GAMMA-RAY BURSTS IN THE MULTI-MESSENGER ERA

Frédéric Daigne
(Institut d'Astrophysique de Paris; Sorbonne University)

- What are GRBs?
- Recent advances:
  - GRBs at TeV
  - GW170817 / GRB170817A
- What did we learn?
- Perspectives for GRB studies in the MM era
  Application to stellar physics (binaries) & cosmology
- SVOM

International Conference on the Physics of the Two Infinities, Kyoto, March 30, 2023

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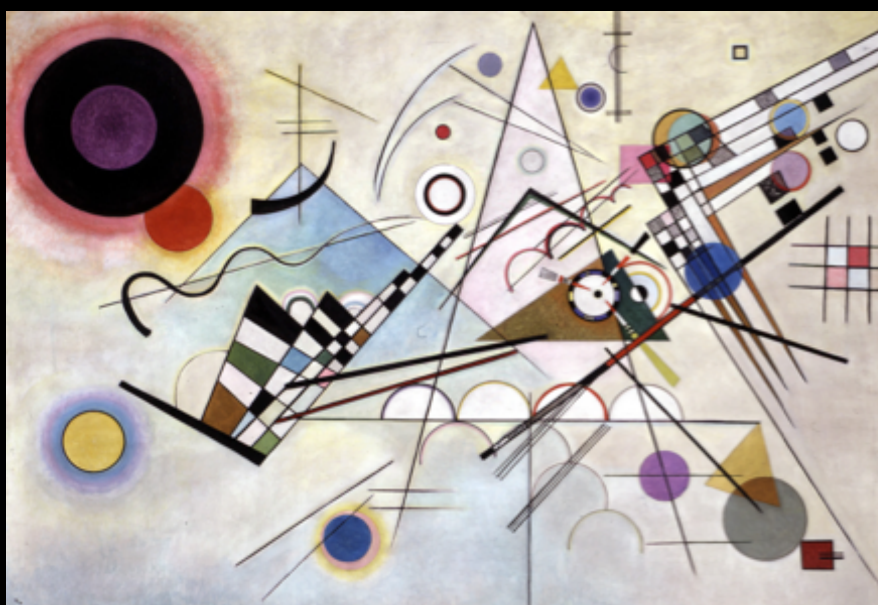

Kandinksy – Composition 8- 1923
Guggenheim Museum, New-York

Kandinksy - Curves and sharp angles - 1923
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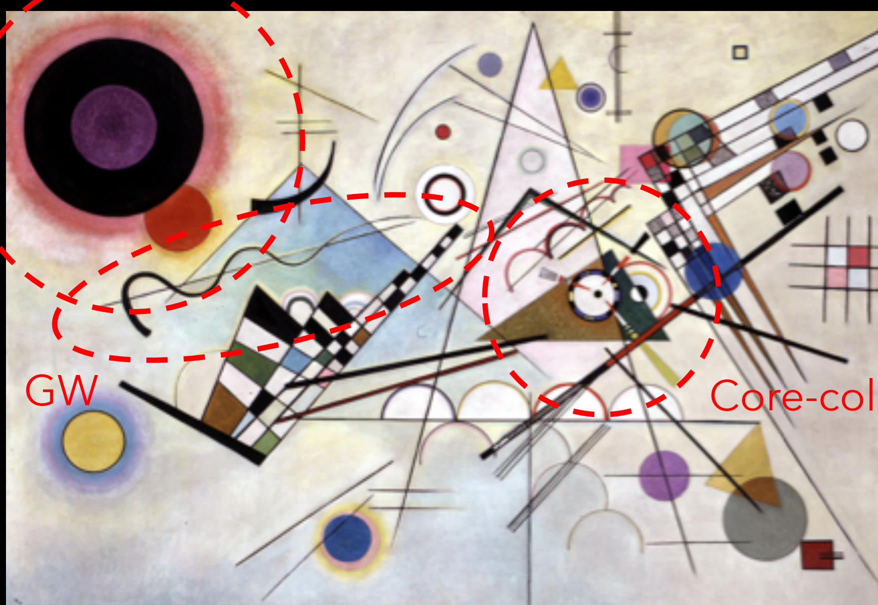

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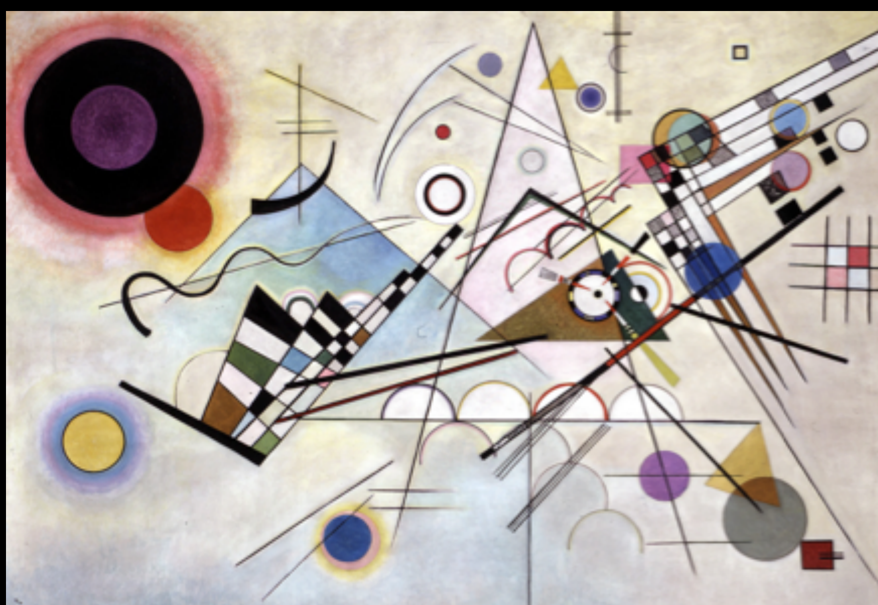

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Ejecta
&
Emission
(em, ν?)

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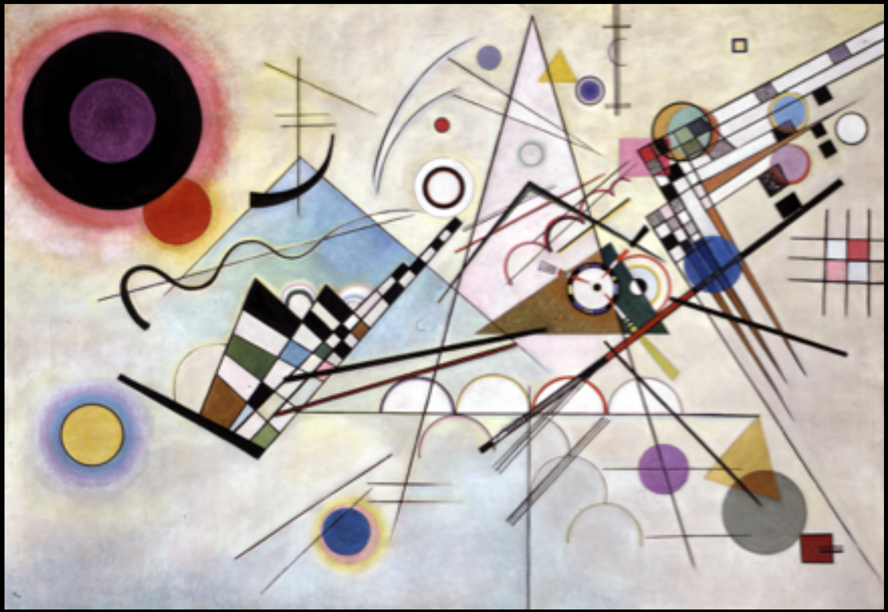

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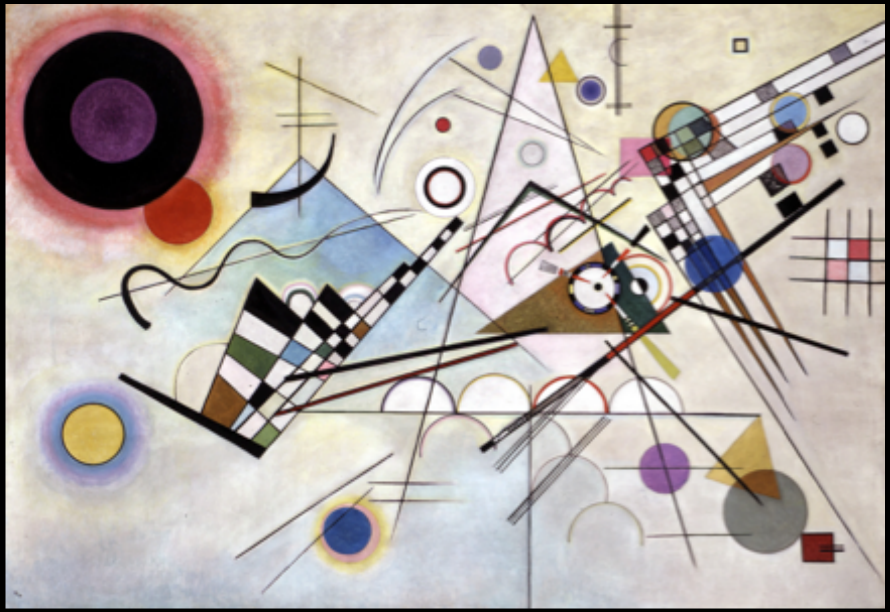

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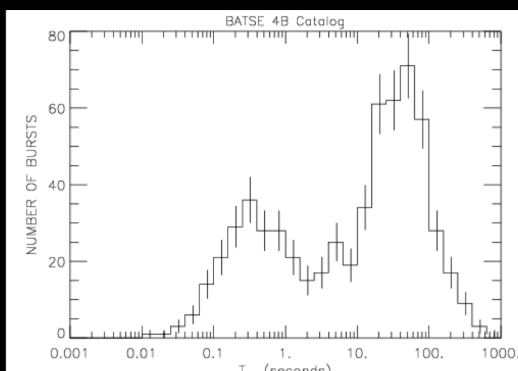
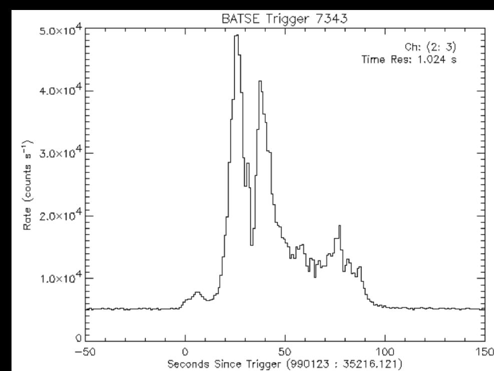
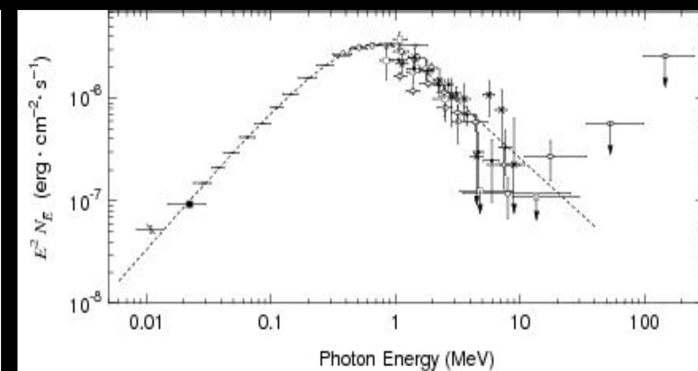
GRBS: PROMPT EMISSION

- **High variability :** ms → 100 ms
- **Short duration:** a few ms to a few min
- **Two classes: short & long GRBs**

BATSE



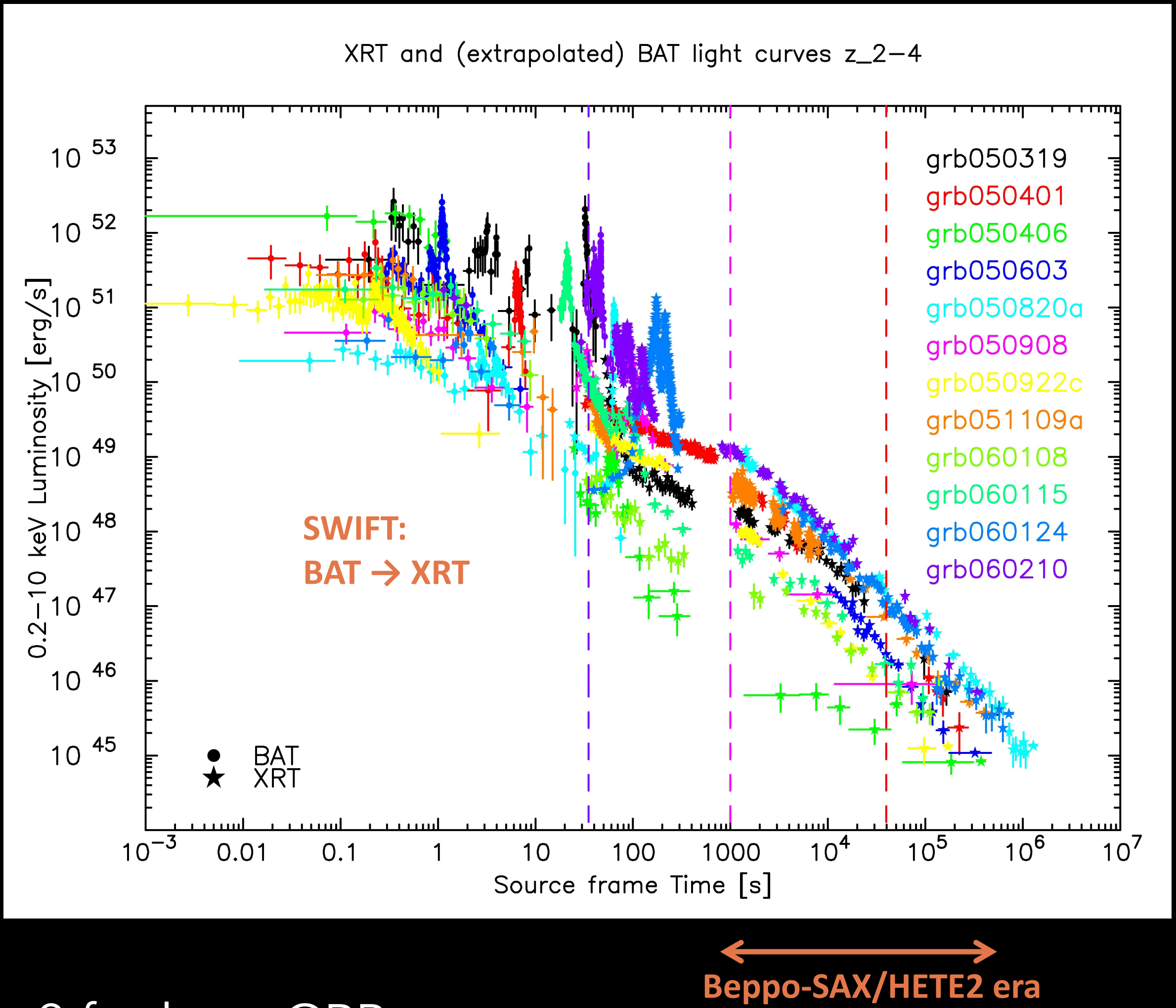




- **Great diversity of lightcurves ; Pulses:** 100 ms → 10 s
- **Non-thermal spect. = cosmic accelerators:** E_{peak} ~ 100 keV → 1 MeV
- **Spectral evolution**
- **Spectral diversity:** classical GRBs, low luminosity-GRBs, X-ray rich GRBs, X-ray Flashes, etc.

GRBS: AFTERGLOW

- **Lightcurves: power-law decay, breaks, variability** (flares, plateaus)
- **Spectral evolution:** X-rays to radio

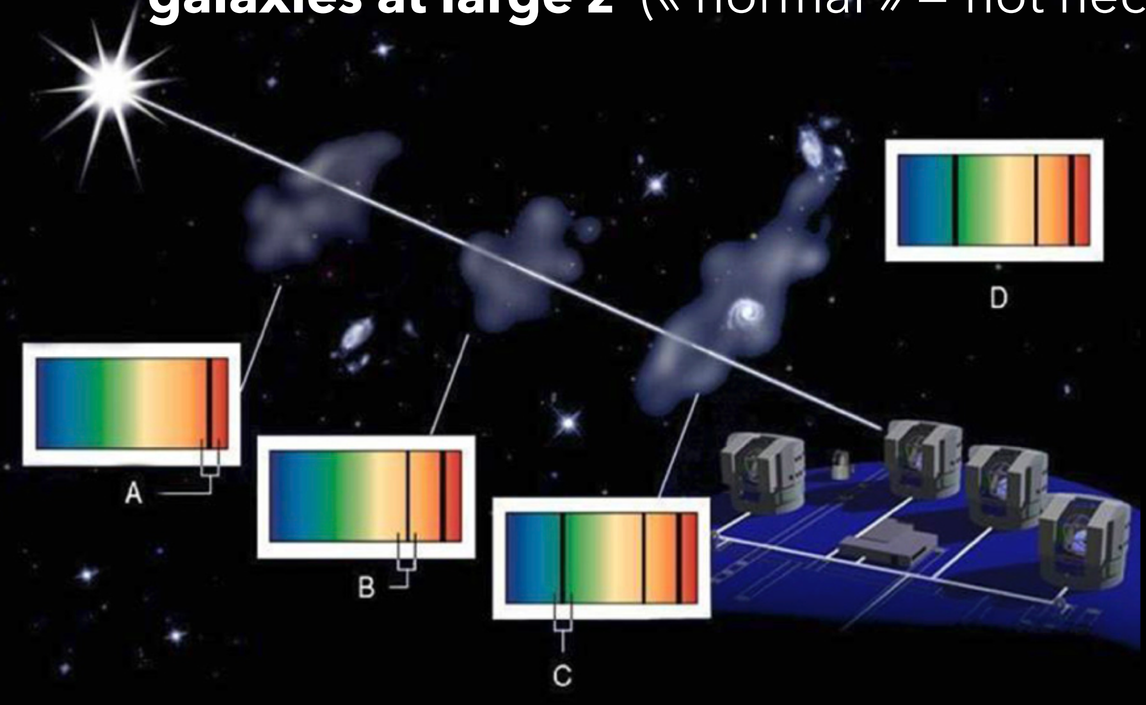


- **Redshift**
  - Mean redshift above 2 for long GRBs
  - Maximum : GRB 090423 at z = 8.2
    GRB 090429B at z = 9.3
  - **E_{iso} ~ 10^{51} to 10^{54} erg (some under-luminous ; some monsters…)**

GRBS: PROGENITORS

Long GRBs: direct evidence for the collapsar scenario

- **Star forming host galaxies / association of nearby LGRBs with SNae**
- **Progenitors = a low fraction of massive stars**
  (conditions to produce a GRB? Mass? Metallicity? Rotation? Binarity?)
- **Using LGRBs to trace the cosmic star formation rate at large z?**
  (see e.g. Palmerio, Vergani et al. 2019 ; Palmerio & Daigne, 2022)
- **Using the sample of LGRB host galaxies to study « normal » galaxies at large z** (« normal » = not necessarily very bright).



Absorption spectro. (afterglow)
neutral medium, metallicity, kinematics, etc. : host galaxy + absorbers along the line-of-sight

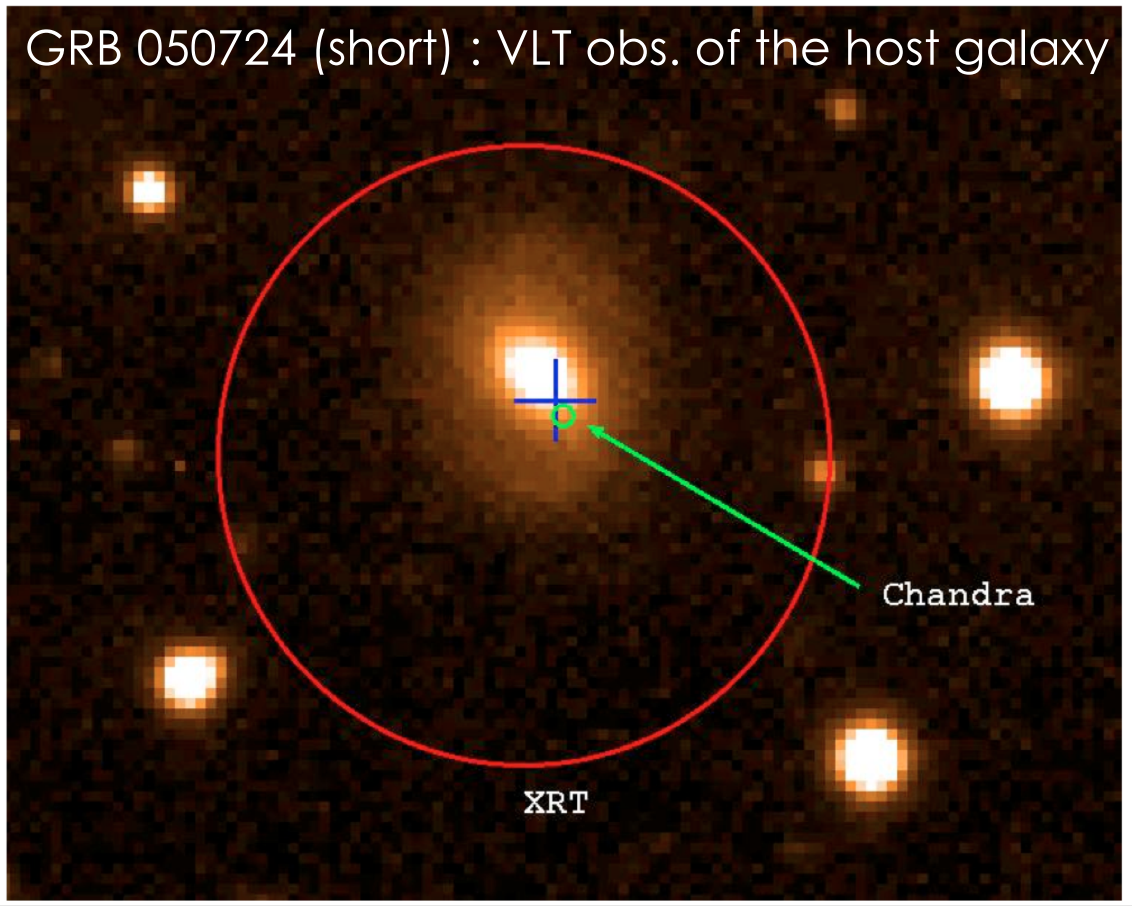
Emission spectro. (host)
ionized medium

(see the recent example of GRB 210905A @ z=6.3 by Saccardi, Vergani et al. 2023)

GRBS: PROGENITORS

Short GRBs: indirect evidence for the merger scenario

- **Host galaxies of any type**
  (not necessarilystar-forming)
- **Possible large offsets ⟹ delay/kicks merger scenario (BNS ; some NSBH ?)**

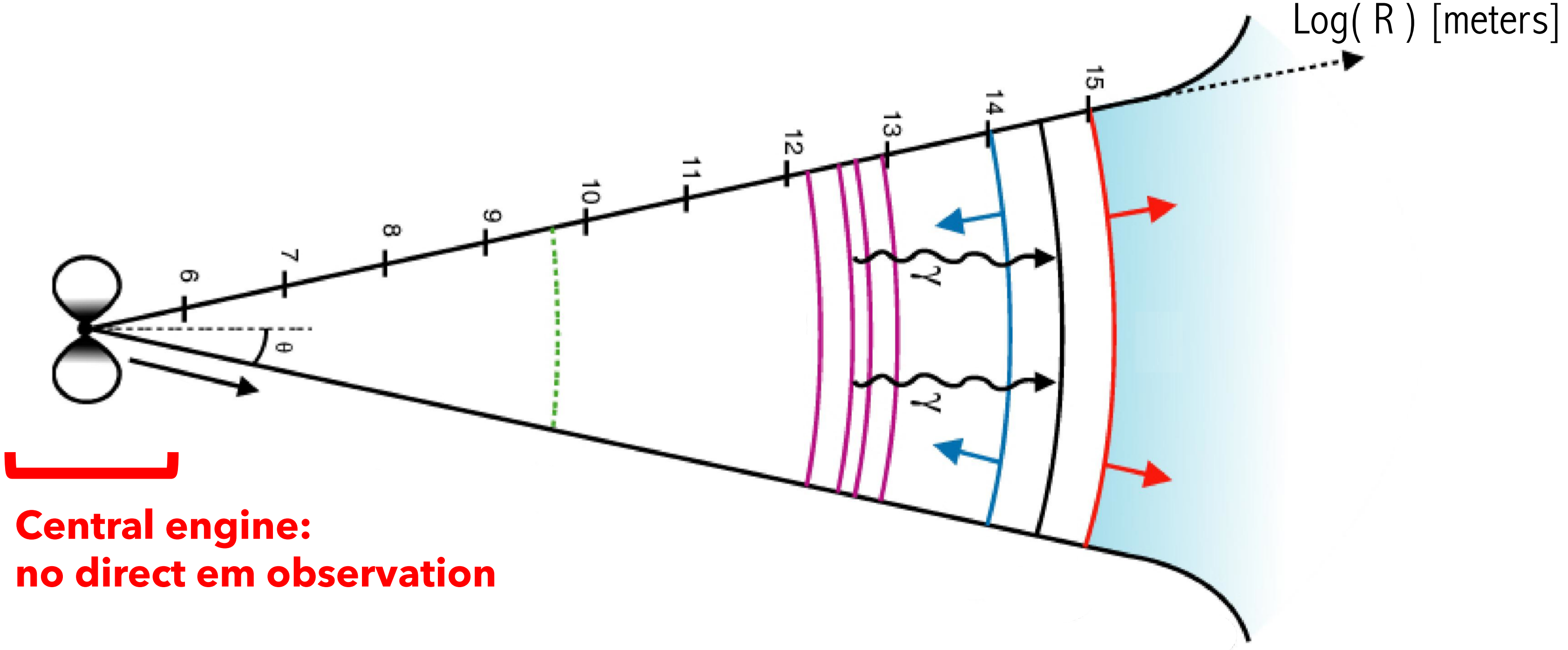


Barthelmy et al. 2005

- **A quasi-direct evidence: association GW 170817 (BNS) / GRB 170817A (short)**
  (some caveats: nature of the GRB emission)

GRBS: THEORY

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

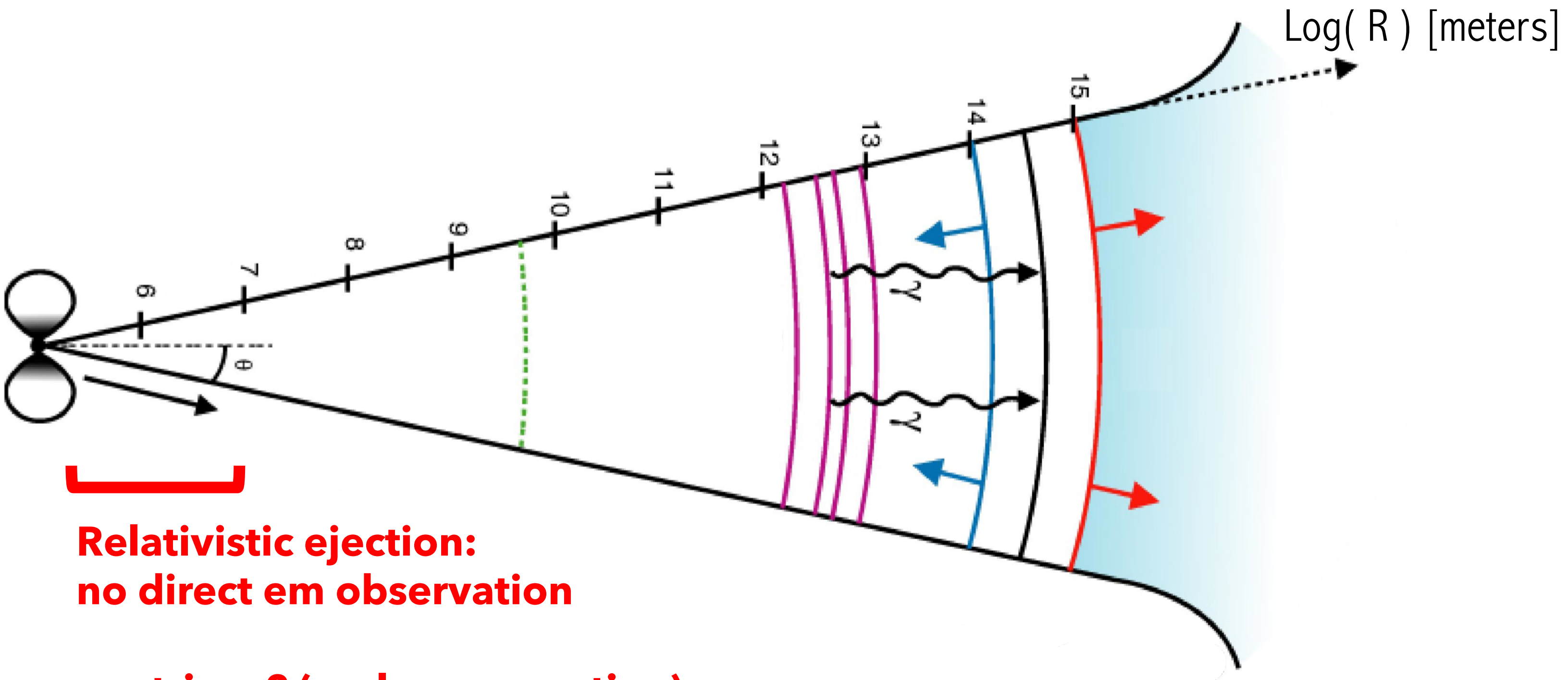


Central engine:
no direct em observation

GW?
Collapsar: currently out of reach / Merger: post-merger signal?

GRBS: THEORY

- Variability + energetics + gamma-ray spectrum: **relativistic ejection**
  (only way to avoid a strong pair production)

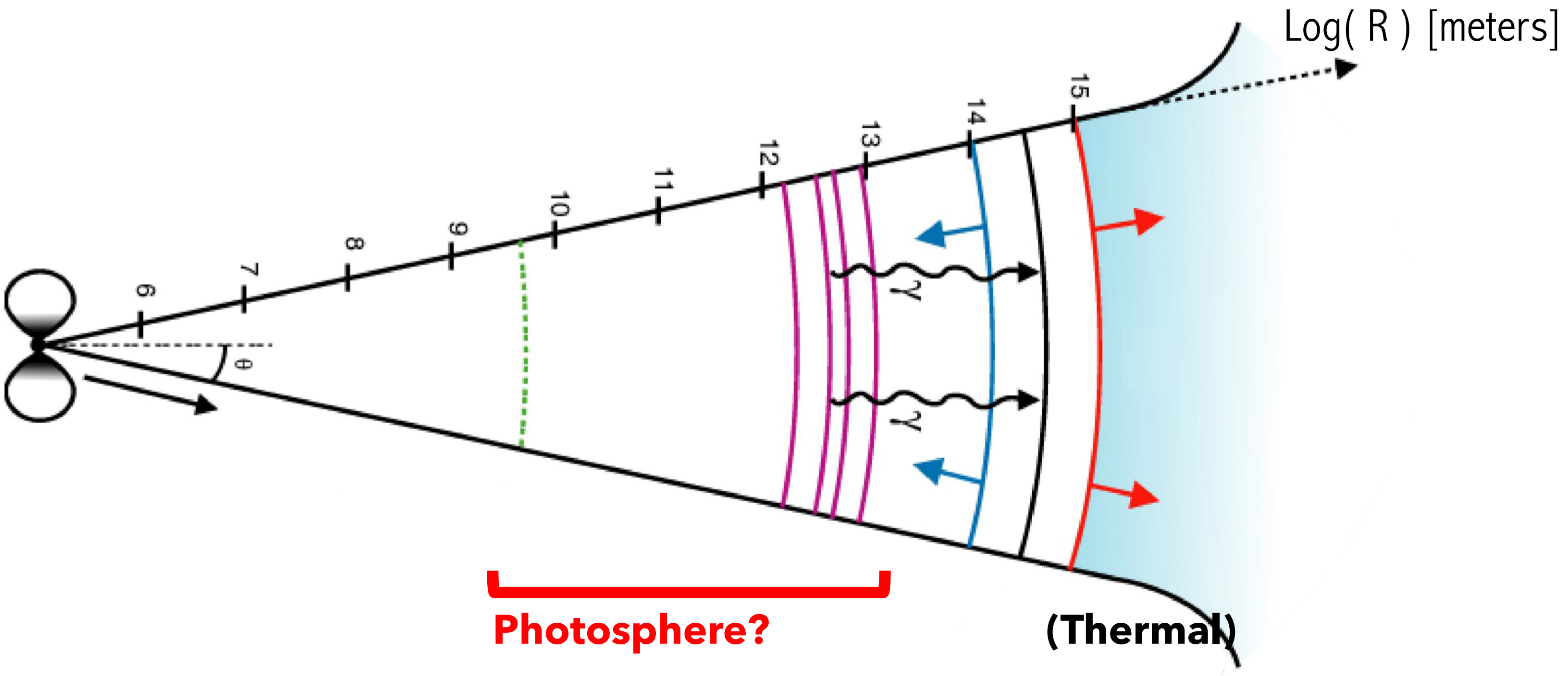


Relativistic ejection:
no direct em observation

neutrinos? (early propagation)

GRBS: THEORY

- **Prompt keV-MeV emission: internal origin in the ejecta**
  (only way to explain the fast variability)

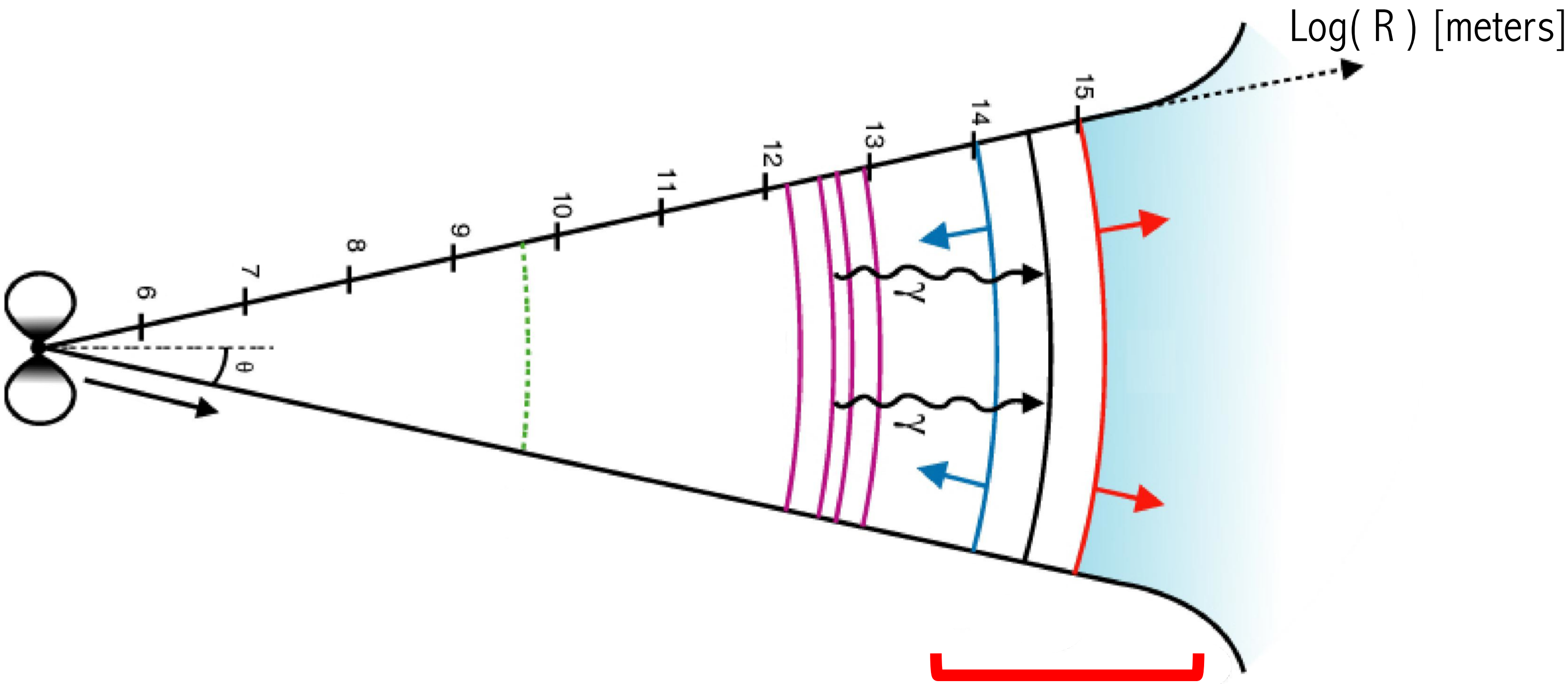


Photosphere? **(Thermal)**

Dissipative Photosphere?
Shocks? **(Particle accel. / Non-thermal rad.)**
Magnetic Reconnection? **(CR/Neutrinos?)**

GRBS: THEORY

- **Afterglow: deceleration by the ambient medium**



Ultra-relativistic forward shock in the external medium
Reverse shock in the ejecta?
⟹ particle acceleration / non-thermal radiation (CR/neutrinos?)

GAMMA-RAY BURSTS AT TEV ENERGIES

Why is it interesting?

GRBs = cosmic accelerators

TeV to better understand:

- the distribution of accelerated particles
- the magnetic field
- the radiative processes (syn, SSC, other?)
- the possible contribution to proton acceleration (U)HECRs? Neutrinos?

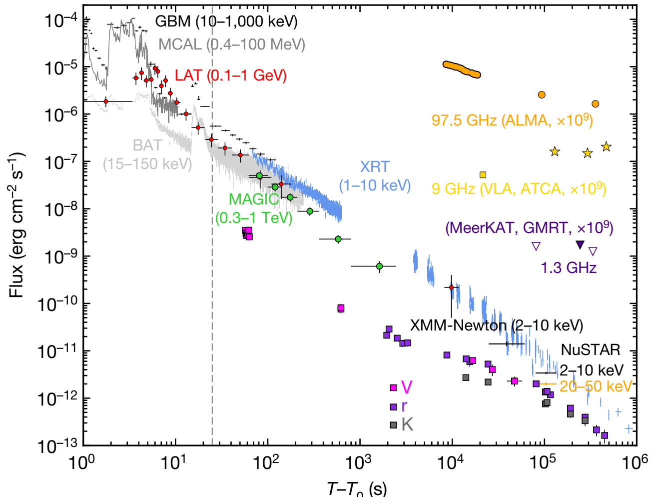
GRBS AT TEV ENERGIES

Already at least four GRBs detected at VHE (afterglow):

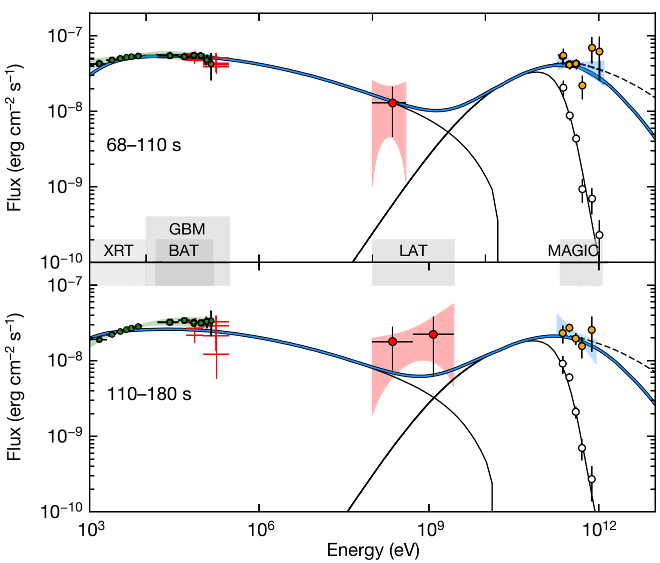
180720B (HESS) ; 190114C (MAGIC) ; 190829A (HESS) ; 201216C (MAGIC)

+ GRB 201009A (the BOAT) / LHASSO

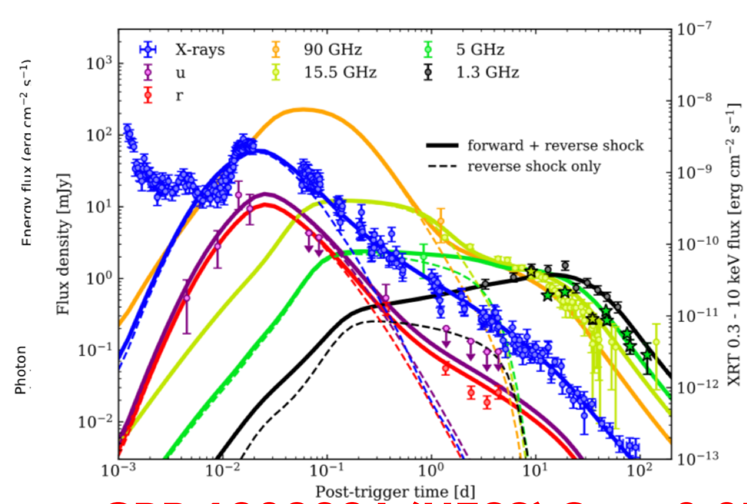
+ some other candidates



GRB 190114C (MAGIC) @ z=0.14



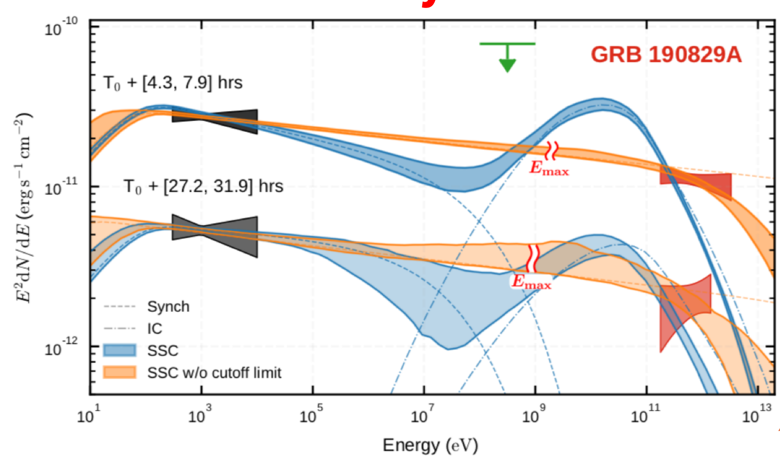
MAGIC collab. 2019a,b



Salafia et al. 2021

GRB 190829A (HESS) @ z = 0.0785

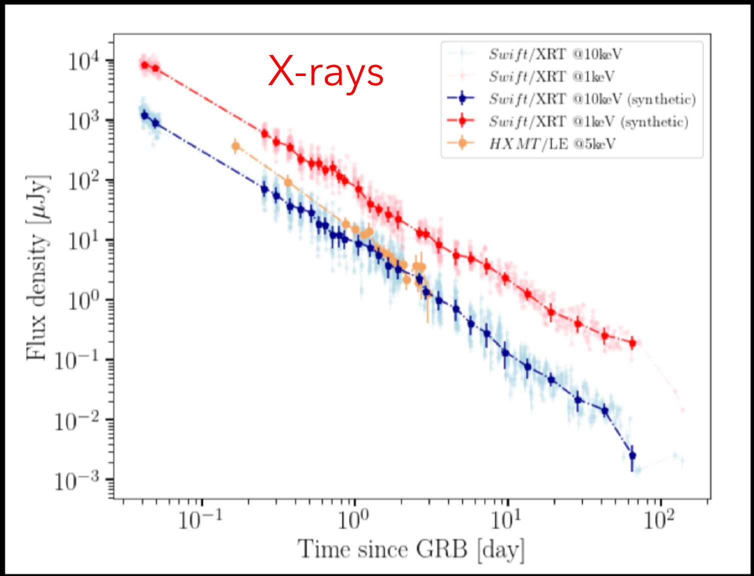
A low-luminosity burst

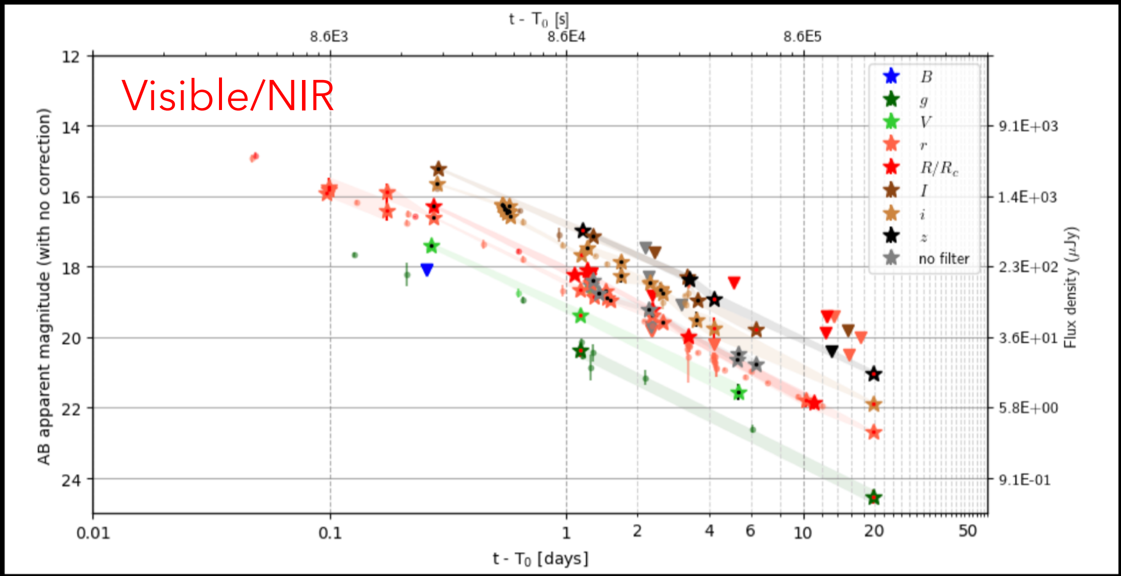


HESS collab. 2021

GRB 221009A

- **The BOAT (the Brightest Of All Times) – $E_{iso,\gamma}$ ~10^{55} erg**
  (Saturation of gamma-ray detectors: Swift, Fermi, INTEGRAL, …)
- **Follow-up by many instruments and collaboration**
  z = 0.151 (de Ugarte Postigo et al. 2022, Castro-Tirado et al. 2022, Izzo et al. 2022, Malesani et al. 2023)





Here: data obtained by HXMT + GRANDMA (Kann et al. [FD] 2023)
GRANDMA = network of > 30 professionnal and amateur telescopes

- **Standard afterglow model does not work well: puzzling event**
  (Laskar et al. 2023, O' Connor et al. 2023, Kann et al. [FD] 2023, …)

GRB 221009A

- **Detection by Fermi-LAT up to ~400 GeV** (Xia et al. 2022a,b)
- **GCN #32677** (Huang et al. 2022)**:**
  detection by LHASSO, >5000 VHE photons (> 500 GeV)
  - LHASSO detection during the first 2000 s:
    Prompt or early afterglow (prompt in soft γ-rays ~600 s)
  - LHASSO detects VHE photons up to E_{max} ~18 TeV:
    Strong tension with EBL

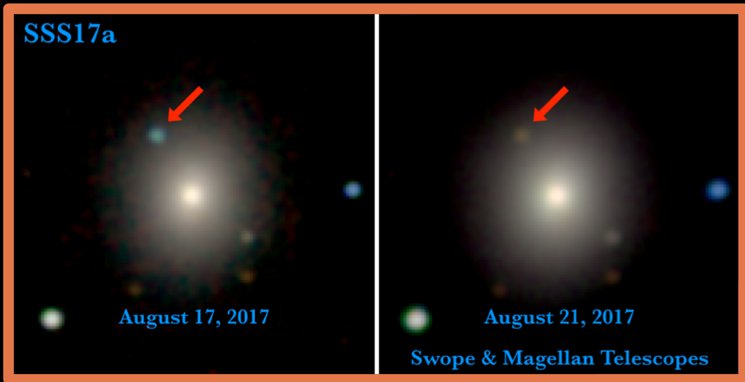
  We should wait for the LHASSO publication with the full analysis: energy calibration?
- **No detection by IceCube or KM3NET**

GRBS AT TEV ENERGIES

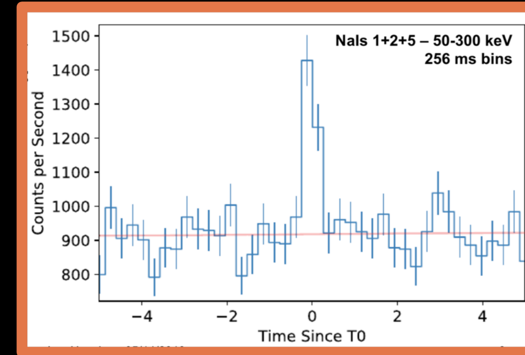
- **Confirmed detections : Afterglow** (including the very early afterglow for 190114C) **= probe the deceleration phase**
- **Standard afterglow model with emission of shock-accelerated electrons (syn + SSC) works**
- **New constraints on electron acceleration, magnetic field, etc.** (most afterglows: synchrotron only, many parameter degeneracies)
- **No need for an hadronic component at this stage?**
- **Prompt emission?**
  Needs a large f.o.v (HAWK/LHASSO) or a fast response (CTA?)

GAMMA-RAY BURSTS
ENTERING THE MULTI-MESSENGER ERA:
GW170817/GRB170817A

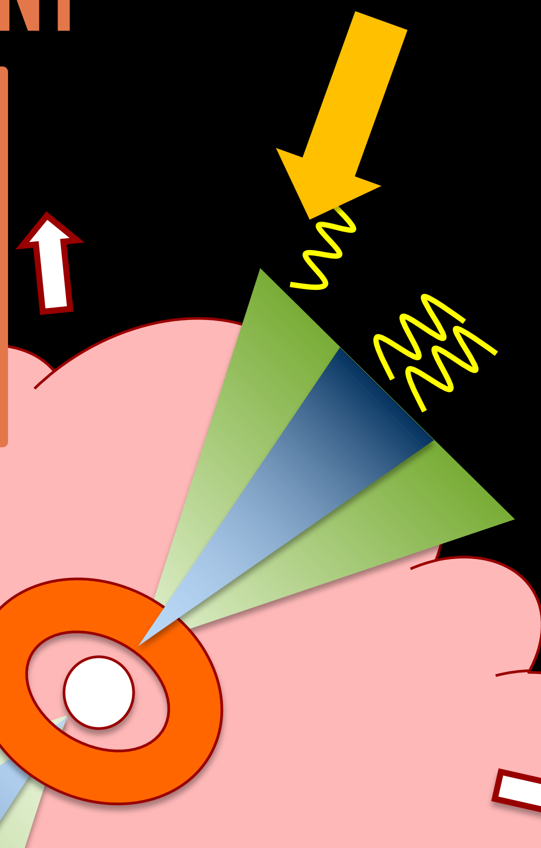
THE 170817 MM EVENT

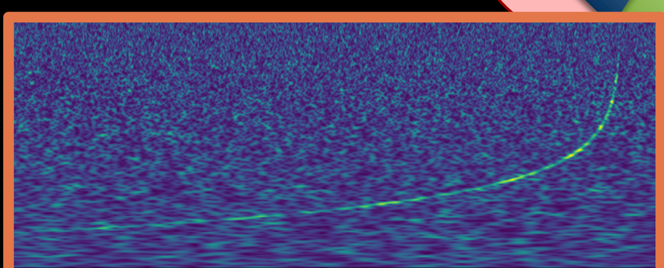


Kilonova: red & blue components

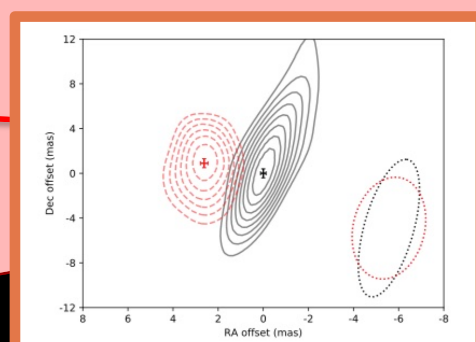


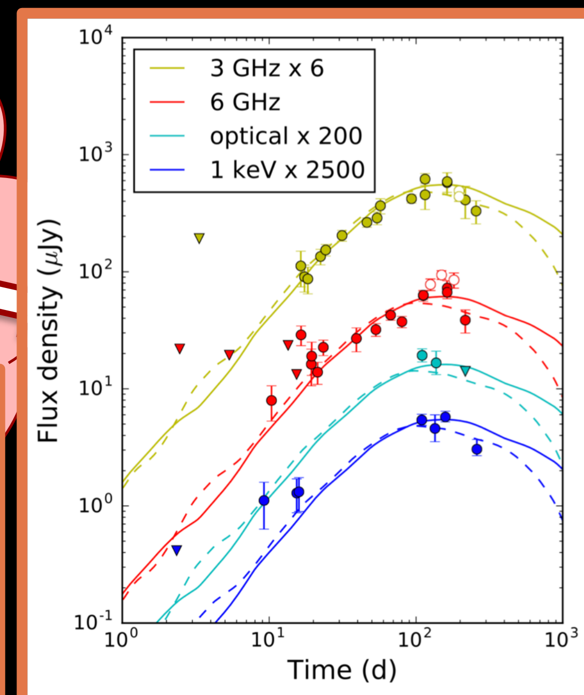
Short gamma-ray burst: physical origin?





Gravitational waves

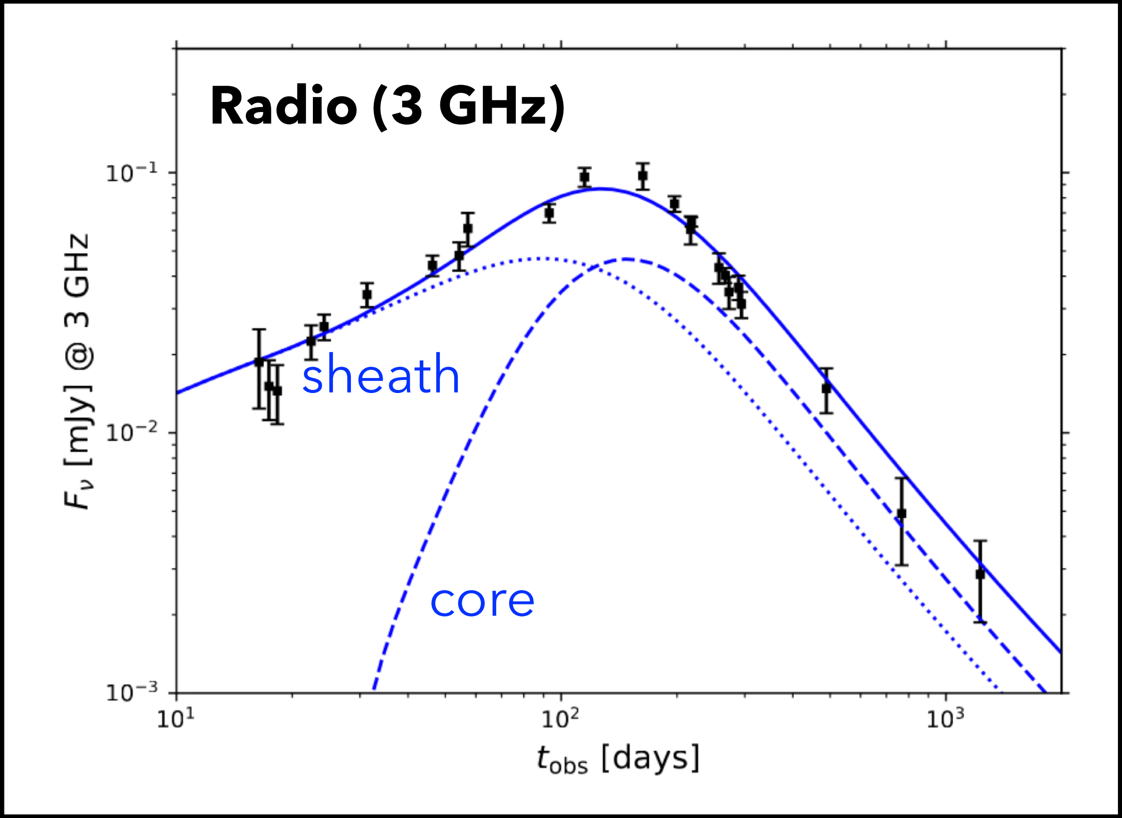




Afterglow: radio to X-rays + VLBI

LATERAL STRUCTURE OF THE JET

- 170817: a unique multi-wavelength data set – peak flux @ > 100 days
- Standard afterglow model (synchrotron from e^- accelerated at the FS) + **lateral structure in the jet**: good fits (late evolution: lateral expansion?)



Pellouin & Daigne in preparation

SIGNATURES OF THE LATERAL STRUCTURE IN GRBS?

- **The lateral structure may be inherited from the early propagation of the ejecta and may be a common features in GRBs.**
    - SGRB: interaction with the kilonova ejecta
    - LGRB: interaction with the collapsing envelope
- **Can we find signatures of this lateral structure in cosmic GRBs?**
  Main difference: large distance/on-axis vs small distance/off-axis
- Note 1 : for SGRBs, this interaction can also explain the origin of GRB170817A (shock breakout) and the GW-GRB delay: see e.g. Bromberg et al. 2018).
- Note 2 : especially in LGRBs, this interaction is also discussed as a possible phase of neutrino emission.

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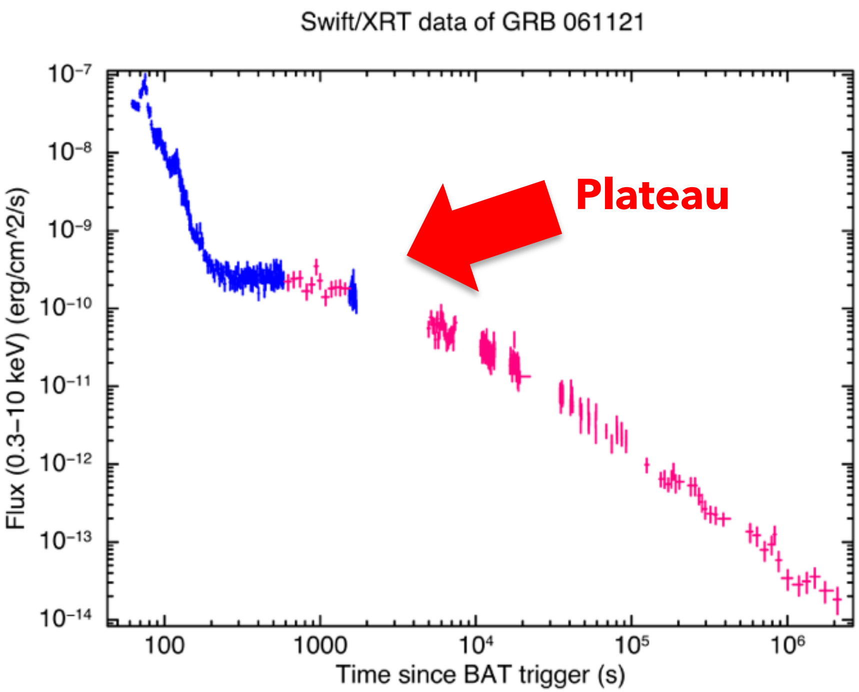
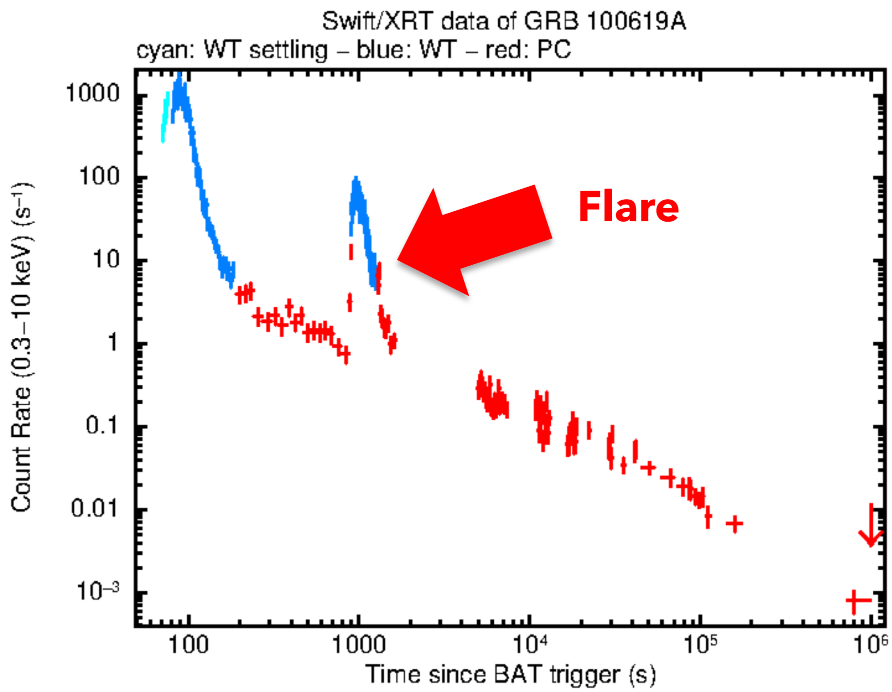
- **The lateral structure may be inherited from the early propagation of the ejecta and may be a common features in GRBs.**
- **Can we find signatures of this lateral structure in cosmic GRBs?**
  Part of the PhD project of R. Duque @ IAP

Puzzling features in the early X-ray afterglow (Swift/XRT)





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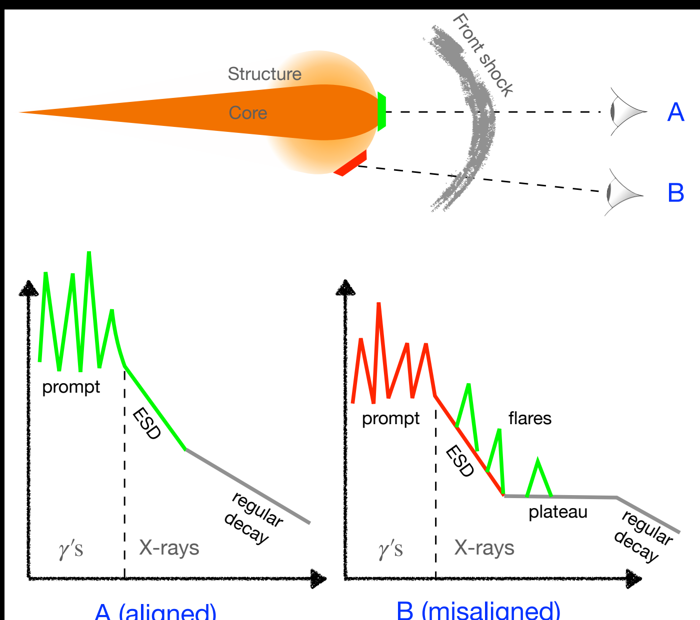
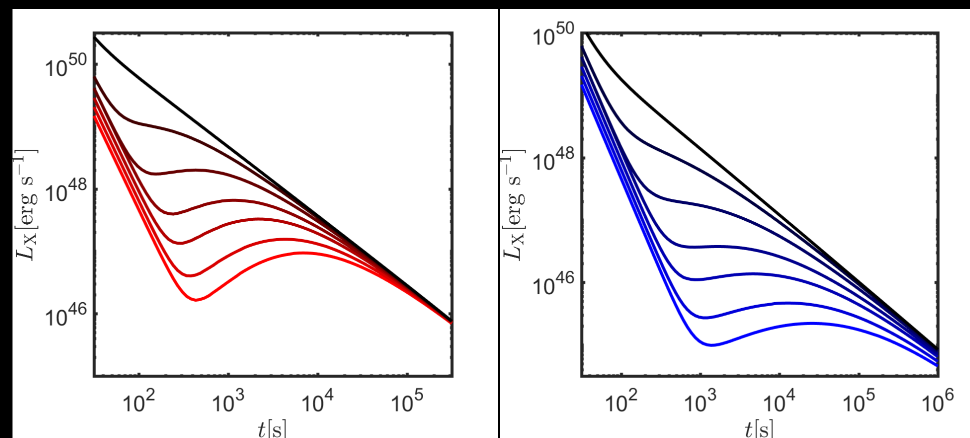
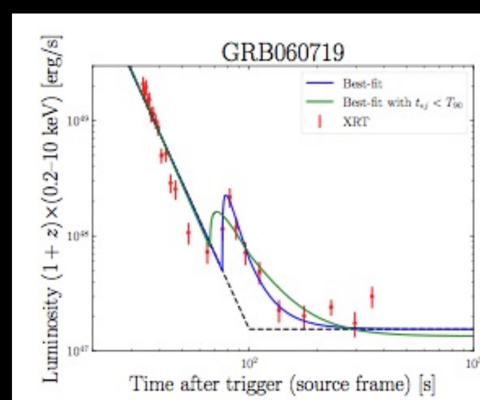


Slightly off-axis jets:
X-ray plateaus and flares?



Beniamini et al. [Duque, FD] 2020



Duque et al. [FD] 2022

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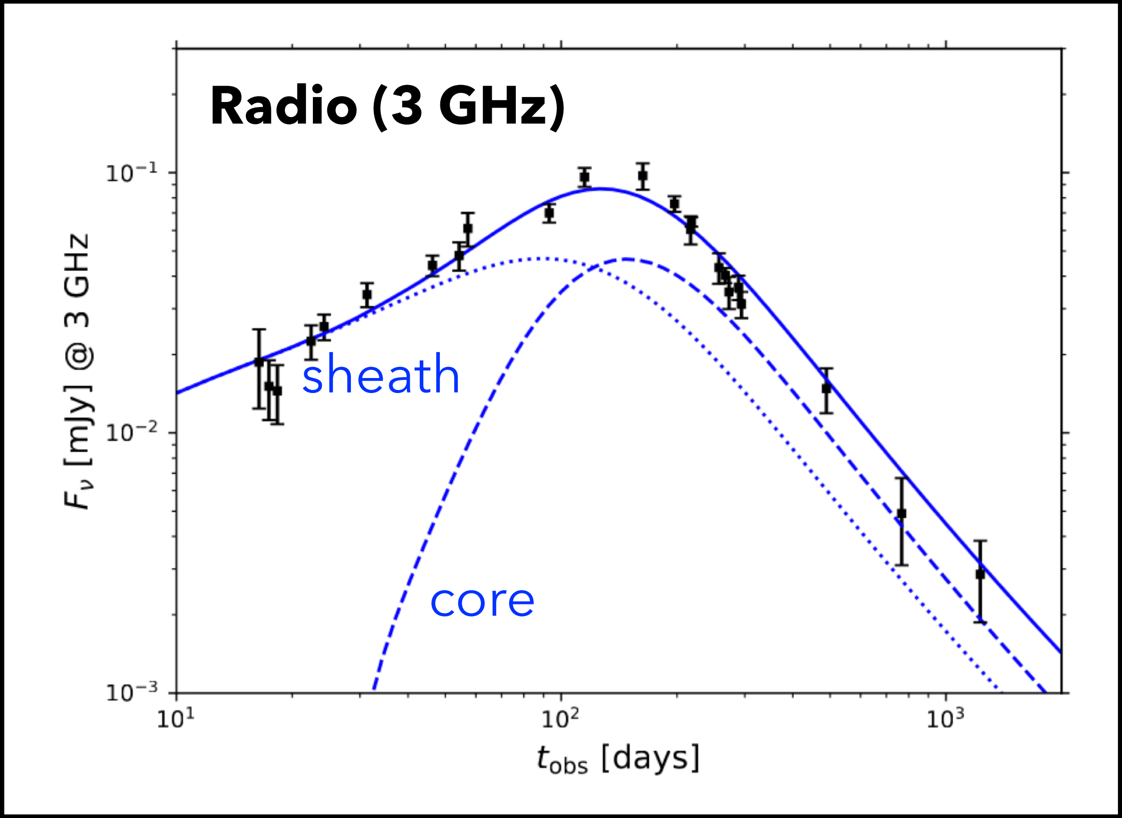

Pellouin & Daigne in preparation

TEV AFTERGLOW OF A BNS MERGER?

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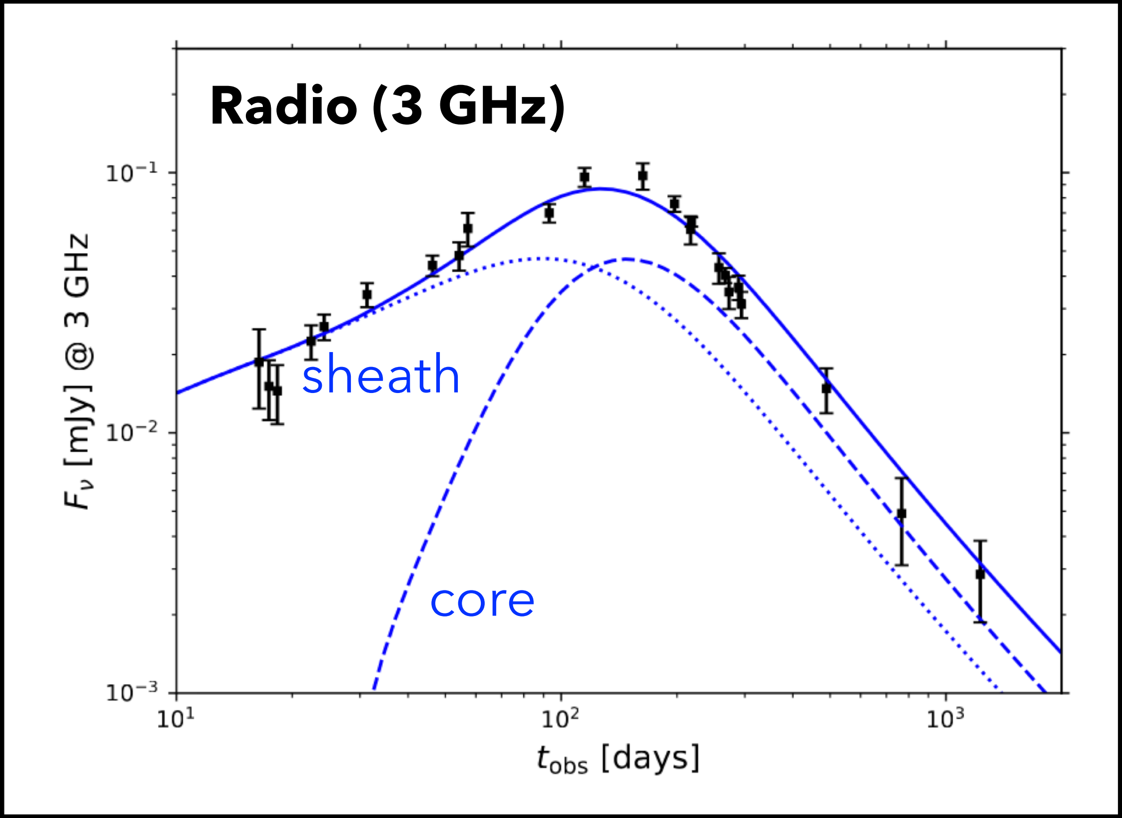
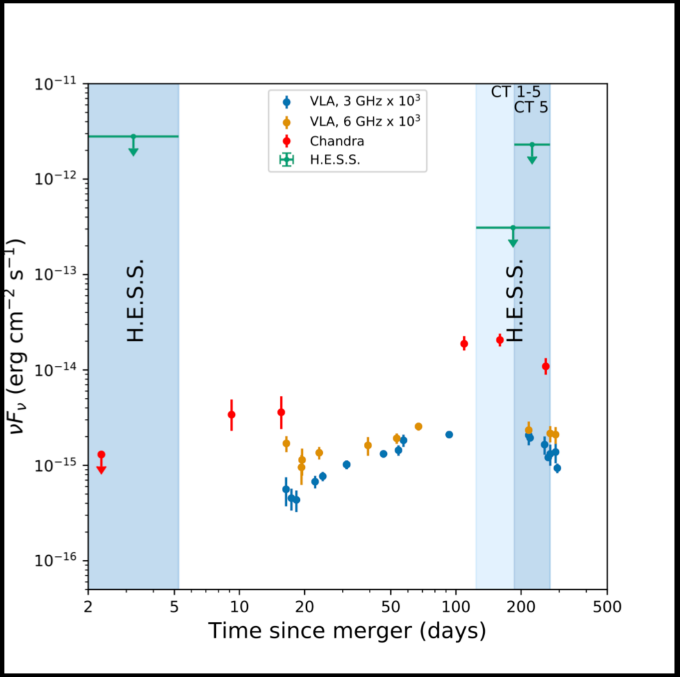


HESS limit at the peak
(HESS Collab 2020)

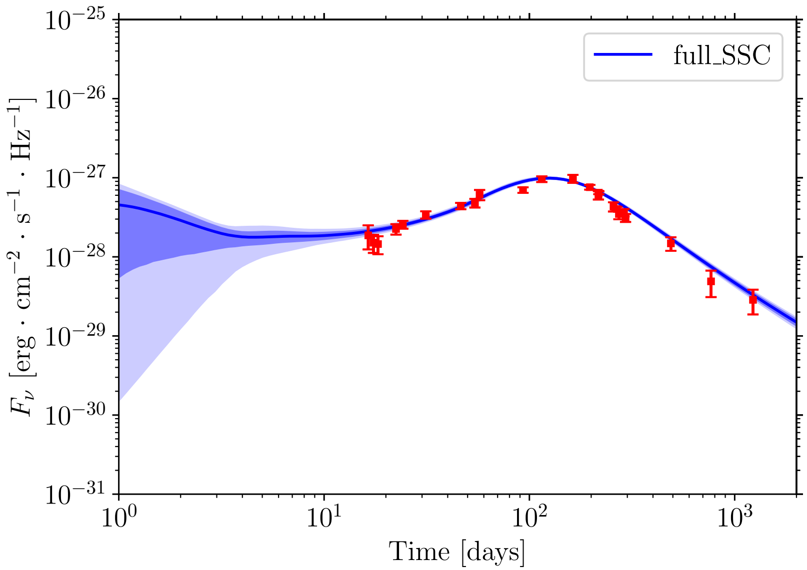


Pellouin & Daigne in preparation

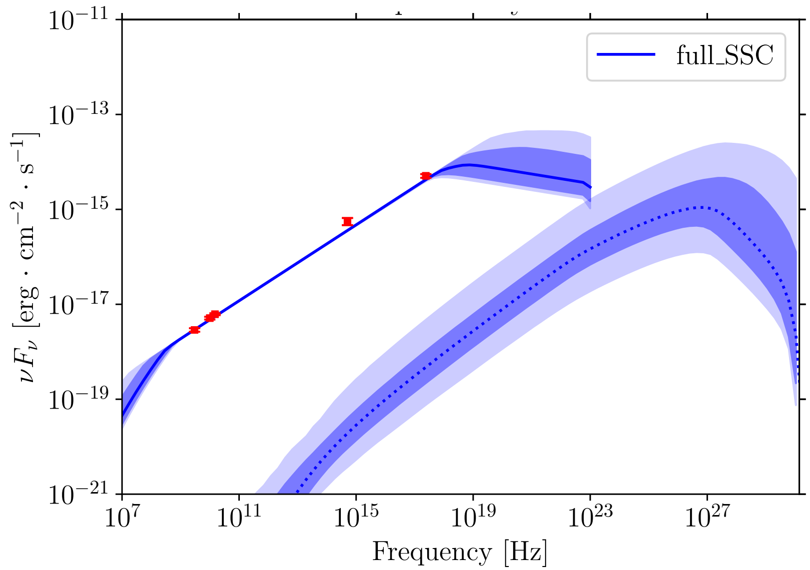
TEV AFTERGLOW OF A BNS MERGER?

- **Full calculation of the afterglow of a structured jet including SSC in Klein-Nishina regime**
  Part of the PhD work of Clément Pellouin @ IAP

Radio lightcurve (3 GHz)



Spectrum at the peak

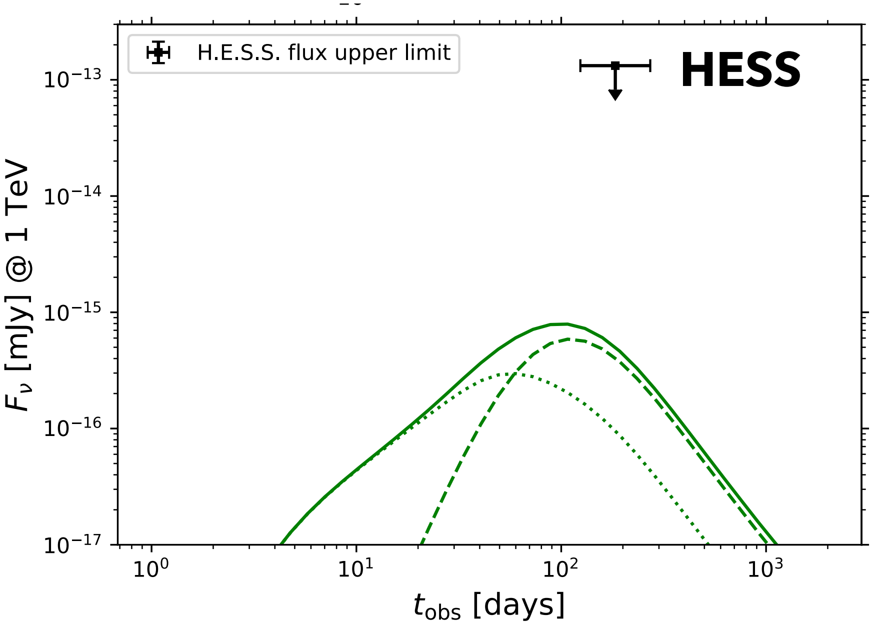


Pellouin & Daigne in preparation

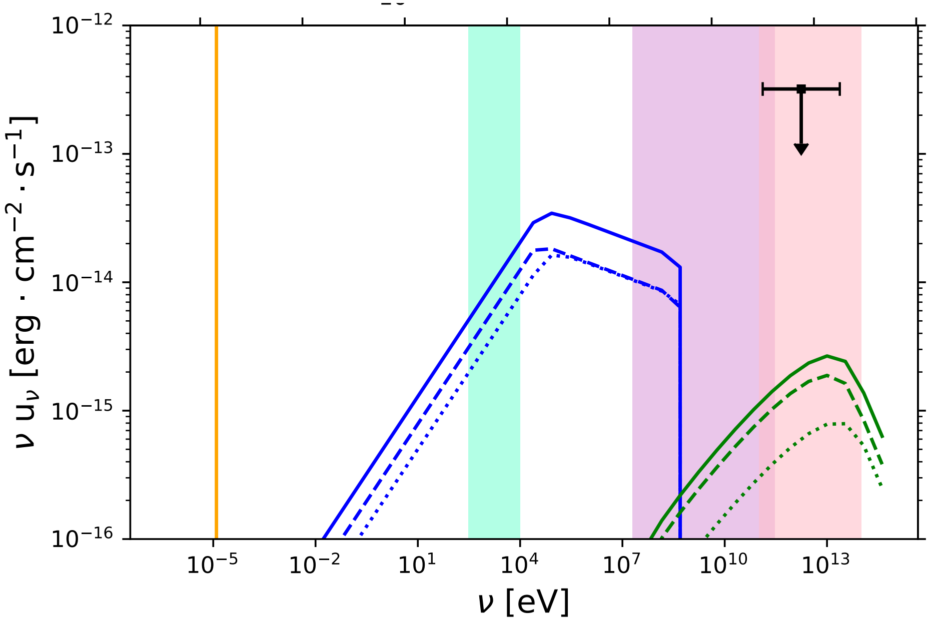
TEV AFTERGLOW OF A BNS MERGER?

- Full calculation including SSC in Klein-Nishina regime
- TeV lightcurve peaks ~2 orders of magnitude below the HESS limit

Lightcurve @ 1TeV



Spectrum@VHE peak (99 days)

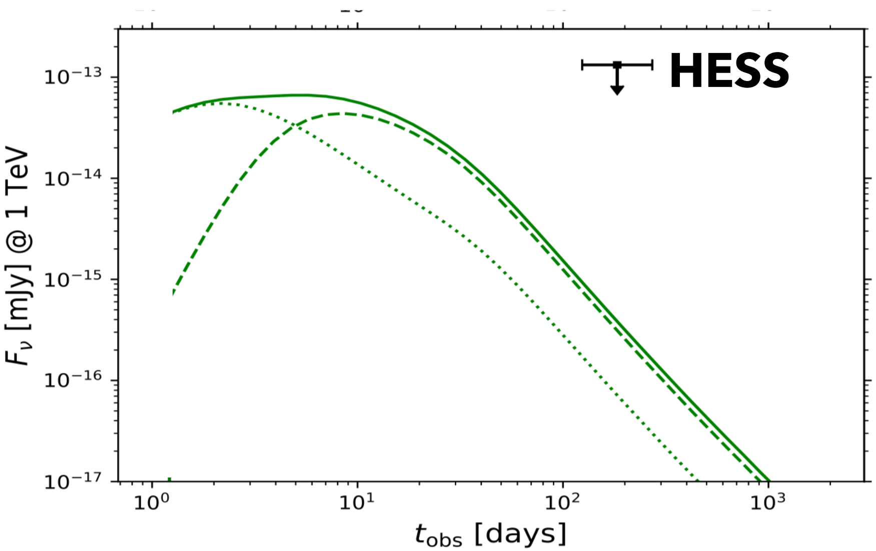


Pellouin & Daigne in preparation

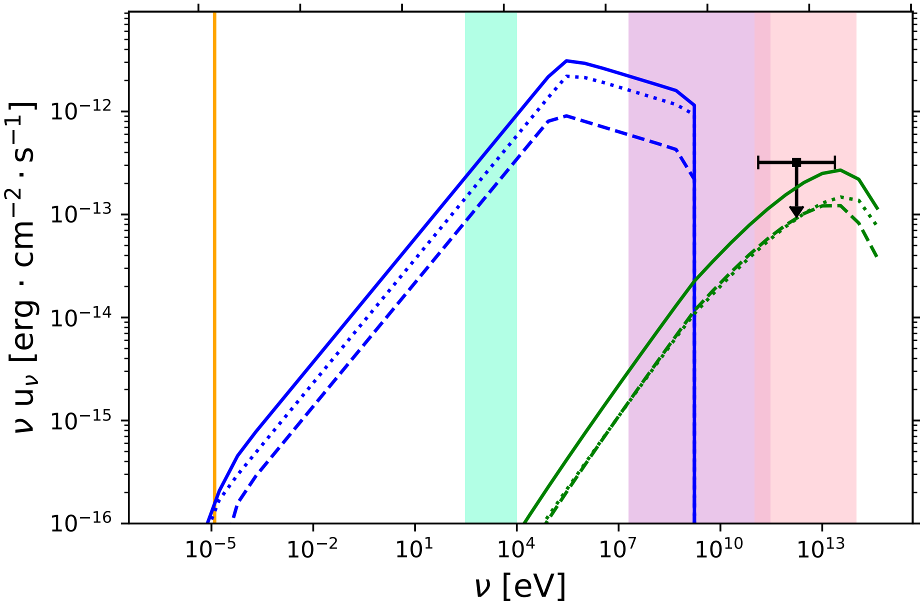
TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow seen less off-axis (~10°) becomes detectable by HESS
- and could be detectable by CTAO at > 100 Mpc

Lightcurve @ 1TeV



Spectrum@VHE peak (5 days)

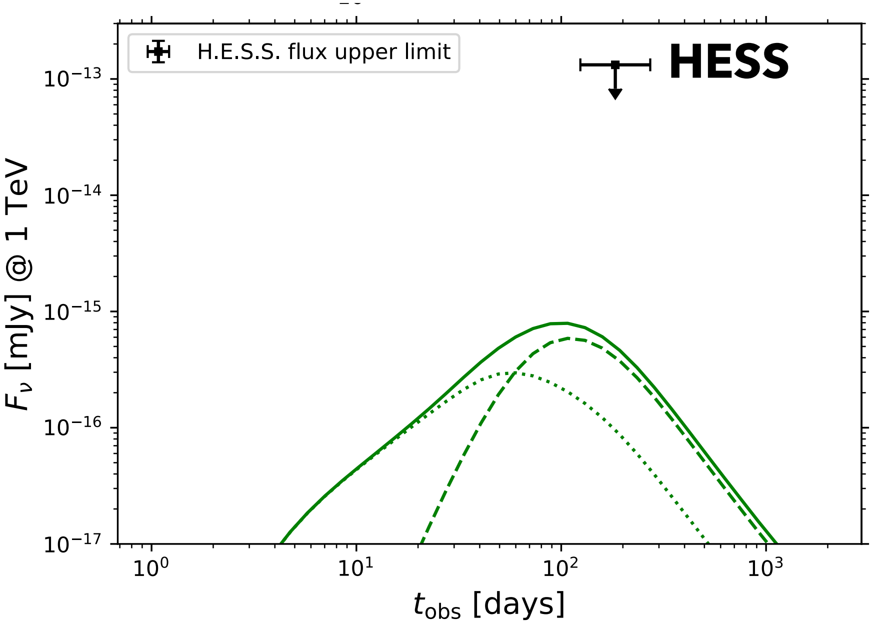


Pellouin & Daigne in preparation

TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable

Lightcurve @ 1TeV – 3 10^{-3} cm^{-3}



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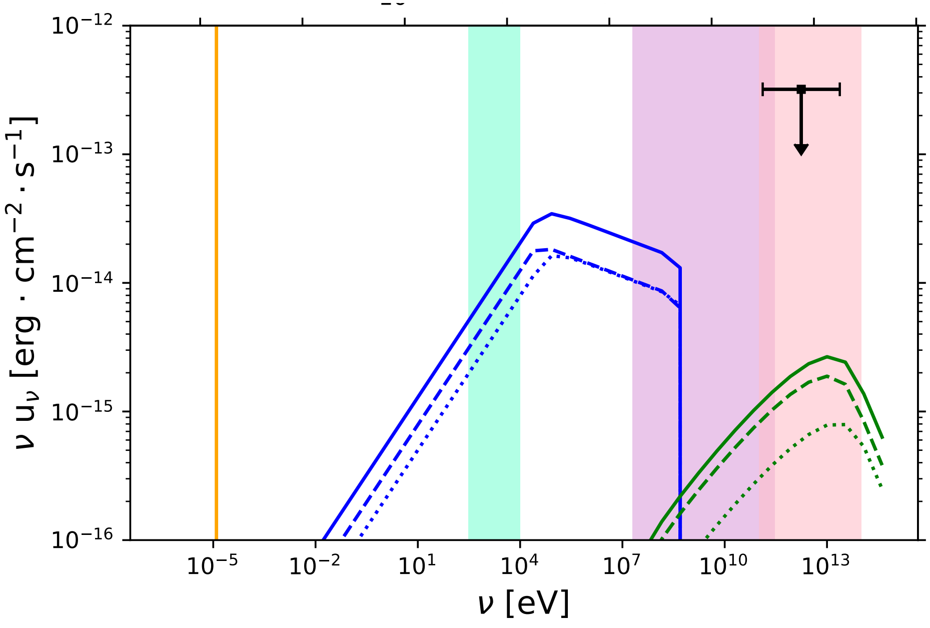
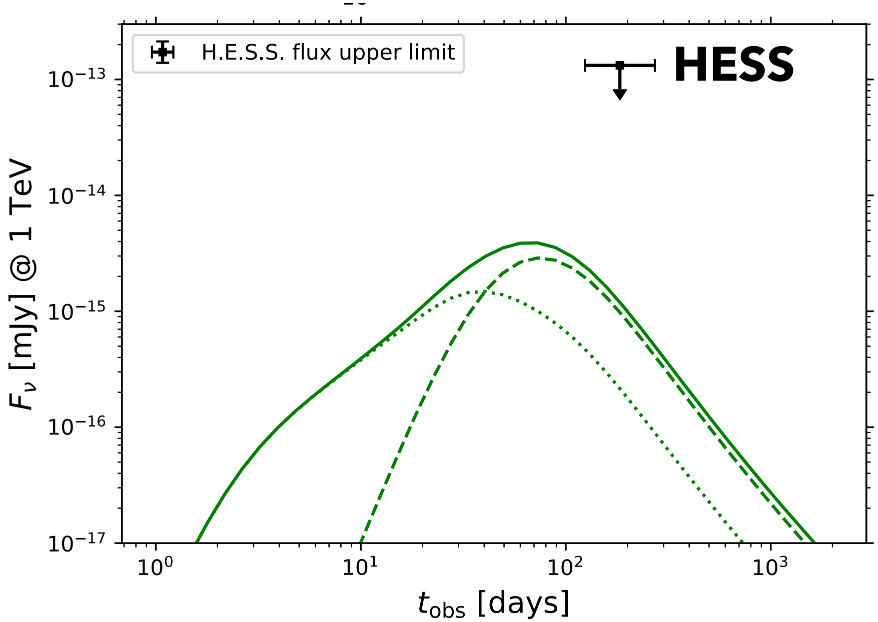


Pellouin & Daigne in preparation

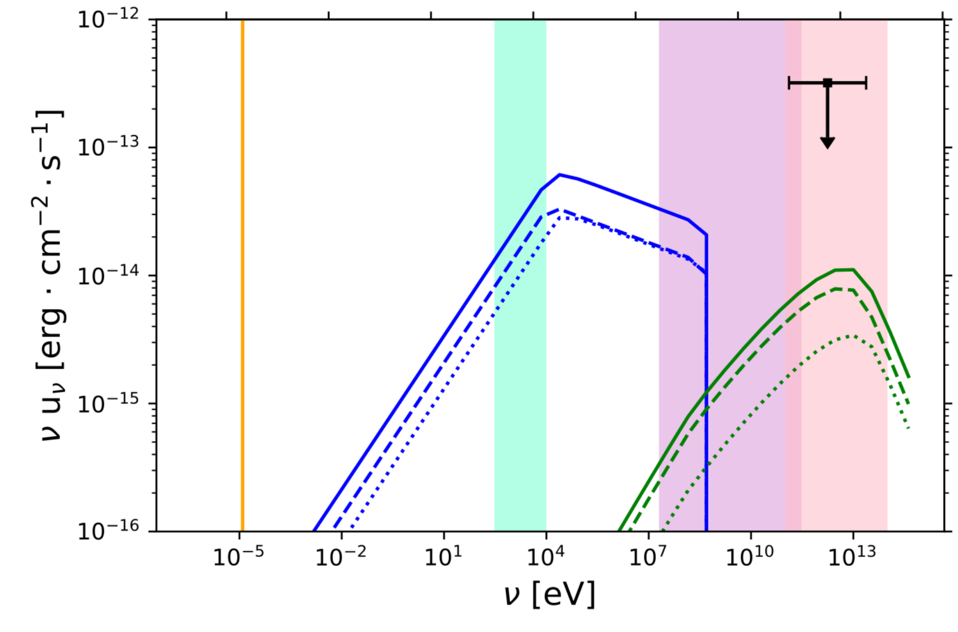
TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable

Lightcurve @ 1TeV – 10^{-2} cm^{-3}



Spectrum@VHE peak (67 days)

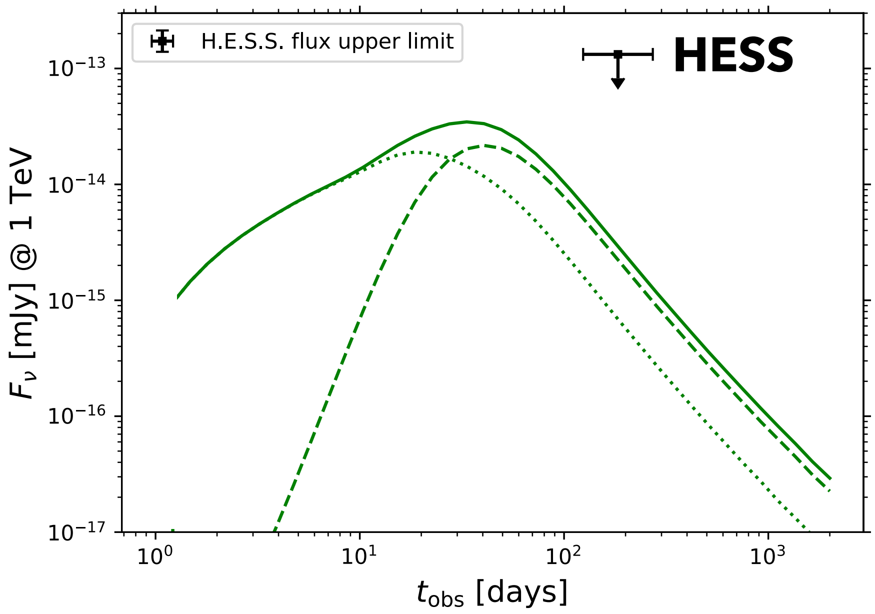


Pellouin & Daigne in preparation

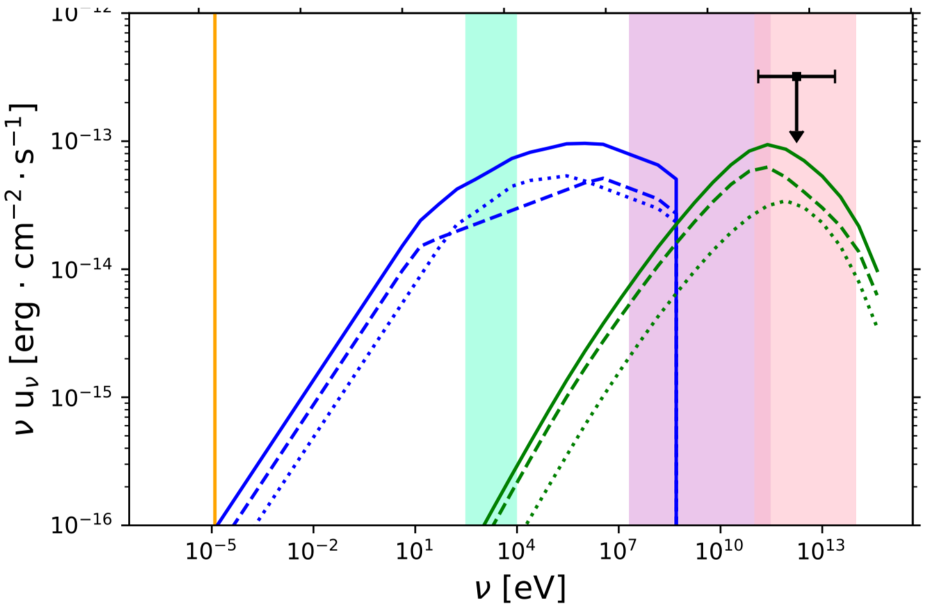
TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable

Lightcurve @ 1TeV – 10^{-1} cm^{-3}



Spectrum@VHE peak (34 days)

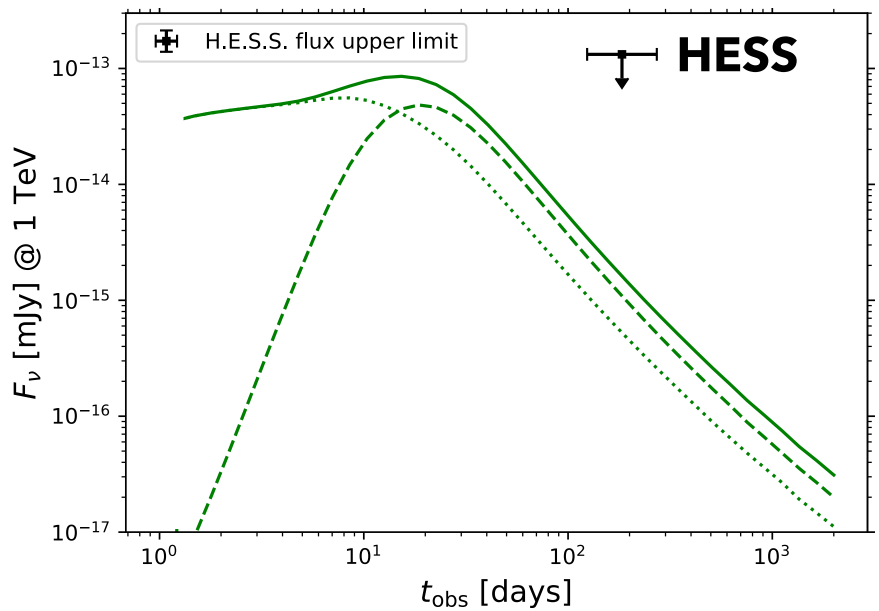


Pellouin & Daigne in preparation

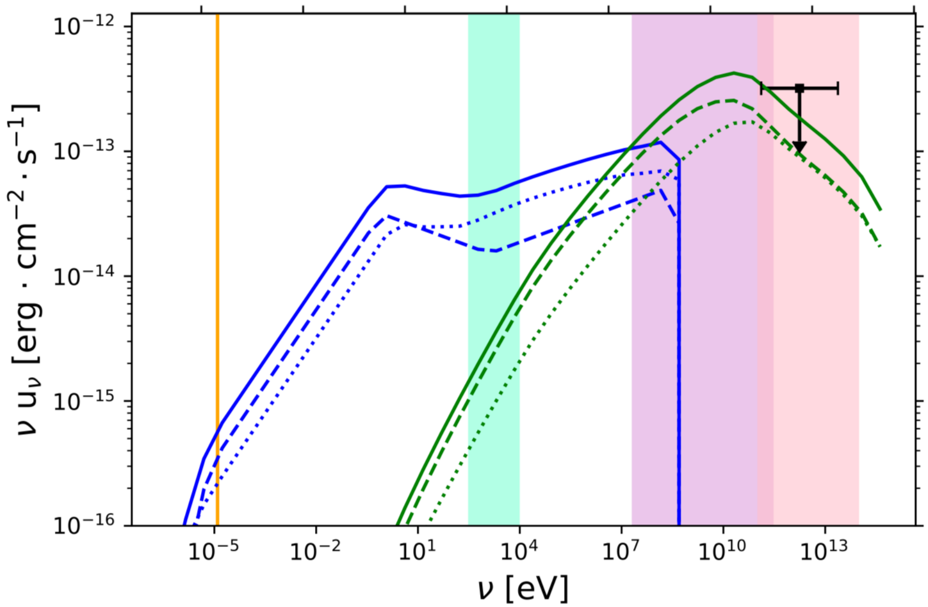
TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable

Lightcurve @ 1TeV – 1 cm^{-3}



Spectrum@VHE peak (15 days)

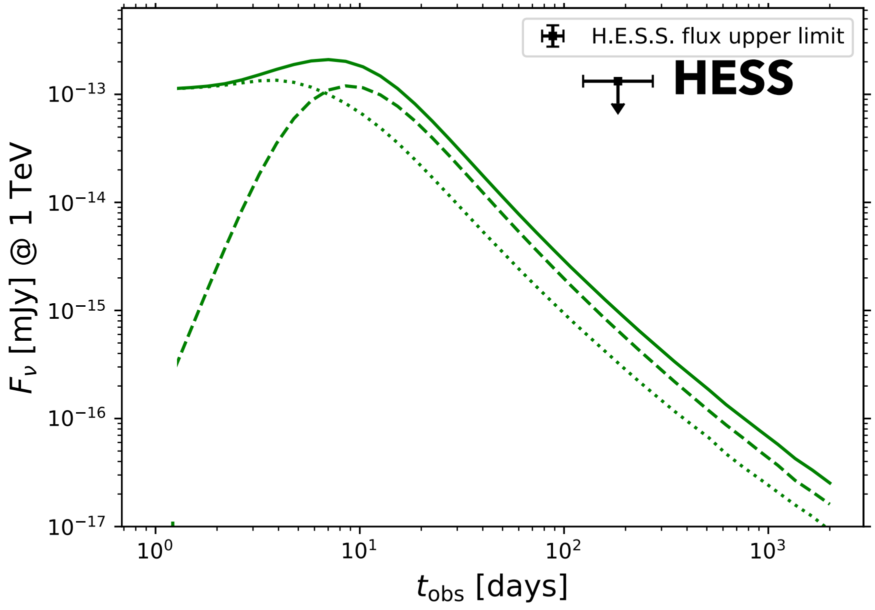


Pellouin & Daigne in preparation

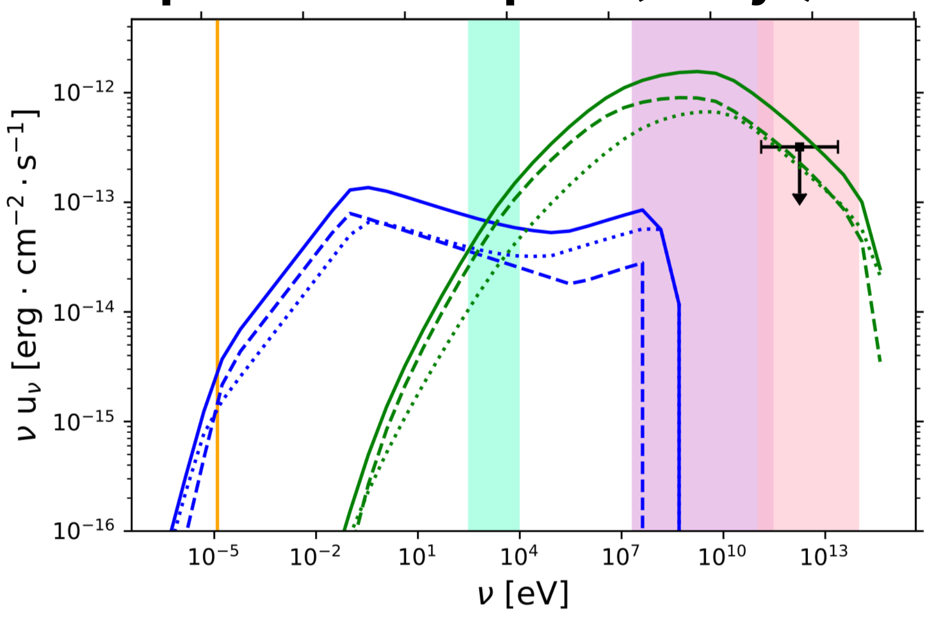
TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable

Lightcurve @ 1TeV – 10 cm^{-3}



Spectrum@VHE peak (7 days)



Pellouin & Daigne in preparation

TEV AFTERGLOW OF A BNS MERGER?

- Same afterglow (same viewing angle) with a higher external density can become detectable
- **If a formation channel leading to fast mergers exists, these systems should be over-represented in the GW-AG sample, due to brighter afterglows** (Duque et al. [FD] 2020)
- **These systems may be the only ones detected at VHE: direct signature of high density environment**
- **Many arguments in favor of such systems: some SGRB afterglow fits, some SGRB low offset in host galaxy, early r-process enrichment, etc.**
- **A possible new constraint on the stellar physics in binaries**

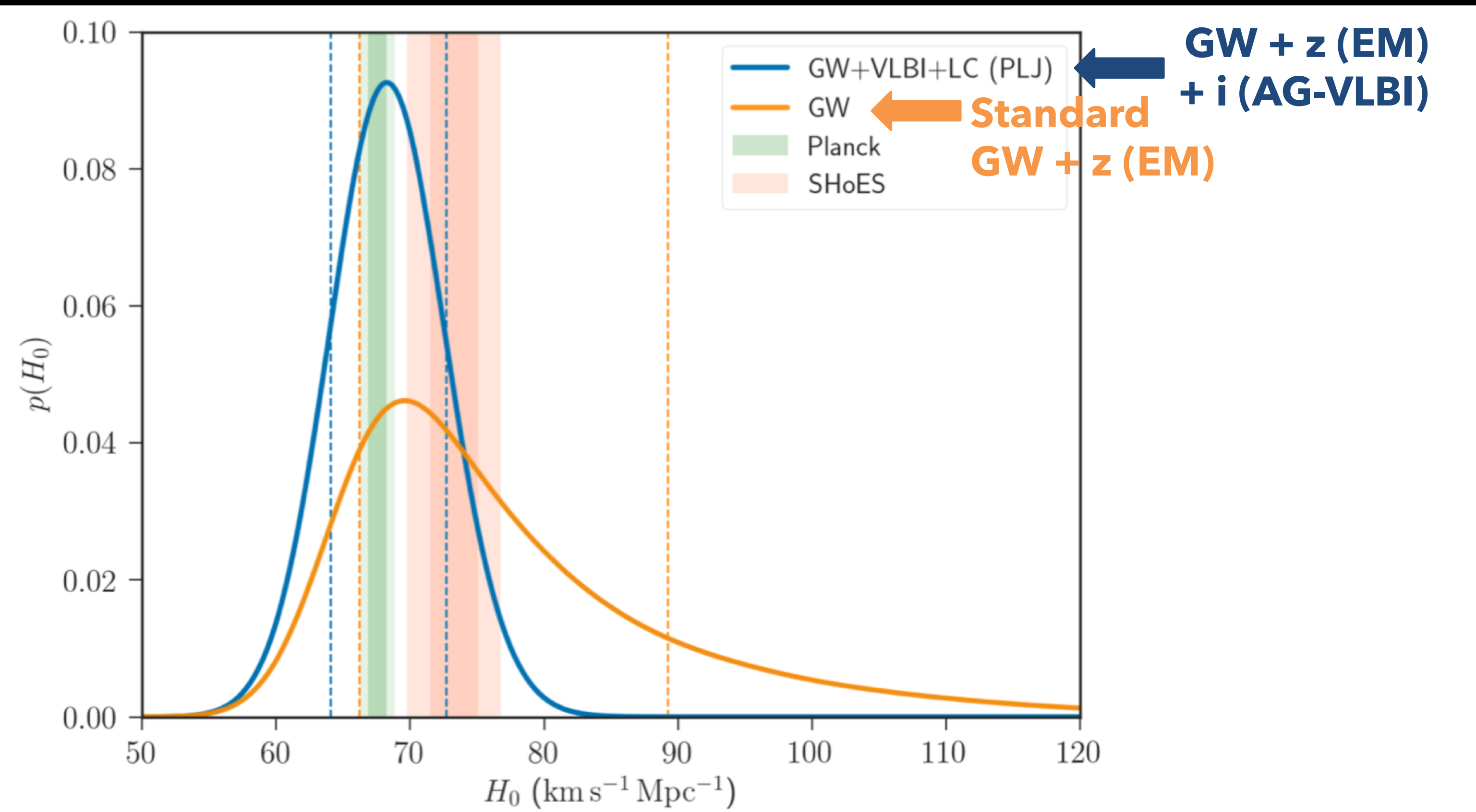
Pellouin & Daigne in preparation

NEW MULTI-MESSENGER DETECTIONS?

170817 & COSMOLOGY: H0

- GW: degeneracy distance-inclination
- AG VLBI: constraint on inclination – improves the measurement of H0

Hotokezaka et al. 2019



- See discussion in Mastrogiovanni et al. [FD] 2021: building a sample with such multiple observations will be slow, but each new event has an impact.

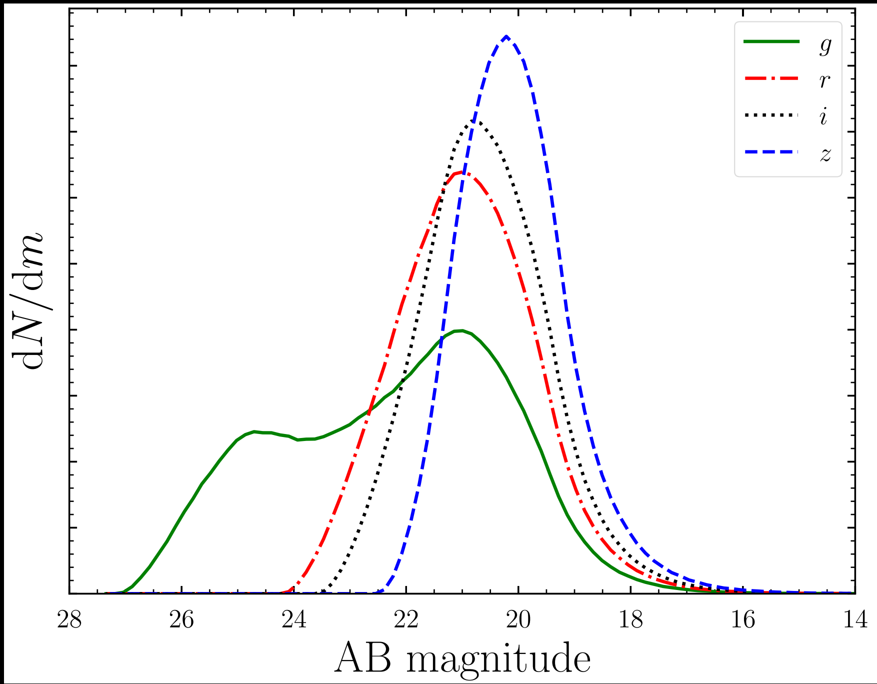
NEW MM ASSOCIATIONS?

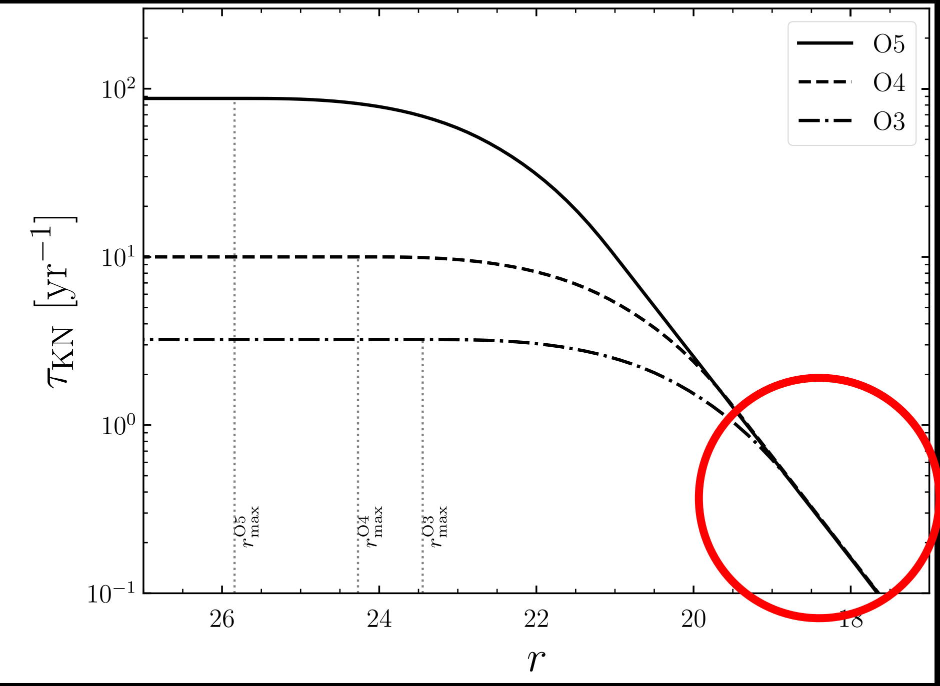
- LVK: run O4 is starting
- What do population models including EM counterparts say?
- Best candidate: KN (quasi-isotropic emission in V-IR)
- If KN is detected: accurate position, multi-wavelength search

NEW MM ASSOCIATIONS?

GW-detected BNS (O4): KN Magnitude @ peak (g,r,i,z)

KN rate above a given limit mag. (rlim)





« Bright » KN r<19
Rate does not evolve beyond O3

Mochkovitch, Daigne, Duque & Zitouni, 2021

(normalization: assumes 10 GW-detected BNS per year in O4)

NEW MM ASSOCIATIONS?

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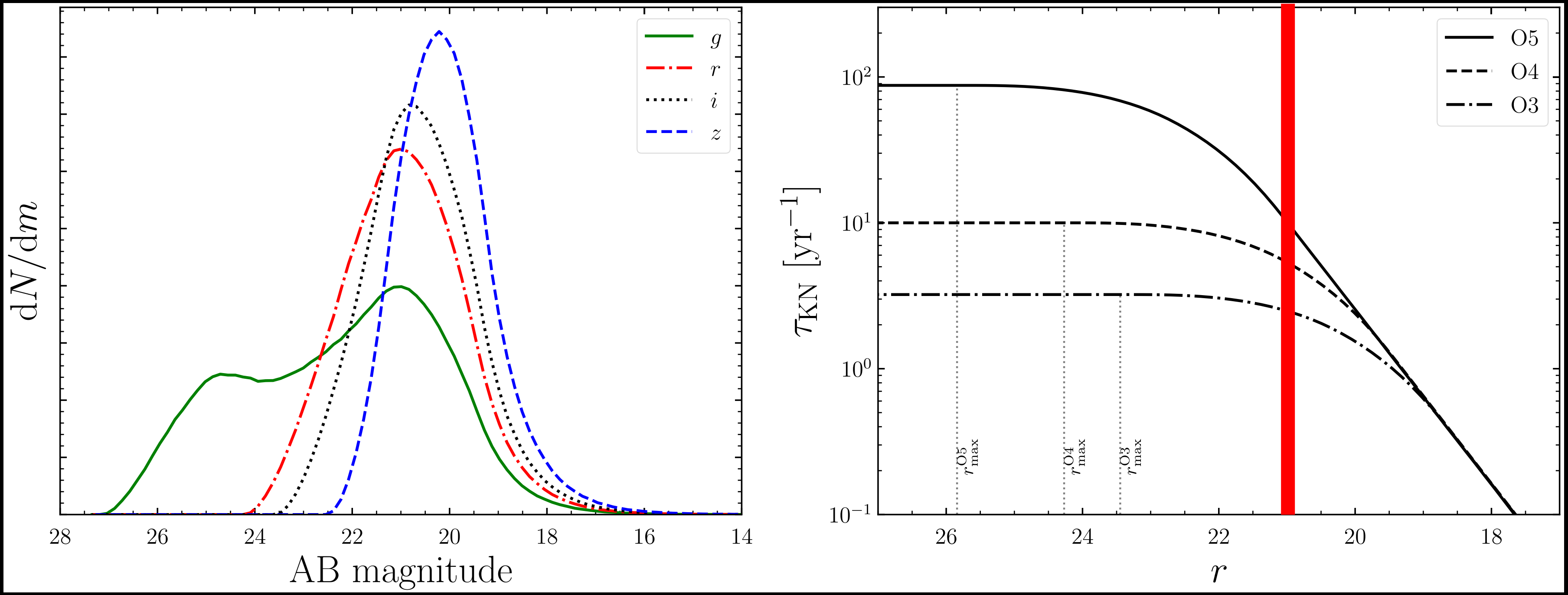


Deeper search: rlim=20-21

Significant increase of the rate with improved GW sensitivity

O4: several detectable KN per year

O5: > 10 detectable KN per year

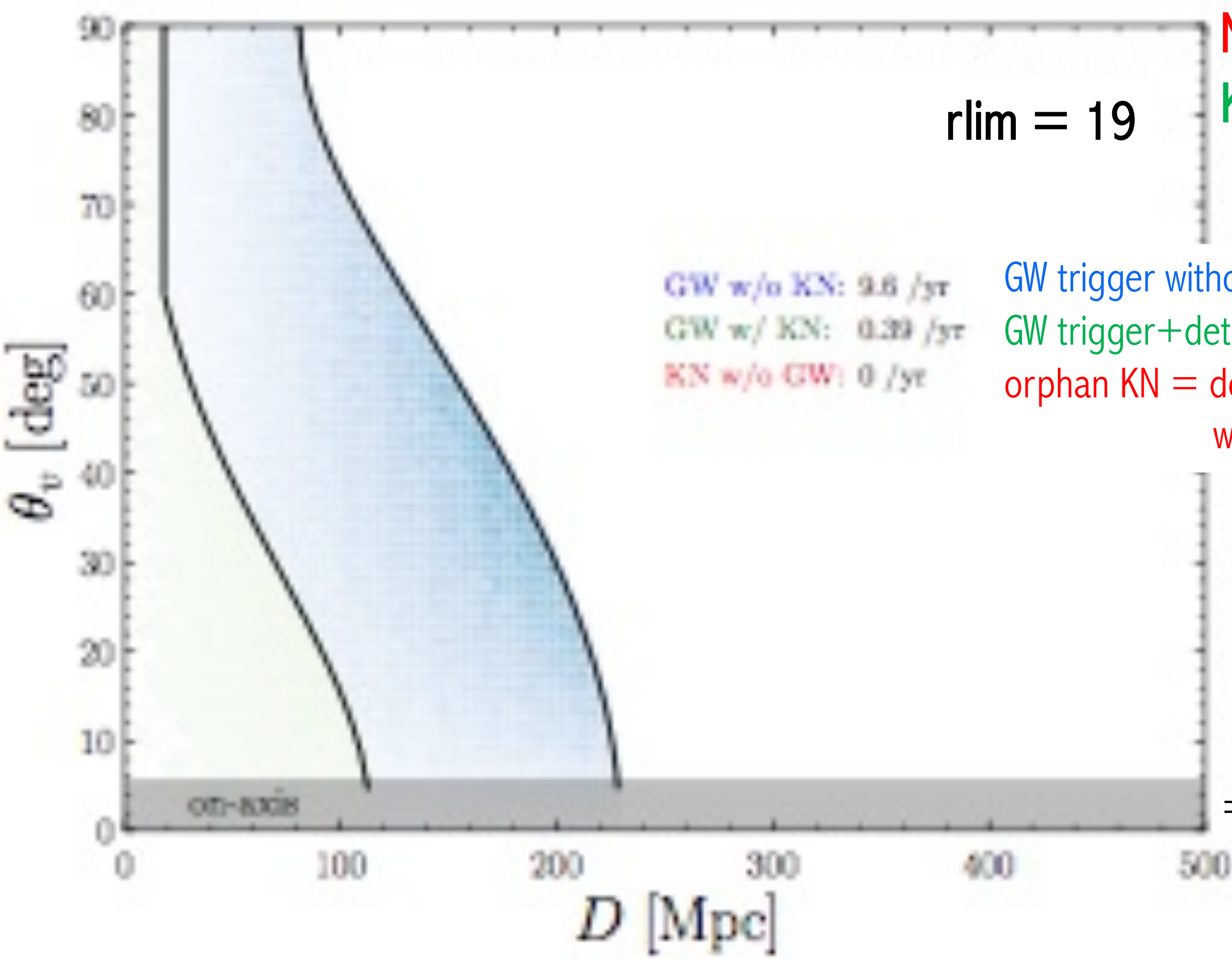
Detectable → Detected: strategy? (ZTF+LSST/Vera Rubin+follow-up telescopes...)

(normalization: assumes 10 GW-detected BNS per year in O4)

Mochkovitch, Daigne, Duque & Zitouni, 2021

NEW MM ASSOCIATIONS?

GW-detected BNS (O4): viewing angle vs distance for a given limit magnitude



No orphan KN

KN+GW= rare

GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN w/o a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

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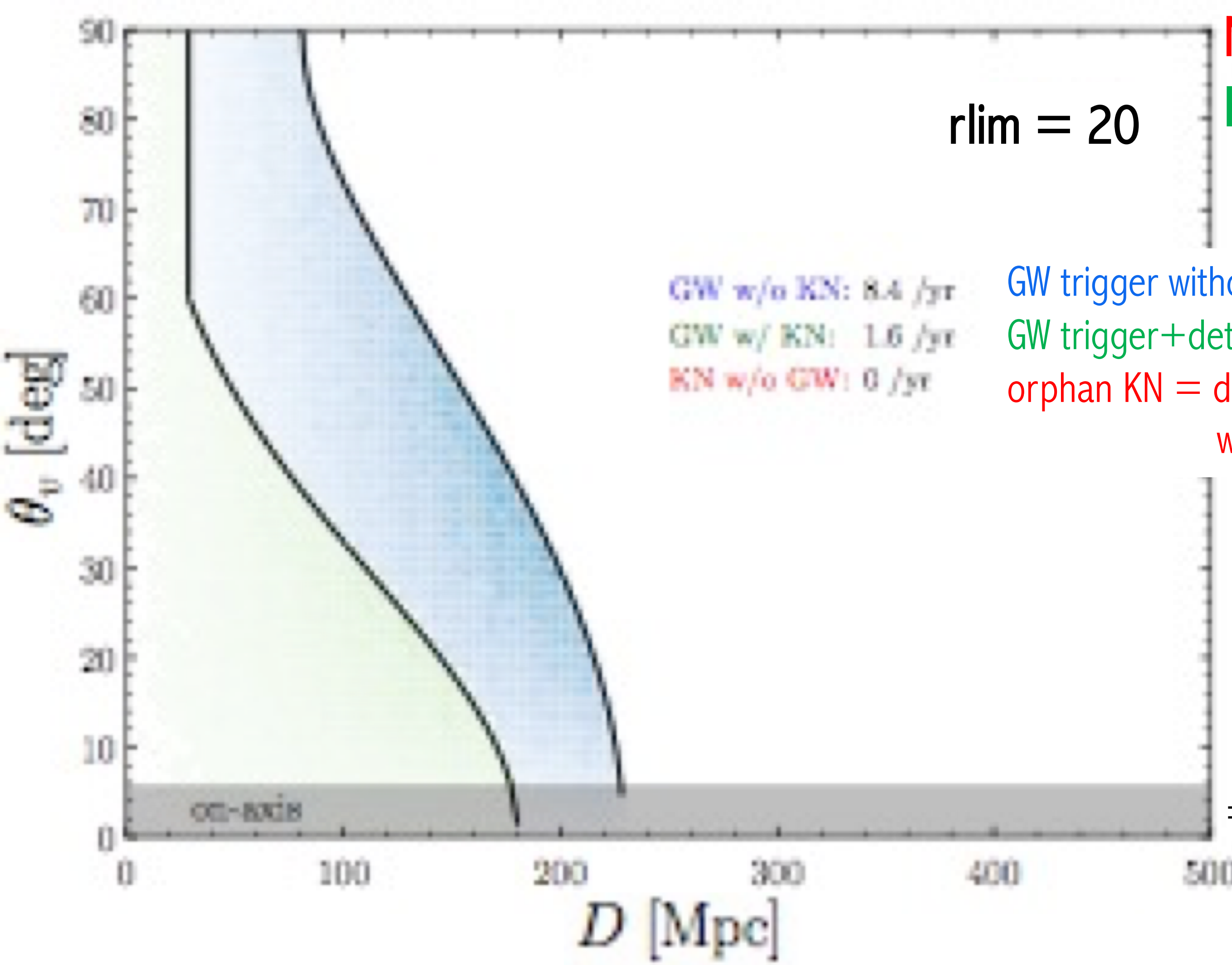

rlim = 20

No orphan KN

KN+GW= still rare

GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN w/o a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

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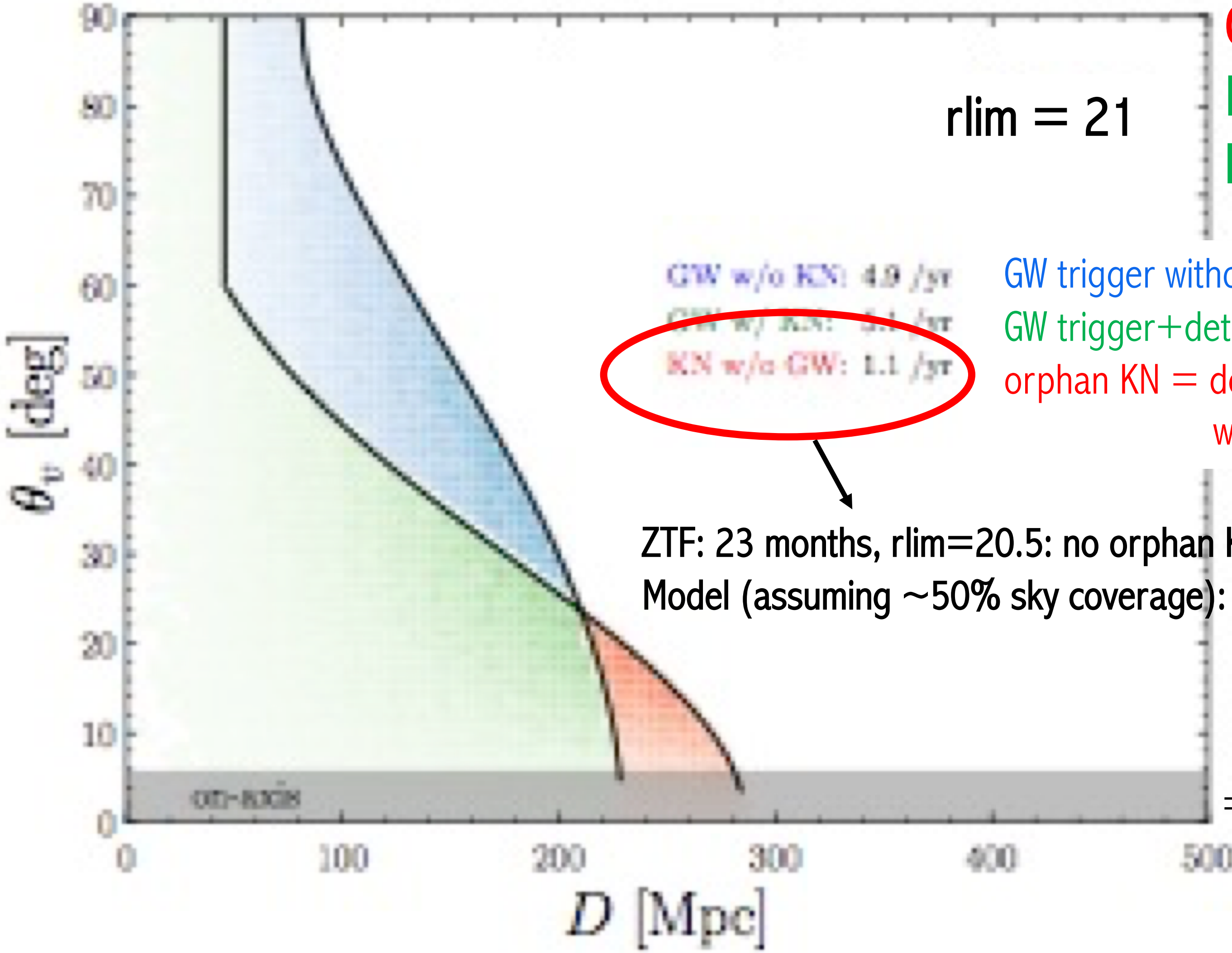


Orphan KN

Most GW-triggers have a detectable KN

GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN w/o a GW trigger

ZTF: 23 months, rlim=20.5: no orphan KN (Andreoni et al. 20)

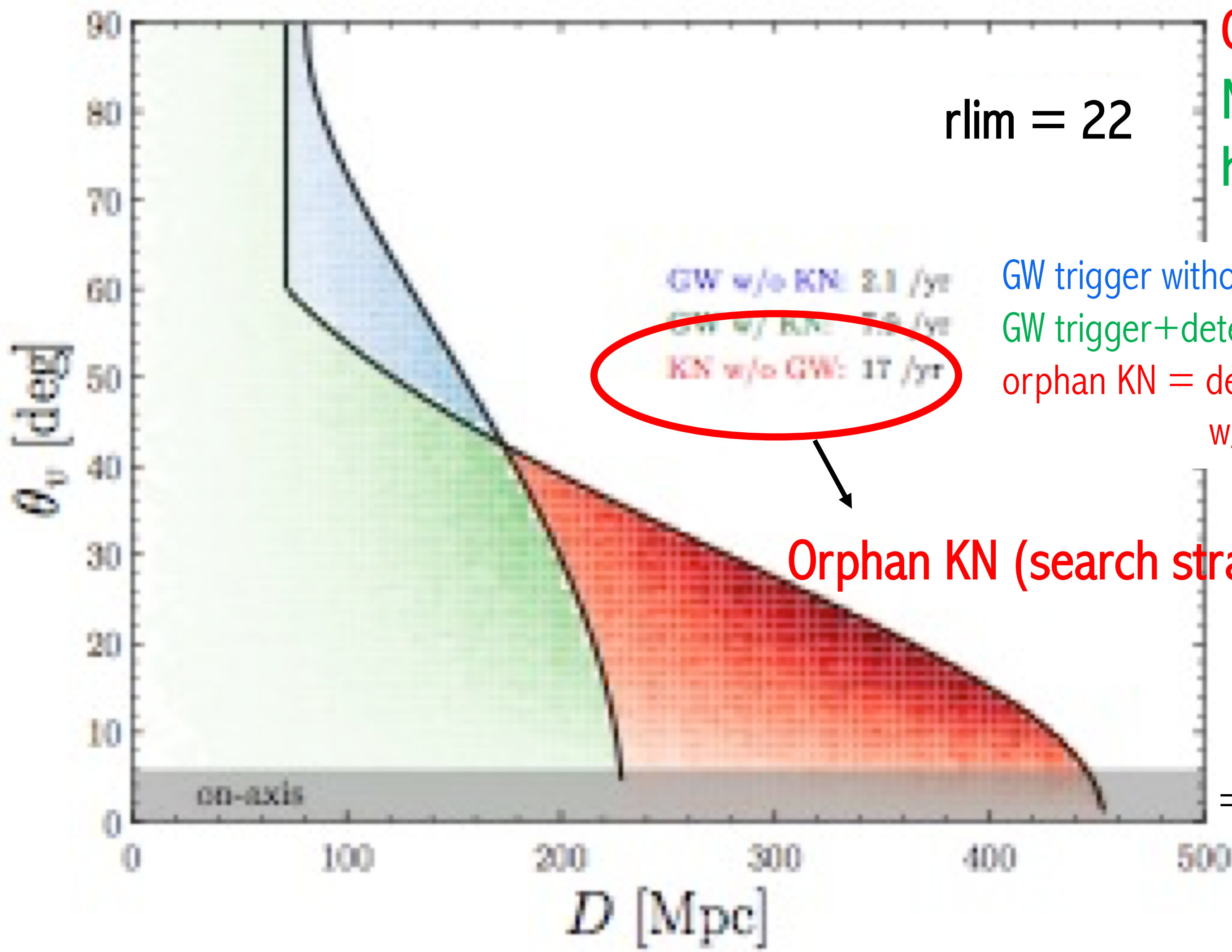
Model (assuming ~50% sky coverage): 0.4-2.6 orphan KNae

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

NEW MM ASSOCIATIONS?

GW-detected BNS (O4): viewing angle vs distance for a given limit magnitude



Orphan KN: high rate

Most GW-triggers have a detectable KN

GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN w/o a GW trigger

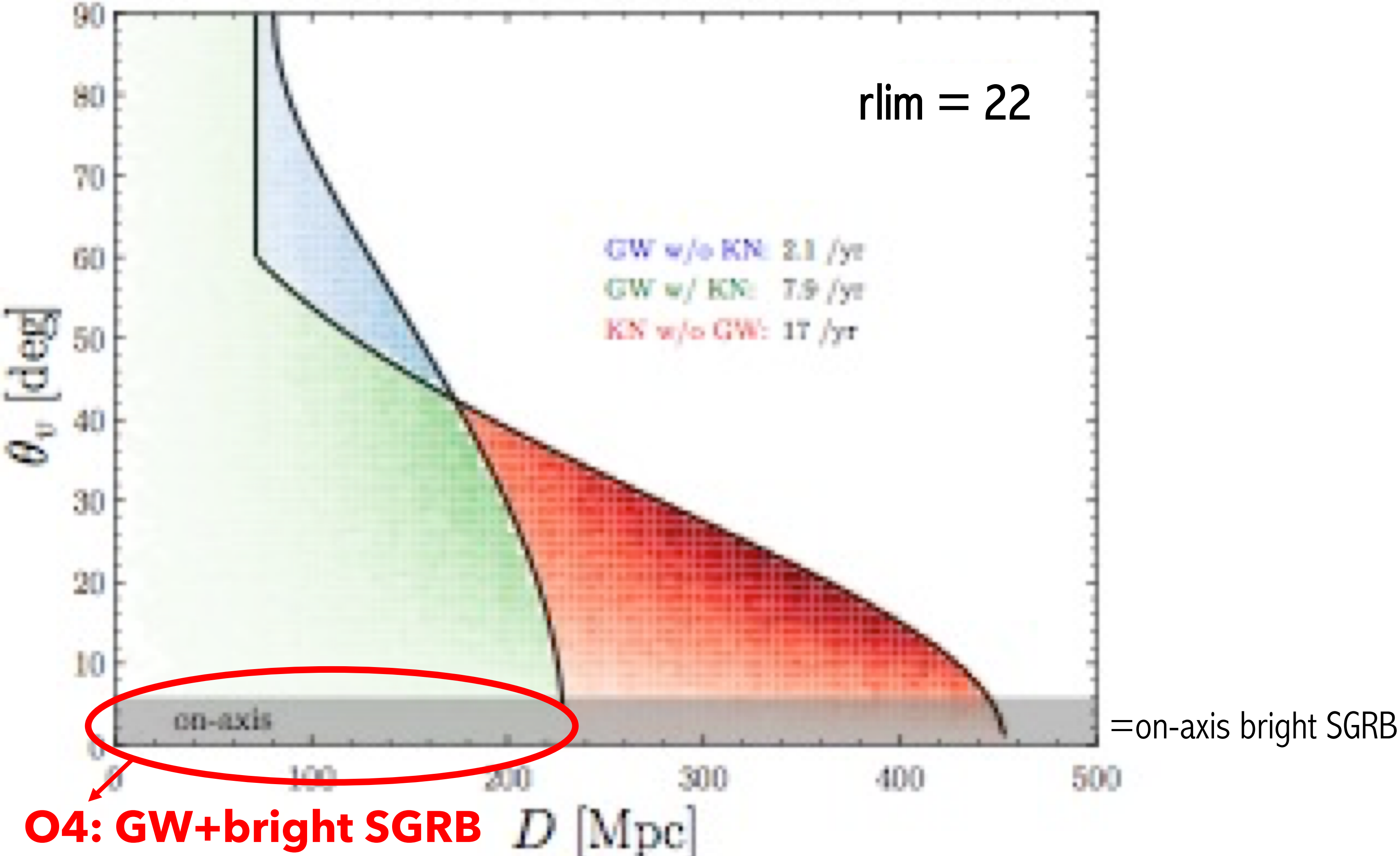
Orphan KN (search strategy for LSST?)

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

NEW MM ASSOCIATIONS?

GW-detected BNS (O4): viewing angle vs distance for a given limit magnitude



O4: GW+bright SGRB are very rare! (1 every 5-20 years in whole sky) – O5? ET?

Mochkovitch, Daigne, Duque & Zitouni, 2021

NEW MM ASSOCIATIONS?

- A major challenge: from « detectable » to « detected » events.
- A key quantity: localization accuracy

- Associations during O4 should remain rare, best candidate = kilonova
- Other channels can be explored to study the post-merger physics:
  - GRB+KN
  - Orphan KN
  - Orphan AG
- In the future: large field-of-view/deep limit magnitude instruments should play a major role in this quest (observation cadence for LSST-Rubin?)
- Association GW – bright short GRB (i.e. on-axis): small probability in O4, better in O5 and much better with Einstein Telescope

SVOM

- **Sino-French mission, to be launched at the end of 2023 (P.I. J. Wei (China) & B. Cordier (France))**

- **A satellite with four instruments (gamma-rays, X-rays, visible)** (Large fov /Narrow fov / Slew / Anti-Solar pointing)
- **Complementary ground-based instruments (visible, near-infrared)**

- **Core program: gamma-ray bursts**
- **MM program multi-wavelength follow-up of GW, ν alerts**

SVOM GRBS

Compared to Swift / Fermi: a smaller sample, but with well-characterized GRBs (prompt, afterglow, redshift).

GRB trigger

ECLAIRs

42-80 GRBs/yr

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ECLAIRs+GRM

Prompt GRB emission over 3 decades (4 keV-5.5 MeV)

Prompt emission

GWAC

prompt visible emission in ~16% of cases

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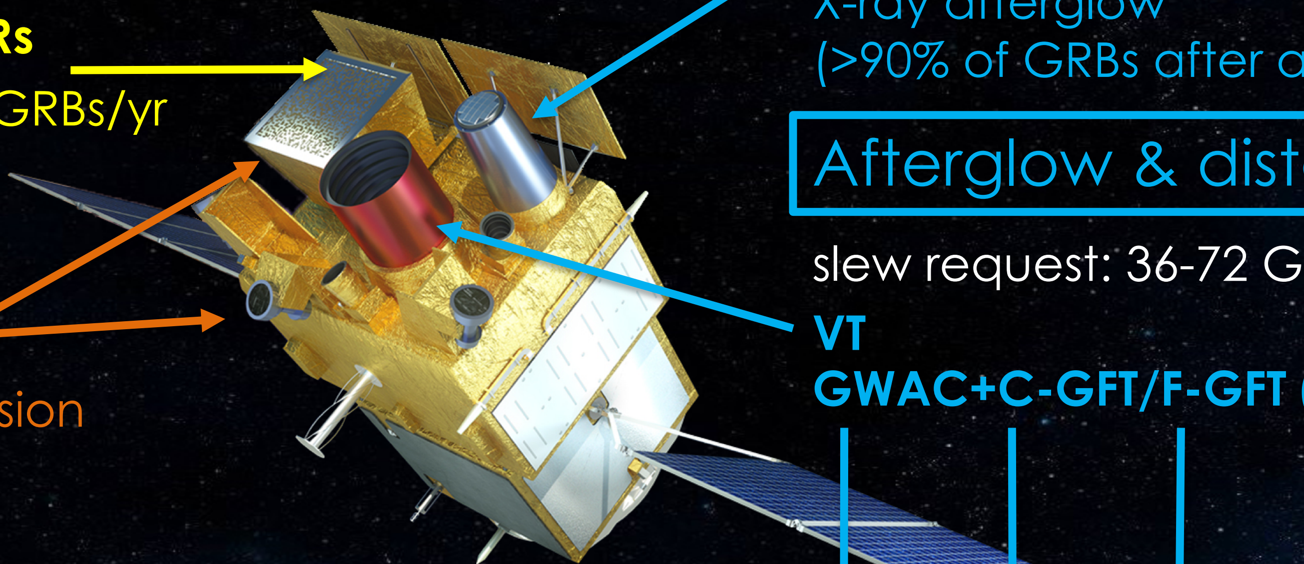
42-80 GRBs/yr

MXT

X-ray afterglow
(>90% of GRBs after a slew)

Afterglow & distance

slew request: 36-72 GRB/yr



ECLAIRs+GRM

Prompt GRB emission
over 3 decades
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VT

GWAC+C-GFT/F-GFT (Colibri)

Prompt emission

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prompt visible emission
in ~16% of cases

Visible/NIR afterglow

Photometric redshift

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GRB trigger

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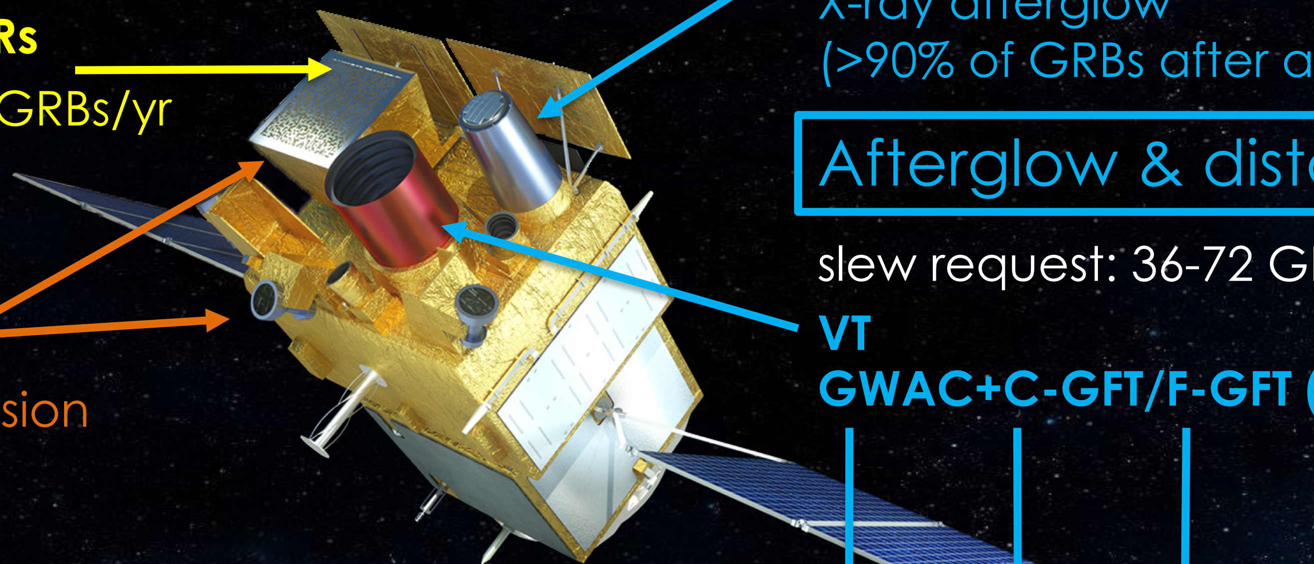
42-80 GRBs/yr



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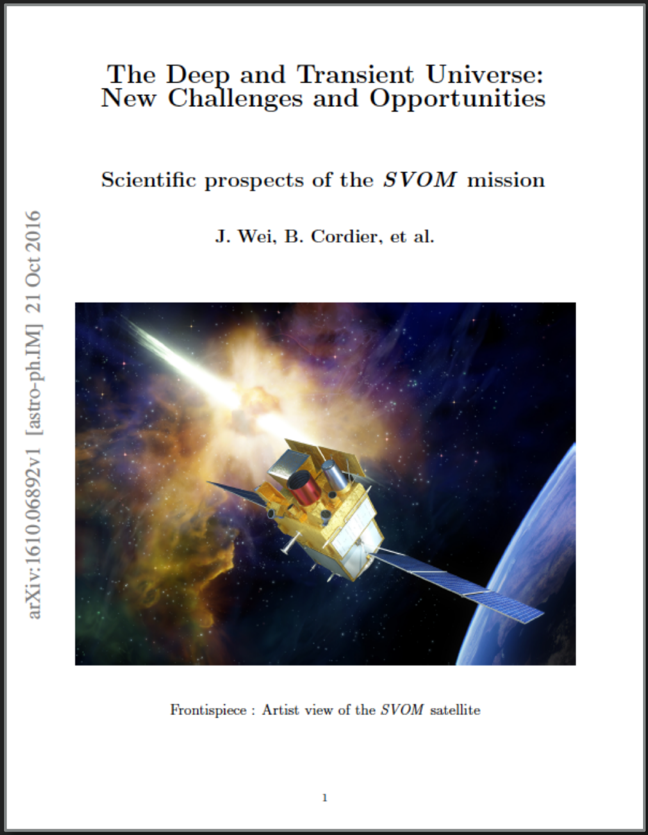
Visible/NIR afterglow

Photometric redshift

Follow-Up by other instruments (including very large telescopes)
Redshift for 2/3 of the sample

SVOM

- Arcier, B., Atteia, J. L., Godet, O., et al. (2020) Detection of short high-energy transients in the local universe with SVOM/ECLAIRs, Astrophysics and Space Science, 365, 185
- Wang, J., Qiu, Y.-L., & Wei, J.-Y. (2020) A pilot study of catching high-z GRBs and exploring circumburst environment in the forthcoming SVOM era, Research in Astronomy and Astrophysics 20, 124
- Dagoneau, N., Schanne, S., Atteia, J.-L., Götz, D., & Cordier, B. (2020) Ultra-Long Gamma-Ray Bursts detection with SVOM/ECLAIRs, Experimental Astronomy 50, 91
- Bernardini, M. G., Xie, F., Sizun, P., et al. (2017) Scientific prospects for spectroscopy of the gamma-ray burst prompt emission with SVOM, Experimental Astronomy 44, 113
- Wei, J., Cordier, B., Antier, S., et al. (2016) The Deep and Transient Universe in the SVOM Era: New Challenges and Opportunities - Scientific prospects of the SVOM mission, arXiv e-prints arXiv:1610.06892


The Deep and Transient Universe:
New Challenges and Opportunities

Scientific prospects of the *SVOM* mission

J. Wei, B. Cordier, et al.

arXiv:1610.06892v1 [astro-ph.IM] 21 Oct 2016

Frontispiece : Artist view of the *SVOM* satellite

1

SUMMARY

- GRBs are extreme phenomena emblematic of high-energy/multi-messenger astrophysics, with potential applications in cosmology.
- 25 years after the discovery of the first afterglow (GRB 970228, BeppoSAX), new windows have open recently: TeV, GW
- A new generation of instruments is coming: more detections expected.

Among them: SVOM to be launched at the end of 2023.

THANKS!