Multi-Messenger Astronomy with Gravitational Waves

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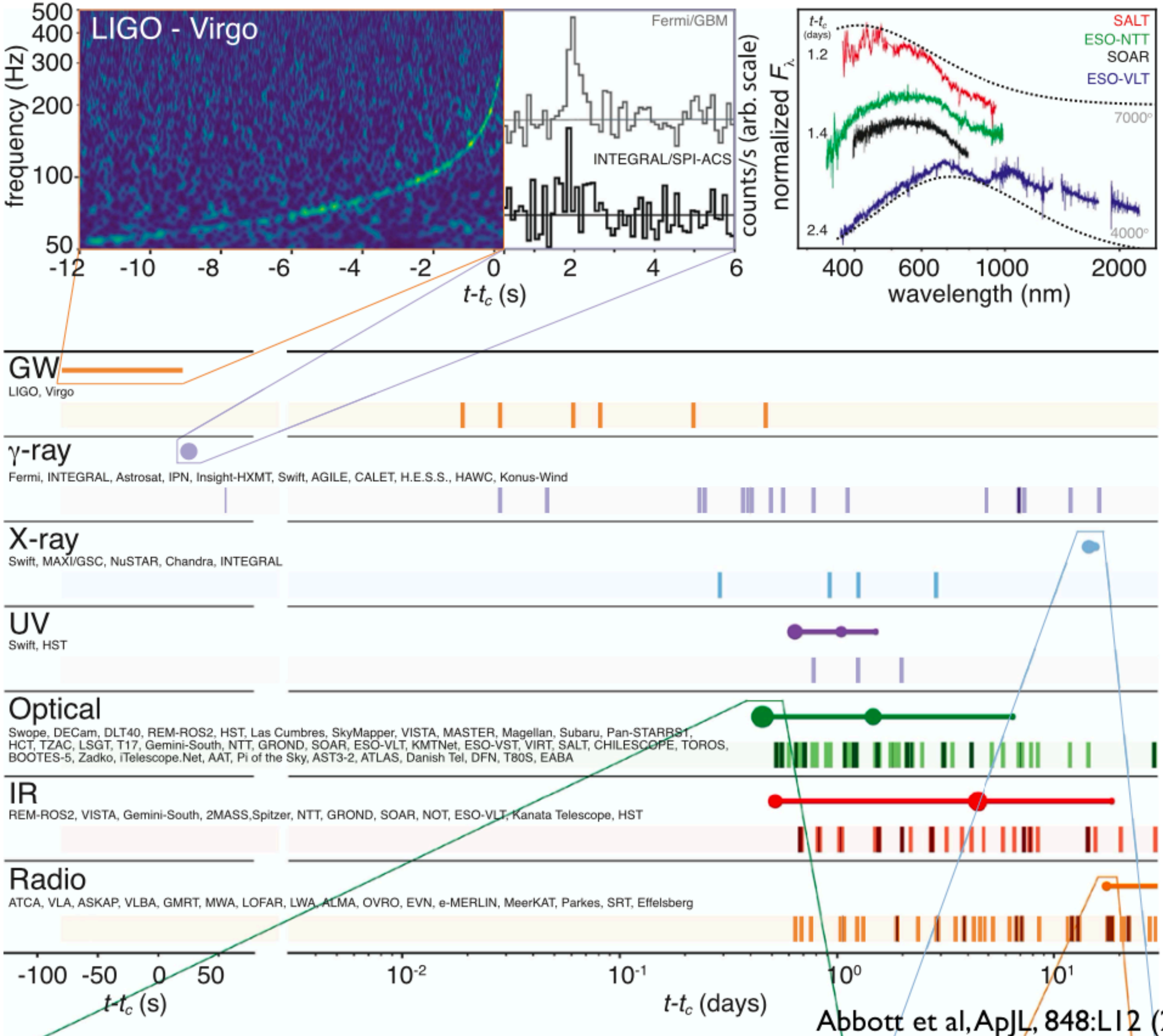
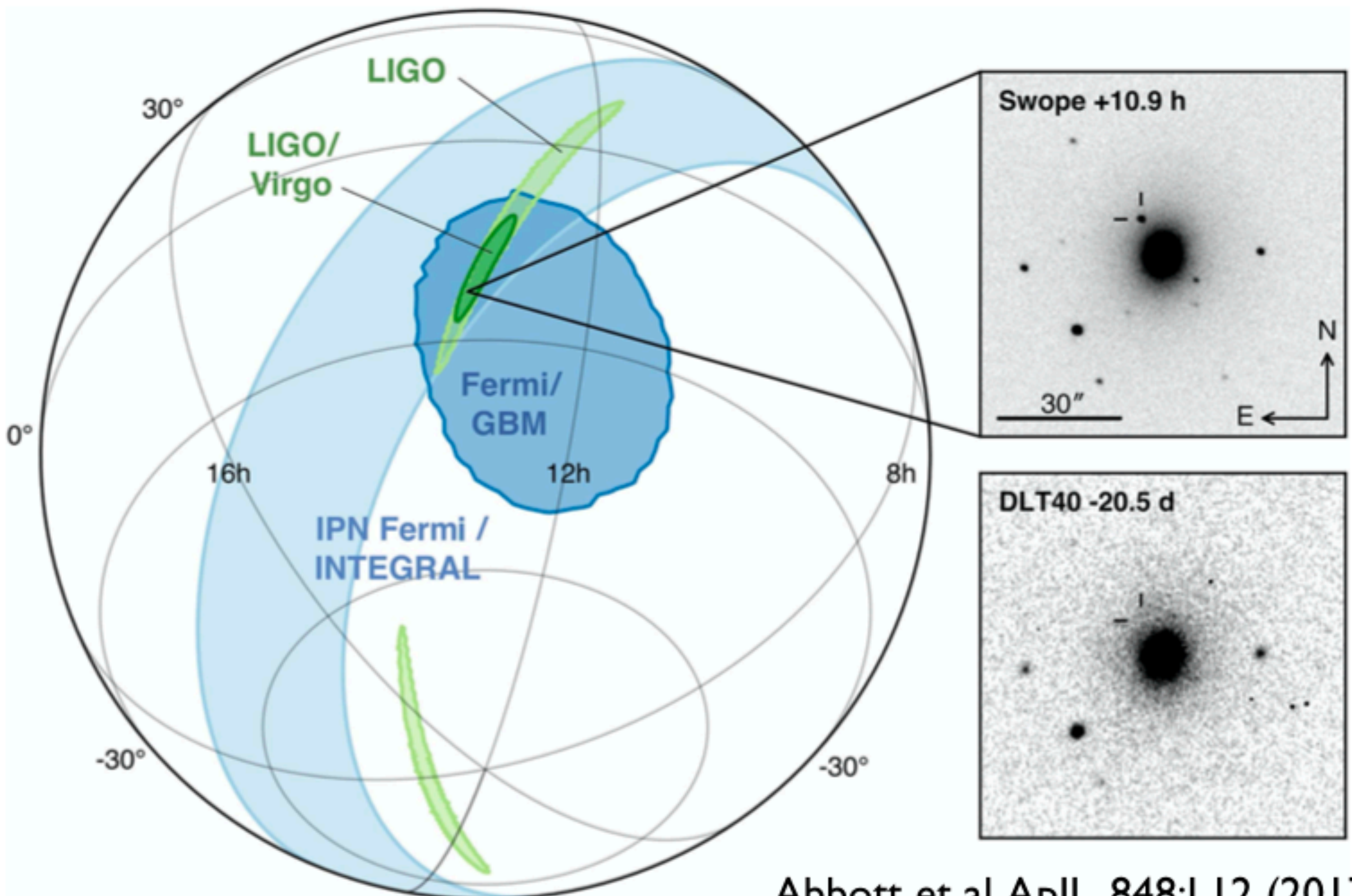
GW170817 + GRB170817A + SSS17a/AT 2017gfo

2017 Aug 17:
Multi-messenger astronomy
using GW became a reality!!



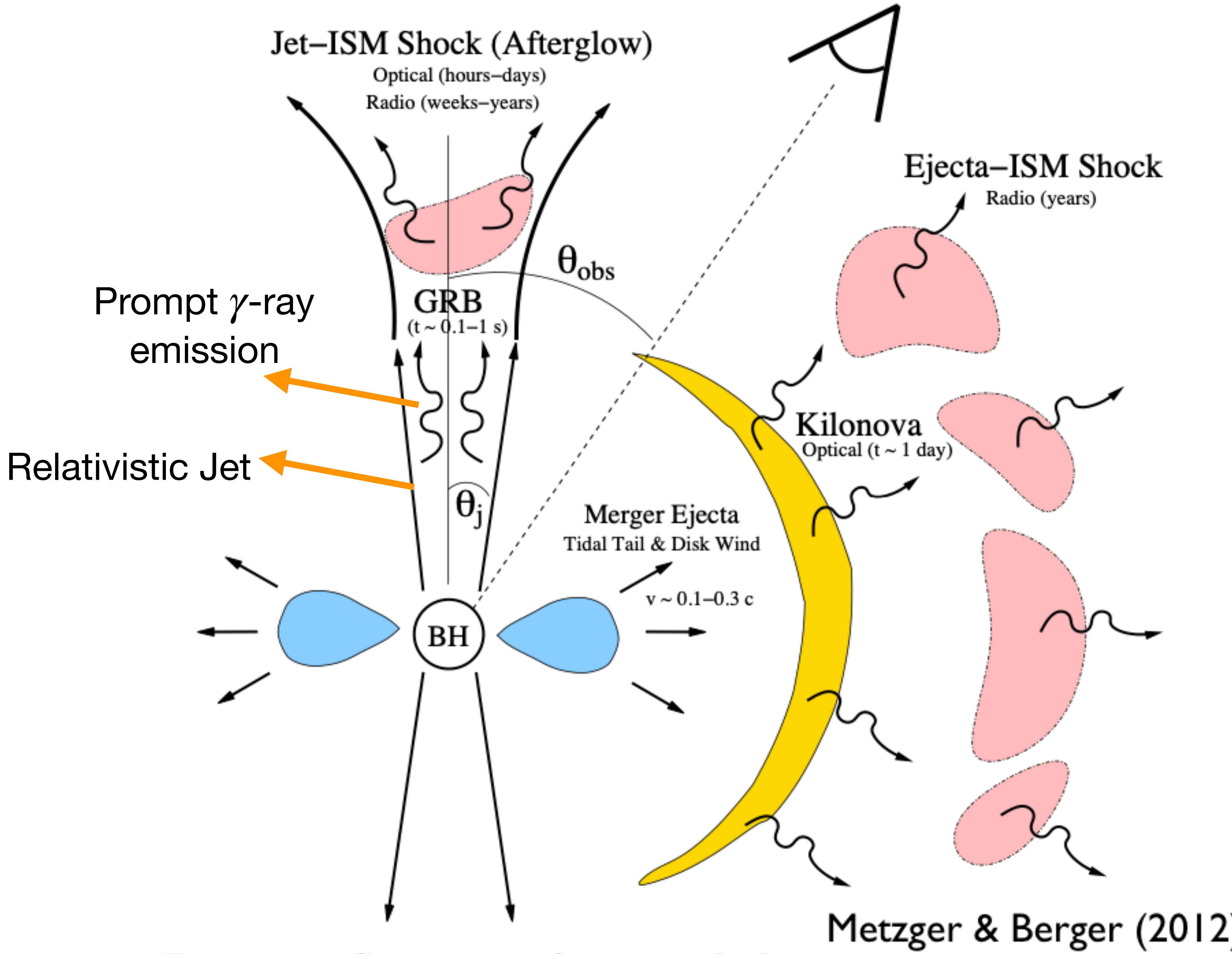
Abbott et al, ApJL, 848:L12 (2017)

GW170817: Sky localization



Abbott et al, ApJL, 848:L12 (2017)

EM counterparts of BNS mergers



Complementary Information

GW Observations

- Masses and spins
- Tidal deformability
- Sky location
- Distance
- Inclination angle

EM Observations

- Precise sky location
- Redshift
- Ejecta properties
- Jet properties such as opening angle, viewing angle etc.

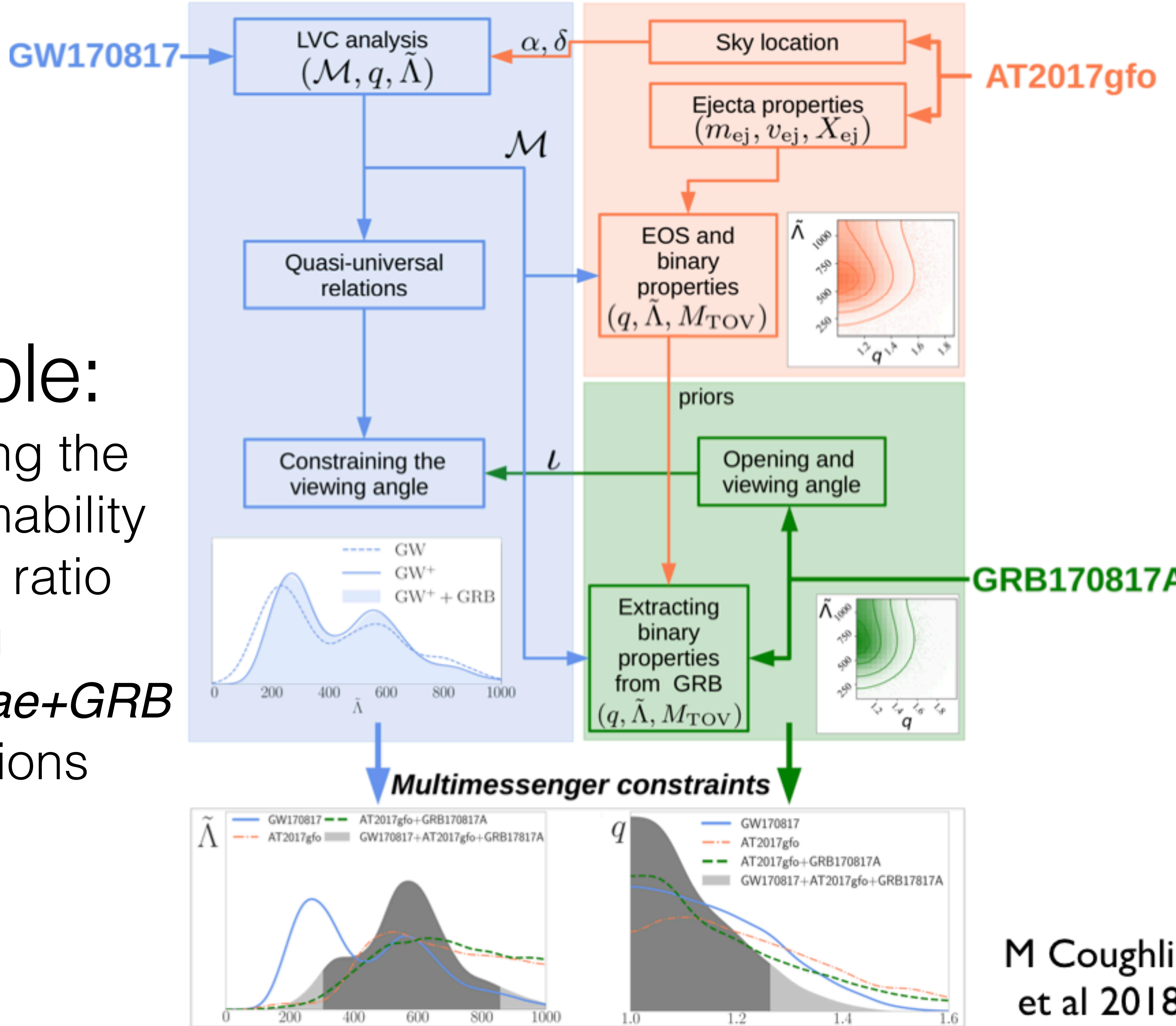
More complete picture of the source!

Physics, Astrophysics and cosmology with Multi-messenger Observations

- Measurement of Hubble constant
- Probing the Neutron Star Equation of State
- Probing the structure of the jets
- Speed of gravity test
- Probing the environment in which the merger happens and hence to probe the formation scenarios
- Many more . .

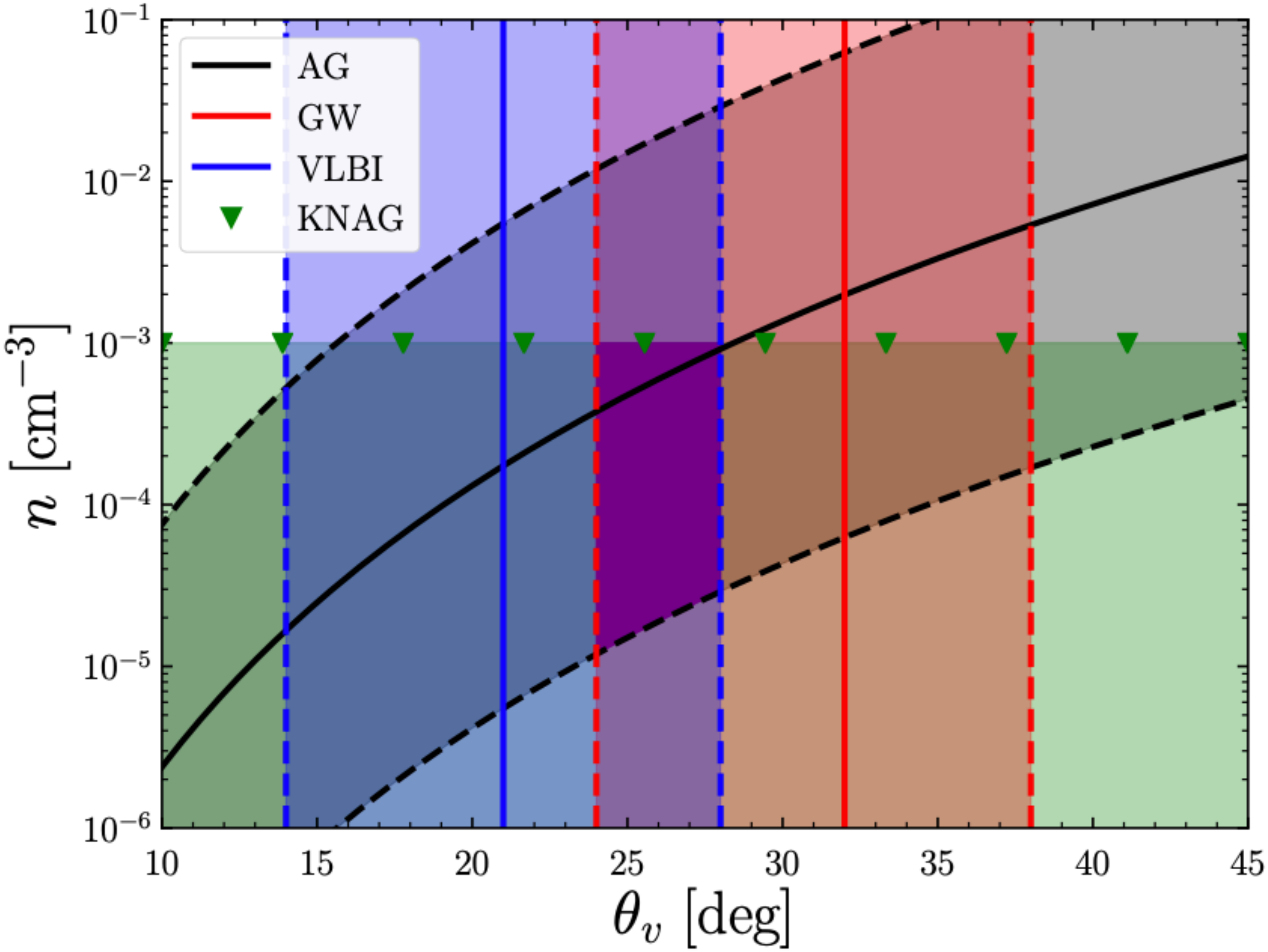
Example:

Constraining the tidal deformability and mass ratio using *GW+Kilonovae+GRB* observations



M Coughlin et al 2018

Example: Constraining the environment



Afterglows +
GW +
Kilonovae +
Kilonovae afterglows

Helps probe the formation scenarios

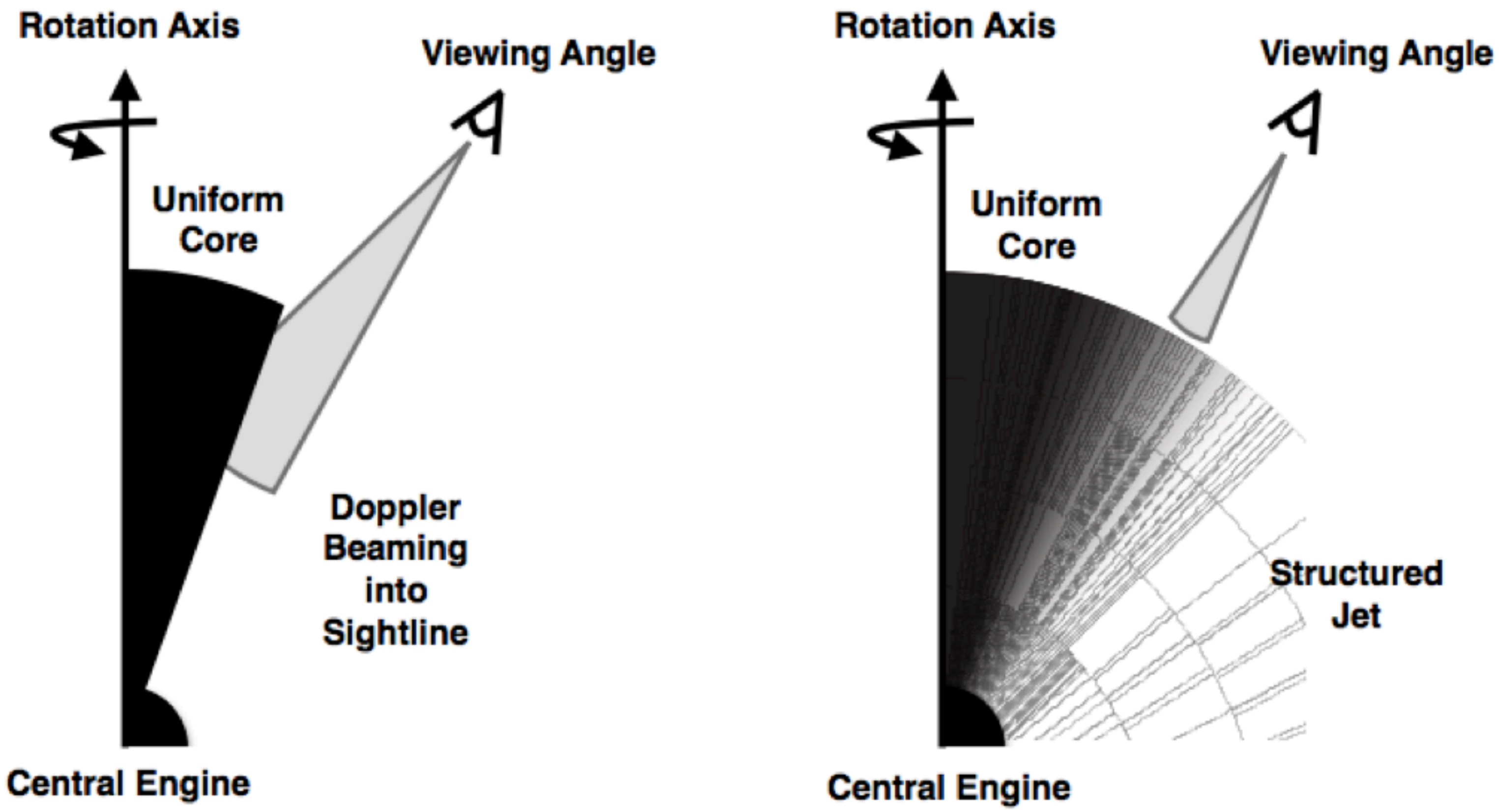
Raphaël Duque et al (2019)

Rest of the talk

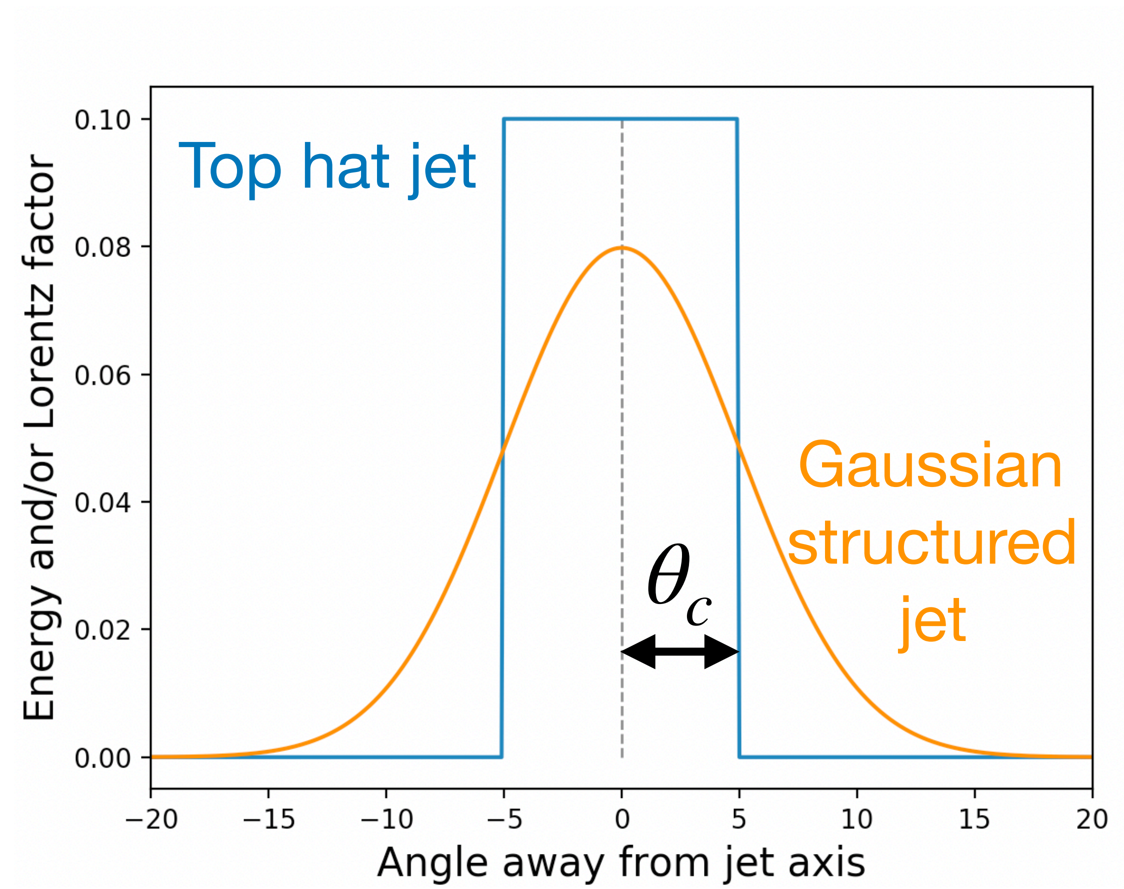
- Empirical models of GRB jet structure and mappong them to observable quantities
- Predictions for the future joint BNS-short GRB detections.
- Discussion on GW190425 and the missing EM counterpart.

Works done in collaboration with L. Resmi, K.G. Arun and Sreelakshmi Mohan

Structure of the GRB Jet



LVC+Fermi+Integral, ApJL, 848:L13, (2017)



For GW+GRB170817 :

- Afterglows showed excellent agreement with structured jet models [Margutti et al. 2018; Lazzati et al. 2017; Lyman et al. 2018; D'Avanzo et al. 2018; Resmi et al. 2018; Lamb et al. 2019].
- Top-hat jet model could not explain the observed features (though successful to explain the classical short-GRBs!)

Jet structure vs Observables

Fluence (erg/sec)
(EM observable)

Total energy
emitted in γ-rays

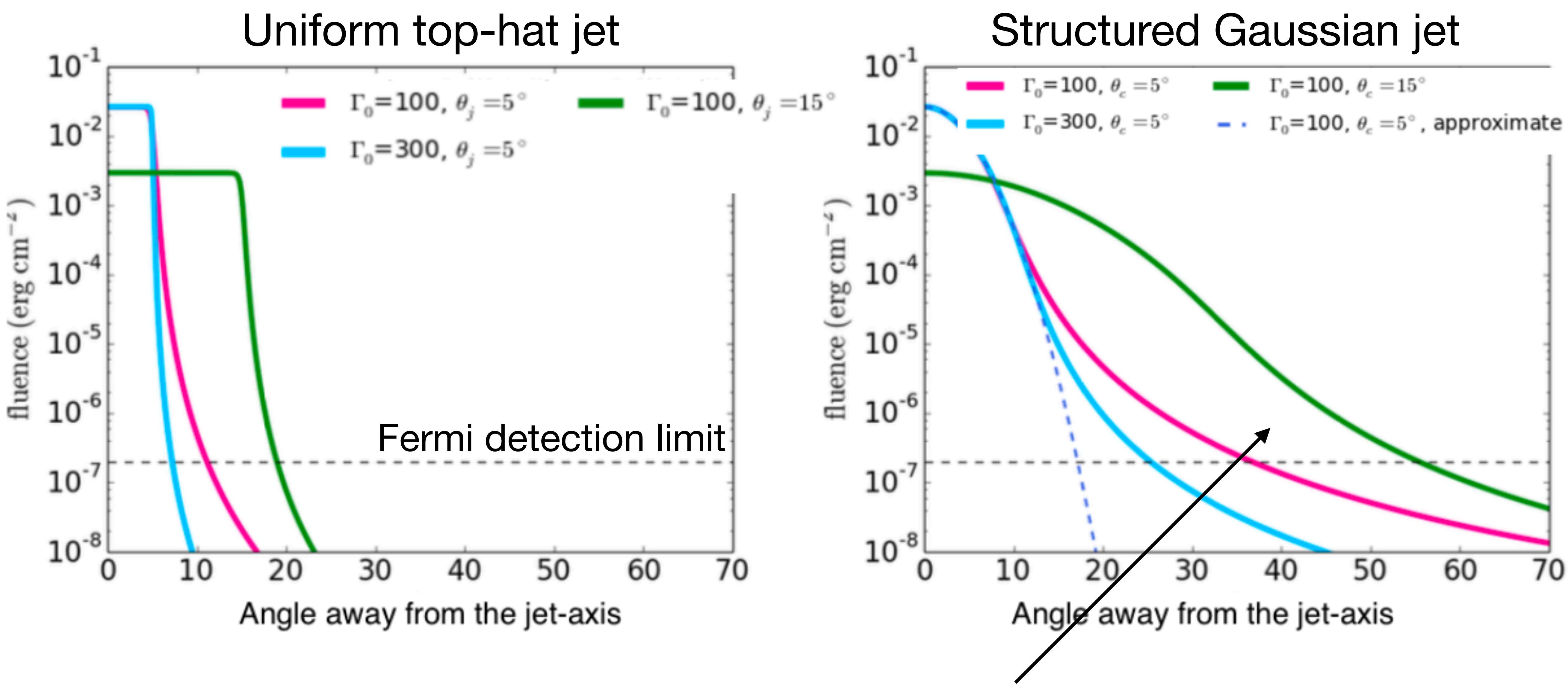
Jet structure profiles for energy
and Lorentz factor
(Model assumption)

$$F(\theta_v) = \frac{E_{\mathrm{tot},\gamma}}{16\pi^2 d_L^2} \int d\Omega \frac{\epsilon(\theta)}{\Gamma(\theta)^4 \left[1 - \beta(\theta)\cos\alpha(\theta,\theta_v)\right]^3}.$$

Distance and Inclination
(Possible inputs from GW observation)

Donaghy (2005), Salafia et al (2014), S Mohan, MS, Resmi (2019)

γ-ray Fluence vs Viewing angle



Structured Gaussian jets: detectable up to relatively larger viewing angles compared to uniform top-hat jets

S Mohan , **MS**, L Resmi

Forecasting future detection rates

Uses a simulated population of BNS mergers and their γ-ray counterparts distributed uniformly in co-moving volume.

Three observing scenarios considered:

1. Untriggered BNS detections

   - Detections from all-sky GW search

2. Short-GRB triggered BNS detections

   - Detections from searches within the spatial and temporal window around short-GRBs triggers.

   - Lower detection threshold compared to Untriggered.

3. Joint BNS-short-GRB detections

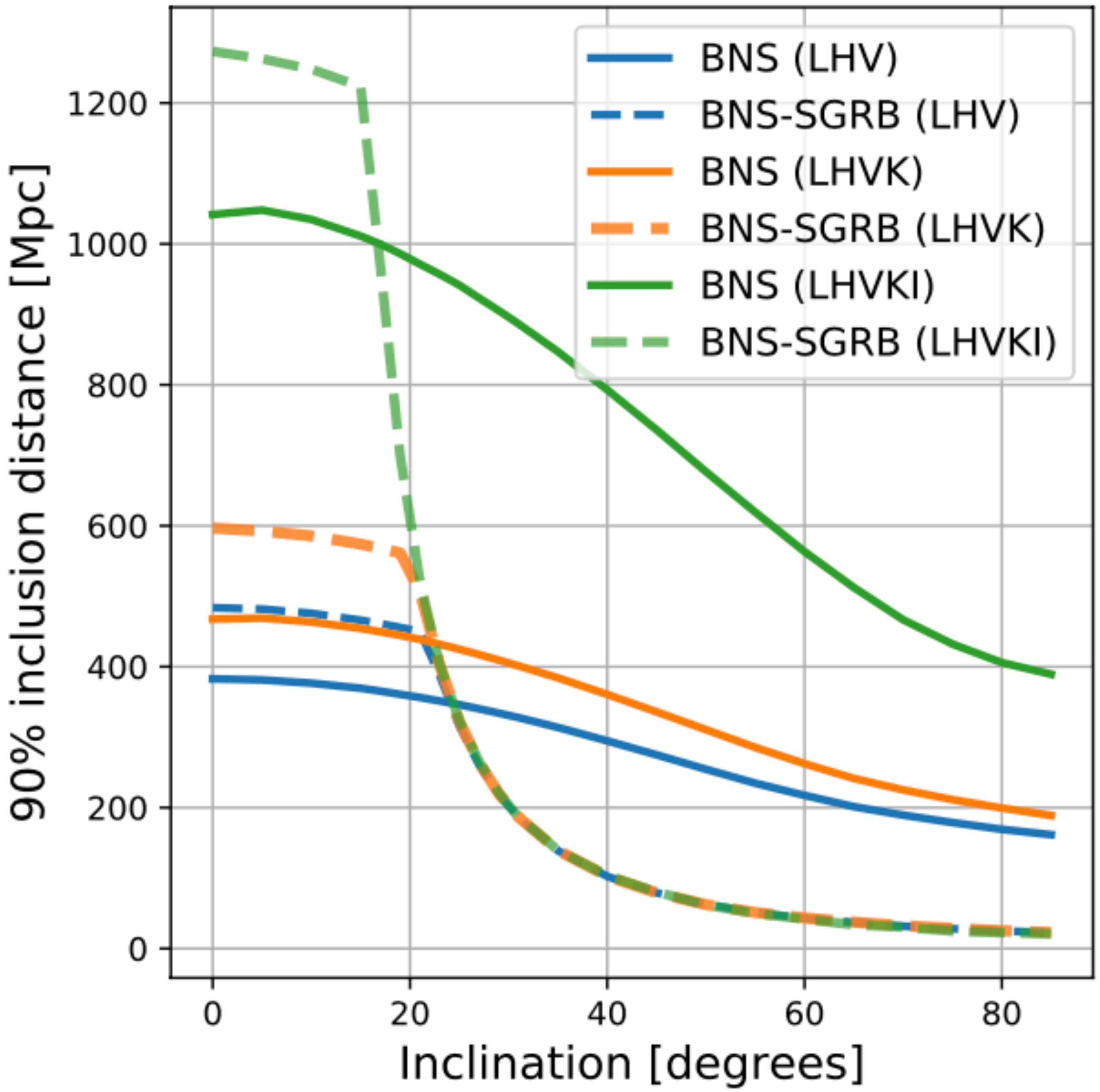
Assumption: All BNS mergers produce structured Gaussian jets with

$$\theta_c = 5^\circ, \Gamma = 100 \ \& \ E_{\gamma,tot} = 10^{50} erg$$

MS (2019)

Distance Reach

How far can the detections be from ?



- LHV: projected O3 sensitivities
- LHVK (including Kagra): At designed sensitivities.
- LHVKI: LIGO at Aplus and V+K at designed sensitivities.
- Joint detections at large inclination possible only if the source nearby

Sensitivities are taken from *https://dcc.ligo.org/LIGO-T1500293/public*

MS (2019)

Expected Future Detection Rates

Case	Any ι	$\iota \leq 20°$	$\iota > 20°$
LHV			
Untriggered BNS	$5.7^{+13.7}_{-4.8}$	$1.1^{+2.6}_{-0.9}$	$4.6^{+11.1}_{-3.9}$
Total BNS	$6.5^{+15.9}_{-5.6}$	$1.7^{+4.1}_{-1.5}$	$4.8^{+11.8}_{-4.1}$
Joint BNS-SGRB	$2.2^{+5.5}_{-1.9}$	$1.3^{+3.2}_{-1.1}$	$0.9^{+2.3}_{-0.8}$
LHVK			
Untriggered BNS	$23.5^{+57.3}_{-20.1}$	$4.3^{+10.5}_{-3.7}$	$19.2^{+46.7}_{-16.4}$
Total BNS	$26.7^{+64.8}_{-22.8}$	$6.8^{+16.4}_{-5.8}$	$19.9^{+48.4}_{-17.0}$
Joint BNS-SGRB	$8.1^{+19.6}_{-6.9}$	$5.1^{+12.3}_{-4.3}$	$3.0^{+7.3}_{-2.6}$
LHVKI			
Untriggered BNS	$164.8^{+400.6}_{-140.7}$	$31.0^{+75.4}_{-26.5}$	$133.8^{+325.3}_{-114.2}$
Total BNS	$178.4^{+433.4}_{-152.2}$	$44.1^{+107.1}_{-37.6}$	$134.3^{+326.3}_{-114.6}$
Joint BNS-SGRB	$34.6^{+84.3}_{-29.6}$	$30.3^{+73.7}_{-25.9}$	$4.3^{+10.6}_{-3.7}$

Numbers shown are detections per year

MS 2019 (arXiv:1905.00314)

MS (2019)

GW190425 + No EM counterpart

(Upper limit from *INTEGRAL*)

What does it imply?

Saleem+ (2019)

GW190425

Information from the public alert (GCN 24168, 24228)

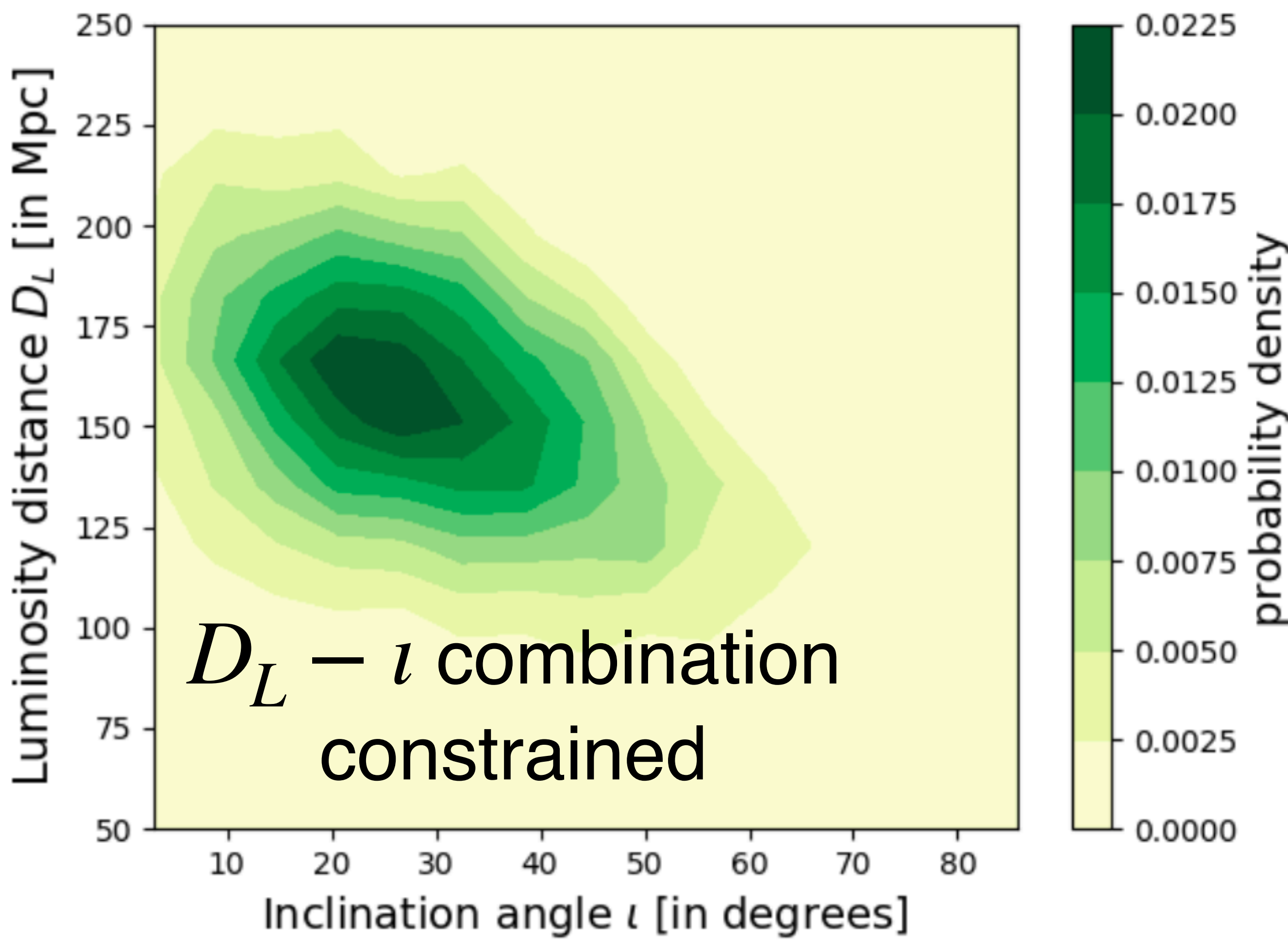
1. p_{astro} (BNS) >> 99%
2. Observed by the network of LIGO Livingston (L1) and Virgo (V1). SNR at Virgo is below the threshold.
3. Luminosity distance estimate is given by $D_L = 155 \pm 41$Mpc

GW polarisations

$$h_+ \sim \frac{1 + \cos^2 \iota}{D_L}$$

$$h_\times \sim \frac{2 \cos \iota}{D_L}$$

+ Sensitivity →



MS, L Resmi, KG Arun, S Mohan (2019)

Constraining the GRB energetics from the non-detection of an EM counterpart

INTEGRAL observation

Prior assumption (Astrophysically motivated)

We assume a Gaussian structure

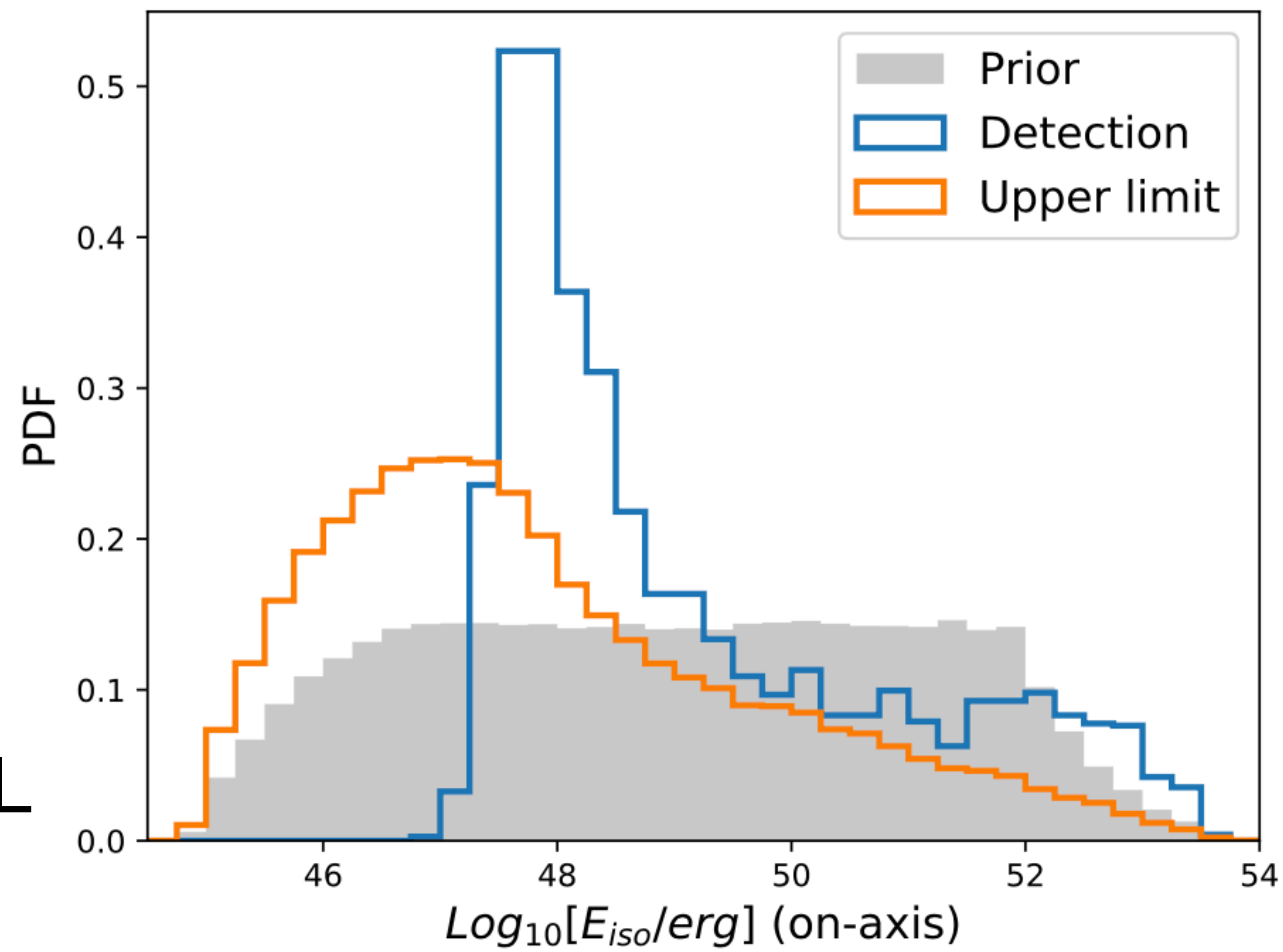
$$F(\theta_v) = \frac{E_{\mathrm{tot},\gamma}}{16\pi^2 d_L^2} \int d\Omega \frac{\epsilon(\theta)}{\Gamma(\theta)^4 \left[1 - \beta(\theta)\cos\alpha(\theta, \theta_v)\right]^3} .$$

Distance and Inclination
(The combination is constrained from GW)

Constraining the GRB energetics from the non-detection of an EM counterpart

- Jet opening angle assumed between $3^\circ < \theta_c < 20^\circ$

- Fluence upper limit applied ($2 \times 10^{-7} erg/cm^2$) corresponding to INTEGRAL upper limit reported (GCN24178)



A short-GRB prompt emission similar to GRG170817can not be ruled out for this candidate event.

MS, L Resmi, KG Arun, S Mohan (2019)

Recently reported detection of GRB counterpart

arXiv.org > astro-ph > arXiv:1912.13112

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Astrophysics > High Energy Astrophysical Phenomena

Observation of the second LIGO/Virgo event connected with binary neutron star merger S190425z in the gamma-ray range

A.S. Pozanenko (1,2), P.Yu. Minaev (1), S.A. Grebenev (1), I.V. Chelovekov (1) ((1) Space Research Institute, Russian Academy of Sciences, (2) National Research University "High School of Economics")

(Submitted on 30 Dec 2019)

Observations of the gravitational-wave (GW) event S190425z registered by the LIGO/Virgo detectors

Summary

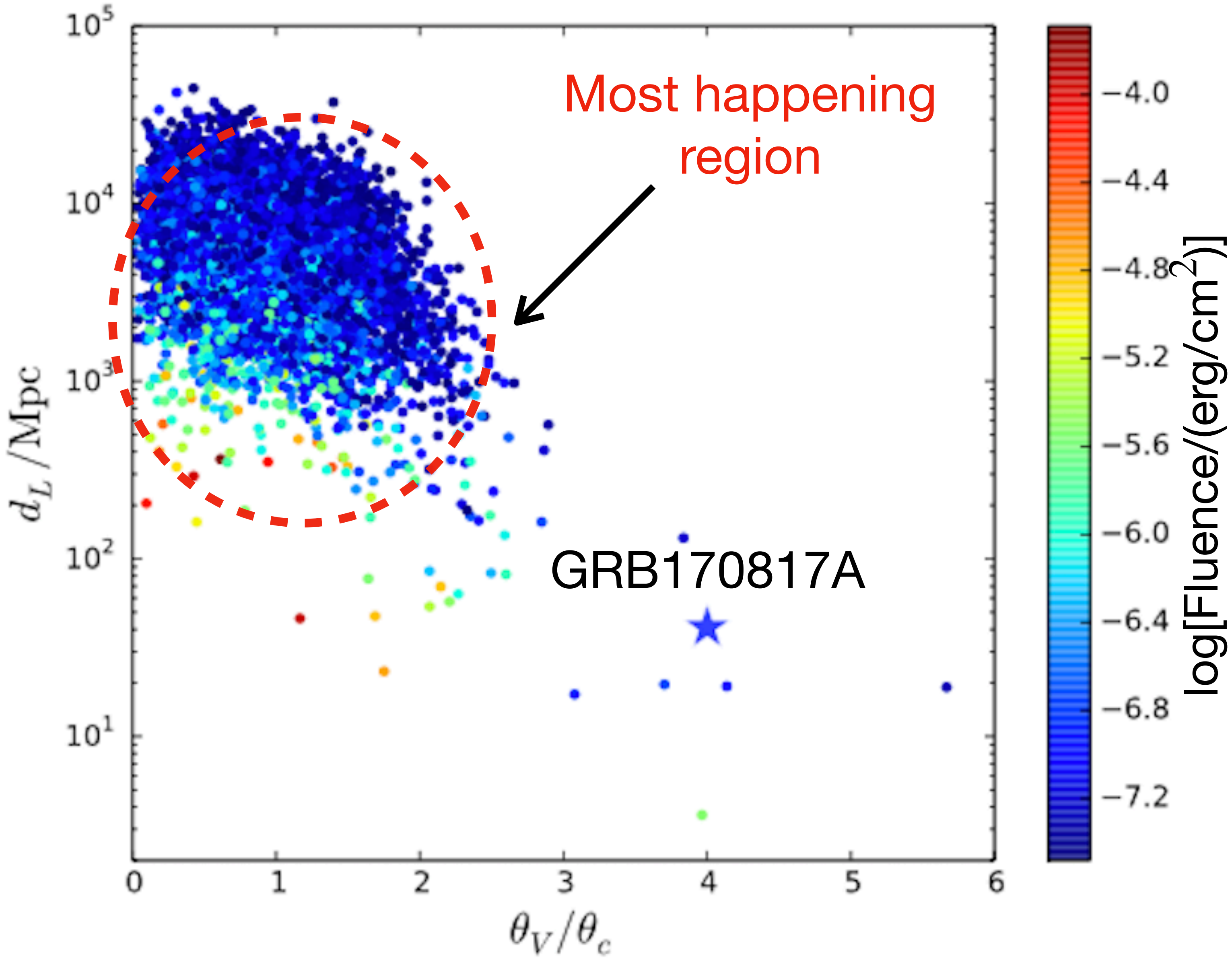
- Joint BNS-short-GRB detections will be rare events in the era of second generation GW detectors.
- GW190425 might have produced relativistic jets but missed because of it’s distance and inclination angle.
- We showed that even non-detections of EM counterparts can be used to extract physical properties of a possible counterpart.

The upcoming few observations will be very important for understanding the physics of EM counterparts

Thank you!

Backup Slides

Population of short-GRBs with Gaussian jets

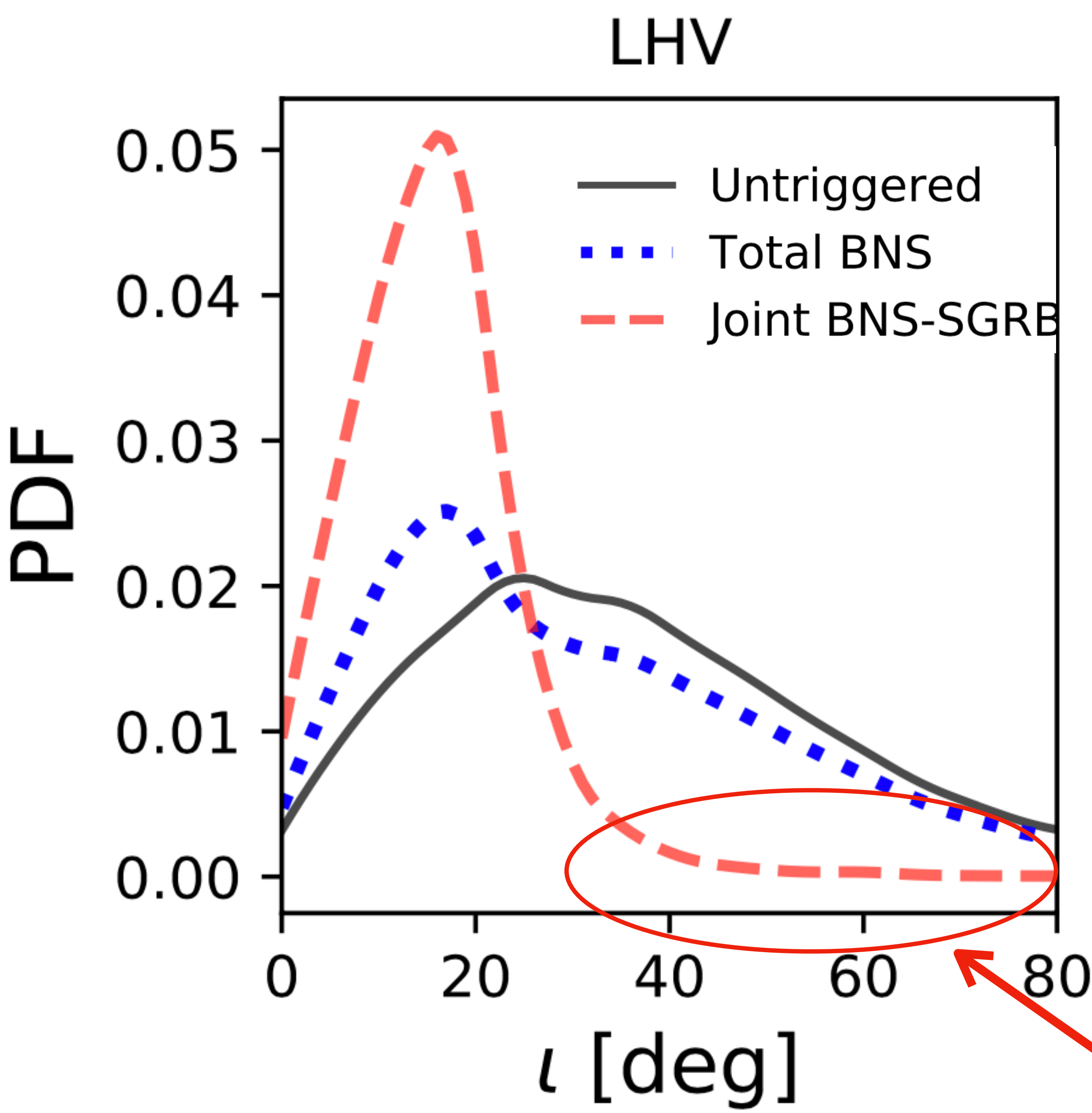


- From simulations of short-GRBs up to redshift ~ 5.
- The population assumes to follow the star formation rate by *Madau&Dickinson (2014)* convolved by a power-law delay time distribution.
- Prompt γ-ray fluence above Fermi-GBM limit.

GRB170817A turns out to be a rare event!

S Mohan , **MS**, L Resmi (in preparation)

Distribution of inclination angles



MS 2019 (arXiv:1905.00314)

- Assumes projected O3 sensitivities and SNR thresholds
  - Network > 10
  - Single detector > 4
- Untriggered BNS detections follow Schutz distribution $p(\iota) \propto (1 + 6\cos^2\iota + \cos^4\iota)^{3/2}\ \sin\iota$ (Schutz (2011))
- Total BNS detections (Untriggered + Triggered). and the joint detections deviate from the Schutz distributions
- Joint detections are very unlikely from large inclinations.