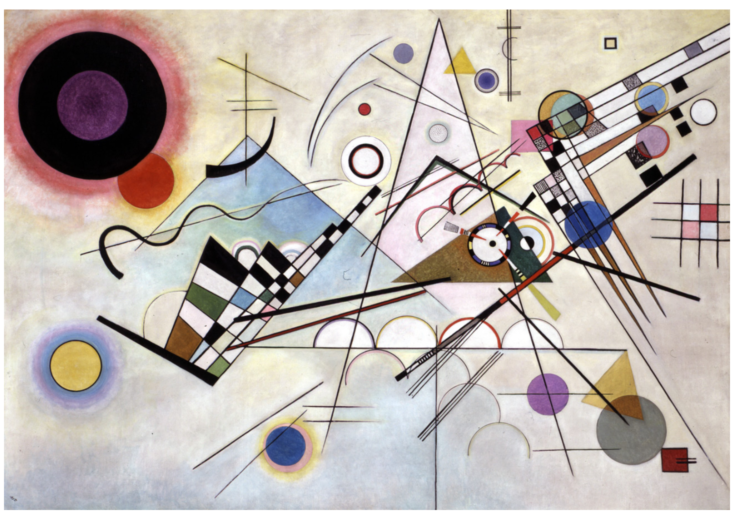
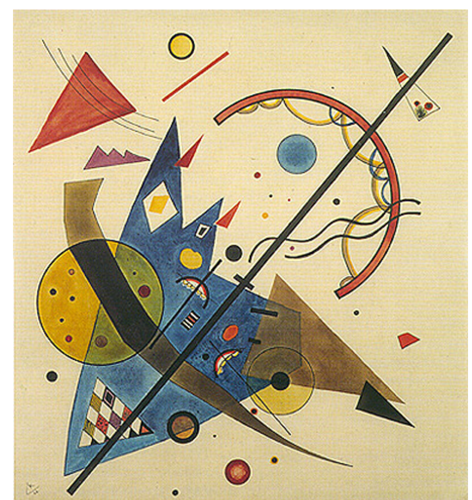
EM counterparts of binary neutron star mergers with the Vera Rubin-LSST (and a few words on long GRBs)

Frédéric Daigne (Institut d'Astrophysique de Paris)

with Jean-Grégoire Ducoin, Raphaël Duque, Robert Mochkovitch & Clément Pellouin



Kandinksy – Ccomposition 8- 1923



Kandinksy – Curves and sharp angles - 1923

Rubin-LSST France, 23 November 2021, LPNHE

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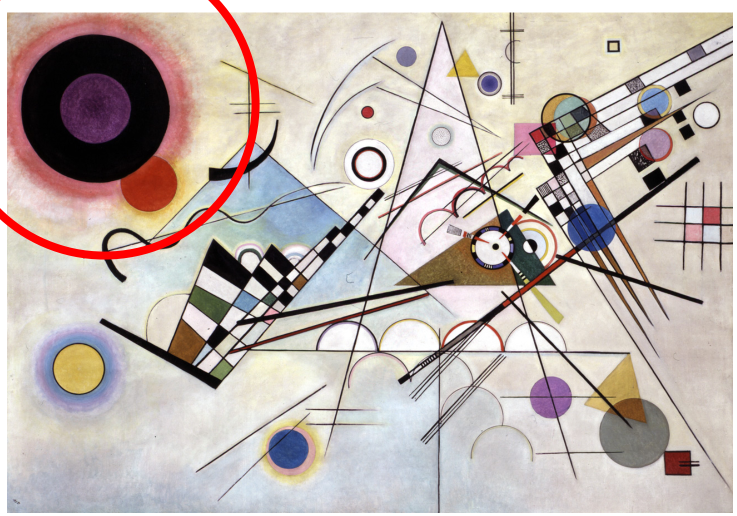
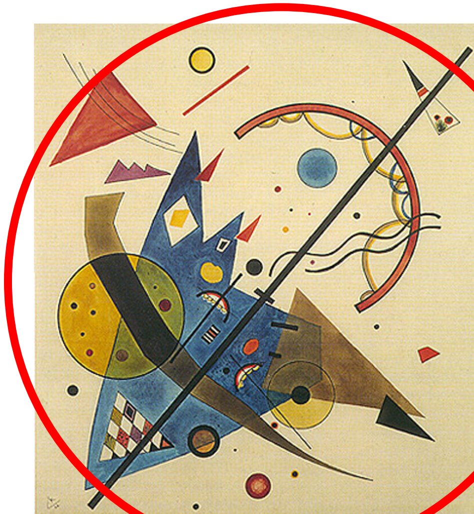
mergers



Kandinksy – Ccomposition 8- 1923



Kandinksy – Curves and sharp angles - 1923

ejecta

Rubin-LSST France, 23 November 2021, LPNHE

EM counterparts of binary neutron star mergers with the Vera Rubin-LSST (and a few words on long GRBs)

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with **Jean-Grégoire Ducoin**, **Raphaël Duque**, Robert Mochkovitch & **Clément Pellouin**

PhD 2021 (IJCLab)
now postdoc at IAP

PhD 2021 (IAP)
now postdoc in Frankfurt

PhD student (IAP, 2020-)

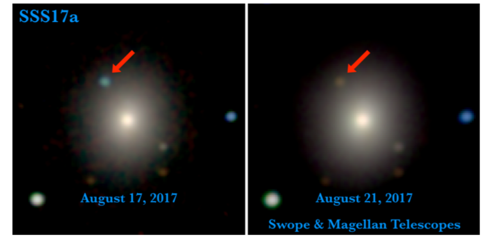
Rubin-LSST France, 23 November 2021, LPNHE

Introduction

BNS: EM counterparts

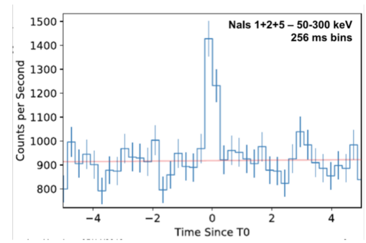
- **Kilonova (KN)** (post merger ejecta, quasi-isotropic, thermal) **(red component; blue component?)**

GW170817: detected (red+blue)



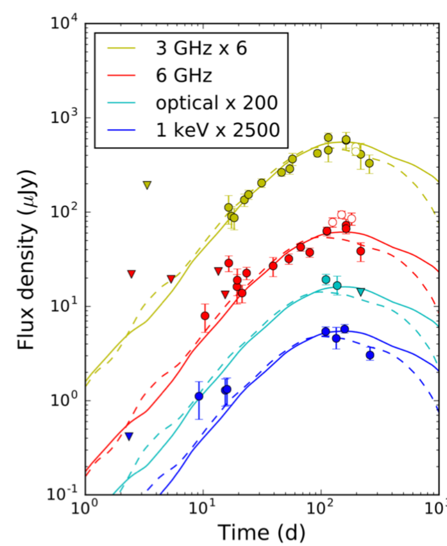
- **Short GRB :** (relativistic jet)
  - **-bright SGRB from the core jet** — **GW170817: not detected**
  - **-weak SGRB from the jet's sheath** — **GW170817: detected**

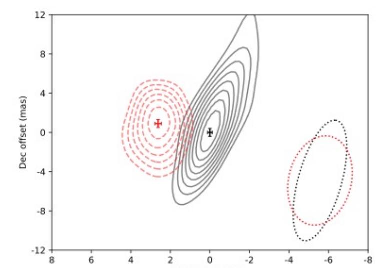
  (Matsumoto et al. 2019)



- **Afterglow: (AG: multi-λ, photometry, VLBI?)** (relativistic jet: deceleration by external medium)

GW170817: detected (with VLBI)





- **Kilonova afterglow?** (deceleration of KN ejecta)

BNS: EM counterparts

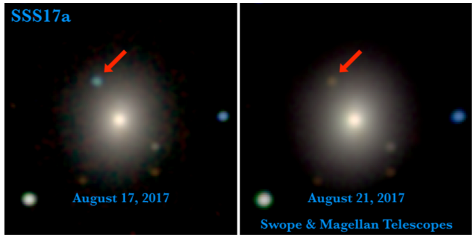
- Kilonova (KN)
  (red component; blue component?)

Kilonova

Timescale ~ week
Peak absolute magnitude (r) ~ -16

with m(lim)=21.5: detectable up to 300 Mpc
with m(lim)=24 ; detectable up to 1 Gpc

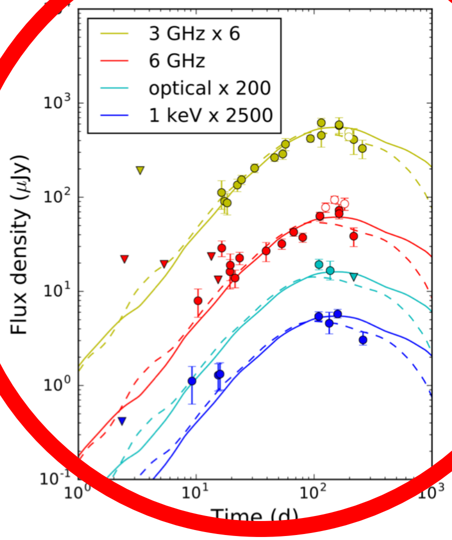
GW170817: detected (red+blue)



DETECTED IN VISIBLE RANGE

- Afterglow: (AG: multi-λ, photometry, VLBI?)

GW170817: detected (with VLBI)



Optical afterglow

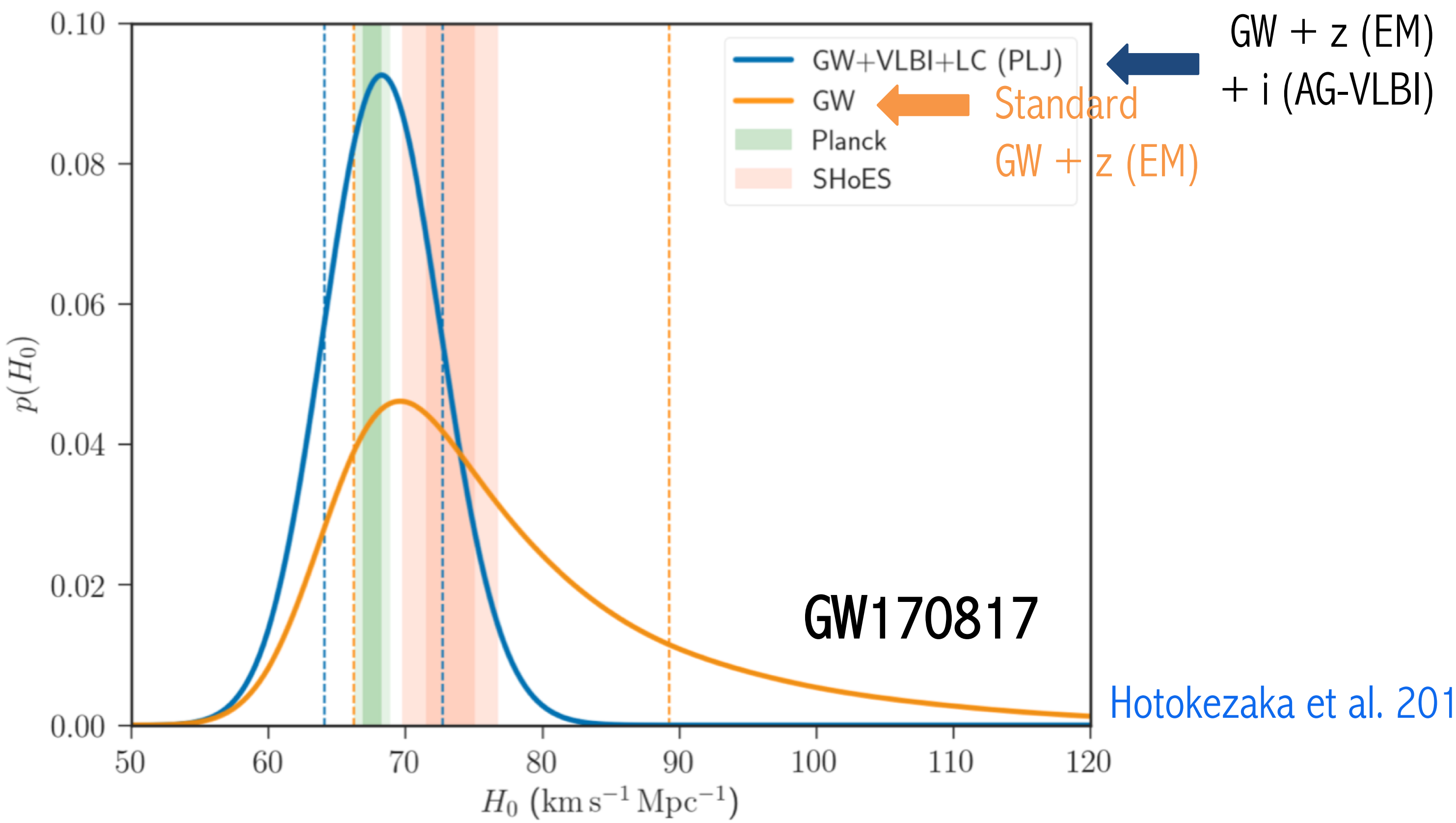
Timescale/absolute mag. : depends strongly
on the viewing angle!

170817: peak at ~170 days, peak absolute mag.(r) ~ -6!

But same event seen more on-axis is brighter.

EM counterparts to BNS: a very rich science

- Cosmology: H0
  - GW: distance (« standard siren ») – degeneracy with viewing angle
  - EM counterparts: host galaxy ⟶ redshift
    (170817: accurate sub arcsec position provided by KN)
  - KN: in the future, constraints on the viewing angle?
  - AG: constraint on the viewing angle (especially strong if VLBI)



Hotokezaka et al. 2019

EM counterparts to BNS: a very rich science

- Cosmology: H0
- Nuclear physics: EOS of ultra dense matter, r process
  - GW: initial binary system ; deformability (EOS)
  - KN: ejected mass (EOS), nucleosynthesis (r process)
- Mergers and short GRBs (GW+KN+GRB+AG)
  - Post merger evolution, various ejectas, …
  - Dissipative processes in the ejectas
  - Jet structure
  - Environment
- Stellar physics (GW+KN)
  - Stellar evolution in binary systems (common envelop, SN kicks, etc.)
- Galaxies: chemical evolution, r process elements (KN)
- Etc.

Predictions from a population model

Possible role of the Vera Rubin LSST

Population model: ingredients

- BNS: uniform rate in the local Universe
- GW detection: simple criterion (Schutz 2011)
- Horizon distances (Abbott et al. 2020):

Run	D_H [Mpc]
O3	157
O4	229
O5	472
O3@GW190425	181

Population model: ingredients

- BNS: uniform rate in the local Universe

- **Kilonova:** (Mochkovitch, Daigne, Duque & Zitouni, 2021)

  - red KN (lanthanide-rich) — always present — quasi-isotropic ; ~week ; peak=IR
  - blue KN (neutron-poor) — not always present? — polar ; ~day ; peak=visible
  - peak absolute magnitude:

$$M_{\lambda,\theta_v} = \begin{cases} M_{\lambda,0} + \Delta M_\lambda \left(\frac{1-\cos\theta_v}{1-\cos\,\theta_0}\right) + \delta M_\lambda, & \theta_v \leq \theta_0 \\ M_{\lambda,0} + \Delta M_\lambda + \delta M_\lambda, & \theta_0 \leq \theta_v, \end{cases}$$

Polar observer (θ_v=0) — Amplitude of polar effect — Variability (uniform [-1;1])

Band	$M_{\lambda,0}$	ΔM_λ
g	−16.3	7
r	−16.3	4
i	−16.4	3.5
z	−16.5	2.5

$\theta_0 = 60°$

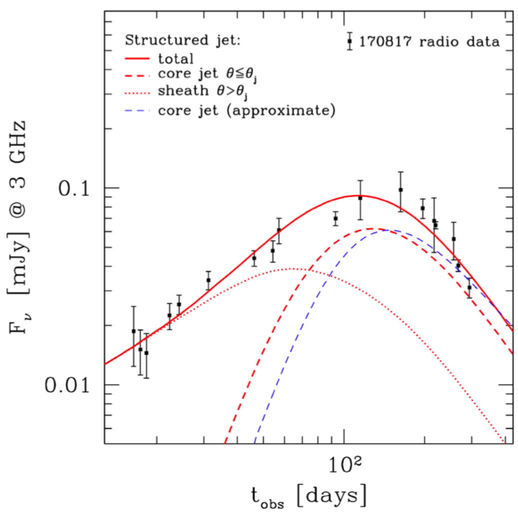
calibrated with 170817

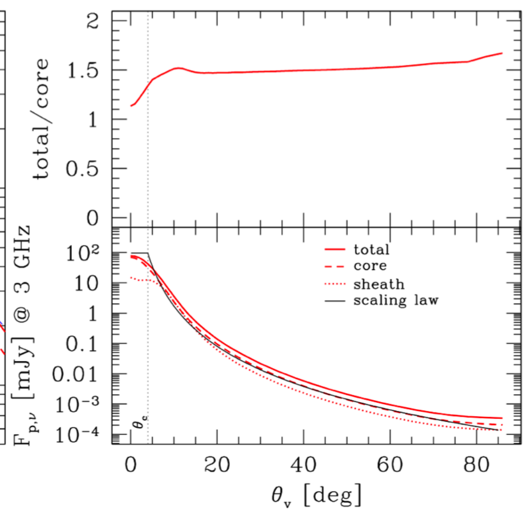
Reproduces the trend of sophisticated models.
(Wollaeger et al. 18; Kawaguchi et al. 20; assymetric model of Villar et al. 17)

Pole/equator contrast: weak in IR, stronger in visible (4 mag in r)

Population model: ingredients

- BNS: uniform rate in the local Universe
- Kilonova: red + blue KN (Mochkovitch, Daigne, Duque & Zitouni, 2021)
- **Afterglow:** **(Duque, Daigne & Mochkovitch, 2019)**
  - Highly anisotropic
  - Peak dominated by core jet (assume θ_j=0.1 rad)
  - Kinetic energy deduced from SGRB luminosity function
  - External medium: assumes low density (log-normal, mean = 10^{-3} cm^{-3})
  - Microphysics: ε_e=0.1 ; p=2.2 ; ε_B=log-normal (mean 10^{-3})





Here: radio lightcurve
optical lightcurve is similar

Population model: ingredients

- BNS: uniform rate in the local Universe
- Kilonova: red + blue KN (Mochkovitch, Daigne, Duque & Zitouni, 2021)
- Afterglow (Duque, Daigne & Mochkovitch, 2019)
- **Kilonova and Afterglow:**
  - **« detectable » if flux above a threshold**
  - **BUT « detectable » does not mean « detected »**

  - **Kilonova: difficult search**
    (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.

Population model: ingredients

- BNS: uniform rate in the local Universe

- Kilonova: red + blue KN

- Afterglow

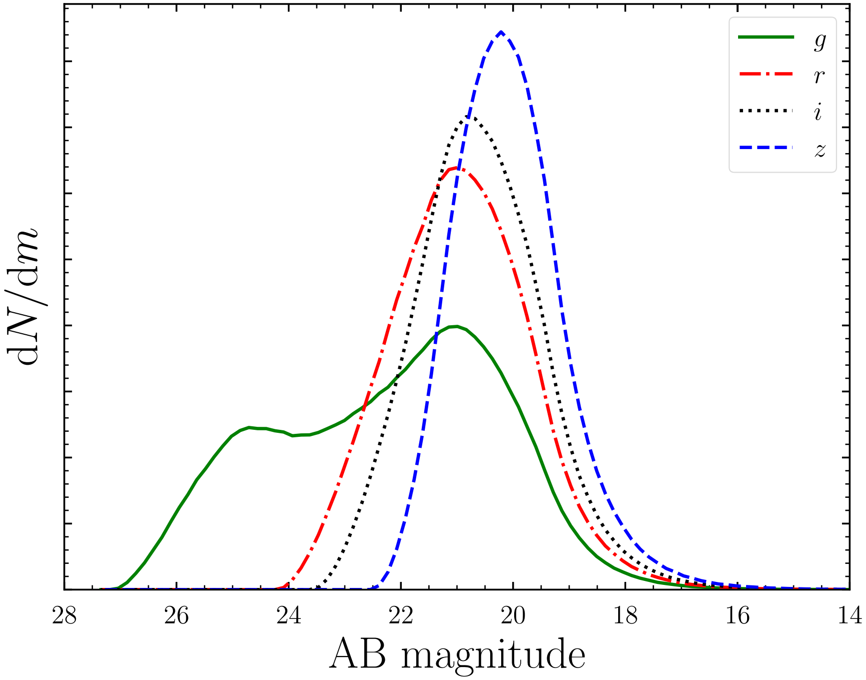
- **Short GRB:** (Mochkovitch, Daigne, Duque & Zitouni, 2021)
  - **Bright SGRB (core jet):**
    strong relativistic beaming: requires on-axis observer ($\theta_v < \theta_j = 0.1$ rad)
    BUT:
    with $L_{peak} > 10^{50}$ erg/s and $E_p \sim 1$ MeV: always detectable up to 600 Mpc
    (limitation= sky coverage of gamma-ray satellites)

  - Weak SGRB (sheath): still uncertain physics, not discussed here.

Results: kilonovae (1) magnitude

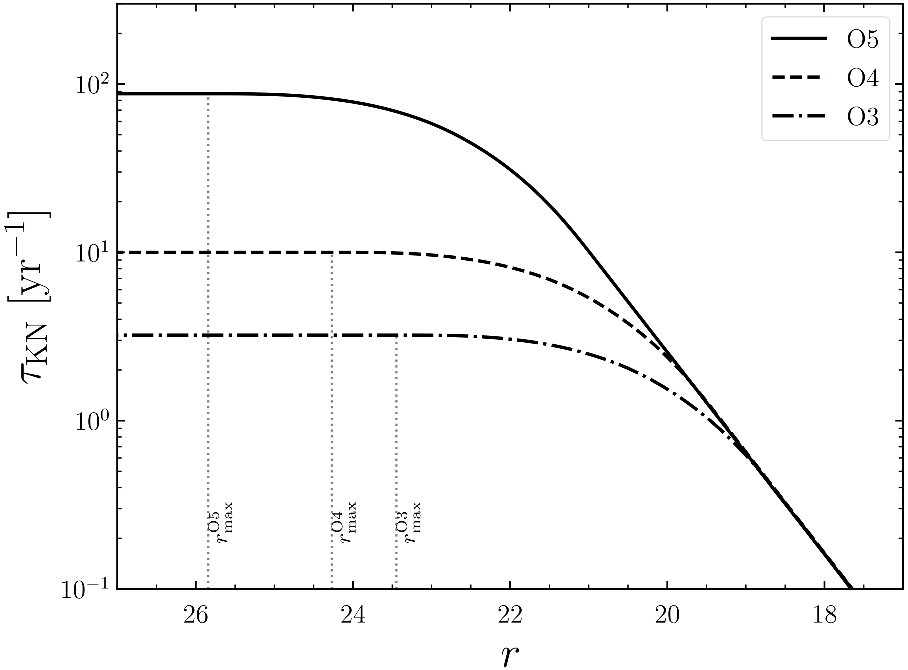
GW-detected BNS (O4):

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



↑ LSST?

KN rate above a given limit mag. (rlim)



↑ LSST?

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

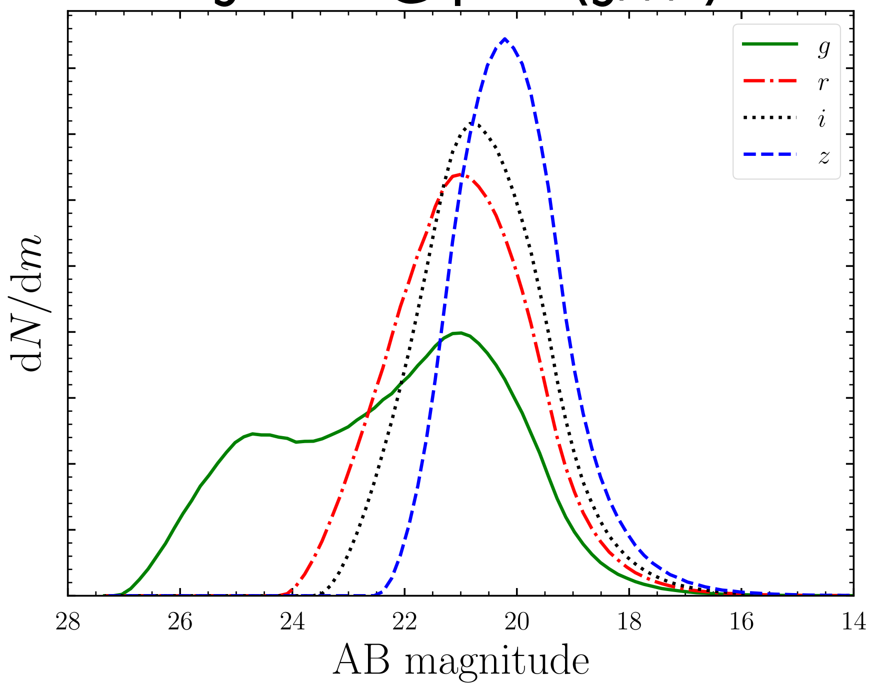
Most recent predictions from LVK: ~6 BNS per year in O4

Mochkovitch, Daigne, Duque & Zitouni, 2021

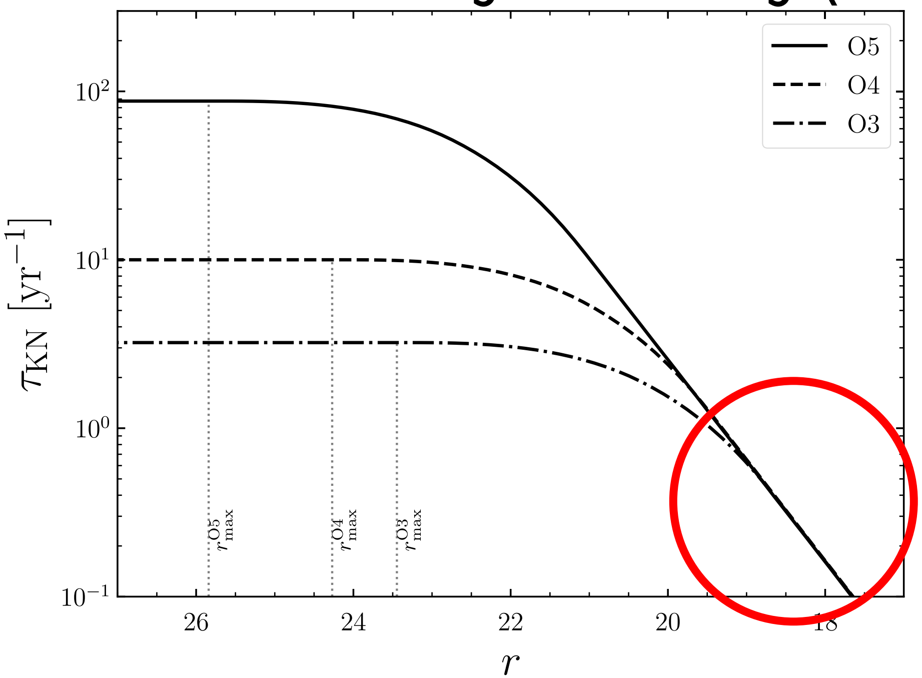
Results: kilonovae (1) magnitude

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

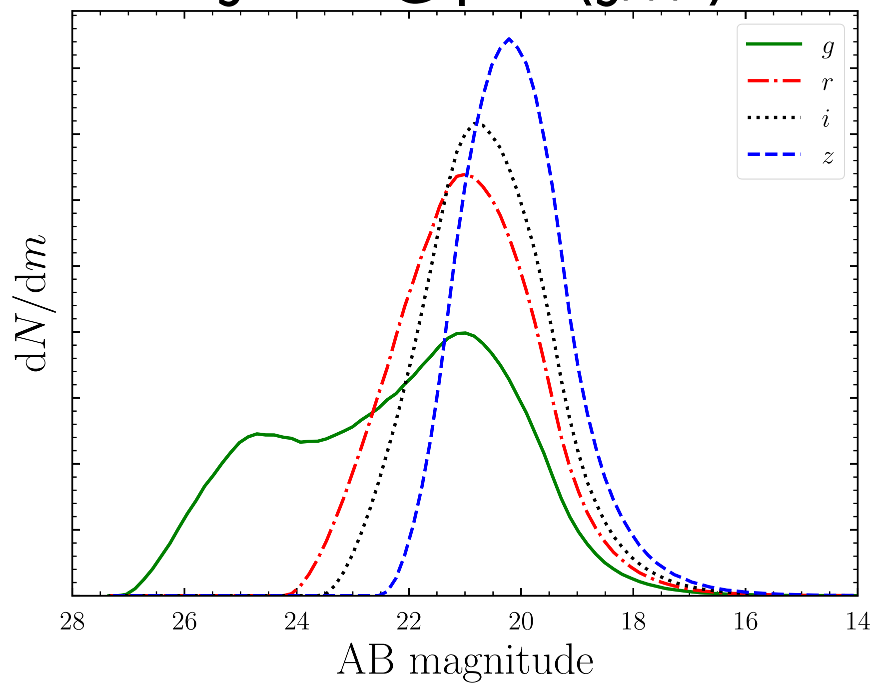
(normalization: assumes 10 GW-detected BNS per year in O4)

Mochkovitch, Daigne, Duque & Zitouni, 2021

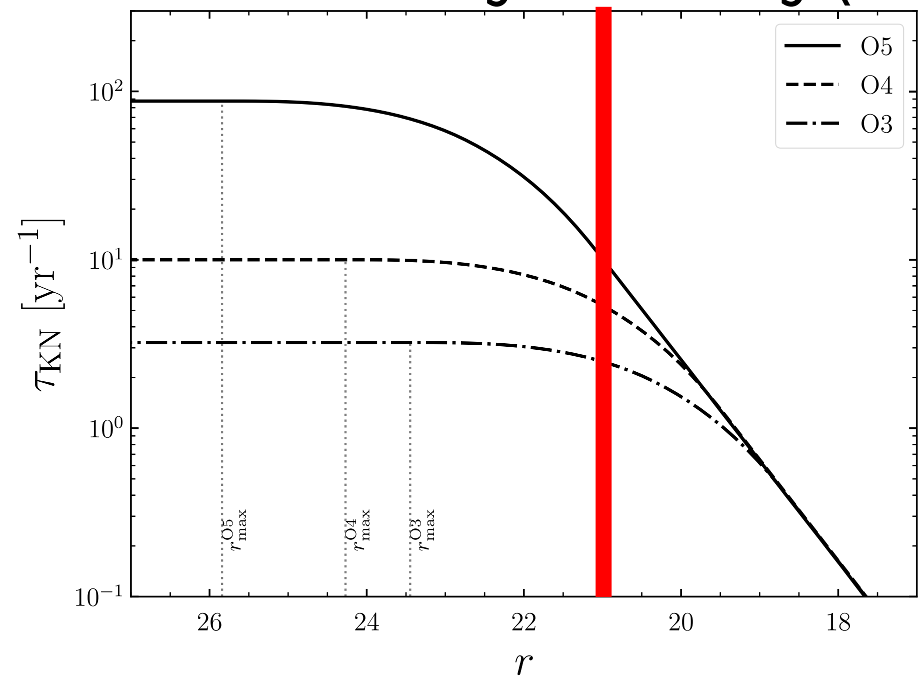
Results: kilonovae (1) magnitude

GW-detected BNS (O4):

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



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

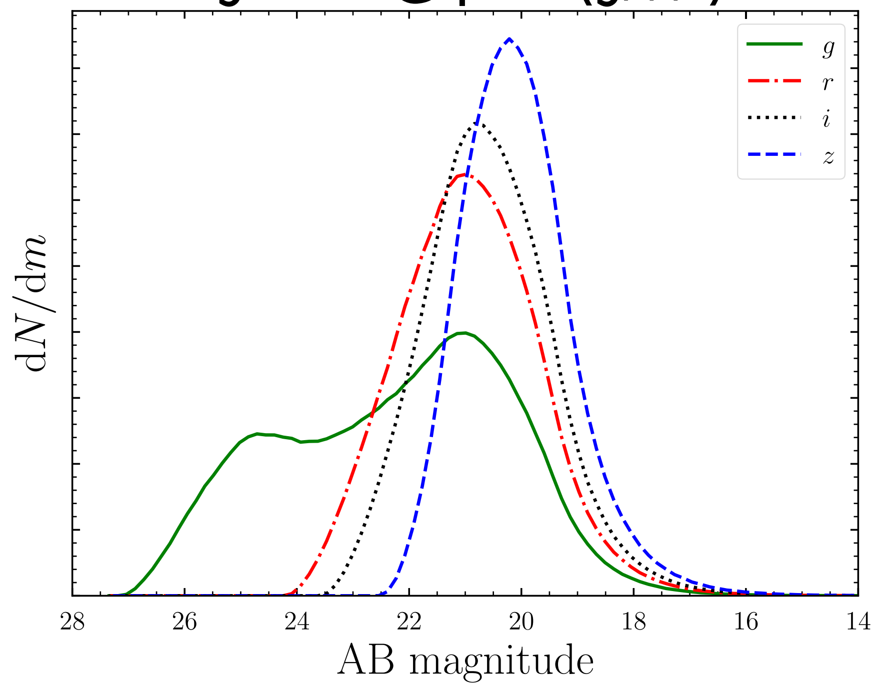
Detectable → Detected: strategy? (ZTF+LSST/Vera Rubin+follow-up telescopes...)

Mochkovitch, Daigne, Duque & Zitouni, 2021

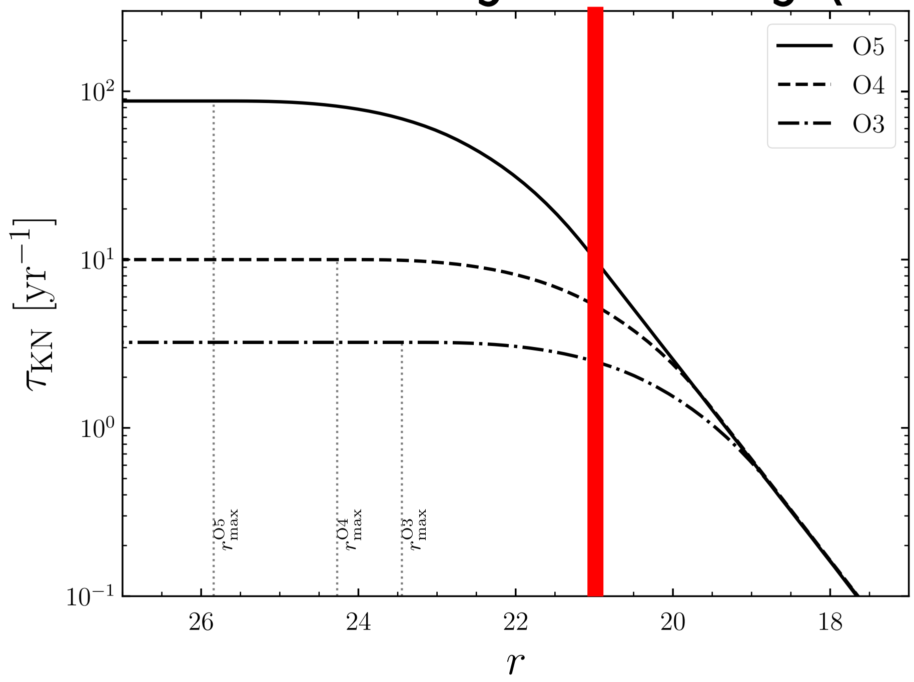
Results: kilonovae (1) magnitude

GW-detected BNS (O4):

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



KN rate above a given limit mag. (rlim)



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.

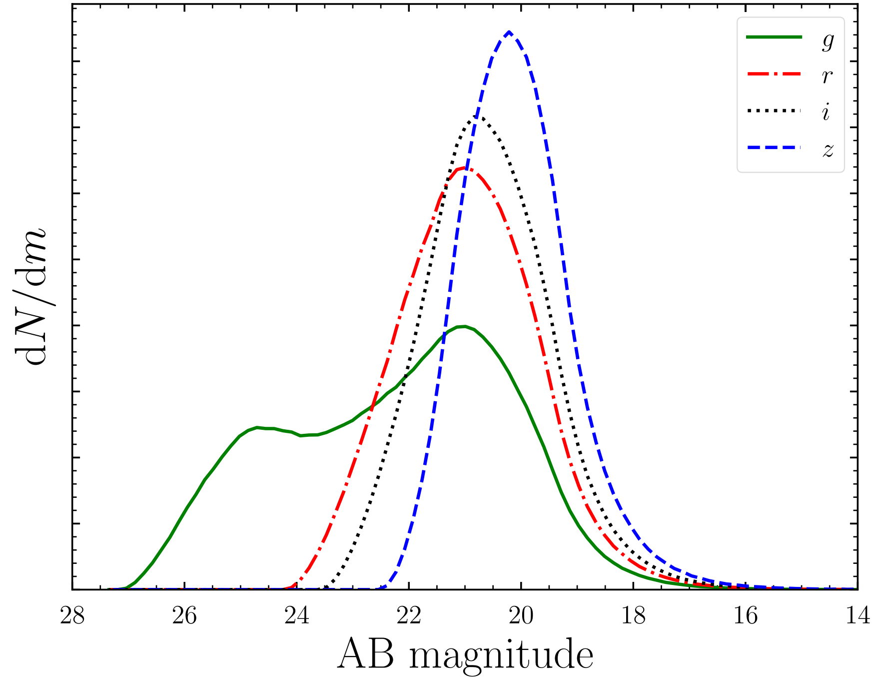
Different mode for GW alerts?

Mochkovitch, Daigne, Duque & Zitouni, 2021

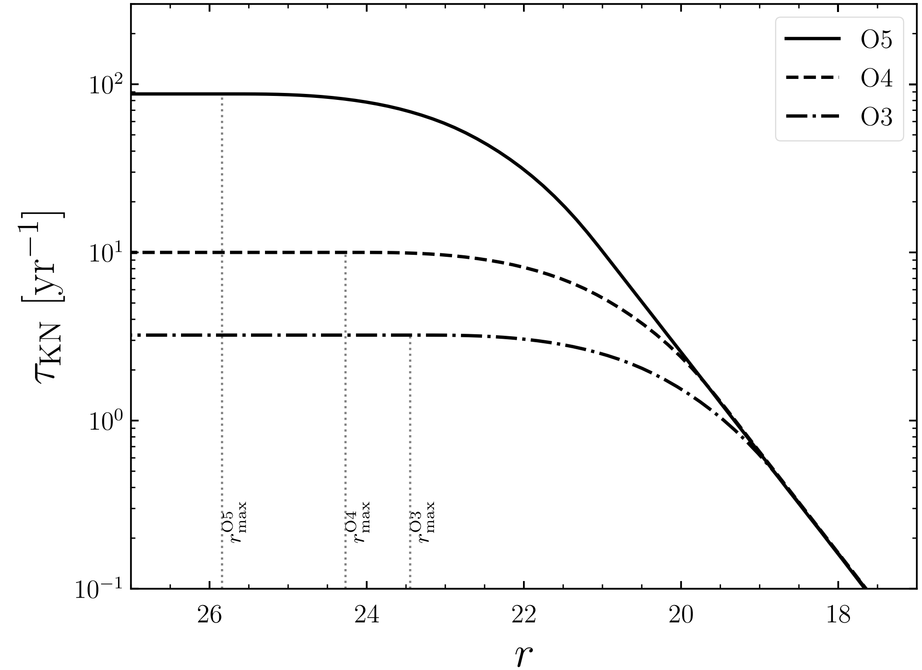
Results: kilonovae (1) magnitude

GW-detected BNS (O4) :

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



KN rate above a given limit mag. (rlim)



Caveats:

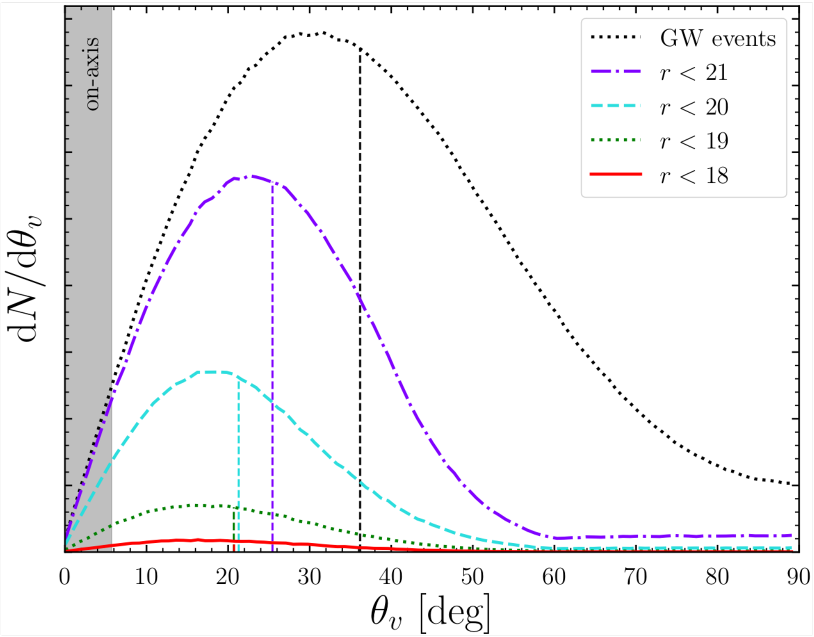
- calibrated on a single event (170817)
- Blue KN may be present only in a fraction of BNS:
  can reduce the rates, especially in the visible

(e.g. 20% of BNS with a blue KN and rlim = 19 : 1 every 2.0 year instead of 1 every 1.6 yr)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (2) viewing angle

GW-detected BNS (O4): viewing angle



Deeper search: mean angle increases

(association with AG/SGRB less probable)

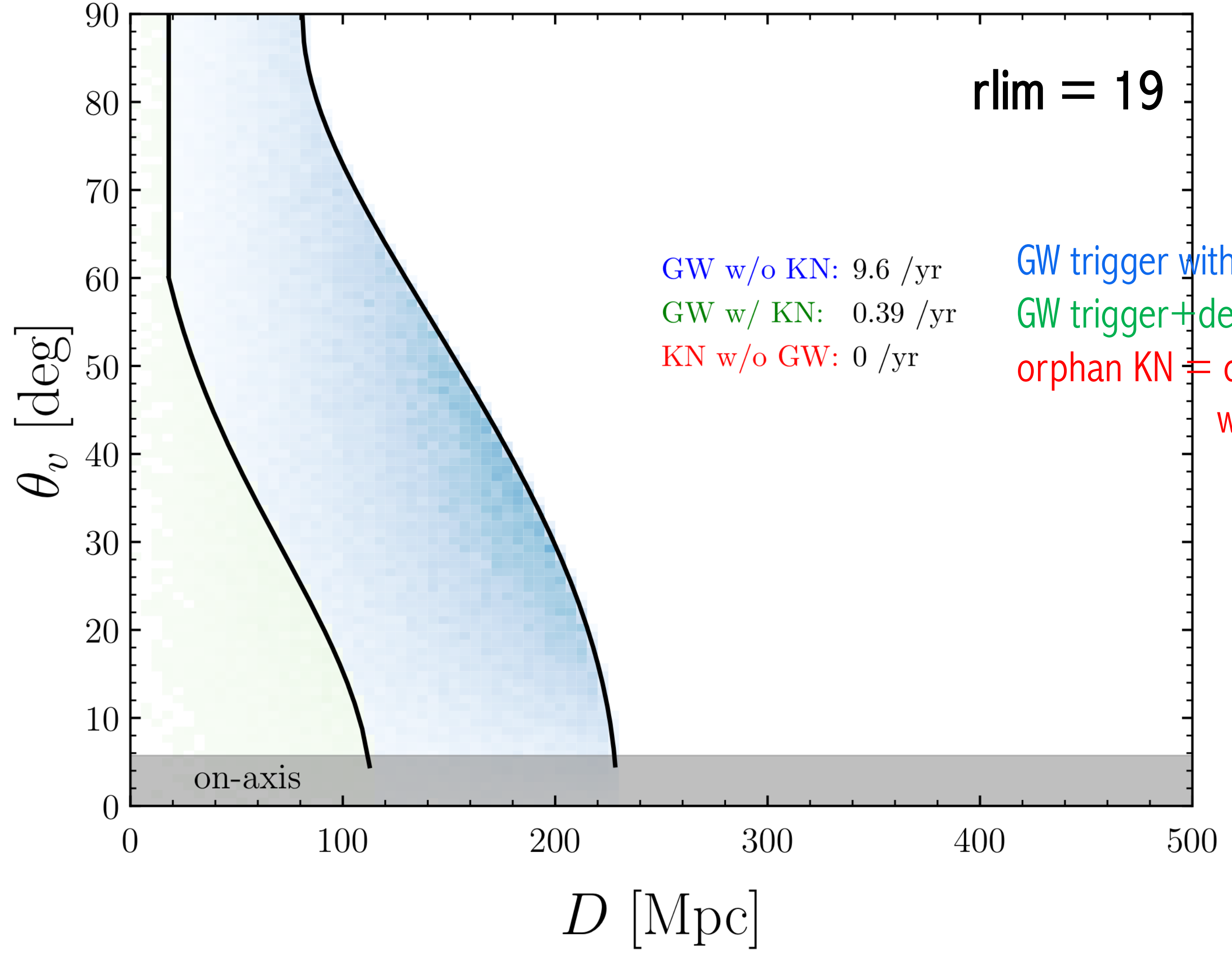
Cosmology: when detected, the afterglow can bring a strong constraint on the viewing angle, but afterglows are very rare.
Important goal: a sample of kilonova would allow to calibrate the mag/color vs viewing angle for kilonovae.

(see discussion in Mastrogiovanni, Duque, Chassande-Mottin, Daigne & Mochkovitch 21)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) distance-viewing angle plane

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

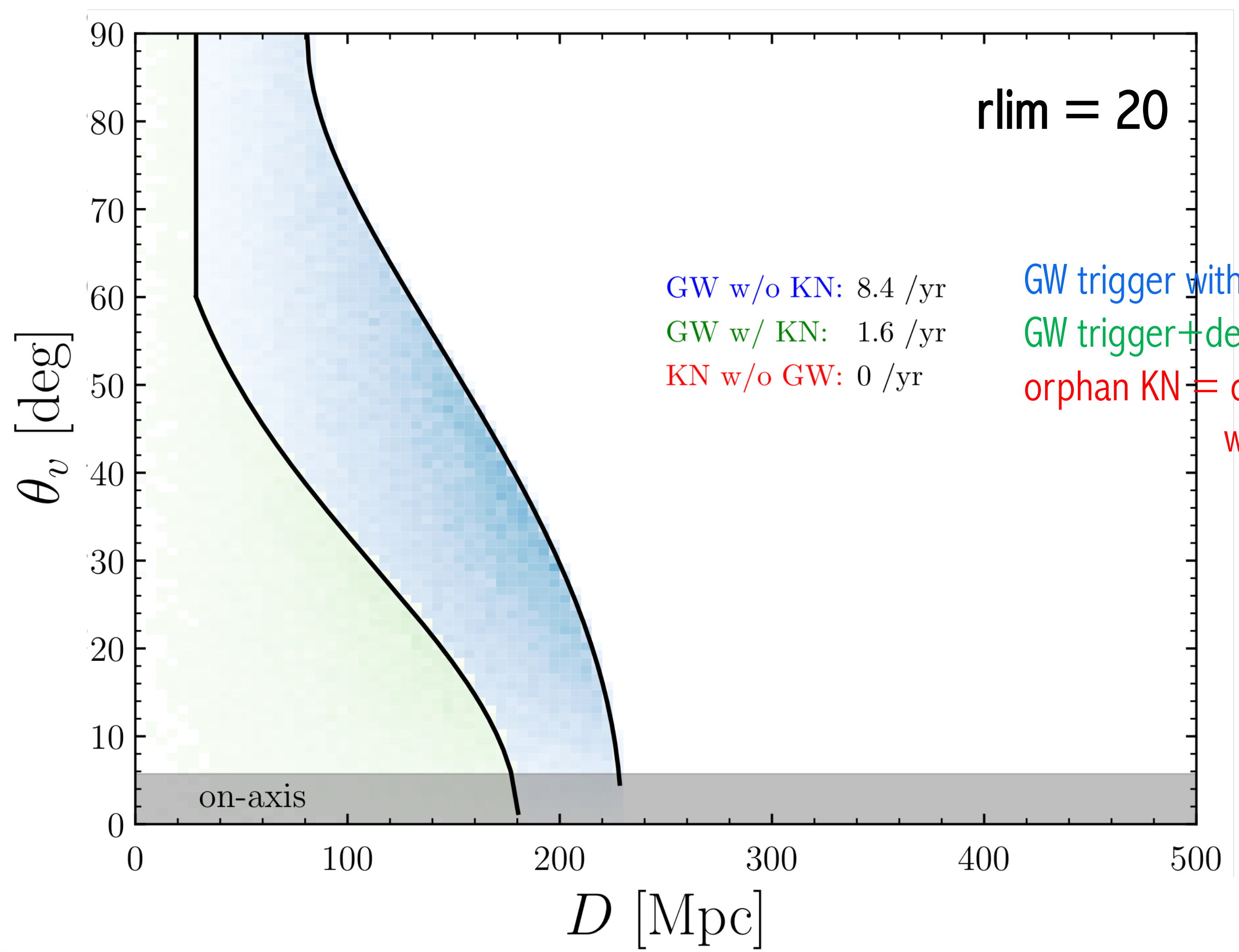
orphan KN = detectable KN without a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) distance-viewing angle plane

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



No orphan KN

KN+GW= remain rare

GW trigger without a detectable KN

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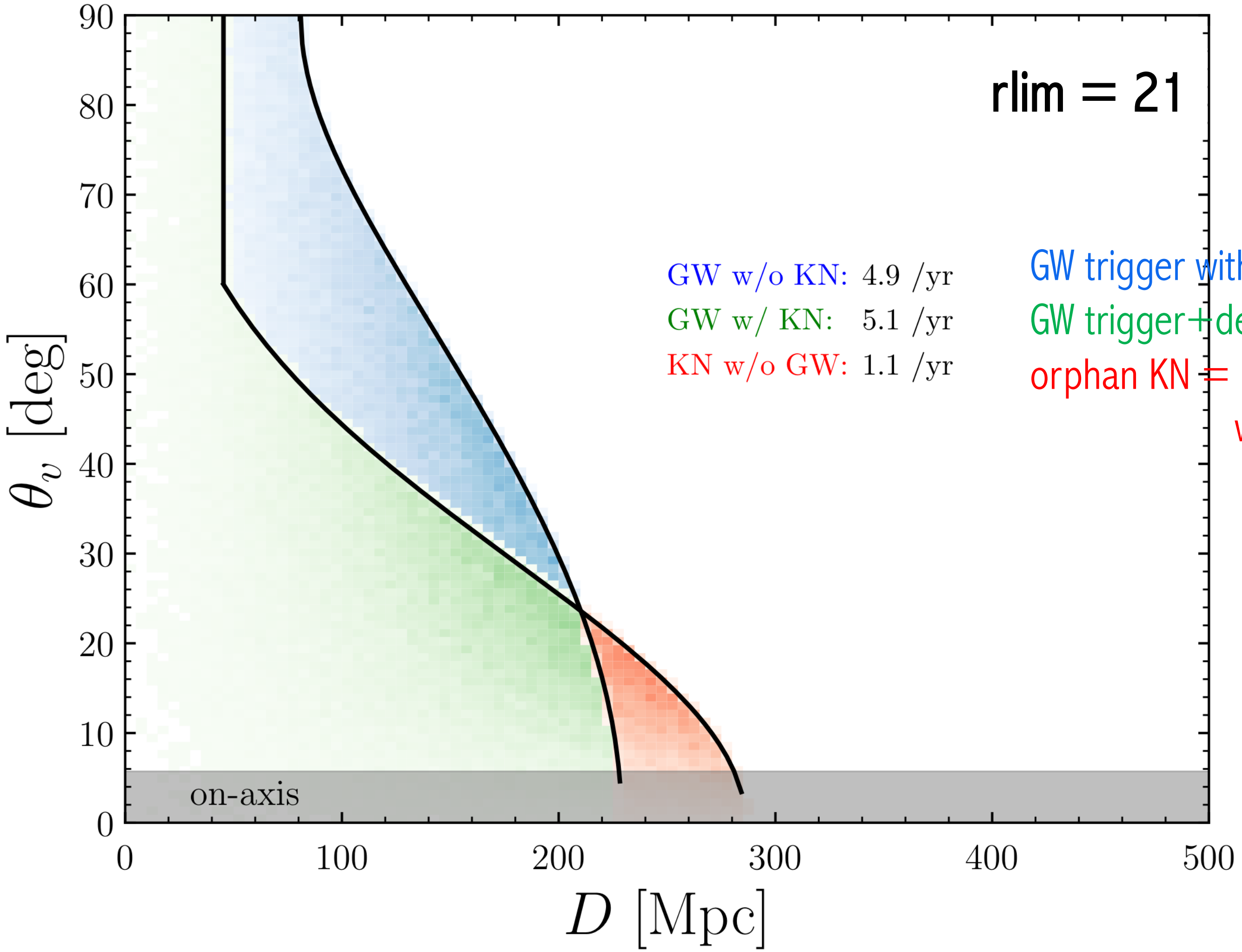
Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) distance-viewing angle plane

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

Orphan KN



Most GW-triggers have a detectable KN

GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN without a GW trigger

=on-axis bright SGRB

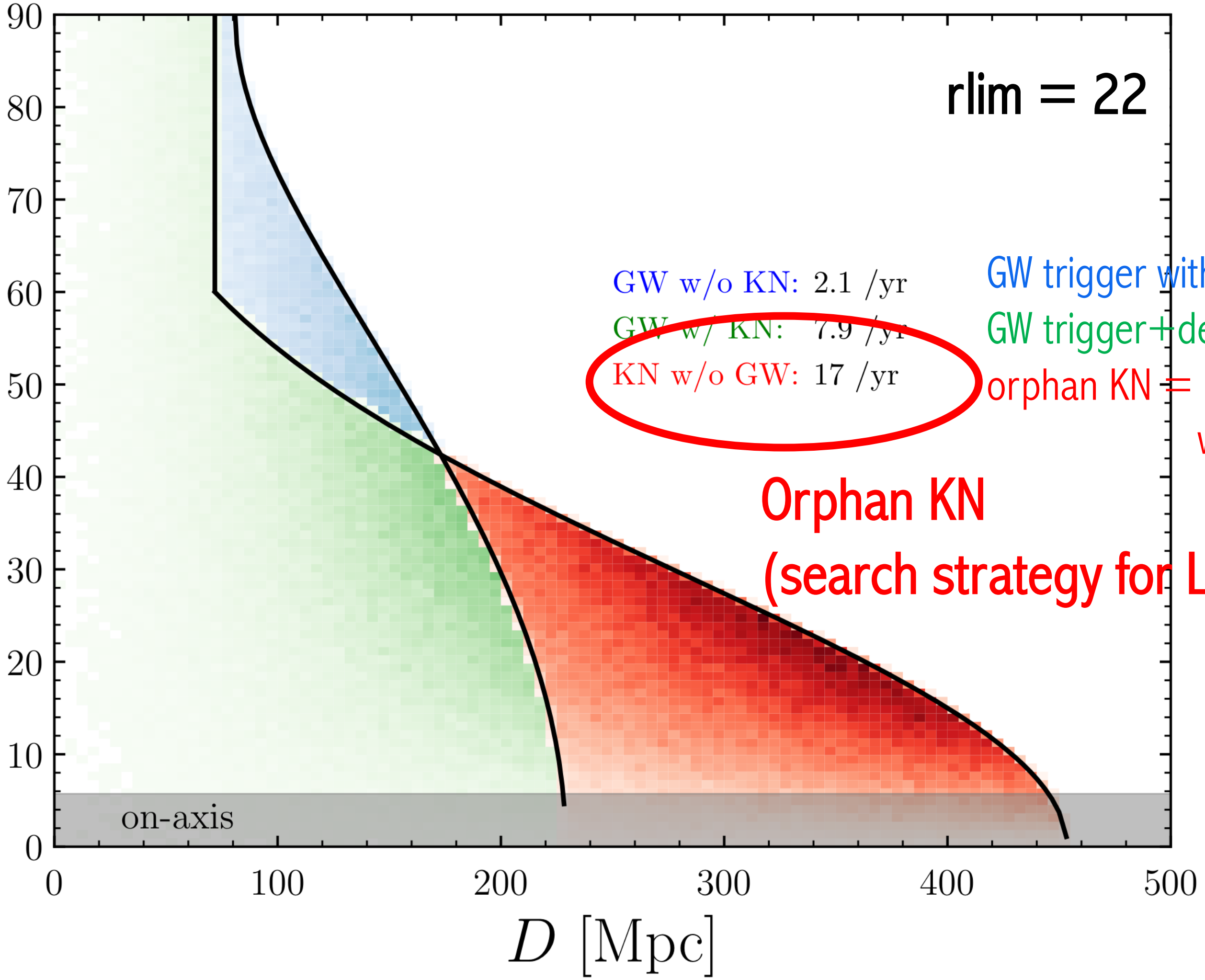
Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) 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

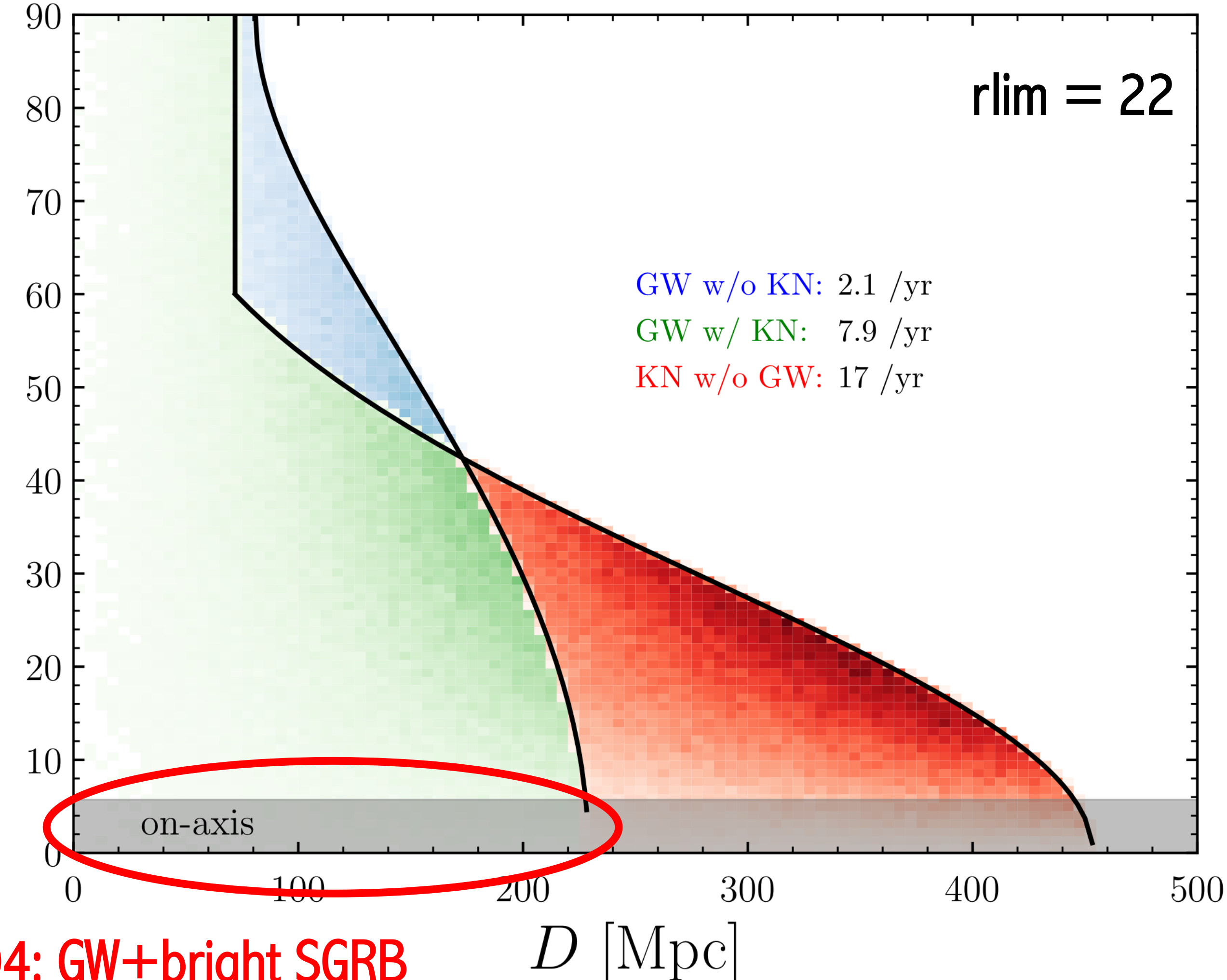
orphan KN = detectable KN without a GW trigger

=on-axis bright SGRB

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) distance-viewing angle plane

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



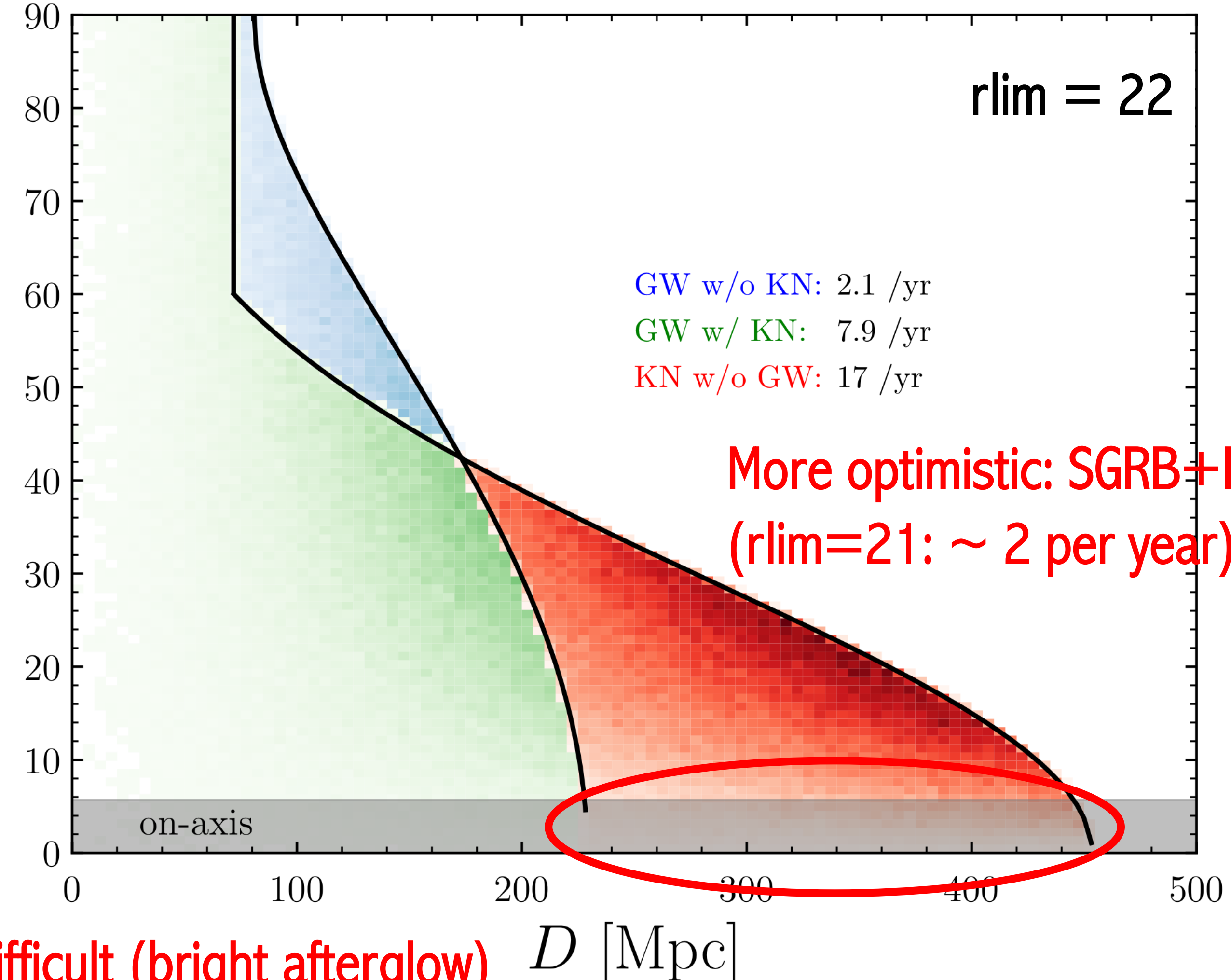
=on-axis bright SGRB

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

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (3) distance-viewing angle plane

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



More optimistic: SGRB+KN w/o a GW trigger (rlim=21: ~ 2 per year)

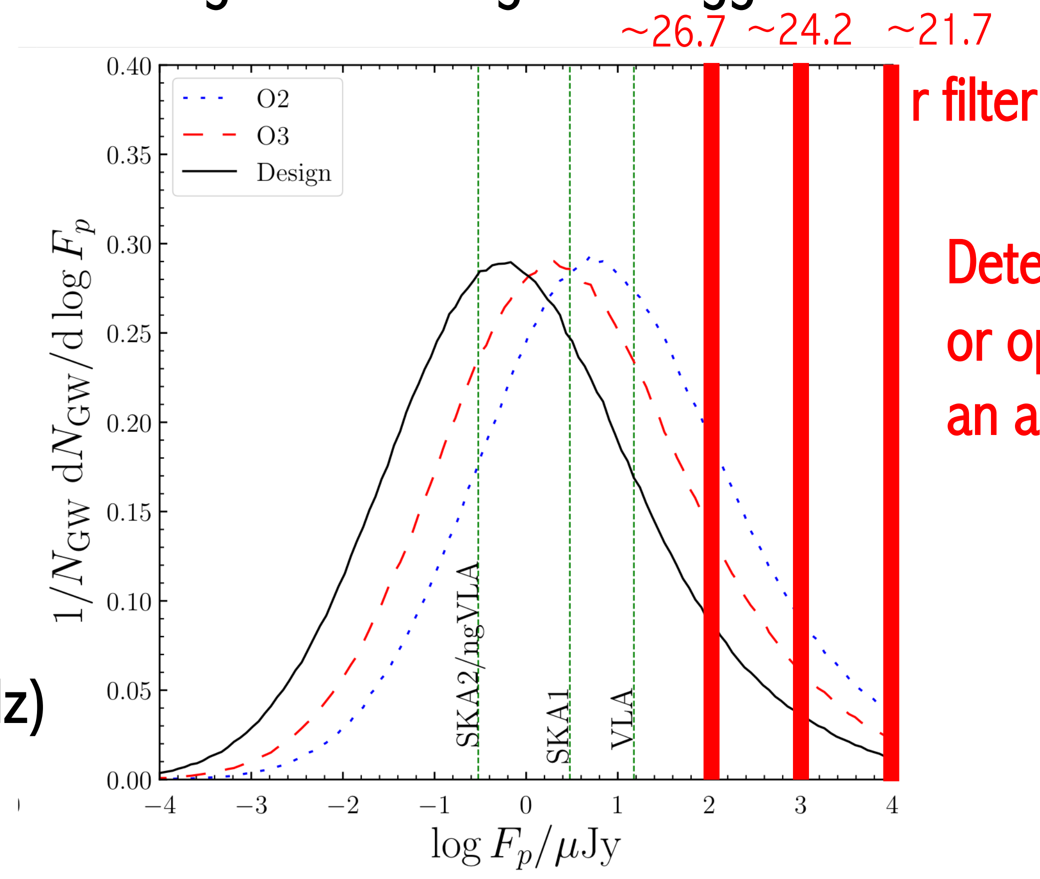
=on-axis bright SGRB

Difficult (bright afterglow) but several candidates (e.g. GRB130603B, Tanvir et al. 13; GRB050709, Lin et al. 16)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: afterglow

Peak flux for afterglows following a GW trigger



Radio (3 GHz)

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

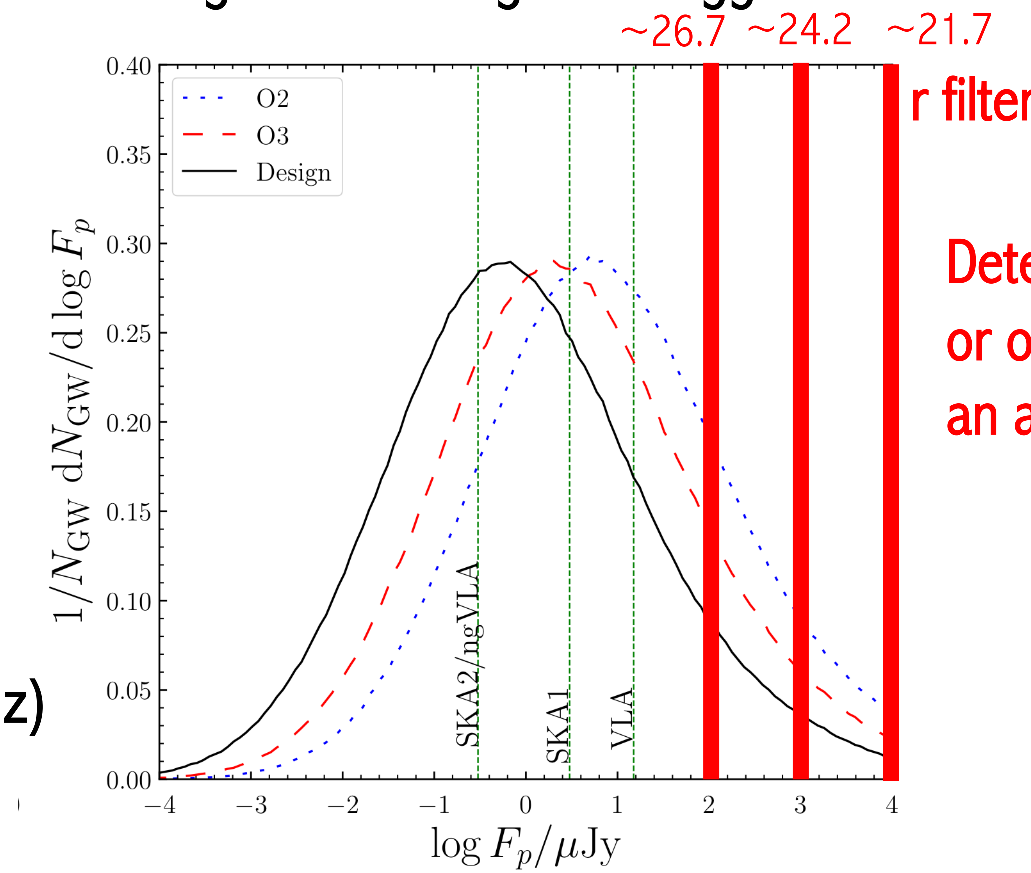
Still: a fraction of AG are brighter than m(r)~24 for O4 and beyond.

To investigate: predictions for orphan afterglows.

Duque, Daigne & Mochkovitch, 2019)

Results: afterglow

Peak flux for afterglows following a GW trigger



Radio (3 GHz)

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

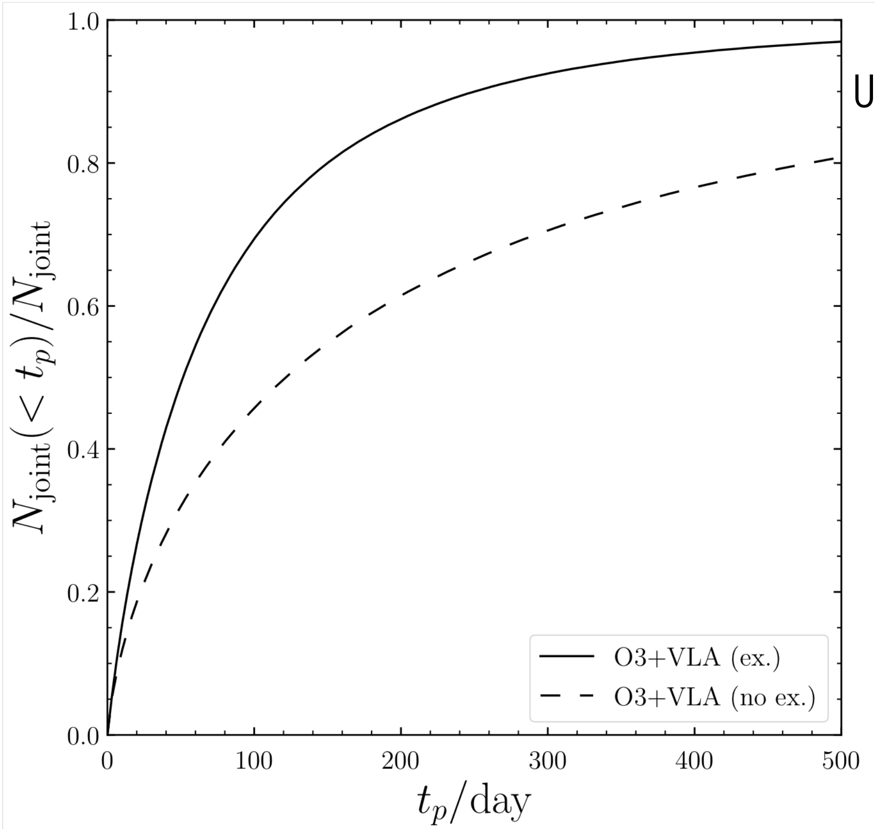
Note that if there is a channel for fast merging BNS, the corresponding afterglows with be brighter (dense external medium)

(see Duque et al. 2020)

Duque, Daigne & Mochkovitch, 2019)

Results: afterglow

Peak time: can be large!



Uncertainty related to late jet dynamics

Strategy for LSST? Cadence may be less an issue than for the KN.

How to identify AG lightcurves: criteria should be based on realistic LC, lateral structure is very important (slope of the slow rise).

Duque, Daigne & Mochkovitch, 2019)

Summary

Duque, Daigne & Mochkovitch, A&A 631, A39 (2019): AG
Mochkovitch, Daigne, Duque & Zitouni, A&A 651, A83 (2021): KN, AG, SGRB
Duque, Beniamini, Daigne & Mochkovitch, A&A 639, A15 (2020): AG and fast merging systems
Mastrogiovanni, Duque, Chassande-Mottin, Daigne & Mochkovitch, A&A (2021): AG and GW-cosmology

- **Kilonovae are the most promising em counterparts to BNS**
  - with rlim = 21 : O4: several detectable KN per year ; O5: >10 detectable KN per year
  - orphan KNae with rlim=21: ~1 per year ; rlim=22: >10 per year
  - SGRB + KN with rlim=21: ~ 2 per year

- **Afterglows are more rare but are extremely important**
  - Following GW+KN (O4+rlim=21+3xVLA sensitivity): 1 to 3 per year, depending on external density
  - Important for jet physics, not enough to have a strong impact on GW-cosmology, useful to probe fast merging systems.

- Short GRBs will remain even rarer as long as the GW horizon does not reach the typical distance of cosmic short GRBs (z=0.5 ?)

- **Observational strategy? Role of Vera Rubin-LSST?**
  - How to identify KN/AG candidates?
  - How to characterize these candidates (photometry/spectroscopy)?
  - Is it possible to detect orphan events (i.e. without a GRB/GW trigger ?)

Perspectives

Kilonovae and afterglows with FINK

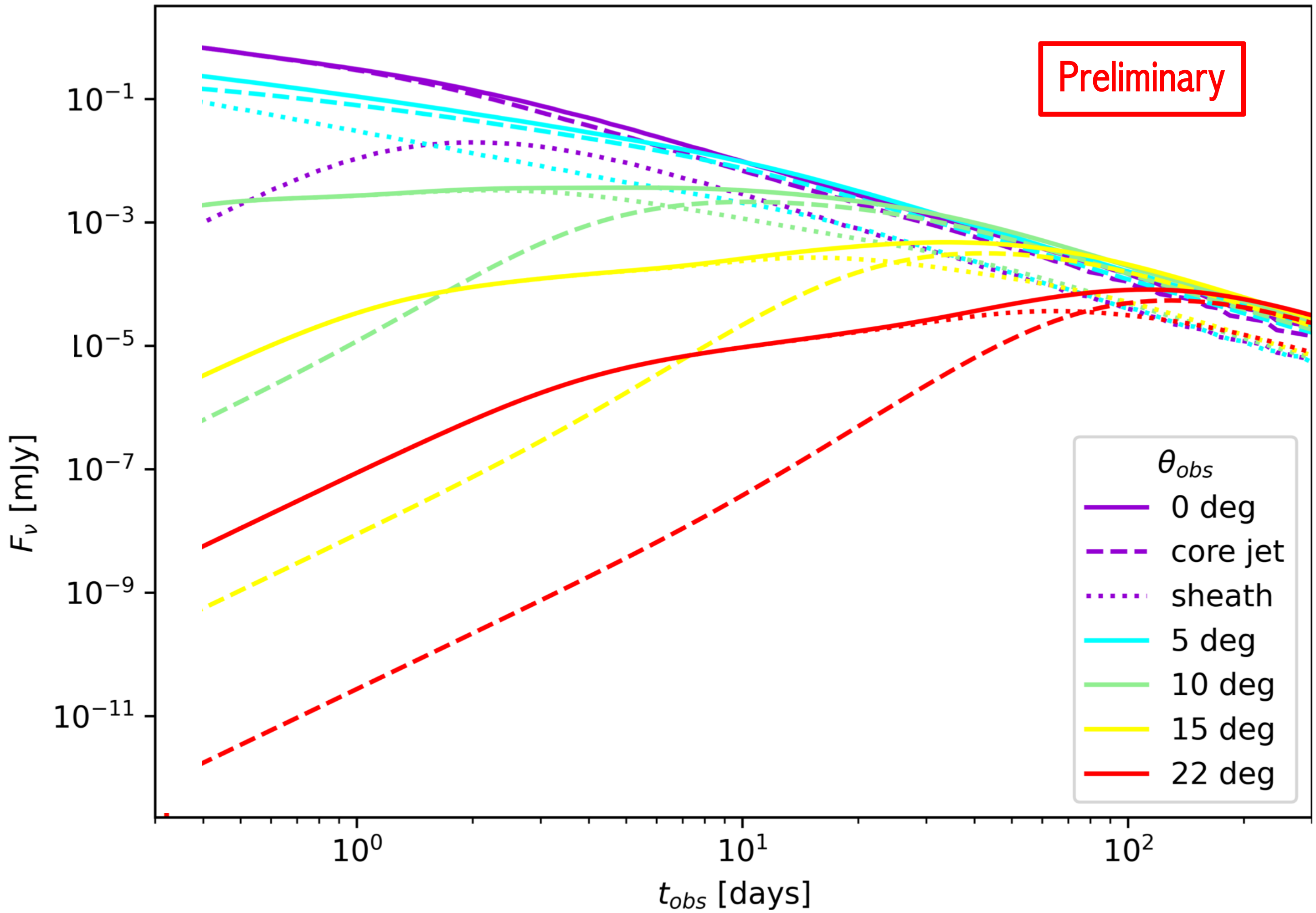
Modelling lightcurves – Filters for KN/AG candidates

Starting project @ IAP led by JG Ducoin with F Daigne (+ C. Pellouin for the AG model)
Already one meeting with FINK team (Julien Peloton, Emille Ishida, Roman Le Montagner)

- **Idea: model realistic lightcurves**
  - **Kilonova**
    - BNS, NSBH?
    - LC dependence on mass (blue KN?), on viewing angle
  - **AG**
    - BNS, NSBH?
    - Also a strong interest for LGRBs (after a GRB trigger or orphan)
    - Strong dependence on several parameters, including the viewing angle, the jet kinetic energy (expected to be larger for LGRBs), the external density (also expected to be higher for LGRBs)
- **Include in population model** (for BNS ; LGRB: work in progress)**: more realistic predictions, influence of lim magnitude, filter, cadence, etc.**
- **Use lightcurves to develop « filters », to train ML-based classification algorithms, etc.**
- **Start with AG (realistic model already available at IAP), KN in a second step**

The afterglow of 170817 at different viewing angles

r filter



Red curve fits 170817

Lateral structure has a strong impact on the rising phase

Figure prepared by JG Ducoin & C. Pellouin

Modelling lightcurves – Filters for KN/AG candidates

Starting project @ IAP led by JG Ducoin with F Daigne (+ C. Pellouin for the AG model)
Already one meeting with FINK team (Julien Peloton, Emille Ishida, Roman Le Montagner)

- Idea: model realistic lightcurves
  - Kilonova
  - AG
- Include in population model: more realistic predictions, influence of lim magnitude, filter, cadence, etc.
- Use lightcurves to develop « filters », to train ML-based classification algorithms, etc.
- Start with AG (realistic model already available at IAP), KN in a second step
- Filters should probably be adapted depending on the available information (GW trigger, GRB trigger, search for orphans)
- Project is just starting, will be a contribution to « INSU ticket » to LSST-France

- See also talks by D. Turpin & J. Bregeon