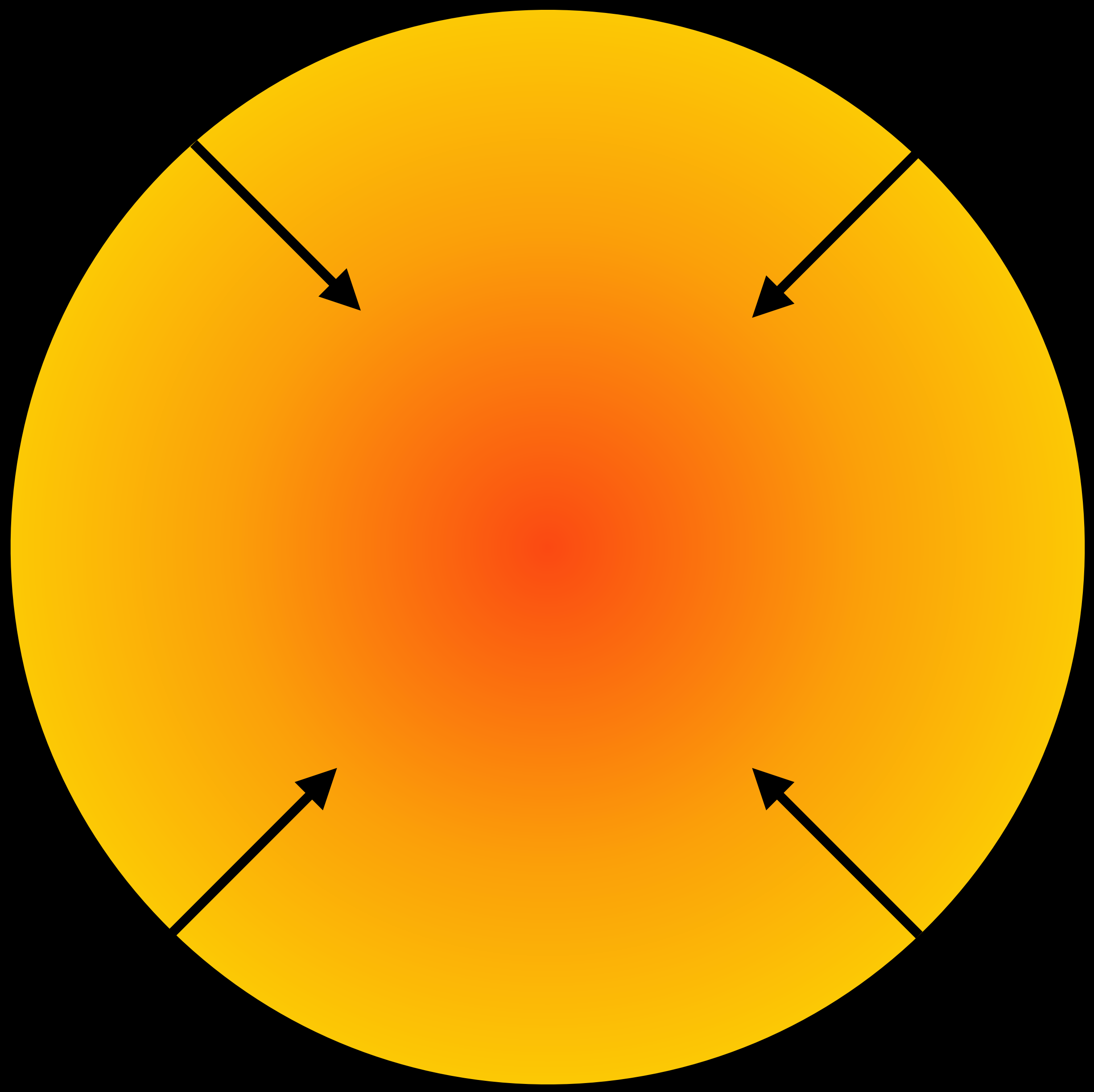
What are supernovae?

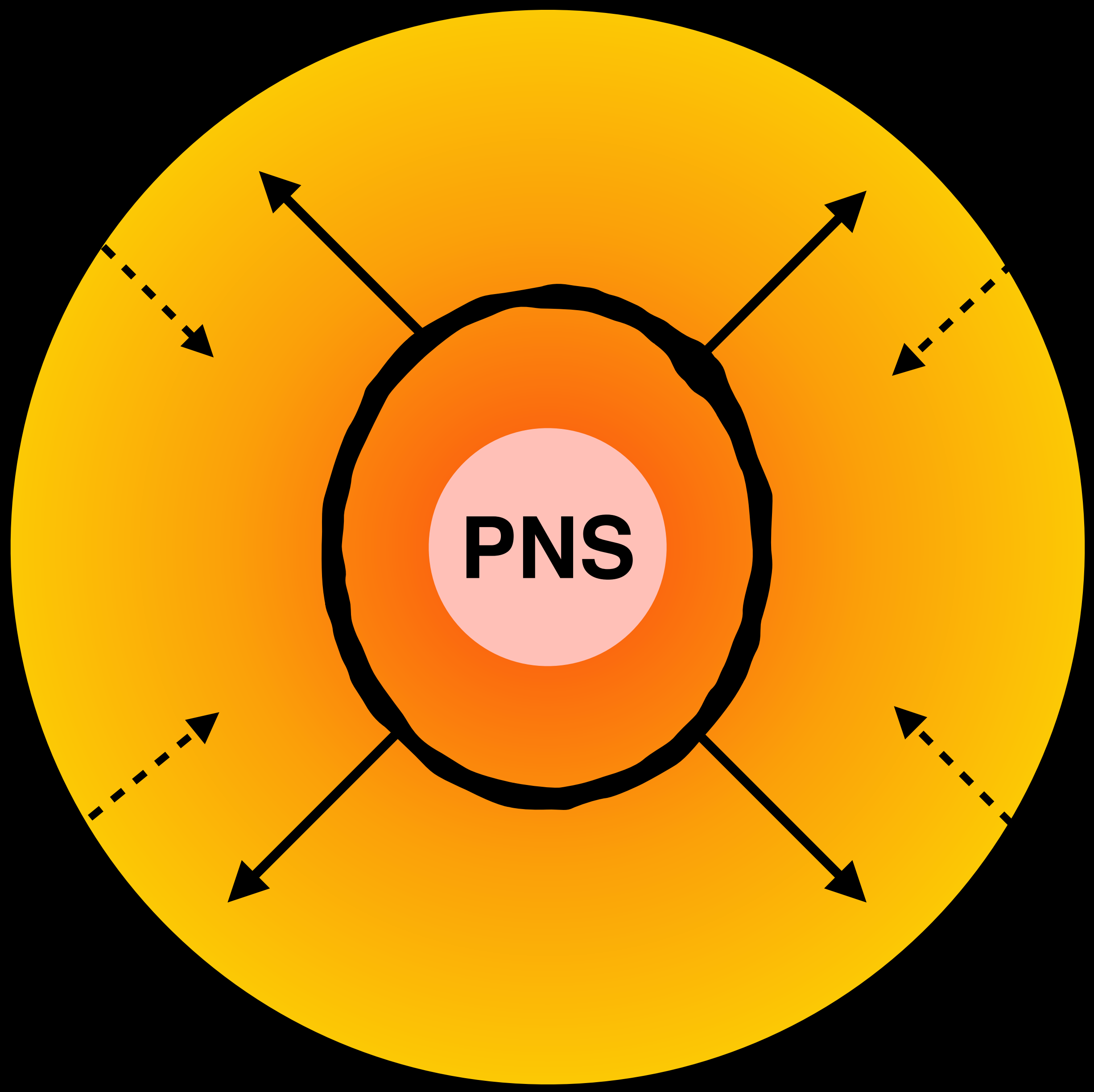
When nuclear fuel ends, massive stars (> 8 $M_\odot$) start collapsing



The density in the core rapidly increases

What are supernovae?

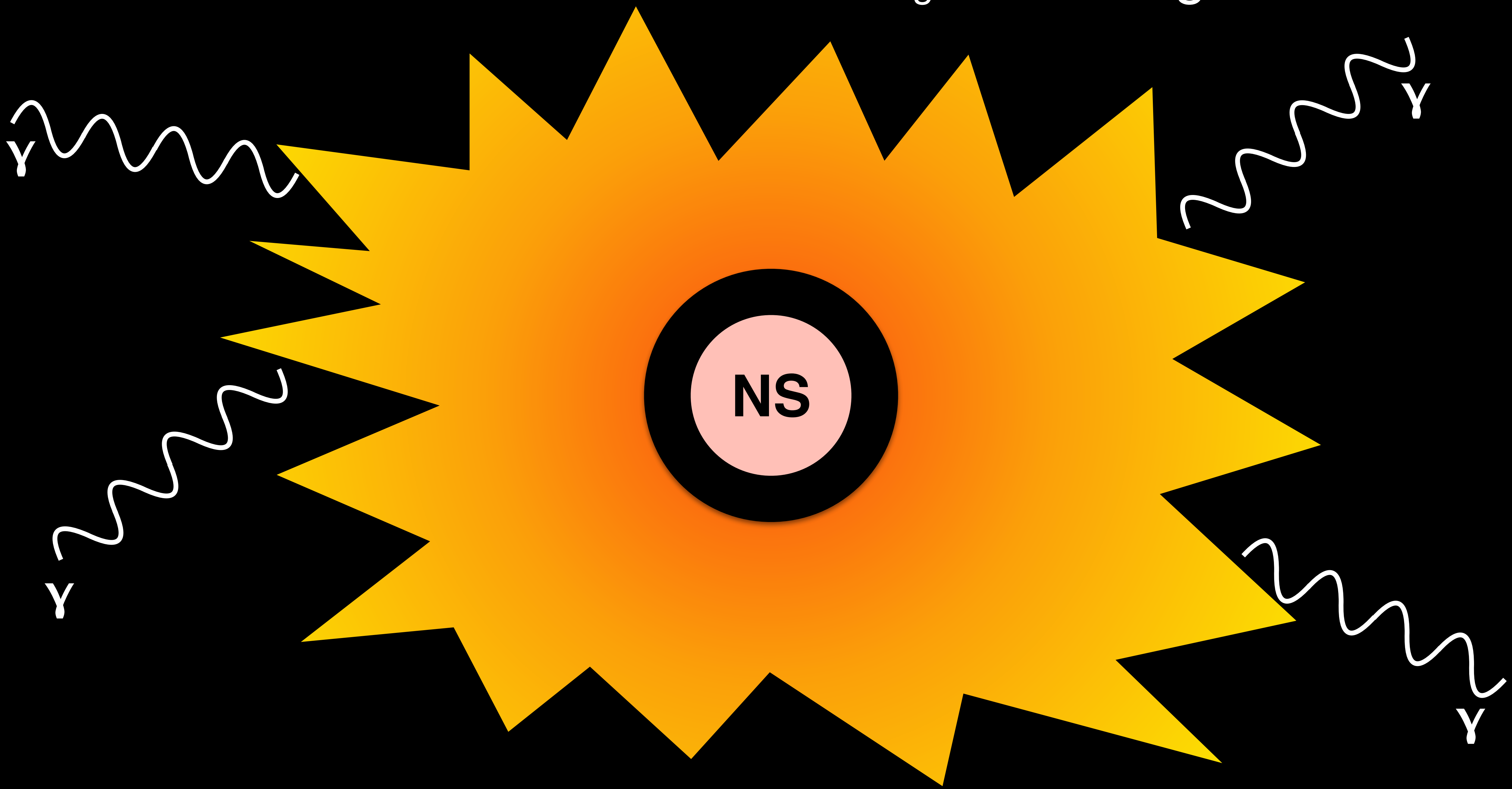
The density reaches nuclear saturation $\rho \sim 10^{14}$ g/cm^3



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

What are supernovae?

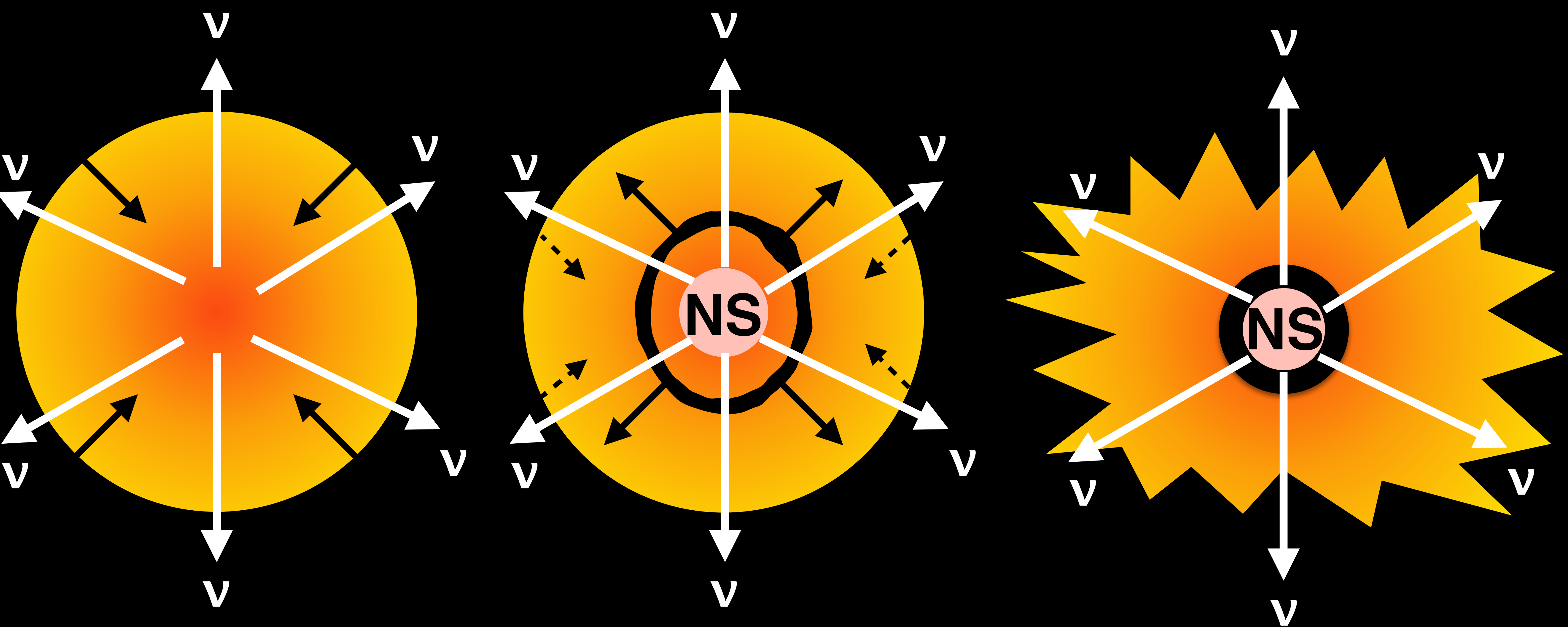
$R_{NS} \sim 10$ km $\quad E_g \sim 10^{53}$ erg



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

What is the role of neutrinos?

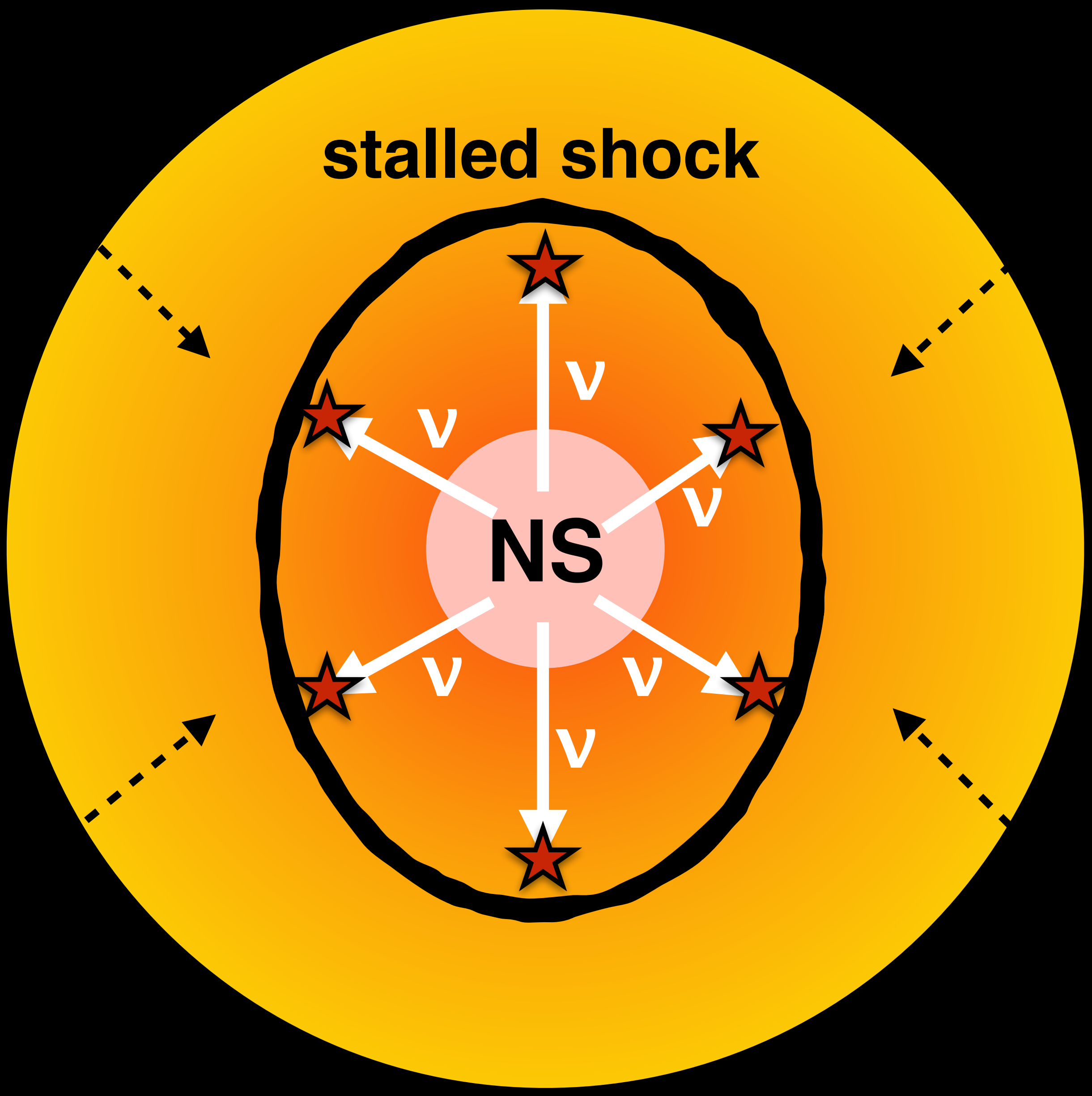
$\nu / \bar{\nu}$ of all flavor carry away 99% of E_g in ~10s seconds



Neutrinos are messengers from the interior of the exploding star

What is the role of neutrinos?

The shock wave stalls after ~ few 10 ms



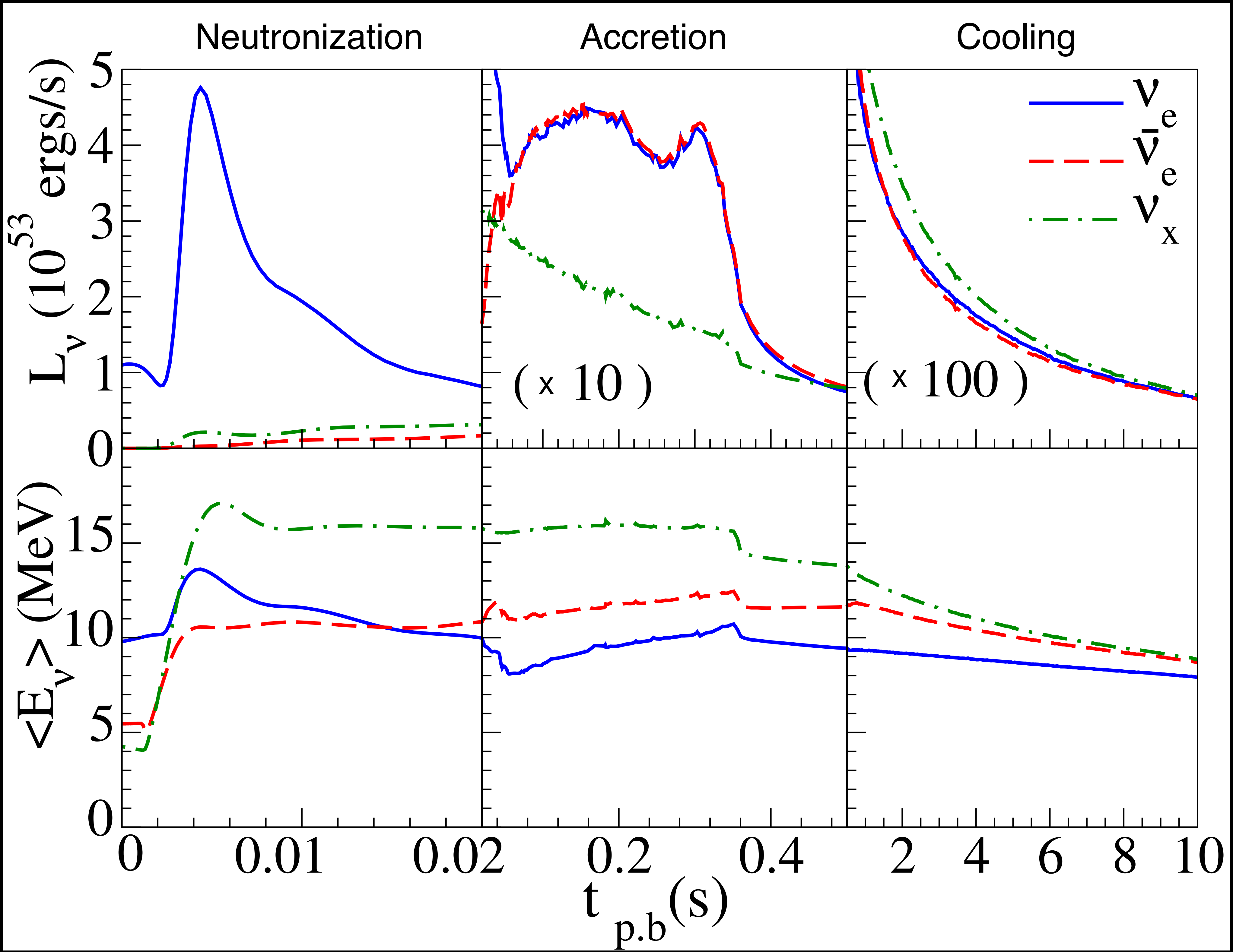
★ $\nu_e + n \longrightarrow e^- + p$

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

Neutrinos **might** revive the shock through energy deposition

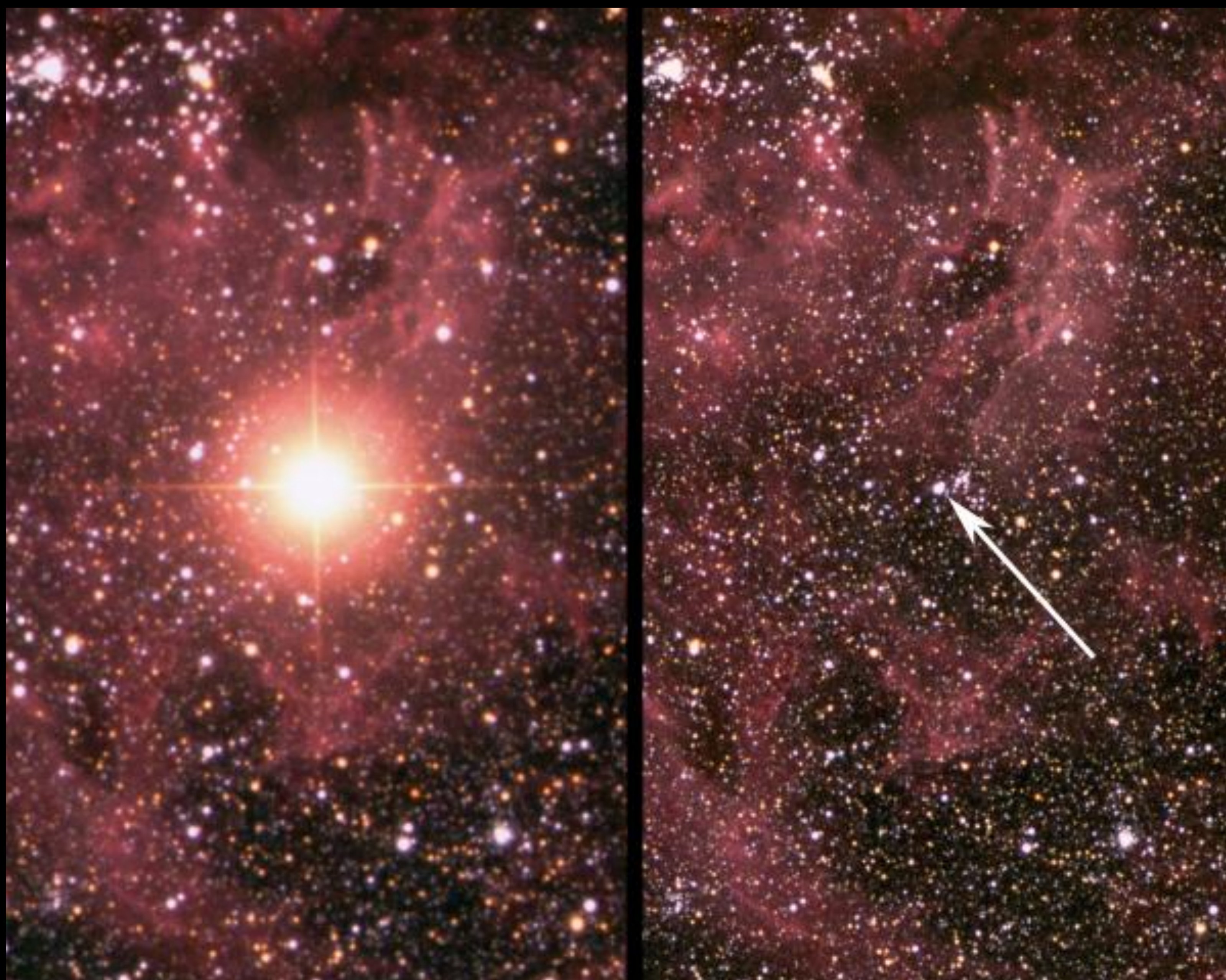
What is the role of neutrinos?

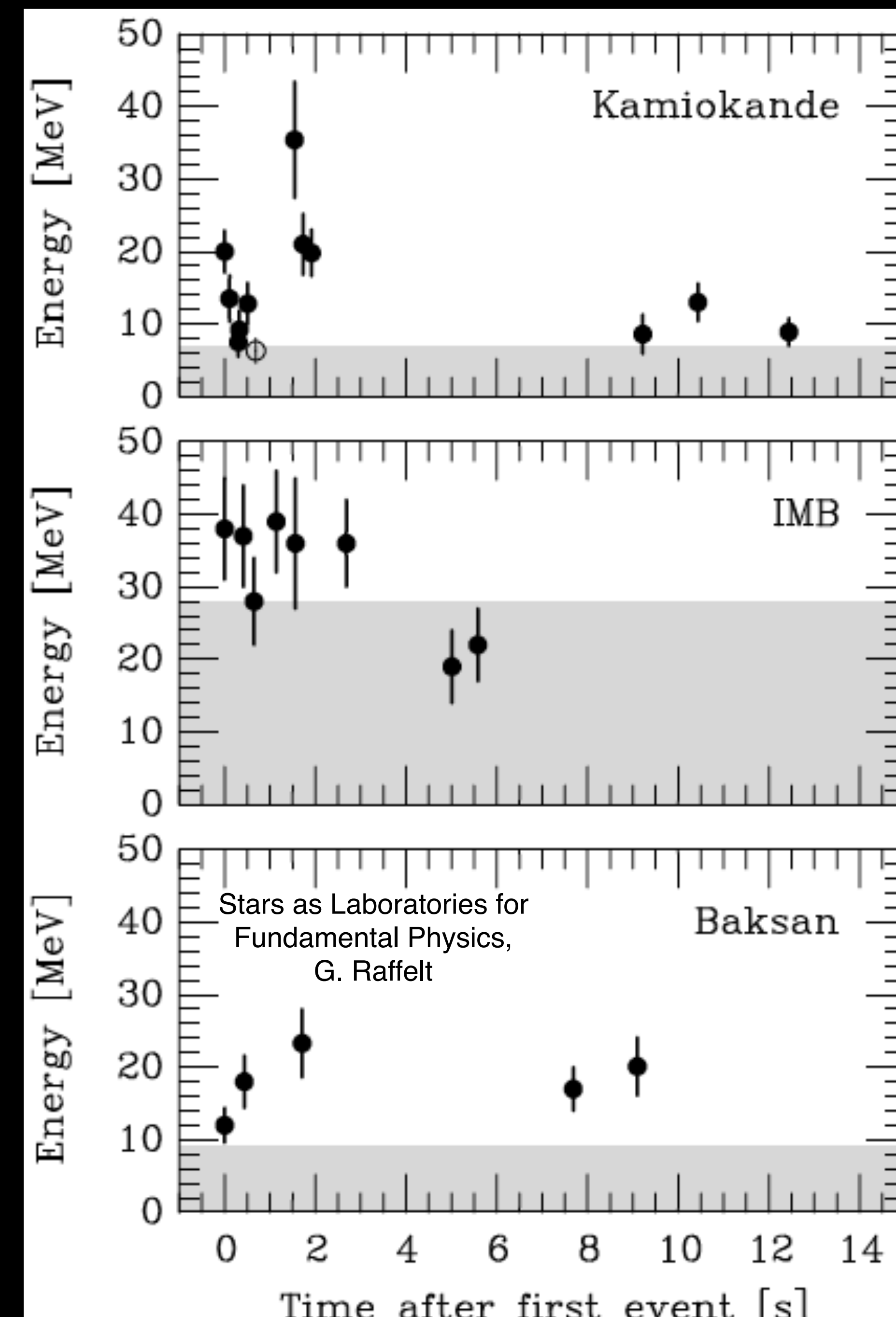
Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011, T. Fischer et al, Astron. Astrophys. 517, A80 (2010)



What have we learnt so far?

Supernova 1987a





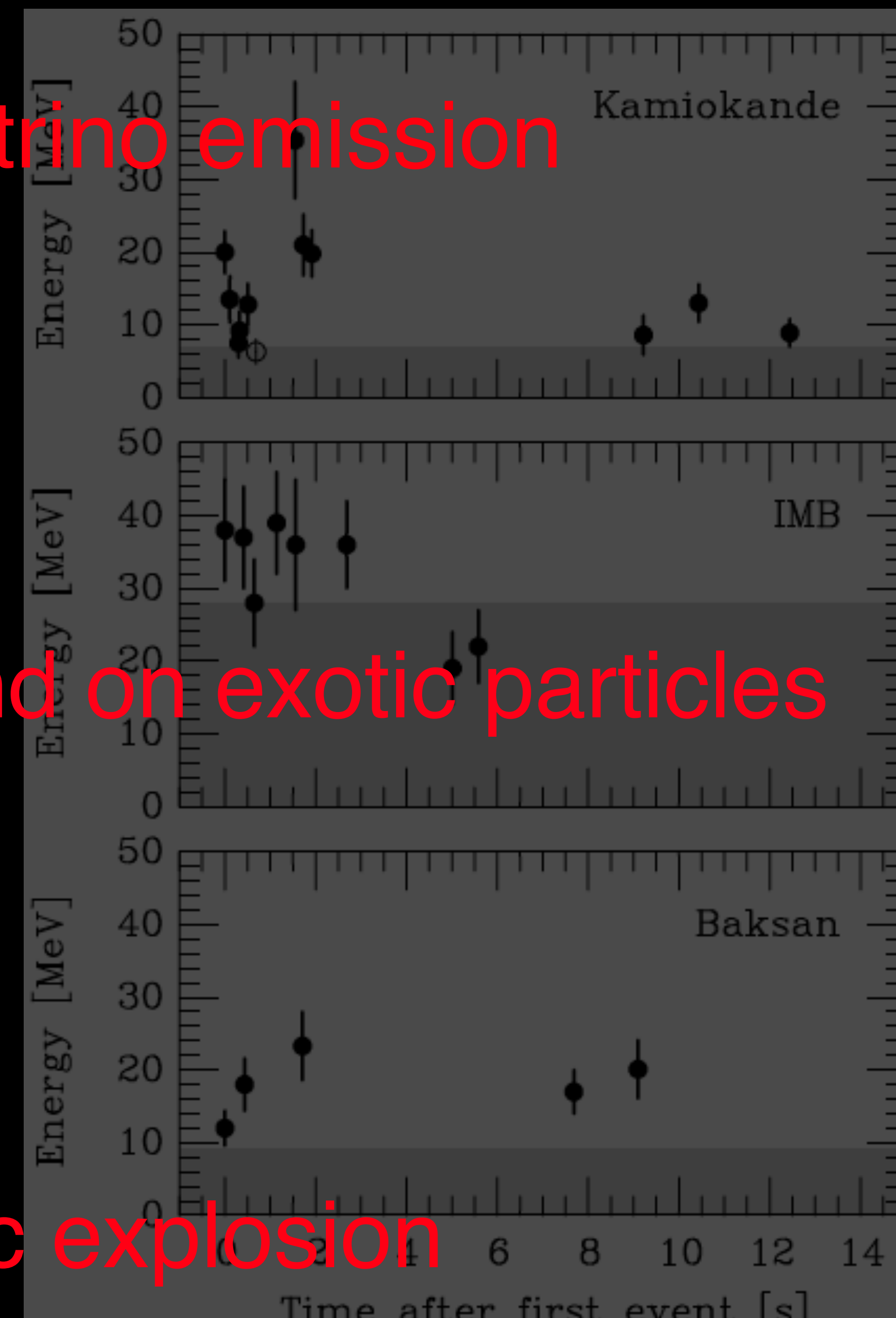
First and only neutrinos observed from a supernova

What have we learnt so far?

Confirmed expectation for neutrino emission

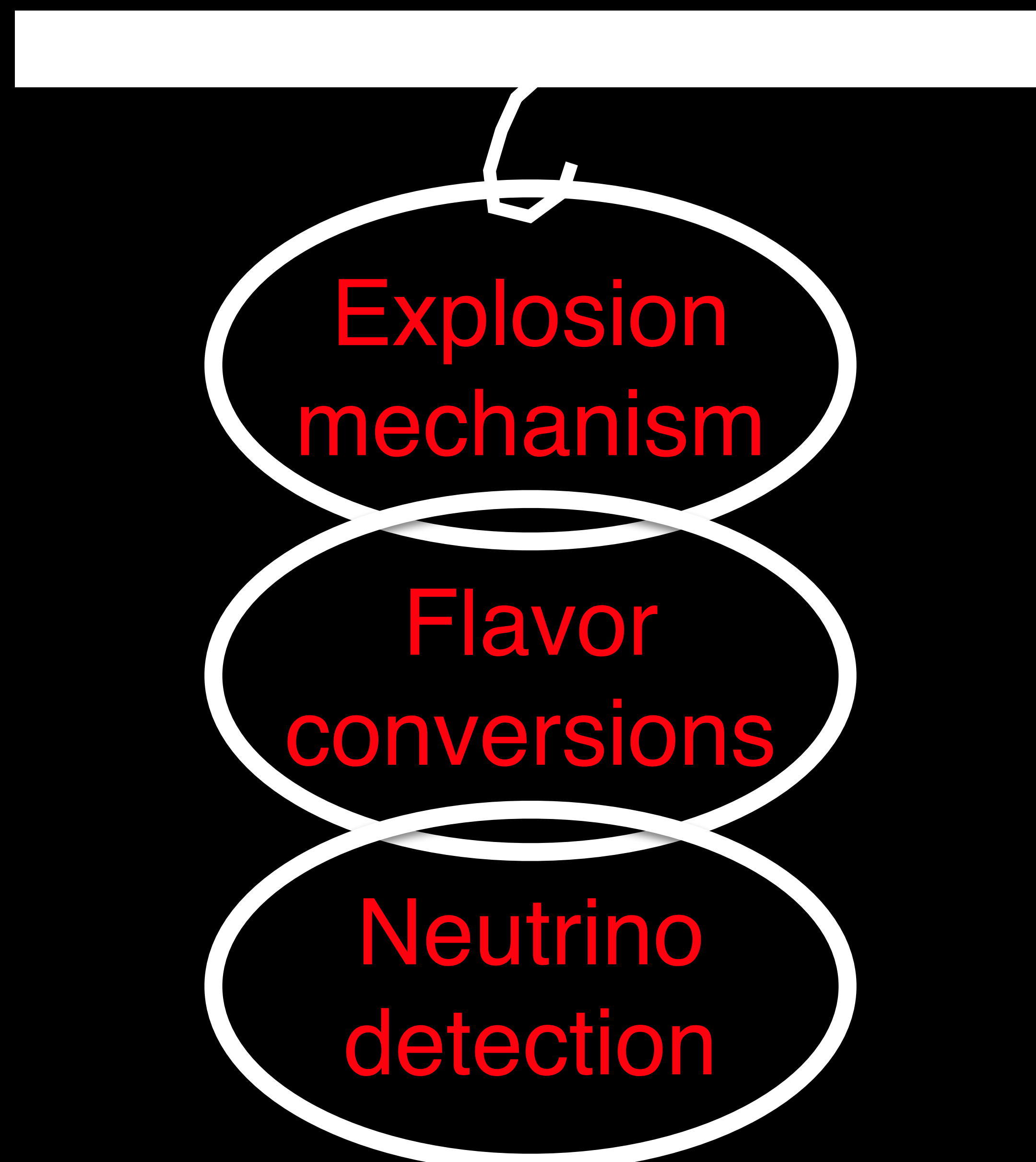
Constraints on neutrino properties and on exotic particles

Indication for an asymmetric explosion



Are we ready for SN20xy?

The supernova neutrinos chain



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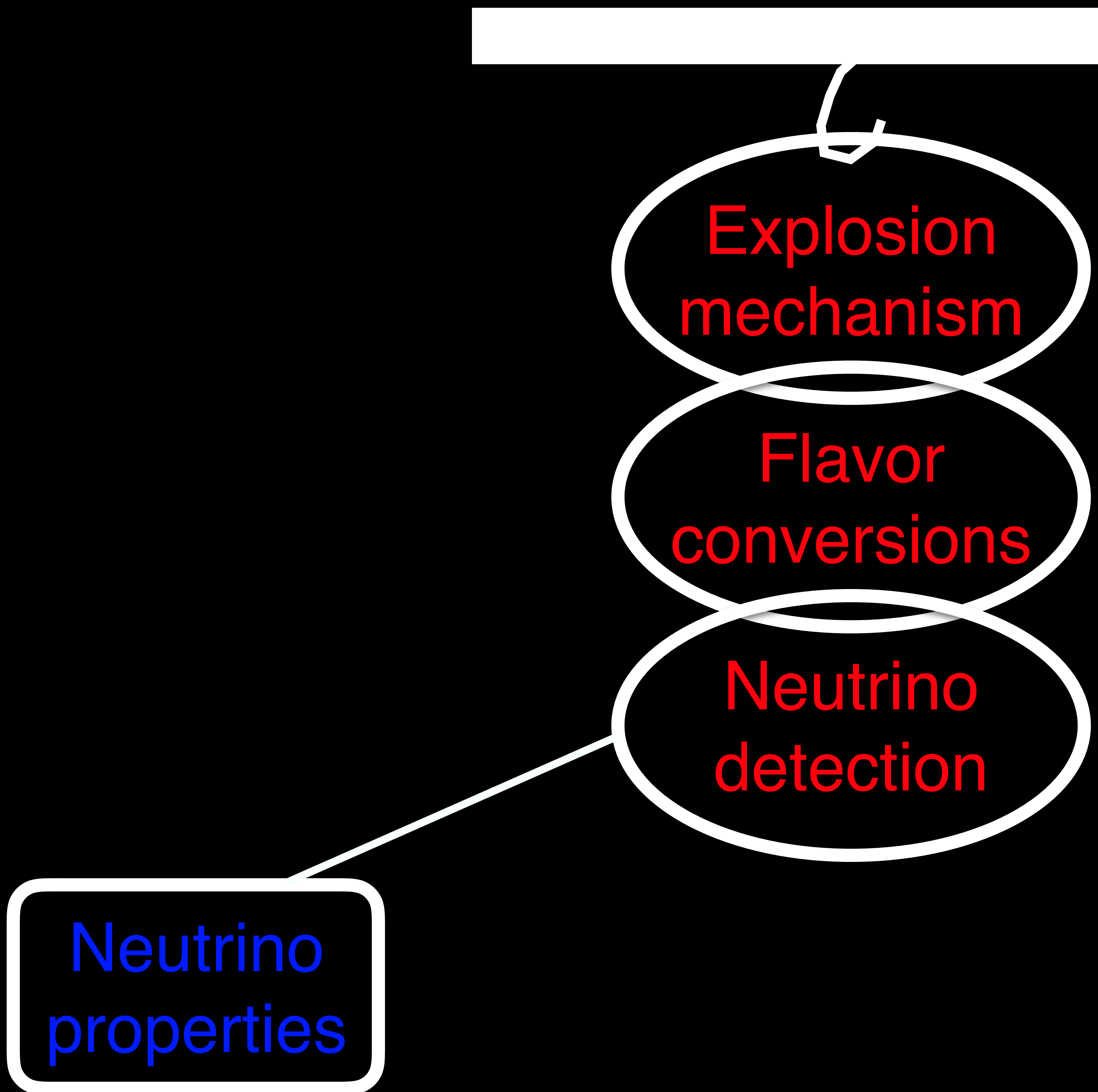

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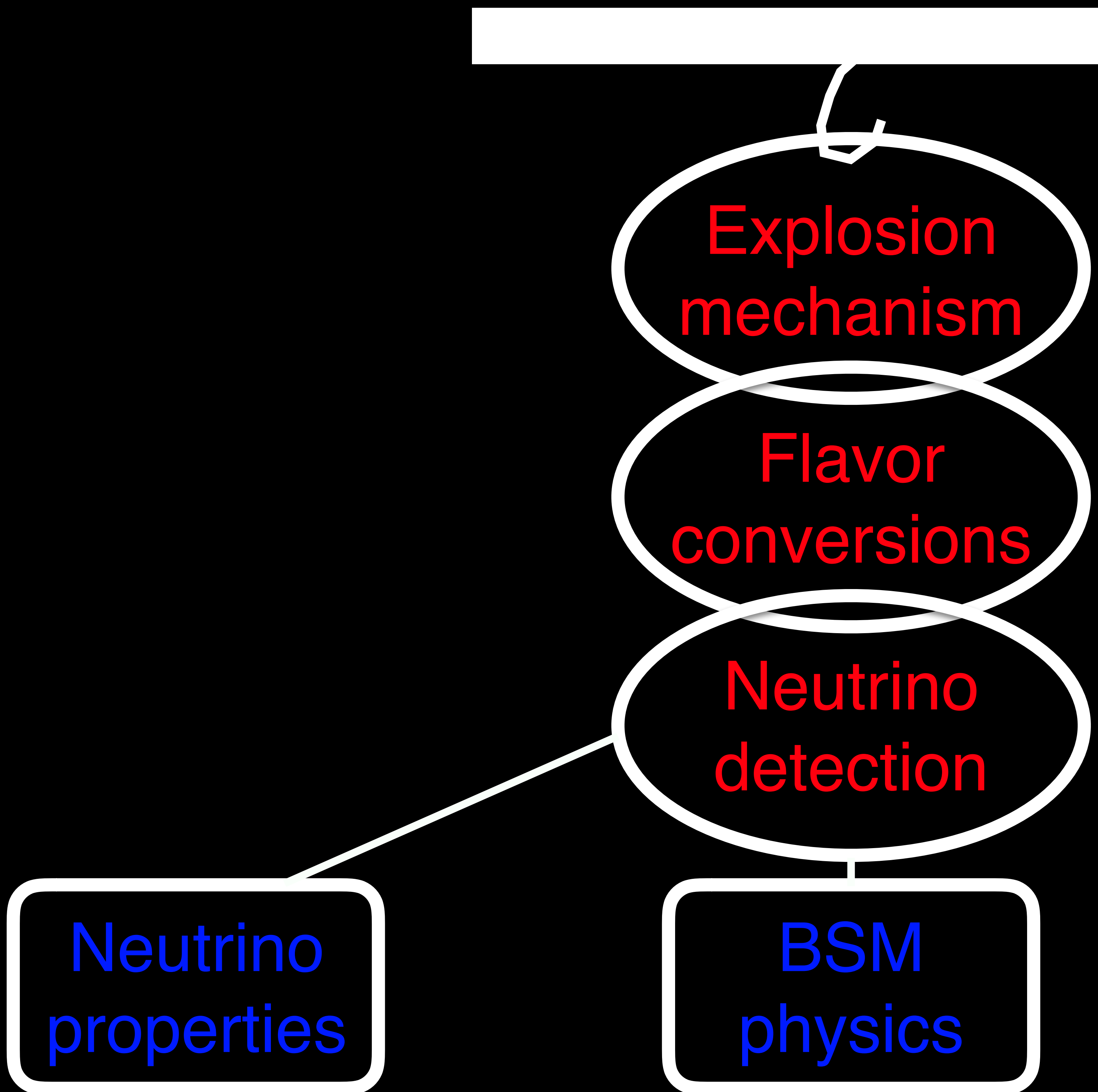
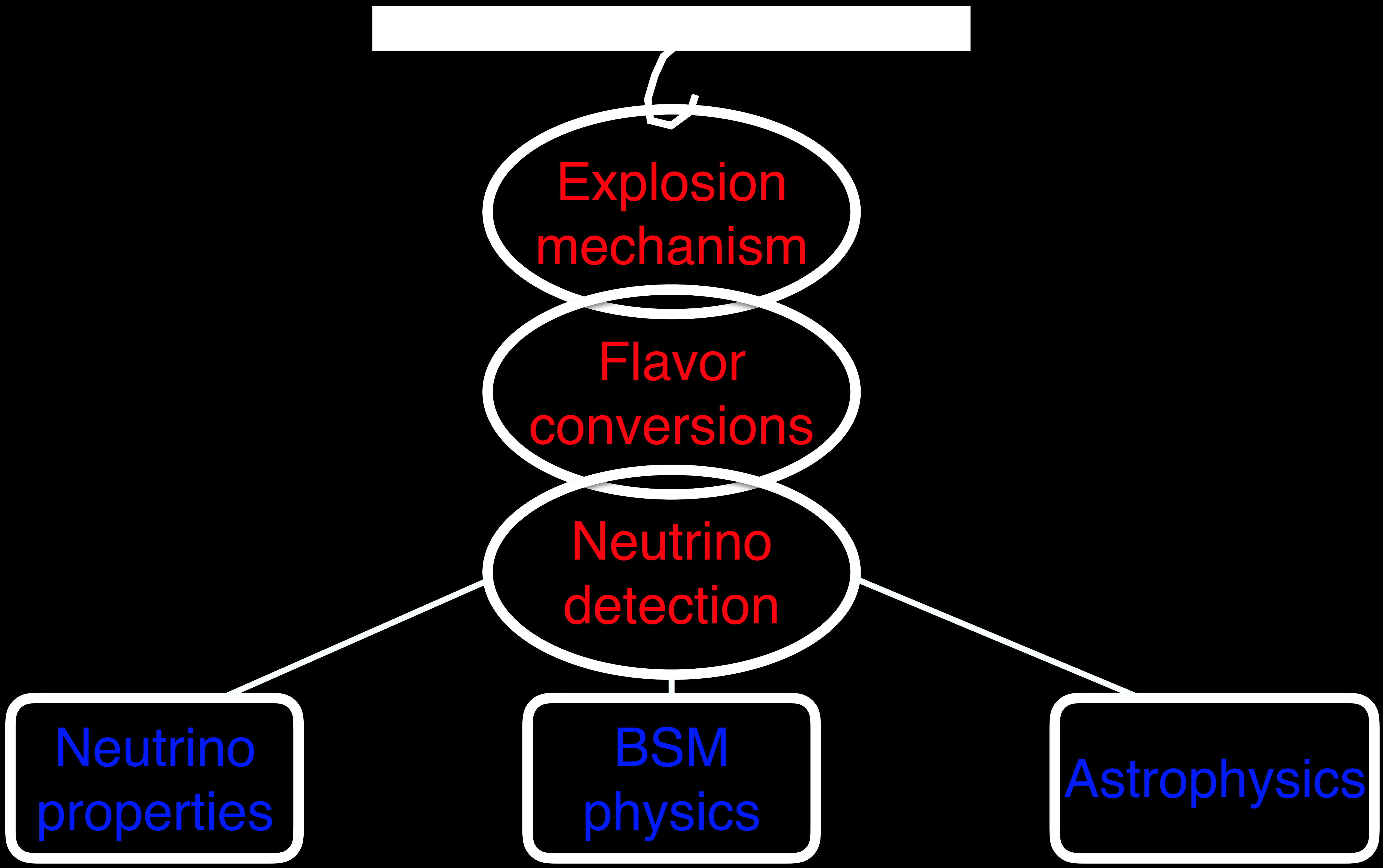


Are we ready for SN20xy?

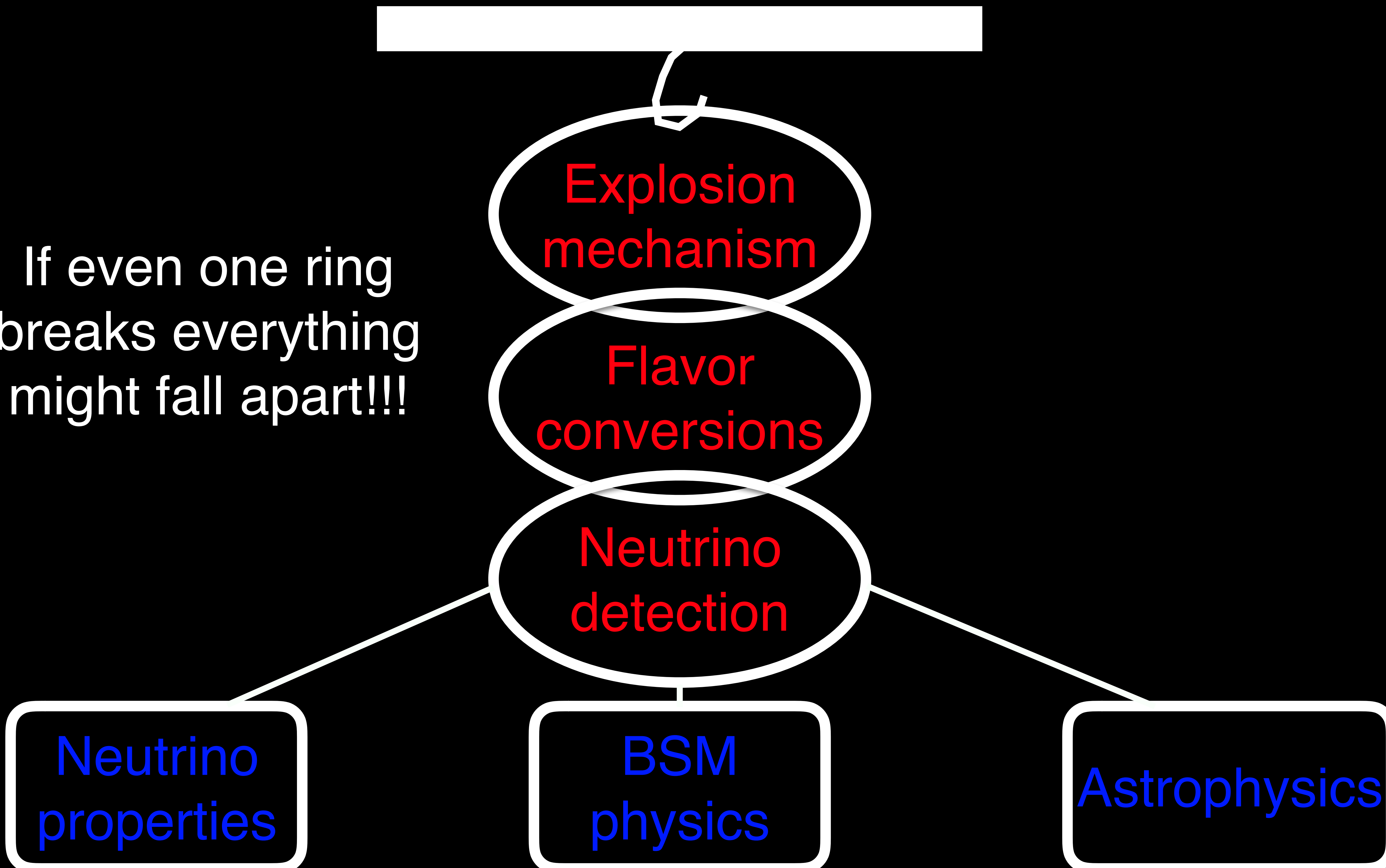
The supernova neutrinos chain



Are we ready for SN20xy?

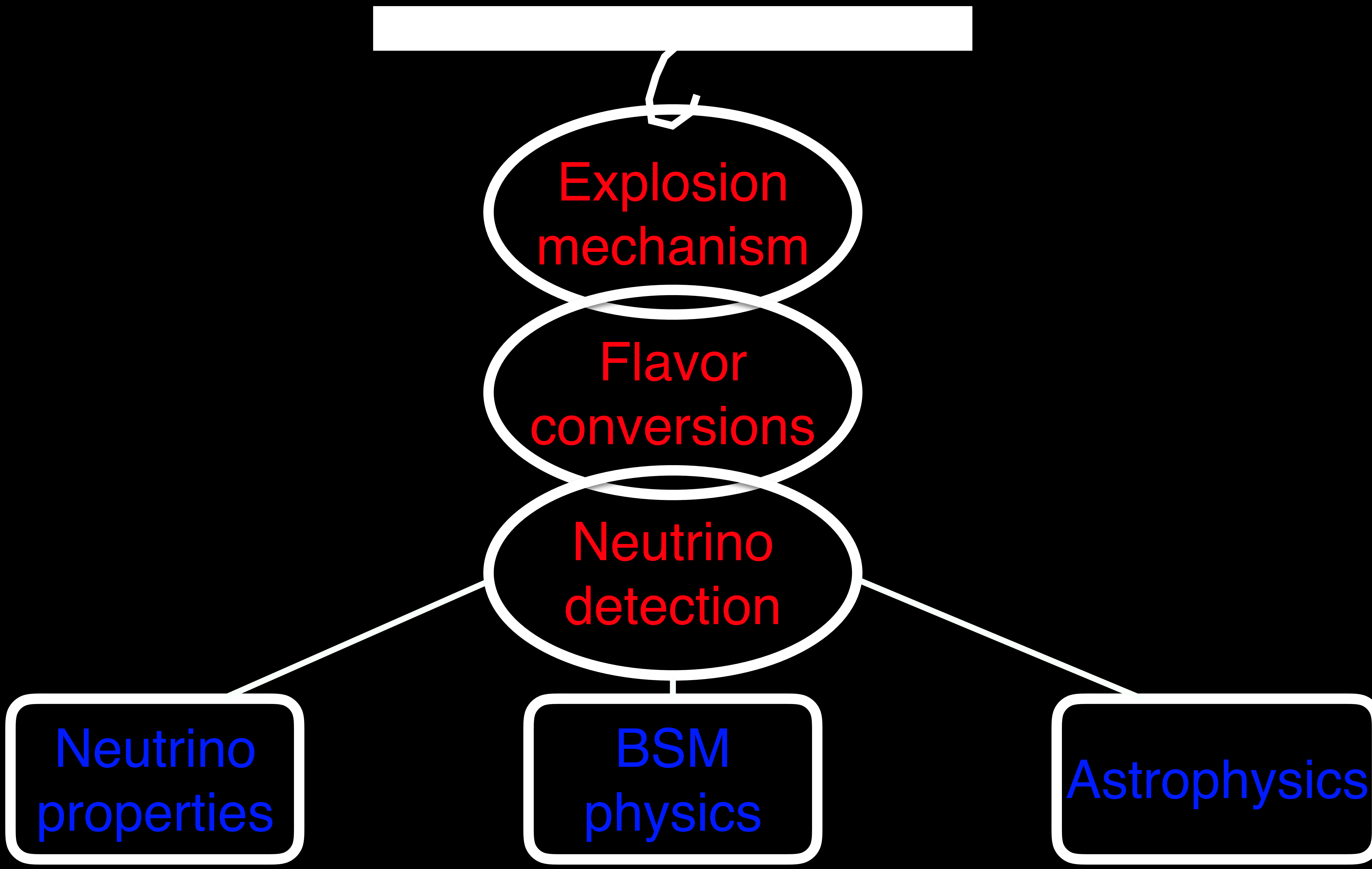
The supernova neutrinos chain

If even one ring breaks everything might fall apart!!!



Are we ready for SN20xy?

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



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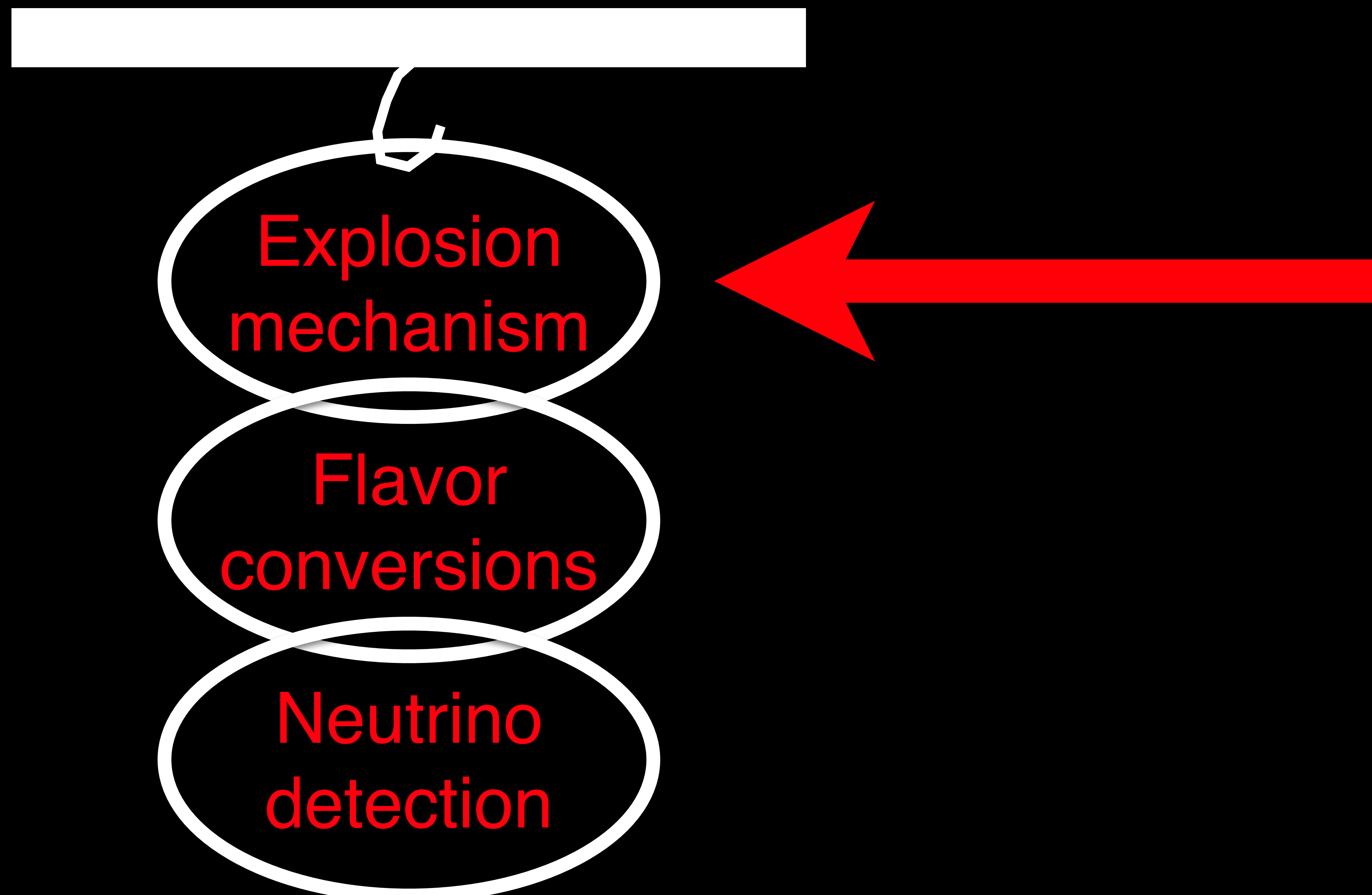
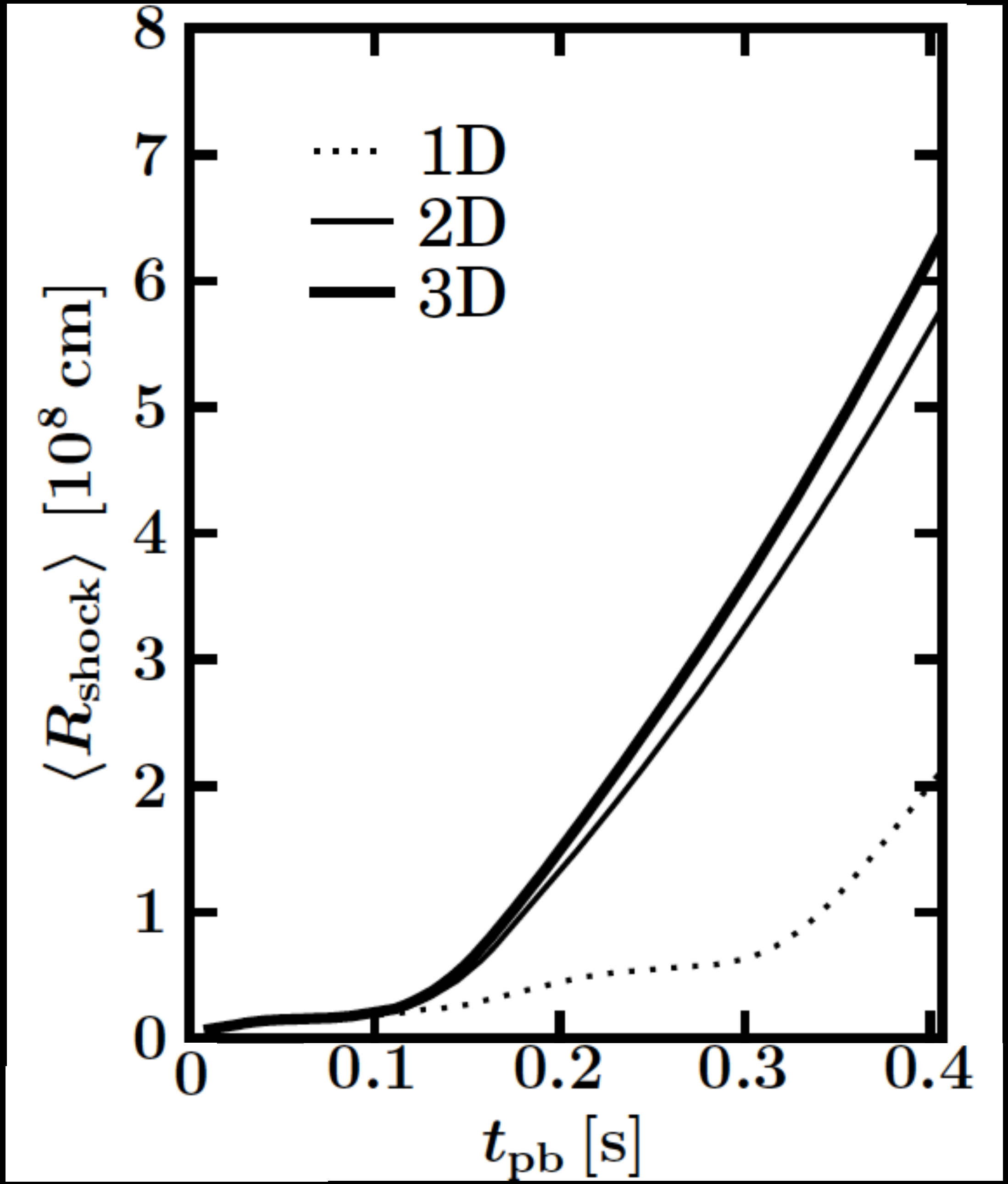


We review the status of each step in the chain

The era of 3D simulations

Successful explosions for low mass progenitors (< 10 $M_\odot$)



Melson, Janka and Marek, Astrophys. J. 801 (2015) no.2, L24

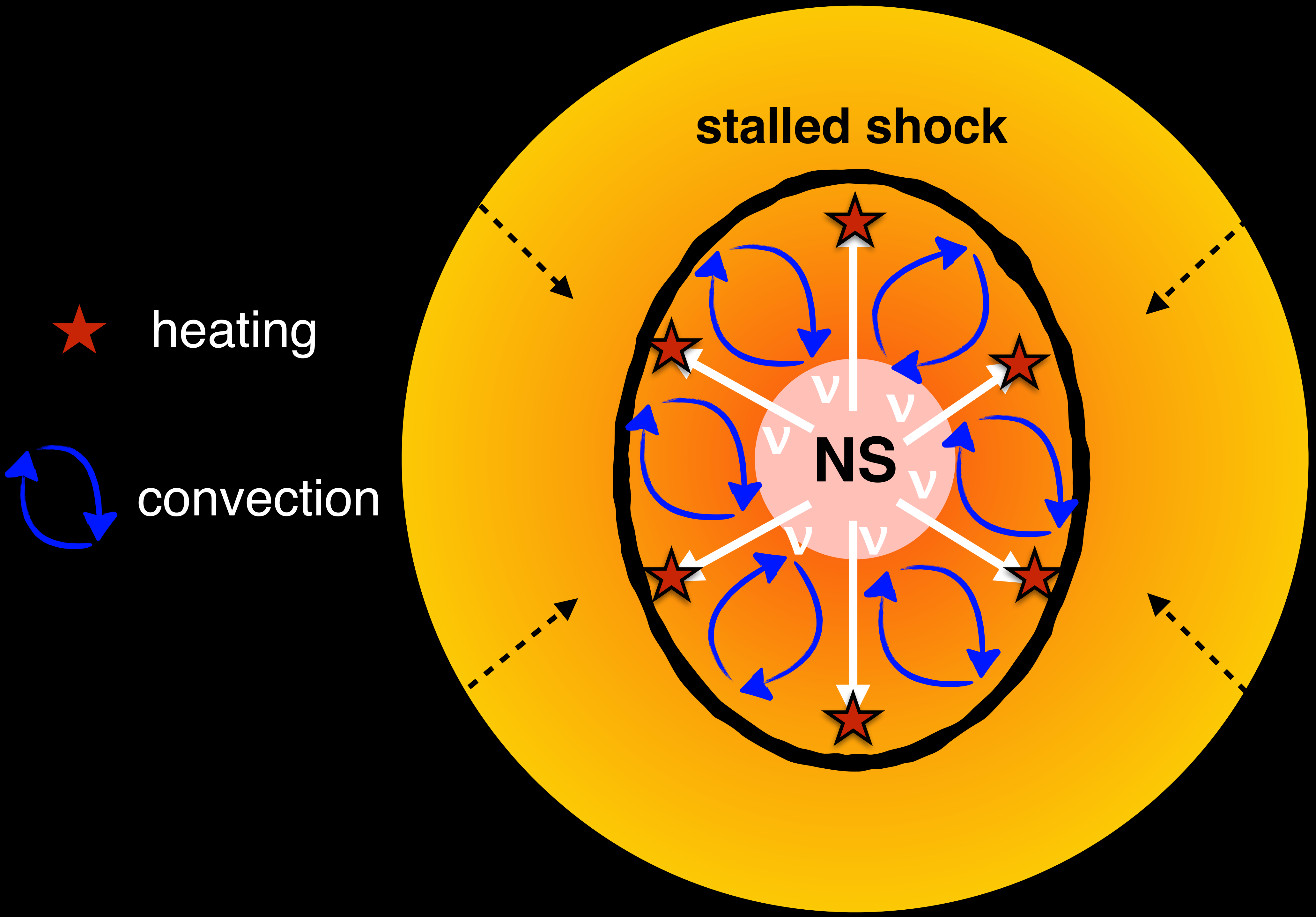
see also

Burrows, Radice and Vartanyan, MNRAS 485 (2019) no.3, 3153

Faster explosions in multi-D compared to 1D

The era of 3D simulations

Multi-D simulations allows convective / turbulent instabilities

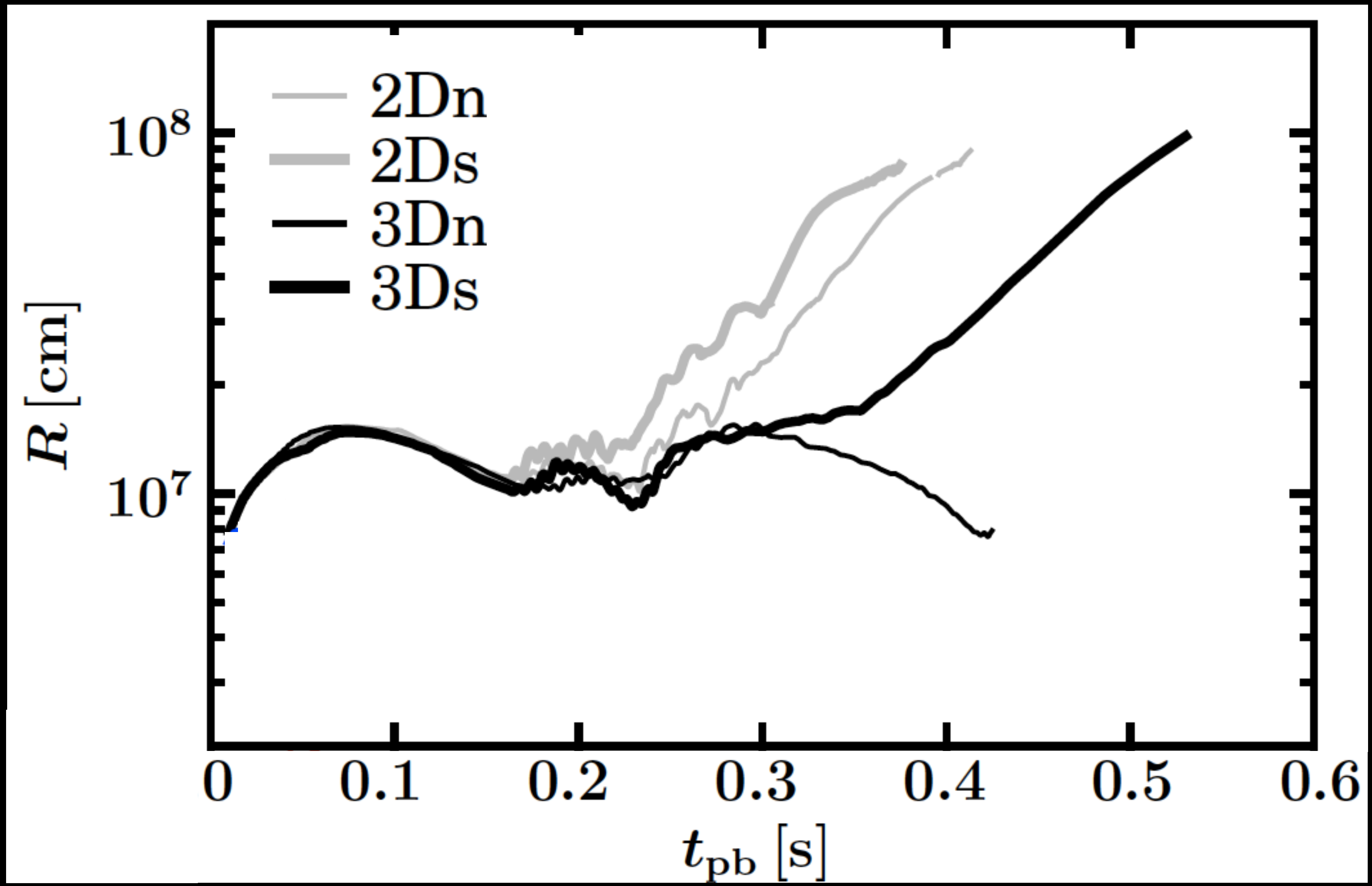


Convective instabilities favor neutrino heating and explosions

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

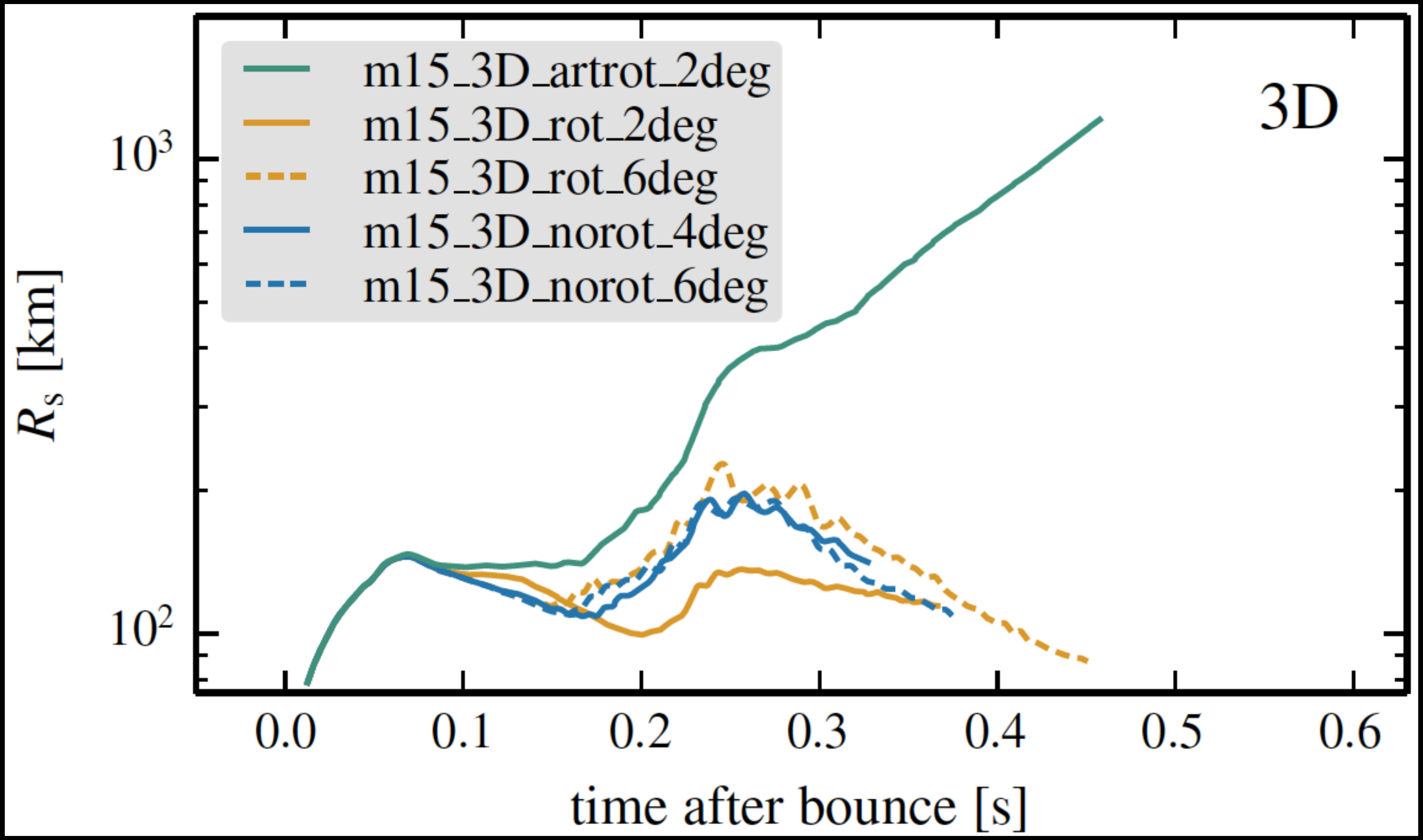


Example: s-quark contribution in ν-n NC creates explosion

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

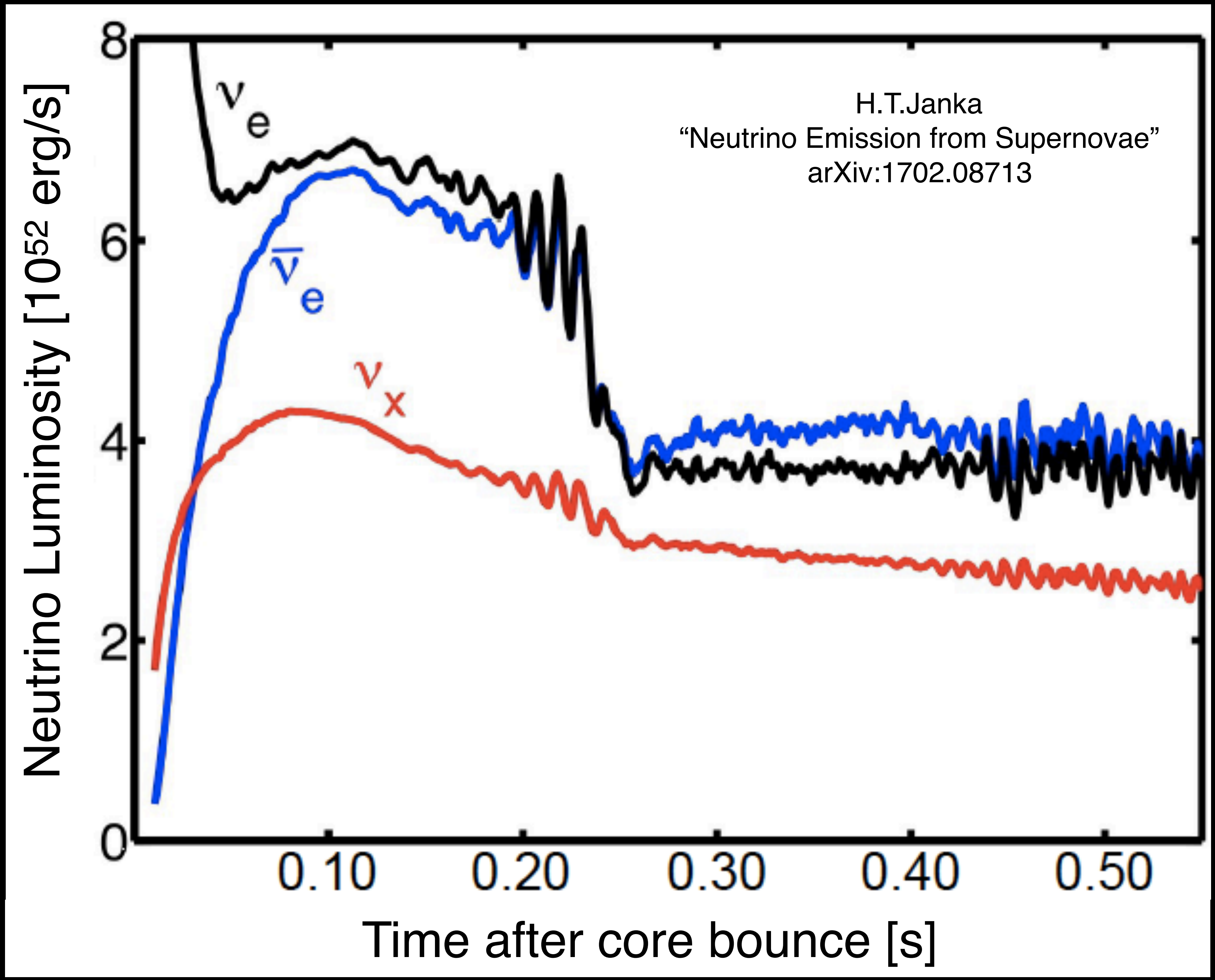
Hypothesis 2

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

More refined simulations will give the answer

Multi-D neutrino signal features

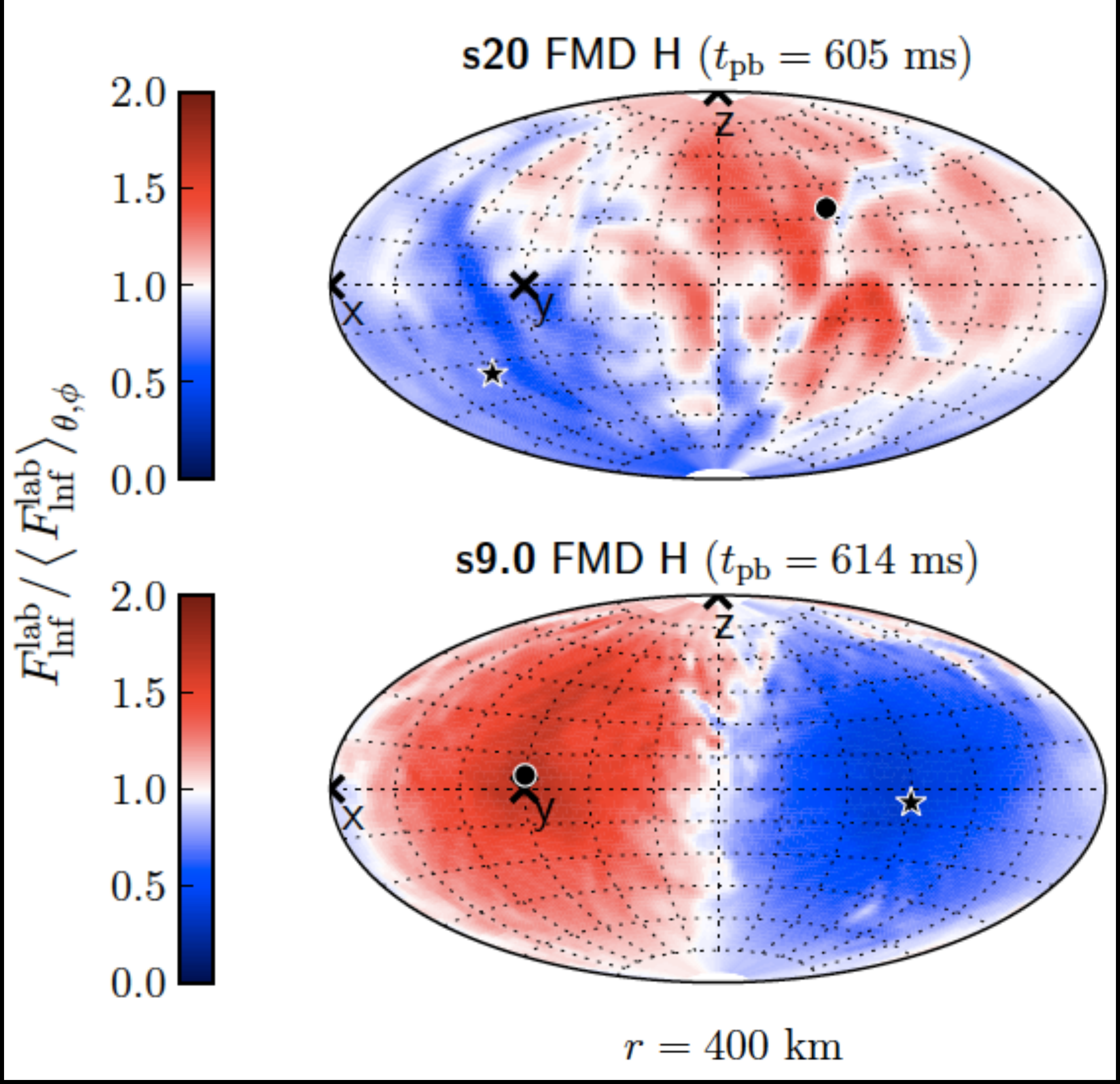
Sloshing/spiraling (SASI) motion of the shock modulates L_ν



Neutrinos are probe of the explosion mechanism

Multi-D neutrino signal features

Lepton number is emitted asymmetrically (LESA)



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

confirmed by

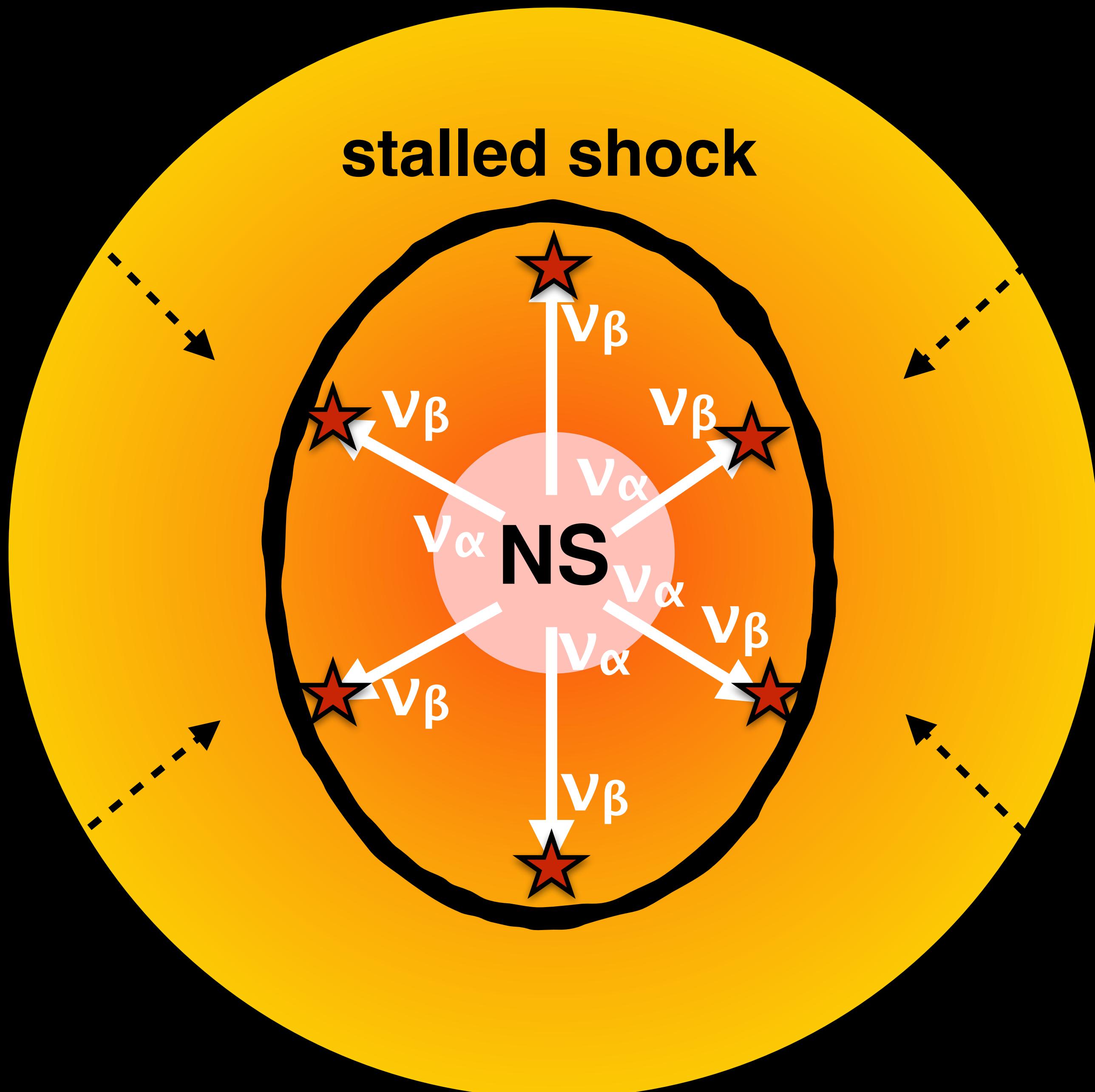
O'Connor and Couch, Astrophys. J. 865 (2018) no.2, 81

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**



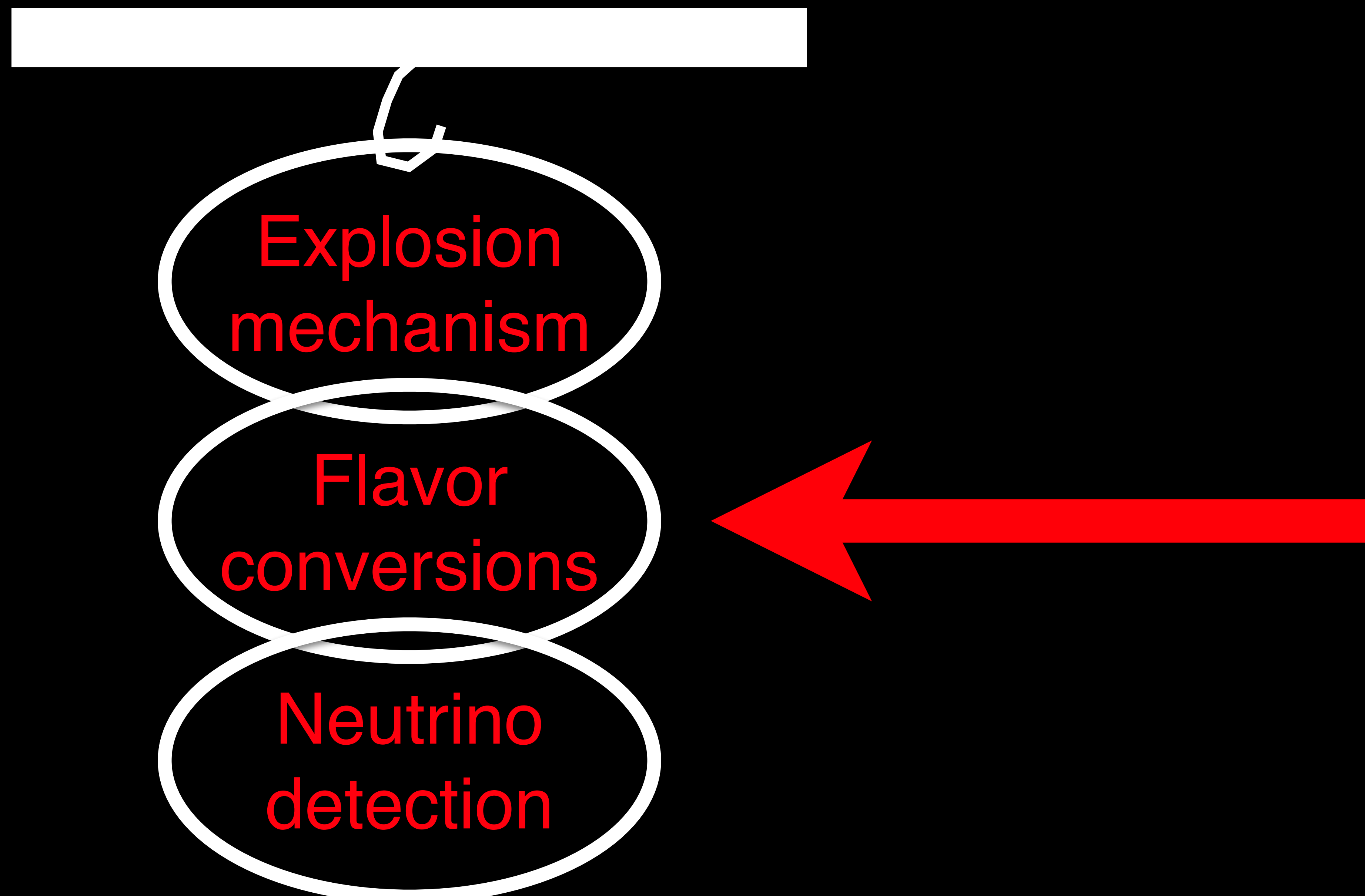
★ $\nu_e + n \longrightarrow e^- + p$

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

Neutrino heating is flavor dependent!!!

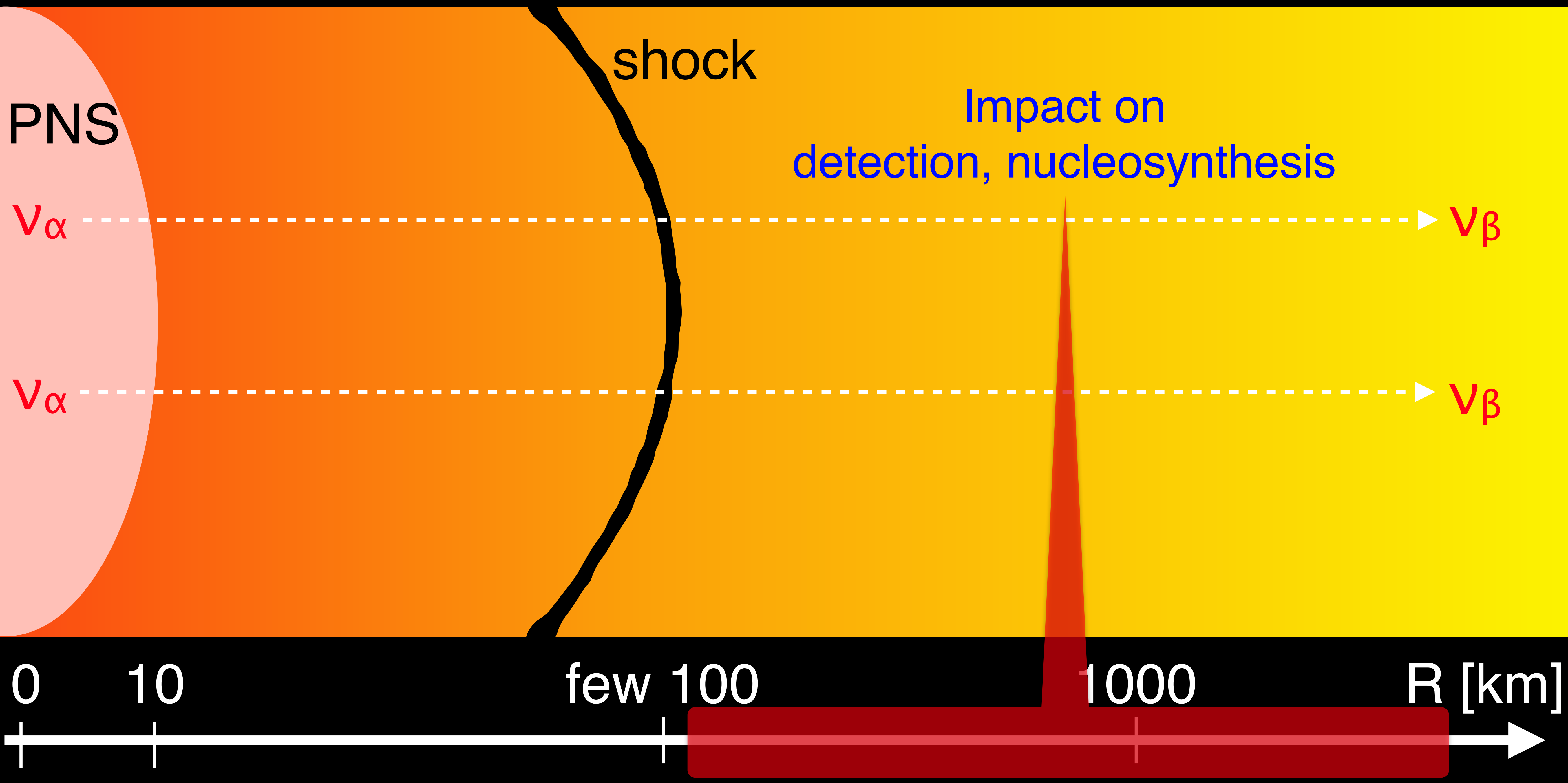
Are we ready for SN20xy?

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

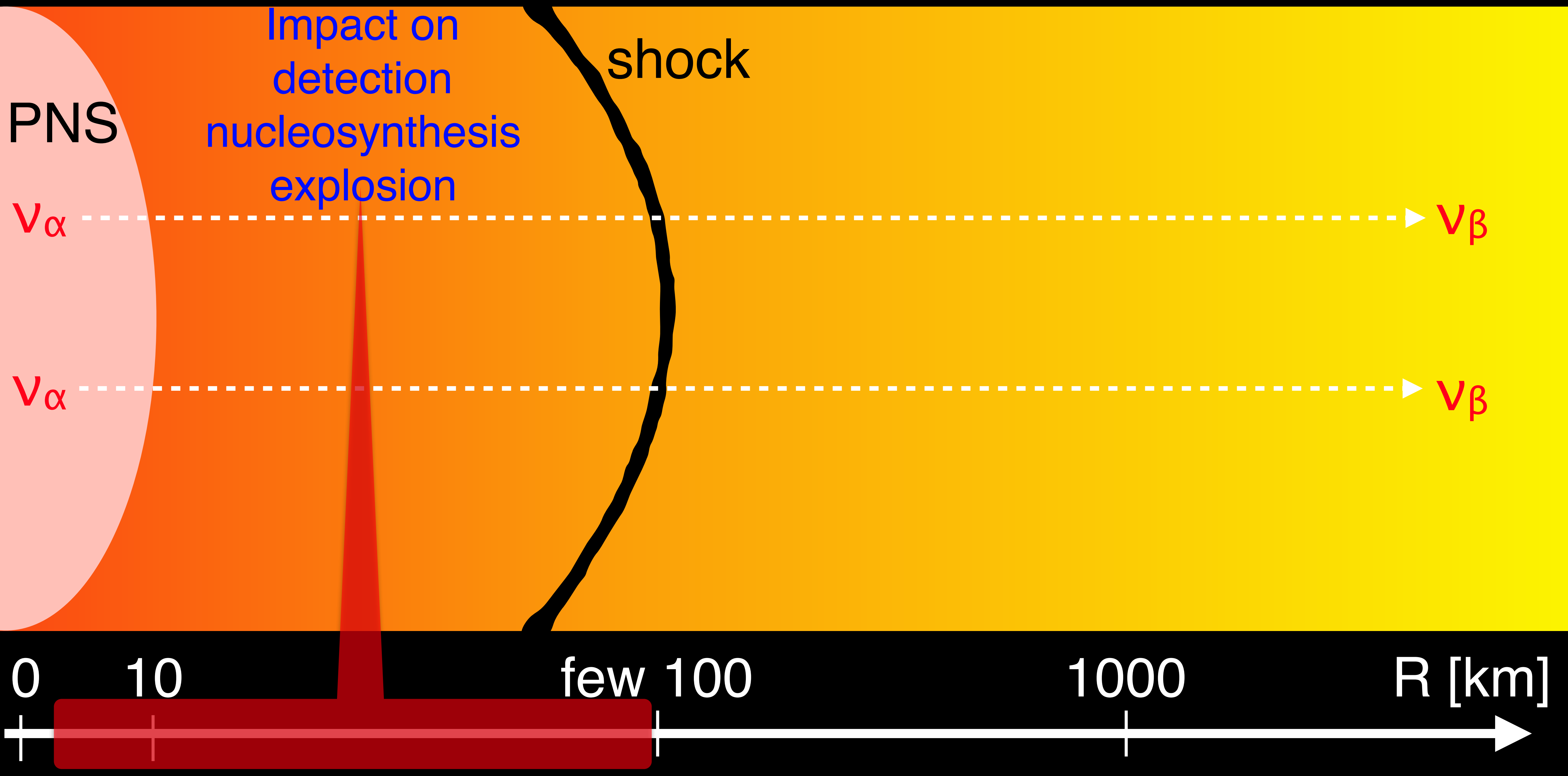


We review the status of each step in the chain

Flavor conversions: overview

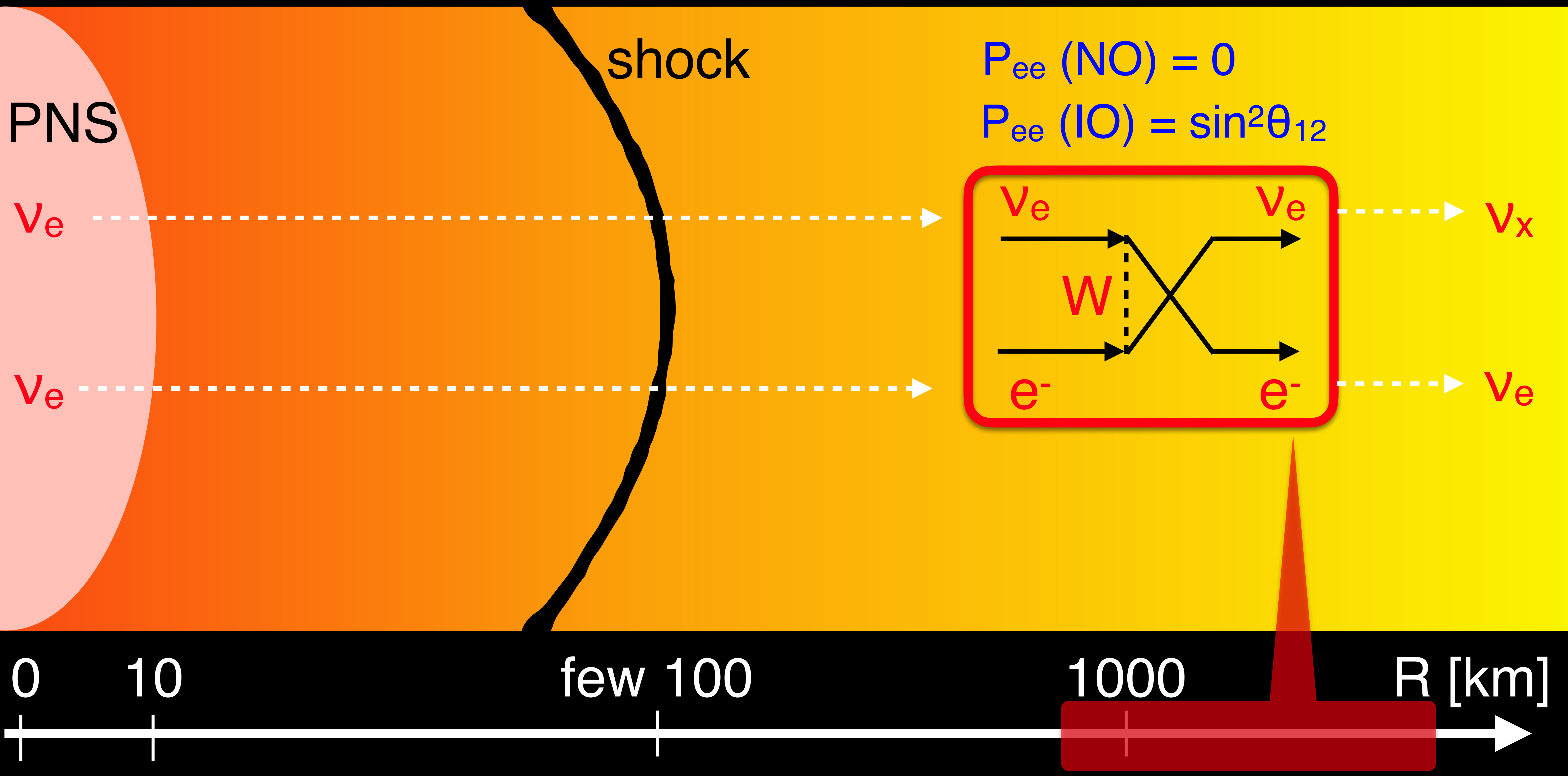


Flavor conversions: overview



MSW resonance

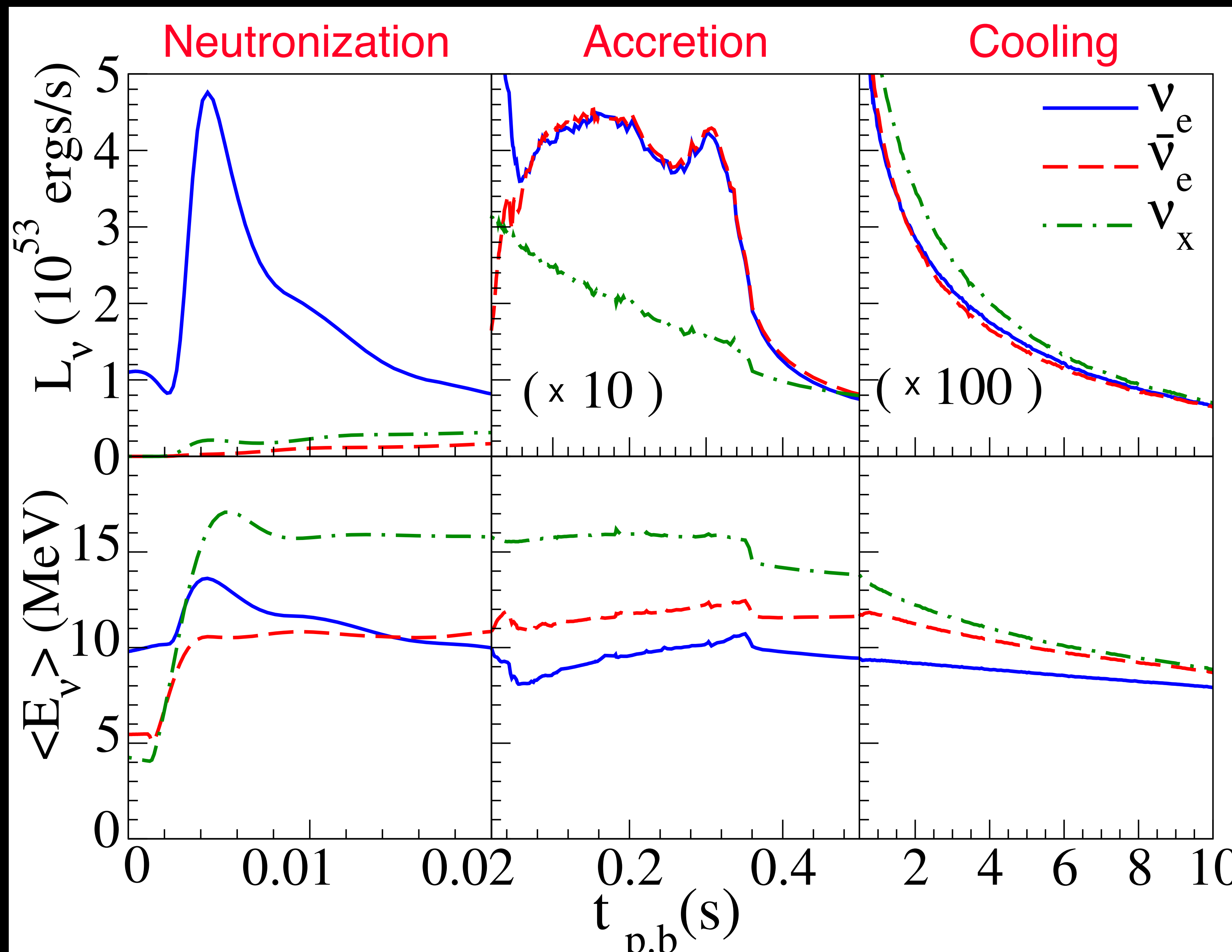
Well known MSW resonances happening in the outer layers



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

MSW resonance

When does it happen?

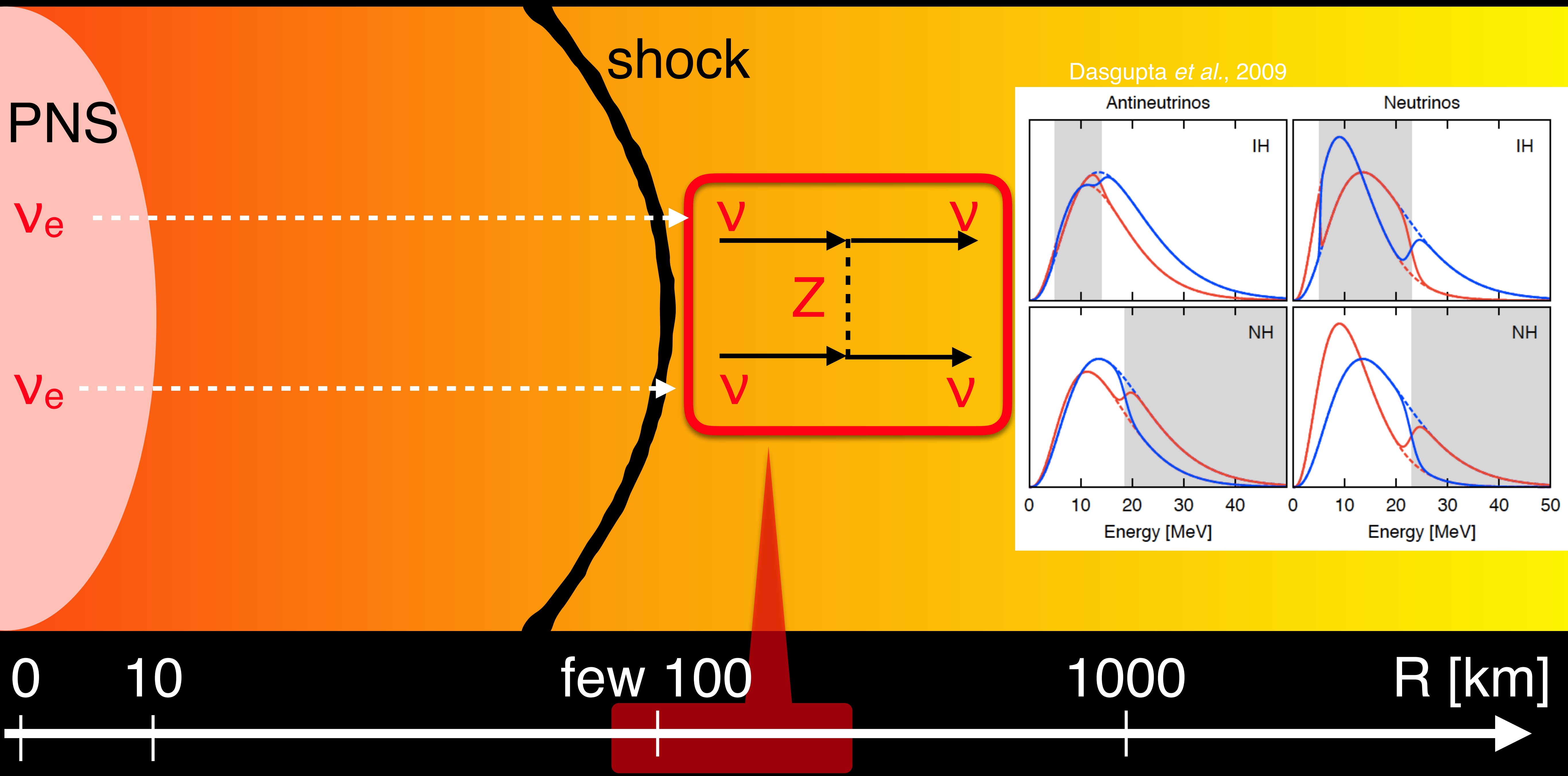


Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011

T. Fischer et al, Astron. Astrophys. 517, A80 (2010)

Self induced flavor conversion

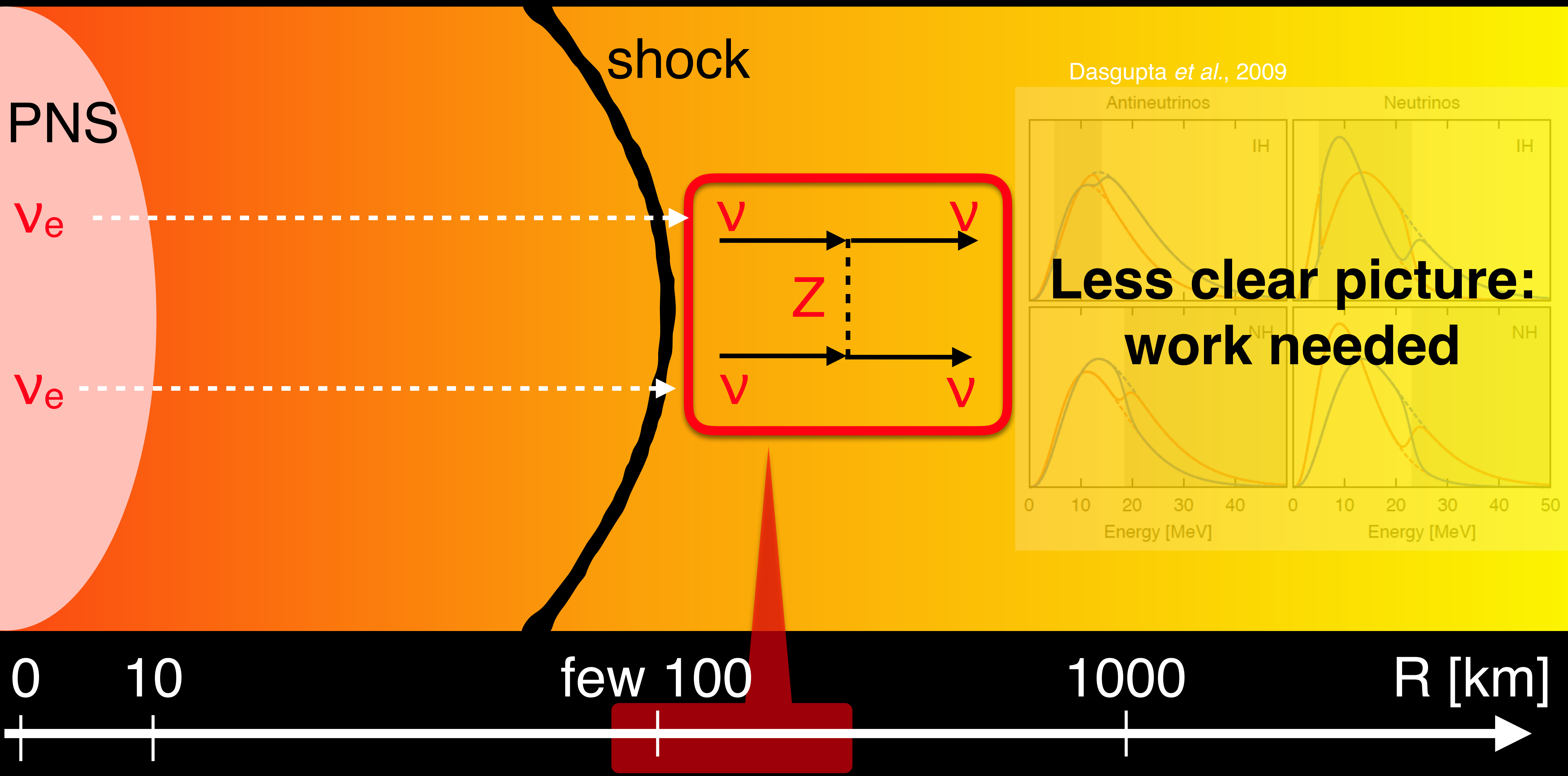
νν interactions are relevant: spectral splits?



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

Self induced flavor conversion

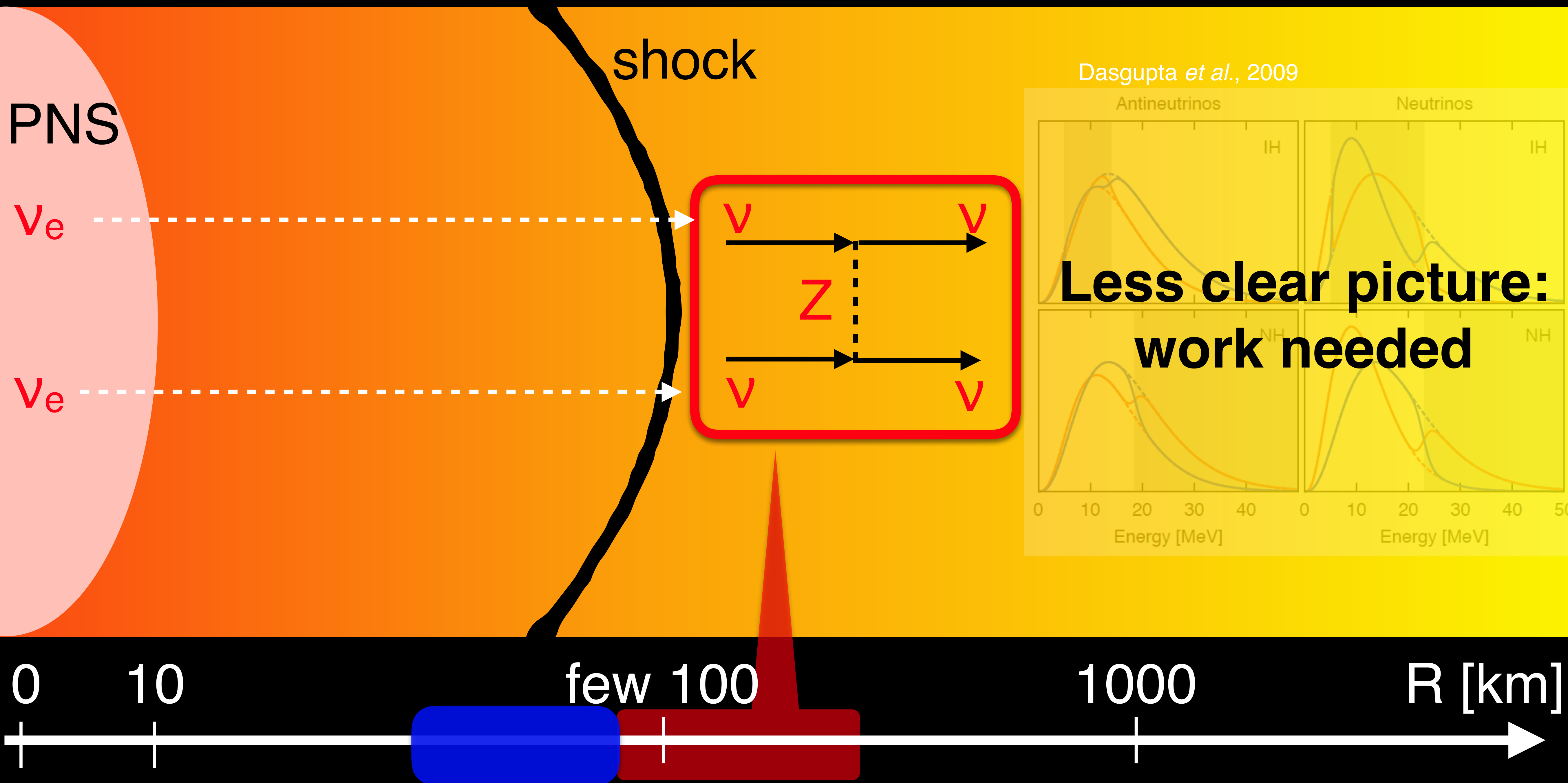
Instability under tiny space inhomogeneities: decoherence?



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

Self induced flavor conversion

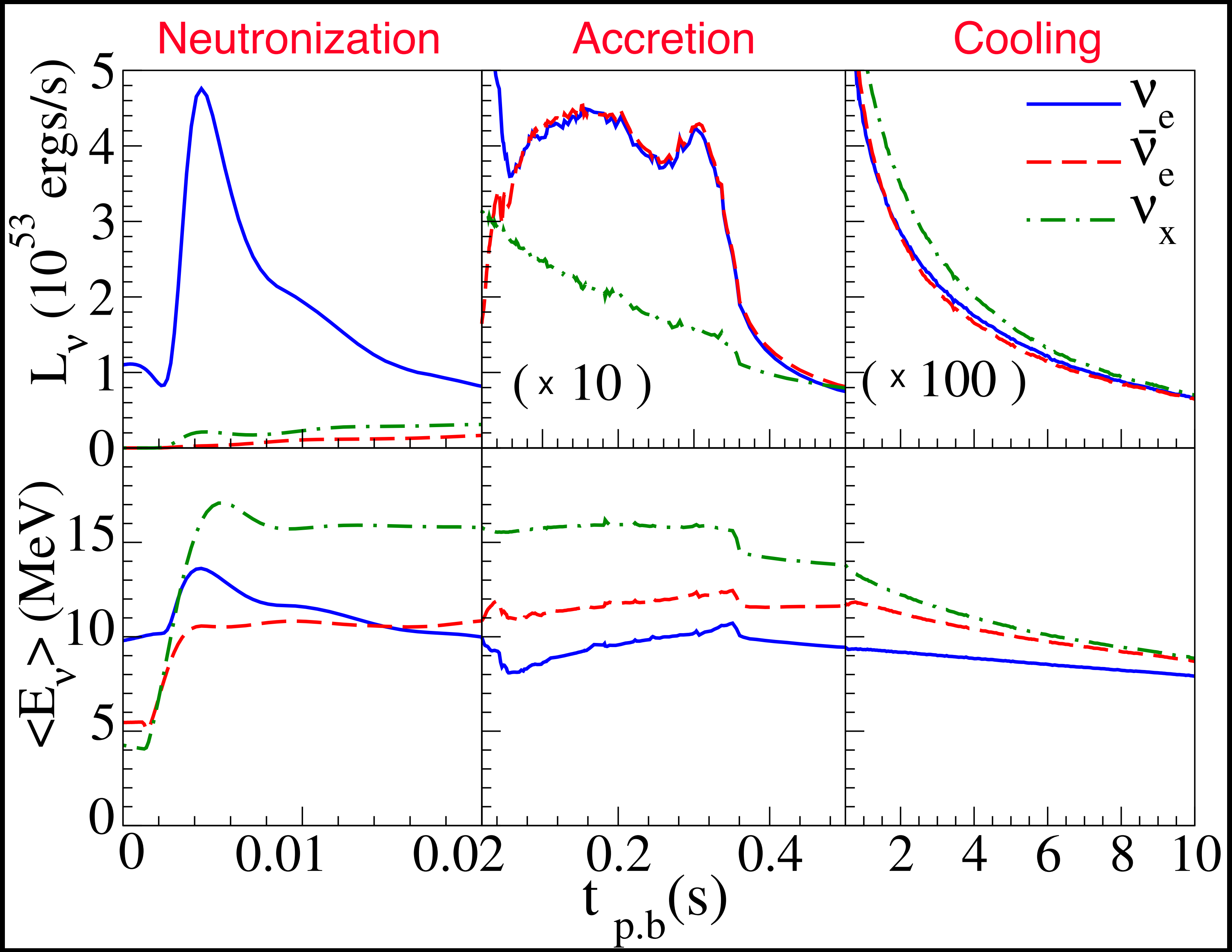
Time instabilities avoid matter suppression?



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

Self induced flavor conversion

When does it happen?

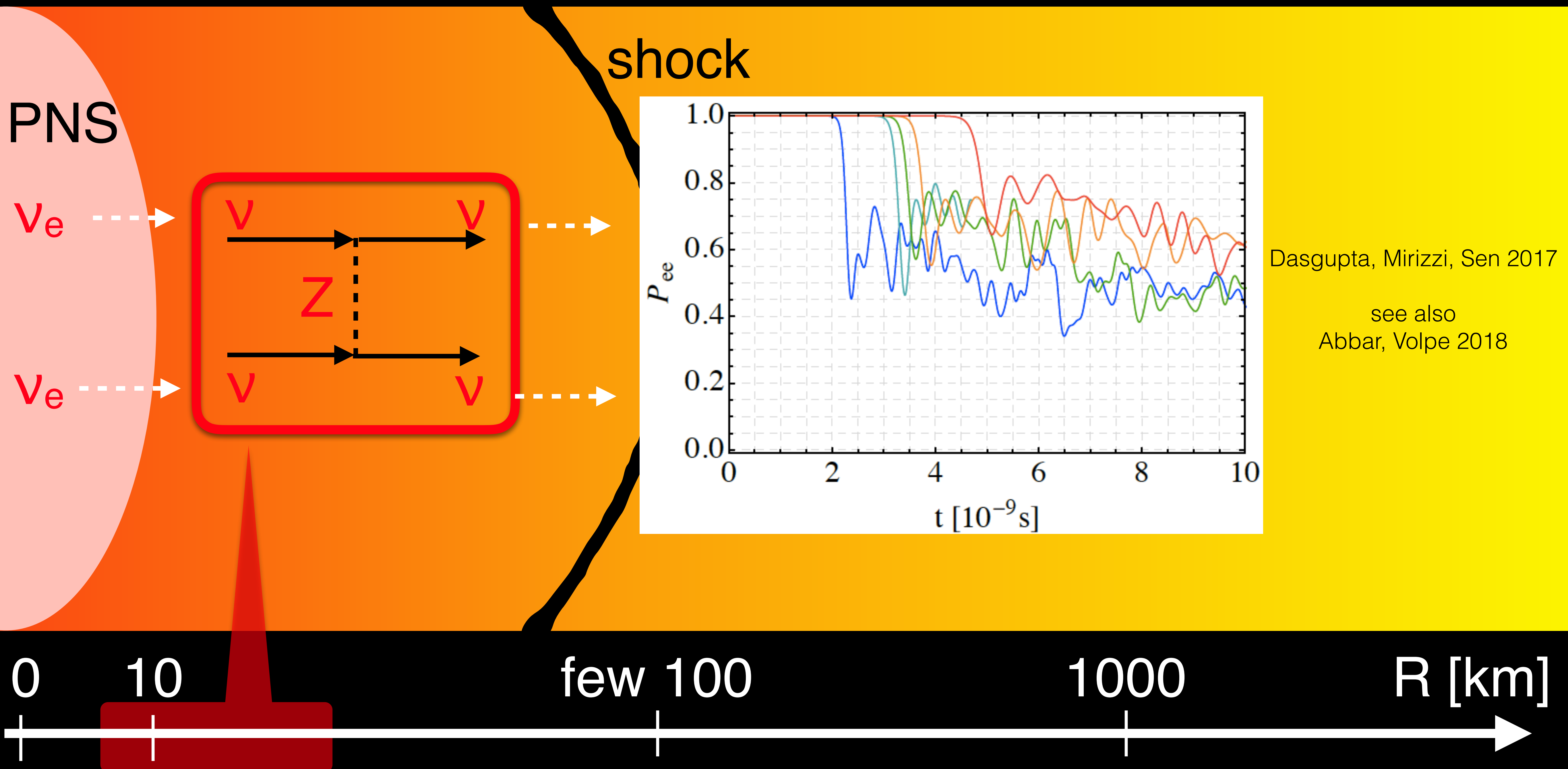


Chakraborty, Bhattacharjee, Kar,
Phys. Rev. D 89 (2014) no.1, 013011

T. Fischer et al,
Astron. Astrophys. 517, A80 (2010)

Fast self induced flavor conversion

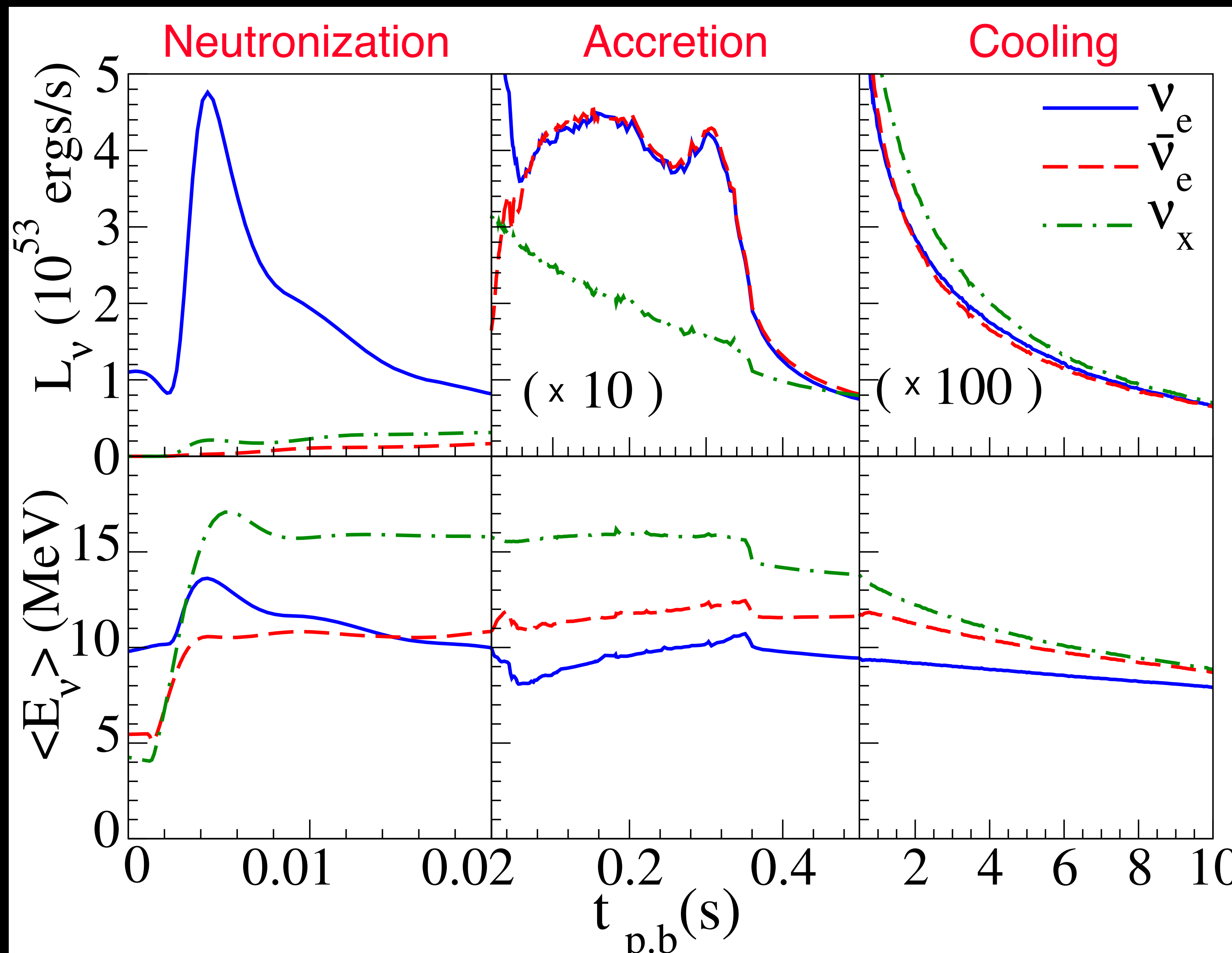
Mixing independent, driven by νν potential: fast decoherence?



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

Self induced flavor conversion

When does it happen?

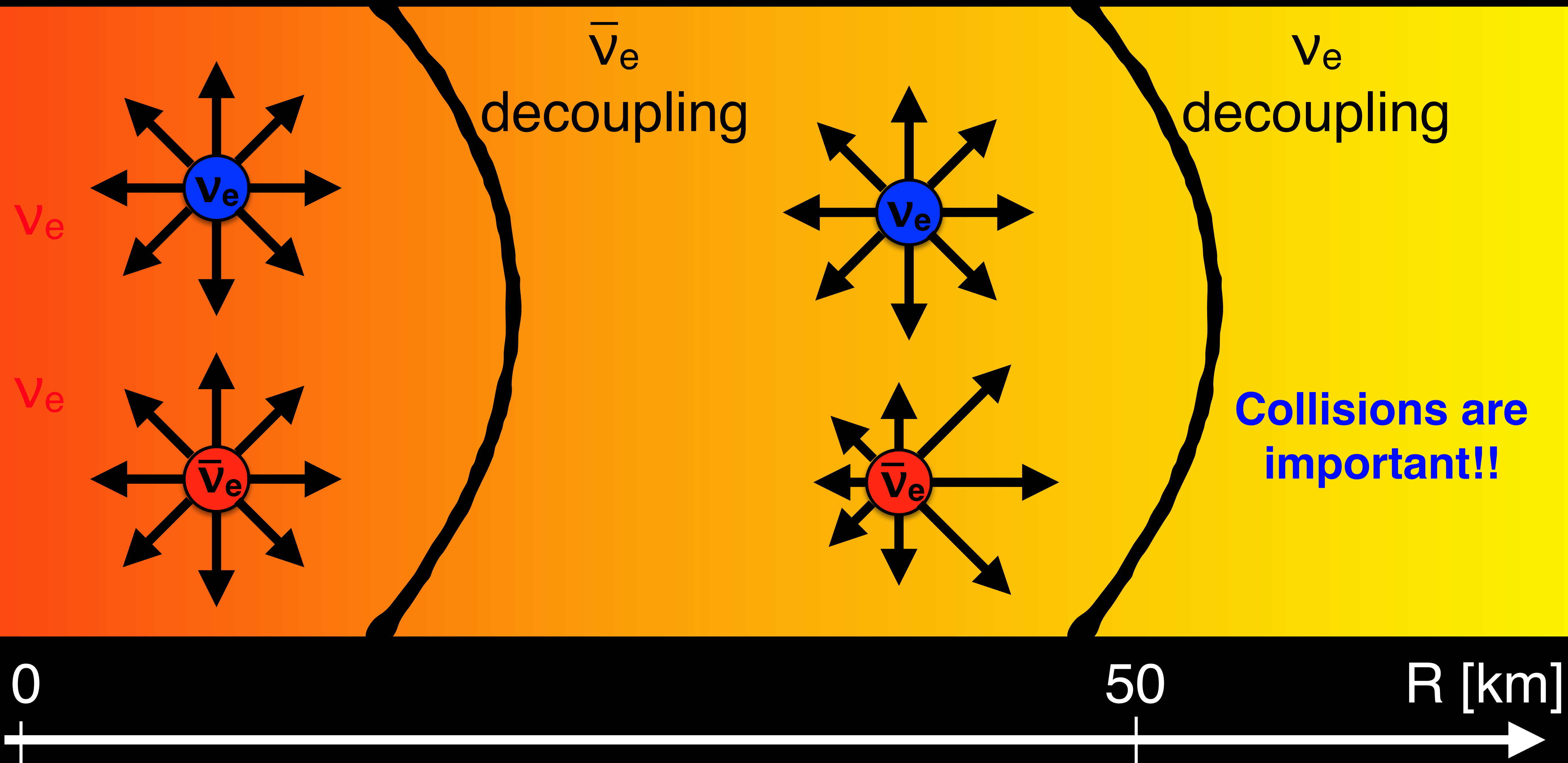


Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011

T. Fischer et al, Astron. Astrophys. 517, A80 (2010)

Fast self induced flavor conversion

Main requirement for **FAST** conversions: **angular crossing**

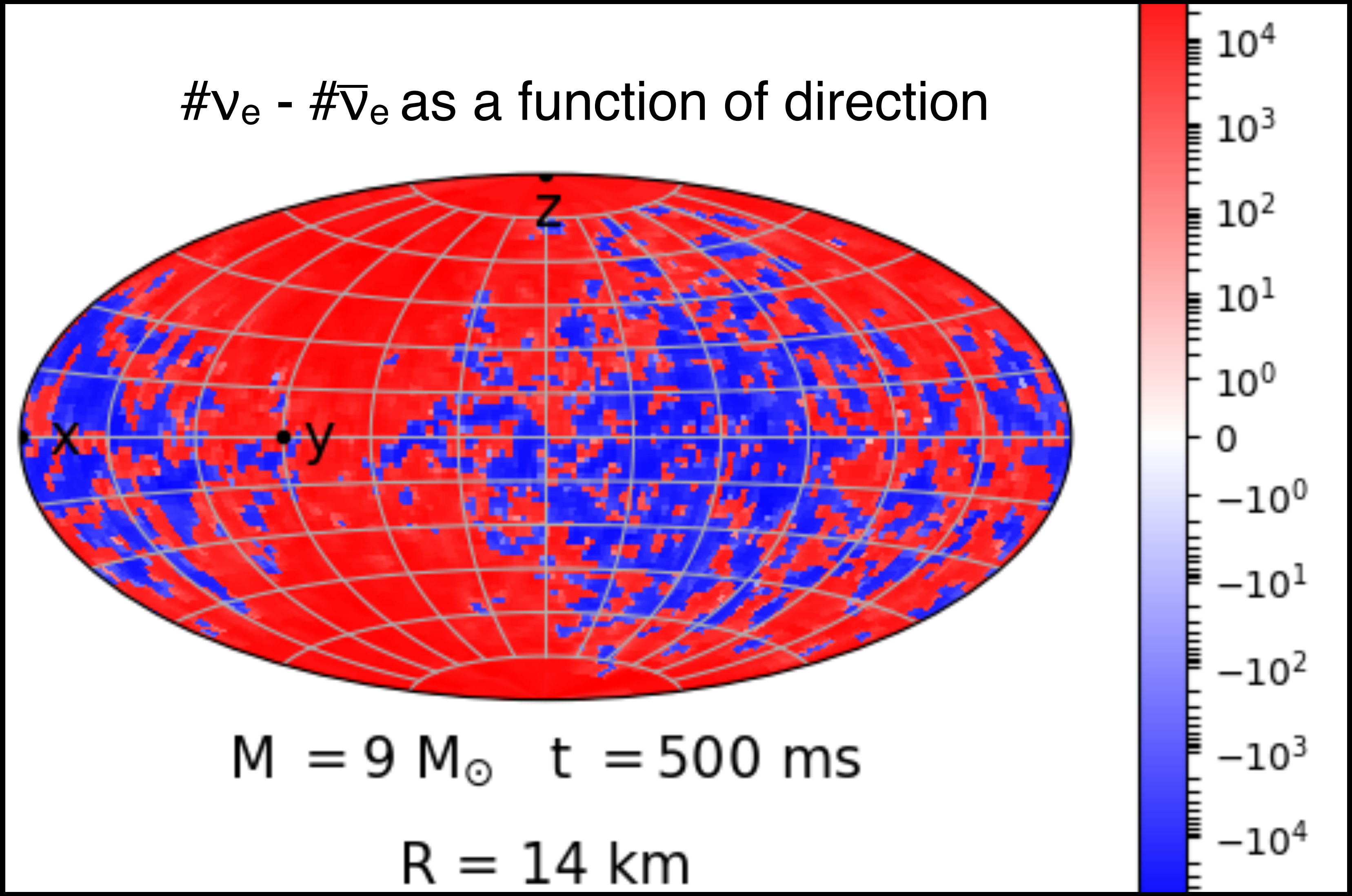


Izaguirre, Raffelt, Tamborra 2016, **Capozzi**, Dasgupta, Lisi, Marrone, Mirizzi 2017, Abbar, Duan 2017, **Capozzi**, Dasgupta, Mirizzi, Sen, Sigl 2018, Shalgar, Tamborra 2018, ...

Fast self induced flavor conversion

Are supernovae simulations showing any sign of crossing?

Capozzi, Dasgupta, Glas, Janka, Mirizzi, Sen, Sigl, in preparation



see also

Tamborra, Huedepohl, Raffelt, Janka, 2017

Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018

Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019

Morinaga, Nakagura, Kato, Yamada, 2019

More work needed for a conclusive assessment

Fast self induced flavor conversion

Assuming they occur, what is their impact on the explosion?

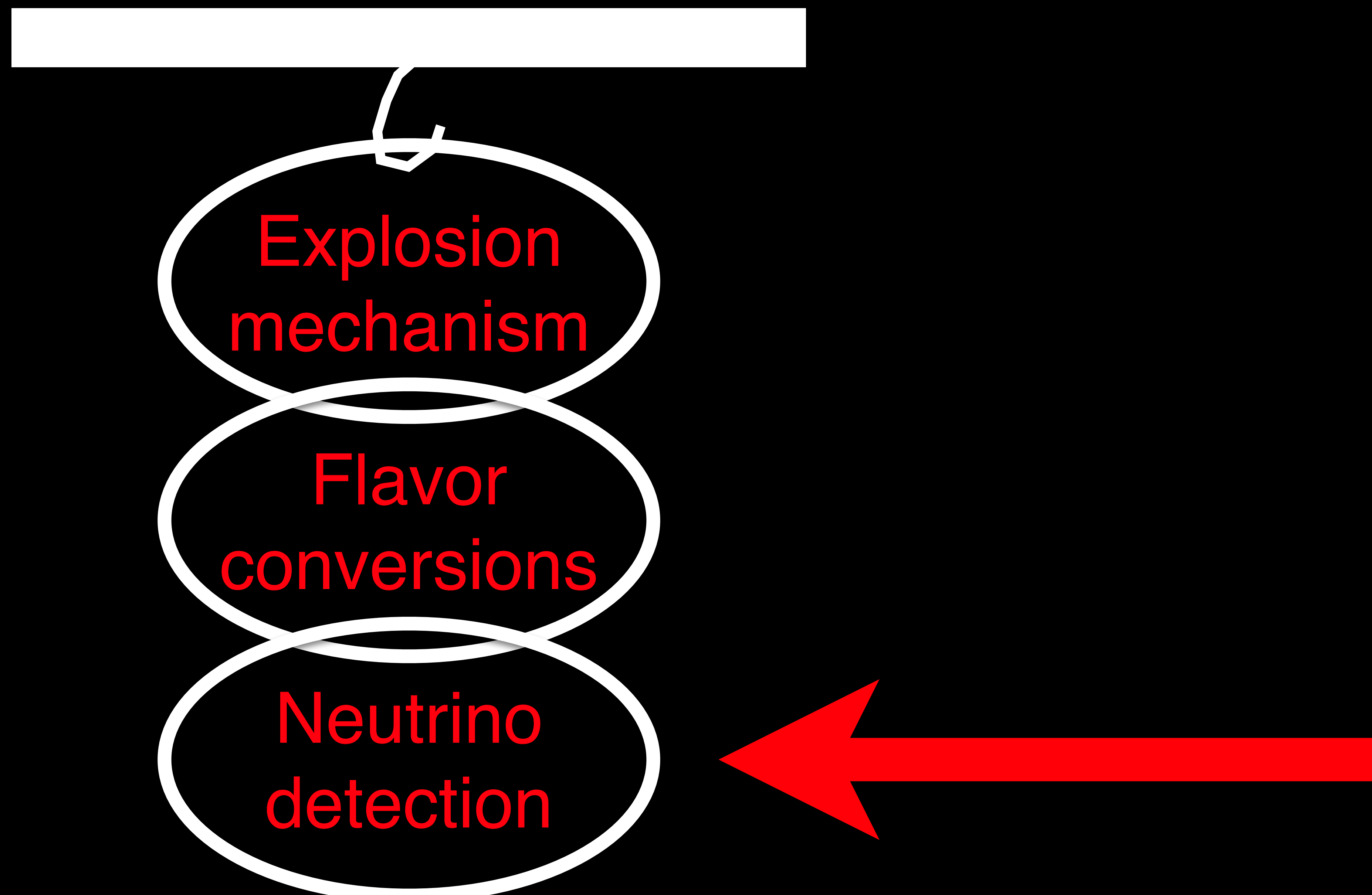
$$\frac{T_{simul}}{T_{conv}} \sim \frac{10^{-3}\ s}{10^{-9}\ s}$$

Very challenging numerically. Effective approach?

see Richers, McLaughlin, Kneller, Vlasenko 2019

Are we ready for SN20xy?

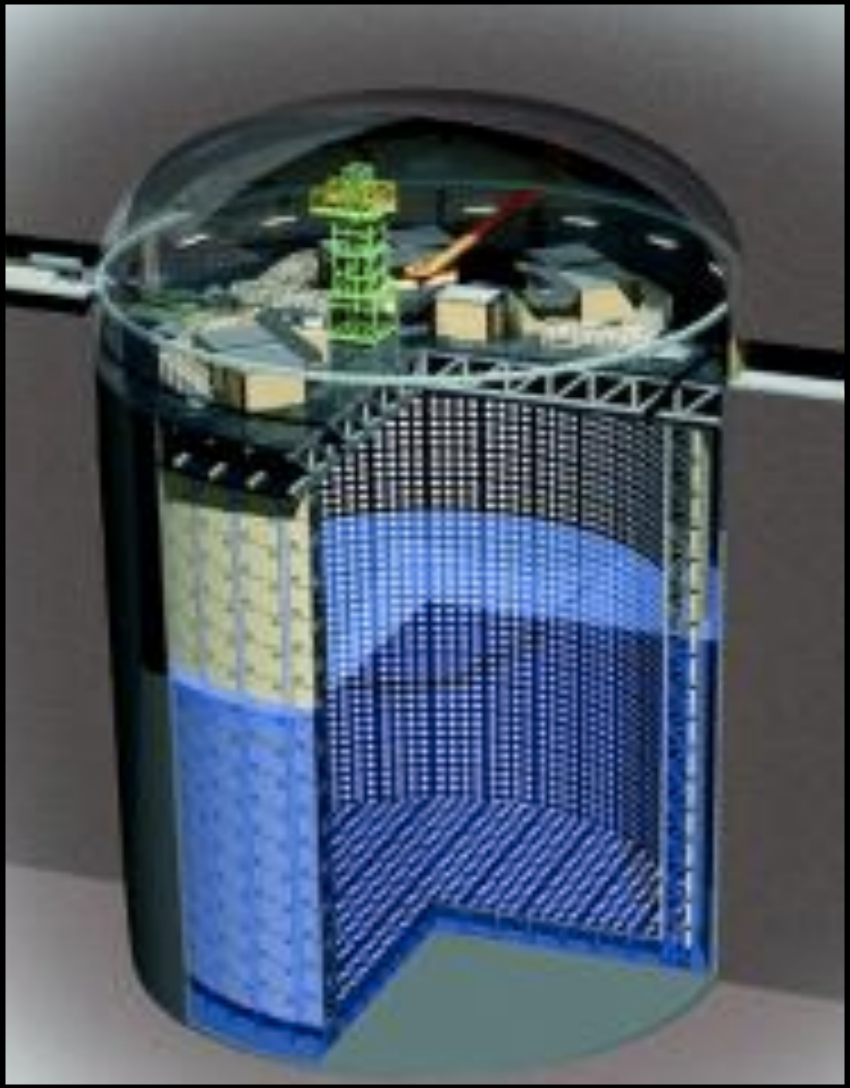
Each aspect of the chain to **MUST** be well understood



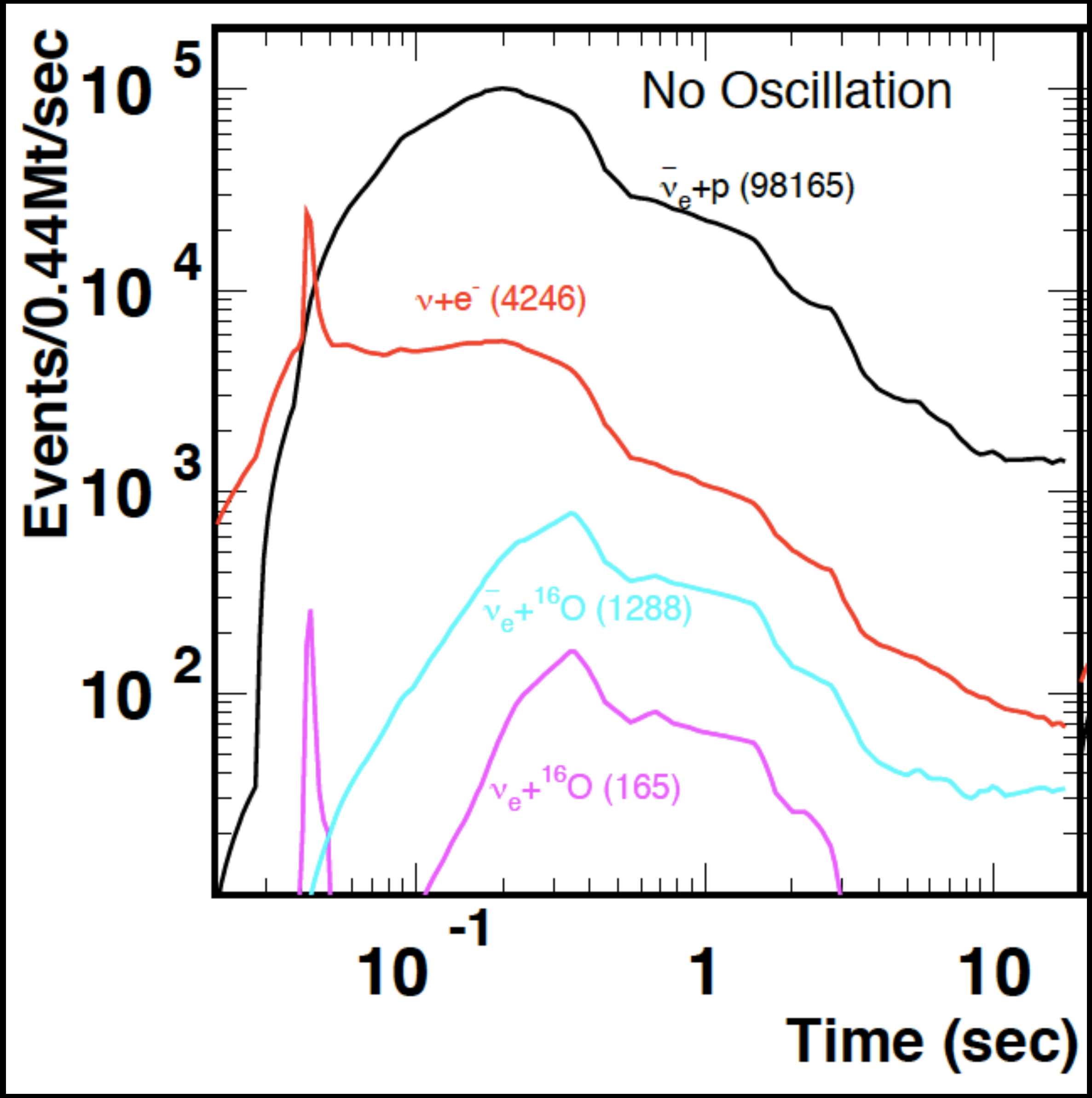
We review the status of each step in the chain

Water Cherenkov

SuperK (32 kton): main channel IBD



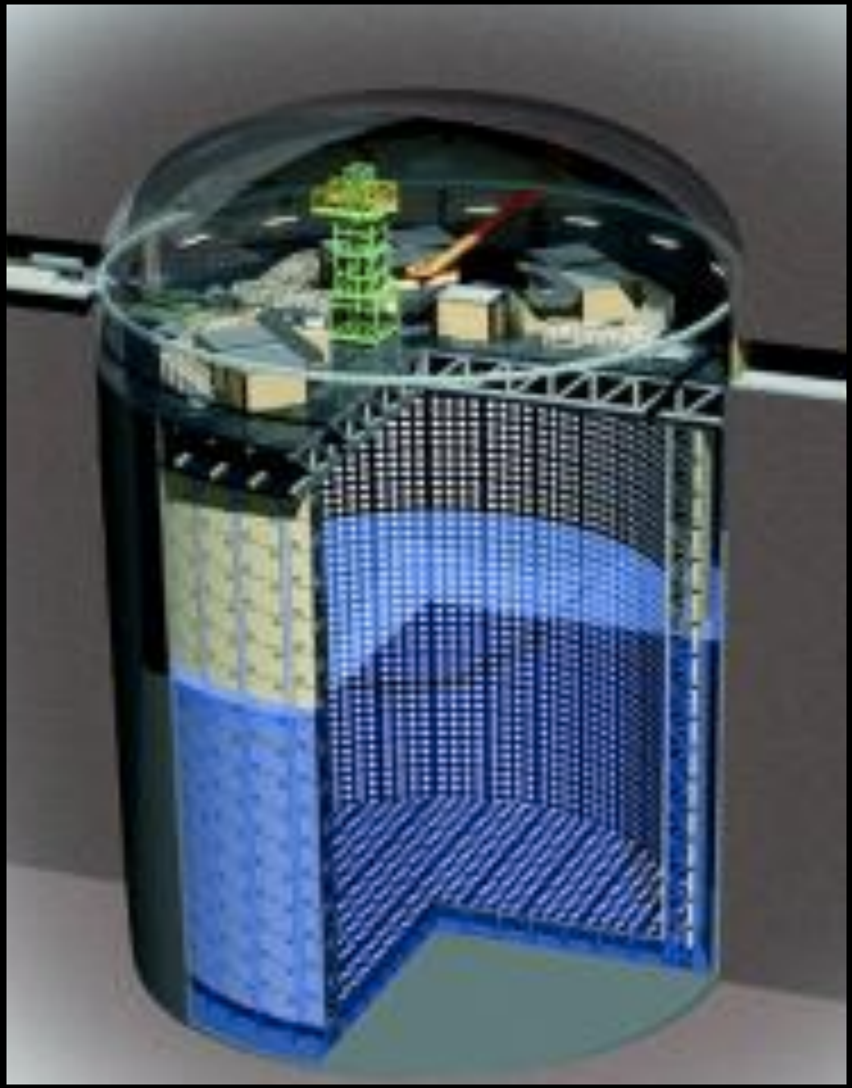
Hyper-Kamiokande Collaboration, ``Hyper-Kamiokande Design Report,''



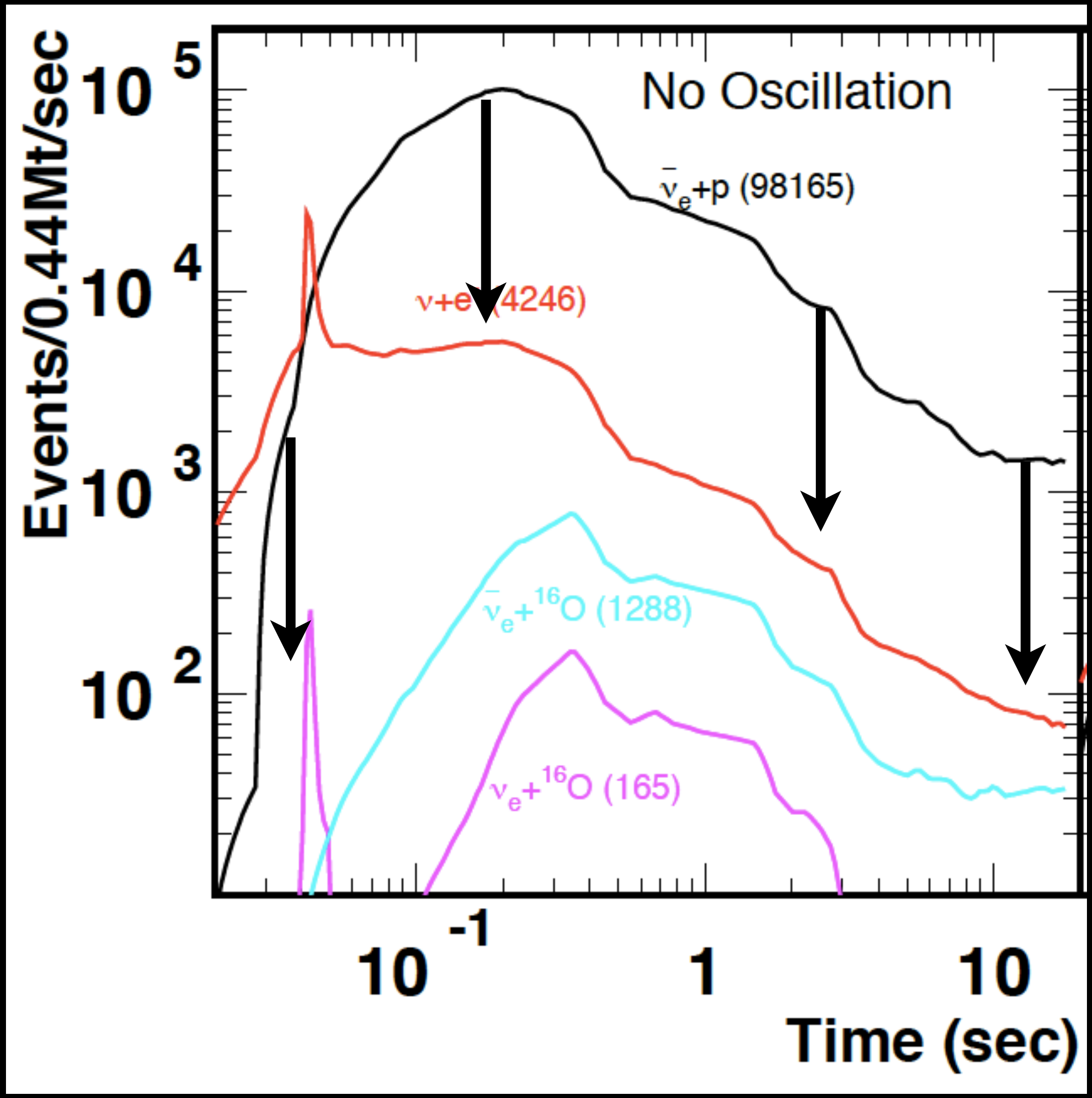
Very precise measurement of $\bar{\nu}_e$, both time and energy

Water Cherenkov

SuperK + Gd (2021): 90% tagging of $\bar{\nu}_e$



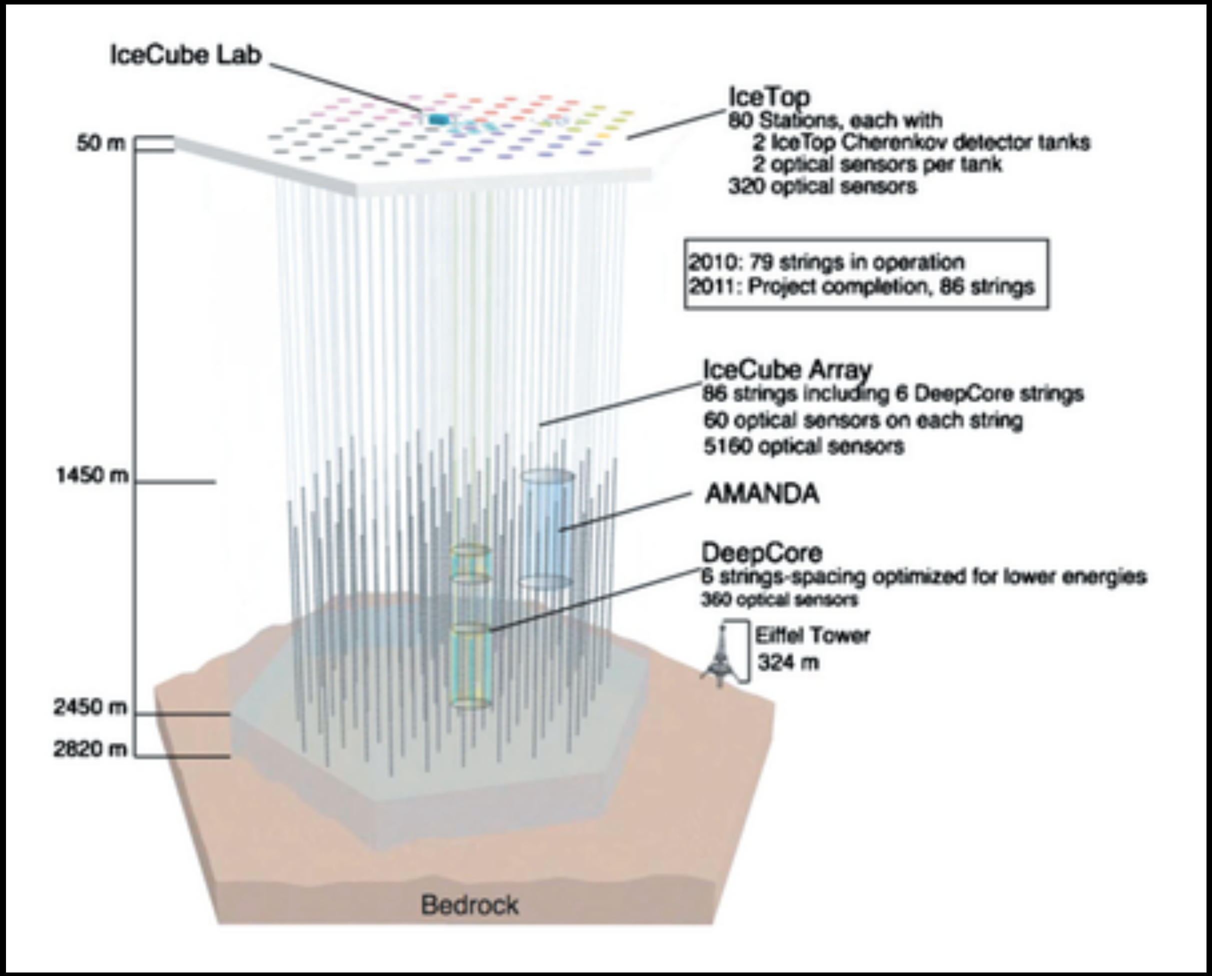
Hyper-Kamiokande Collaboration, ``Hyper-Kamiokande Design Report,''



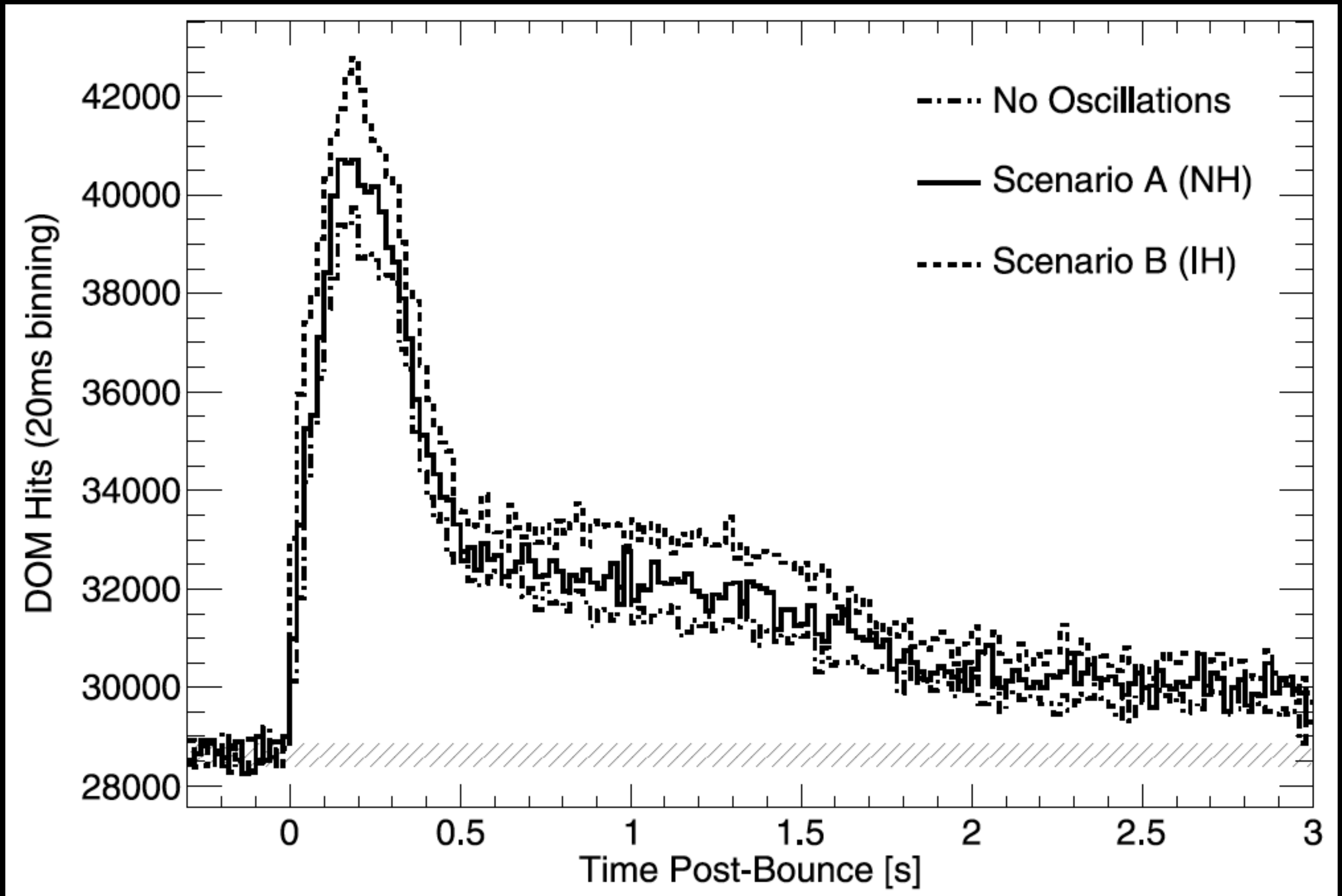
ν_e becomes accessible (~100 events)

Water Cherenkov

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



R. Abbasi et al., Astron. Astrophys. 535 (2011) A109

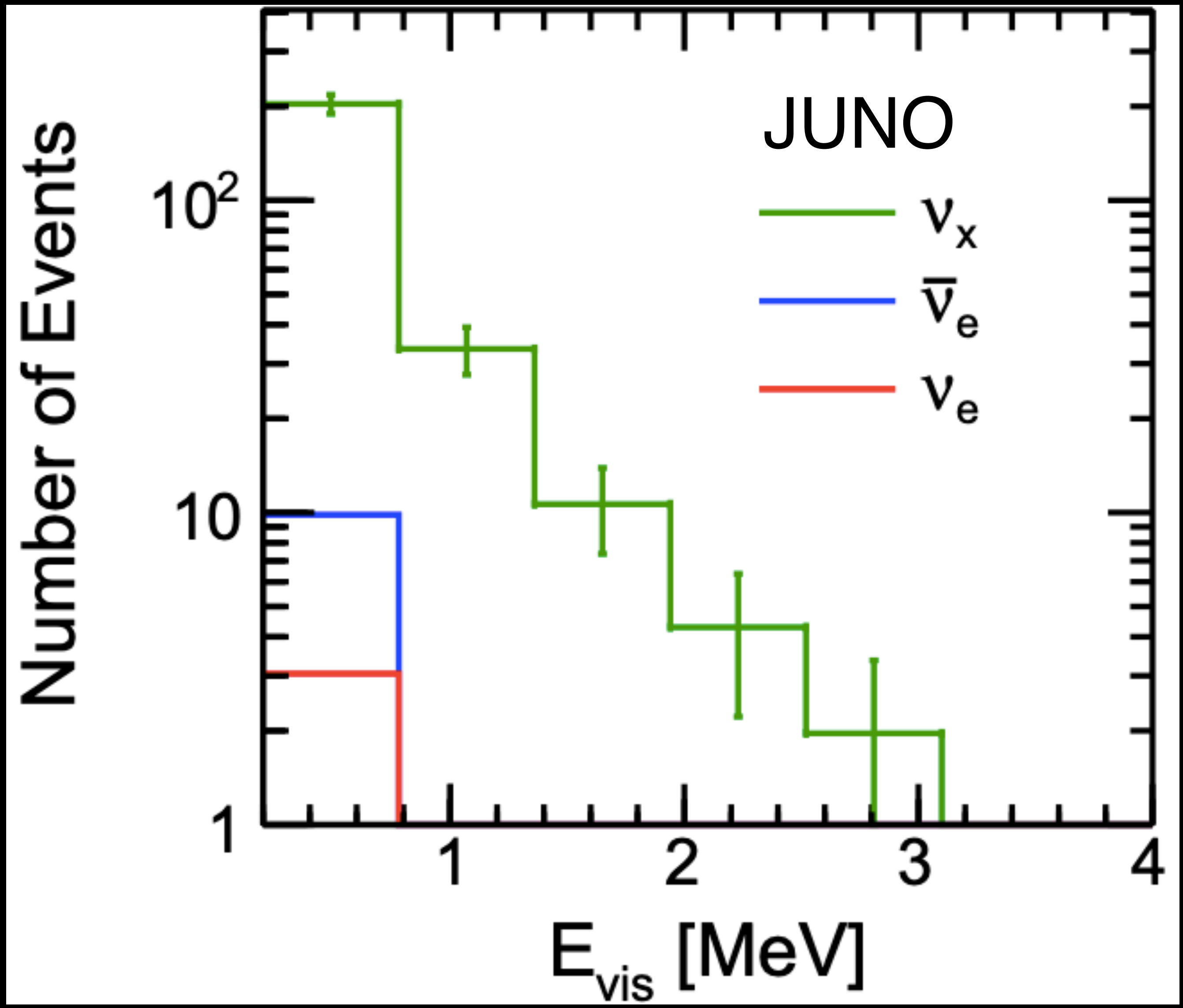


Most precise for studying temporal evolution (SASI,…)

Liquid scintillator

Low threshold allows sensitivity for ν-proton elastic scattering

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

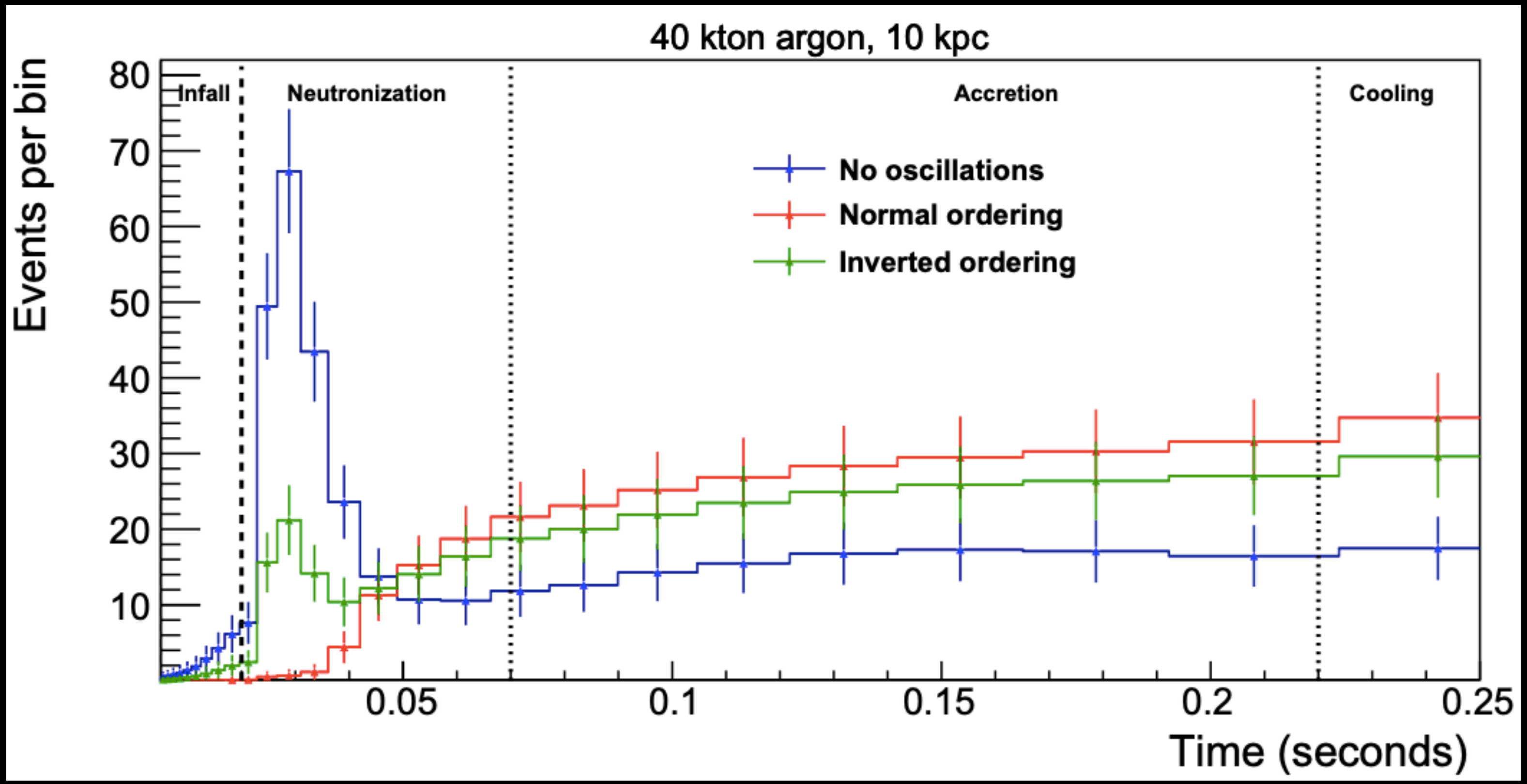


Unique probe for ν_x

Liquid Argon

Dominant channel: $\nu_e + {}^{40}Ar \longrightarrow e^- + {}^{40}K^*$

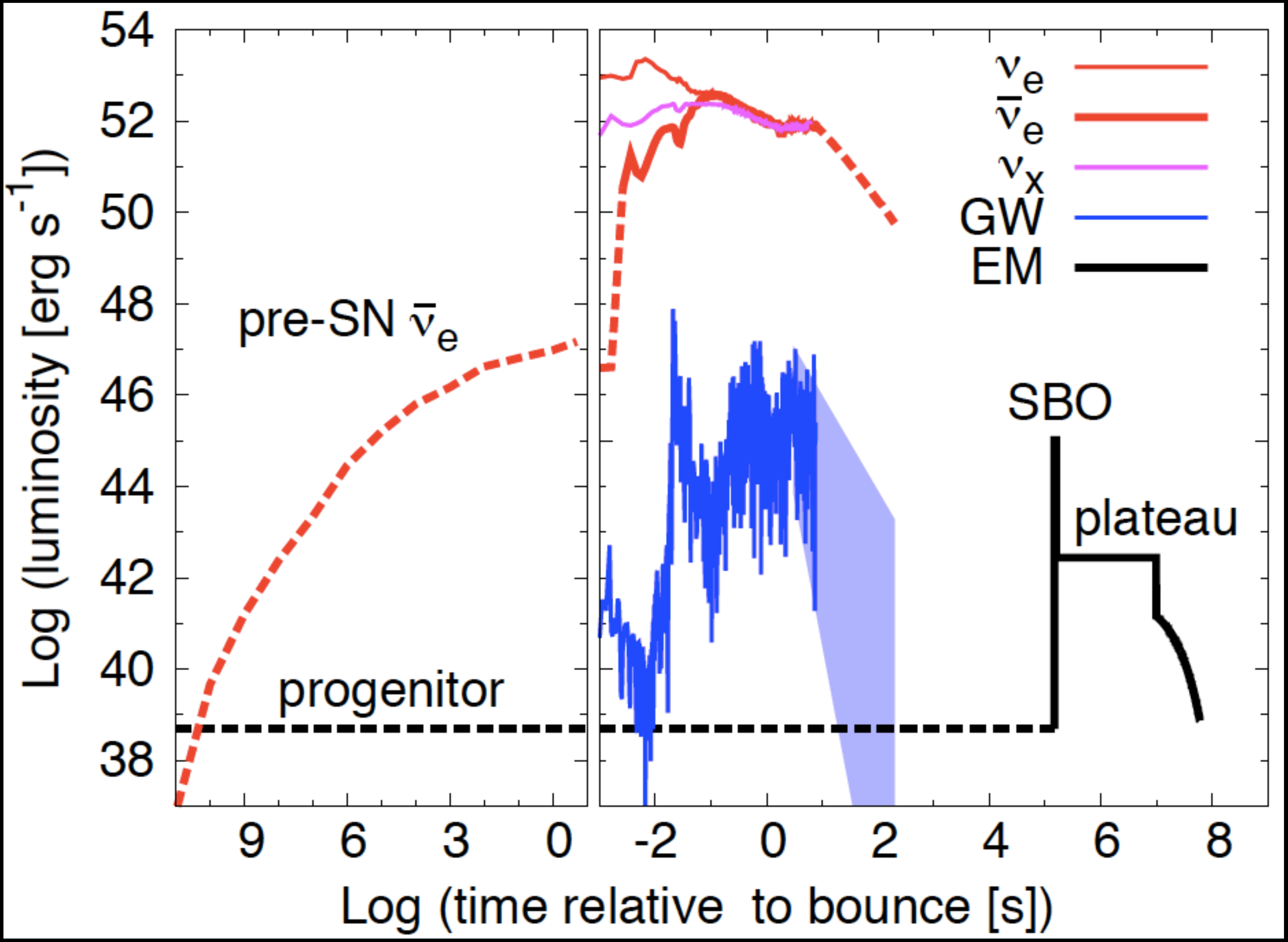
Jost Migenda, talk at Nuphys 2017



Best precision on ν_e (need improvements on cross section)

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

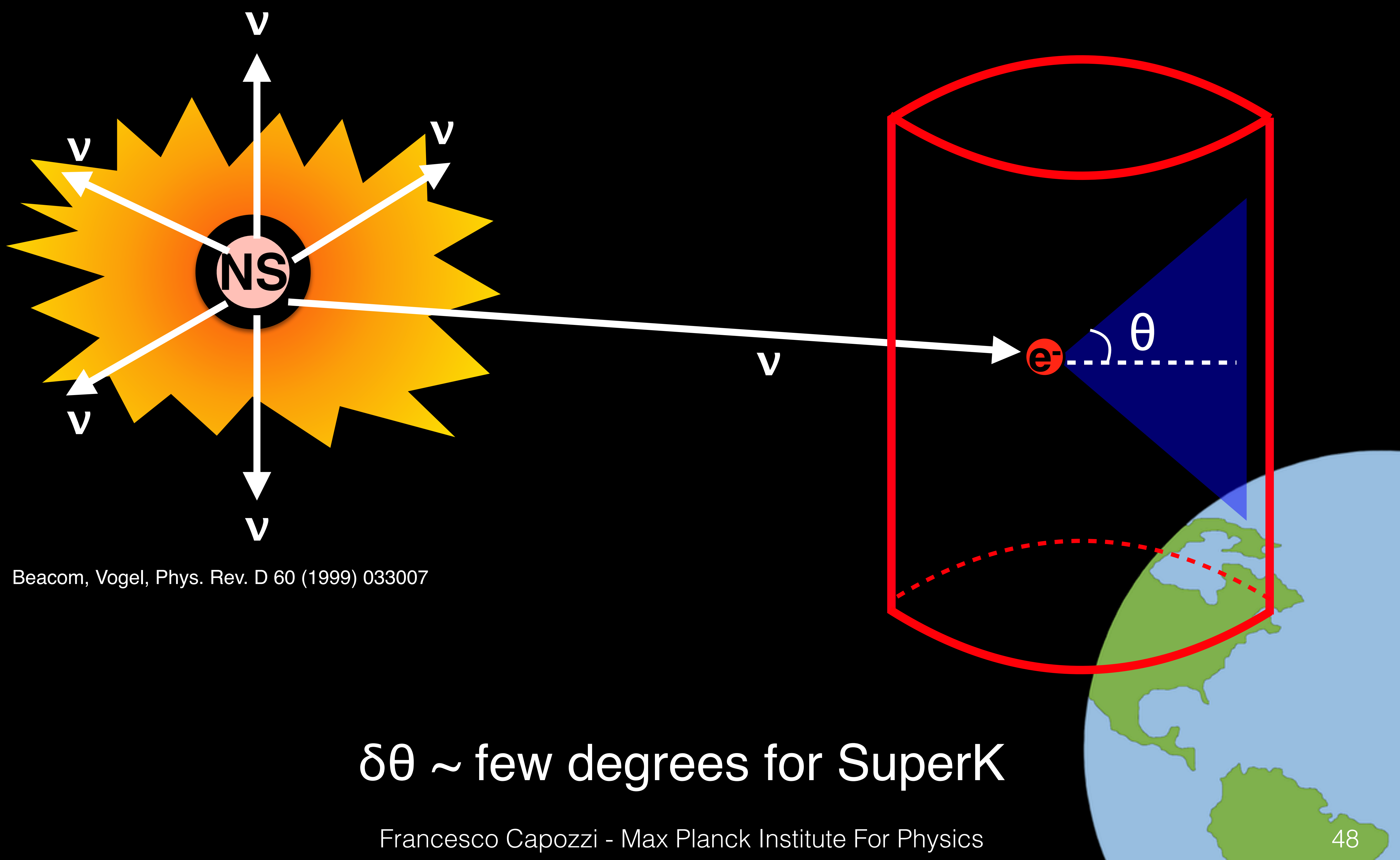
Liquid Scintillator

Liquid Argon

Telescopes LIGO,VIRGO, ...

Multi-messenger

Neutrino pointing help light collection in telescopes



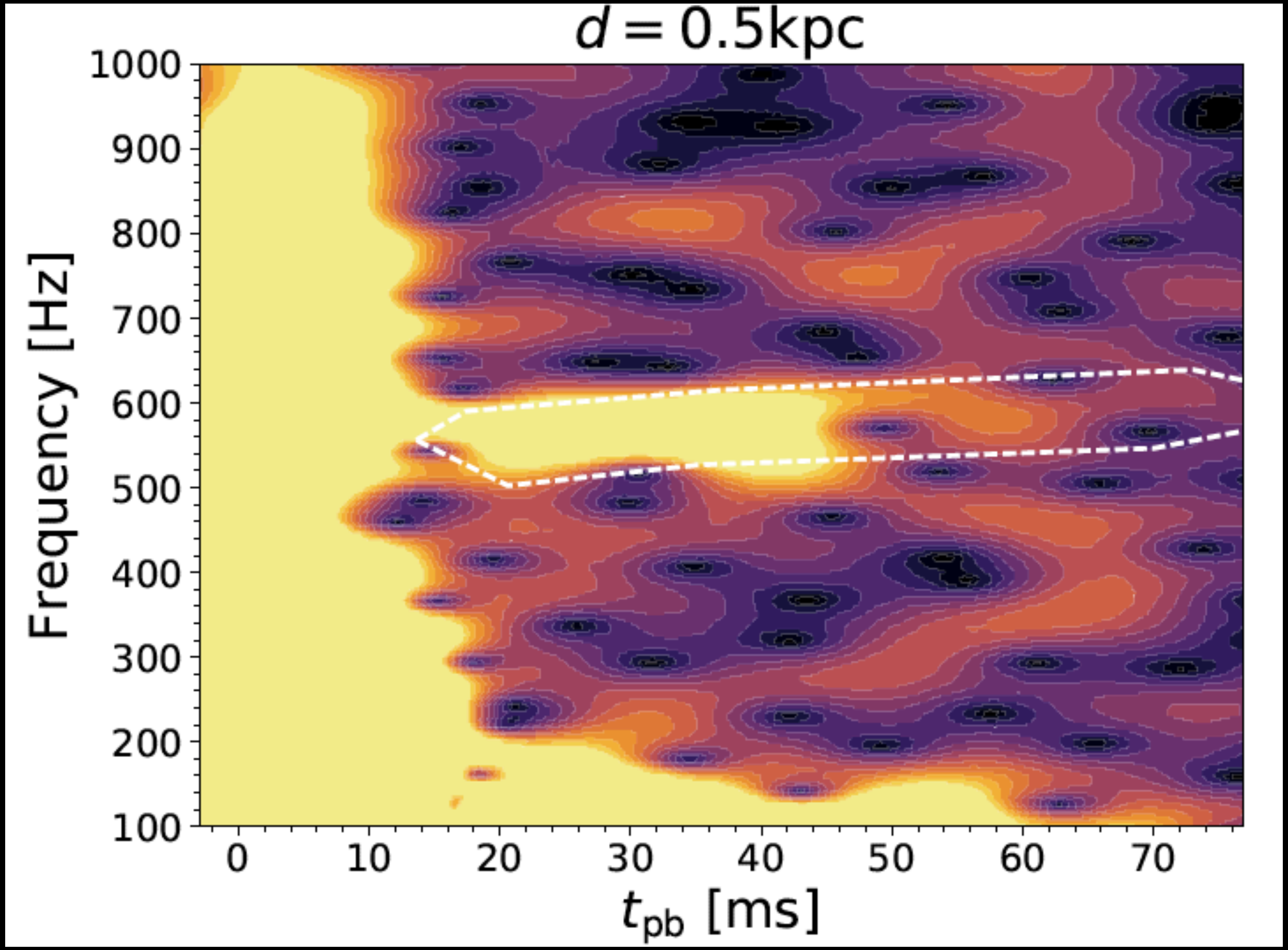
Beacom, Vogel, Phys. Rev. D 60 (1999) 033007

$\delta\theta \sim$ few degrees for SuperK

Multi-messenger

Neutrinos and GW carry important information from the PNS

Westernacher-Schneider, O'Connor, O'Sullivan, Tamborra, Wu, Couch and Malmenbeck, arXiv:1907.01138



Oscillation modes (asteroseismology) can be probed

Conclusions

- A lot of progress made so far, but still plenty of work ahead

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- Everything is equally important: explosion, flavor, detection

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- **ν** + GW + γ are the key for a full understanding

Thank you