Core collapse supernova, r-process nucleosynthesis, gravitational waves & neutrinos astrophysics

Propositions:

- “Understanding the core collapse supernova explosion mechanism with gravitational waves”, Marie Anne Bizouard (ARTEMIS)
- “Neutrinos Astrophysics: from core-collapse supernovae and kilonovae to the discovery of the diffuse supernova neutrino background”, Cristina Volpe (APC)
- “Detecting low-energy transient neutrino signals with KM3NeT”, Gwenhael de Wasseige (APC)

Labs involved: APC, ARTEMIS, CEA/AIM, CPPM, IAP, IPHC, LAL, LAPTH, LAPP, LLR, LUTH, Subatech

The key questions of these 3 proposals

- NS are the result of the collapse of a 9-30 solar mass star but the CCSN explosion mechanism is still an open question. GWs are a unique probe to witness the dynamics of the collapse.
- Low-energy neutrinos are playing a key role in CCSN and BNS mergers/r-process nucleosynthesis.
- Can we detect the diffuse supernova neutrino background ?

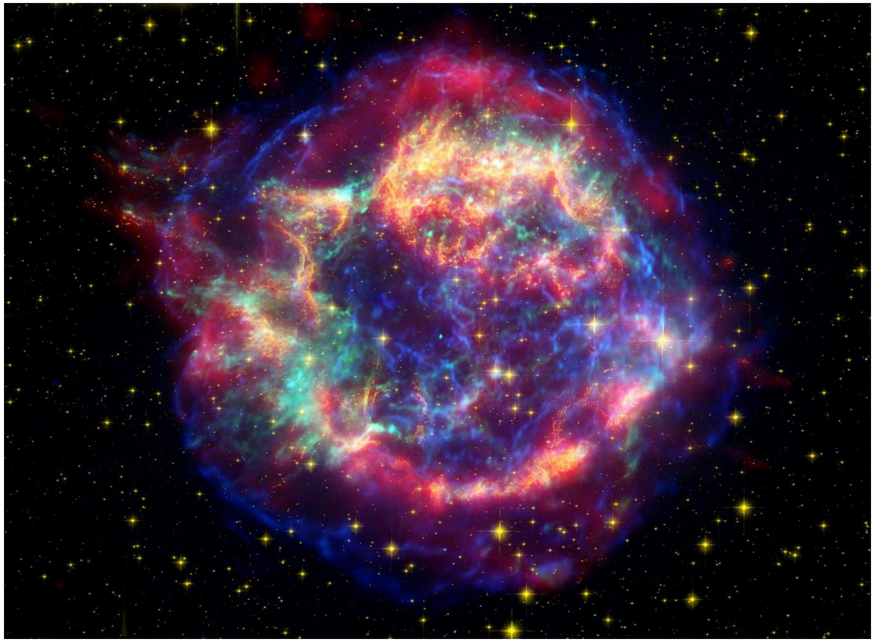
This is a domain where observations are needed.

- Pb: CCSN and kilonovae are rare events → third generation GW detectors are mandatory.

This is a domain where theory developments are also mandatory to help observations and interpretation.

- Pb: turbulent environment and many micro-physics ingredients including neutrinos interactions play a role in neutrino transport and flavor evolution..

CCSN facts and open questions?



Credit: NASA Spitzer Space Telescope (red) / Hubble Space Telescope (yellow) / Chandra X-ray Observatory (green and blue)

- ~ $(30\ \mathrm{yr})^{-1}$ per galaxy
- ~ tens every second in the observable universe
- Peak luminosity ~$10^{10}\ L_{\odot}$
- 10^{46} erg gravitational waves
- 10^{48} erg EM radiation
- 10^{51} erg kinetic energy
- 10^{53} erg neutrinos

- Is the delayed neutrino mechanism responsible for the majority of CCSNe, or is there something missing? What is the role of rotation?
- Which stars explode and which stars do not?
- How can we use neutrino and gravitational wave observations to learn about the CCSN explosion engine?

Neutrino-driven CCSN explosion mechanism

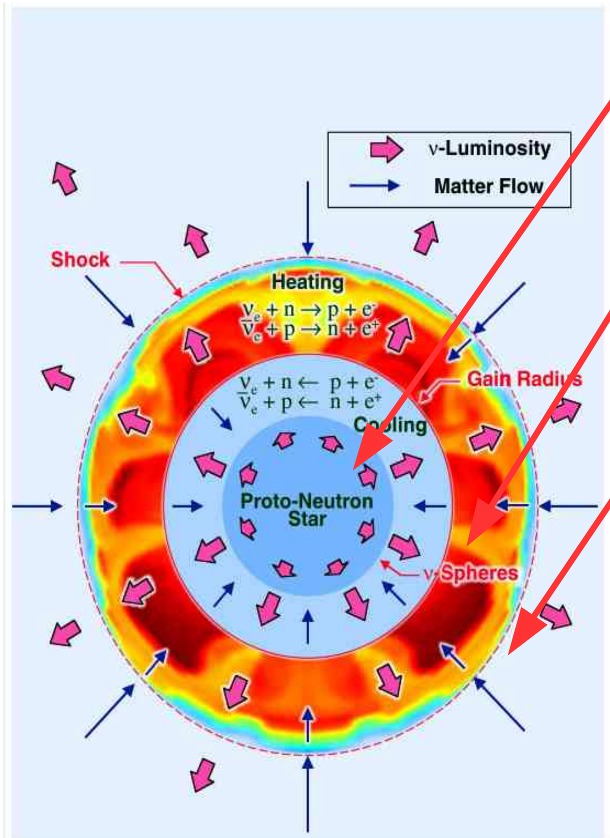


Figure credit : A. Mezzacappa

1. Trapped neutrinos diffuse out ($\tau_{\nu\text{-diff}} >> 1$) of the opaque PNS

2. Neutrinos heat matter in semi-transparant ($\tau_{\nu\text{-diff}} \sim 1$) post-shock region and drive convective flow in hot bubble region between gain radius and shock

3. Neutrinos stream freely ($\tau_{\nu\text{-diff}} << 1$) through transparent stellar envelope.

Additional key ingredients for explosion :

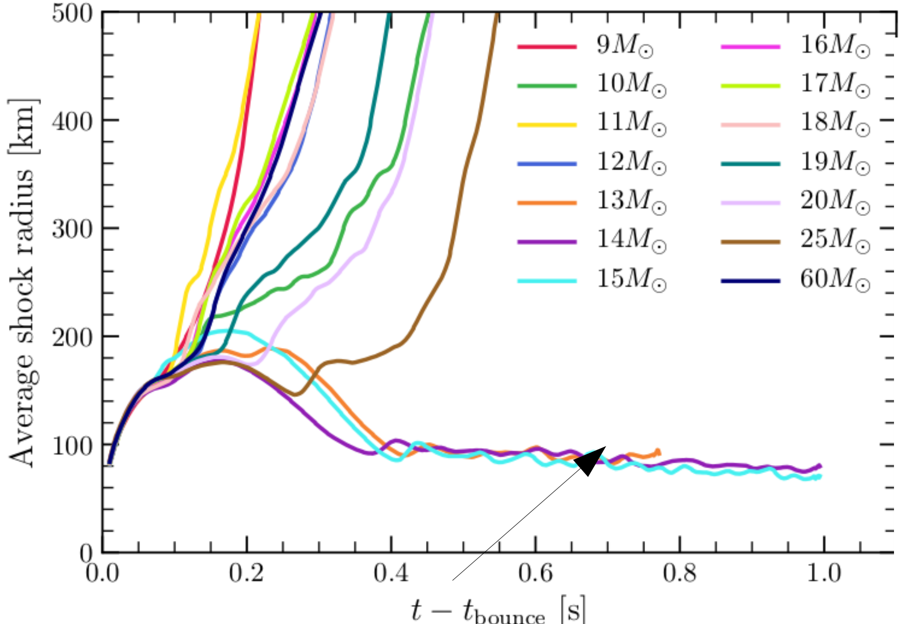
- Nuclear burning.
- Standing accretion shock instability (SASI) is an instability of the shock wave itself. SASI aids the explosion and determines the asphericity.

- Recent breakthrough in (2D-3D) numerical simulations : almost all codes observe the same « signatures », but still not yet a complete code that includes all ingredients.

- In case of initial rotation, clear bounce signal.

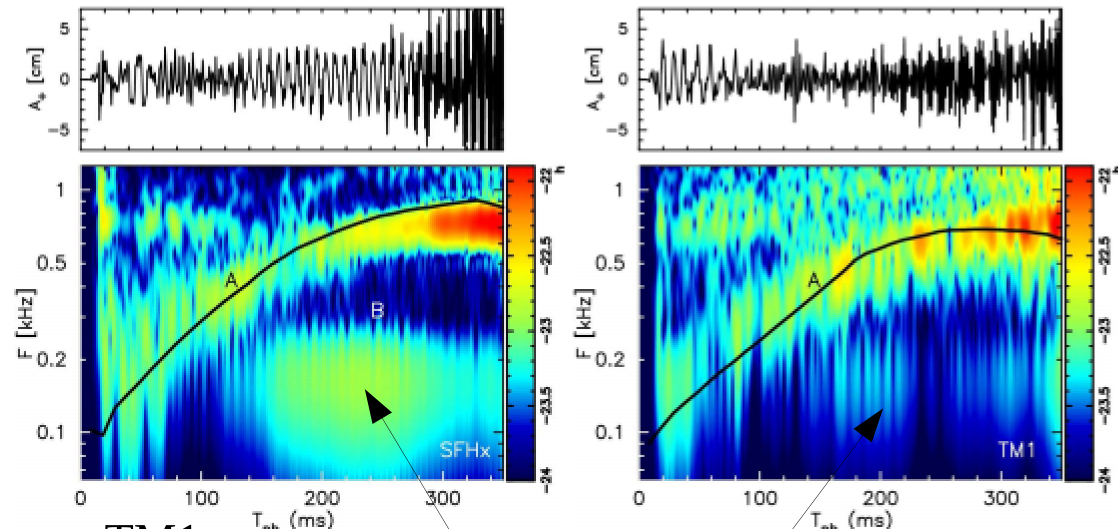
Why we need more precise simulation?

Burrows et al. arXiv:1909.04152



Why do not 13-15 Msun mass stars explode in these simulations?

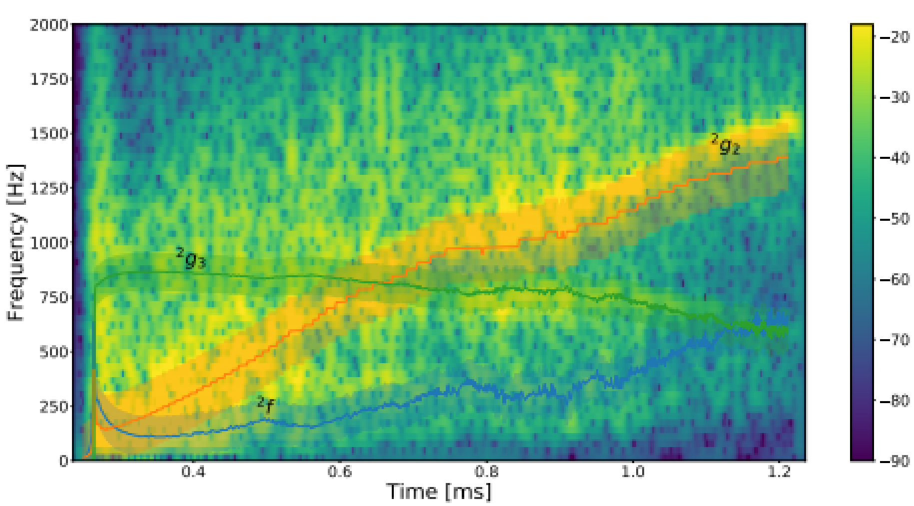
Kuroda et al. ArXiv: 1605.09215



TM1 SFHx

Effect of the EOS

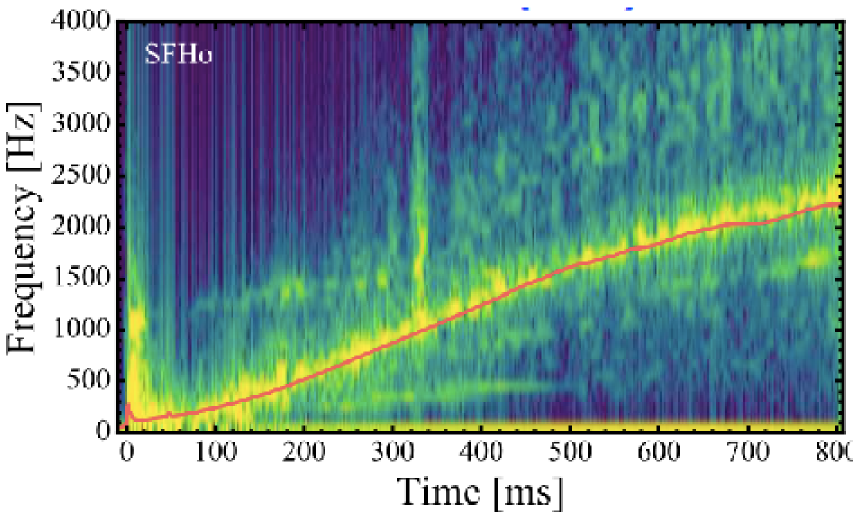
Torres-Forne et al. arXiv:1902.10048



The GW signal is extremely complex and stochastic in nature, but there are common Features such that PNS excitation modes, SASI, convection ...

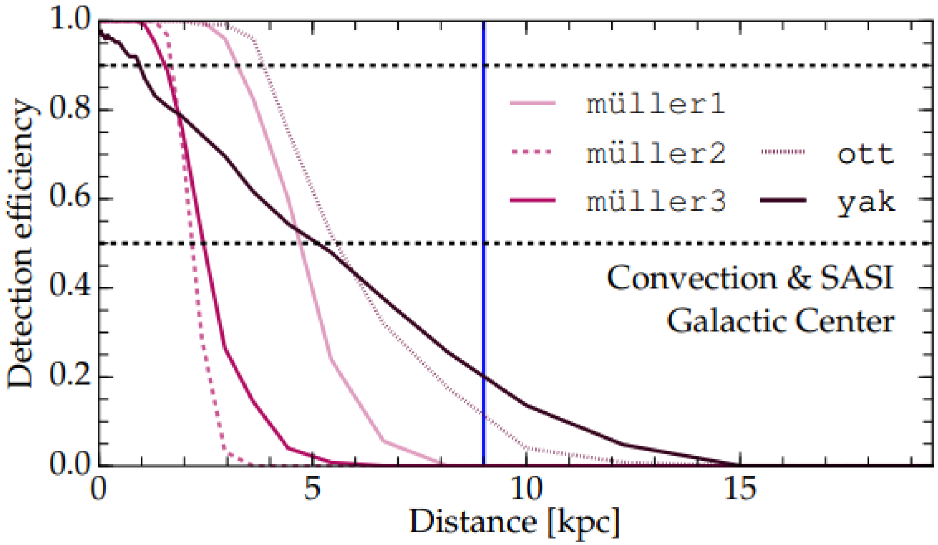
The CCSN GW detection panorama in the next 10 years

- Advanced LIGO / advanced Virgo / KAGRA: 2 types of searches:
  - All-sky/ all-time searches (silent supernova)
  - Targeted searches (neutrino & optical alerts):
    - false alarm rate reduced,
    - a short on source window allows to use signal extraction methods that are computing time limited (Bayesian methods using CCSN waveforms or simplified models).



Sensitivity: limited to the Galaxy

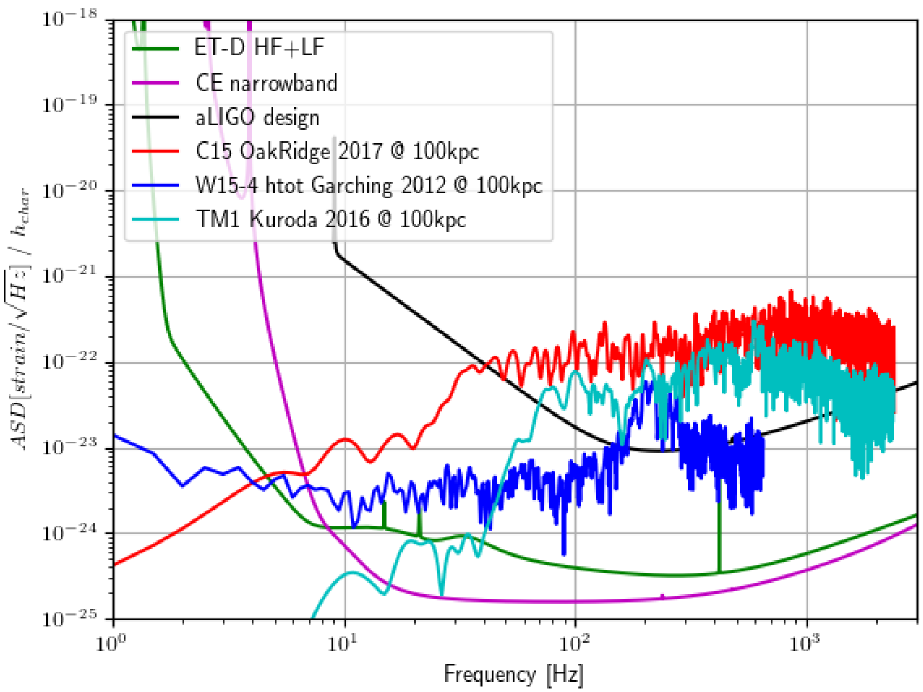
Gossan et al, arXiv: 1511.02836



- Source parameter estimation :
  - Agnostic waveform reconstruction using the coherence of the GW polarizations in 2 or more GW detectors data.
  - Identify some of the (loudest) features expected in the different phases : rotation at bounce, quiessence phase, SASI, PNS oscillation modes, …
  - Determine the explosion mechanism : neutrinos or MHD.
  - Constrain EOS, progenitor mass, ..

The CCSN GW detection panorama in the next 10 years

- 3rd generation of GW detectors: Eintsein Telescope (Europe) and Cosmic Explorer (US): proposed, not yet founded. See roadmap next slide
- 3G detector science case document release in July 2019: https://gwic.ligo.org/3Gsubcomm/documents/science-case.pdf

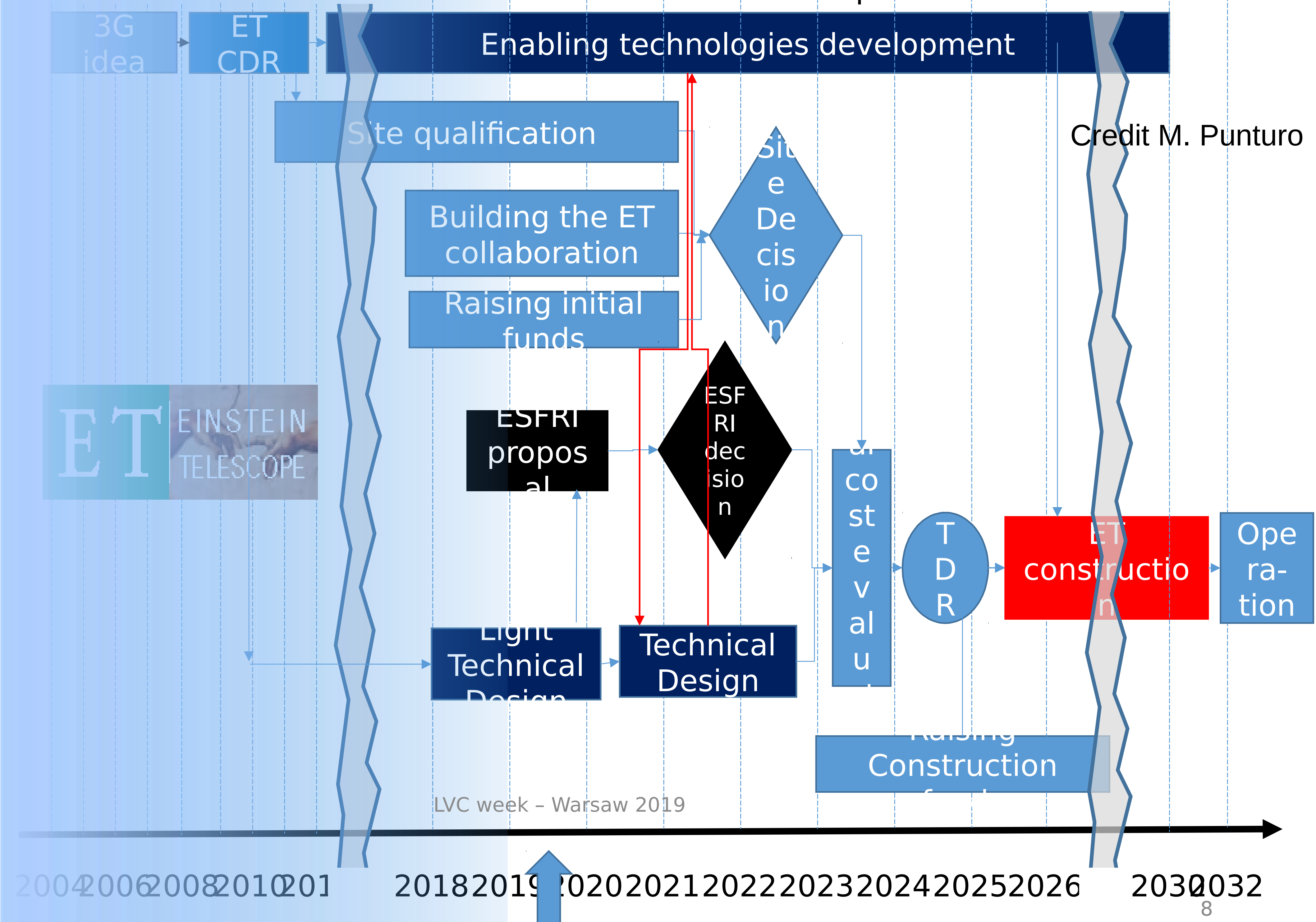


	Yakunin 2017	Mueller 2012			Kuroda 2016	
	C15	L15-3	N20-3	W15-1	SFHX	TM1
ET-D	54	12	4	6	24	18
CE	129	26	11	11.5	51	37
aLIGO	5.9	1.3	0.4	0.6	2.7	2.0

Table 4.1: Matched-filter SNRs of six 3D neutrino-driven explosion simulations for a source located at 100 kpc recorded in 1) the Einstein Telescope (ET-D), 2) the Cosmic Explorer (CE), and 3) and advanced LIGO at design sensitivity (aLIGO) are provided here. The matched-filter SNRs do not include a detector's antenna function.

Gain of a factor 10 in sensitivity/distance

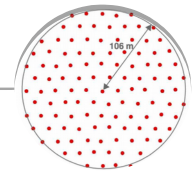
ET Roadmap


3G idea
ET CDR
Enabling technologies development
Site qualification
Credit M. Punturo
Building the ET collaboration
Raising initial funds
Site Decision
EINSTEIN TELESCOPE
ESFRI proposal
ESFRI decision
co st e v al u
T D R
ET construction
Ope ra- tion
Light Technical Design
Technical Design
Construction
2004 2006 2008 2010 201
2018 2019 2020 2021 2022 2023 2024 2025 2026
2030 2032

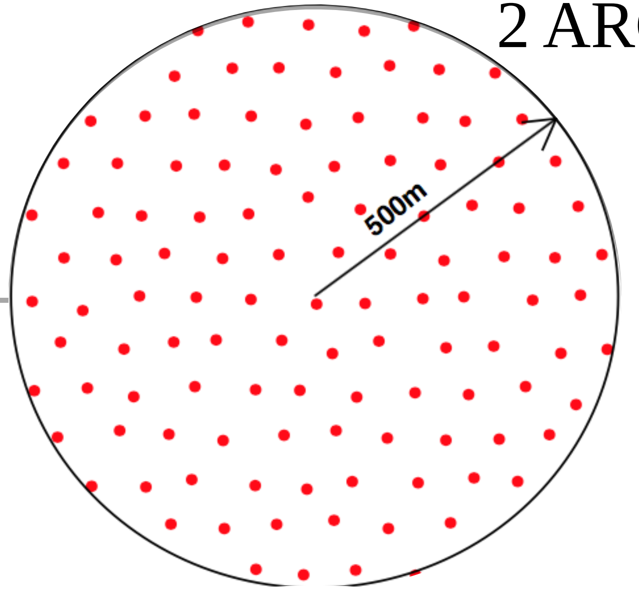
The CCSN neutrinos detection panorama in the next 10 years

- PNS oscillation frequencies and damping times are directly affected by the high-density EOS as well as the neutrino emission.
- Neutrino cooling and deleptonization determine the thermal structure of the PNS and its rate of contraction, setting the rate at which the dominant f-mode frequency increases.
- To observe this phenomena, one will need high-resolution neutrino “light curve" data obtained from a galactic supernova via underground neutrino detectors that should be available at the horizon of 2030: Super-K/Hyper-K, DUNE, JUNO, IceCube, LVD, Borexino, KamLAND.
- SNEWS (Super-K, LVD, IceCube, KamLand, Borexino, Daya Bay, HALO, KM3NeT): 5-sigma neutrino CCSN alert system.
- French groups involved in KM3NeT that is sensitive to CCSN neutrinos.

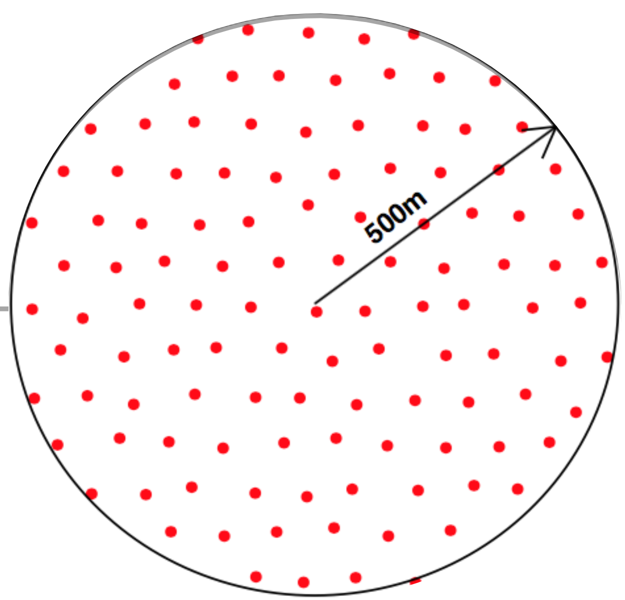
KM3NeT



2 ARCA blocks
+ ORCA



Astroparticle Research with Cosmics in the Abyss

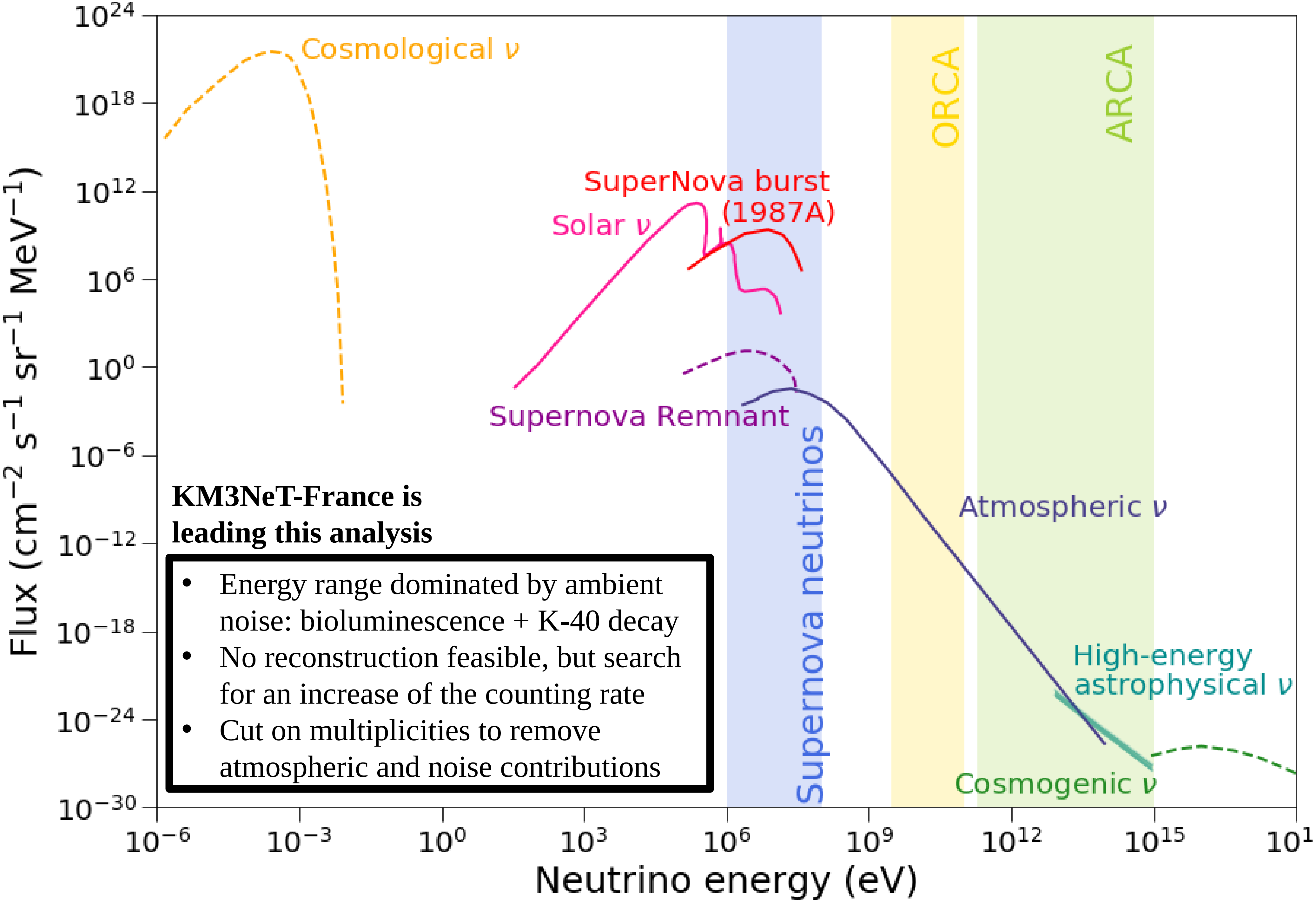


- 3 x 115 Detector Units
  InterDU spacing: 20m or 90m
- 18 DOMs
  InterDOM spacing: 9m or 36m

31 PMTs

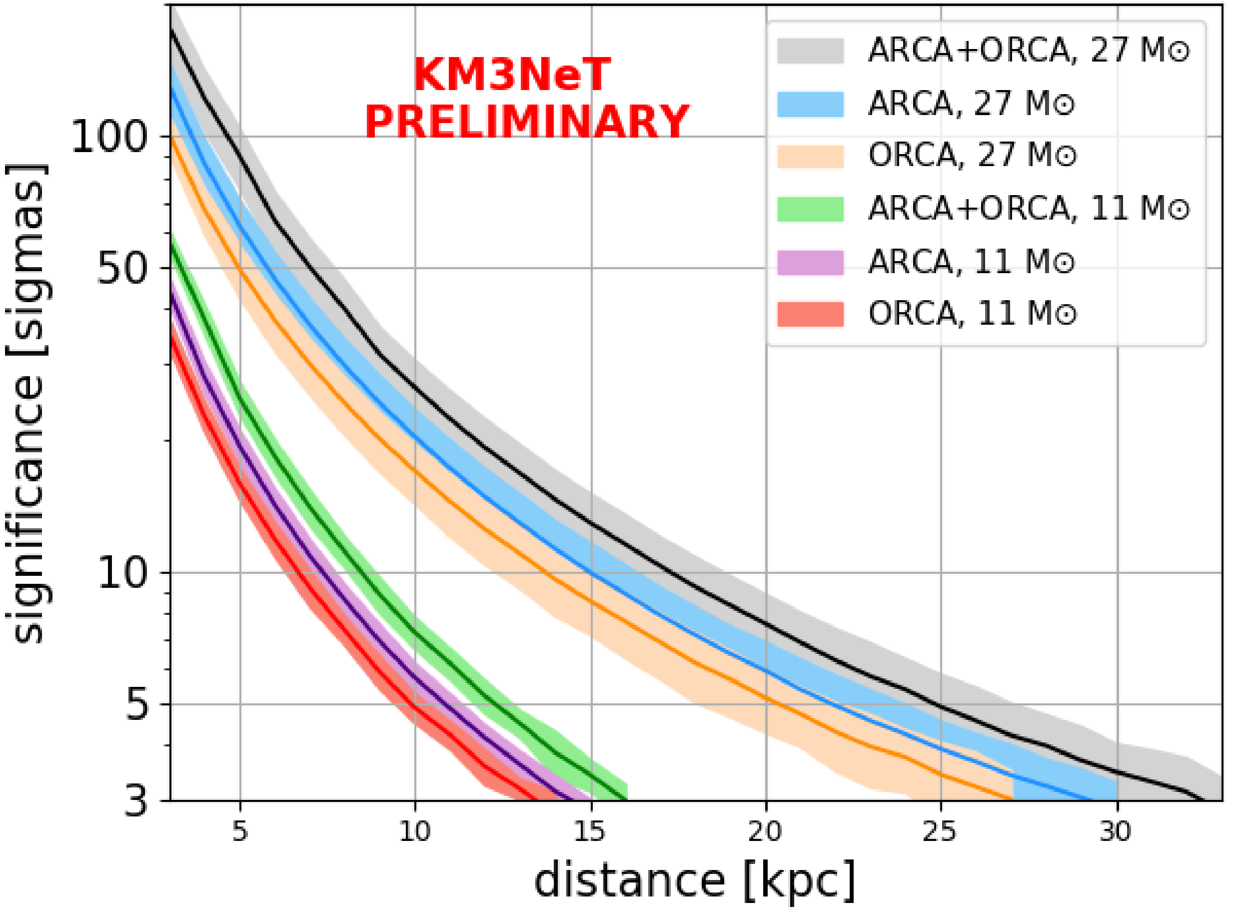
Currently 1 ARCA + 4 ORCA DUs taking data

KM3NeT for SN neutrino searches



KM3NeT-France is leading this analysis

- Energy range dominated by ambient noise: bioluminescence + K-40 decay
- No reconstruction feasible, but search for an increase of the counting rate
- Cut on multiplicities to remove atmospheric and noise contributions



Sensitivity

KM3NeT is sensitive to electron anti-neutrinos via inverse beta decay

	2025 ORCA115 + ARCA230	
27 M_{sun}	5 σ	25 kpc
11 M_{sun}	5 σ	Galactic center (even with just ORCA)

(conservative estimate)

Physics reach with KM3NeT

- Part of SuperNova Early Warning System (SNEWS) since last June
- Members of the group active in the SNEWS 2.0 working groups
- Triangulation of the SN position when combining with other neutrino detectors' light curves
- Sensitivity to fast-time variations of the neutrino light curves (e.g., SASI)
- Estimate of the mean neutrino energy

<u>Improvements in the coming decade:</u>

- Enhanced sensitivities thanks to the completion of KM3NeT
- Detailed studies of the ambient noise to further improve the sensitivities for detection and different SN models
- Cleaner light curves expected with a better noise rejection
- Study of the synergies with other neutrino experiments (e.g., DUNE, DarkSide) to better understand supernova with MeV neutrinos

Coming back to theory … neutrinos in dense environments

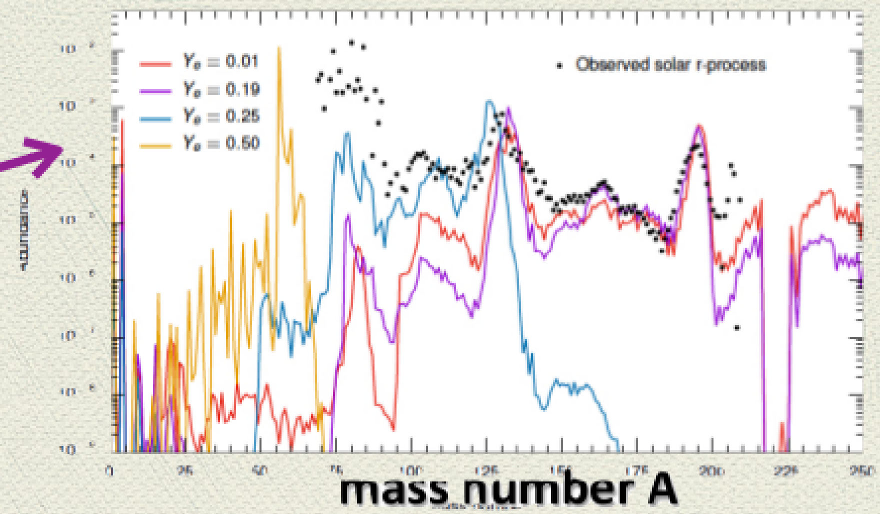
Neutrino Astrophysics

For the future measurements

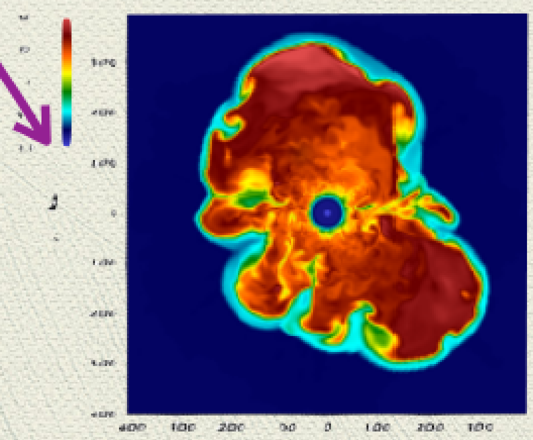
- the discovery of the diffuse supernova neutrino background - **Super-K + Gd**
- an (extra)galactic supernova - 10^{4-6} events -**SNEWS, Hyper-K, JUNO**

Understanding
the role of neutrinos
and of flavor conversion
in dense environments
important

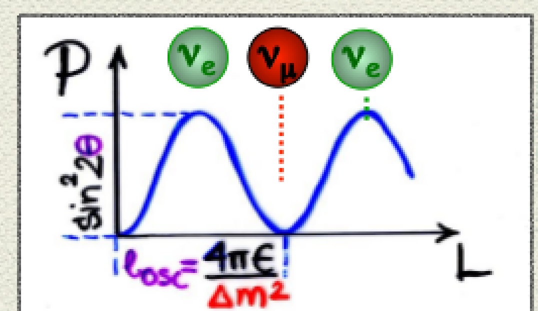
The site(s) for the r-process ?



Supernova explosion mechanism ?



Mueller et al, 1705.00620

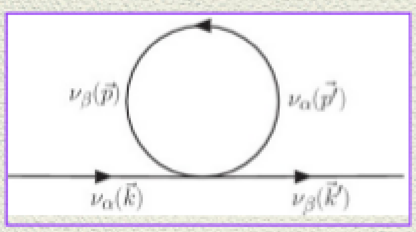


more complex than vacuum oscillations…

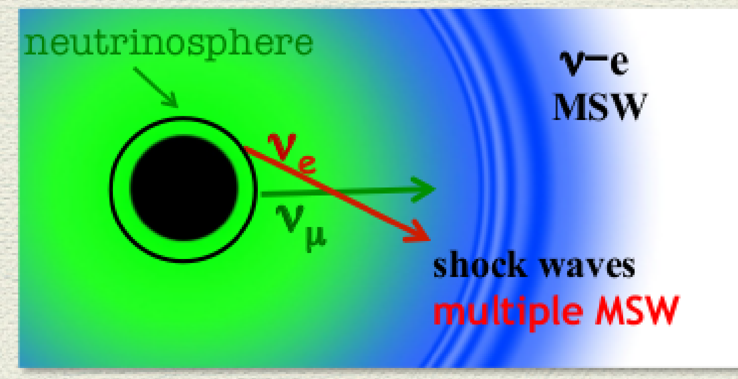
Neutrino flavor evolution in dense environments

A complex many-body problem

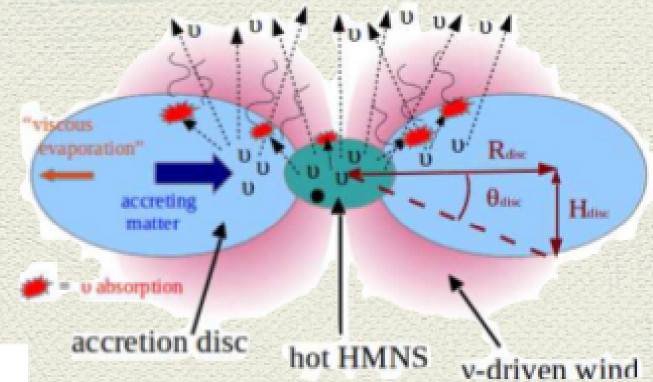
- Novel conversion phenomena due to neutrino self-interactions, shock waves and turbulence.

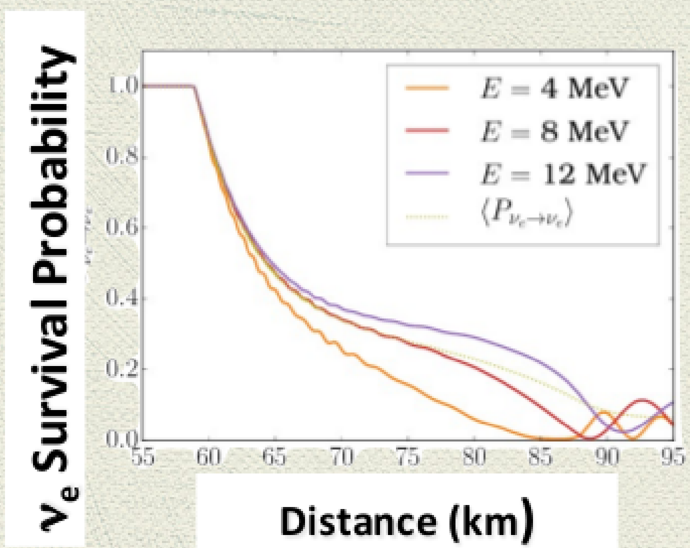


Pantaleone, 1992

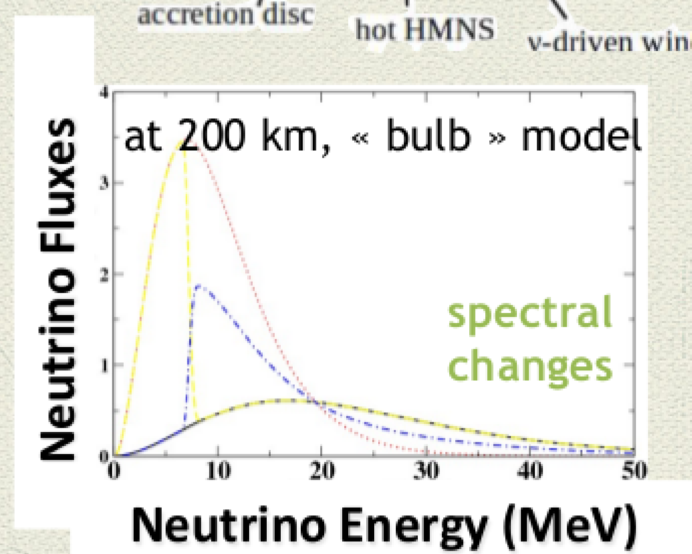


- $\phi_{\nu_e}(E) = P(\nu_e \to \nu_e)\phi^0_{\nu_e}(E) + [1 - P(\nu_e \to \nu_e)]\phi^0_{\nu_x}(E)$



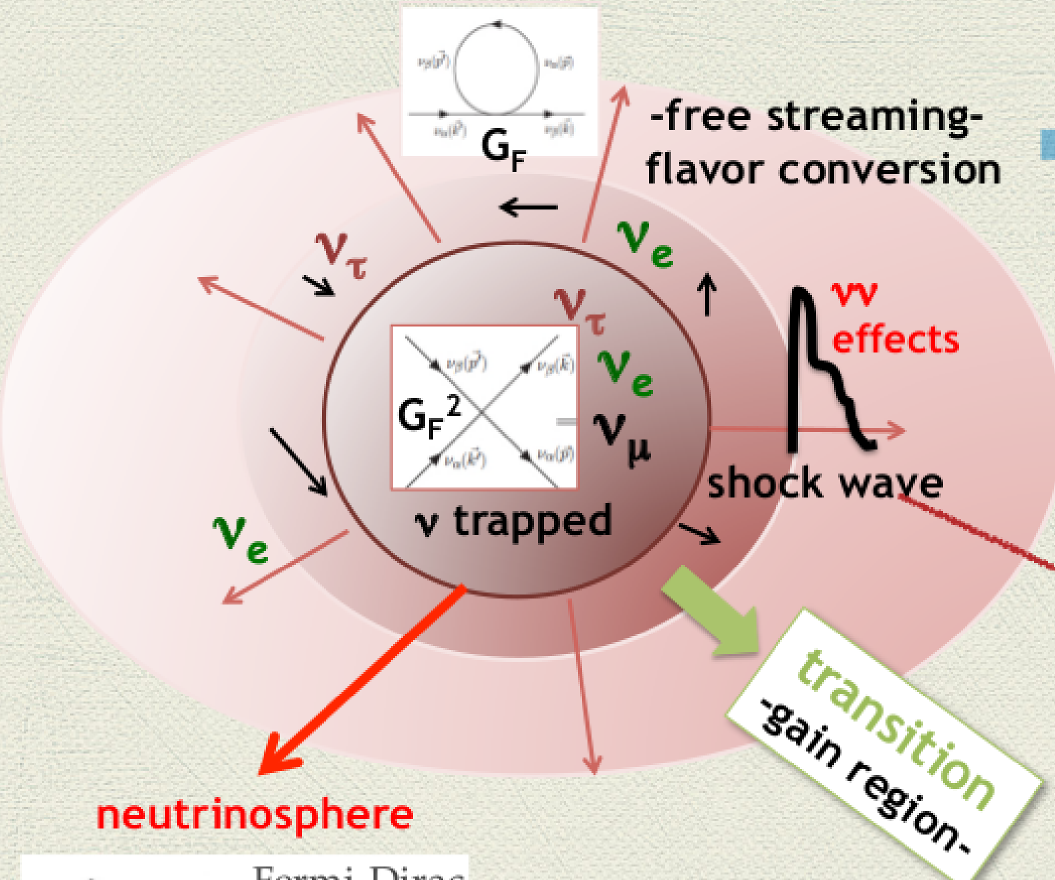


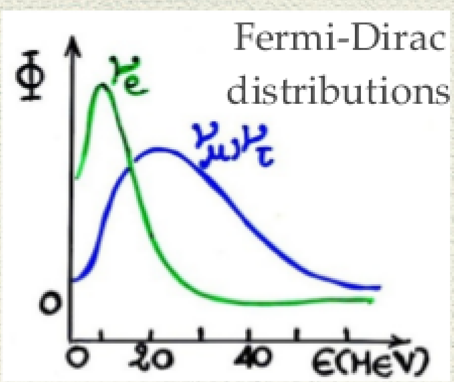
Chatelain, Volpe, PRD 95, 2017



Conditions and mechanisms for flavor evolution in dense environments need to be elucidated

Supernovae explosions and flavor evolution





$< E_{\nu_e} >< < E_{\bar{\nu}_e} >< < E_{\nu_{\mu,\tau}} >$

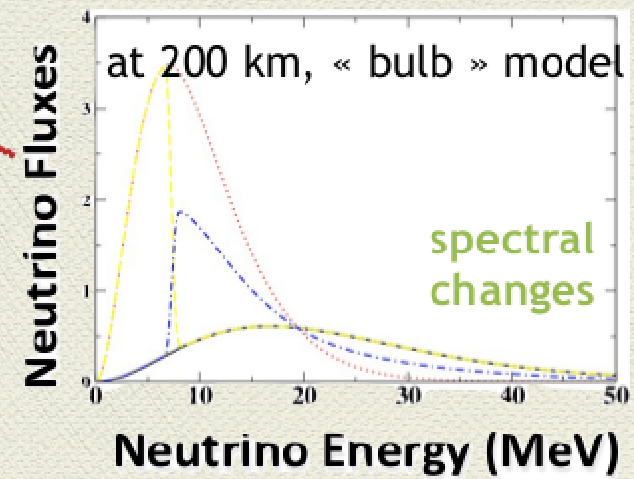
- Neutrinos interact with p, n :

$\bar{\nu}_e + p \rightarrow n + e^+ \qquad \nu_e + n \rightarrow p + e^-$

- The rates depend on the neutrino spectra :

$$\lambda_{\nu_e n} = \int dE_\nu \sigma_{\nu_e n}(E_\nu) \phi_{\nu_e}(E_\nu)$$

$$\lambda_{\bar{\nu}_e p} = \int dE_\nu \sigma_{\bar{\nu}_e p}(E_\nu) \phi_{\bar{\nu}_e}(E_\nu)$$



The heating rate could be enhanced
by modifications of the neutrino spectra

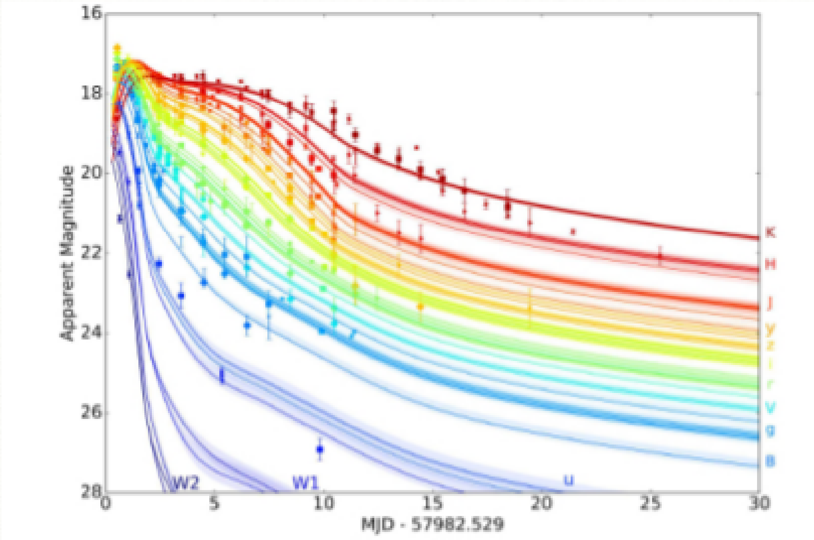
GW170817 and the kilonova

- First measurement of gravitational waves from a binary neutron star merger, in coincidence with a short gamma ray burst and a kilonova.

- The comparison of electromagnetic emission with kilonova models reveals two main facts.

  1- *Ejecta have two components :*
  dynamical from the early merging phase (subdominant) and neutrino-driven winds and viscous ejecta from late time post-merger phase (dominant)

  2- *Presence of* lanthanide free ejecta (blue component) and ejecta with lanthanides (red component).



Villar et al, Ap. Jl. (2017) 851, L21

Neutrinos interactions and flavor evolution influence r-process elements abundances
A lot of work needed to quantify their impact

The discovery of the Diffuse Supernova Neutrino Background

- The relic neutrino flux depends on <u>core-collapse supernova fluxes</u>, the <u>supernova rate</u> (related to the star formation rate), integrated over redshift :

$$\phi^{relic}_{\nu_\alpha}(E'_\nu) = \int dz \left|\frac{dt}{dz}\right| (1+z) R_{SN}(z) \underline{\phi_\alpha(E'_\nu)}$$

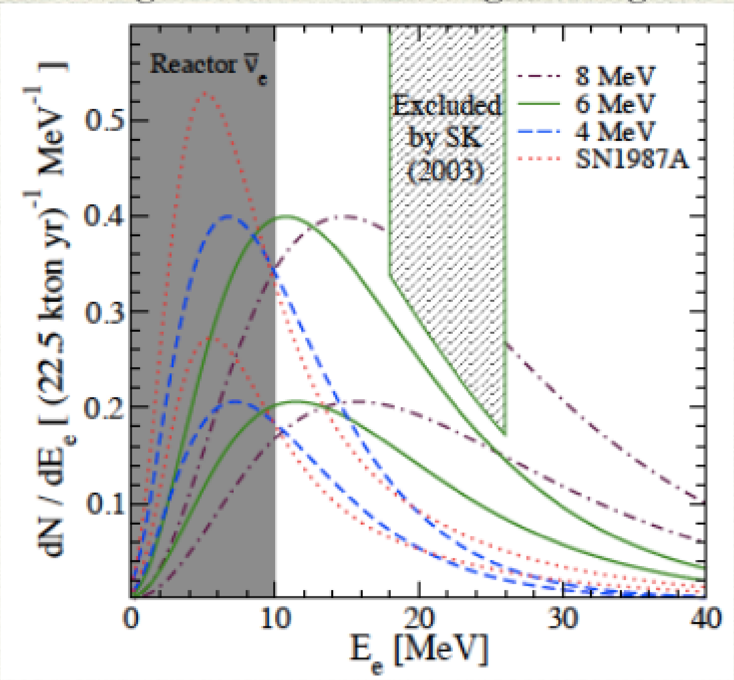
$E'_{\nu_\alpha} = (1+z)E_\nu$ redshifted neutrino energy (only the spectra tail matters) since *<u>z = 0,1,2 only contribute</u>*

Super-Kamiokande with Gd
- neutron tagging (reduced backgrounds)
  Beacom, Vagins, PRL 93 (2004)

from EGADS to **SuperK-VI+Gd (2019/20)**

Hyper-K (258 ktons) - several hundreds

SK (2003) : excluded SN rate models and high neutrino average energies



Beacom, Ann. Rev. 60 (2010)

Crucial measurement of the R_{SN} and of the neutrino fluxes

Conclusions

- Physics questions to be answered:
  - CCSN explosion mechanism, neutrinos flavor evolution in dense environment, r-process nucleosynthesis abundances, …
- GWs and neutrinos are unique probes to understand the dynamics and the micro-physics.
- Challenges:
  - with the current generation of detectors, we will be limited to rare events studies → need 3G GW detectors
  - Very complex many-body physics.