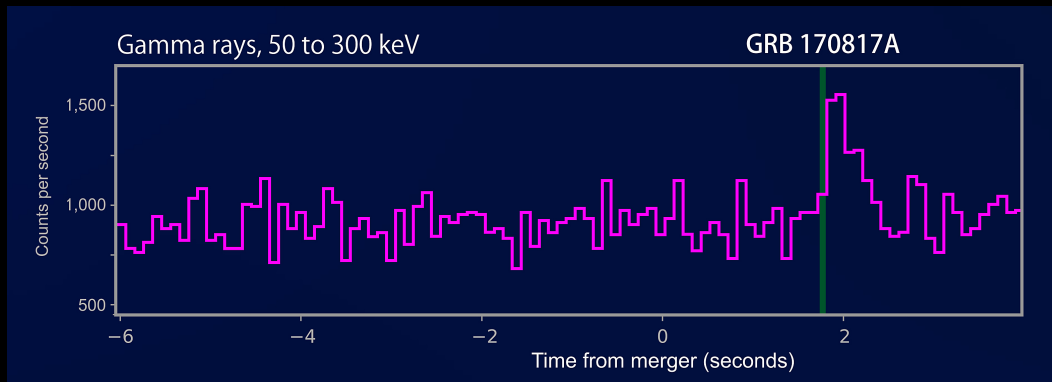
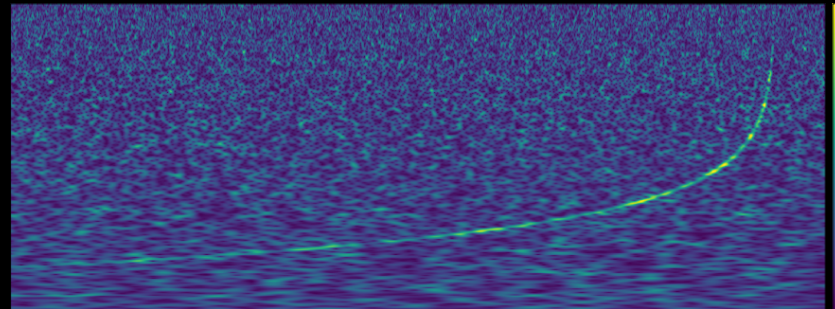


# Gamma-ray bursts and gravitational waves

Frédéric Daigne (Institut d'Astrophysique de Paris; UPMC)



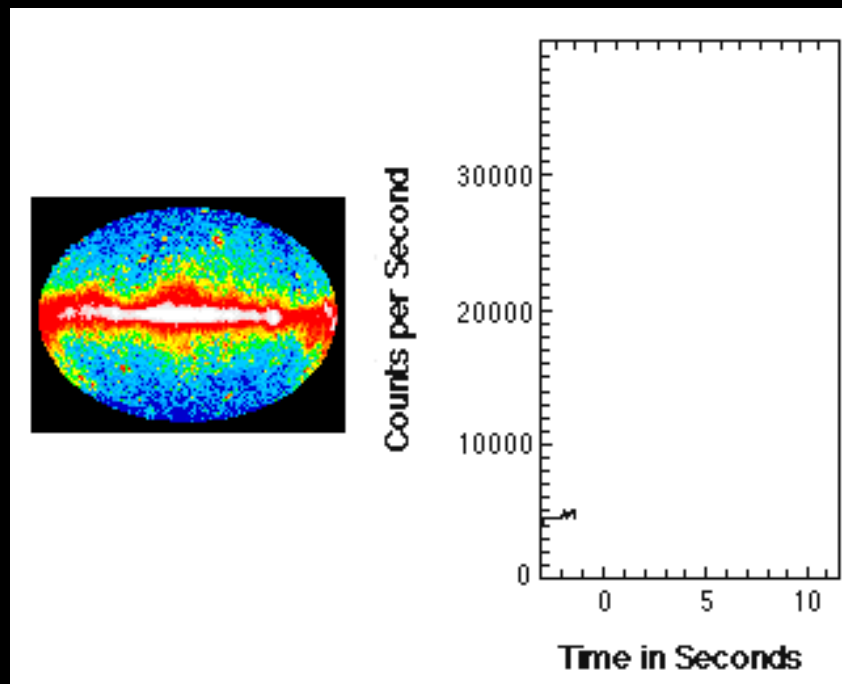
SSS17a



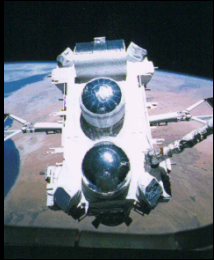
---

# Gamma-ray bursts: observations and theory

---

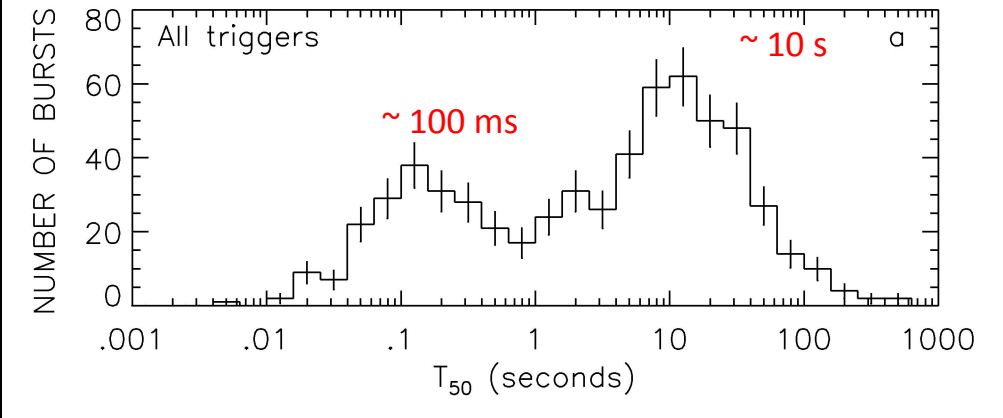


# Gamma-ray bursts: prompt emission

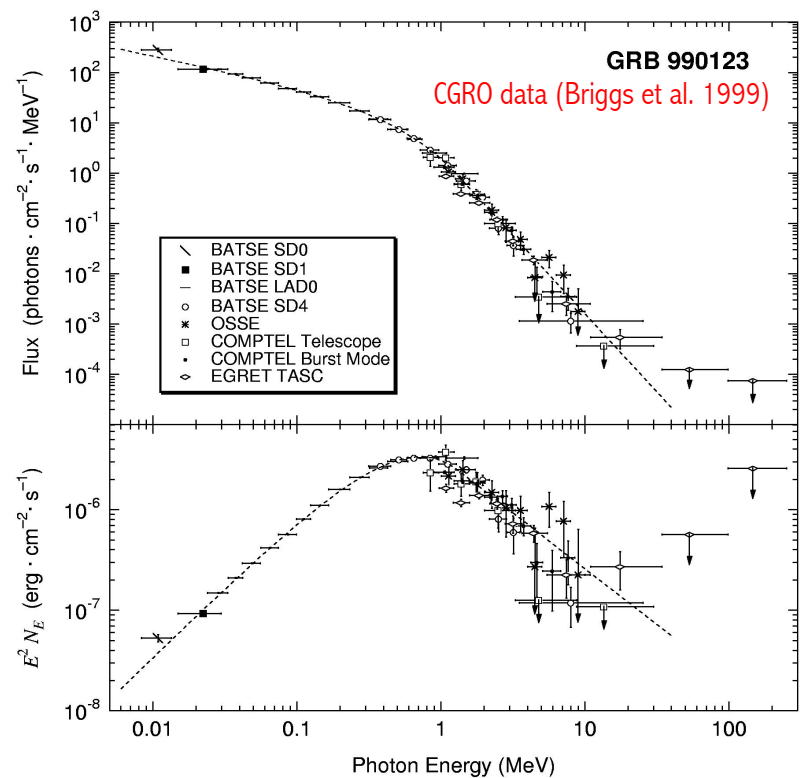
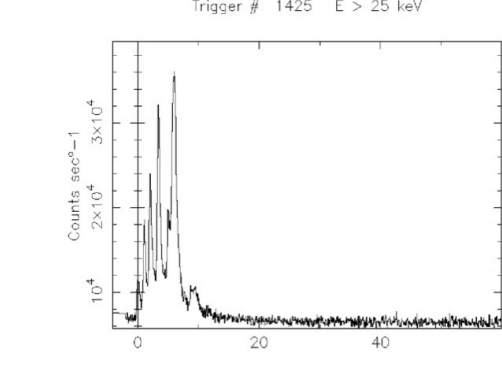
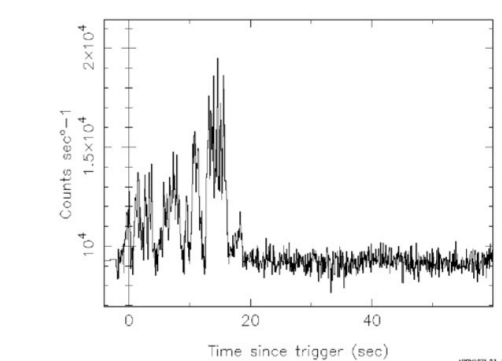
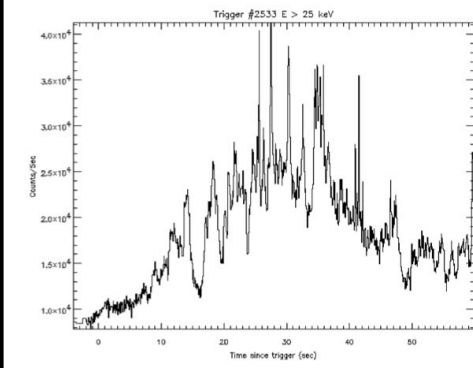
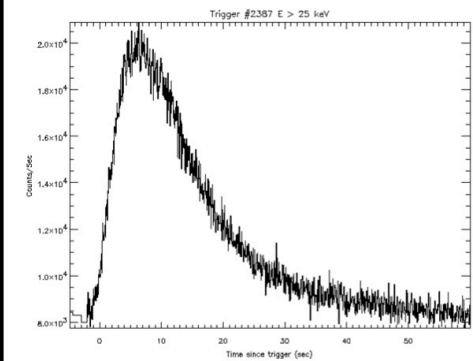


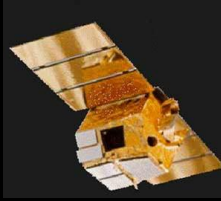
CGRO/BATSE

- Apparent rate:  
~ 1 GRB / day
- Duration:  
two groups
- Lightcurves : variability & diversity



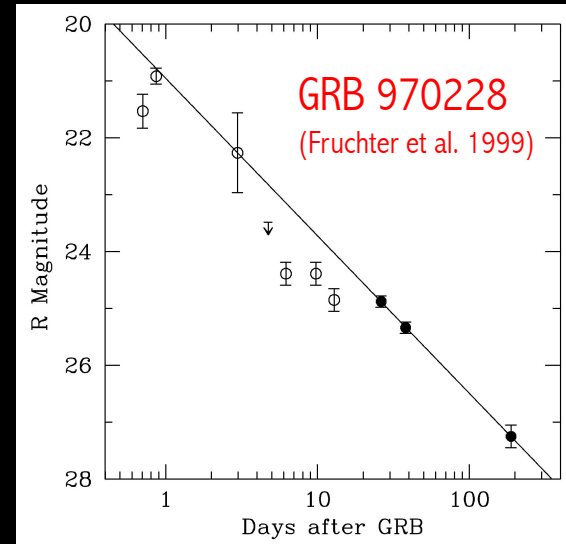
- Spectrum: non-thermal



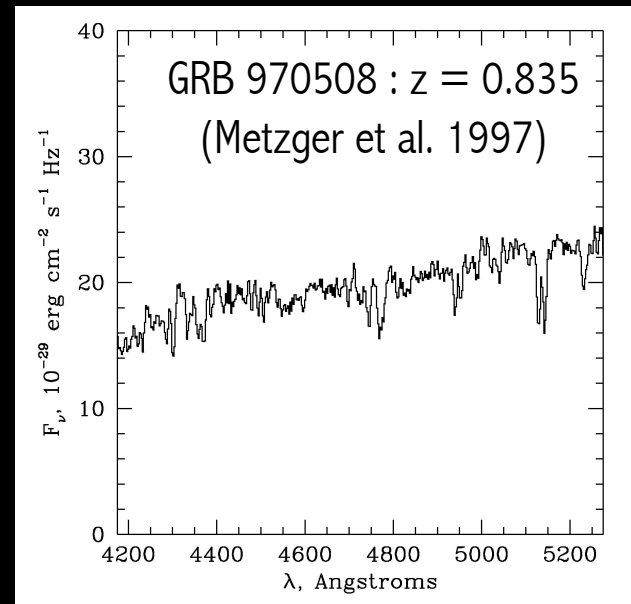


# Gamma-ray bursts: afterglow

- Discovery: 1997 (X-rays: Beppo-SAX ; V: van Paradijs et al. 1997)
- Flux: power-law decay
- Non-thermal spectrum
- Spectral evolution: X-rays  $\rightarrow$  V  $\rightarrow$  radio

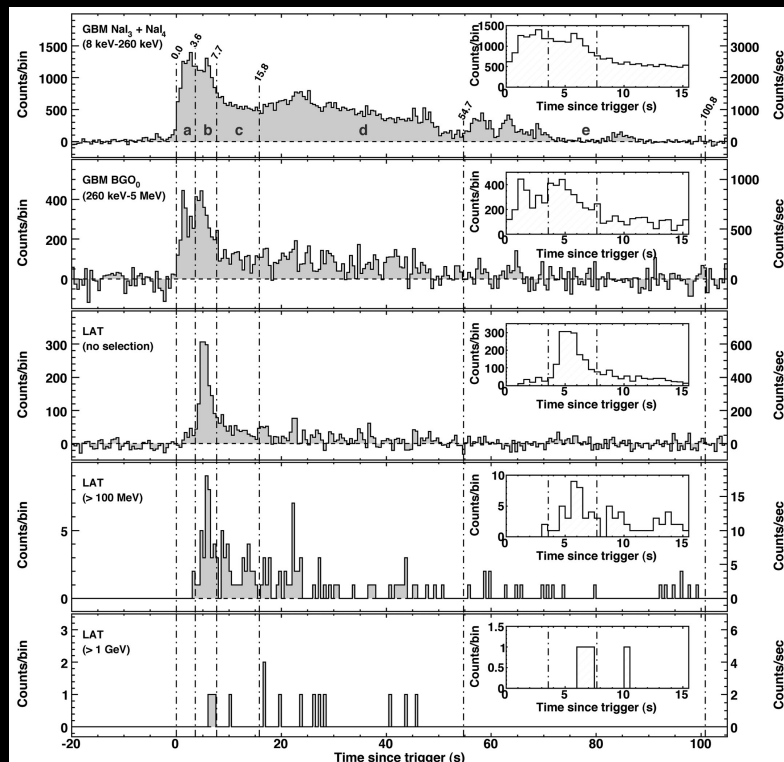


- Follow-up: redshift & host galaxy
- High redshift ( $z_{\text{max,obs}} > 9$ ): huge luminosities!  
 $E_{\text{iso},\gamma} \sim 10^{51} - 10^{54} \text{ erg}$

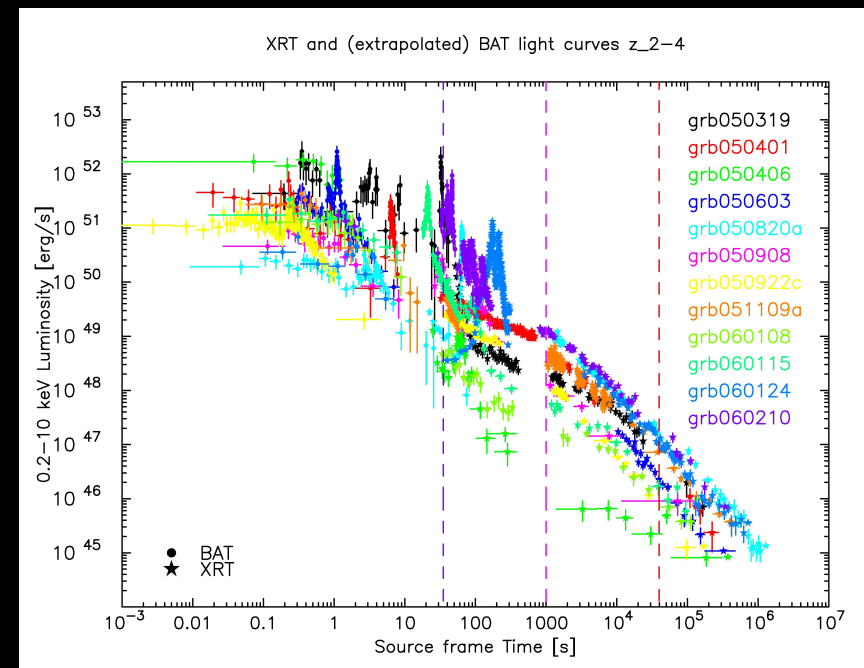




# Swift & Fermi

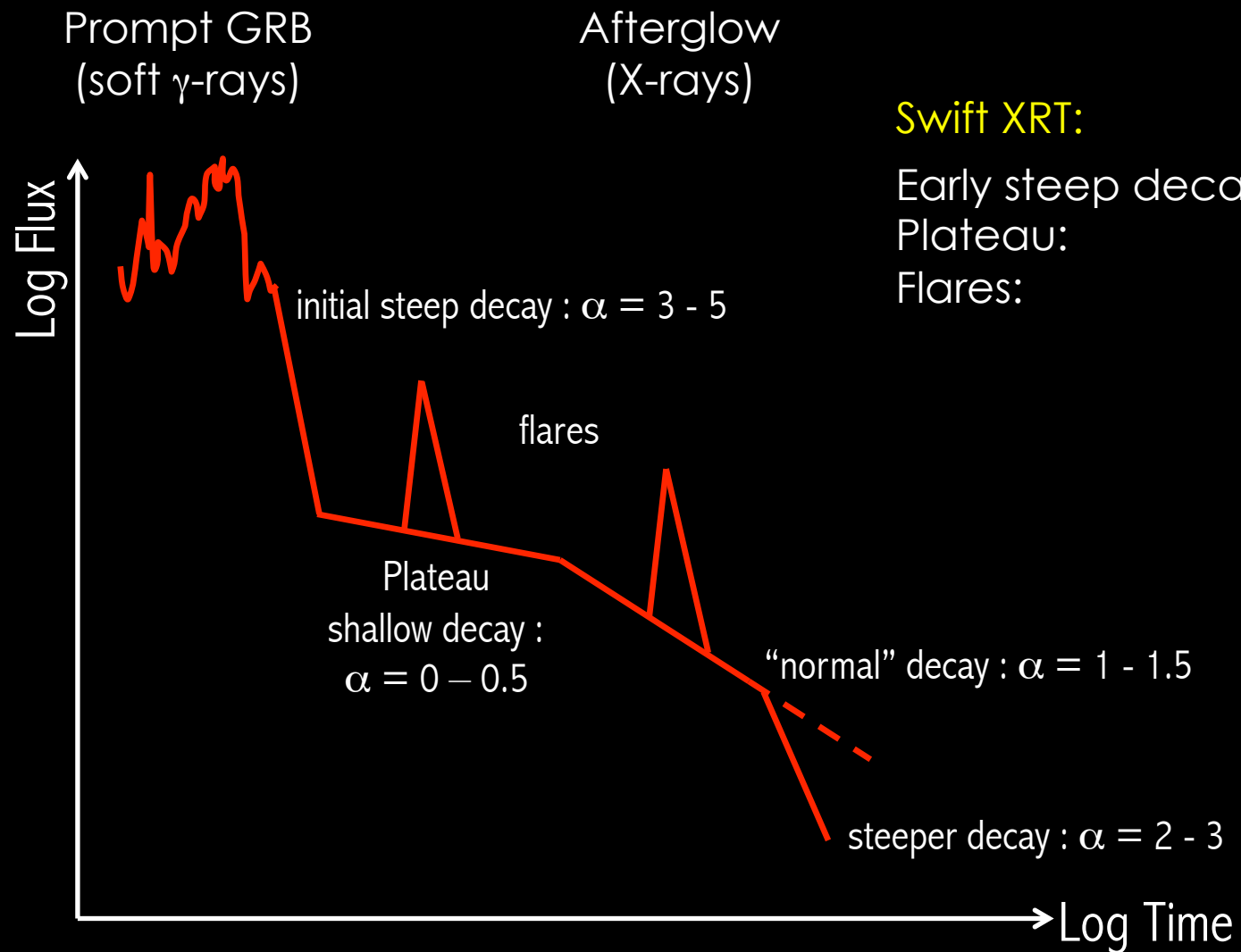


Prompt emission keV  $\rightarrow$  GeV (Fermi)



X-ray afterglow (Swift)

# Observed emission: light curve



Also: prompt  
optical, GeV

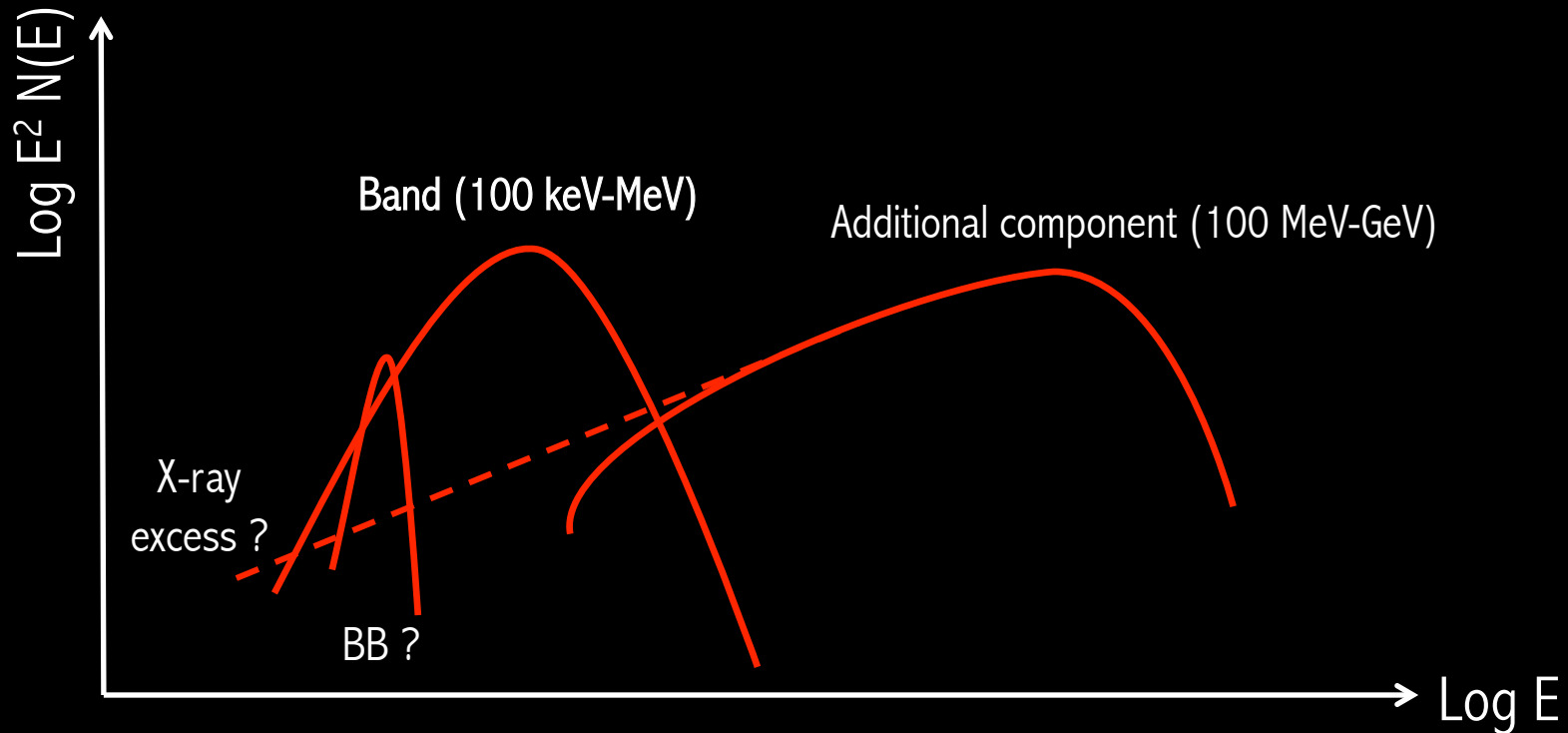
Also: optical, radio afterglow  
long-lasting Fermi/LAT  
emission

# Observed emission: $\gamma$ -ray spectrum

Fermi/GBM:

BB looked for in bright cases  
& found in many cases

Fermi/LAT: 1st catalog  
extra-component in 4/28

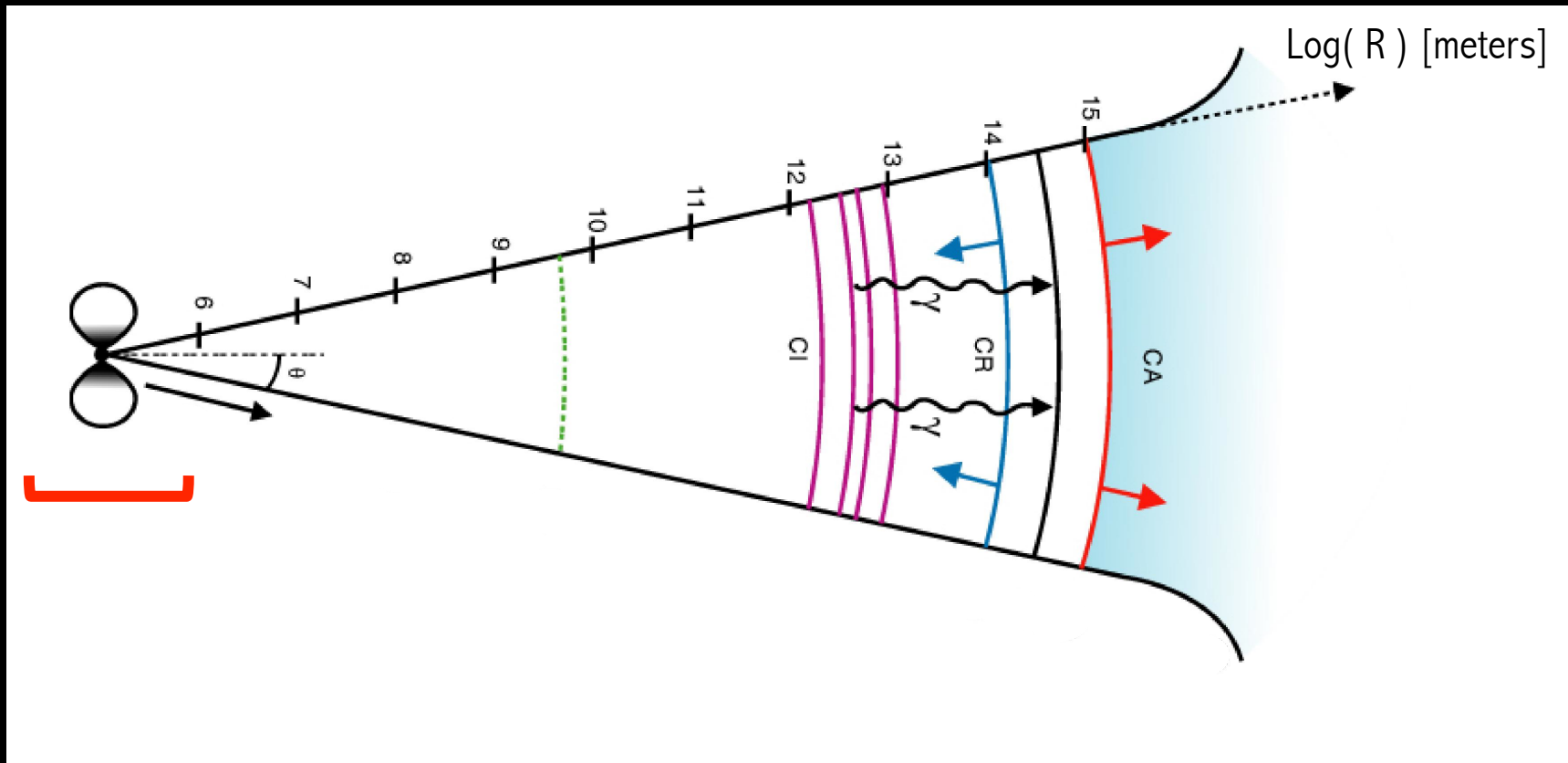


# GRB Physics

- Cosmological distance: huge radiated energy ( $E_{\text{iso},\gamma} \sim 10^{50}\text{-}10^{55}$  erg)
- Variability + energetics: violent formation of a stellar mass BH

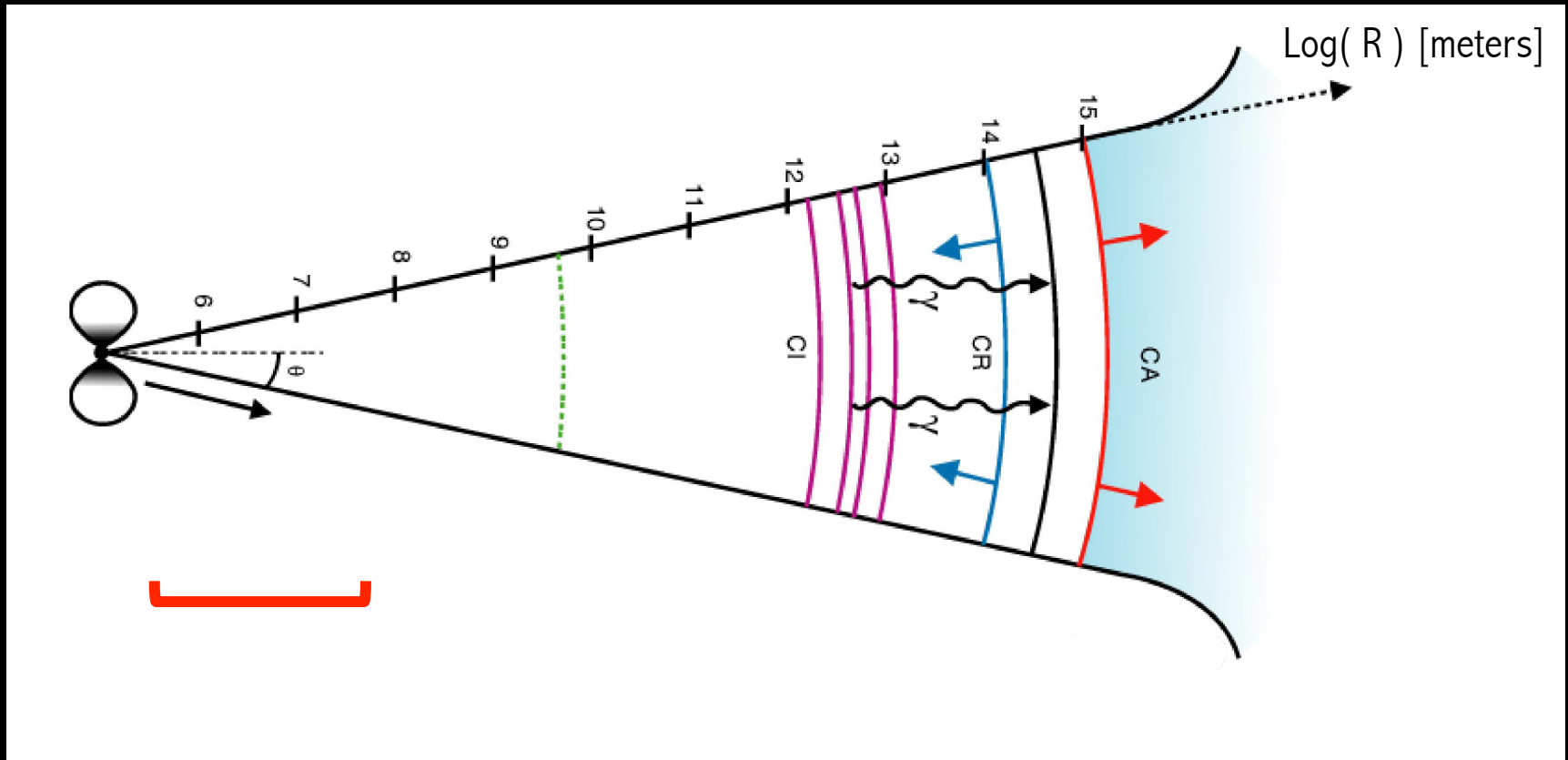
Long GRBs: collapse of a massive star

Short GRBs: NS+NS/BH merger? (link with GW)



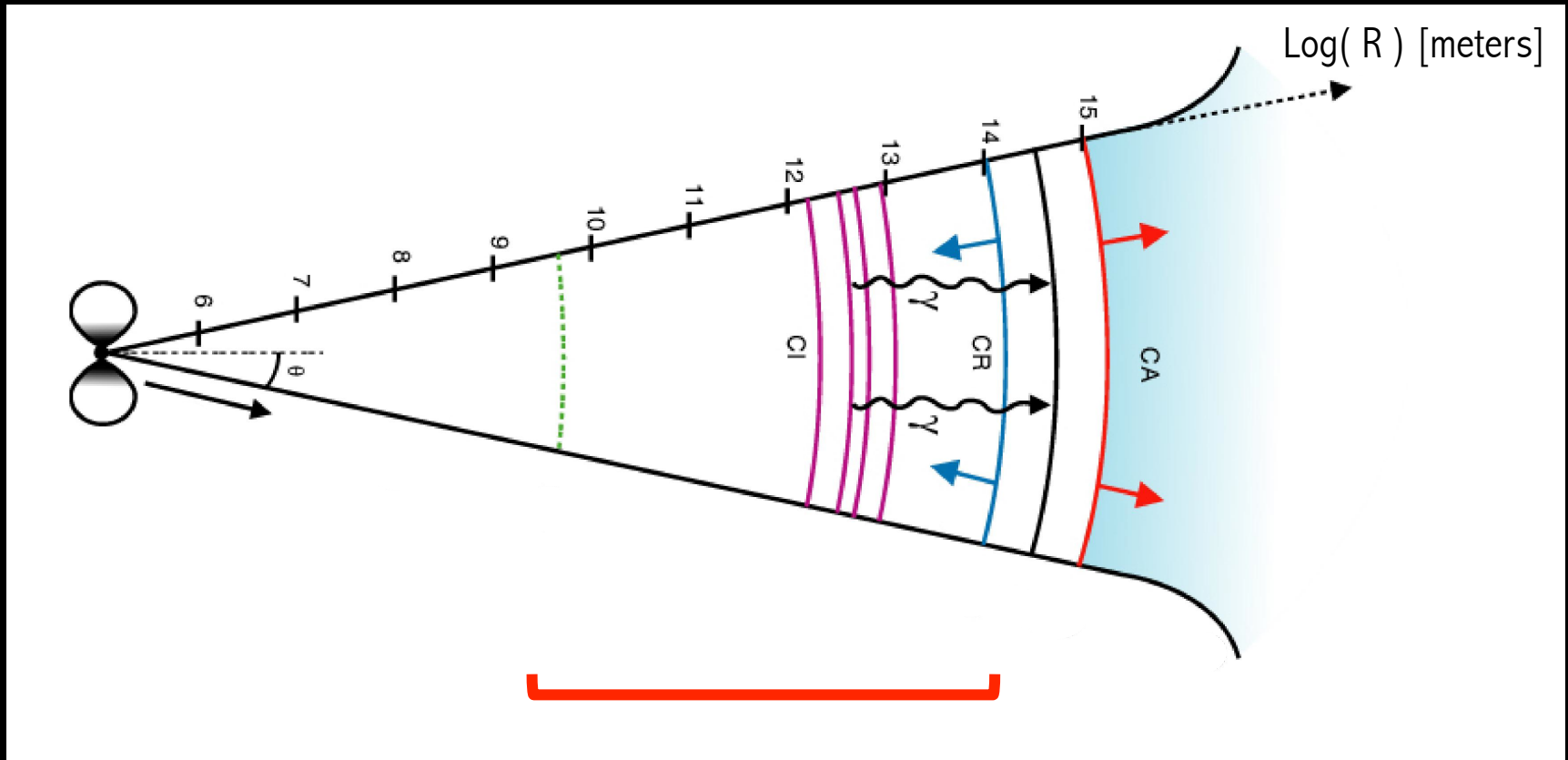
# GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection



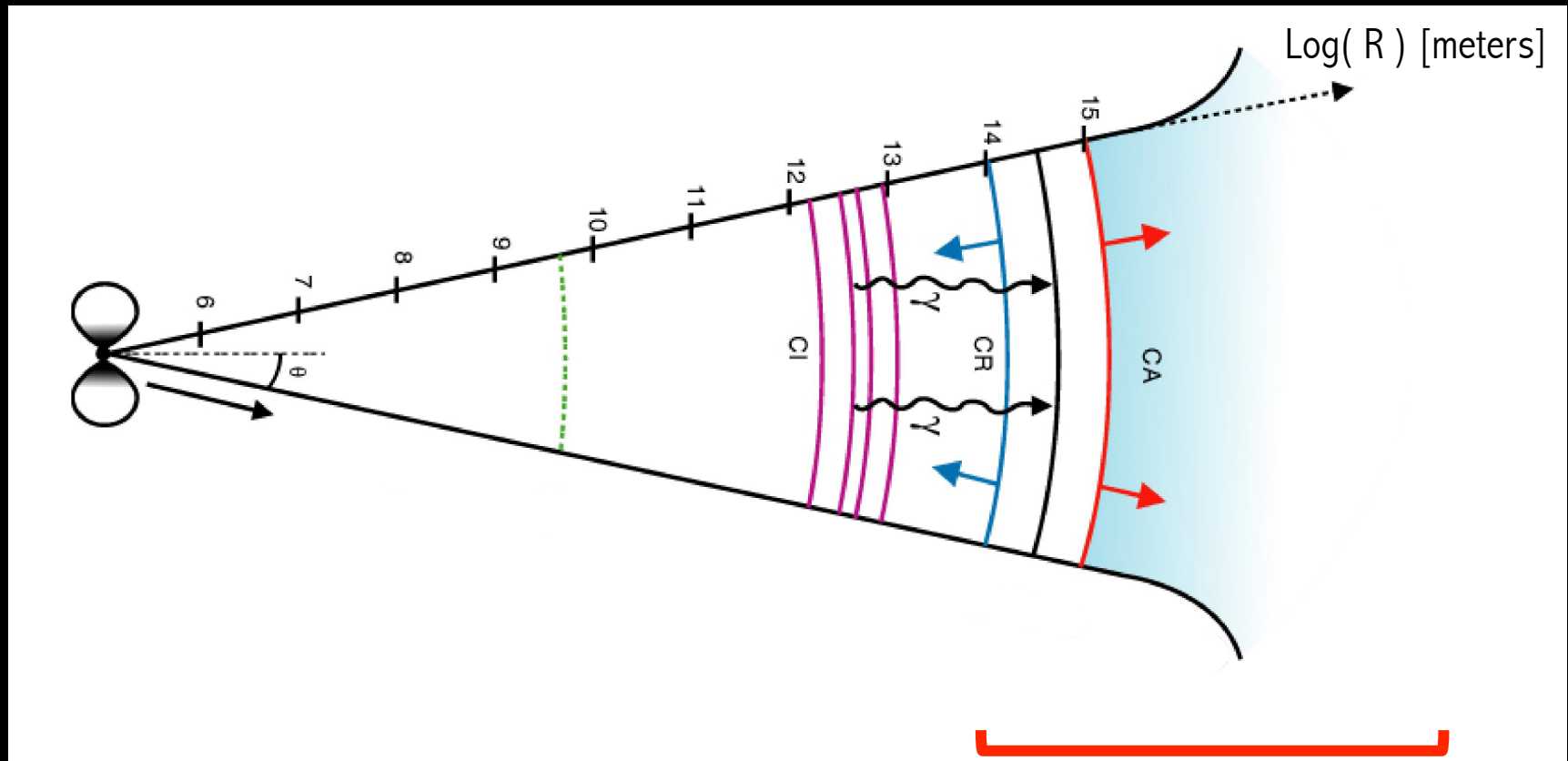
# GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta



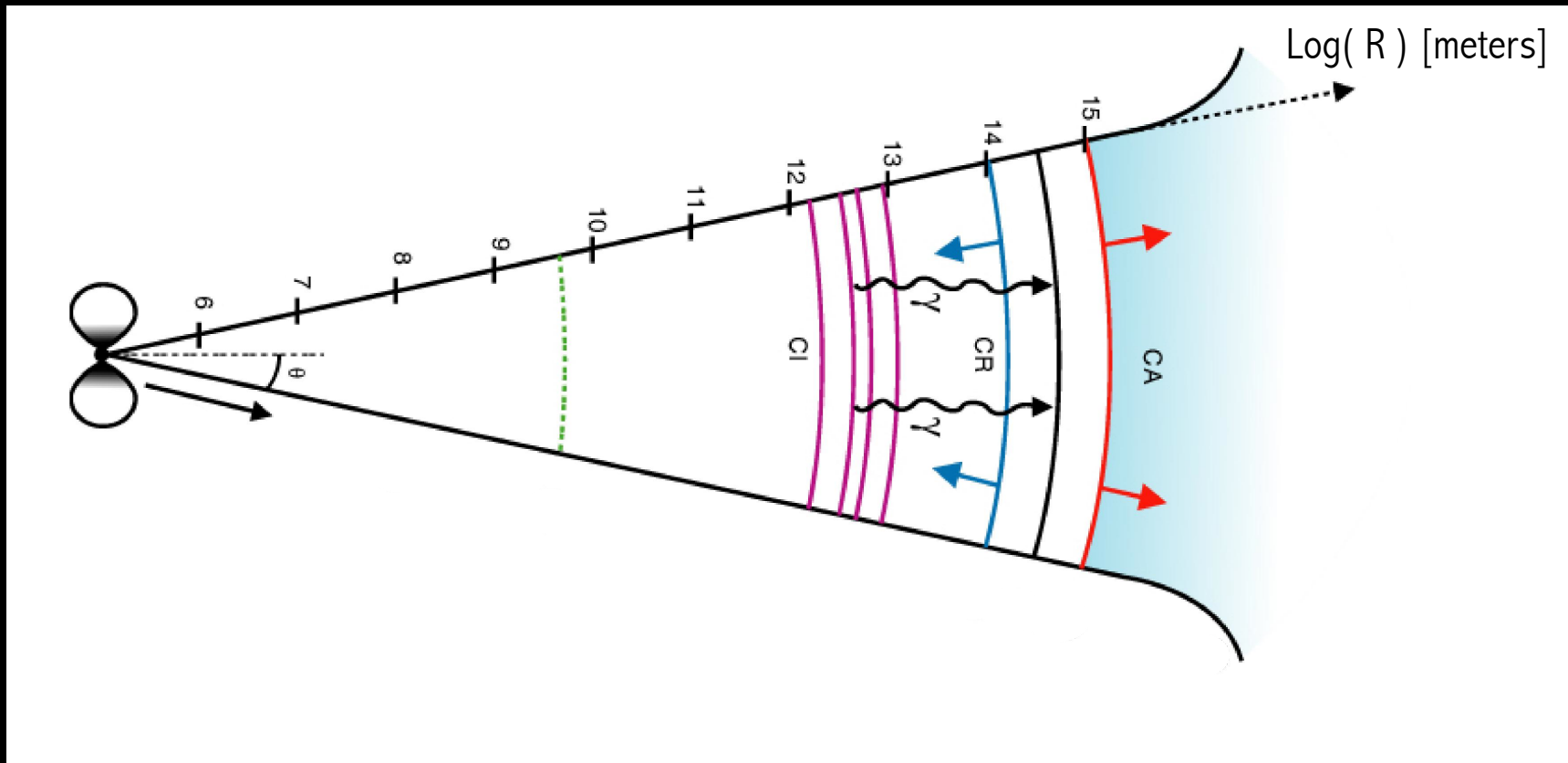
# GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium



# GRB Physics

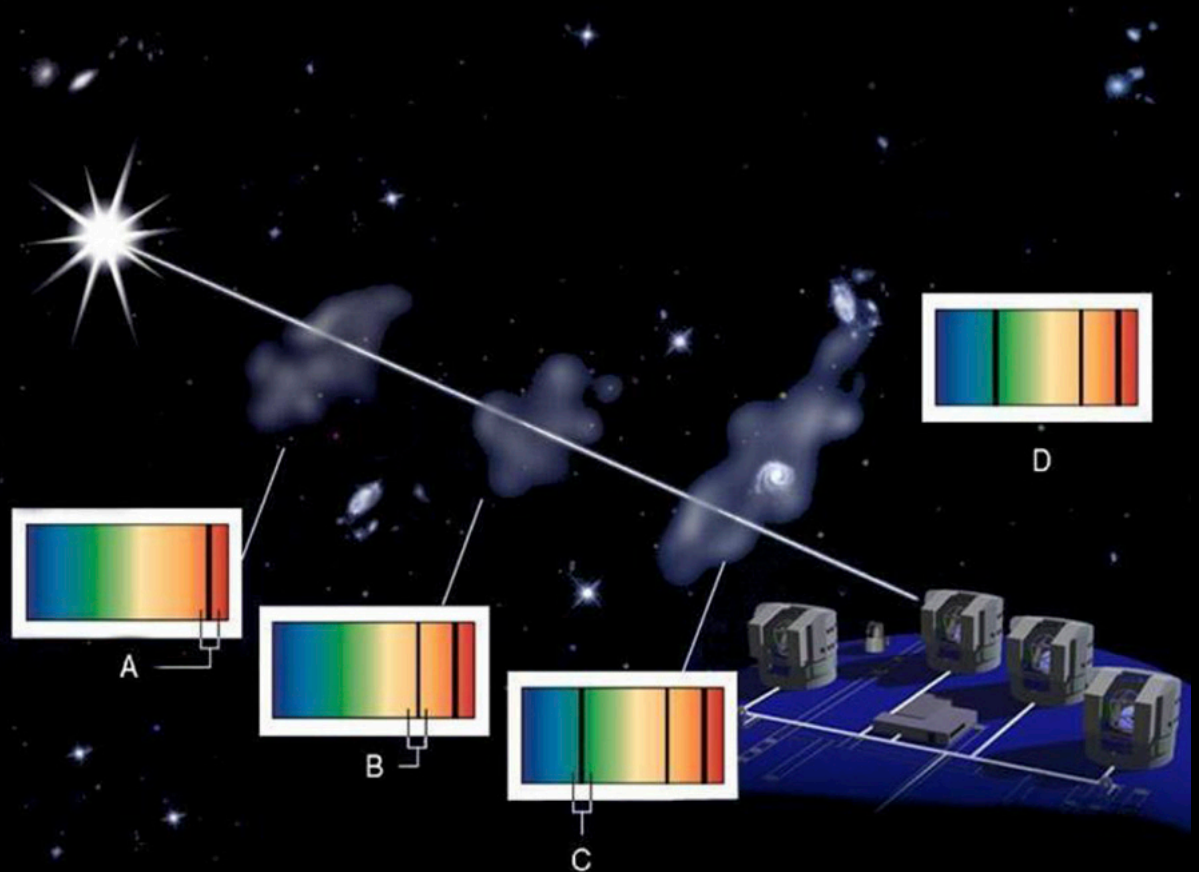
- Final state of massive stars
  - Compact objects / relativistic ejecta
  - Particle acceleration / non-thermal emission
  - Non-photon emission (GW ? Neutrinos ? CRs ?)
- Etc.





# GRB as a tool for cosmology

- A sample of weak high-z galaxies (absorption & emission spectroscopy)
- Tracing the star formation rate
- Hubble diagram? Very difficult
- Absorption spectroscopy on the line of sight (ISM, IGM)
  - chemical evolution
  - reionization
  - etc.
- First stars ?

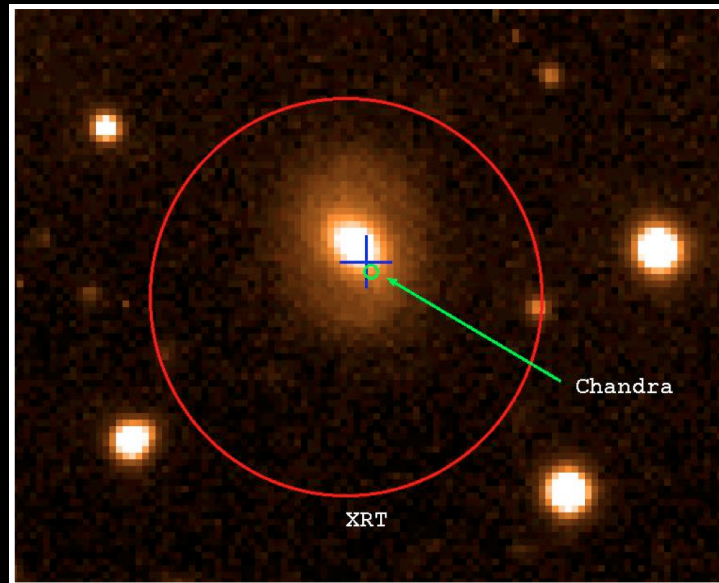


---

# Gamma-ray bursts: progenitors

---

# Short GRBs: NS+NS?



GRB 050724 @ VLT

Barthelmy et al. 2005

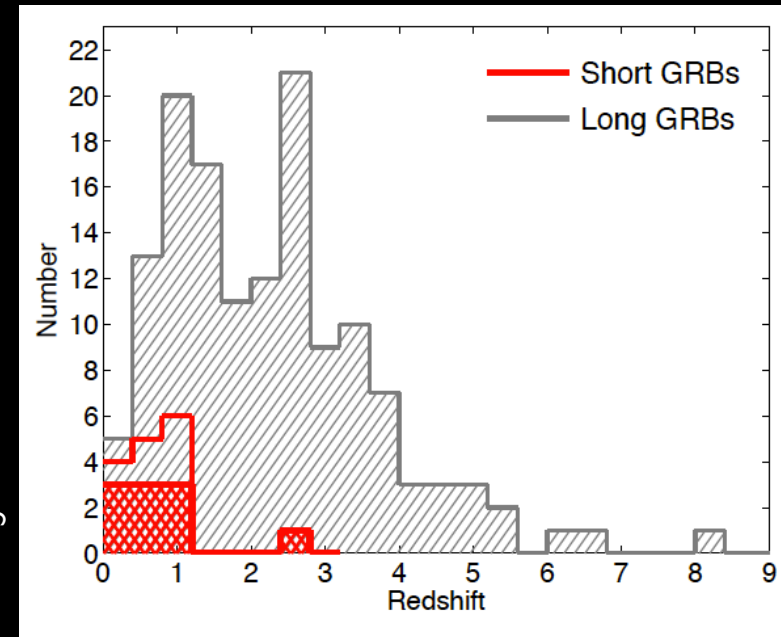
Long GRBs: gravitational collapse of a massive star  
(correlation with star formation)

Short GRBs: merger scenario

- no correlation with star formation
- offsets
- etc.

(see review by Berger 2014)

Berger et al. 2011

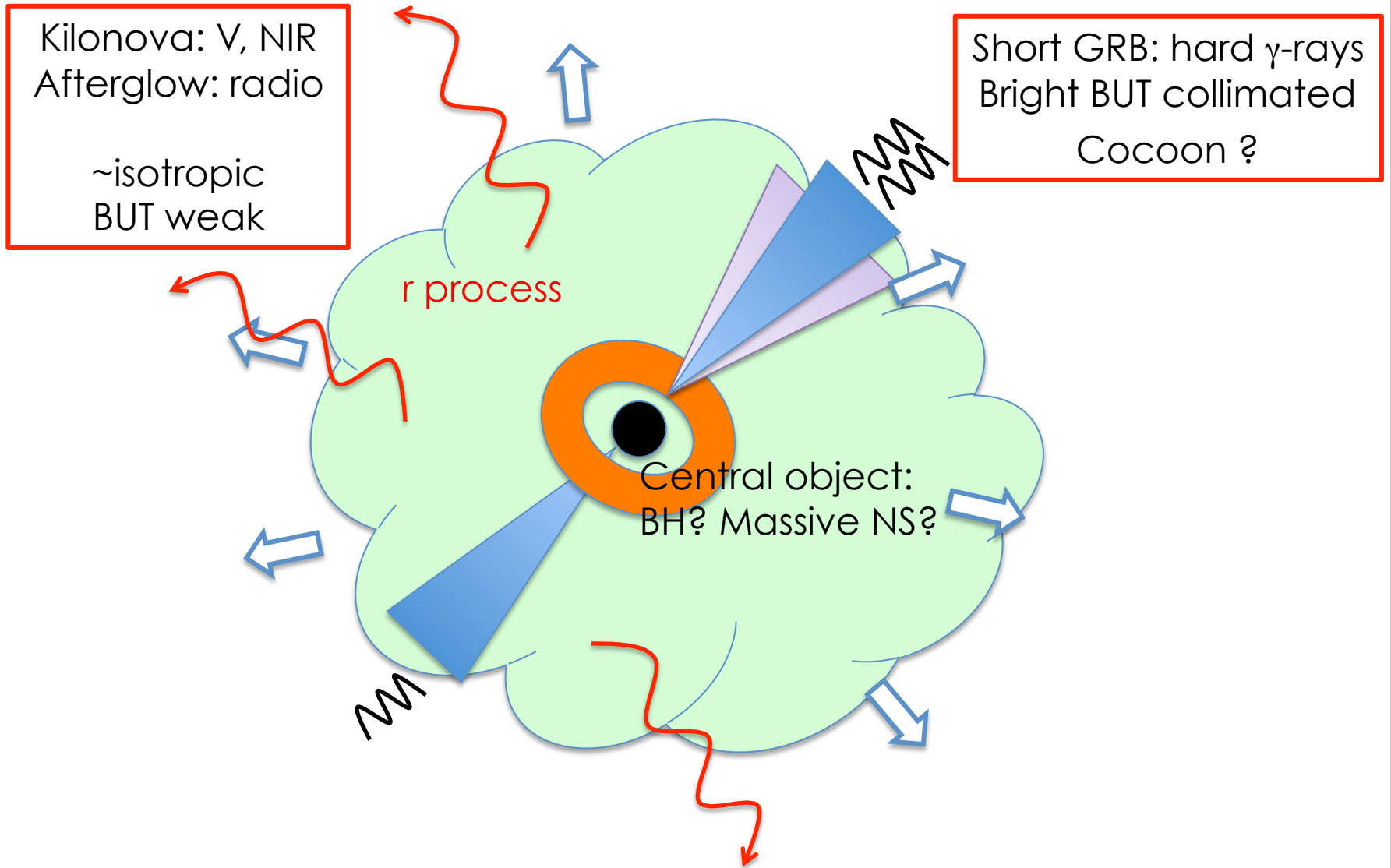


---

NS+NS mergers: predictions

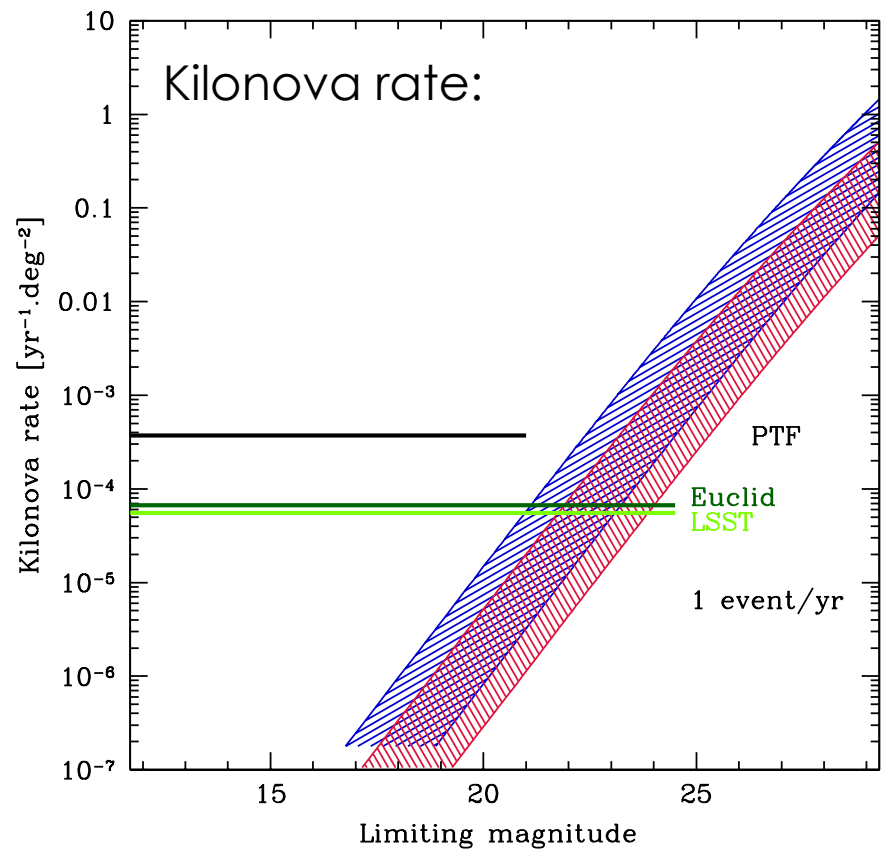
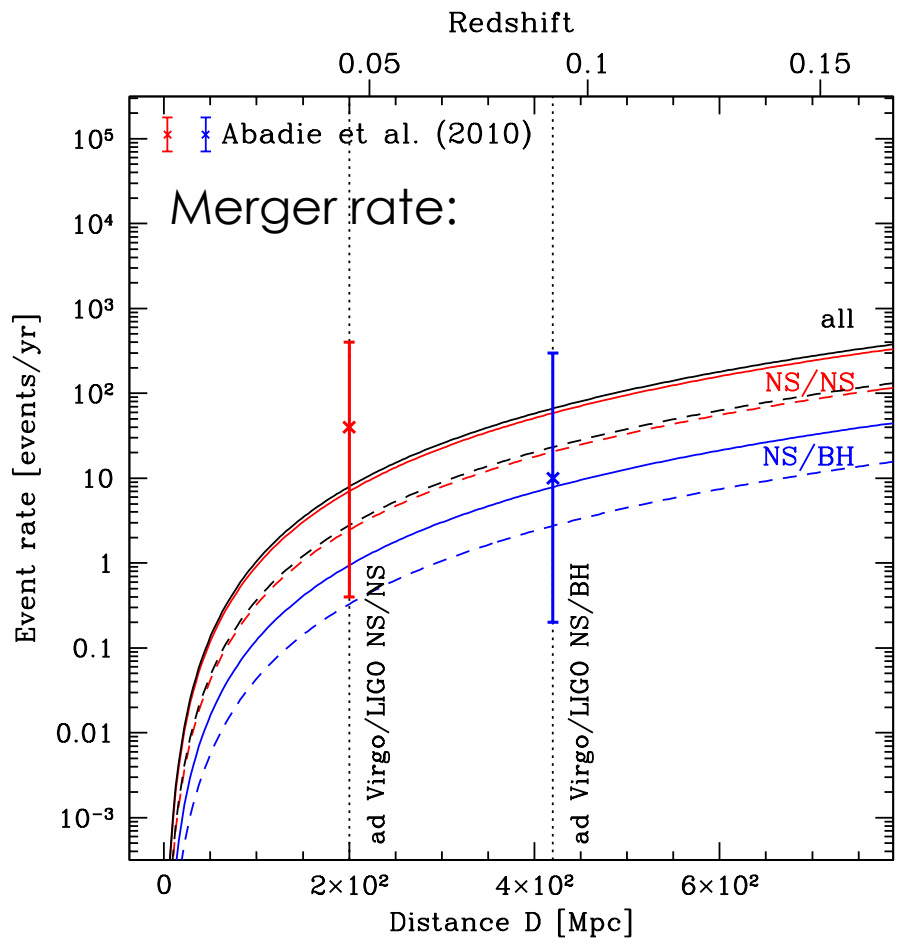
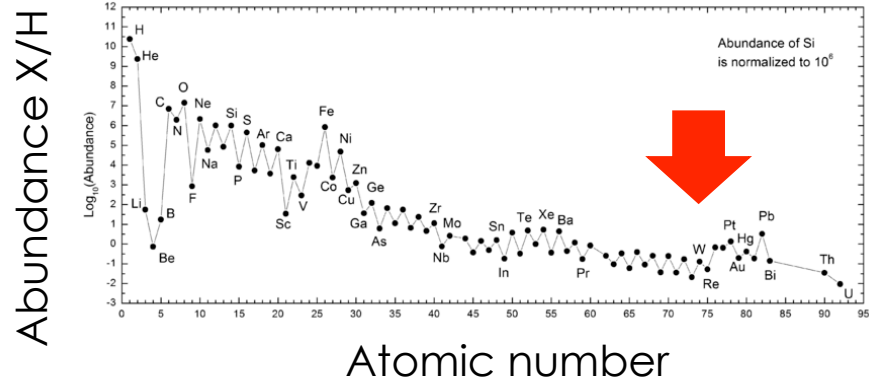
---

# Final state of a merger: pre-summer 2017 theory



# R process: constraints on the merger rate

Observations: Eu in stars, including very old (metal-poor) stars = trace evolution of r process.



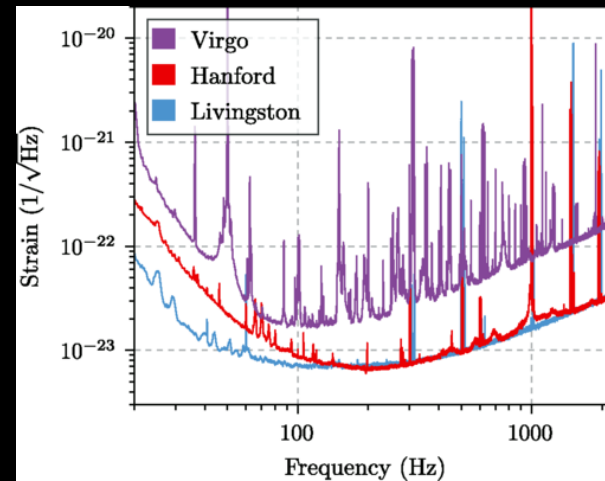
---

The first multi-messenger observation of a NS+NS merger

---



# August 17<sup>th</sup>, 2017 – Status of LIGO/Virgo

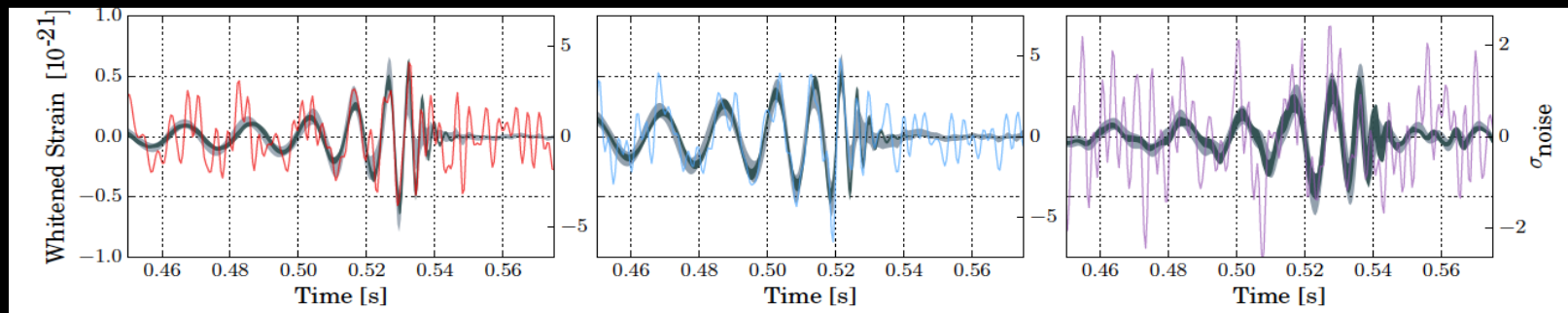


LIGO Hanford

LIGO Livingston

Virgo

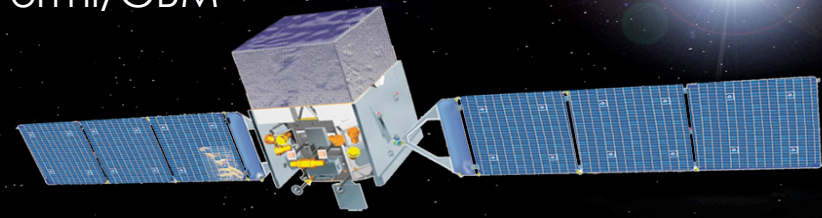
Three days before: three-detector observation of GW 170814 (BH+BH)



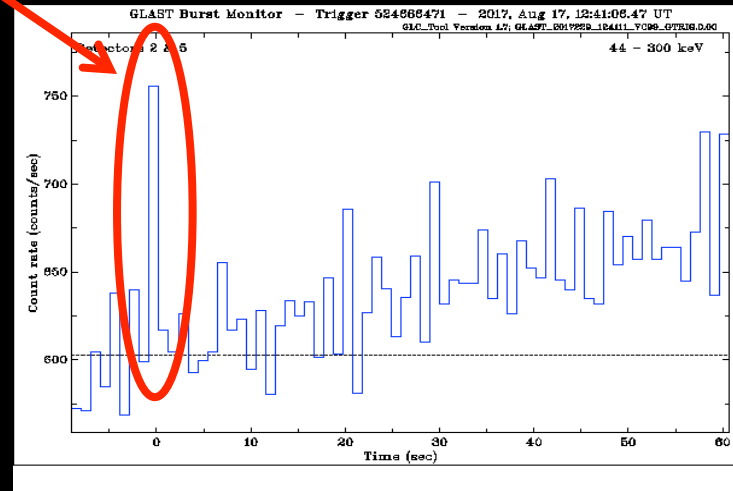


August 17<sup>th</sup>, 2017 – 12:41

Fermi/GBM



```
////////////////////////////////////  
TITLE:          GCN/FERMI NOTICE NOTICE_DATE:    Thu 17 Aug 17 12:41:20 UT  
NOTICE_TYPE:    Fermi-GBM Alert RECORD_NUM:        1  
TRIGGER_NUM:    524666471  
GRB_DATE:       17982 TJD;   229 DOY;   17/08/17  
GRB_TIME:       12066.47 SCD {12:41:06.47} UT  
TRIGGER_SIGNIF: 4.8 [sigma]  
TRIGGER_DUR:    0.256 [sec]  
E_RANGE:        3-4 [chan]   47-291 [keV]  
...  
COMMENTS:       Fermi-GBM Trigger Alert.  
COMMENTS:       This trigger occurred at longitude,latitude = 321.53,3.90 [deg].  COMMENTS:  
The LC_URL file will not be created until ~15 min after the trigger.  
////////////////////////////////////
```



GRB 170817A

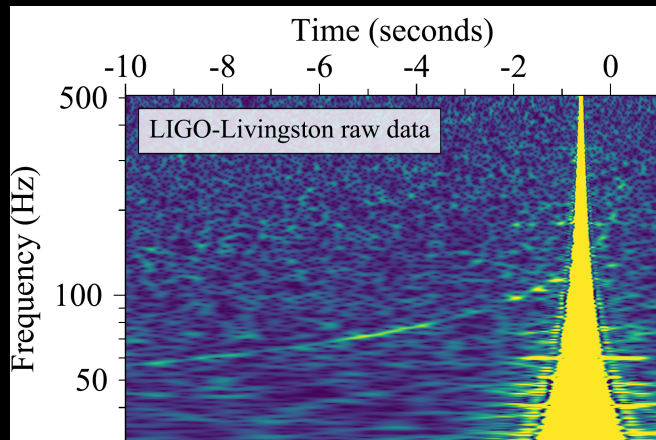
A weak short GRB...

August 17<sup>th</sup>, 2017 – 12:47

## GW 170817

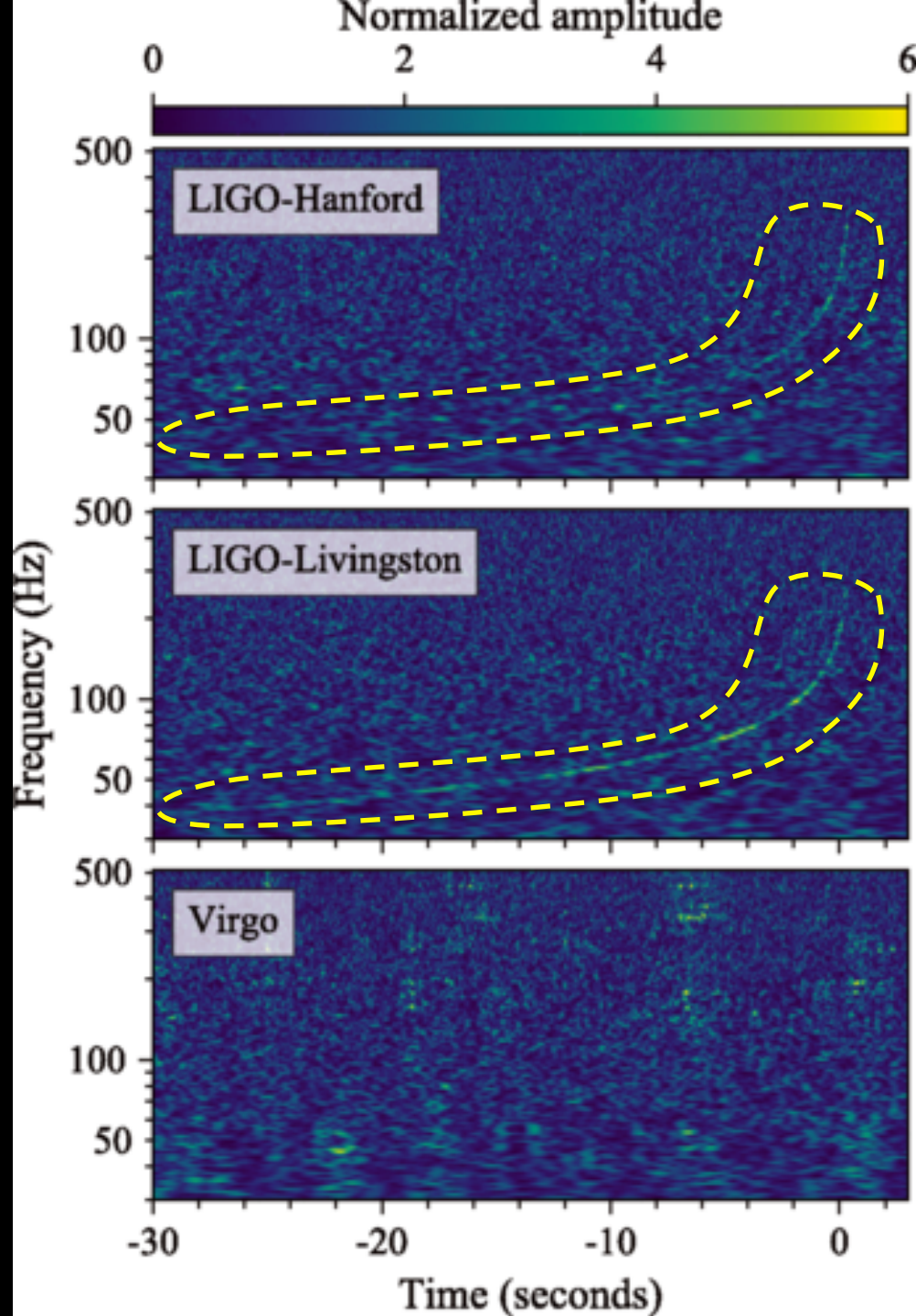
Automatic alert

- 1 detector (H1)  
+ 1 detector (L1) with a glitch

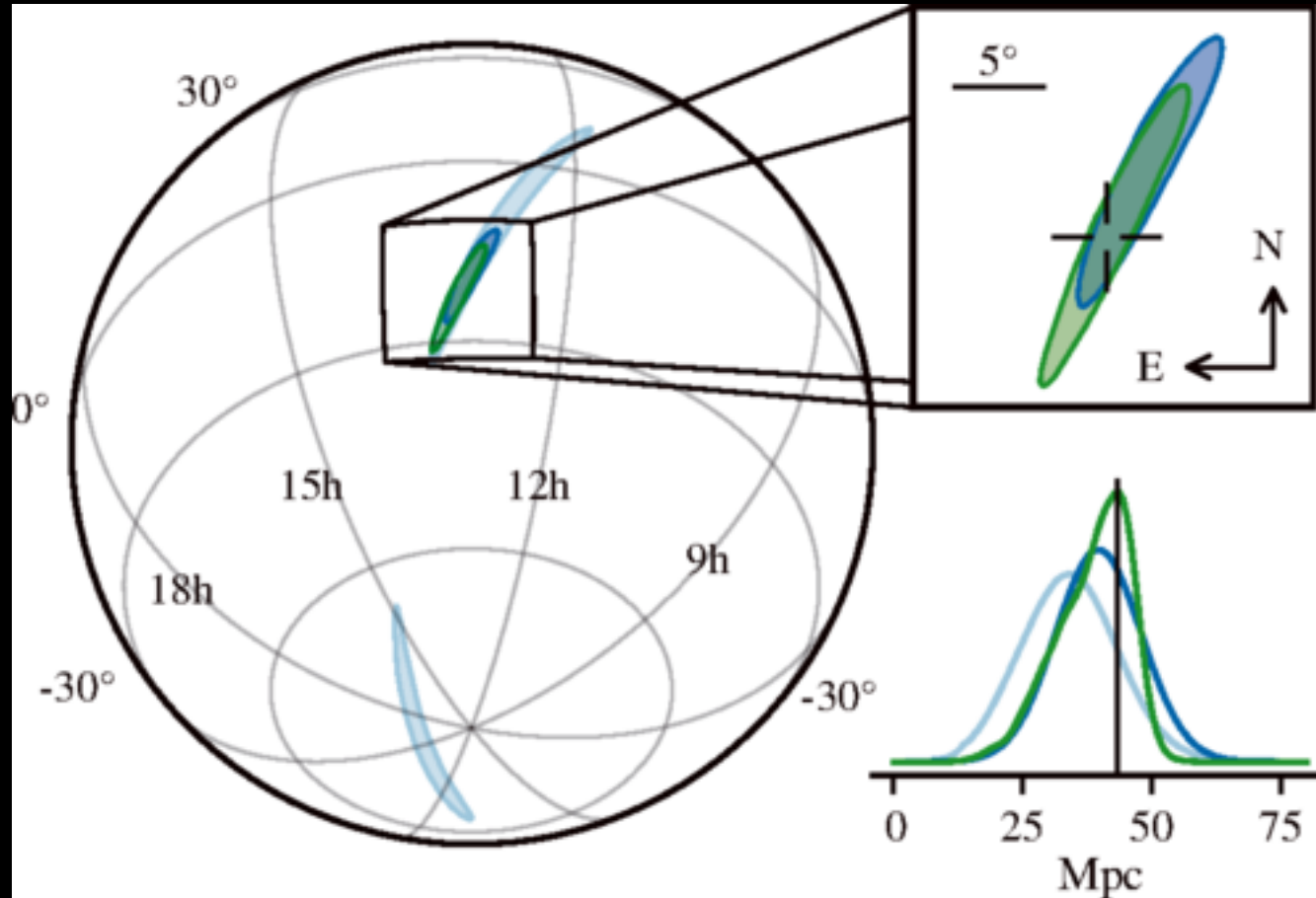


- strong signal
- NS+NS !
- merger 6 min ago  
i.e. ~2 s before GRB 170817A

13:21 LIGO-Virgo alert !  
i.e. 40 minutes after the merger



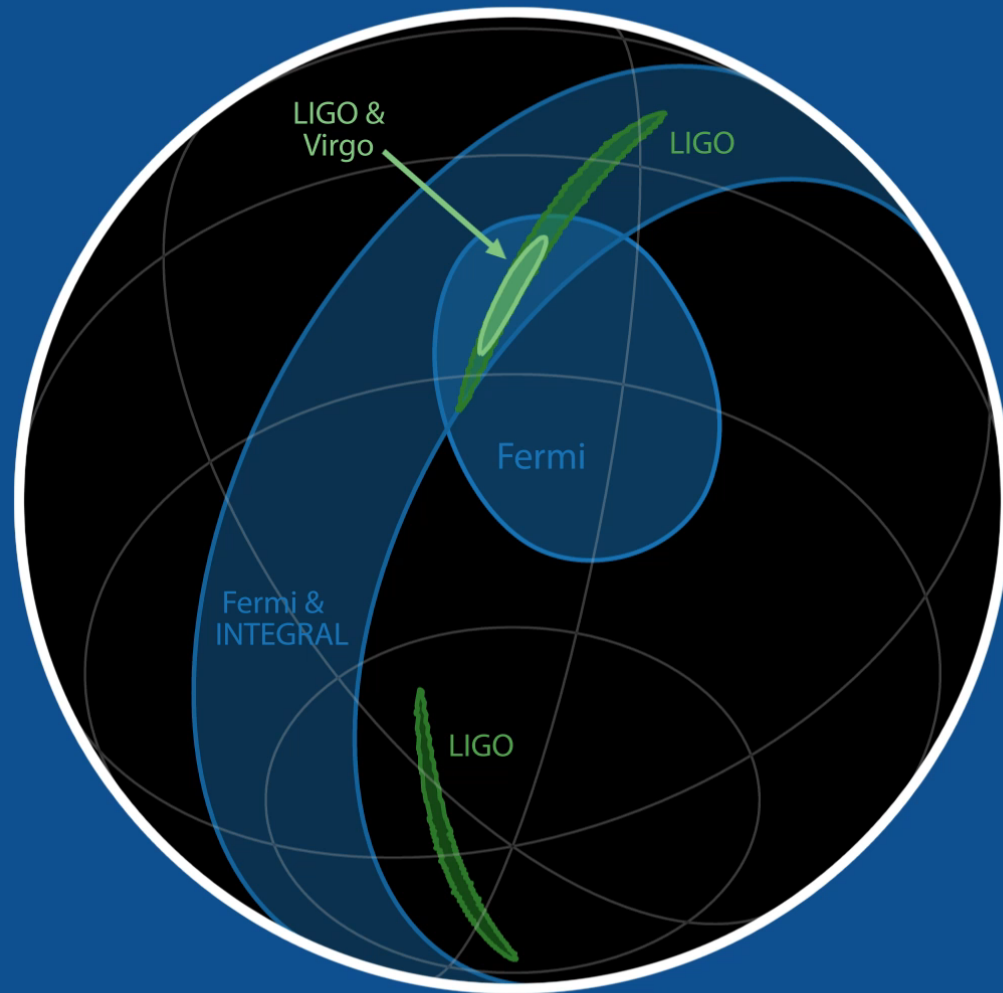
# GW170817: localization



- LIGO: 190 deg<sup>2</sup> ; LIGO+Virgo: 30 deg<sup>2</sup> !
- 3D error box : distance ~40 Mpc
- Sky map sent at 17:54, i.e. 5 hours after the merger

# GW170817: localization

About 50 galaxies in the error box at 40 Mpc...

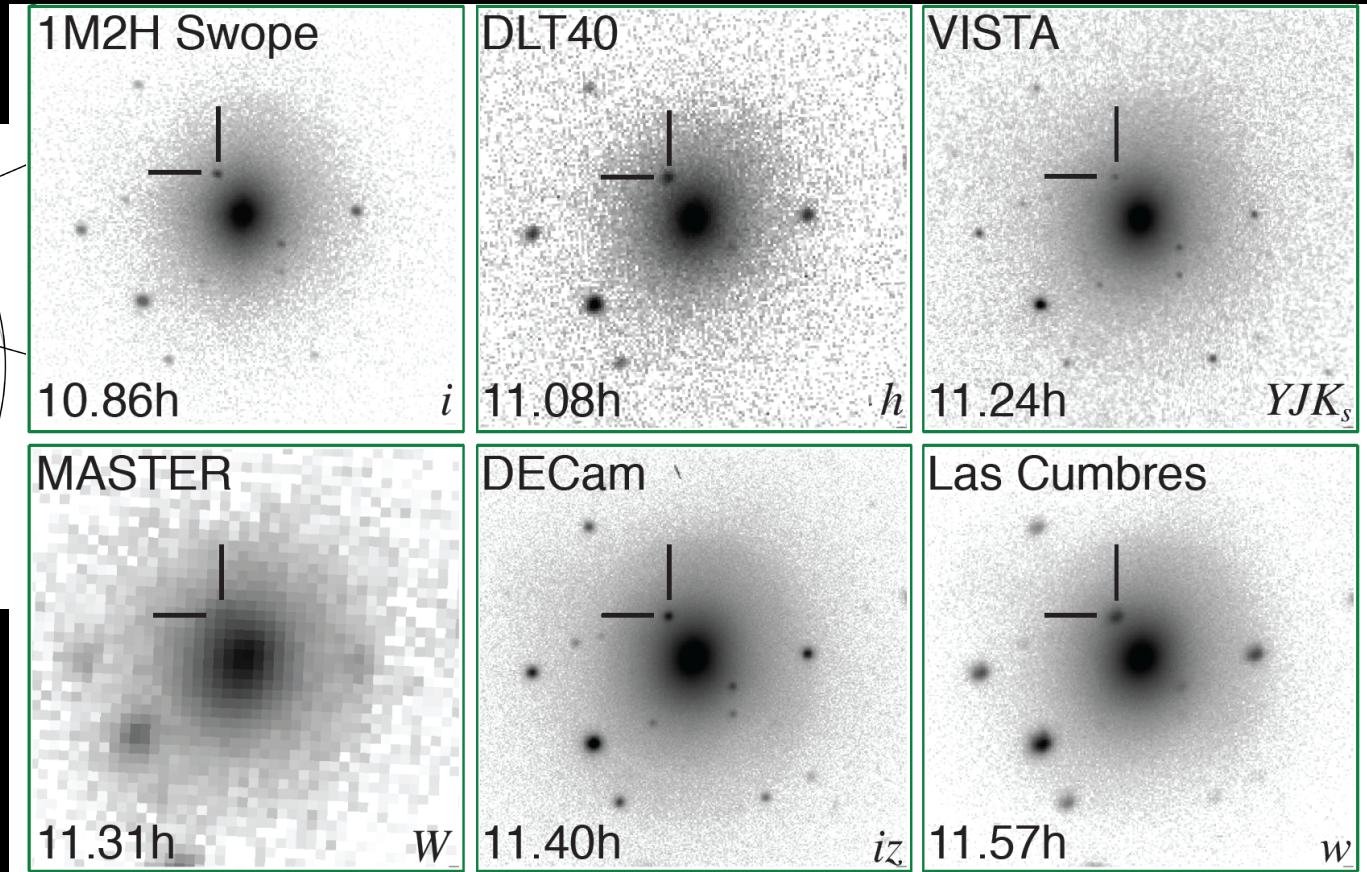
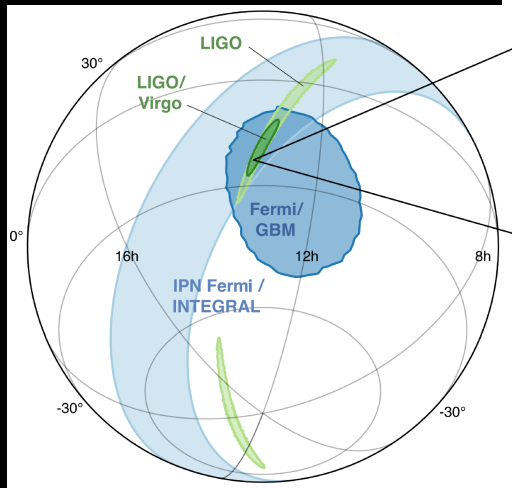


The search starts ~10 h after the merger (night in Chili)



# SSS17a / AT 2017gfo = KN 170817

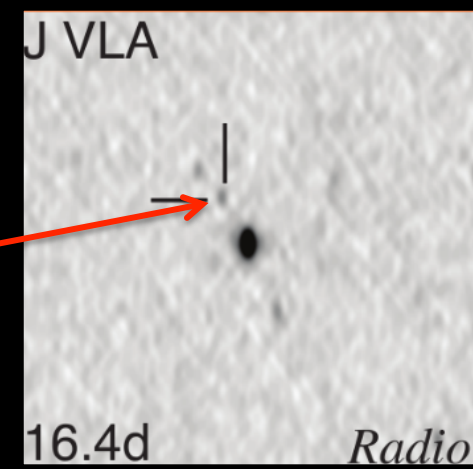
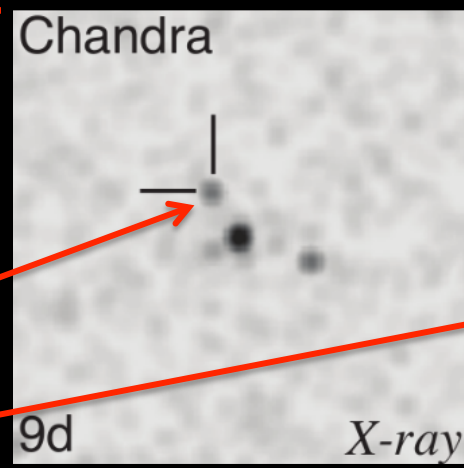
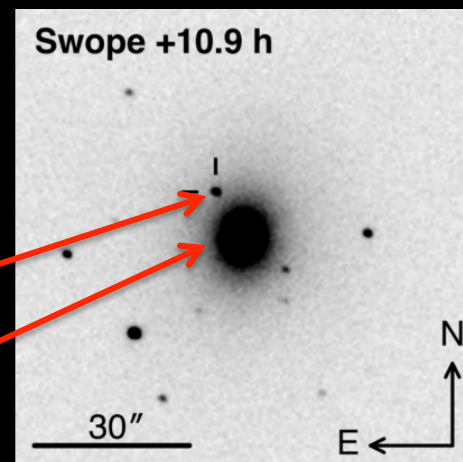
Detection at ~merger+11h  
of a new transient in NGC 4993 by SWOPE + 5 other groups



Spectro-photometric follow-up: first detection of a kilonova !

# Timeline

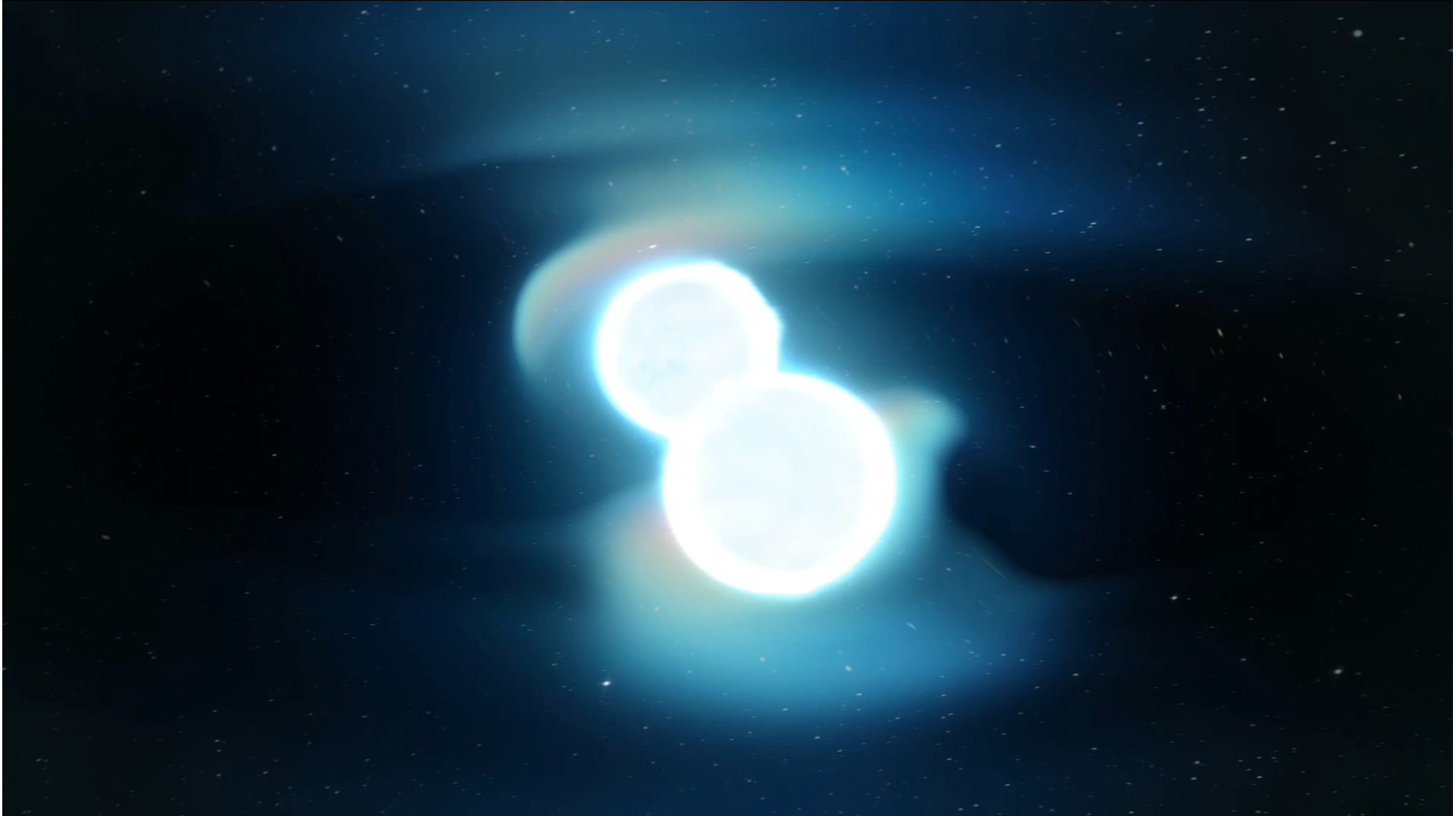
- 17/08/2017 12:41:04 Gravitational waves GW170817 (*LIGO-Virgo*)
- +2 s Short Gamma-ray burst GRB170817A (*Fermi*)
- +5 h GW localization Distance 40 Mpc ; 30 deg<sup>2</sup>
- +11h Visible counterpart Kilonova AT2017gfo (*SWOPE* + 5 other groups)  
Host galaxy NGC4993
- +1.2j First spectrum of the kilonova
- +9 j X-ray counterpart (*Chandra*)
- +16 j Radio counterpart (*VLA*)



# The first multi-messenger observation of a NS+NS merger!

---

---



# GW signal:



- BNS inspiral detected for  $\sim 100$  s

- Preliminary analysis:  
NS+NS, total mass = 2.7-2.8  $M_{\odot}$

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ( $ \chi  \leq 0.05$ )	High-spin priors ( $ \chi  \leq 0.89$ )
Primary mass $m_1$	1.36–1.60 $M_{\odot}$	1.36–2.26 $M_{\odot}$
Secondary mass $m_2$	1.17–1.36 $M_{\odot}$	0.86–1.36 $M_{\odot}$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_{\odot}$	$1.188^{+0.004}_{-0.002} M_{\odot}$
Mass ratio $m_2/m_1$	0.7–1.0	0.4–1.0
Total mass $m_{\text{tot}}$	$2.74^{+0.04}_{-0.01} M_{\odot}$	$2.82^{+0.47}_{-0.09} M_{\odot}$
Radiated energy $E_{\text{rad}}$	$> 0.025 M_{\odot} c^2$	$> 0.025 M_{\odot} c^2$
Luminosity distance $D_L$	$40^{+8}_{-14}$ Mpc	$40^{+8}_{-14}$ Mpc
Viewing angle $\Theta$	$\leq 55^{\circ}$	$\leq 56^{\circ}$
Using NGC 4993 location	$\leq 28^{\circ}$	$\leq 28^{\circ}$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leq 800$	$\leq 700$
Dimensionless tidal deformability $\Lambda(1.4M_{\odot})$	$\leq 800$	$\leq 1400$

NS+NS

(NS+BH with a low probability)

Viewing angle

E.O.S





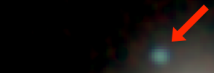
# Kilonova

- Rapid evolution (blue → red)
- Cooling post-merger ejecta ( $\sim 0.2c$ )

Heating:  
radioactivity of freshly synthesized heavy elements (r process)

- Spectrum: absorption features associated to Cs and Te
- Spectro-photometric evolution: large opacity at late times (lanthanides)

SSS17a

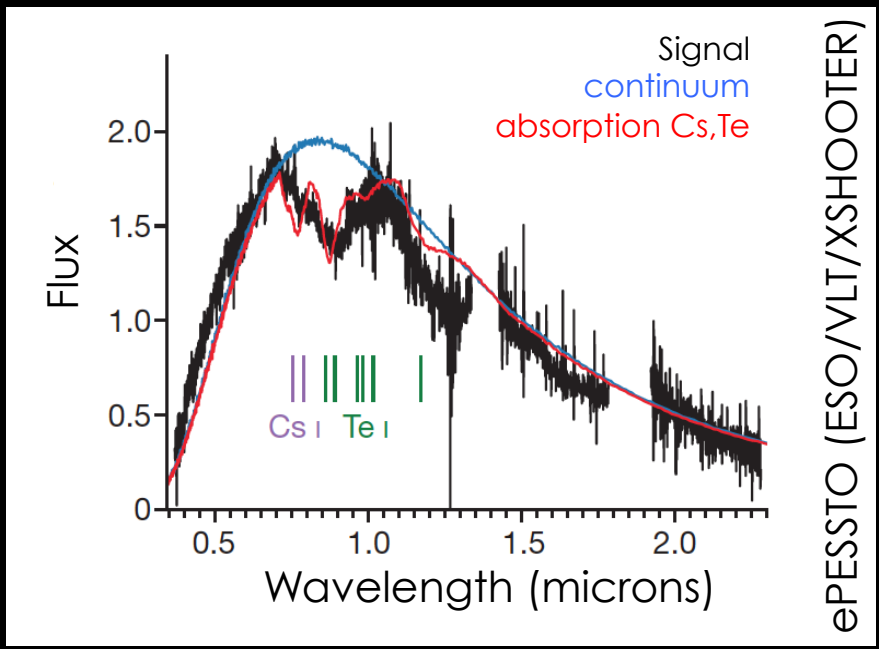
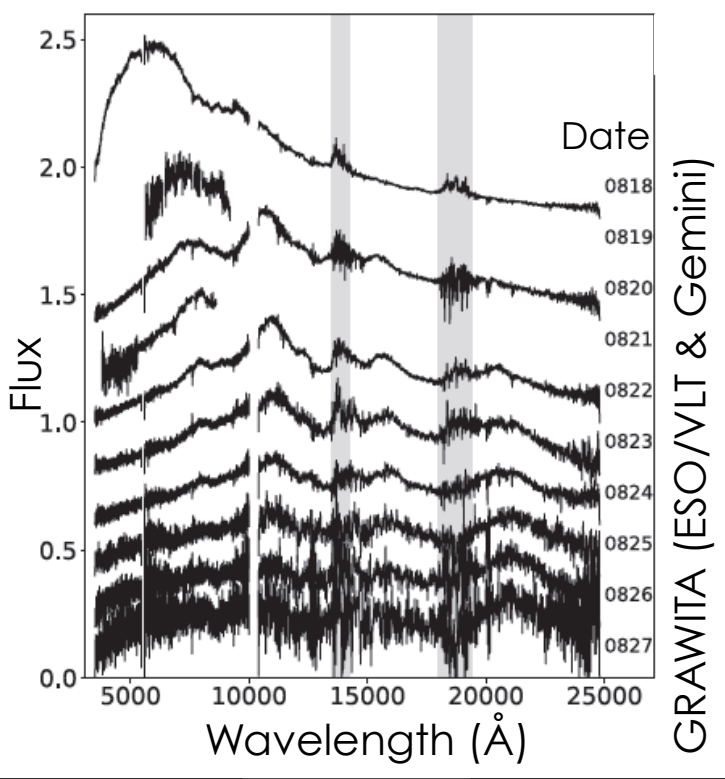


August 17, 2017



August 21, 2017

Swope & Magellan Telescopes



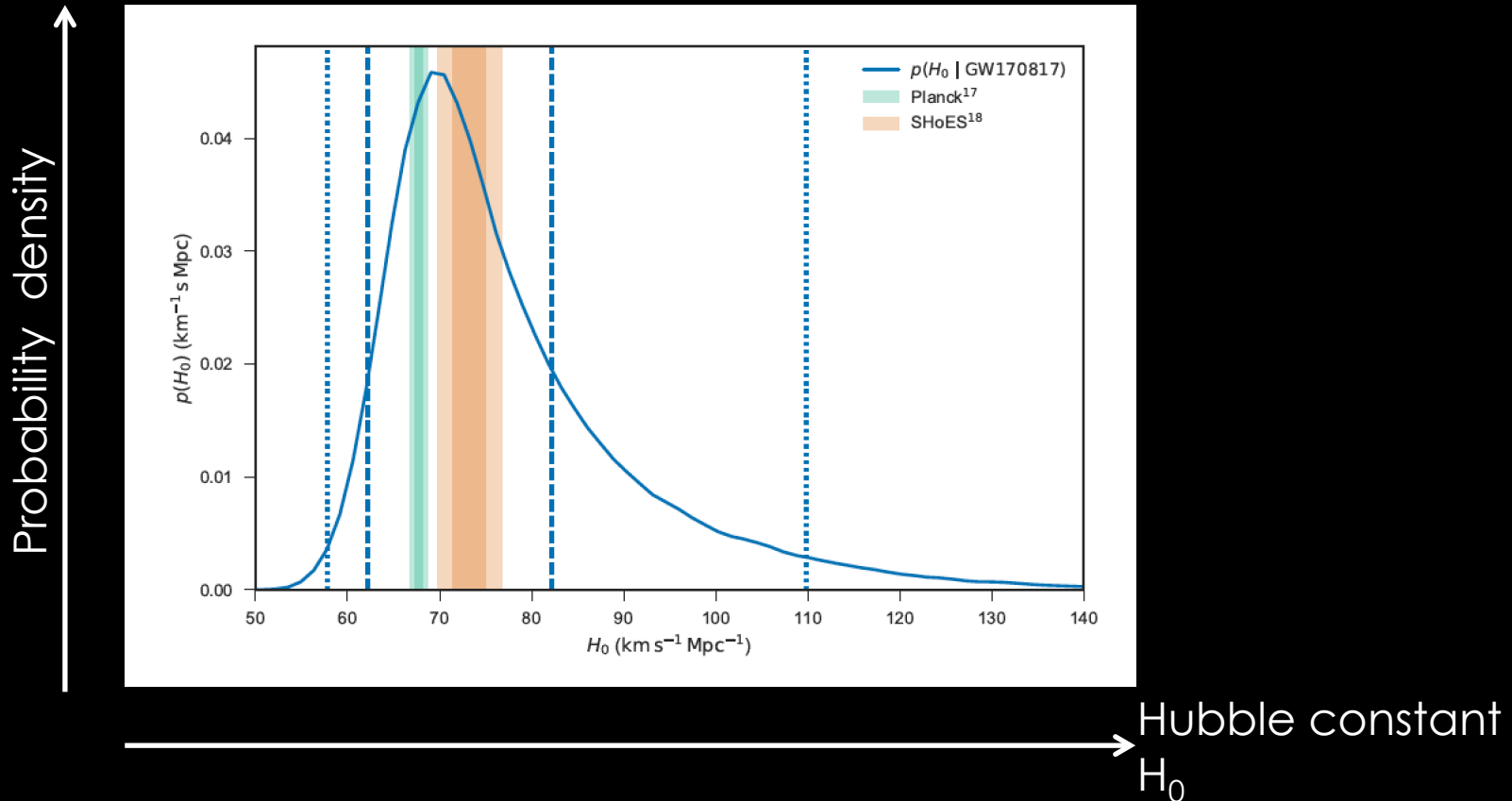
- Host galaxy: lenticular galaxy (gaz poor, no star formation) ; KN shows an offset

# GW+host galaxy: Hubble constant

$$D_{\text{GW}} = 43.8_{-6.9}^{+2.9} \text{ Mpc}$$

$$D_{\text{NGC4993,TF}} = 41.1 \pm 5.8 \text{ Mpc}$$

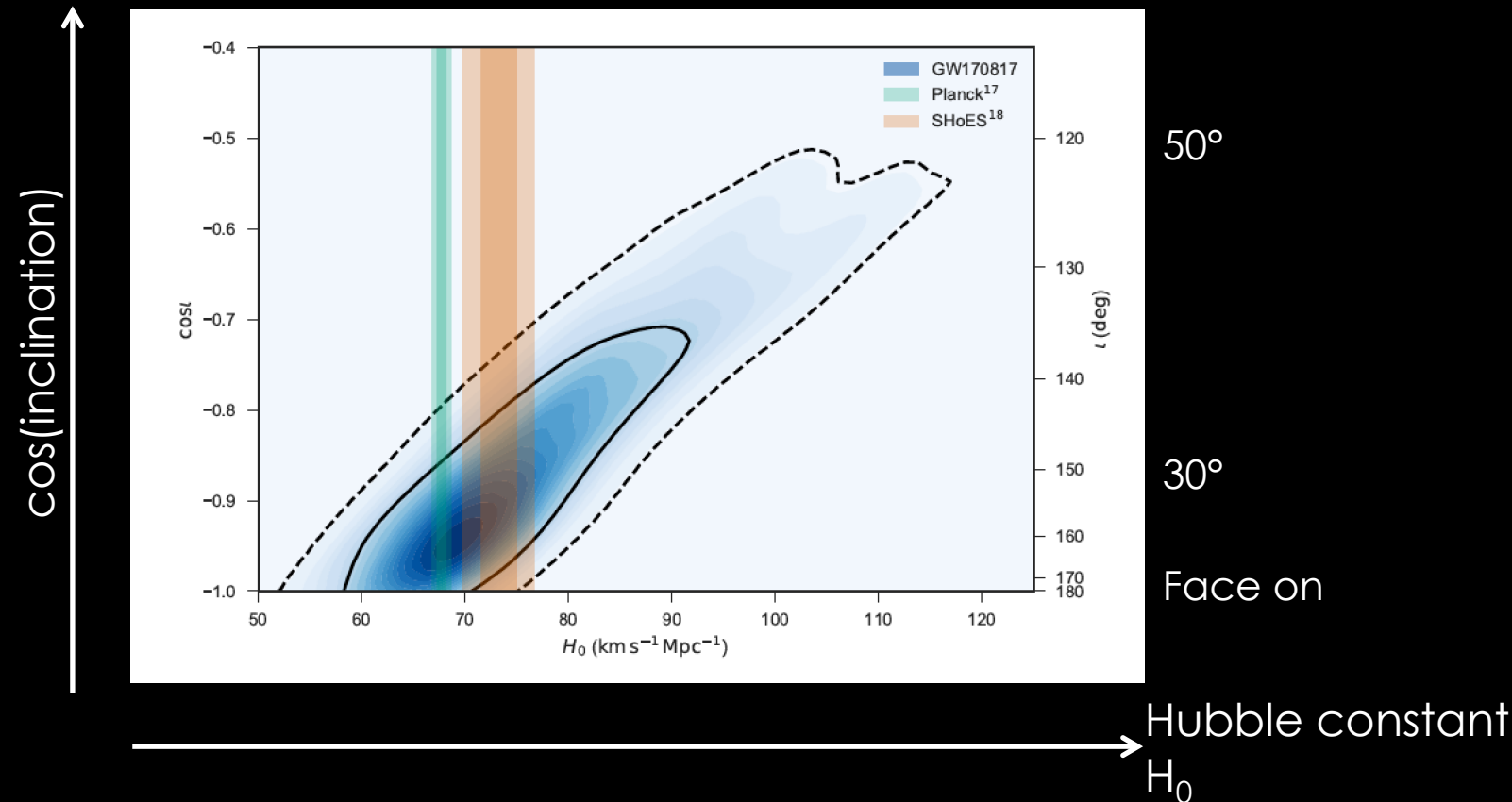
- GW : distance ; Host galaxy : redshift  
(but low distance: proper motion  $\sim 10\%$  recessional velocity)



$$H_0 = 70.0_{-8.0}^{+12.0} \text{ km.s}^{-1} .\text{Mpc}^{-1}$$

# GW+host galaxy: Hubble constant

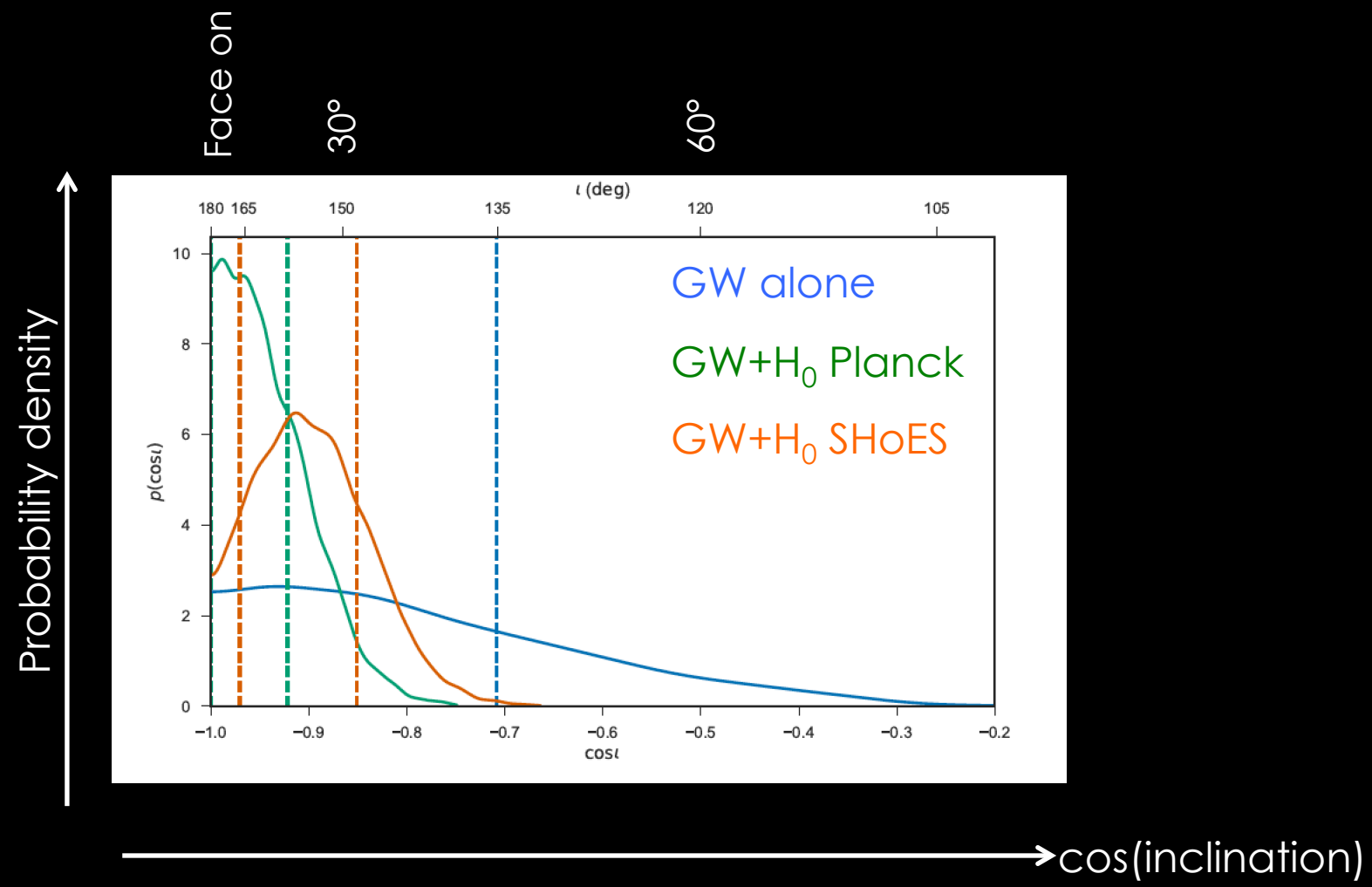
- GW : distance ; Host galaxy : redshift  
(but low distance: proper motion ~10% recessional velocity)
- Degeneracy  $H_0$ -binary system orientation



$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km.s}^{-1} .\text{Mpc}^{-1}$$

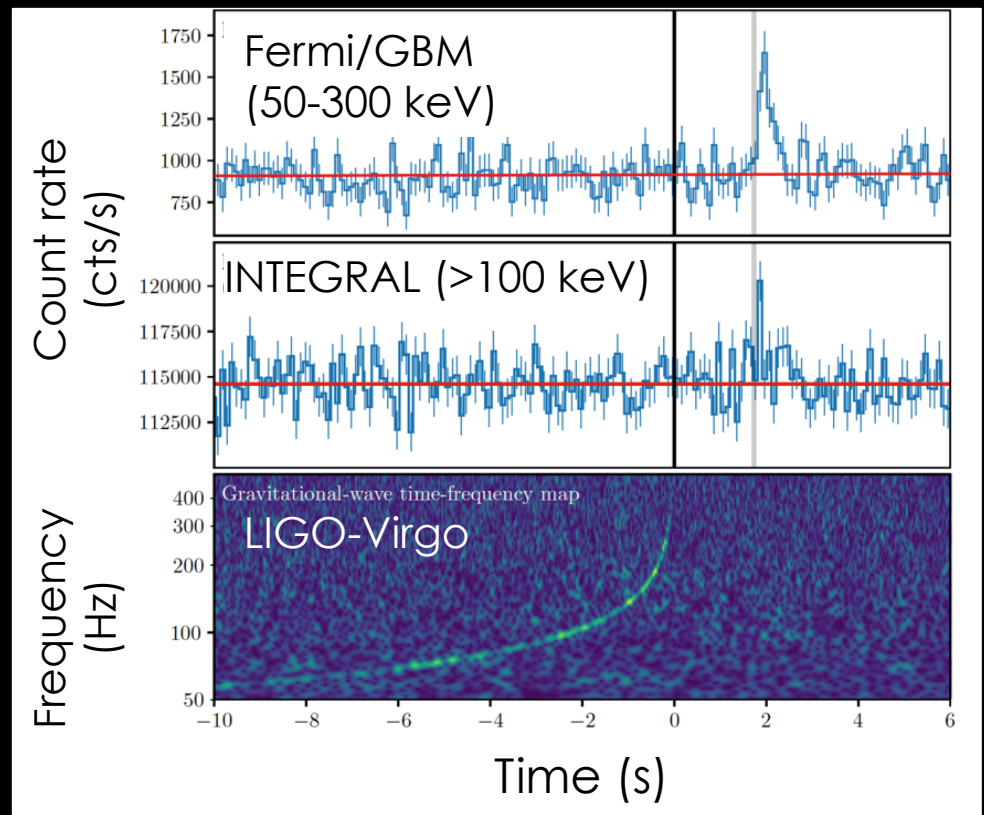
# GW+host galaxy: Hubble constant

- GW : distance ; Host galaxy : redshift  
(but low distance: proper motion  $\sim 10\%$  recessional velocity)
- Degeneracy Luminosity distance-binary orbital inclination angle



# Gamma-ray burst

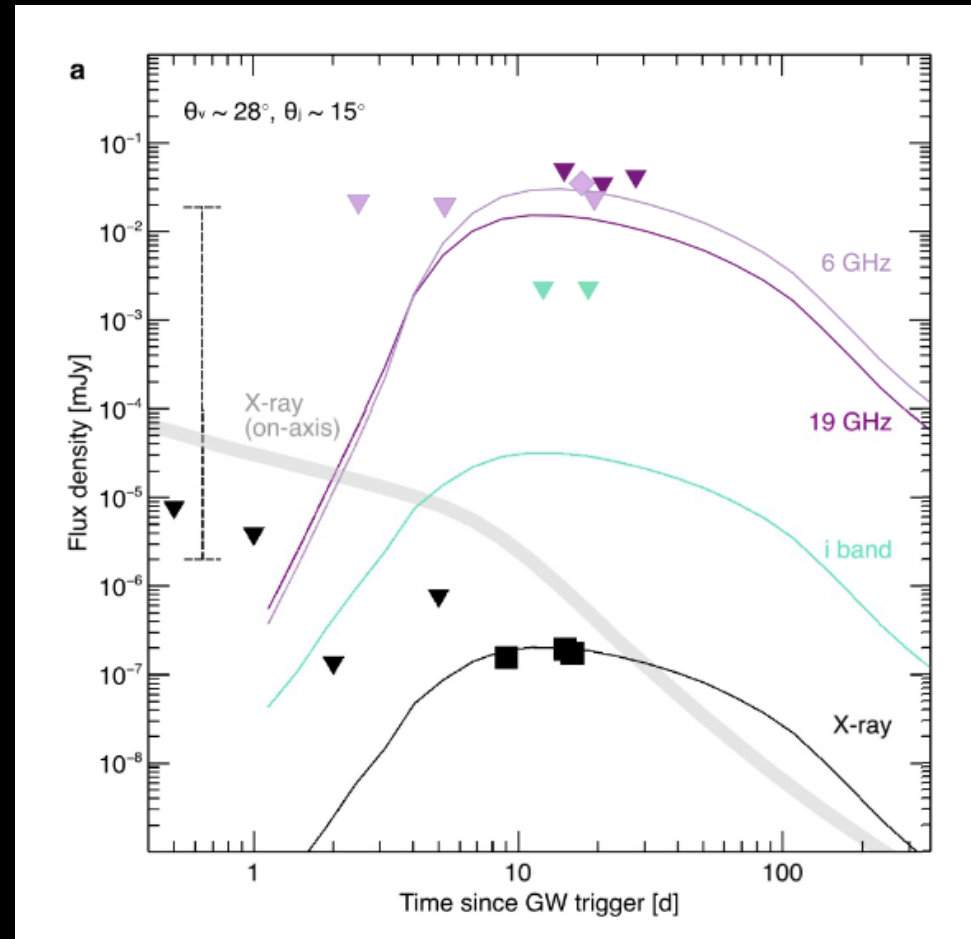
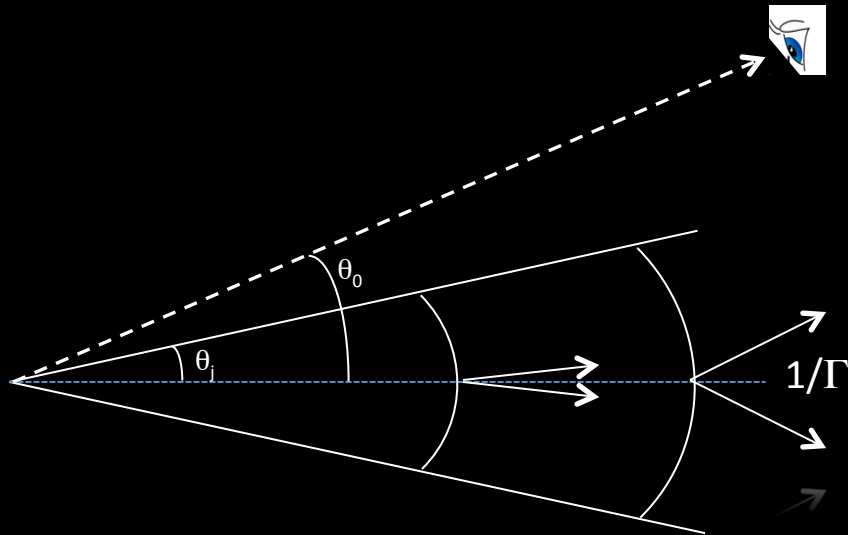
- At least some short GRBs are associated to NS+NS mergers!
- GW-GRB delay  $\sim 1.7$  s
  - strong limit on GW propagation speed/LIV = test for modified gravity
  - expected intrinsic delay (merger-ejection ; jet propagation)



- Not a typical short GRB
  - Weak: 4-5 orders of magnitude
  - But emits photons above 100 keV
  - Afterglow?
- Origin of the observed emission? Geometry of the KN ejecta/relativistic ejecta?
- Connection to the classical population of short GRBs?

# Afterglow?

- Late detection in X-rays and radio
- Chandra: 0.3-10 keV  
1st detection @ 9 days
- VLA: 6 GHz  
1st detection @ 16.4 days
- Off-axis emission?



X-rays: Chandra ; Radio: VLA

Model:  $\theta_j = 15^\circ$   
 $\theta_0 = 28^\circ$

# Models

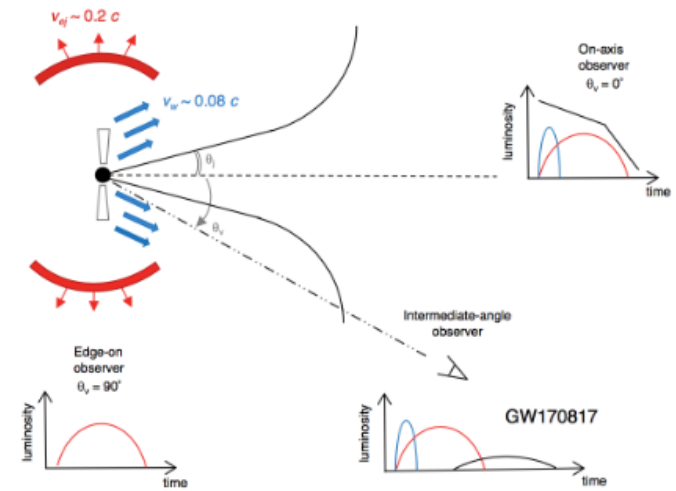
- Kilonova: at least two ejecta (blue and red components)

- Gamma-ray burst+afterglow:
    - ultra-relativistic jet in the core?
- and
- mildly-relativistic/-energetic jet/coocon?

or  
choked jet/shock breakout

- Central object: BH or hypermassive NS?

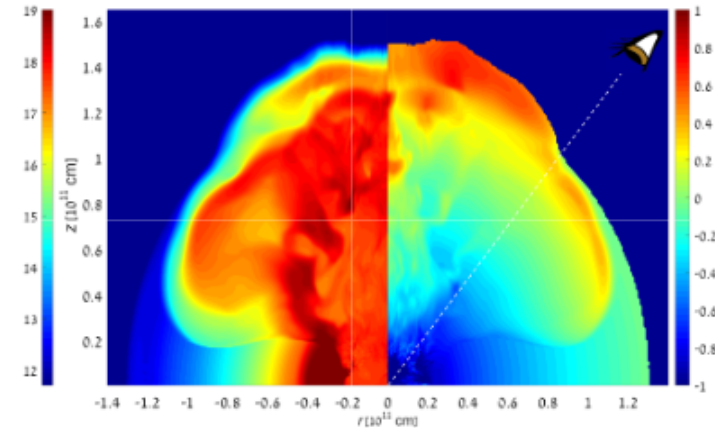
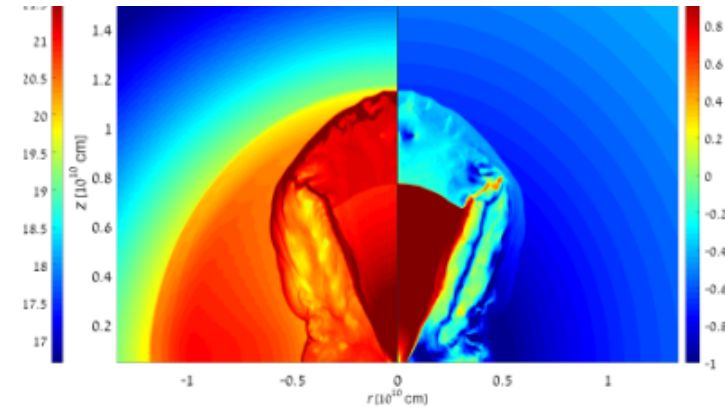
Troja et al. 2017



(X,R)

( $\gamma$ )

Bromberg et al. 2017



---

# Conclusion

---



# Conclusion: a new multi-messenger astronomy

---

---

- More mergers to come
- GW: future detection of the post-merger signal? Nature of the central source?
- More kilonovae? (nearby events)
- Origin of the heaviest elements: merger rate? Mass ejected? Composition?
- Geometry of the KN ejection?
- Gamma-ray burst: origin of the emission? Geometry?  
(jet on/off-axis? ; cocoon? ; shock breakout? ...)  
(impact for  $H_0$  measurement?)
- How would GW/GRB/KN 170818 appear at different distance/orientation?
- NS+NS mergers: diversity of the electromagnetic counterpart?
- NS+BH mergers?
- Merger rate? Distribution of merger times?
- GW followup: organization / strategy / well-adapted instruments
- SVOM (2021+)