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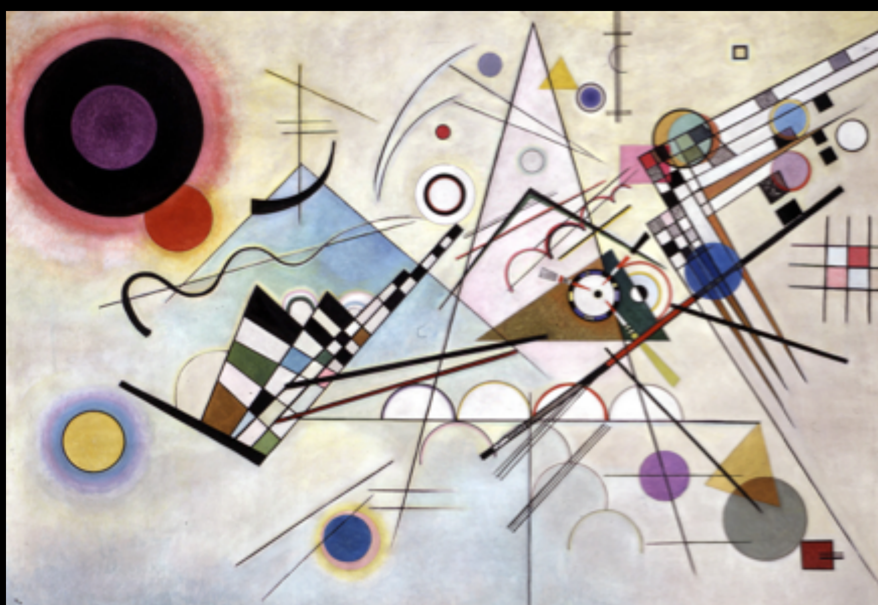
GAMMA-RAY BURSTS IN THE MULTI-MESSENGER ERA

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



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

Kandinksy - Curves and sharp angles - 1923
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12th CosPa Meeting: Multi-Messenger Sources and Observations – Louvain-la-Neuve, April 21, 2022

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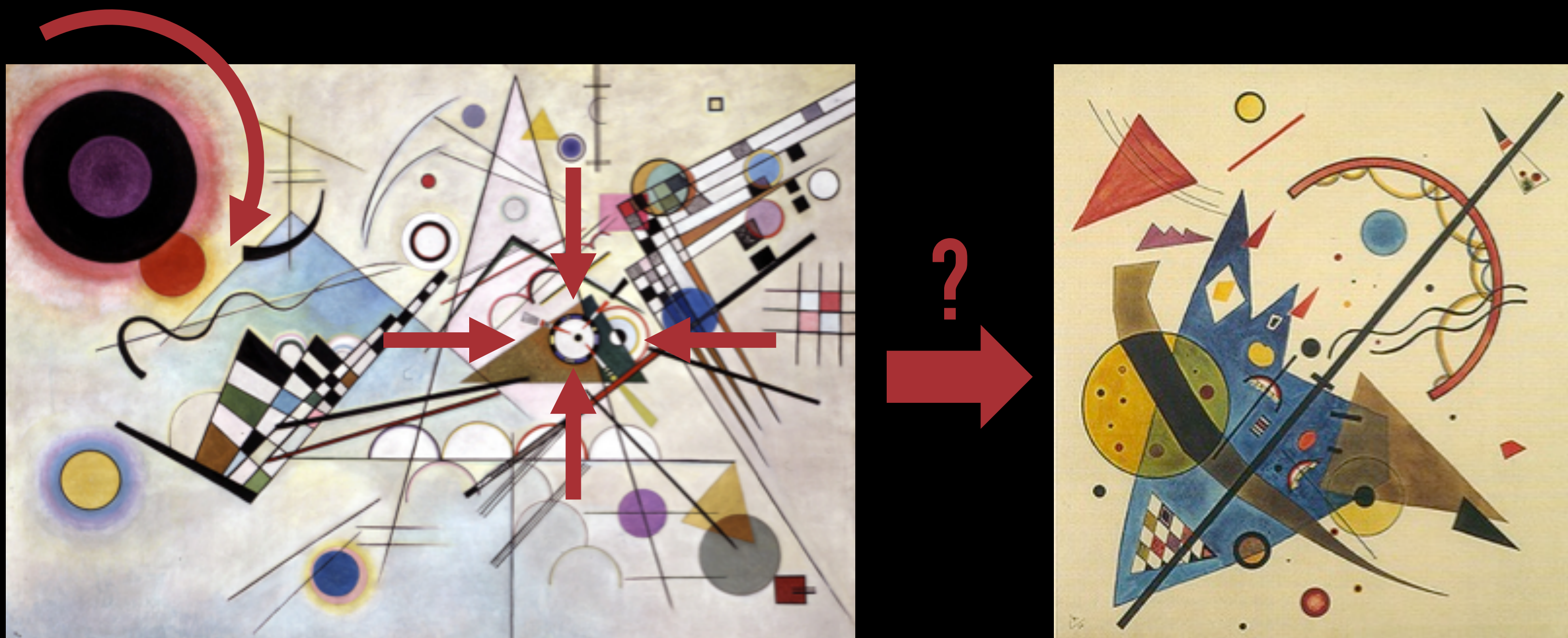

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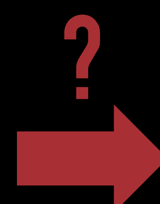

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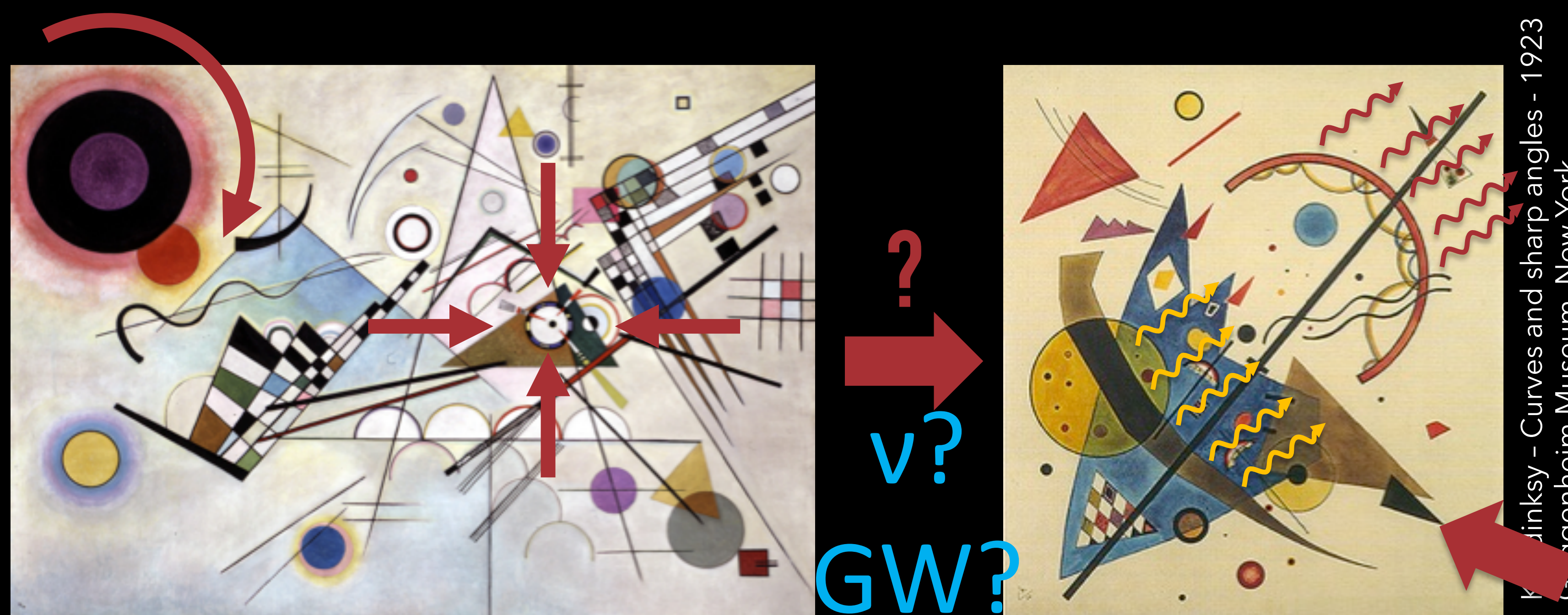

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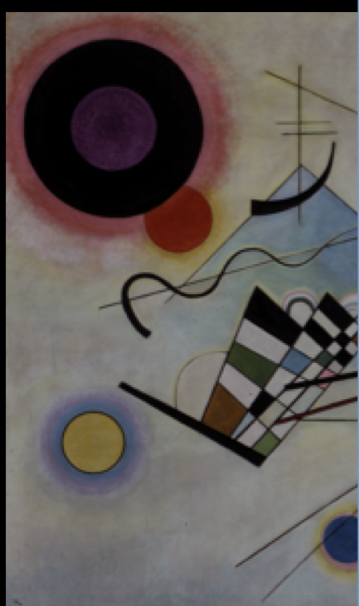

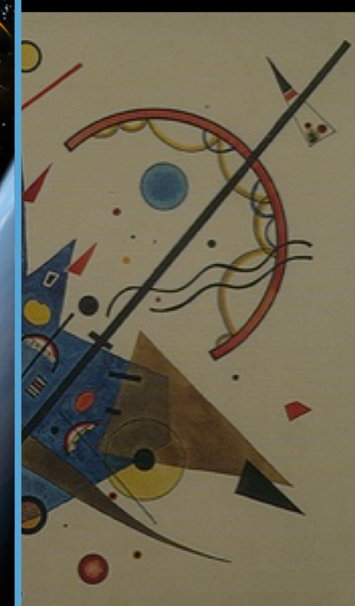

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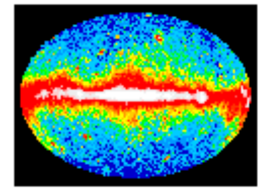
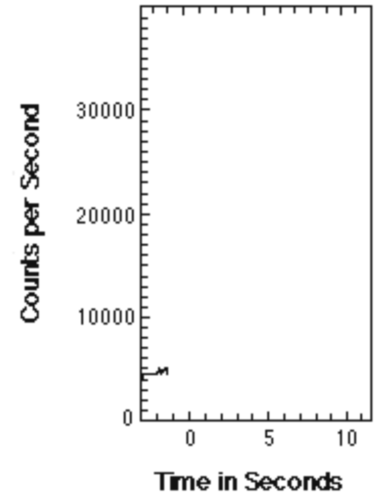
GAMMA-RAY BURSTS

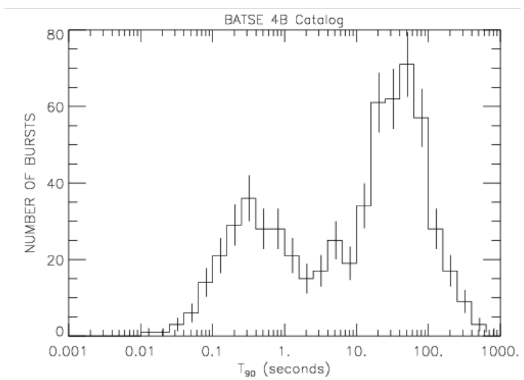
MAIN OBSERVATIONAL FACTS (1) PROMPT EMISSION

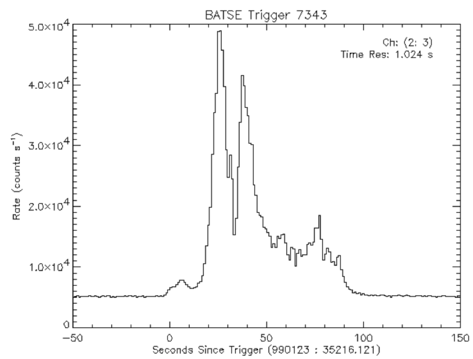


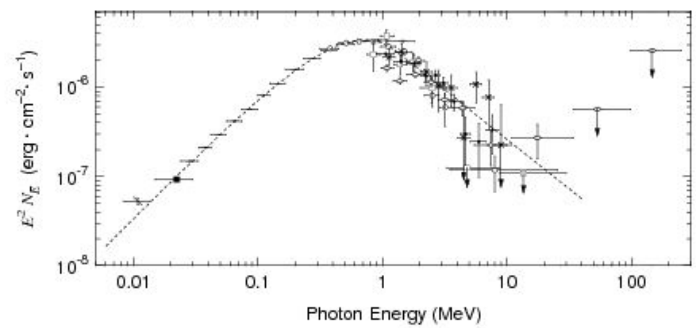


- **High variability :** ms ⟶ 100 ms
- **Short duration:** a few ms to a few min
- **Two classes: short & long GRBs**

BATSE



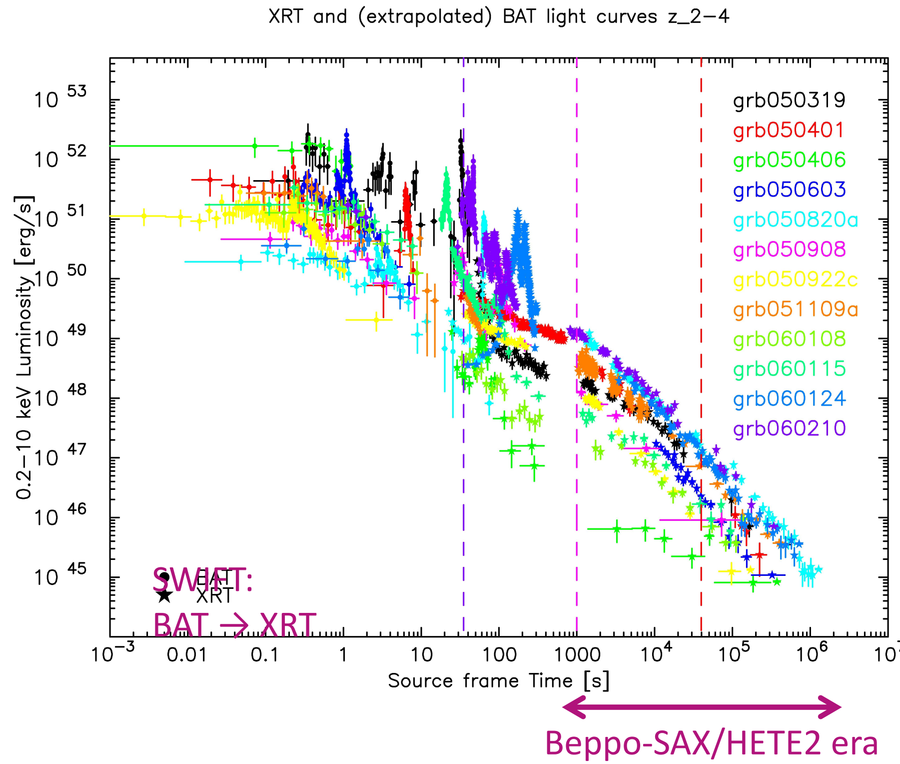




- **Great diversity of lightcurves ; Pulses:** 100 ms ⟶ 10 s
- **Non-thermal spectrum:** peak energy 100 keV → 1 MeV
- **Spectral evolution**
- **Spectral diversity:** classical GRBs, X-ray rich GRBs, X-ray Flashes, etc.

MAIN OBSERVATIONAL FACTS (2) AFTERGLOW

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

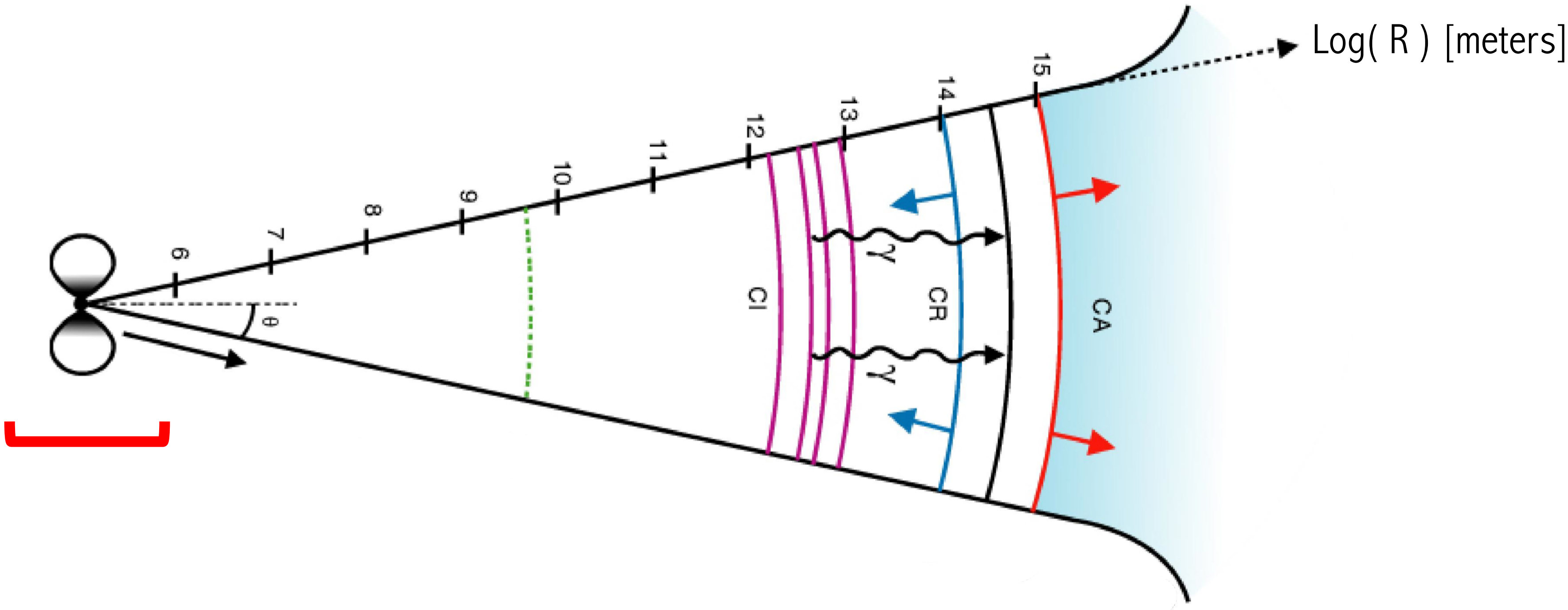


- **Redshift**
  - Mean redshift above 2 for long GRBs
  - Maximum : GRB 090423 at z = 8.2
    GRB 090429B at z = 9.3
  - **E_{iso} ~ 10^{51} to 10^{54} erg**
    (some under-luminous ; some monsters…)

- **Host galaxy**
  - Clear difference between short & long bursts (long GRBs: only star-forming galaxies)
  - Different progenitors

THEORY

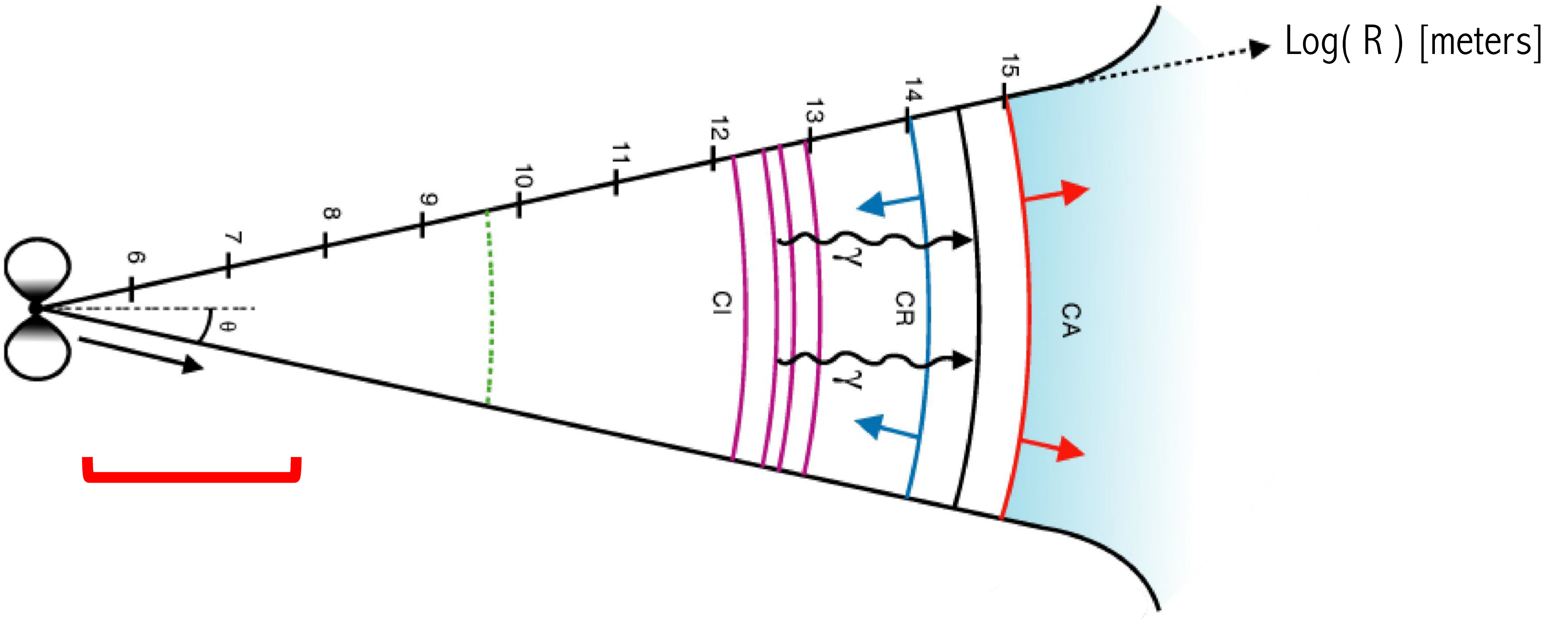
- Cosmological distance: huge radiated energy ($E_{iso,\gamma} \sim 10^{50}$-$10^{55}$ erg)
- Variability + energetics: violent formation of a stellar mass BH/magnetar



Progenitors: Long GRBs: collapse of some massive stars / probable diversity
Short GRBs: NS+NS(/BH ?)merger

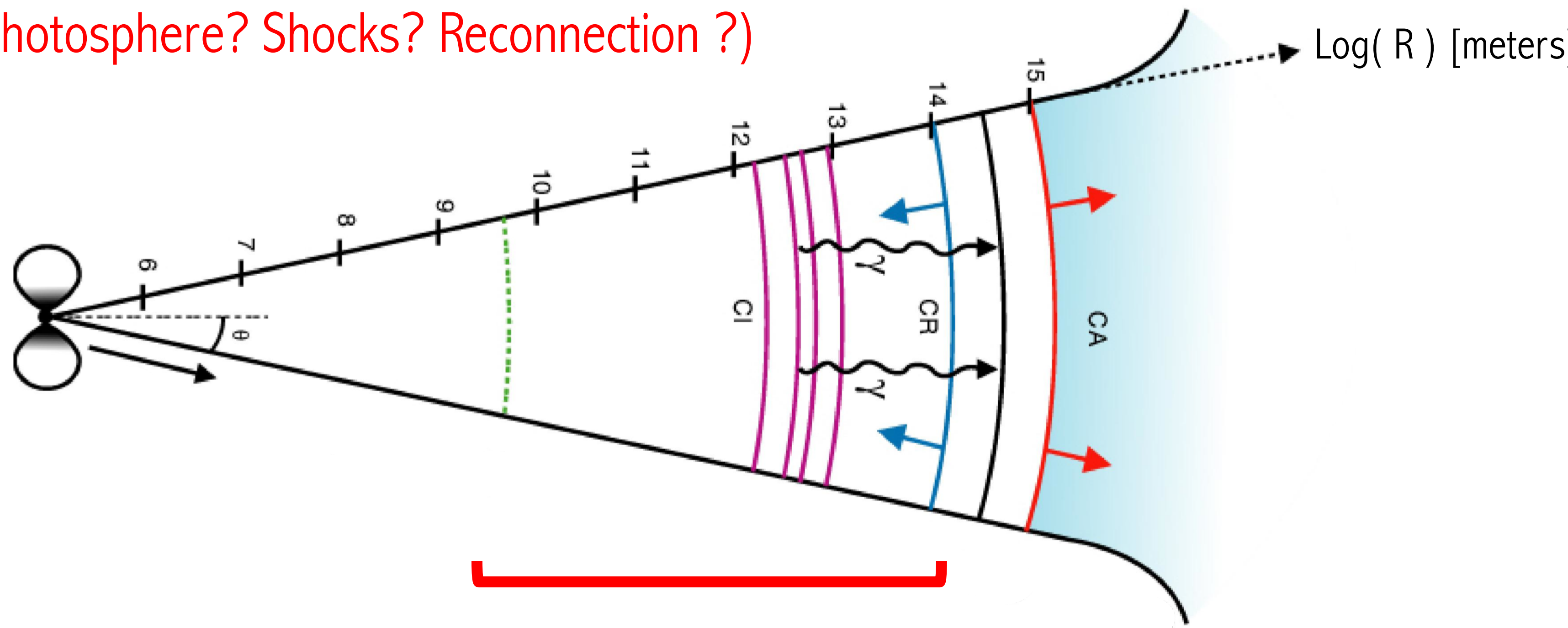
THEORY

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



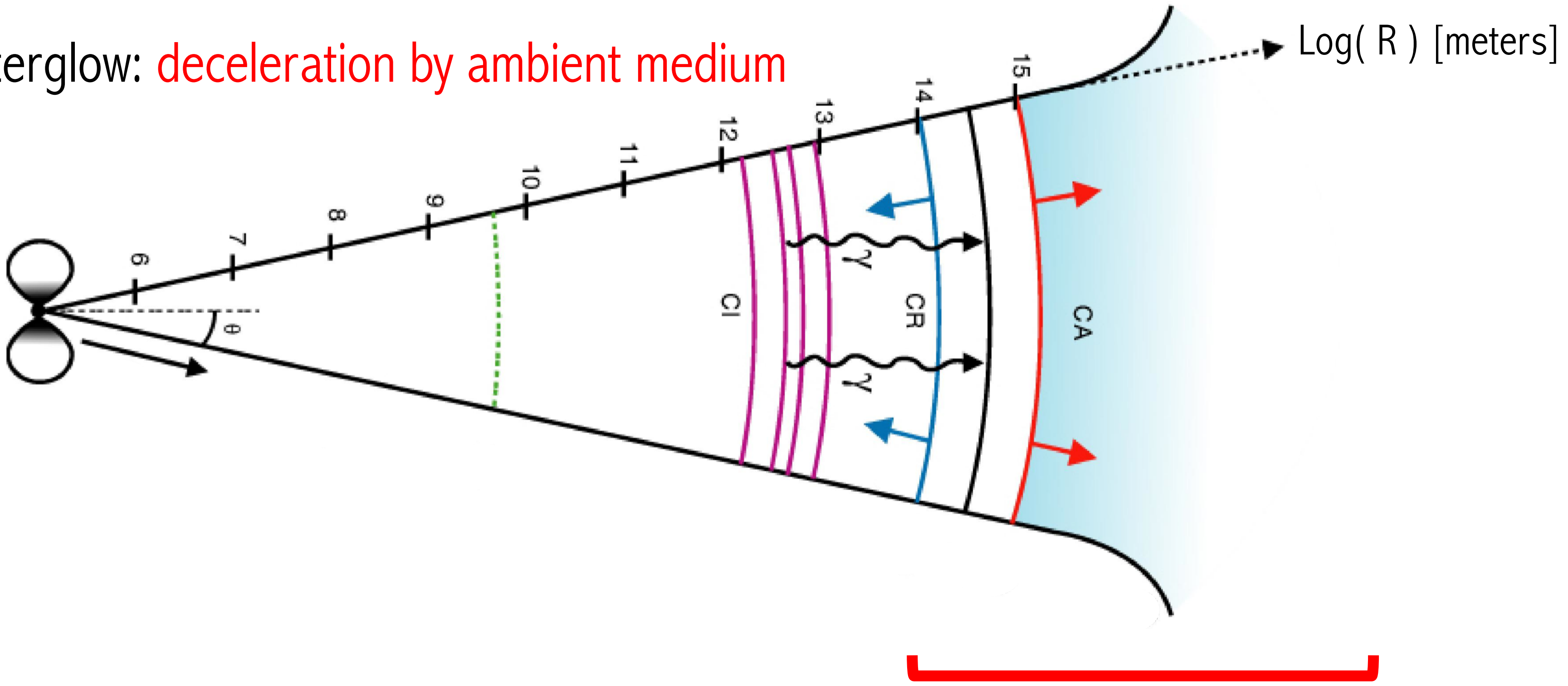
THEORY

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta (photosphere? Shocks? Reconnection ?)

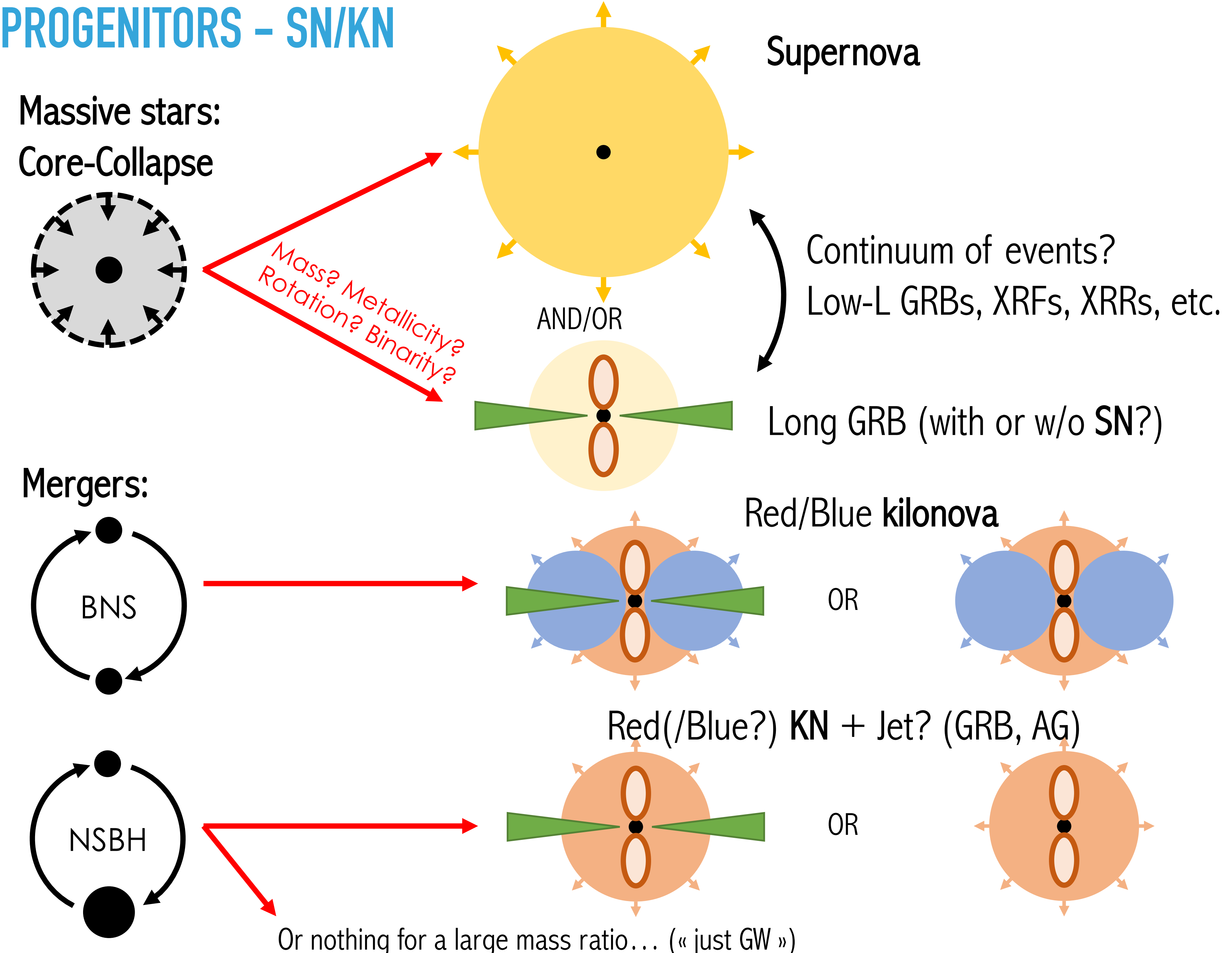


THEORY

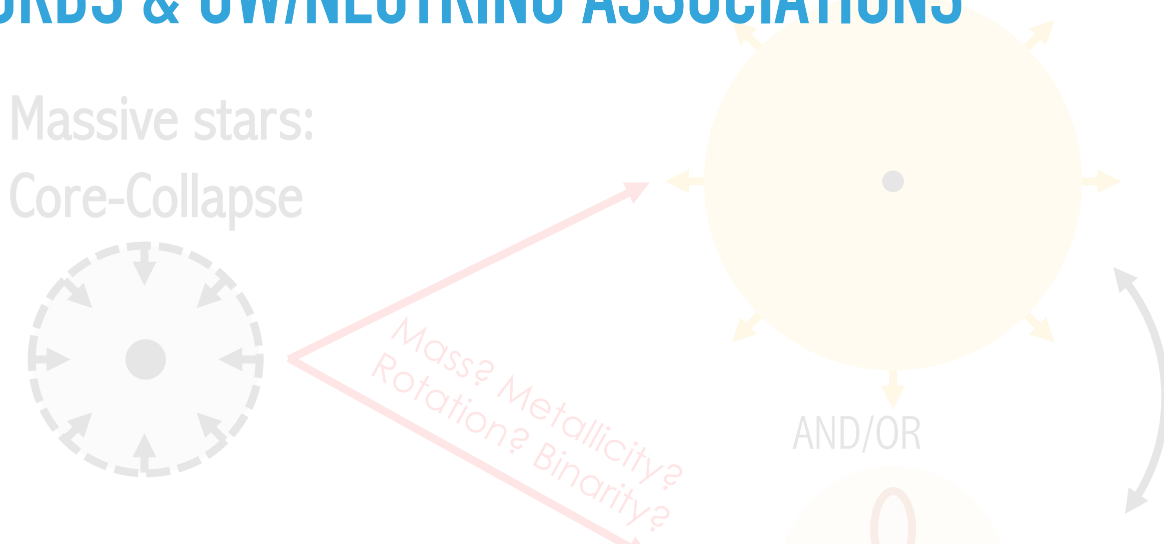
- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium



PROGENITORS – SN/KN

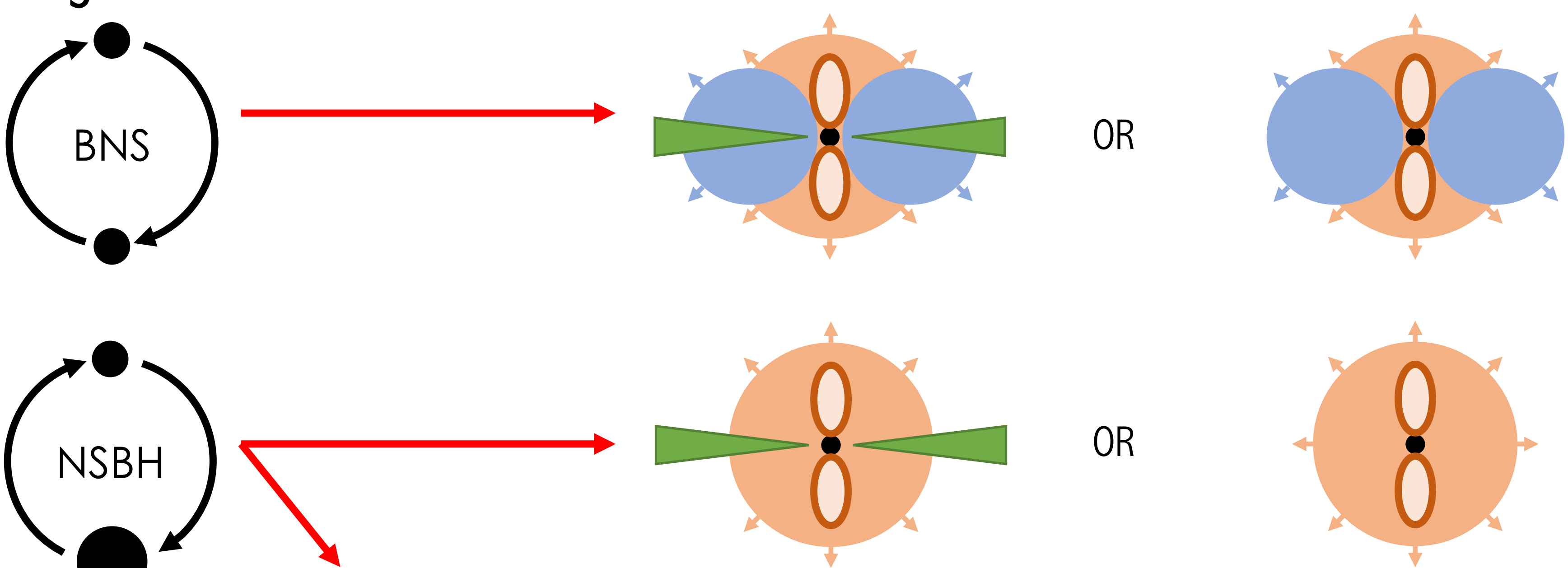


GRBS & GW/NEUTRINO ASSOCIATIONS



Best case for GRB-GW associations (already 1 MMA event: 170817 = GW+SGRB+AG+KN)

Mergers:

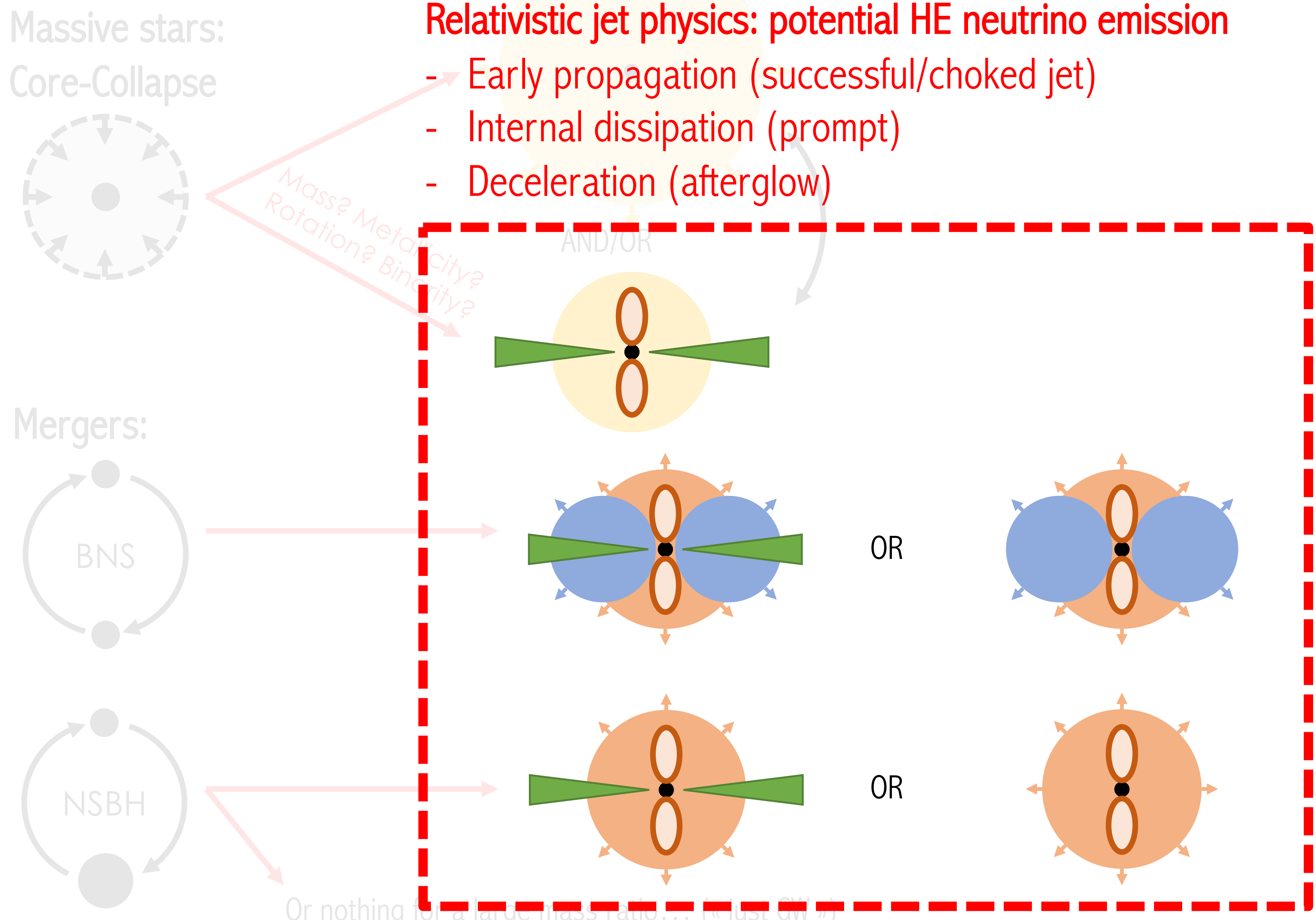


Or nothing for a large mass ratio… (« just GW »)

GRBS & GW/NEUTRINO ASSOCIATIONS

Relativistic jet physics: potential HE neutrino emission

- Early propagation (successful/choked jet)
- Internal dissipation (prompt)
- Deceleration (afterglow)



GRBS AS NEUTRINO SOURCES

GRBS: NEUTRINO EMISSION?

Relativistic jet physics: potential HE neutrino emission

- Early propagation (successful/choked jet)
- Internal dissipation (prompt)
- Deceleration (afterglow)

Proton acceleration?

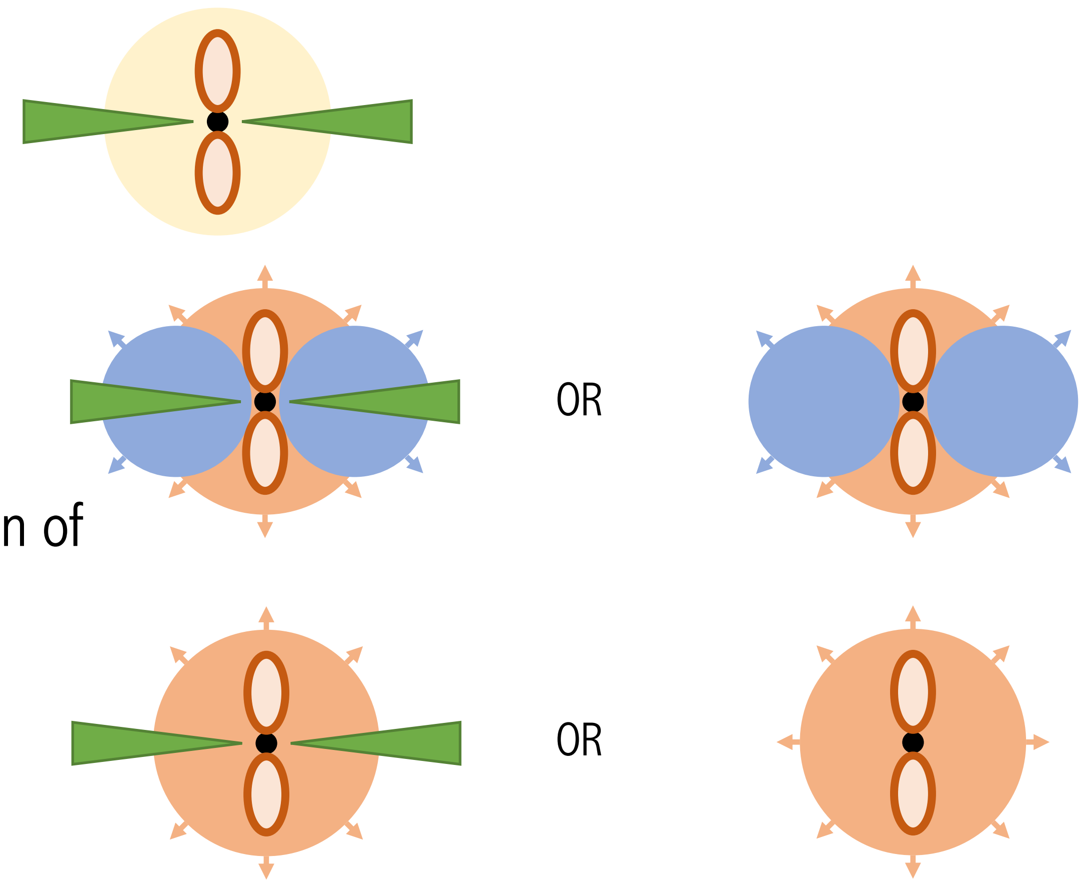
- many possible sites
- no direct evidence from em emission

+ photo-hadronic interactions

.$10^{14\text{-}15}$ eV neutrinos?

.does not require the production of UHECRs.

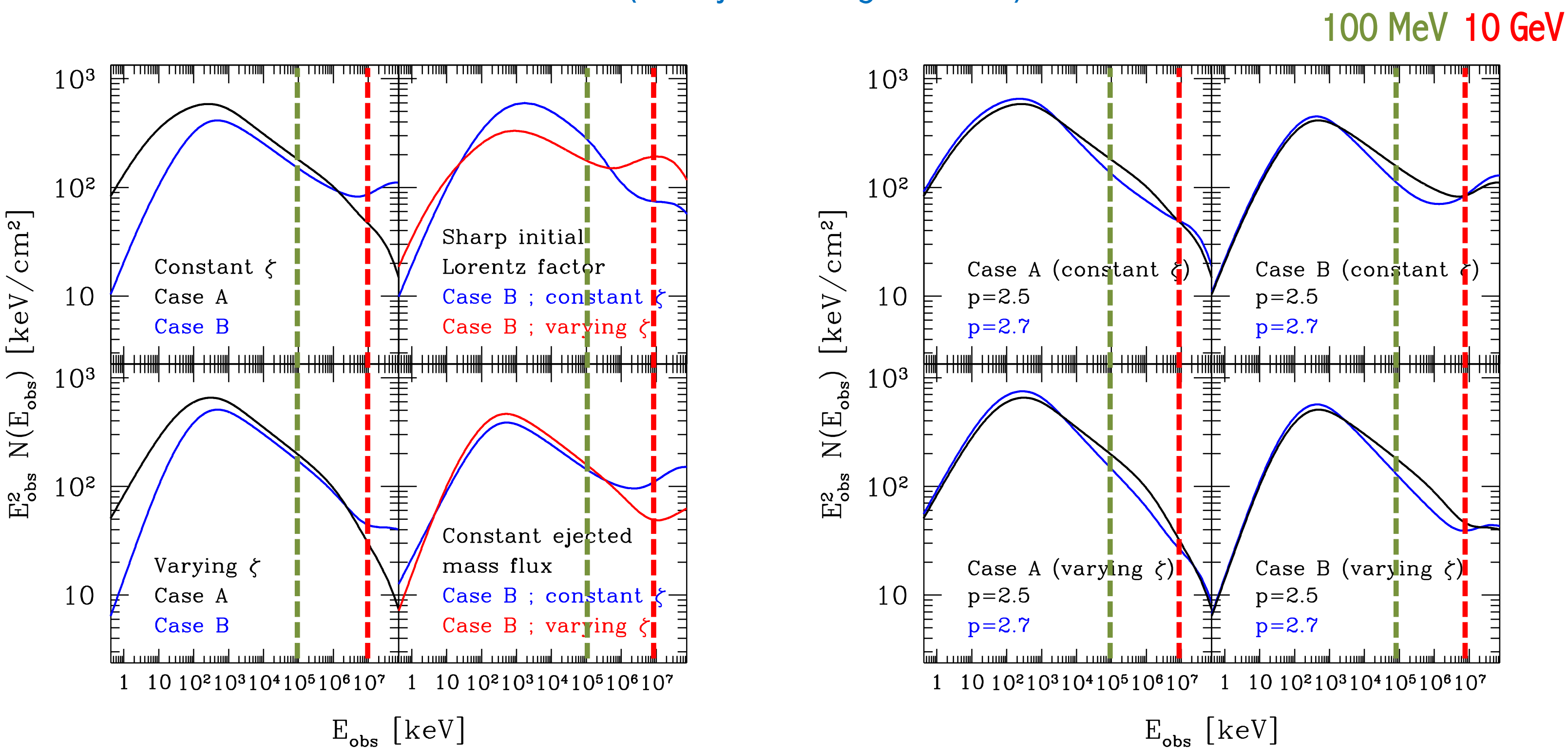
(other processes?
neutron decay?
pp collisions in external medium?)



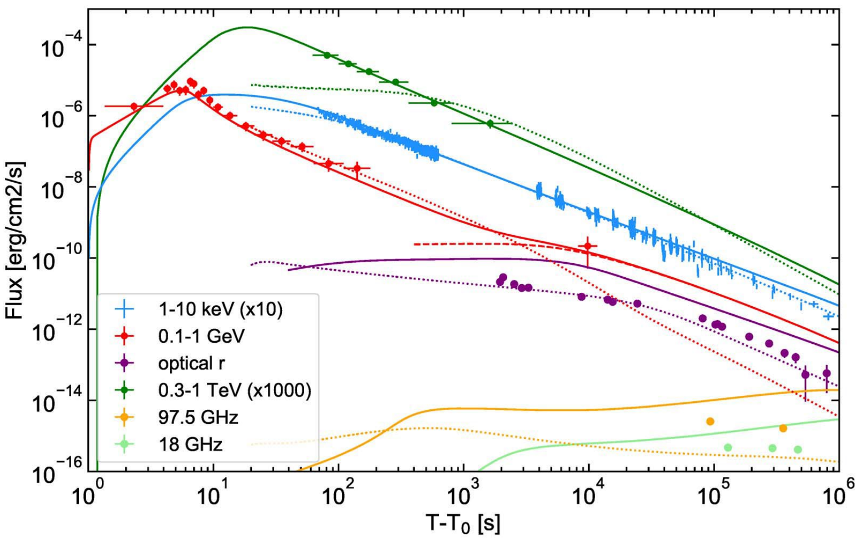
CONSTRAINTS ON PROTON ACCELERATION?

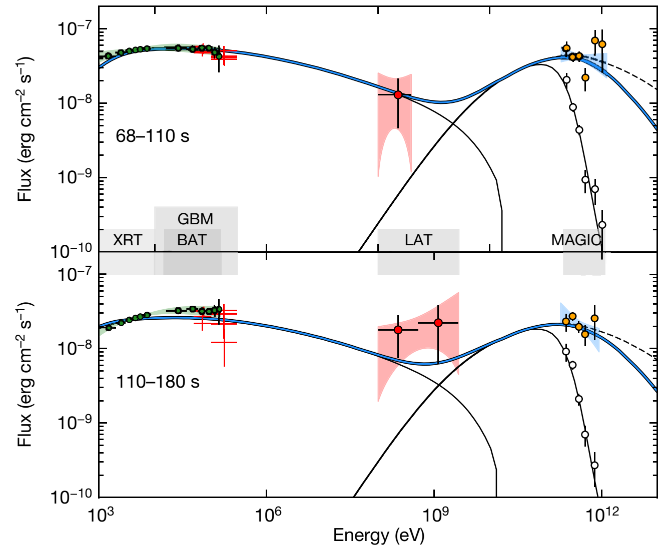
- **Emission from GRBs is usually assumed to be produced by non-thermal <u>electrons</u>.**
- Dissipation mechanism/radiation process still uncertain: electron acceleration poorly constrained.
- **Requires broad-band spectra including VHE gamma-rays.**
- **Specific proton signatures at VHE?**

Example: predictions for the internal shock model (Bosnjak & Daigne 2014)

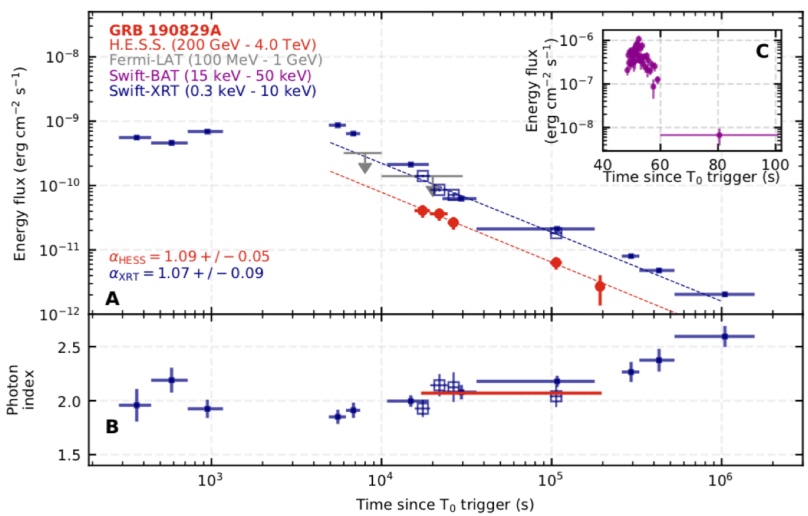


RECENT DETECTIONS OF GRB AFTERGLOWS AT VHE, SOME DIVERSITY





GRB 190114C (MAGIC) @ z=0.14 (MAGIC collab. 2019a,b)



GRB 190829A (HESS) @z = 0.0785 (360 Mpc)
(HESS collab. 2021)

Local low-luminosity GRB!

- CTA: rapid reaction (~30 s) – prompt VHE emission?

NEUTRINO BACKGROUND: CONSTRAINTS?

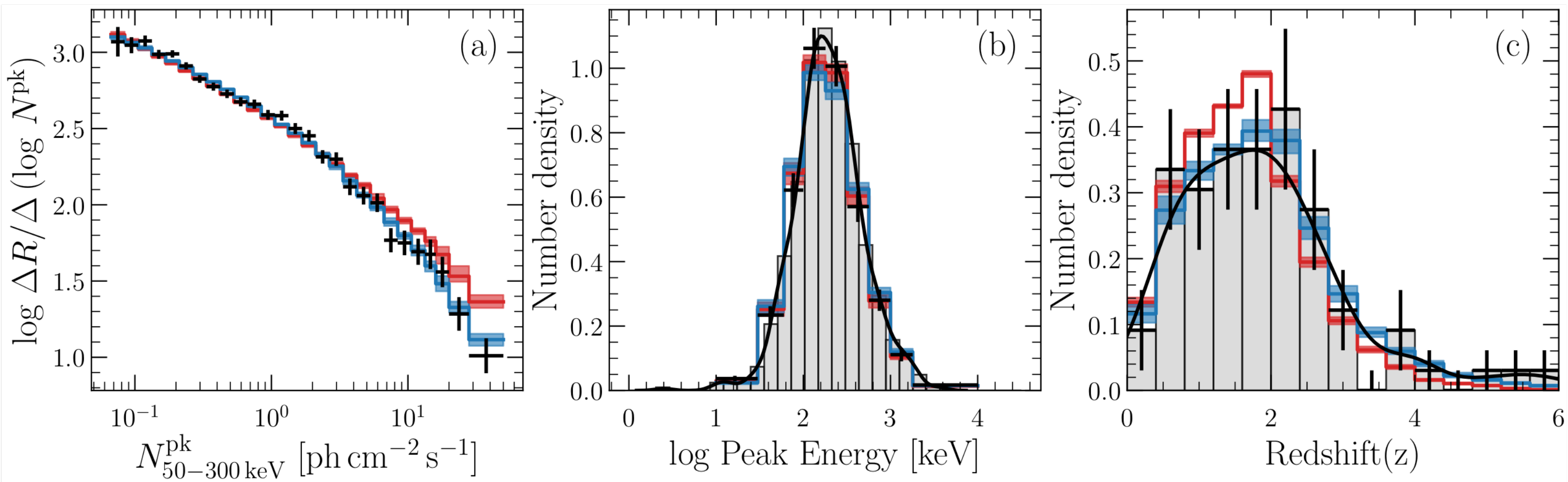
- HE Neutrino background: which contribution from GRBs?
  Initial constraint derived by IceCube collab. Max ~1%

- Several uncertainties should be included when deriving such a constraint:
  - emission from a given burst
  - intrinsic population (diversity)
  - best constrained population = bright long GRBs.

INTRINSIC POPULATION OF BRIGHT LONG GRBS

- Pop. model based on BATSE+Fermi/GBM+Swift BAT6 sample (Palmerio & Daigne, 2021)
- Parameters: luminosity function + comoving rate + spectral parameters.
- Best fit models: evolution with redshift is needed.
- Impossible to distinguish between luminosity/rate evolution.

Peak Flux (BATSE) **Peak Energy (Fermi/GBM)** **Redshift (Swift eBAT6)**



Red: model without evolution

Blue: model with evolution (here: comoving rate)

(Palmerio & Daigne 2021)

INTRINSIC POPULATION OF BRIGHT LONG GRBS

- LGRB comoving rate (top) and LGRB production efficiency by massive stars (bottom)

  Dark Blue: no L evolution, strong evolution of the GRB production efficiency by stars

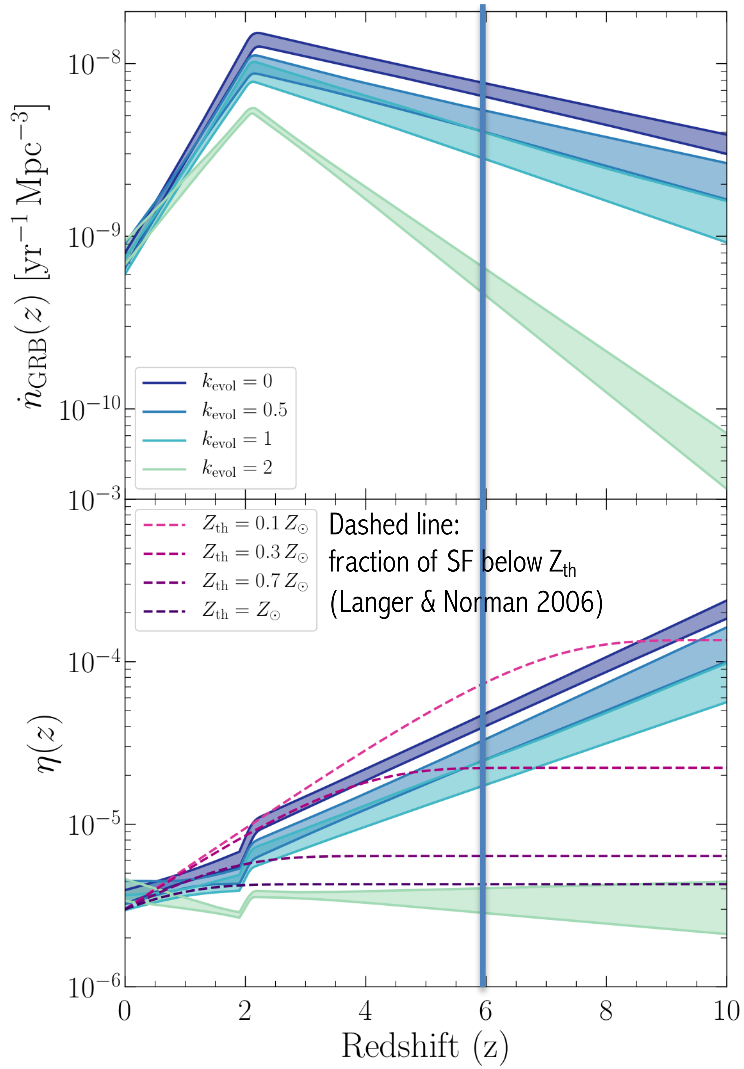
  Light green: strong L evolution ($(1+z)^2$)

  Other colors: mixed scenarios

  (equally good fits to the observed sample)

- Other populations (e.g. low-L GRBs): not constrained!

Very uncertain

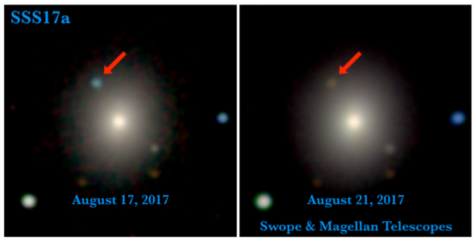


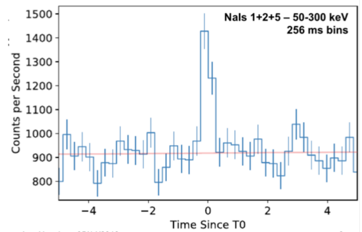
(Palmerio & Daigne 2021)

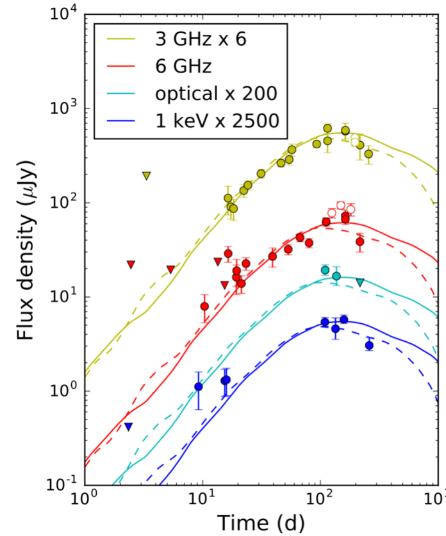
PROSPECTS FOR MMA OBSERVATIONS OF BNS MERGERS (GW+KN+SGRB+AG)

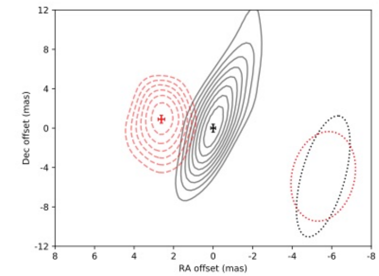
170817

- KN (red/blue) + SGRB + AG (with VLBI)









- A unique science (post merger physics, jet physics, r process, NS EOS, cosmology: H0, fundamental physics, etc.)
- But a very lucky observation
- Prospects for more MM associations?

POPULATION MODEL

- Local universe: uniform rate of BNS mergers
  GW detection: depends on distance + viewing angle
- KN model calibrated with 170817
  Detection: expected weak anisotropy for color/peak magnitude
  Diversity: blue component may not be always present
- AG model calibrated with 170817+distribution of cosmic SGRBs
  Strong anisotropy (relativistic structured jet)
- SGRB: on-axis = always detectable in the local universe
  off-axis : uncertain, probably very weak
- **Simulate a large population**
  Estimate which events (GW/KN/AG/SGRB) are <u>detectable</u>
  (i.e. > threshold for a given instrumental configuration)

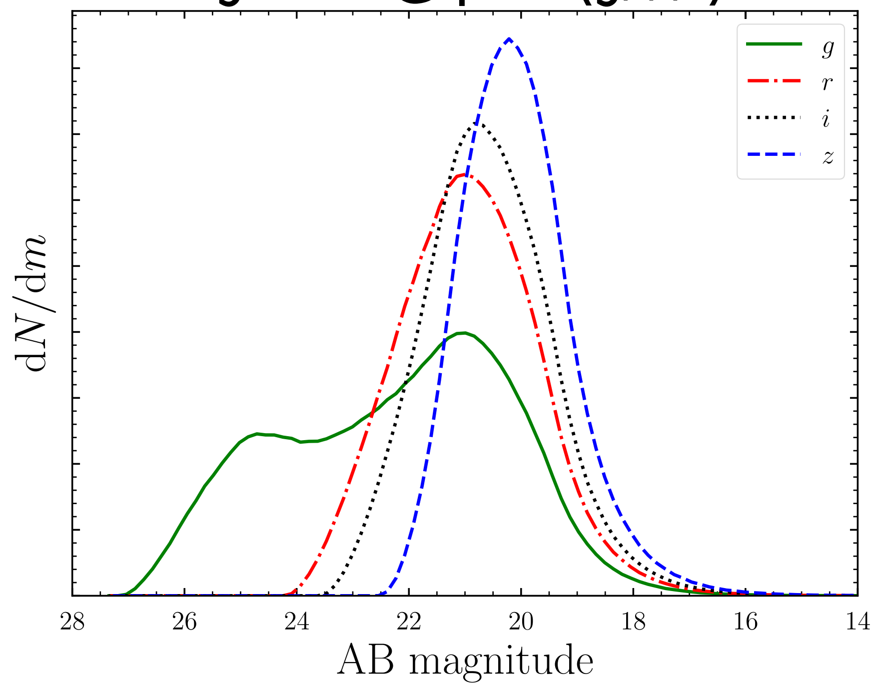
DETECTABLE OR DETECTED?

- GW: large error boxes
  (will improve when more instruments will be in the network: O5?)
- **KN search is very difficult (large error box, many optical transients, host gal., etc.)**
  Efficiency of the search?
- Afterglow: assuming that the KN is detected, easier search (position known)
  Without the KN: extremely difficult.

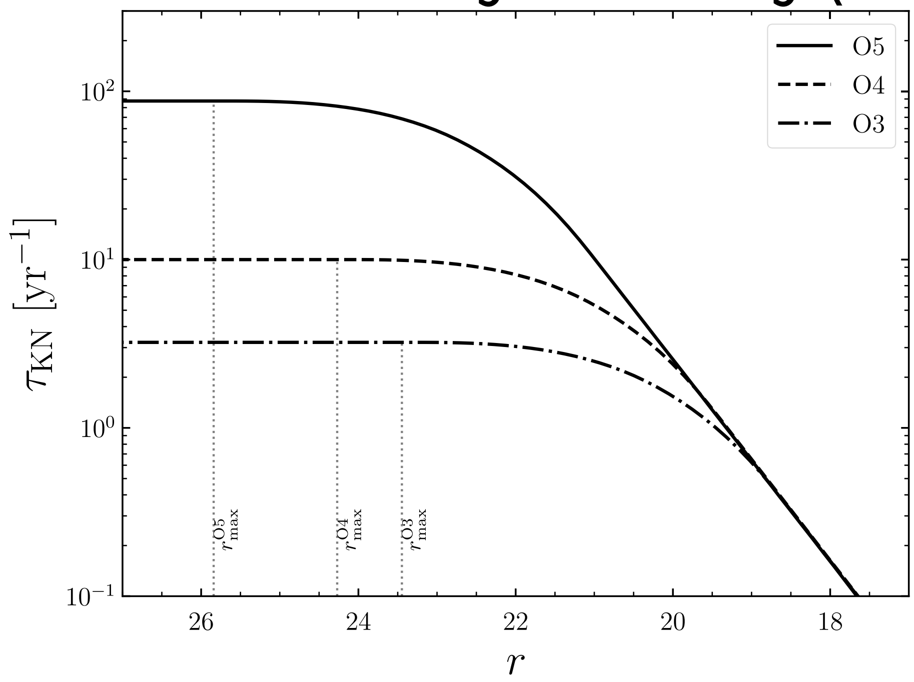
KILONOVA: MAGNITUDE

GW-detected BNS (O4):

KN Magnitude @ peak (g,r,i,z)



KN rate above a given limit mag. (rlim)



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

Mochkovitch, Daigne, Duque & Zitouni, 2021

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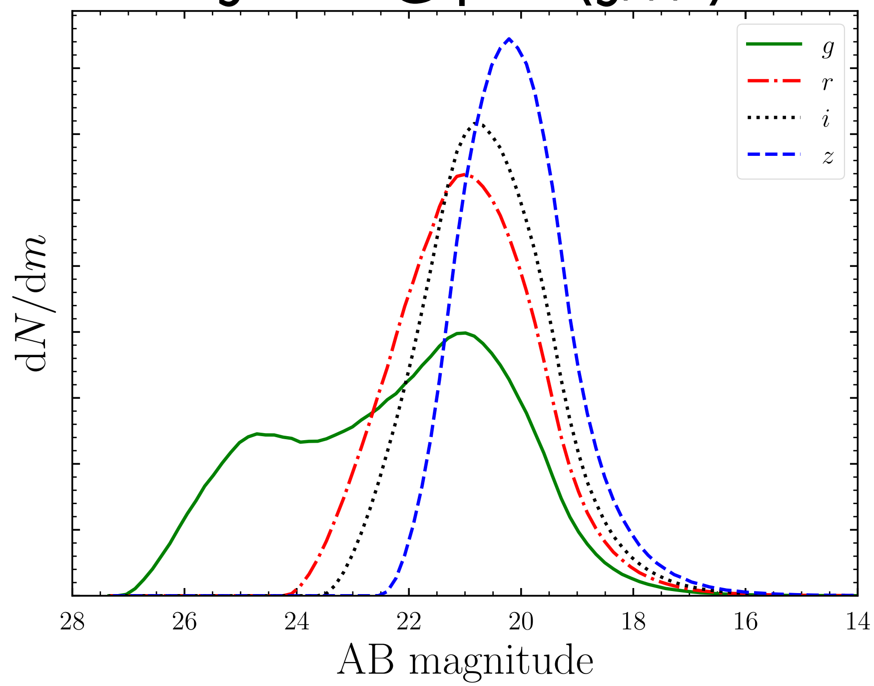

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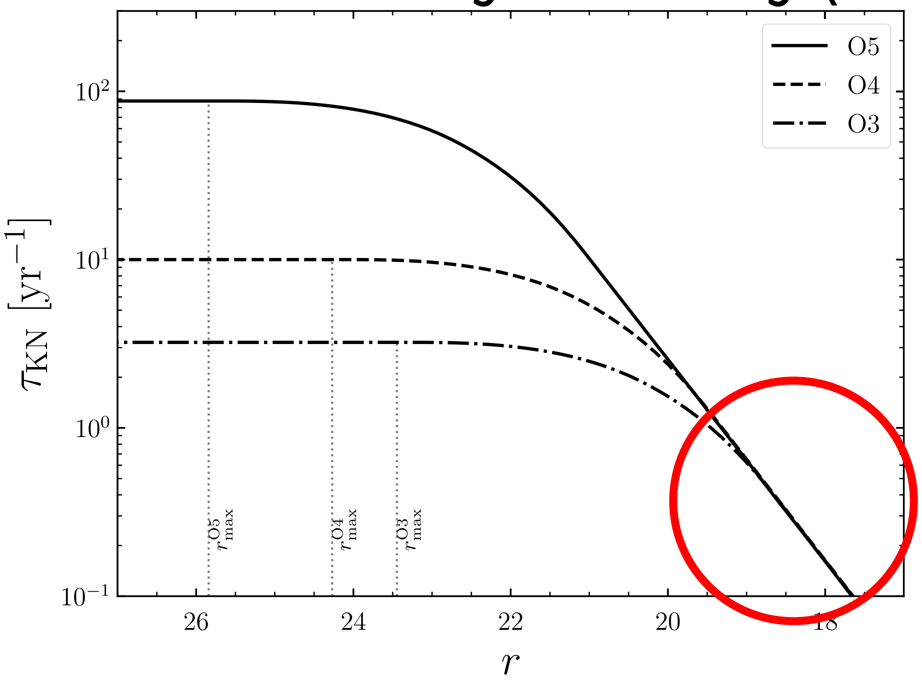

« Bright » KN r<19

Rate does not evolve beyond O3

Mochkovitch, Daigne, Duque & Zitouni, 2021

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

KILONOVA: MAGNITUDE

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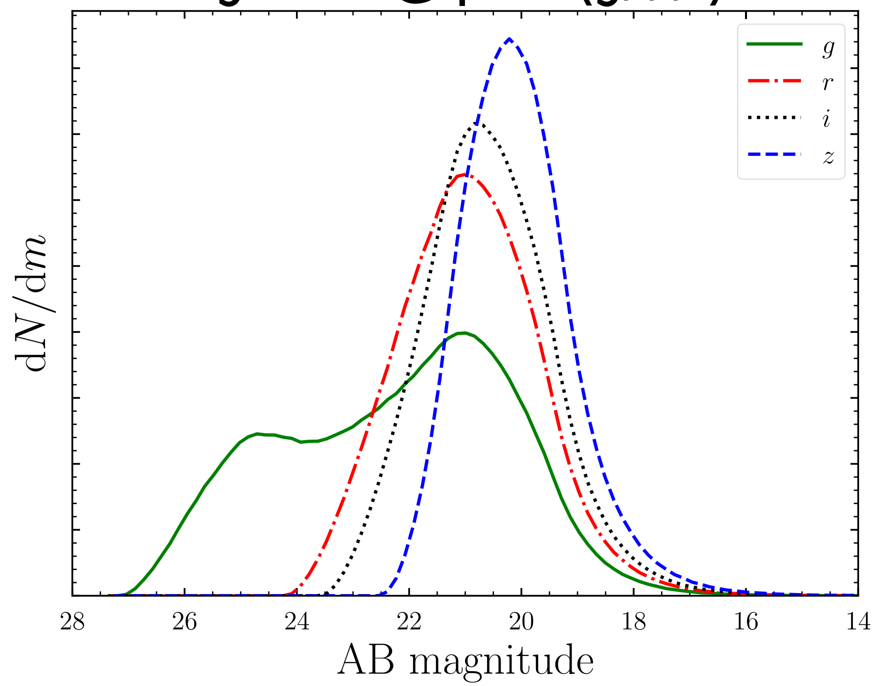
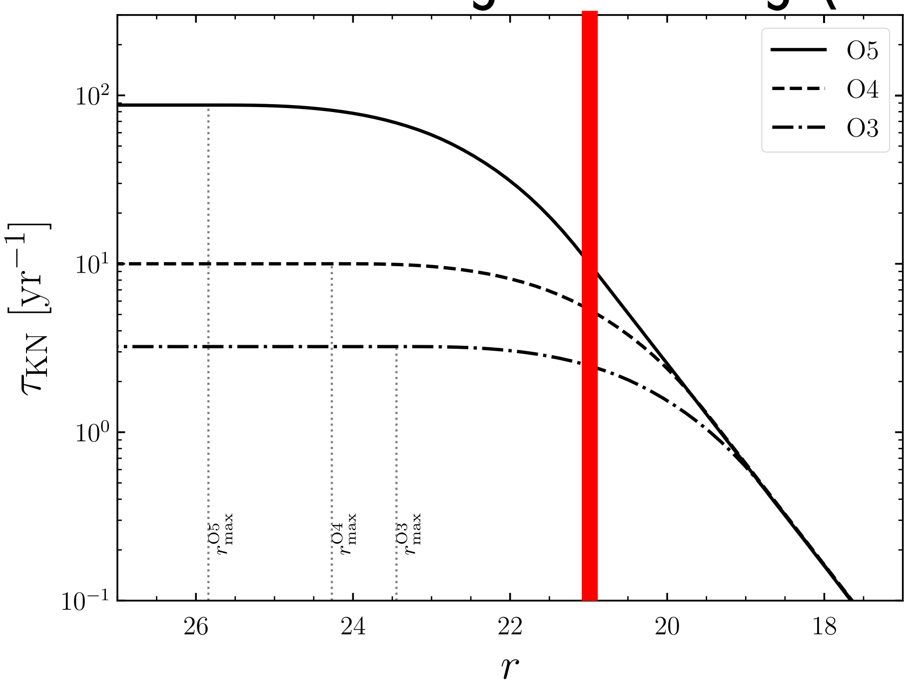


KN rate above a given limit mag. (rlim)



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

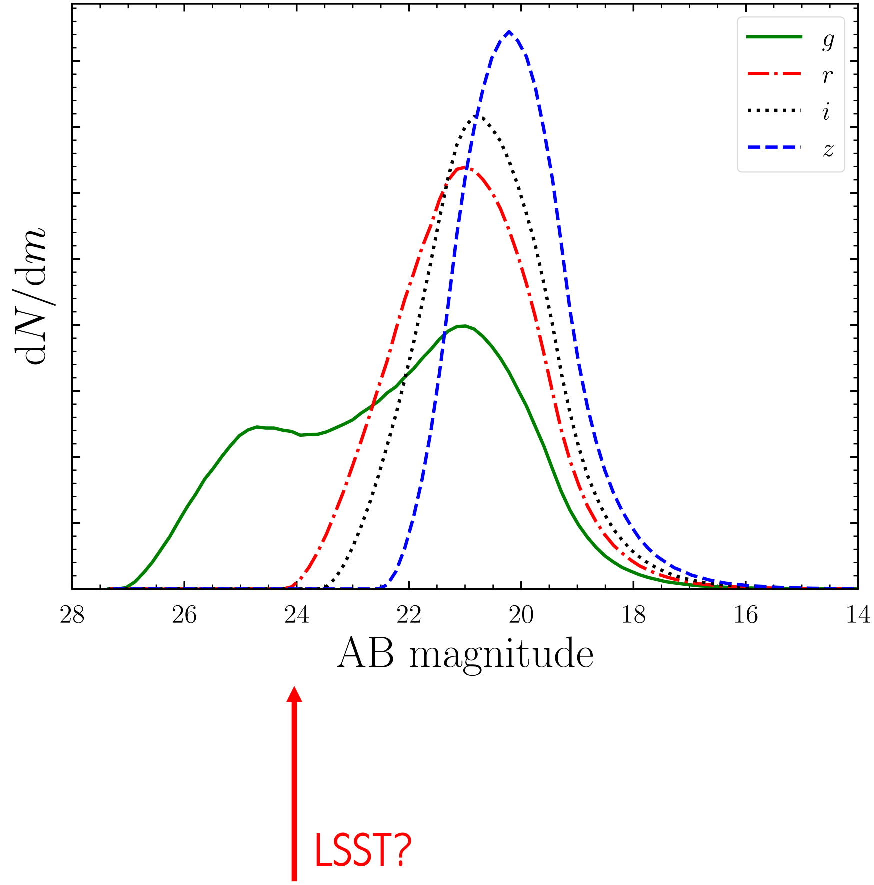
Detectable → Detected: strategy? (ZTF+LSST/Vera Rubin+follow-up telescopes…)

Mochkovitch, Daigne, Duque & Zitouni, 2021

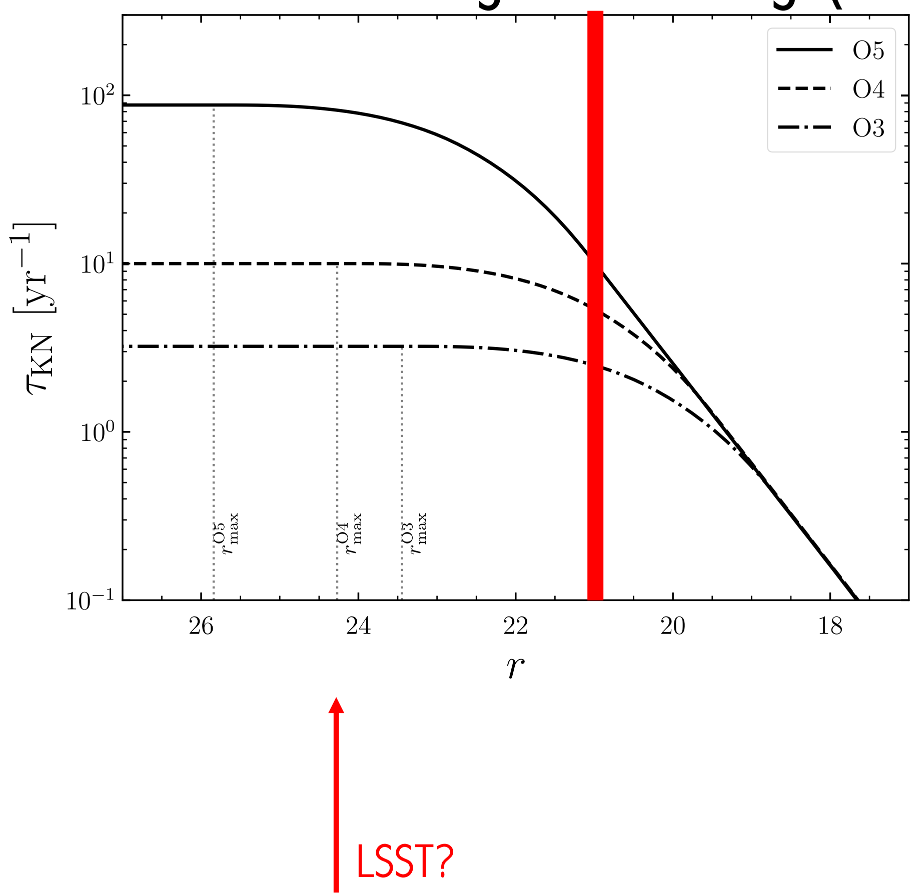
KILONOVA: MAGNITUDE

GW-detected BNS (O4):

KN Magnitude @ peak (g,r,i,z)



KN rate above a given limit mag. (rlim)



Mochkovitch, Daigne, Duque & Zitouni, 2021

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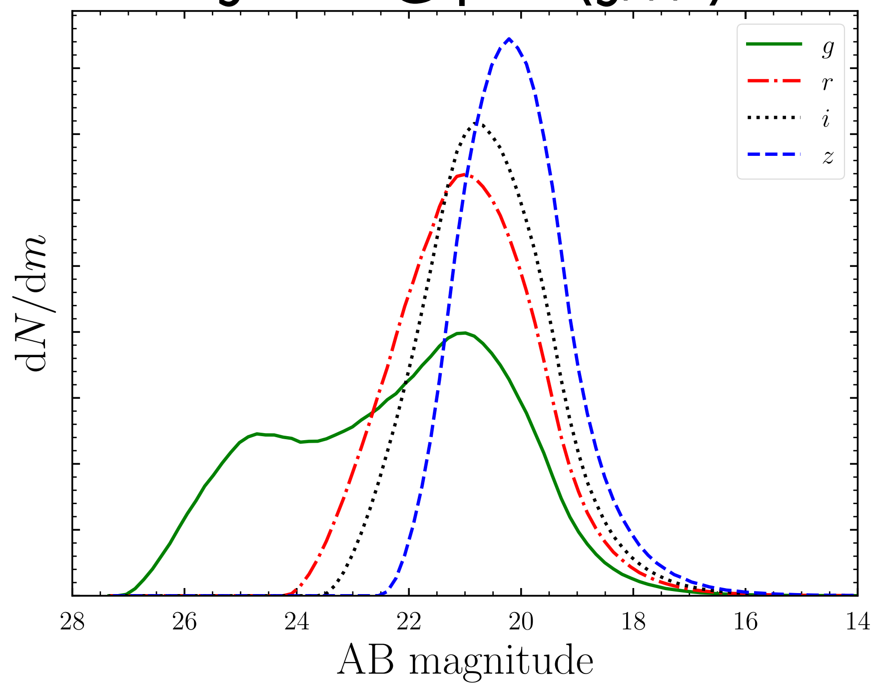

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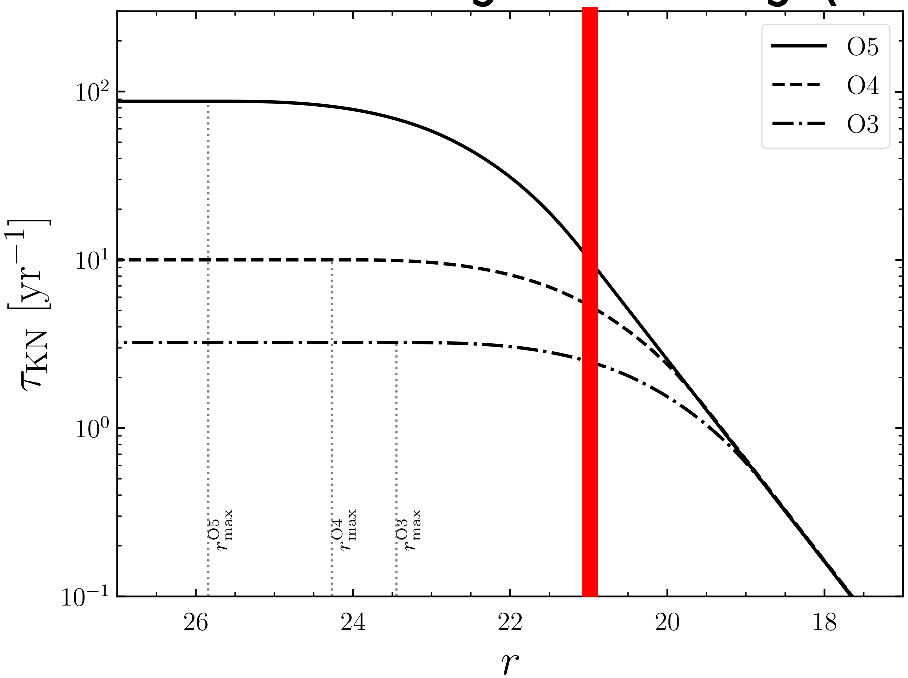


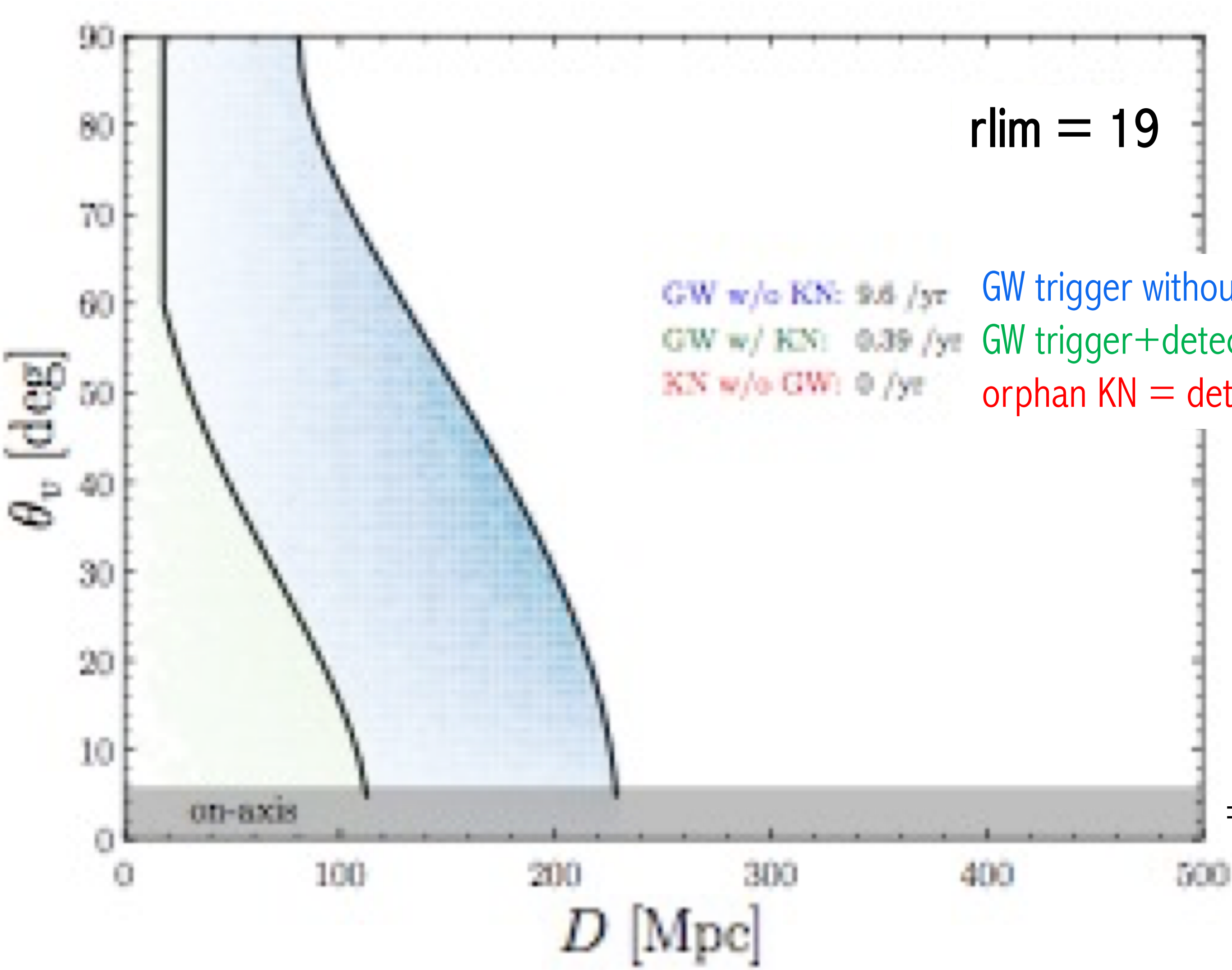
Vera Rubin-LSST: field of view and limit magnitude are especially well adapted (even beyond O5 for 3rd generation GW detectors like the Einstein Telescope)

Major issue: observation cadence in standard survey mode.
Different mode for GW alerts?

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE–VIEWING ANGLE PLANE

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



rlim = 19

No orphan KN

KN+GW= rare

GW trigger without a detectable KN

GW trigger+detectable KN

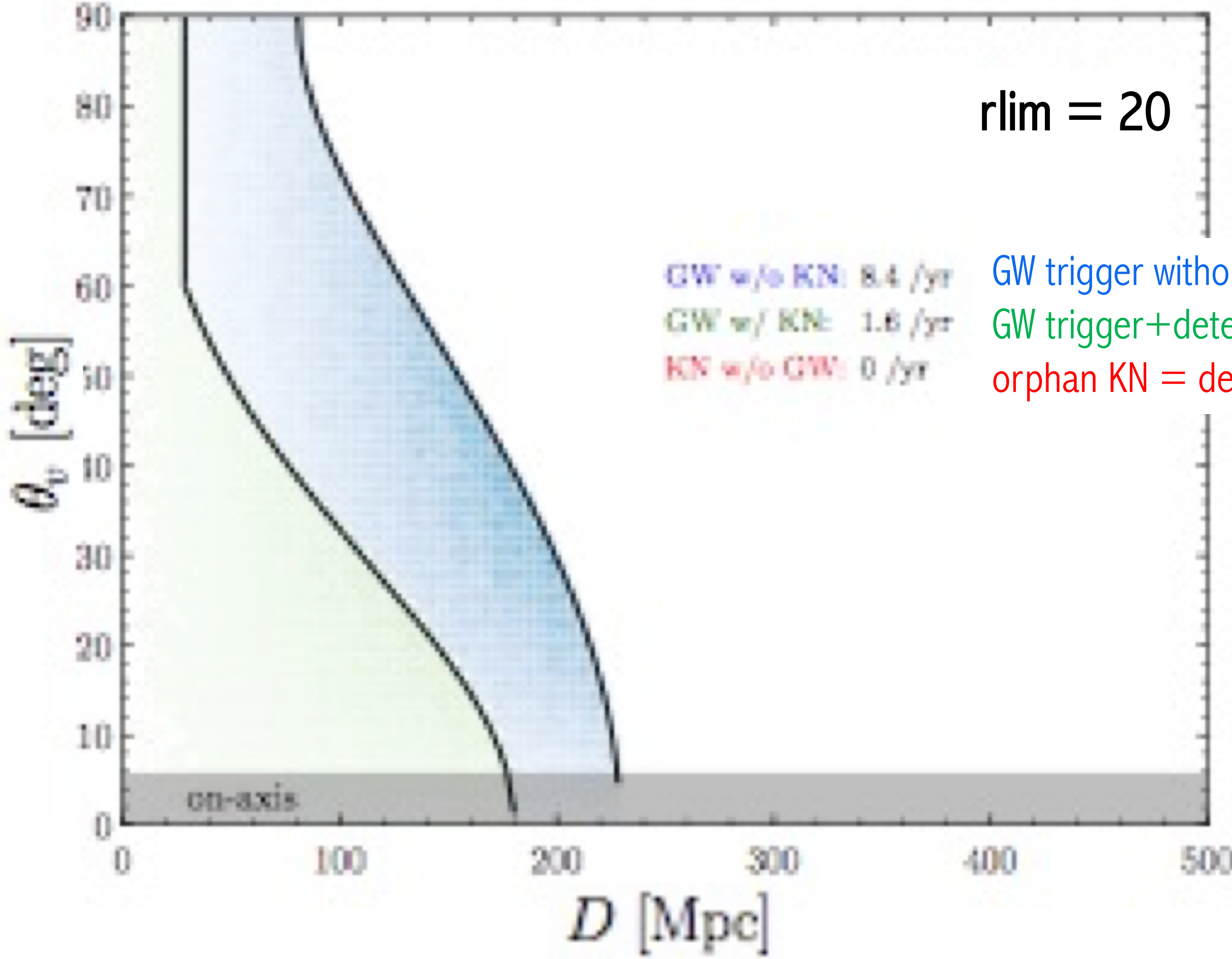
orphan KN = detectable KN w/o a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE-VIEWING ANGLE PLANE

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



rlim = 20

No orphan KN

KN+GW= remain rare

GW trigger without a detectable KN

GW trigger+detectable KN

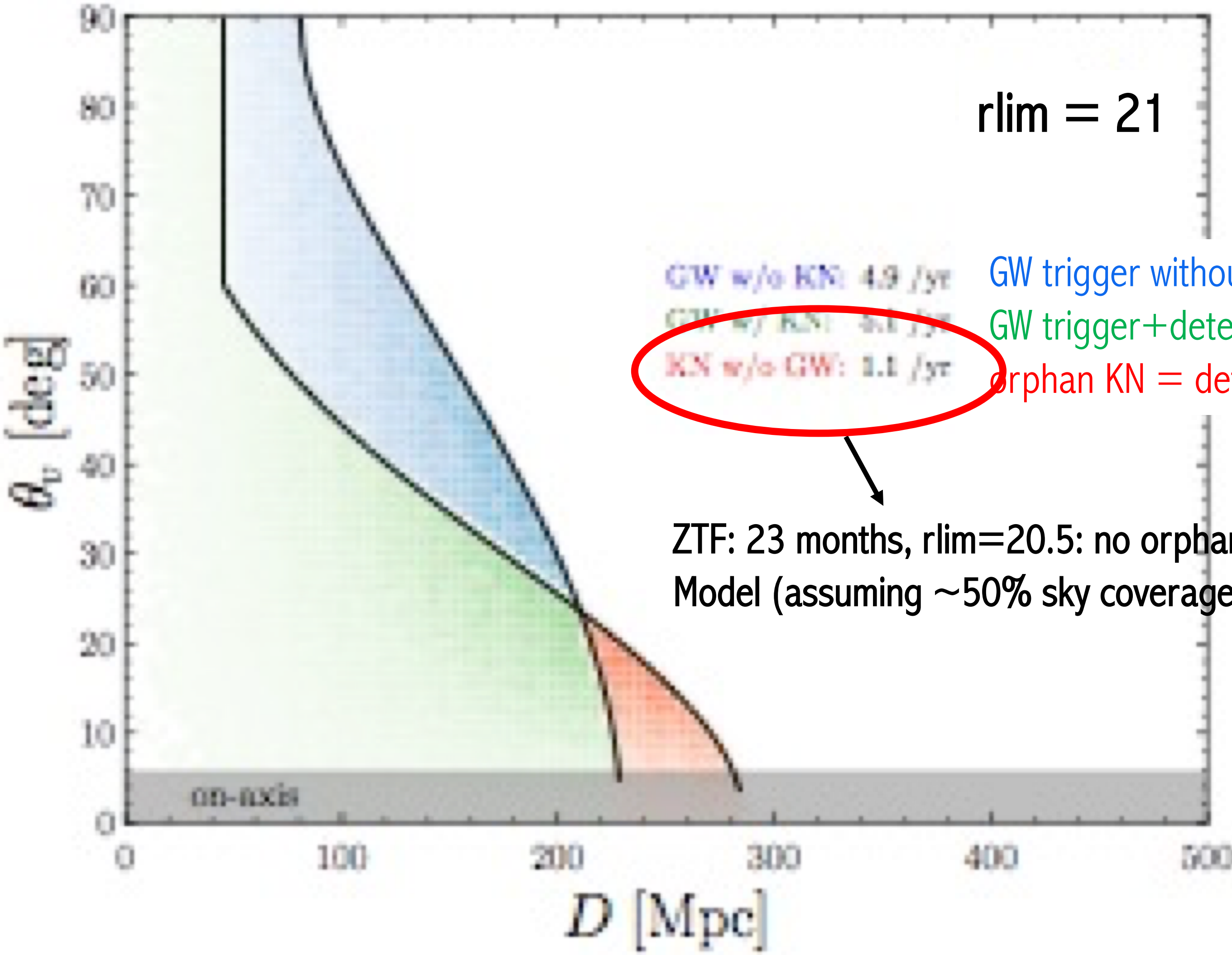
orphan KN = detectable KN w/o a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE-VIEWING ANGLE PLANE

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



rlim = 21

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)

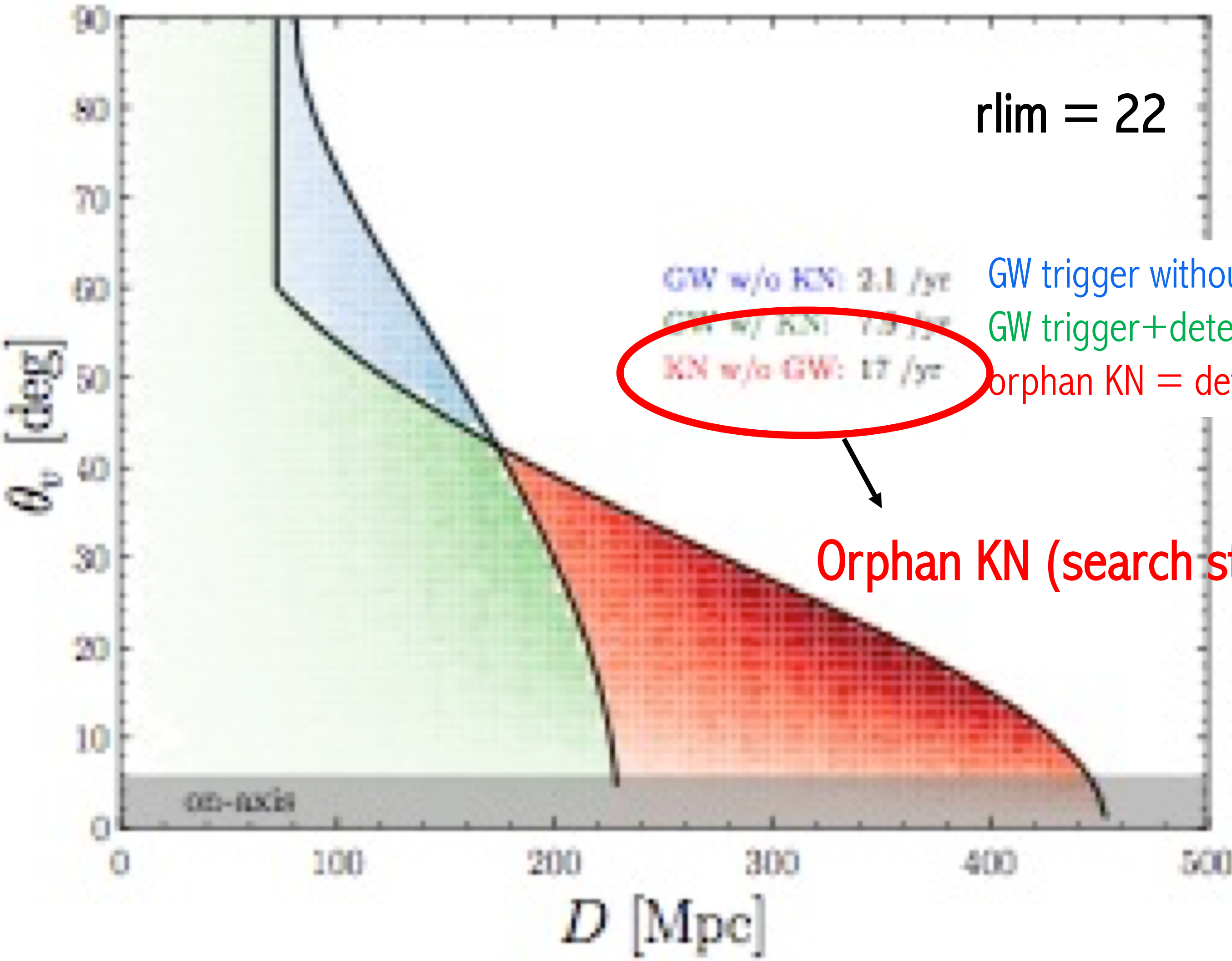
Model (assuming ~50% sky coverage): 0.4-2.6 orphan KNae

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE-VIEWING ANGLE PLANE

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

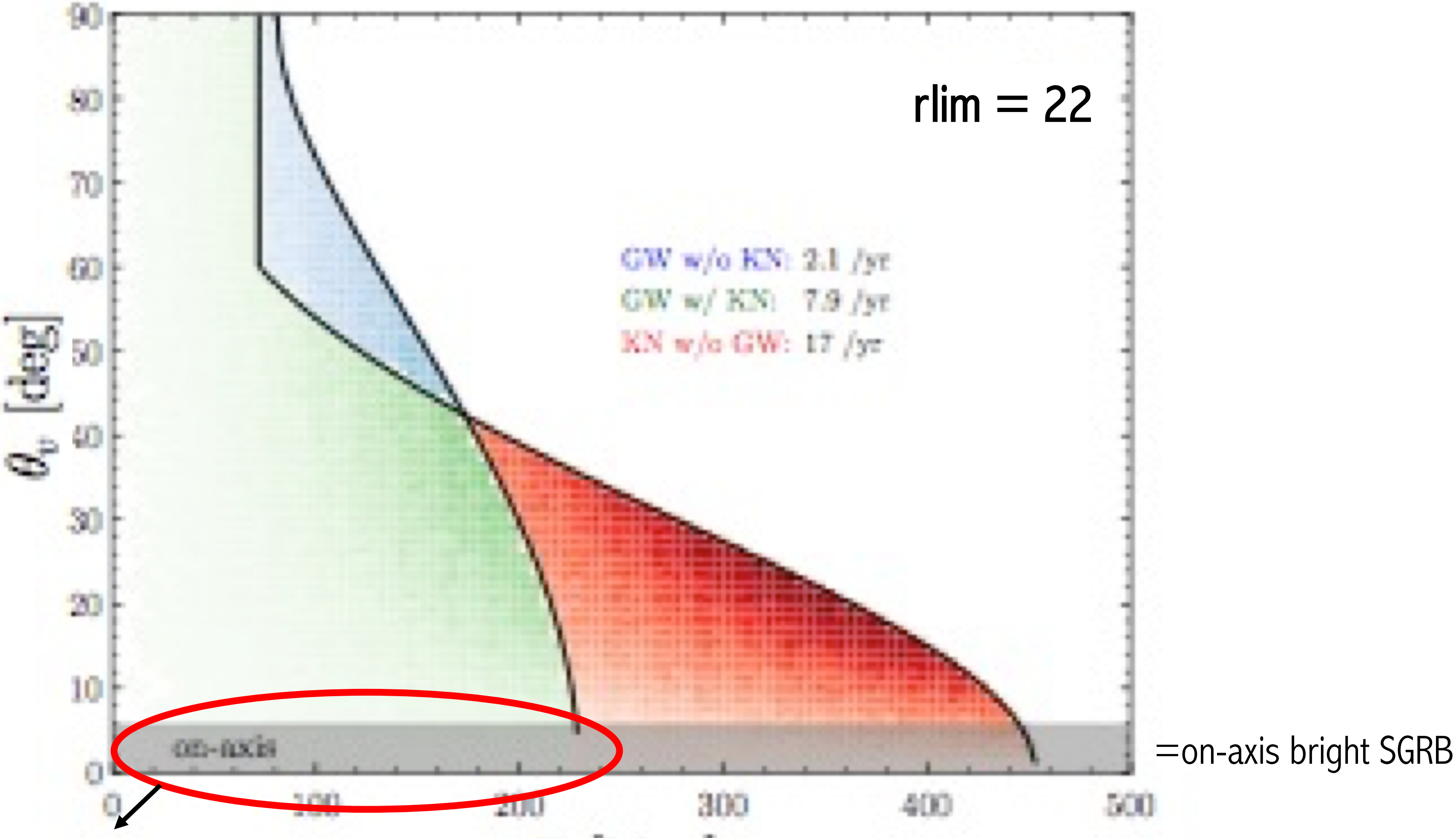
Orphan KN (search strategy for LSST?)

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE–VIEWING ANGLE PLANE

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

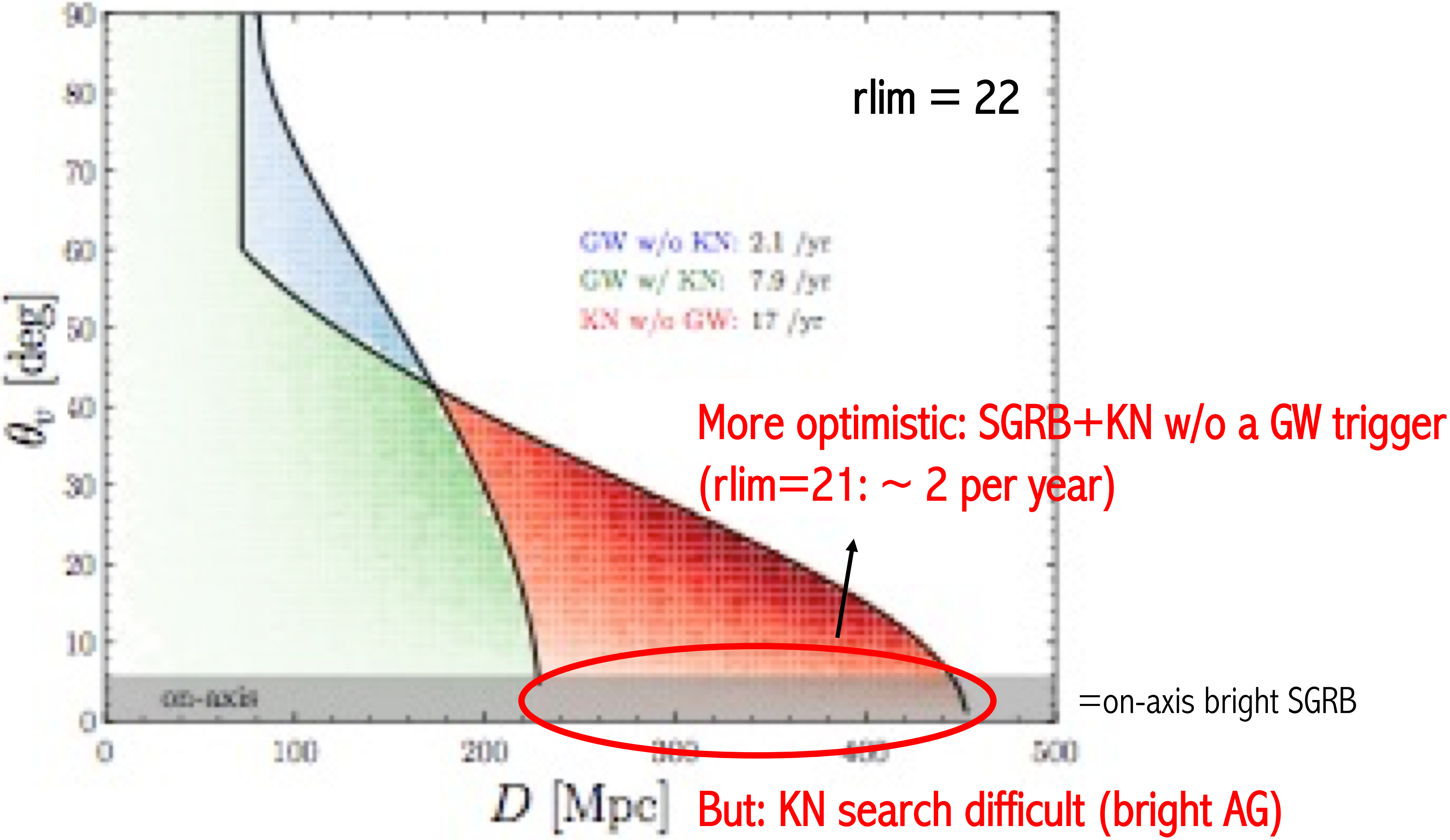


O4: GW+bright SGRB
are very rare! (1 very 5-20 years in whole sky) – O5? ET?

Mochkovitch, Daigne, Duque & Zitouni, 2021

GW/KILONOVA/SGRB: DISTANCE–VIEWING ANGLE PLANE

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

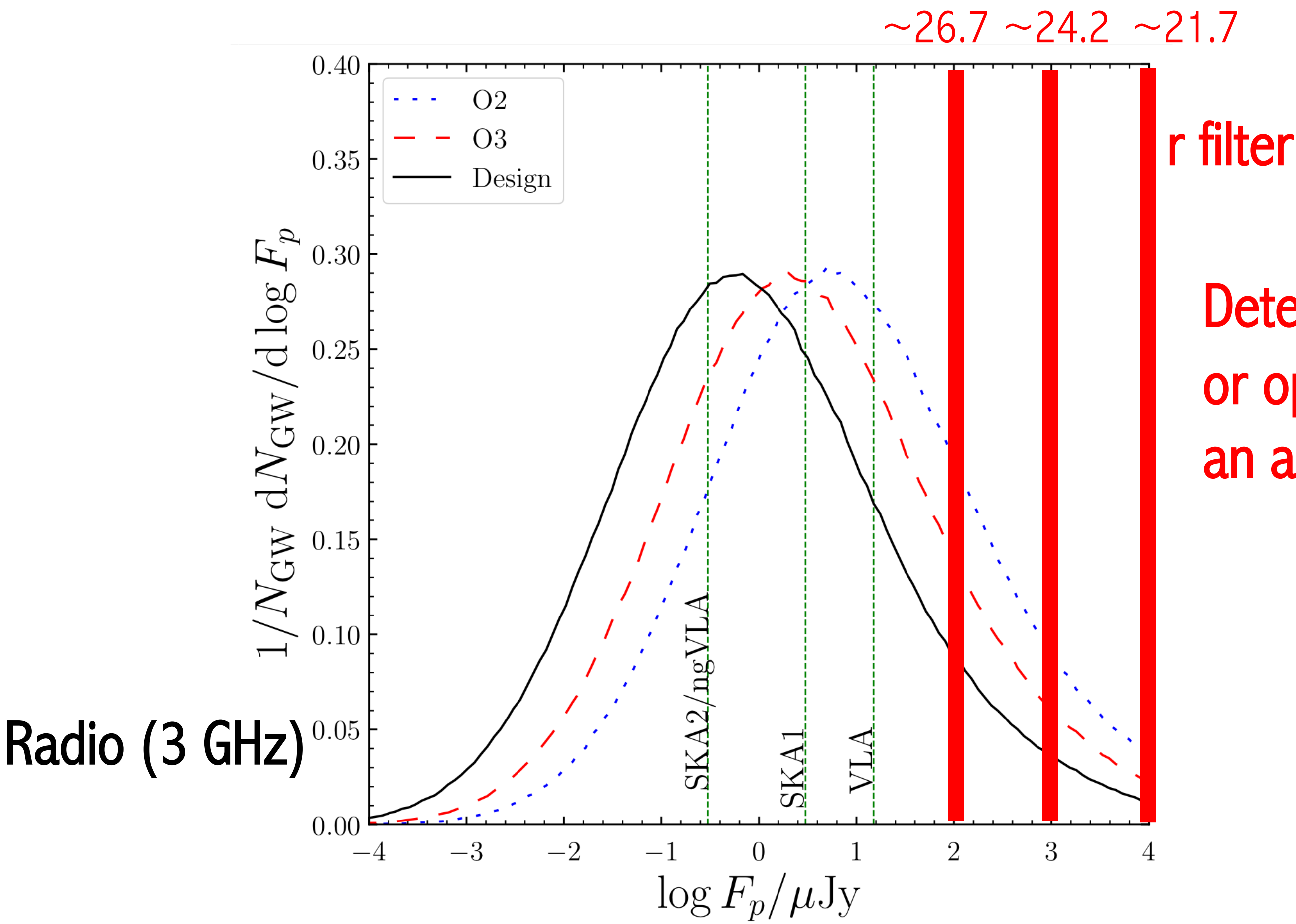


Several candidates (e.g. GRB130603B, Tanvir et al. 13; GRB050709, Lin et al. 16)

Mochkovitch, Daigne, Duque & Zitouni, 2021

AFTERGLOW: PEAK FLUX

Peak flux for afterglows following a GW trigger



Detecting the AG in radio or optical is difficult without an accurate localization.

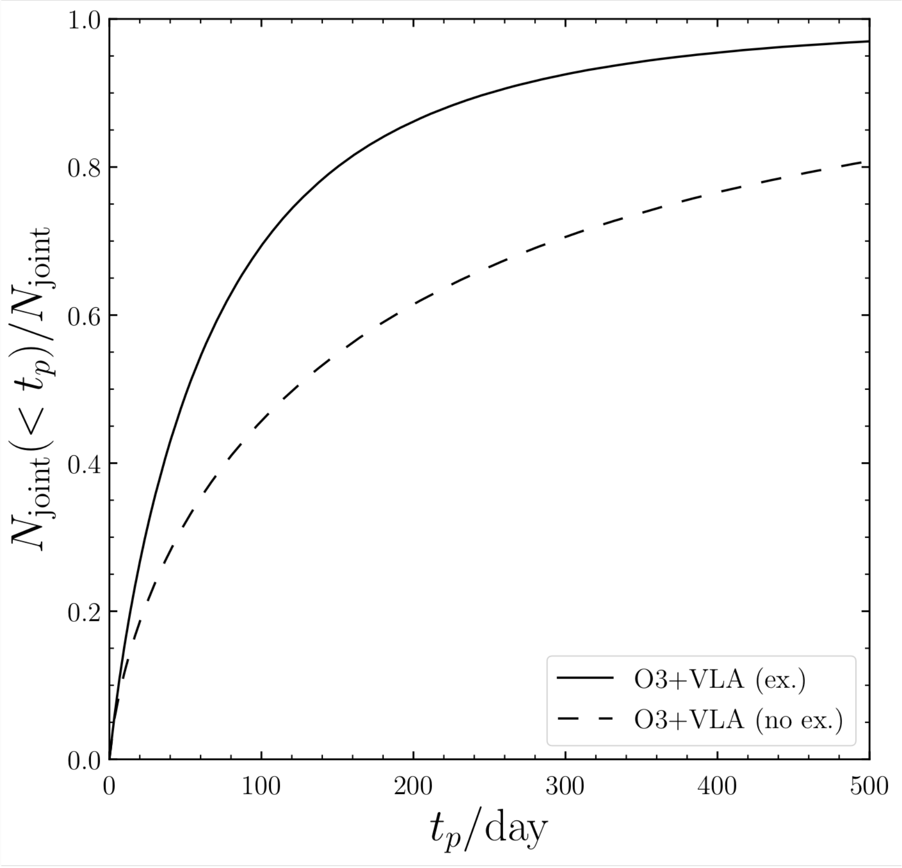
Still: a fraction of AG are brighter than m(r)~24 (LSST) for O4 and beyond.

To investigate: predictions for orphan afterglows (on going study by JG Ducoin)

Duque, Daigne & Mochkovitch, 2019)

AFTERGLOW: PEAK TIME

Peak time: can be large!



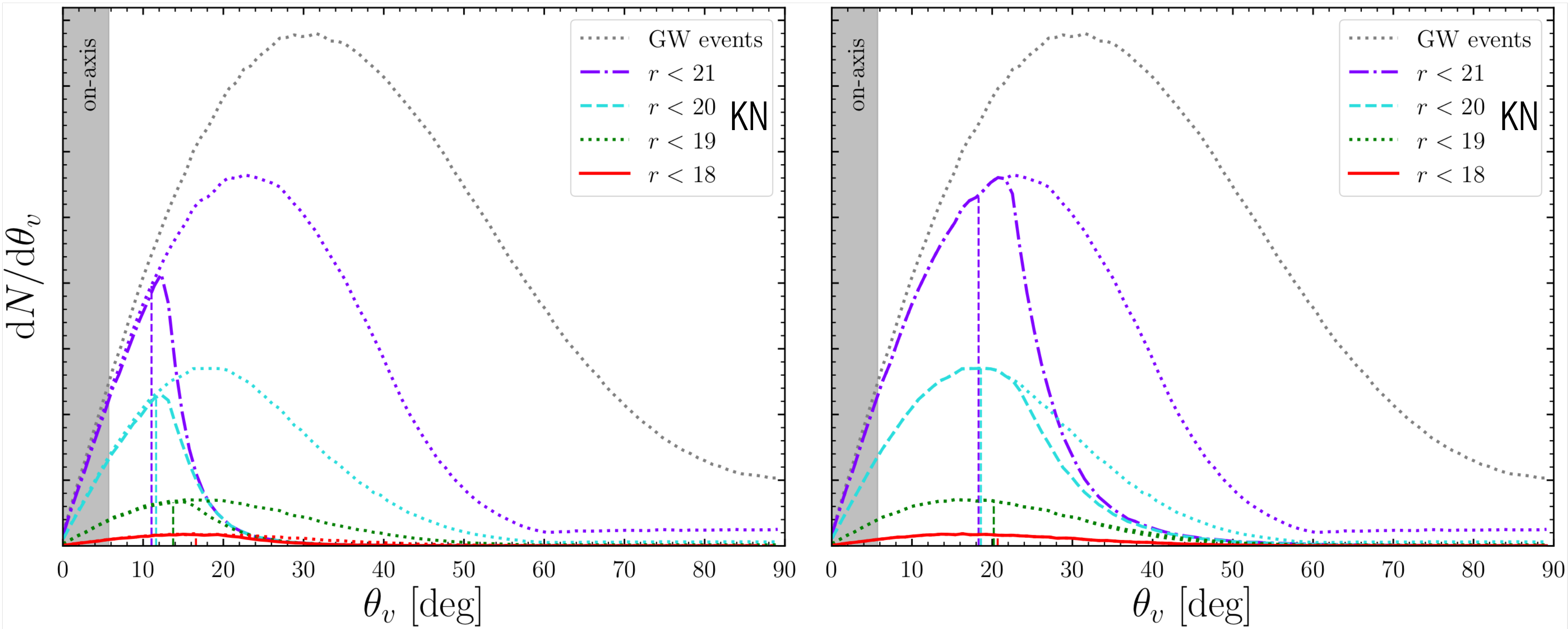
Uncertainty related to late jet dynamics

Observation strategy ?

(LSST: cadence may be less an issue than for the KN)

Duque, Daigne & Mochkovitch, 2019)

GW-detected BNS (O4) + KN + 3xVLA sensitivity @ 3 GHz = 45 μJy



Standard prescription

rlim	detectable AG
19	53% (0.3 per year)
20	36% (0.7 per year)
21	23% (1.1 per year)

Brighter afterglows (more energetic jets/denser environments)

rlim	detectable AG
19	97% (0.5 per year)
20	81% (1.5 per year)
21	59% (2.9 per year)

Mochkovitch, Daigne, Duque & Zitouni, 2021

BNS MERGERS: GW+EM

- **GW/bright SGRB: current limitation = GW horizon (wait for O5? ET?)**
- **Other counterparts: best case = kilonova (less anisotropic)**

  Searching the KN remains very difficult
  (a weak transient on a week timescale in a large error box)

  Some expected improvments:
  - more interferometers in the GW network: better localization
  - LSTT (large fov + deep limit mag. – cadence?)

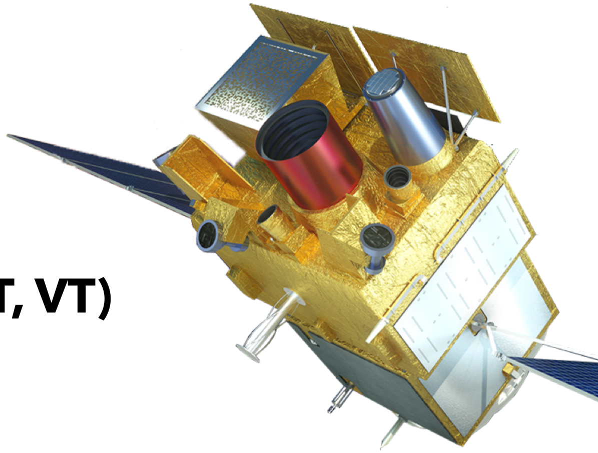
  Needs dedicated follow-up instruments (an example: GRANDMA)

- **Afterglow: very difficult without an accurate localization with the KN**
- **Rare MM-detections can be complemented by other (EM-only) channels:**
  SGRB+AG ; SGRB+AG+KN ; orphan KN? ; orphan AG?

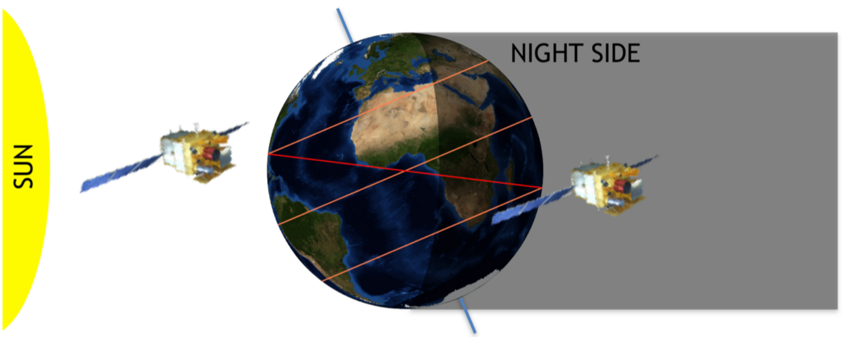
THE SVOM MISSION

THE SVOM MISSION

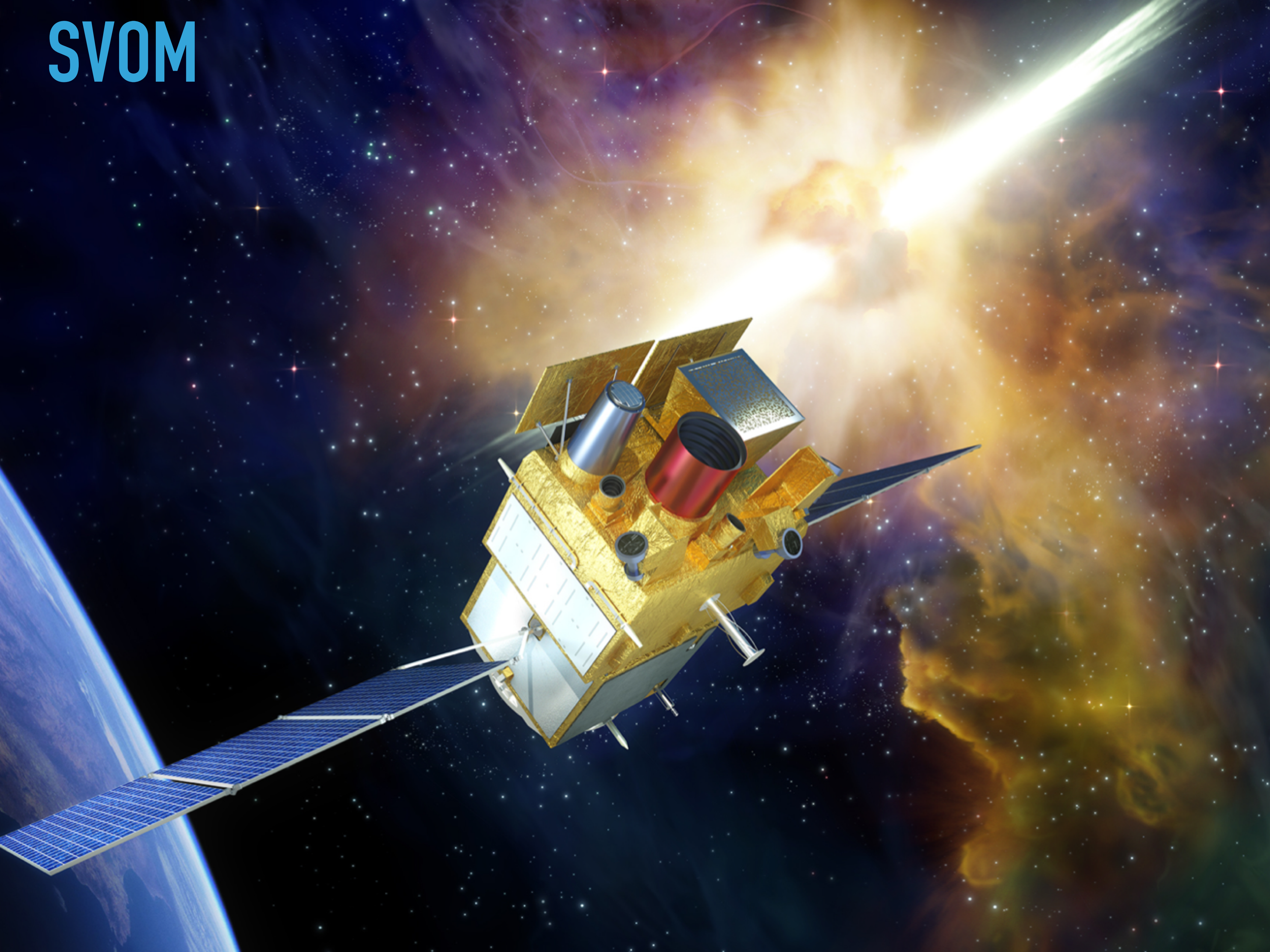
- **“Space-based multi-band astronomical Variable Objects Monitor”**
- China (P.I. J. Wei) + France (P.I. B. Cordier)
  France: 12 labs + partners in Mexico, UK, Germany



- **Launch: mid-2023 ; for 3+2 years(+extension)**
- **A spacecraft with 4 instruments (ECLAIRs, GRM, MXT, VT) and rapid slewing capabilities**
- **A VHF alert network for near-real time alerts**
- **A ground segment for a rapid follow-up (GWAC, C-GFT, F-GFT=Colibri)**
- **A nearly anti-solar pointing for optimizing the follow-up of GRBs**



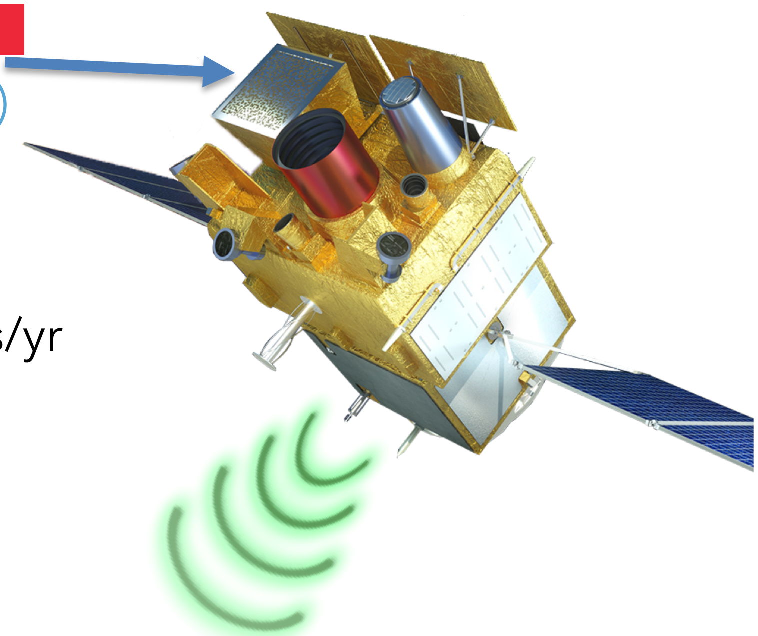
- **Core Program: GRB science**
  (25% of time, GRB observation have the highest priority)
- **Other programs: MM follow-up (GW, neutrinos)** – General program


SVOM

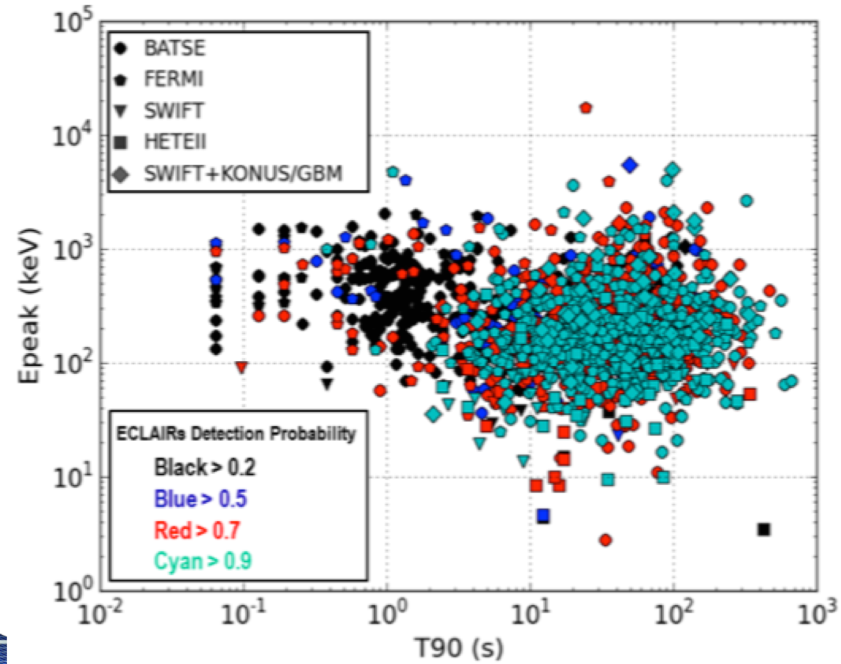
GRB TRIGGER/PROMPT EMISSION

ECLAIRS
(4 -150 keV)
~ 2 sr
Loc. < 12′

42-80 GRBs/yr



Simulation in ECLAIRs



Detection probability by ECLAIRs (simulations by S. Antier)
(Wei, Cordier et al. « Scientific prospects of the SVOM mission », arXiv:1610.06892)

ECLAIRs is sensitive to all classes of GRBs

Classical long GRBs

Soft GRBs (XRR, XRF)

Short GRBs
(but with a moderate efficiency)

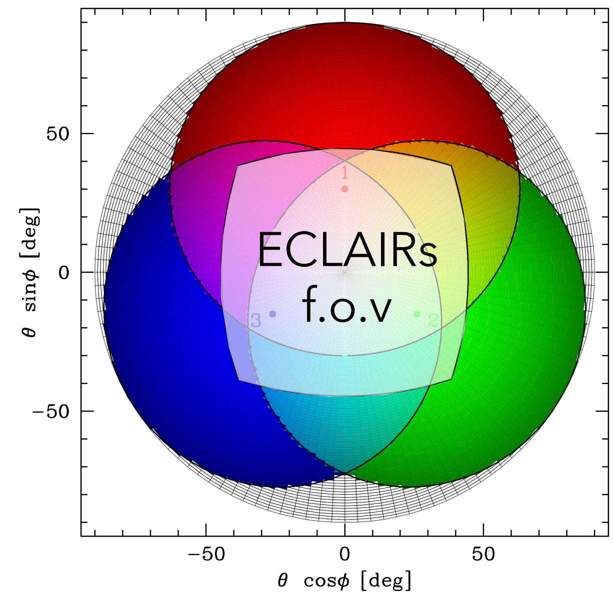
GRB TRIGGER/PROMPT EMISSION

GRM

(30 keV-5 MeV) ~ 5.6 sr Loc.: 5-10° (3 GRDs)

~90 GRBs/yr

GRM field of view:



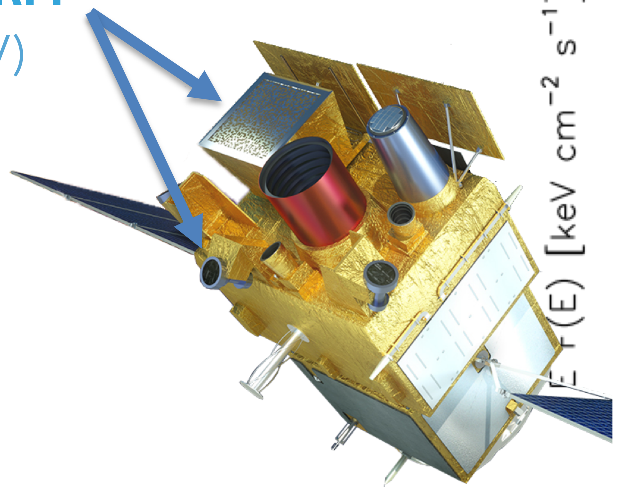
GRM has a larger field of view than ECLAIRs

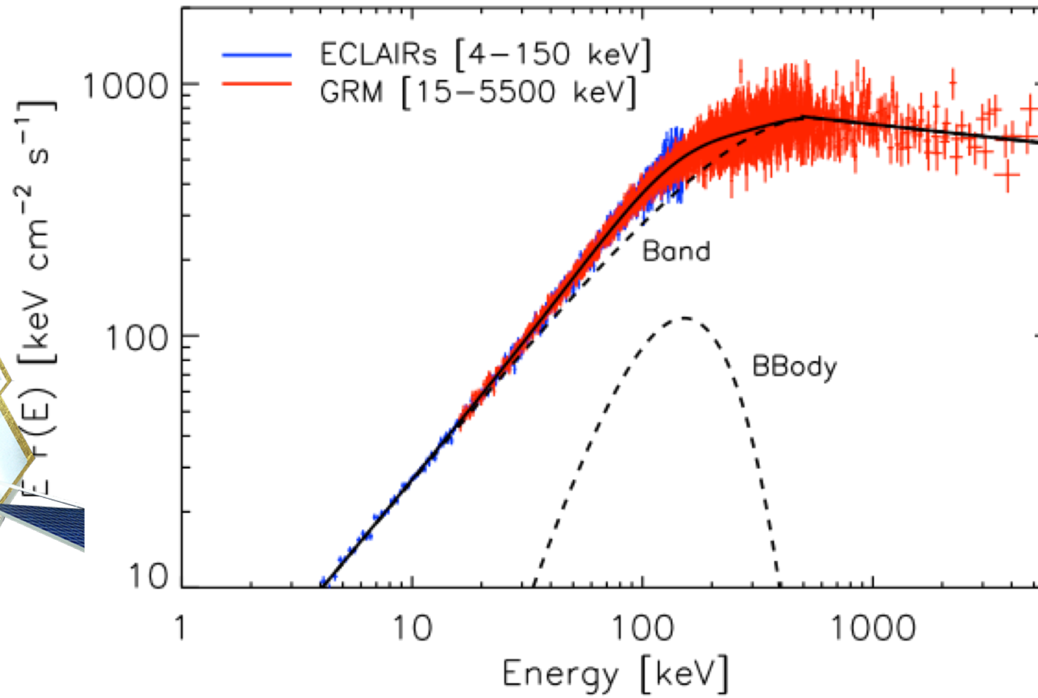
ECLAIRs sensitivity to short GRBs can be improved by combining ECLAIRs+GRM

PROMPT EMISSION

ECLAIRS+GRM

(4 keV-5 MeV)





Multi-component spectrum of the Fermi burst GRB 100724B simulated in ECLAIRs+GRM. (Bernardini et al. 2017)

GWAC

2x5000 deg^2 – 500-800 nm

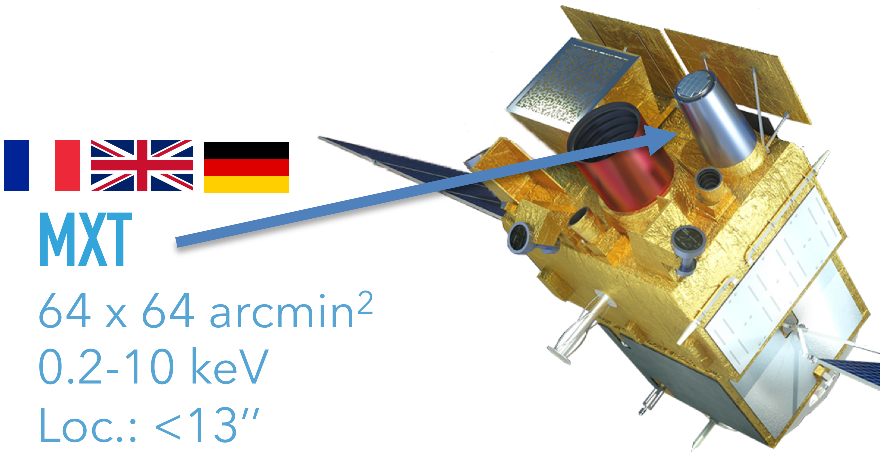
m_{lim} ~ 16-17 (10 s exposure)

prompt visible emission in ~16% of cases

ECLAIRs+GRM can measure the prompt spectrum over 3 decades in energy

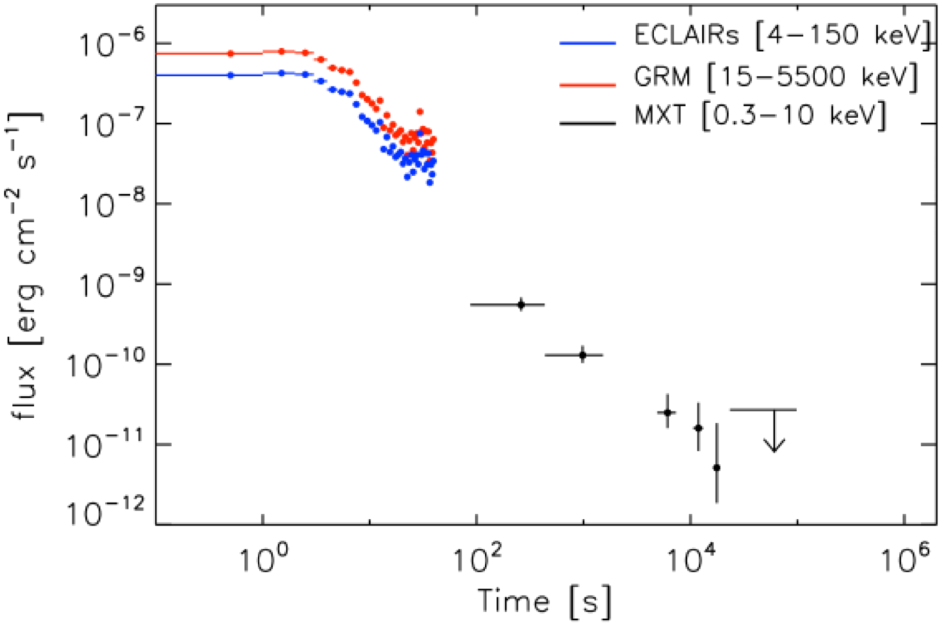
GWAC will add a constraint on the associated prompt optical emission in a good fraction of cases.

AFTERGLOW



MXT

64 x 64 arcmin^2
0.2-10 keV
Loc.: <13″

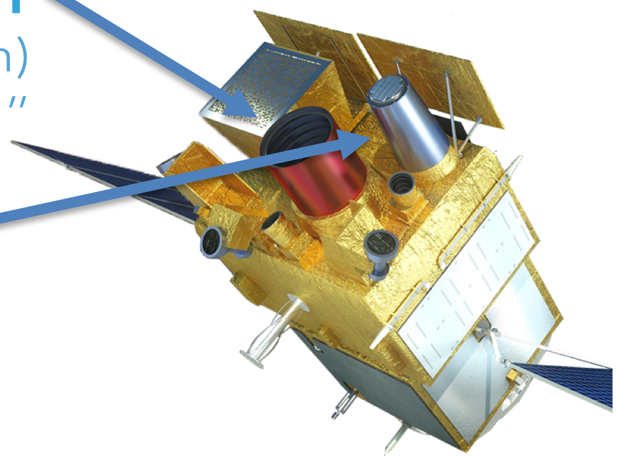


The X-ray afterglow of the Swift burst GRB 091020 simulated in MXT.
(Wei, Cordier et al. « Scientific prospects of the SVOM mission », arXiv:1610.06892)

MXT can detect and localize the X-ray afterglow in >90% of GRBs after a slew.

AFTERGLOW & DISTANCE

VT
(400-1000 nm)
Loc.: <1″



MXT
(0.2-10 keV)
Loc.: <13″

VT, C-GFT and F-GFT will detect, localize and characterize the V-NIR afterglows (lightcurve+photo-z).

Early observation by large telescopes are favored by SVOM's pointing strategy.

Redshift measurement is expected in ~2/3 of cases

GWAC
2x4000 deg^2
m_{lim} ~ 16-17

C-GFT
1.2 m
400-950 nm

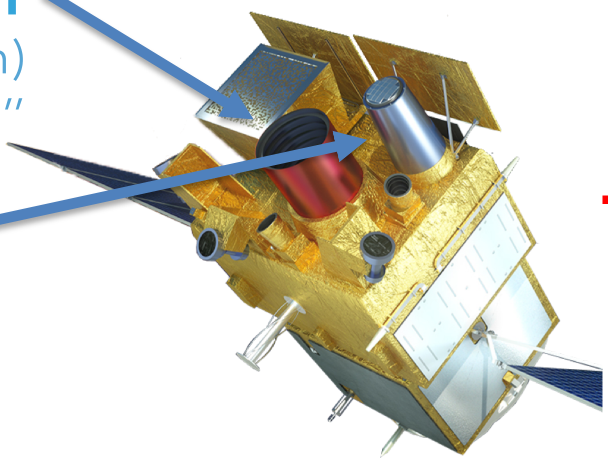
F-GFT (COLIBRI)
1.3 m
400-1700 nm
multi-band

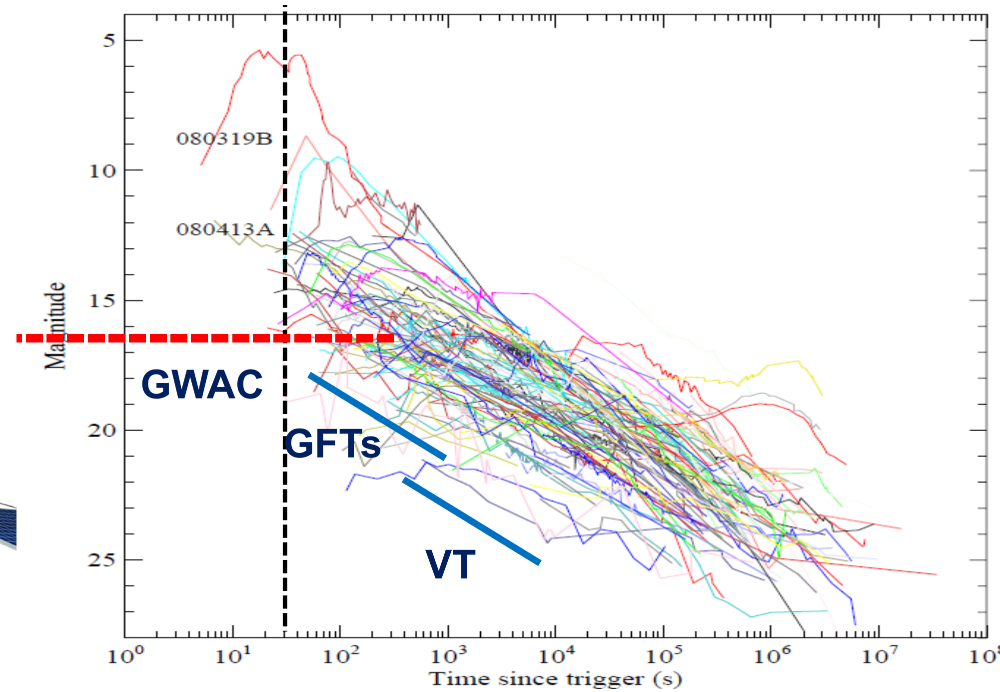
(Very) Large telescopes

AFTERGLOW & DISTANCE

VT
(400-1000 nm)
Loc.: <1″

MXT
(0.2-10 keV)
Loc.: <13″





(Wang et al. 2013)

GWAC
2x4000 deg^2
m_{lim} ~ 16-17

C-GFT
1.2 m
400-950 nm

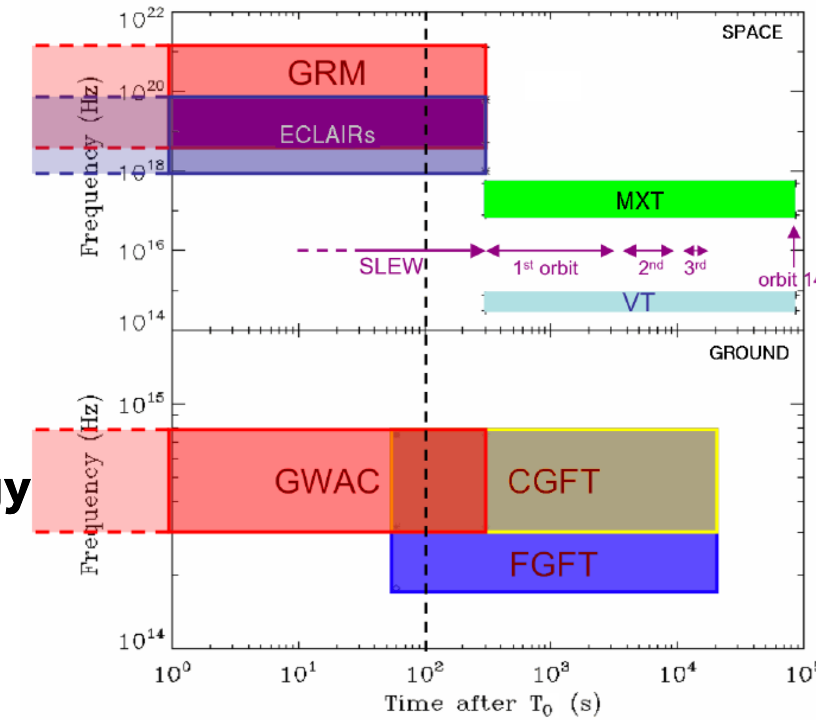
F-GFT (COLIBRI)
1.3 m
400-1700 nm
multi-band

(Very) Large telescopes

A GRB SAMPLE WITH A COMPLETE DESCRIPTION

A unique sample of 30-40 GRB/yr with

- prompt emission over 3 decades
  (+ optical flux/limit: 16%)
- X/V/NIR afterglow
- redshift



Science:
GRB physics + GRB as a tool for cosmology

SVOM is sensitive to all classes of GRBs
= adapted to MM-searches

SVOM will benefit of a good synergy with other instruments
(LVK-O5, KM3NET/IceCube-2, Fermi/CTA + many other: SKA-precursors, JWST, …)

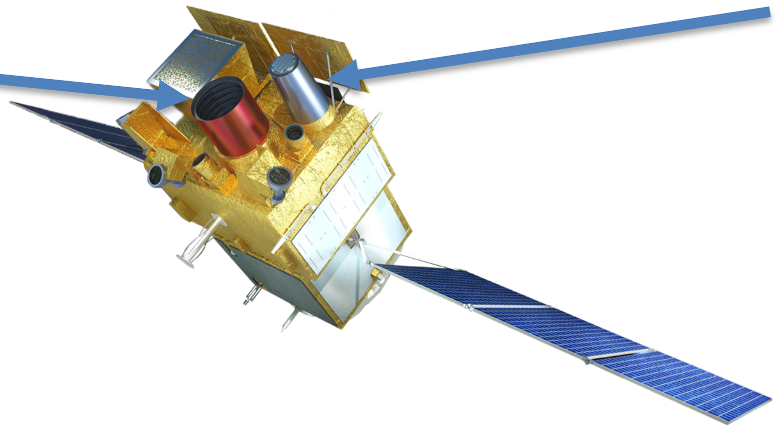
	Swift	Fermi	SVOM
Prompt	Poor	Excellent 8 keV -100 GeV	**Very Good 4 keV - 5 MeV**
Afterglow	Excellent	> 100 MeV for LAT GRBs	**Excellent**
Redshift	~1/3	Low fraction	**~2/3**

SVOM IN THE MULTI-MESSENGER ERA

SVOM instruments with small f.o.v. in space

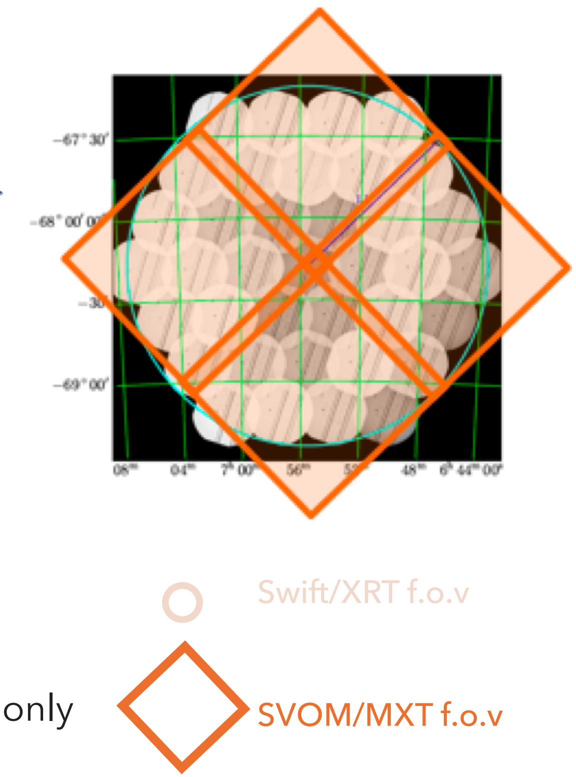
VT

400-1000 nm
26^2 arcmin^2
Loc: < 1 arcsec



MXT

0.2-10 keV, 64^2 arcmin^2
Loc: <13 arcsec



- **Search for X-ray/V counterparts to MM events** (e.g. GW: large error boxes – KN/AG expectations depend on the viewing angle, HE neutrino: ~deg^2)
- Requires a **slew** of the satellite
- Large error boxes: requires a **tiling strategy**

MXT vs XRT: very competitive to rapidly cover large error boxes with only a slightly reduced sensitivity thanks to its large field of view (1 deg2).

SVOM IN THE MULTI-MESSENGER ERA

SVOM instruments with small f.o.v. on ground

C-GFT

(1.2 m, Changchun) 400-950 nm, 21^2 arcmin^2

F-GFT « COLIBRI »

(1.3 m, San Pedro Martir) 400-1700 nm, 26^2 arcmin^2
multiband photometry

- Search: galaxy targeting with error box
- **Characterize V-NIR counterparts to MM events: photometric follow-up** (e.g. a kilonova associated to a BNS)
- Needs an identified counterpart with an accurate localization (<30 arcmin)

SVOM

A unique sample of GRBs with a complete description:

prompt (γ-rays: 3 decades; optical) + afterglow (X, V, NIR) + redshift.

Exploration of the diversity of the GRB population.

Excellent synergy with other instruments (including Fermi+CTA, GW/ν detectors).

SVOM will be launched in 2023: be ready!

SOME REFERENCES ON THE PERSPECTIVES FOR GRB STUDIES WITH SVOM

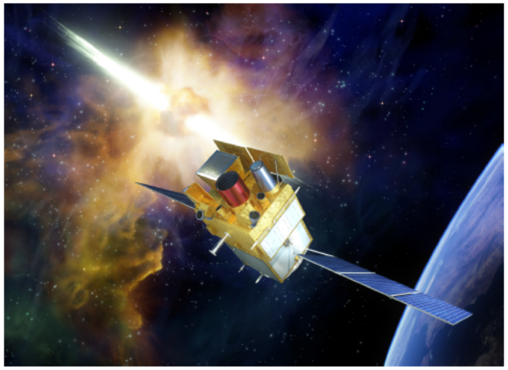
- Arcier, B., Atteia, J. L., Godet, O., et al. (2020) Detection of short high-energy transients in the local universe with SVOM/ECLAIRs, Astrophysics and Space Science, 365, 185
- Wang, J., Qiu, Y.-L., & Wei, J.-Y. (2020) A pilot study of catching high-z GRBs and exploring circumburst environment in 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.

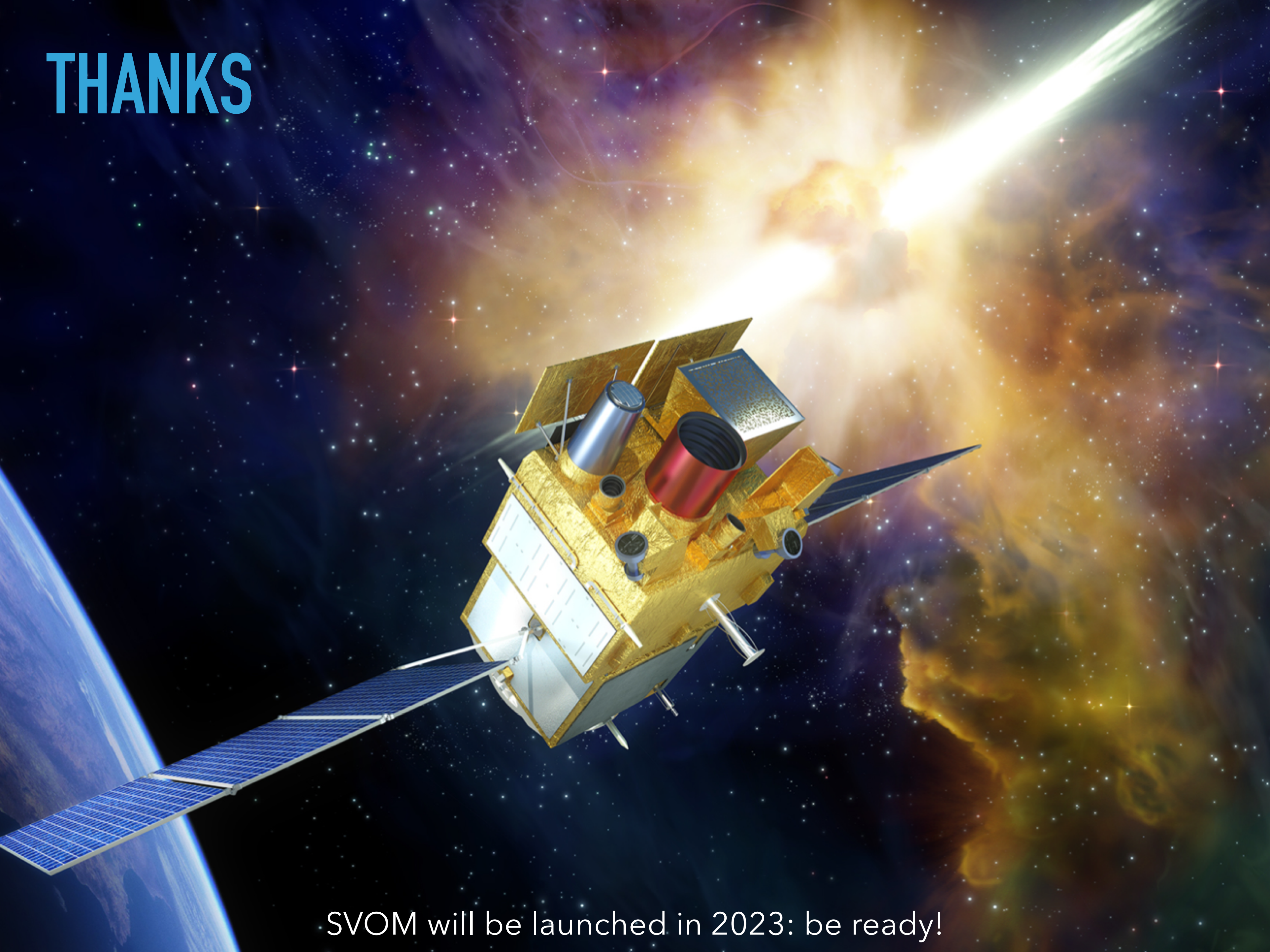
arXiv:1610.06892v1 [astro-ph.IM] 21 Oct 2016



Frontispiece : Artist view of the *SVOM* satellite

1

THANKS



SVOM will be launched in 2023: be ready!