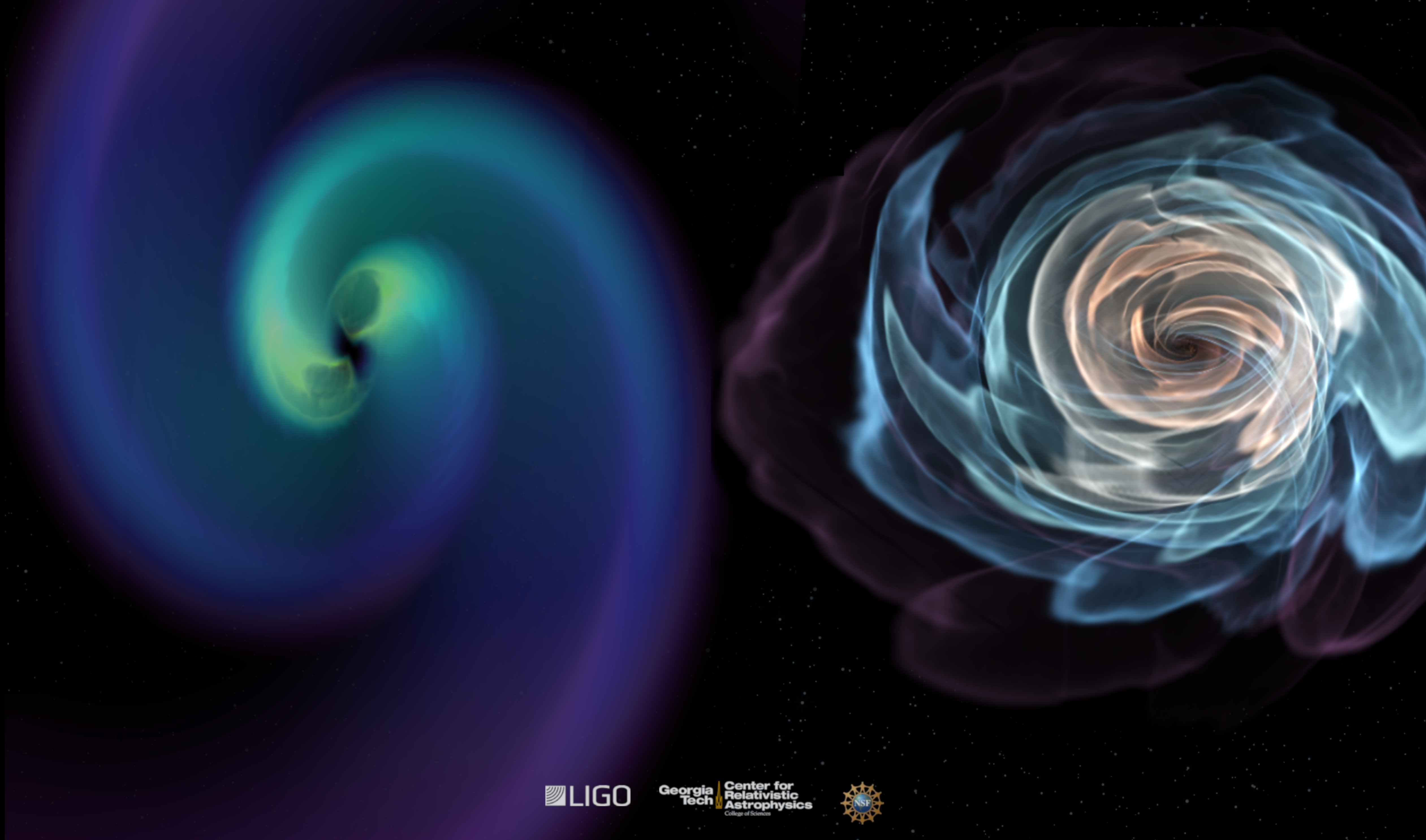
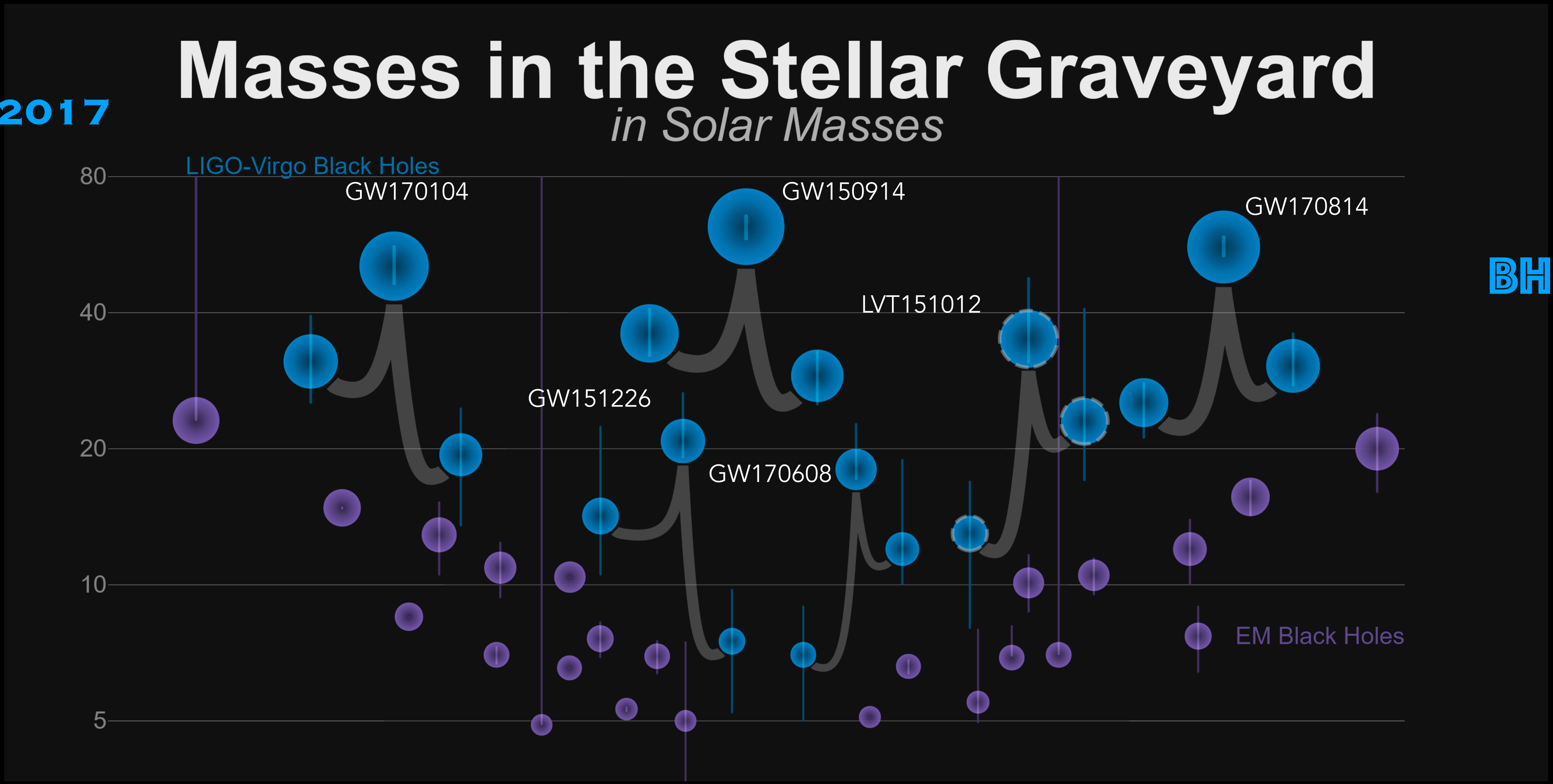
Silvia Piranomonte
INAF - Osservatorio Astronomico di Roma

The elettromagnetic follow-up of GW170817. What we learned and what can we expect in the future.



The GW Era Is Started!

2015-2017



BH-BH

No EM counterpart of BH-BH systems found (despite huge observational effort)

No significant EM emission expected from BBH
EM emission expected for NSNS and/or NSBH

LIGO-Virgo | Frank Elavsky | Northwestern

Why EM counterparts are interesting?

GW

- Mass
- Spins
- Eccentricity
- NS compactness
- tidal deformability
- System orientations
- Luminosity distance
- Explosion asymmetry

Astrophysics side

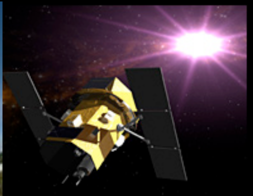
- identify host galaxy (H0, progenitors contstraint)
- connect to wealth of transients phenomenology (SN, GRB, new sources)
- uniquely constraint models: know masses, spin, orientation

GW physics side

- improve parameter estimation and detection
- cross correlate GW w/ EM searches
- gain factor of ~2 in sensitivity and ~10 in rate

EM

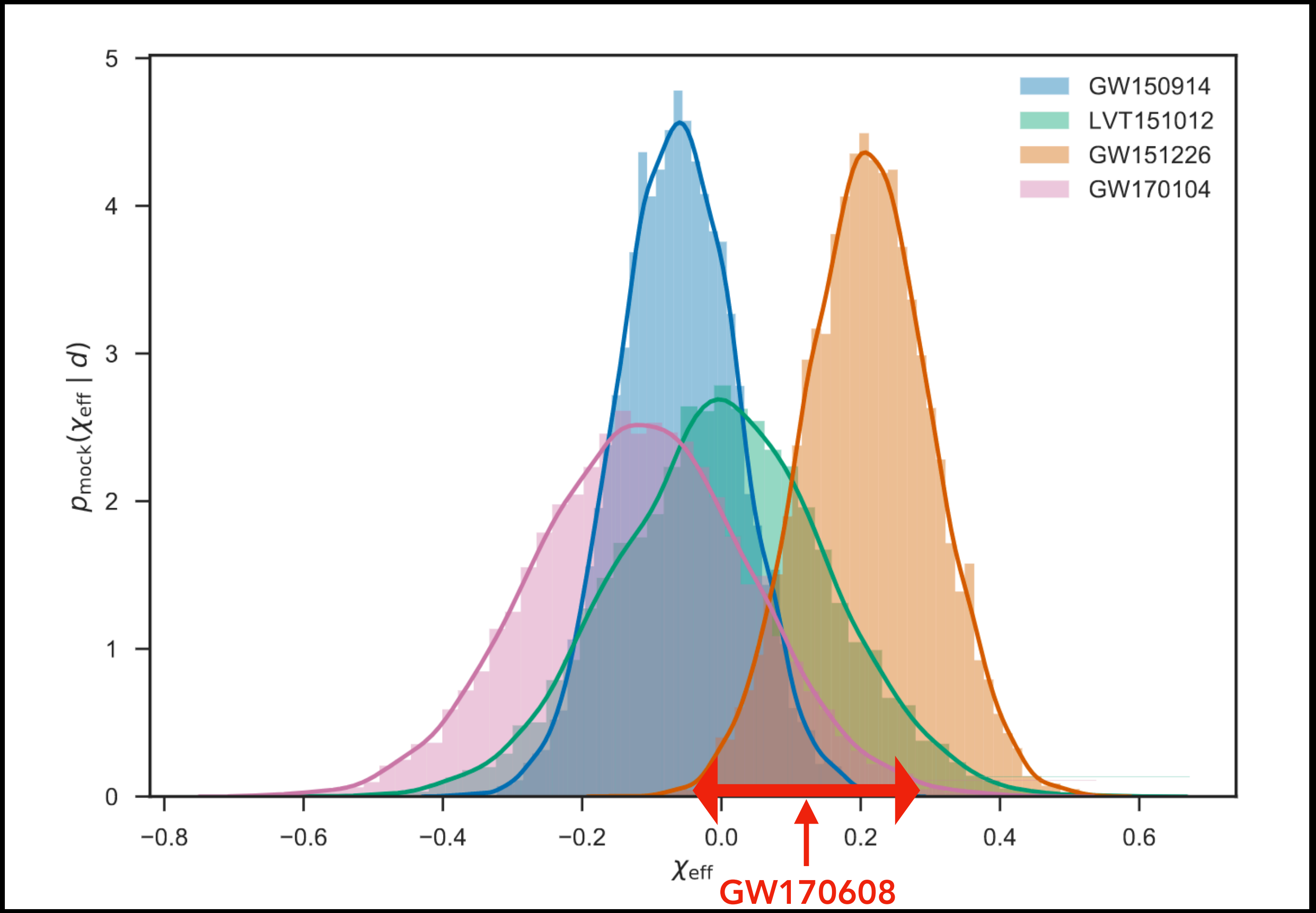
- Energetics and beaming
- Magnetic field strength
- Precise (arcsec) sky localization
- Host galaxy
- Redshift
- Nuclear astrophyisics



O1-O2 runs

Parameters of the BBH systems

Approximate posteriors on χ_{eff}



W. Farr et al 2017, Nature, Volume 548, Issue 7667

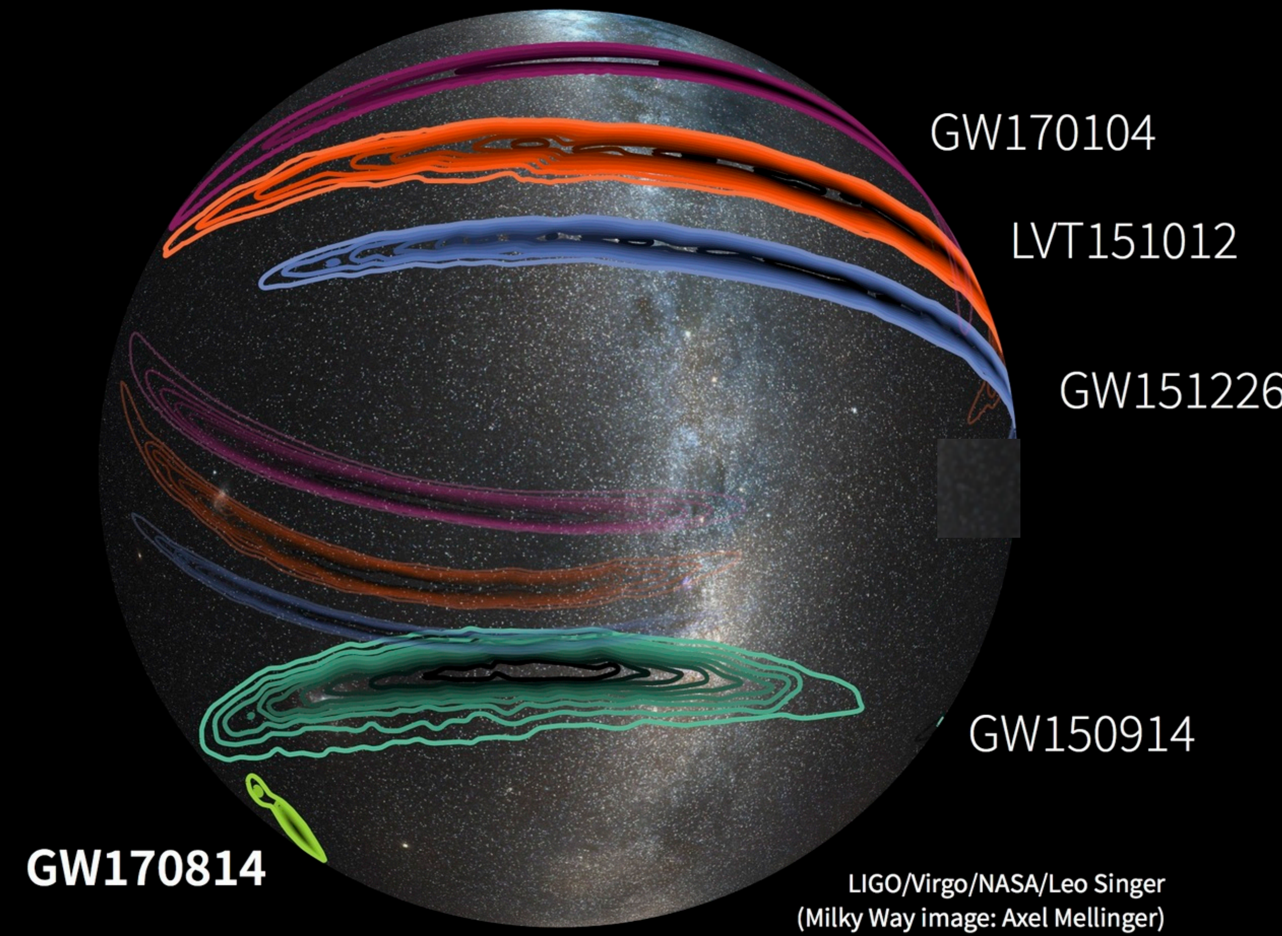
Distances

Event	GW150914	GW151226	LVT151012	GW170104	GW170608
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}	880^{+450}_{-390}	340^{+140}_{-140}

O1-O2 runs

Parameters of the BBH systems

Sky localizations



600 deg^2 GW150914

1600 deg^2 LVT151012

1000 deg^2 GW151226

1200 deg^2 GW170104

520 deg^2 GW170608

60(!!) deg^2 GW170814 (with VIRGO)

(90% credible areas)

THE BBH DISCOVERY

Where do BH forms?

Galaxy field

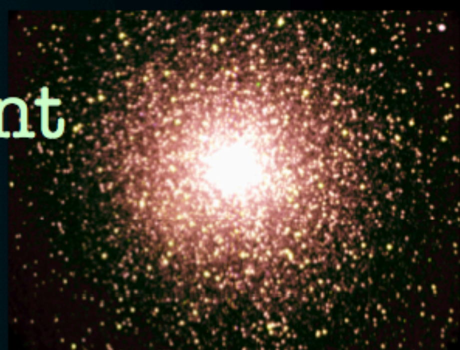
R~10 kpc,

N ~ 10^{10} stars

Dense environment star clusters

R~1-10 pc,

N ~ 10^{3-7} stars



How do they form binary systems?

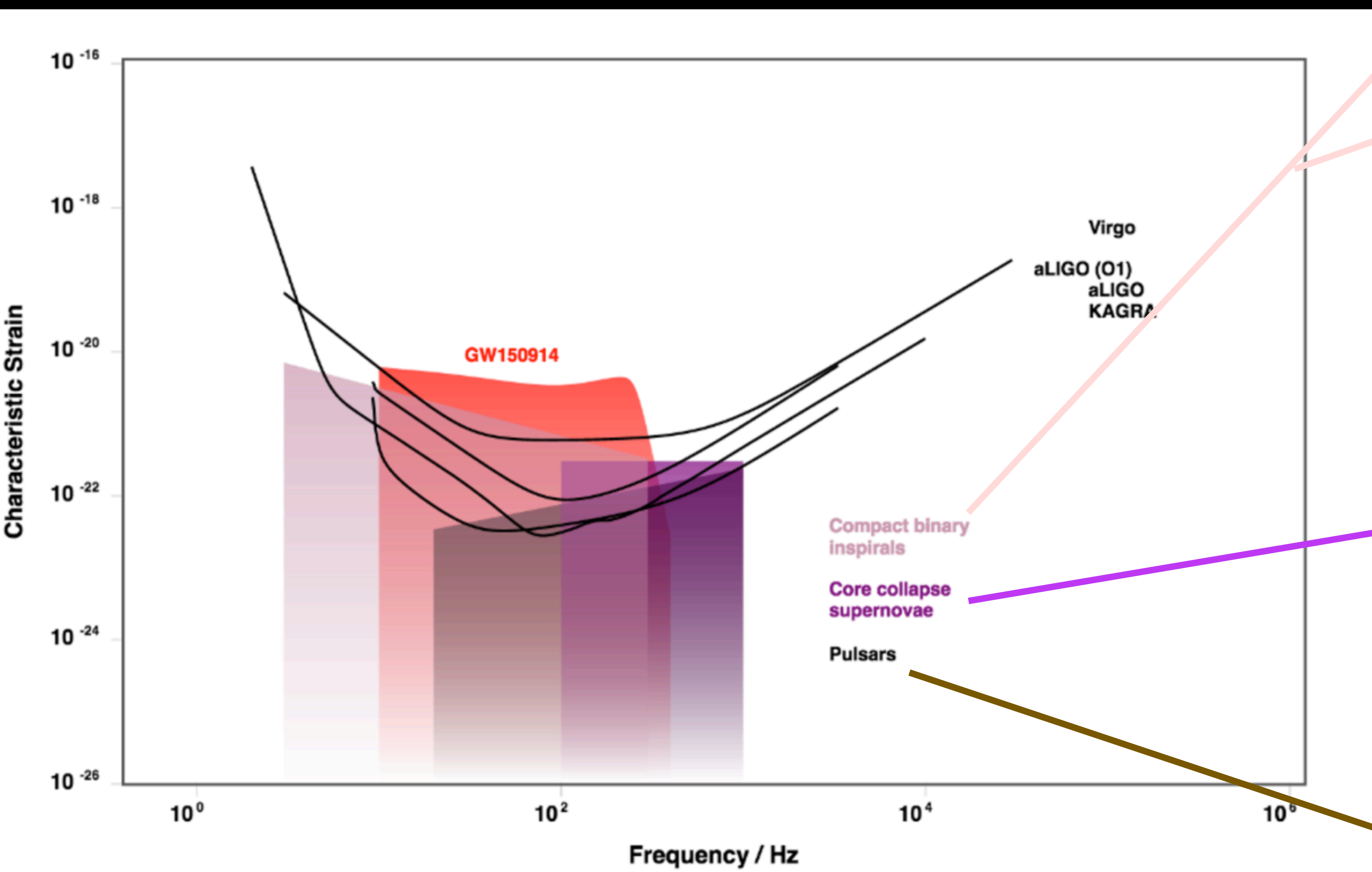
ISOLATED BINARIES? **DYNAMICAL INTERACTION?**

Crucial: host galaxy and GW source environment studies!

WHAT SHOULD WE EXPECT

In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 and GW170104 there are <u>ONLY</u> 10^5-10^6 galaxies

LIGO & VIRGO WILL GIVE US
(SIGNALS WITHIN 10-1000 HZ)

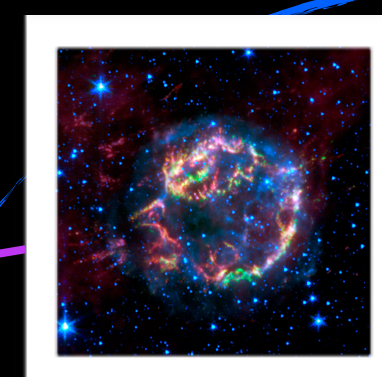


Matched-filter model searches

Precise waveforms

Coalescence of binary system of neutron stars and/or stellar mass black holes

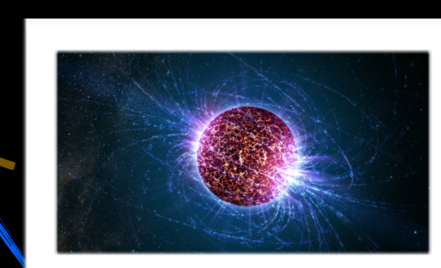
E_{GW} ~0.02 $M_{o}c^{2}$



Core Collapse Massive stars

E_{GW} ~10^{-8} - 10^{-4} $M_{o}c^{2}$

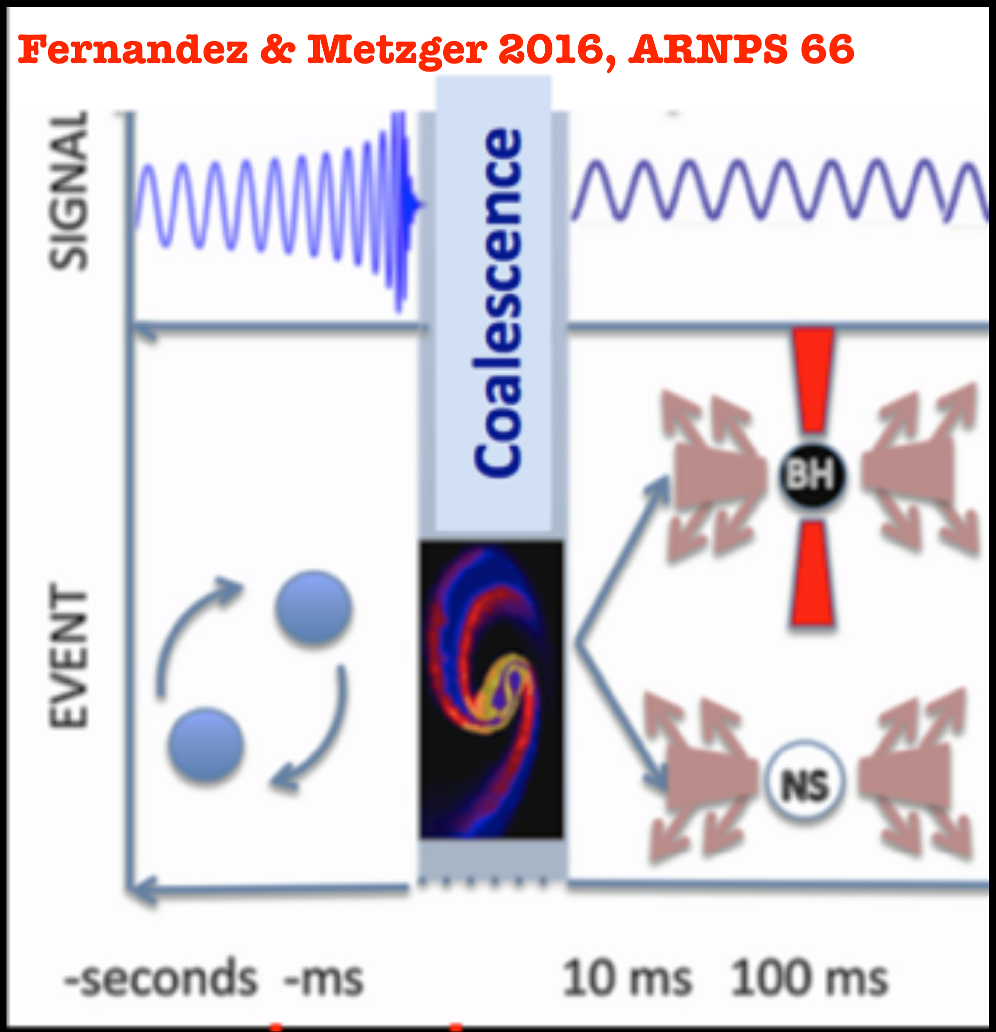
Uncertain waveforms



Isolated Neutron Stars

E_{GW} ~10^{-16} - 10^{-6} $M_{o}c^{2}$

Unmodeled searches

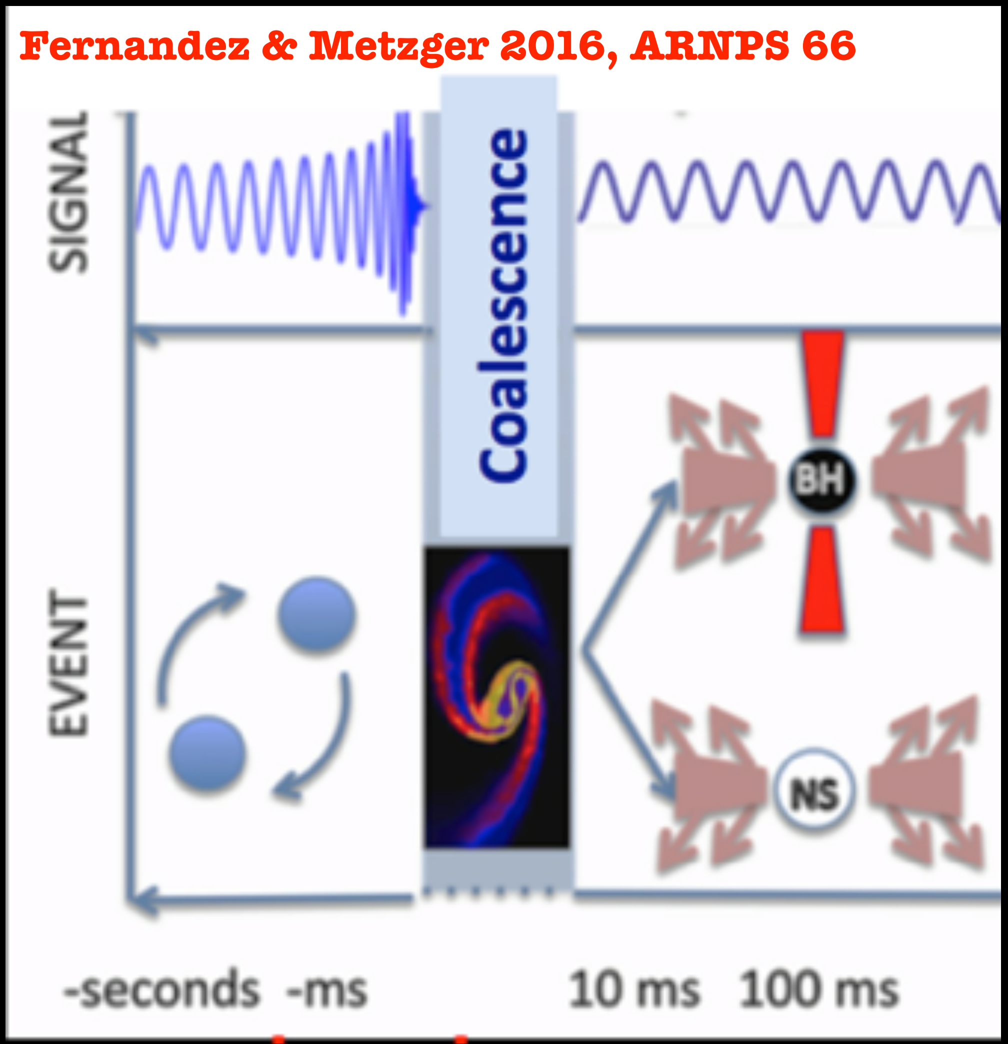


- Mass ejected by tidal forces: dynamically unbound matter
- Ejected mass gravitationally bound to the central remnant —> accretion disk
- Final remnant: 90% of the initial binary mass

NS-NS: unbound mass of 10^(-4) - 10^(-2) Mo ejected at 0.1-0.3c

NS-BH: unbound mass up to 0.1Mo

Dynamical phase: tidal effects



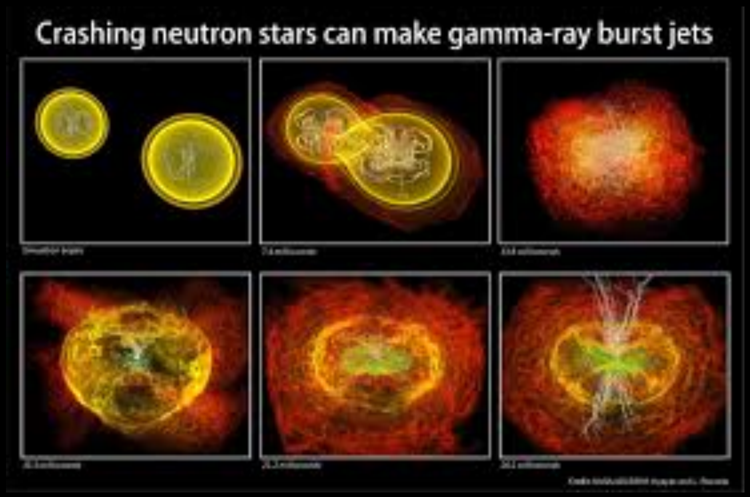
Ejected material gravitationally bound from the central remnant —> fall back or circularize into an accretion disk

Disk mass up to 0.3 Mo

Accretion phase:
BH-Torus —> relativistic jets

Outflow mass and geometry influence the EM emission

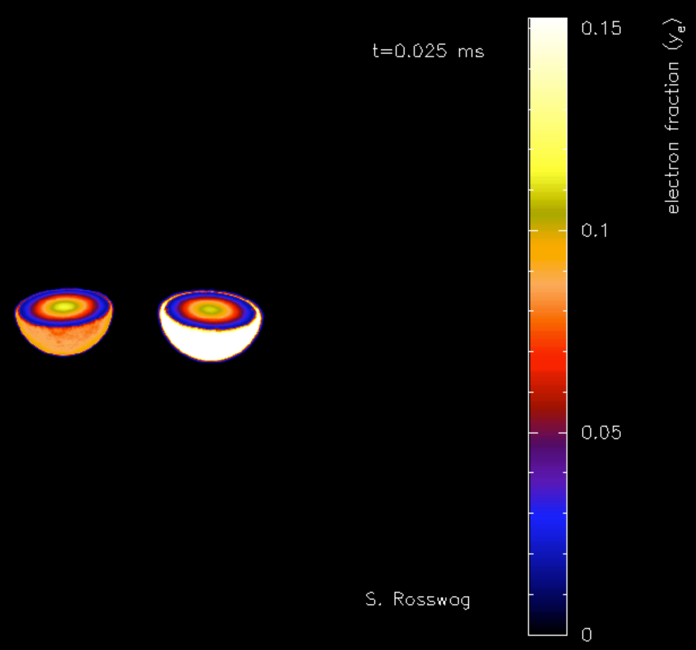
★ **NS-NS / NS-BH mergers:** Collimated EM emission from **Short GRBs**



Short GRBs WITH a detectable X-ray/ UV/optical/IR/radio counterpart (afterglow)

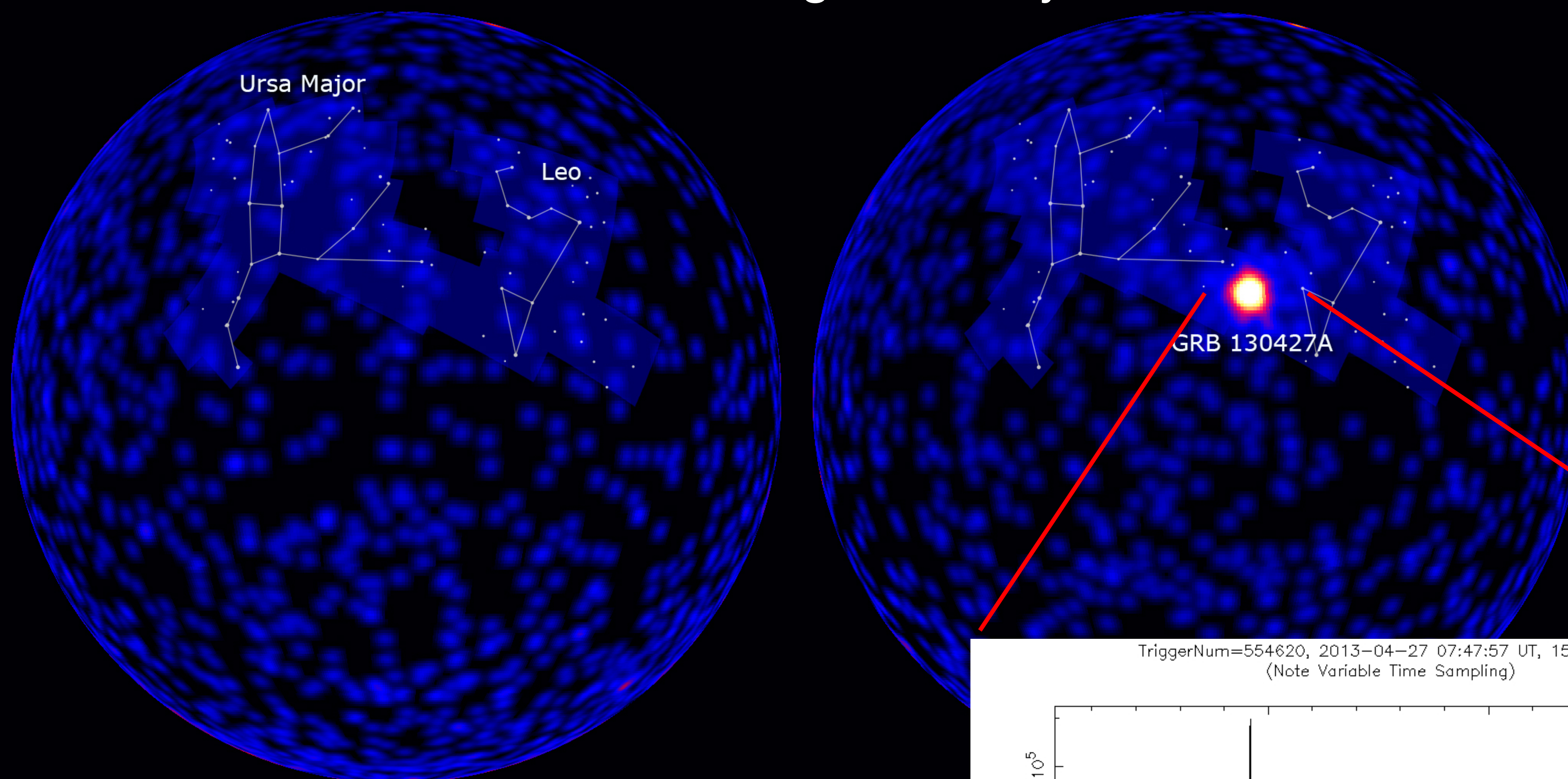
NS-NS / NS-BH mergers: Optical/NIR isotropic emissions

Kilonova or Macronova

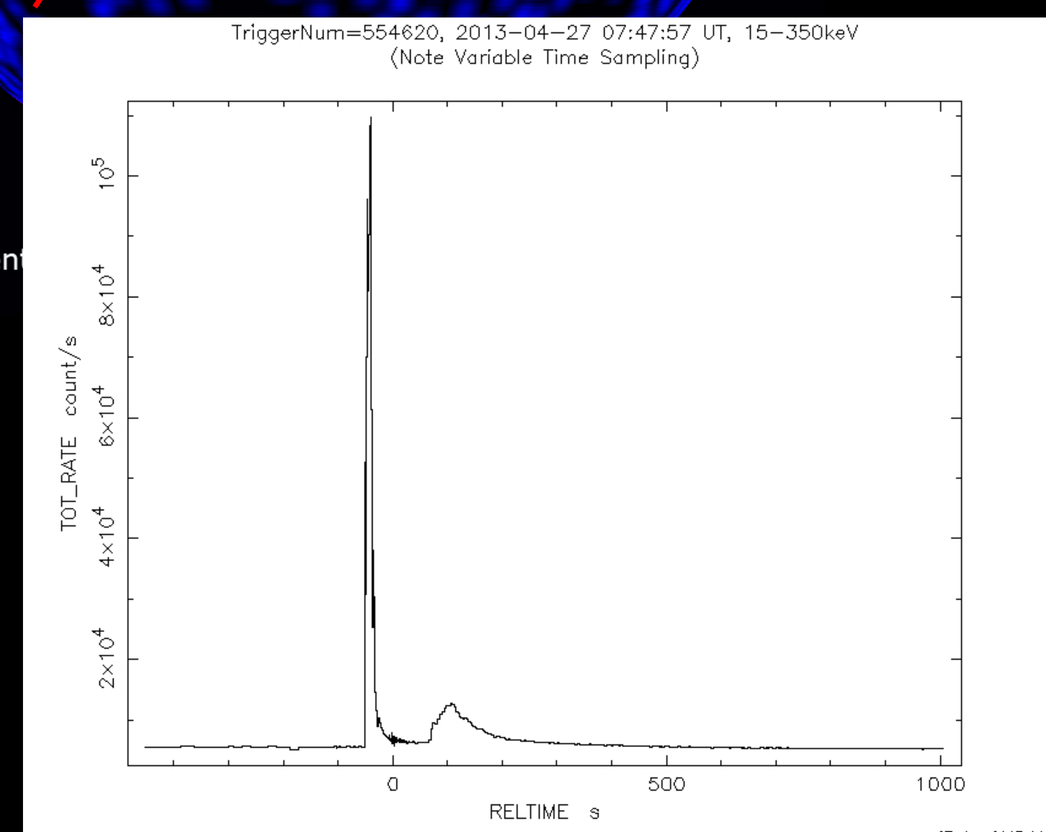


EM emission: Gamma-ray bursts (GRBs)

Brief, intense flash of gamma-ray radiation



Before and after Fermi LAT views of GRB 130427A, cen

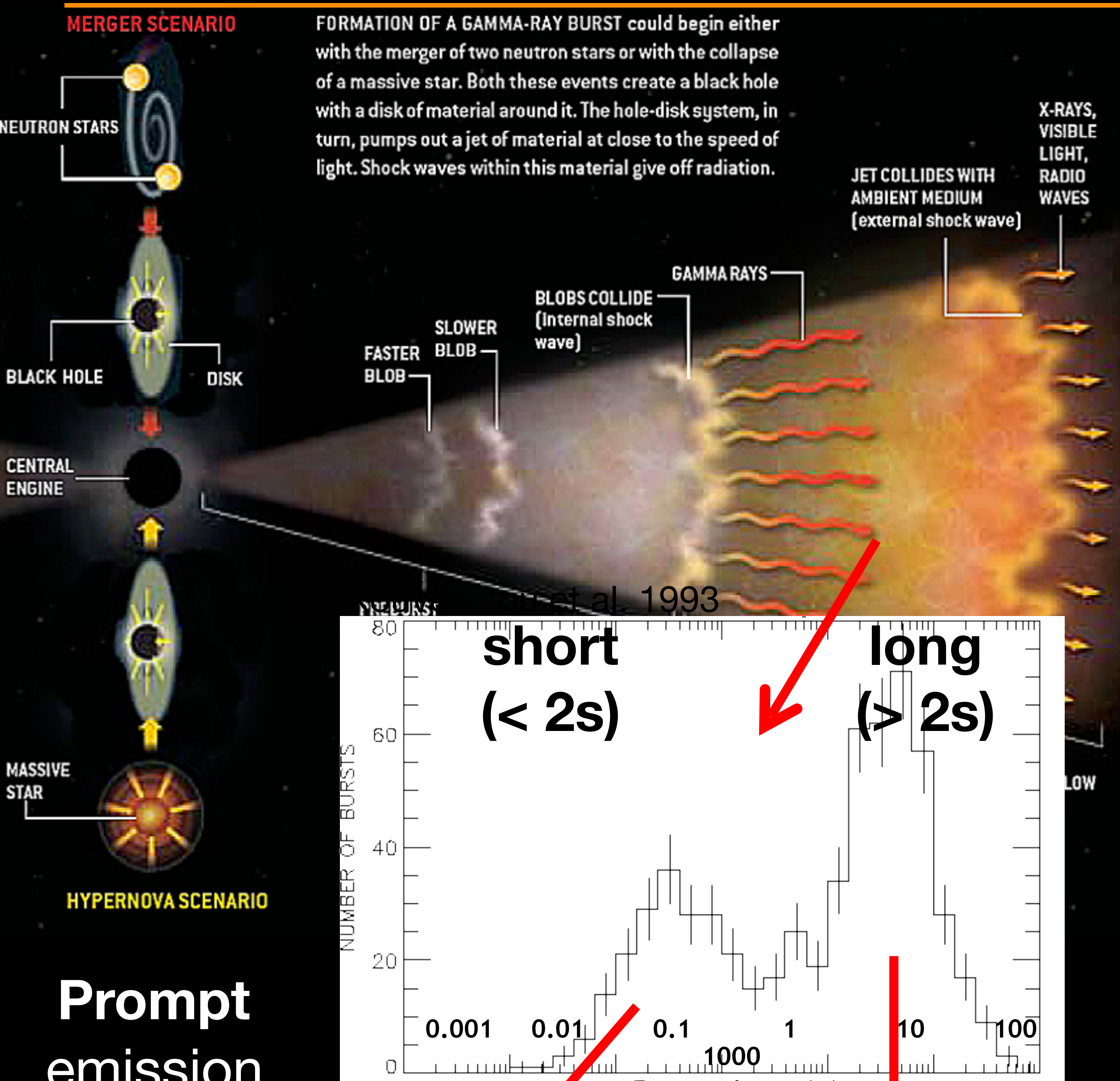


Fast: from few ms to hundreds of s

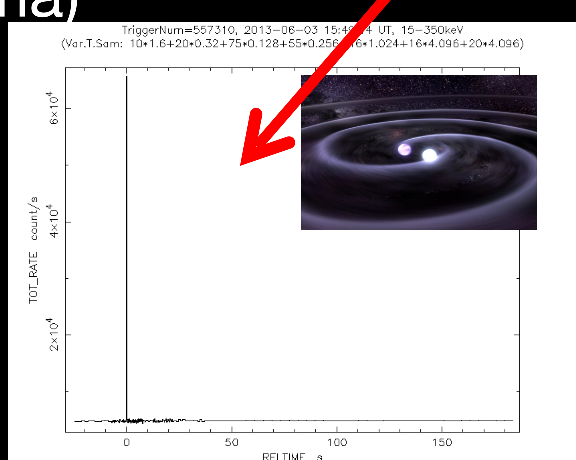
Energetic: 10^{-7} - 10^{-3} erg cm^{-2}

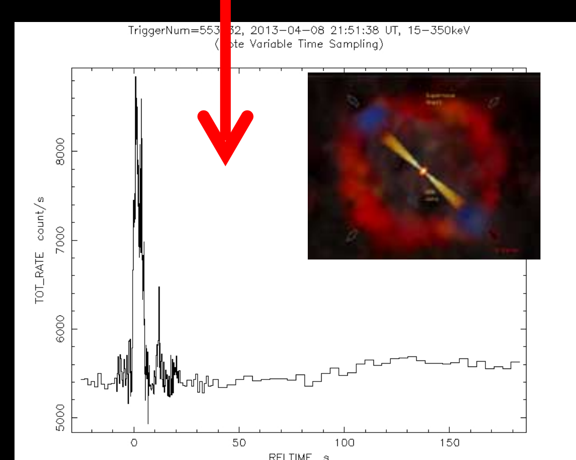
Bright: 10^{-8} - 10^{-4} erg cm^{-2} s^{-1}

EM emission: Gamma-ray bursts (GRBs)



Prompt emission (gamma)

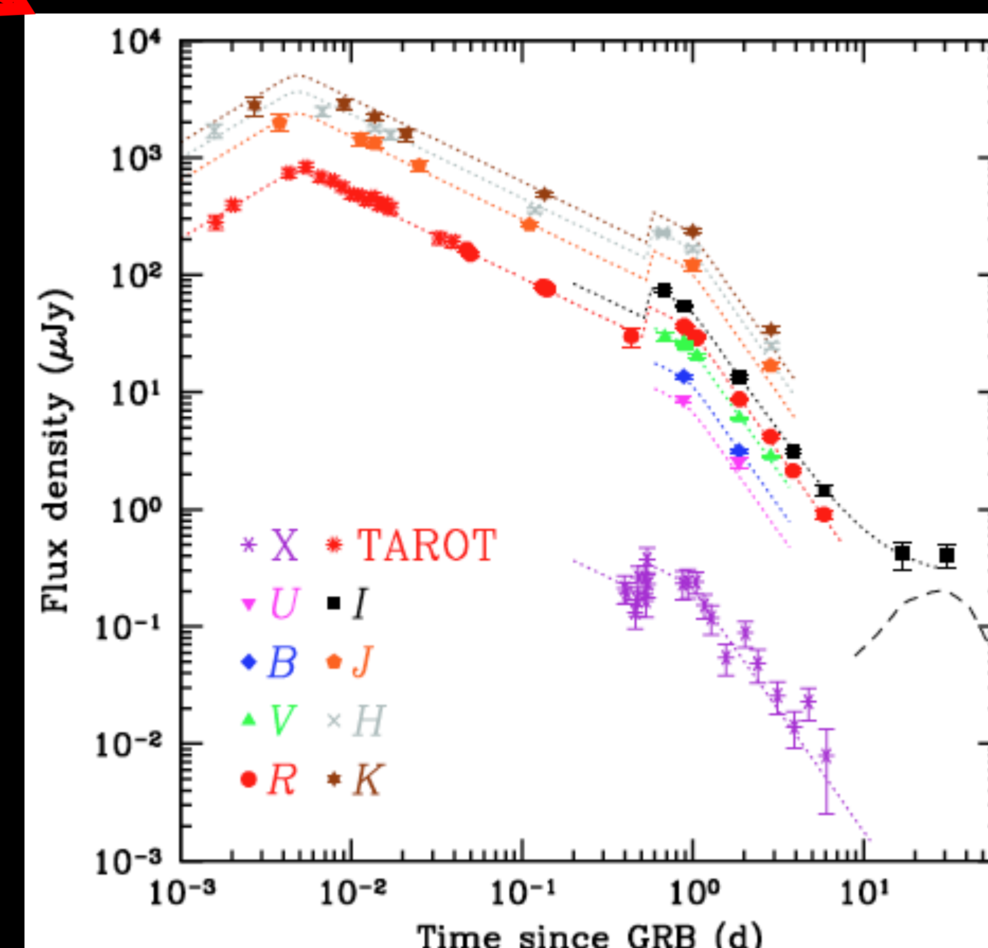




GRBs are cosmological: <z> = 2.1

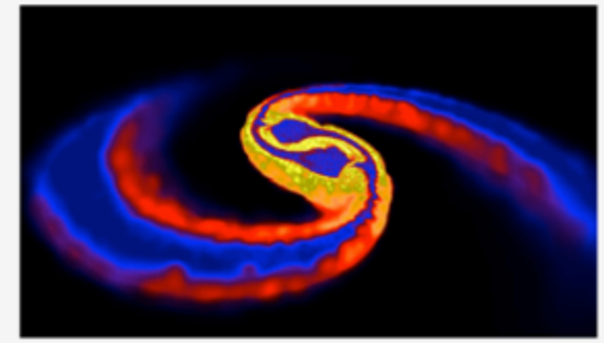
This implies they are powerful: E ~ 10^{52} erg

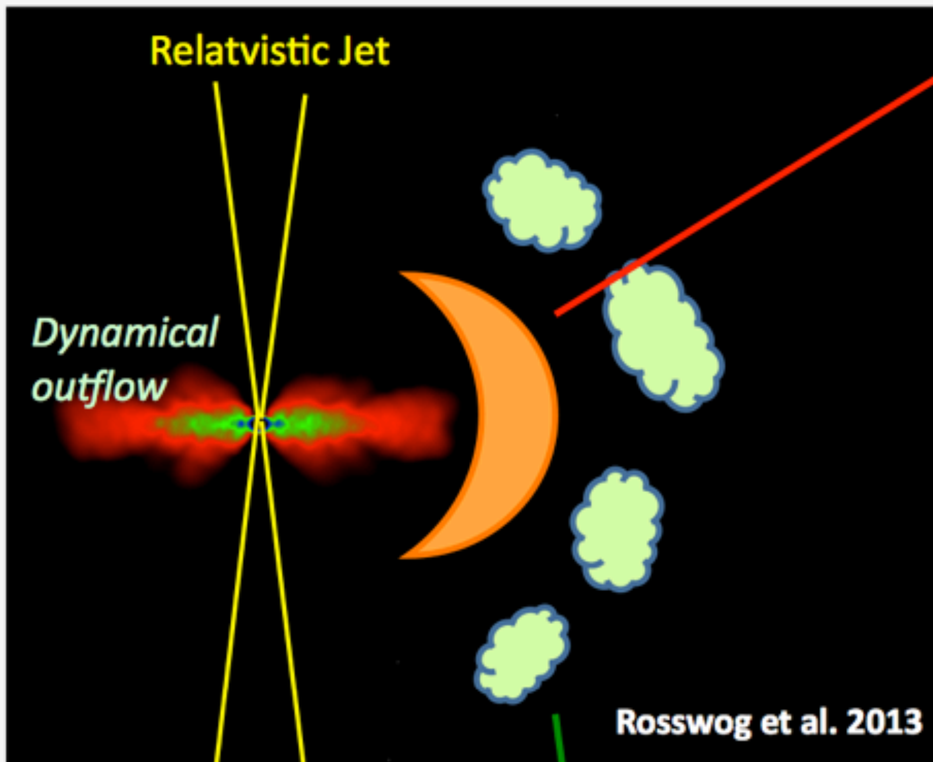
Long lasting, multiwavelength (X, opt, radio) emission: **afterglow**



EM emission: Kilonova/Macronova emission

Significant mass (0.01-0.1 $M_{\odot}$) is dynamically ejected
during NS-NS NS-BH mergers
at sub-relativistic velocity (0.1-0.3 c)





r-process

Neutron capture rate much faster than decay, special conditions:
T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

↓

radioactive decay of heavy elements

↓

Power MACRONOVA
short lived IR-UV signal (days)

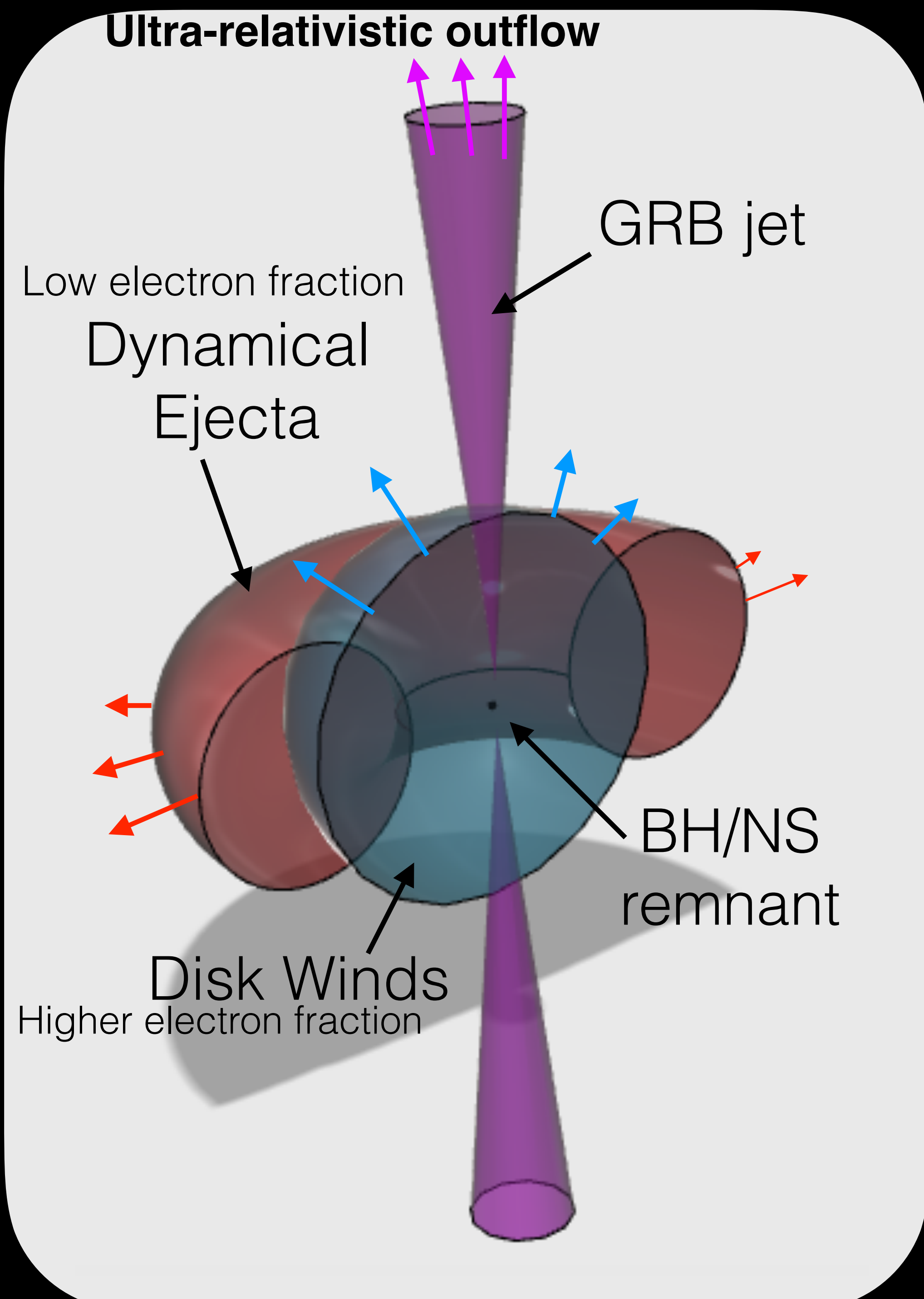
Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406; Tanaka et al. 2014 ApJ, 780;
Barnes & Kasen 2013, ApJ, 775. See Kasen et al. 2015, MNRAS, 450 for the accretion disk wind outflow component.

RADIO REMNANT
long lasting radio signals (years)
produced by interaction of sub-relativistic outflow with surrounding matter

Piran et al. 2013, MNRAS, 430

Morphology of the Ejecta

(Two different channels)

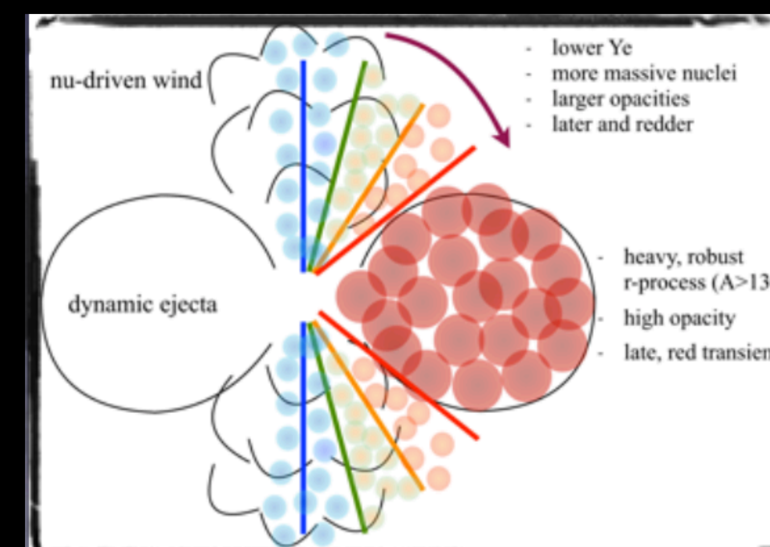


Courtesy of S. Ascenzi

Dynamical Ejecta → **Red Macronova**

unbound by hydrodynamic interaction and gravitational torques

Peaks at days - 1 week after the merger



Disk Winds → **Blue Macronova**

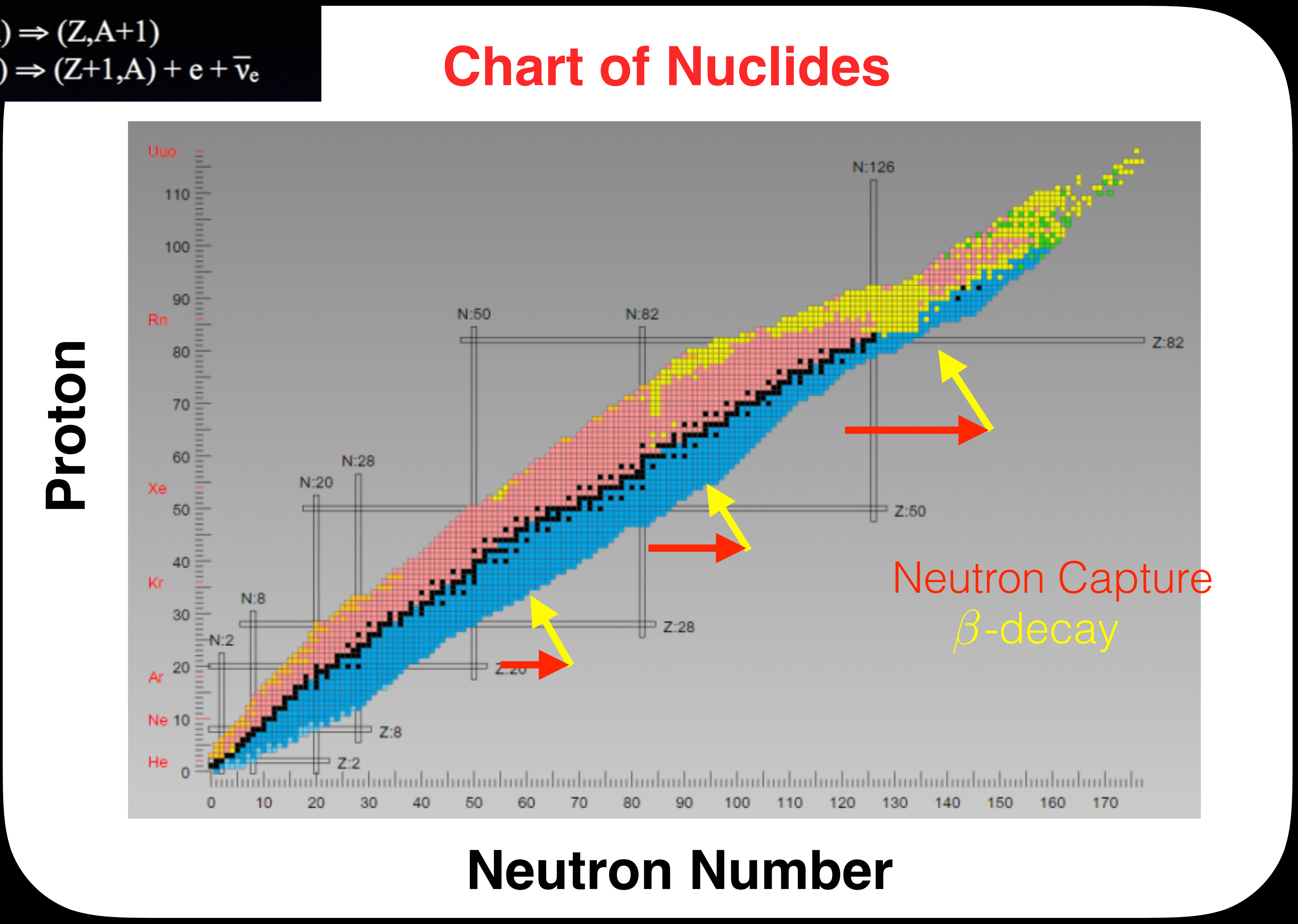
neutrino absorption, magnetically launched winds or accretion disk matter that becomes unbound by viscous and nuclear heating

Peaks at 1 day after the merger

2-3 magnitude brighter than the red macronova

R-Process Nucleosynthesis

basic reactions:
a) n-capture: $n + (Z,A) \Rightarrow (Z,A+1)$
b) β-decay: $(Z,A) \Rightarrow (Z+1,A) + e + \overline{\nu}_e$



A key signature of an NS–NS/NS–BH binary merger is the production of a so-called "kilonova" (aka "macronova") due to the decay of heavy radioactive species produced by the *r*-process and ejected during the merger that is expected to provide a source of heating and radiation (Li and Paczynski 1998; Rosswog, 2005; Metzger et al., 2010).

Macronova: Main Ingredients

k ← Opacity

m_{ej} ← Mass of the Ejecta

v_{ej} ← Velocity of the Ejecta

$$t_{peak} \simeq 4.9\, days \left(\frac{k}{10\, cm^2/g} \frac{m_{ej}}{0.01\, M_\odot} \frac{0.1\, c}{v_{ej}} \right)^{1/2}$$

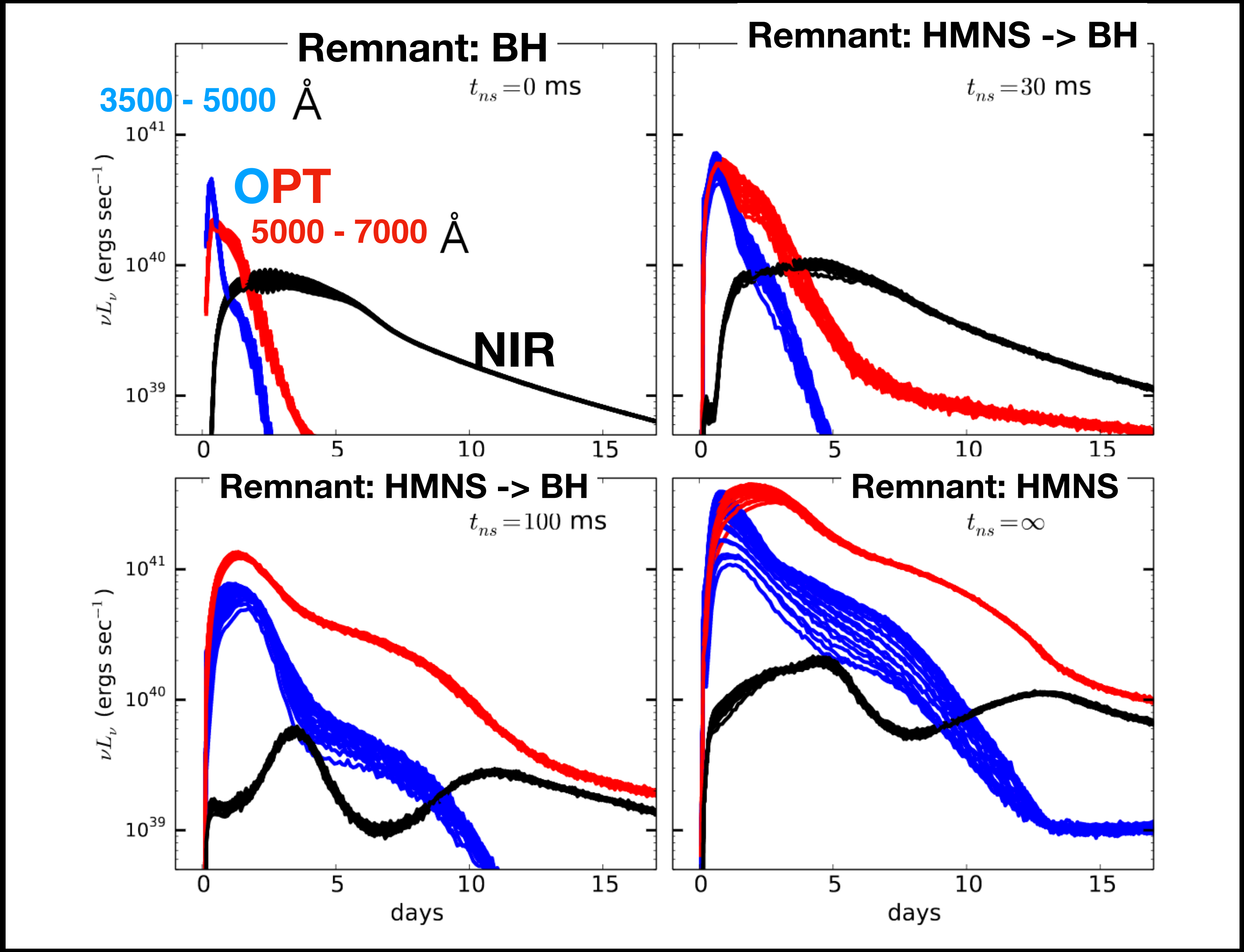
$$L_{peak} \simeq 2.5 \times 10^{40}\, \frac{erg}{s} \left(\frac{v_{ej}}{0.1\, c} \frac{10\, cm^2/g}{k} \right)^{0.65} \left(\frac{m_{ej}}{0.01\, M_\odot} \right)^{0.35}$$

(Grossman et al. 2014)

Courtesy of S. Ascenzi

Kilonova expected light curves

Kasen+2015



PRO: emitted in essentially all directions

CONS: likely weak, and will only be observable by the largest telescopes

OPTICAL COMPONENT (from disk outflow) : peaks at 1 day with L=5-500x10^{40} erg/s (r=19-24 mag at 200 Mpc)

NIR COMPONENT (from ejecta) : peaks at few up to 10 days with L=0.1-1x10^{40} erg/s

Kilonova expected spectra

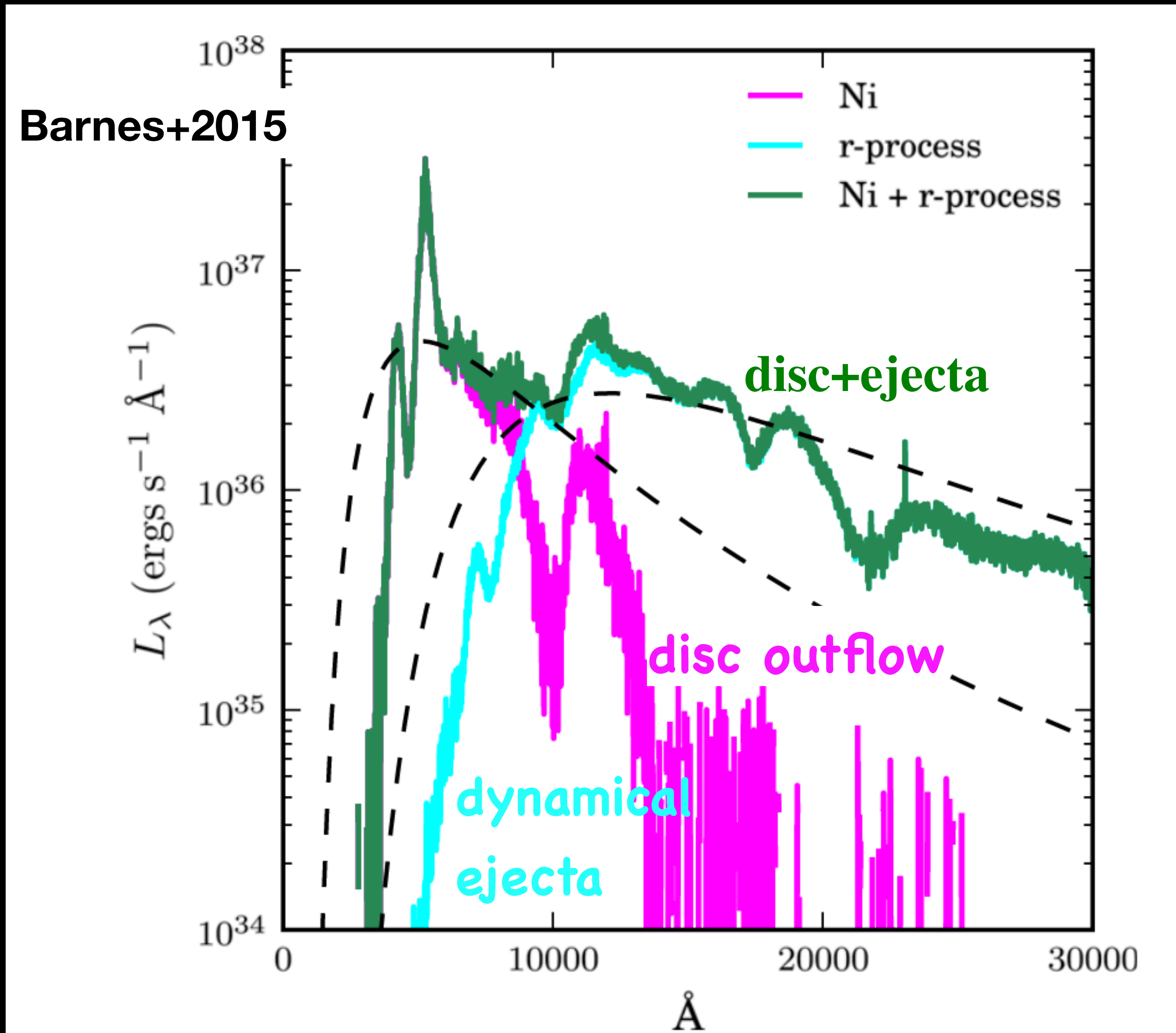


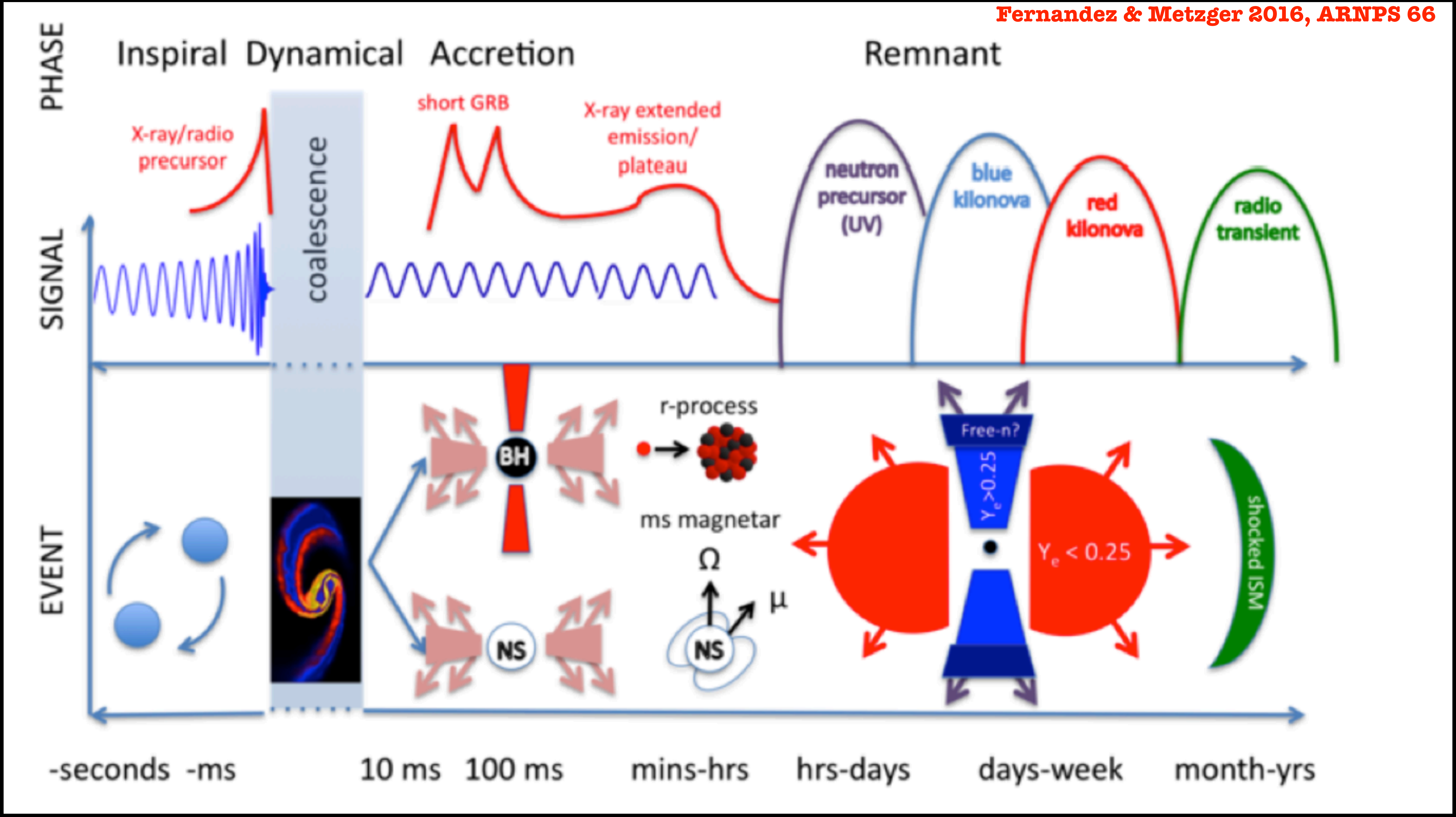
Figure 10. A combined ^{56}Ni and r-process spectrum at $t = 7$ days, taking $M_{ni} = M_{rp} = 10^{-2}\, M_\odot$. The peak at blue wavelengths is due to the ^{56}Ni, while the r-process material supplies the red and infrared emission. The best-fit blackbody curves to the individual spectra are overplotted in dashed black lines ($T_{ni} \simeq 5700$ K, $T_{rp} \simeq 2400$ K). The combined spectrum generally resembles a superposition of two blackbodies at different temperatures.

thermal (BB) spectra which evolve from optical to NIR due to different opacities predicted in the disc outflows and in the middle-relativistic ejecta

NS-NS NS-BH Merger: a global picture

EM

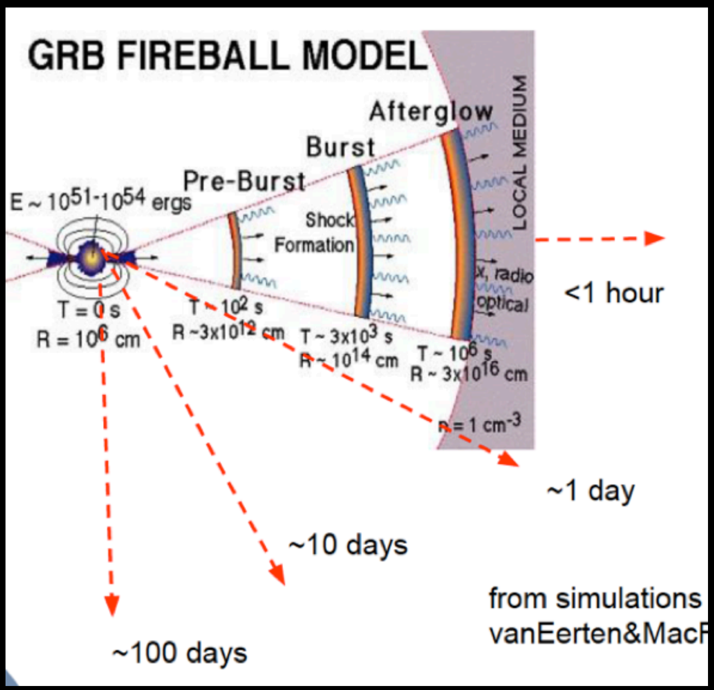
GW

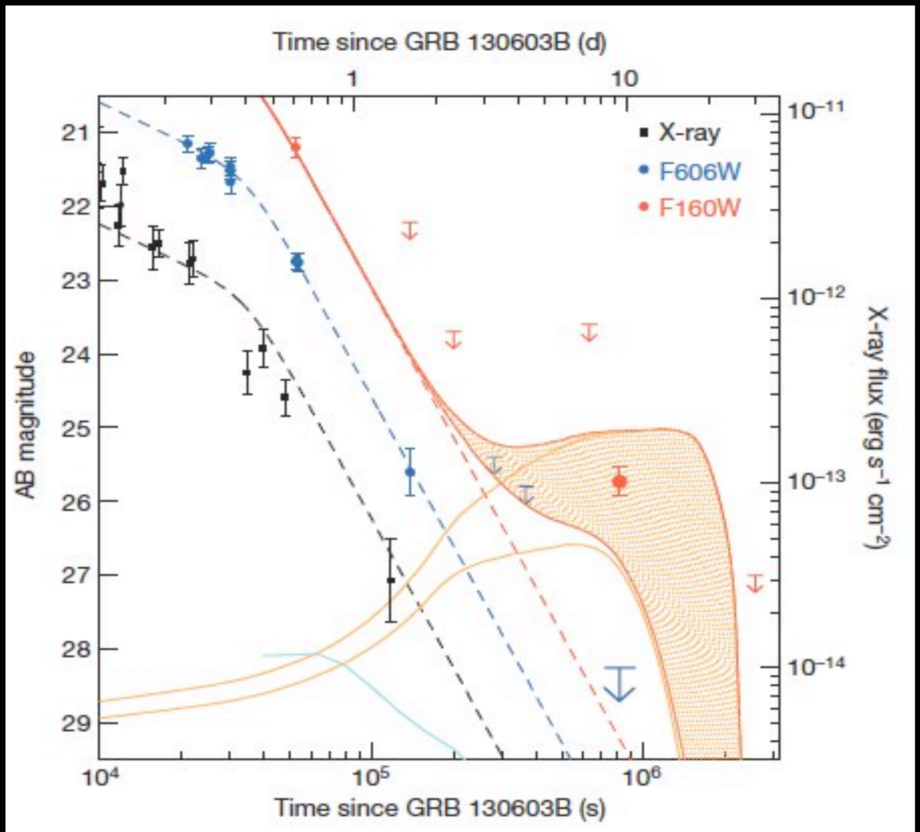


Request for network of multi-wavelenght observatories which cover huge region of the sky and repeat observations over different timescales

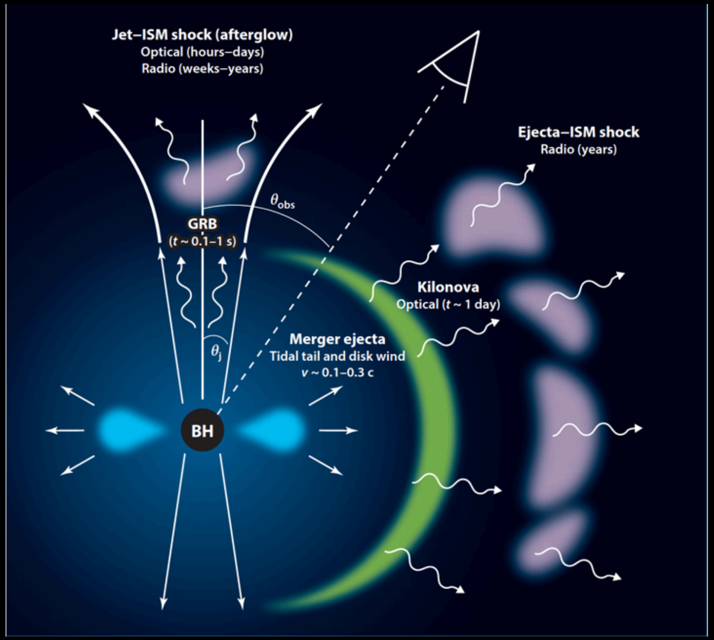
NS-NS NS-BH Merger EM-Emission: SGRBs? Kilonove?

BEFORE AUG 17 2017



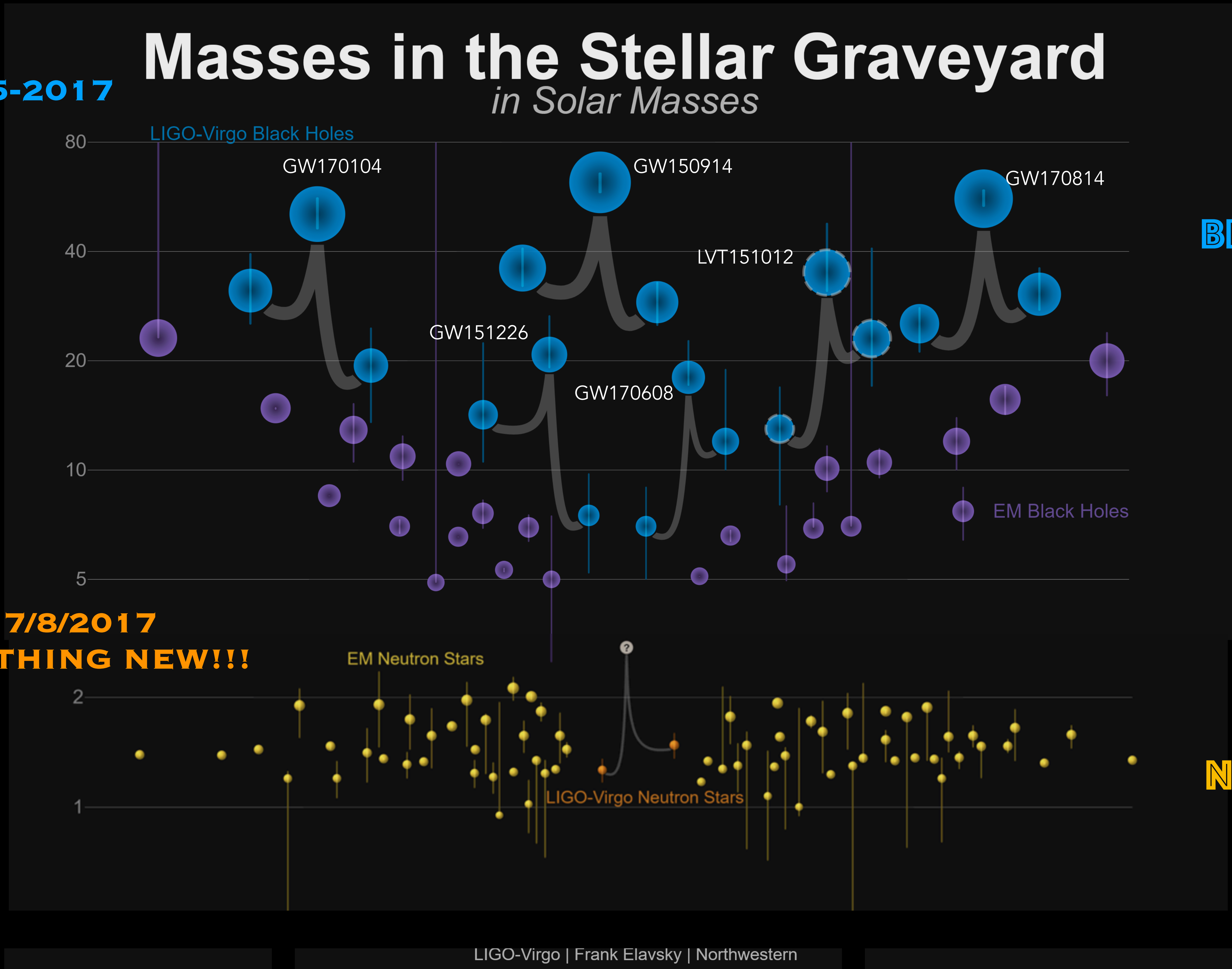


- **SGRB on-axis emission**
- **Evidence of kilonova emission**
- **Evidence of off-axis emission**



✓GRB130603B Tanvir et al. 2013; Berger et al. 2013
✓ GRB 060614 Yang et al. 2015
✓ GRB 050709 Jin et al. 2016

O1-O2 runs: Aug 17 2017!



2015-2017

BH-BH

17/8/2017
SOMETHING NEW!!!

NS-NS

Our Group

GRAvitational Waves Inaf TeAm

www.grawita.inaf.it

INAF OA Roma:* E. Brocato (P.I.), S. Piranomonte**, *S. Ascenzi,* ***L. Stella, *A. Stamerra, P. Casella, G. Israel, L. Pulone,*

***INAF OA Napoli:* A. Grado, F. Getman, L. Limatola, M.T. Botticella,** *M. della Valle, M. Capaccioli, P. Schipani*

***INAF IASF Bologna:* E. Palazzi, L. Nicastro, A. Rossi,** *L. Amati, L. Masetti, A. Bulgarelli, D. Vergani, G. De Cesare*

***INAF OA Brera / IASF Milano:* S. Campana, S. Covino, P. D'Avanzo, A. Melandri,** *G. Ghisellini, G.Ghirlanda, R. Salvaterra*

***INAF OA Padova:* E. Cappellaro, L. Tomasella, S. Benetti,** *S. Yang, M. Mapelli*

INAF OA Cagliari: *A. Possenti, M. Burgay*

***GSSI:* M. Branchesi**

***University of Urbino:* G. Stratta, G. Greco**

SNS Pisa: *F. Longo, M. Razzano, G. Pivato, B. Patricelli, G. Cella*

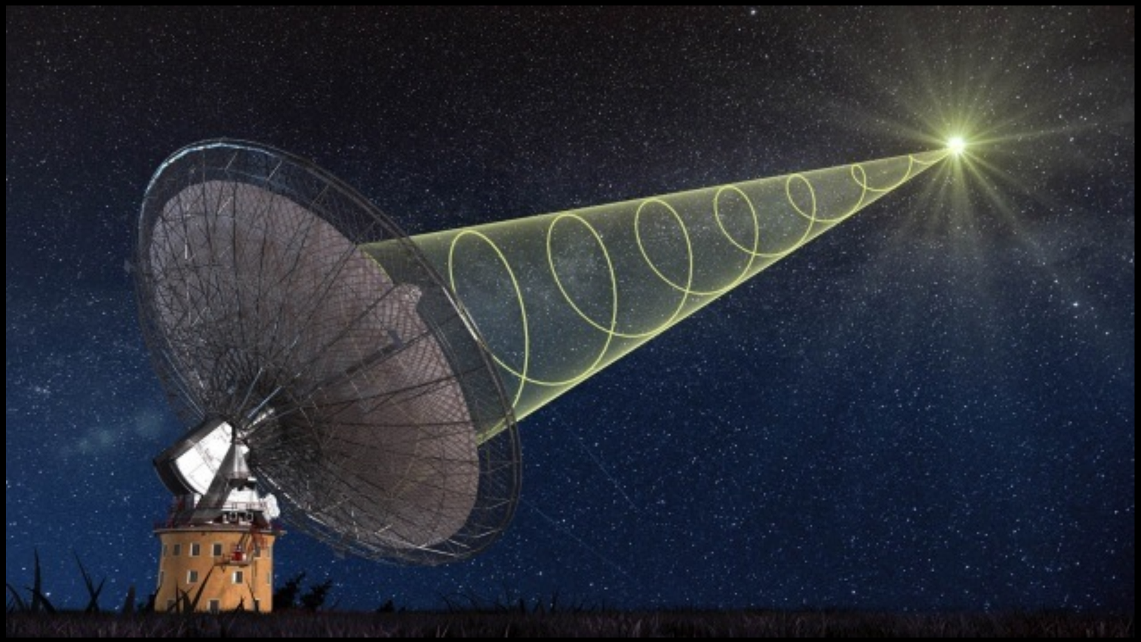
Space Science Data Center:* L.**A. *Antonelli,* ***V. D'Elia, *G. Giuffrida, S. Marinoni, P. Marrese,*

GRAWITA KNOW HOW

TIME DOMAIN ASTRONOMY

- GRBs, FRBs and SNe studies and follow-ups
- Multi-wavelength observational strategies on transients sources
- Multi-wavelength data analysis
- Accurate Photometry in crowded fields
- Theoretical models and data interpretation

- <u>more than 1800 referred papers in 2010–2017</u>



GRAWITA Facilities

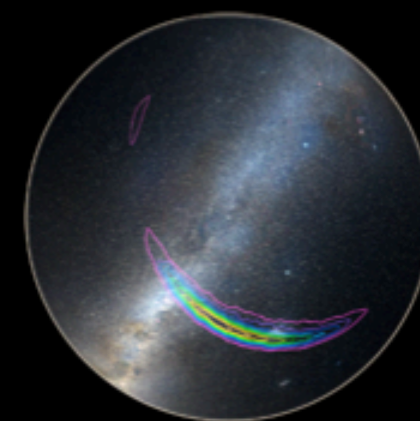
FOLLOW-UP STRATEGY

(NOT AN EASY GAME)

LIGO-H LIGO-L

Virgo

Low-latency Search
to identify the GW-candidates



Event validation

GW sky maps
15-30 minutes

Software analysis to

- statistically select the GW-triggers wrt bkg
- sanity and data quality checks
- generate localisation sky maps

Parameters estimation codes
to GW-candidates update
(hours-days)

?

EM follow-ups

SO IT BEGINS....

highly significant FAR = 1/100 yr

significant

low significance FAR = 1/yr

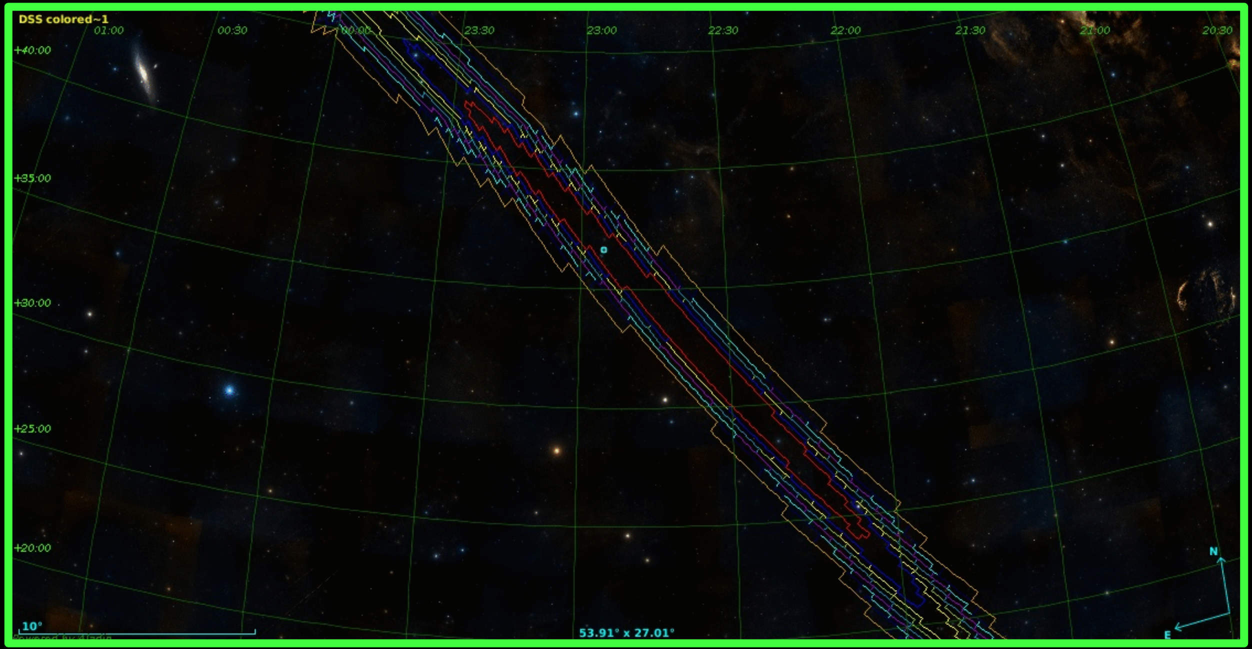
FAR = 1/month

FAR = Rate of noise events louder than the candidate event

Candidates to be observed selected based on the observer's choice of FAR threshold

Sky map + basic source classification (NS presence, distance...)

Credit: G. Greco, GWsky https://github.com/ggreco77/GWsky

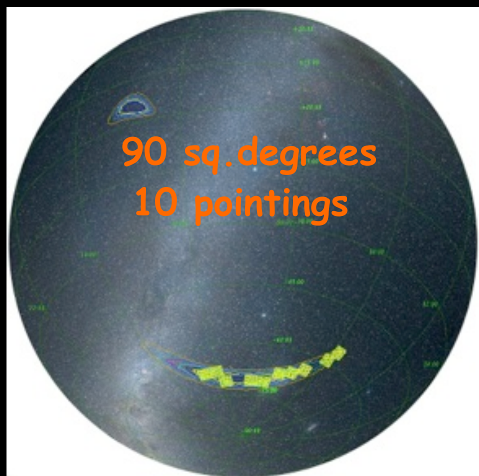


decide the best observational strategy

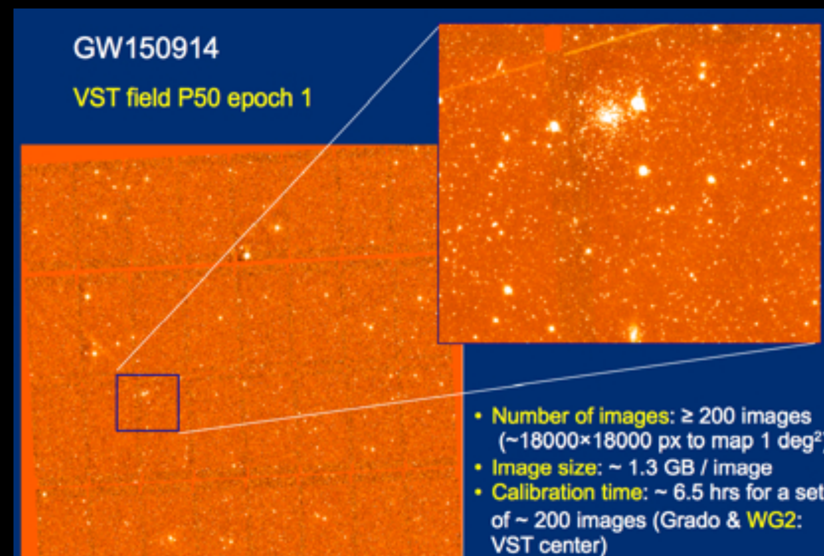
Tiling the sky map to maximize the enclosed localization probability

EXAMPLE OF GRAWITA RESPONSE

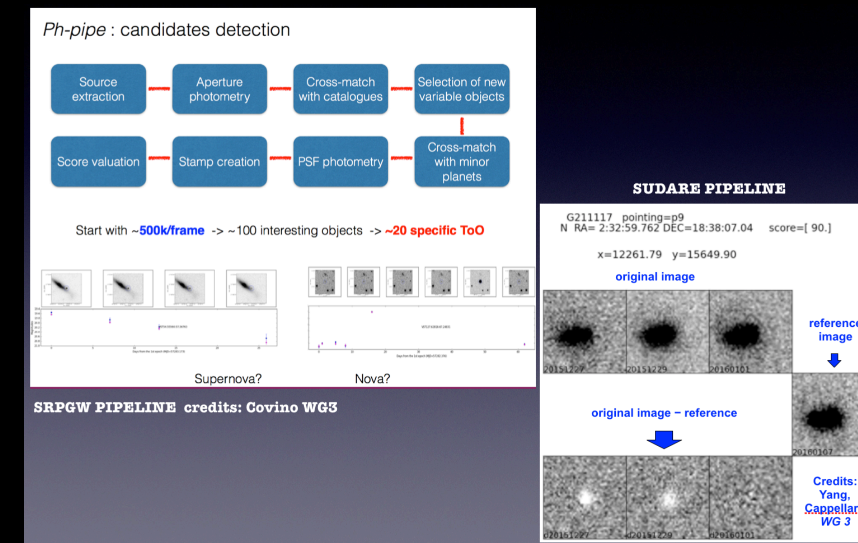
1. Tiling



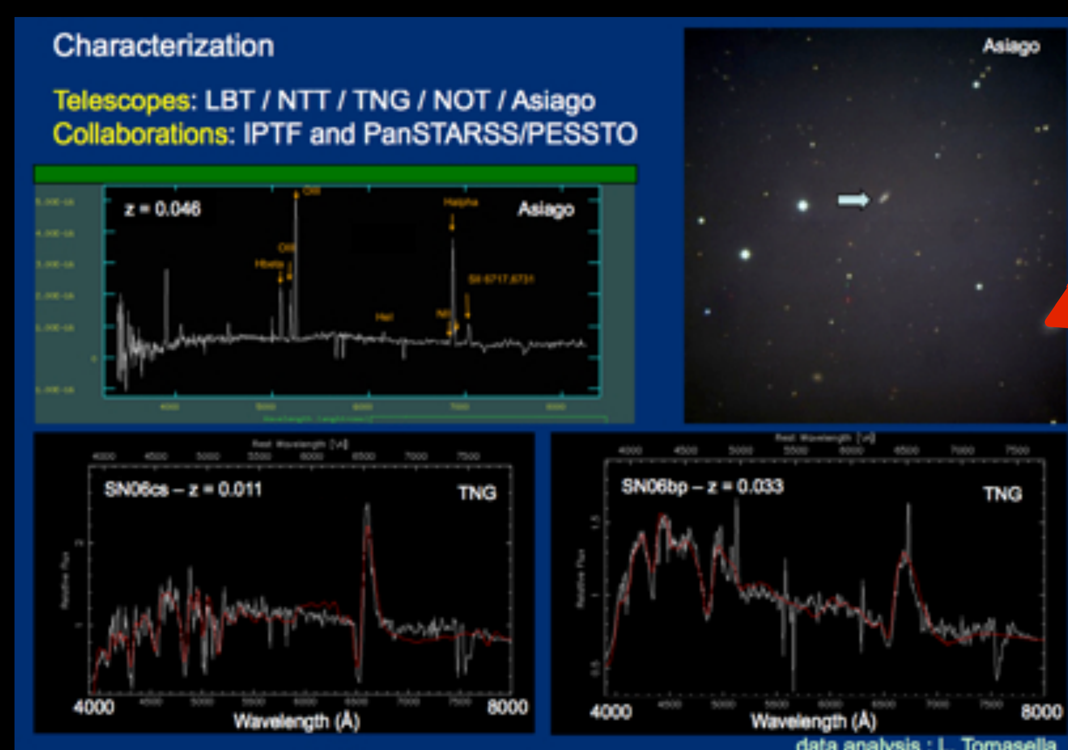
2. Observations



3. Search



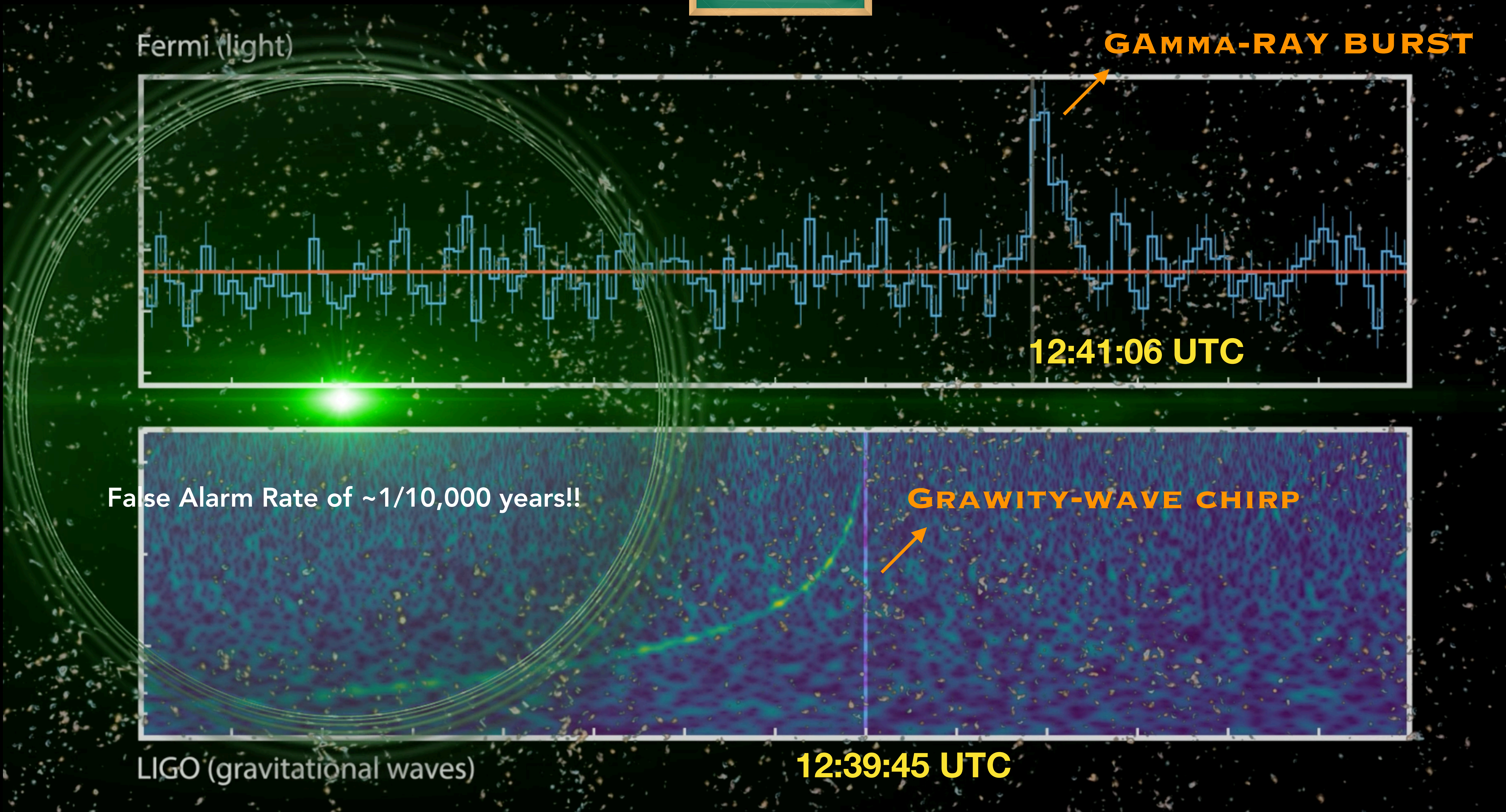
4. Characterization and follow-up



Collaborations with high energy facilities and iPTF, PANSTARRS,/PESSTO

GW170817-GRB170817

17 August

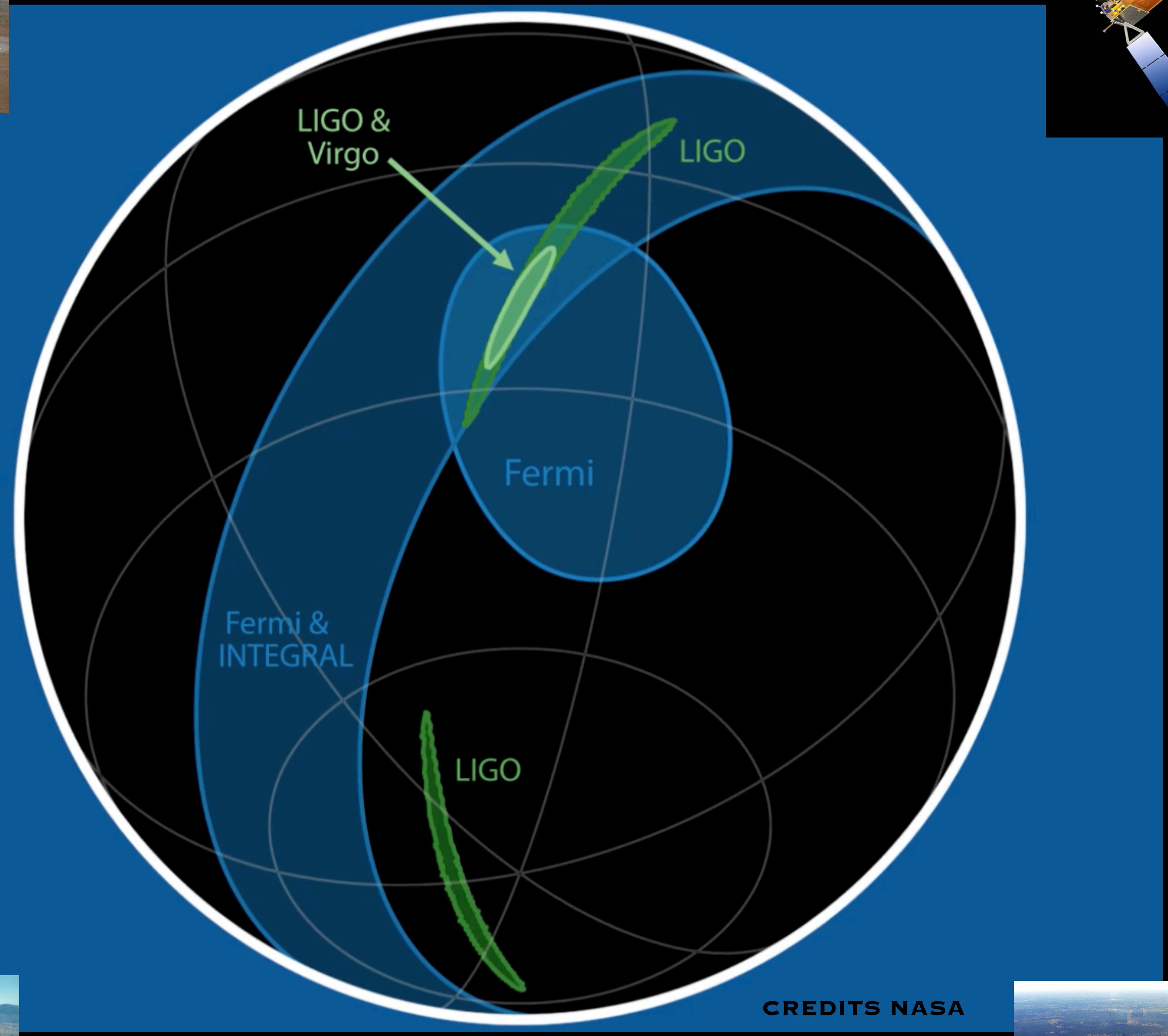


NS-NS MERGER AT 40Mpc!!!

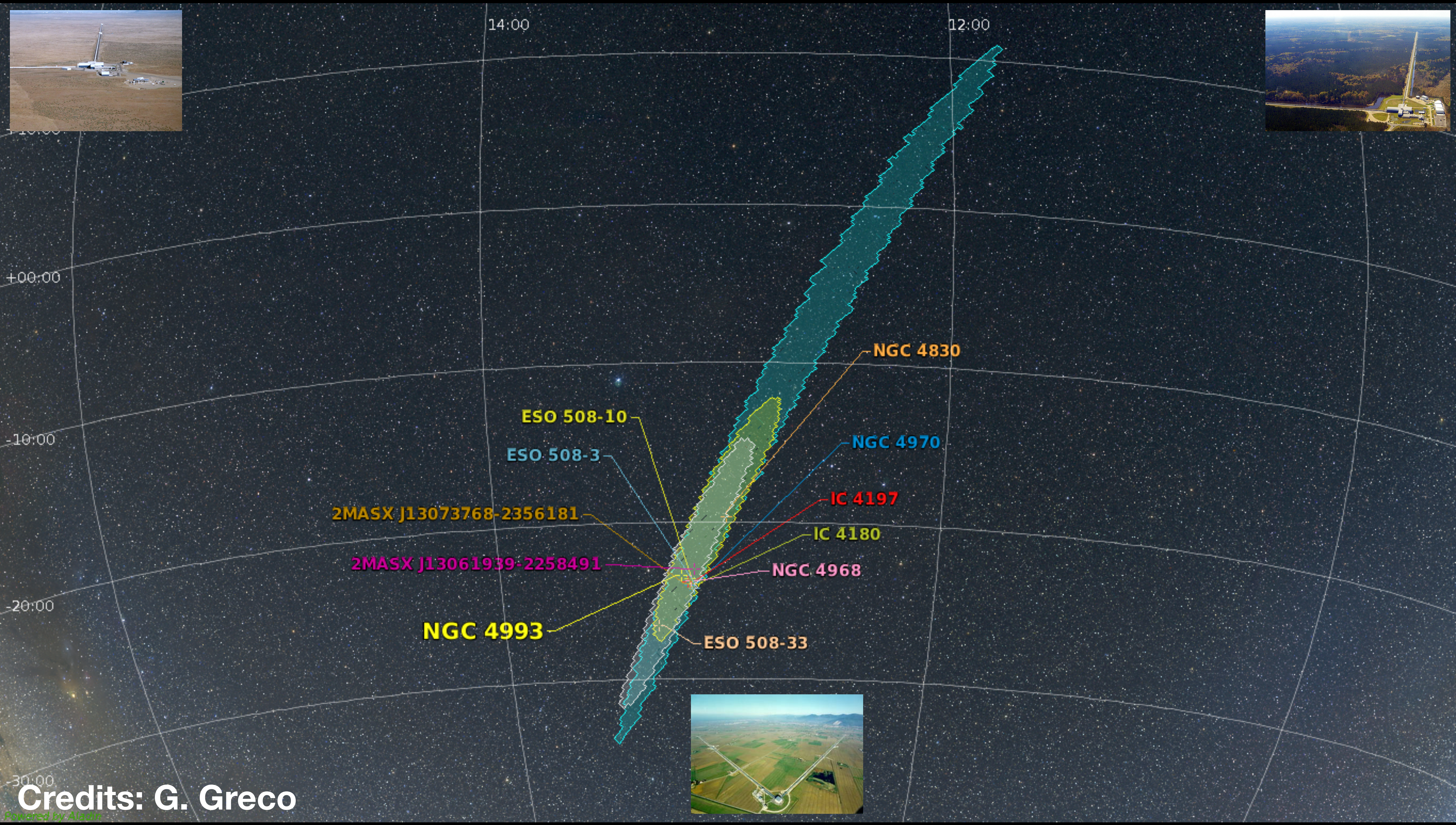
An impressive observational campaign

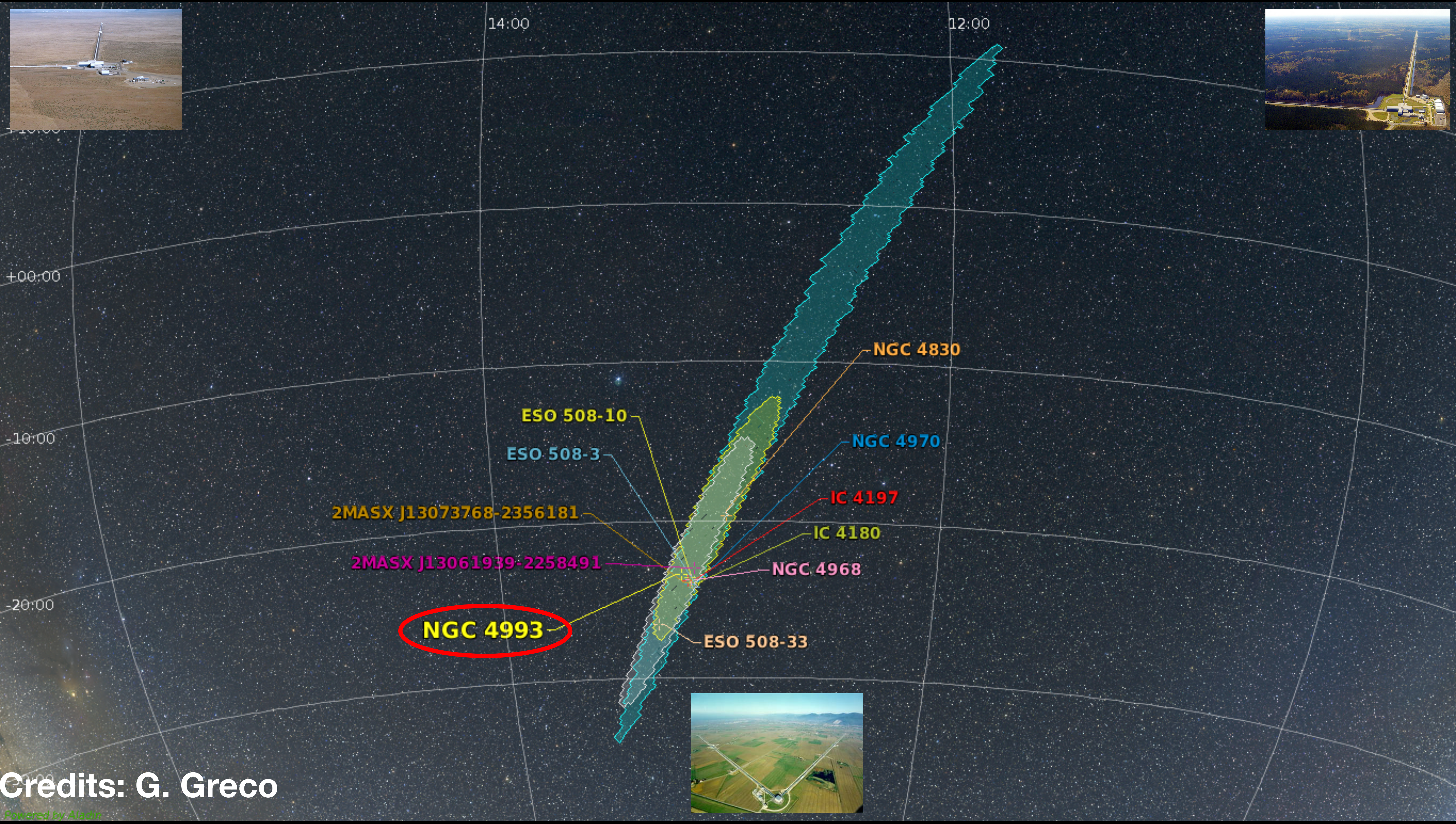
LVC + "partner astronomy groups" (2017)

17 August




17
August


14:00
12:00
+00:00
-10:00
-20:00
-30:00
NGC 4830
ESO 508-10
ESO 508-3
NGC 4970
IC 4197
2MASX J13073768-2356181
IC 4180
2MASX J13061939-2258491
NGC 4968
NGC 4993
ESO 508-33
Credits: G. Greco
Powered by Aladin


14:00
12:00
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-10:00
-20:00
NGC 4830
ESO 508-10
ESO 508-3
NGC 4970
IC 4197
2MASX J13073768-2356181
IC 4180
2MASX J13061939-2258491
NGC 4968
NGC 4993
ESO 508-33
Credits: G. Greco

GW170817-GRB170817

The arrival
Stardate:
14/08/17 12:39:45-12:41:04 UTC

Fermi-GBM GRB170817A
Detected 12:41:06 UTC
GCN circular sent out :
50-300keV, 12:41:20 UTC

Gamma-ray counterpart

Rapid Response Call
GCN circular sent out about :
13:08:16 UTC

GCN circular about temporally
coincident BNS merger LSC+VC:
13:21:42 UTC

GCN BNS merger

First three instrument
Sky Map
17:54:51 UTC

first sky map with 3 instruments

First Coherent
Analysis produces
Sky Map
sent out at 23:54:40 UTC

Coulter et al GCN
23:33 UTC (tc + 10.87 hr)

1st optical counterpart, AT2017gfo

GeminiSouth FLAMINGO2
IR (tc + 12.8 hr)

IR counterpart,

Swift (tc + 15.37 hr)

Swift UV counterpart

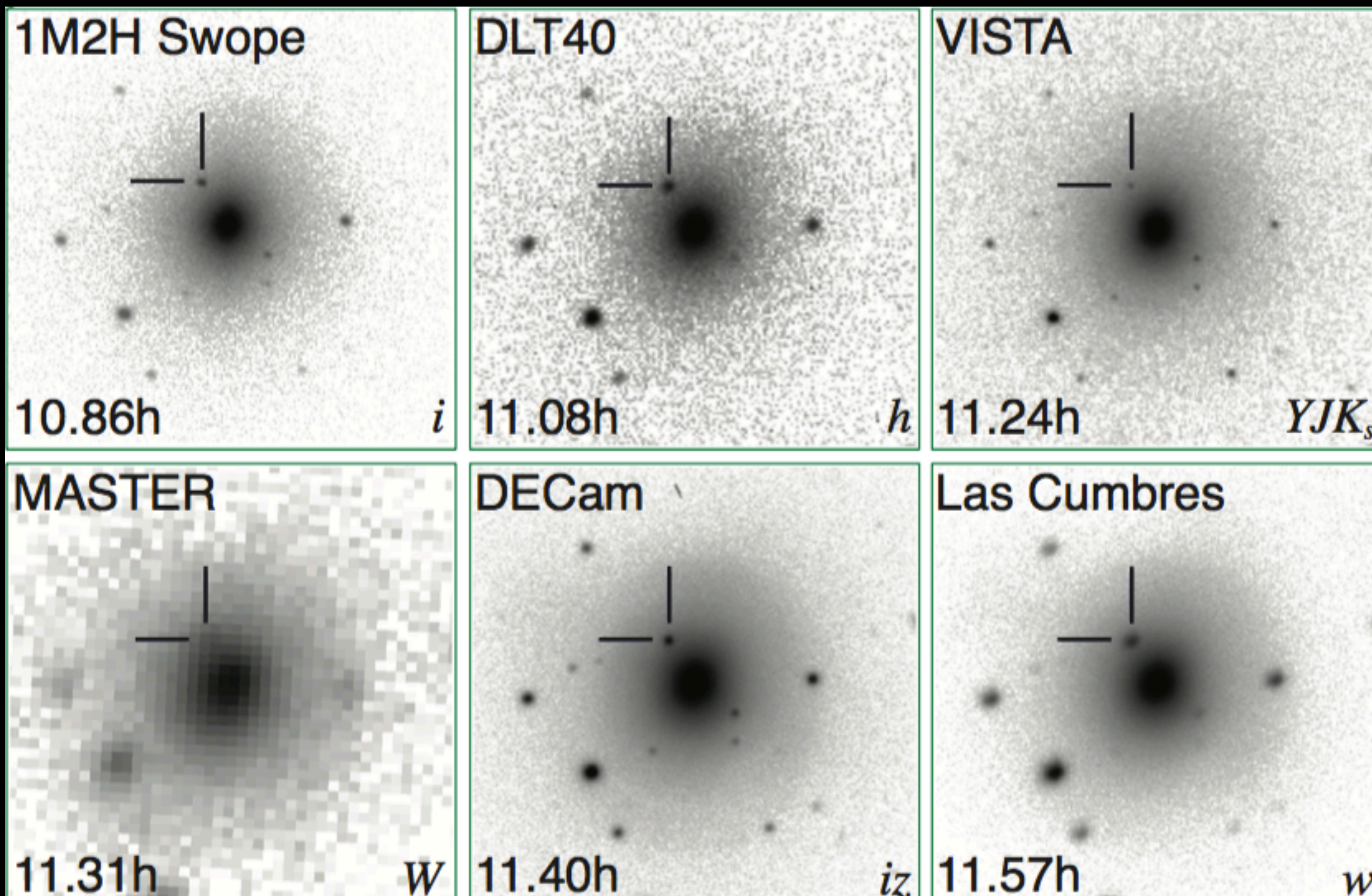
tc + 12.8 hr, GeminiSouth FLAMINGO2
first near-infrared Ksband
Constrains the early optical to infrared color

At tc + 15.3 hr, the Swift - bright, UV emission
Constrains the effective temperature

Swift and Hubble Space Telescope monitoring
UV evolution

Next two days, a rapid dimming of UV–blue
Unusual brightening of the nearinfrared
|
After roughly a week, the redder optical and
near-infrared bands began to fade
|
Unusual rapid luminosity decline.
In bluer optical bands (i.e., in the g band),
Fast decay between daily photometric
measurements

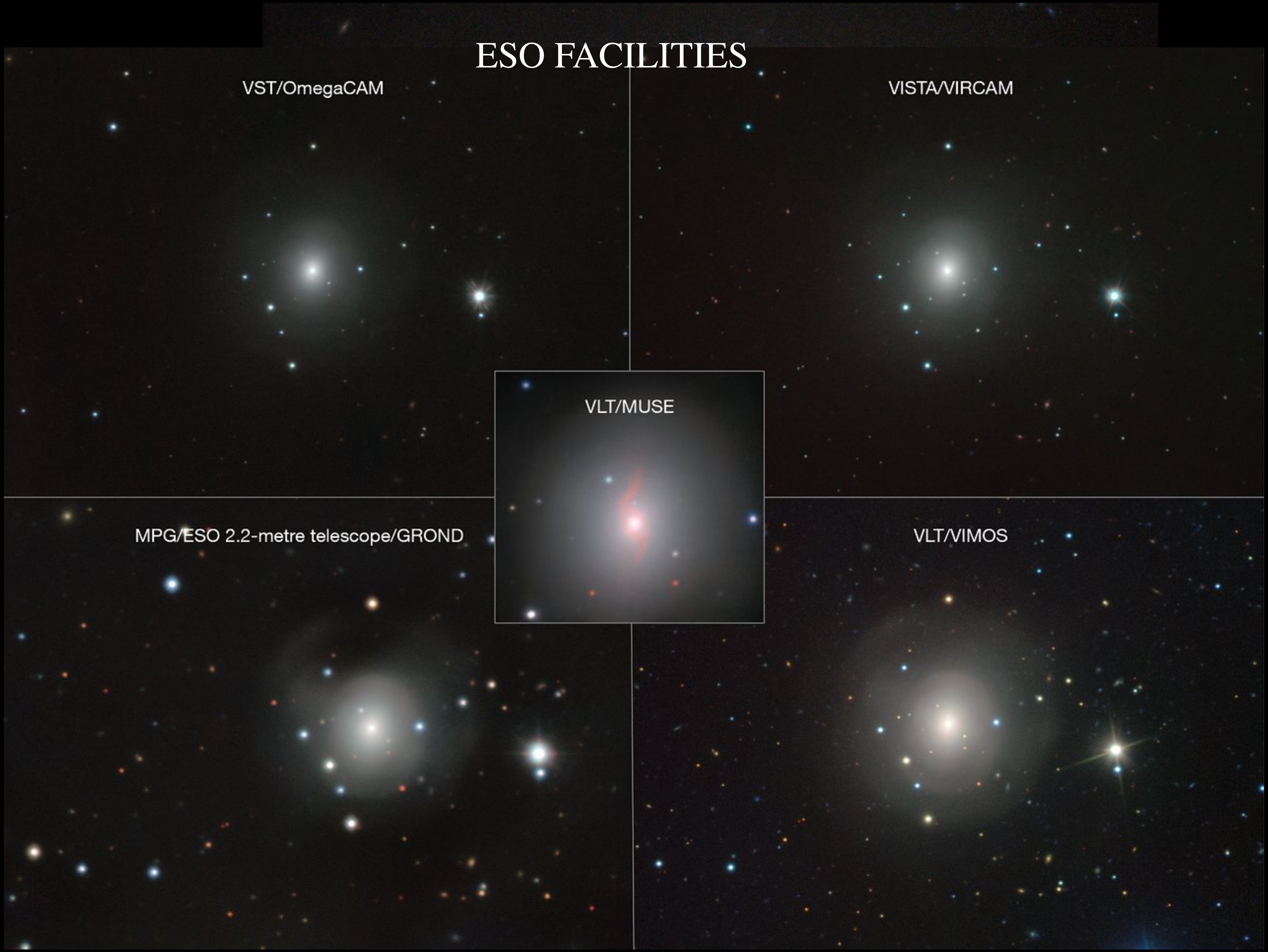
Optical counterpart in NGC 4993



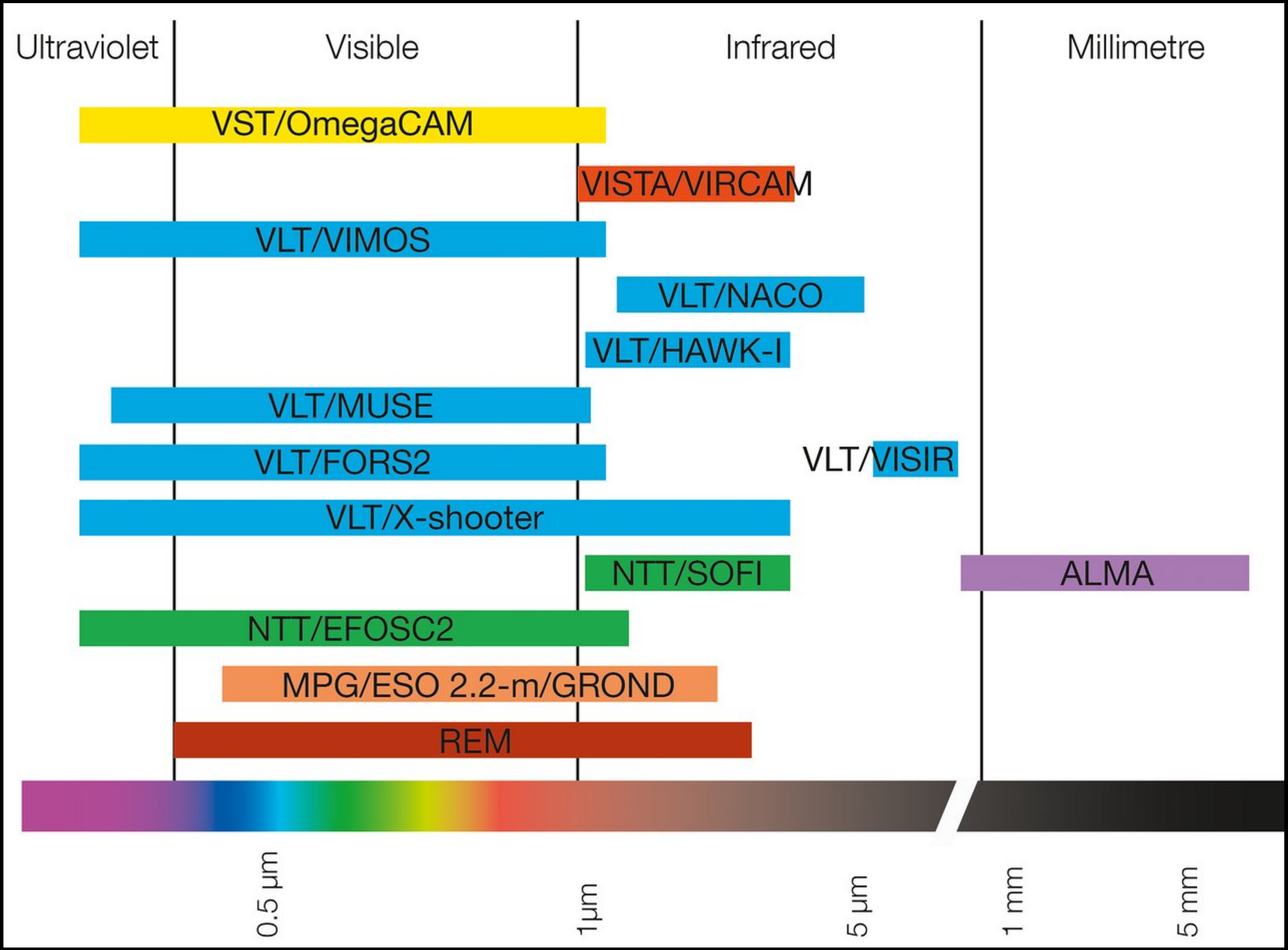
Lipunov et al. (2017) Allam et al. (2017) Arcavi et al. (2017)

NGC 4993, S0 galaxy @ D = 41 Mpc, z = 0.00968 (Hjorth et al. 2017)

ESO FACILITIES

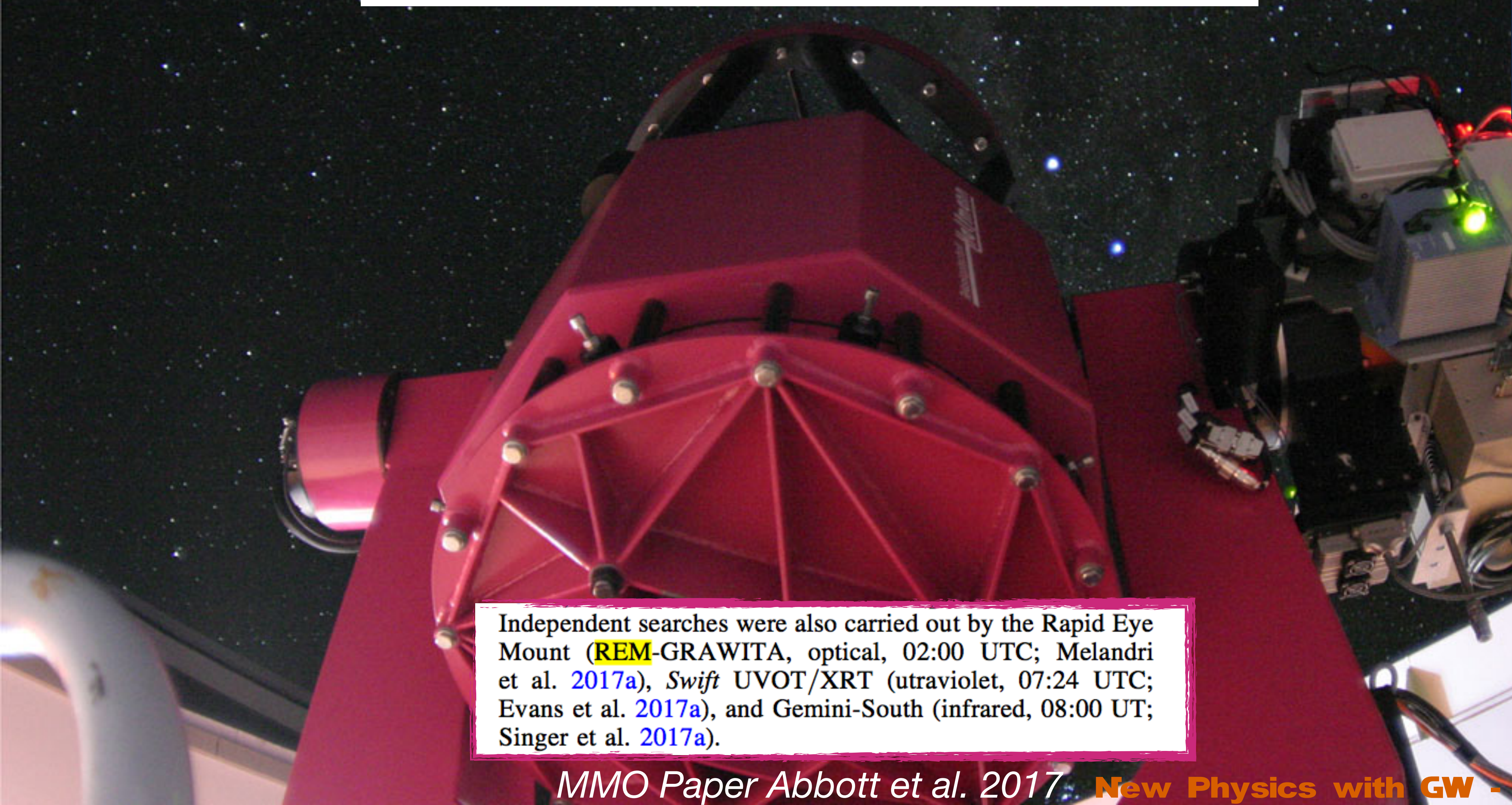


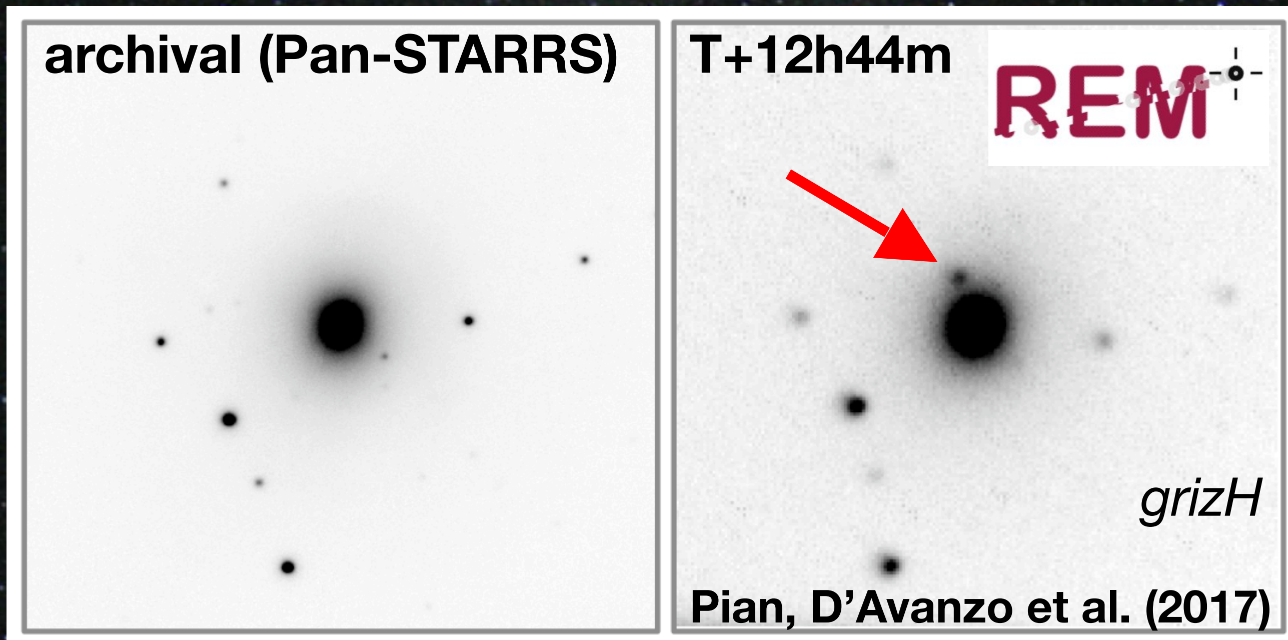
An impressive observational campaign



ESO launched one of the biggest ToO campaign

Optical counterpart in NGC 4993



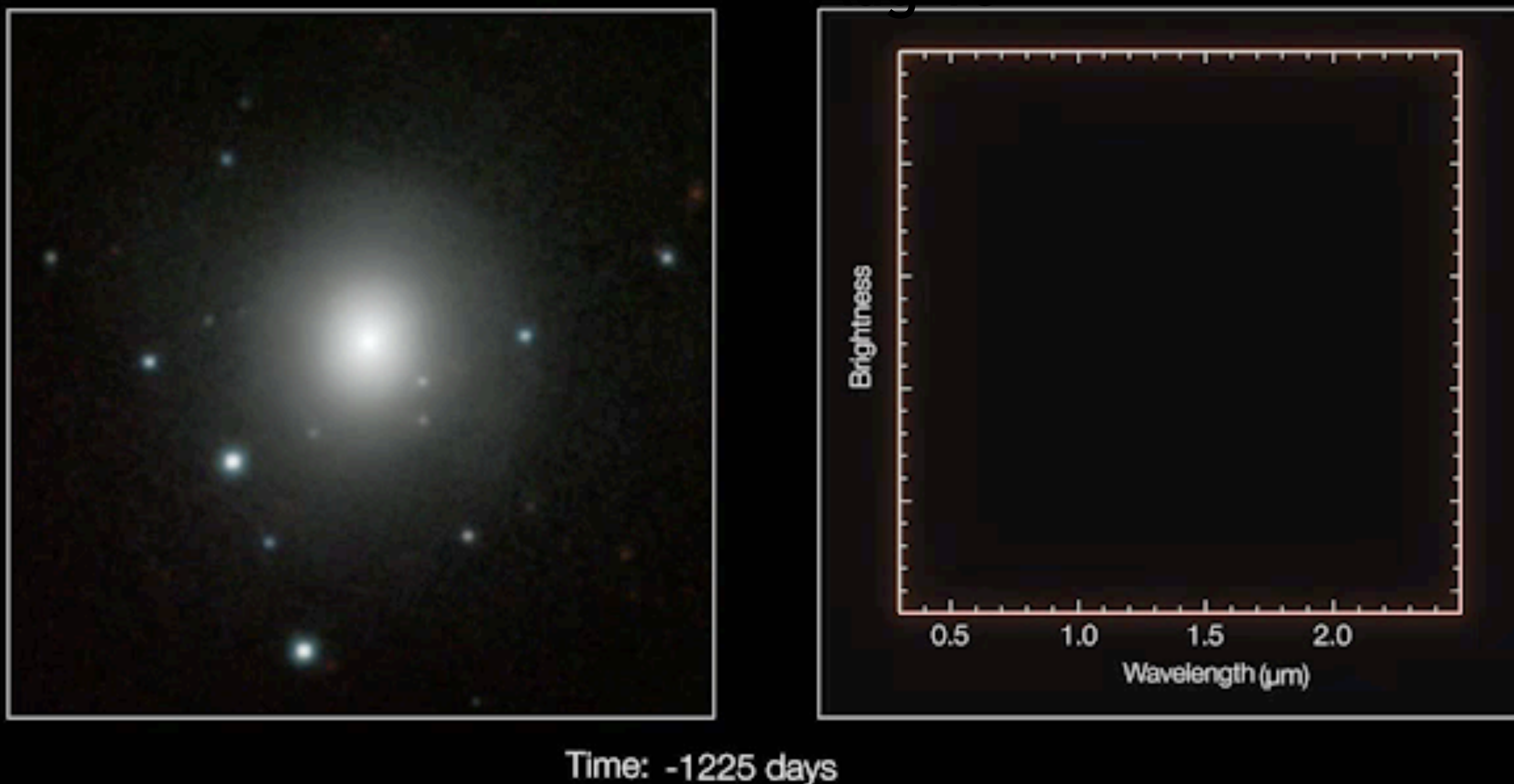


Independent searches were also carried out by the Rapid Eye Mount (REM-GRAWITA, optical, 02:00 UTC; Melandri et al. 2017a), *Swift* UVOT/XRT (ultraviolet, 07:24 UTC; Evans et al. 2017a), and Gemini-South (infrared, 08:00 UT; Singer et al. 2017a).

MMO Paper Abbott et al. 2017

Optical/NIR Spectra

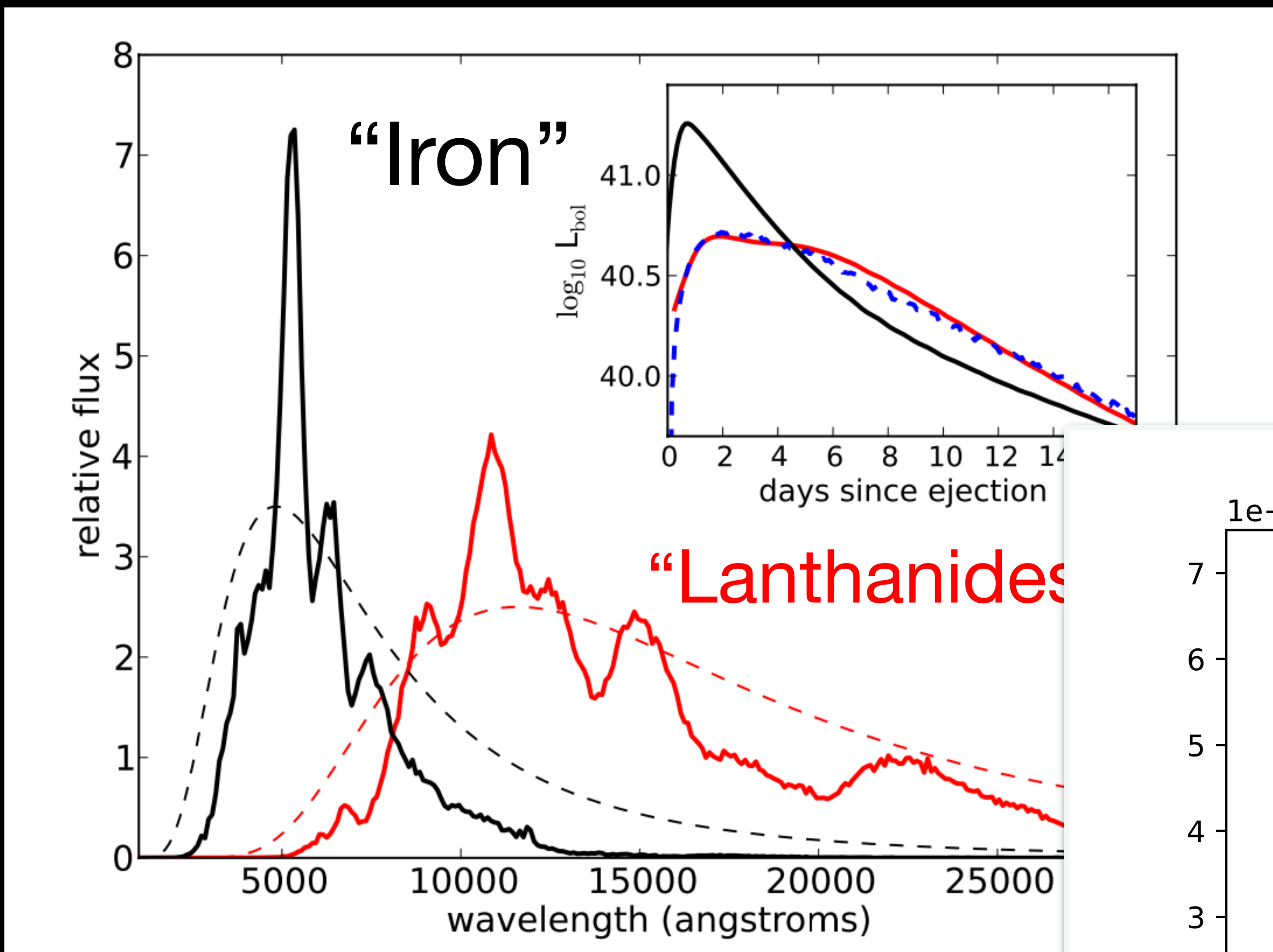
16 days of X-Shooter observations



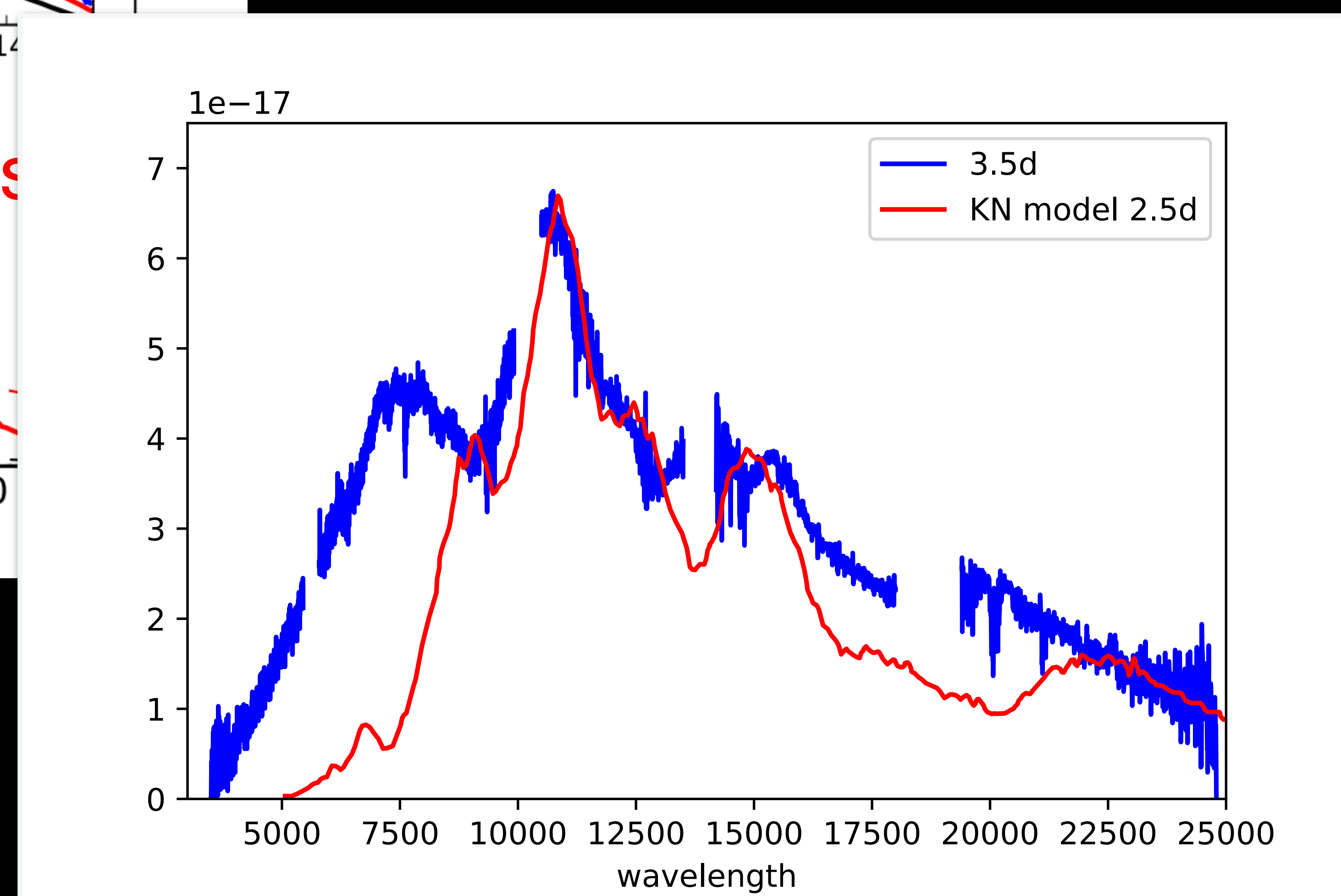
ESO/E. Pian/S. Smartt & ePESSTO/N. Tanvir/VIN-ROUGE

Nucleosynthesis

Kasen et al. 2013



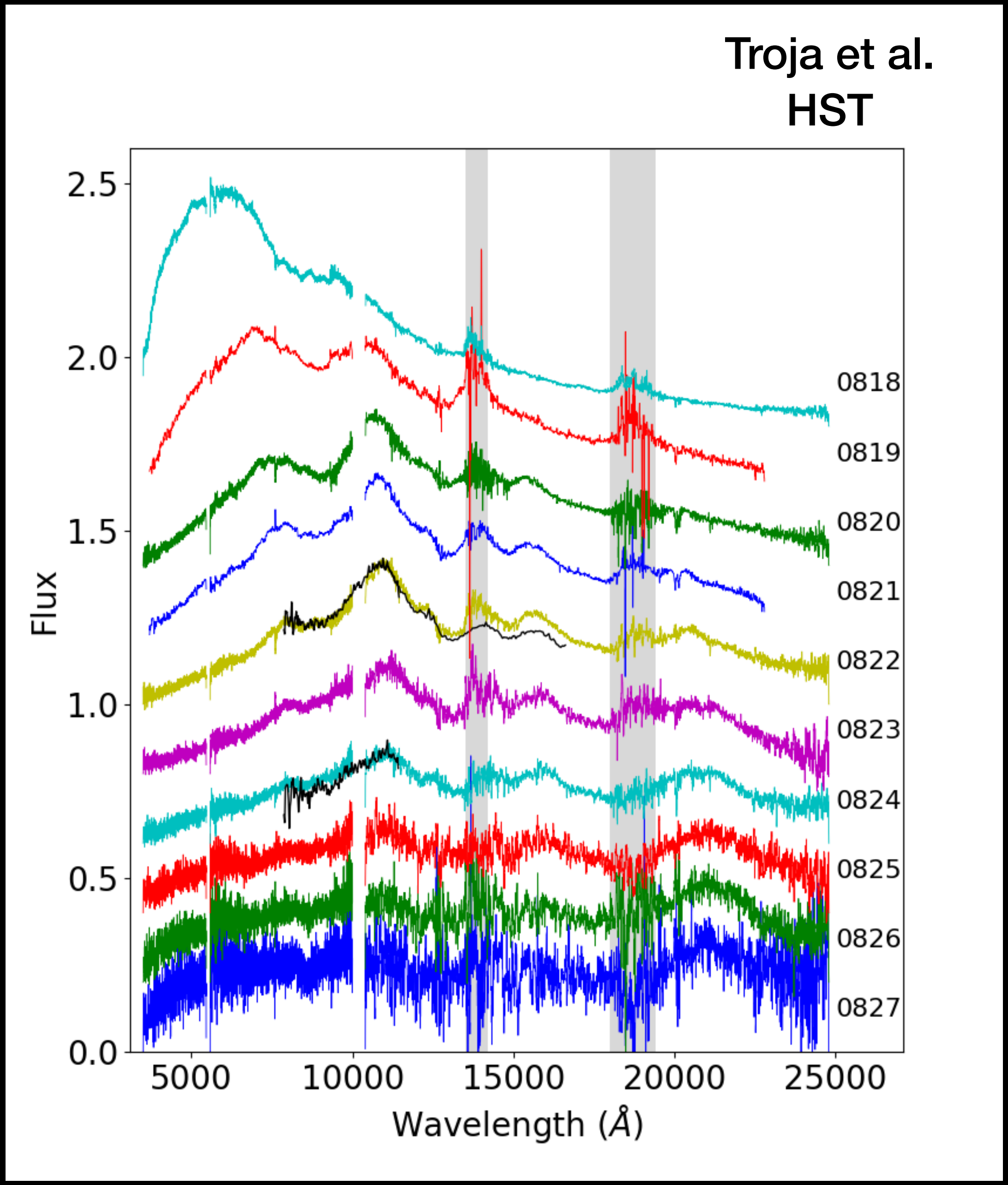
Kilonova models predict nucleosynthesis of r-process elements. Lanthanides dominate radiation transport because of high opacity

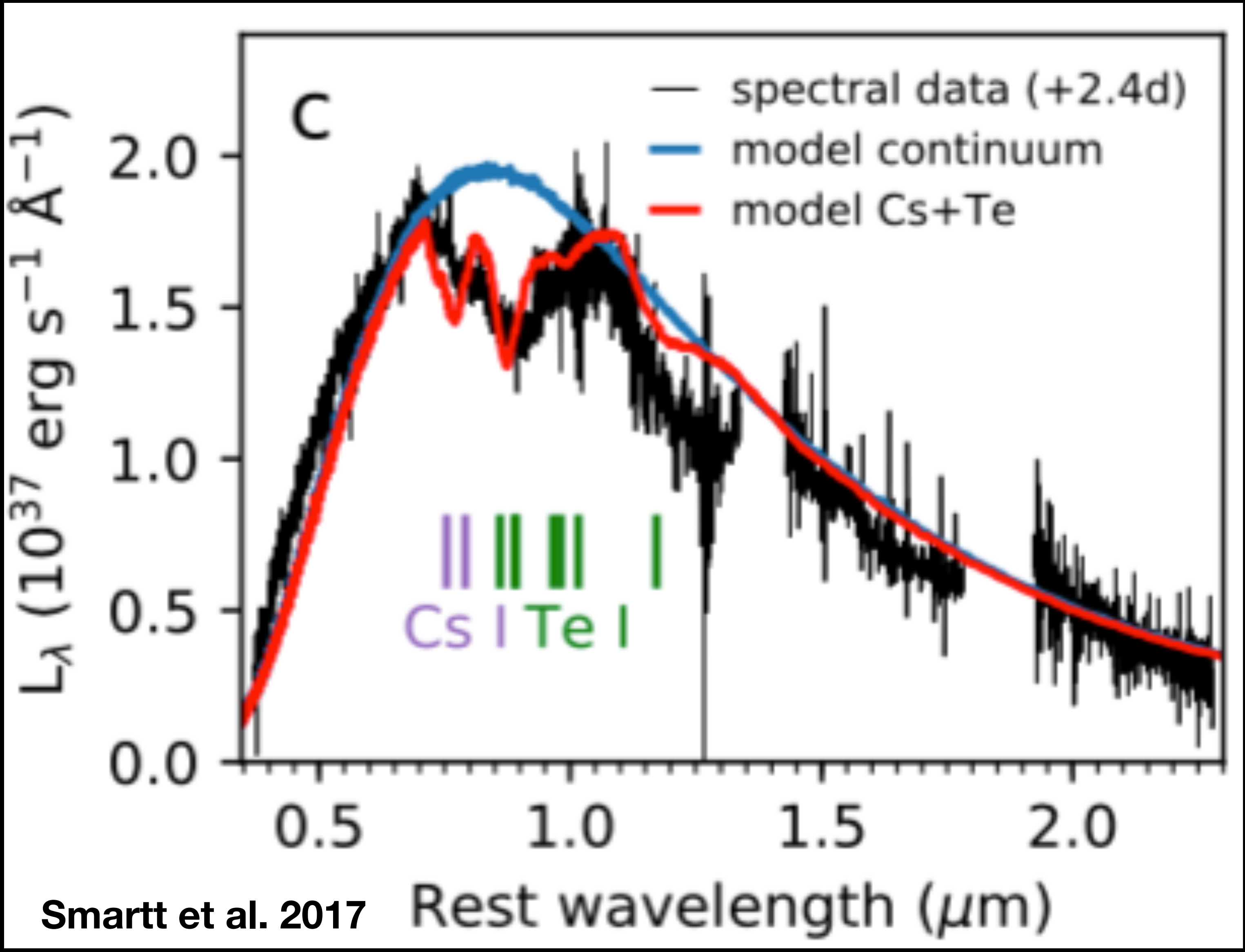


Observations at 3 days are in excellent agreement with lanthanide predictions. There seems to be a blue component

Optical/NIR Spectra

Pian, D'Avanzo et al. (2017) + Smartt et al. 2017



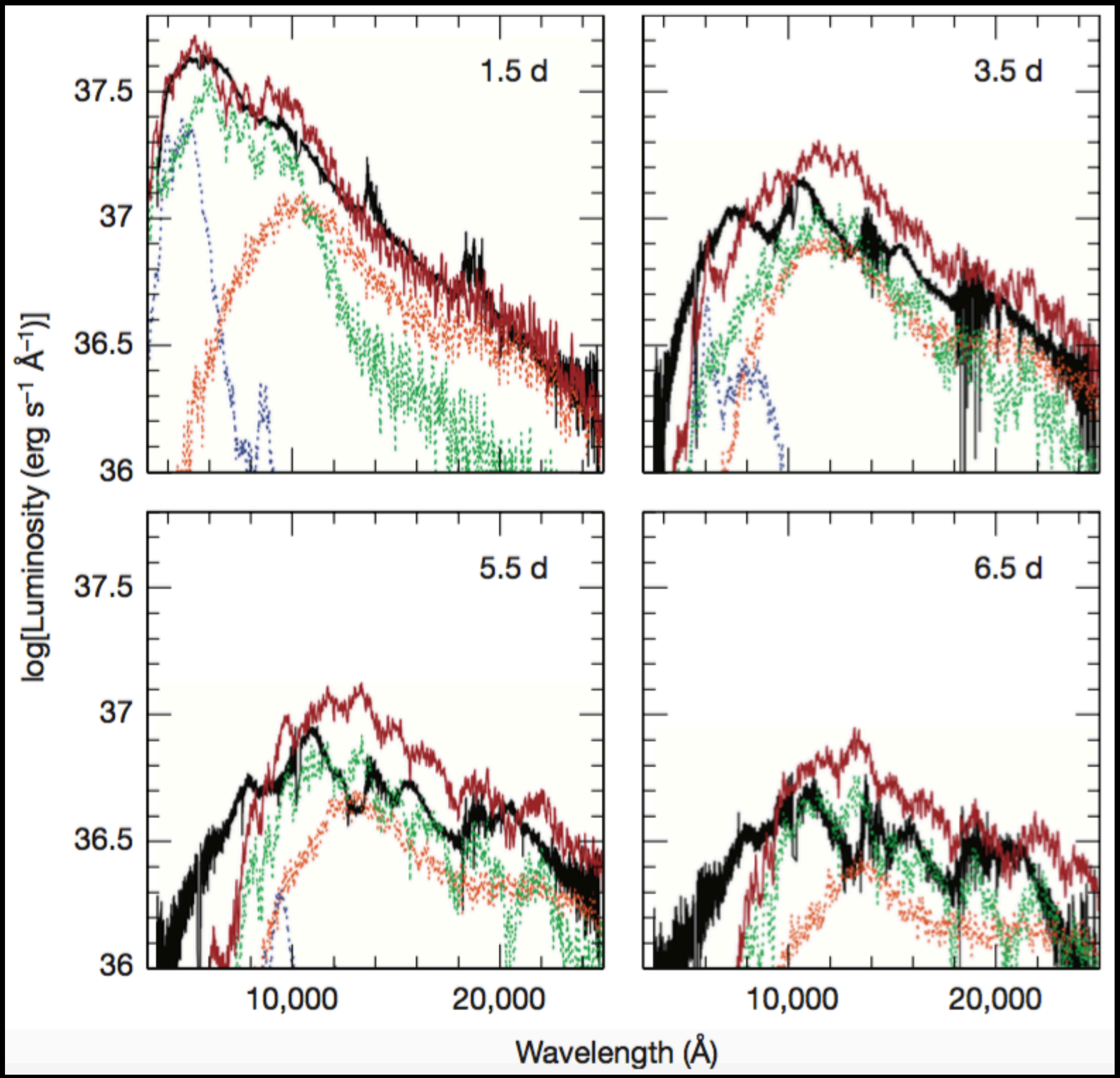


Smartt et al. 2017

Spectrum with TARDIS spectral model that includes Cs I and Te I consistent with the broad features observed

Optical/NIR spectra: evidences for KN

Tanaka model in Pian, D'Avanzo et al. (2017)

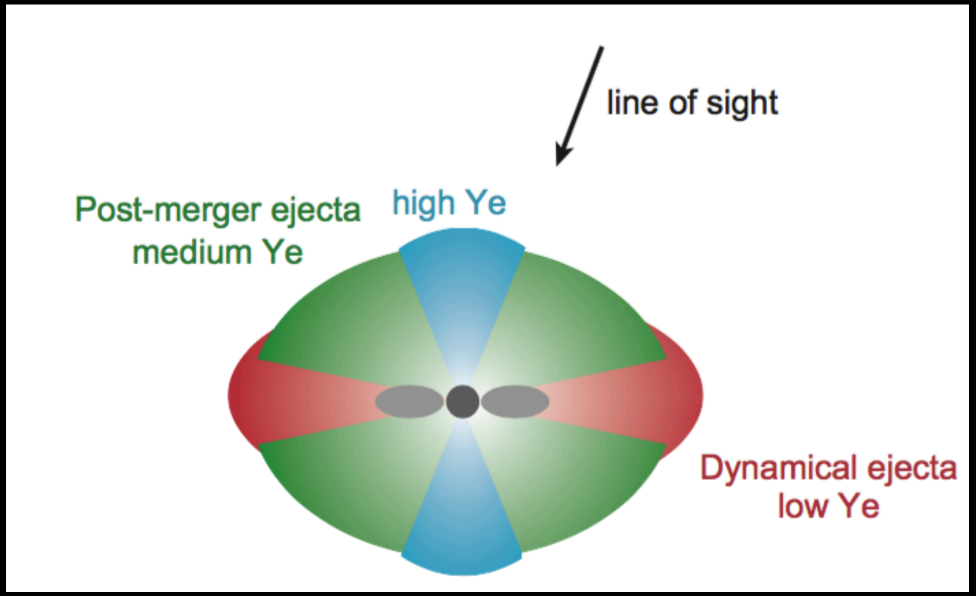


0.05c wind lanth.-free

0.05c wind lanth.-mixed

0.2c ejecta lanthanide-rich

Tanaka et al. (2017)



Three components Kilonova model with different velocity, composition and electron (proton) fraction (low Ye: lanthanide-rich; high Ye: lanthanide-poor)

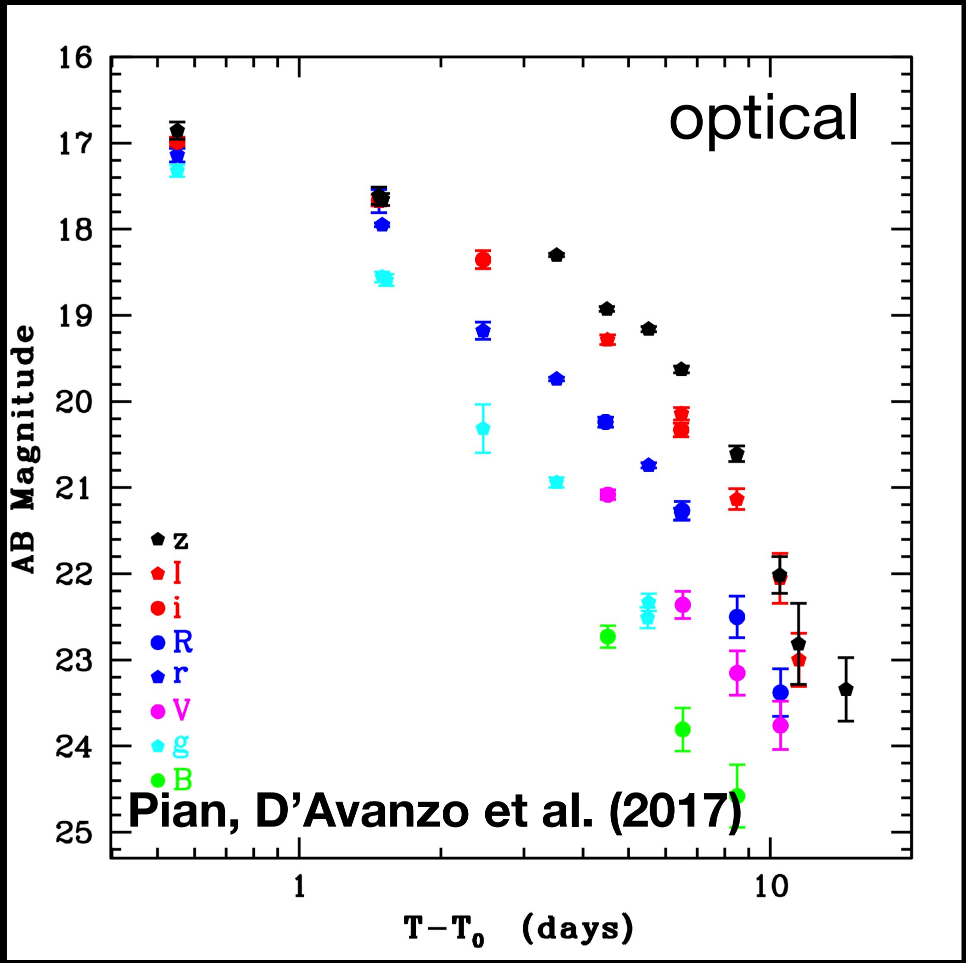
Their sum and rescaling (red) can reproduce the observed spectra (black)

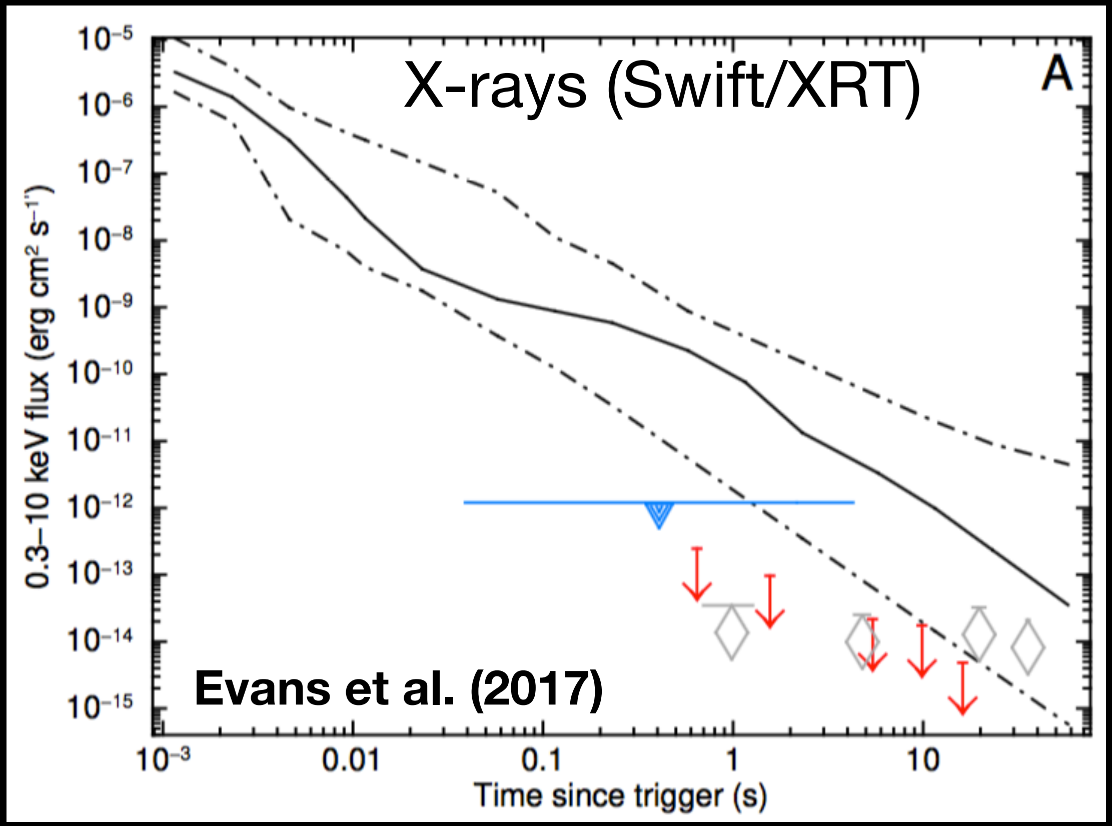
0.03-0.05 M_{Sun} ejected mass

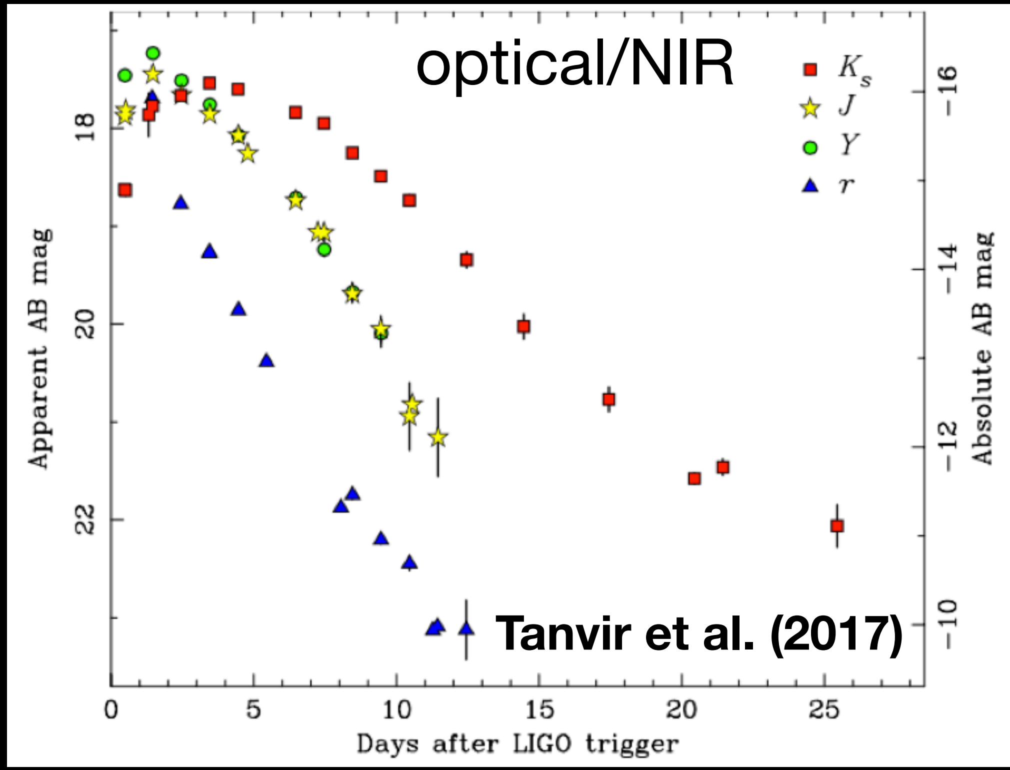
Fast moving dynamical ejecta (blue, 0.2c) + slower wind (red/green, 0.05c)

Best fit requires three components. However, models are not able to reproduce consistently all the observed spectral features.

Light curves





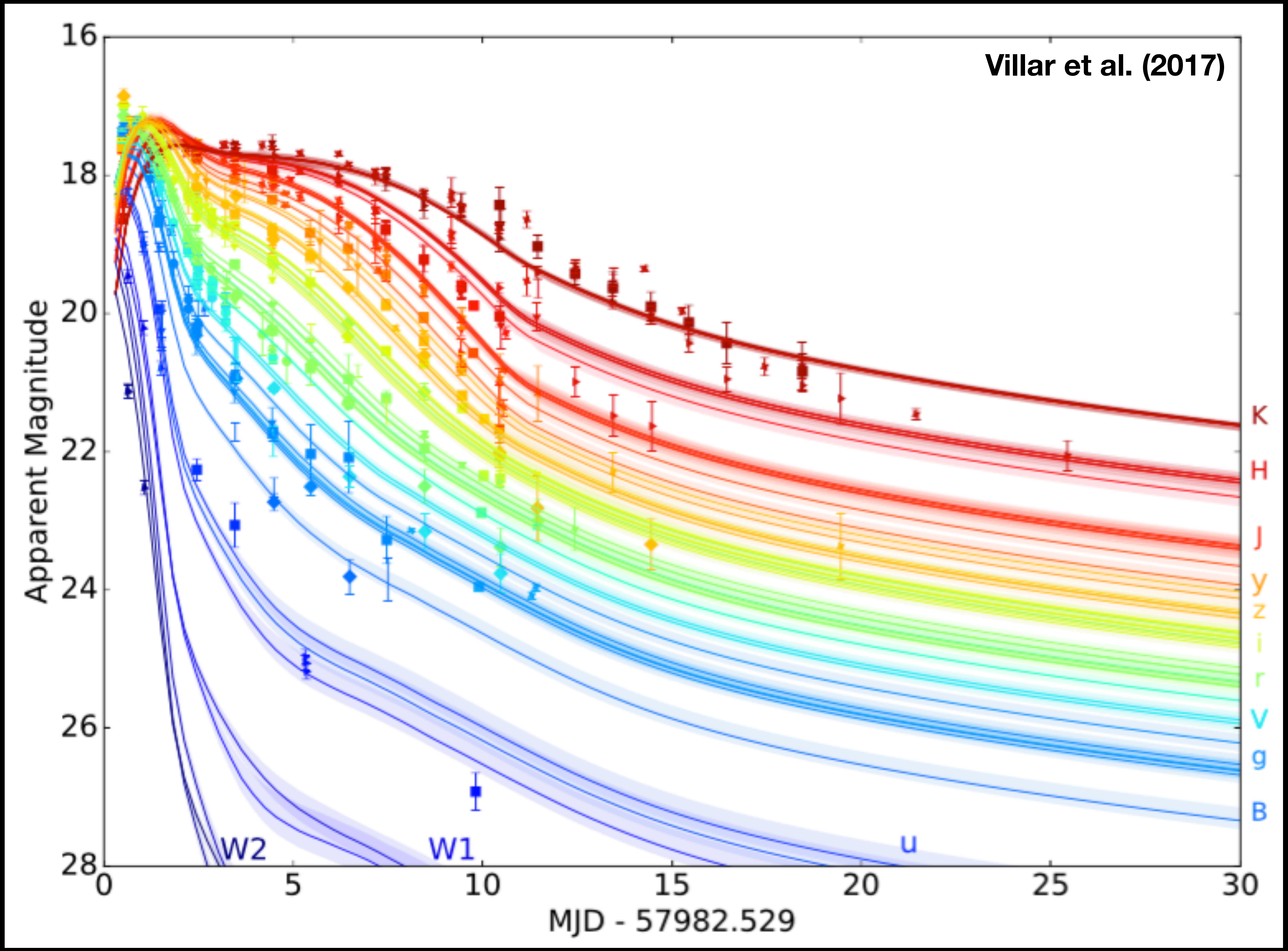


Bright UV/Opt/NIR source

Slower fading in the NIR

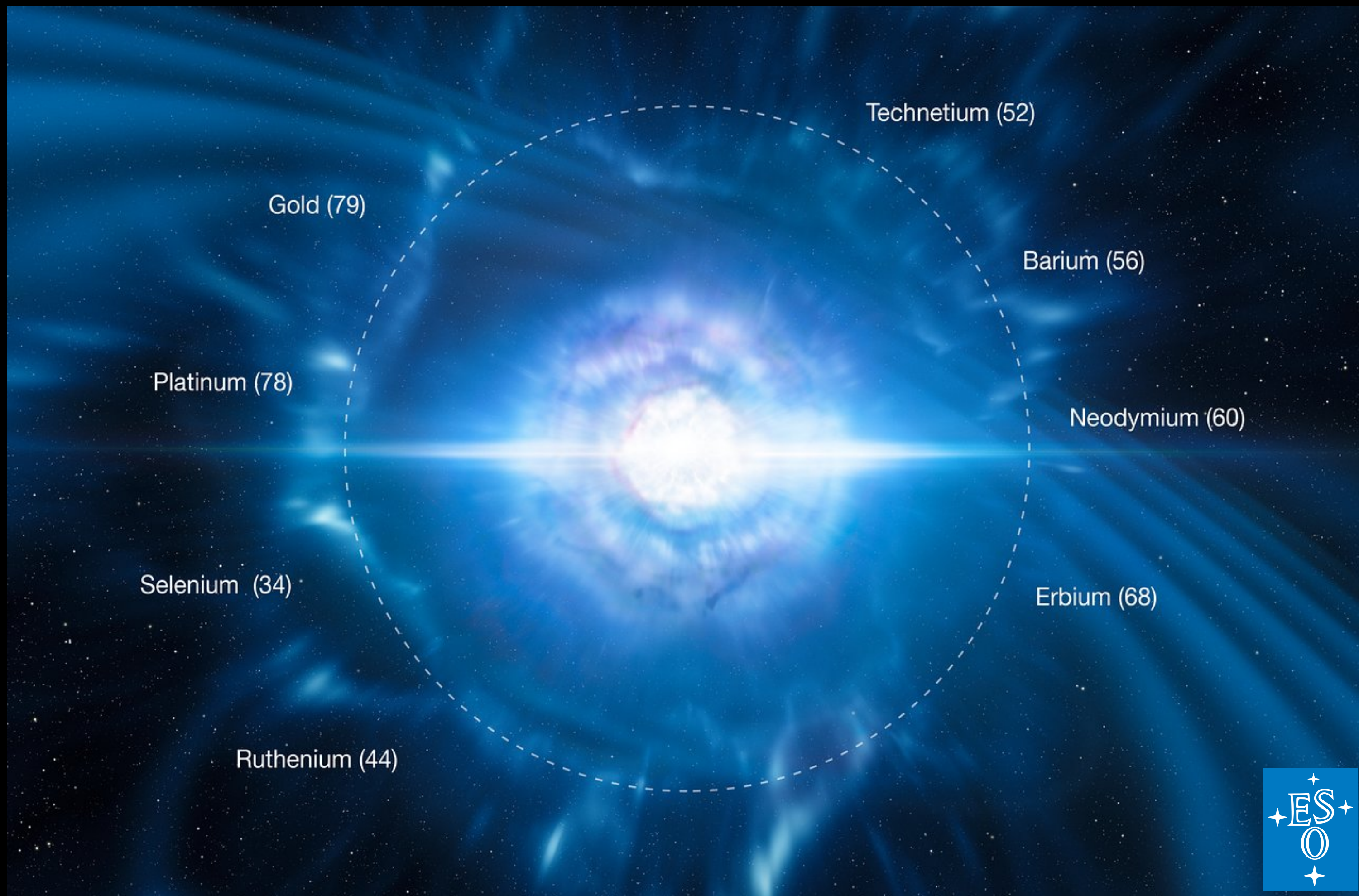
No early-time X-ray (and no radio) emission: inconsistent with on-axis GRB

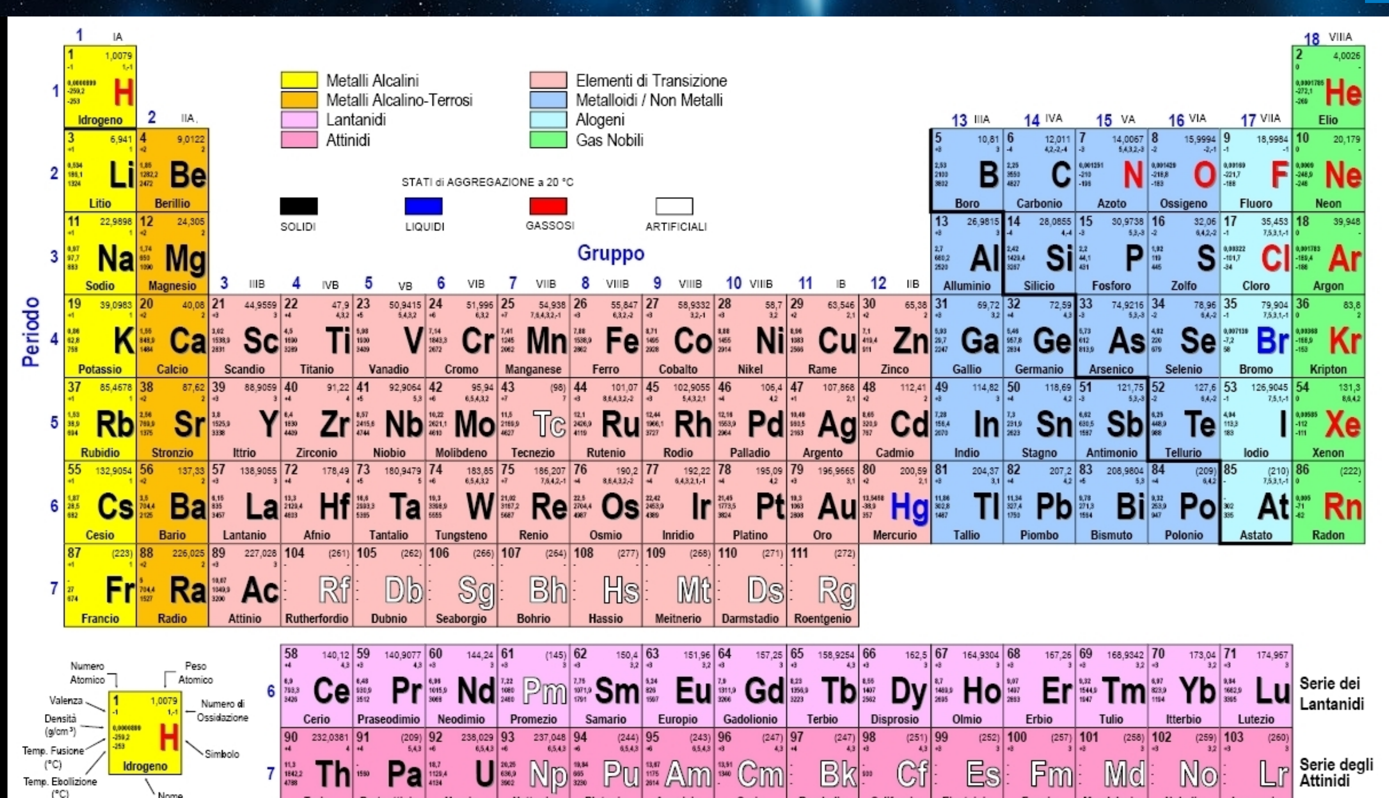
UV/Optical/NIR LCs: evidences for KN

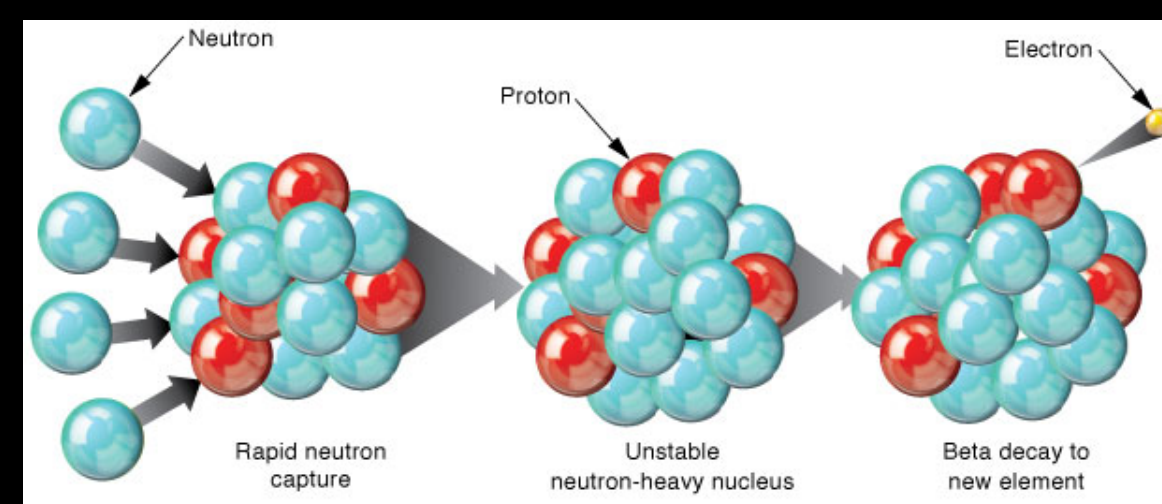


Multi-wavelength light curves best fitted with 3-component KN model

Kilonova: a heavy elements factory







GraWITA

GW170817-GRB170817

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Gamma-ray Observations

- Persistent emission limits for the 48 hr period
- Constraining upper limits on precursor and extended emission

UV, Optical and IR observations

Mapped the emission from the sub-rel ejecta

NEWS!: with HST the transient is visible in both optical filters, but not in the infrared. Mag are are consistent with the extrapolation from the 93 day radio epoch to the near contemporaneous observations with Chandra

X-Ray counterpart

- Earliest limits: MAXI GSC, no localization
  First Pointed X-ray observations of GW170817
- Swift - T0 0.6+2 days and NuStar T0 0.7 + days
  No X-ray emission was detected

Swift continued to monitor and stacked several epochs of observations

- X-Ray source near the location of GW170817
  2.6x10^-14 erg cm-2 s-1
  INTEGRAL - JEM -X 1-6 days after
  CHANDRA - Tc+2 non detection+extended emission
  Tc+9 days 50ks exposure — X-ray counterpart
  Tc+ 15 - still there!

NEWS!: tc + 108-111 - still there!

Radio counterpart

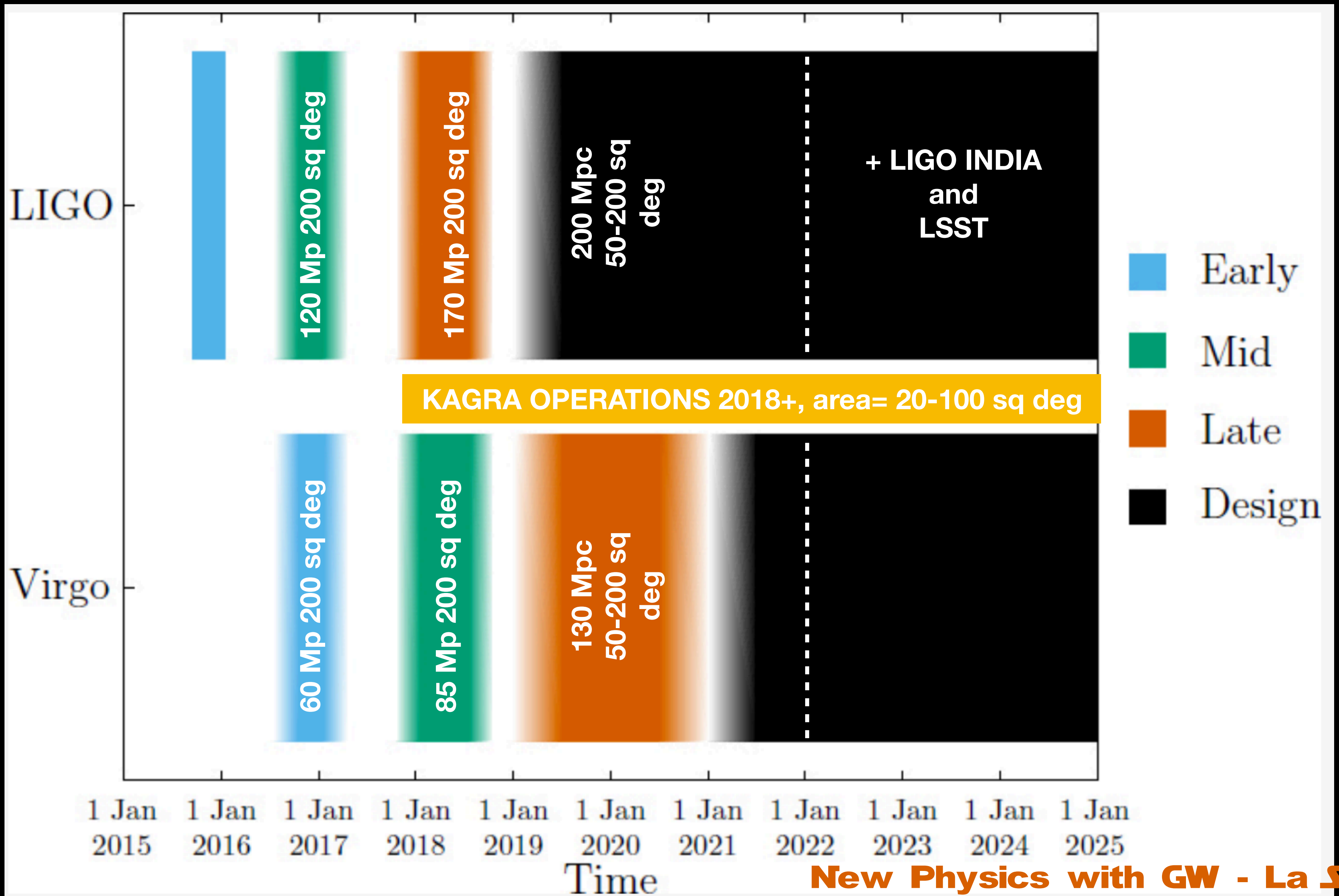
- ATCA: blind survey
  2017 Aug 18 at 01:46 UTC
- LWA: tc + 6.5 hr then Aug 23 and 30
  Four beams (one centered on NGC4993 one off center and two off NCG 4993
- 3sigma upper limits
- NGC4993, about 8 hours after the GW event as 200 Jy at 25MHz and 100 Jy at 45MHz
- First detection: Aug 18 at 02:09:00 (T0 + 13.5hr)

NEWS! from tc+16 to tc+93 increases its energy by a factor of ~10

WHAT'S NEXT? O3 and beyond

Prospects of Observing and Localizing GWs

Target sensitivity i-band magnitude	20.4	21.2	21.5
Number of NS-NS mergers (yr^{-1})	0.01-20	0.04-100	0.2–200



ADAPTED from Abbott et al (LRR, 2016)

Summary

- First NS-NS GW event

- First EM counterpart (at all wavelengths)

- **First unambiguous observational evidence for a kilonova**

- **Evidence for KN as a heavy elements factory (r-process nucleosynthesis)**

- `Smoking gun' for short GRB progenitors

- Evidence for off-beam GRB or not?

-Characterisation of the **transient Universe**
new transients, FRBs, novae, orphan GRBs, SNe

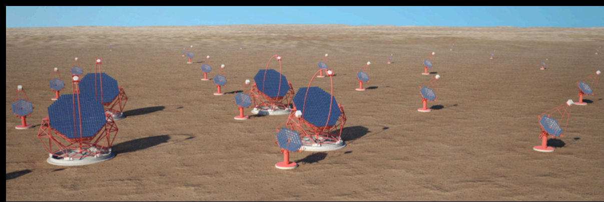
- preparatory studies for LSST and future facilities at all wavelengths

- more than 100 papers in two months

- the dawn of multi-messenger astronomy era **(this is just the beginning!)**

.....waiting for O3 LVC run all together!

We are only at the dawn of the multi-messenger era!

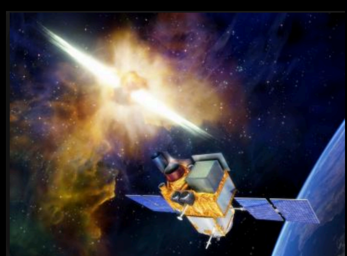


CTA 2021

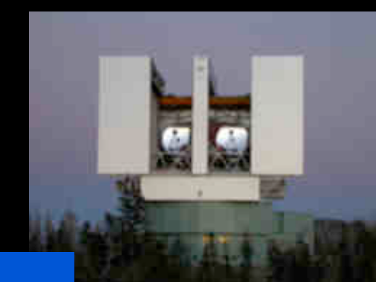
ESA M5

Athena - 2028

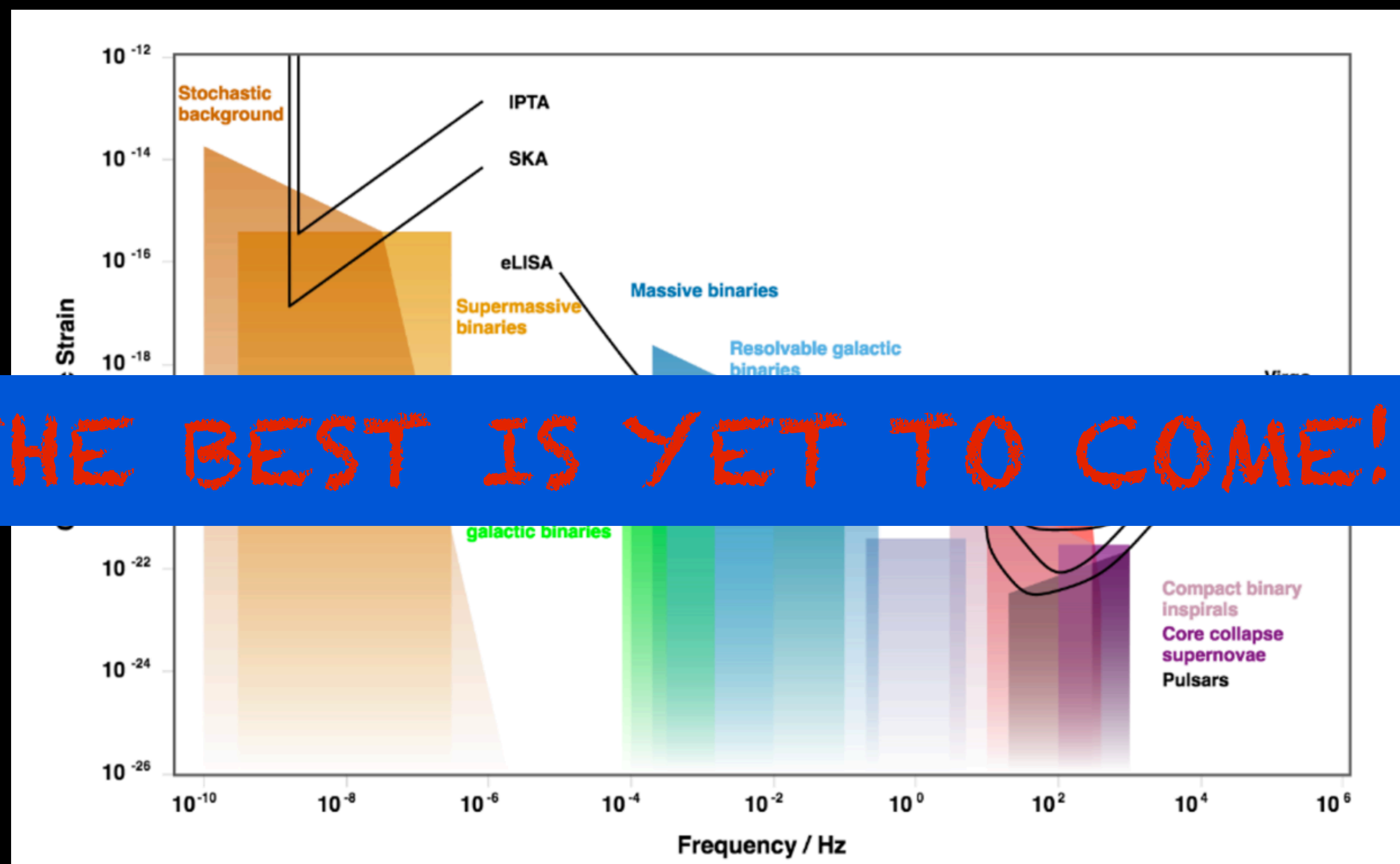
VLT - 1998-2000



SVOM 2021



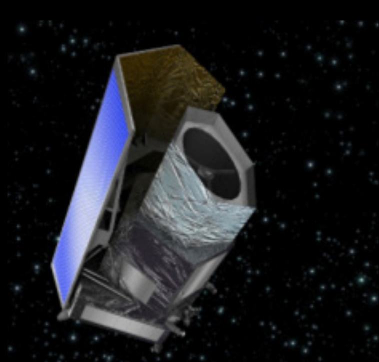
LBT



THE BEST IS YET TO COME!!!

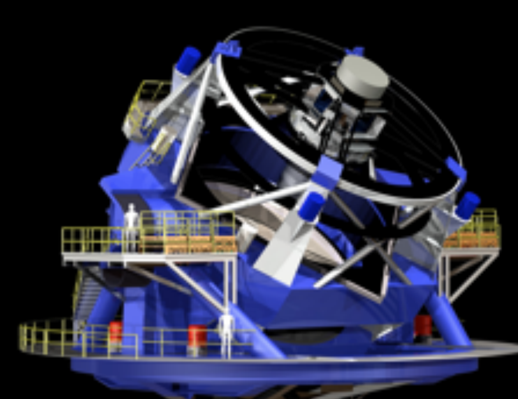
SKA 2025

EELT - 2024



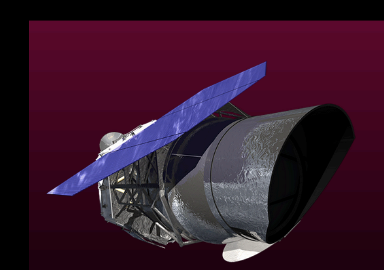
EUCLID - 2020

ALMA - 2013



LSST - 2023

JWST - 2018



WFIRST - 2020

THANKS!

Corso Astrofisica delle Alte Energie

Luigi Stella

- Fondamenti

  Meccanismi di emissione e trasporto radiativo
  Stelle compatte: nane bianche,
  stelle di neutroni,
  buchi neri
  Massa critica, collasso gravitazionale, supernovae
  Fisica dell'accrescimento
  Emissione da Gamma-ray burst and Kilonova