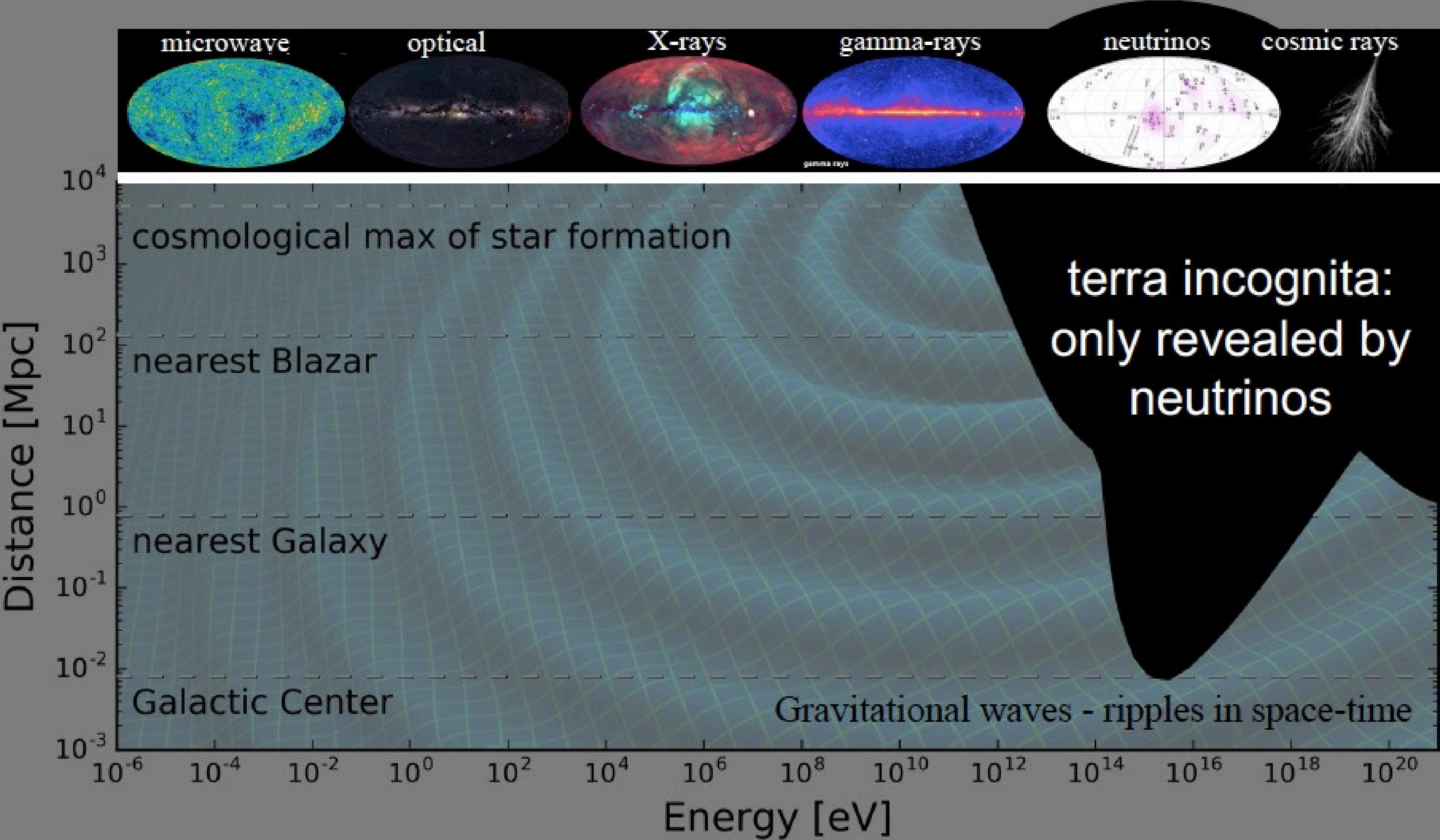
Multimessenger observations, status and future perspectives

Irene Di Palma
University of Rome
La Sapienza and INFN
Irene.DiPalma@uniroma1.it

- **Multimessenger observations:**
  - ✓ SN1987A
  - ✓ GW170817
  - ✓ IC170922

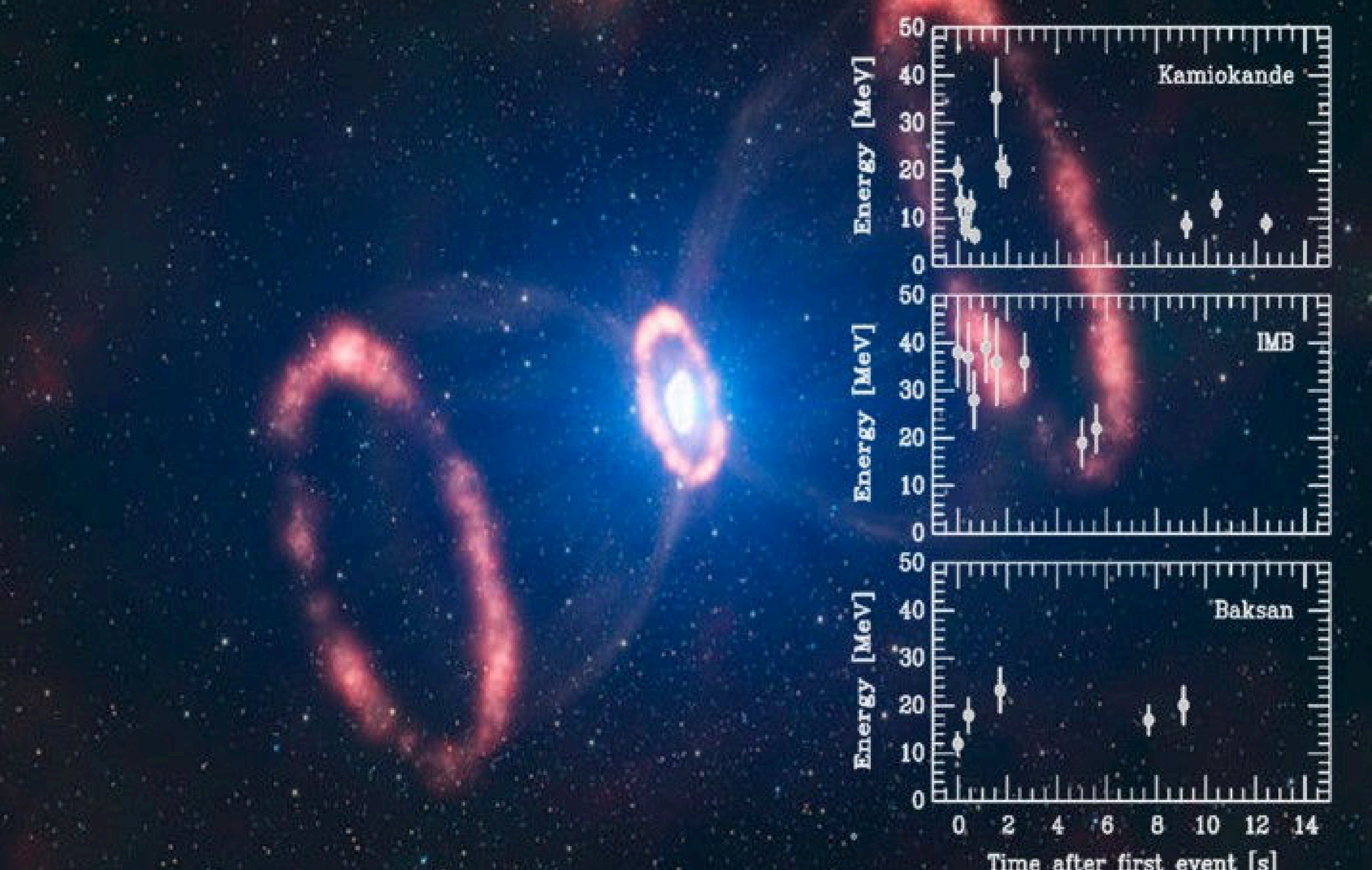
- The role of Core Collapse Supernovae

- The future challenges



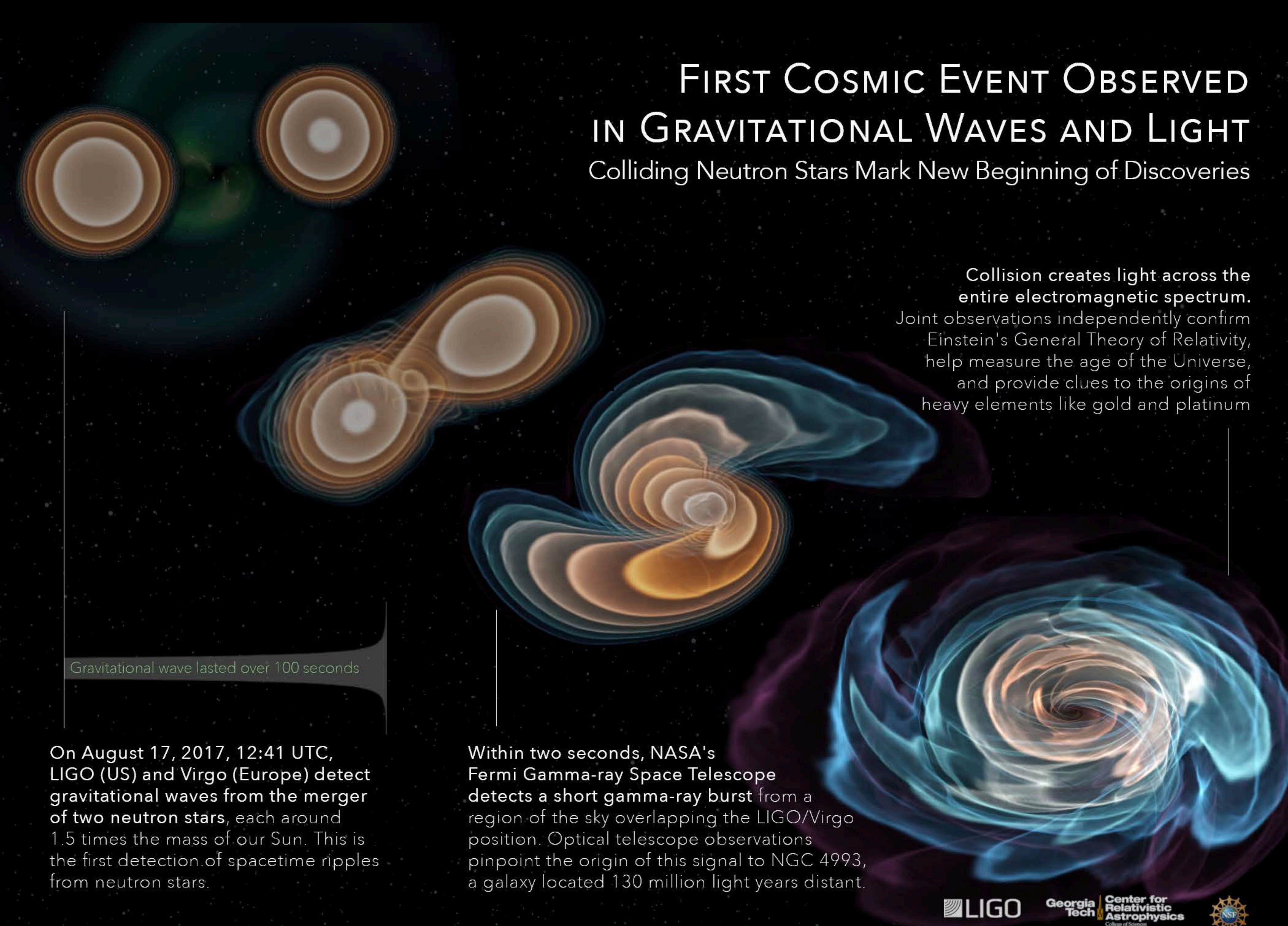
- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos

MeV Neutrinos from SN1987A

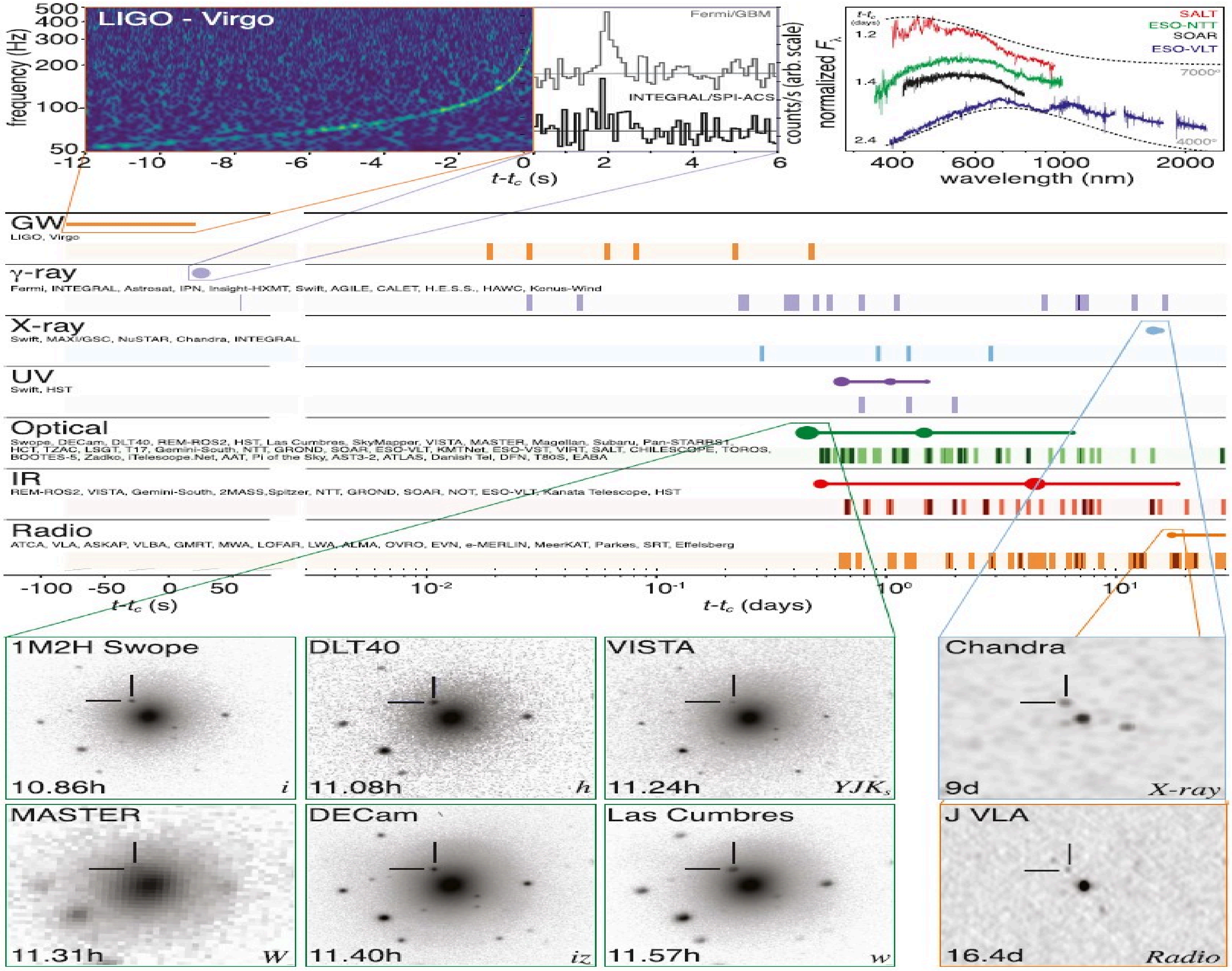


February 23, 1987.

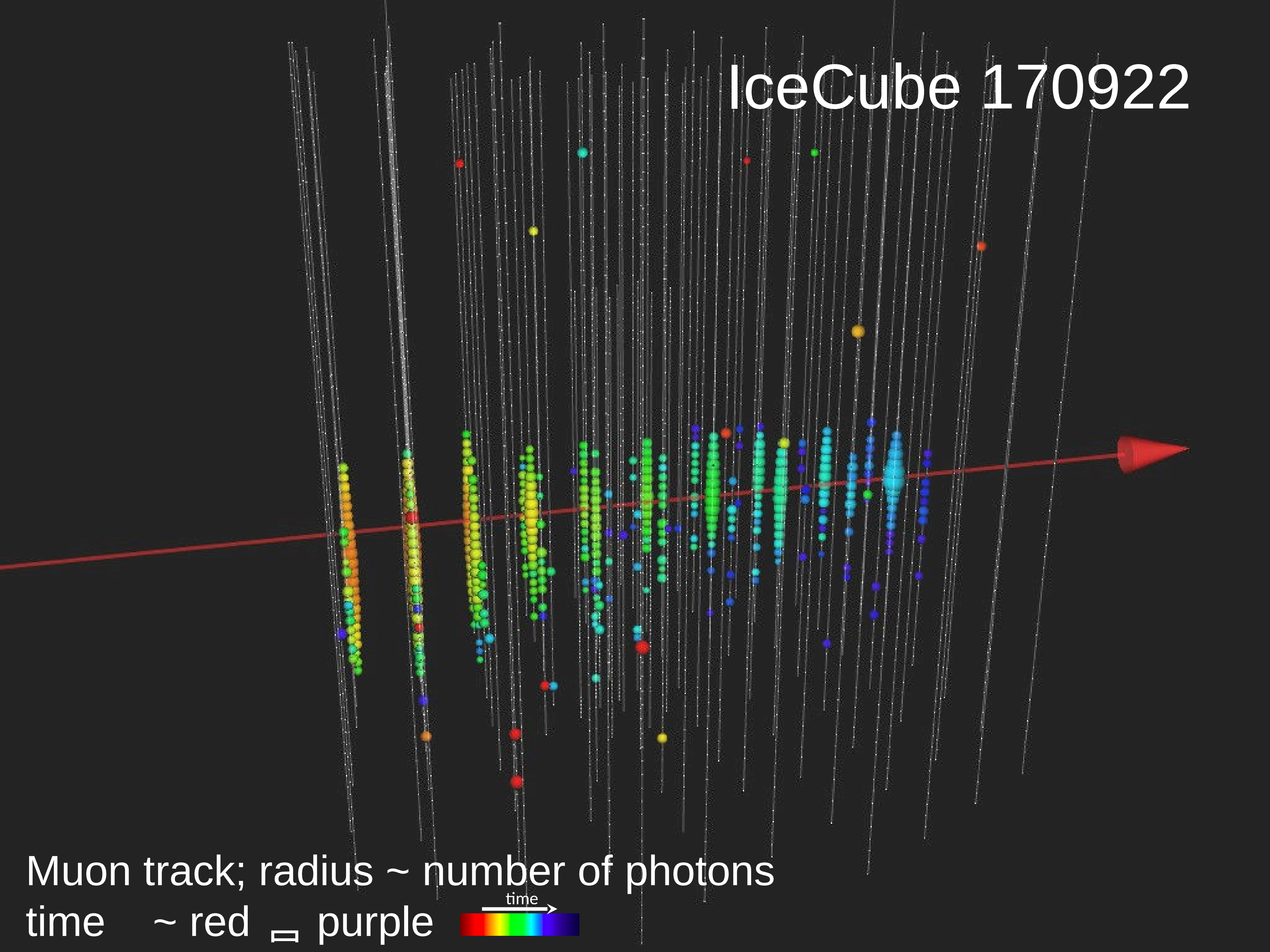
K. Hirata et al., Phys. Rev. Lett. 58, 1490 (1987)



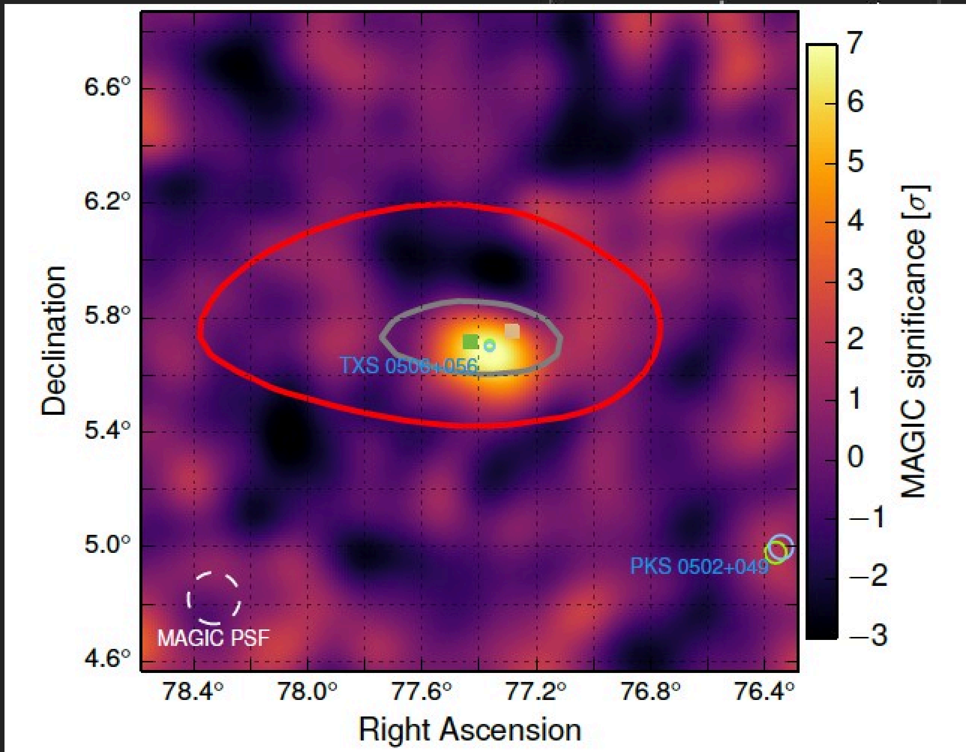
Astrophys.J.Lett. 848 (2017) 2, L12; Astrophys.J.Lett. 848 (2017) 2, L13; Nature volume 551, pages 85–88 (2017)



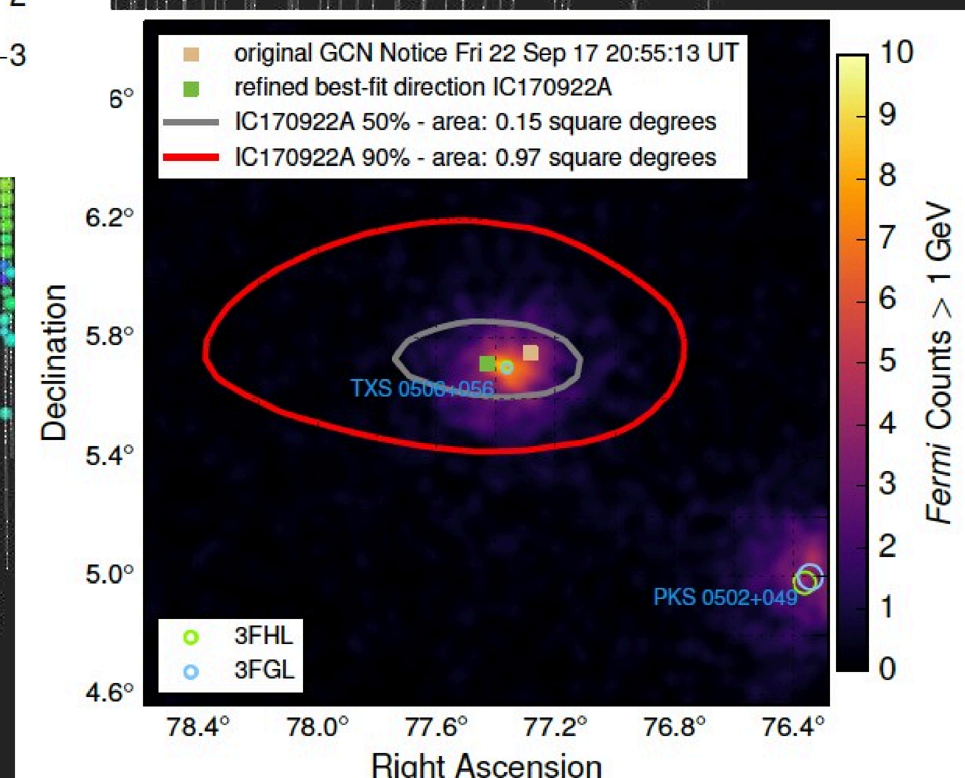
LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio


IceCube 170922
Muon track; radius ~ number of photons
time ~ red ⊏ purple
time

IceCube 170922

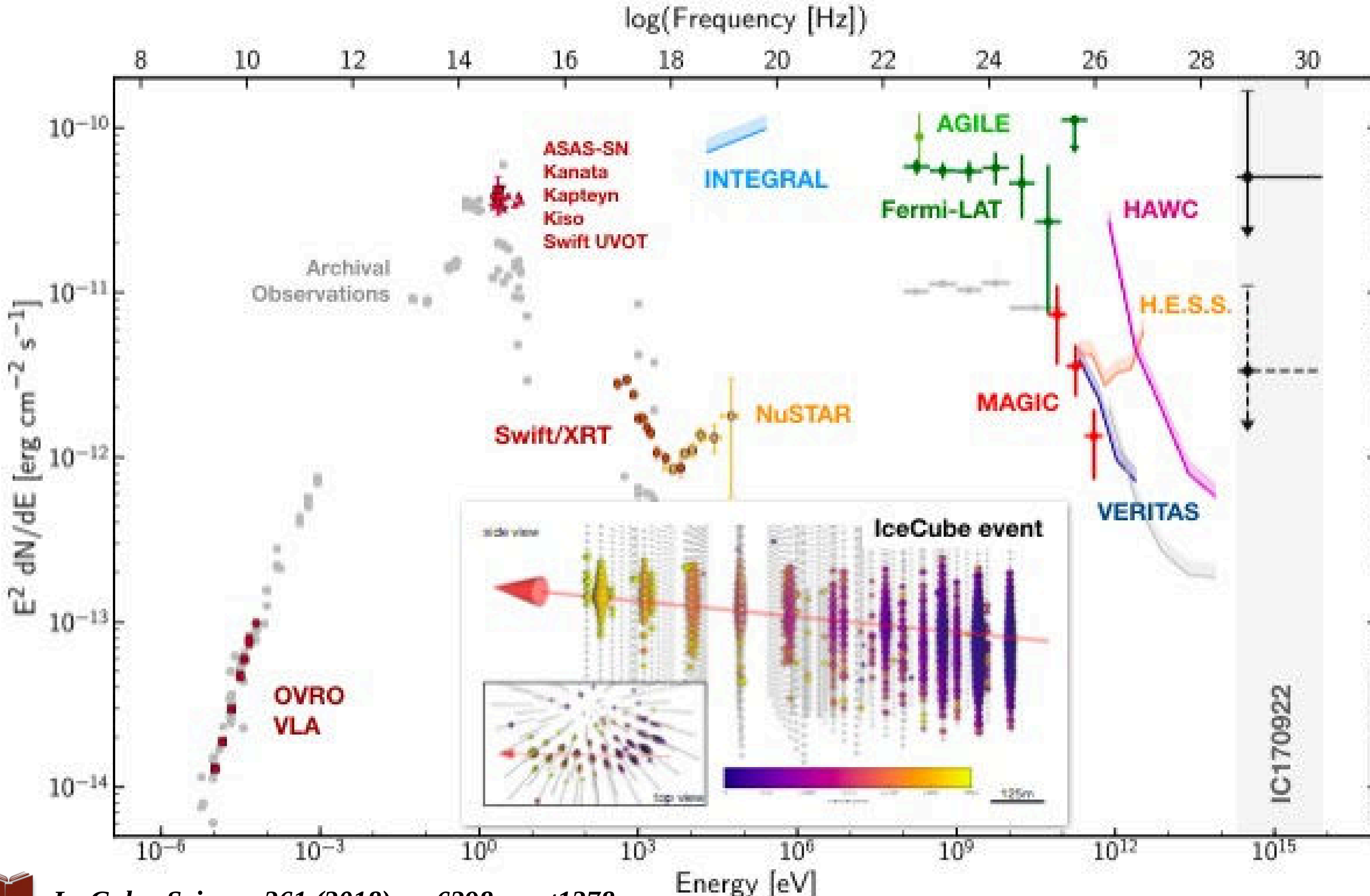


Fermi
detects a flaring
blazar within 0.1°



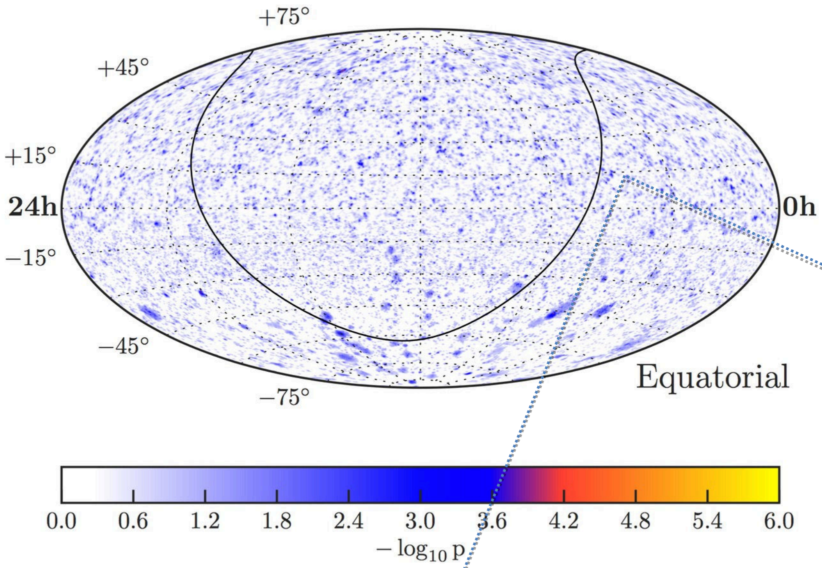
MAGIC
detects emission of
TeV gammas

Observational spectrum of TSX 0506+056

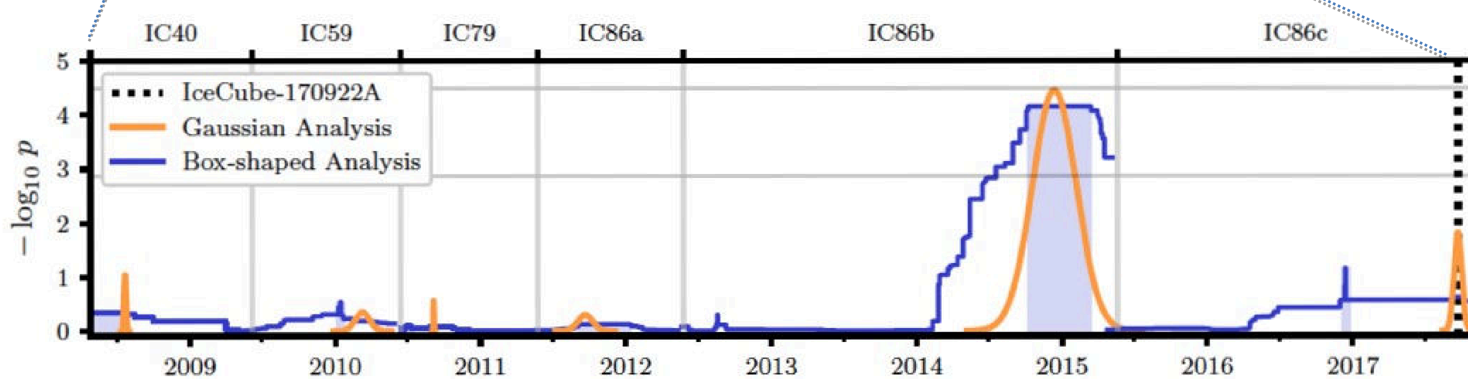


IceCube, Science 361 (2018) no.6398, eaat1378

TSX 0506+056



More neutrinos (~10) emission from the direction of the blazar TXS 0506+056 IceCube-170922A alert" pointing to TXS0506+056.



3.5σ evidence (a-priori following predefined tests procedures)

IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)

- **Multimessenger observations:**
  - ✓ SN1987A
  - ✓ GW170817
  - ✓ IC170922

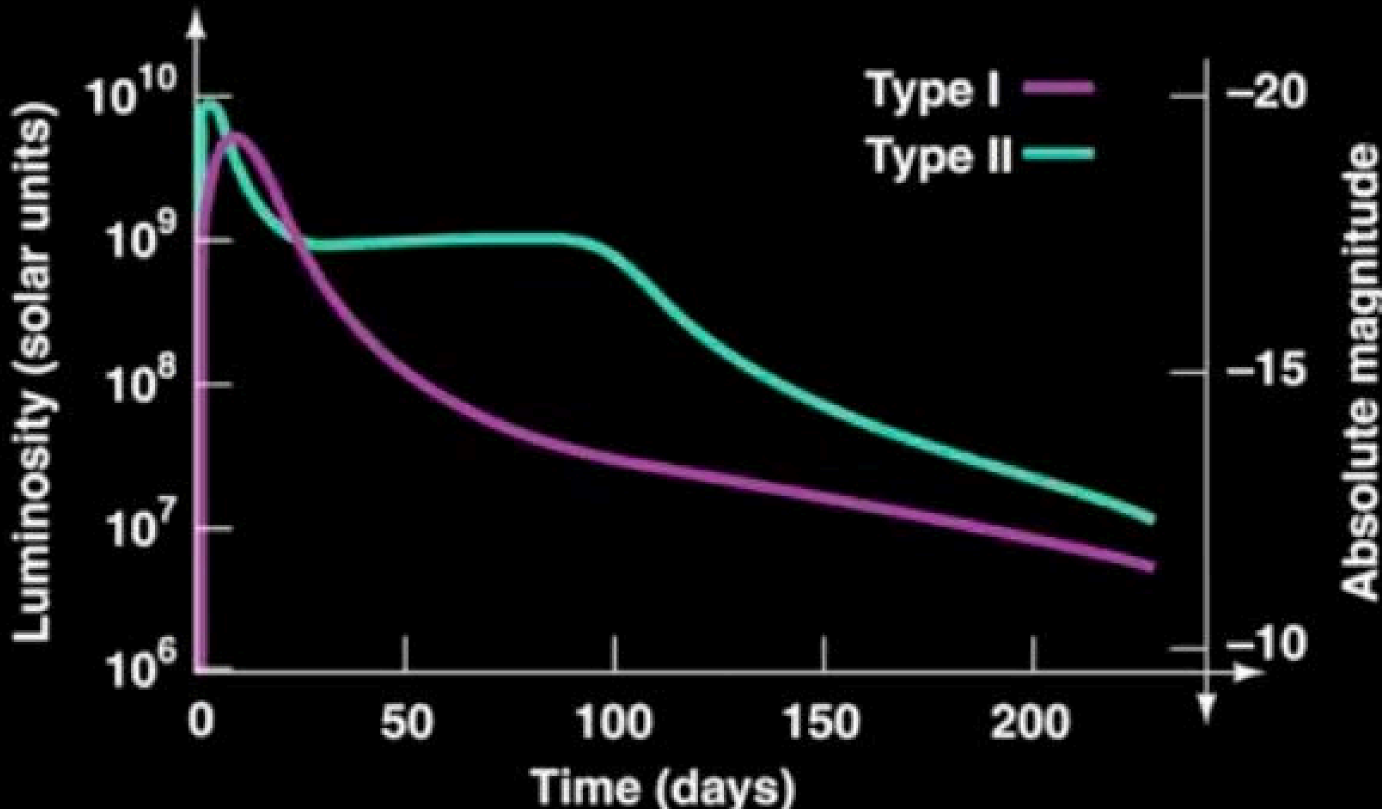
- The role of Core Collapse Supernovae

- The future challenges

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.

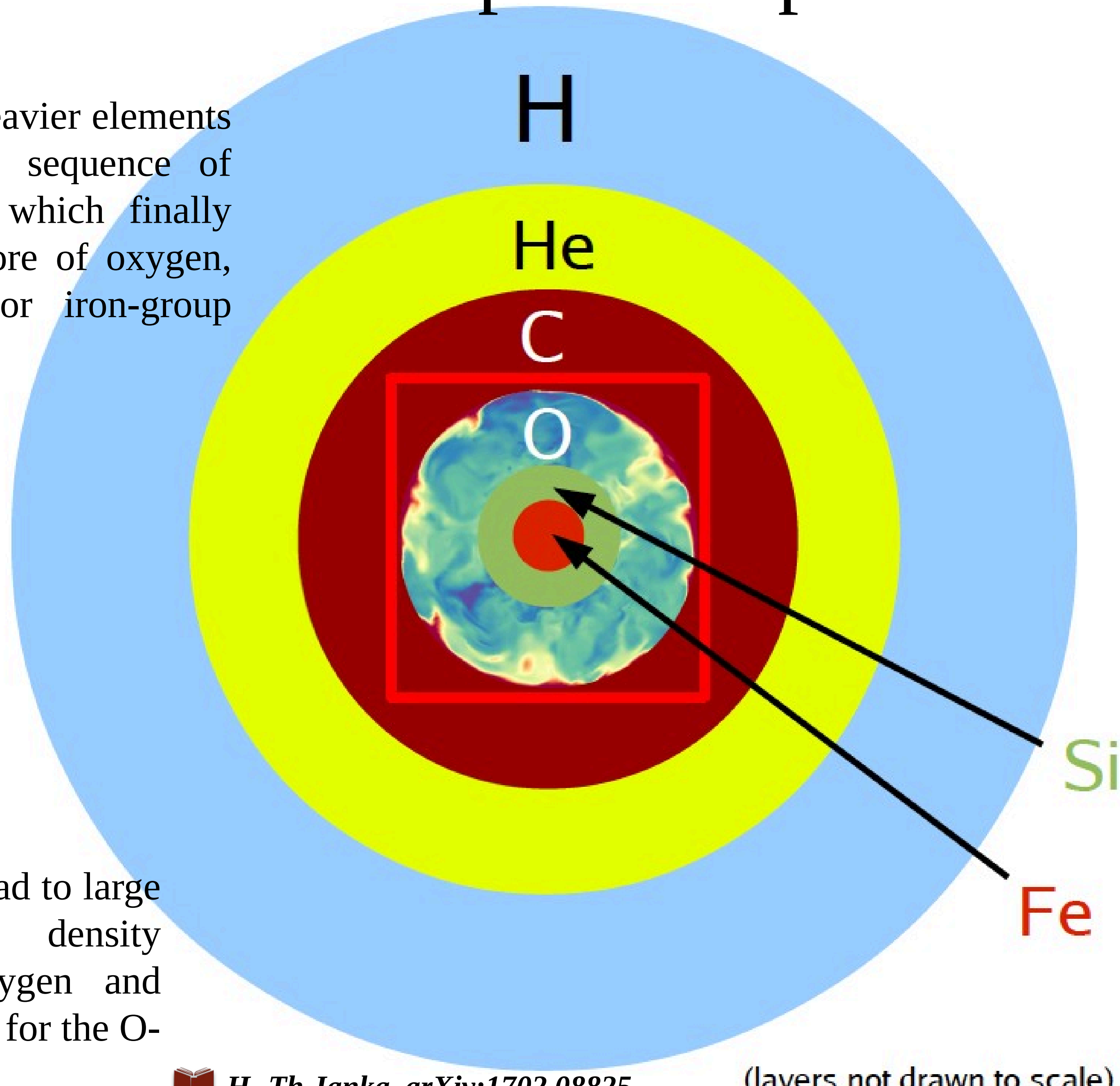
S. Al Kharusi et al, New J. Phys. 23 031201 (2021)



- **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

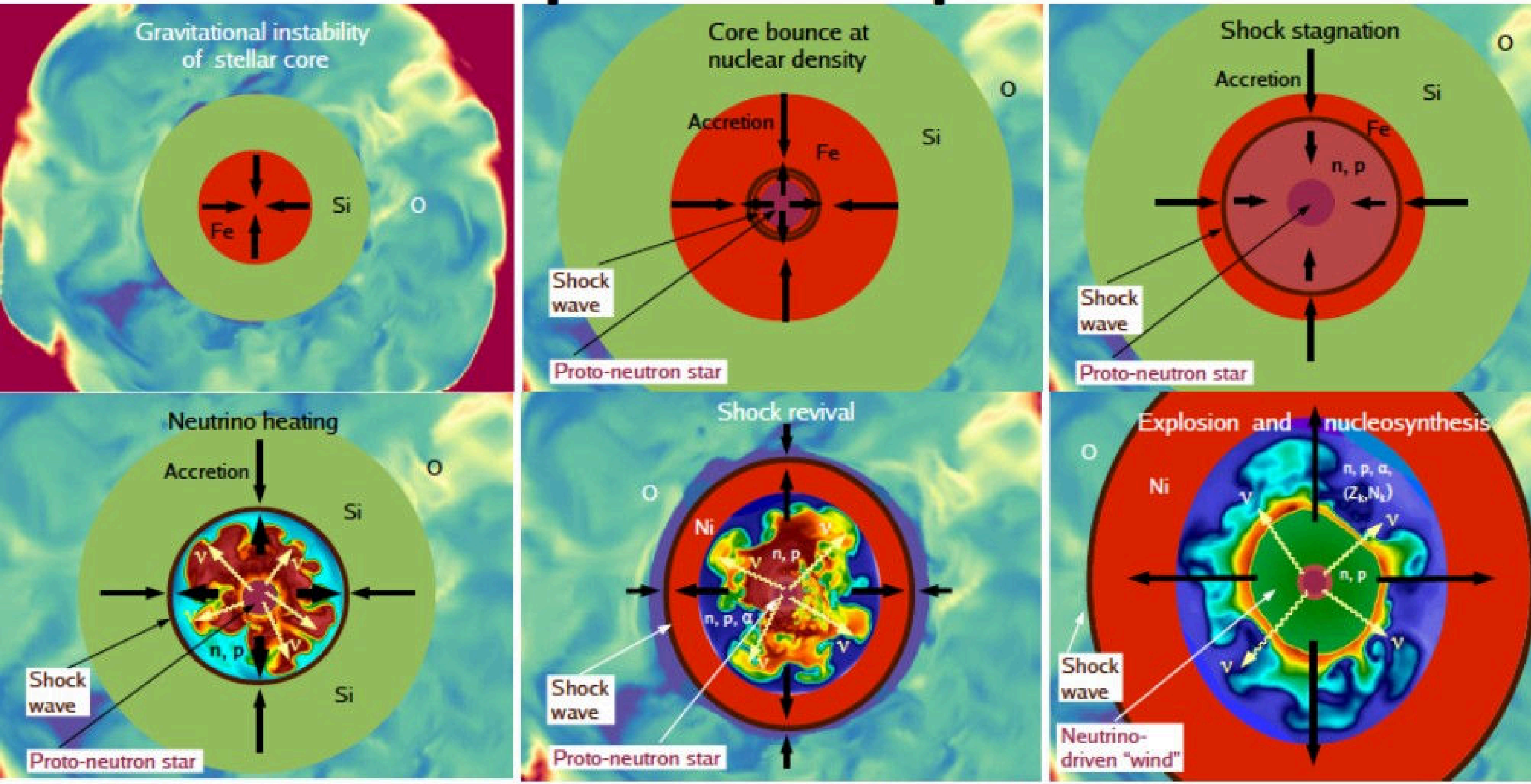
Shells of progressively heavier elements contain the ashes of a sequence of nuclear burning stages, which finally build up a degenerate core of oxygen, neon and magnesium or iron-group elements at the center.



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

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.

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

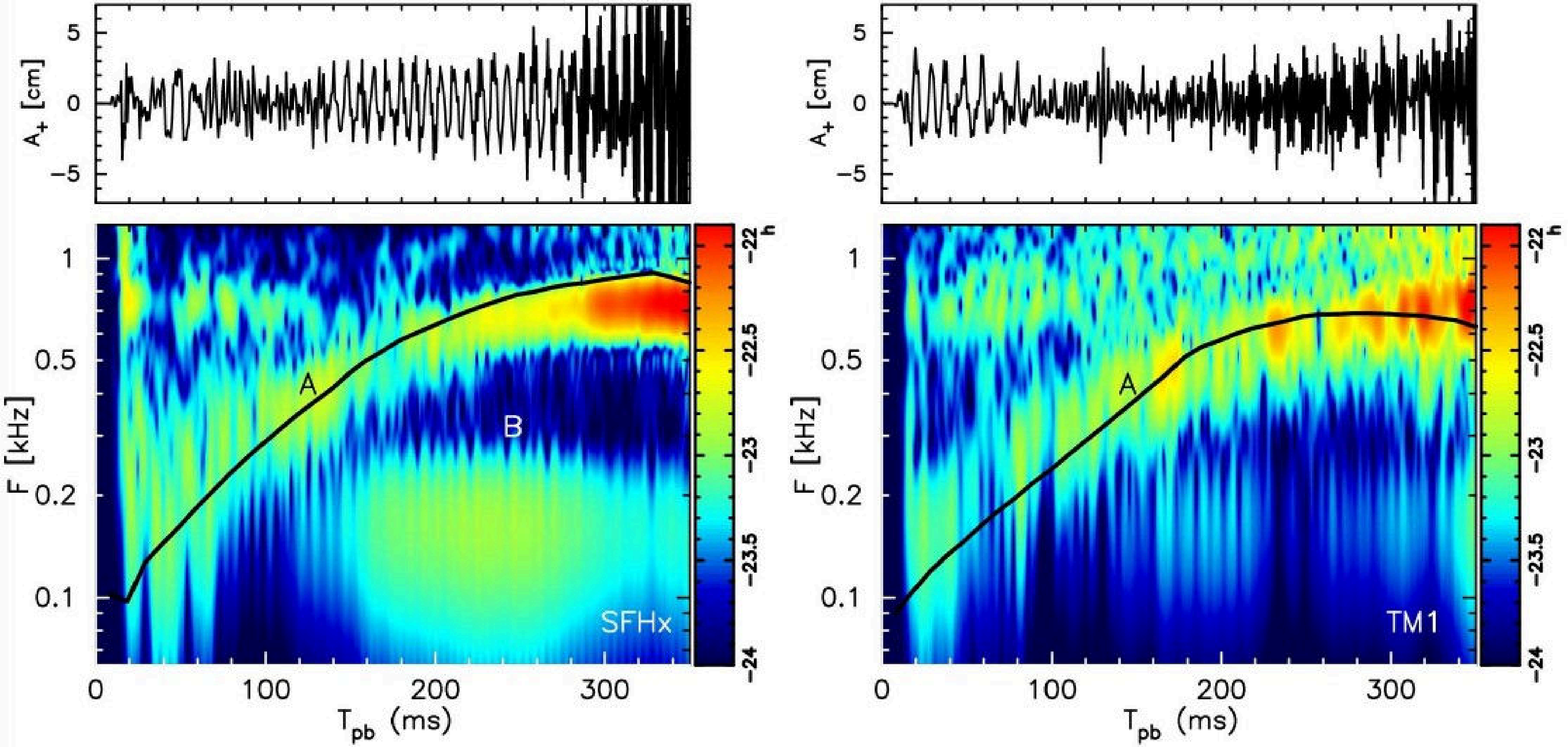
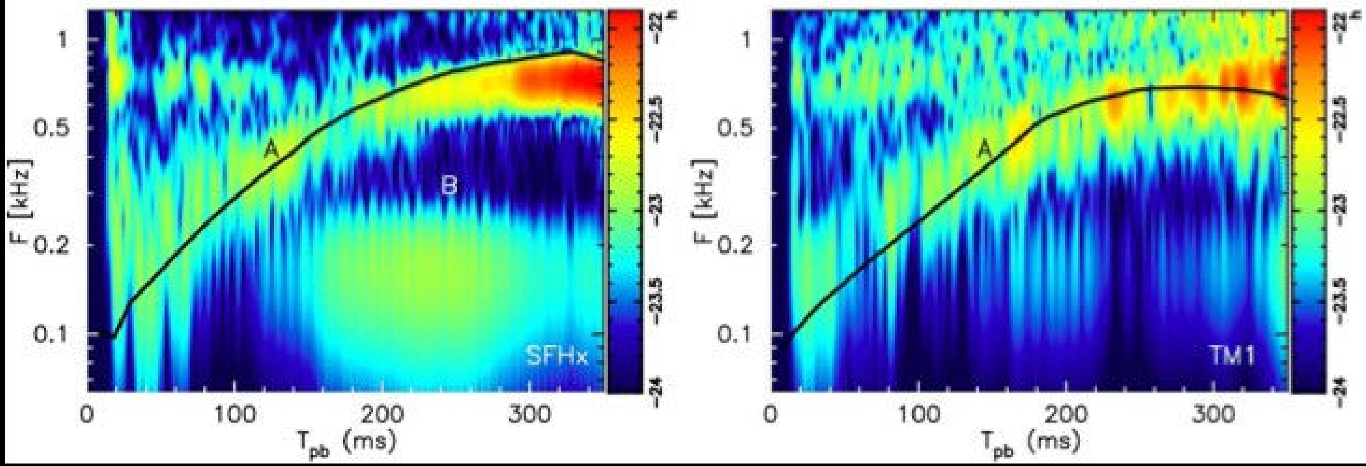


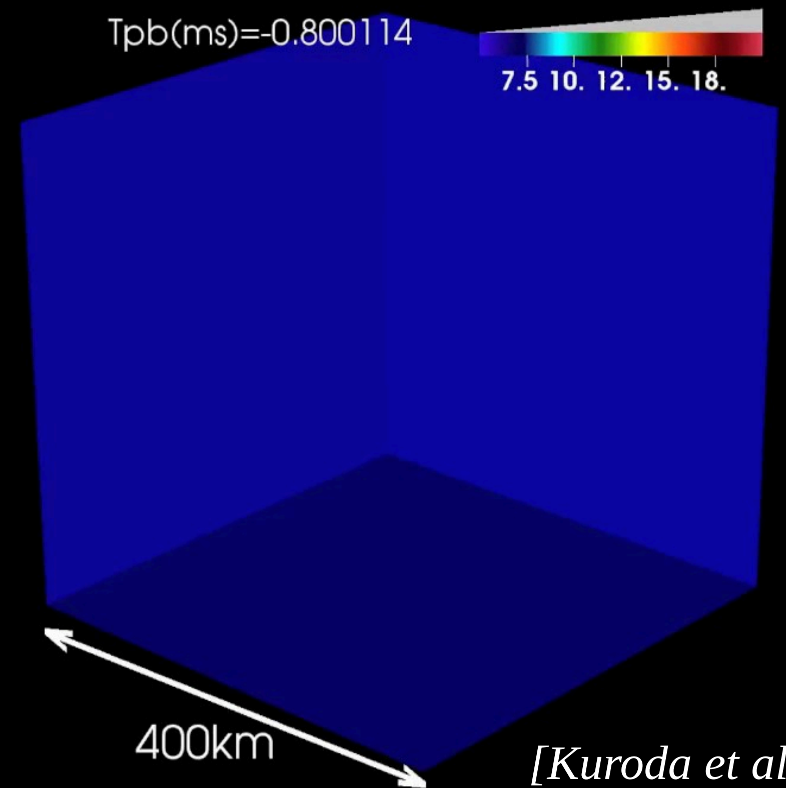
FIG. 1.— In each set of panels, we plot, top; gravitational wave amplitude of plus mode A_+ [cm], bottom; the characteristic wave strain in frequency-time domain $\tilde{h}$ in a logarithmic scale which is over plotted by the expected peak frequency F_{peak} (black line denoted by "A"). "B" indicates 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.

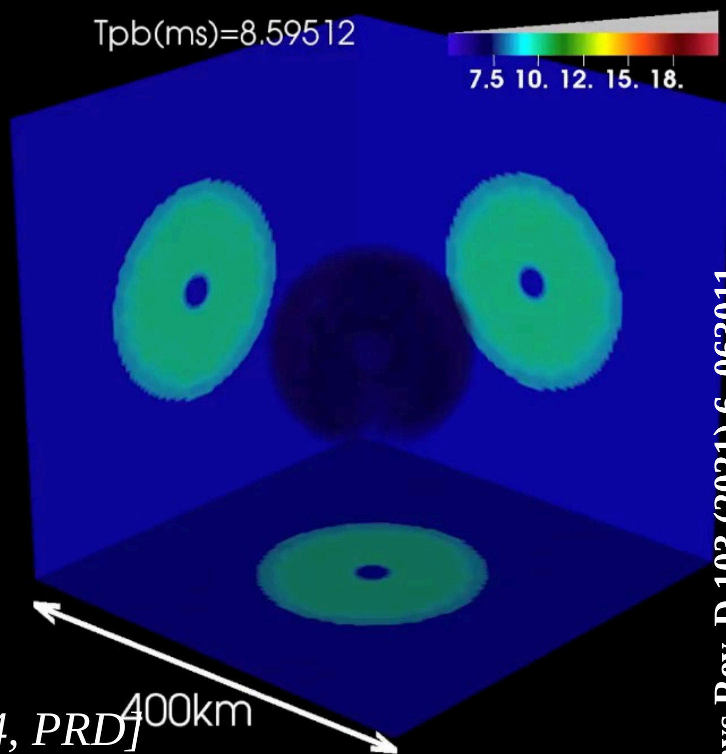
T. Kuroda et al.,Astrophys.J. 829 (2016) no.1, L14



SFHx :softer

TM1 :stiffer





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

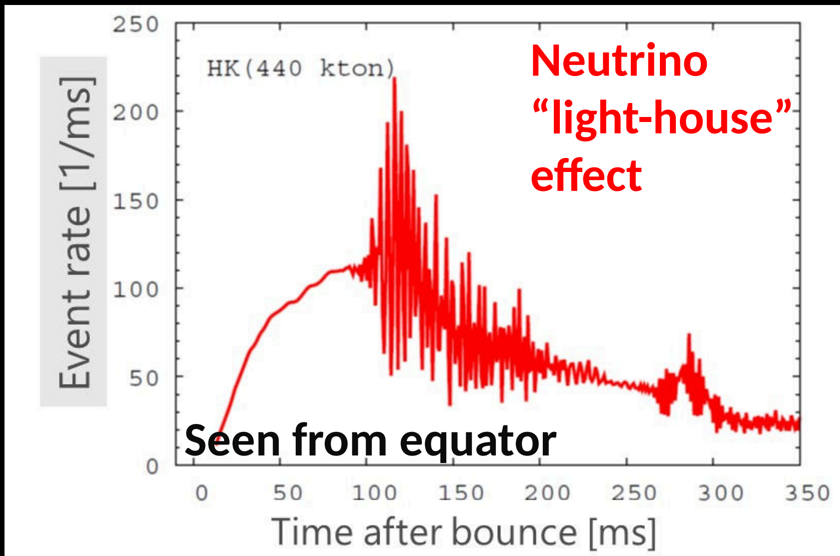
Phys.Rev. D 103 (2021) 6, 063011

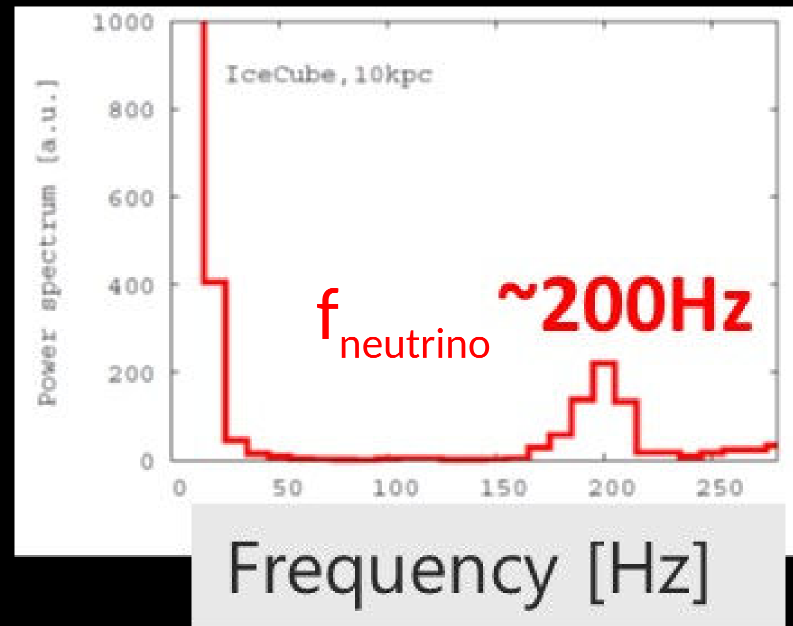
✓**SASI activity higher for softer EOS** (due to high growth rate, e.g., Foglizzo et al. ('06)).

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

Takiwaki, KK, Foglizzo, (2021)

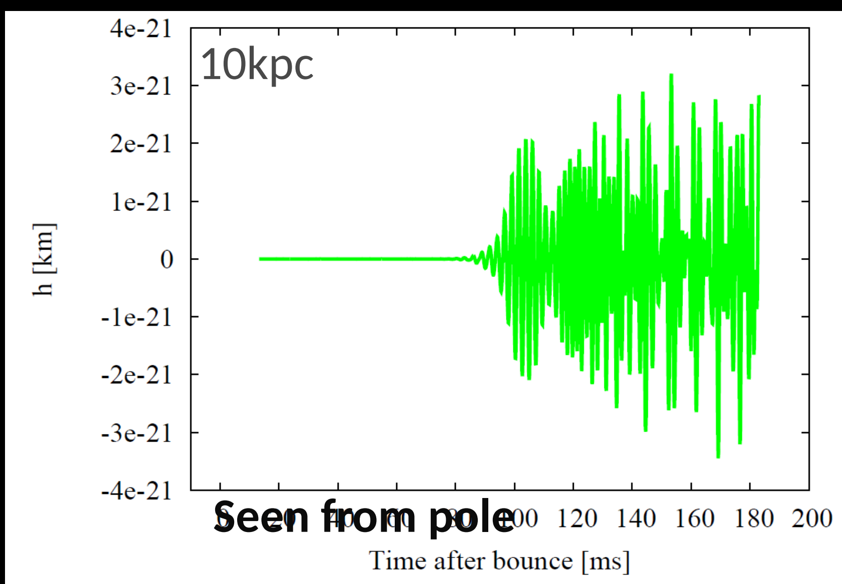
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

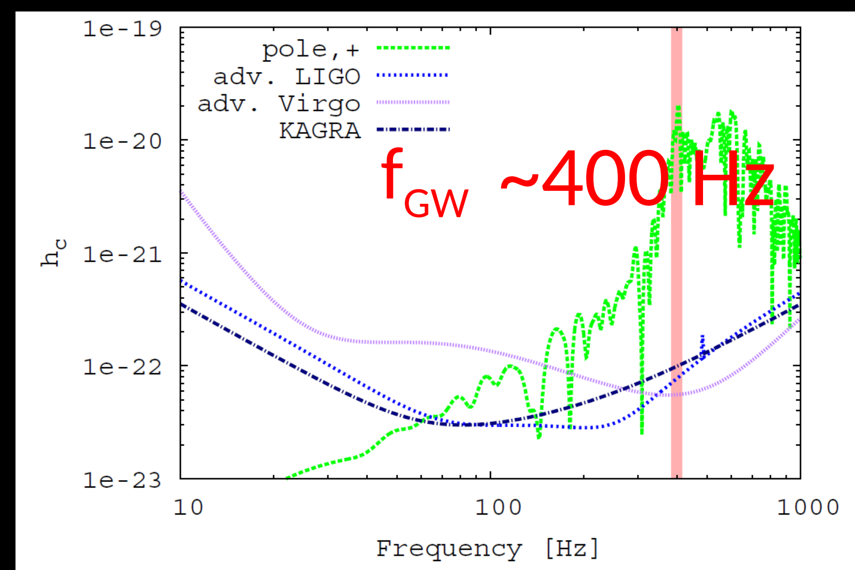




Courtesy of K. Kotake

Gravitational waveform

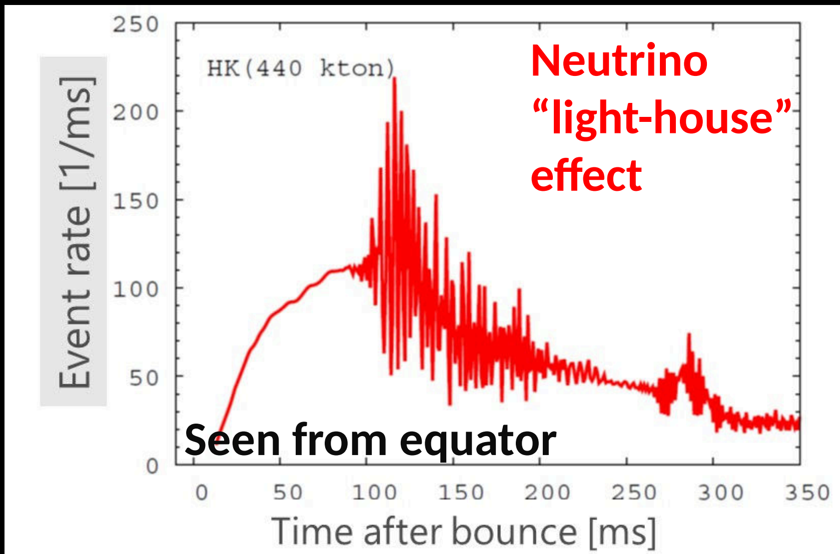


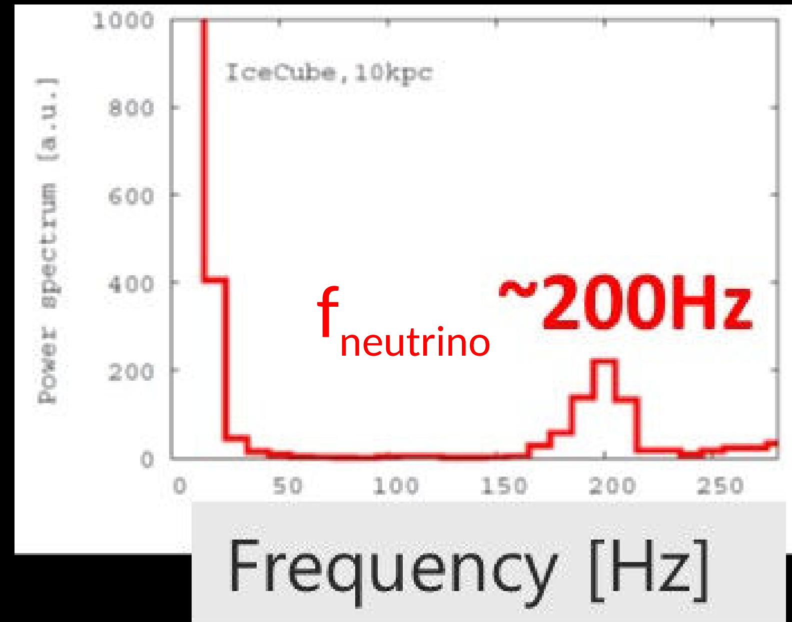


Correlation of ν and GW signals from a rapidly rotating 3D model

Takiwaki, KK, Foglizzo, (2021)

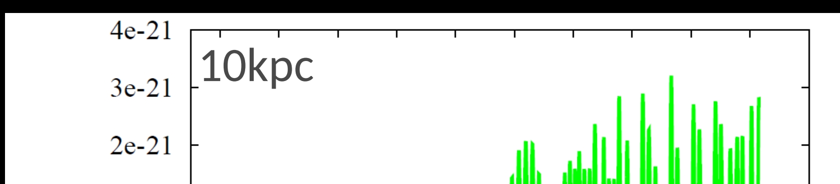
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

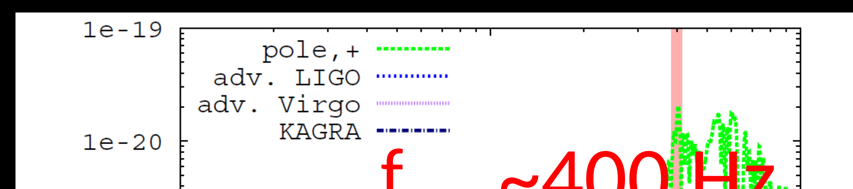




Courtesy of K. Kotake

Gravitational waveform

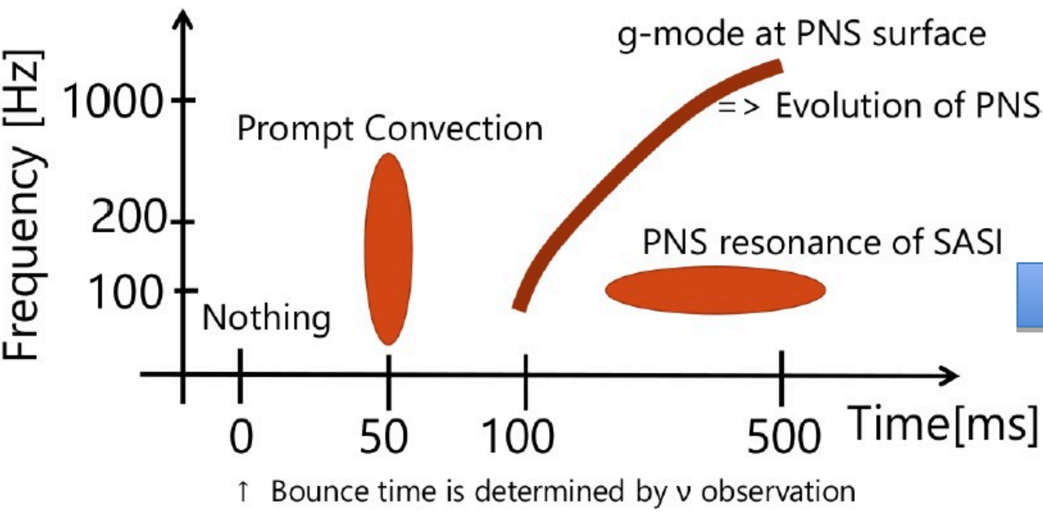




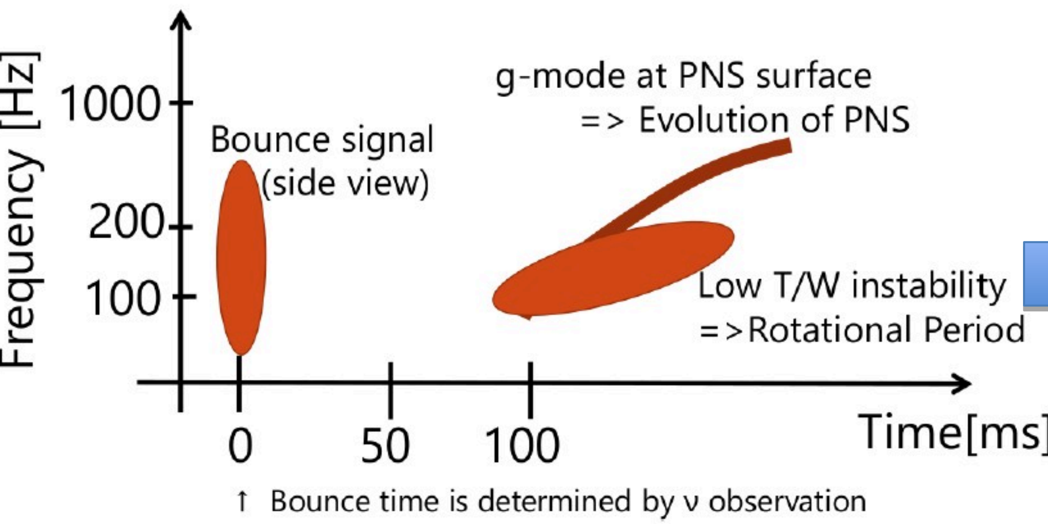
- ✓ Peak frequency of GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$)! Due to the quadrupole GW emission
- ✓ Also the case for non-rotating progenitor, $f_{neutrino,SASI}$~80Hz, f_{gw}~160Hz
- ✓ Coincident detection between GW and ν: smoking gun signature of rapid core rotation!

Different scenarios

Non rotating scenario

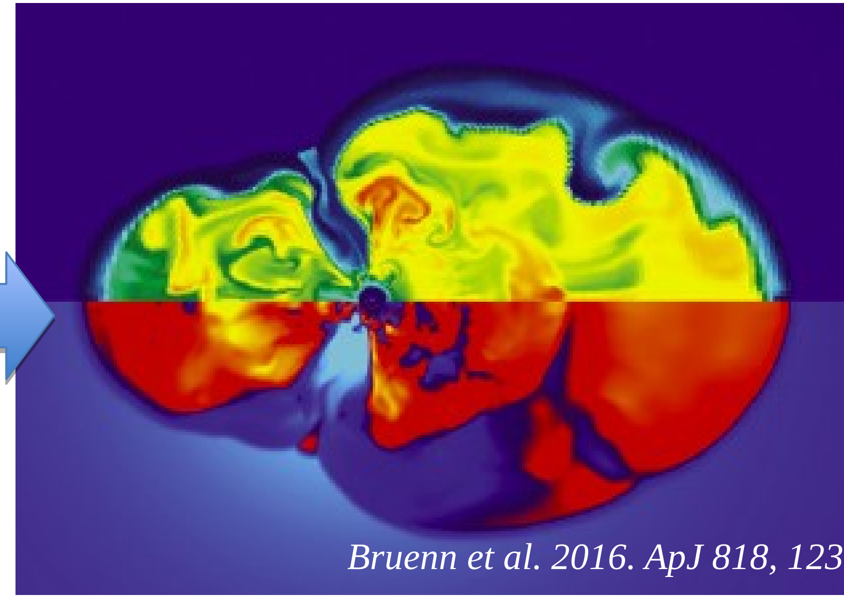


Rapidly rotating scenario



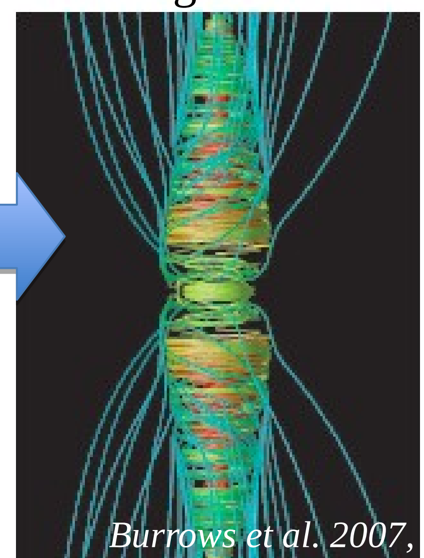
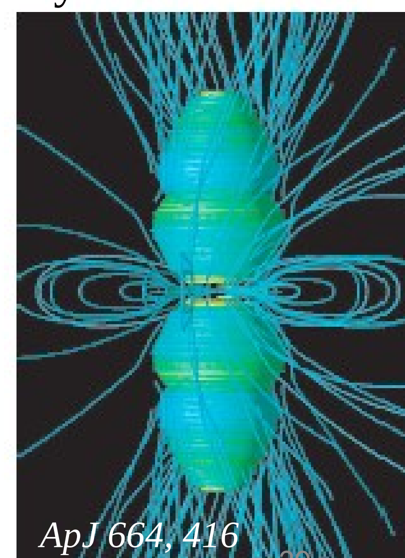
Credit: Tomoya Takiwaki

Neutrino driven CCSNe



Bruenn et al. 2016. ApJ 818, 123

Magneto-rotationally-driven CCSNe

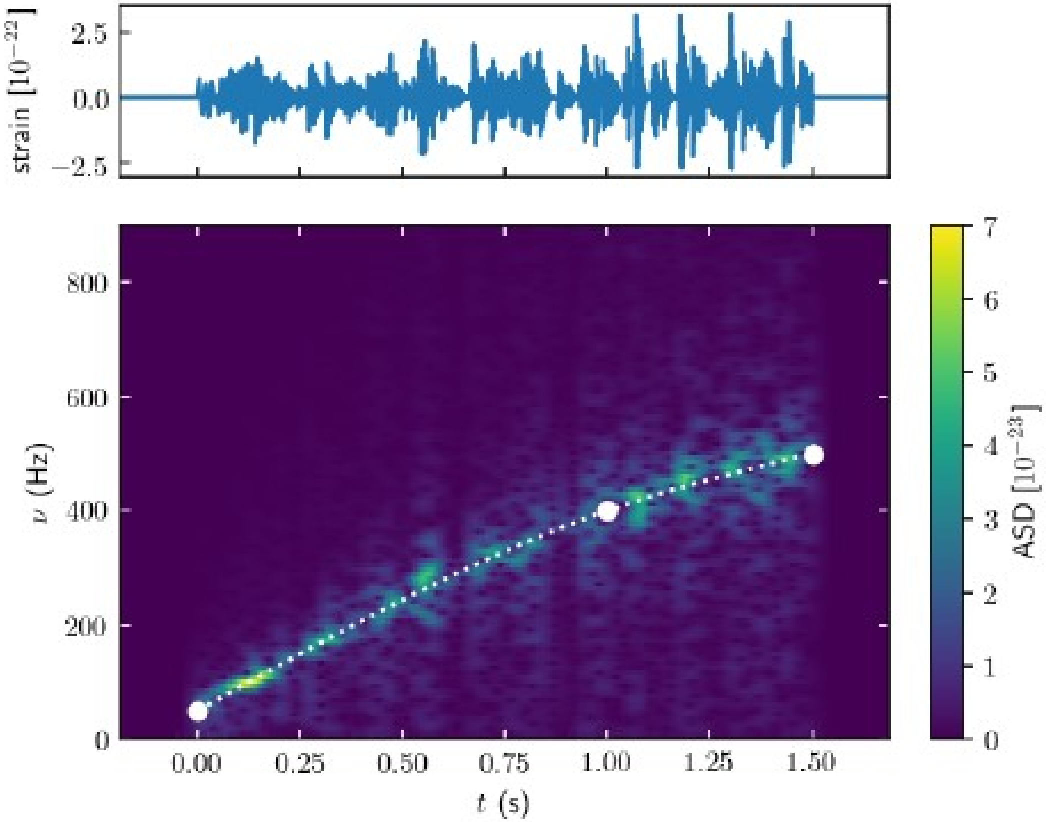
Burrows et al. 2007, ApJ 664, 416

- **Multimessenger observations:**
  - ✓ SN1987A
  - ✓ GW170817
  - ✓ IC170922

- The role of Core Collapse Supernovae

- The future challenges

Phenomenological Waveforms



parameter	min.	max.	Δ	description
$t_{\rm ini}$ [s]	0	0.2	0.1	beginning of the waveform
$t_{\rm end}$ [s]	0.2	1.5	0.1	end of the waveform
ν_0 [Hz]	50	150	50	frequency at bounce
ν_1 [Hz]	1000	2000	500	frequency at 1 s
ν_2 [Hz]	1500	4500	1000	frequency at 1.5 s
$\nu_{\rm driver}$ [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.

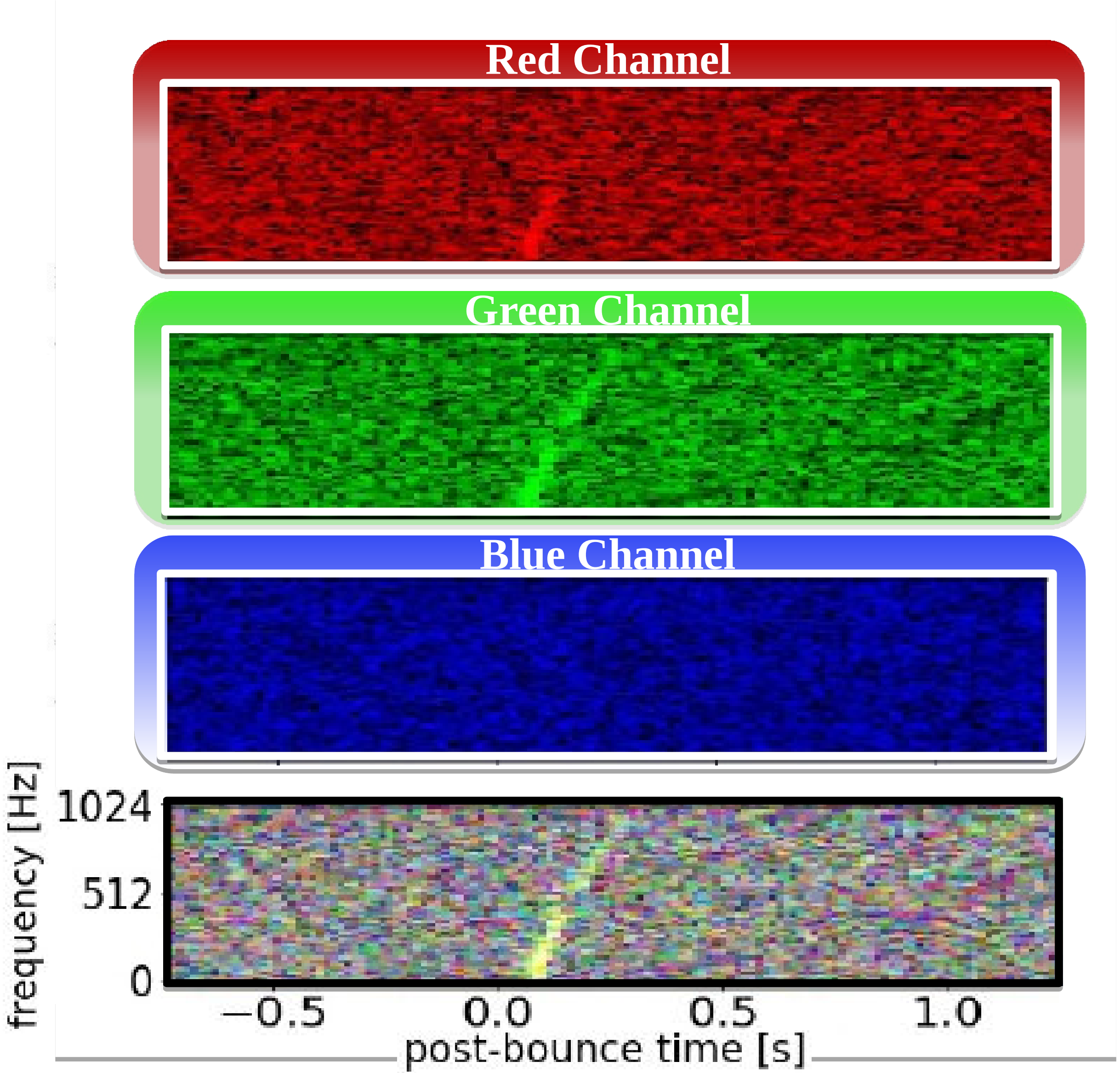
Creation of the time-frequency plots that are the input for the deep learning algorithm.

Analysis of these images through the neural network.

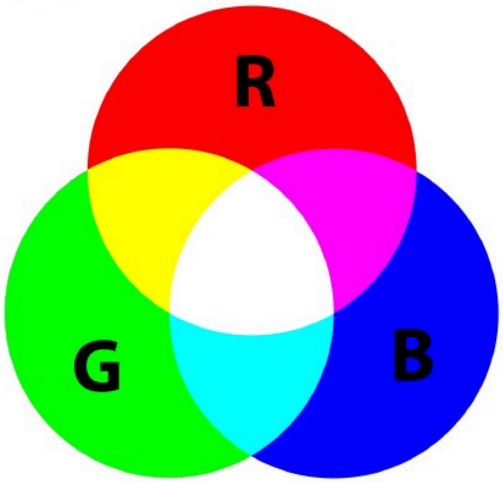
Classification of images as signal or noise.

RGB time-frequency plane

Coincidences among detectors



Additive colour synthesis



LIGO Hanford = red

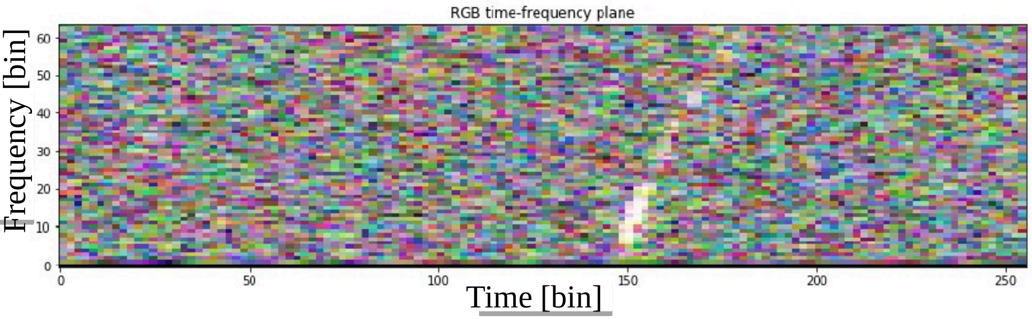
LIGO Livingston = green

Virgo = blue

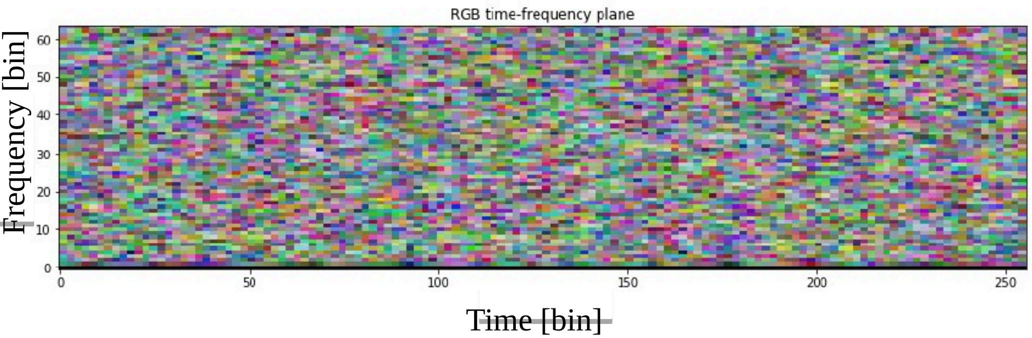
RGB time-frequency plane

Coincidences among detectors

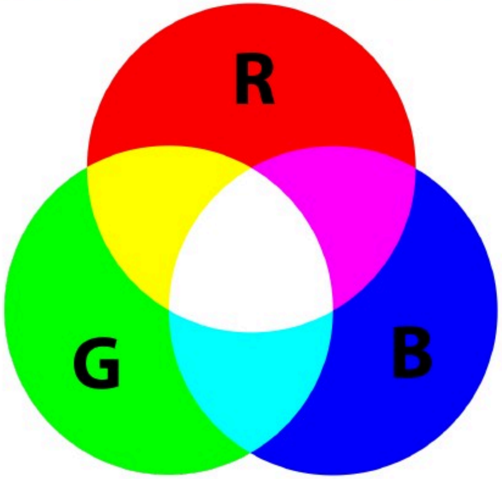
Signal+Noise



Only Noise



Additive colour synthesis

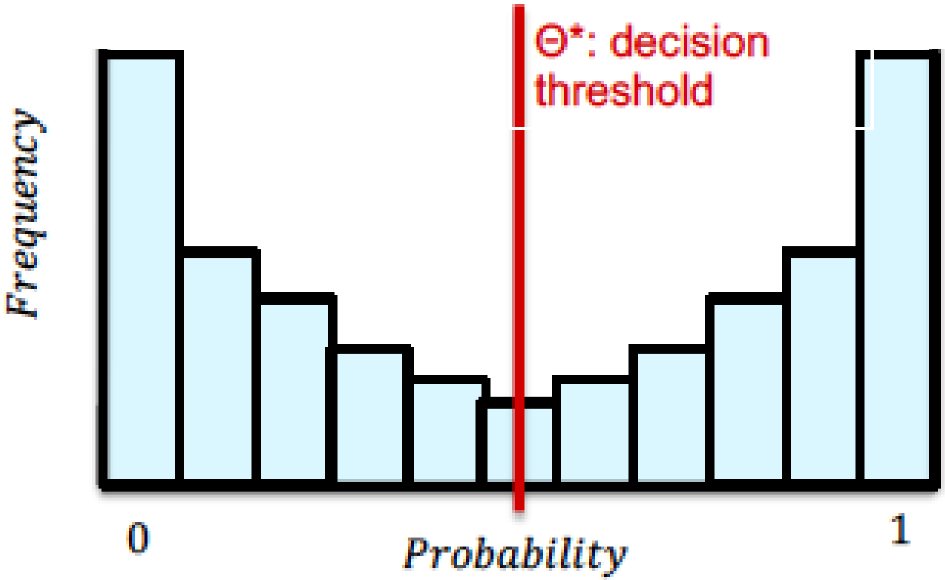


LIGO Hanford = red

LIGO Livingston = green

Virgo = blue

Measuring and constraining the learning



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

Confusion matrix

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

Efficiency:

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

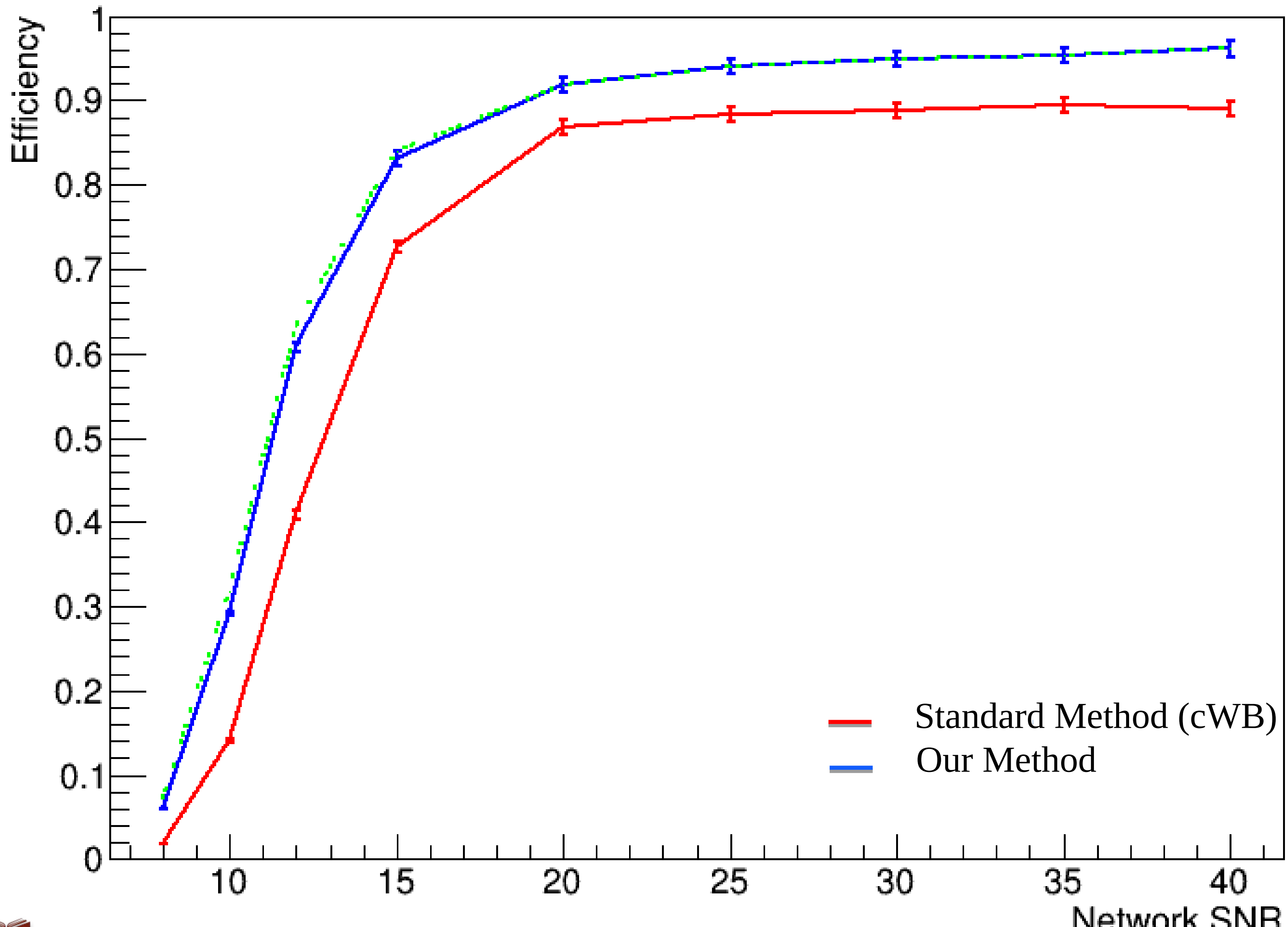
False Alarm Rate:

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

False Positive Rate:

$$FPR = \frac{FP}{FP+TN}$$

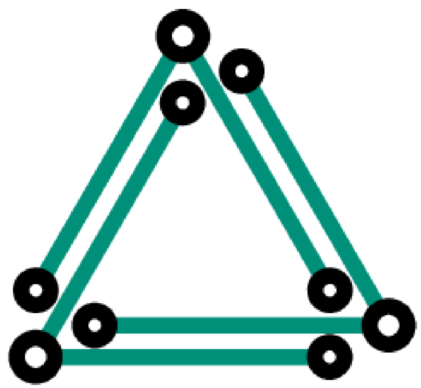
General results

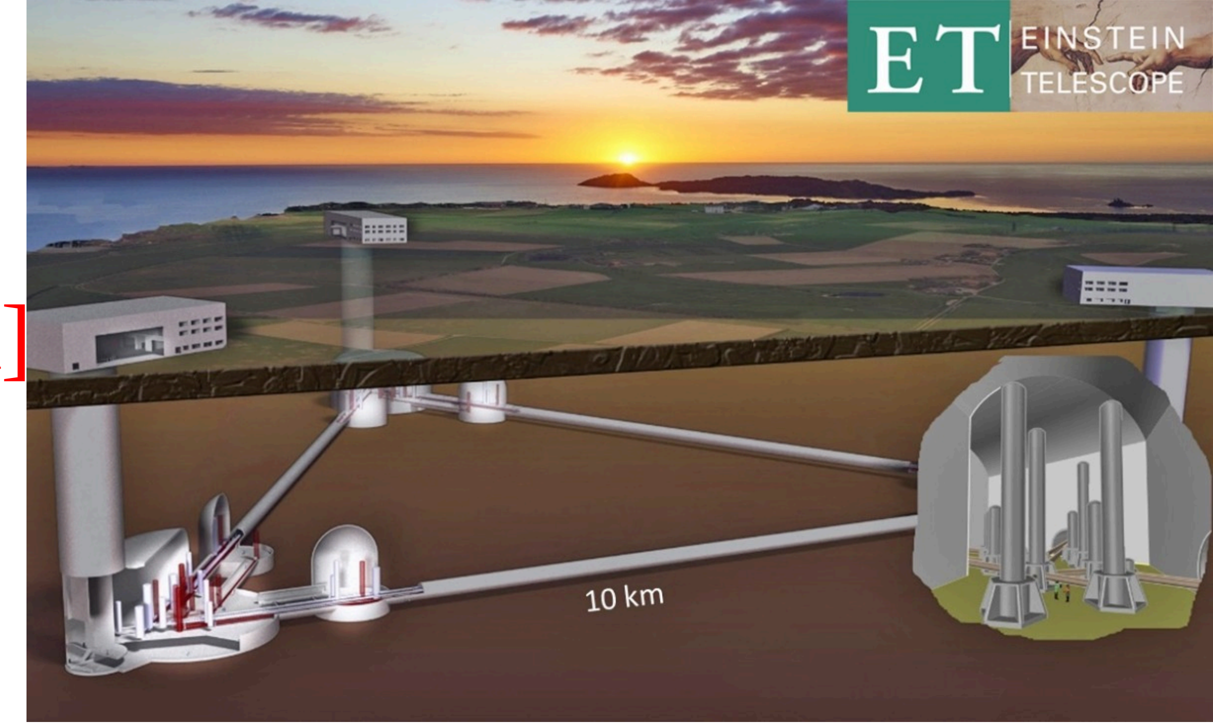


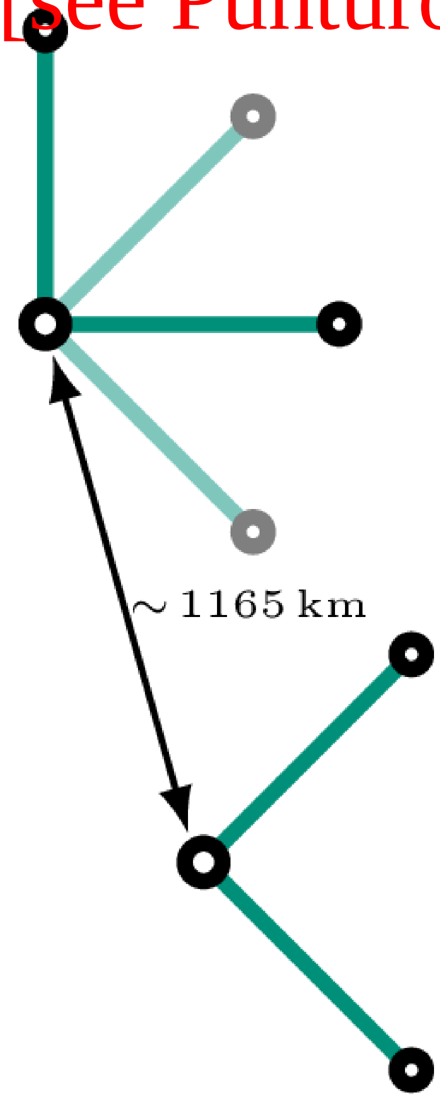
P. Astone, IDP et al. Phys.Rev. D 98 (2018) 12, 122002

Einstein Telescope

[see Punturo’s talk]







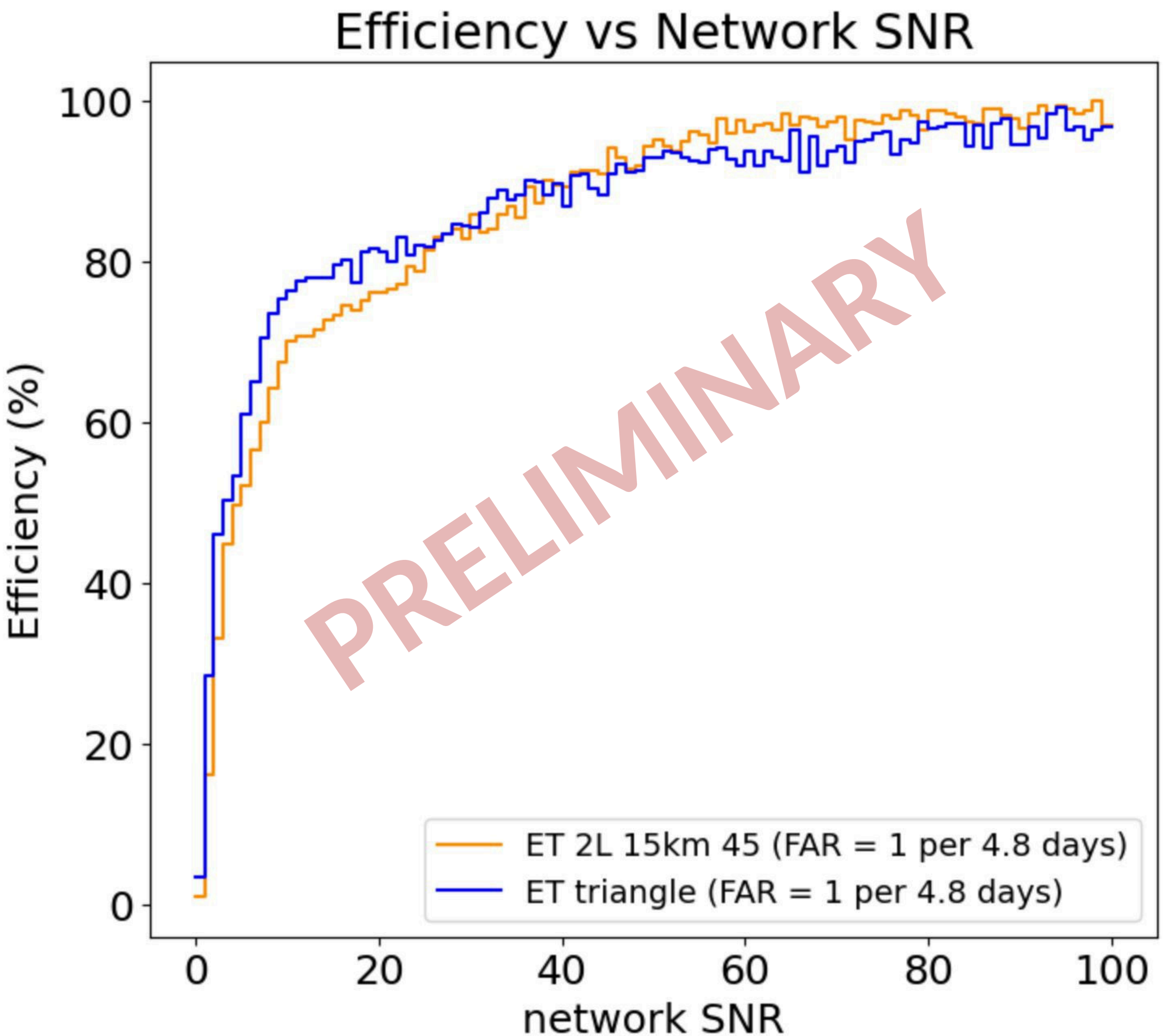
Gaussian noise: 10^5 images for each value of Network SNR $\in$ [1,100]

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

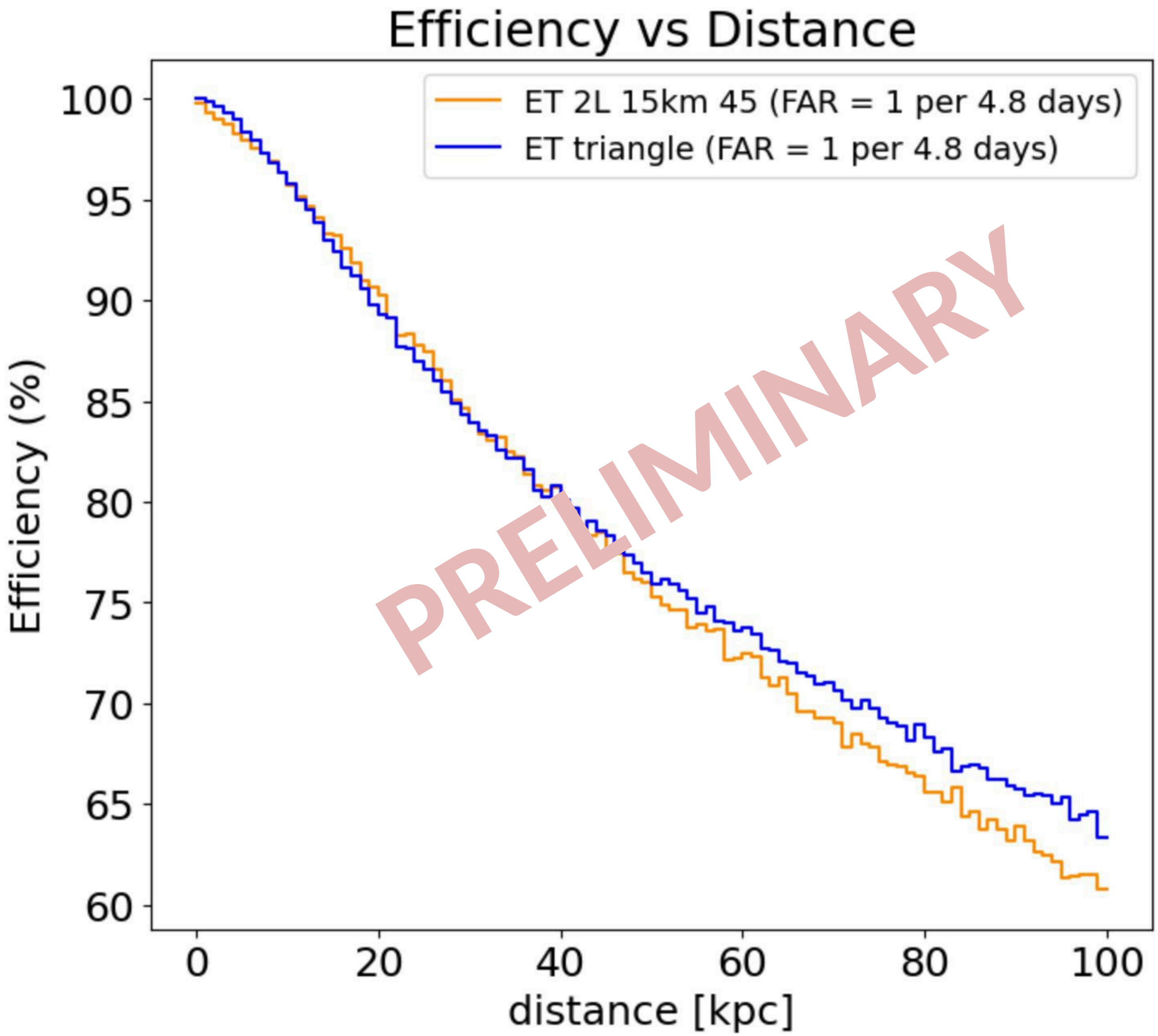
Test set - numerical simulations from the literature: 10^6 images with distances $\in$ [0.1, 100] kpc

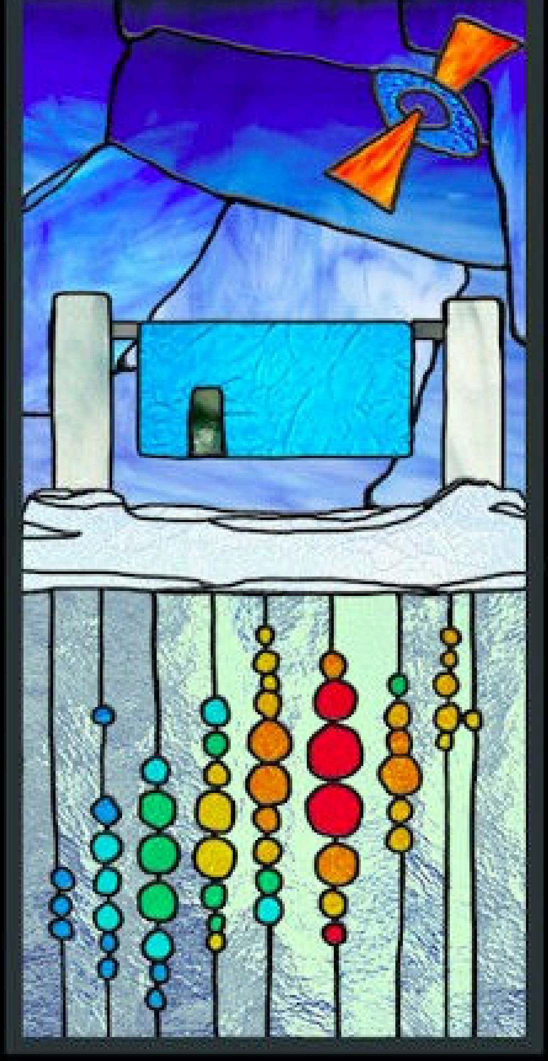
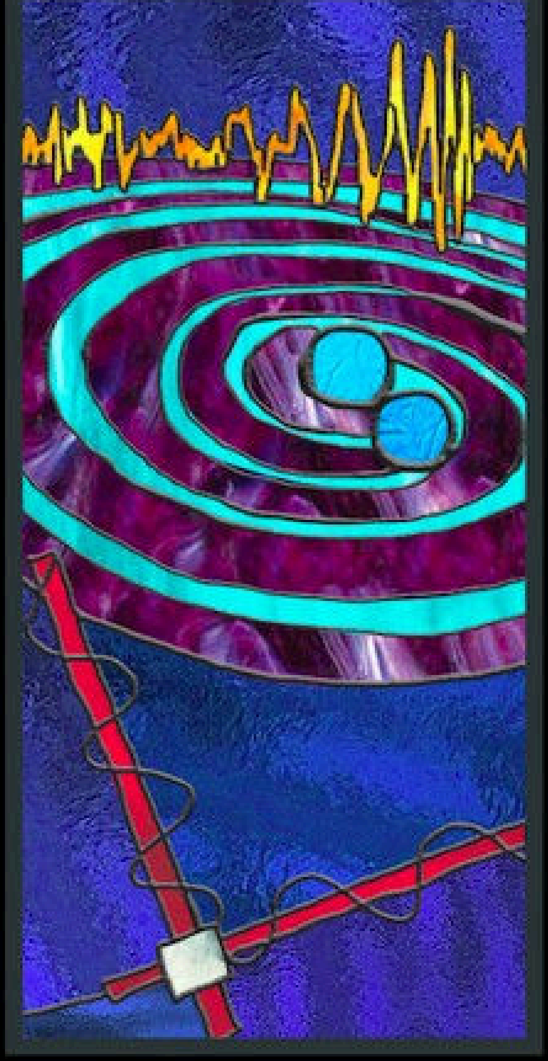
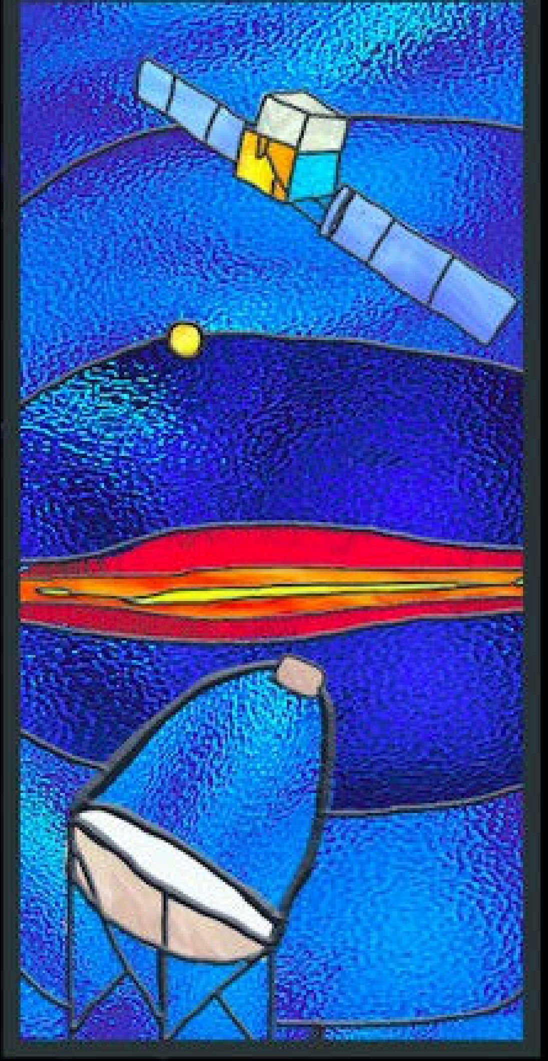
M. Branchesi et al. JCAP 07 (2023) 068

ET-2L 15km 45° vs ET triangle



ET-2L 15km 45° vs ET triangle



Waveforms for the test set

TABLE II: List of models of the test set used in the injections. $M_{\rm ZAMS}$ corresponds to the progenitor mass at zero-age in the main sequence (ZAMS). Unless commented, all progenitors have solar metallicity, result in explosions and their GW signal do not show signatures of the standing-shock accretion instability (SASI).

Model name	reference	$M_{\rm ZAMS}$	comments
s9	[47]	$9M_\odot$	Low mass progenitor, low GW amplitude.
s25	[47]	$25M_\odot$	Develops SASI.
s13	[47]	$13M_\odot$	Non-exploding model.
s18	[48]	$18M_\odot$	Higher GW amplitude.
he3.5	[48]	-	Ultra-stripped progenitor ($3.5M_\odot$ He core).
SFHx	[49]	$15M_\odot$	Non-exploding model. Develops SASI.
mesa20	[50]	$20M_\odot$	
mesa20_pert	[50]	$20M_\odot$	Same as mesa20, but including perturbations.
s11.2	[31]	$11.2M_\odot$	
L15	[28]	$15M_\odot$	Simplified neutrino treatment.

[28] T. Kuroda et al., 851(1):62, 2017.
[31] H. Andresen et al., MNRAS 468(2):2032-2051, 03 2017.
[47] D. Radice et al., ApJ 876(1):L9, 4 2019.
[48] J. Powell et al., MNRAS 487(1):1178-1190, 05 2019.
[49] T. Kuroda et al., ApJ 829(1):L14, 9 2016.
[50] E. O’Connor et al., ApJ 865(2):81, 9 2018.