Understanding the dynamics of core-collapse supernovae through neutrinos

Brookhaven Neutrino Theory
Virtual Seminars

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July 13, 2020

Outline

- **Neutrinos from supernovae**

- **Neutrinos as probes:**
  - Hydrodynamical instabilities:
    - Convection
    - SASI
    - LESA
  - Progenitor rotation
  - Black-hole formation

- **Conclusions**

Based on:

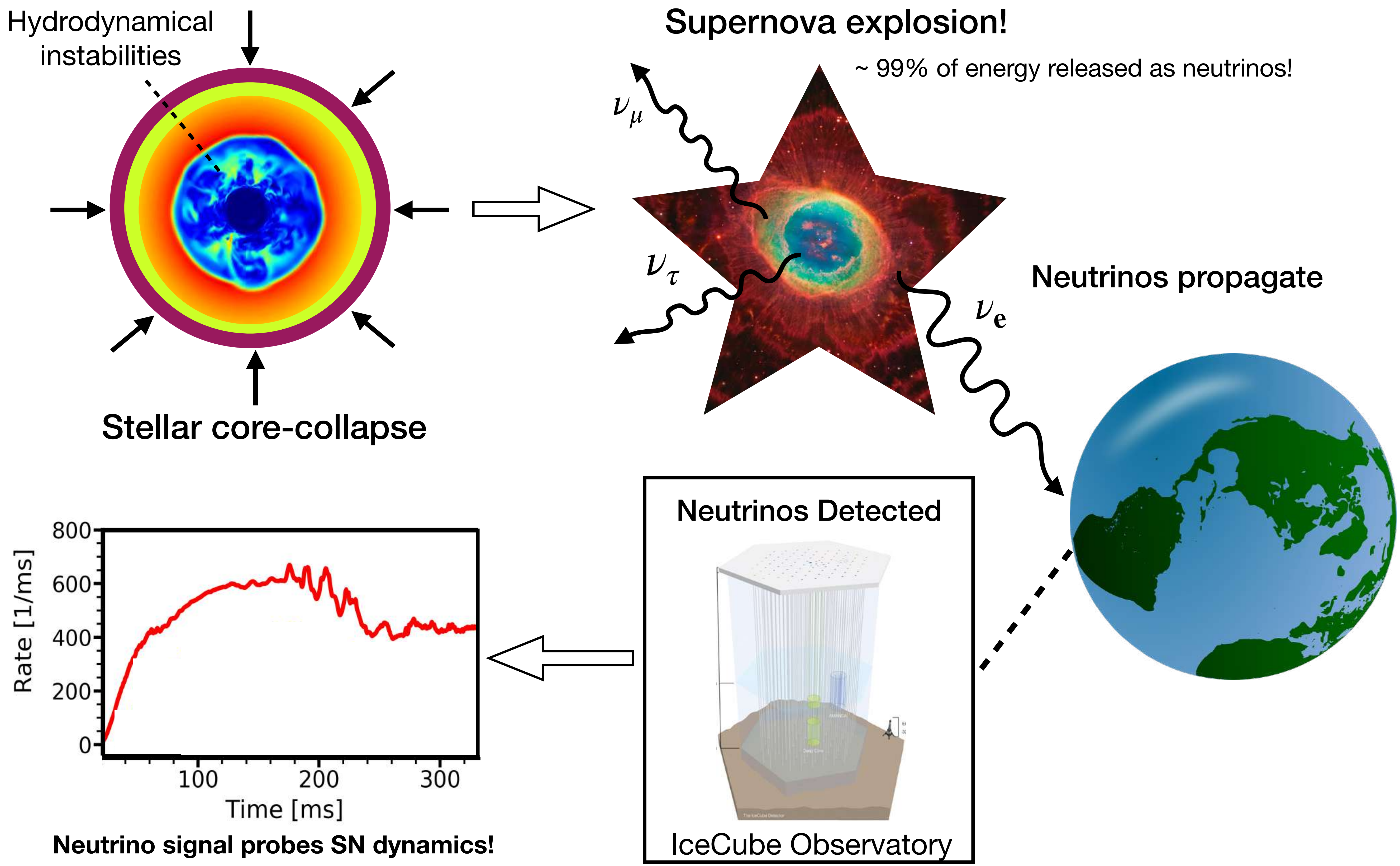
Walk, Tamborra, Janka, Summa. *Phys. Rev. D. 98 (2018)*

Walk, Tamborra, Janka, Summa. *Phys. Rev. D. 100 (2019)*

Walk, Tamborra, Janka, Summa, Kresse. *Phys. Rev. D. 101 (2020)*

Neutrinos from supernovae

Neutrinos from supernovae



Neutrinos as probes

1. **Hydrodynamical instabilities**
2. Progenitor rotation
3. Black-hole formation

Neutrinos as probes :
Hydrodynamical instabilities

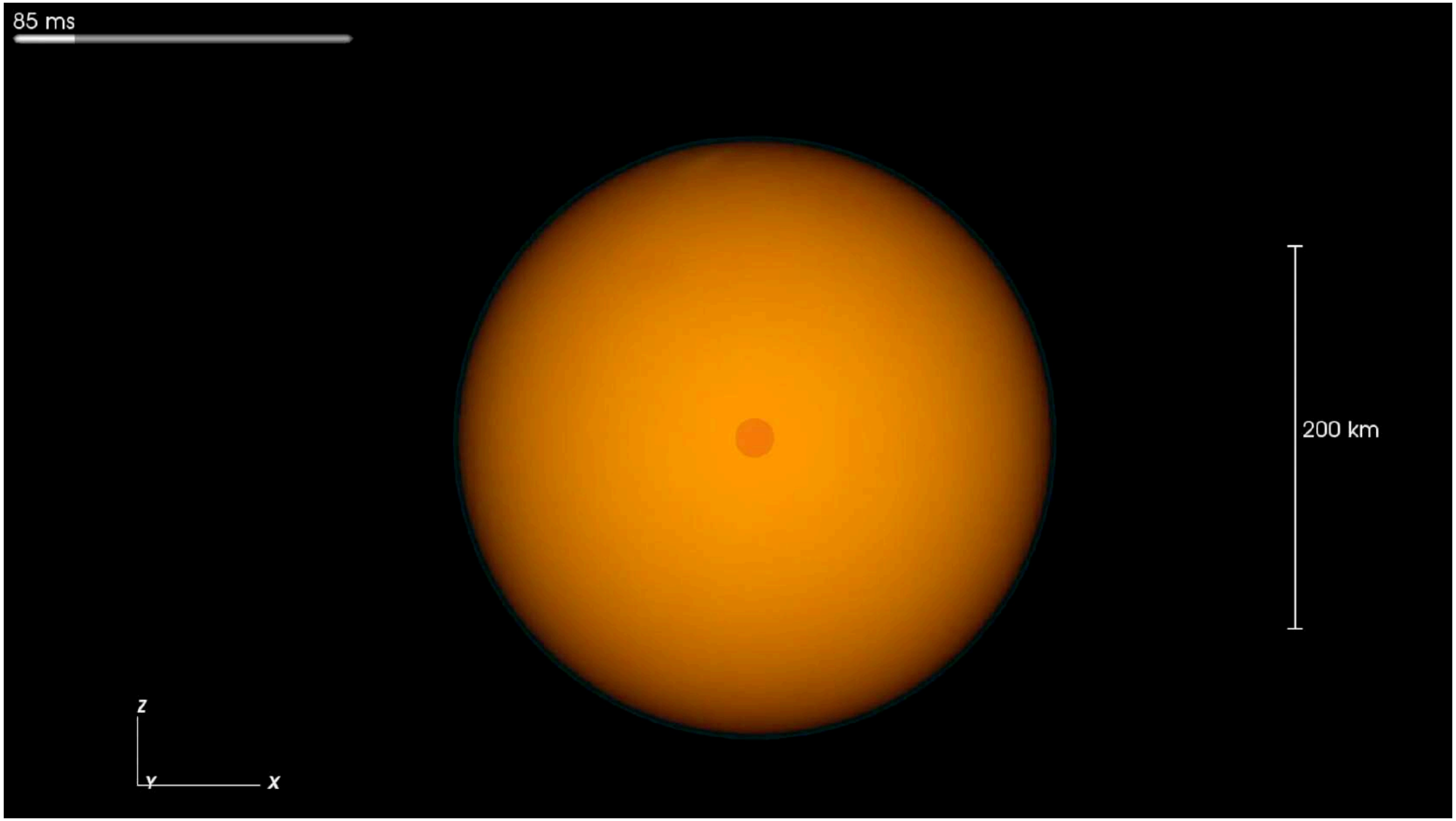
What hydrodynamical instabilities can form during the core-collapse?

How are these reflected in the neutrino emission?

$\longrightarrow$ Based on 3D model of 27 and 15 $\mathrm{M}_\odot$ progenitor

For details please see: Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. D 90 (2014)

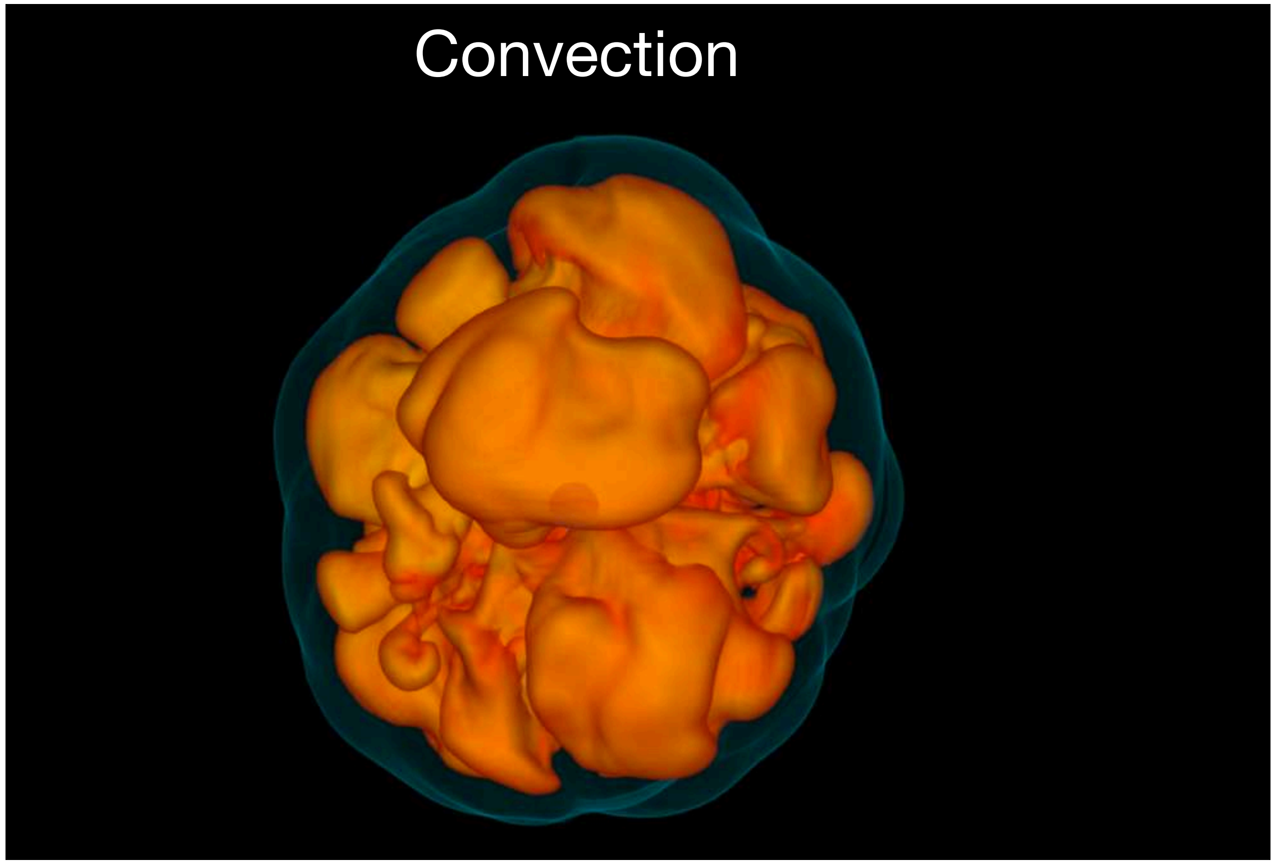
Neutrinos as probes - Hydrodynamics

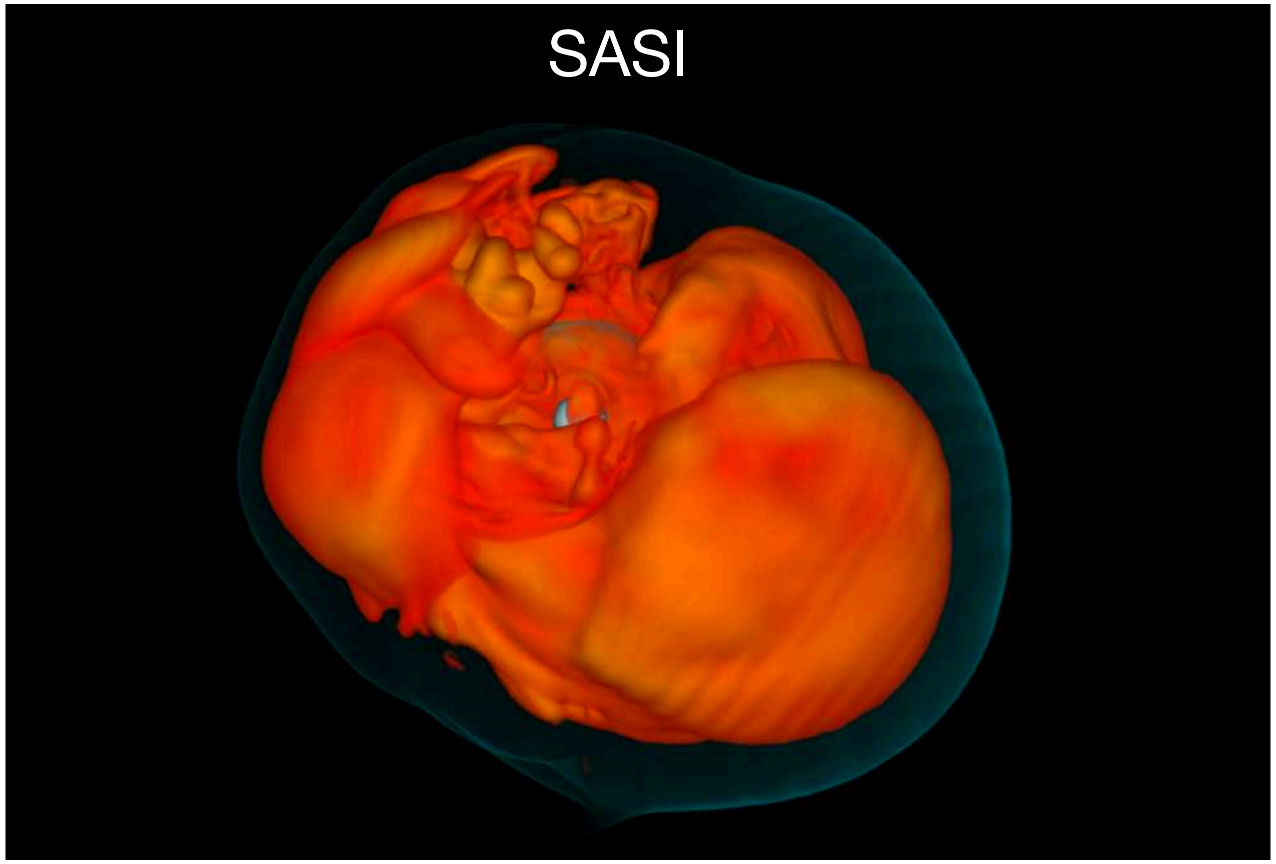


Garching Group
Max-Planck-Institut für Astrophysik

Neutrinos as probes - Hydrodynamics

What hydrodynamical instabilities can form during the core-collapse?



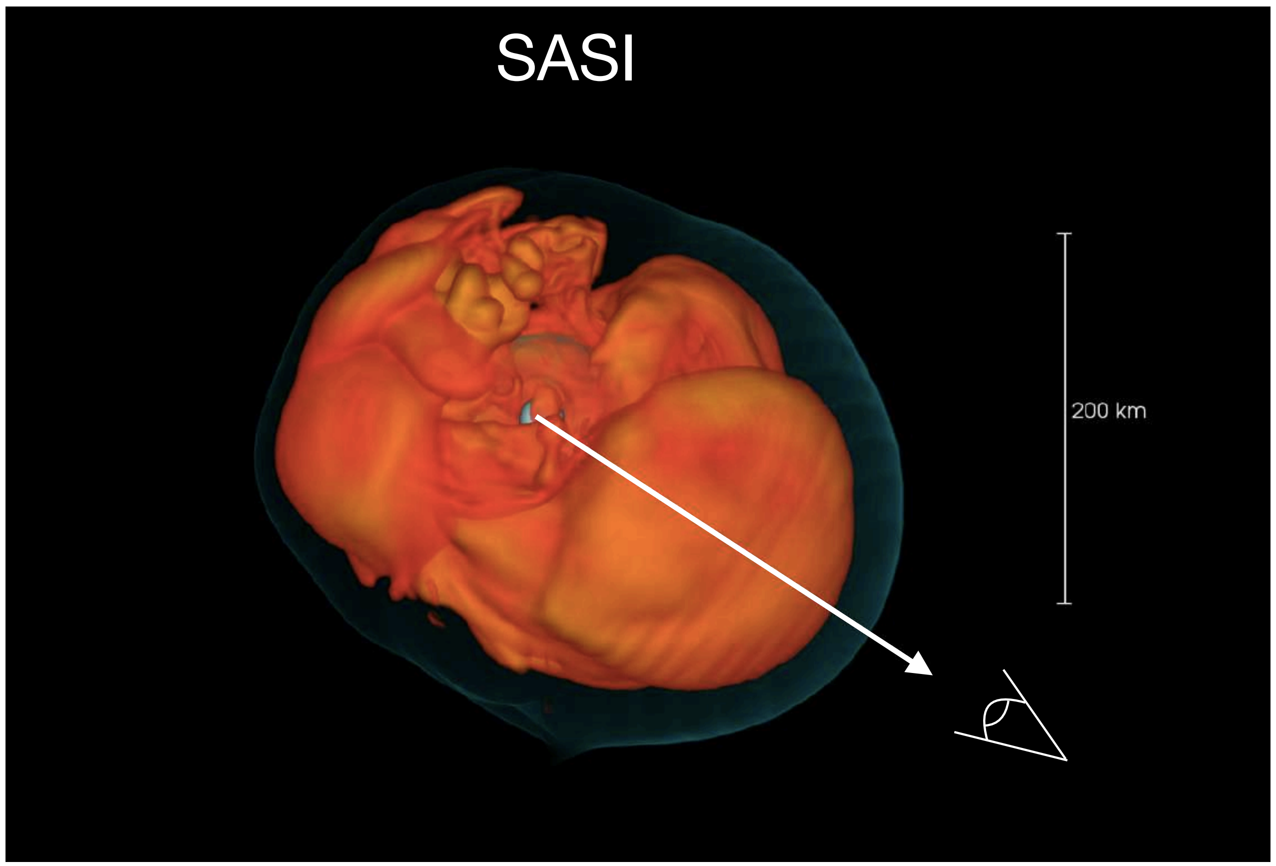


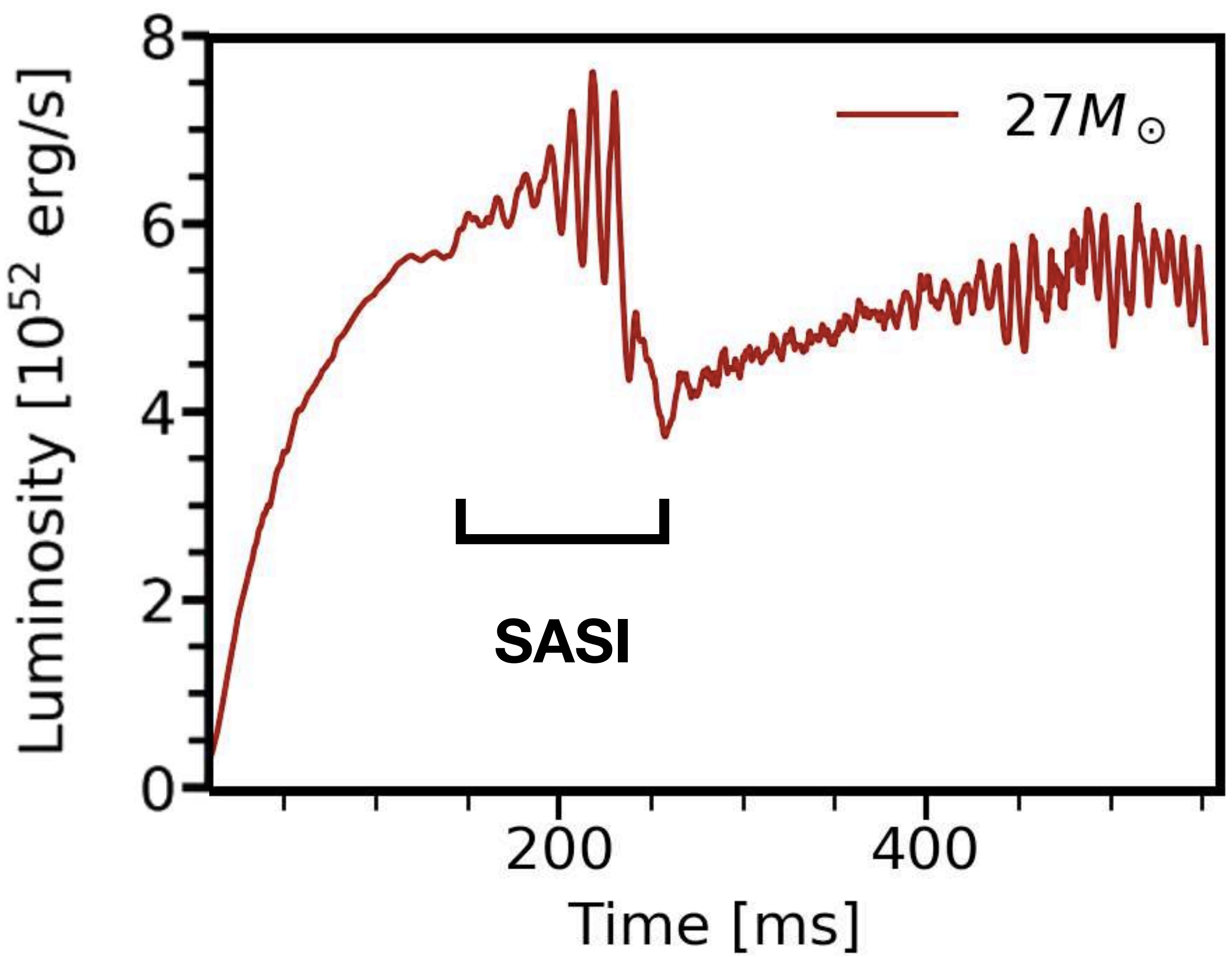
SASI ⟶ dipolar oscillating deformation of the shockwave along a plane

Convection ⟶ higher order/frequency deformations of the shockwave

Neutrinos as probes - Hydrodynamics (SASI)

How are the hydrodynamics reflected in the neutrino emission?





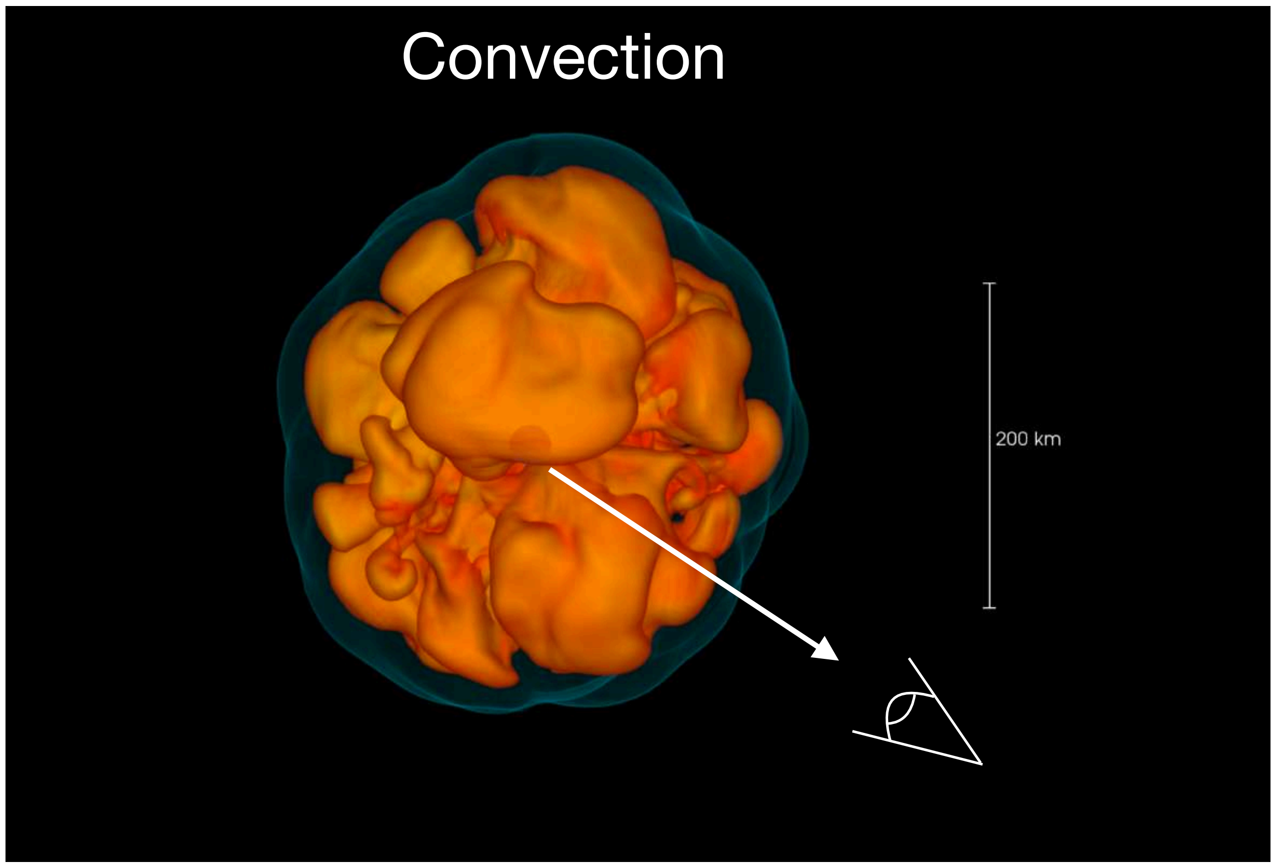
- SASI presents as sinusoidal modulations of the neutrino luminosity

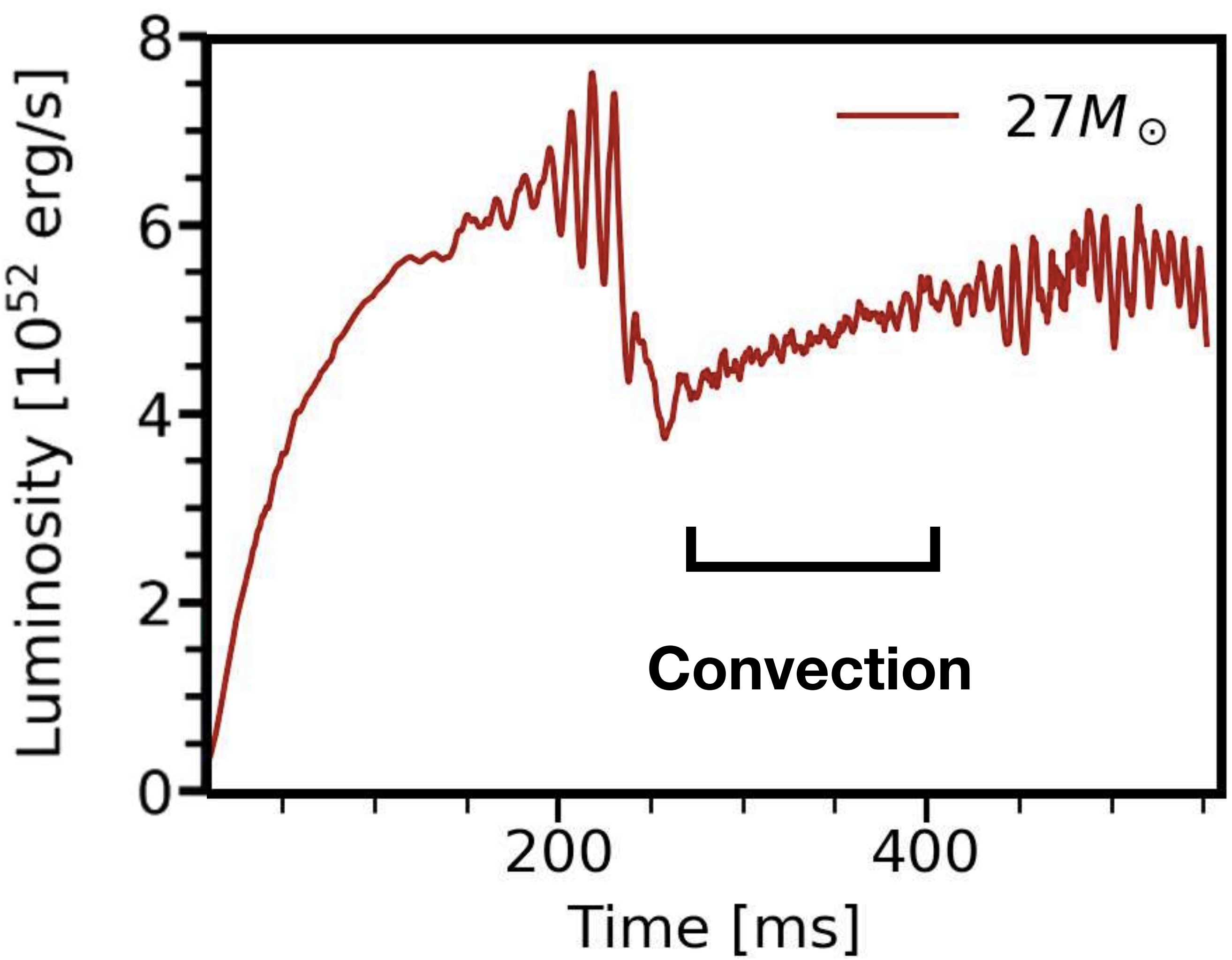
$$f_{\mathrm{SASI}} \propto R_s^{-3/4}$$

See also: *Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. D 90 (2014)*

Neutrinos as probes - Hydrodynamics (Convection)

How are the hydrodynamics reflected in the neutrino emission?





- Convection presents as small-scale fluctuations of the neutrino luminosity

See also: *Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. D 90 (2014)*

Hydrodynamical instabilities - LESA

What hydrodynamical instabilities can form during the core-collapse?

$\longrightarrow$ Lepton-number Emission Self-sustained Asymmetry

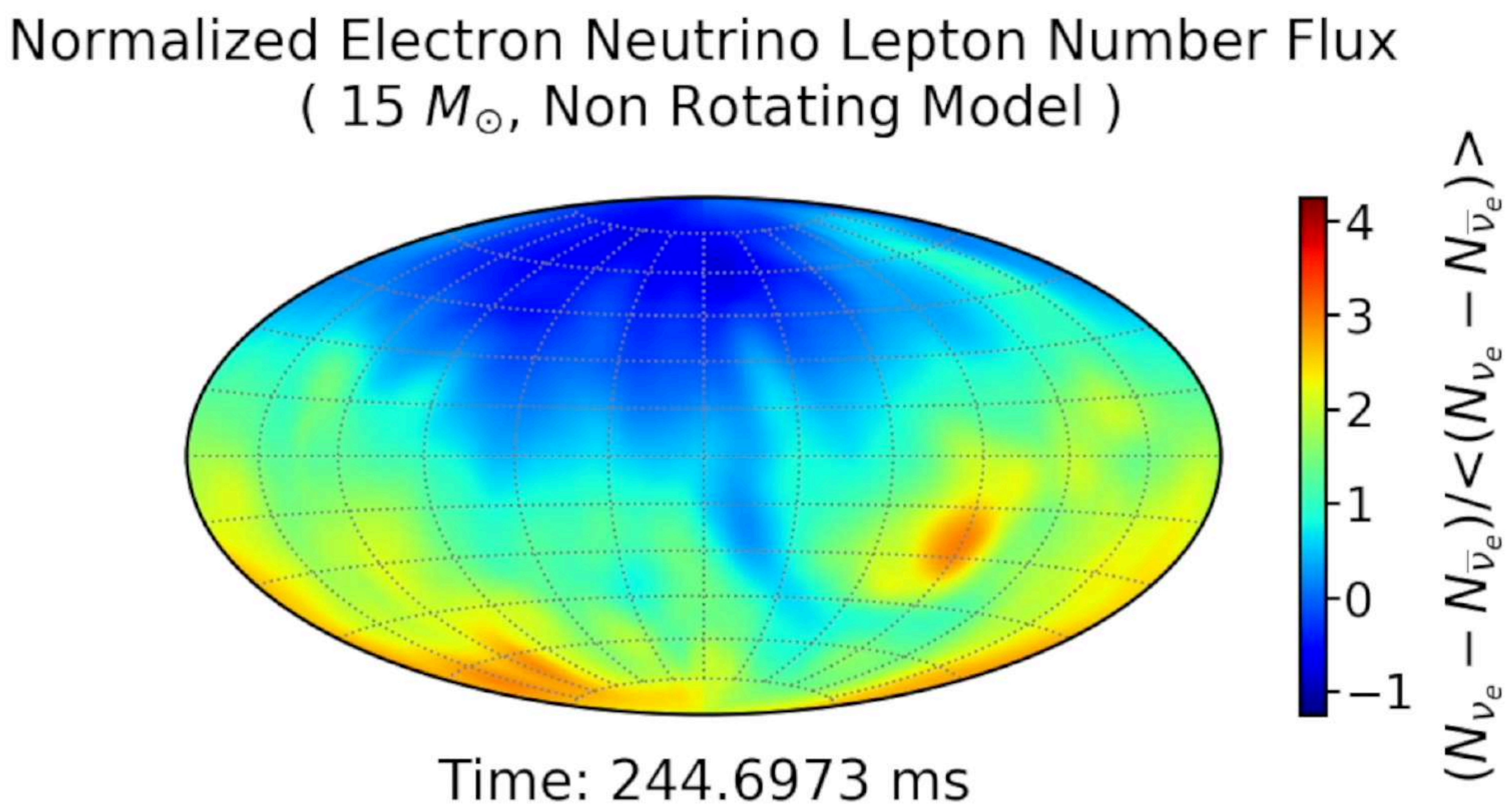
Caused by asymmetric convection in the PNS which leads to:

1. Hemispheric asymmetric electron fraction profile
2. Excess of ν_e compared to $\bar{\nu}_e$ flowing from one hemisphere

Tamborra, Hanke, Janka, Müller, Raffelt, Marek. ApJ. 792 (2014)

Neutrinos as probes - Hydrodynamics (LESA)

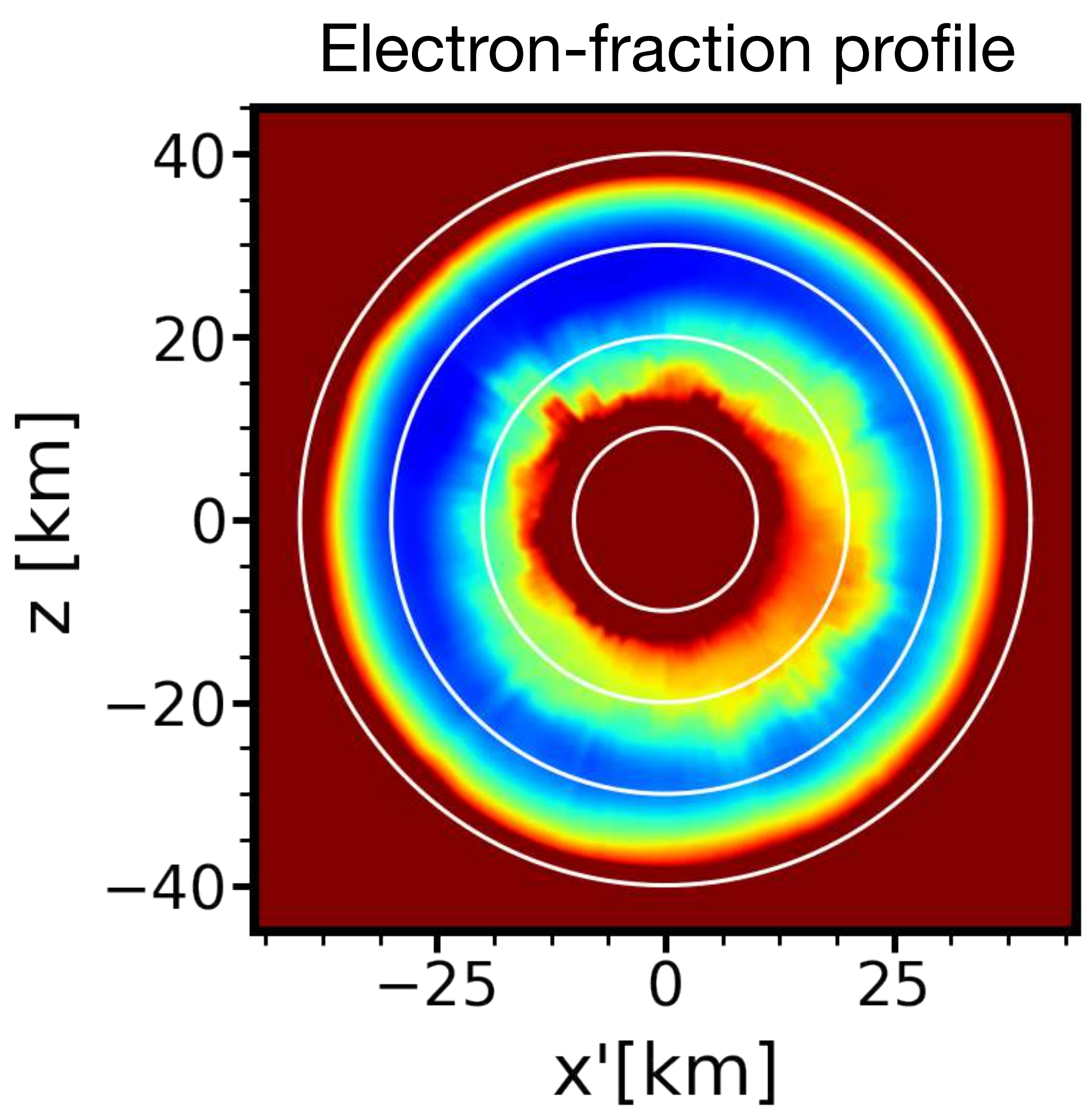
How are the hydrodynamics reflected in the neutrino emission?

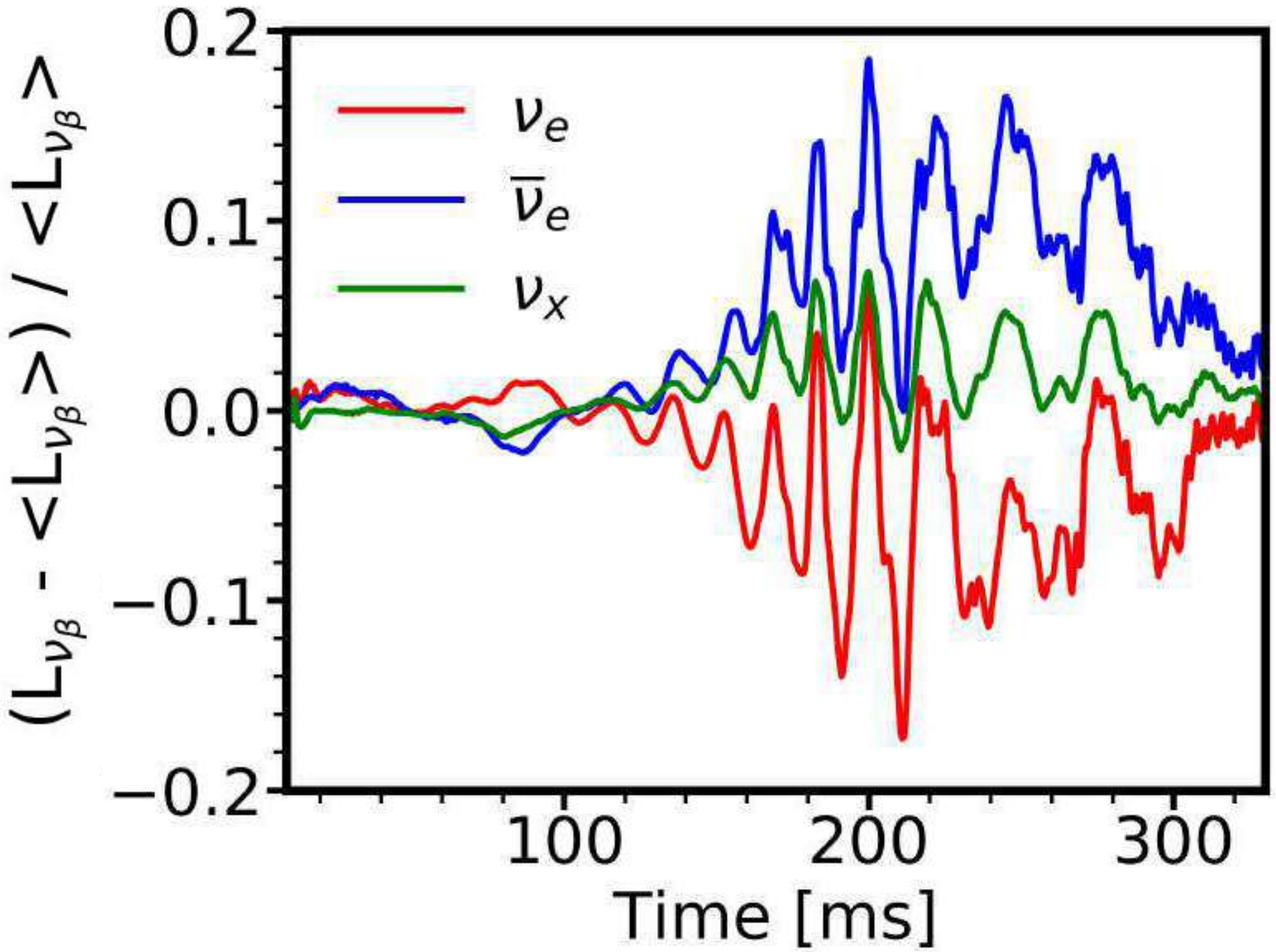


LESA ⟶ (dipolar) asymmetry of electron-lepton number flux

Neutrinos as probes - Hydrodynamics (LESA)

How are the hydrodynamics reflected in the neutrino emission?





LESA ⟶ (dipolar) anti-correlation between emitted electron neutrino flavors

See also: *Tamborra, Hanke, Janka, Müller, Raffelt, Marek. ApJ. 792 (2014)*

Neutrinos as probes - Hydrodynamics

How are the hydrodynamics reflected in the neutrino emission?

Hydrodynamics reflected in neutrino luminosity:

1. Sinusoidal modulations characteristic of SASI
2. Small-scale fluctuations characteristic of convection
3. Regions of excess ELN flux characteristic of LESA

Neutrinos as probes

1. Hydrodynamical instabilities
2. **Progenitor rotation**
3. Black-hole formation

Neutrinos as probes - Progenitor rotation

What are the effects of rotation on hydrodynamical instabilities?

Can we constrain rotational velocity through neutrinos?

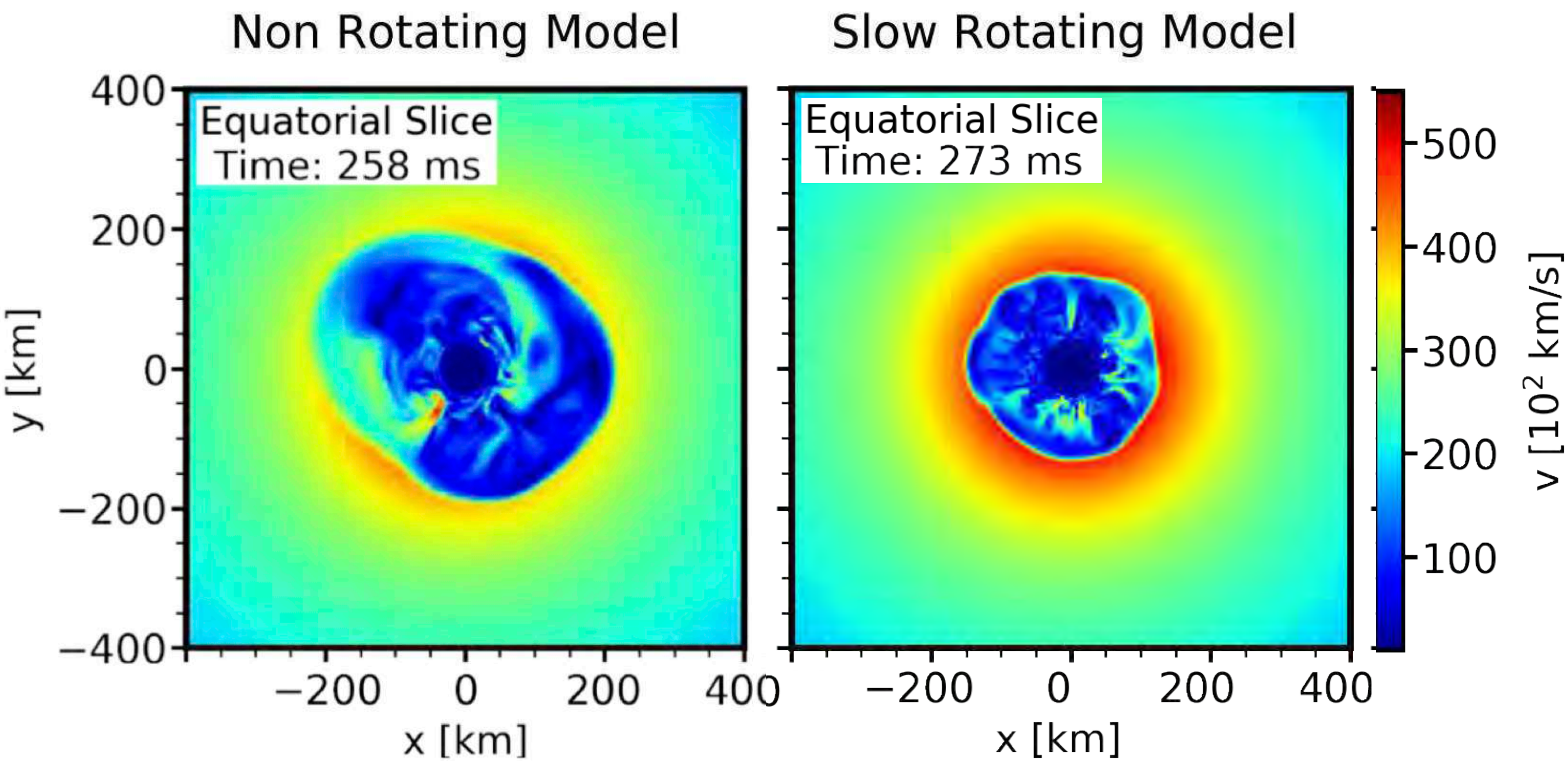
Three self-consistent $15M_\odot$ models:

1. Non-rotating model
2. Slow rotating (spin period of 6000 s)
3. Fast rotating model (spin period of 20 s)

Summa, Janka, Melson, Marek, Astrophys. J. 852, 28 (2018)

Neutrinos as probes - Progenitor rotation

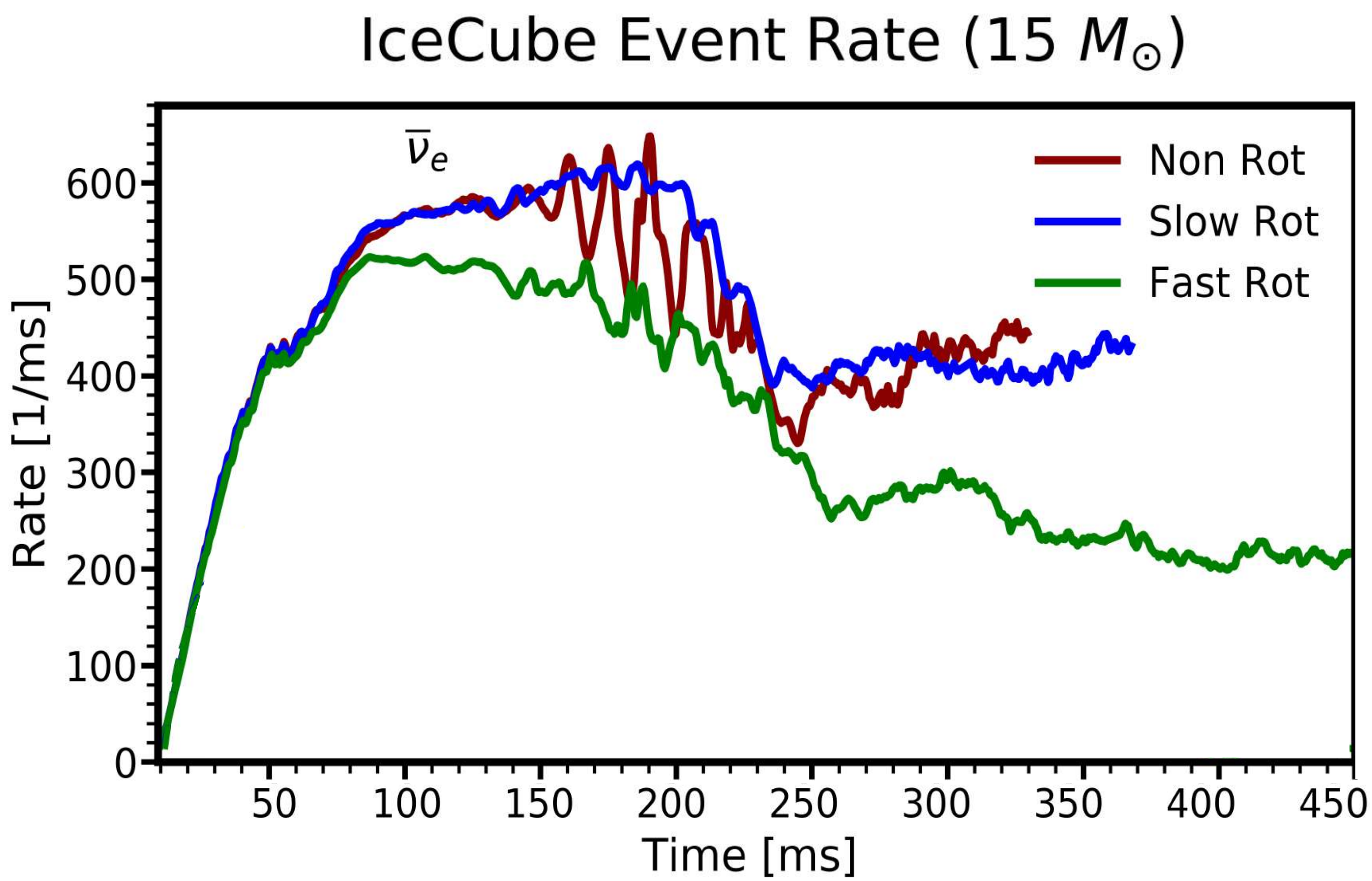
What are the effects of rotation on hydrodynamical instabilities?



- Large-scale deformations indicate SASI in the non rotating model
- Dampened in the slow rotating model, instead stronger convection

Neutrinos as probes - Progenitor rotation

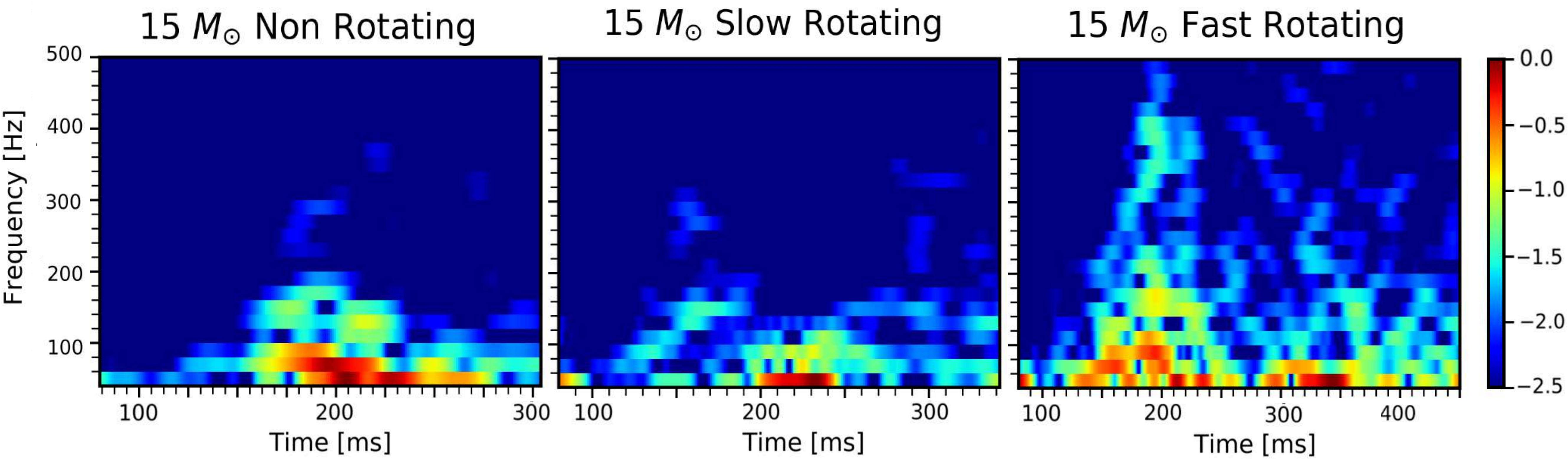
What are the effects of rotation on hydrodynamical instabilities?



- Sinusoidal SASI modulations present in non-rotating model
- Amplitude decreased in the slow rotating model
- Small-scale fluctuations present in fast rotating model

Neutrinos as probes - Progenitor rotation

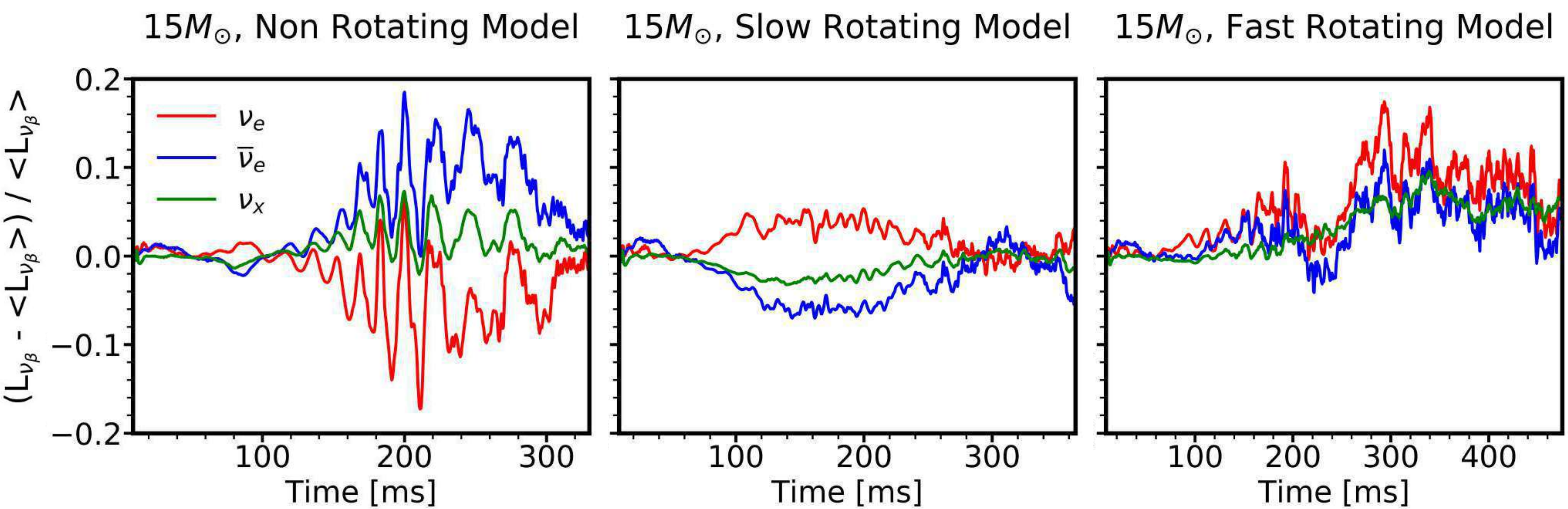
Can we constrain rotational velocity through detectable neutrinos?



- Rotation weakens the SASI peak
- Less dominant SASI region, wider spread in high frequencies
- i.e. Small-scale fluctuations are resolved by spectrograms
- Suggests again an interplay between SASI and convection, brought on by rotation

Neutrinos as probes - Progenitor rotation

What are the effects of rotation on hydrodynamical instabilities?

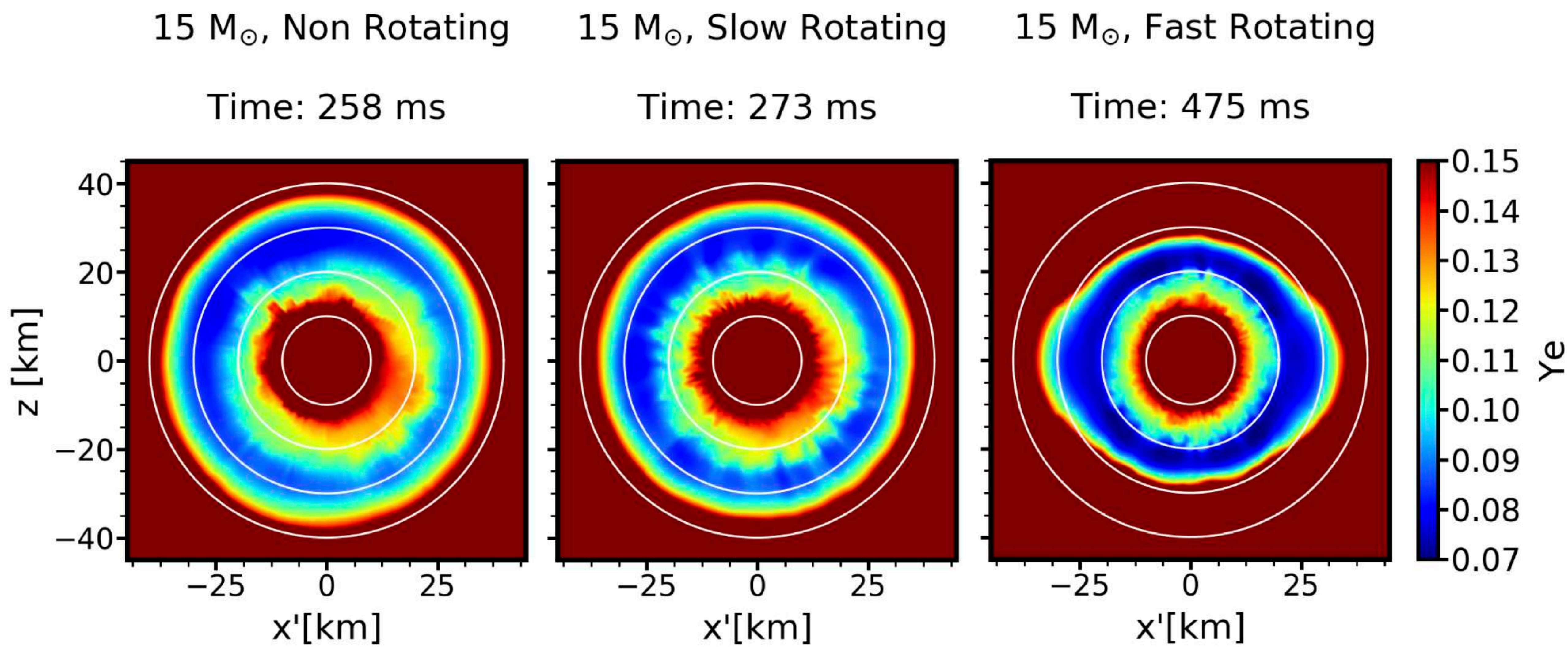


- Anti-correlation between ν_e and $\bar{\nu}_e$ luminosities dampened by rotation

- Suggests regions of excess ELN flux smeared out by rotating matter

Neutrinos as probes - Progenitor rotation

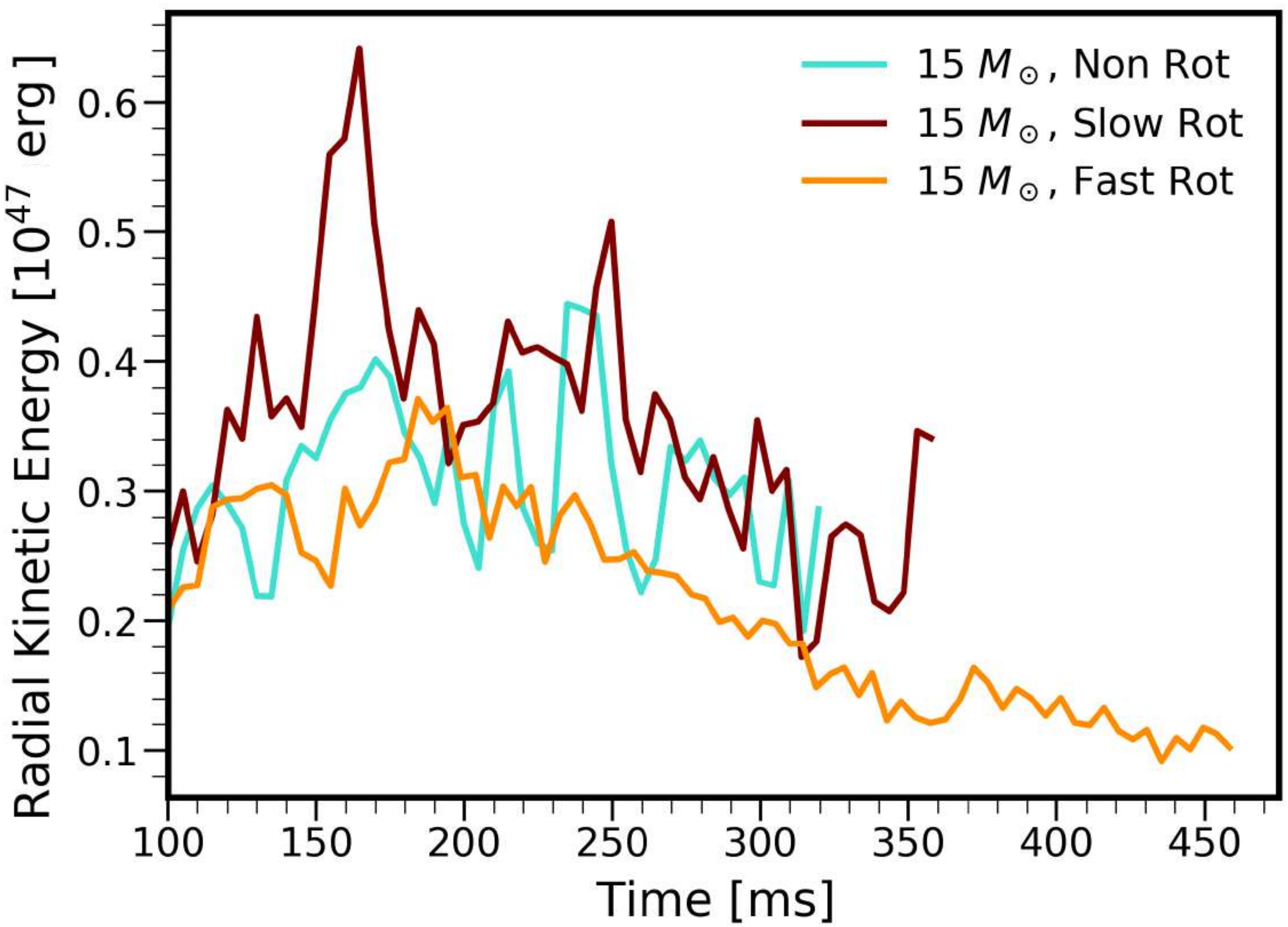
What are the effects of rotation on hydrodynamical instabilities?



- Radial electron-fraction asymmetry in the non-rotating model
- Becomes increasingly spherically symmetric with rotational velocity

Neutrinos as probes - Progenitor rotation

What are the effects of rotation on hydrodynamical instabilities?



- Radial kinetic energy suppressed in the fast rotating model
- Rotation weakens convective activity along the radial direction
- LESA is suppressed by rotation

Neutrinos as probes - Progenitor rotation

What are the effects of rotation on hydrodynamical instabilities?

- Rotation destroys large-scale dipolar deformation of the shockwave

- Induces instead, small-scale features

- Suggests more intricate interplay between SASI and convection

- Rotation weakens radial convection in PNS

- LESA is suppressed by rapid rotation

Neutrinos as probes

1. Hydrodynamical instabilities
2. Progenitor rotation
3. **Black-hole formation**

Neutrinos as probes : Black-hole formation

Can we see black-hole forming stellar collapses through neutrinos?

Are there unique signatures in the neutrino emission?

$\longrightarrow$ Based on two 3D progenitor models of 40 and 75 $\mathrm{M}_\odot$

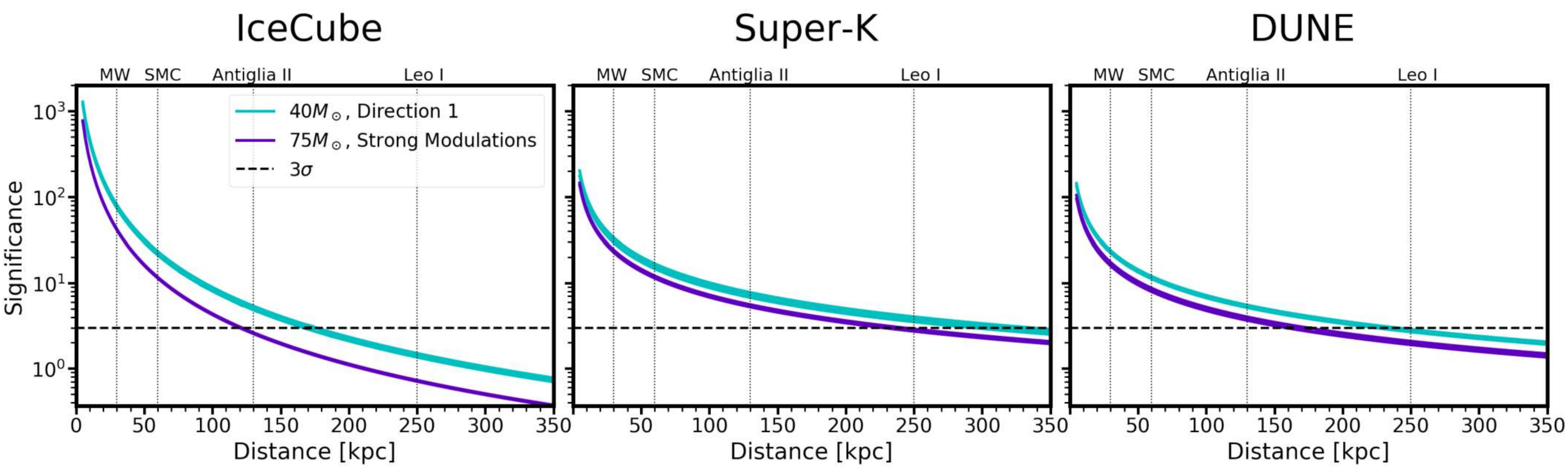
For details please see: Walk, Tamborra, Janka, Summa, Kresse. *Phys. Rev. D. 101 (2020)*

Neutrinos as probes - Black-hole formation

Can we see black-hole-forming stellar collapses through neutrinos?

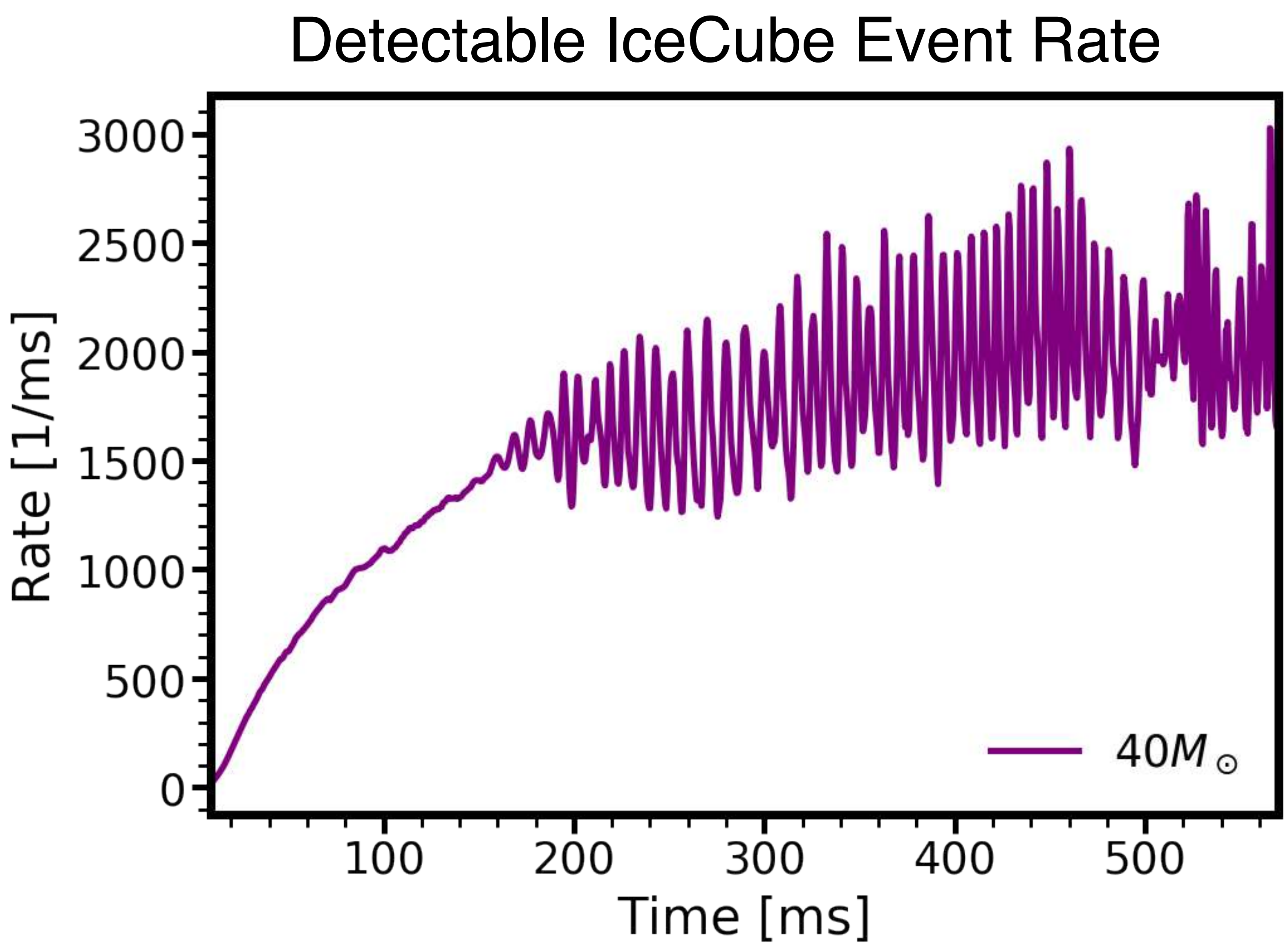
- Neutrinos are amongst the only probes of BH-forming collapses

- High event statistics makes BH-forming collapses detectable up to great distances



Neutrinos as probes - Black-hole formation

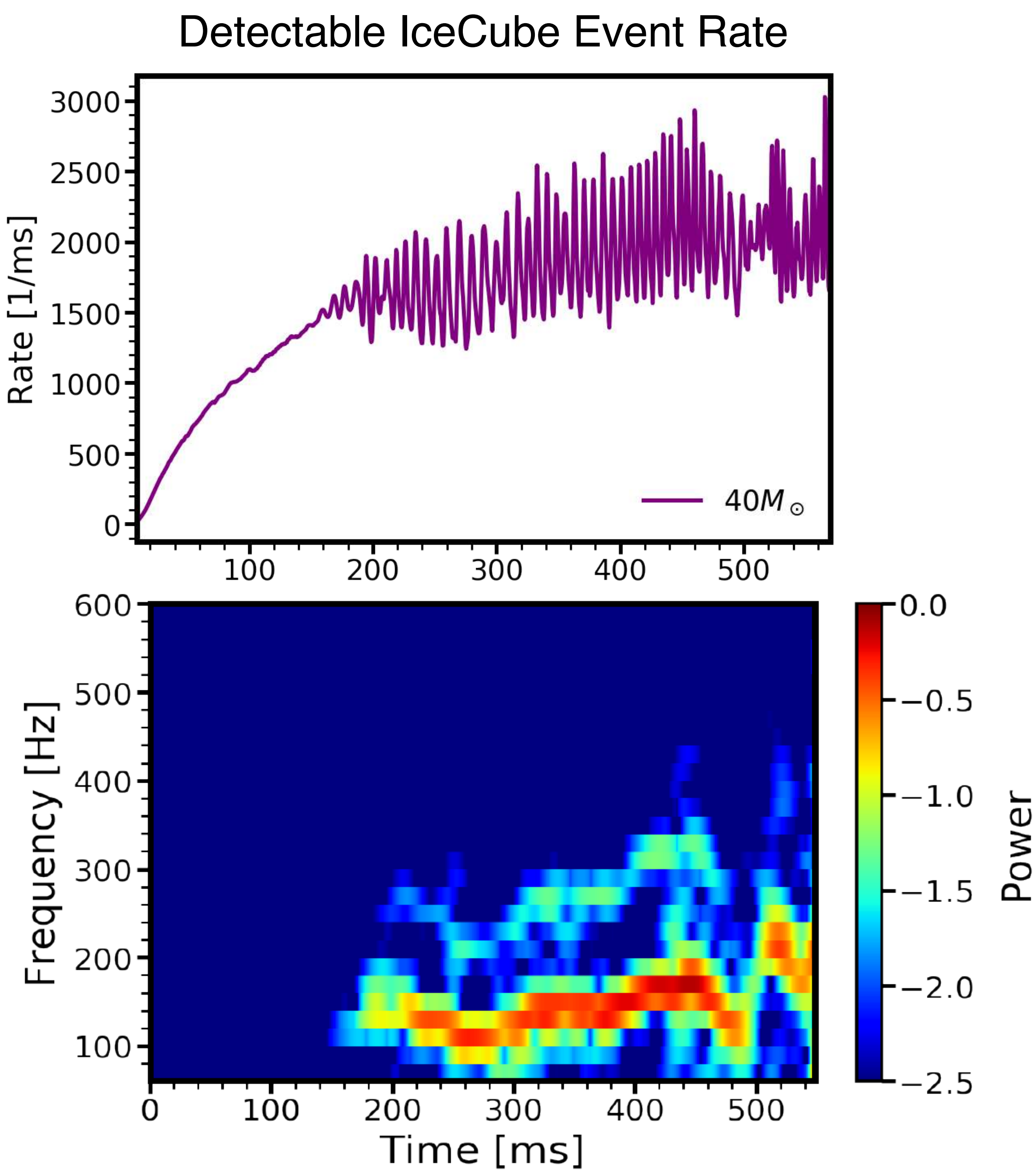
Are there unique signatures in the neutrino emission?



- Two long, strong SASI episodes detectable for the $40M_\odot$ BH-forming progenitor

Neutrinos as probes - Black-hole formation

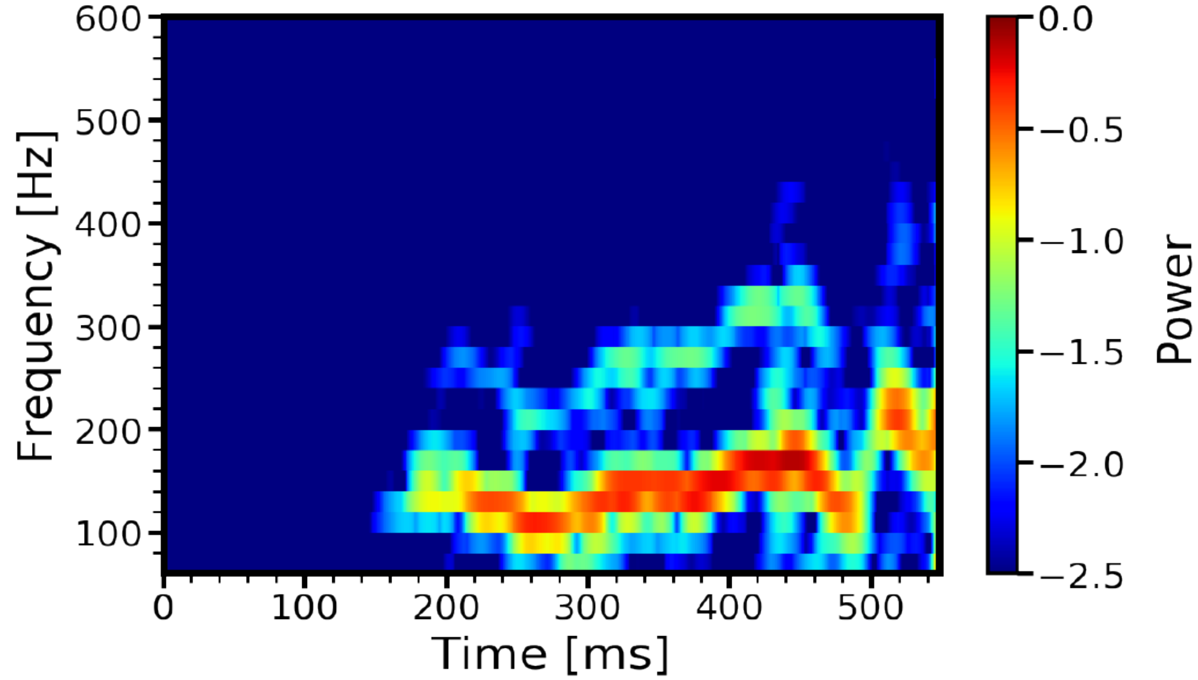
Are there unique signatures in the neutrino emission?

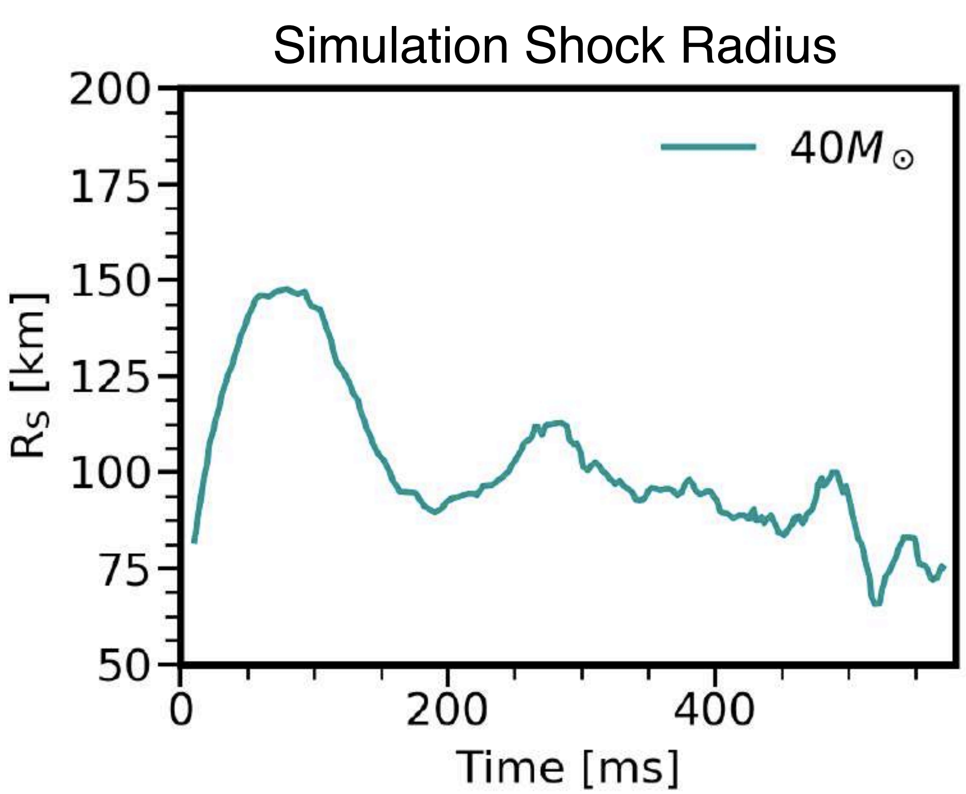


- Model shows two SASI episodes
- SASI frequency clearly traceable
- i.e. evolves (oscillates) with time
- Second SASI episode has a higher frequency than the first

Neutrinos as probes - Black-hole formation

Are there unique signatures in the neutrino emission?





$$f_{\mathrm{SASI}} \propto R_{\mathrm{s}}^{-3/4}$$

- SASI frequency and shock radius inversely proportional
- Tracks the contraction and expansion of the shock-front
- Clear, detectable imprints of the explosion physics through neutrinos!

Conclusions

- Neutrino signal reflects hydrodynamics of the core-collapse
- Rotation destroys large-scale global deformations of the shockwave
- Induces small-scale fluctuations instead
- Rotation suppresses dipolar radial flow from the PNS
- Thus, LESA is inhibited by strong rotation
- Neutrinos are key probes of BH formation, offering excellent detection prospects
- Neutrino emission prior to BH formation reflects interesting physics

Neutrinos as essential in exploring core-collapse supernovae!


Thank you!