Neutrino Gyroscopes!

Neutrinos as probes of rotation in core-collapse supernovae

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Workshop: SN Neutrinos at a Crossroads

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Outline

1. Neutrinos from supernovae
2. Rotating 3D supernovae models
3. Effects of rotation on:
   - SASI
   - LESA
4. Conclusions

Based on:

L. Walk, I. Tamborra, H.-T. Janka, and A. Summa. Phys. Rev. D98, 123001 (2018)

L. Walk, I. Tamborra, H.-T. Janka, and A. Summa. arXiv:1901.0623

Neutrinos from Supernovae

$\longrightarrow$ abundantly produced inside the core

$\longrightarrow$ essential role in explosion mechanism

$\longrightarrow$ affect nucleosynthesis

$\longrightarrow$ **probe progenitor rotation**

Aim of this work:

1. Explore effects of rotation on the development of hydrodynamical instabilities
2. Determine detectable imprints of rotation in the neutrino signal

3D Simulations

$\longrightarrow$ 3D hydrodynamical simulations (Garching group)

$\longrightarrow$ Three self-consistent 15 $M_{\odot}$ models :

1. Non rotating
2. Slow rotating $\left(\text{spin period of } 6000 \text{ s}\right)$
3. Fast rotating $\left(\text{spin period of } 20 \text{ s}\right)$

$\longrightarrow$ Fast rotating model successfully explodes

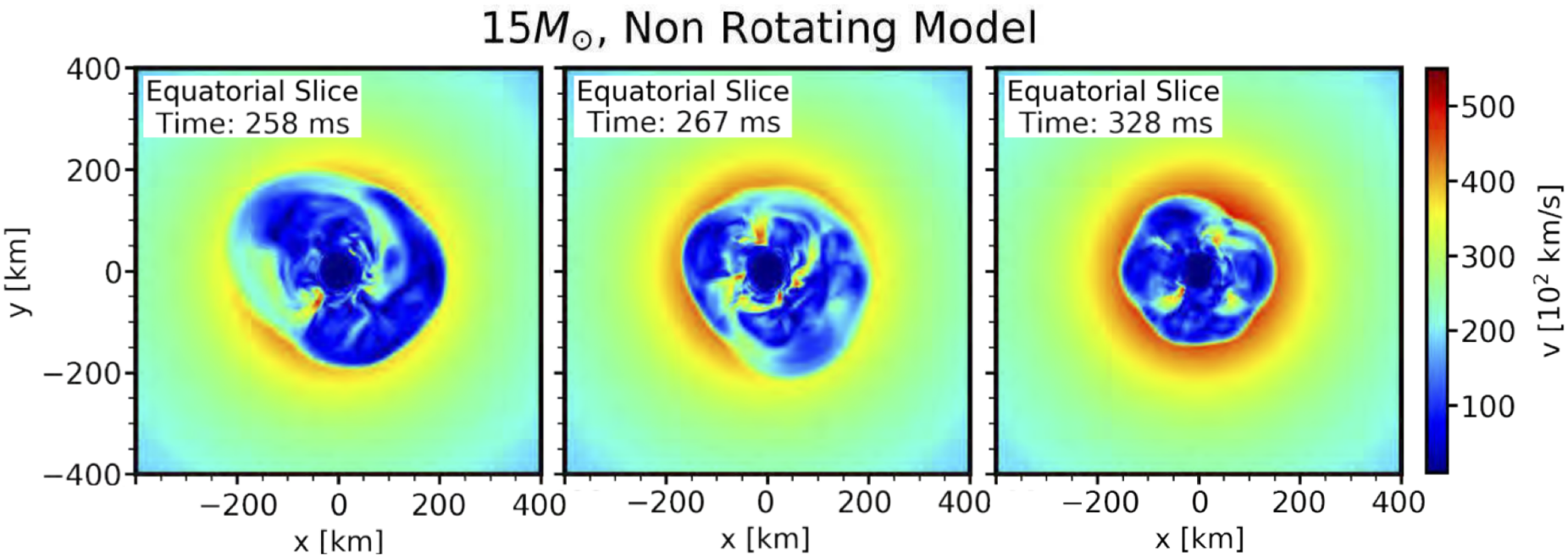
Summa, Janka, Melson, Marek, Astrophys. J. 852, 28 (2018)

Effects of rotation on SASI

(Standing Accretion-Shock Instability)

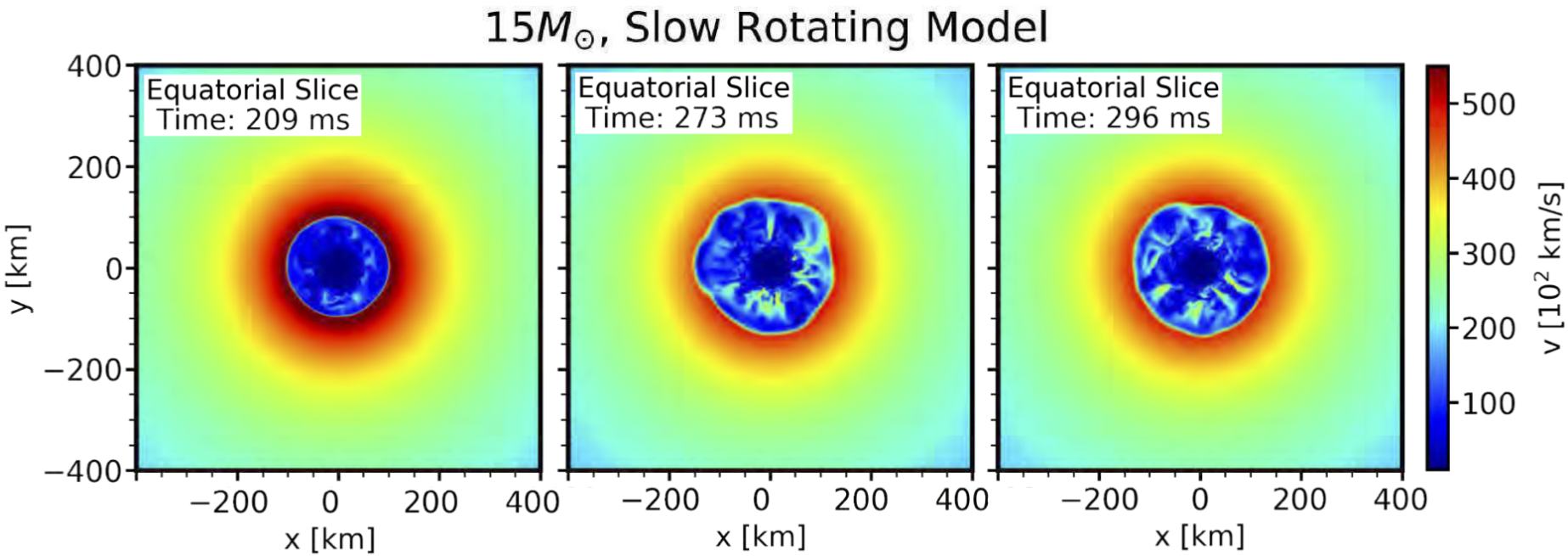
Blondin, Mezzacappa, DeMarino, Astrophys. J. 584, 971 (2003)
Blondin, Mezzacappa, Nature (London) 445, 58 (2007)
Foglizzo, Masset, Guilet, Durand, Phys. Rev. Lett. 108, 051103 (2012)
Fernandez, Astrophys. J. 725, 1563 (2010).

Effects of rotation on SASI



$\longrightarrow$ Large-scale deformation of the shockwave indicate SASI sloshing motions

Effects of rotation on SASI

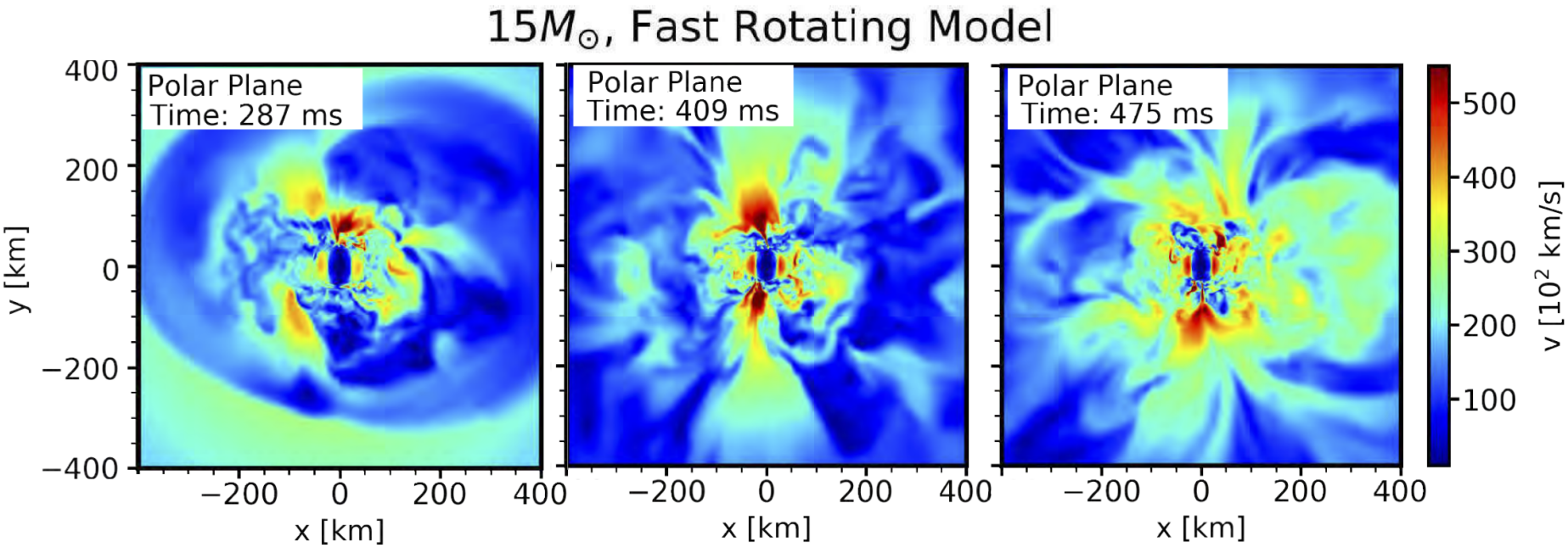


⟶ Rotation weakens effect of SASI

⟶ Smaller deformations of the shockwave

⟶ More prominent convective flow

Effects of rotation on SASI

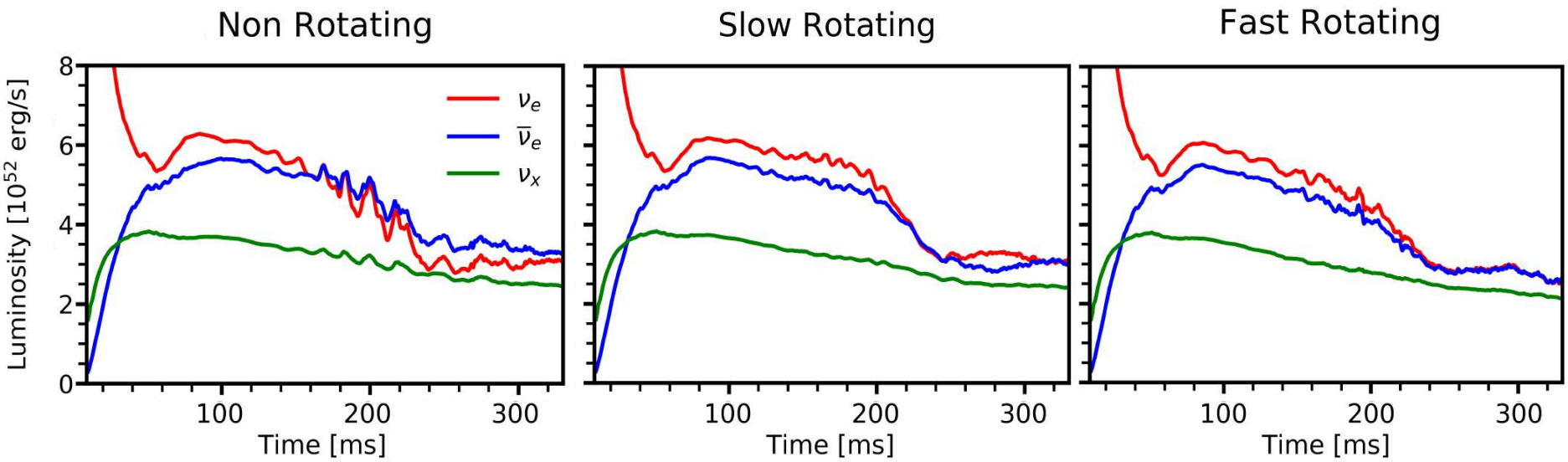


$\longrightarrow$ Model explodes at $\sim$220 ms

$\longrightarrow$ Massive polar downflows of matter due to rapid rotation

$\longrightarrow$ Oblate deformation along the equator

Effects of rotation on SASI



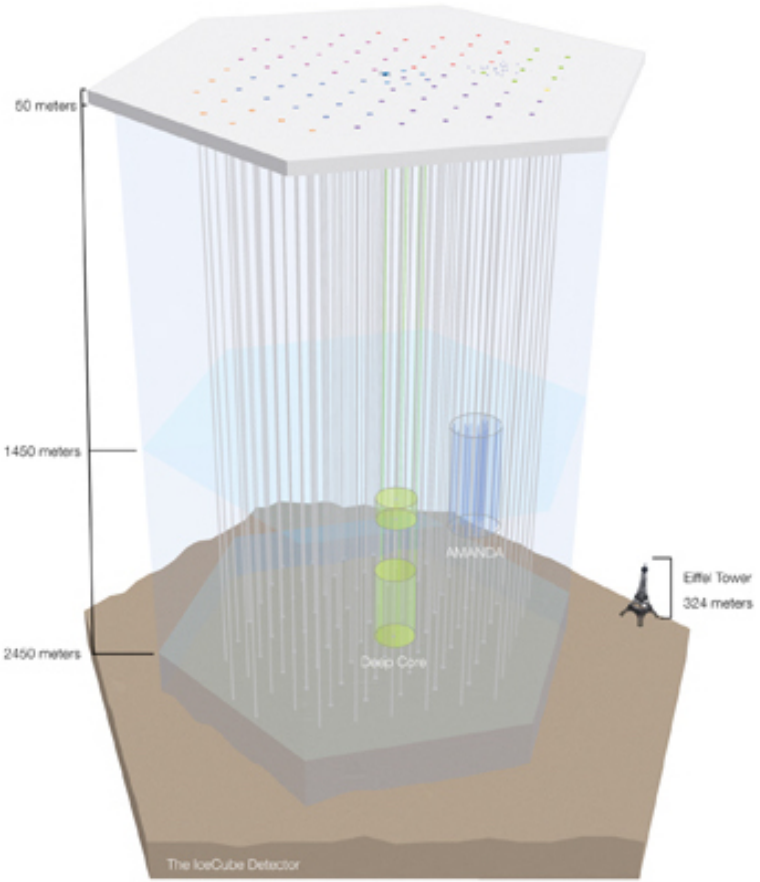
$\longrightarrow$ Sinusoidal modulation characteristic of SASI in non rotating model

$\longrightarrow$ Amplitude decreased in slow rotating model

$\longrightarrow$ Small-scale fluctuations present in neutrino emission of fast rotating model

See also: *Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. Lett. 111, 121104 (2013)*
Janka, Melson, Summa, Ann. Rev. Nucl. Part. Sci. 66, 341 (2016)

Detectable Features - IceCube



IceCube Neutrino Observatory

$\longrightarrow$ Inverse beta decay:
$(\overline{\nu}_e + p \rightarrow n + e^+)$

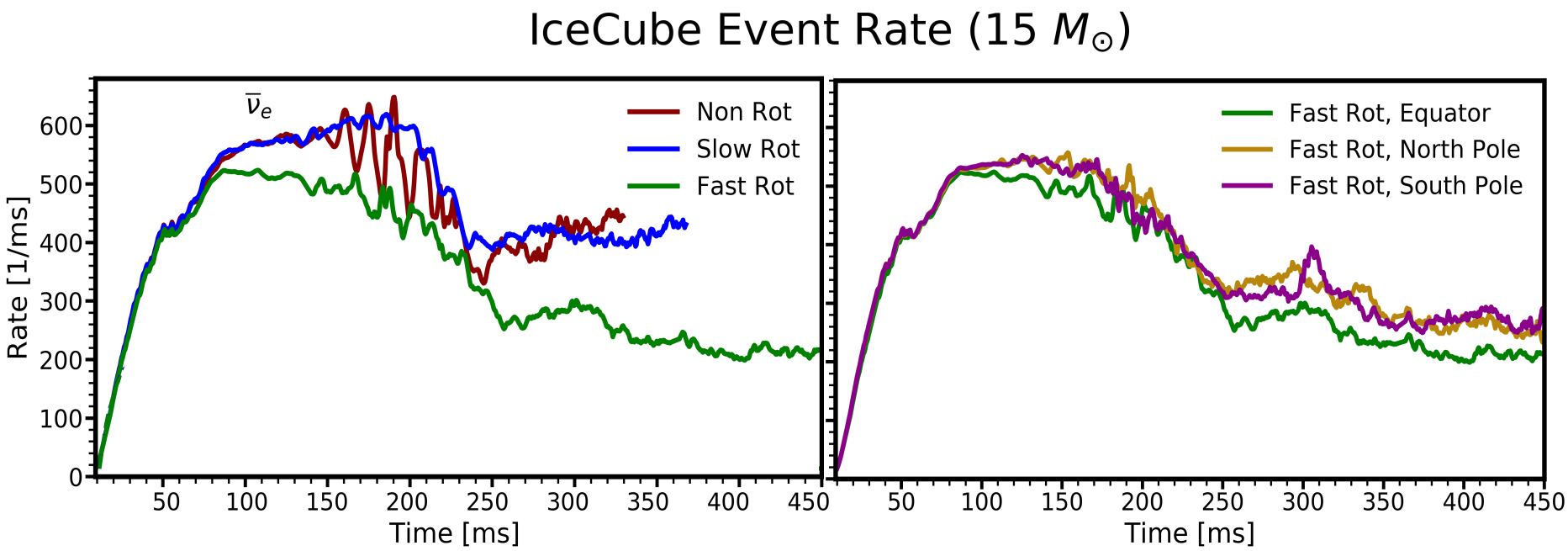
$\longrightarrow$ detects Cherenkov radiation of positron

$\longrightarrow$ largest event statistics ($\sim 10^6$ events)

Rotational imprints in neutrino signal:

1. estimate IceCube event rate
2. Fourier power spectrum analysis

Detectable Features

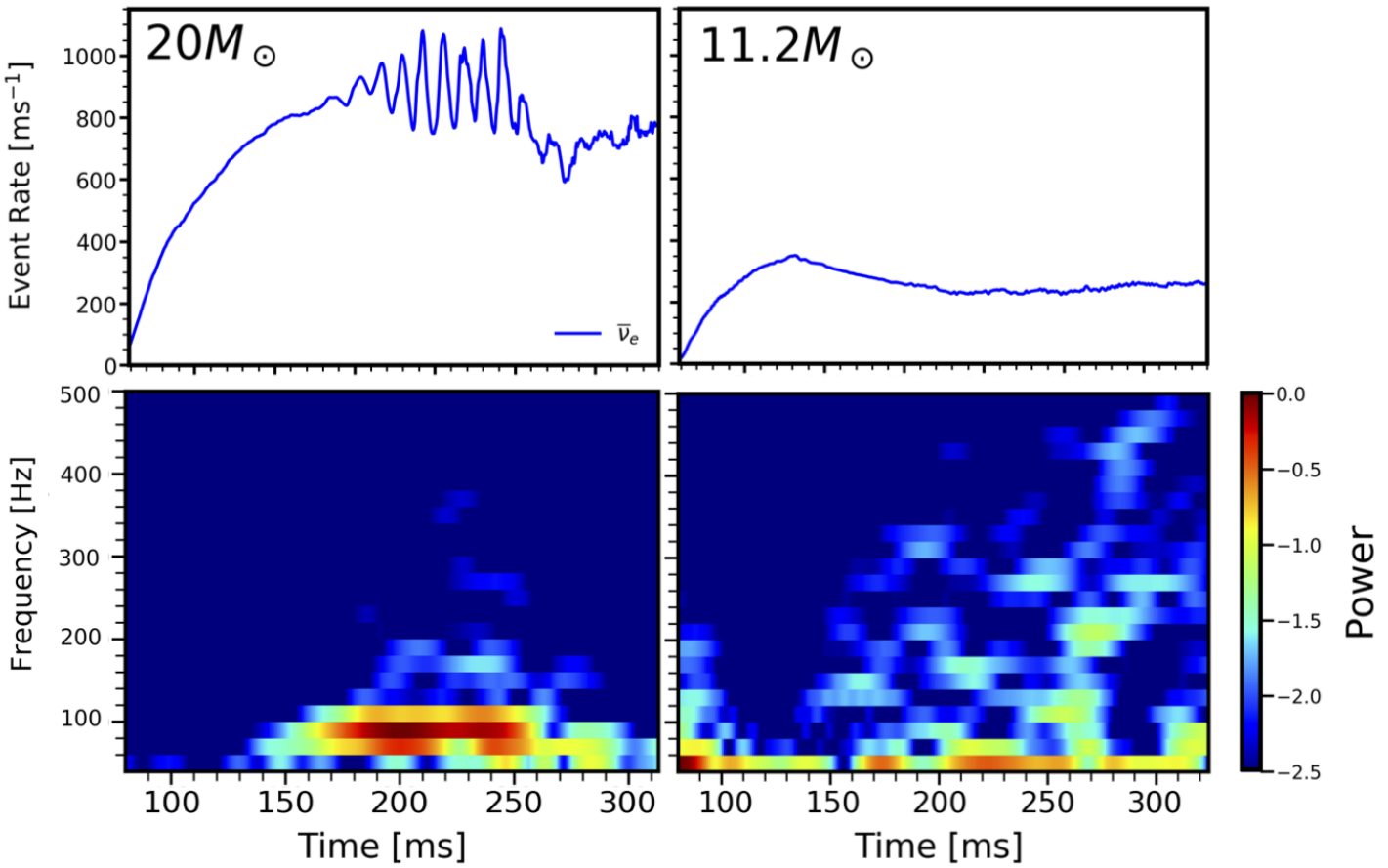


$\longrightarrow$ Properties reflected in IceCube event rate

$\longrightarrow$ Detectability prospects are directionally dependant

$\longrightarrow$ Fast rotating model has higher neutrino emission at the poles due to downflows

Detectable Features - Non rotating progenitors

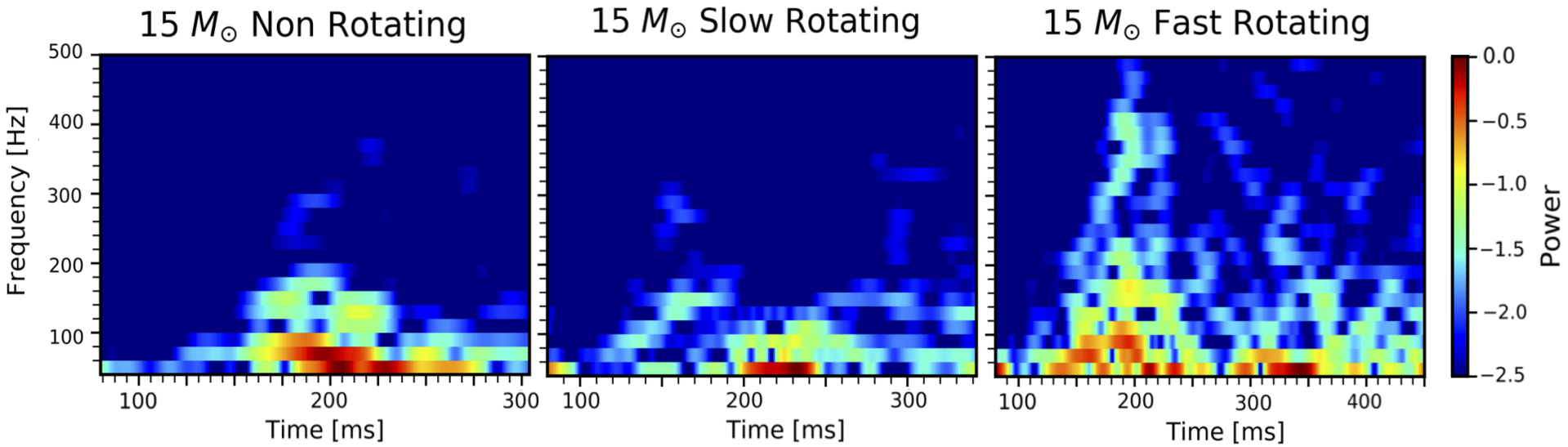


⟶ Strong SASI characterized by dominant low frequency region

⟶ Convection characterized by a homogeneous spread in frequencies

See also: *Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. Lett. 111, 121104 (2013)*

Detectable Features- Rotating progenitors



⟶ Rotation weakens the SASI peak

⟶ Less dominant SASI give wider spread in high frequencies

⟶ i.e. small scale fluctuations resolved in spectrograms

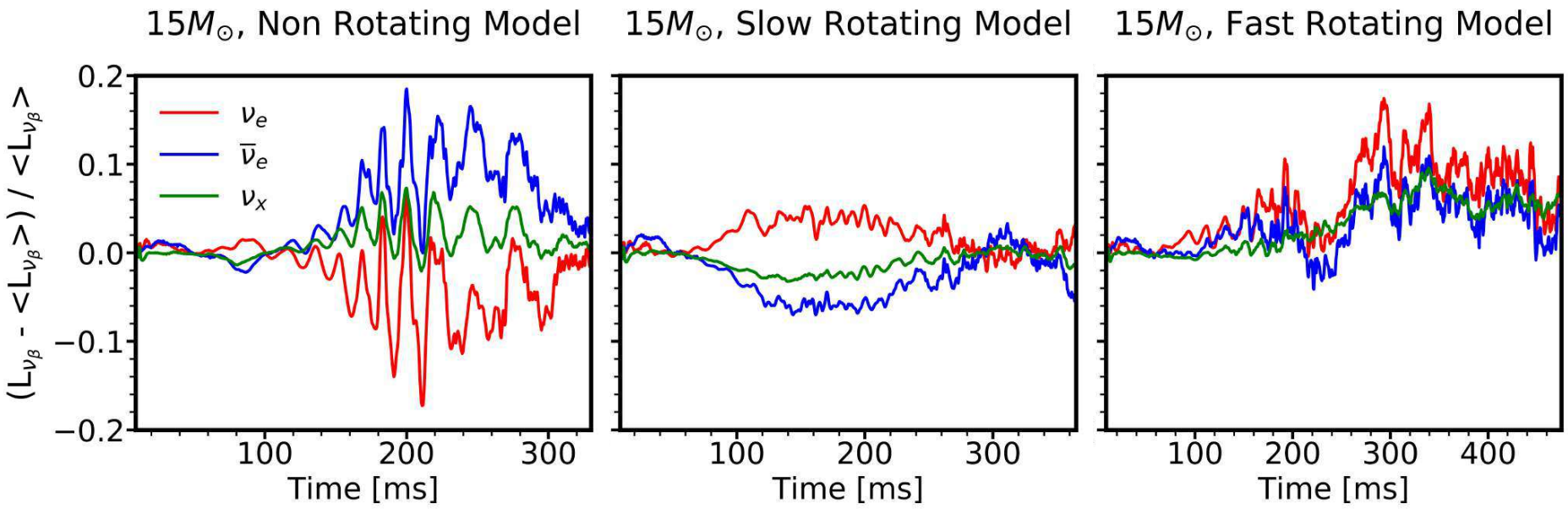
⟶ Suggests an interplay between SASI and convection brought on by rotation

Effects of rotation on LESA

(Lepton-Emission Self-sustained Asymmetry)

Tamborra, Hanke, Janka, Müller, Raffelt, Marek, Astrophys. J. 792, 96 (2014)
O'Connor, Couch, Astrophys. J. 865, 81 (2018)
Glas, Janka, Melson, Stockinger, Just, (2018), arXiv:1809.10150
Vartanyan, Burrows, Radice, Skinner, Dolence, Mon. Not. Roy. Astron. Soc. 482, 351 (2019)

Effects of rotation on LESA

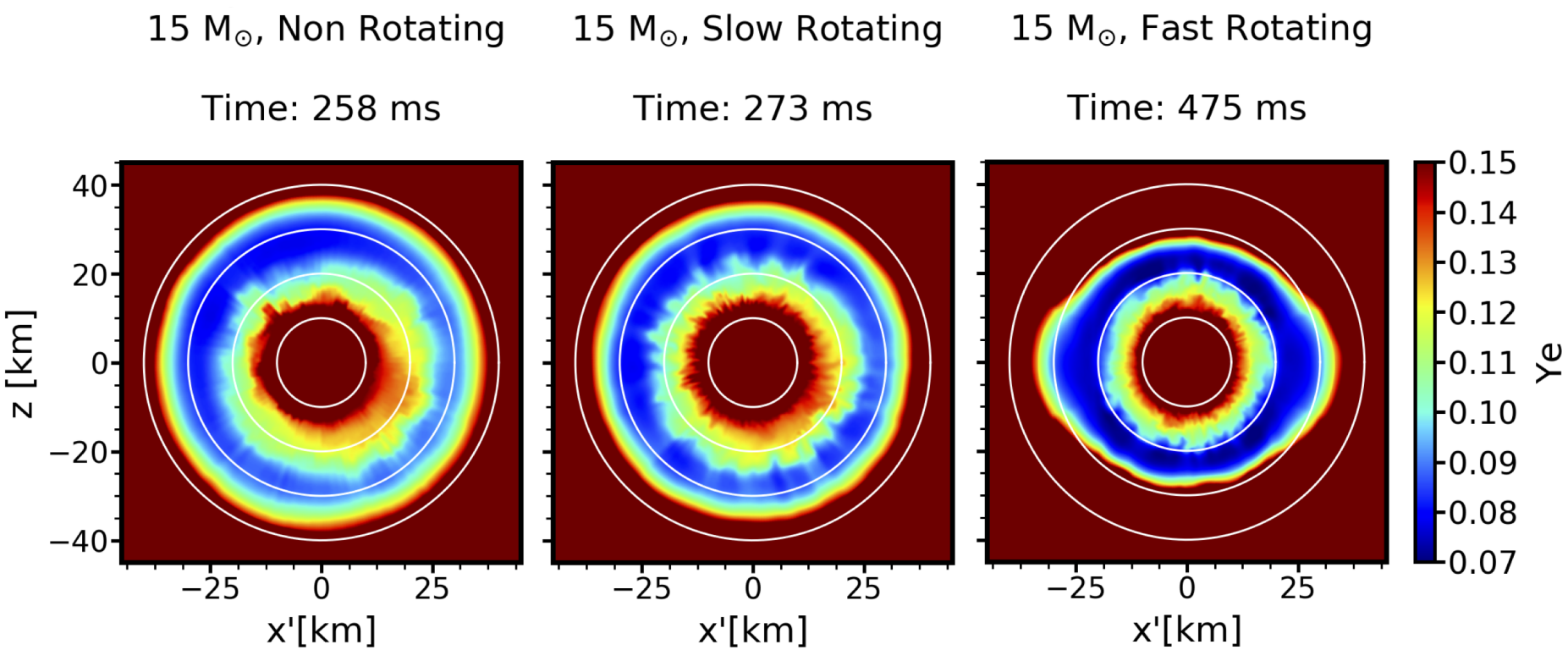


$\longrightarrow$ Anti-correlation between the ν_e and $\overline{\nu}_e$ luminosities dampened by rotation

$\longrightarrow$ Suggests regions of excess $(\nu_e - \overline{\nu}_e)$ flux smeared out by rotating matter

See also: *Tamborra, Hanke, Janka, Müller, Raffelt, Marek, Astrophys. J. 792, 96 (2014)*
Tamborra, Raffelt, Hanke, Janka, Müller, Phys. Rev. D90, 045032 (2014)

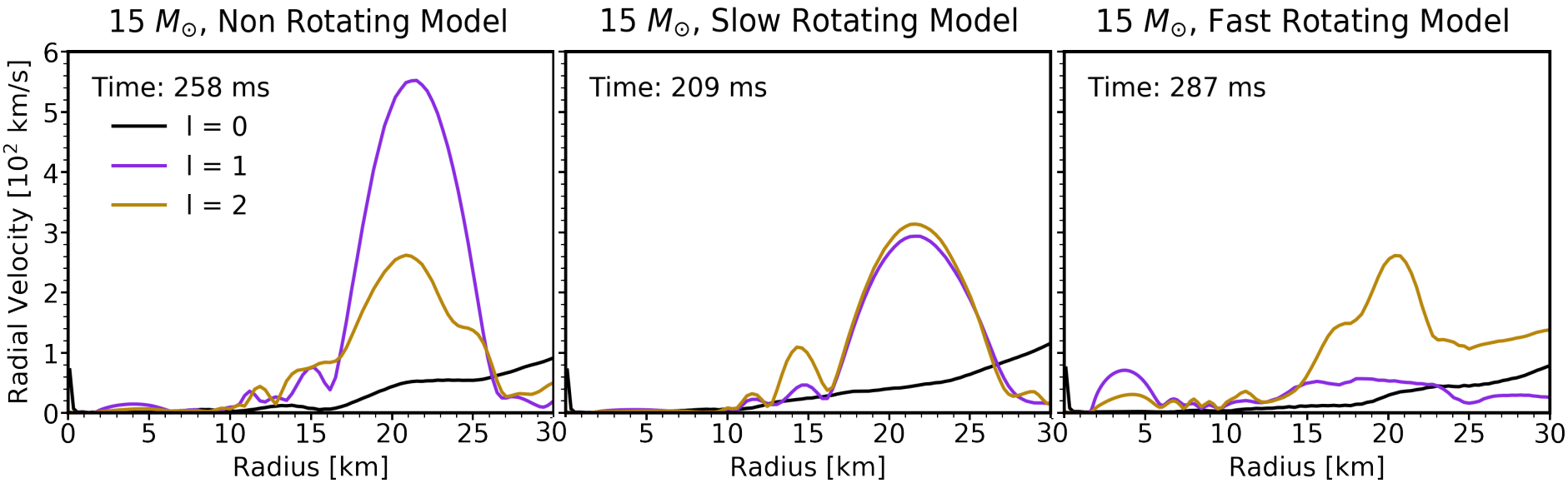
Effects of rotation on LESA



$\longrightarrow$ Radial Y_e asymmetry in the non rotating model

$\longrightarrow$ Becomes increasingly spherically symmetric with rotational velocity

Effects of rotation on LESA



$\longrightarrow$ Asymmetric radial flow prevented by rotation

$\longrightarrow$ Formation of hemispheric asymmetries inside the PNS is disfavored

$\longrightarrow$ **Rotation inhibits the growth of LESA rather than damping it**

Conclusions

Explored the effects of rotation on hydrodynamical asymmetries using neutrinos as gyroscopes!

$\longrightarrow$ Rotation destroys signatures of large-scale global deformations

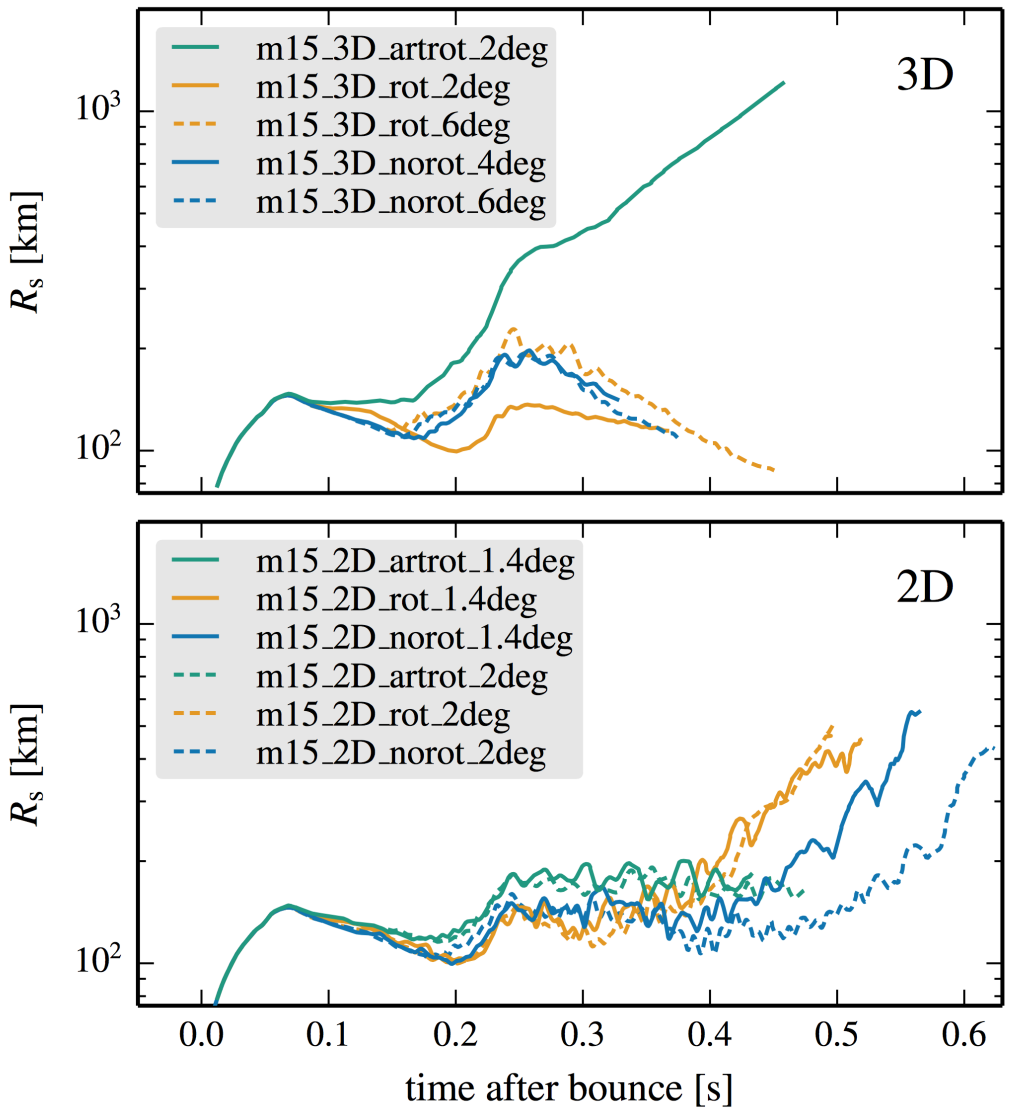
$\longrightarrow$ Induces small scale fluctuations in the neutrino signal

$\longrightarrow$ Rotation inhibits the growth of LESA

$\longrightarrow$ Constrained with relative order of low/high frequencies, given a favorable observer direction

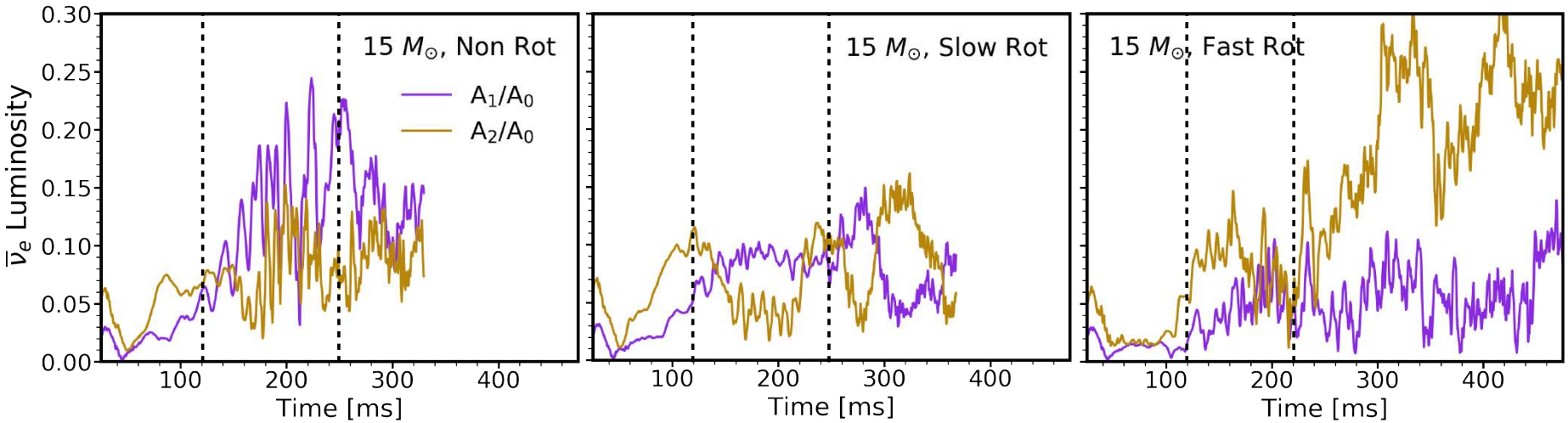

Thank You!

Effects of rotation



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

Effects of rotation



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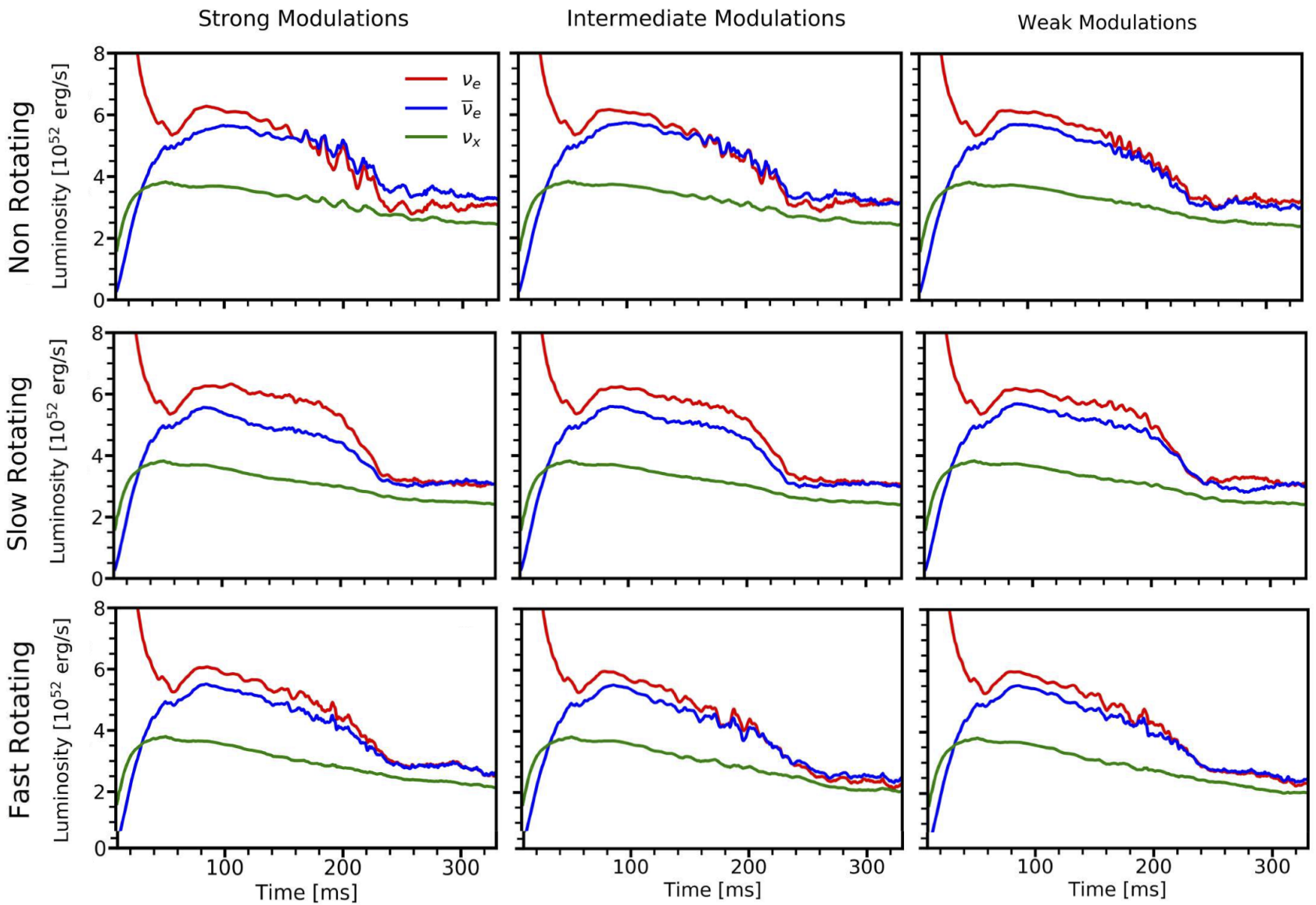

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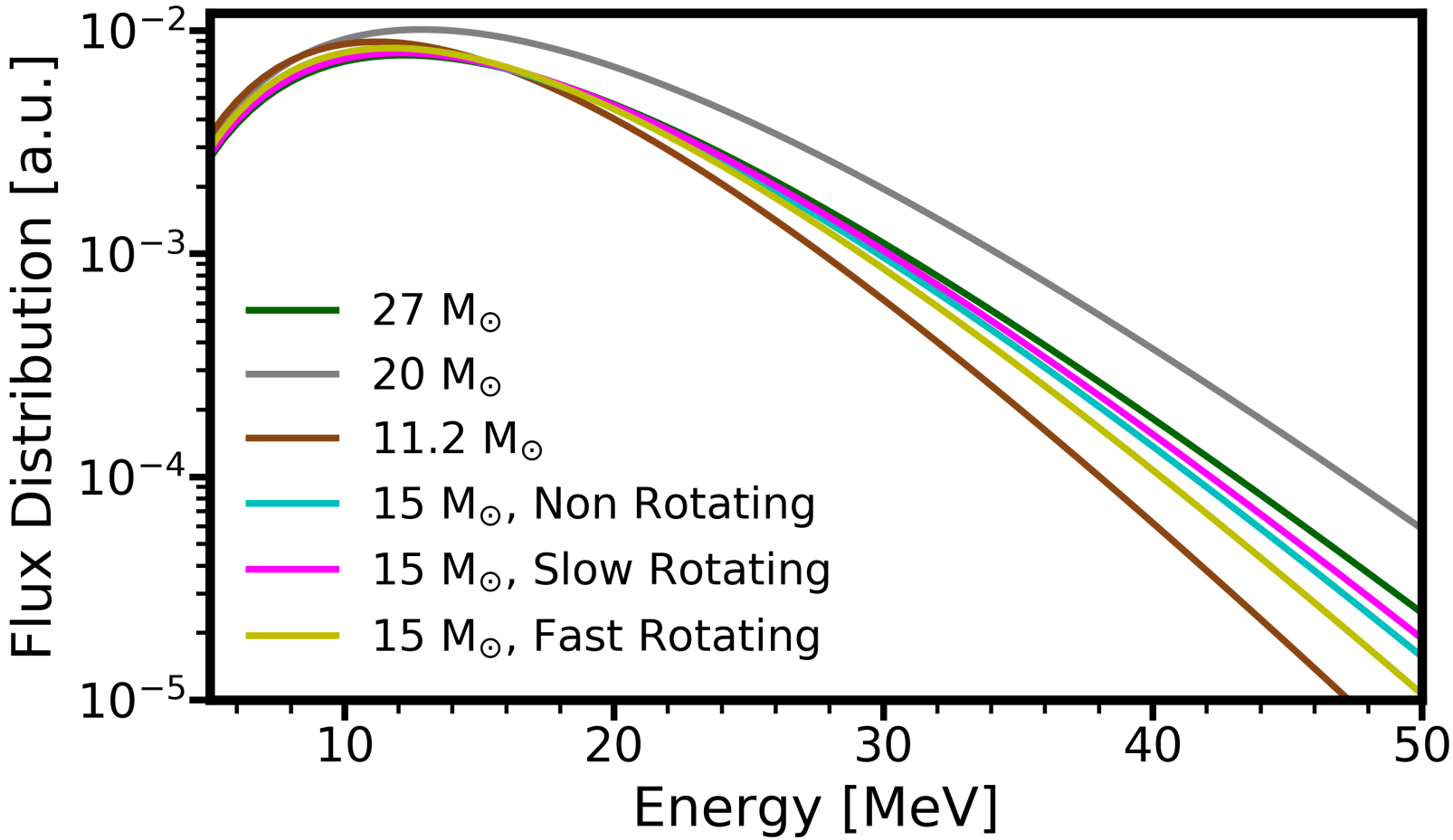

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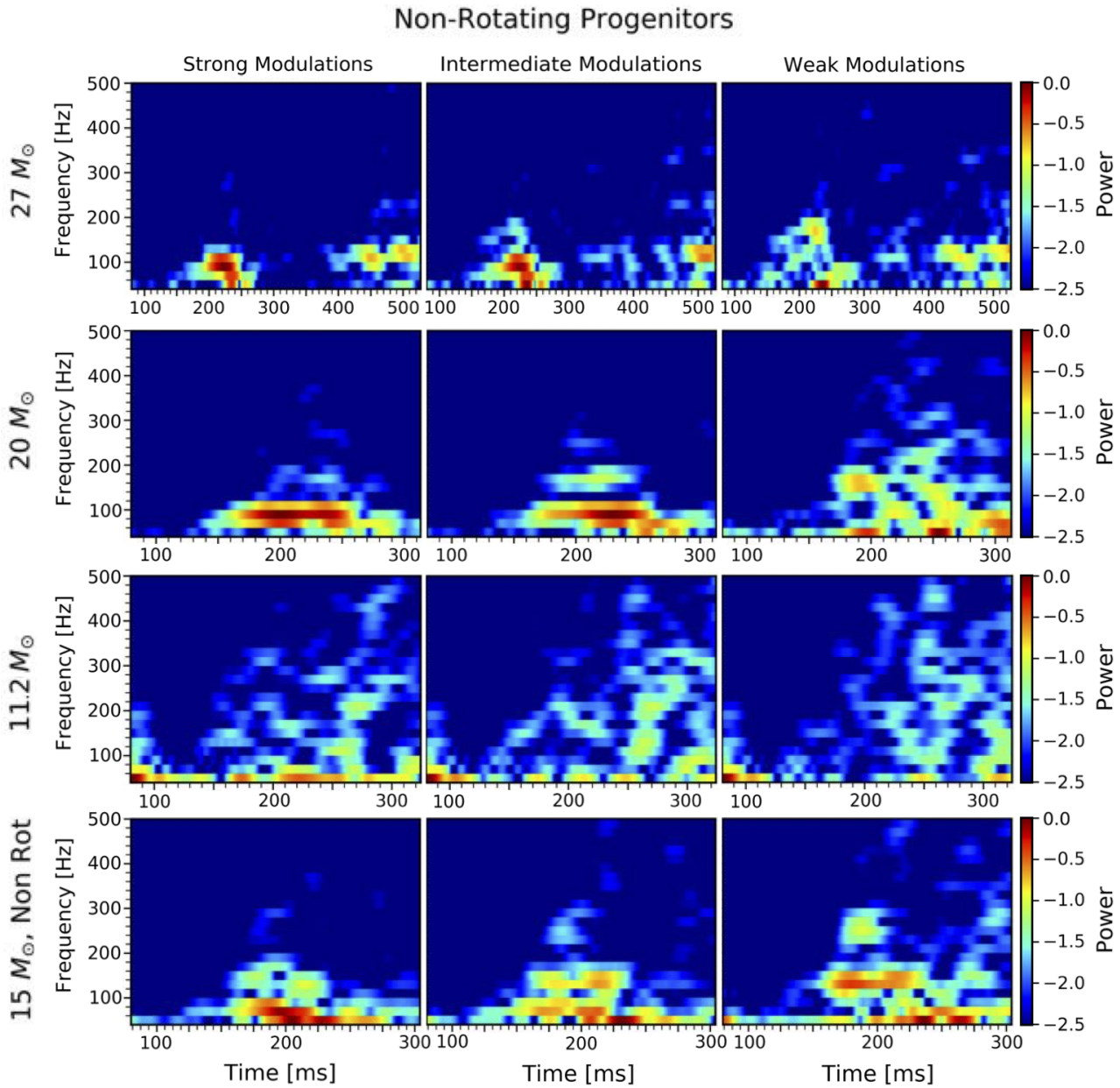

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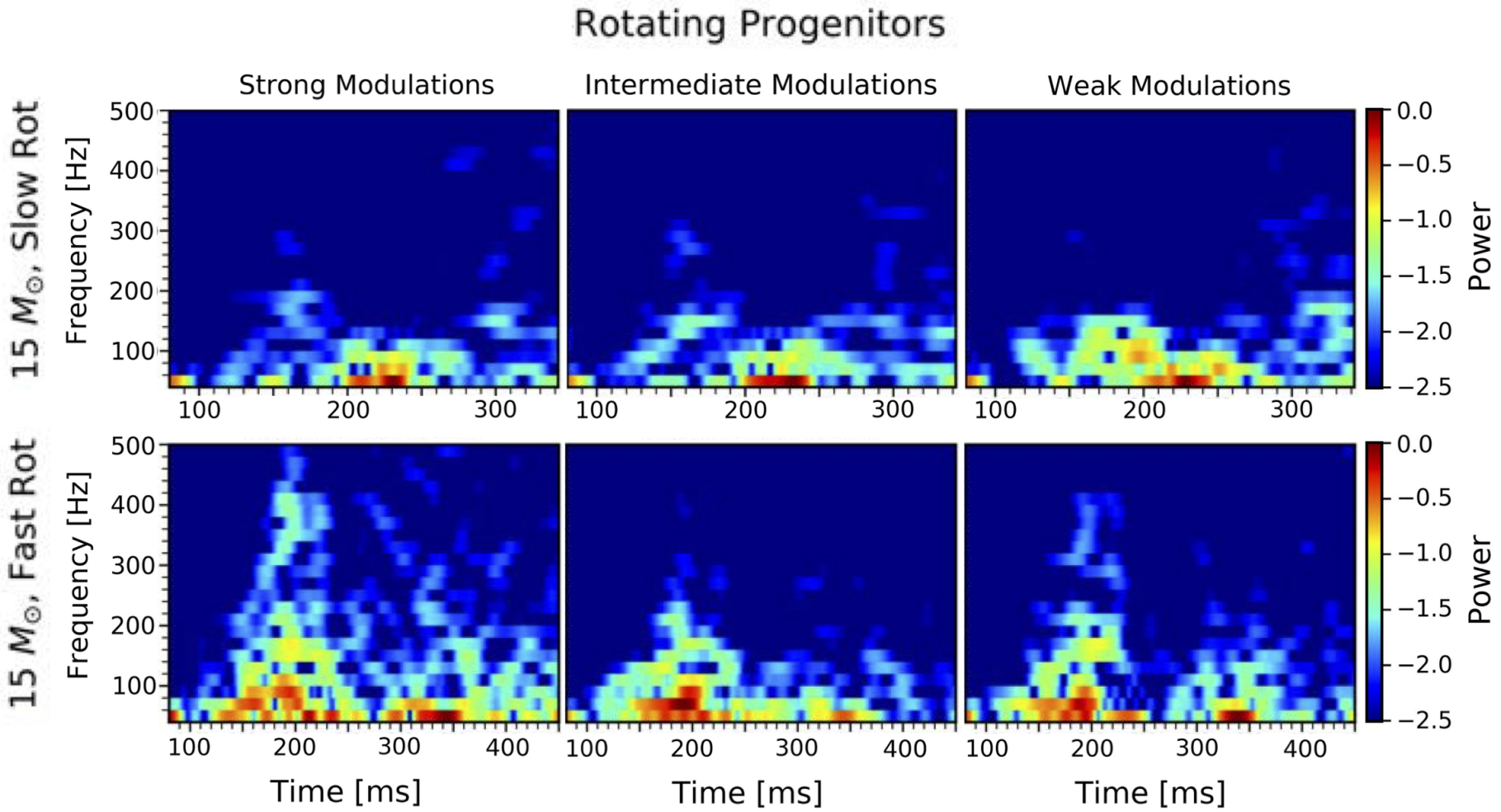
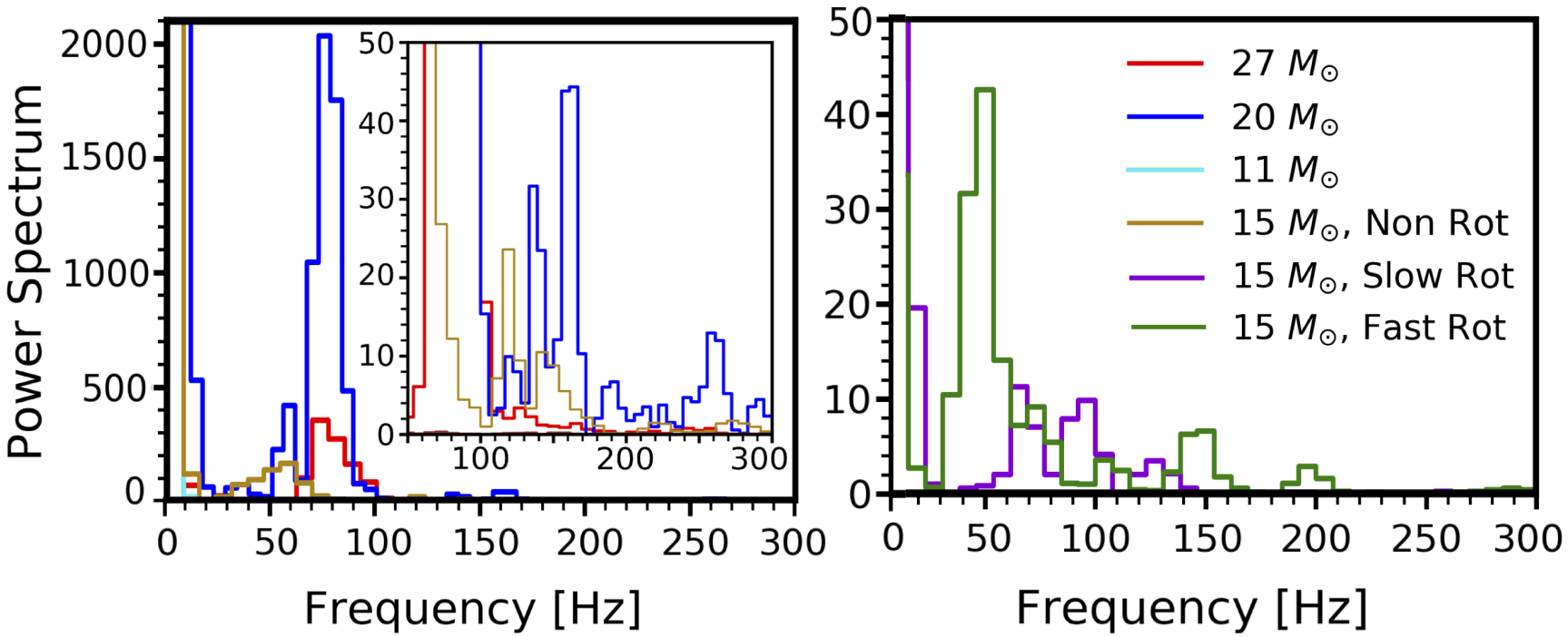


Detectable Features



$\longrightarrow$ Spectra show SASI peak and high frequency peak

$\longrightarrow$ SASI peak broader in rotating models

$\longrightarrow$ Relative height between SASI and high frequency peak decreases with angular momentum

Effects of rotation on LESA

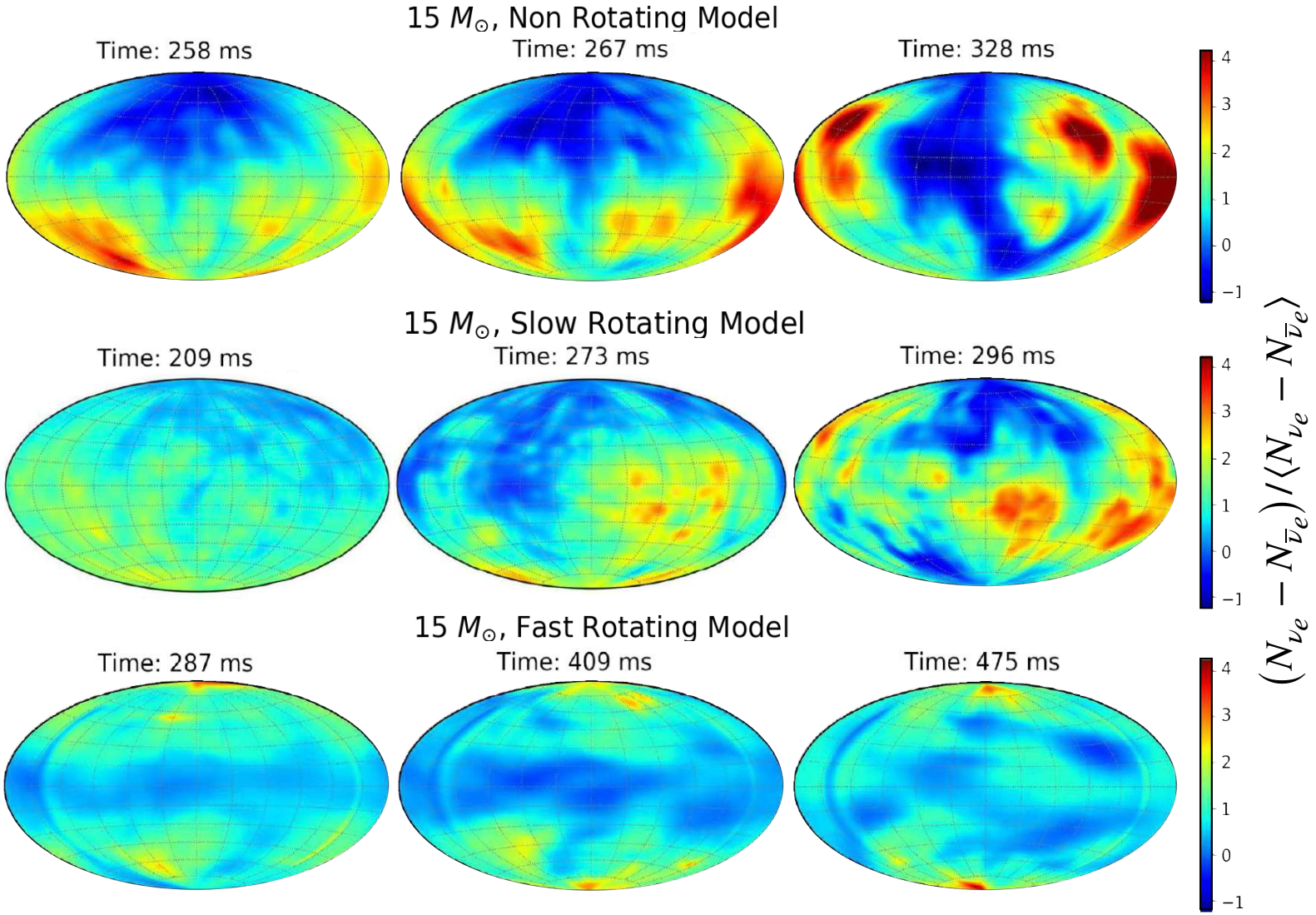
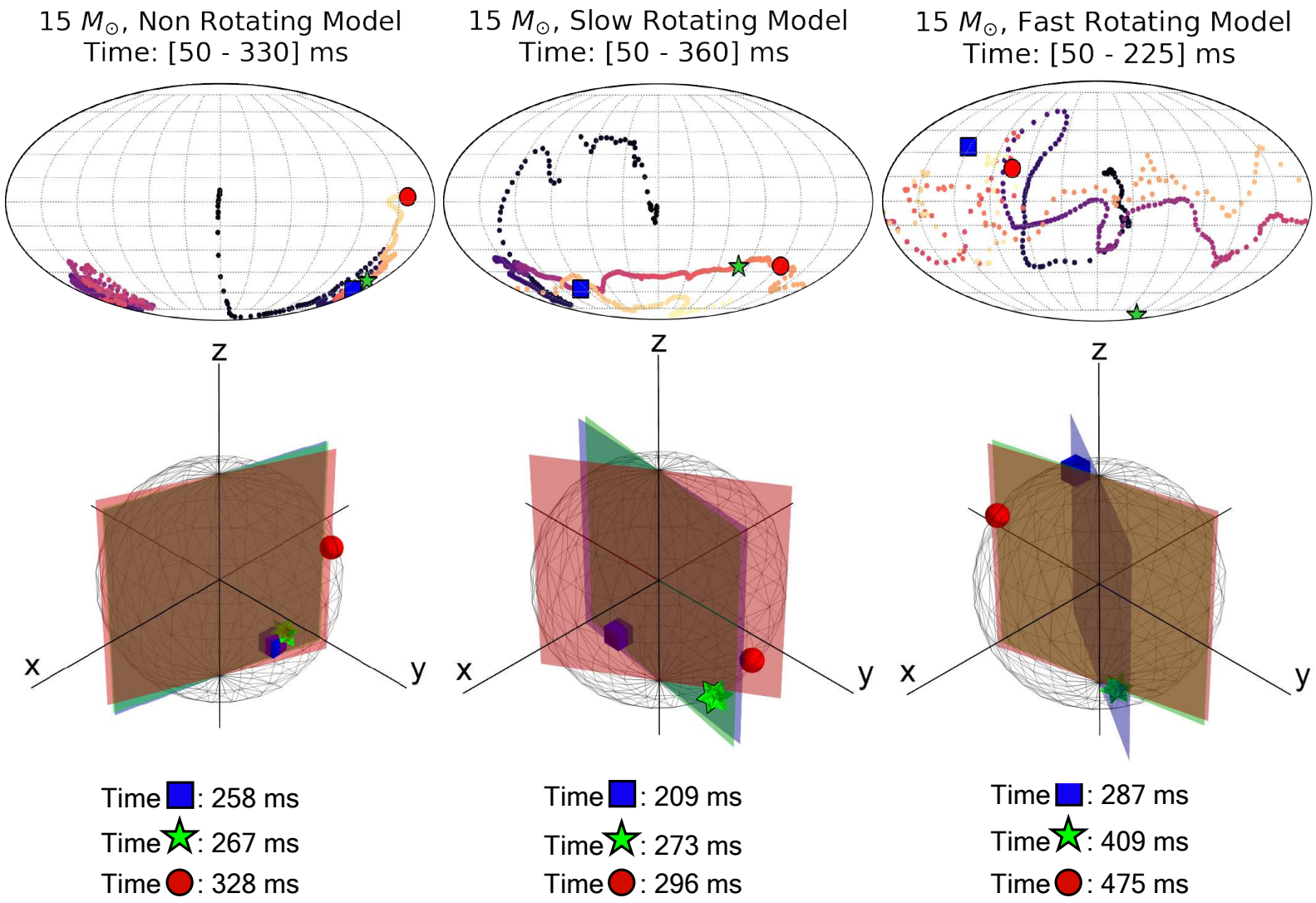


Figure: Snapshots of the ELN flux relative to the 4π-average projected on Mollweide maps.

Effects of rotation on LESA



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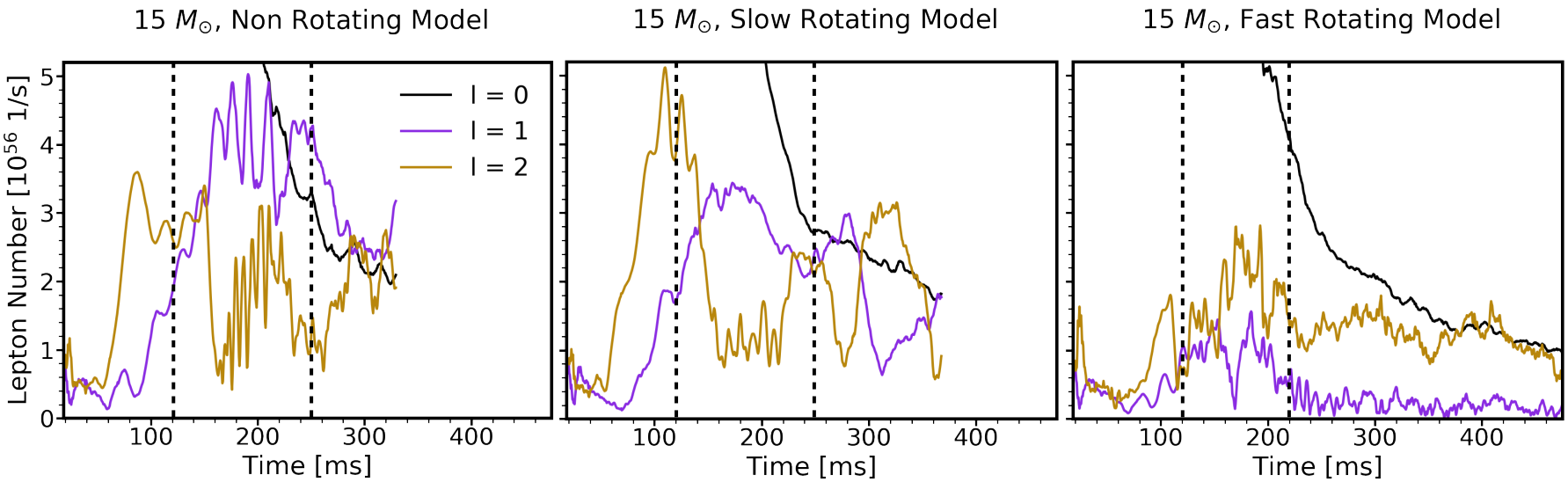

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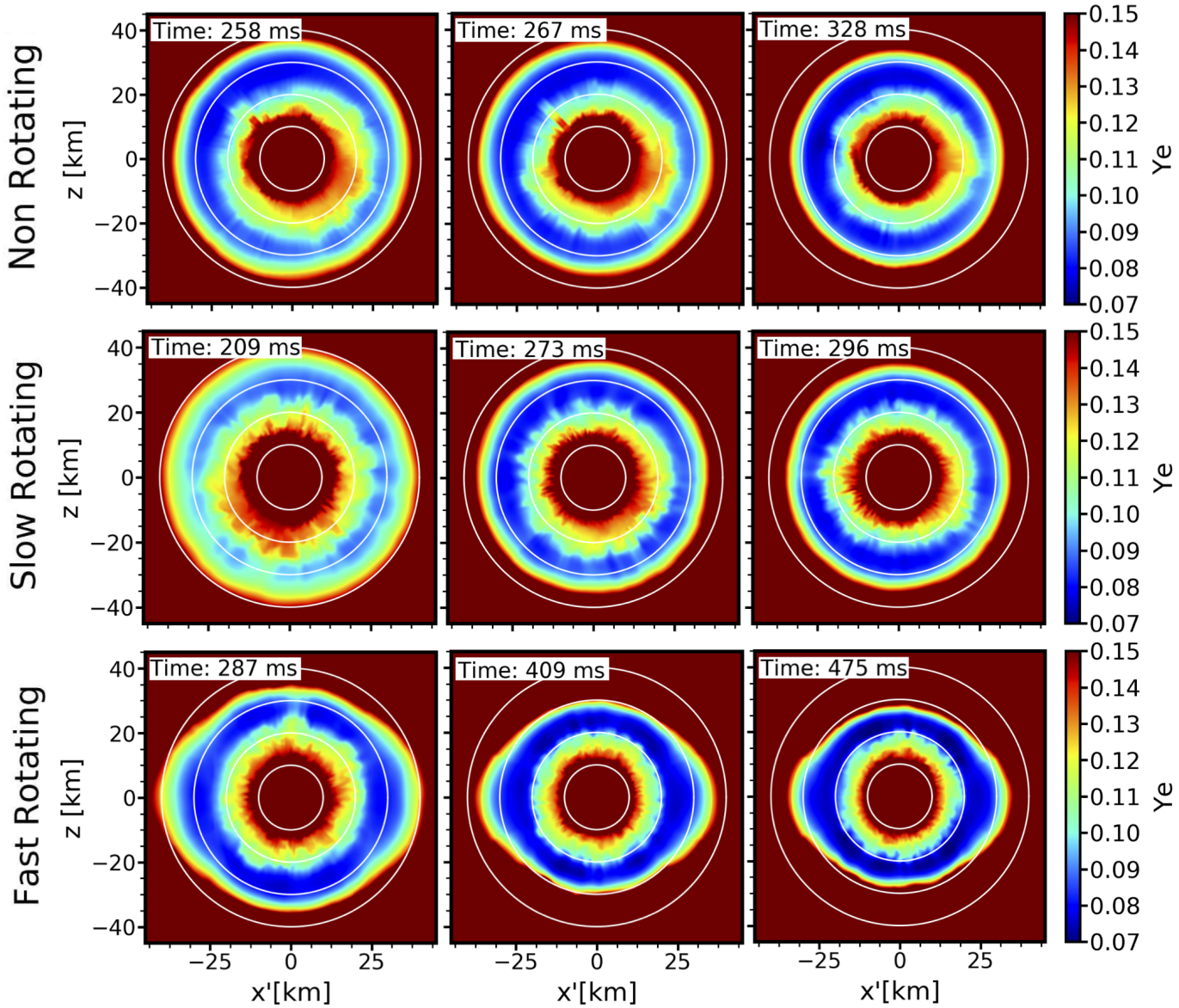

Figure: Cross-sectional slices showing spatial electron fraction distributions for each time.

Effects of rotation on LESA

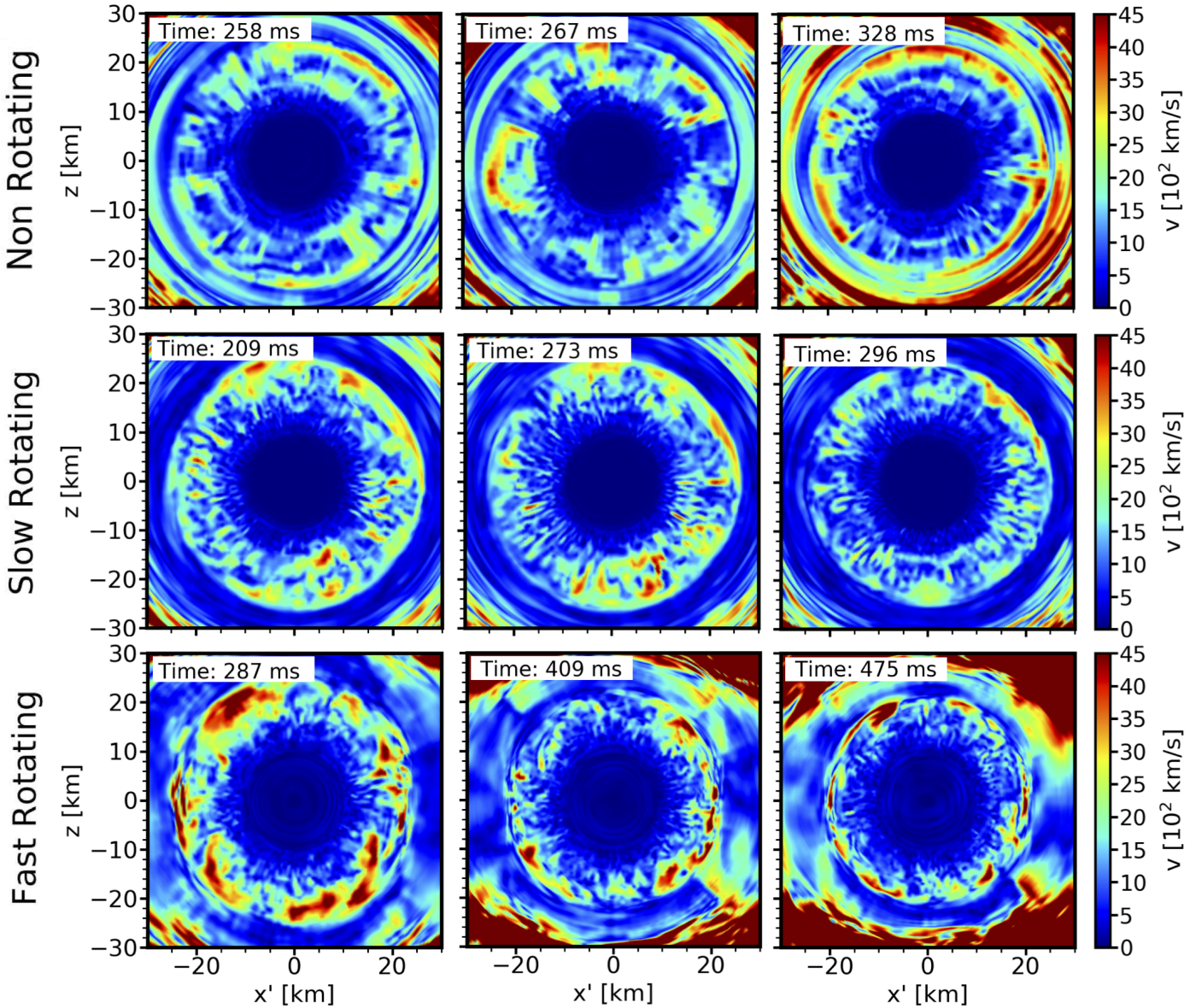

Figure: Cross-sectional slices aboslute fluid velocity distributions for each time.

Effects of rotation on LESA