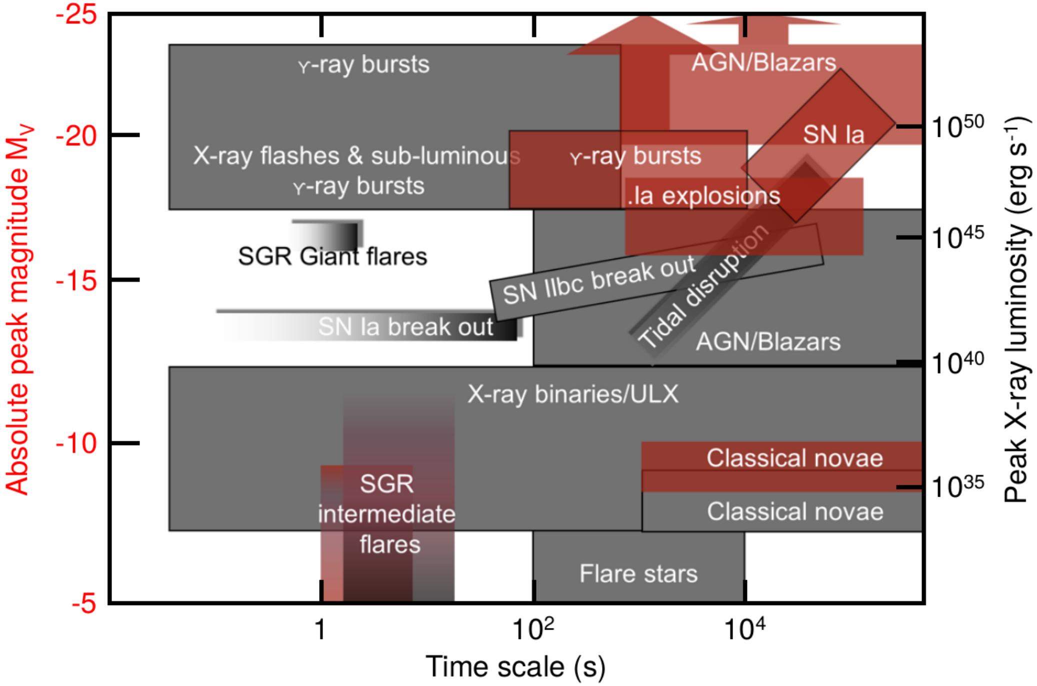
MULTI-MESSENGER & TRANSIENT SKY ASTRONOMY

Olivier GODET



- Very energetic and violent phenomena releasing huge amount of energy in various forms (EM, neutrinos, GW, …)
- Imply the birth, destruction or feeding of compact objects (stellar mass BHs, supermassive BHs, NS & WD)
- Deep feedback impacts on the source surroundings on multiple scales

⇒ Role of COs in the structuration of matter in the Universe

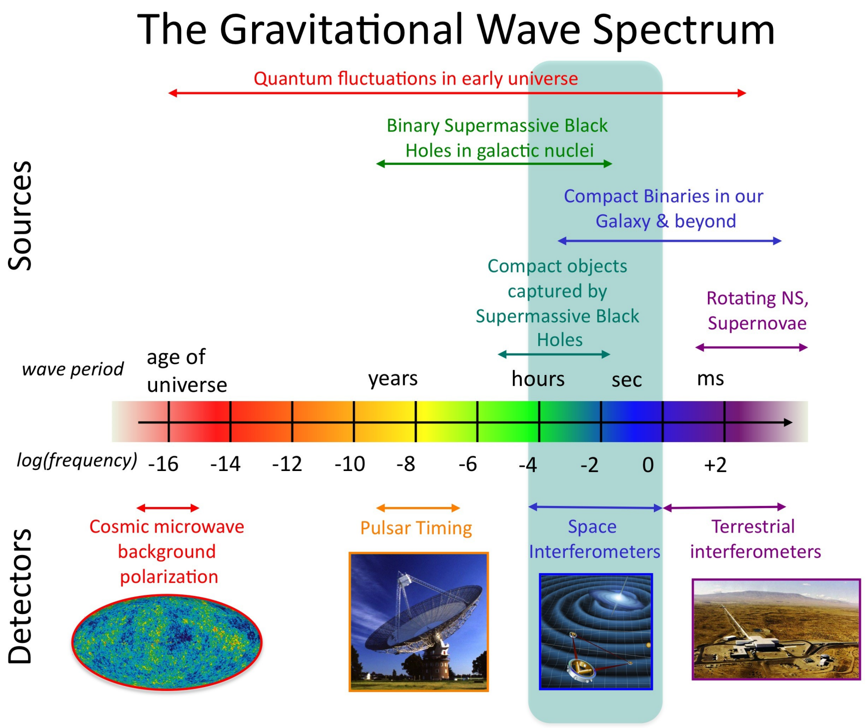
- Demography of COs over cosmological timescales
- Growth of supermassive BHs / co-evolution with host galaxy
- Reprocessing of baryons / r-process nucleosynthesis

See talks during the « source populations » session this afternoon

- Up to very recently, only use of light across the entire electromagnetic (EM) spectrum to study the Universe contents

- The advent of sensitive neutrinos (IceCube, SK, KM3Net) & GW (LVK, LISA, ET/CE) detectors opens a new window on the Universe

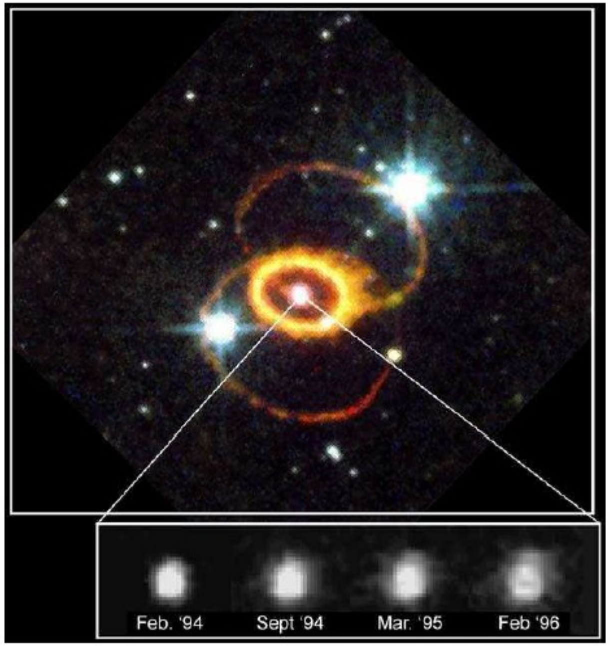
⇒ MM astronomy has the power to deeply transform our understanding of the formation and contents of the Universe

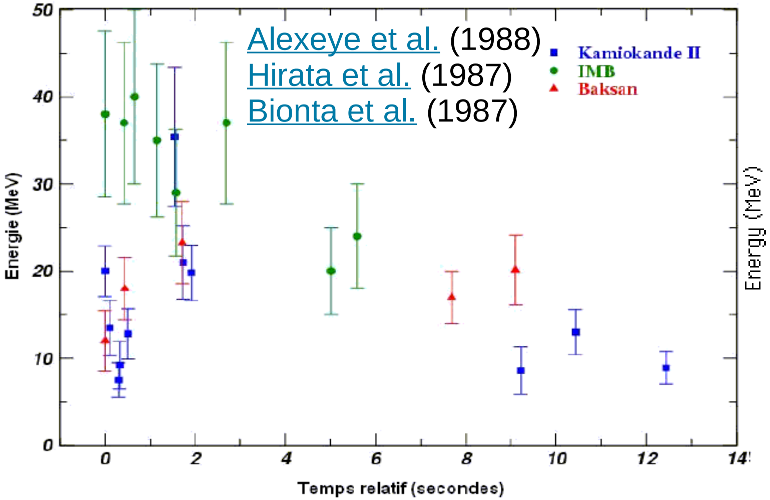


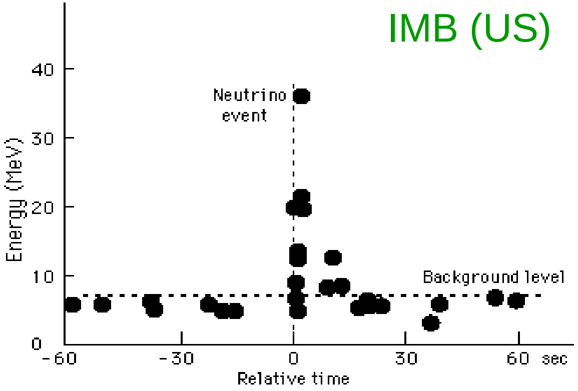
Credit: NASA Goddard Space Flight Center

- 23rd Feb 1987, SN 1987 A in the Large Magellanic Cloud (e.g. Arnett et al. 1989)

- Observations in optical showed material ejected by the shock wave.







- Detection of electronic neutrinos by several experiments [Japon (11), US (8) and Russia (5)] a few hours prior to the SN observation in optical.

  ⇒ **First evidence for neutronisation of matter following the gravitational core collapse of a massive (> 10 M_{Sun}) star!!**

- 24 neutrinos detected from the SN over 10^{56} emitted neutrinos based on various models (very low cross section)!

- Galactic or within MC core-collapse SNe: ideal targets for MM studies (GW + neutrinos + EM)

- Understand the SN hydrodynamical evolution from the onset of the collapse to the CO formation (Arimoto et al. 2021, arXiv:2104.02445)

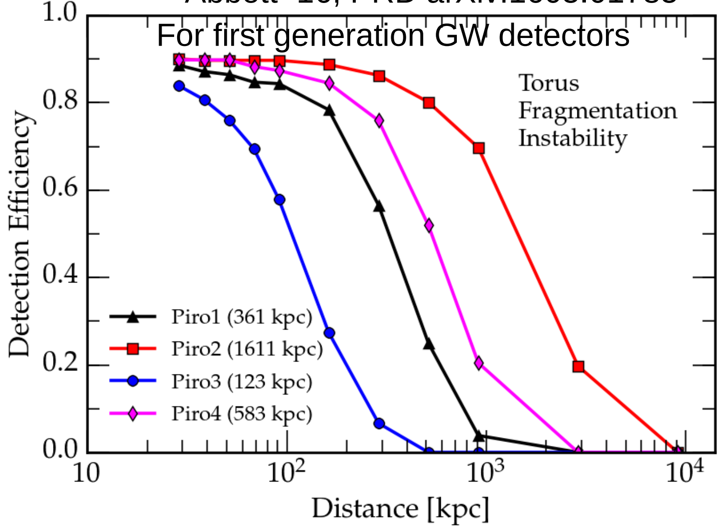
  ⇒ Formation stages of the CO remnant (NS, BH), different phases of the explosion and predominance of physical processes, explosive nucleosynthesis of heavy elements, enrichment of ISM, etc.

- CCSN rate in MW ~ 1.63 ± 0.46 per century (2 – 3 per century)
  (e.g. Rozwadowska et al. 2021 and therein references)

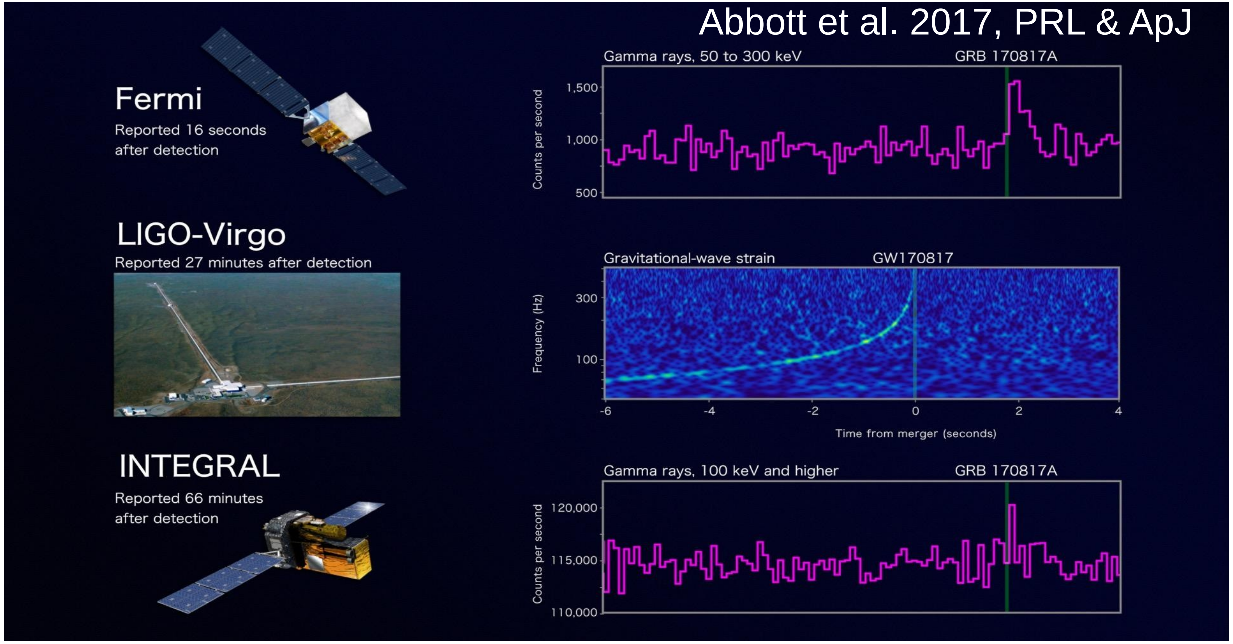
- Kepler SN = last observed SN in the MW in 1604!

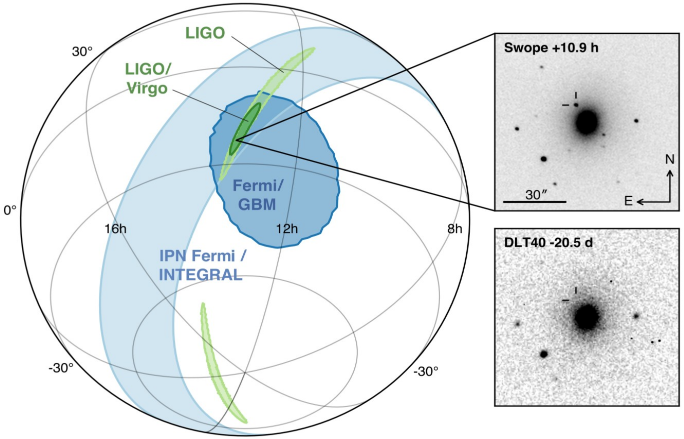
- EM observations depend on the SN location within the MW and the GW/neutrino error sizes.

Abbott+16, PRD arXiv:1605.01785

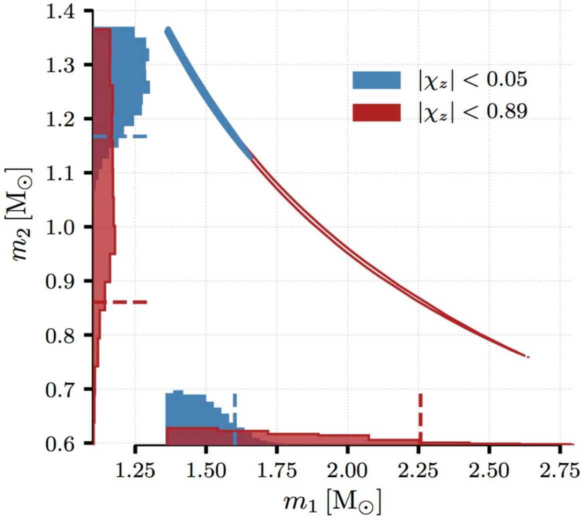


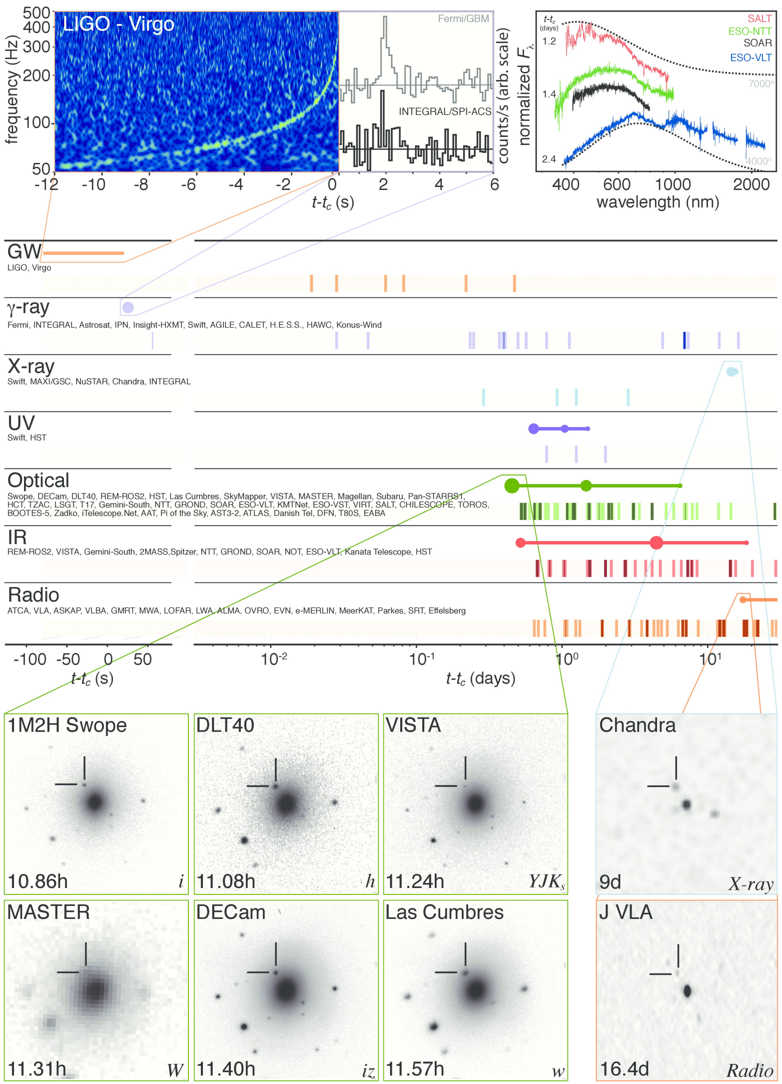
Dist. (LMC) ~ 50 kpc
Dist. (Andromeda) ~ 770 kpc





- First detected and only EM+GW event!
- BNS merger followed 1.7 s later by a short GRB
- Host galaxy located at 40 Mpc
- Nature of the post-merger CO unknown (mass < 2.8 M_{Sun})



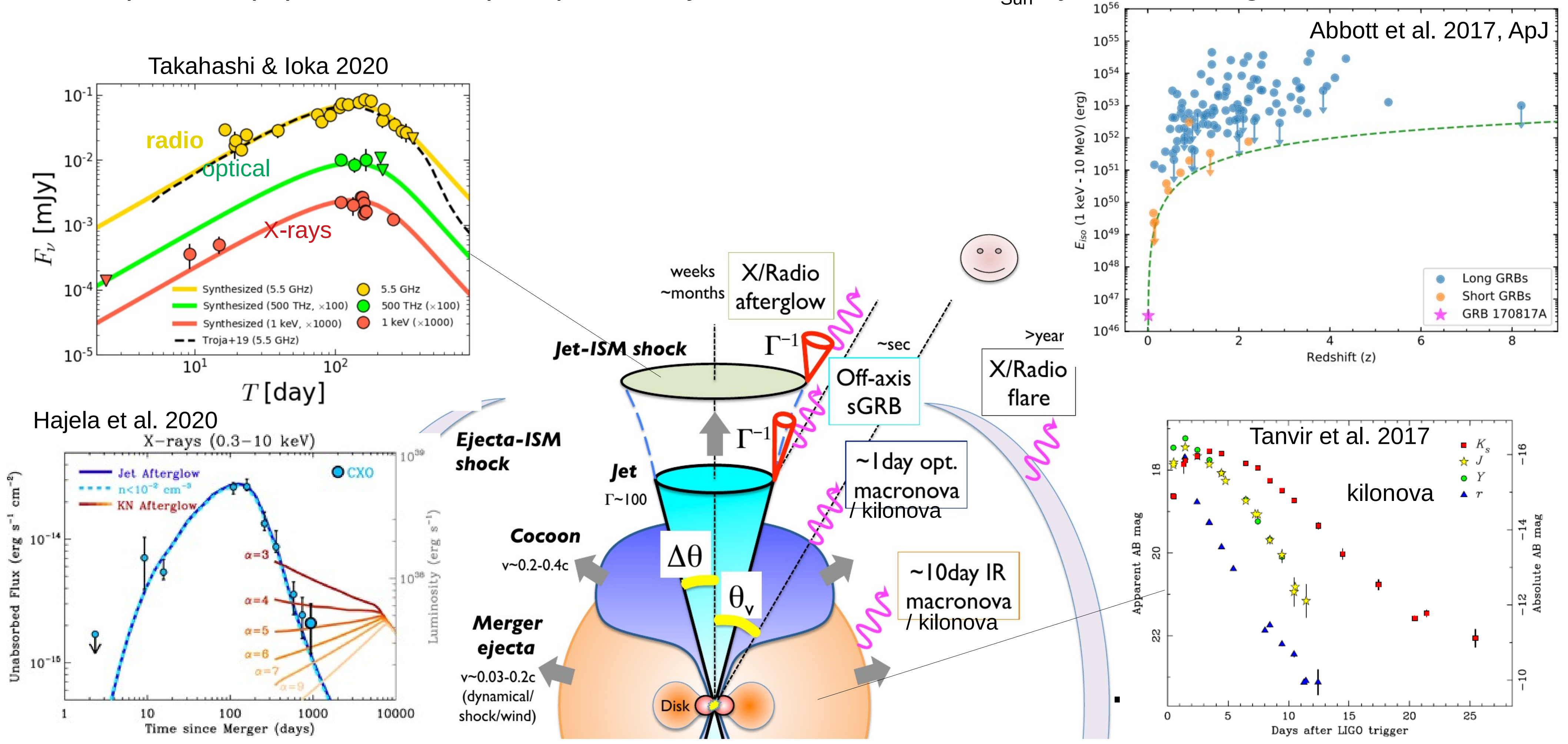


GW170817/GRB170817A

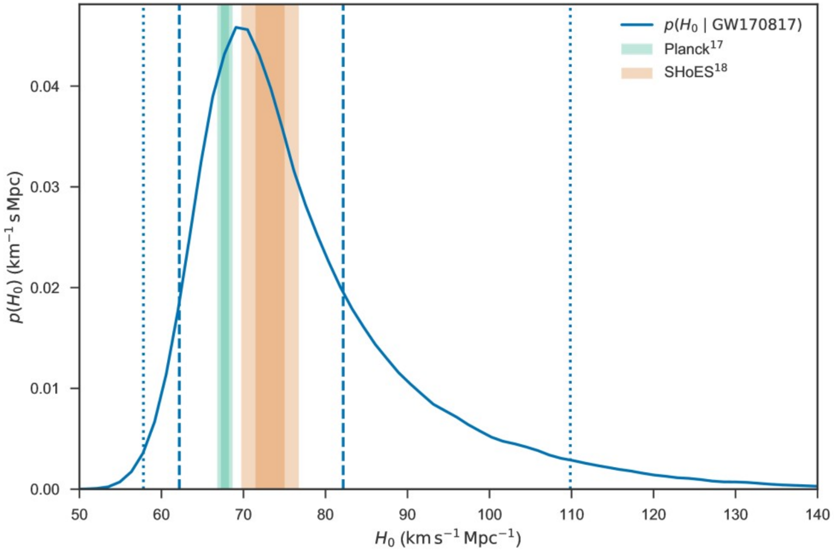
- The most followed astrophysical object ever!
- Very good sampling of EM emission accross the EM spectrum
- Generate a lot of scientific activities leading to really a lot of papers!

GW170817/GRB170817A

- Off-axis relativistic structured jet (~20° ; e.g. Ghirlanda+19)
- R-process (rapid neutron capture) nucleosynthesis from ~0.05 M_{Sun} ejecta including lanthanide elements



- GW from binaries = standard sirens (Schultz 1986) to measure in an independent way the cosmic expansion history
- Direct measure of luminosity distance with GW signals to be compared with redshift measure from EM (Abbott et al. 2017, Nature)

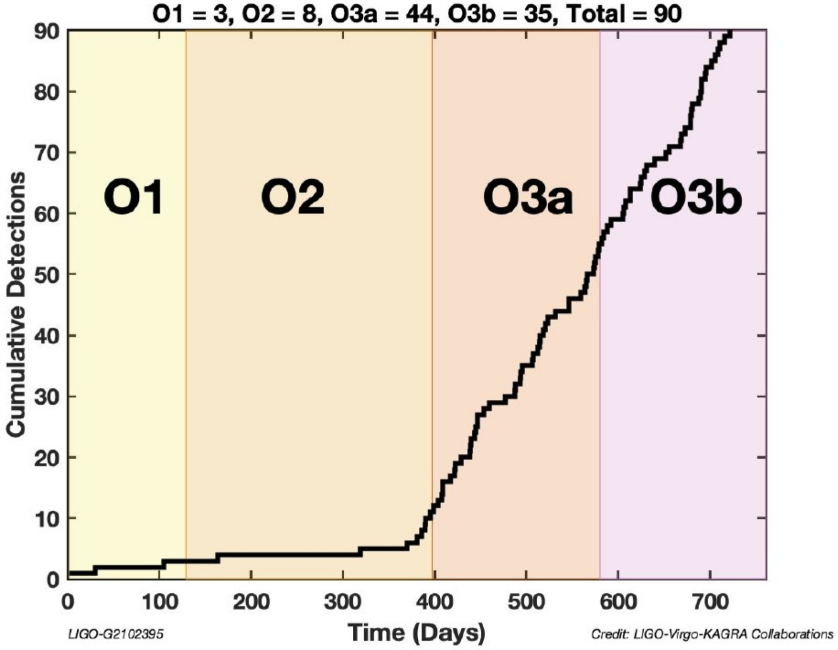


- Fractional GW/EM speed difference (Abbott+17, ApJ):

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

- Test of the equivalence principle using Shapiro effect (Abbott+17, ApJ)
- Modelling of the kilonova puts constraints on the r-process efficiency, the system inclination i & on the post-merger object nature (Arimoto et al. 2021).
- Modelling of AG also provides clues on i => improve GW luminosity distance estimates (e.g. Ghirlanda+19, Hajela+20)

- With the O3 run (2019–2020), a total of 90 merger events (Abbott+21)
- Mostly BBH mergers
- 1 confirmed BNS merger (GW190425) at a distance of 89 – 228 Mpc – No EM counterpart
- Still fairly large error regions (typically 100s of sq. deg.)
- 3 confirmed potential NSBH mergers ⇒ no EM counterparts



- O4 run in ~2023 – distance horizon larger
  ⇒ More BNS events detected at higher distances

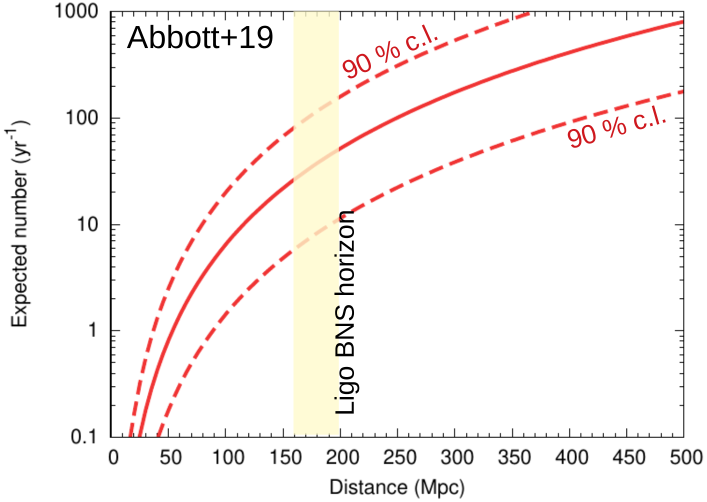
  ⇒ However, off-axis GRBs more difficult to catch promptly at HE

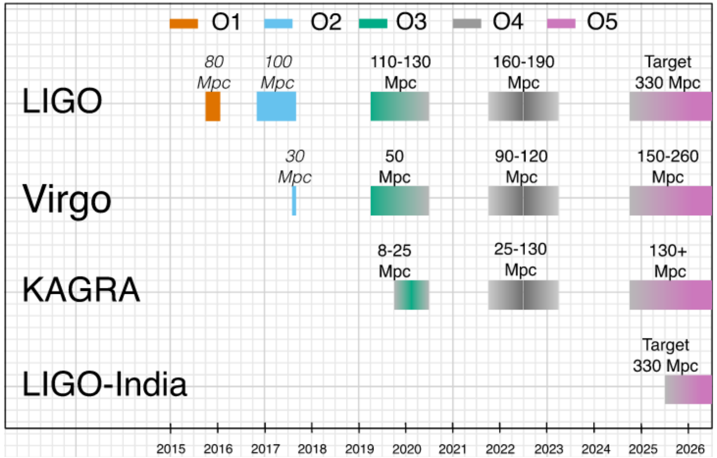
  ⇒ could increase the probability to detect a classical on-axis SGRB

- Kilonovae also more difficult to detect – large uncertainties on what to expect in term of range/evolution of luminosity

- Improve GW event localization with new GW detectors (Ligo-India for O5 run – dozen of sq deg.)
  ⇒ ease the search with any EM counterpart

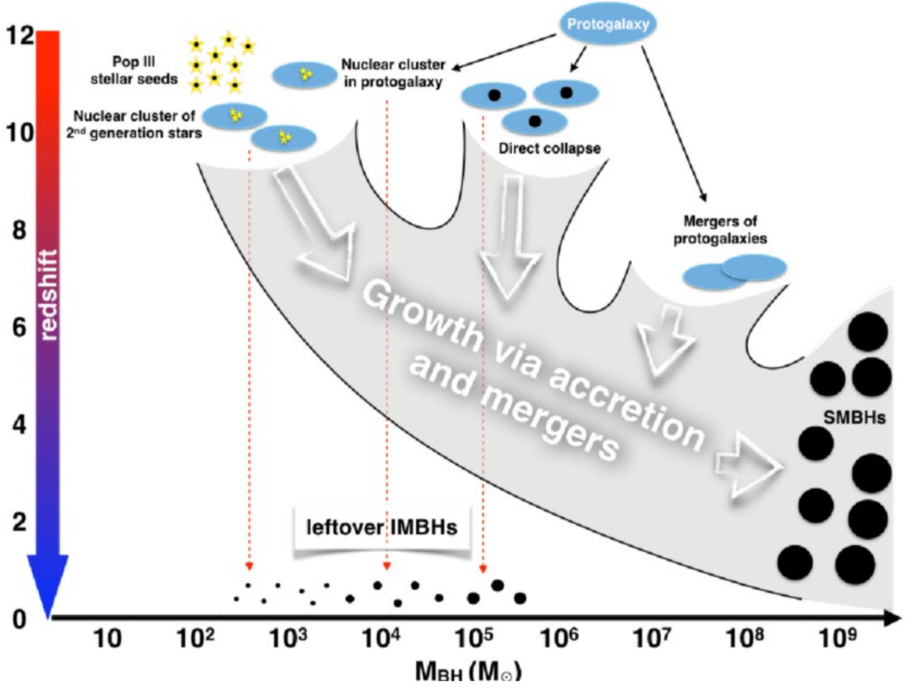
BNS merger estimates from O2 run





Mezcua 2017

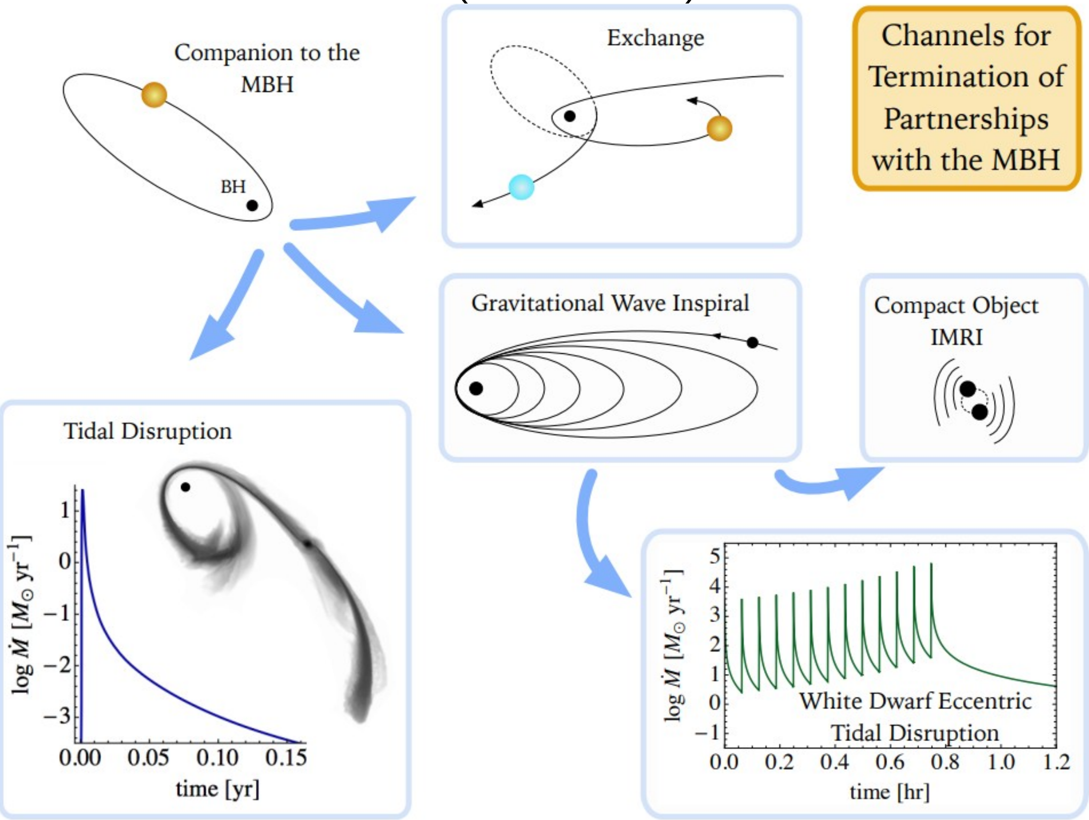
- SMBH (10^{6-10} M_{Sun}) in the core of most massive galaxies
- SMBH occupation fraction in less massive galaxies (< 10^9 M_{Sun}) & mass distribution of MBH in galaxies in the early Universe still unknown
- Important for cosmological simulations (i.e. BH seeding of galaxies in the early Universe)
- Growth of SMBH is one of fundamental open questions of modern astrophysics to understand the formation of large structures, baryon reprocessing, the galaxy formation & evolution
- 2 leading scenarios : mergers of lighter seeds (IMBHs with masses from ~10^2 to ~10^5 M_{Sun}) & intense episodes of (super-Eddington) accretion



- MBH unlikely to live alone in their host – likely to have some stars graviting around them
- Example of SgrA* with S2 and possibility to find stars in tight orbits around our ~4 x 10^6 M_{Sun} hole (Pfahl & Loeb 2004; Liu et al. 2012).
- IMBH possibly hosted in dense star clusters ⇒ formation of eccentric and unstable binaries with central hole (MacLeod+16)
- See also Arcodia+21 about quasi-periodic emission in X-rays maybe associated with E/IMRI

See talks of N. Webb & M. Toscani

(MacLeod+16)

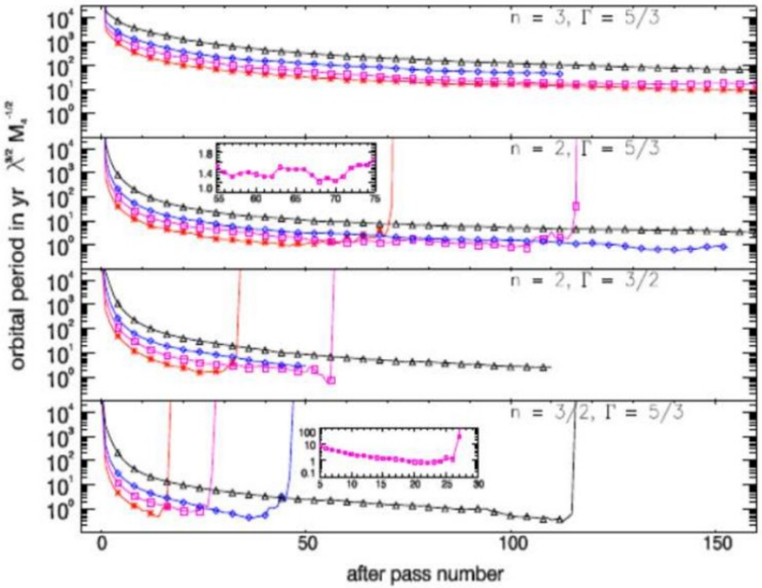


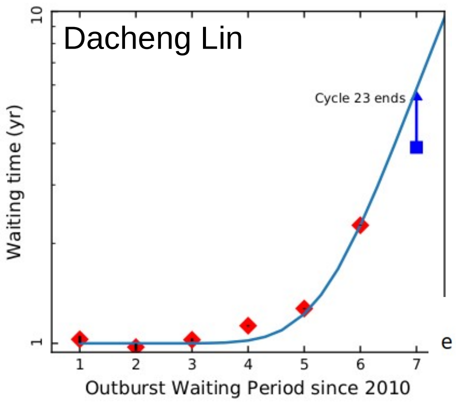
ES0 243-49 HLX-1

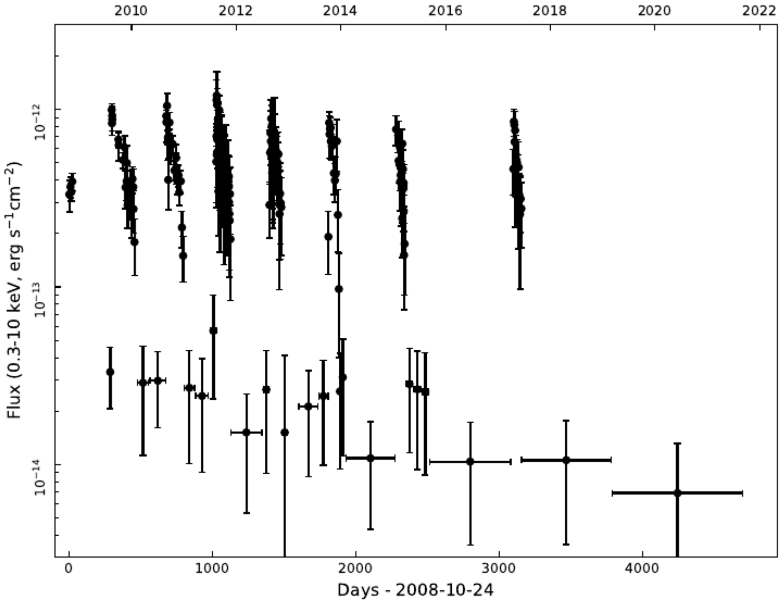
- One of the strongest IMBH candidates – M ~ a few 10^4 M_{sun} (Farrell+09, Godet+12, Webb+12, incl. D. Barret)
- Located at 95 Mpc – reach at peak 10^{42} erg/s in X-rays

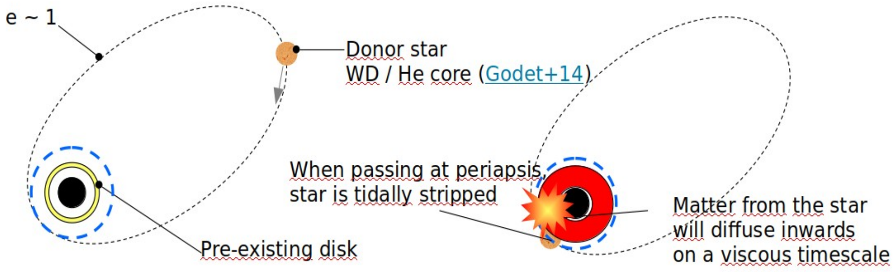
- Hosted in a stellar cluster or the stripped core of a dwarf galaxy (Farrell+12)

- Failed TDE: a WD-type donor orbiting an IMBH
  ⇒ unstable system ⇒ donor ejected at some point
  (Godet+14)



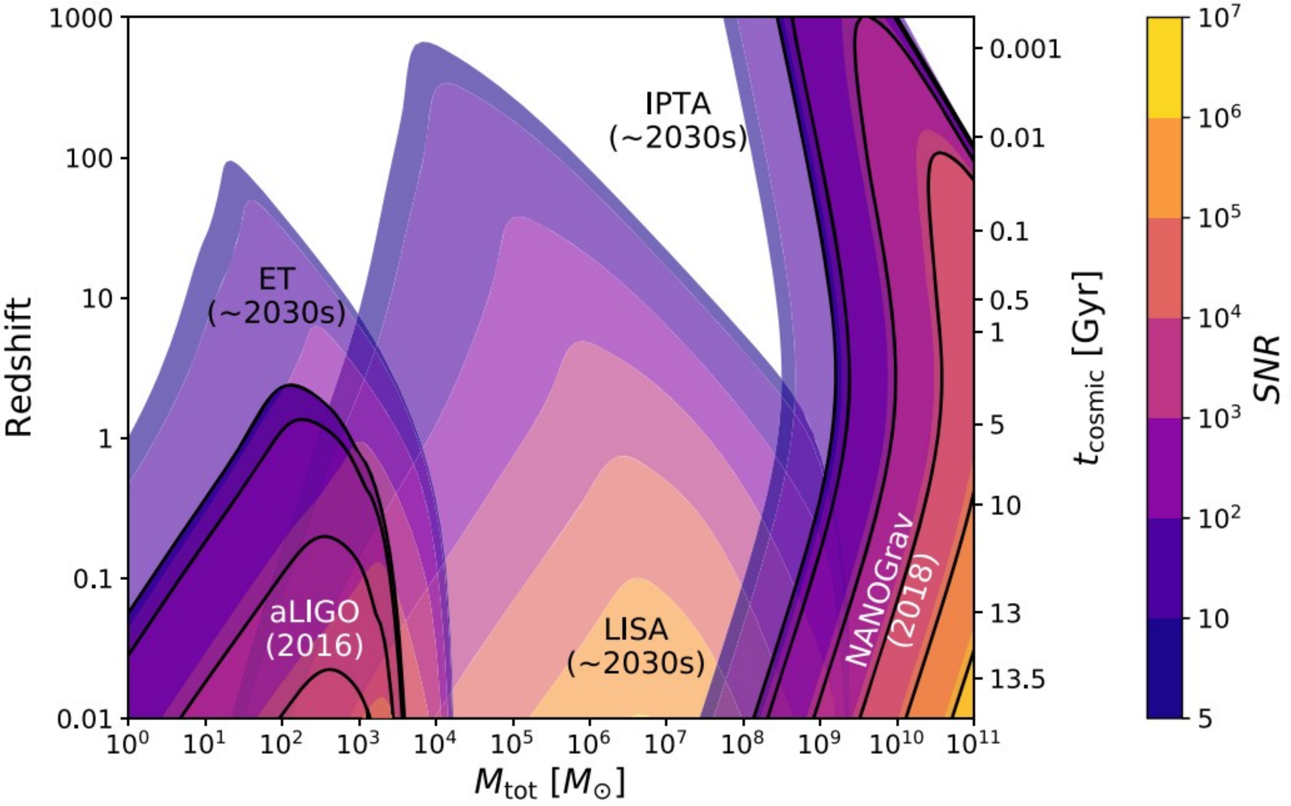






- The ultimate beasts!
- To understand growth of SMBH synergy between LISA (mHz – Hz) and Pulsar Timing Arrays (nHz range)

Burke-Spolaor+19

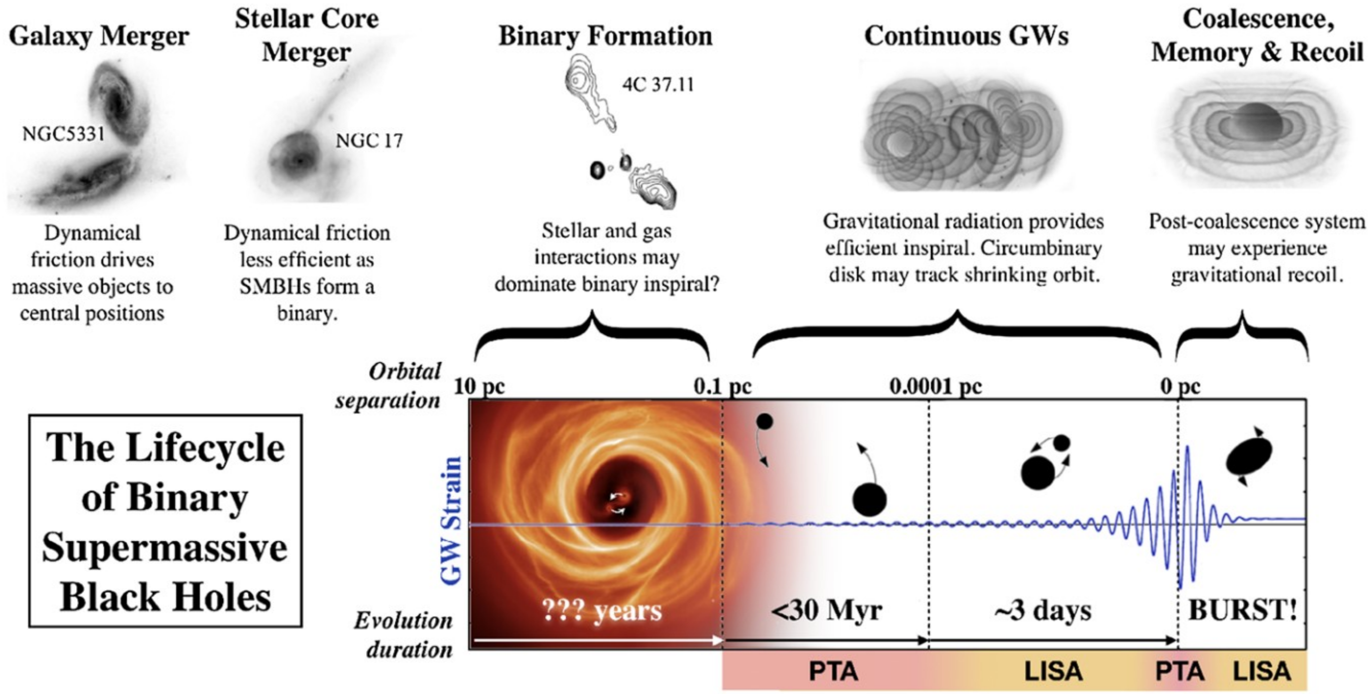


- The physical processes leading to the formation and the evolution of the SMBHB are still poorly known (in particular from ~10 pc down to ~0.1 pc scales, after which GW emission starts to be the dominant process to further harden the orbit).

- How to identify SMBHB inspiral, merger and post-merger EM emission?

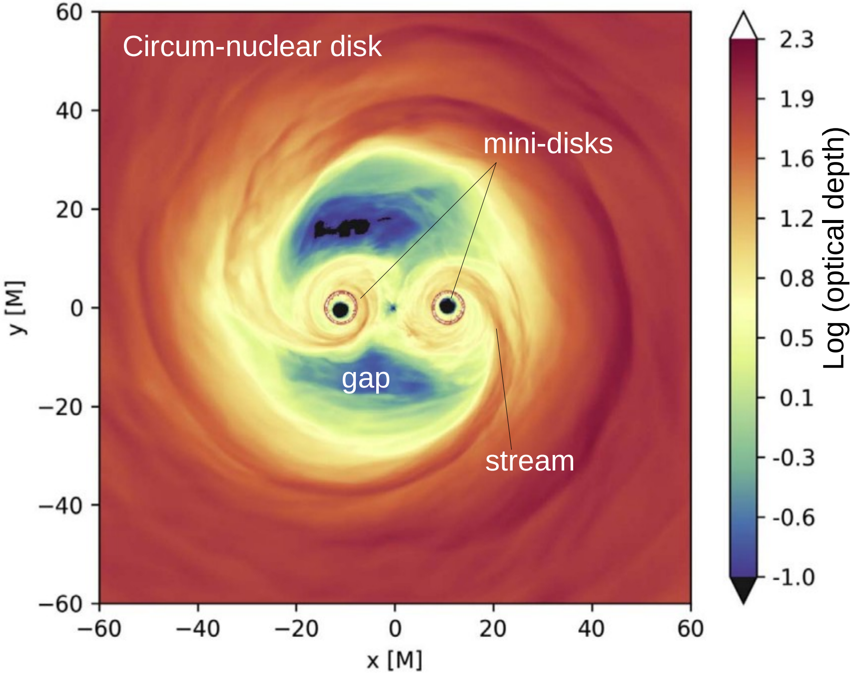
- SMBHB formed in galaxy mergers showing distinctive observational EM features ...

- Lots of uncertainties on EM/GW signatures because multi-scale astrophysical problem



- In the inspiral phase
  - Possible periodicities in the light curve
  - Double peaked emission line profiles
  - Shocks when streams hit the edges of mini-discs
  - EM emission depends on system inclination

D’Ascoli+18



Armitage & Natarajan 02; MacFadyen & Milosavljevic 08; Bogdanovic+08; Cuadra+09; Sesana+12; Roedig+12; Noble+12; D’Ascoli+19

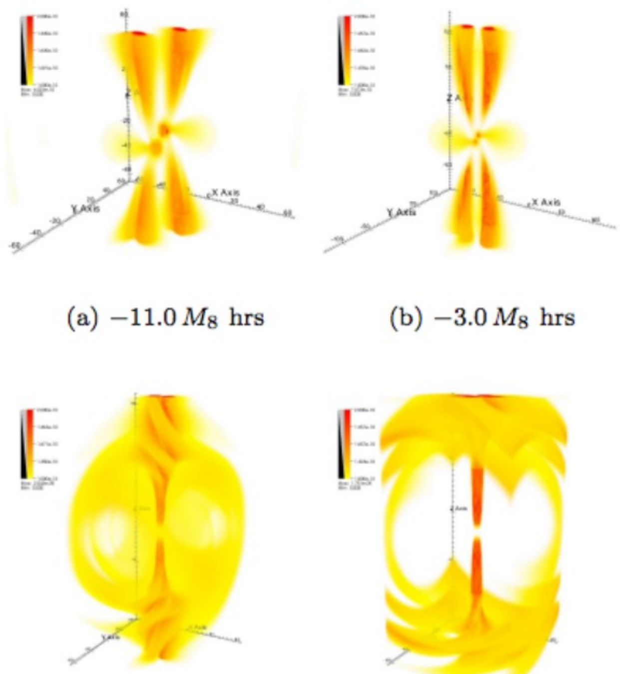
- In the post-merger phase

  - Gas plunging in the cavity left by the binary SMBH over viscous timescales

  - Effect of recoil

  - Jets colliding surrounding gas ⇒ forward shock afterglow over the EM spectrum ?

  - Delay of the EM emission by how much (days to years) ??

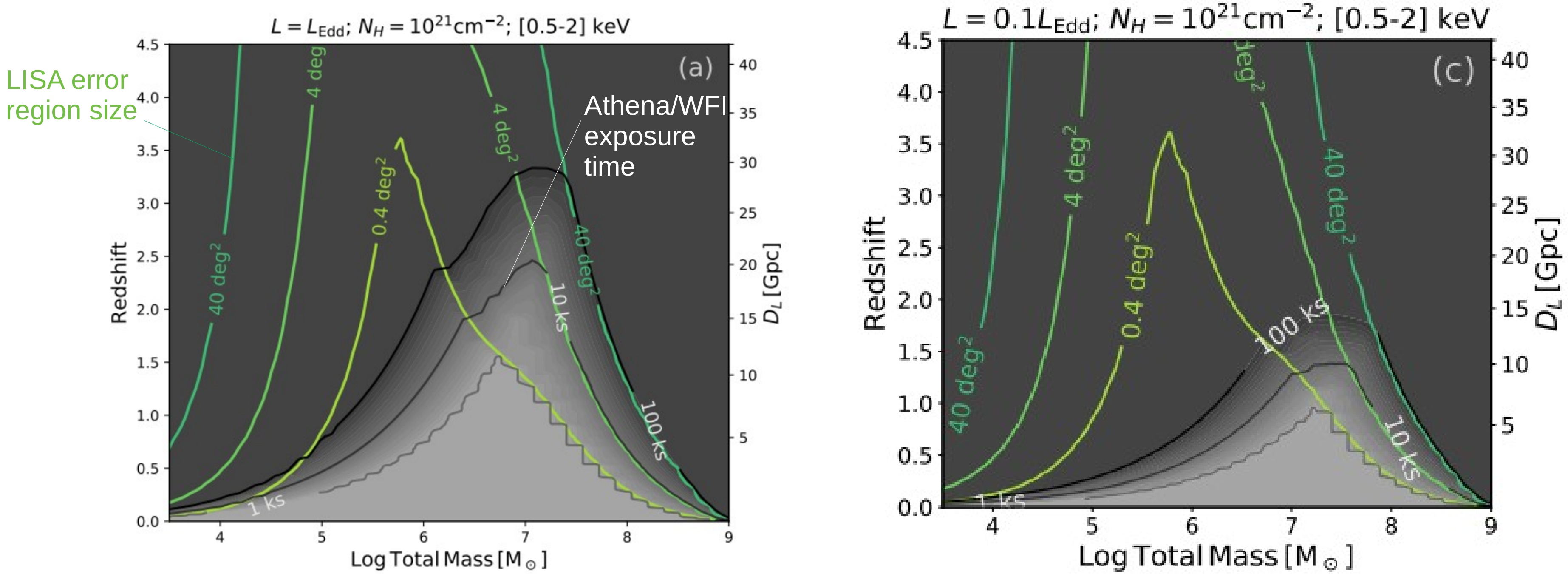


(a) $-11.0\,M_8$ hrs (b) $-3.0\,M_8$ hrs

(c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs

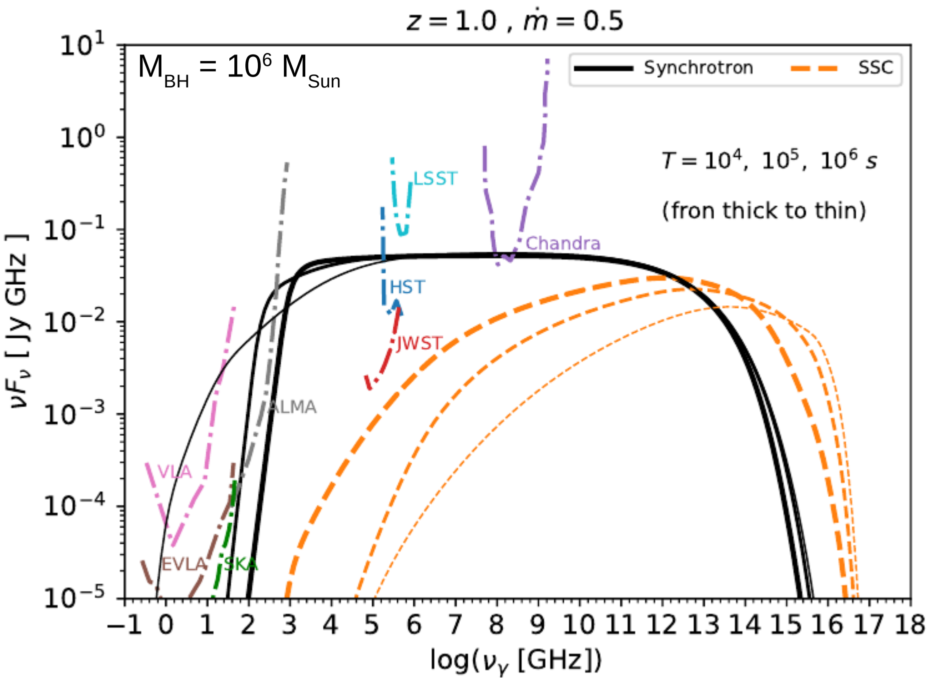
Armitage & Natarajan 02; Milosavljević & Phinney 05; Schnittman & Krolik 08; KhanPaschalidis+18, Yuan+21,

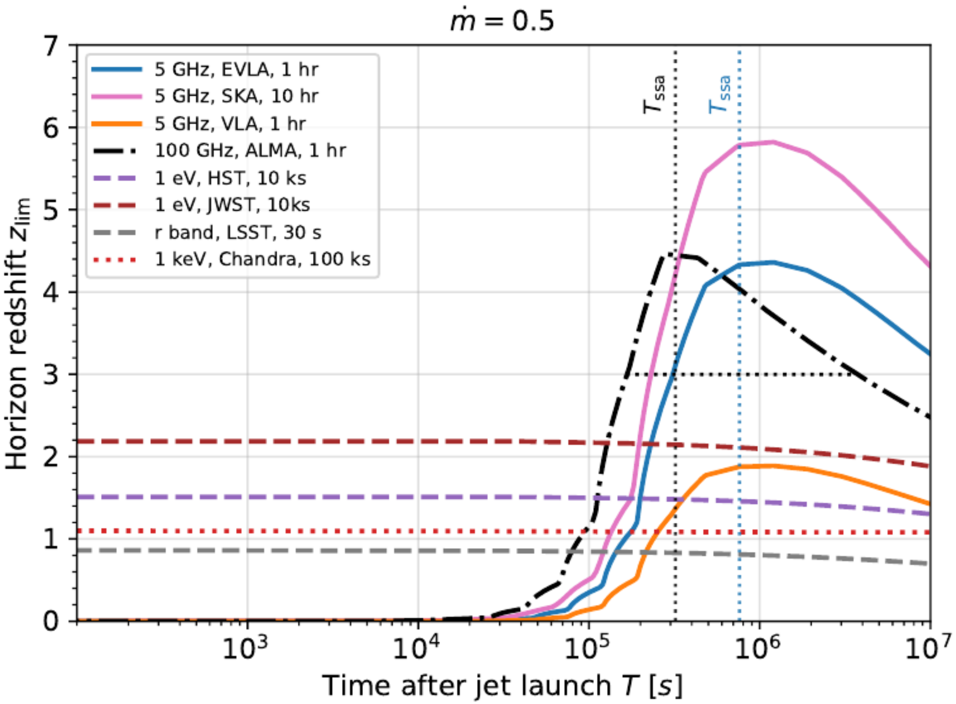
- EM detection (for instance with Athena) will also crucially depend on localization accuracy that improves with SNR



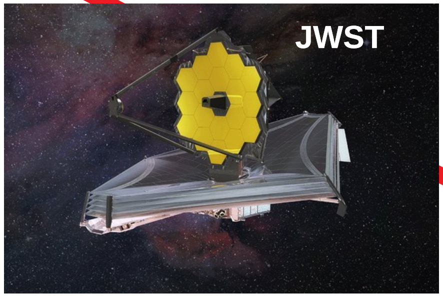
Predictions of LISA/Athena-WFI synergy – McGee+20
Nb of joint LISA/Athena detections over 4 yrs ~ 0.1 to 10 depending on the EM luminosity

- Post-merger jet induced afterglow emission – Yuan+21

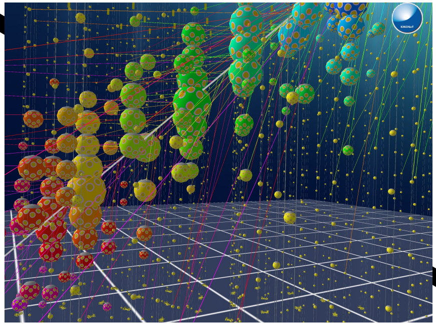




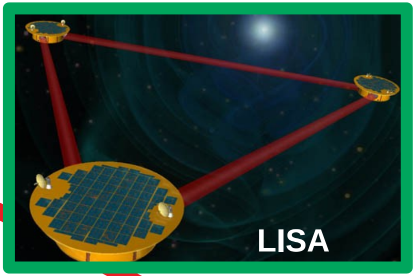
DEVELOPING MM LANDSCAPE

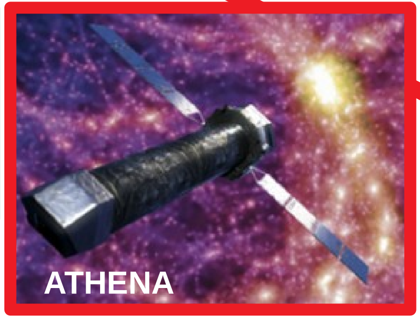


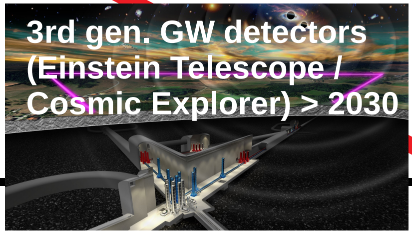
3U TRANSAT



Neutrino facilities (KM3Net, DUNE, Hyper-Kamiokande)







Hardware/software contribution / Instr./science responsability

Scientific implication

Not yet confirmed project with IRAP leading role

Detectability → MM detection → Identification

Detectability

What you may expect

Depends on observational constraints, theoretical and simulation predictions)

Important caveats in some cases

MM detection

Depends on the available instrumentation and its sensitivity, strategy of observations, coordination when possible, etc.

Identification

- Infer the nature of the detected events either from EM data alone and/or MM data
- Need data to be put in proper & standard units to make most of it
- Need to be quick & reliable

Go back to look in recorded data

Put constraints on models

MM follow-up

Selection of events to follow

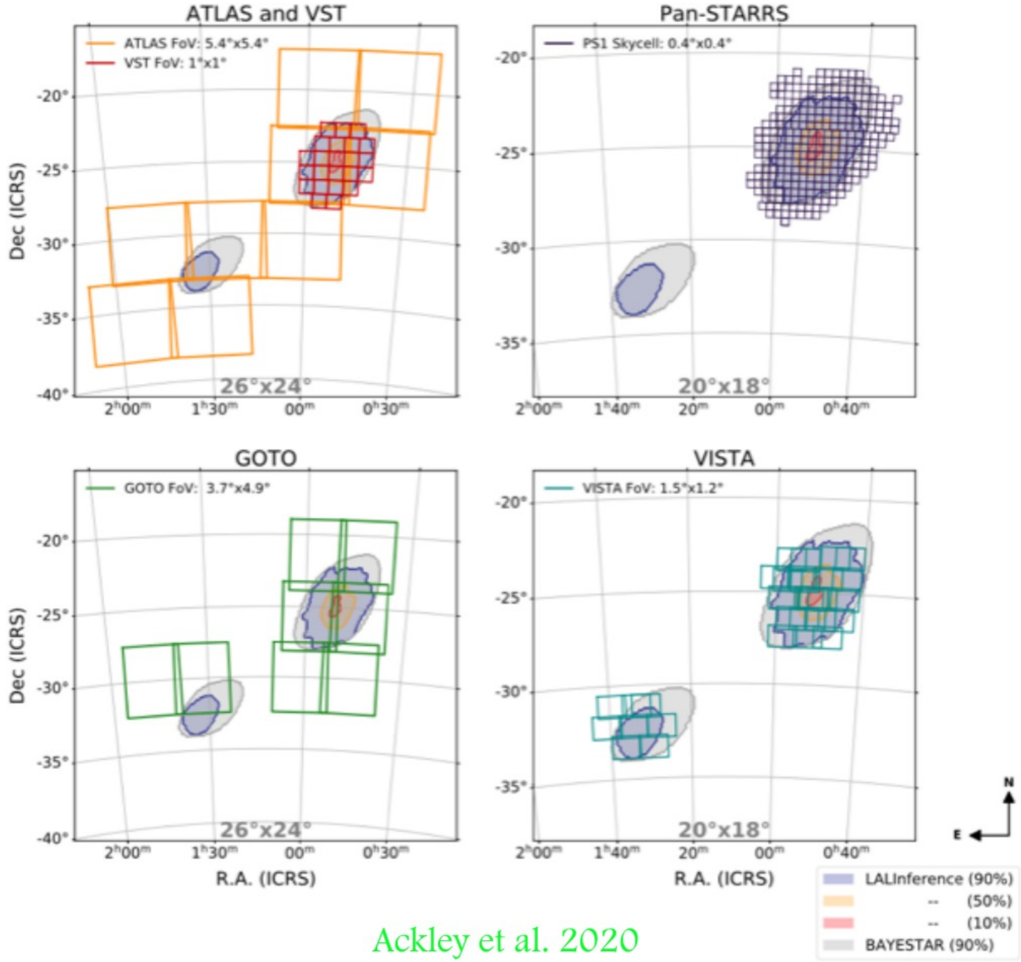
- Need way to dissiminate information and to track what's going on (Transient Name Server, GCN Viewer)
- Need worldwide coordination (e.g. GROWTH, GRANDMA, ENGRAVE)

- nIR/optical robotic telescopes networks spread around the Earth (e.g. Tarot/Zadko & Colibri working with SVOM)

- Cover several 10s of sq. deg in one go

- Tilling strategy to probe GW error regions in optical & X-rays (Swift/XRT, SVOM/MXT)

GW190814 (NSBH) – 38 deg^2 → 23 deg^2



Ackley et al. 2020

OBSERVING STRATEGY

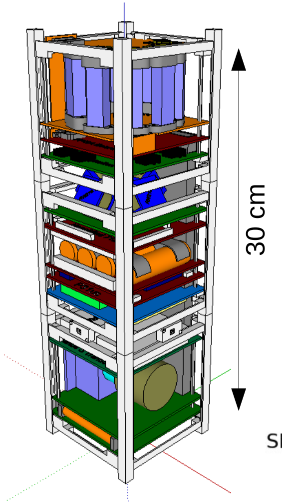
- Current HE instrumentation only cover a small fraction of the sky (~16 % with Swift-BAT, ~10 % with SVOM-ECLAIRs)

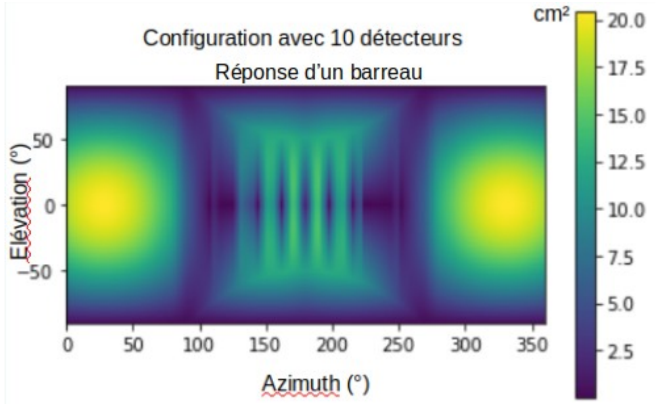
- Need to develop an all-sky HE instrumentation with sufficient senstivity to detect rare events like GRB170718A in the local Universe

- Several projects of constellation of LEO nano-satellites embarking a few 100s cm² effective area detectors on each satellite (e.g. Camelot, Blackcat, BurstCube)

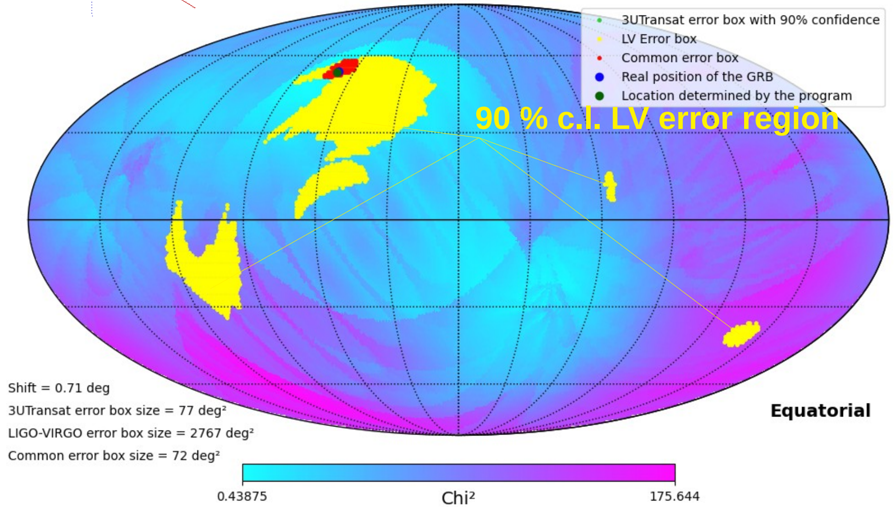
- Only few demonstrators already launched (GECAM = 2 x 6U (China) / GRBAlpha 1U, demonstrator for Camelot) – 1U = 10 x 10 x 10 cm³

- **3U Transient SATellite** project (CNES Phase 0) from IRAP – 3 sat. demonstrator // detection & localization done on-ground < 2-3 h after on-board detection // launch target for run O5 (2025)
If interested, please contact : O. Godet





Sky-map of Chi² for GRB F180703949, Case 1



10 satellites in SSO orbits

3U TRANSAT

- Several on-going activities in GAHEC regarding source catalogs and identification:

  - SVOM/Trigger offline (B. Arcier, M. Llamas / L. Bouchet) to extend on-board capability
  - « Quick » XMM on-ground trigger (E. Quintin) to search for all types of transients
  - Pipeline to search for objects showing rapid variability (e.g. QPE – M. Gupta) using XMM data
  - Development of source classification scheme for X-ray sources (Tranin, Godet, Webb+21) & Classification of X-ray Sources for Novices website for citizen science (H. Tranin)

    ⇒ Allow synergy with other MM facilities (for follow-up/ for source identification)

  - LSST-FINK broker (Möller+21, incl. O. Godet & N. Webb) – Vera Rubin Obs./LSST is a TS game changer with millions of alerts per night
    - FINK broker (selected officially in mid-2021): Multi-science transient broker
    - Include SVOM module // Define metrics to identify desired types of transients // work in synergy with offline trigger (M. Llamas, M. Yassine / O. Godet, E. Quintin / N. Webb)

- Build of catalogs (Fermi, XMM)
  - 4XMM-DR11 (> 6 10^5 X-ray sources – Webb+20)
  - New features to be added (multi-wavelength & MM counterparts, upper limits, source identification, lightcurves) – H2020 SPACE project XMM2Athena (N. Webb) // Preparation of Athena/X-IFU ground segment

- MM & TS astronomy will likely transform our understanding of the formation/evolution of the Universe contents in forthcoming years.

- Need to assess carefully how MM data could be used to do so

- Need worldwide & **local** science coordination between various scientific communties for MM follow-ups to be successful

- Need to brigde some instrumentation gaps at HE to have all-sky capability ⇒ 3U Transat