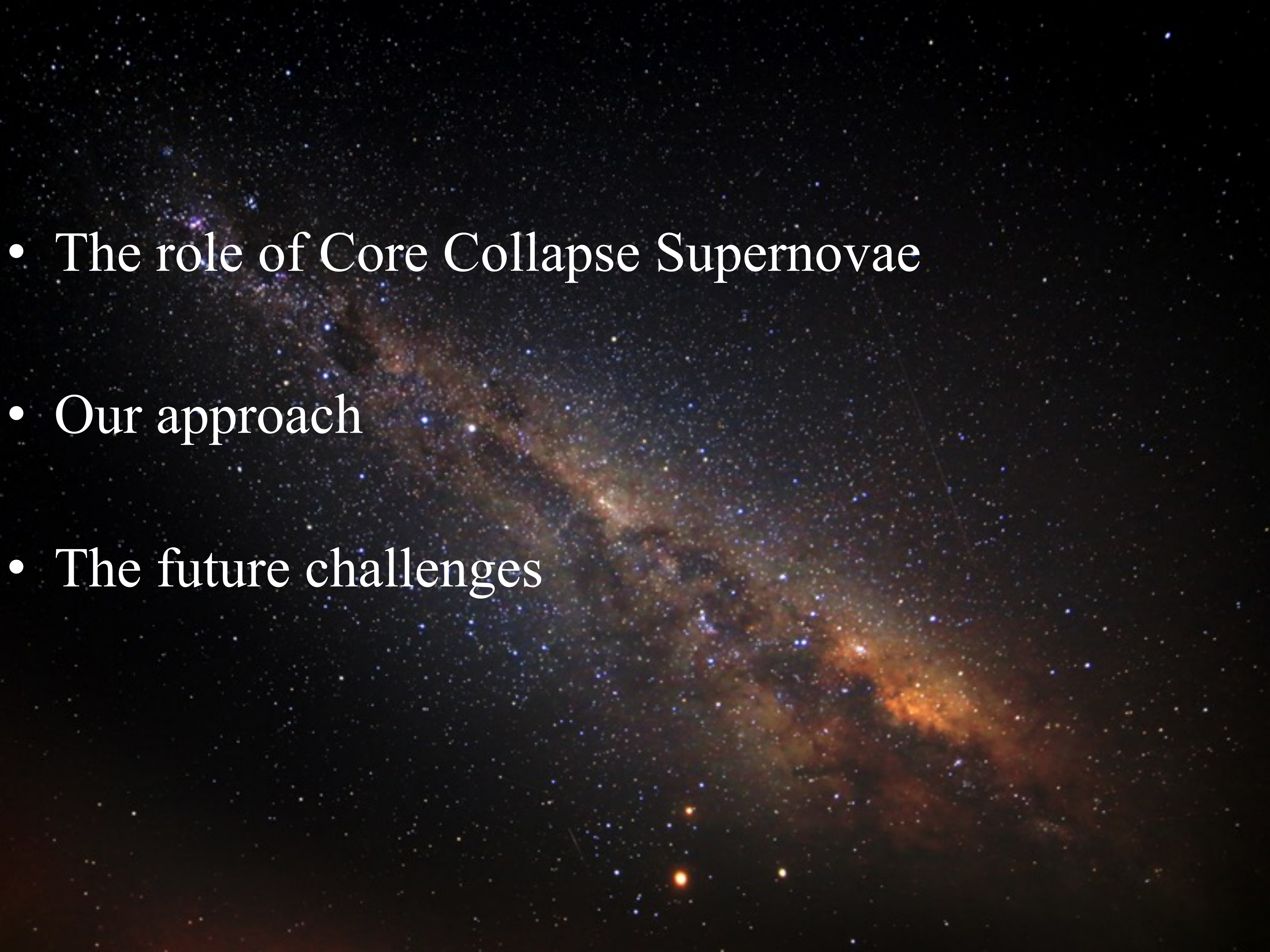
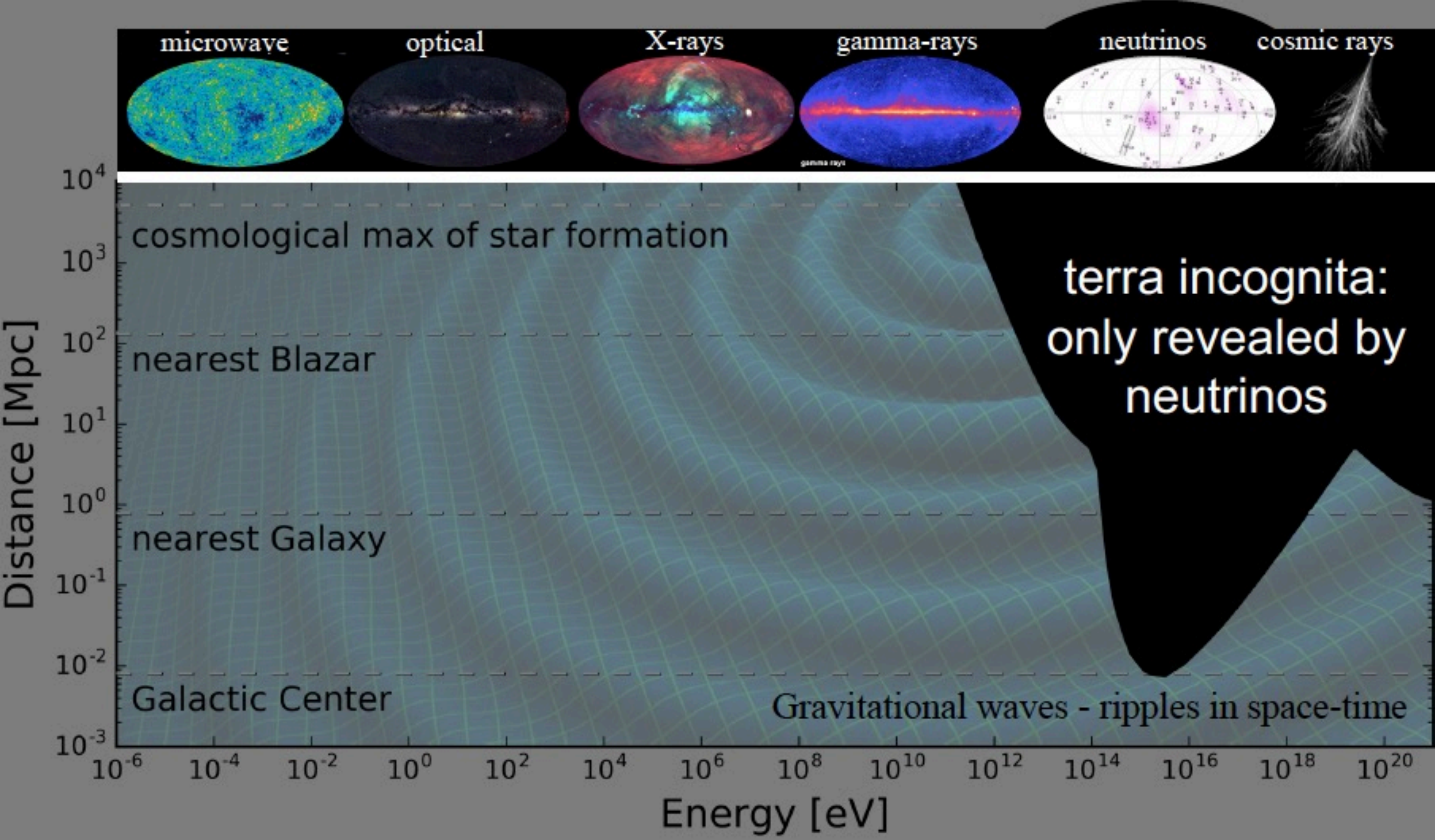
# Neutrino counterpart of kHz Gravitational Wave sources

**Irene Di Palma**

On behalf of
P. Cerda-Duran, M. Drago, M. Portilla, F. Ricci, A. Veutro

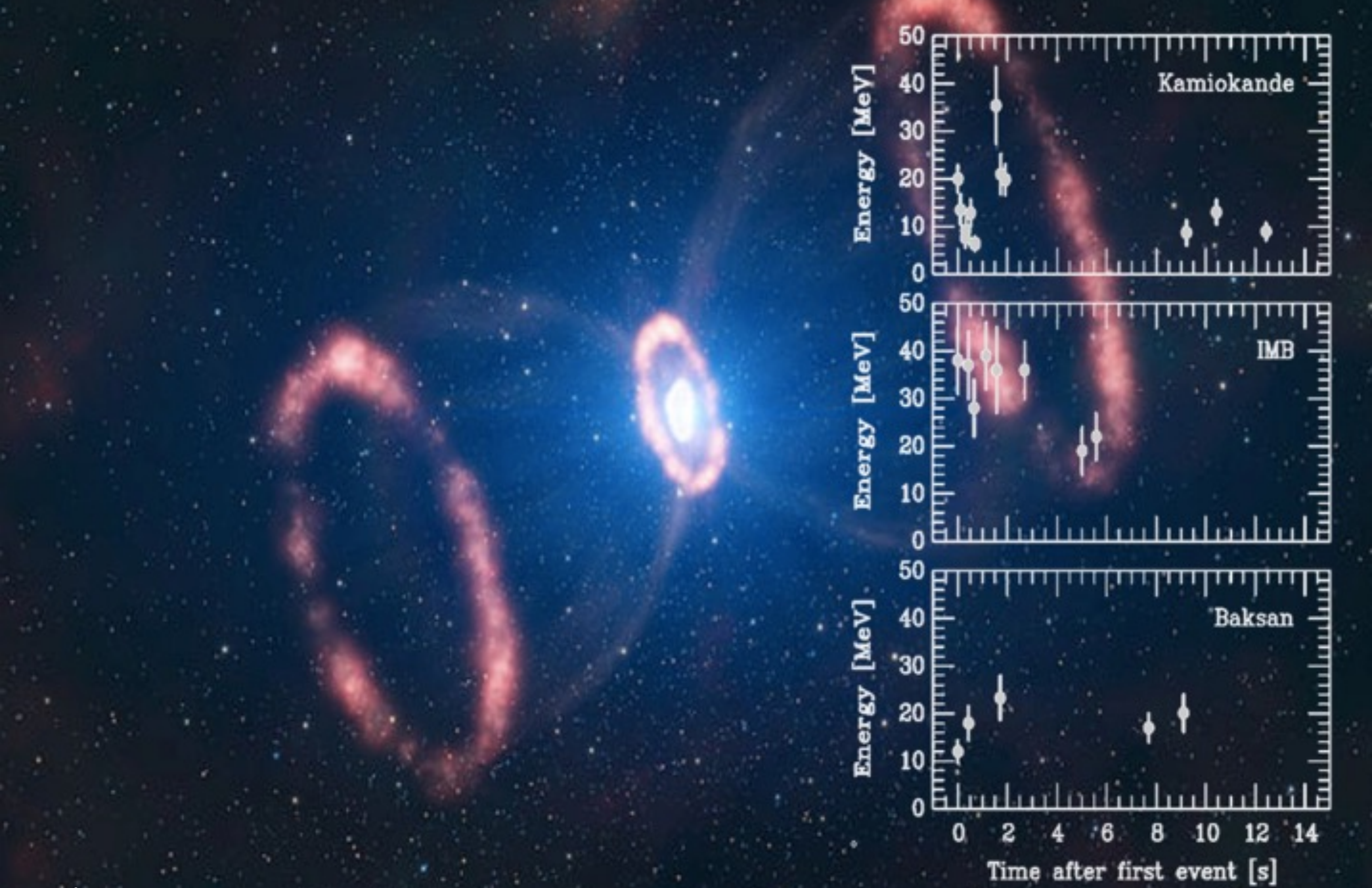


- The role of Core Collapse Supernovae
- Our approach
- The future challenges



- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos

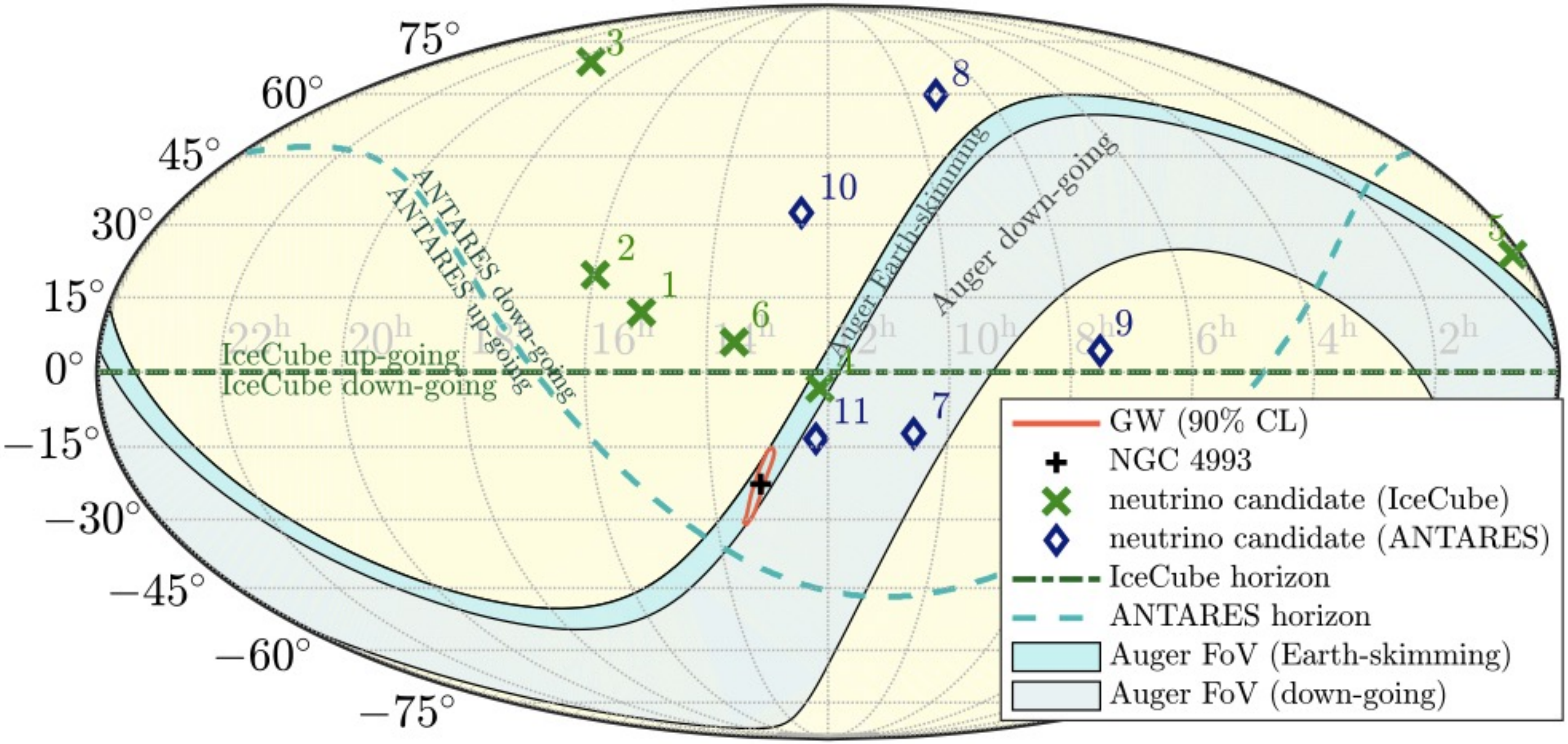
# MeV Neutrinos from SN1987A



February 23, 1987.

*K. Hirata et al., Phys. Rev. Lett. 58, 1490 (1987)*

# Search for High-energy Neutrinos from GW170817

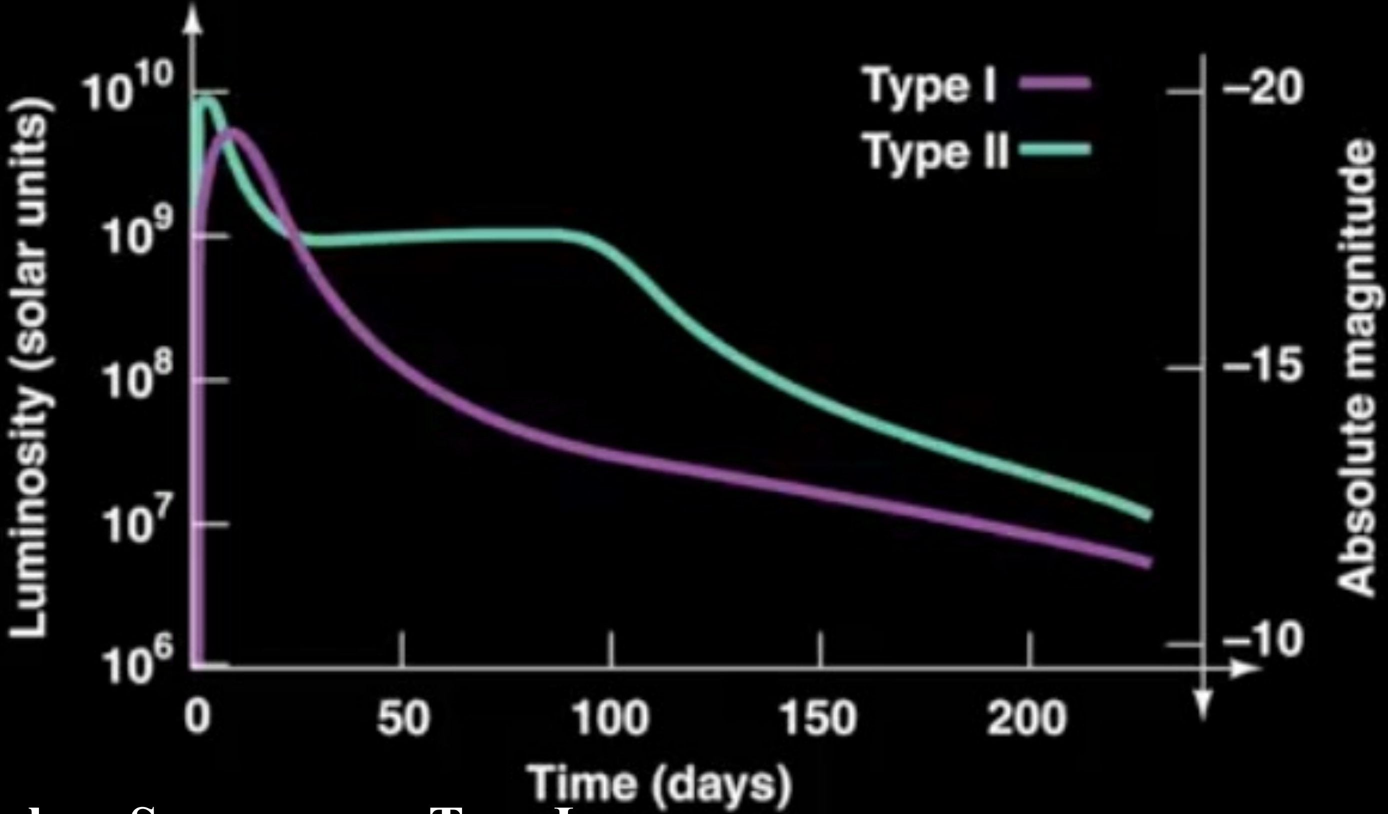


*A. Albert et al. Astrophys. J. Lett. 850, L35 (2017)*

# SNEWS 2.0

The SuperNova Early Warning System (SNEWS) is a global network of neutrino experiments sensitive to supernova neutrinos. The goal of SNEWS is to provide the astronomical community with a prompt alert of an imminent Galactic core-collapse event. This will allow for complete multi-messenger observations of the supernova across the electromagnetic spectrum, in gravitational waves, and in neutrinos.

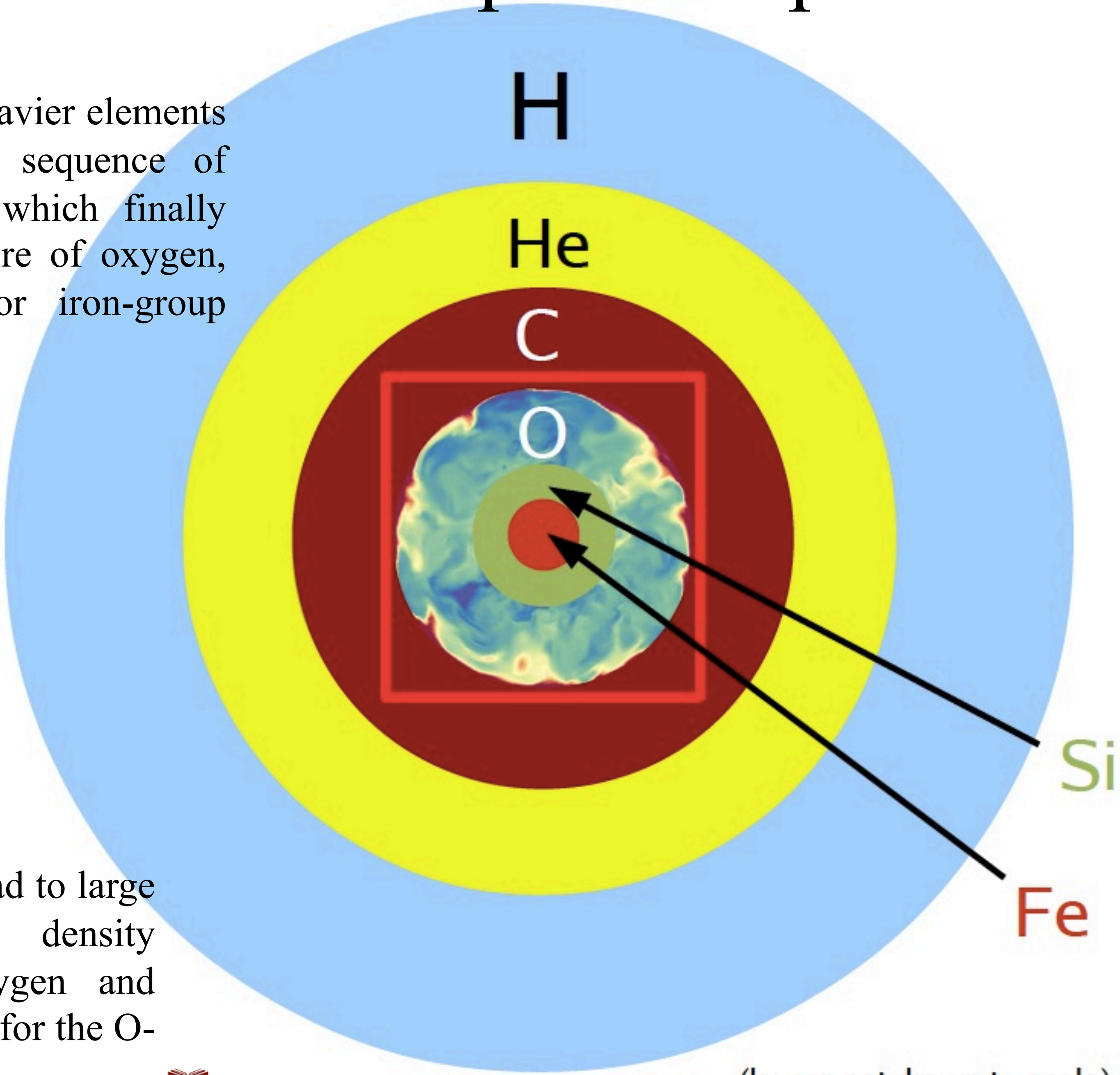
*S. Al Kharusi et al, New J. Phys. 23 031201 (2021)*



- **Thermonuclear Supernovae: Type Ia**
  - Caused by runaway thermonuclear burning of white dwarf fuel to Nickel
  - Roughly of $10^{51}$ ergs released
  - Very bright, used as standard candles
  - No remnant
- **Core Collapse Supernovae: Type II, Ib, Ic**
  - Result from the collapse of an iron core in an evolved massive star ($M_{ZAMS}$ >8-10 $M_{SUN}$)
  - Few x $10^{53}$ ergs released in gravitational collapse, most (99%) radiated in neutrinos
  - Spread stellar evolution elemental products throughout galaxy
  - Neutron star or black hole remnant

# Onion shell structure of pre-collapse star

Shells of progressively heavier elements contain the ashes of a sequence of nuclear burning stages, which finally build up a degenerate core of oxygen, neon and magnesium or iron-group elements at the center.

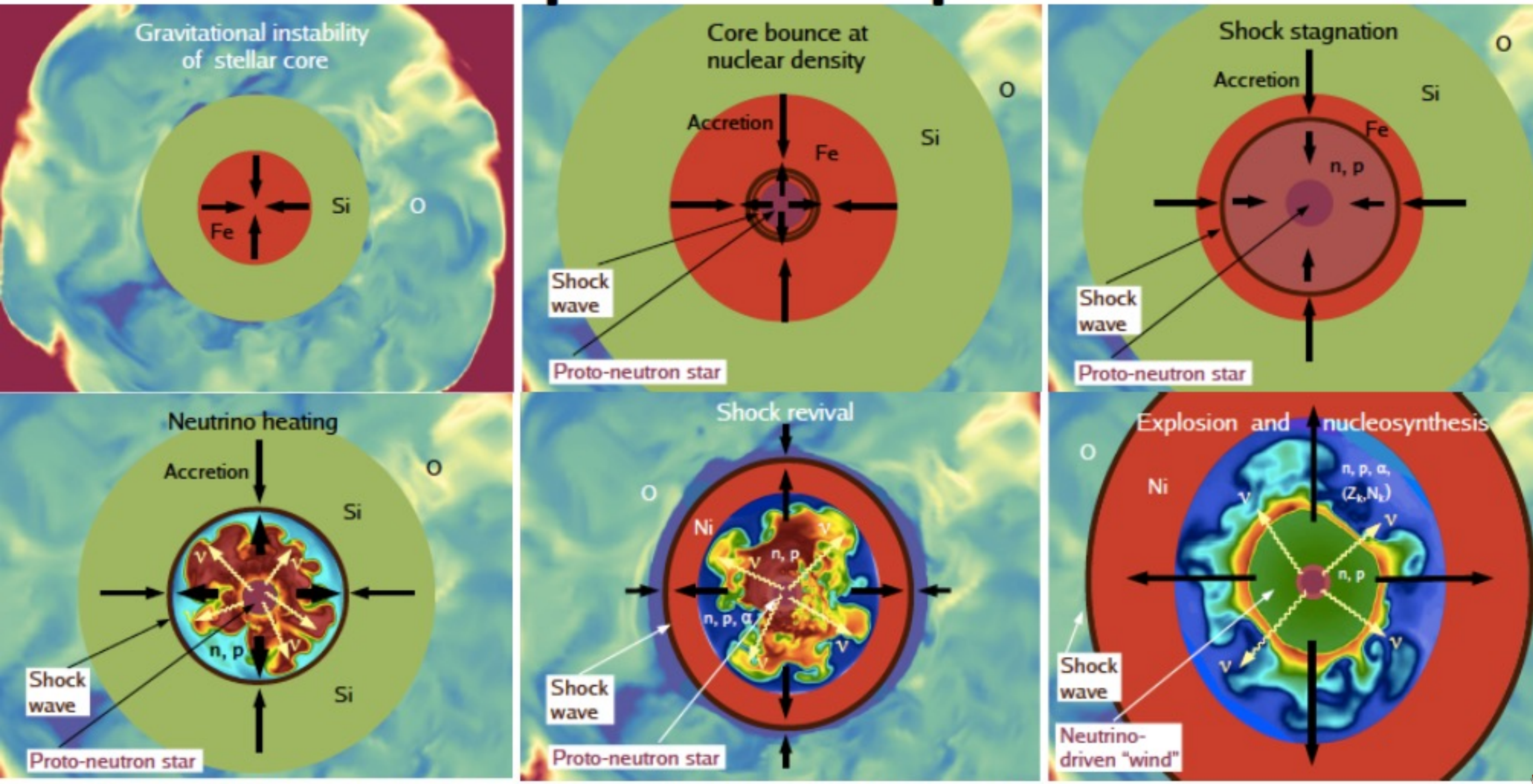


Convective burning can lead to large scale velocity and density perturbations in the oxygen and silicon layers (as indicated for the O-shell).

*H.-Th Janka, arXiv:1702.08825*

(layers not drawn to scale)

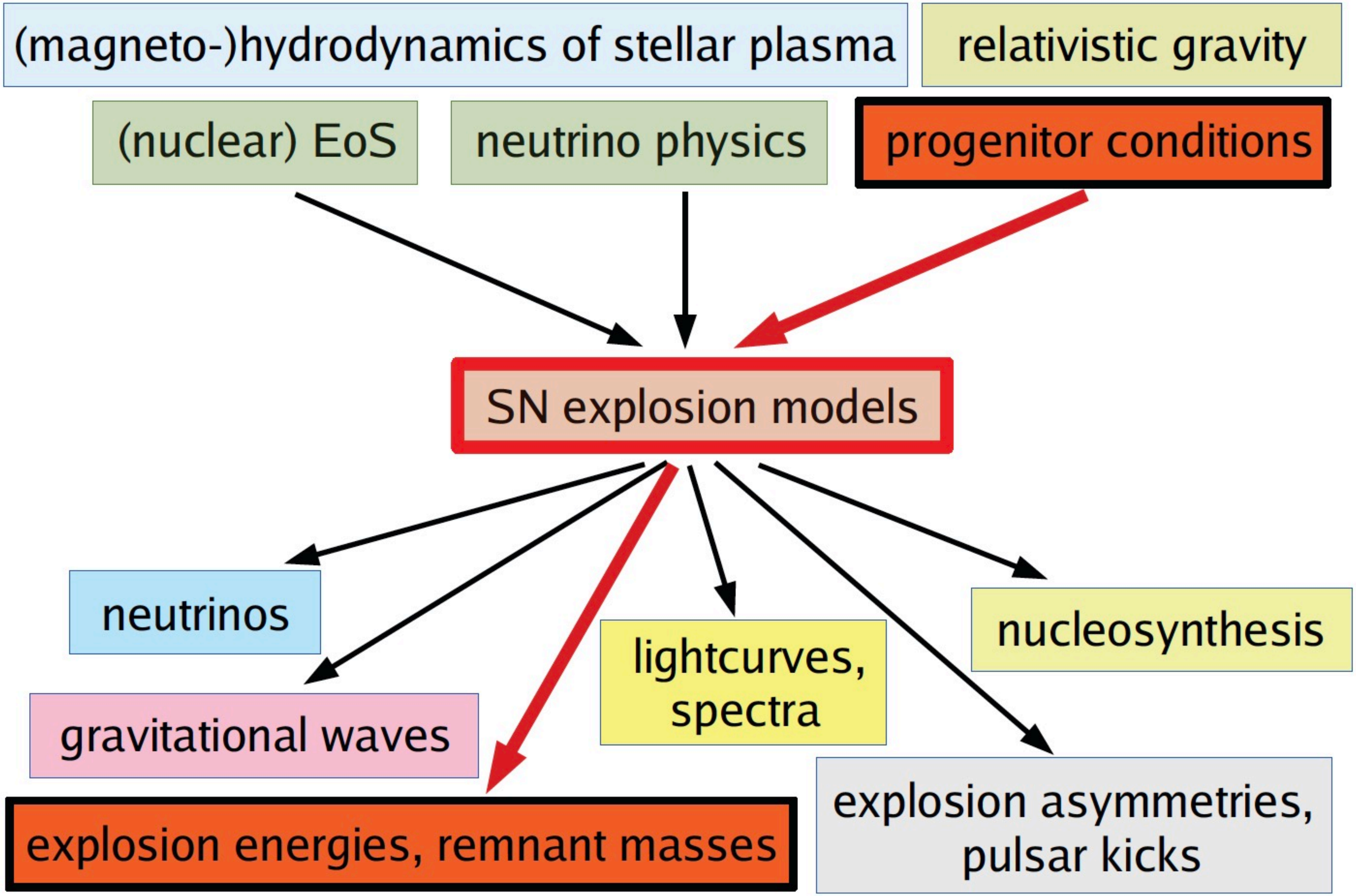
# Dynamical phases of stellar core collapse and explosion



[H.-Th Janka, arXiv:1702.08825]

- When the radiation pressure doesn't balance gravity anymore the collapse starts.
- The implosion of the inner core is stopped abruptly when nuclear saturation density is reached at the center.
- The inner core bounces back and its expansion creates pressure waves.
- The newly formed shock begins to propagate outwards in radius as well as in mass.
- Shortly after core bounce neutrino emission carries away energy from the postshock layer.
- If the heating by neutrinos is strong enough, the shock can be pushed outwards and the SN explosion can be launched.

# Predictions of Signals from Supernovae



(magneto-)hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

gravitational waves

explosion energies, remnant masses

lightcurves, spectra

nucleosynthesis

explosion asymmetries, pulsar kicks

# A NEW GRAVITATIONAL-WAVE SIGNATURE FROM STANDING ACCRETION SHOCK INSTABILITIES IN SUPERNOVAE

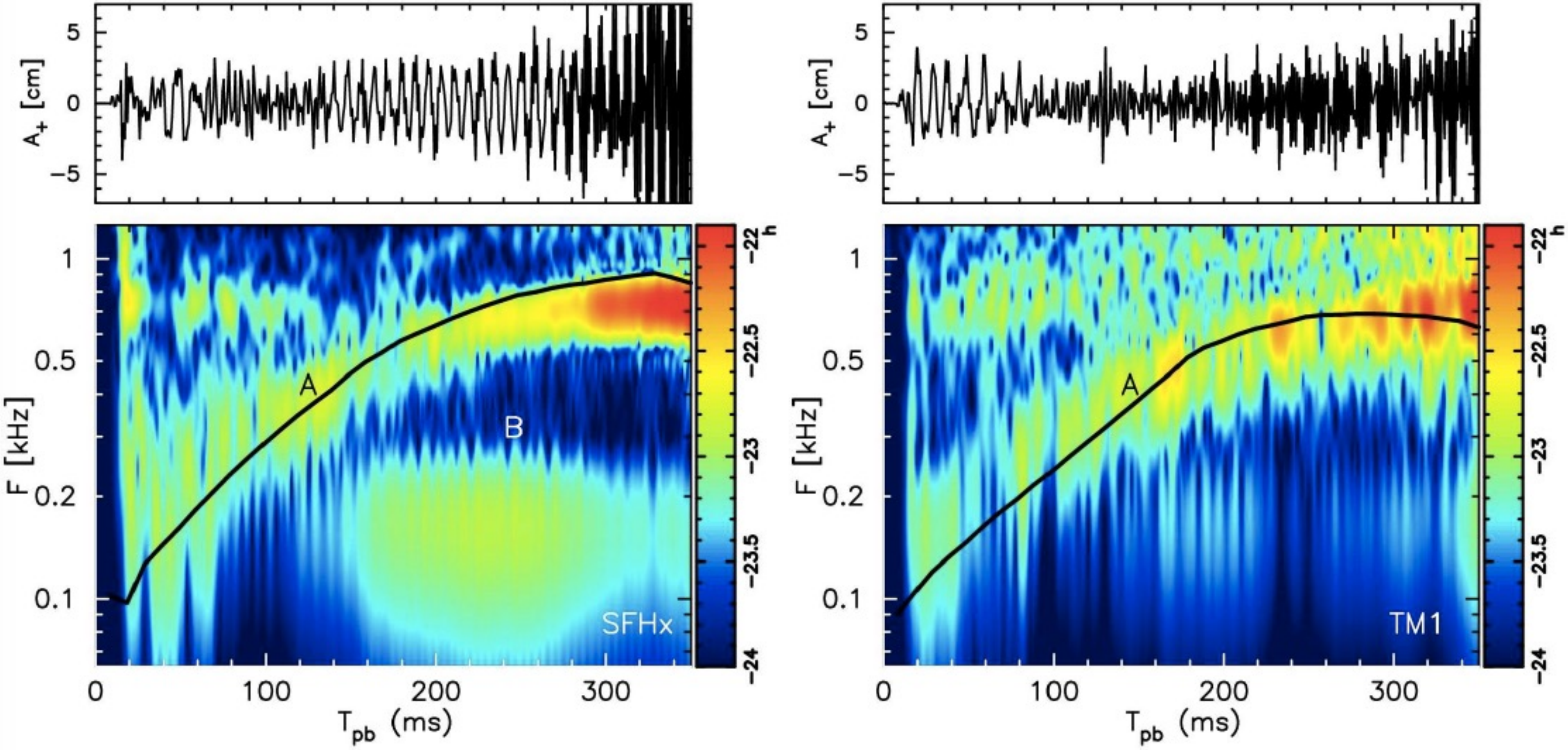
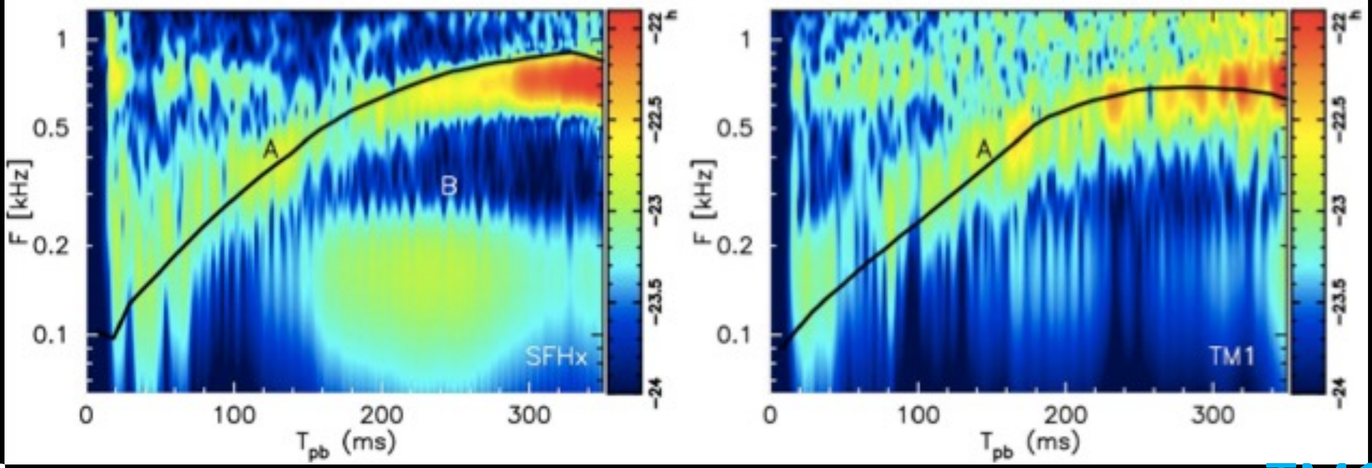


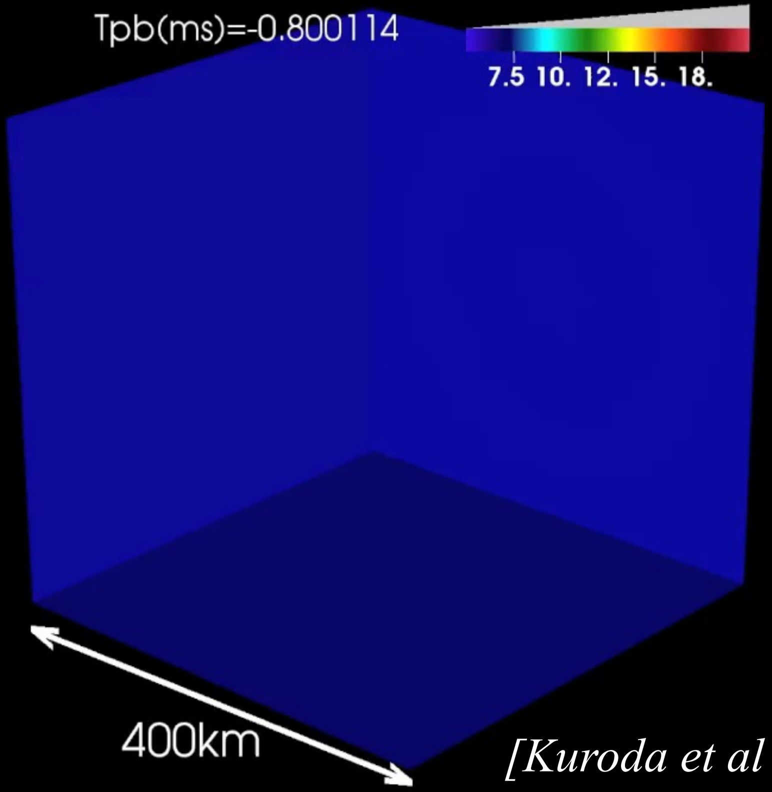
FIG. 1.— In each set of panels, we plot, top; gravitational wave amplitude of plus mode $A_+$ [cm], bottom; the characteristic wave strain in frequency-time domain $\tilde{h}$ in a logarithmic scale which is over plotted by the expected peak frequency $F_{\rm peak}$ (black line denoted by "A"). "B" indicates the low frequency component. The component "A" is originated from the PNS $g$-mode oscillation (Marek & Janka 2009; Müller et al. 2013). The component "B" is considered to be associated with the SASI activities (see Sec. 3). Left and right panels are for TM1 and SFHx, respectively. We mention that SFHx (left) and TM1 (right) are softer and stiffer EoS models, respectively.

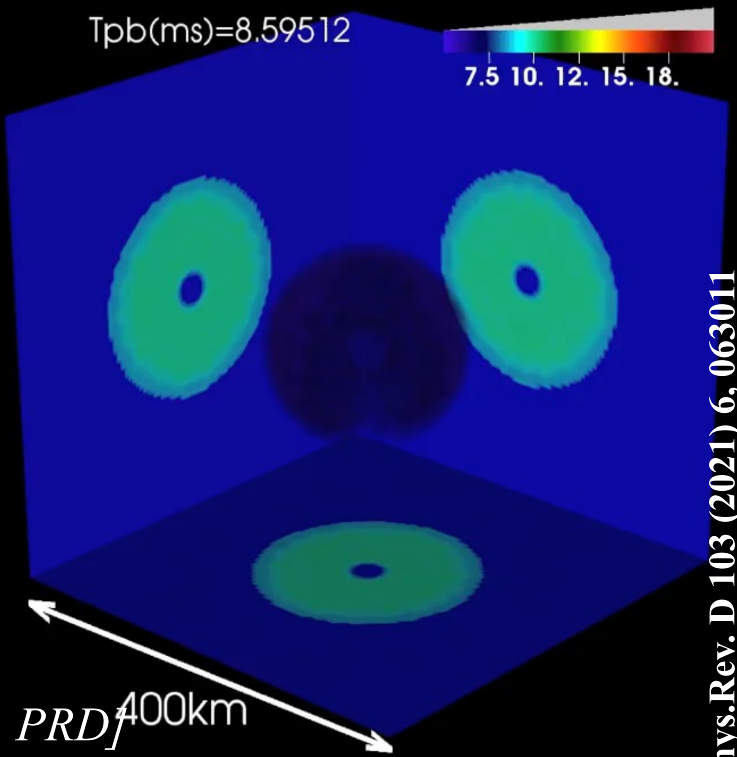
*T. Kuroda et al.,Astrophys.J. 829 (2016) no.1, L14*



SFHx :softer

TM1 :stiffer





*[Kuroda et al 2016, ApJL, 2014, PRD]*

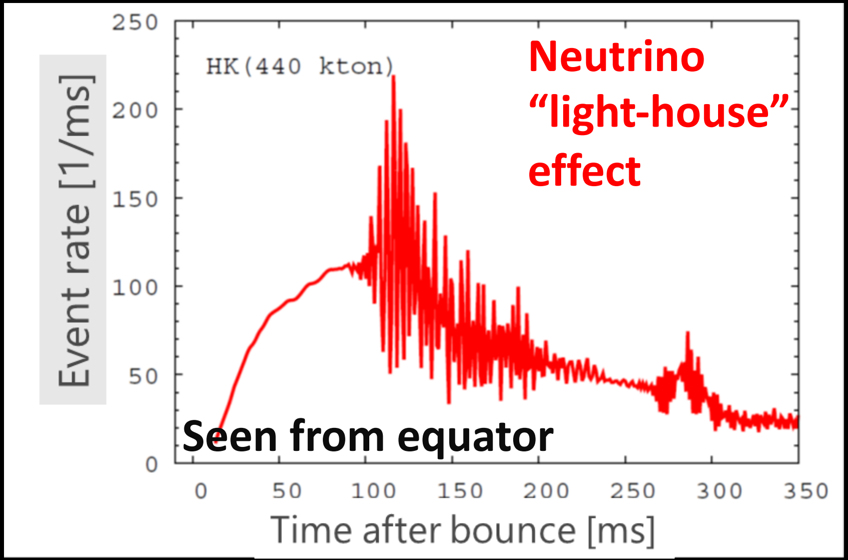
✓ **SASI activity higher for softer EOS** (due to high growth rate, e.g., Foglizzo et al. ('06)).

Phys.Rev. D 103 (2021) 6, 063011

# Correlation of ν and GW signals from a rapidly rotating 3D model

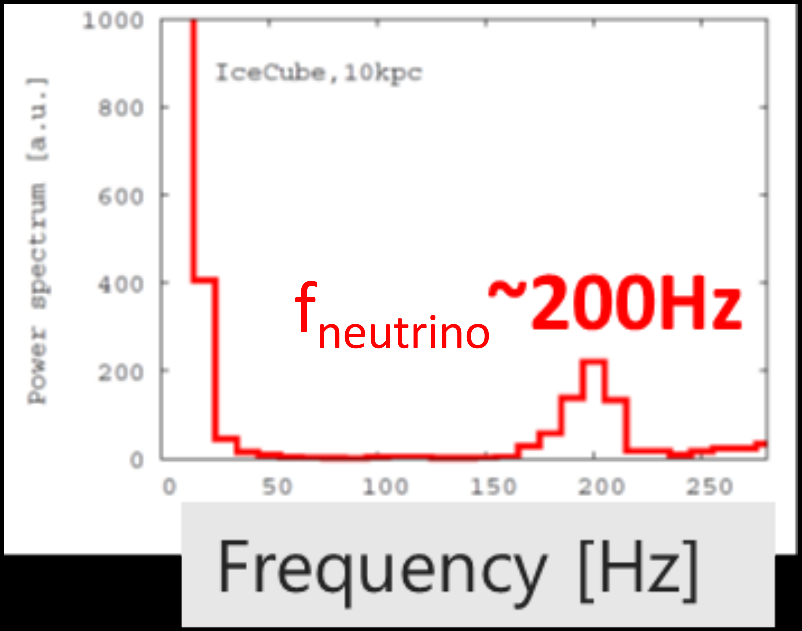
**Takiwaki, KK, Foglizzo, (2021)**

Neutrino event rate (27 $M_{sun}$, $\Omega_0$ = 2rad/s)



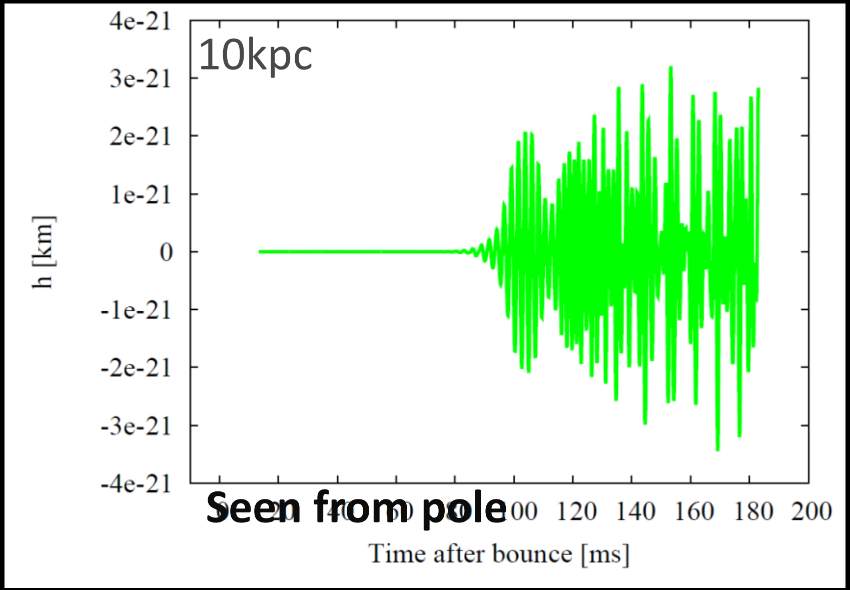
**Neutrino "light-house" effect**

**Seen from equator**



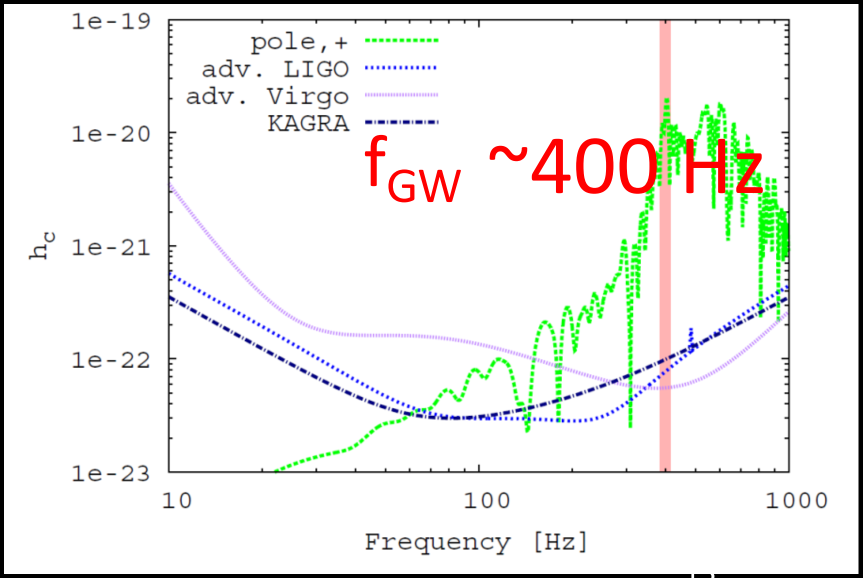
$f_{neutrino}$ ~200Hz

Gravitational waveform



10kpc

**Seen from pole**



$f_{GW}$ ~400 Hz

**Courtesy of K. Kotake**

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Takiwaki, KK, Foglizzo, (2021)

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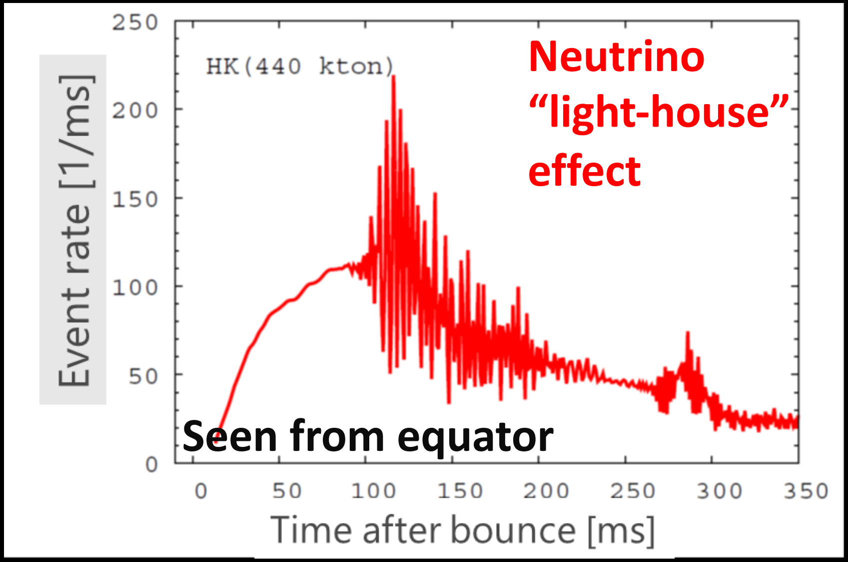

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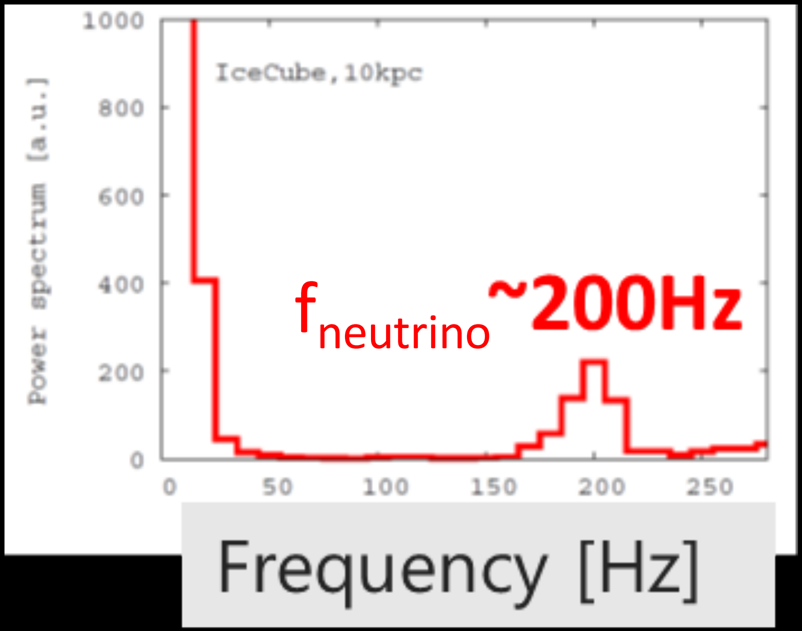

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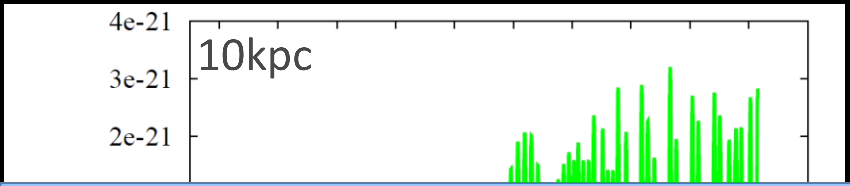
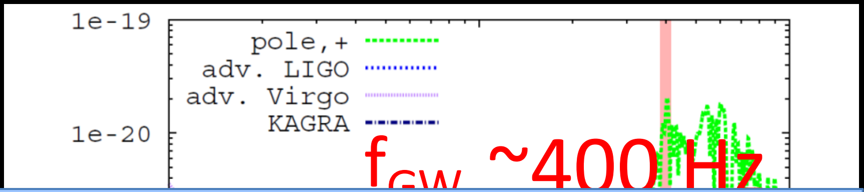
Gravitational waveform

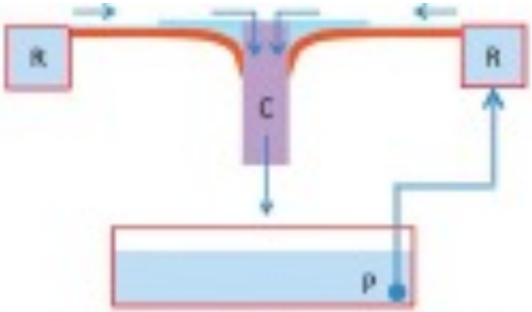


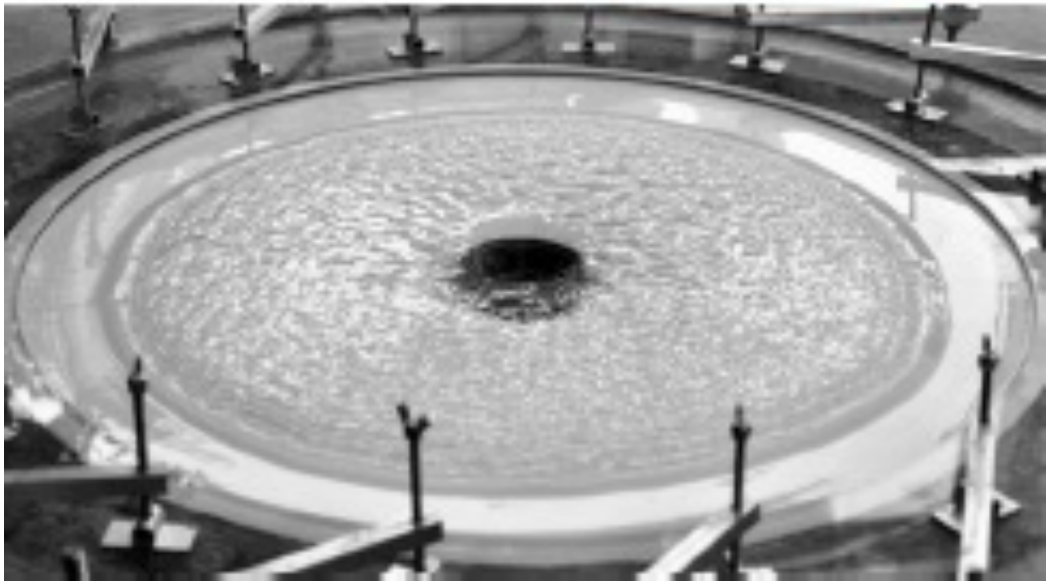


$f_{GW}$ ~400 Hz

- ✓ Peak frequency of GW signals ($f_{gw}$) is twice of the neutrino modulation freq ($f_{neutrino}$)! Due to the quadrupole GW emission
- ✓ Also the case for non-rotating progenitor, $f_{neutrino,SASI}$~80Hz, $f_{gw}$~160Hz
- ✓ Coincident detection between GW and ν: smoking gun signature of rapid core rotation!

# Shallow Water Analogue of the Standing Accretion Shock Instability





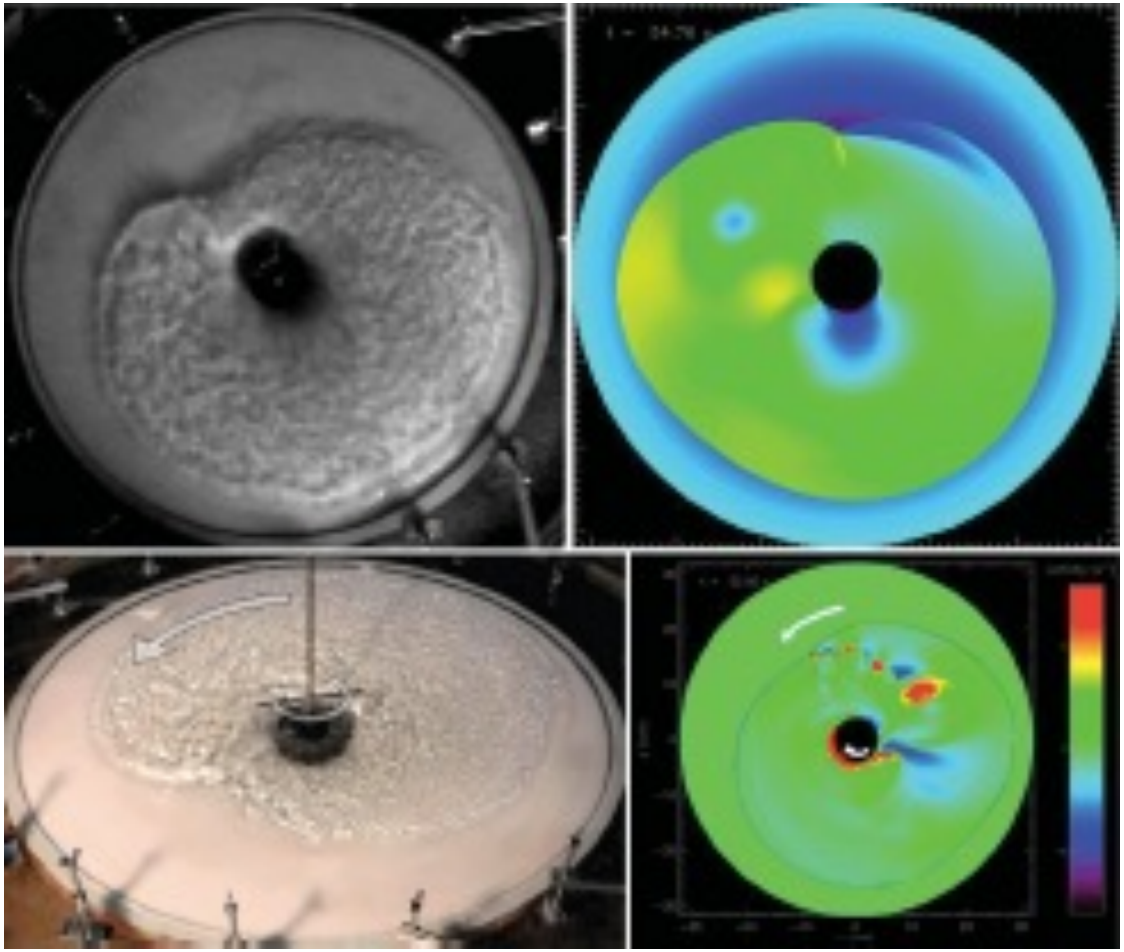
Like the classical hydraulic jump in a kitchen sink (upper left), involves a hydraulic jump associated to the deceleration of a radial flow of water. Water is injected inward from an annular injection reservoir (R) along a hyperbolic potential well, and evacuated through a vertical cylinder (C), whose walls mimic the surface of the neutron star. A pump (P) distributes collected water.

Drawing a parallel between stellar explosions and shallow water physics is unexpected but it is deeply rooted in the universality of the laws of fluid mechanics.

***T. Foglietto et al., PRL 108, 051103 (2012)***

# ShallowWater Analogue of the Standing Accretion Shock Instability

As the water flux is increased, a large scale instability sets in through growing oscillations of the hydraulic jump. The shape and dynamical evolution of the hydraulic jump in the nonlinear regime is remarkably akin to the astrophysical numerical simulations when the spiral mode reaches nonlinear amplitudes

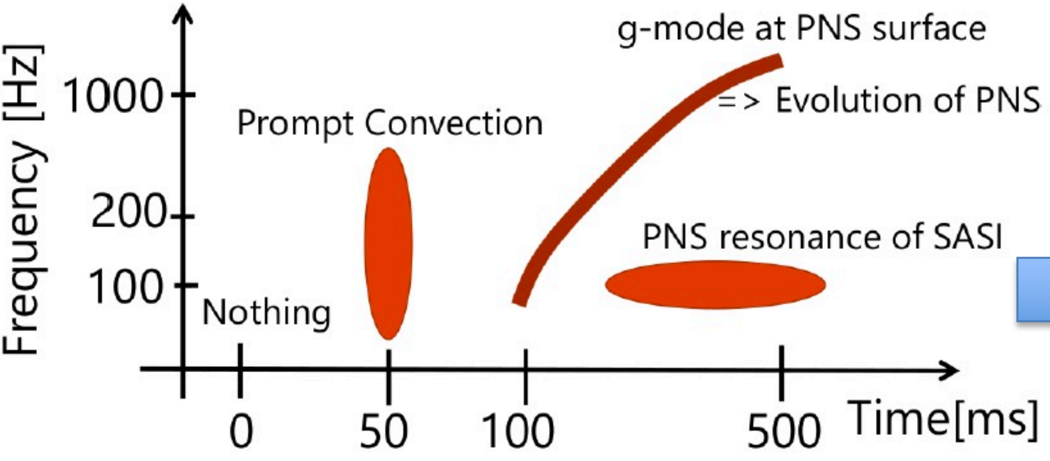


Another striking similarity is the fact that the angular momentum of the accreted fluid is opposite to the direction of rotation of the hydraulic jump.

*T. Foglietto et al., PRL 108, 051103 (2012)*

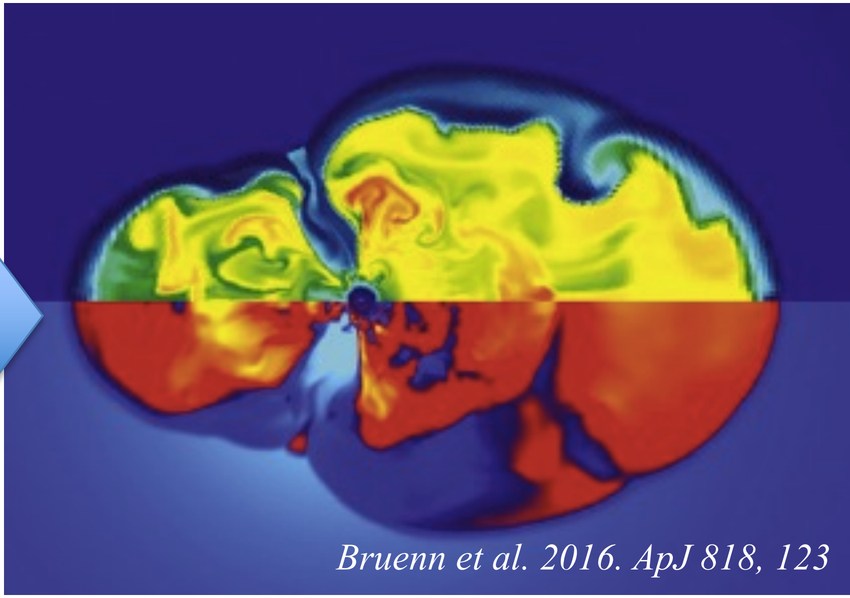
# Different scenarios

Non rotating scenario



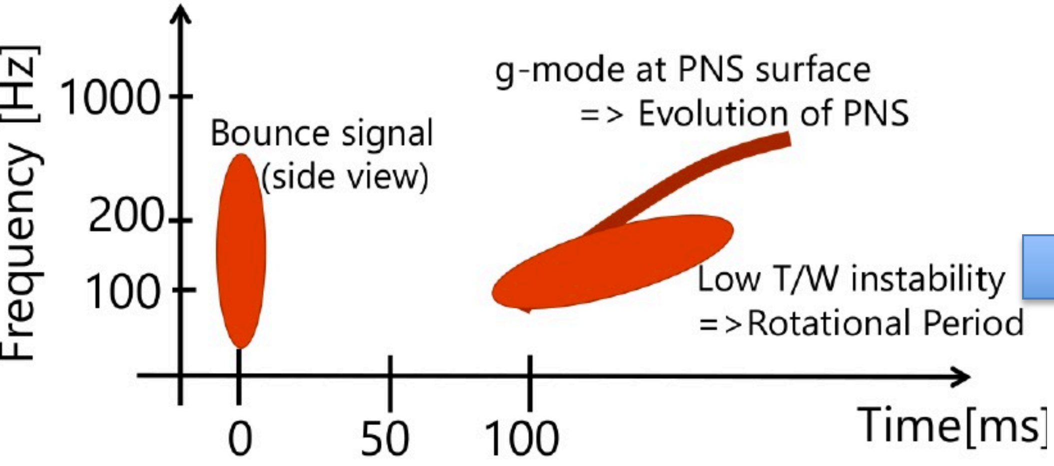
↑ Bounce time is determined by ν observation

Neutrino driven CCSNe



*Bruenn et al. 2016. ApJ 818, 123*

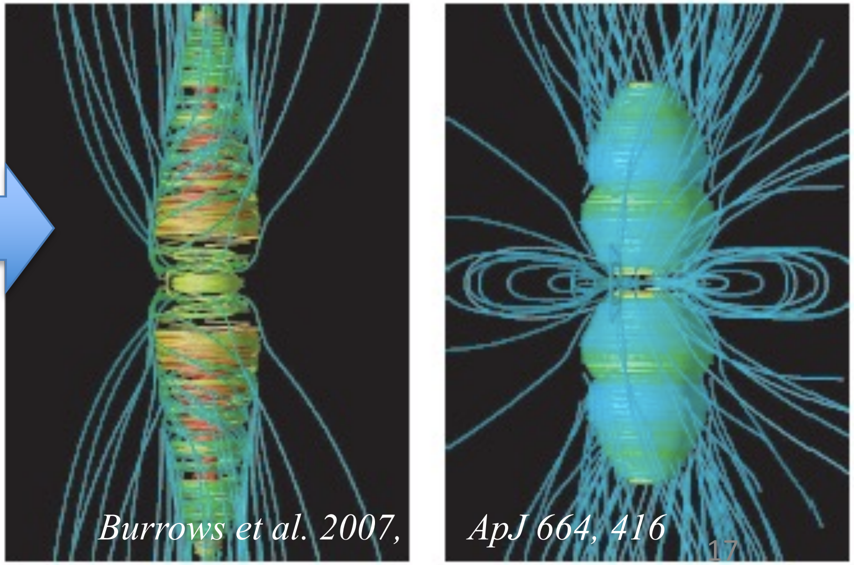
Rapidly rotating scenario



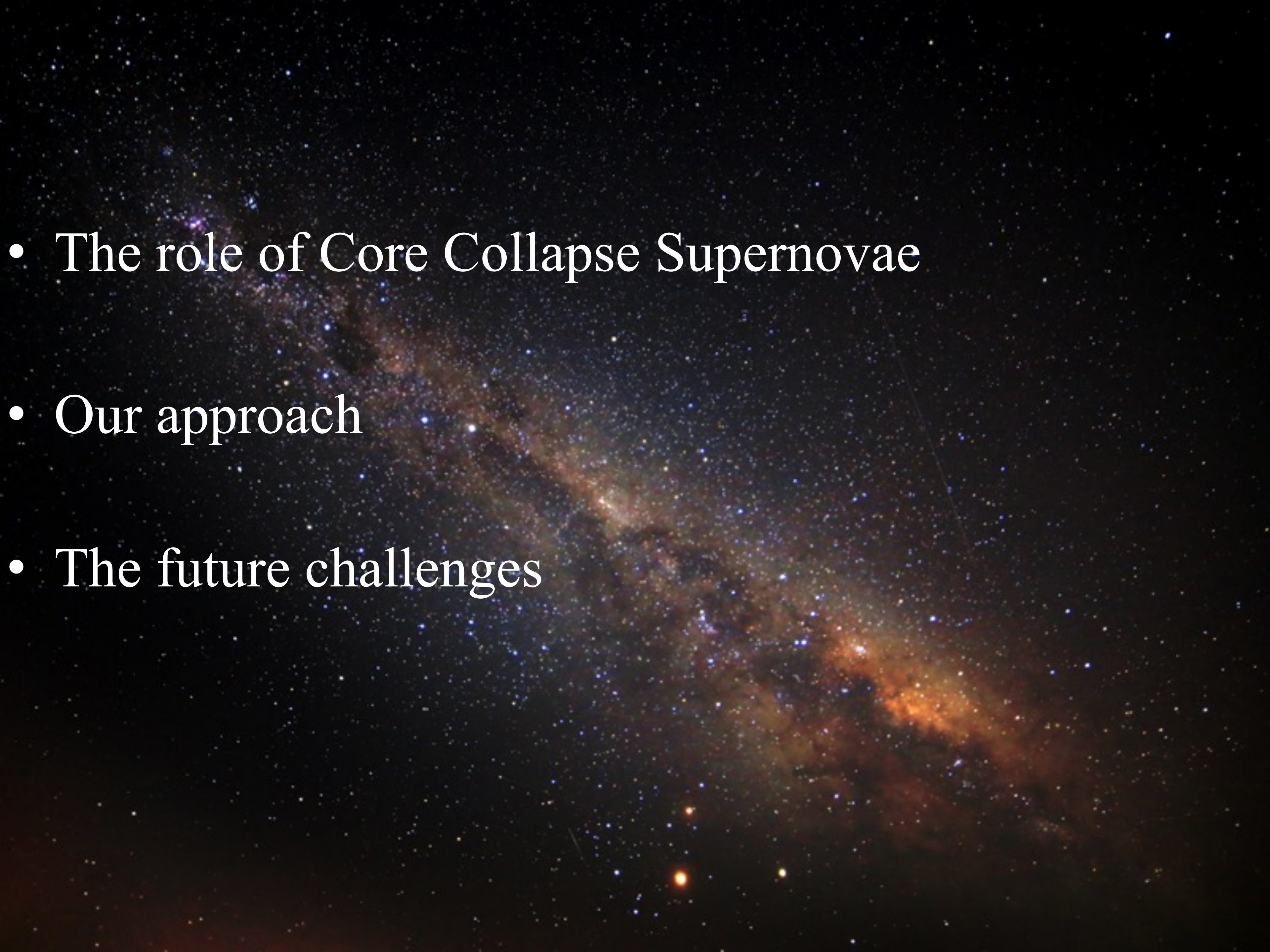
↑ Bounce time is determined by ν observation

*Credit: Tomoya Takiwaki*

Magneto-rotationally-driven CCSNe



*Burrows et al. 2007, ApJ 664, 416*



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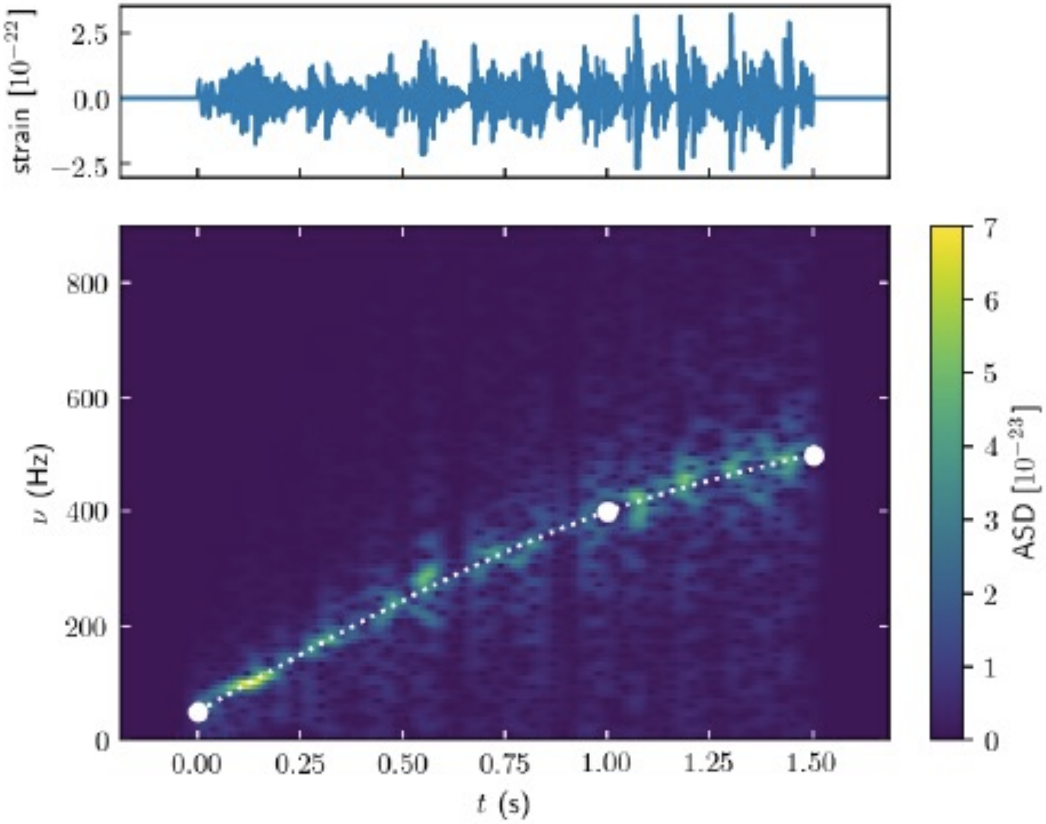
# Phenomenological Waveforms



| parameter | min. | max. | $\Delta$ | description |
|---|---|---|---|---|
| $t_{\text{ini}}$ [s] | 0 | 0.2 | 0.1 | beginning of the waveform |
| $t_{\text{end}}$ [s] | 0.2 | 1.5 | 0.1 | end of the waveform |
| $\nu_0$ [Hz] | 50 | 150 | 50 | frequency at bounce |
| $\nu_1$ [Hz] | 1000 | 2000 | 500 | frequency at 1 s |
| $\nu_2$ [Hz] | 1500 | 4500 | 1000 | frequency at 1.5 s |
| $\nu_{\text{driver}}$ [Hz] | 100 | 200 | 100 | driver frequency |
| $Q$ | $(1, 5, 10)$ | | | quality factor |
| $D$ [kpc] | $(1, 2, 5, 10, 15)$ | | | distance to source |

- New and flexible parametrisation for the frequency evolution.
- The distance is used as a parameter.

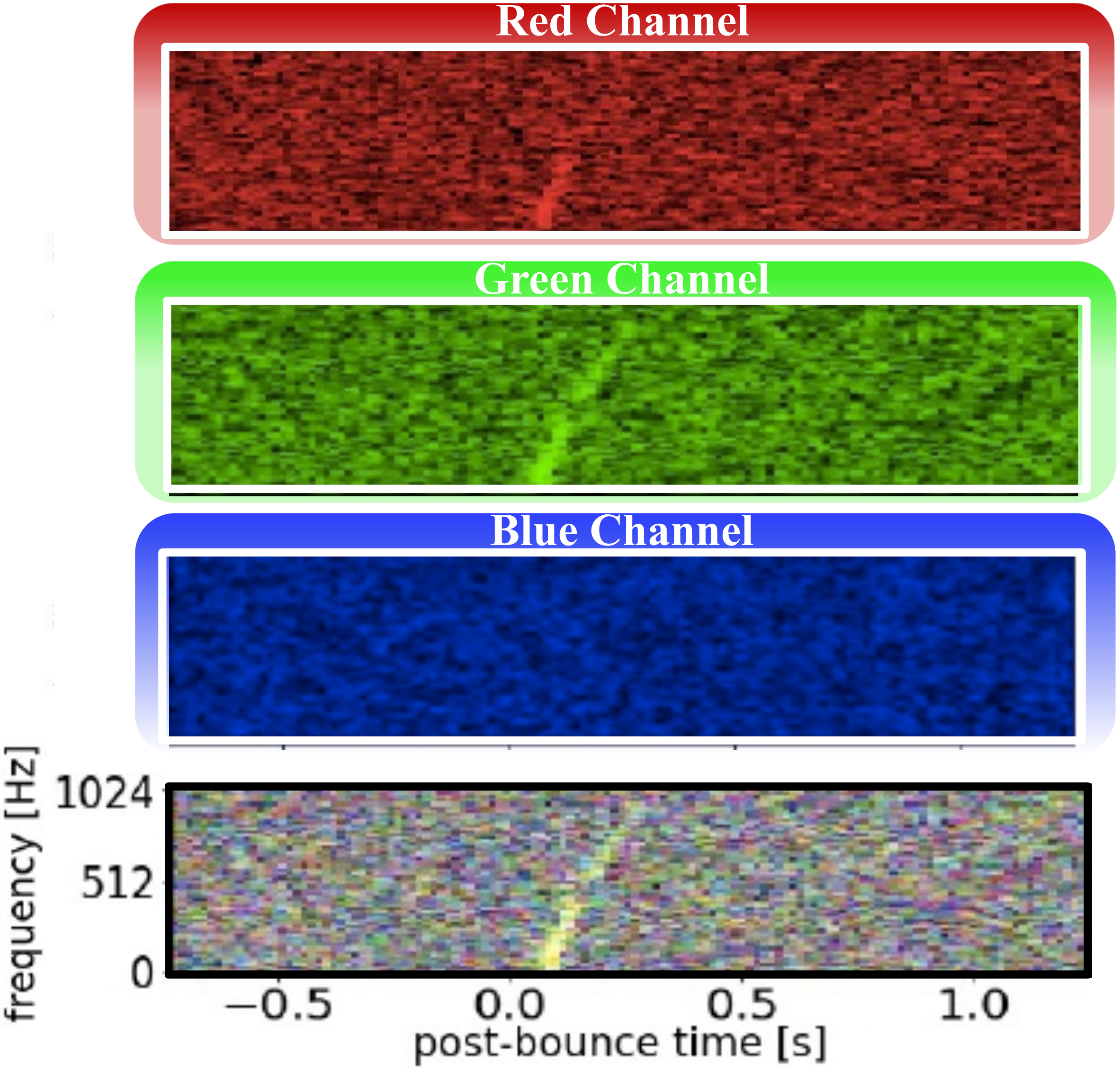
***M. Portilla, IDP et al. Phys.Rev.D 103 (2021) 6, 063011***

# Strategy

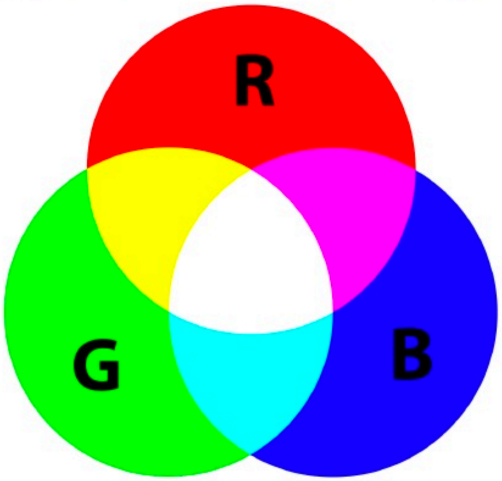
- While the neutrino information are used as an external trigger, it is necessary the generation of a data set of CCSN waveforms through a phenomenological approach.
- Creation of the time-frequency plots that are the input for the deep learning algorithm.
- Analysis of these images through the neural network.
- Classification of images as signal or noise.

# RGB time-frequency plane

## Coincidences among detectors



Additive colour synthesis



LIGO Hanford = red

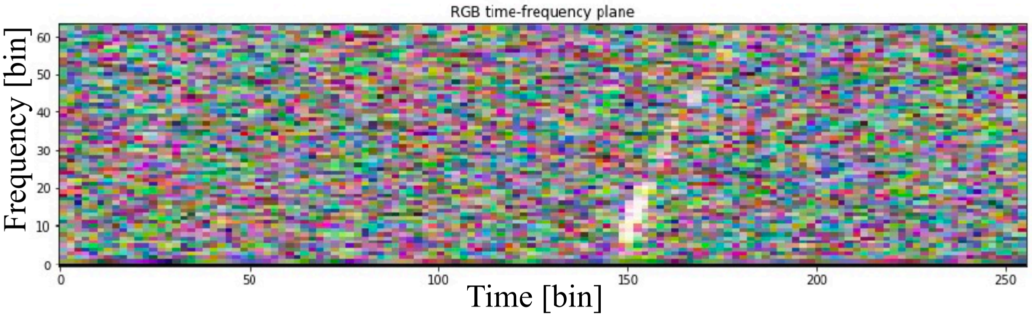
LIGO Livingston = green

Virgo = blue

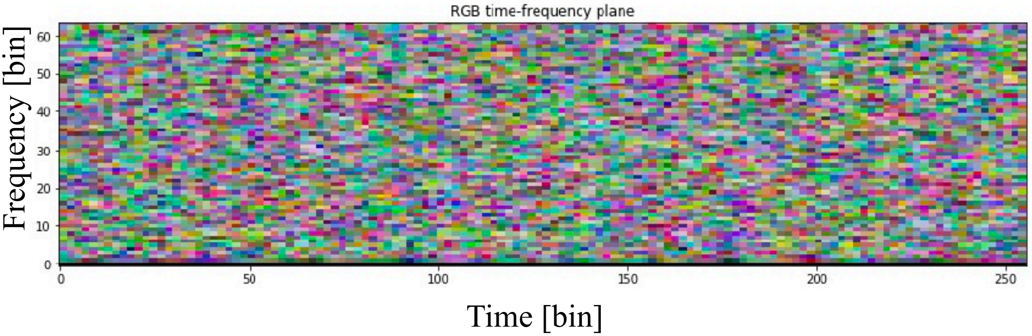
# RGB time-frequency plane

## Coincidences among detectors

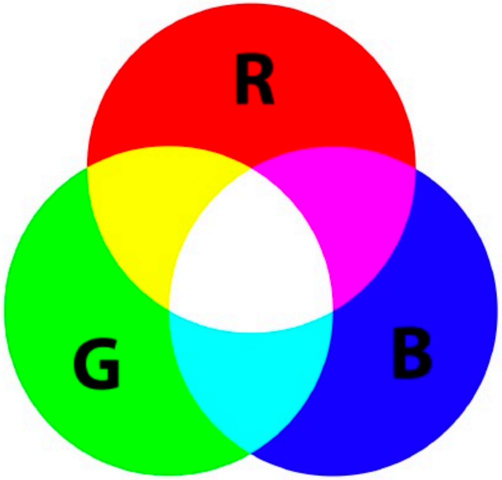
**Signal+Noise**



**Only Noise**



Additive colour synthesis



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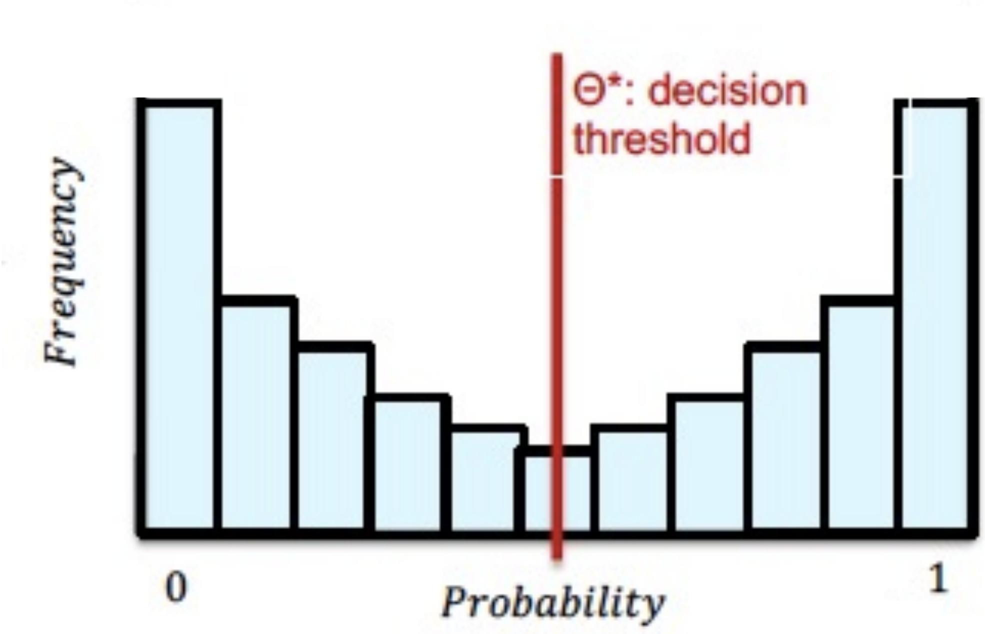
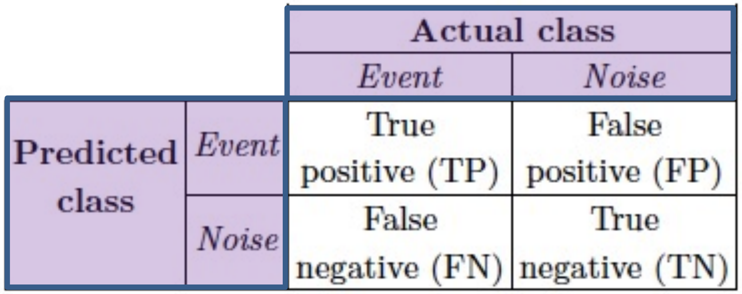
# Measuring and constraining the learning



- The output of the network is a probability vector $\vartheta$, which contains the probabilities of the template belonging to one class or another.
- The classification task is performed according to a threshold $\vartheta^*$, the template will be classified as event class only if its probability overcomes $\vartheta^*$.

**Confusion matrix**



| | | Actual class | |
|---|---|---|---|
| | | *Event* | *Noise* |
| Predicted class | *Event* | True positive (TP) | False positive (FP) |
| | *Noise* | False negative (FN) | True negative (TN) |

**Efficiency:**

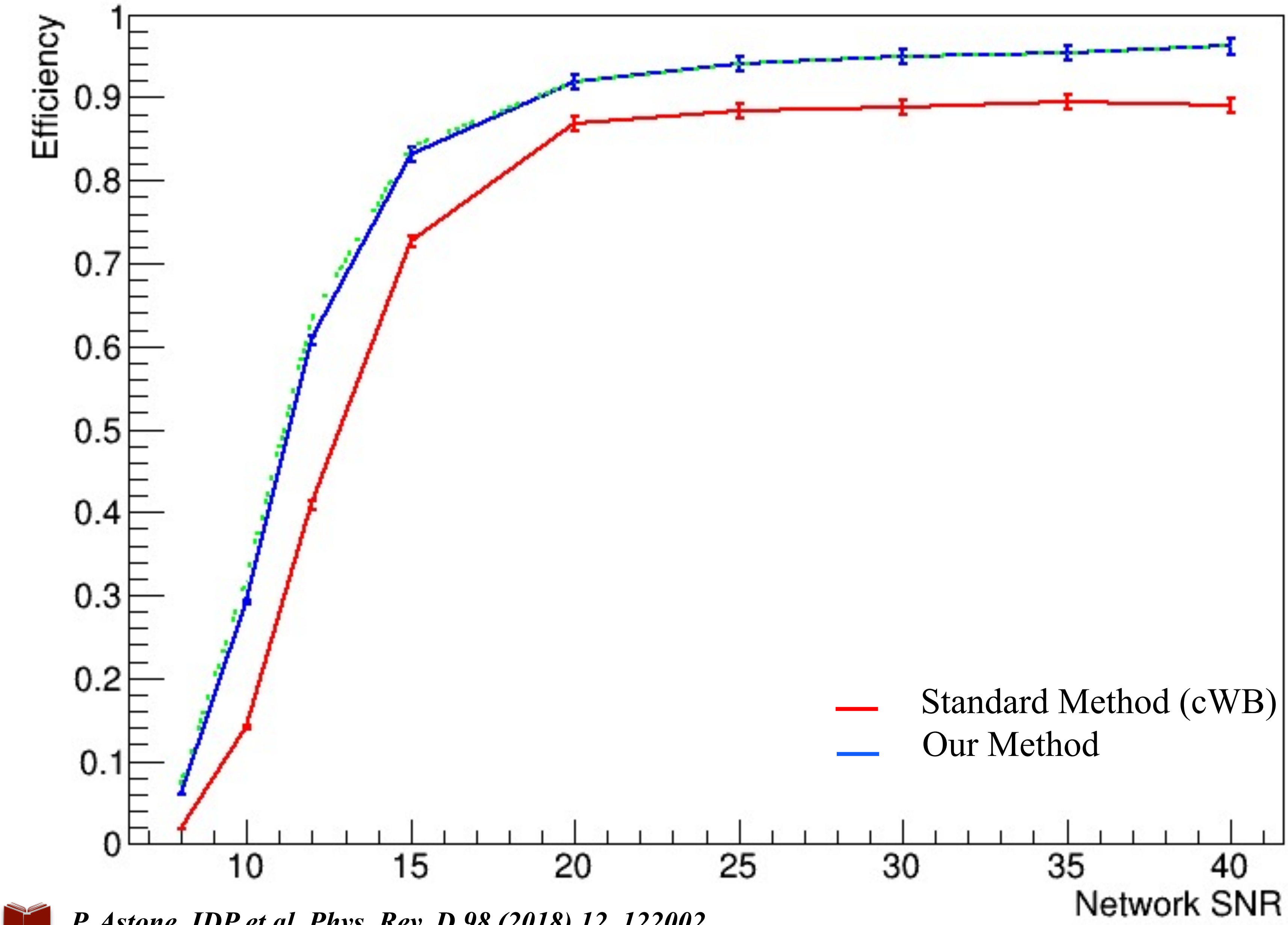
$$\eta_{CNN} = \frac{\text{correctly classified signals}}{\text{all the signals at CNN input}} = \frac{TP}{TP + FN}$$

**False Alarm Rate:**

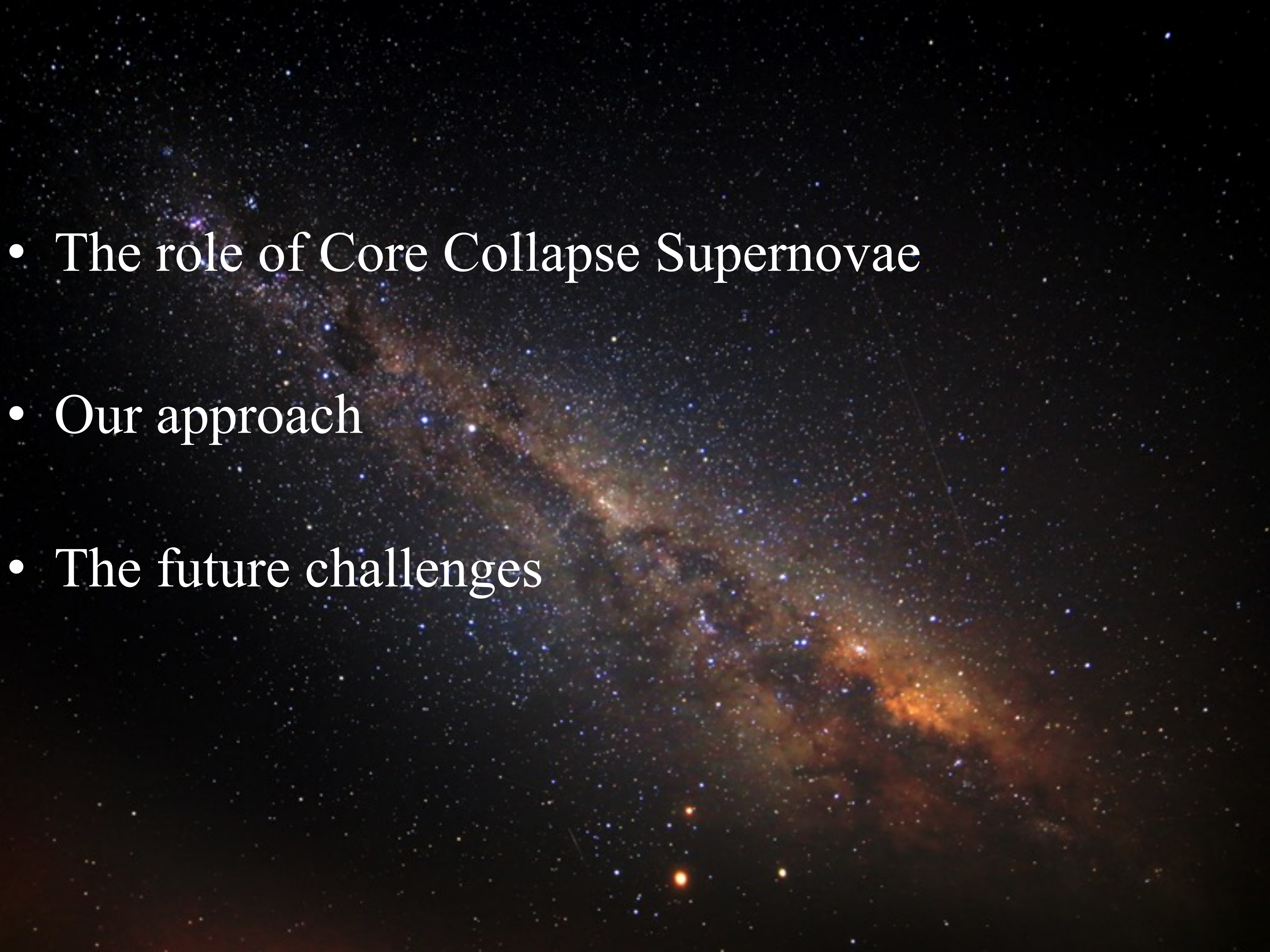
$$FAR_{CNN} = \frac{\text{misclassified noise}}{\text{all classified events}} = \frac{FP}{FP + TP}$$

**False Positive Rate:** $$FPR = \frac{FP}{FP + TN}$$

# General results



*P. Astone, IDP et al. Phys. Rev. D 98 (2018) 12, 122002*



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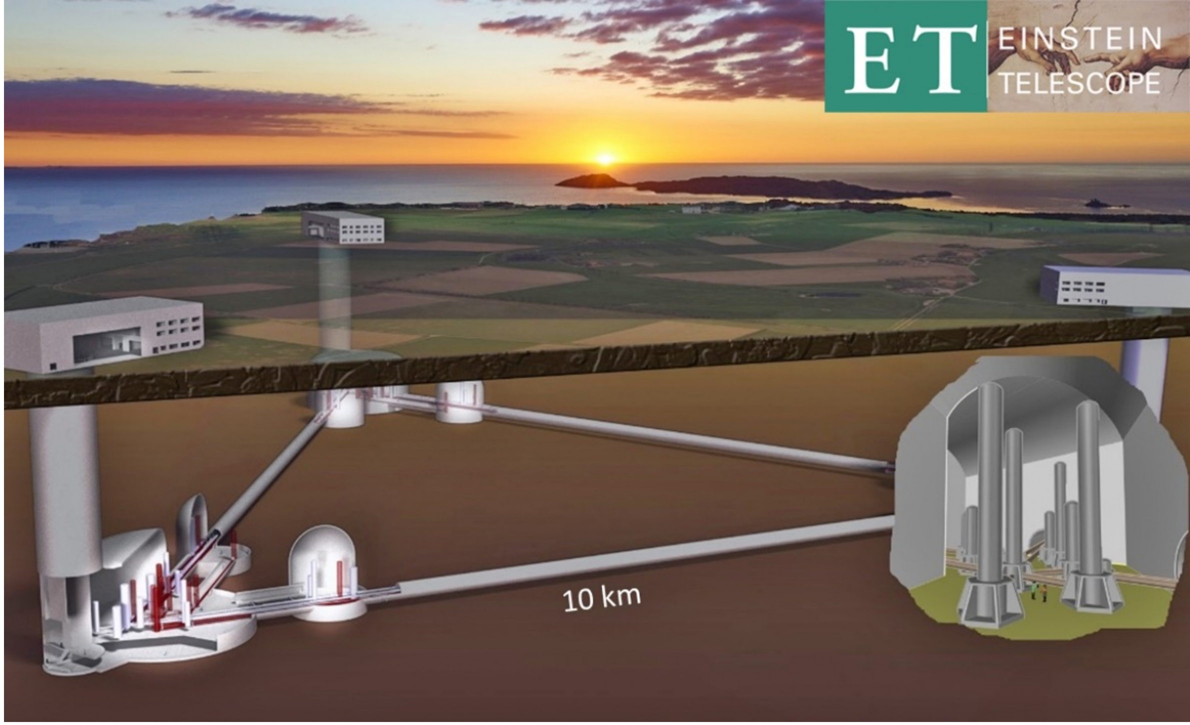
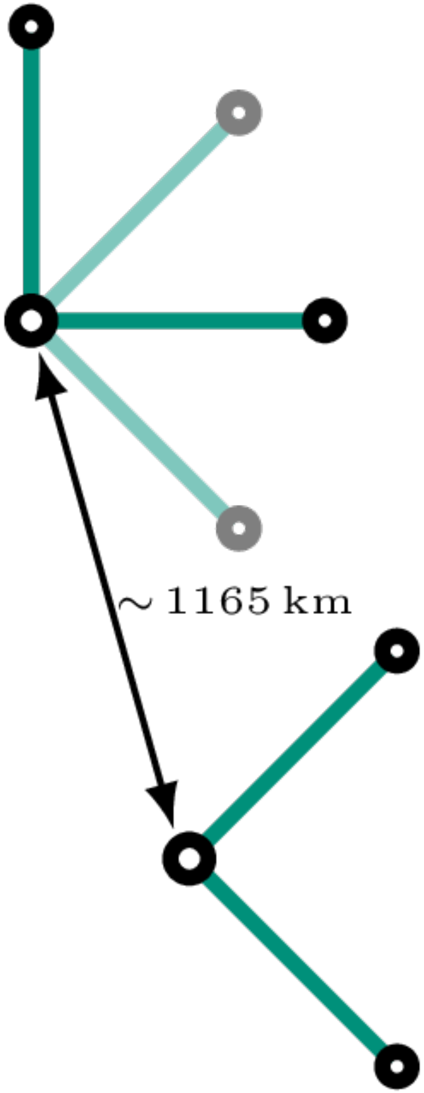
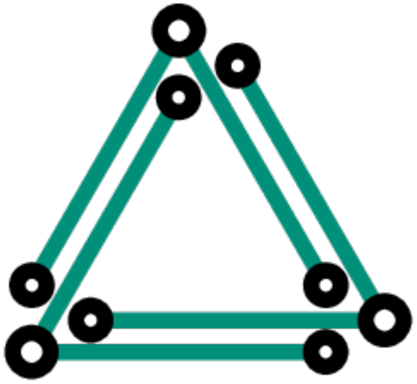
# Einstein Telescope







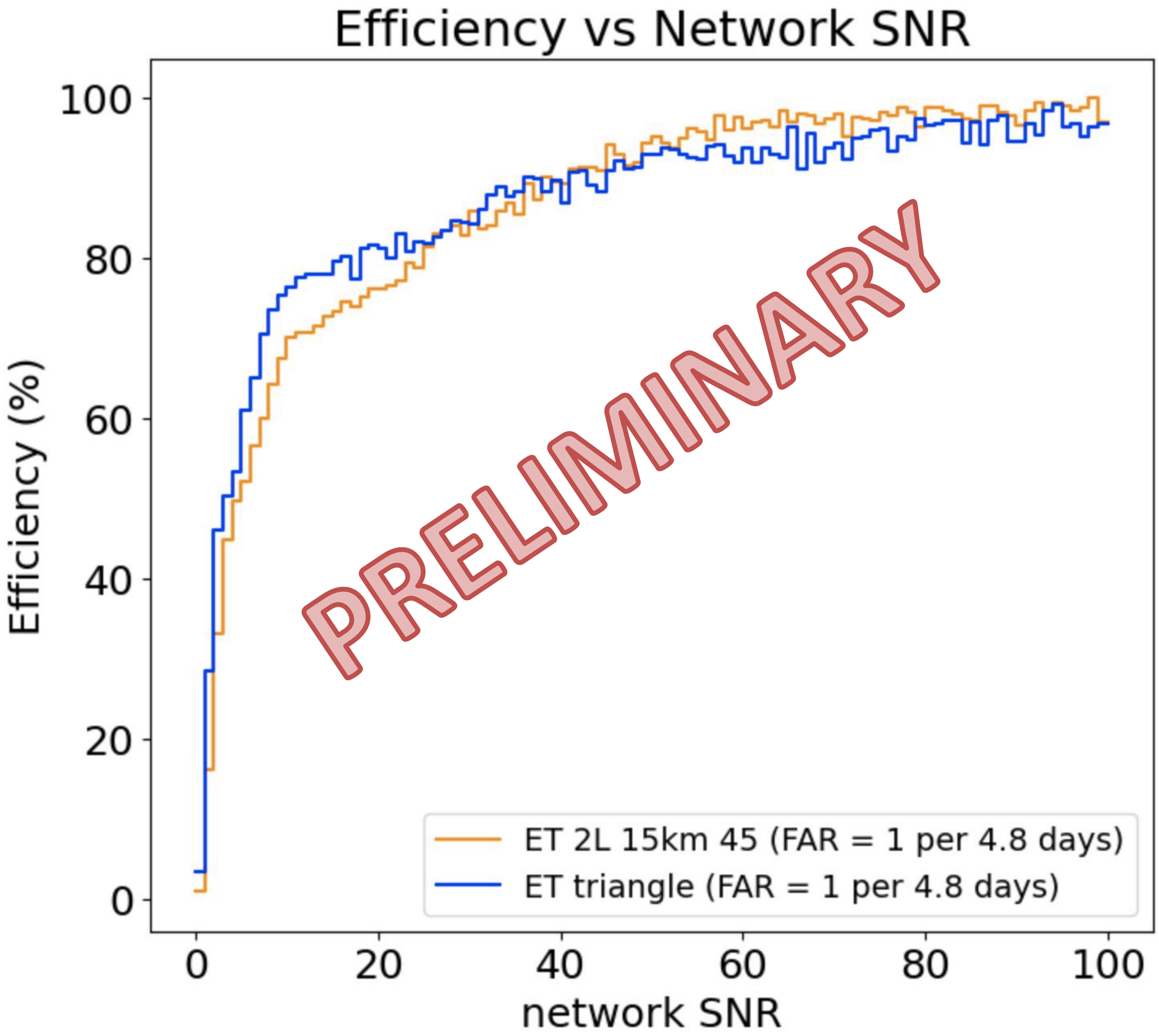
**Gaussian noise:** $10^5$ images for each value of Network SNR ∈ [1,100]

**Training set – phenomenological waveforms:** 7 x $10^5$ images for each distance ∈ [0.1, 100] kpc and random sky localisation.

**Test set - numerical simulations from the literature:** $10^6$ images with distances ∈ [0.1, 100] kpc

*M. Branchesi et al. JCAP 07 (2023) 068*

# ET-2L 15km 45° vs ET triangle



# ET-2L 15km 45° vs ET triangle