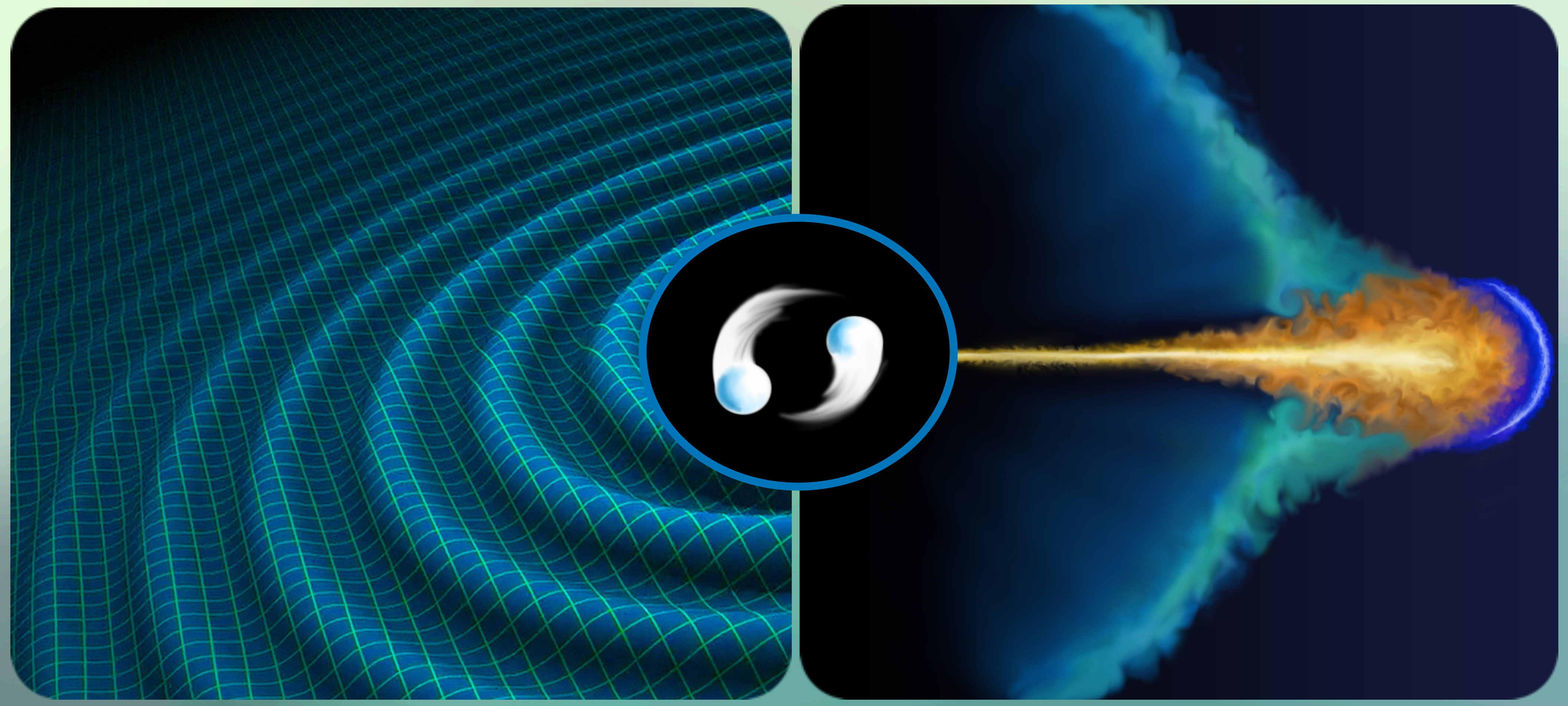
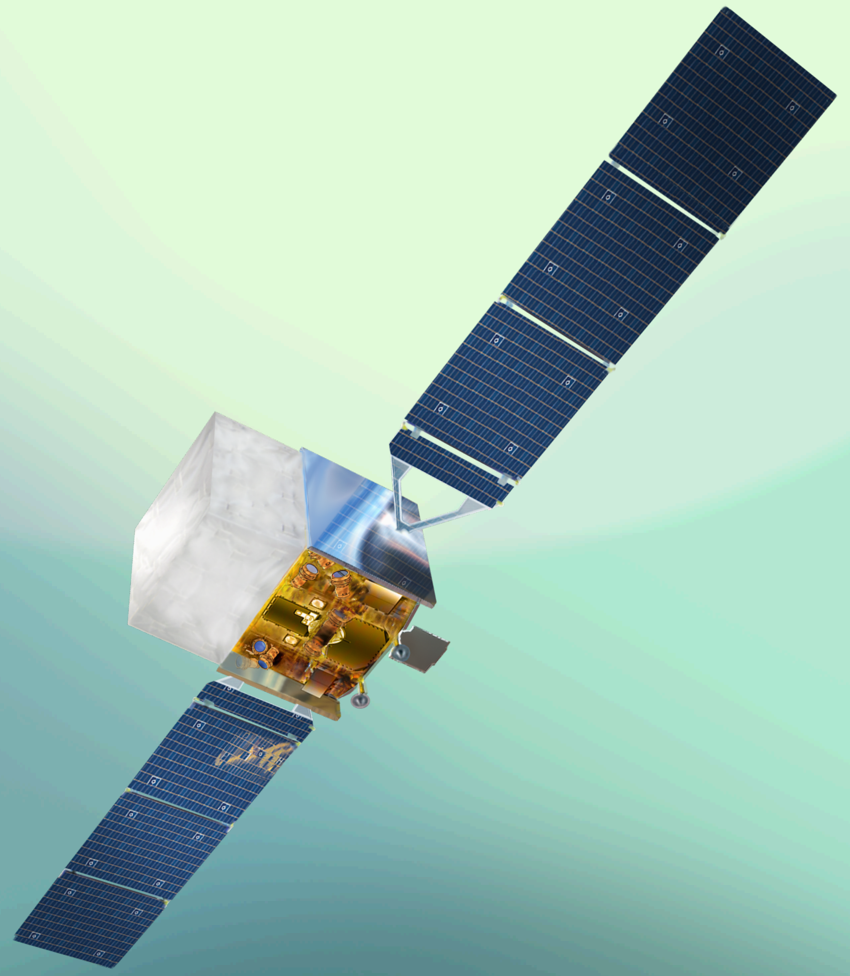
# Detecting High-Energy counterparts of gravitational waves with the Fermi Telescope

## Past achievements, current efforts and future challenges of multi-messenger astronomy

**Samuele Ronchini, PennState University**





# Outline

## Past achievements:

- ☆ GW170817 and GRB170817A
- ☆ Detection of long merger-driven GRBs

## Current efforts:

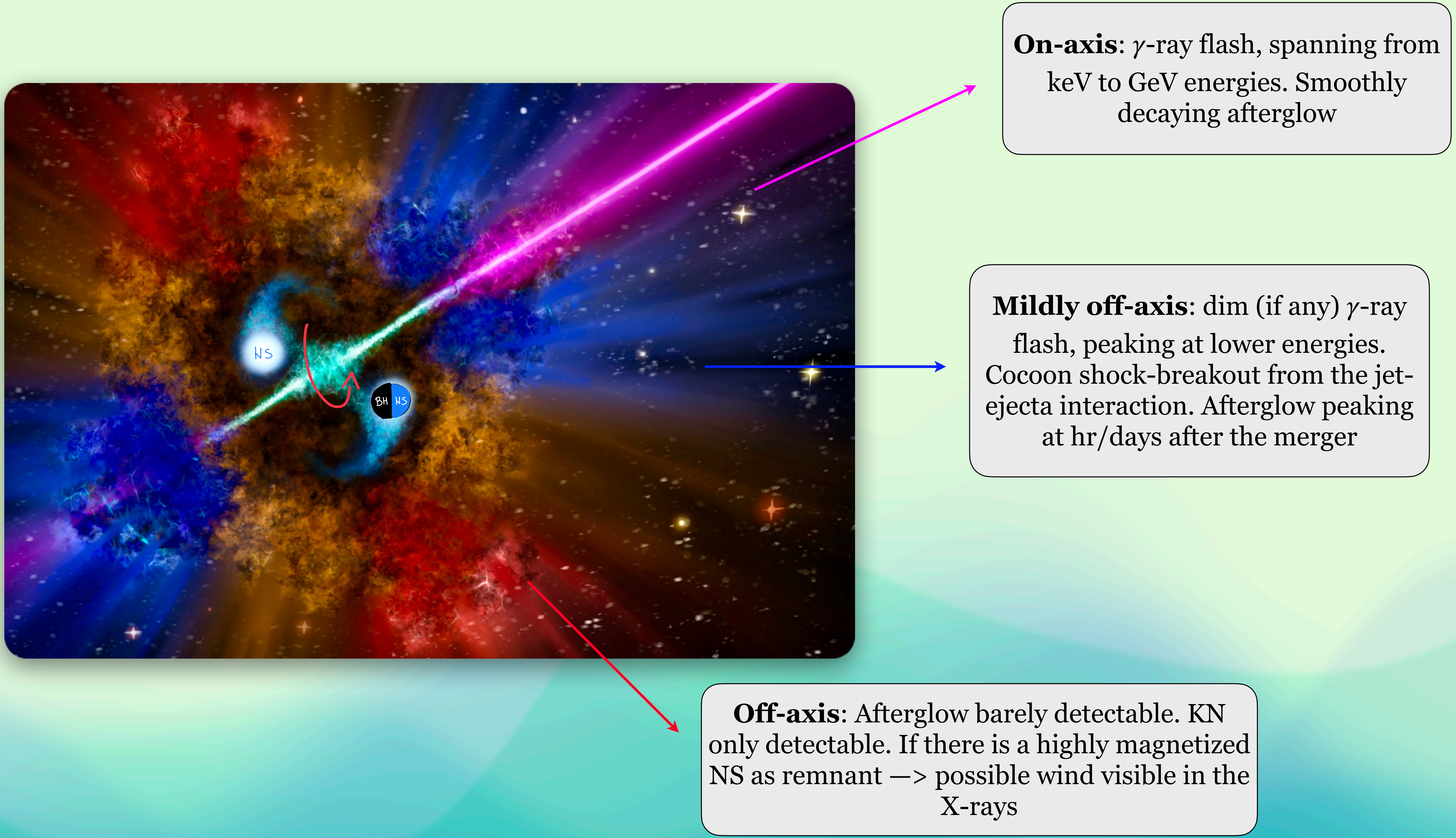
- ☆ Real-time monitoring of GW counterparts
- ☆ Subthreshold searches targeted on GW candidates

## Future challenges:

- ☆ Multi-messenger detections in the 3G GW era
- ☆ Synergies with other EM facilities

# Past achievements

# GWs and related high-energy EM counterparts



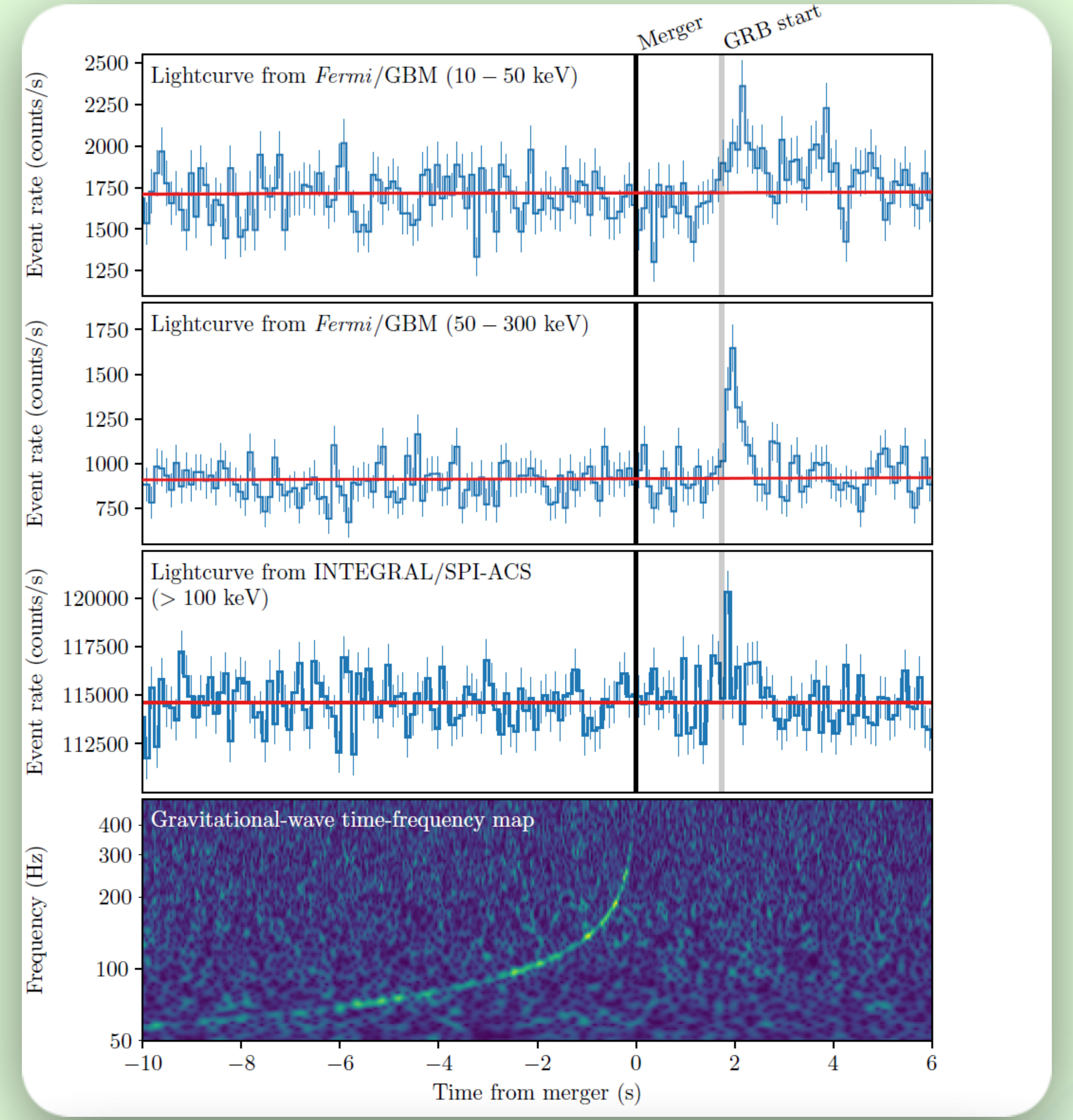
**On-axis**: $\gamma$-ray flash, spanning from keV to GeV energies. Smoothly decaying afterglow

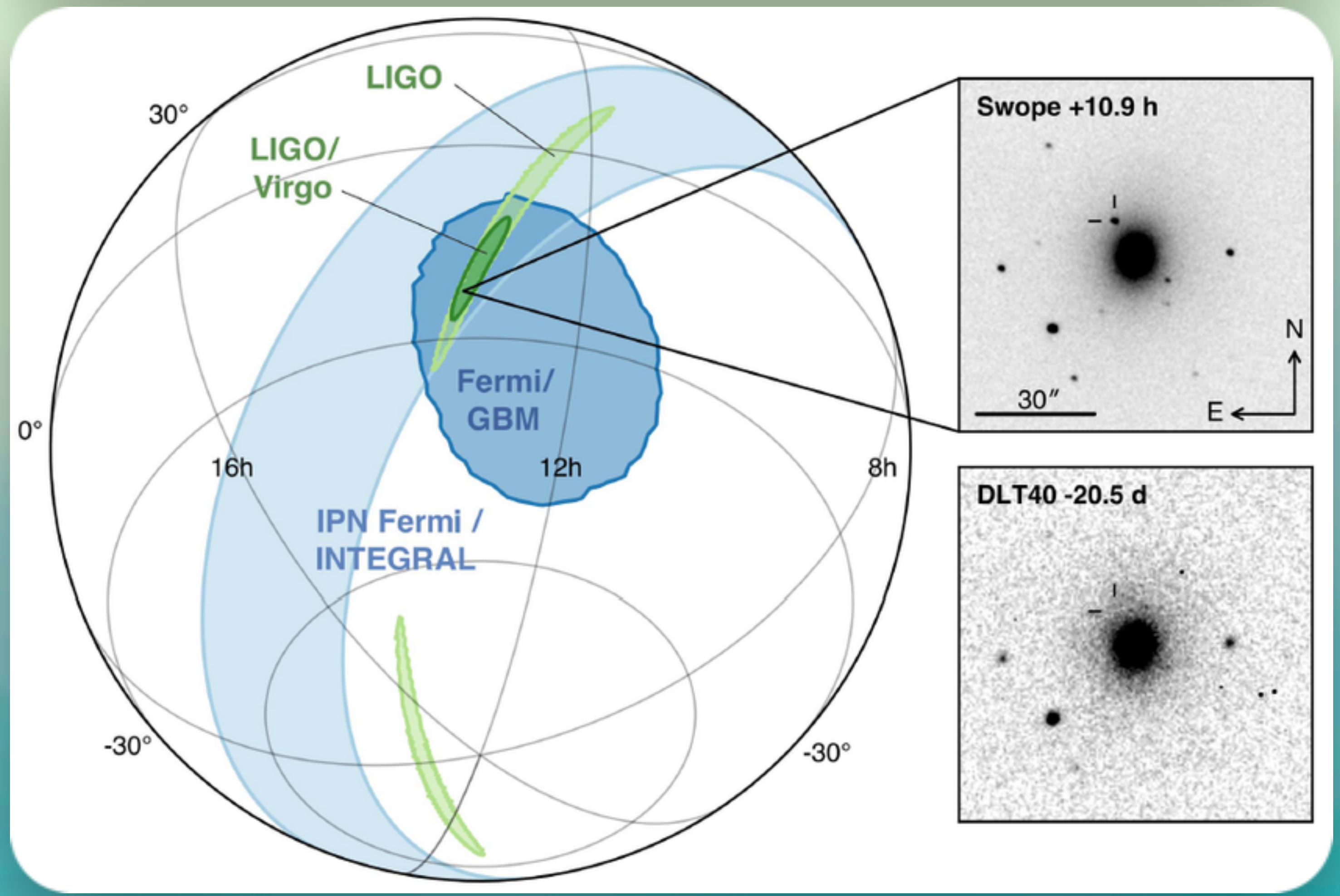
**Mildly off-axis**: dim (if any) $\gamma$-ray flash, peaking at lower energies. Cocoon shock-breakout from the jet-ejecta interaction. Afterglow peaking at hr/days after the merger

**Off-axis**: Afterglow barely detectable. KN only detectable. If there is a highly magnetized NS as remnant —> possible wind visible in the X-rays

# GW 170817 and GRB 170817A

Abbott+17





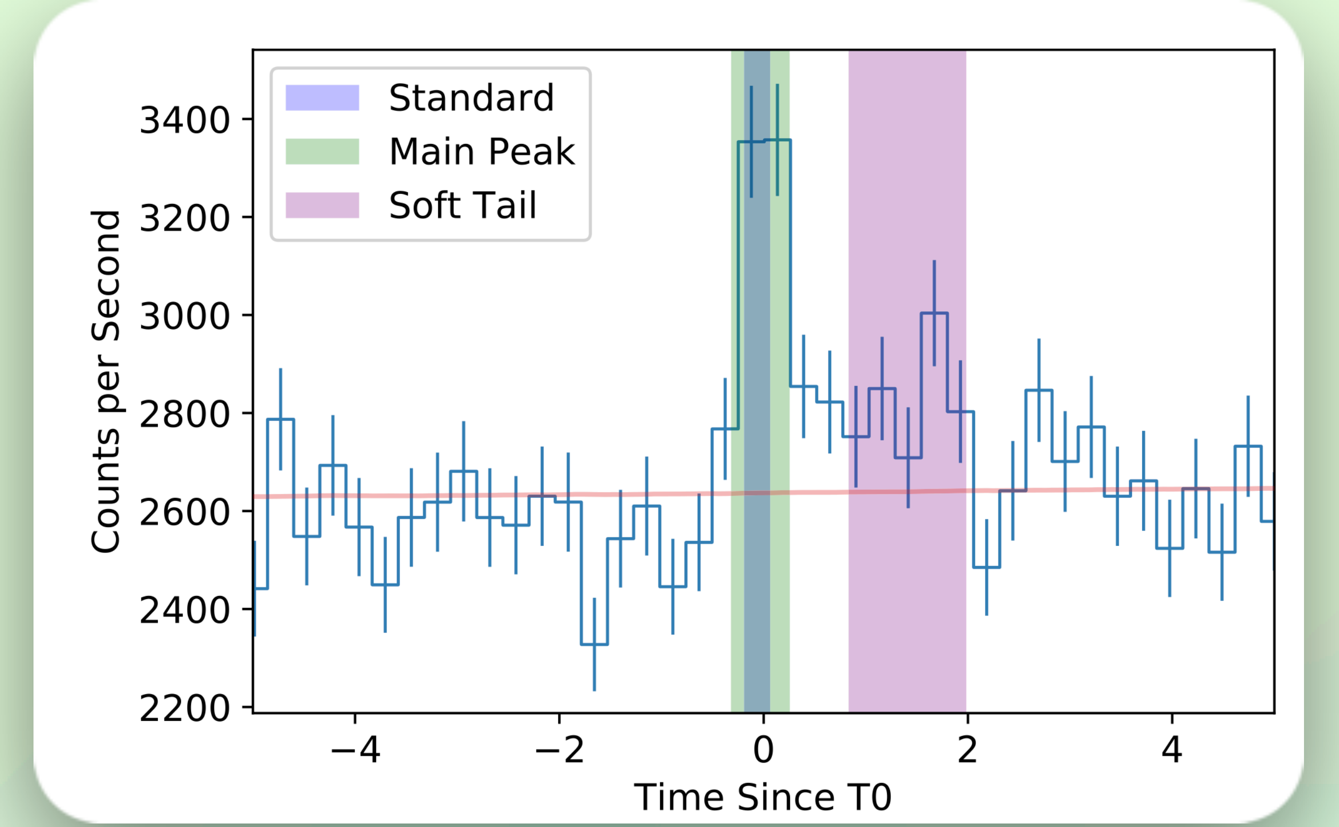
Dim $\gamma$-ray flash, 1.7 s after the merger of two NS. Duration ~2 sec

$$L_{iso} = 1.6 \times 10^{47} \mathrm{erg/s}$$

Probability of random Fermi-GW coincidence of

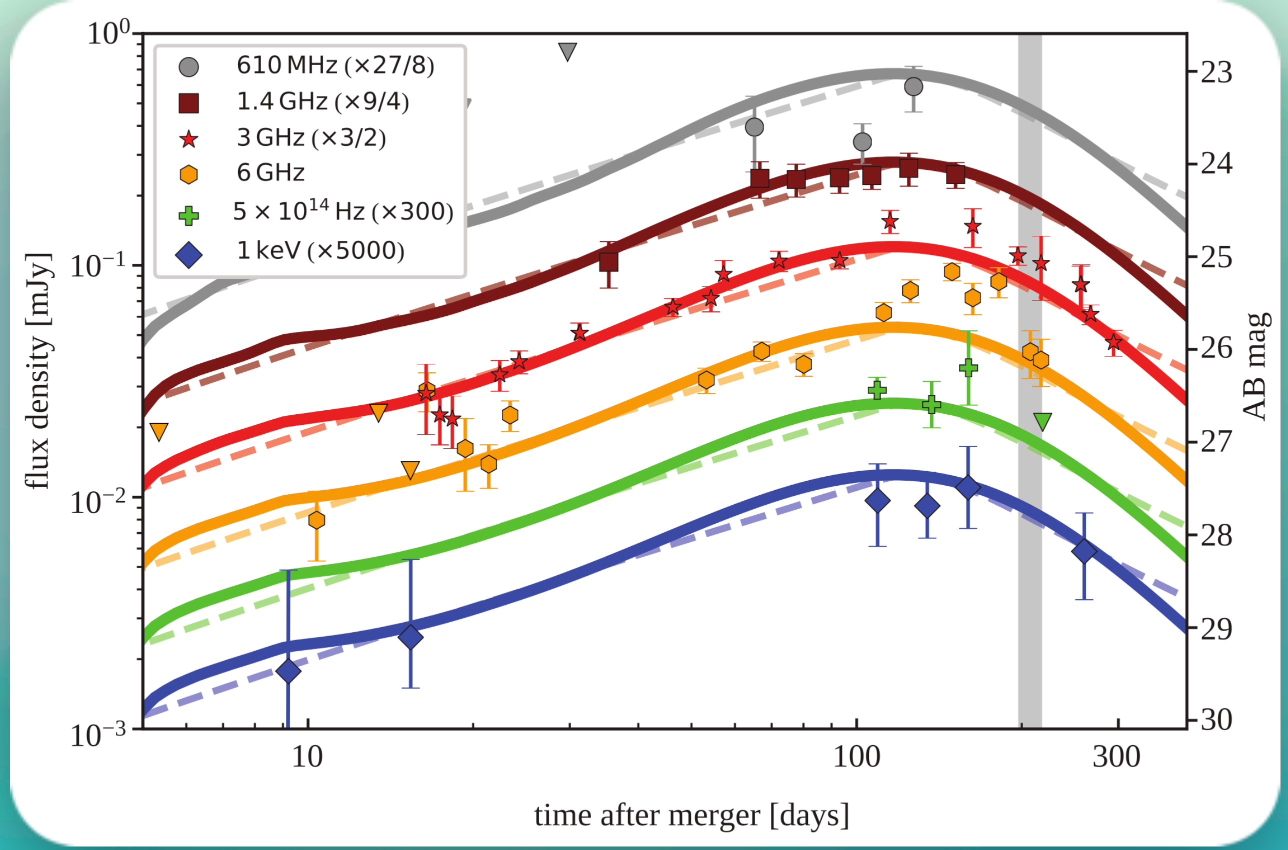
$$P_{coinc} = 5 \times 10^{-8} = 5.3\sigma$$

Goldstein+17

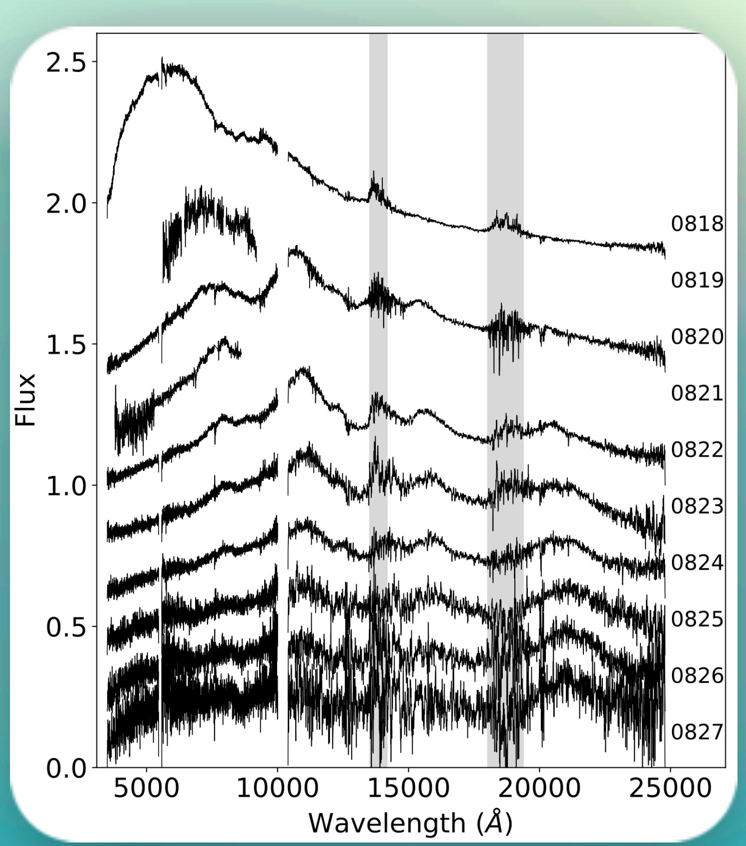


- Main peak (Comptonized spectrum E_p ~ 180 keV) +soft tail (thermal spectrum)
- Minimum time scale variability of ~ 0.125 s
- No evidence of precursor emission
- No evidence of extended emission (possibly related to a long-lived NS remnant)

D'Avanzo+18



Pian+17

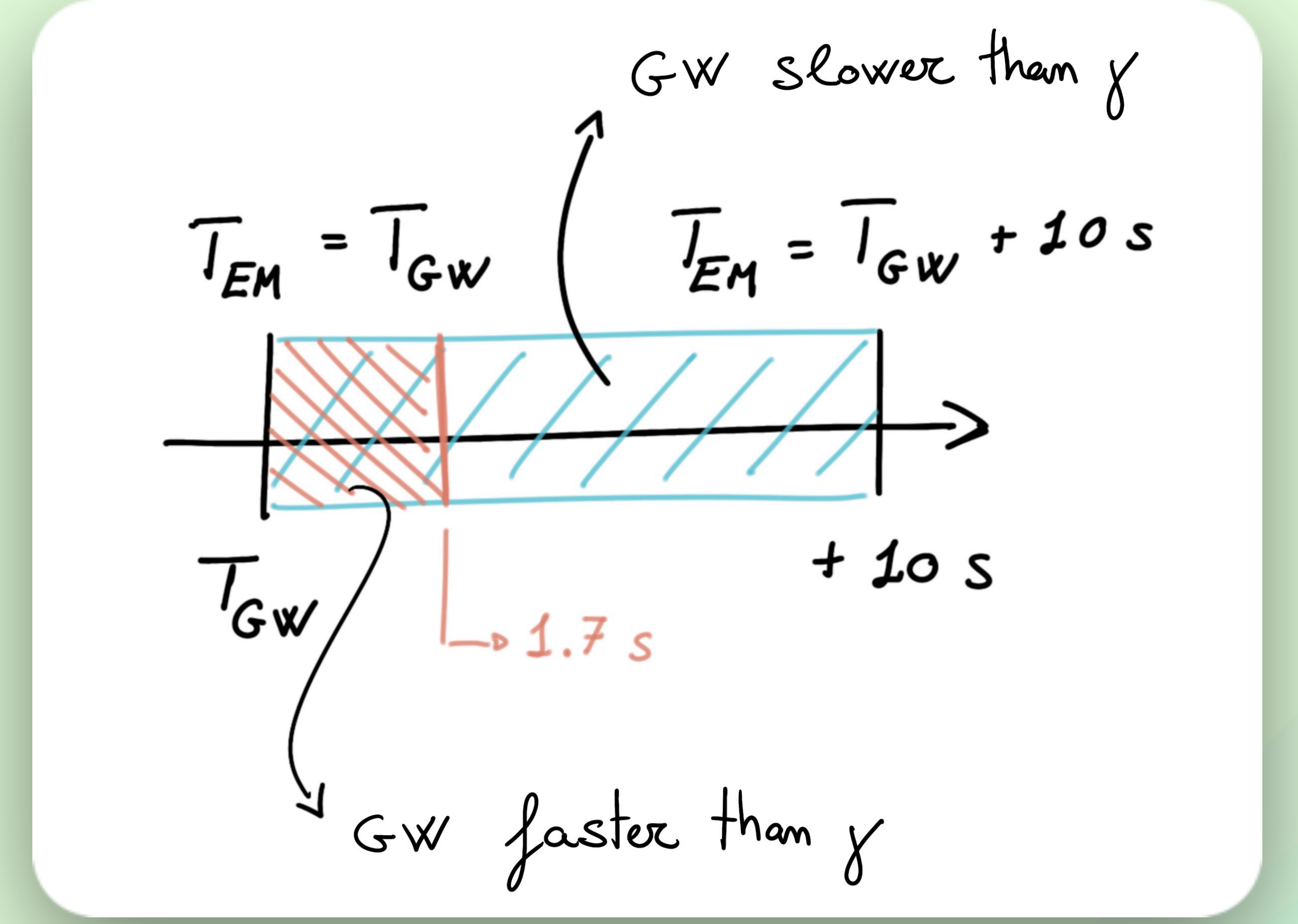


Broad picture completed with the observation of the GRB afterglow and Kilonova

# What we know thanks to Fermi: origin of the $\gamma$-GW delay

## Speed of gravity

Abbott+17



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

$$\Delta v = v_{GW} - v_{EM}$$

## Time delay budget

$$\Delta t = (1+z)(\Delta t_{jet} + \Delta t_{bo} + \Delta t_{GRB})$$

e.g., Zhang+18

Connected to:

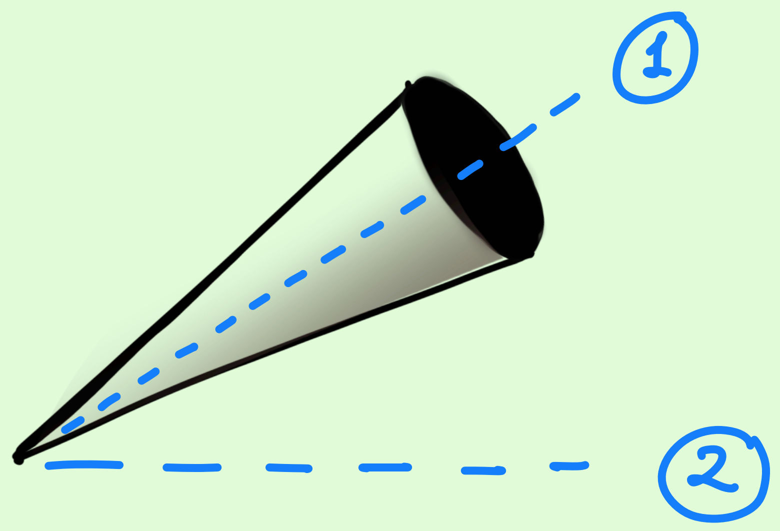
- Time needed to **launch the jet** —> merger remnant and launching mechanism
- Time to **break out** —> jet needs to move faster than the merger ejecta
- Time to **reach the dissipation radius** —> depending on the specific prompt emission mechanism

How to distinguish different scenarios with future joint detections:

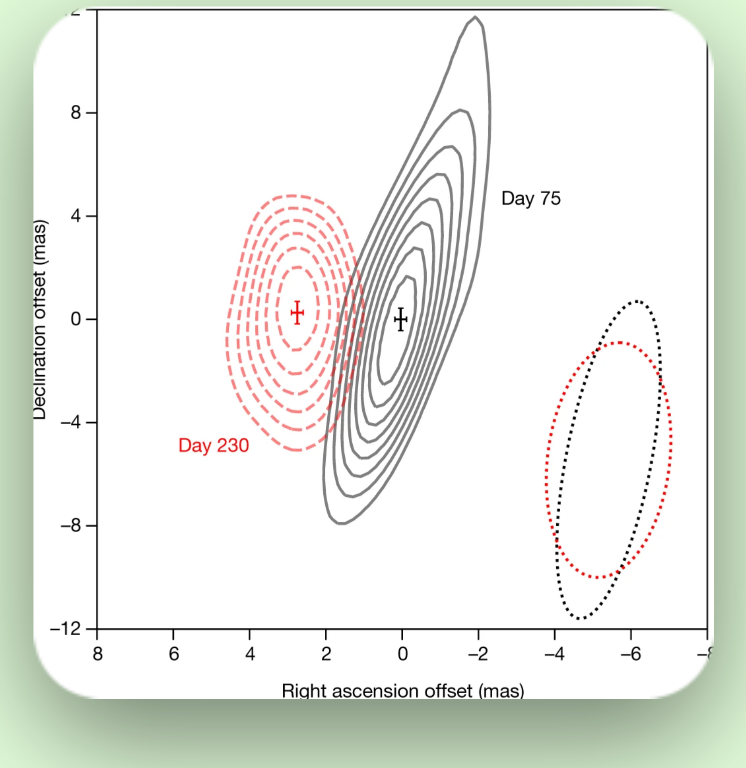
1. If the total delay is **independent** and uncorrelated to the **GRB duration**, the former is mainly controlled by the jet launching process
2. If the delay is **correlated** with the **GRB duration** (connected with the dissipation radius) —> jet formation delay and break-out negligible

# What we know thanks to Fermi: origin of the $\gamma$-ray flash

1. On-axis *intrinsically* faint jet
2. Off-axis top-hat jet?
3. Off-axis structured jet
4. Cocoon shock breakout

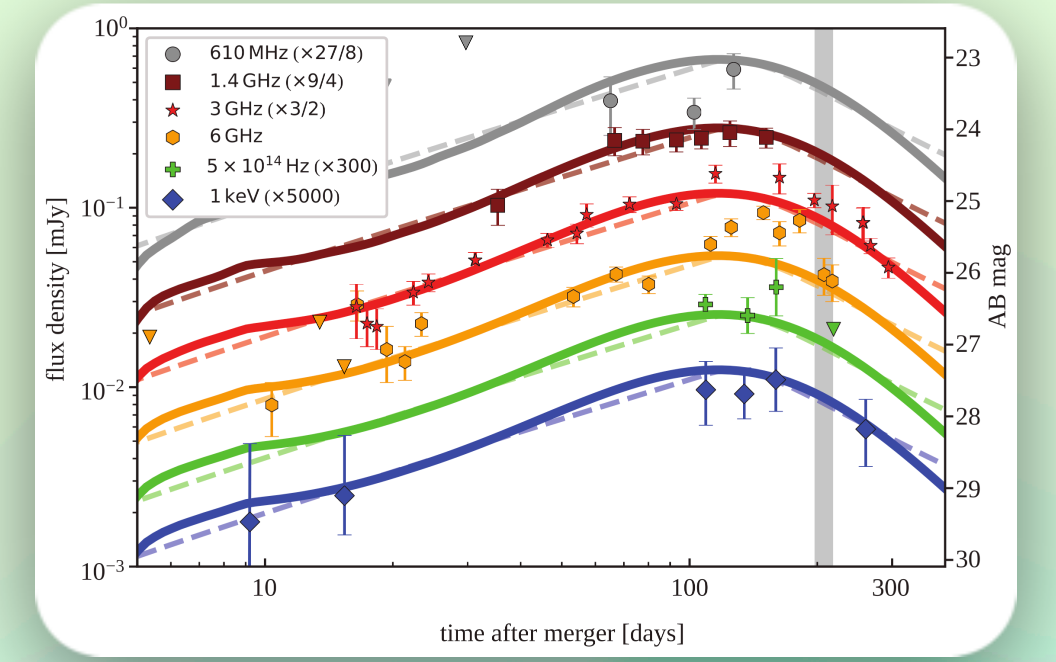


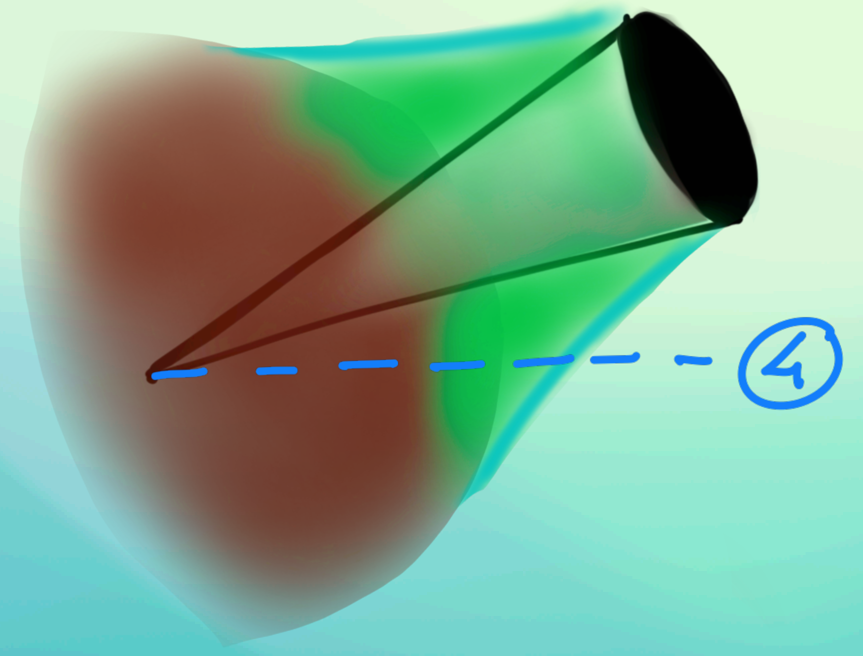
Mooley+18

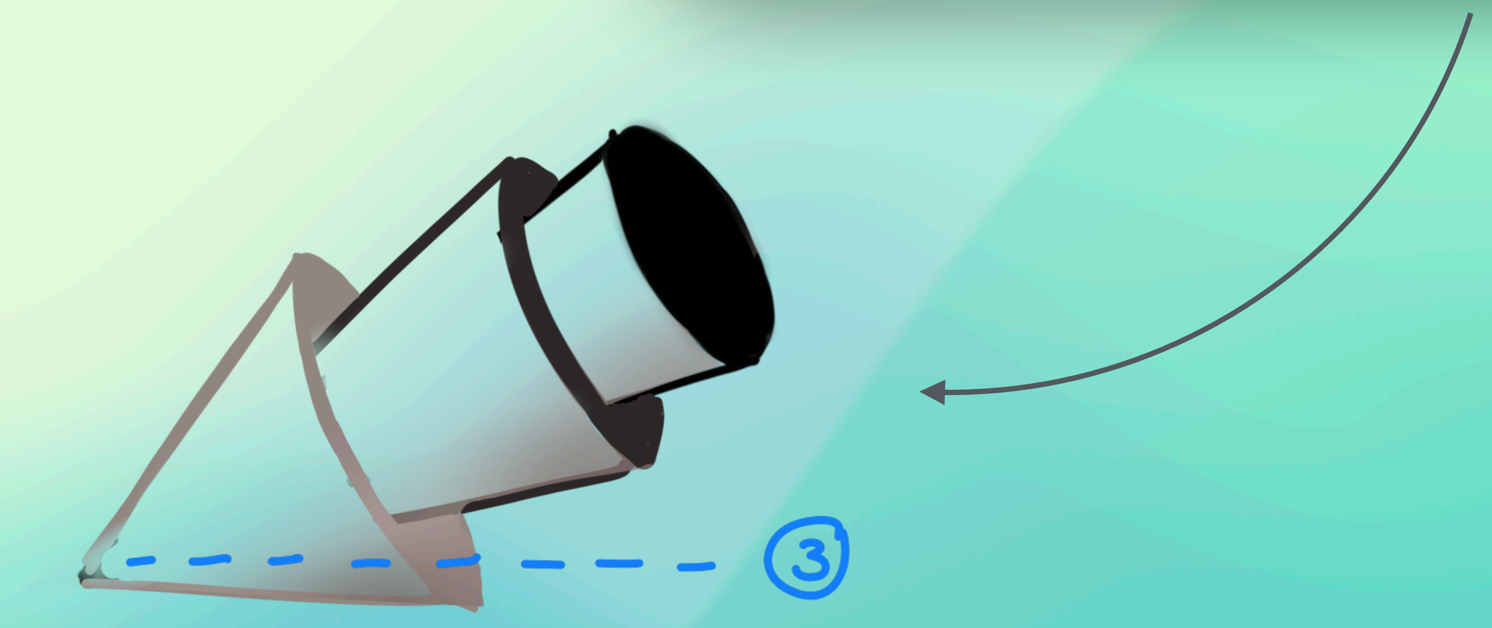


+

Ghirlanda+18







Multi-wavelength observation of the afterglow + apparent superluminal motion of the radio centroid —> **strongly supports the structured jet scenario**

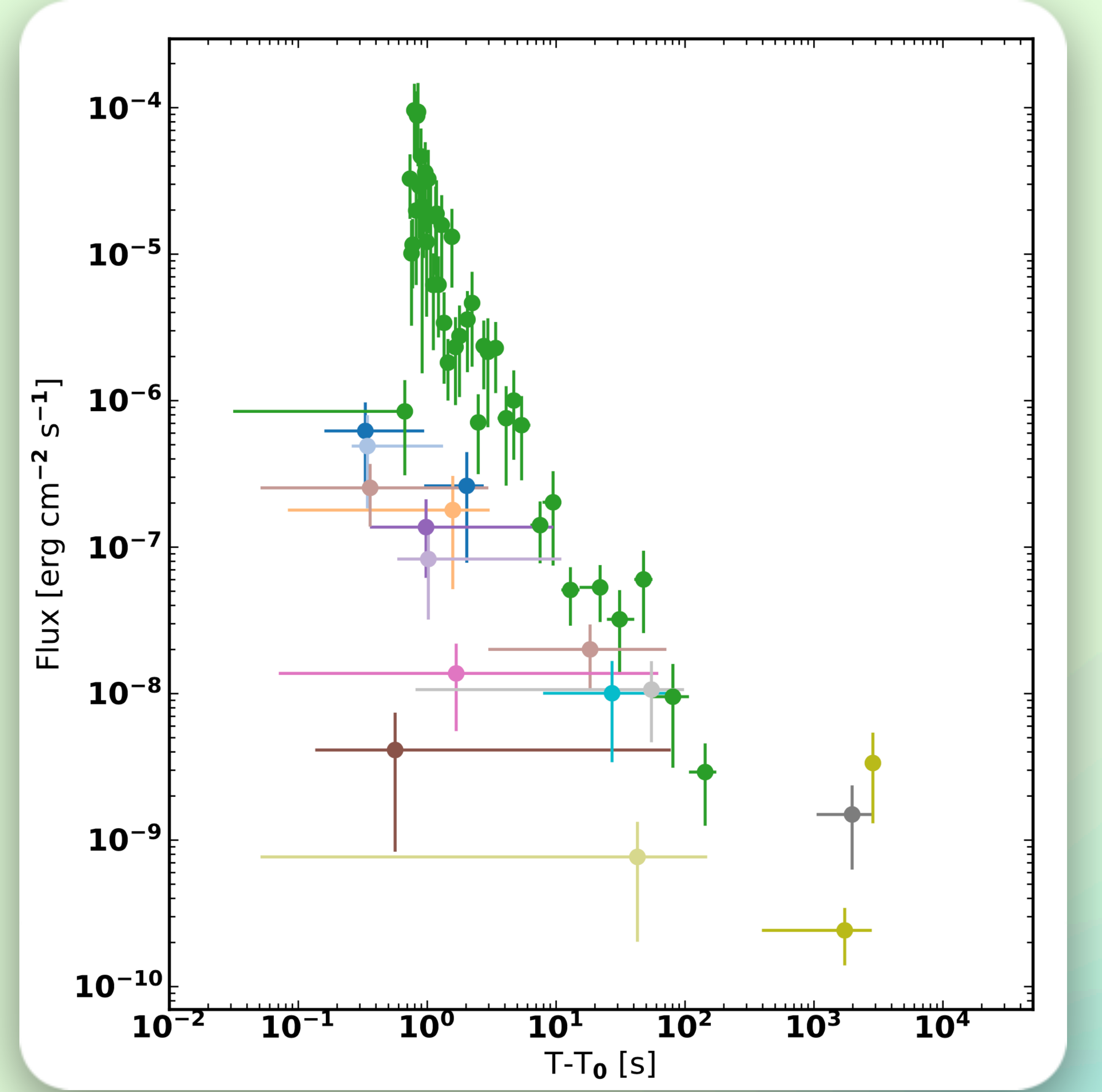
<u>Attention</u>: even if the afterglow demonstrates the presence of a jet, the $\gamma$-ray flash could be still due to a cocoon emission

Time delay + luminosity + spectrum can help to understand the **origin of prompt emission, dissipation mechanism**, **emission radius**, **angular jet structure** of NS mergers

# GW 170817 and Fermi-LAT

## Fermi-LAT and short GRBs

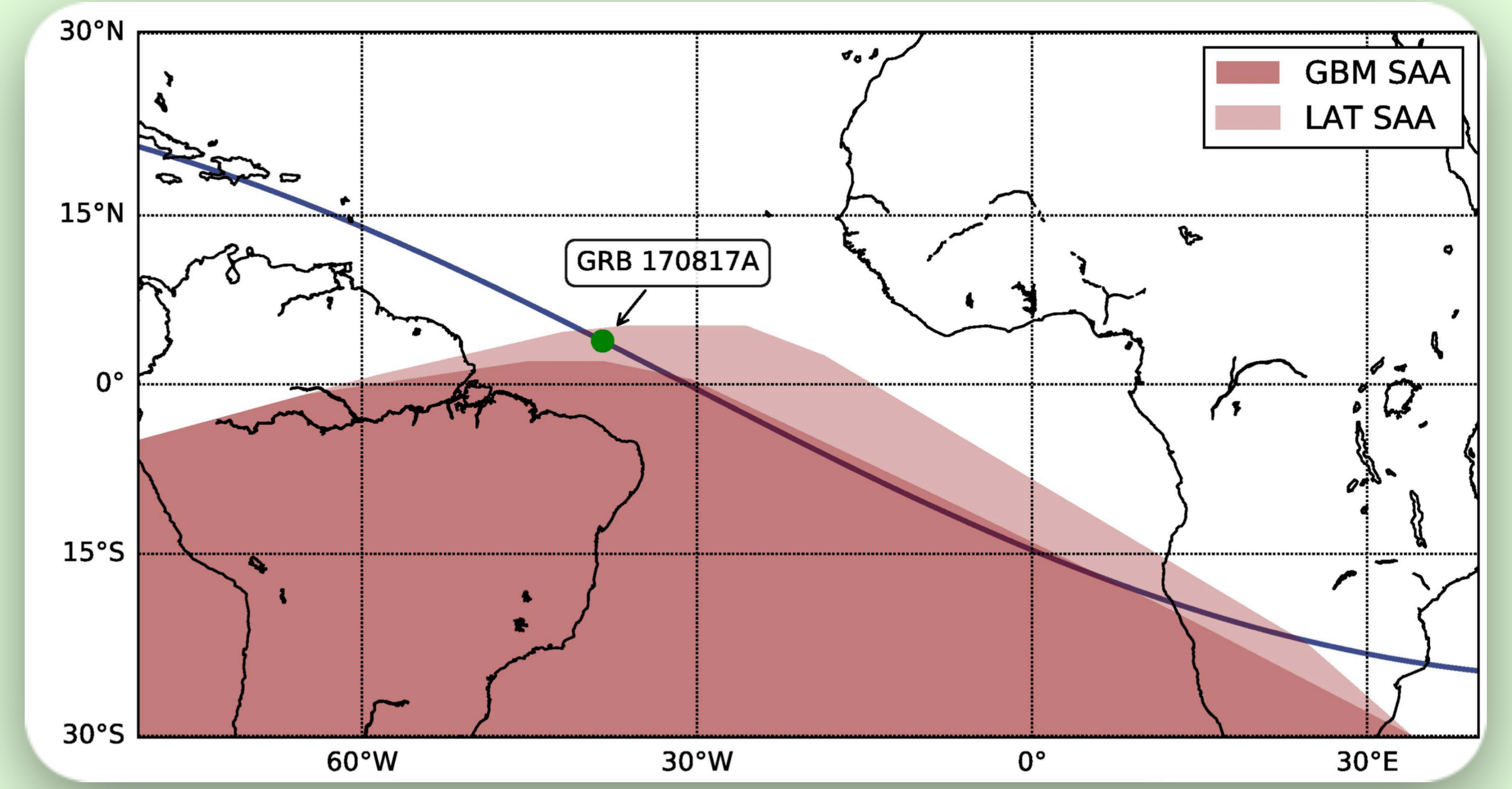
Ajello+19



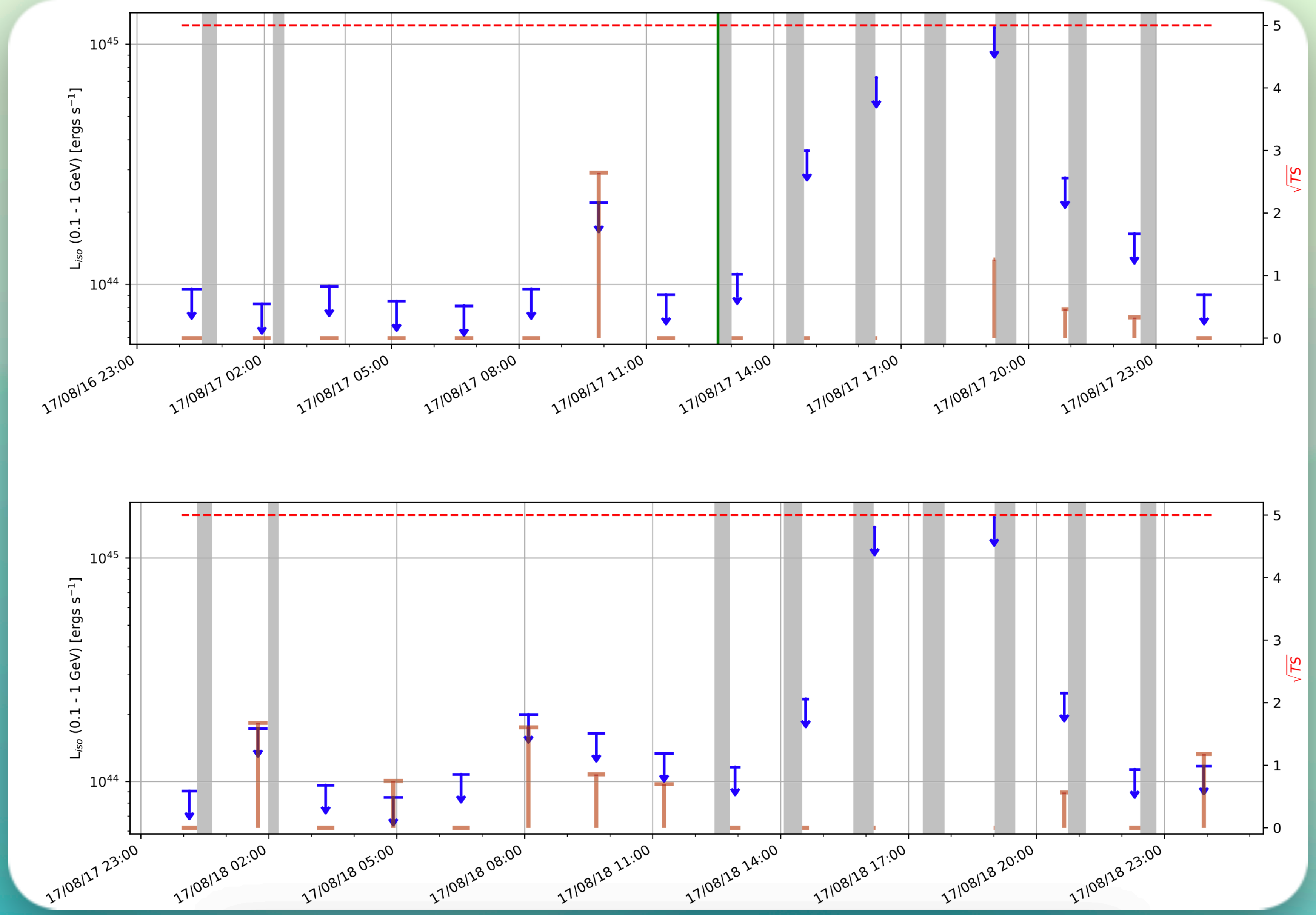
LAT detected 5% of the GBM-detected short GRBs

Expected joint GW-LAT detection rate of 1-2 /yr

Ajello+18



## Earliest upper limit at T0+1000 s



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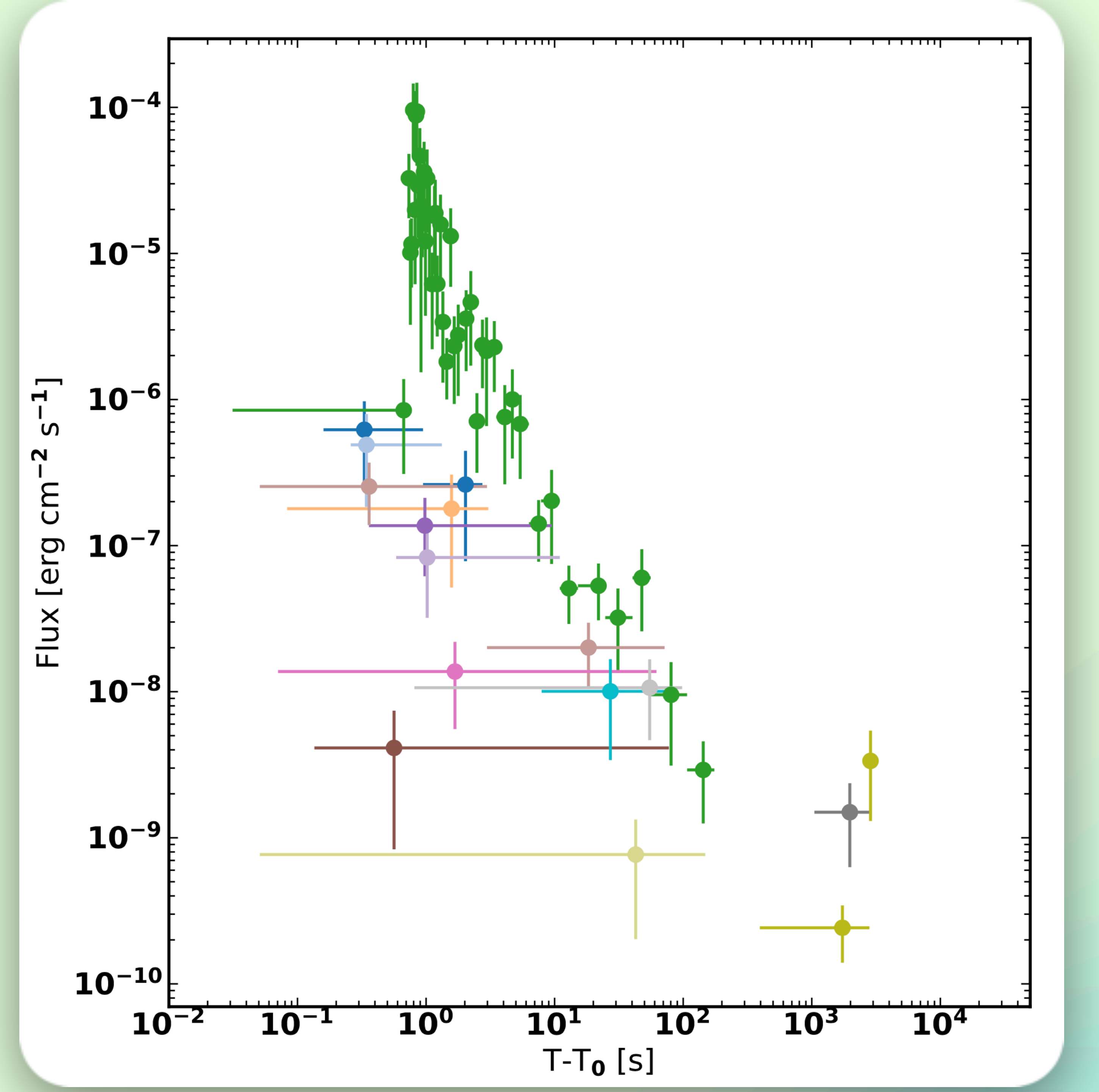

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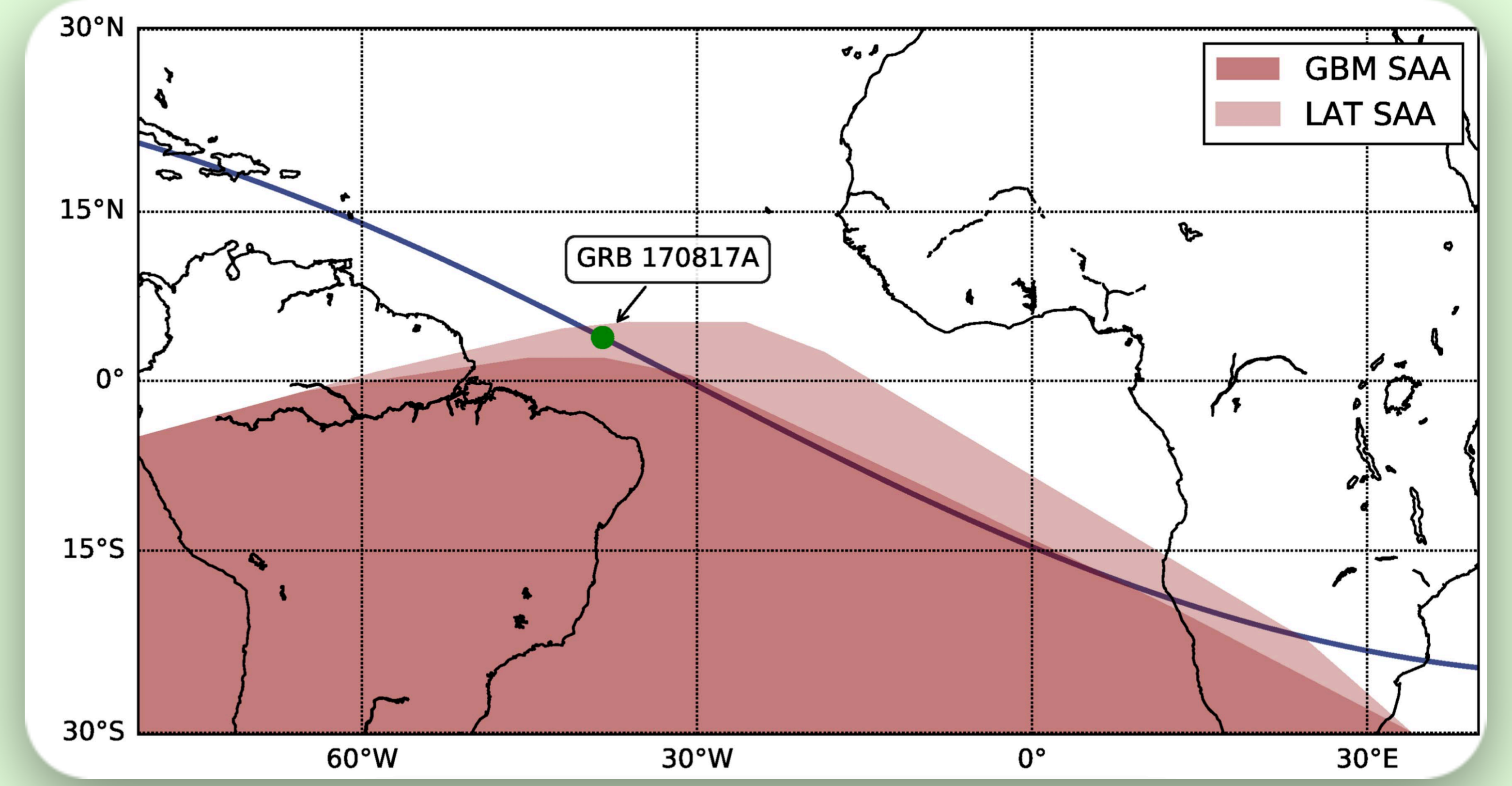

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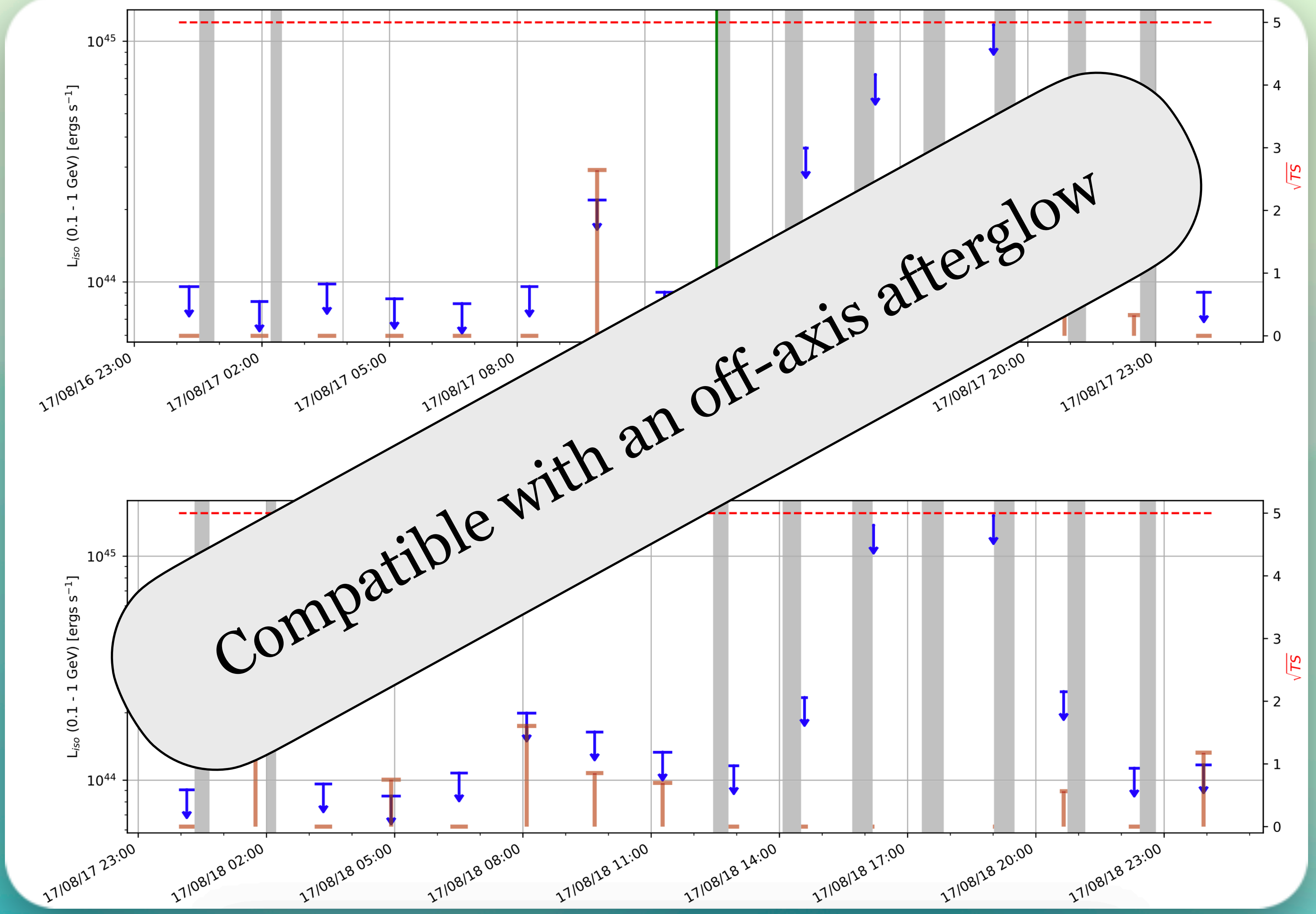
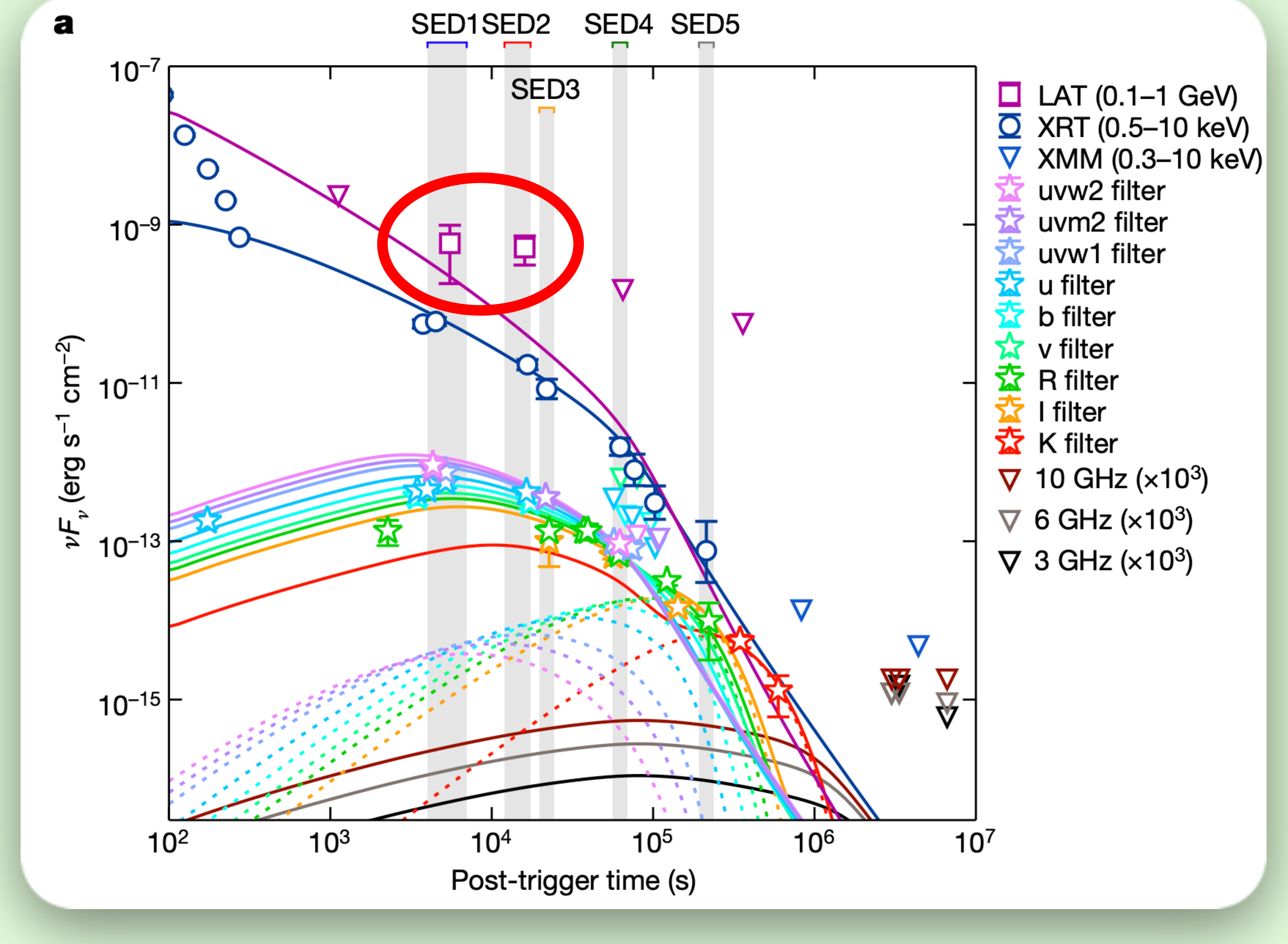


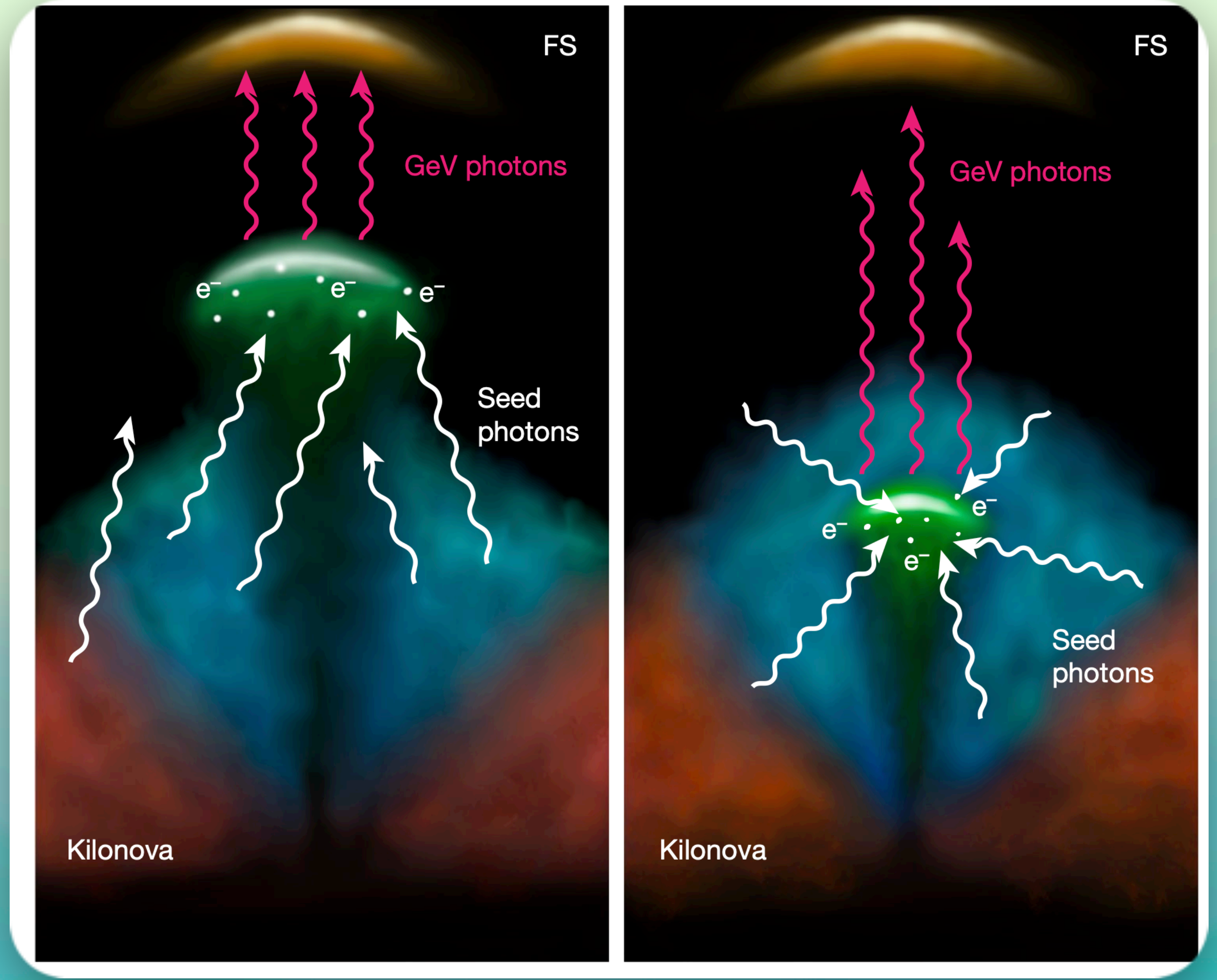
Compatible with an off-axis afterglow

# Fermi-LAT and GRB 211211A

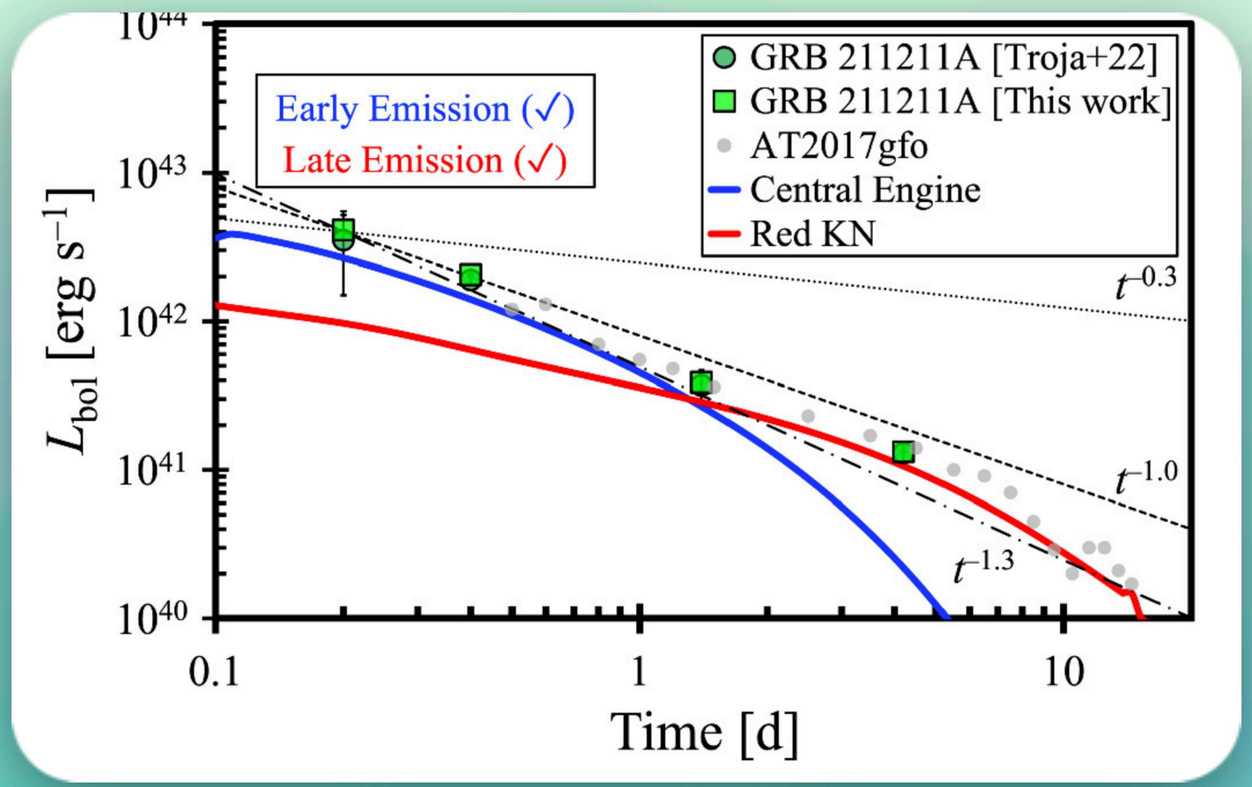
Mei+22



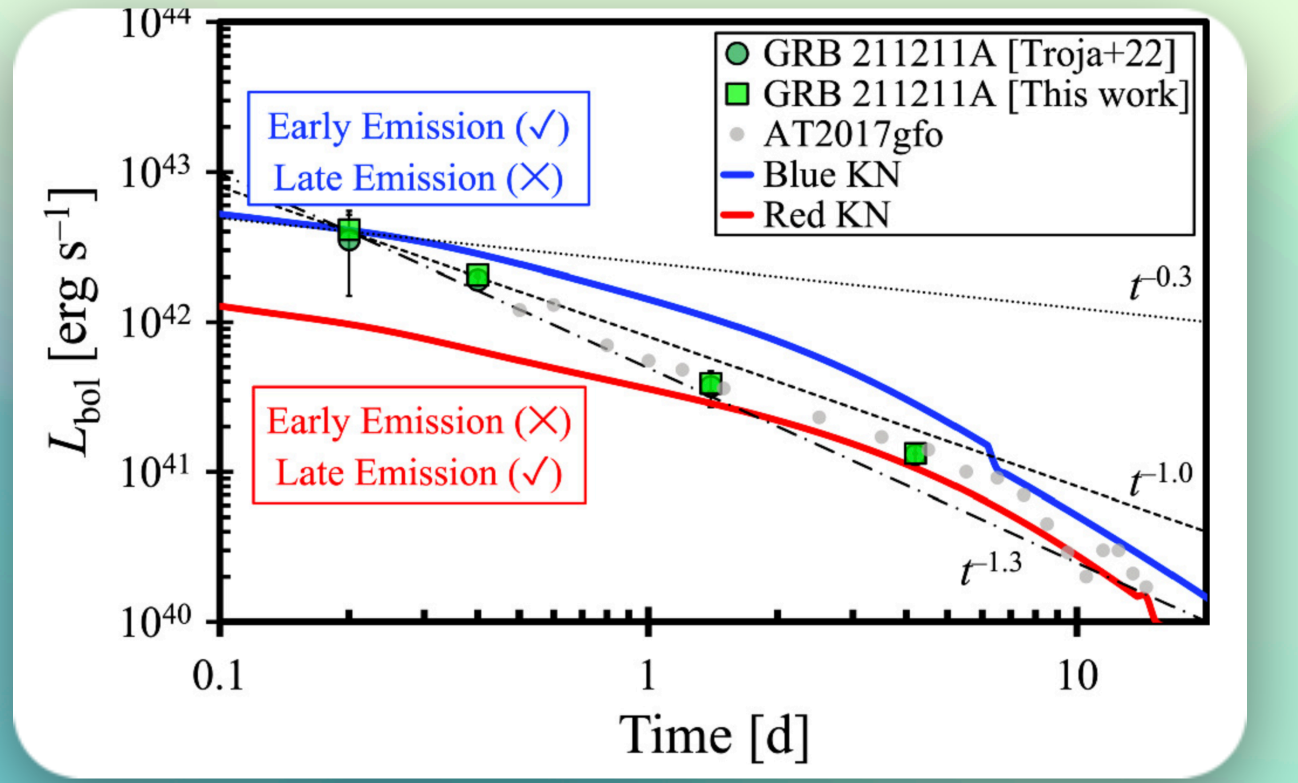
- First long-duration GRB followed by the detection of a KN —> **first merger-driven long GRB**
- Located at 350 Mpc —> **potentially detectable by LVK**
- **Detected by LAT** at ~10^4 s
- Emission not compatible with the forward shock, but requires a thermal source of photons (likely the KN) as seeds photons for an Inverse Compton on the hot electrons accelerated by a lowly magnetized late jet



Hamidani+24



Adding a late low-power jet



# There might be more merger-driven GRBs out there than what we think

## GRB 211211A

## GRB 230327A

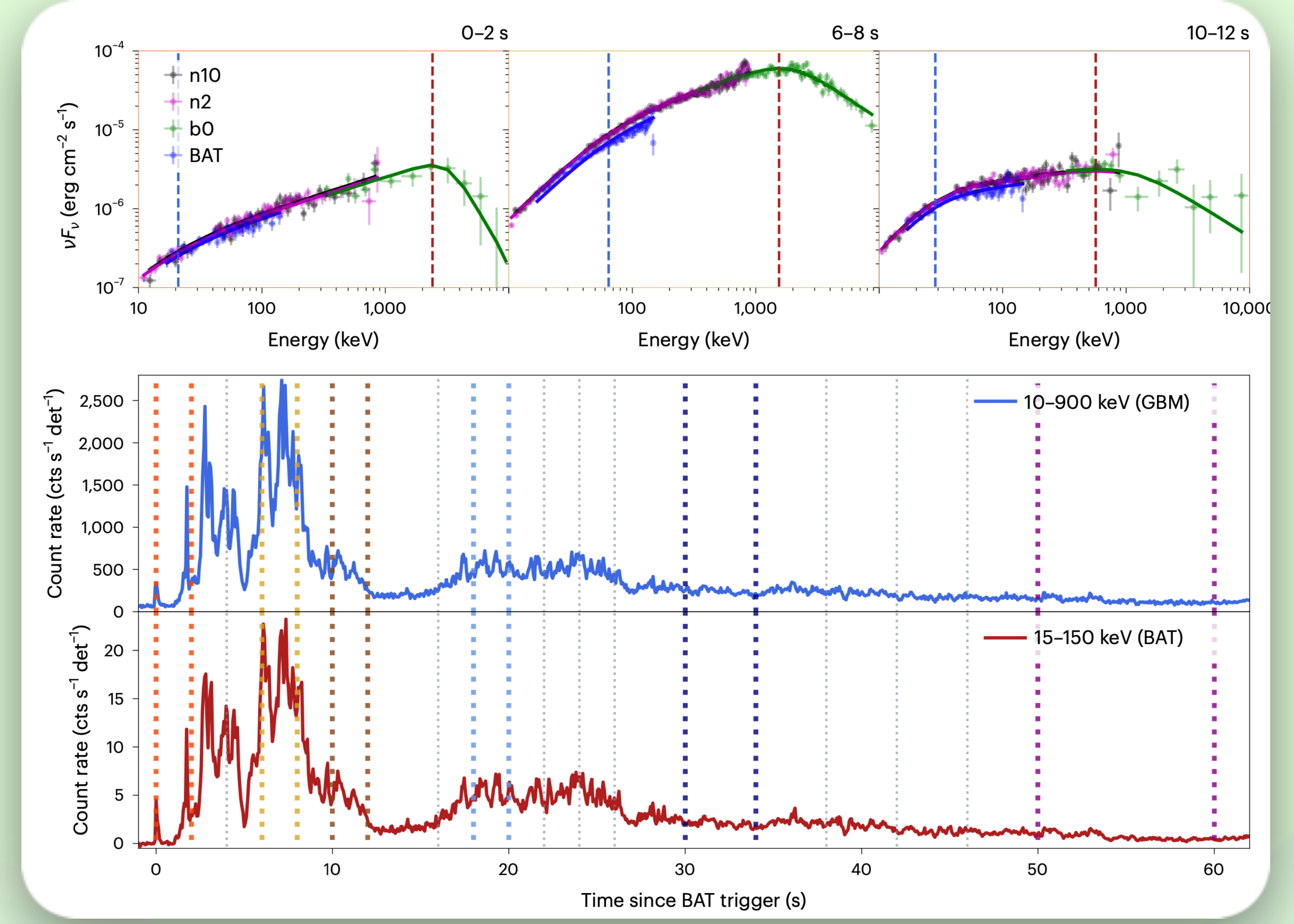
D = 350 Mpc

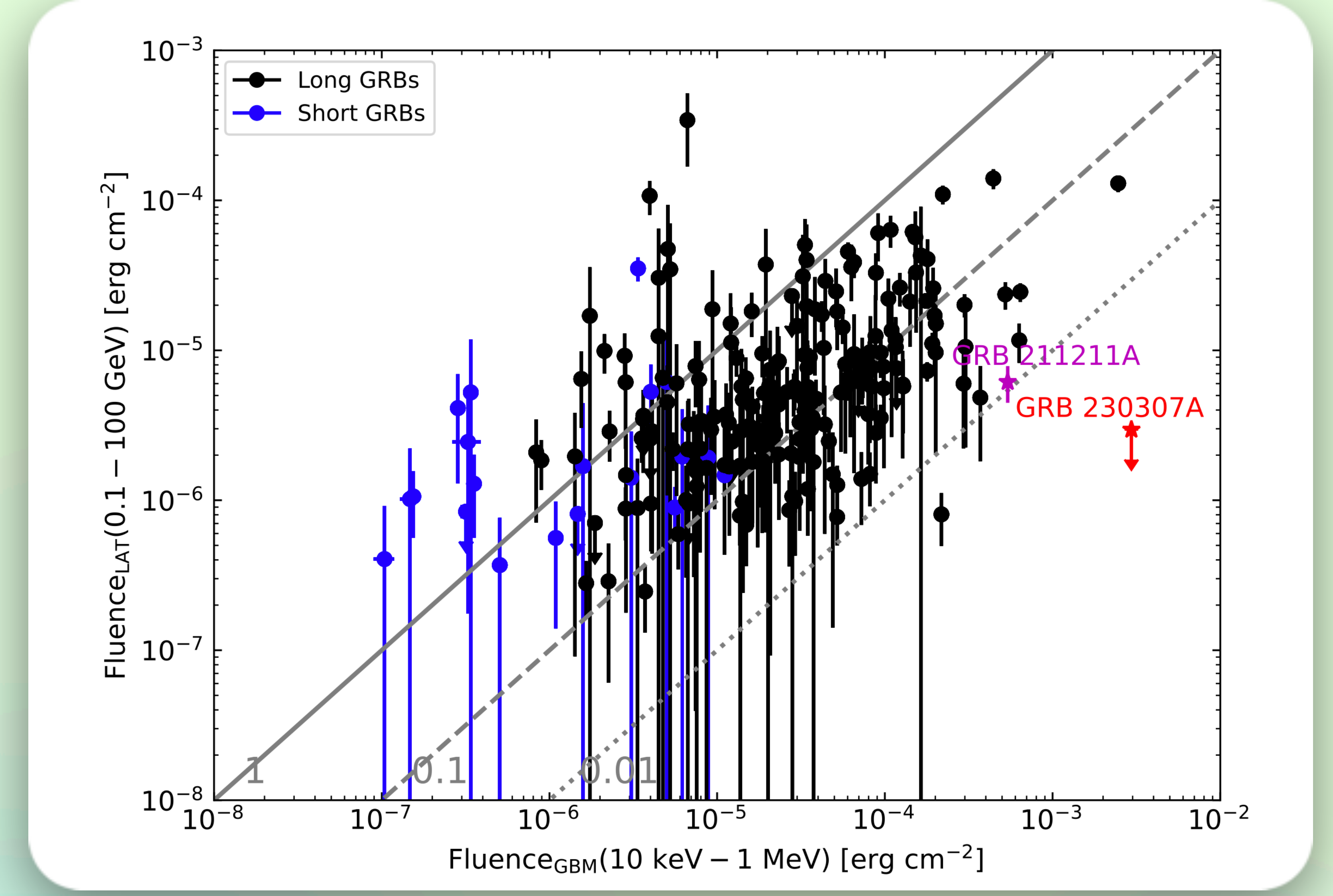
Both potentially detectable in GW if driven by NS+NS/BH

D = 290 Mpc

Gompertz+22

Dai+24





- Long duration and high S/N allowed time-resolved spectral analysis with GBM+BAT
- Evidence of **compatibility with Synchrotron emission in marginally fast cooling regime —> first time** demonstrated **for a merger-driven GRB**
- Spectral softening explains the extended emission

- Non-detection by Fermi-LAT puts this GRB as **one with the lowest ratio fluence_LAT/ fluence_GBM**
- Very sub-luminous afterglow and **no GeV emission requires a very low density of the circum-burst medium** n = 10^-4-10^-5 cm^-3
- Values typical of circus-galactic medium and consistent with a merger with a **large galaxy offset**

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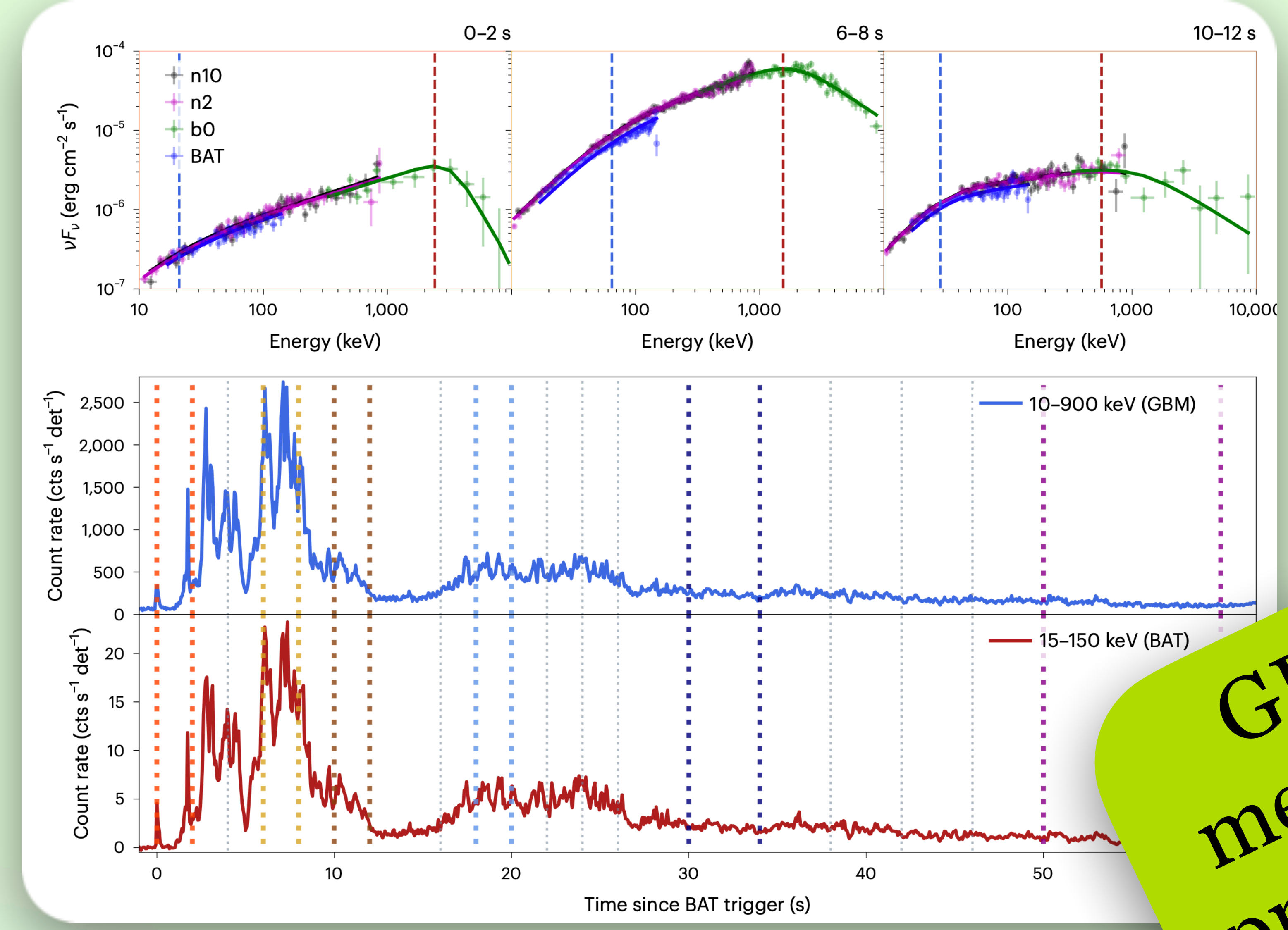

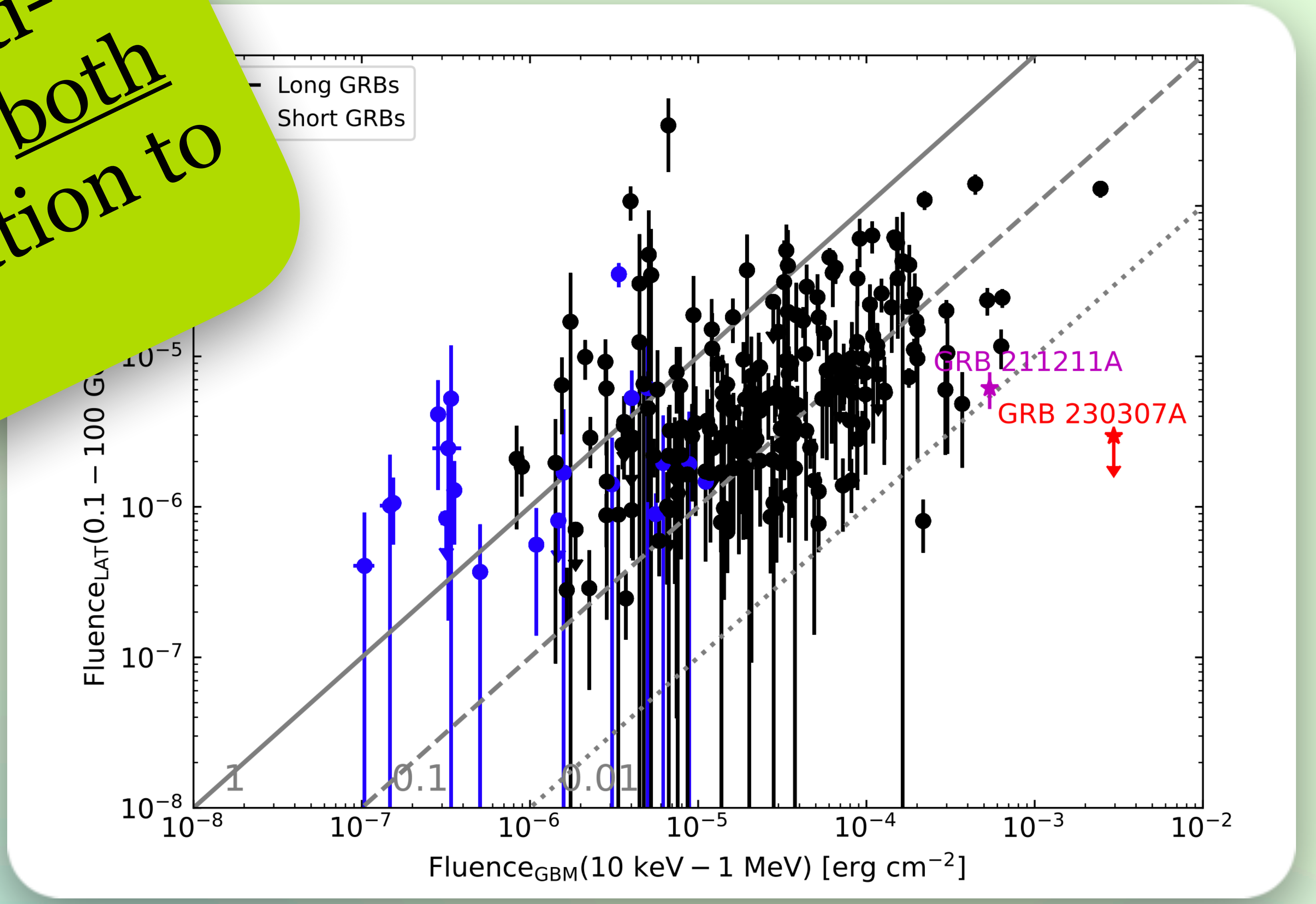

GBM + LAT play a crucial role in the multi-messenger context, probing the physics of both prompt and afterglow emission in association to compact binary mergers

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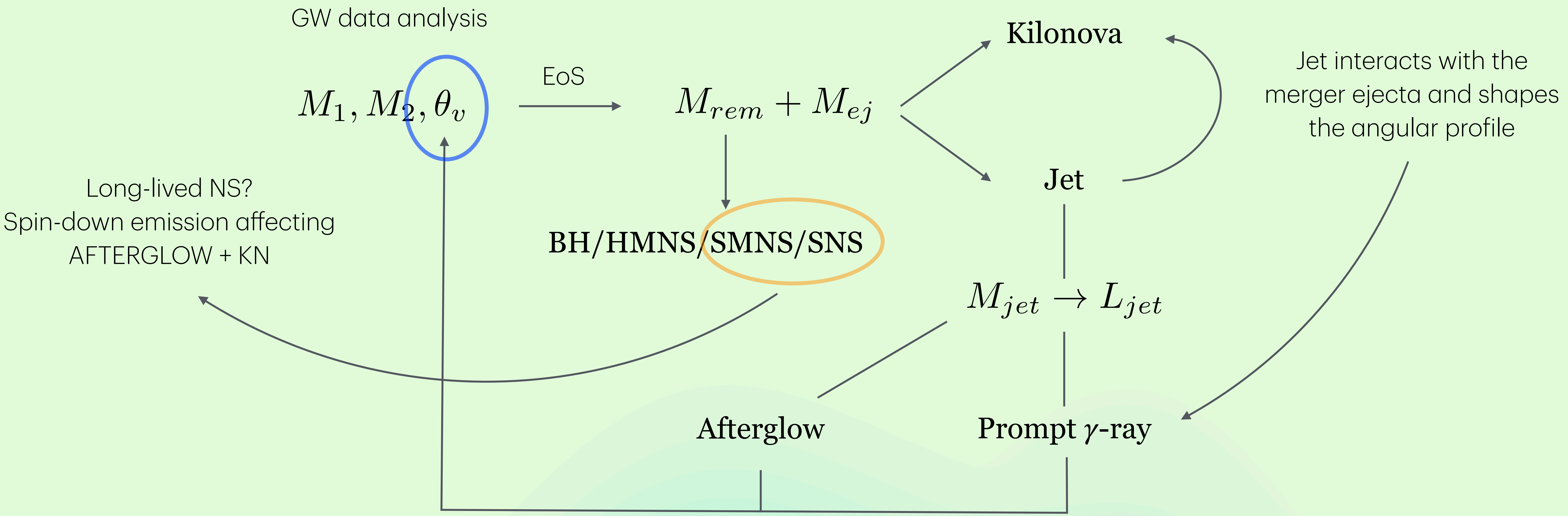
# Broad multi-messenger picture



GW data analysis

$M_1, M_2, \theta_v$ $\xrightarrow{\text{EoS}}$ $M_{rem} + M_{ej}$

Kilonova

Jet

Jet interacts with the merger ejecta and shapes the angular profile

Long-lived NS?
Spin-down emission affecting
AFTERGLOW + KN

BH/HMNS/SMNS/SNS

$M_{jet} \rightarrow L_{jet}$

Afterglow

Prompt $\gamma$-ray

Central engine of merger-driven GRBs

Jet-KN interaction and relative structure

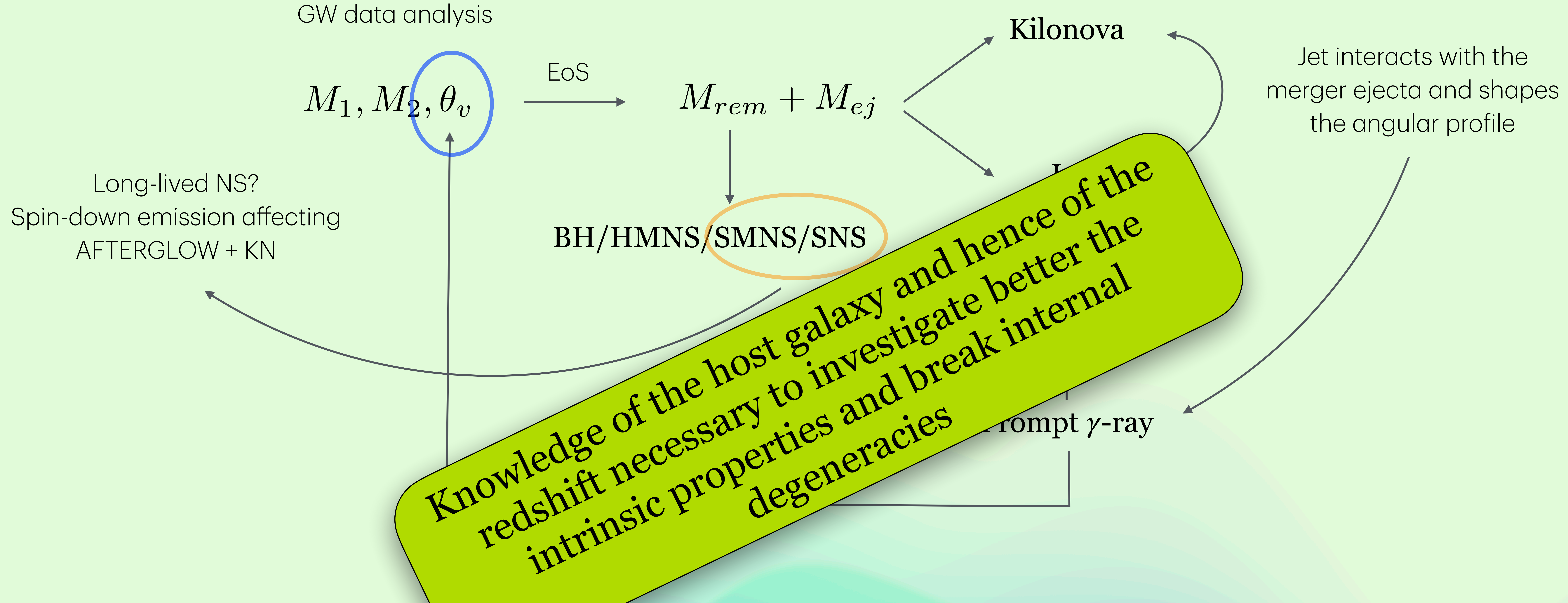
Tests of General Relativity

Fraction of NS mergers
able to launch a jet

Physics of NS matter

Cosmological studies

# Broad multi-messenger picture



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Knowledge of the host galaxy and hence of the redshift necessary to investigate better the intrinsic properties and break internal degeneracies

Central engine of merger-driven GRBs

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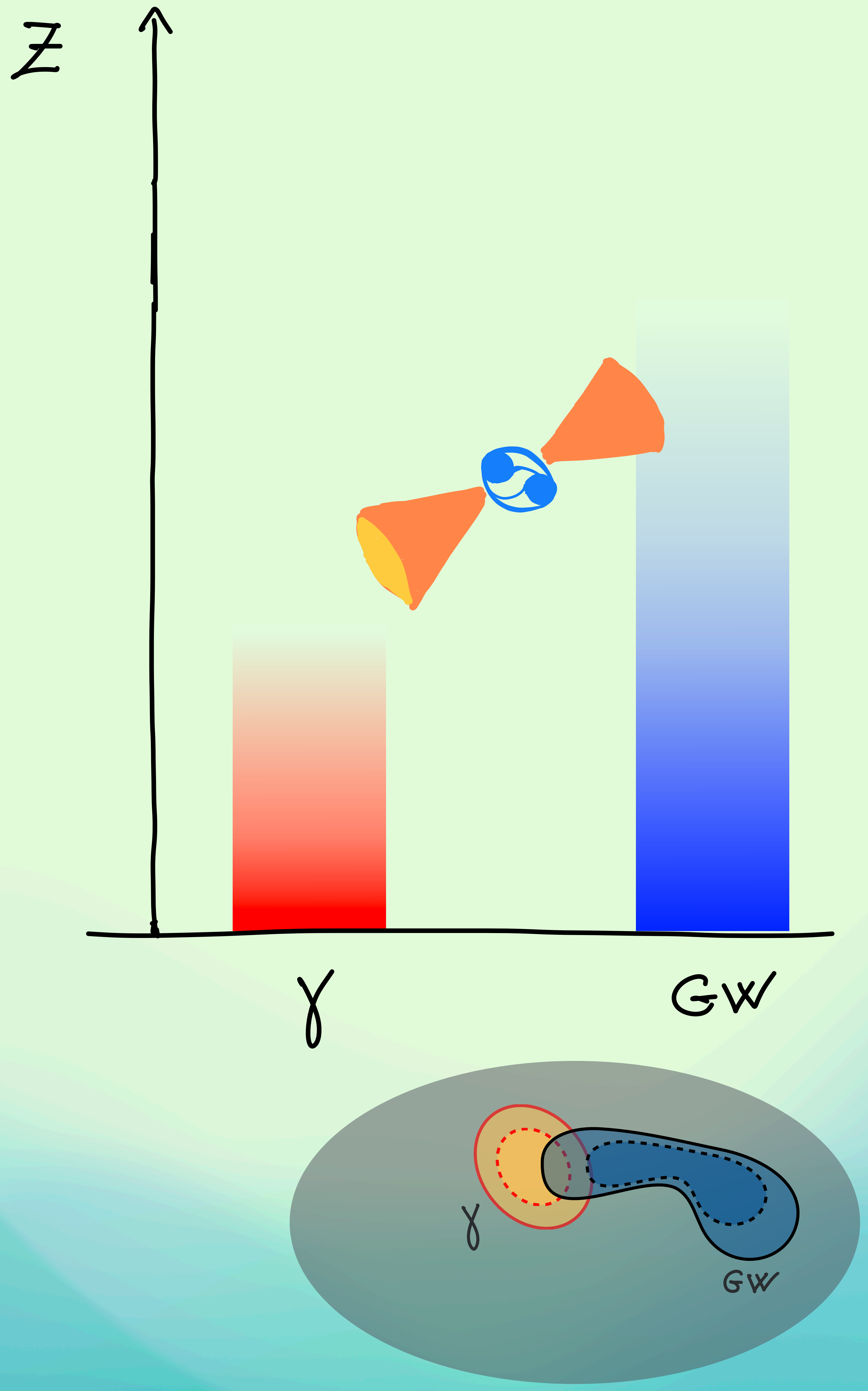
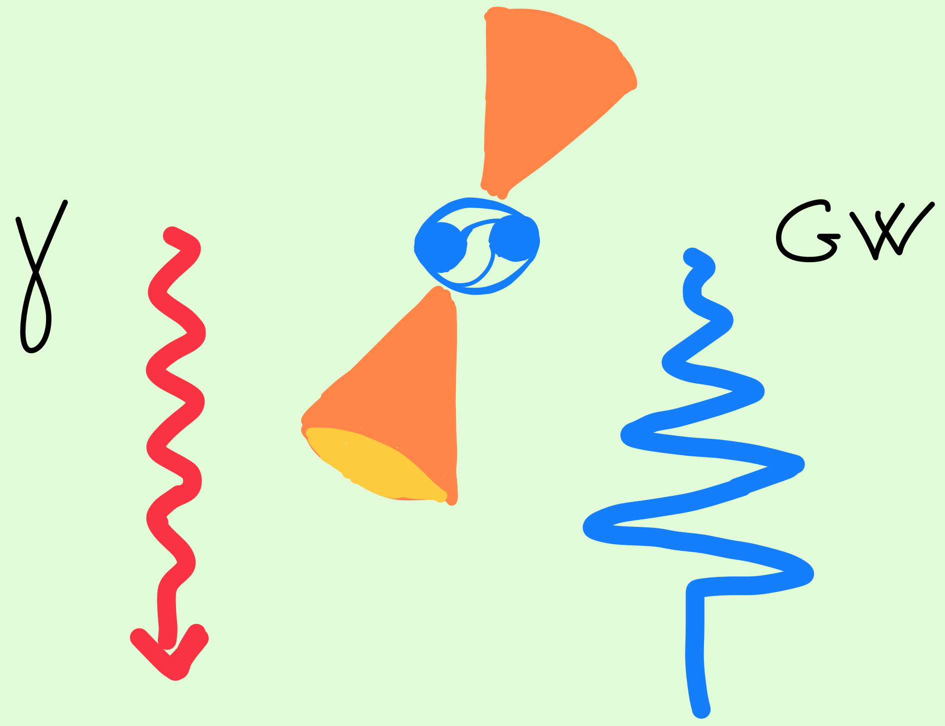
# Current efforts

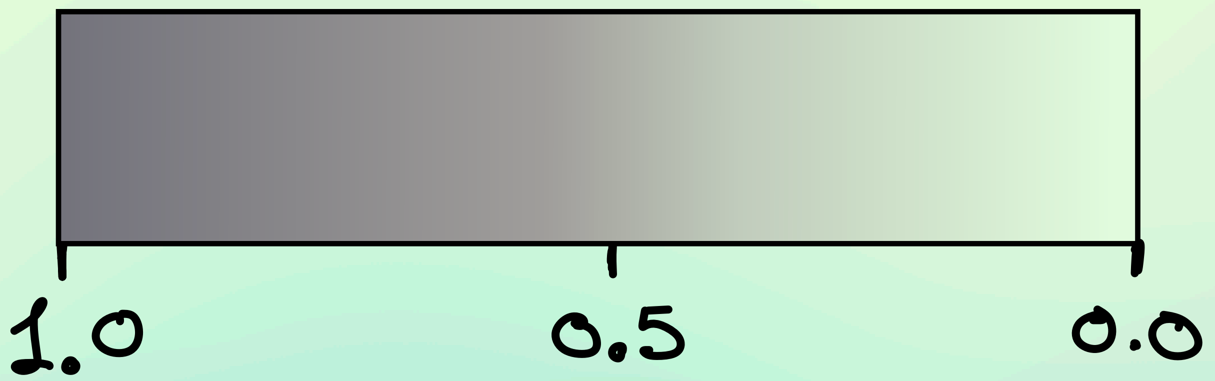
# Subthreshold searches with Fermi-GBM

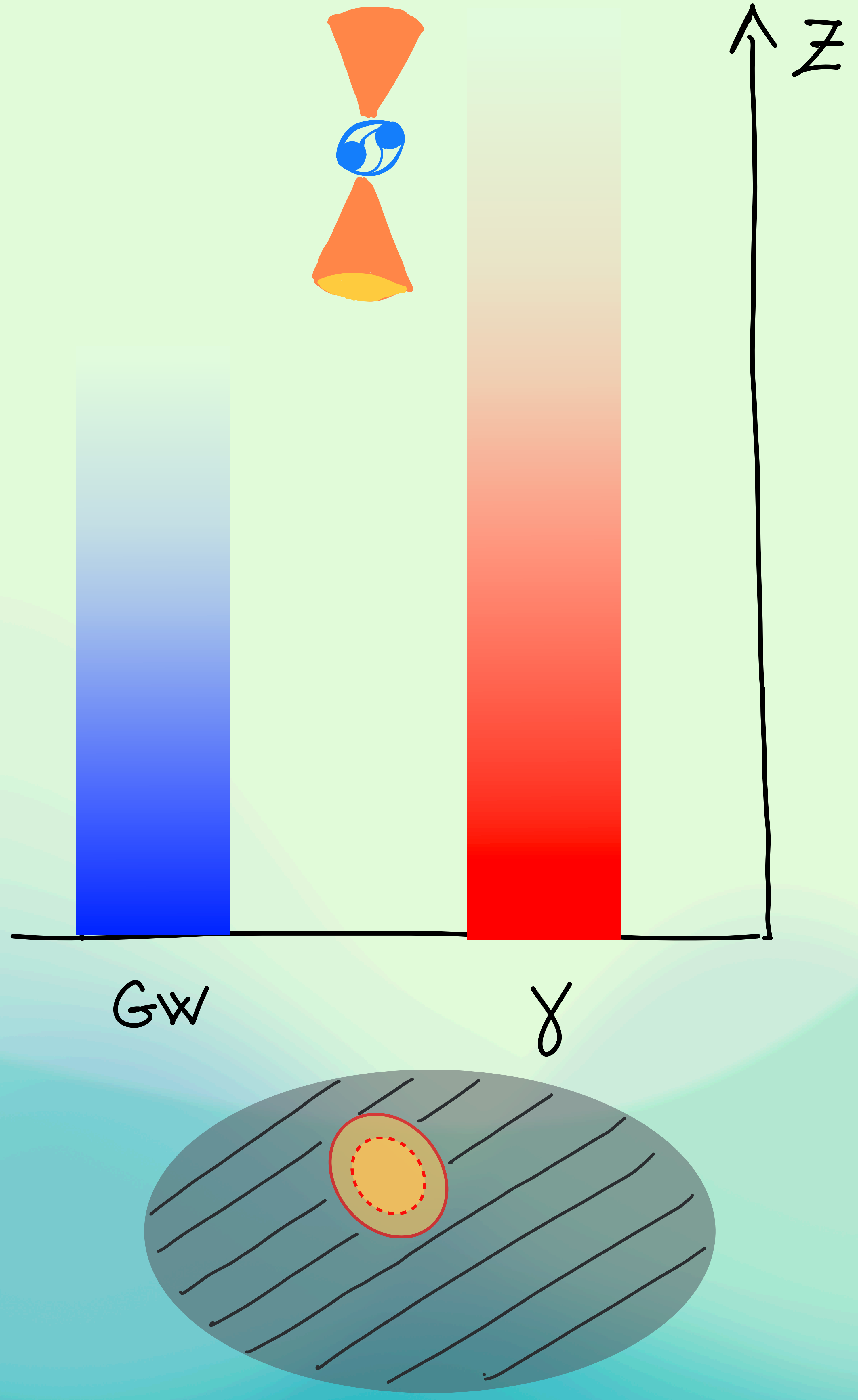
## Why to go subthreshold?





Detection efficiency





Joint sub-threshold searches essential to:

- discover more EM-bright GW mergers
- trigger possible EM follow-up campaigns —> the discovery of other EM candidates could increase even more the joint detection significance.

# Subthreshold searches with Fermi-GBM

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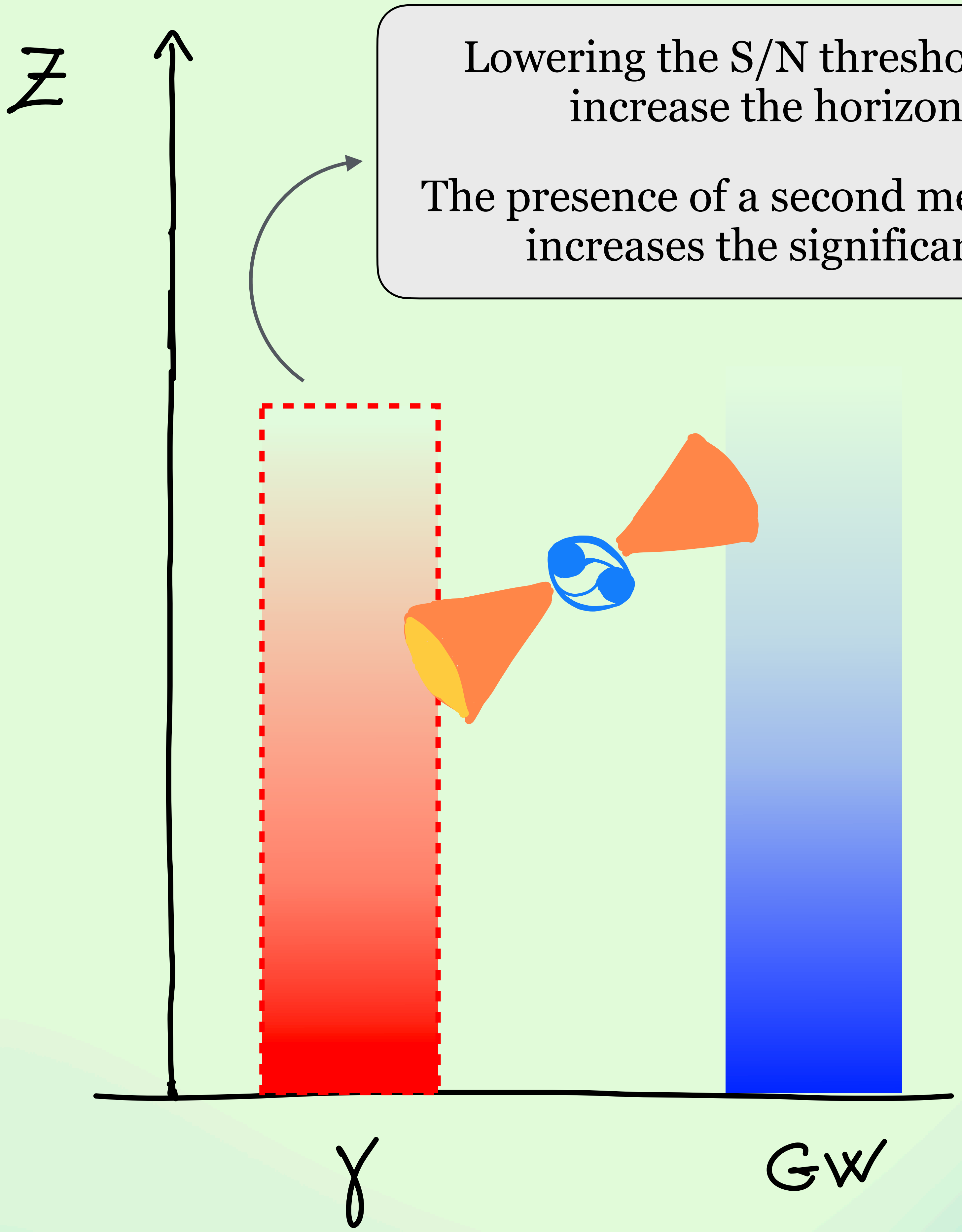
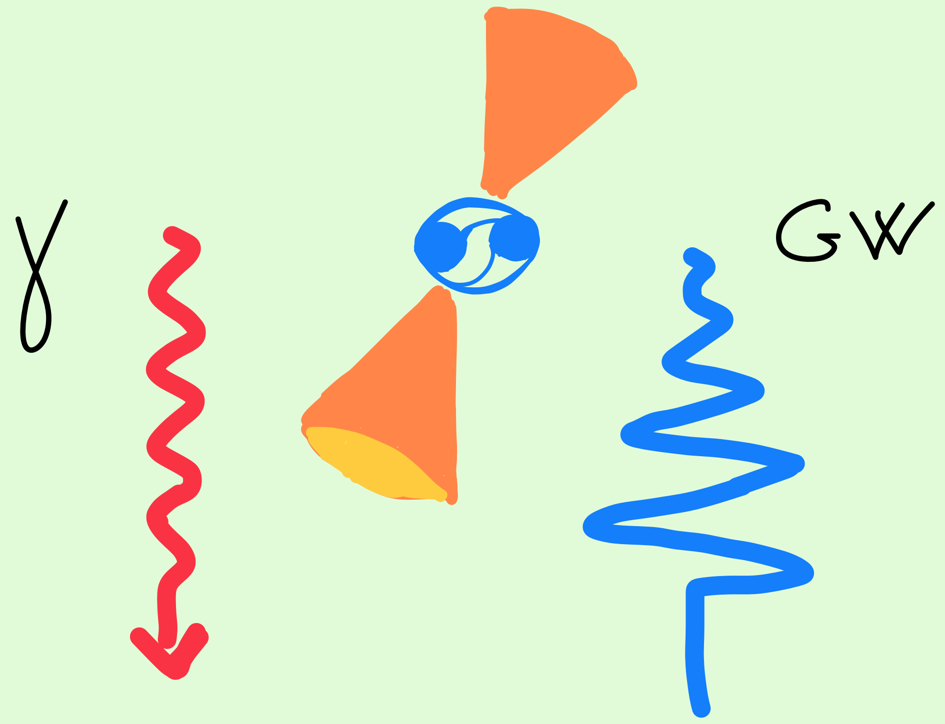


Lowering the S/N threshold, we increase the horizon.

The presence of a second messenger increases the significance



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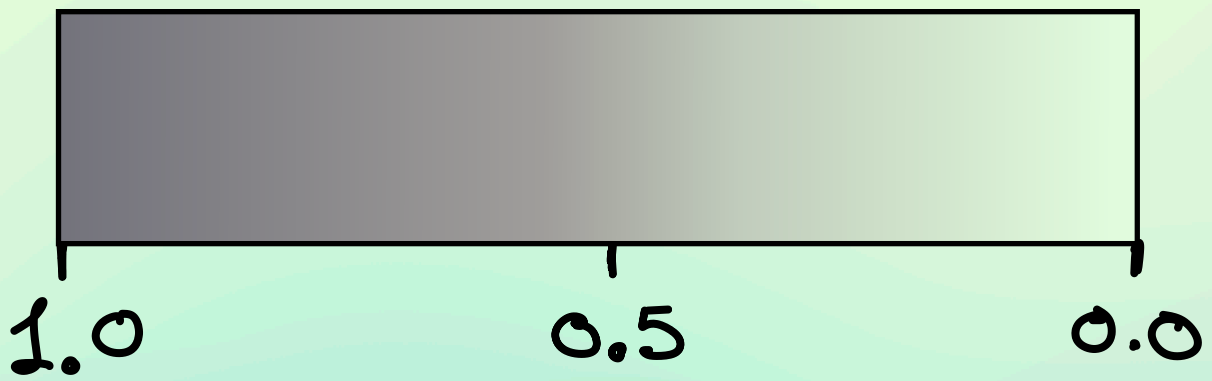

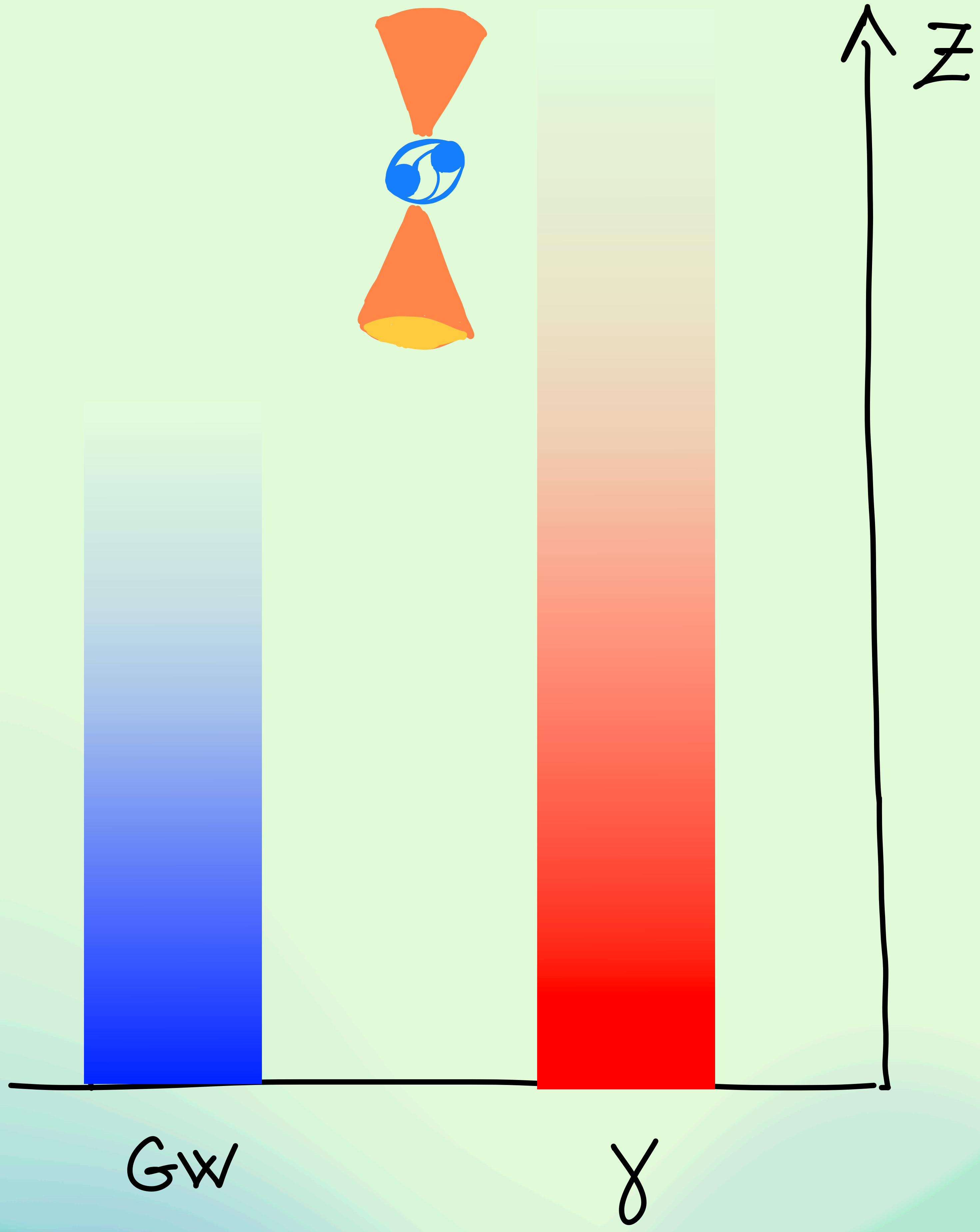

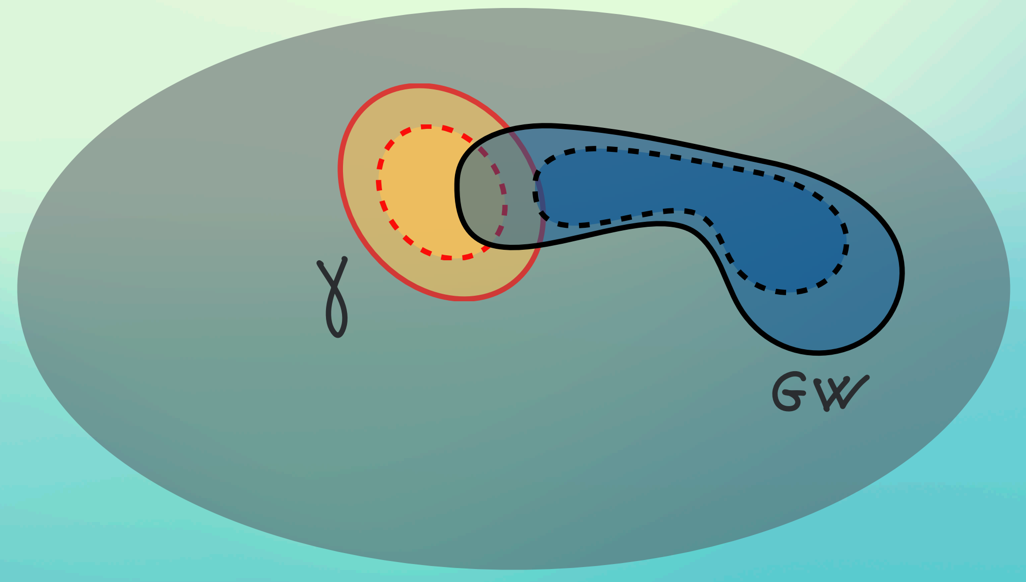

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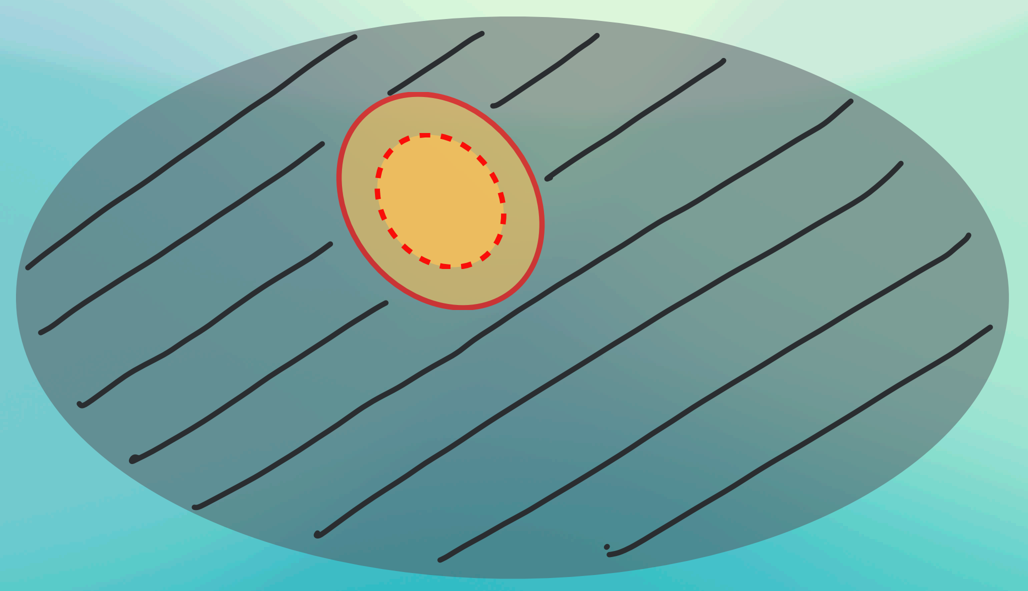

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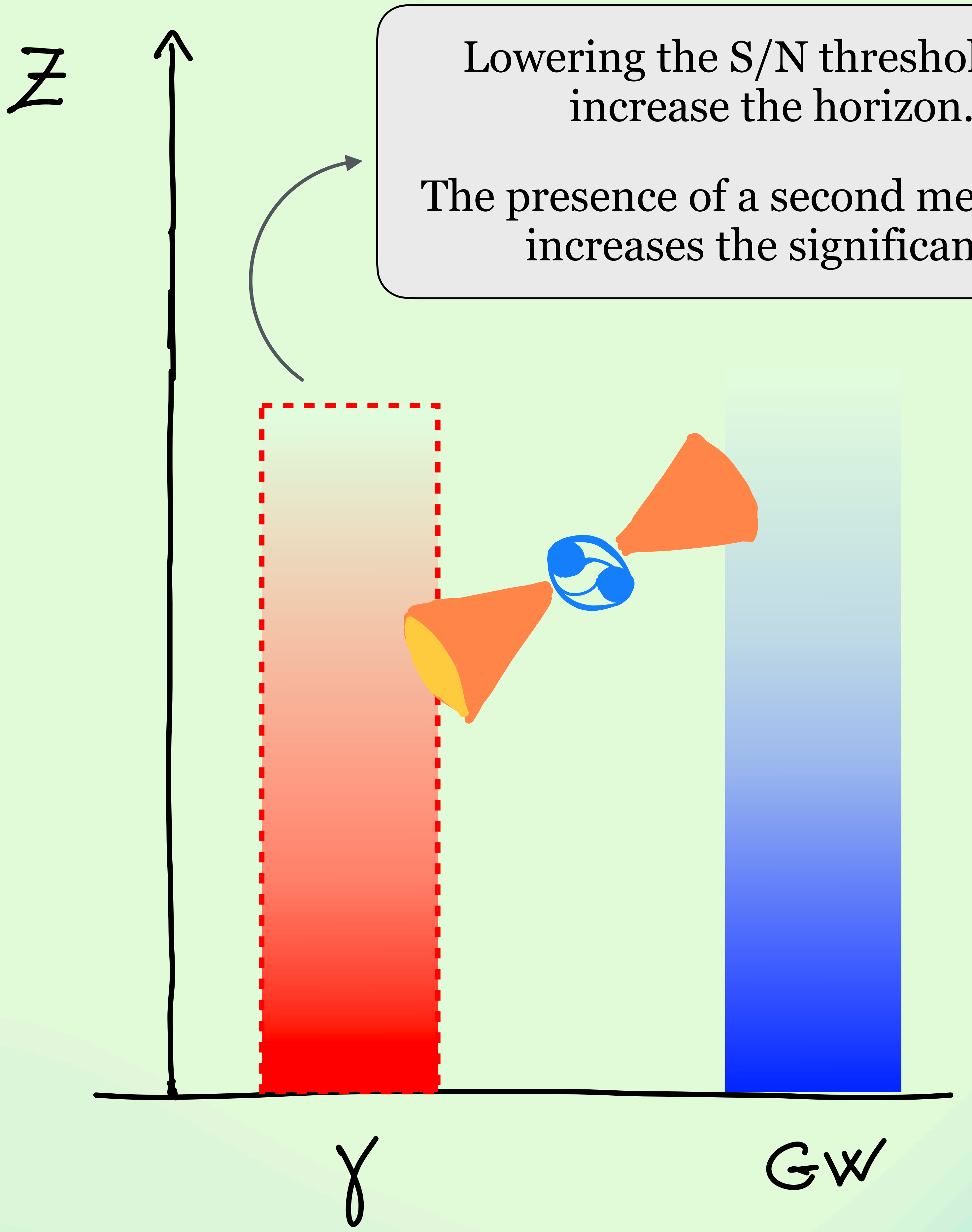

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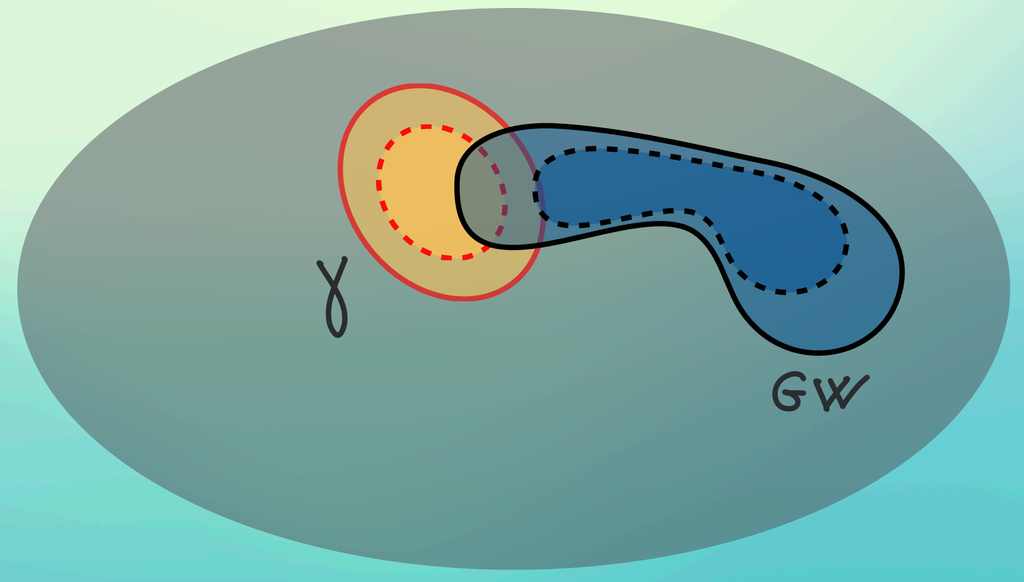

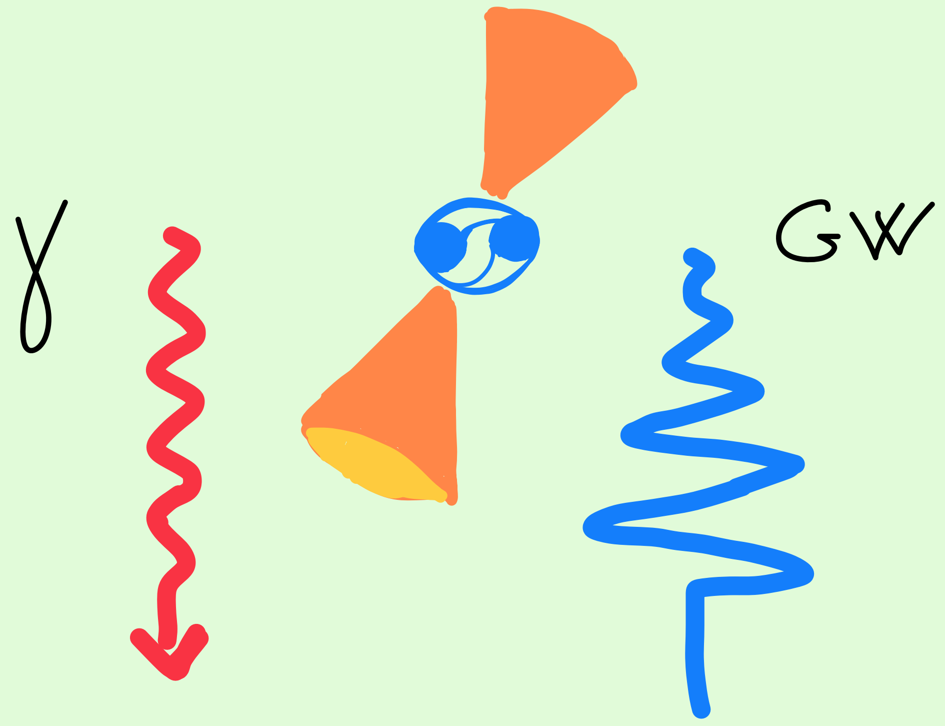

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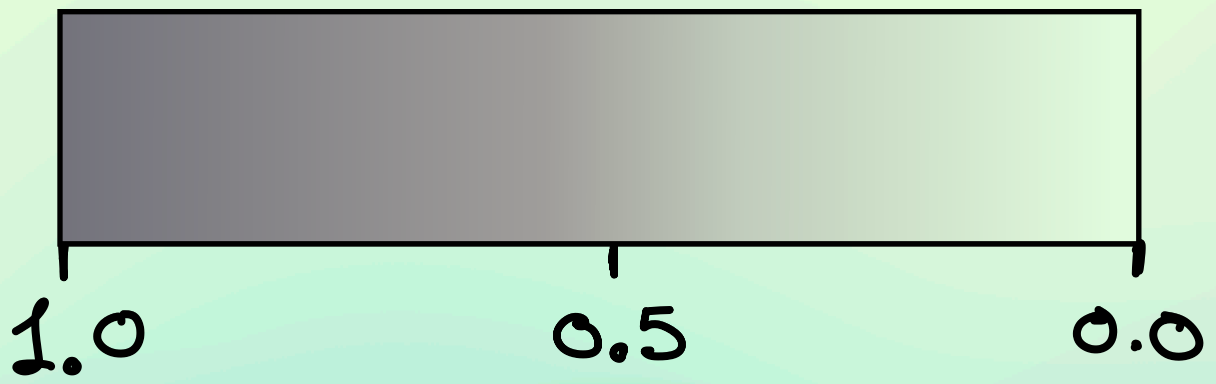

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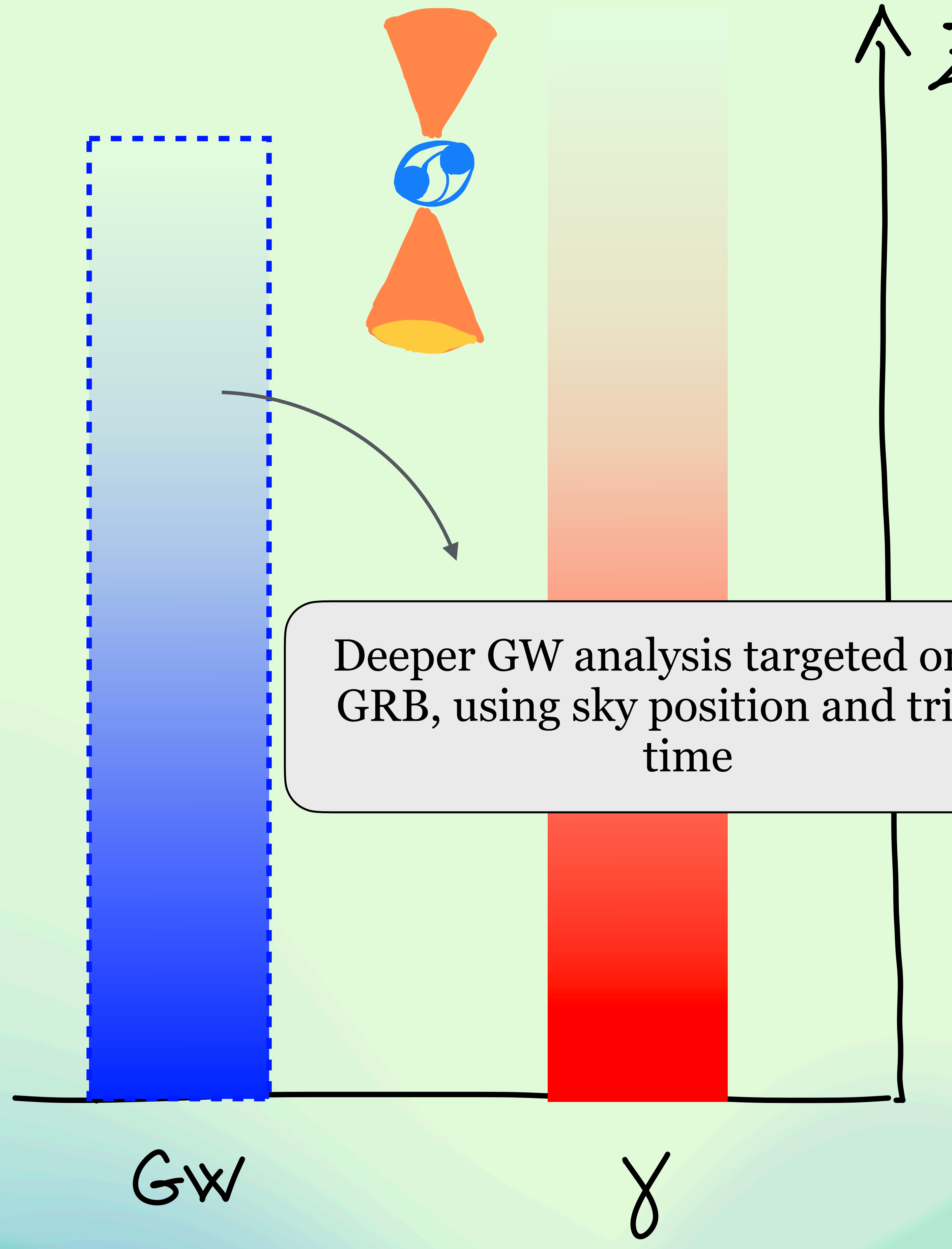
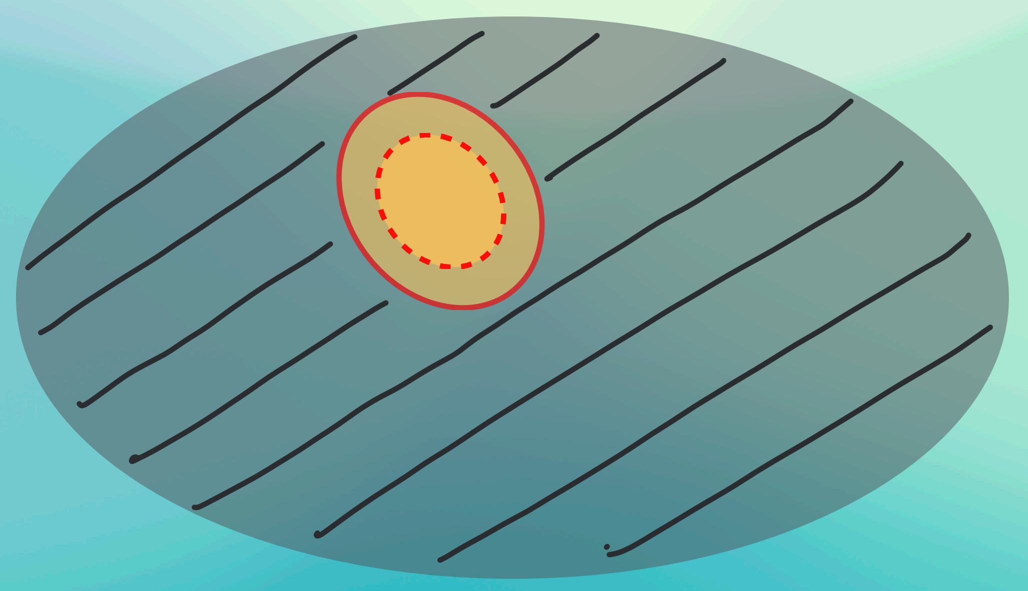
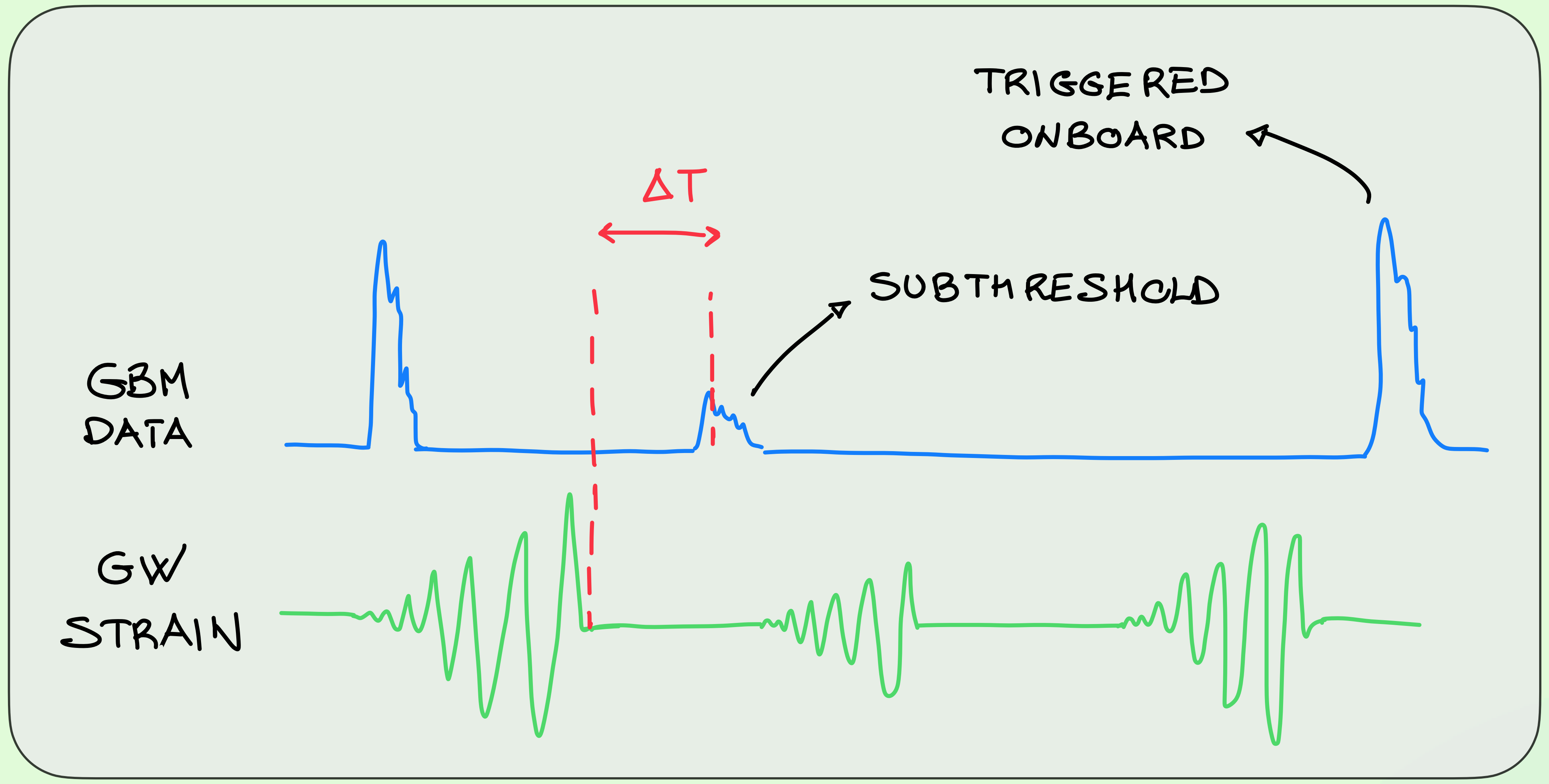


Deeper GW analysis targeted on the GRB, using sky position and trigger time



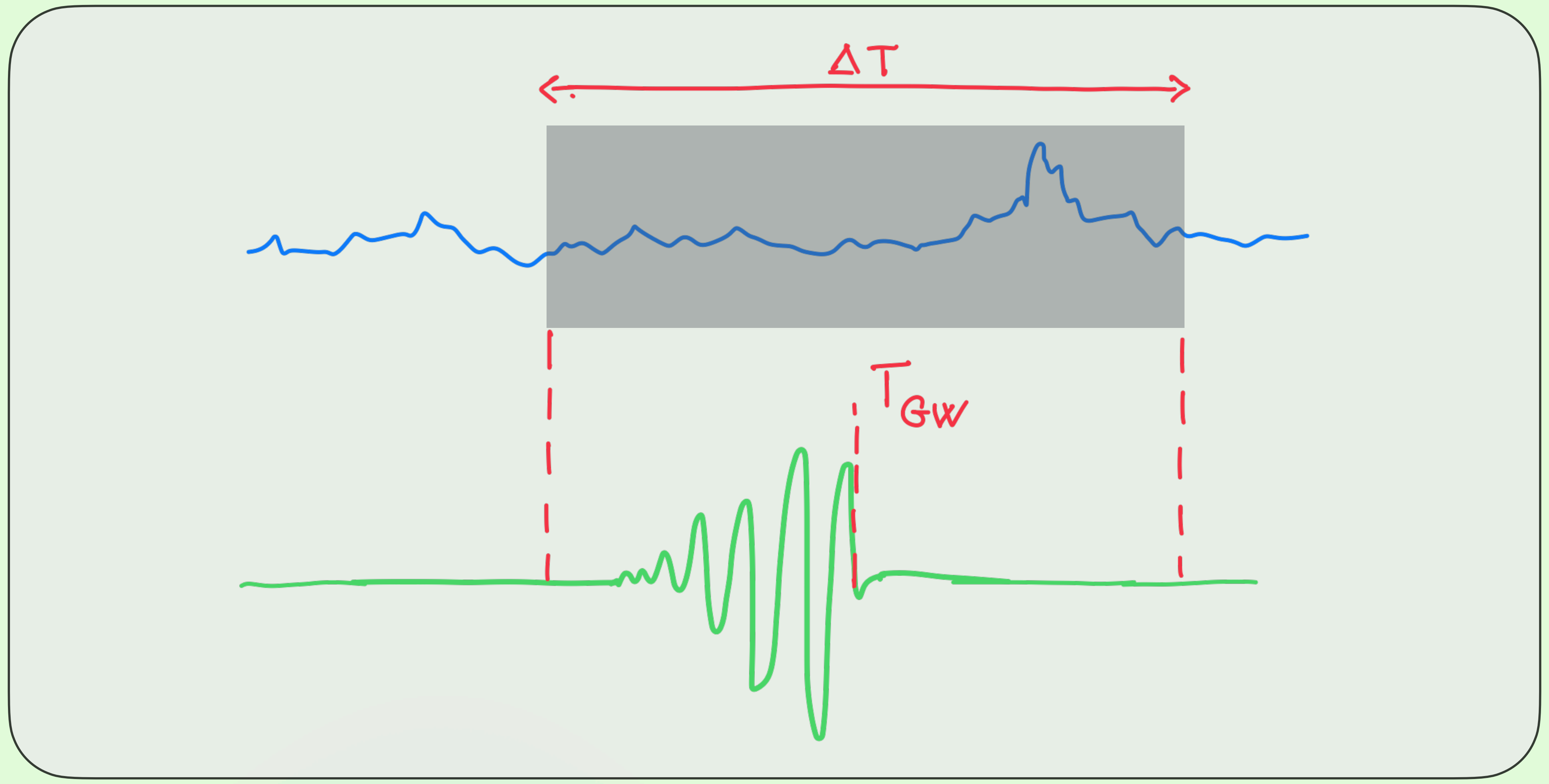
# Subthreshold searches with Fermi-GBM

## Untargeted



- **Onboard** triggering algorithm **finds around 40 short GRBs / yr** —> the **untargeted search adds 80 short GRBs/yr** (Burns+19)
- Candidate GBM events are required to have excess counts greater than 2.5σ relative to background in one detector and at least 1.25σ in a second detector
- Background population simulated shifting randomly in time the GW trigger times

## Targeted



- The targeted search uses three template spectra to coherently forward model the detector response
- Search performed on several durations of time bins
- Candidates searched on a fixed time window around the GW trigger time

O1 and O2: ΔT = T_GW ± 30 s

O3: ΔT = [T_GW - 1 s, T_GW+ 30 s]

# Subthreshold searches with Fermi-GBM

## Untargeted

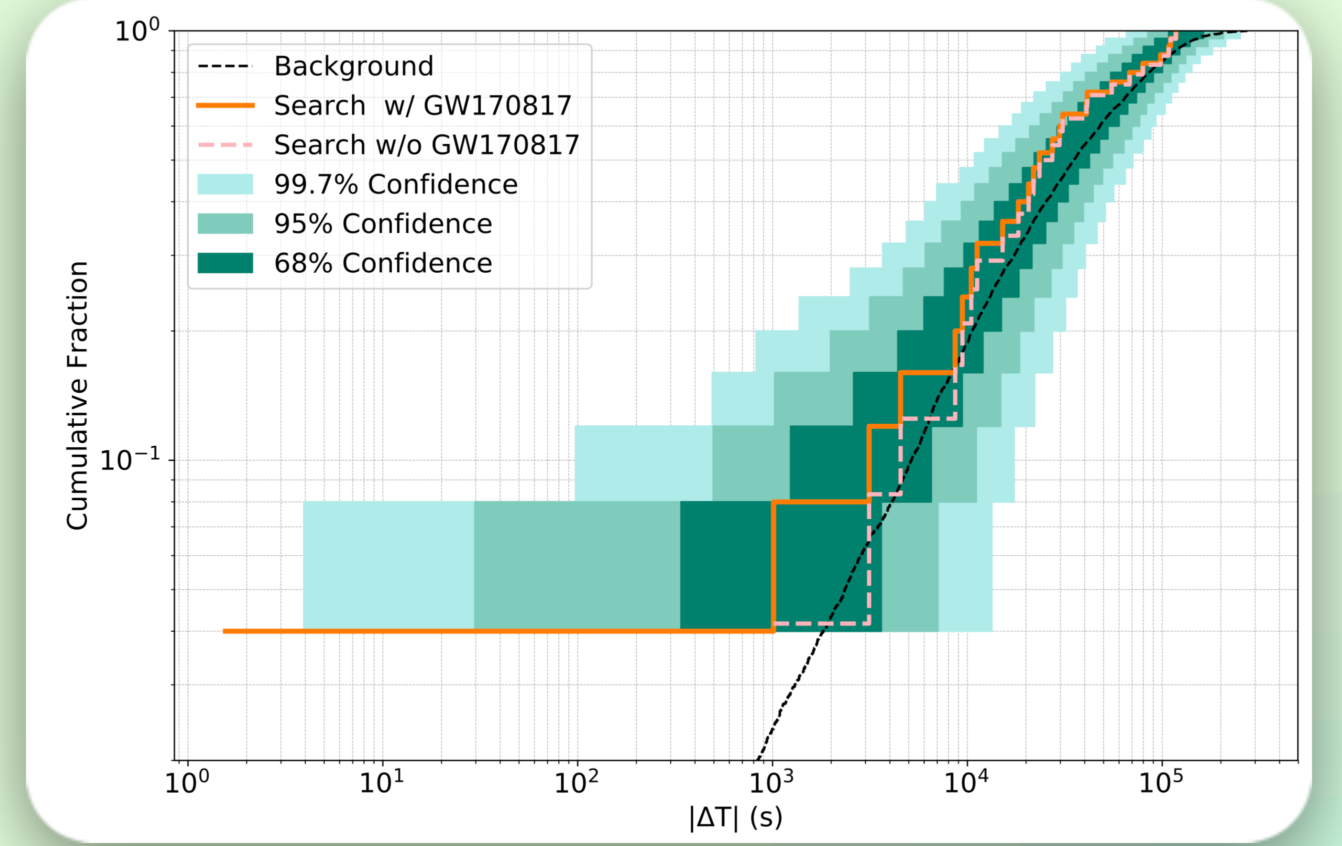
## Targeted

Distribution of the time delays, compared to the BKG

P-value associated to the ranking statistics R

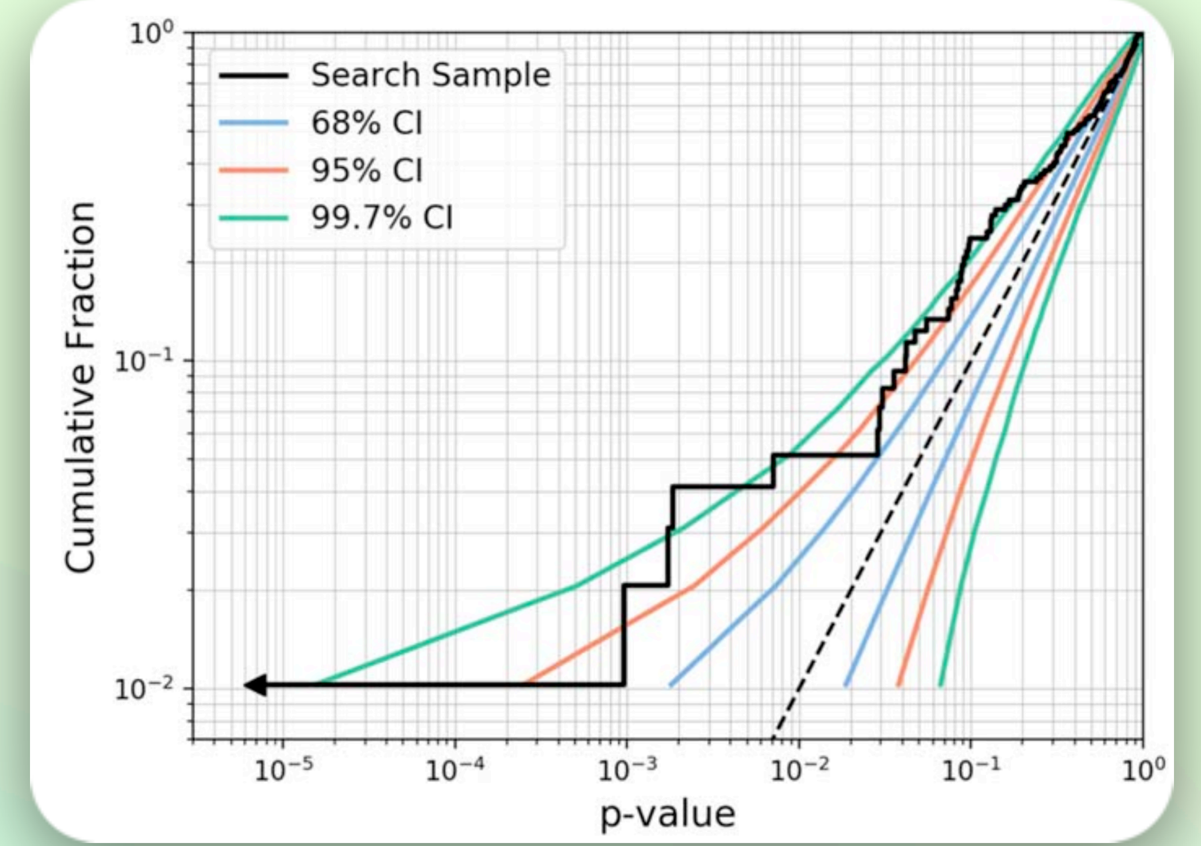
Fraction of GW localization visible to GBM

- 287 GRBs from onboard trigger + 187 from subthreshold search
- 25 GWs, only from the CBC pipelines, with FAR < 1/30 days



O1+O2

Hamburg+20

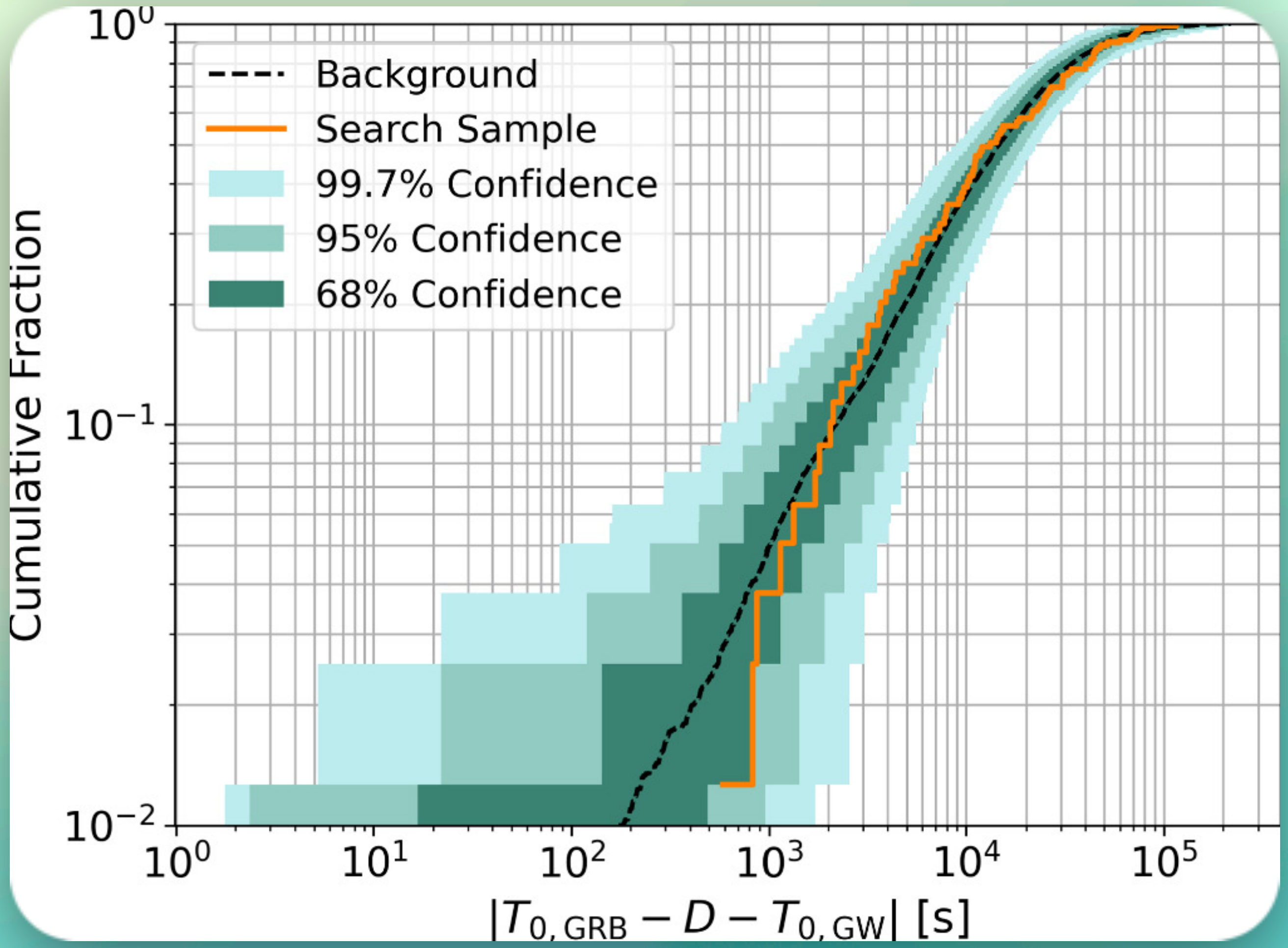


$$R = \frac{p_{\mathrm{astro}} \times p_{\mathrm{visible}}}{|\Delta t| \times \mathrm{FAR}_{\mathrm{GBM}}}$$

From the log-likelihood ratio

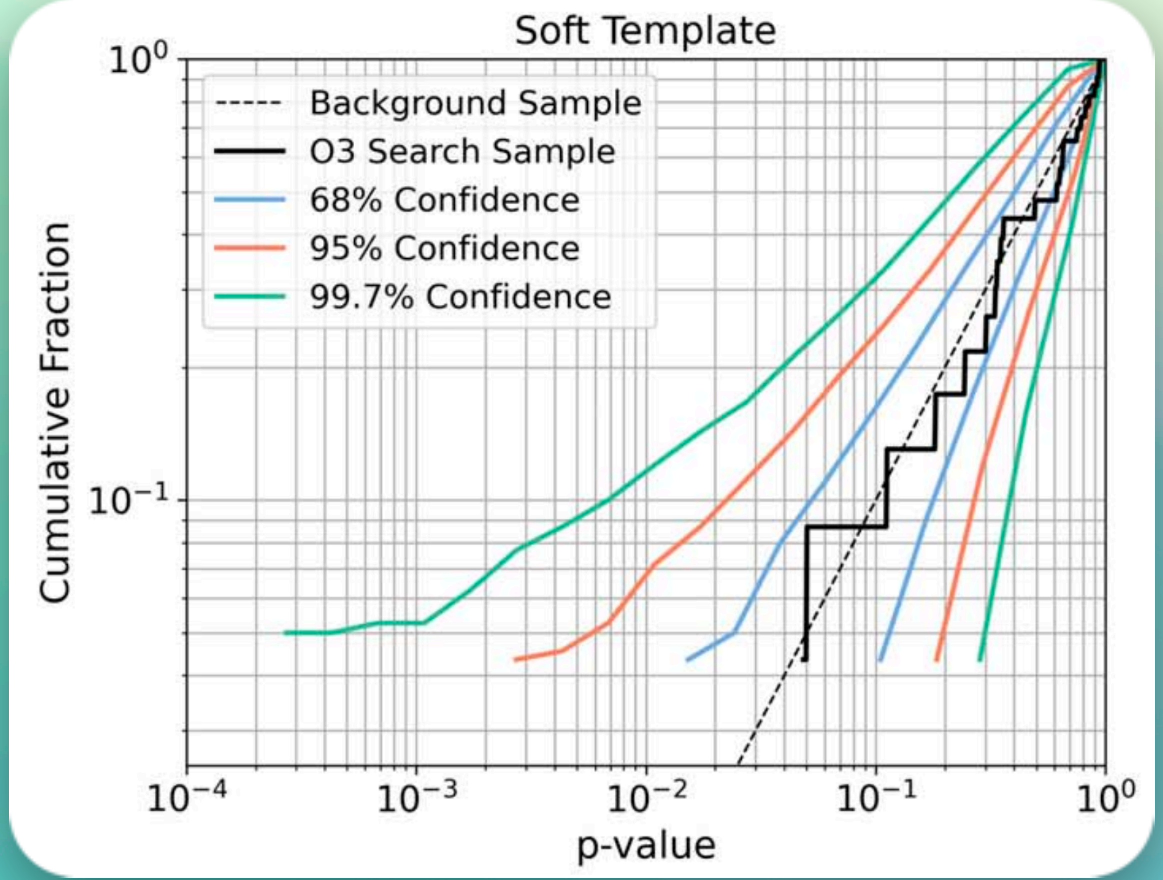
Quantifies the spatial overlap between the GW and the GBM candidate

- 214 GRBs from onboard trigger + 479 from subthreshold search
- 79 GWs CBC+bursts with p_astro >0.5



O3

Fletcher+24



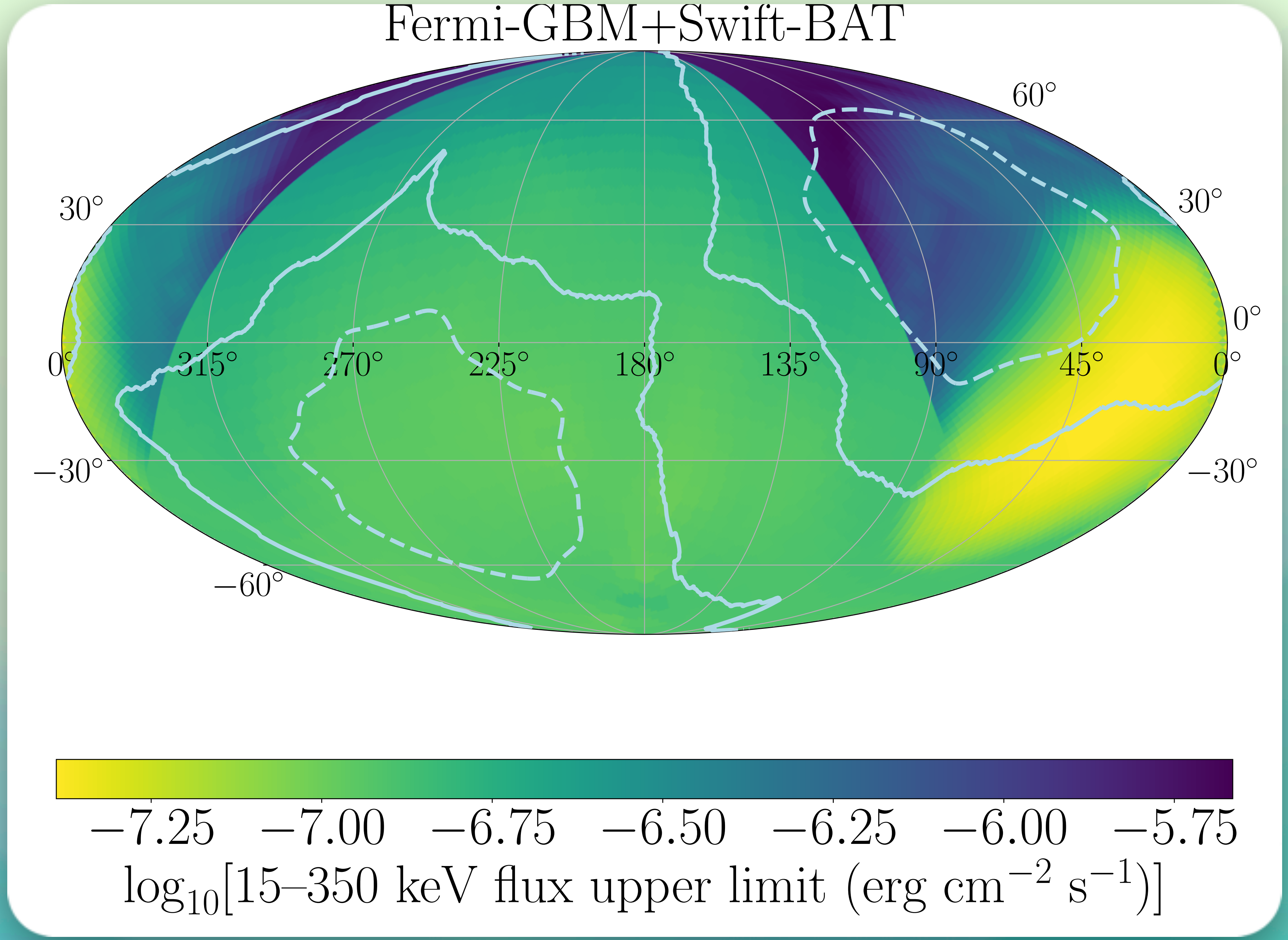
$$R = \frac{p_{\mathrm{astro}} \times p_{\mathrm{visible}} \times p_{\mathrm{assoc}}}{|\Delta t - D| \times \mathrm{FAR}_{\mathrm{GBM}}}$$

GRB duration, added to consider possible correlation between GW-gamma delay and duration

# What to do with non-detections: GW 230529

Case of GW230529

1. First NS merger with a component in **the mass gap 3-5 M$_\odot$**
2. **Low mass ratio** —> relatively high chance to have a remnant mass > zero
3. **Potentially EM-bright**

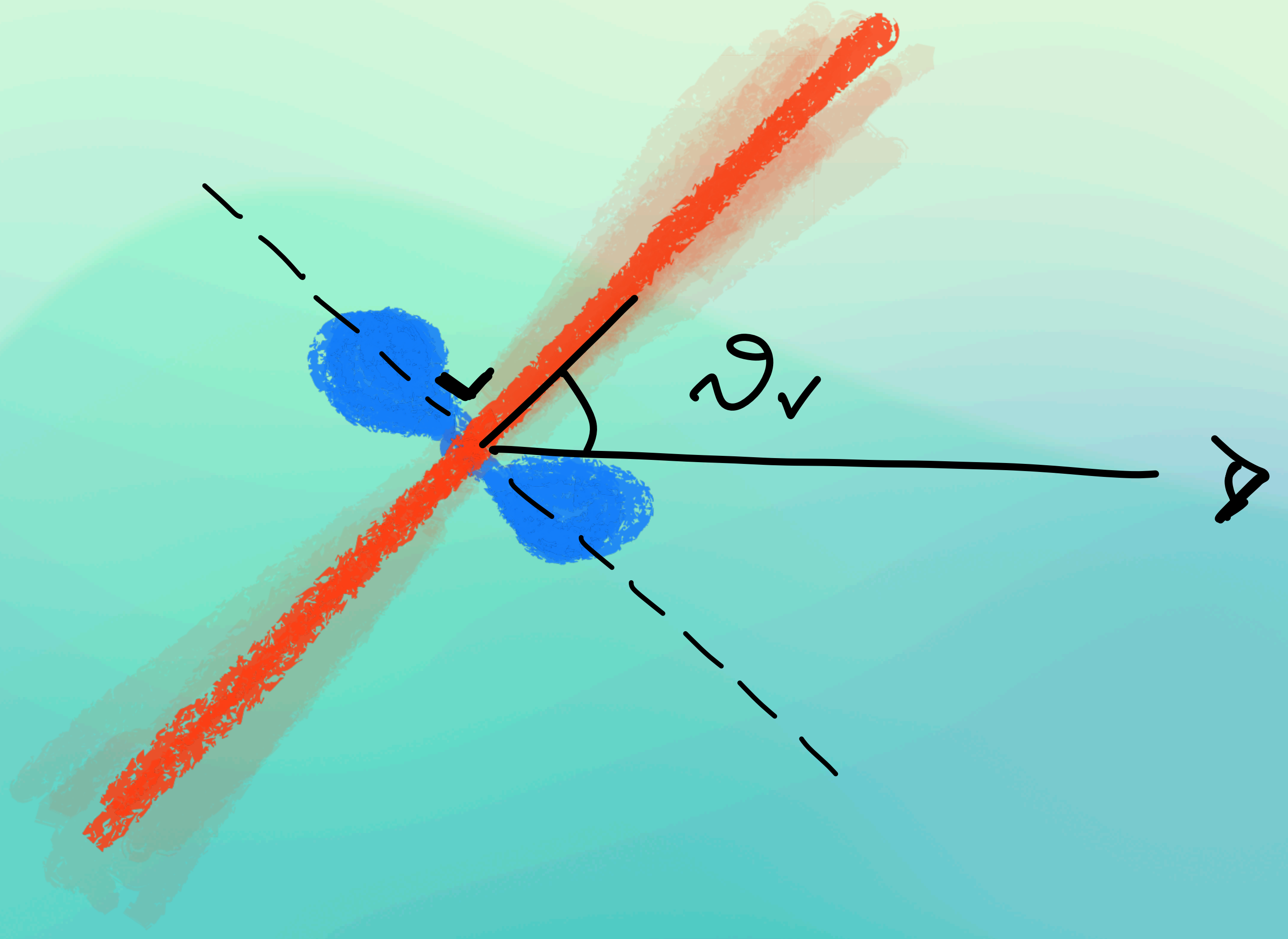


Ronchini+24

$$\mathrm{UL}_{\mathrm{joint}}\ (\Omega) = \min\left[\mathrm{UL}_{\mathrm{BAT}}(\Omega), \mathrm{UL}_{\mathrm{GBM}}(\Omega)\right]$$

The upper limits are computed for several spectral templates, and the most conservative value is adopted

Several structures profiles for the jet are tested, modeling the structure as



$$L\left(\theta_v\right) = L_0 l\left(\theta_v\right)$$

$$L_0 = L(\theta = 0)$$

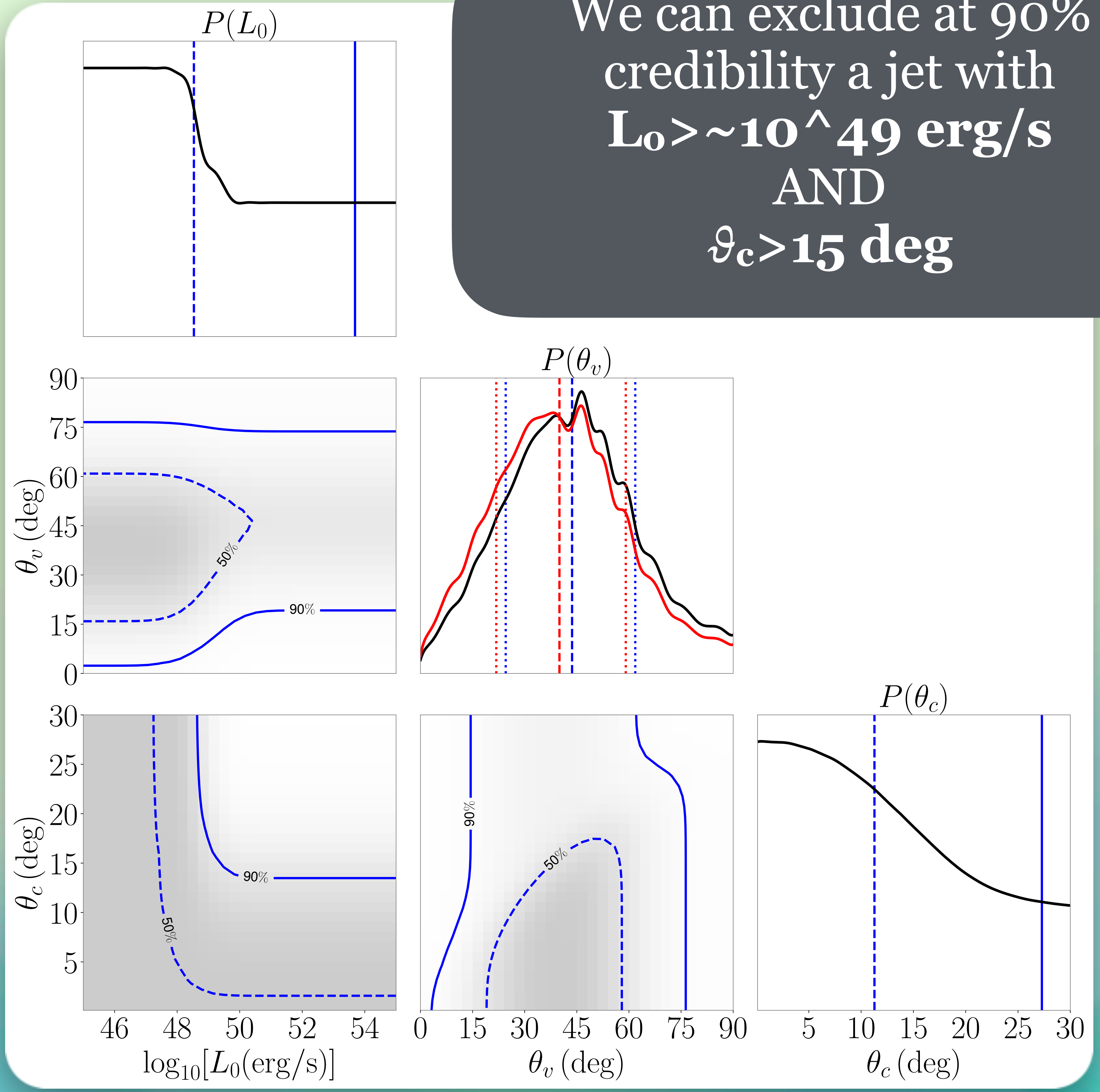
$$l\left(\theta_v\right) = \begin{cases} \sim 1, & \theta < \theta_c \\ f\left(\theta_v\right), & \theta > \theta_c \end{cases}$$

# Constraints on the $\gamma$-ray emission from GW230529

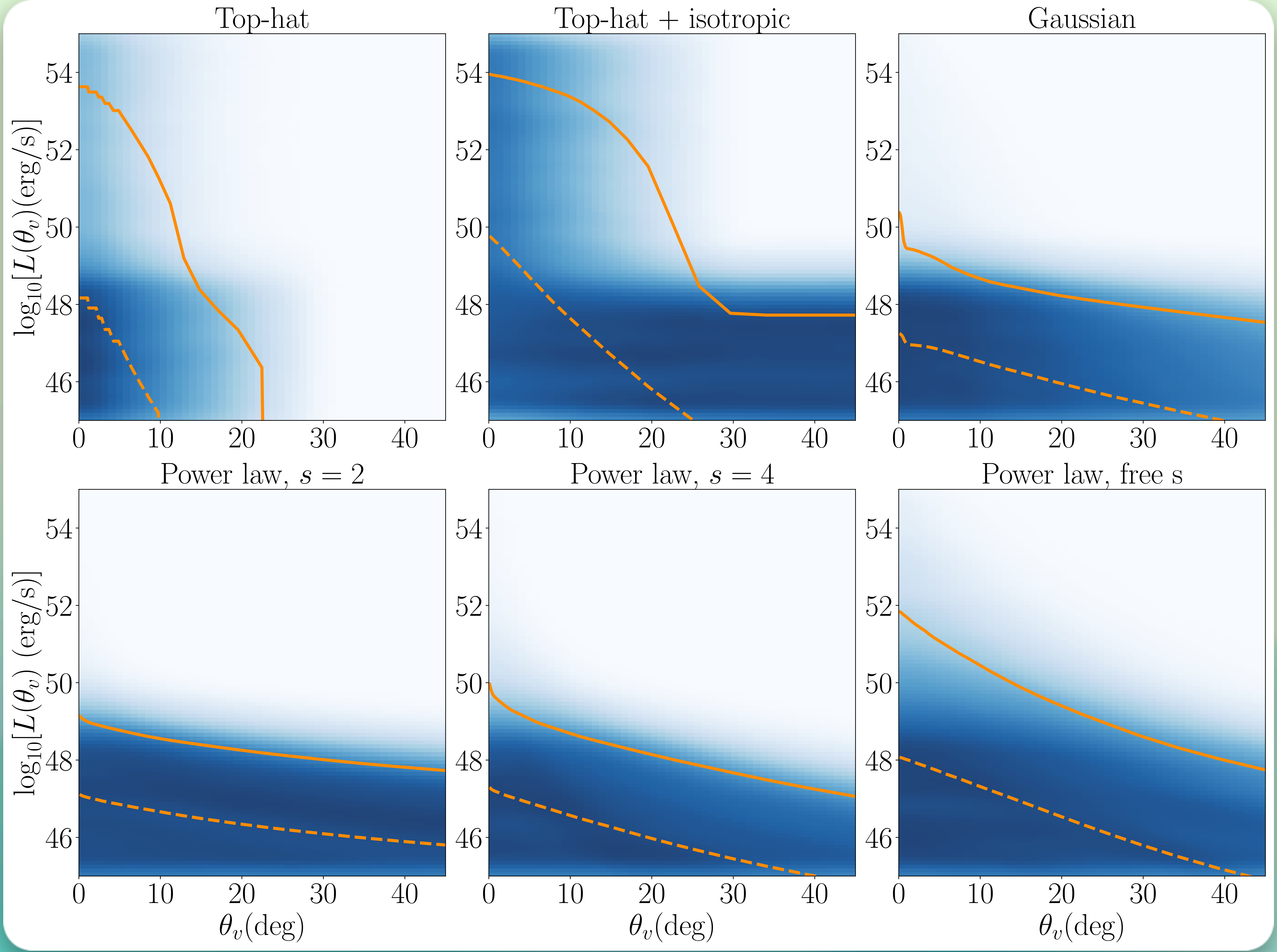
$$P_{ND}\left(\vec{\theta},\theta_v\right)=$$

$$\int P(F<\mathrm{UL}(\Omega))P_{GW}\left(\Omega,D_L\mid\theta_v\right)d\Omega dD_L$$

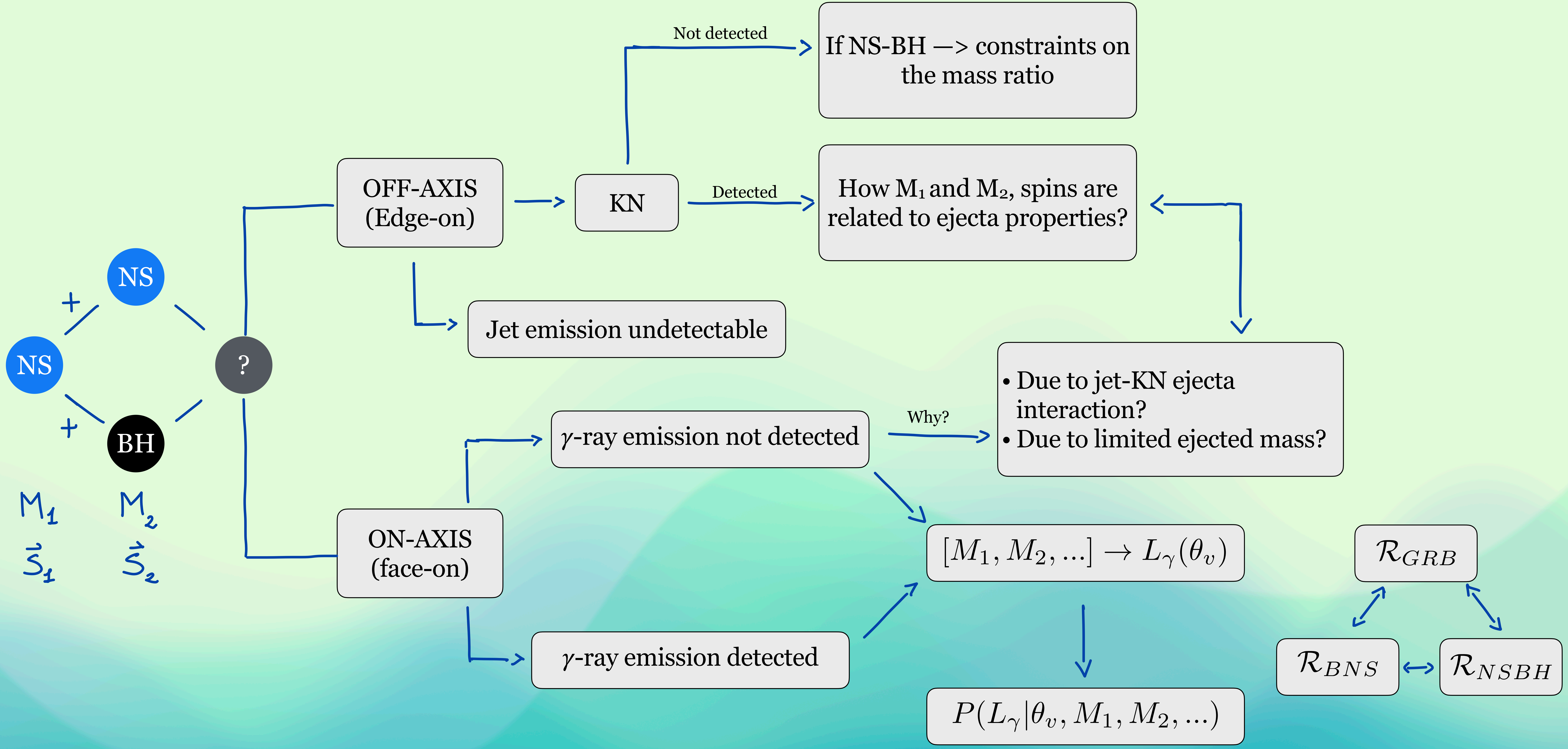
We can exclude at 90% credibility a jet with
**L₀>~10^49 erg/s**
AND
**ϑc>15 deg**



Constraints with different assumptions on the jet structure



# What we can constrain with future $\gamma$+GW detections (and non-detections)



NS

NS

BH

?

+

+

$M_1$ $M_2$

$\vec{S}_1$ $\vec{S}_2$

OFF-AXIS
(Edge-on)

KN

Not detected

If NS-BH —> constraints on the mass ratio

Detected

How $M_1$ and $M_2$, spins are related to ejecta properties?

Jet emission undetectable

ON-AXIS
(face-on)

$\gamma$-ray emission not detected

Why?

- Due to jet-KN ejecta interaction?
- Due to limited ejected mass?

$\gamma$-ray emission detected

$[M_1, M_2, ...] \rightarrow L_\gamma(\theta_v)$

$P(L_\gamma|\theta_v, M_1, M_2, ...)$

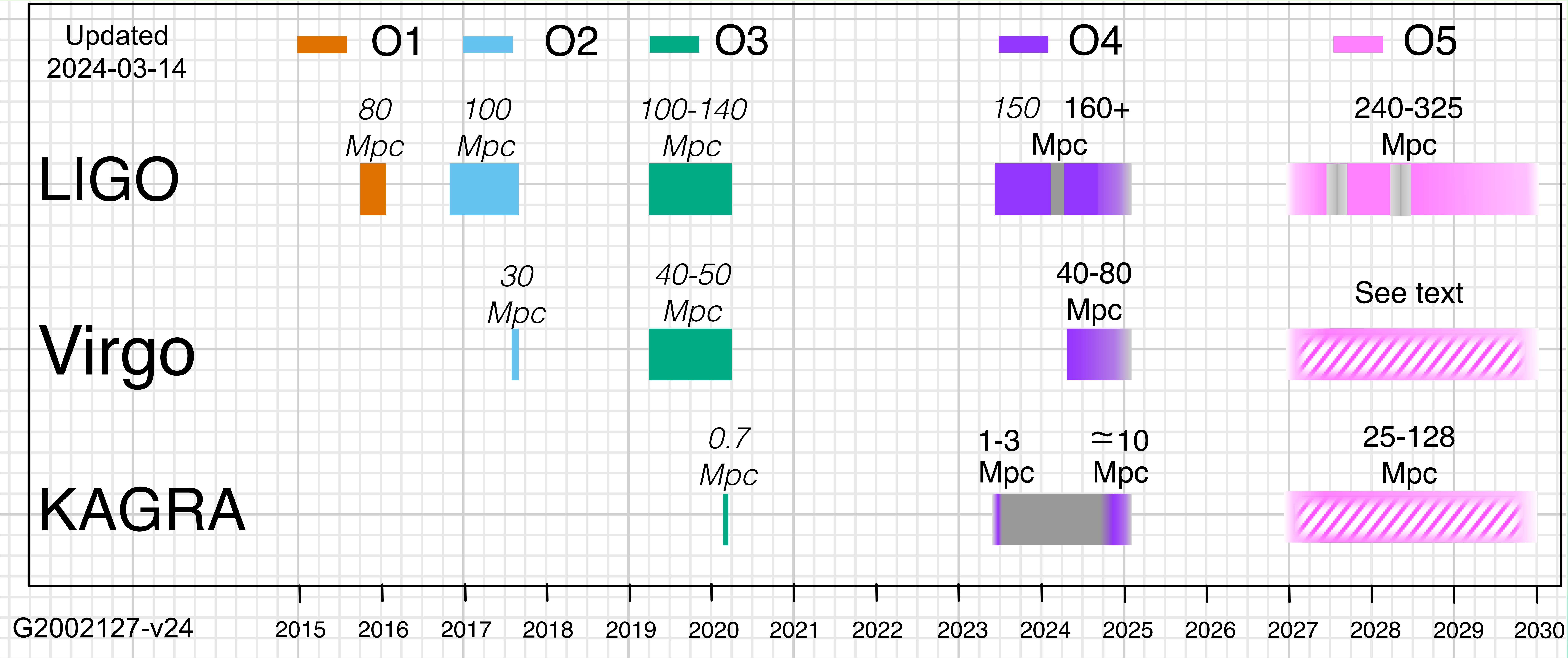
$\mathcal{R}_{GRB}$

$\mathcal{R}_{BNS}$

$\mathcal{R}_{NSBH}$

# Future challenges

# Prospects for O4 and O5



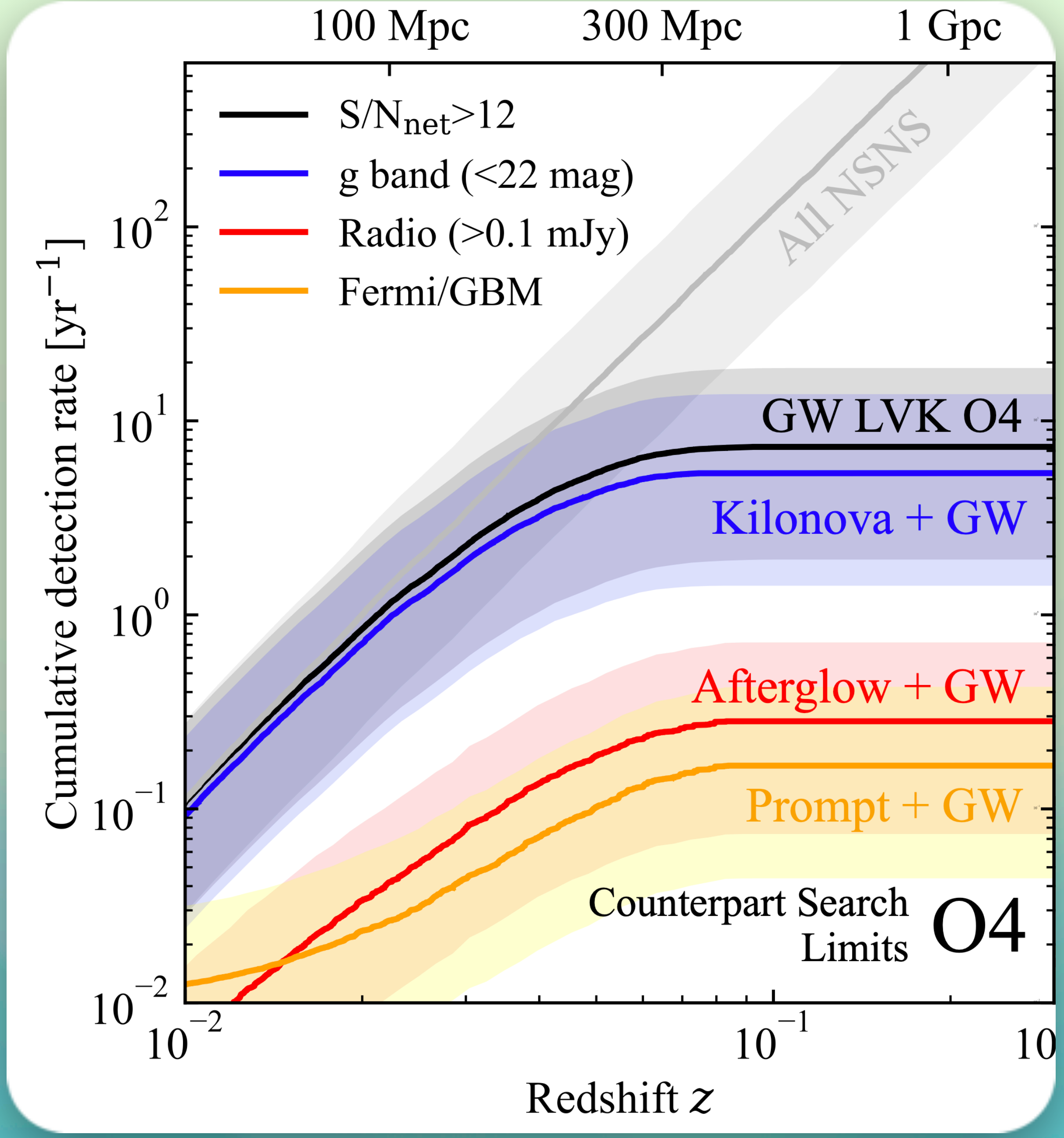
# Prospects for O4 and O5

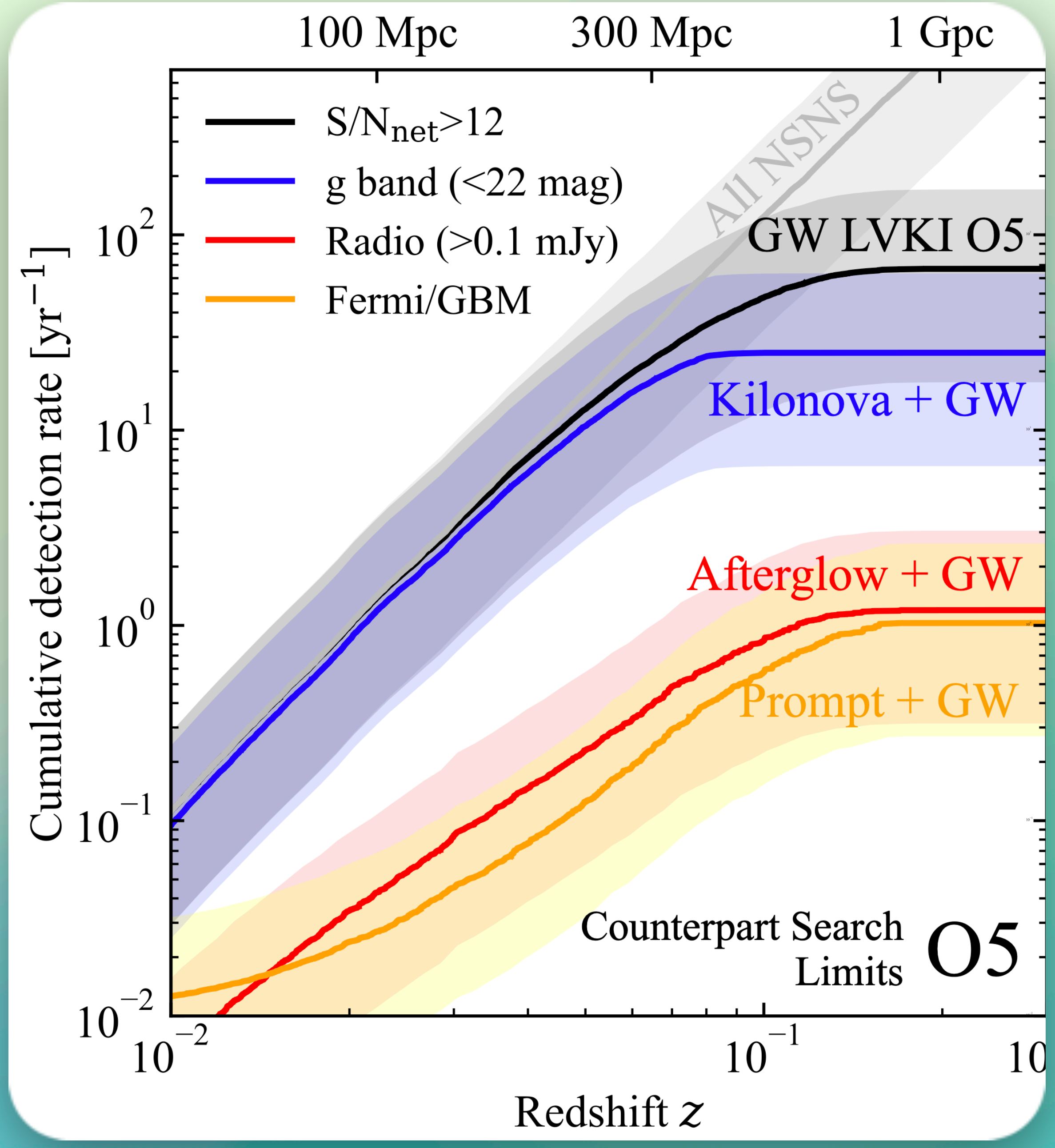
|  | BNS / yr |  | NSBH / yr |  |
|---|---|---|---|---|
|  | GW | GW+GBM | GW | GW+GBM |
| O4 | $7.4^{+11.3}_{-5.5}$ | $0.17^{+0.26}_{-0.13}$ | $15^{+15}_{-9}$ | $< 1$ |
| O5 | $67^{+104}_{-50}$ | $1^{+1.6}_{-0.8}$ | $140^{+143}_{-81}$ | $0.02 - 4.4$ |

What we can do:

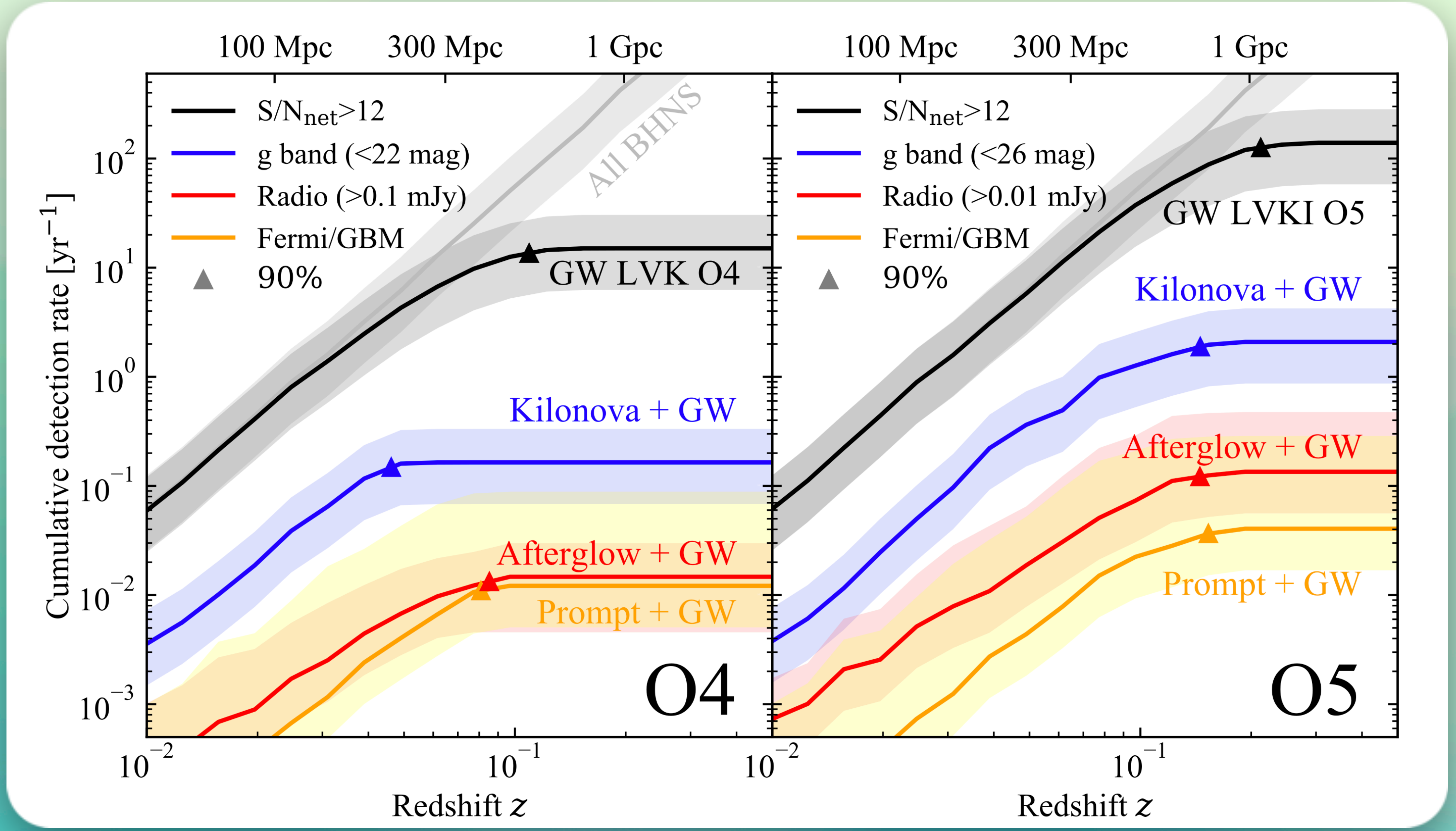
- Reasonably assume that **most of short GRBs are driven by BNS mergers**, while NSBH rarely have an emerging jet
- Consider the uncertainties in the rate of BNS and NSBH mergers
- For **BNS** —> Take into account the average detection rate of Fermi-GBM and **build a GRB population model calibrated on past data**
- For **NSBH** —> **much more model dependent** and subject to uncertainty in the EoS, jet launch mechanism, absence of any joint EM-GW detection

**BNS** Colombo+22

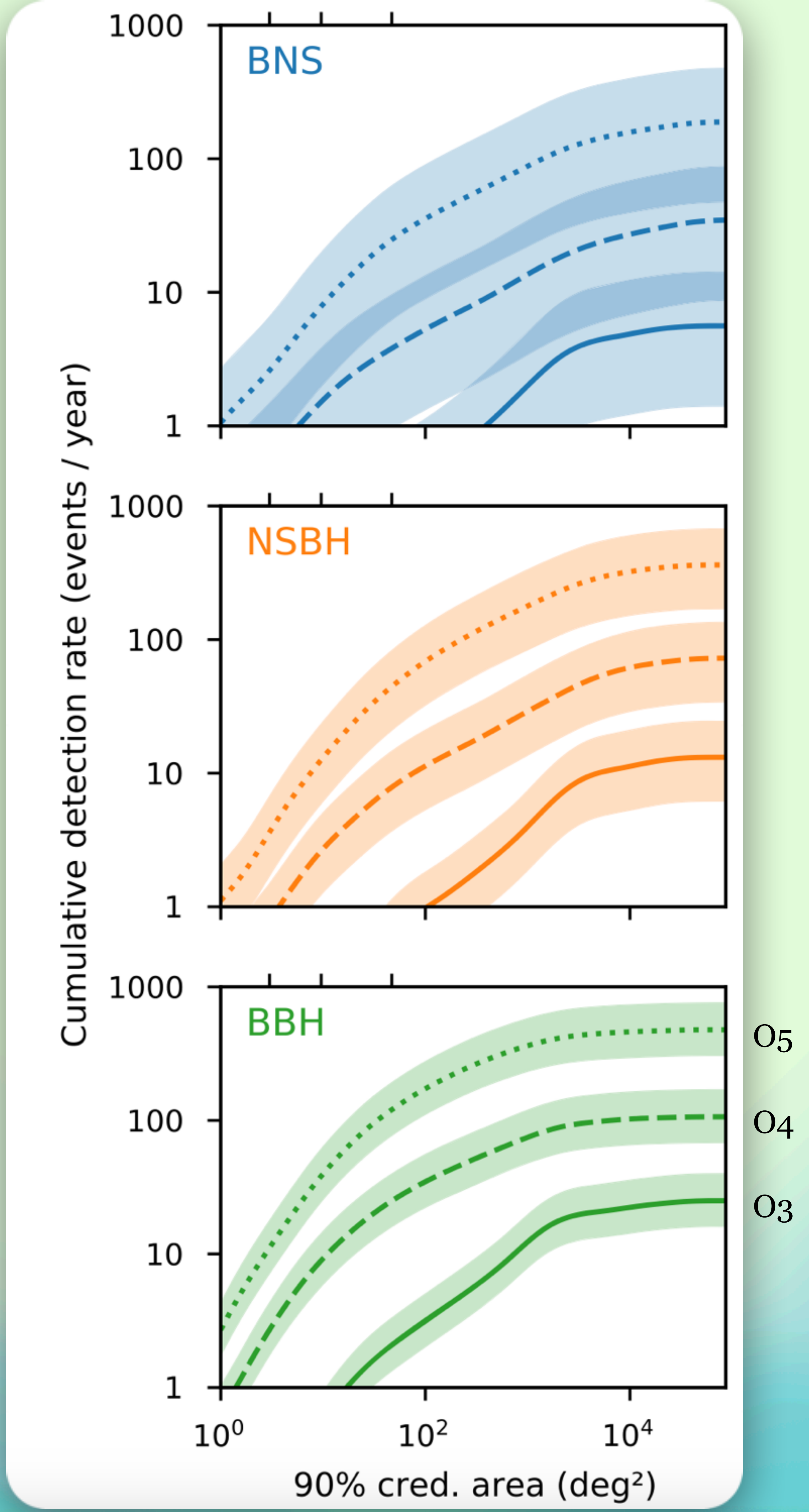




**NSBH** Colombo+23



# GW sky localization



Petrov+22

$\Delta\Omega_{90\%}$ 90% credible area of the sky localization

| | Fraction of BNS over the total | | Fraction of NSBH over the total | |
|---|---|---|---|---|
| | $\Delta\Omega_{90\%} < 100\ \mathrm{deg}^2$ | $\Delta\Omega_{90\%} < 10\ \mathrm{deg}^2$ | $\Delta\Omega_{90\%} < 100\ \mathrm{deg}^2$ | $\Delta\Omega_{90\%} < 10\ \mathrm{deg}^2$ |
| O4 | 15 % | 5 % | 16 % | 3.6 % |
| O5 | 18 % | 4.2 % | 19 % | 3.6 % |

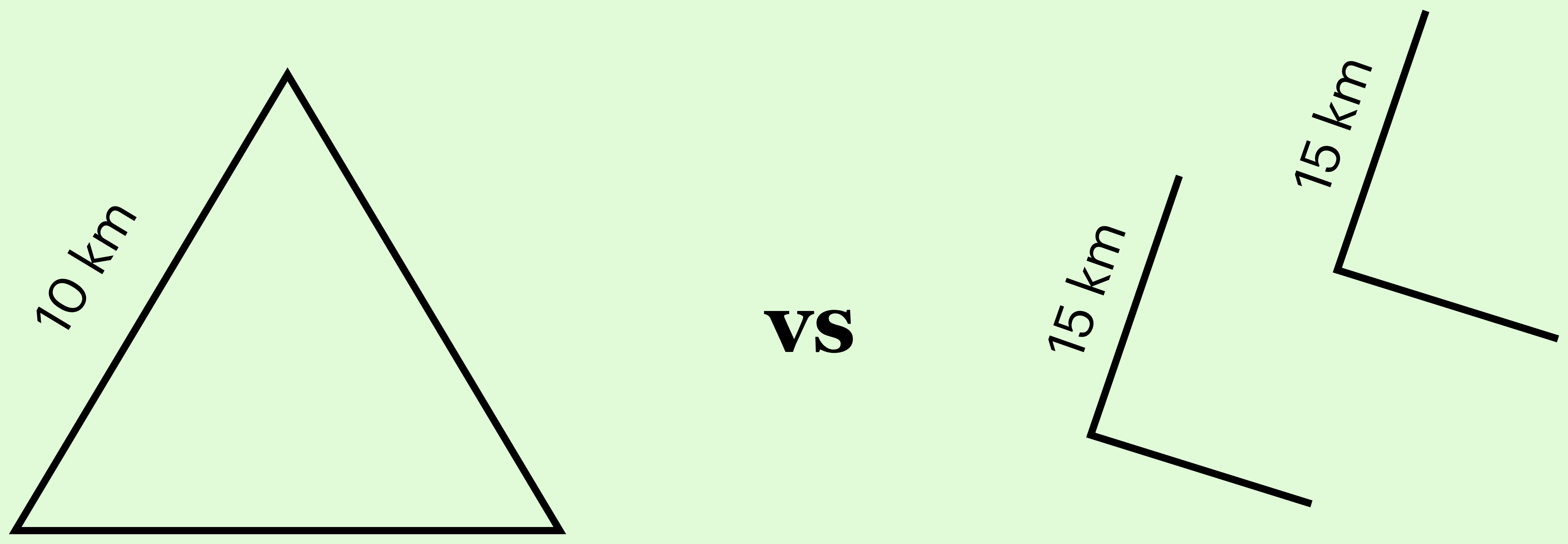
For both BNS and NSBH:

$\Delta\Omega_{90\%} \sim 2000\ \mathrm{deg}^2$ For S/N > 8

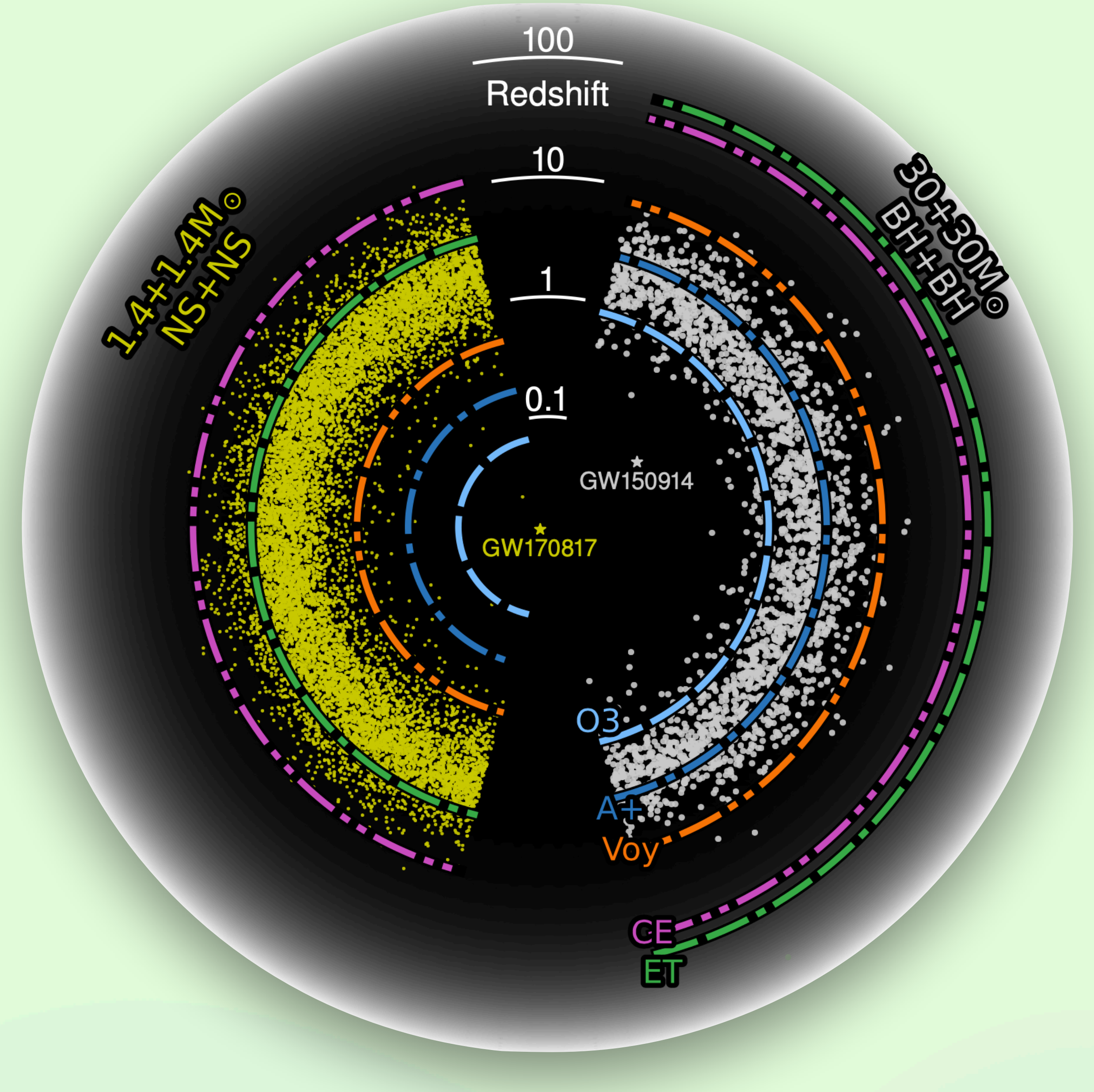
$\Delta\Omega_{90\%} \sim 30 - 50\ \mathrm{deg}^2$ For S/N > 12

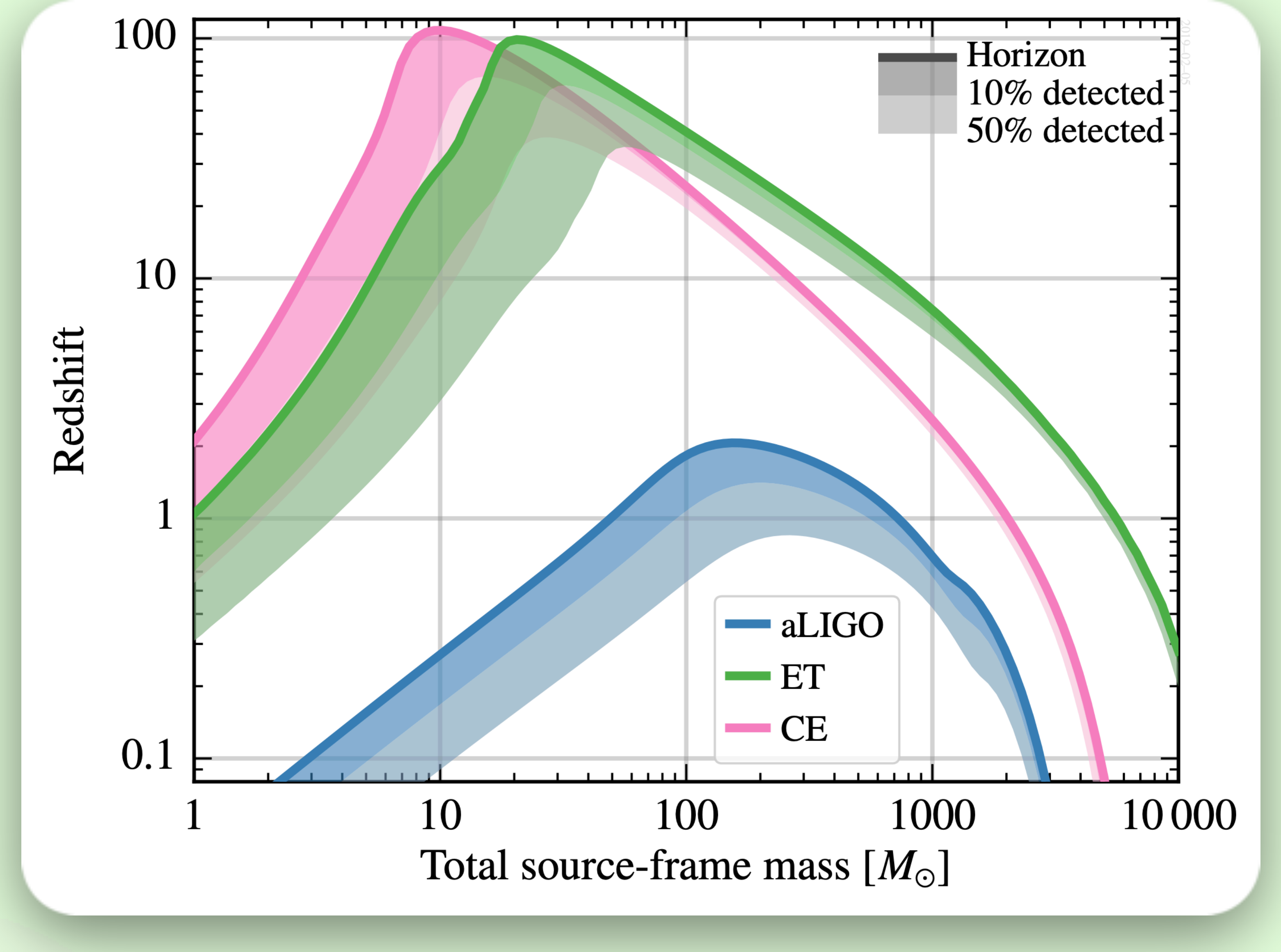
# The 3G GW era

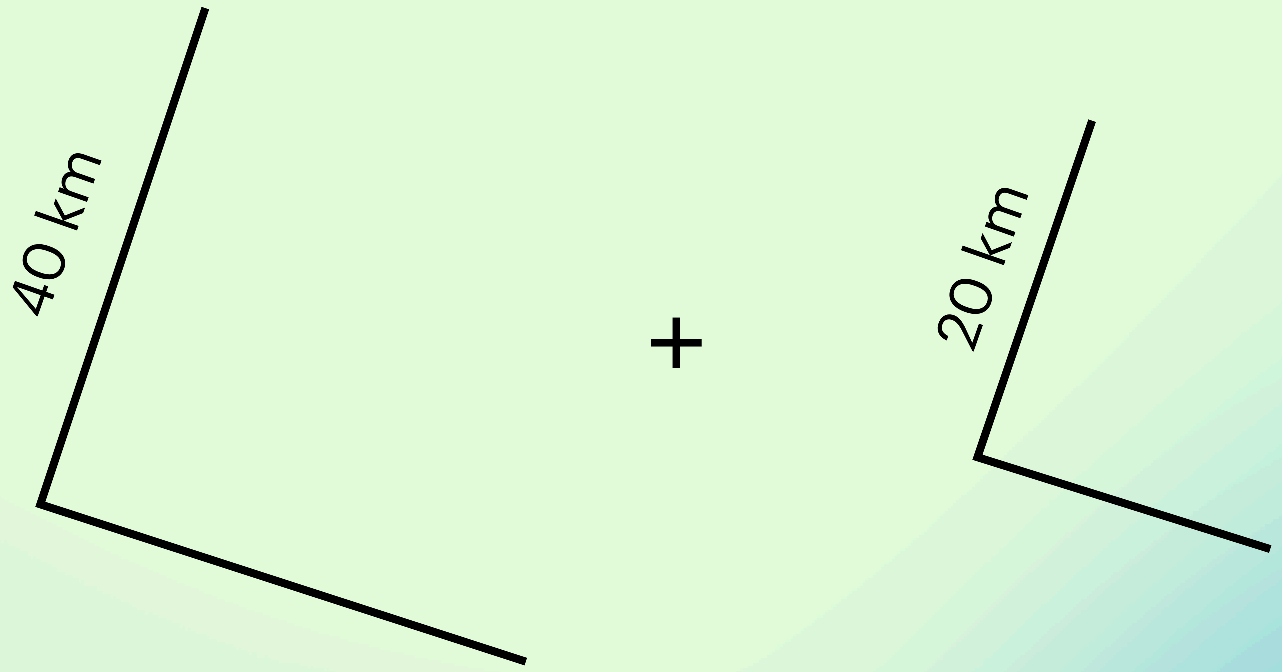
Branchesi+23



**Einstein Telescope** (ET)







**Cosmic Explorer** (CE)

Evans+23

Main milestones for multi-messenger science

- Detection of NS mergers beyond the star formation peak
- Detection of **post-merger** signal —> nature of remnant
- Possibility to **detect and localize** minutes **before the merger**
- Drastic improvement in the **sky localization**

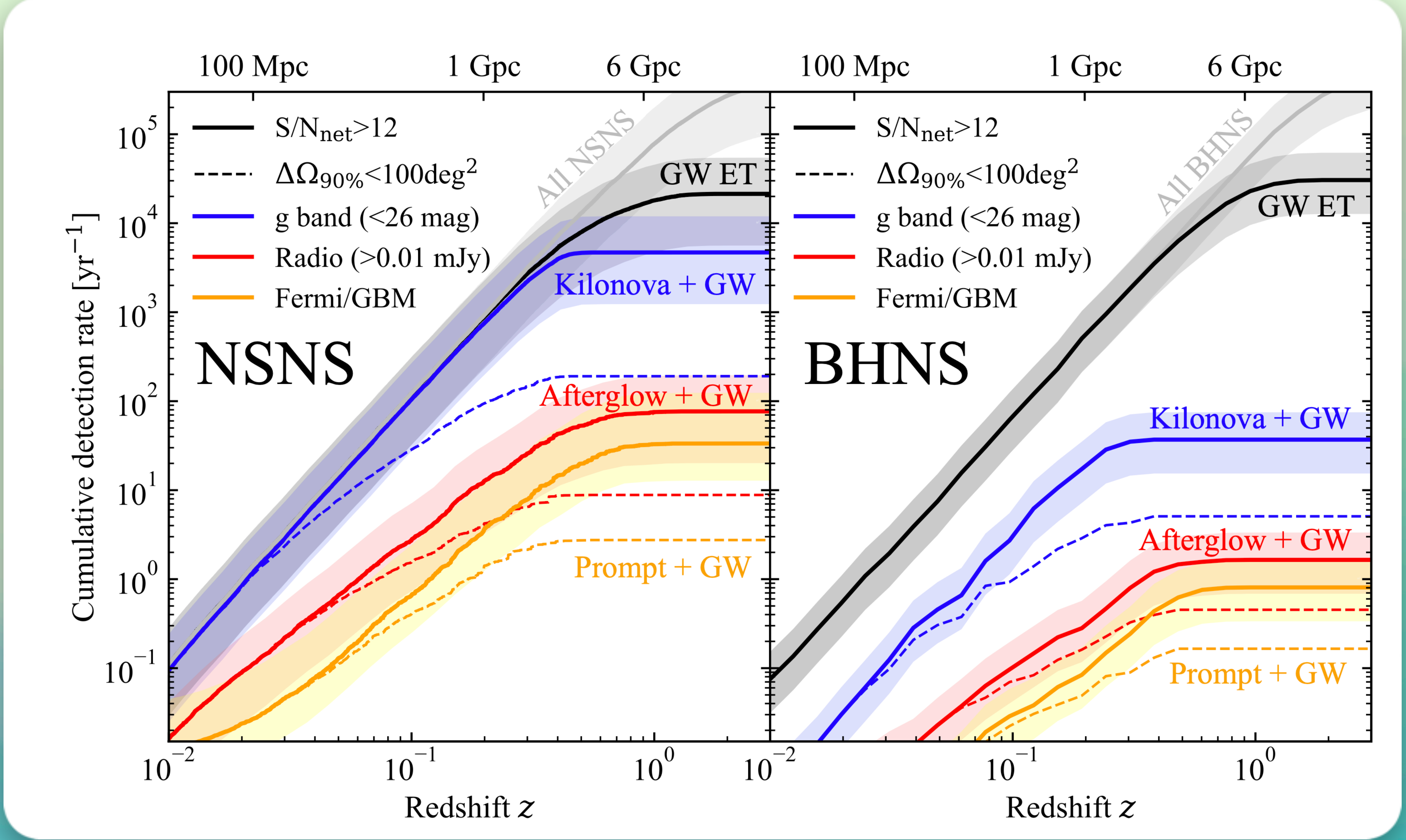
# The 3G GW era

| S/N cut at 12 | BNS / yr | | NSBH / yr | |
|---|---|---|---|---|
| | GW | GW+GBM | GW | GW+GBM |
| ET | $2 \times 10^4$ | $34^{+91}_{-21}$ | $3 \times 10^4$ | $0.81^{+0.83}_{-0.47}$ |

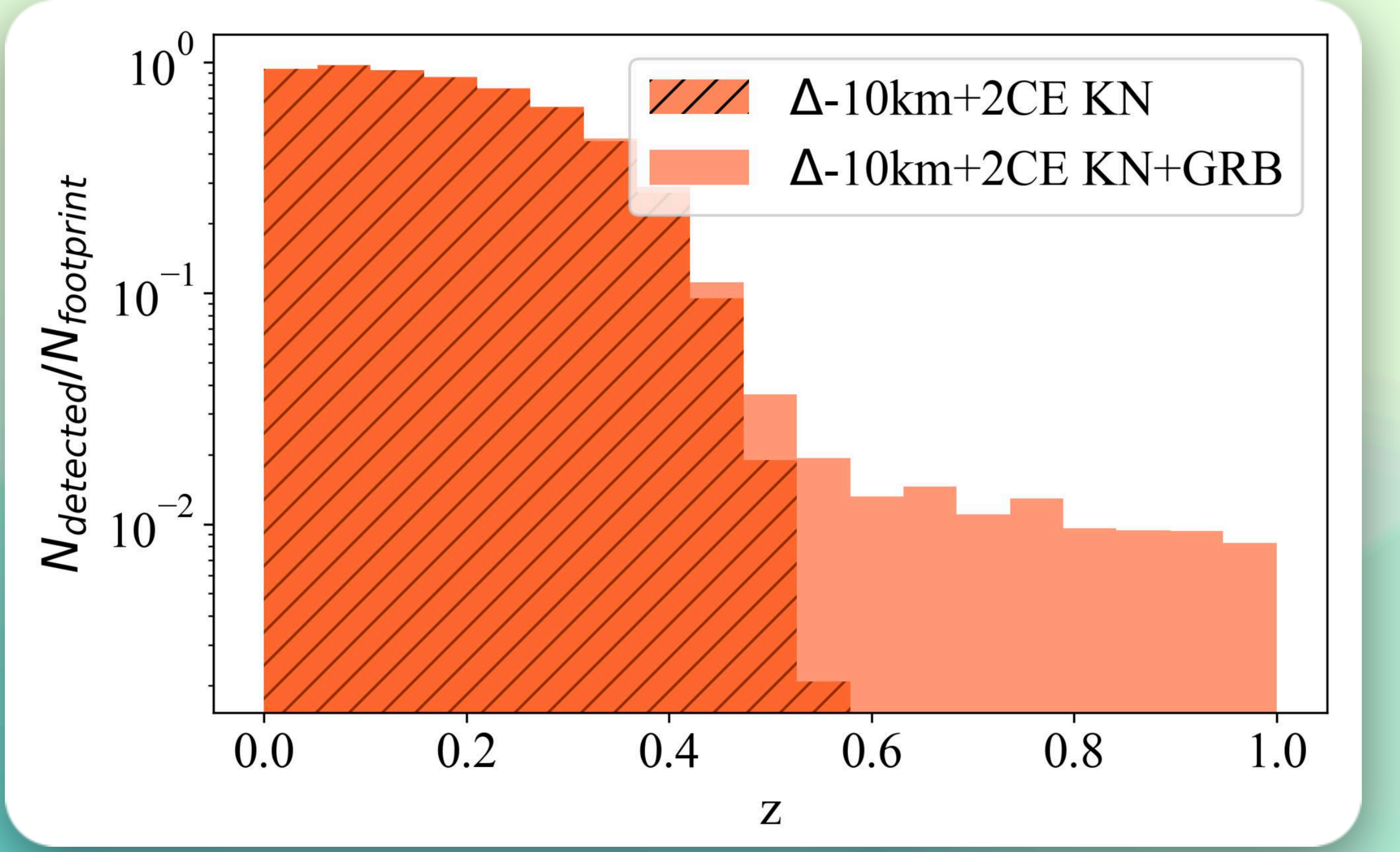
Considering only BNS and short GRBs:

- around **70% of all short GRB will have a detectable GW signal in ET**
- Around **95%** of will have a detectable GW signal in **ET+CE**

Colombo+ in prep.



Detection efficiency for KN detectable by VRO



Loffredo+ in prep.

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Colombo+ in prep.

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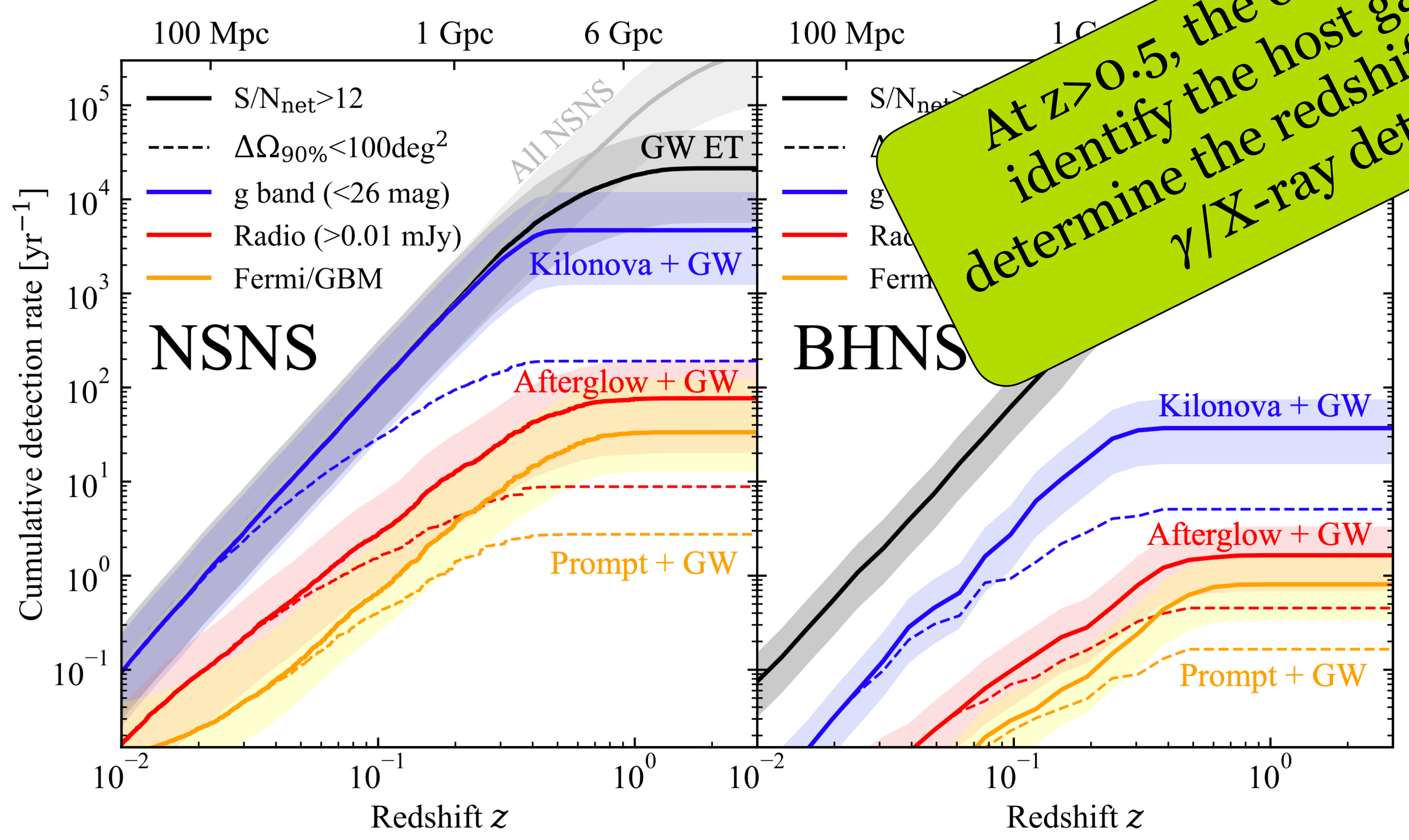
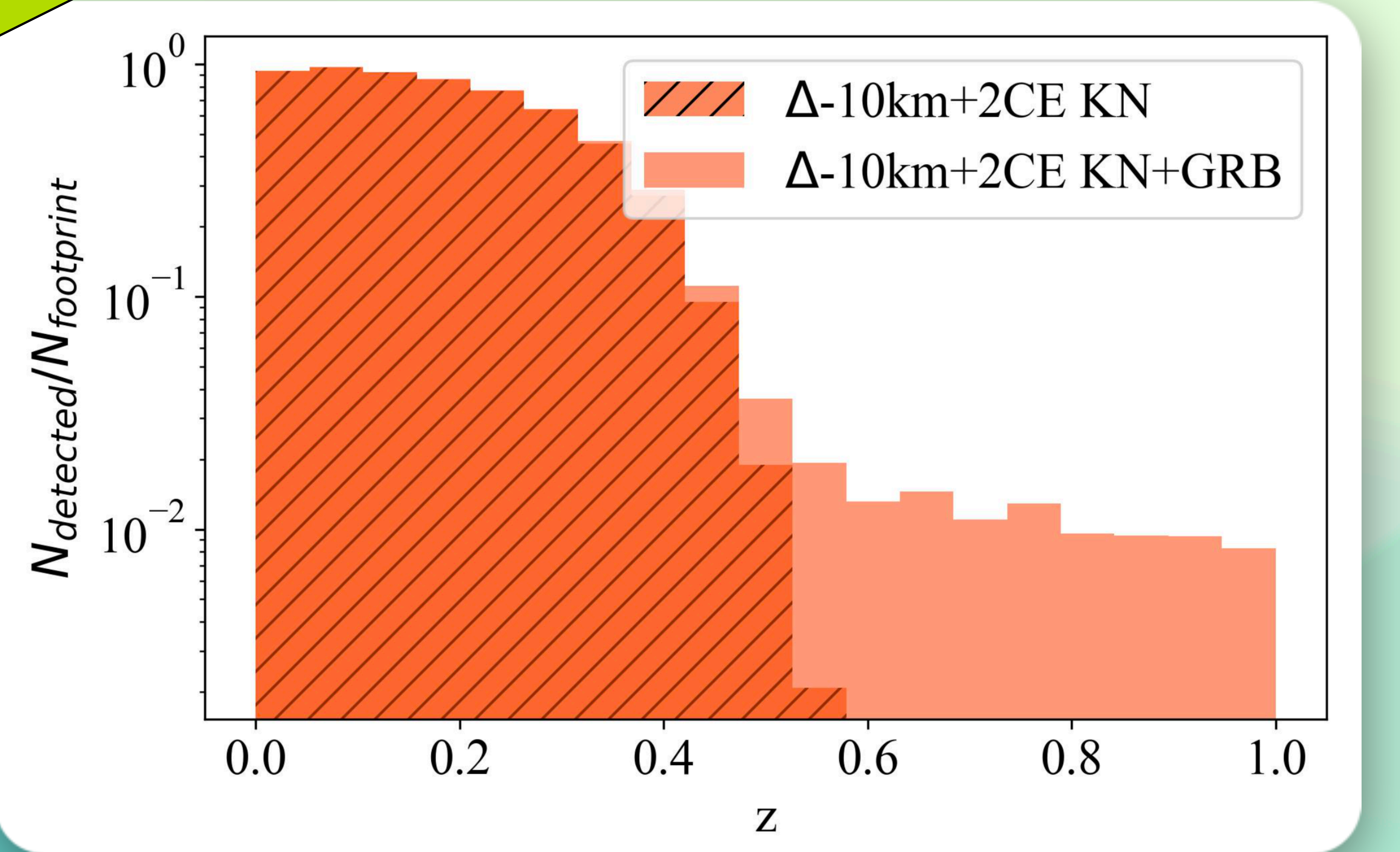
- around **70% of all short GRB will have a detectable GW signal in ET**
- Around **95%** of will have a detectable GW signal in **ET+CE**

At z>0.5, the only chance to identify the host galaxy and determine the redshift is to rely on $\gamma$/X-ray detectors

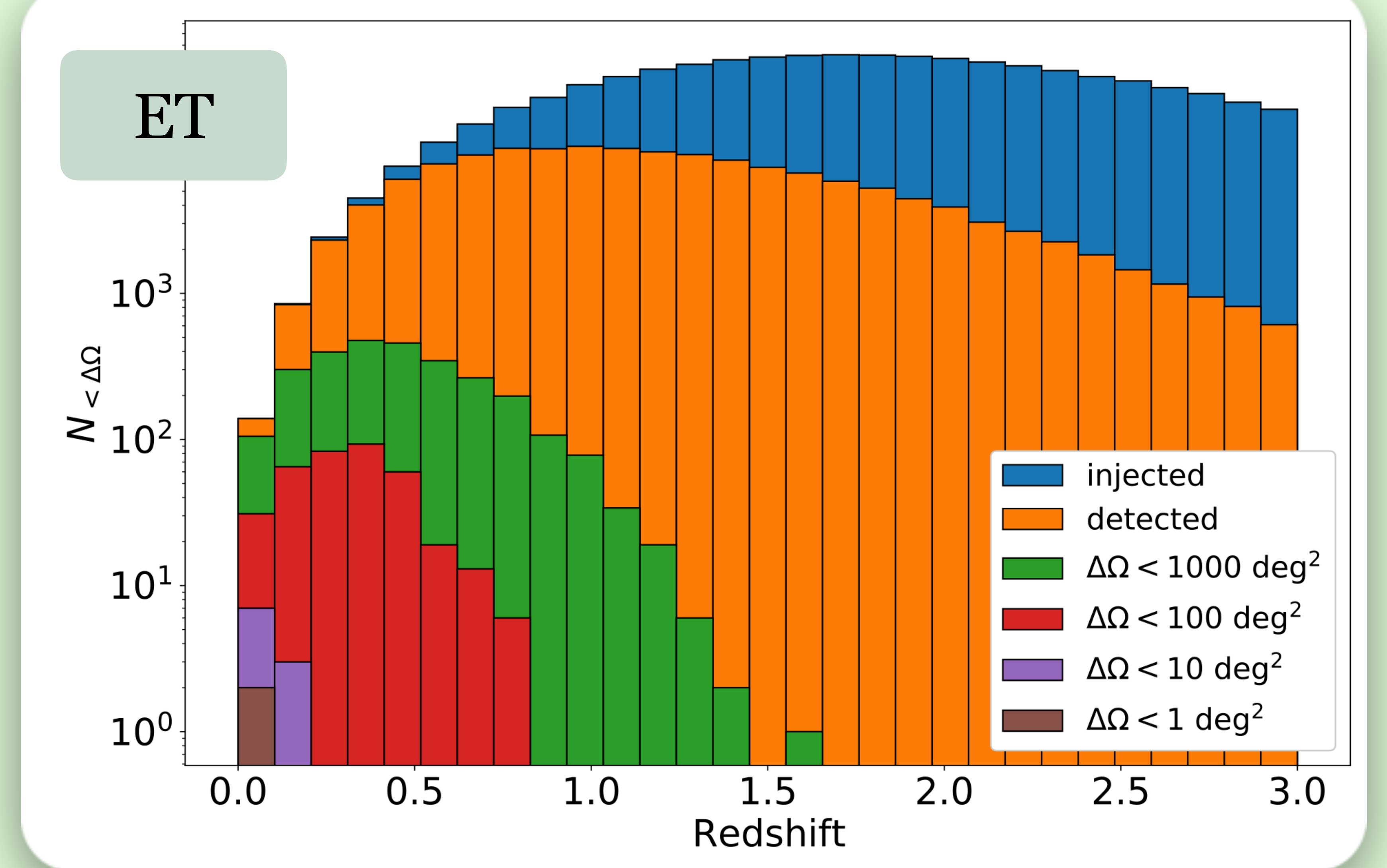


Detection efficiency for KN detectable by VRO



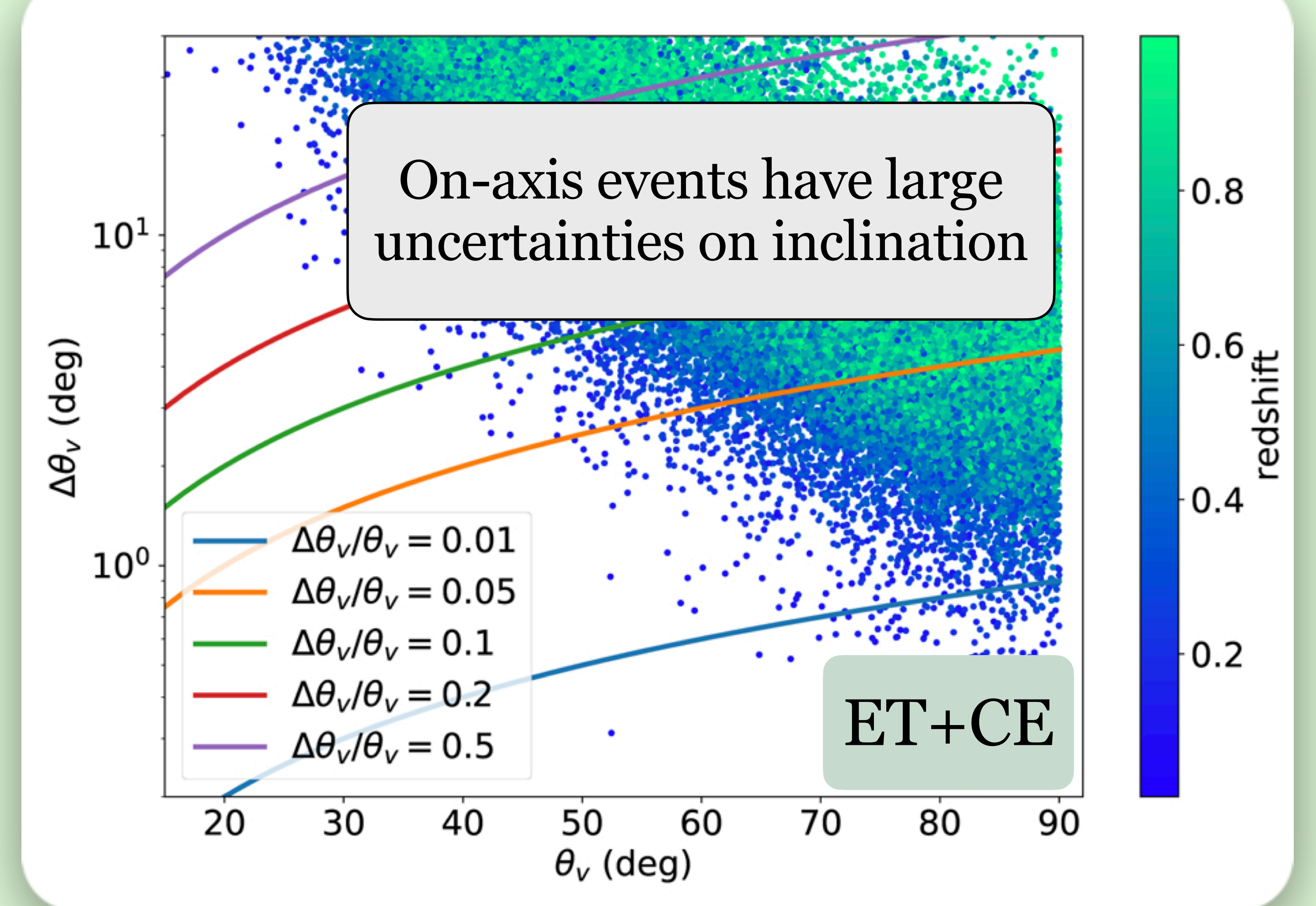
Loffredo+ in prep.

# The 3G GW era



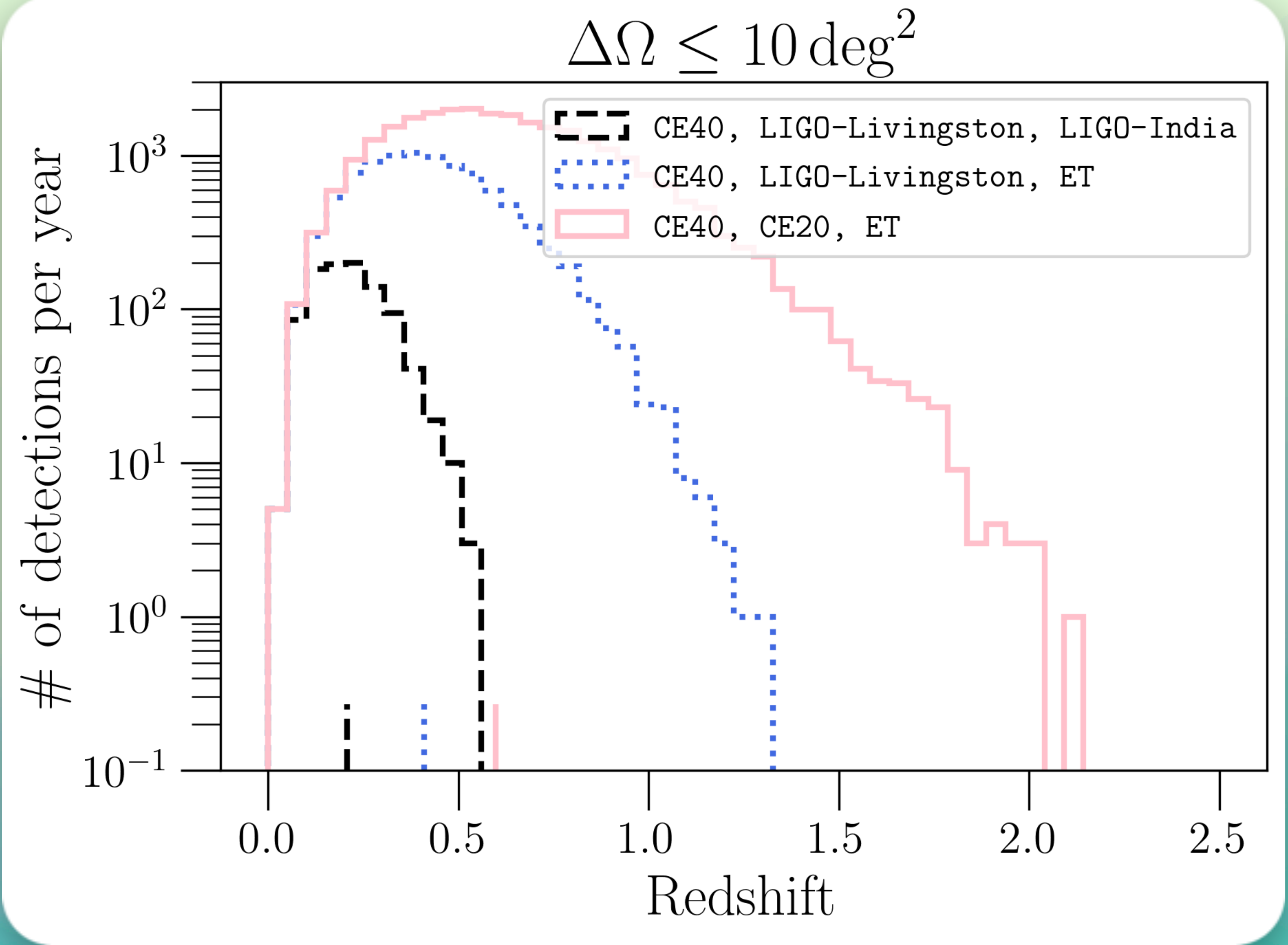
Ronchini+22

The detection of the gamma-ray counterpart at high z can give strong constraints on the inclination angle, otherwise unavailable from the GW analysis alone



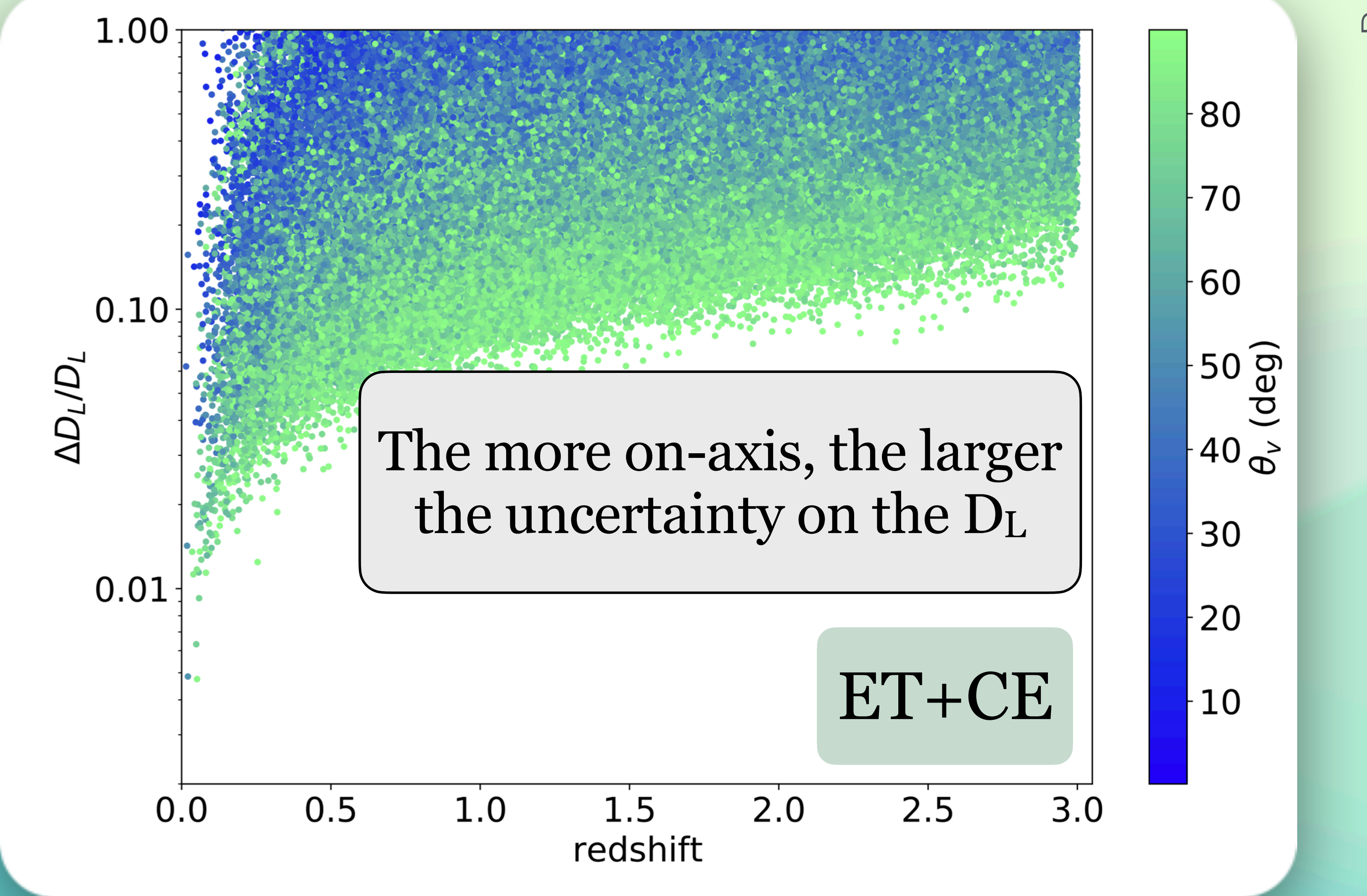
On-axis events have large uncertainties on inclination

Ronchini+22



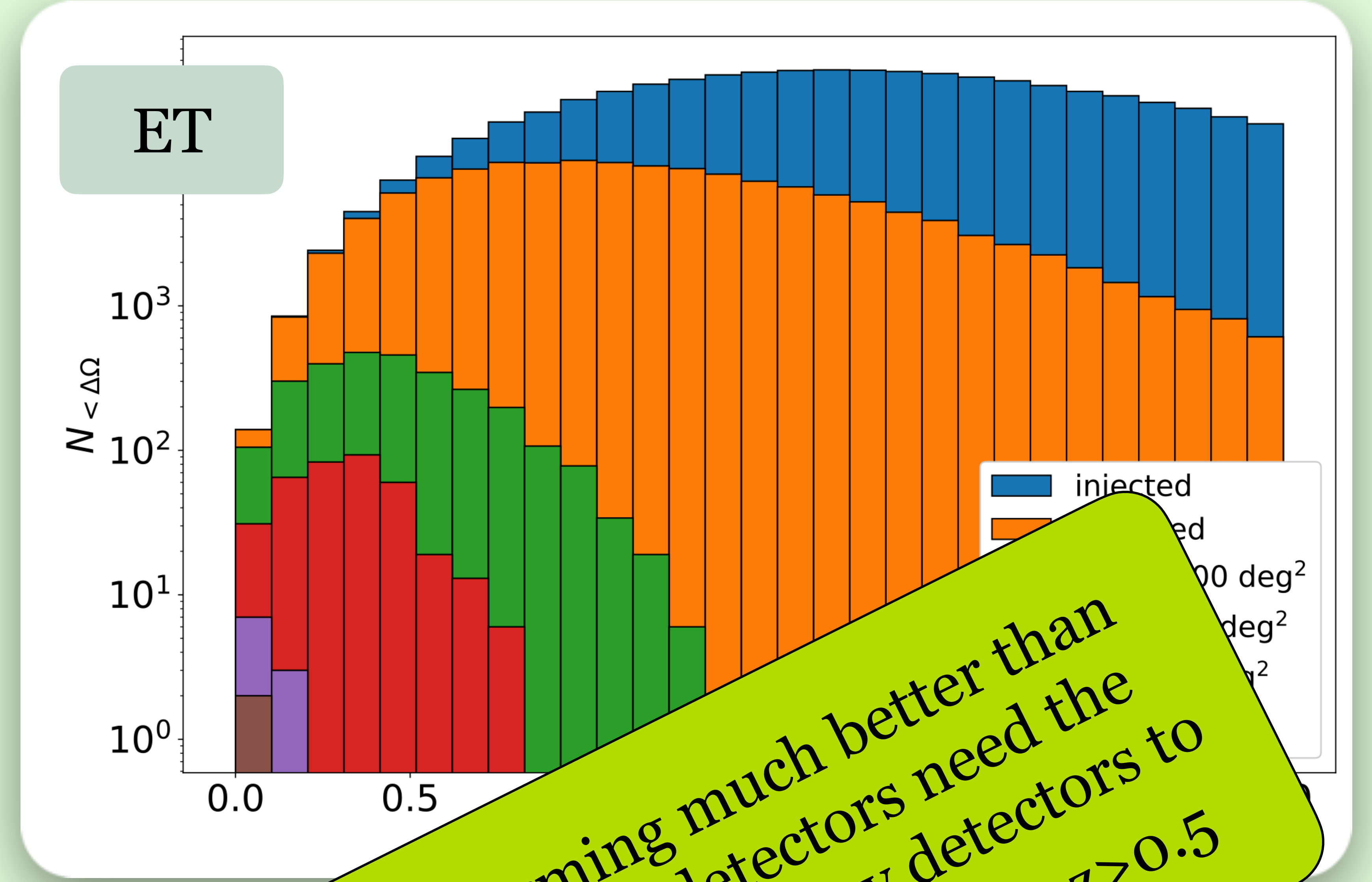
Gupta+24

Inclination angle and distance are degenerate, so the localization in space through EM observations can break such degeneracy



The more on-axis, the larger the uncertainty on the $D_L$

# The 3G GW era



Ronchini+22

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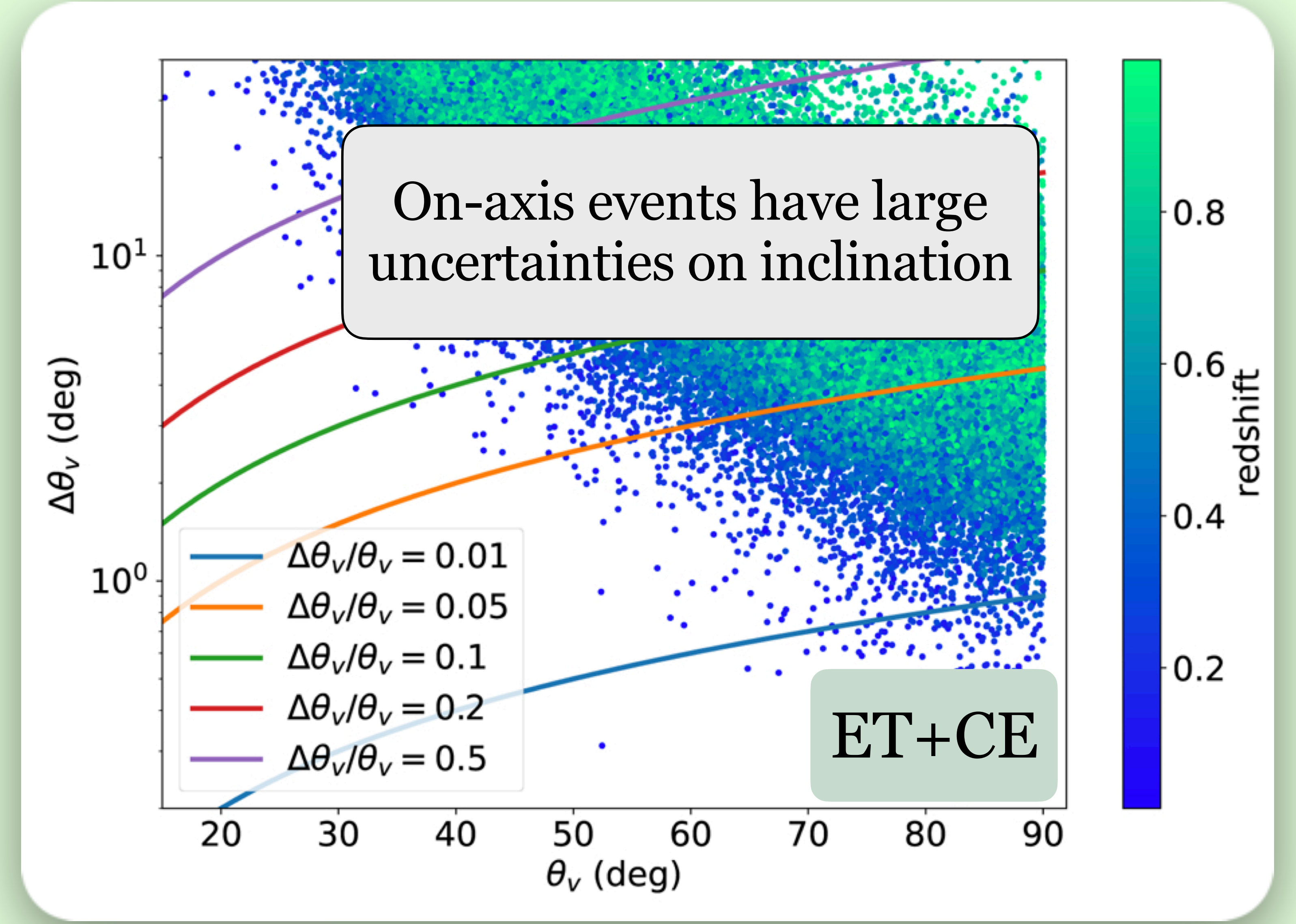
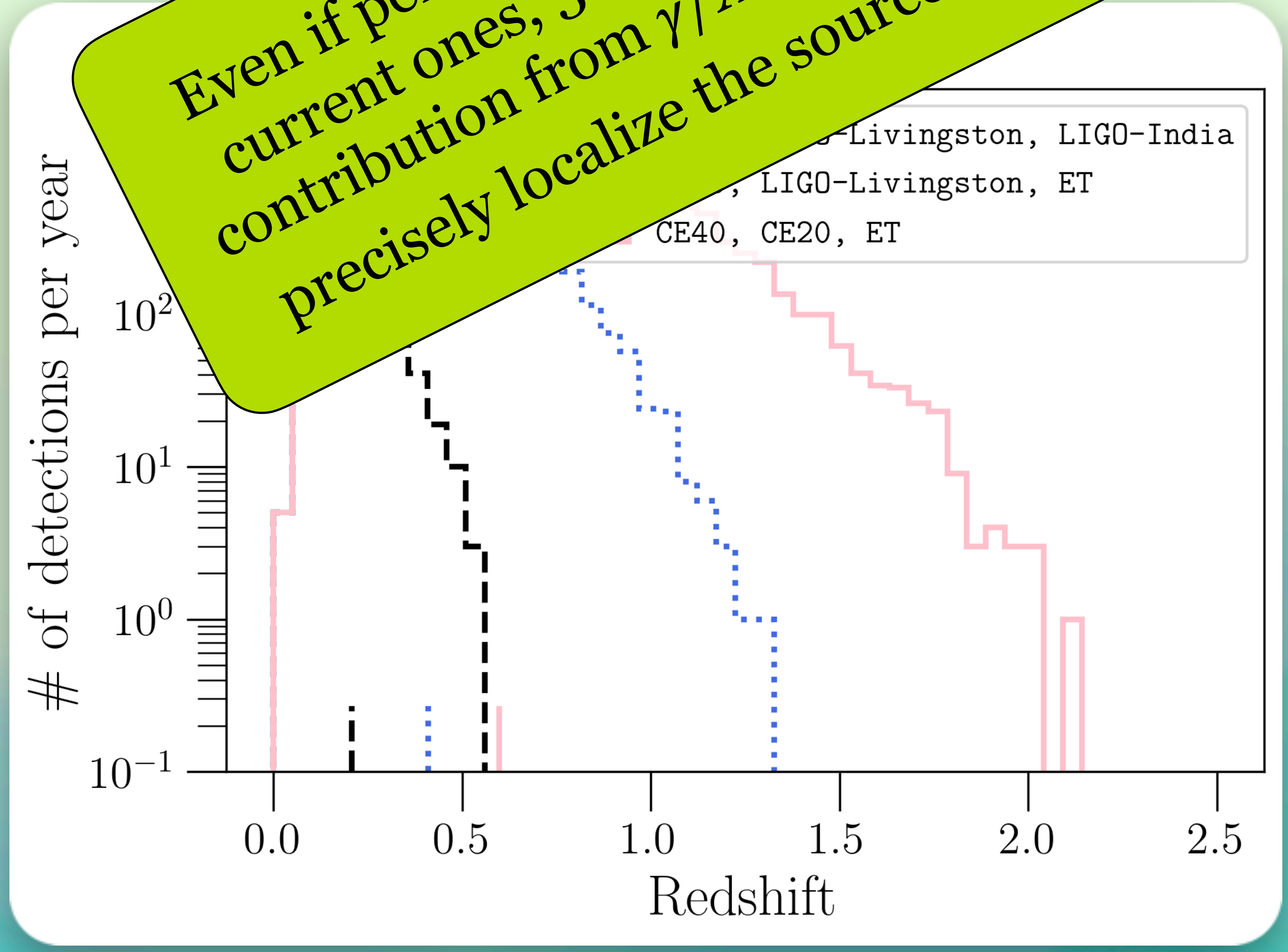


On-axis events have large uncertainties on inclination

Ronchini+22

Even if performing much better than current ones, 3G detectors need the contribution from γ/X-ray detectors to precisely localize the source at z>0.5



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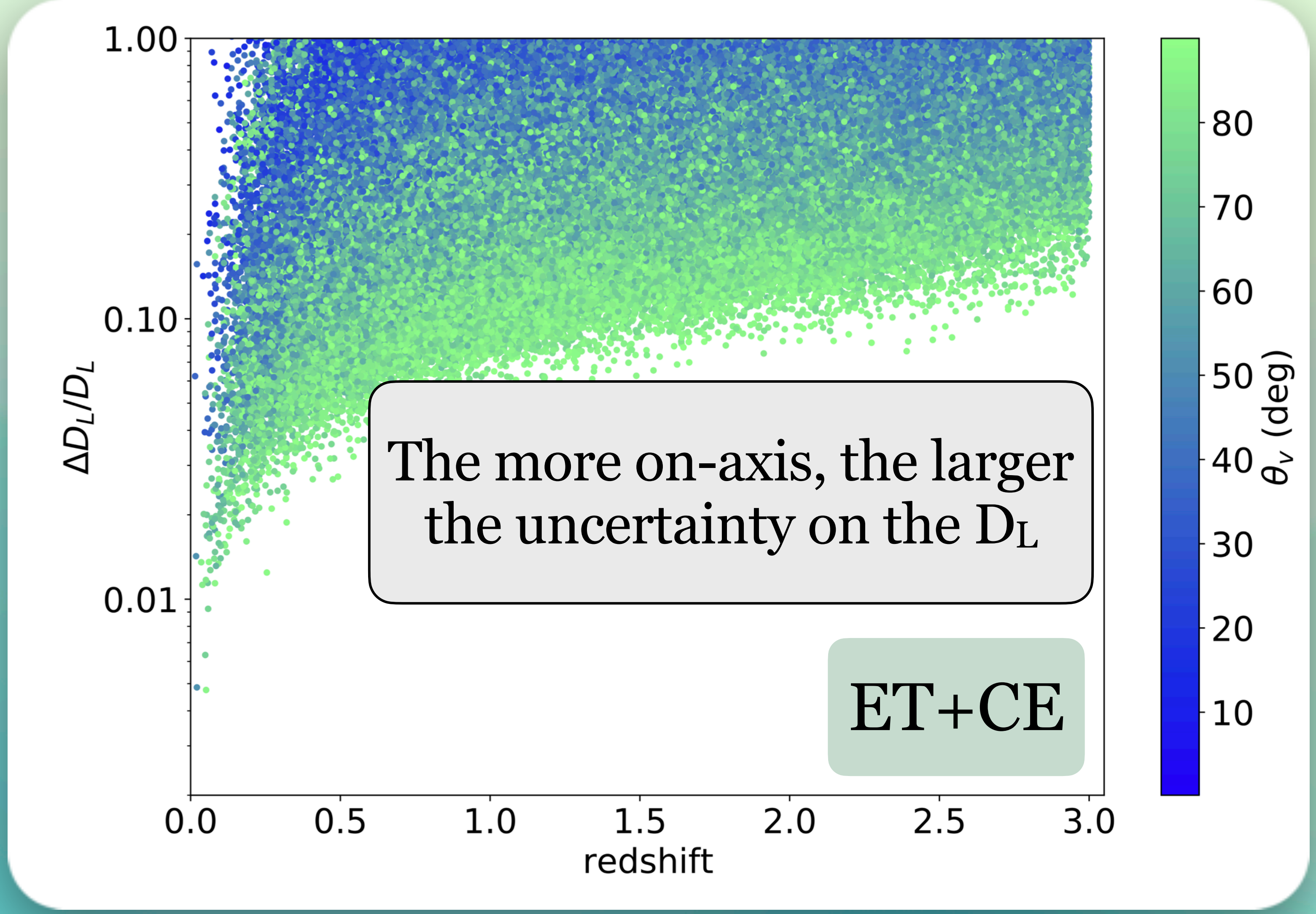
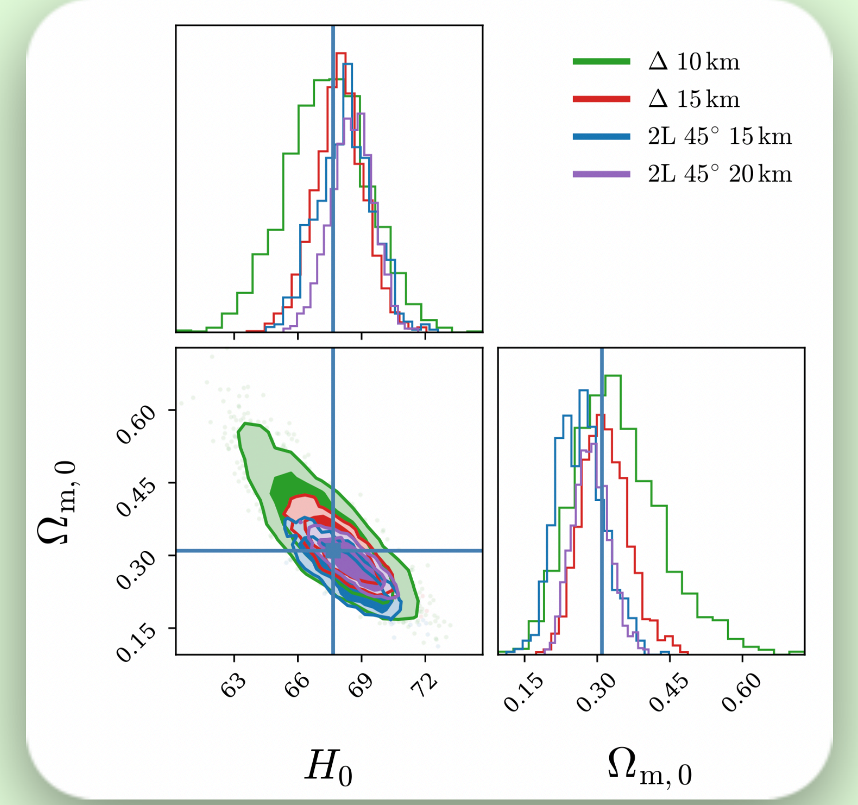


The more on-axis, the larger the uncertainty on the $D_L$

# Multi-messenger science in the 3G GW era

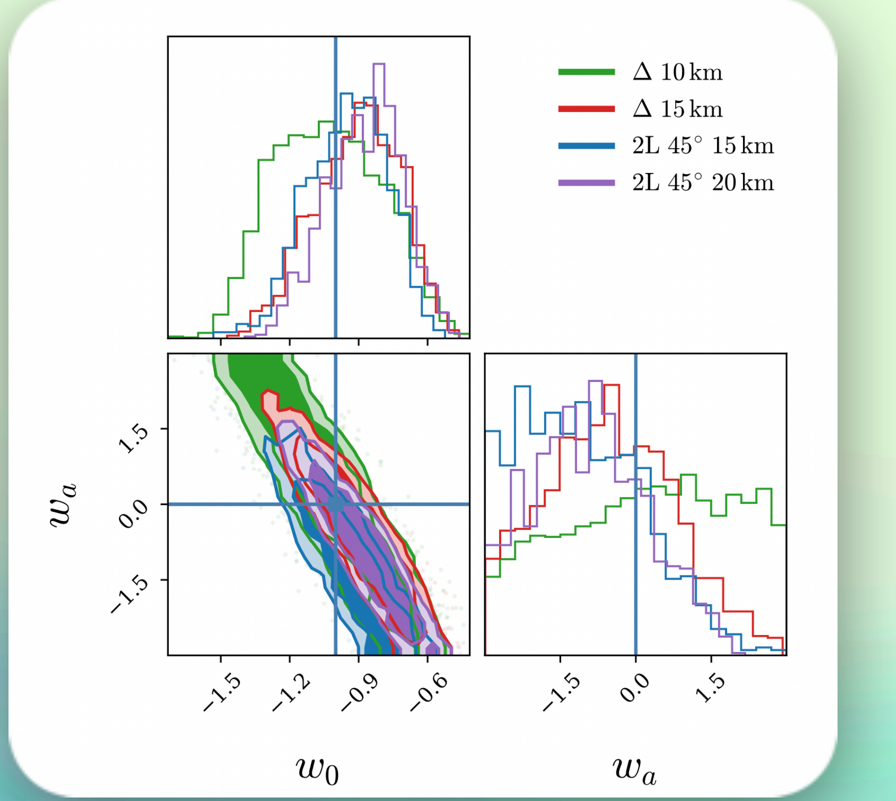
## Cosmology with standard sirens

**Hubble constant**

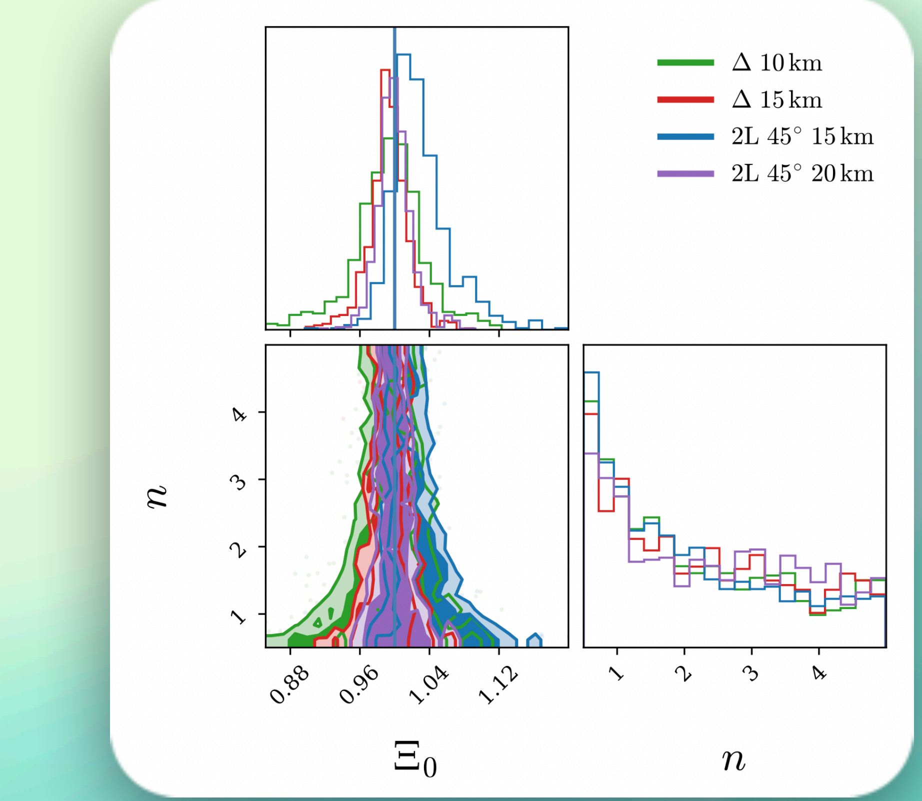


Having a sample of joint detections GW-$\gamma$ with available redshift

**Dark energy EoS**

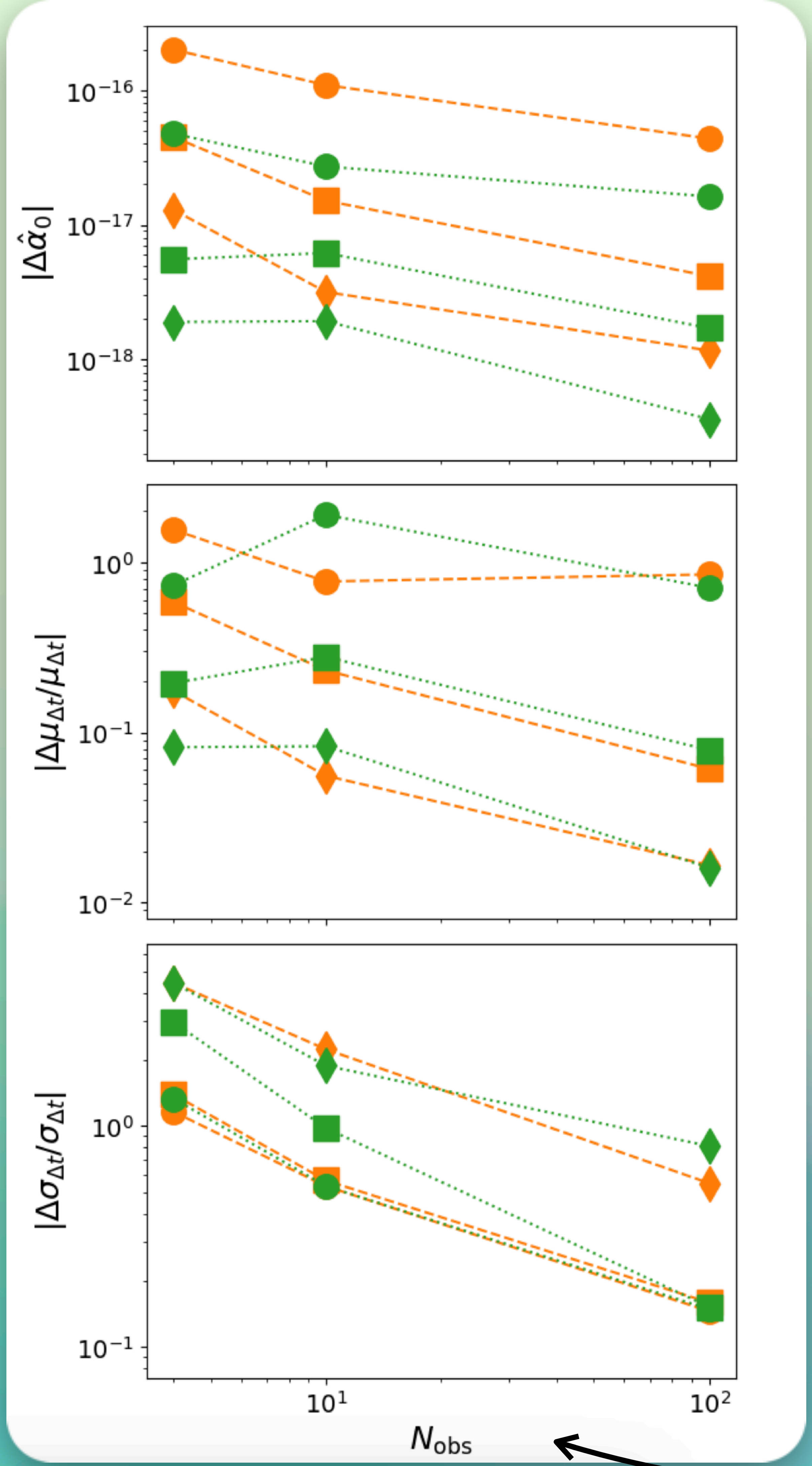


**Modified GW propagation**



Branchesi+23

## Origin of GW-$\gamma$ time delays



$$P(\Delta t) = N(\mu_{\Delta t}, \sigma_{\Delta t})$$

$$\hat{\alpha}_0 = 2\frac{v_{\rm GW} - c}{c}$$

Iampieri+24

Number of joint Fermi+GW detections

# Conclusions

**Past achievements:**

☆ Fundamental role for the epochal multi messenger observation of GW170817 and GRB170817A

**Present efforts:**

☆ Fermi ensures a constant monitoring of the high-energy sky and the joint efforts with the LVK collaboration allow us to

- optimize the chance of detecting the next MM event
- obtain the most stringent limits in the case of a non-detection

**Future challenges:**

☆ Presence of (and coordination among) $\gamma$/X-ray detectors indispensable in 3G GW era to maximize the scientific return

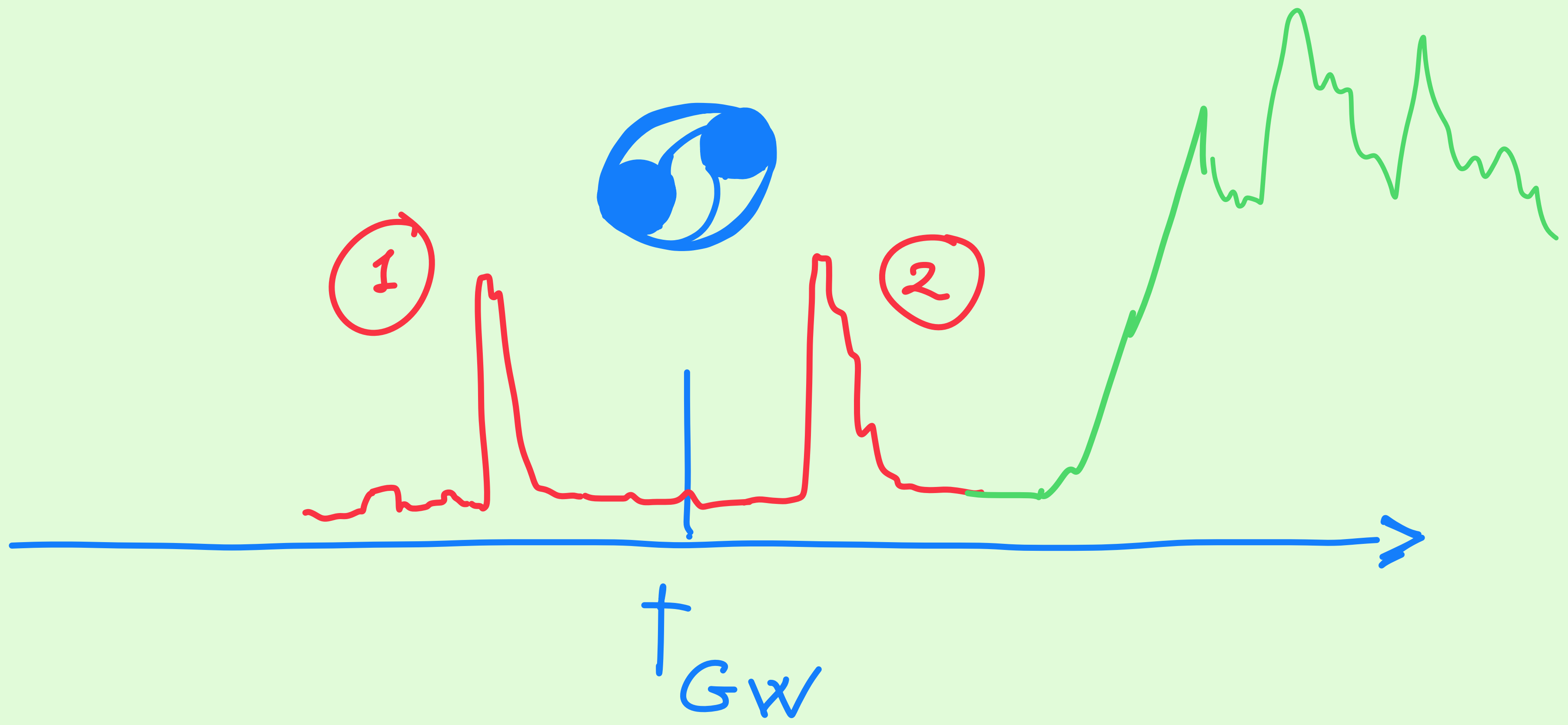
# Fermi and the origin of precursor in merger-driven GRBs

- PRECURSOR: short emission anterior and detached from the main emission episode, sometimes showing a softer spectrum
- Observed in ≲10% of short GRBs
- Open question:
  - just a fraction (and same origin) of the main prompt emission
  - Separate mechanism

Possible scenarios:

- Pre-merger emission from the disruption of the NS crust
- Magnetospheric interaction

Expected to be more isotropic than the usual prompt emission —> suitable for joint GW-$\gamma$ detection



e.g., Dichiara+23

Measuring the delay

$t_{GW} - t_{precursor}$

can disentangle between models

# Connection between accreted mass and luminosity

$$L_b = \eta \frac{M_{acc} c^2}{t_{acc}}$$

$\eta < 1, M_{acc} < 0.052 M_\odot$

Mass priors

EoS

$P(M_1, M_2) \rightarrow P(M_{acc})$