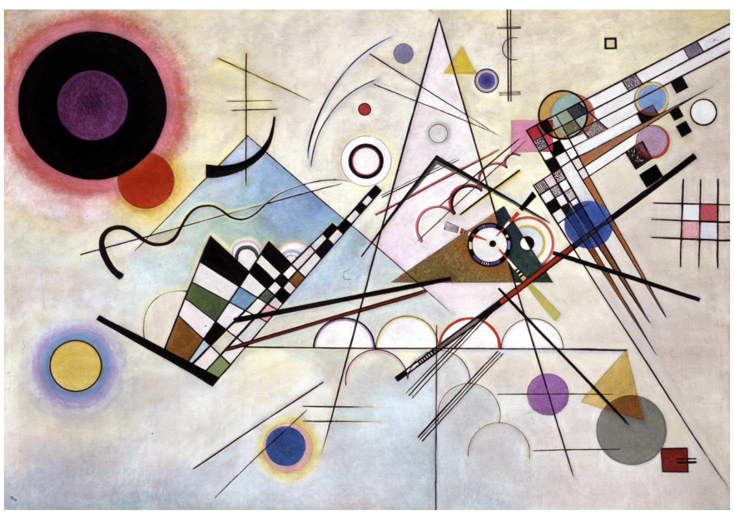
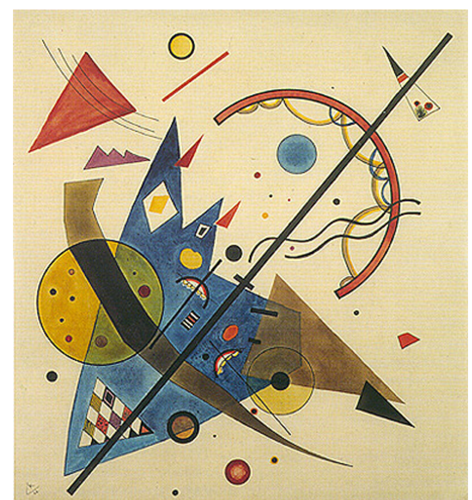
EM counterparts of binary neutron star mergers: perspectives for future detections & MM studies

Frédéric Daigne (Institut d'Astrophysique de Paris)
with Robert Mochkovitch & Raphaël Duque



Kandinksy – Ccomposition 8- 1923

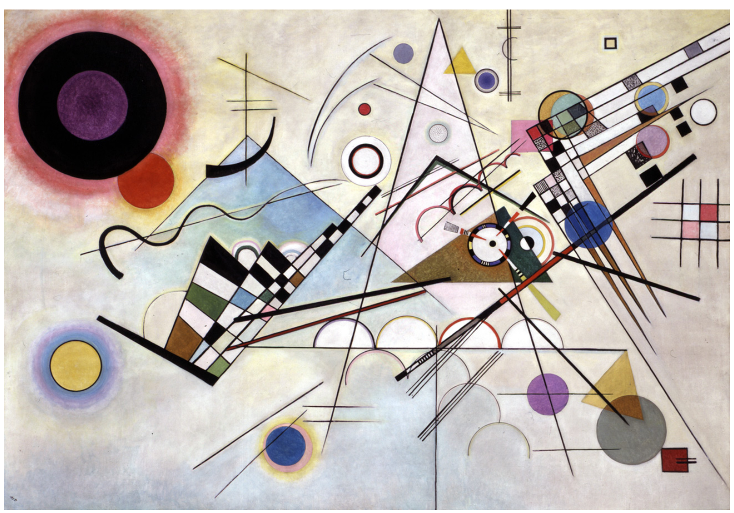


Kandinksy – Curves and sharp angles - 1923

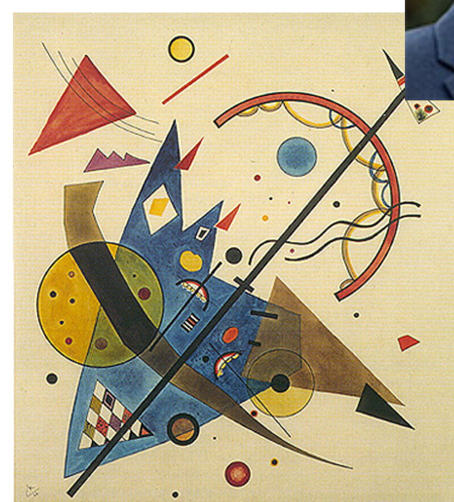
Cinquième assemblée générale du GDR Ondes Gravitationnelles – Mardi 12 octobre 2021 – Annecy

EM counterparts of binary neutron star mergers: perspectives for future detections & MM studies

Frédéric Daigne (Institut d'Astrophysique de Paris)
with Robert Mochkovitch & **Raphaël Duque**



Kandinksy – Ccomposition 8- 1923



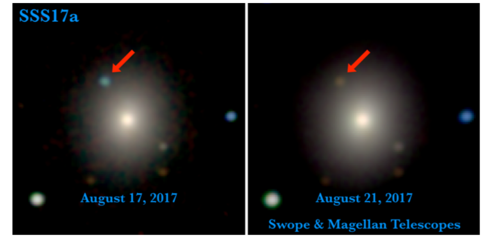
Kandinksy – Curves and sharp angles -

Cinquième assemblée générale du GDR Ondes Gravitationnelles – Mardi 12 octobre 2021 – Annecy

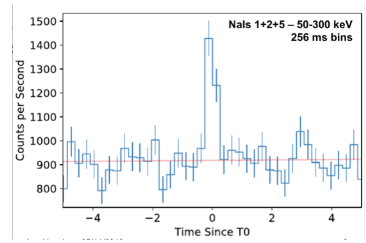
BNS: EM counterparts

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

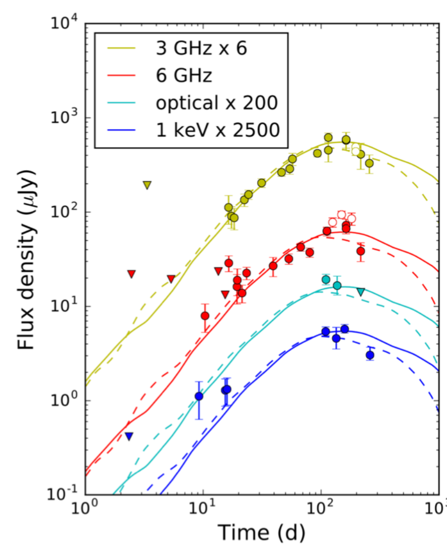
GW170817: detected (red+blue)

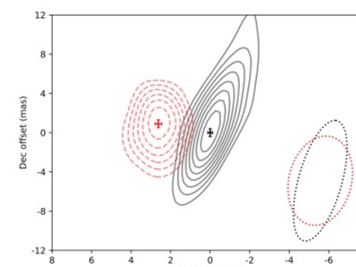


- Short GRB: -bright SGRB from the core jet — GW170817: not detected
  -weak SGRB from the jet's sheath — GW170817: detected
  (Matsumoto et al. 2019)



- Afterglow: (AG: multi-λ, photometry, VLBI?) — GW170817: detected (with VLBI)





- Kilonova afterglow?

Motivation for a population model

- MM event EM+GW: just a single case (GW170817=GW+KN+SGRB+AG), huge number of major results

  How many MM events in the future? With what EM signals?
  What science will be possible with these events?

- O3: at least another BNS, no em counterpart

  Is it expected? What information can bring a non-detection?

- O3: at least two NSBH, no em counterpart (expected with this mass ratio/BH spin)

  In the future, NSBH with em counterparts?

- When detections will become more frequent: properties of the underlying population?

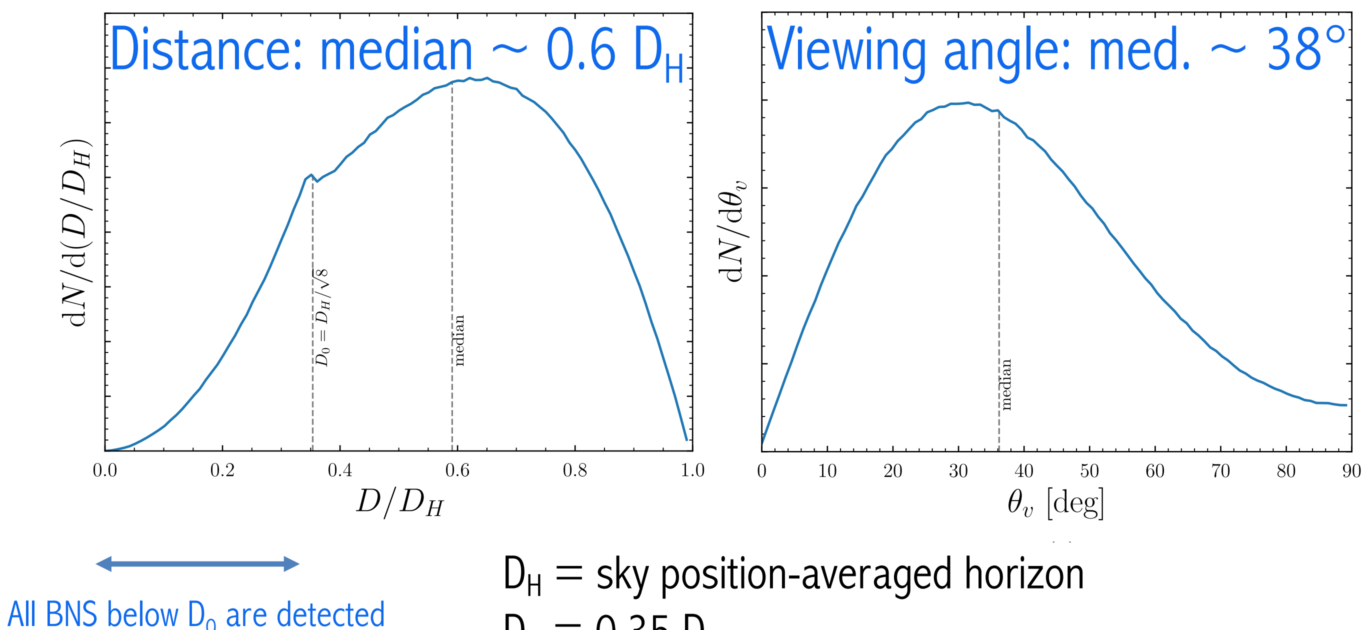
  Selection effects must be understood.

How lucky were we to observe 170817?

- Rate of BNS merger within 40 Mpc: 1 event every 12_{-7}^{+36} years (80-800 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$)
- GW point of view: no strong selection, can now be detected under any viewing angle

Simplified GW detection criterion: $$\frac{D}{D_H} \leq \sqrt{\frac{1 + 6\cos^2\theta_v + \cos^4\theta_v}{8}}.$$ (Schutz 2011)

Properties of detected BNS (GW only):



D_H = sky position-averaged horizon
$D_0 = 0.35\ D_H$

Mochkovitch, Daigne, Duque & Zitouni, 2021

How lucky were we to observe 170817?

- Rate of BNS merger within 40 Mpc: 1 event every 12_{-7}^{+36} years
- GW point of view: no strong selection, can now be detected under any viewing angle
- **EM point of view: 170817 view. Angle < 18-20°** (VLBI, Mooley et al. 18, Ghirlanda et al. 19)
  -KN was probably detectable under any viewing angle
  -radio AG + source proper motion detectable up to ~40° (Duque, Daigne & Mochkovitch 19)
  -short GRB detectable up to 18-20°? (170817 already very weak in Fermi/GBM)

  If we require a viewing angle < 40° to have a rich dataset (KN+AG+VLBI):
  1 event every 50_{-31}^{+149} years.

  If we require a view. angle <18-20° to have a exceptional 170817-like dataset (KN+SGRB+AG): 1 event every 239_{-146}^{+713} years…
- **What can we expect with the new sensitivity of GW detectors?**
  How the sensitiviy of EM detectors should adapt?

Mochkovitch, Daigne, Duque & Zitouni, 2021

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:

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

$M_{\lambda,0}$: Polar observer (θ_v=0)

ΔM_λ: Amplitude of polar effect

δM_λ: 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

$\theta_0 = 60^\circ$

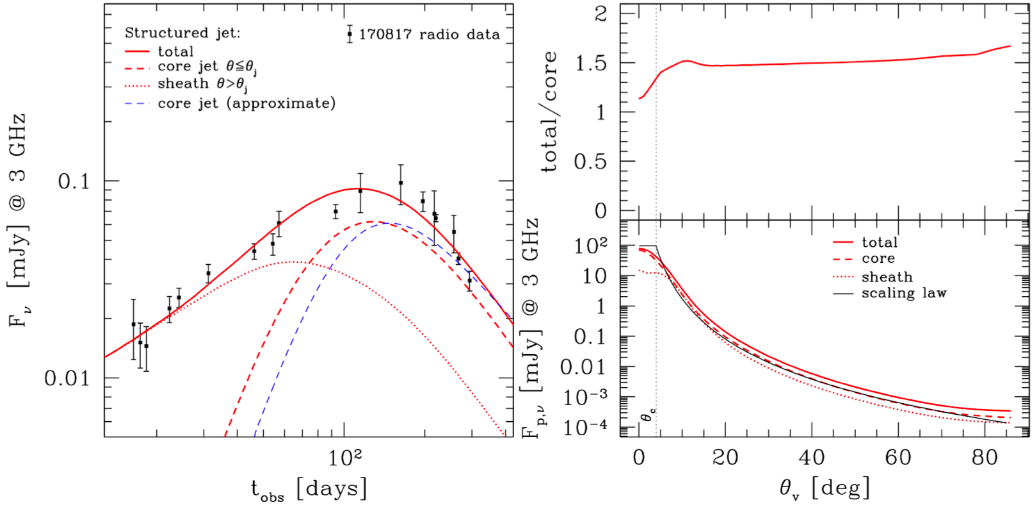
calibrated with 170817

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)
- **Radio 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})



Population model: ingredients

- BNS: uniform rate in the local Universe

- Kilonova: red + blue KN (Mochkovitch, Daigne, Duque & Zitouni, 2021)

- Radio afterglow (Duque, Daigne & Mochkovitch, 2019)

- **Kilonova and Radio 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

- Radio afterglow

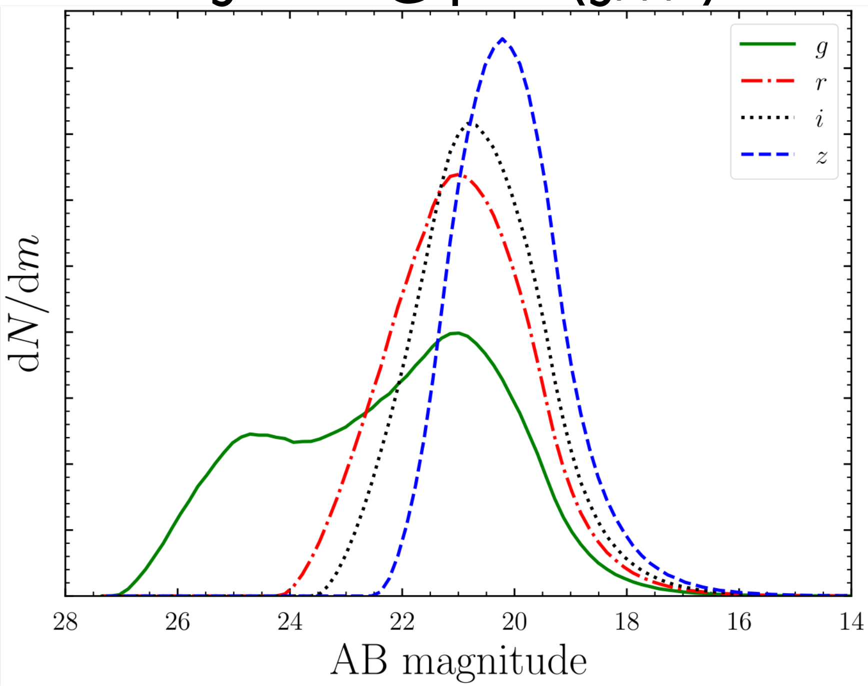
- **Short GRB:** (Mochkovitch, Daigne, Duque & Zitouni, 2021)
  - **Bright SGRB (core jet):**
    strong relativistic beaming: requires on-axis observer ($\theta_v < \theta_j = 0.1$ rad)
    BUT:
    with $L_{peak} > 10^{50}$ erg/s and $E_p \sim 1$ MeV: always detectable up to 600 Mpc
    (limitation=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

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

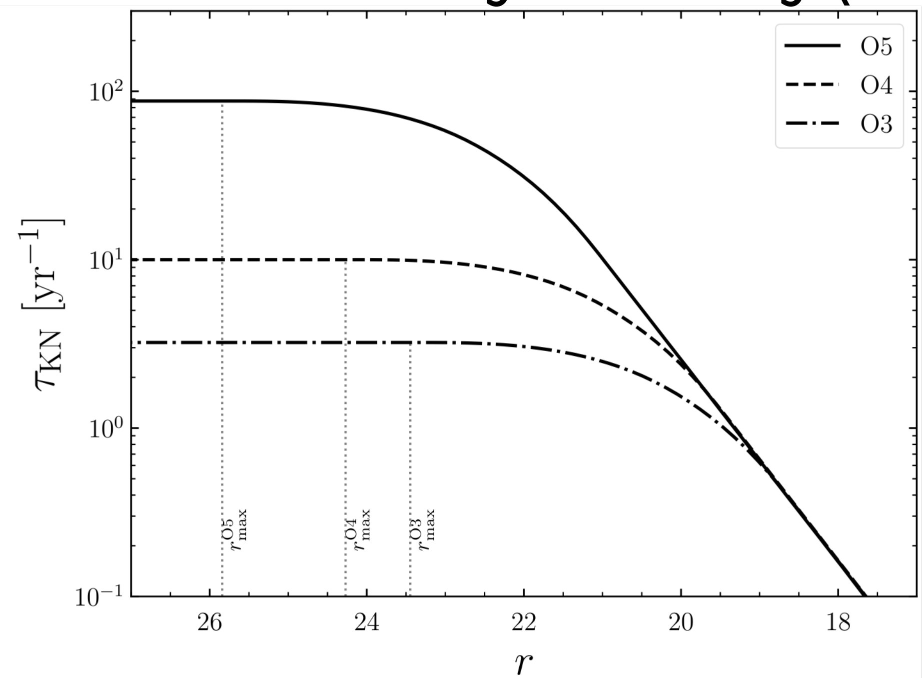
Results: kilonovae (1) magnitude

GW-detected BNS (O4):

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



KN rate above a given limit mag. (rlim)



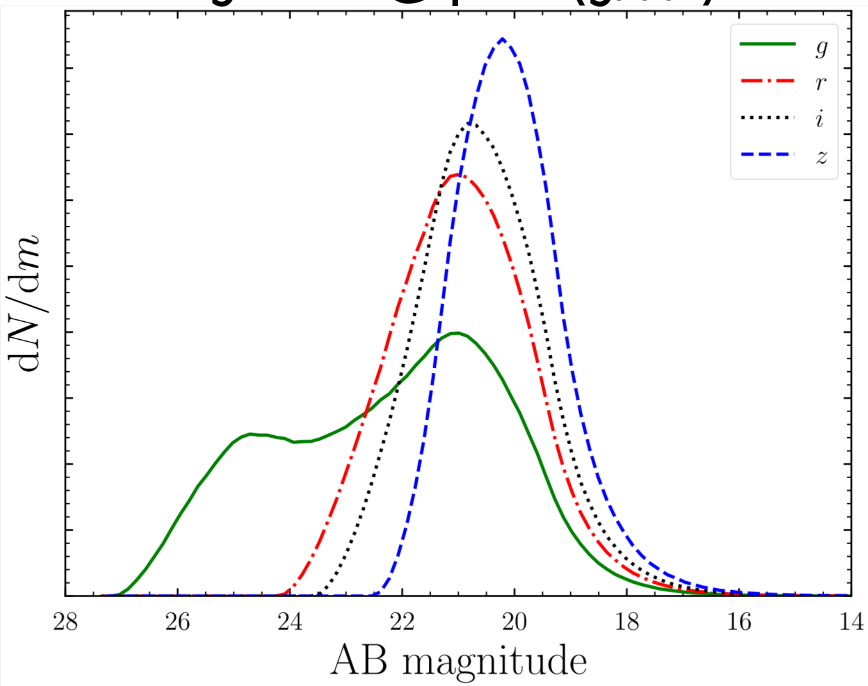
Mochkovitch, Daigne, Duque & Zitouni, 2021

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

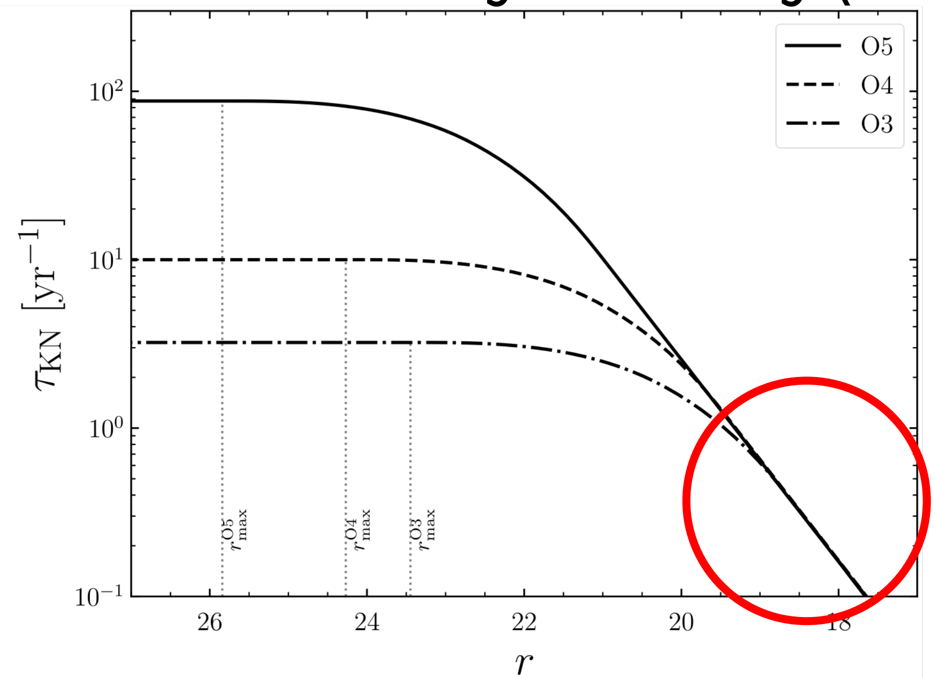
Results: kilonovae (1) magnitude

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

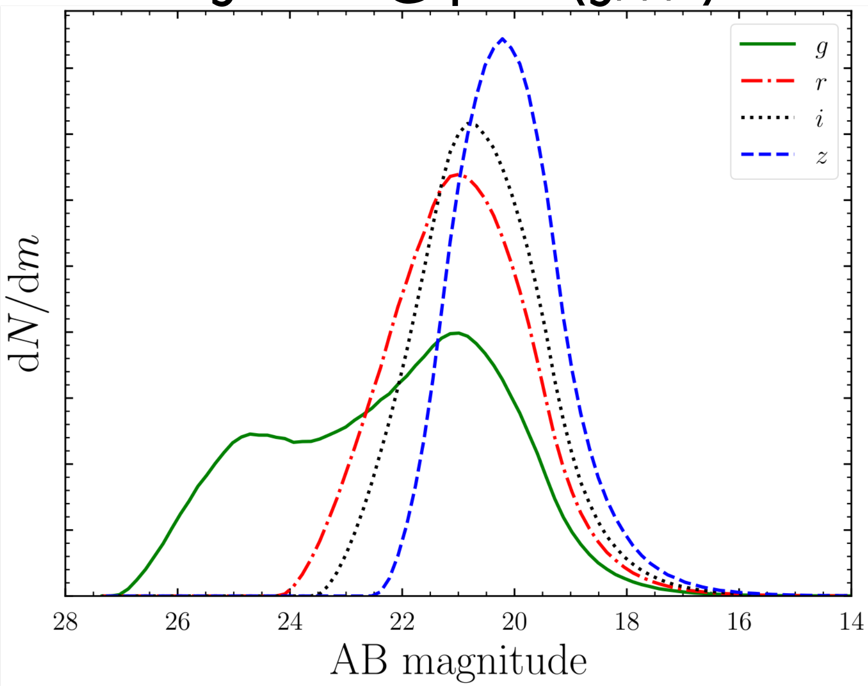
Mochkovitch, Daigne, Duque & Zitouni, 2021

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

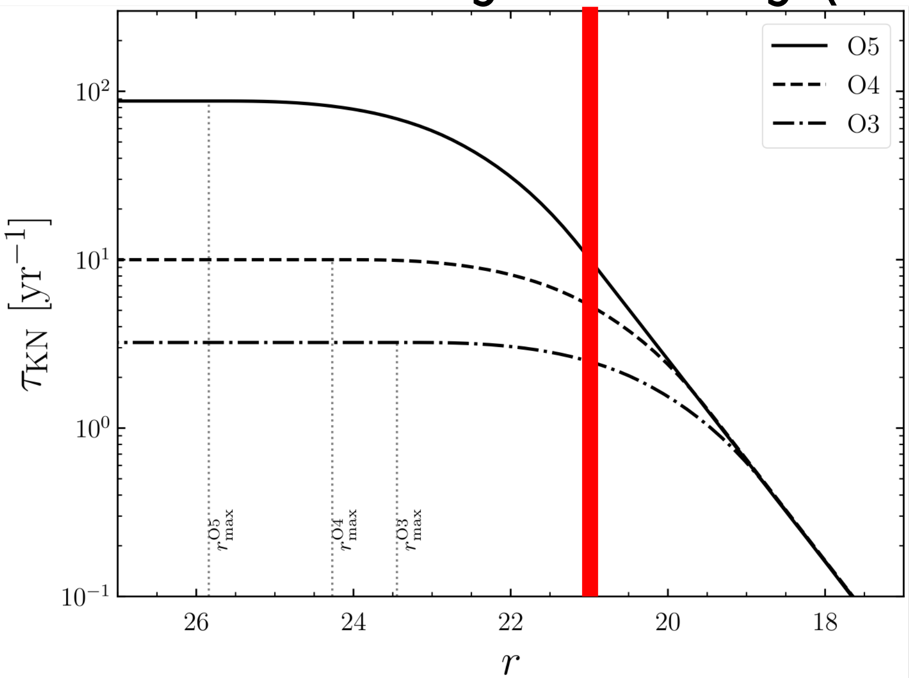
Results: kilonovae (1) magnitude

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

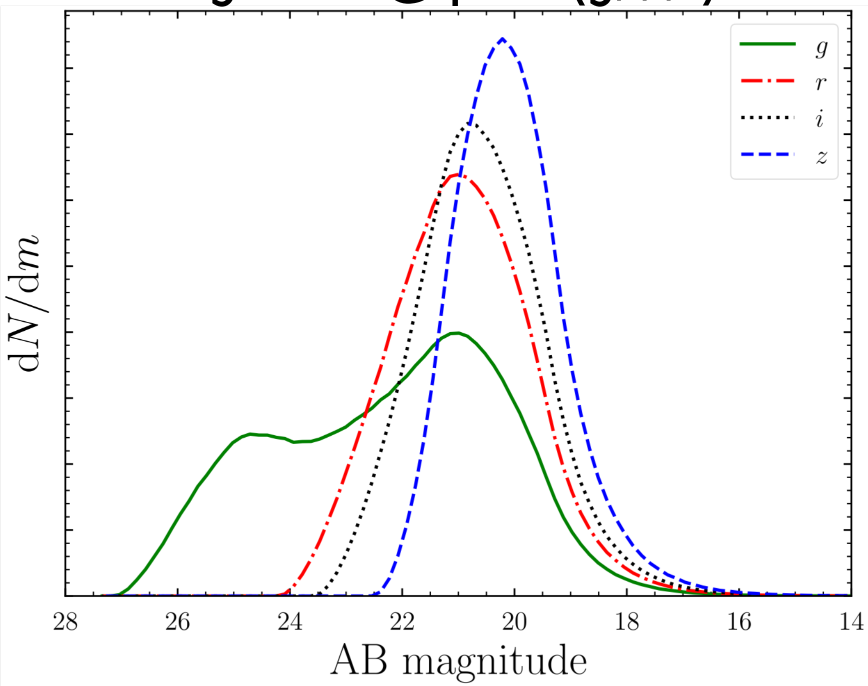
Detectable → Detected: strategy? (ZTF+LSST/Vera Rubin+follow-up telescopes...)

Mochkovitch, Daigne, Duque & Zitouni, 2021

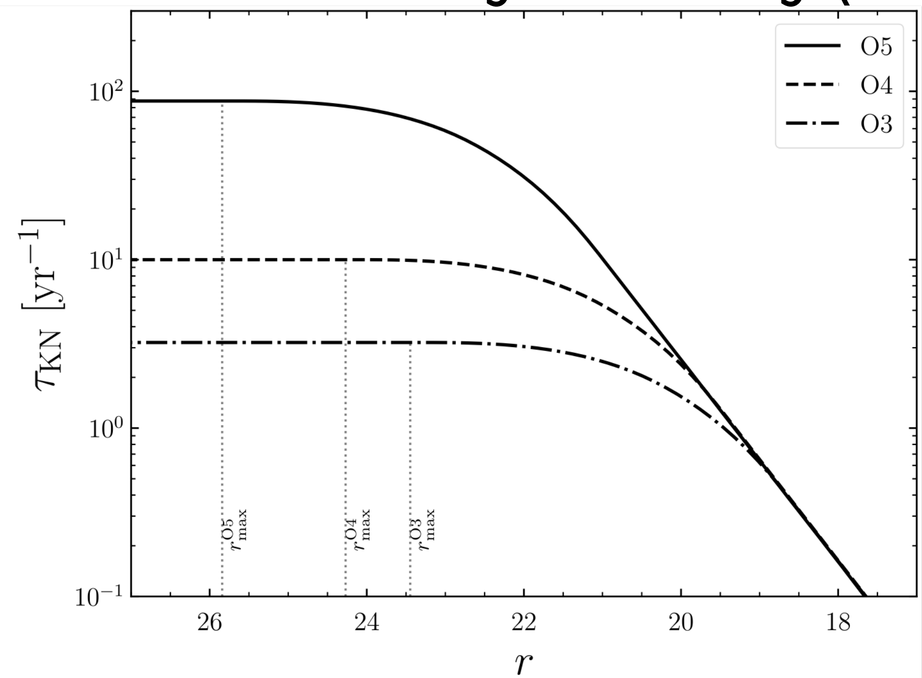
Results: kilonovae (1) magnitude

GW-detected BNS (O4) :

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



KN rate above a given limit mag. (rlim)



Caveats:

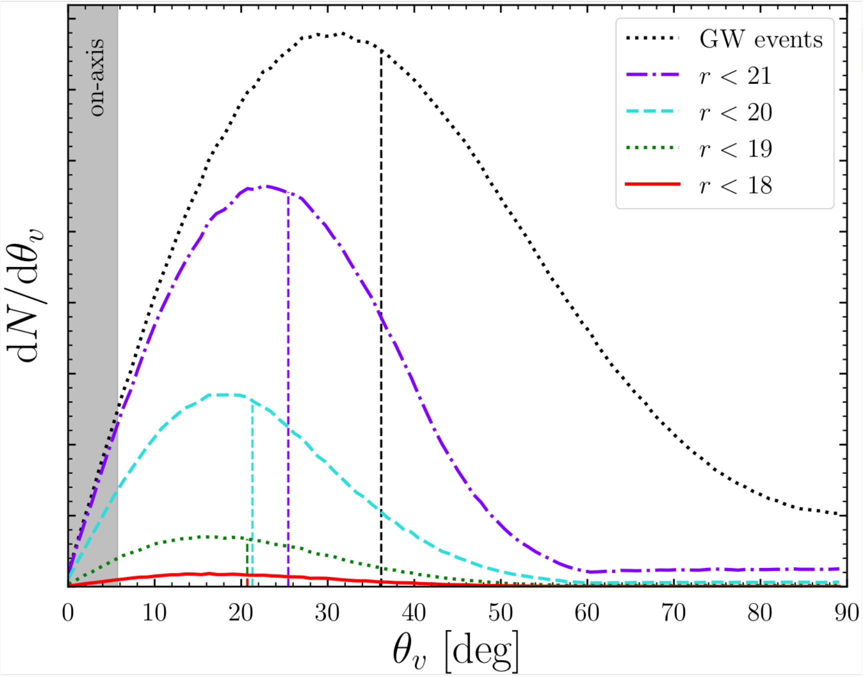
- calibrated on a single event (170817)
- Blue KN may be present only in a fraction of BNS:
  can reduce the rates, especially in the visible

(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)

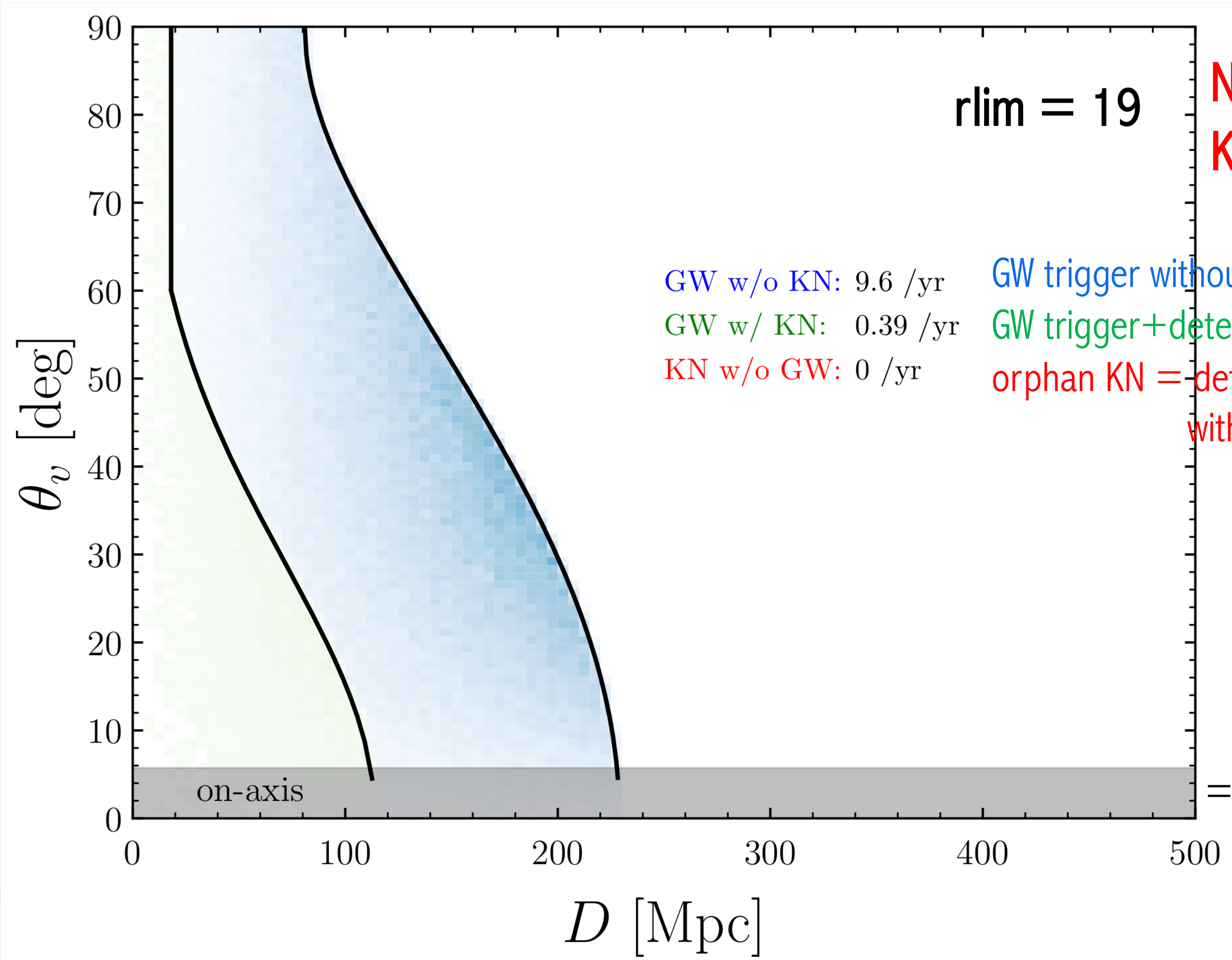
Cosmology: when detected, the afterglow can bring a strong constraint on the viewing angle, but afterglows are very rare.
Important goal: a sample of kilonova would allow to calibrate the mag/color vs viewing angle for kilonovae.

(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

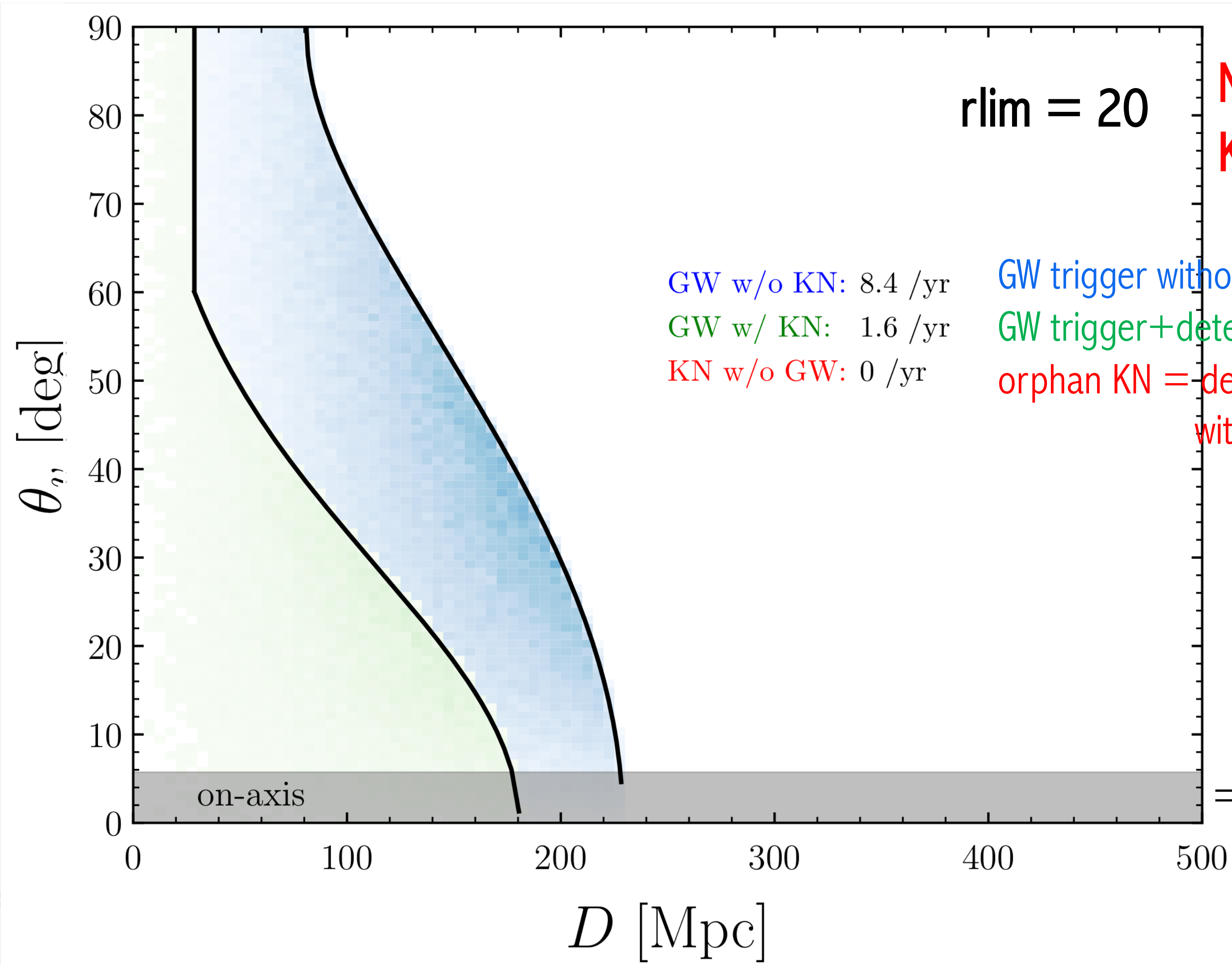
orphan KN = detectable KN without a GW trigger

=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

GW trigger+detectable KN

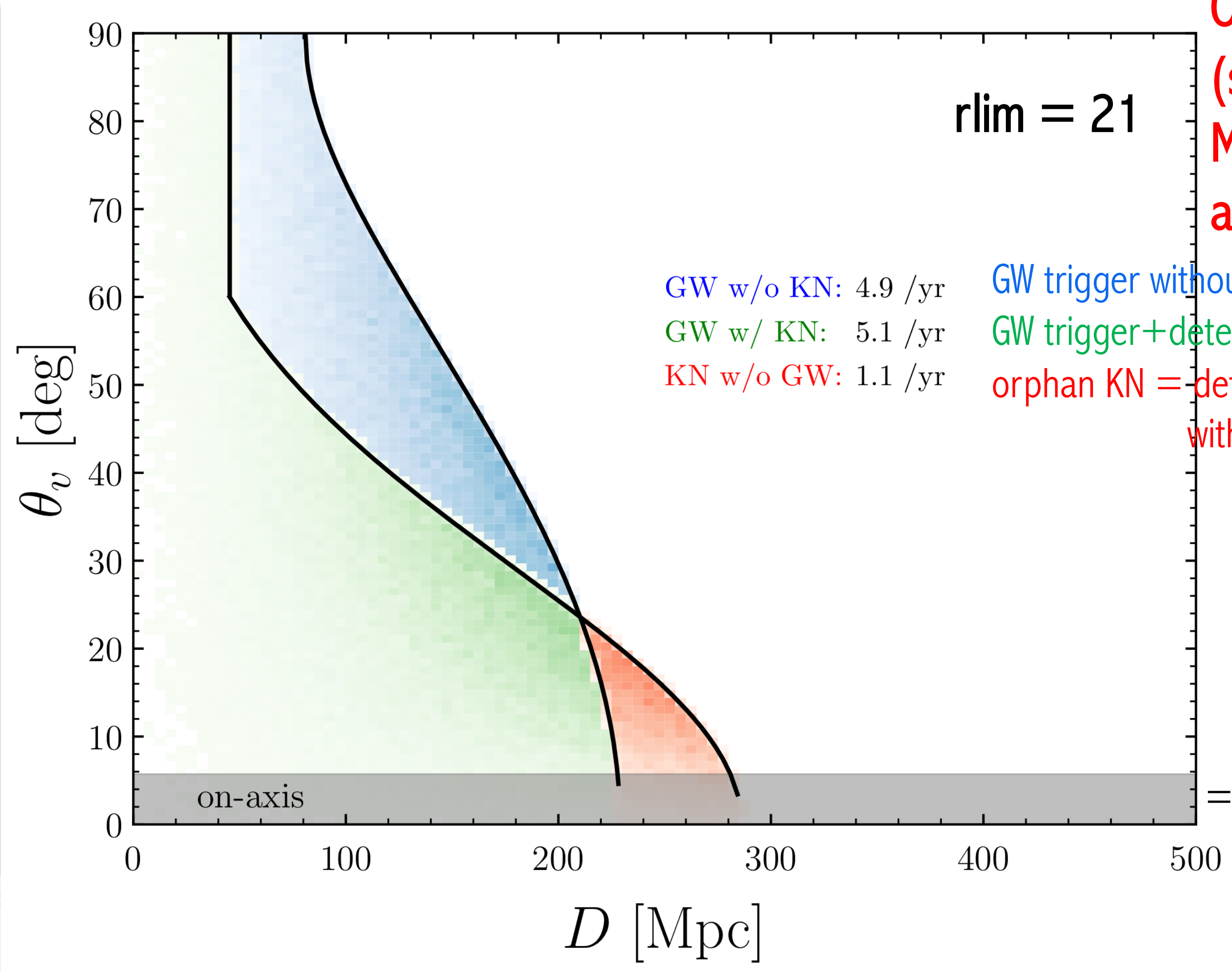
orphan KN = detectable KN without a GW trigger

=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
(search strategy?)
Most GW-triggers have a detectable KN

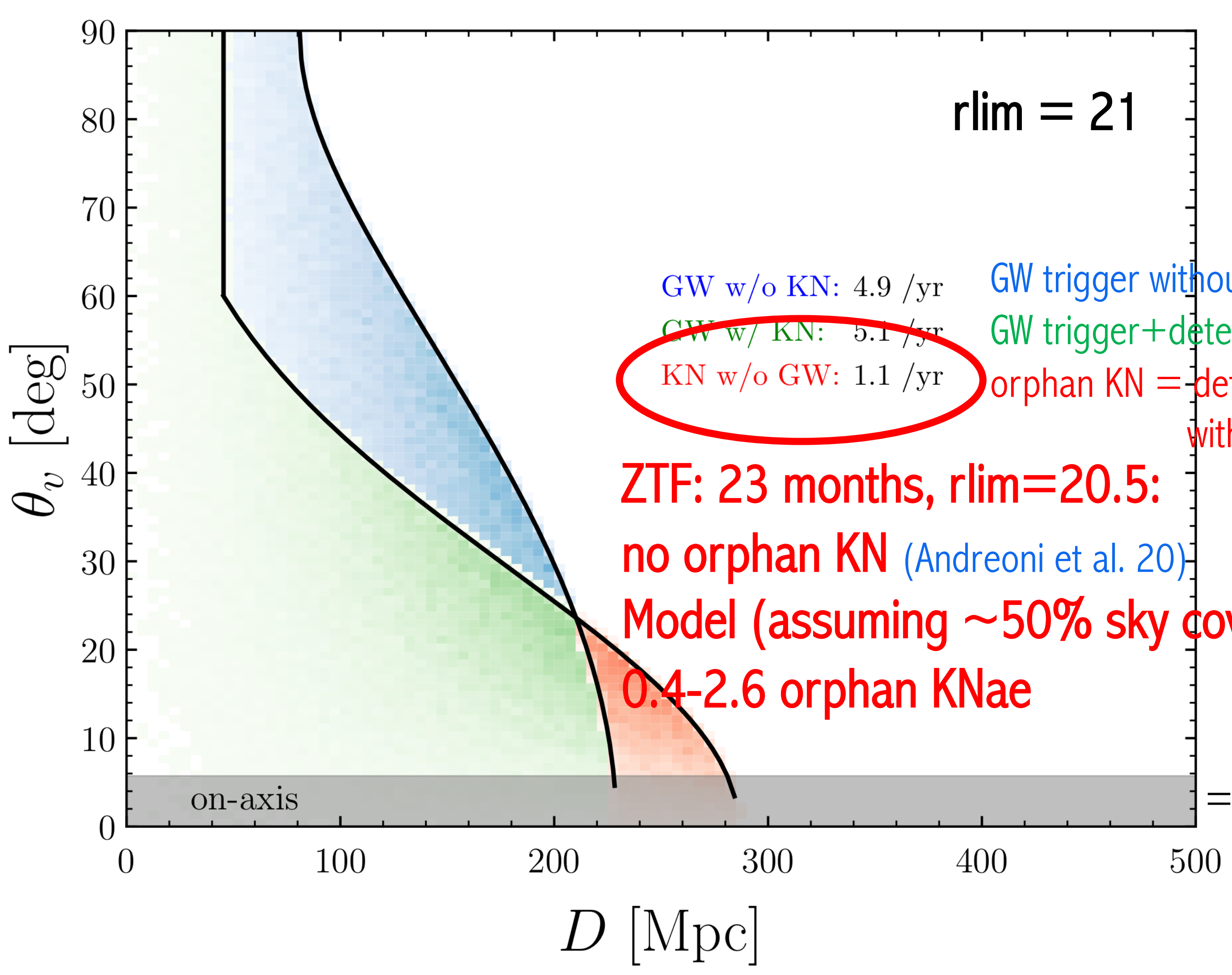
GW trigger without a detectable KN
GW trigger+detectable KN
orphan KN = detectable KN without a GW trigger

=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



GW trigger without a detectable KN

GW trigger+detectable KN

orphan KN = detectable KN without a GW trigger

=on-axis bright SGRB

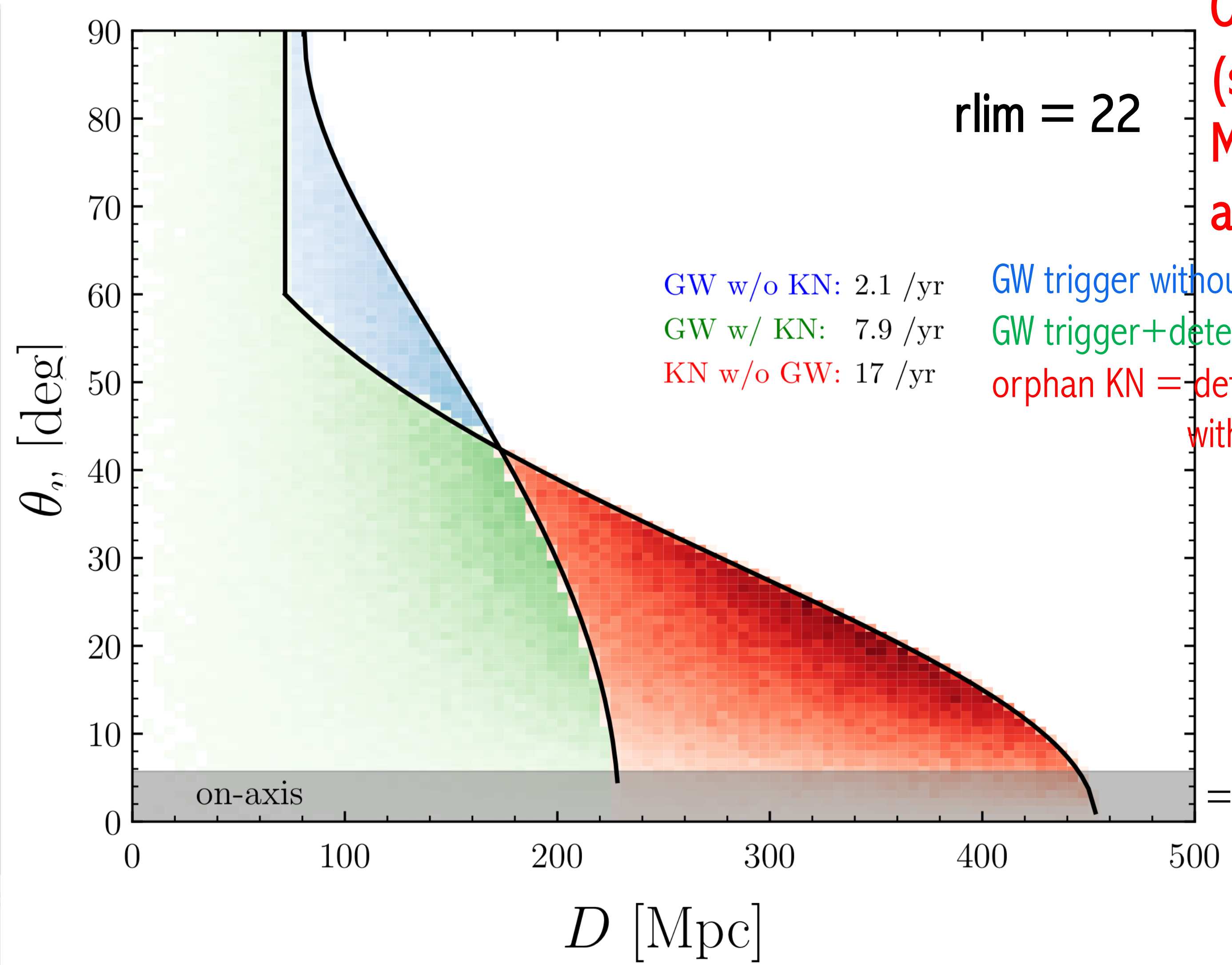
ZTF: 23 months, rlim=20.5: no orphan KN (Andreoni et al. 20)

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

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 (search strategy?)
Most GW-triggers have a detectable KN

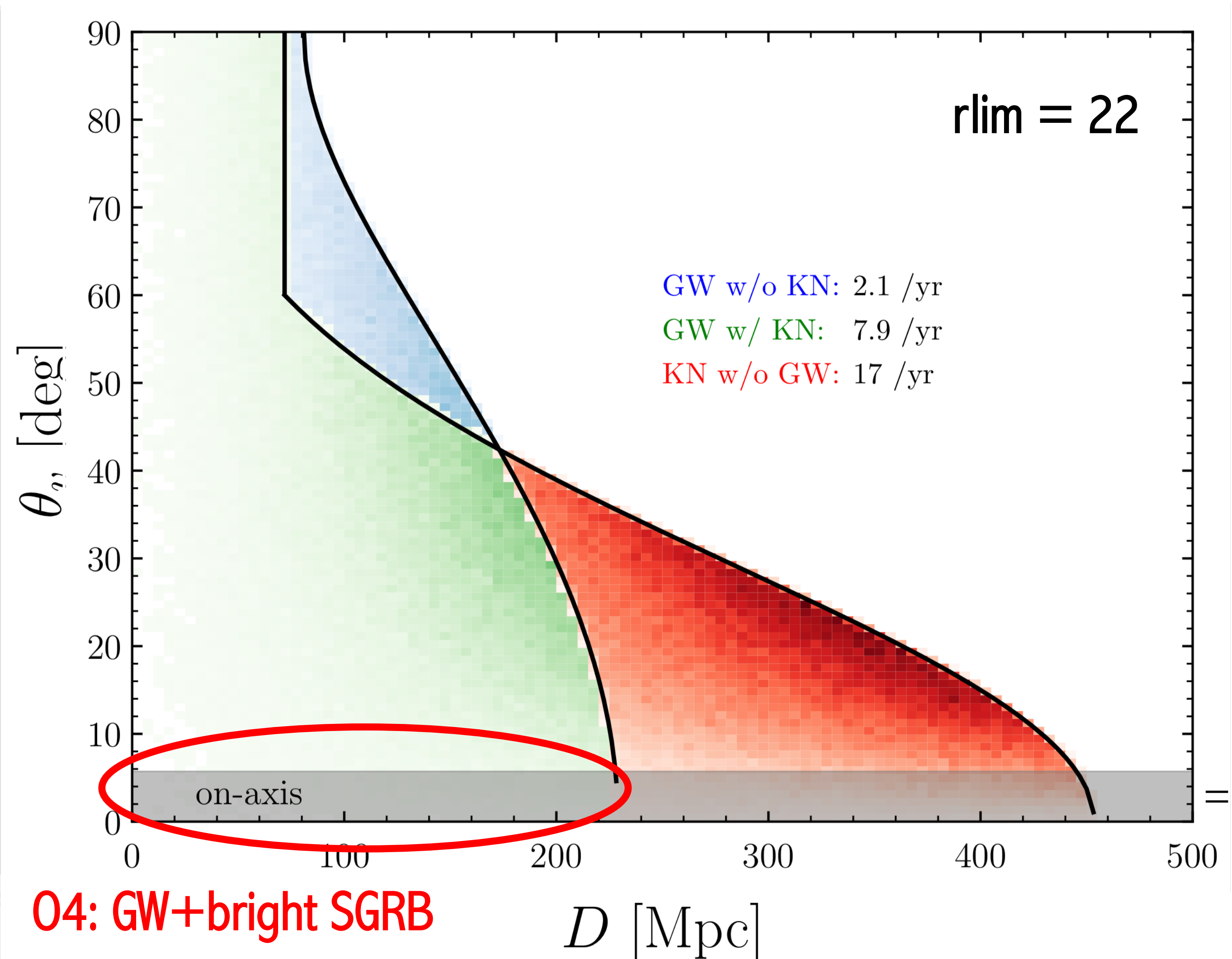
GW trigger without a detectable KN
GW trigger+detectable KN
orphan KN = detectable KN without a GW trigger

=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

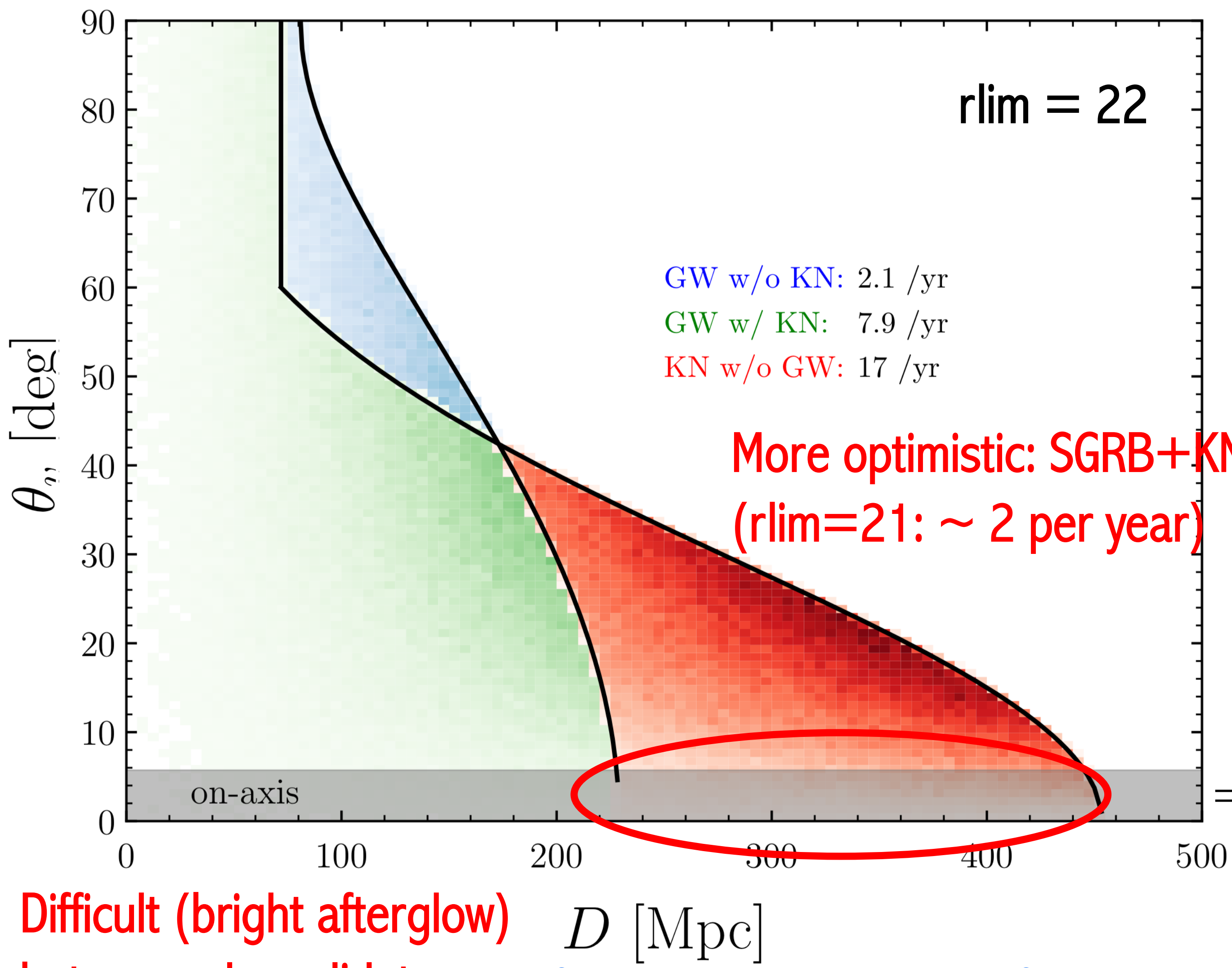


O4: GW+bright SGRB
are very rare! (1 very 5-20 years in whole sky)

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



=on-axis bright SGRB

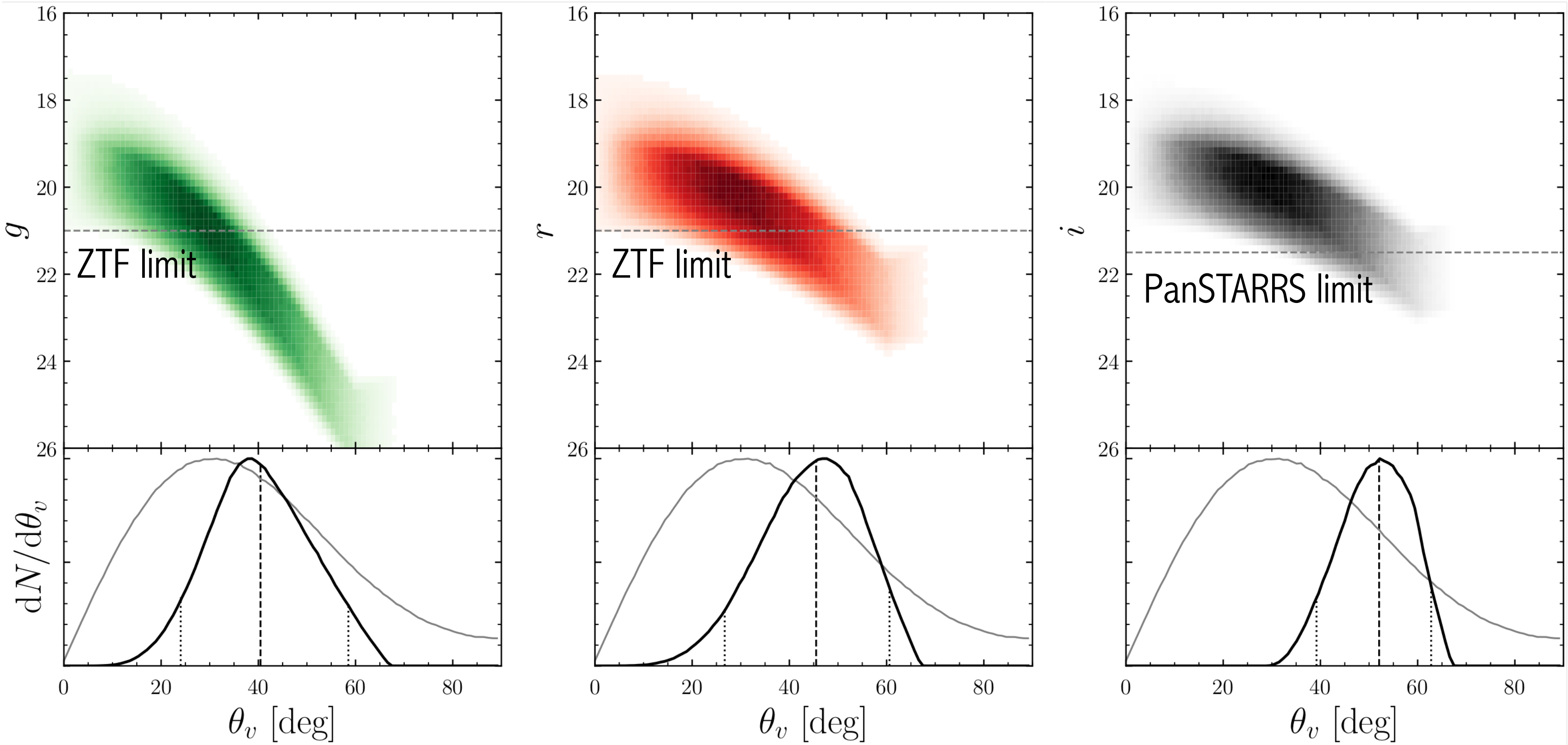
More optimistic: SGRB+KN w/o a GW trigger (rlim=21: ~ 2 per year)

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

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: kilonovae (4) no detection case

GW190425: magnitude vs viewing angle plane

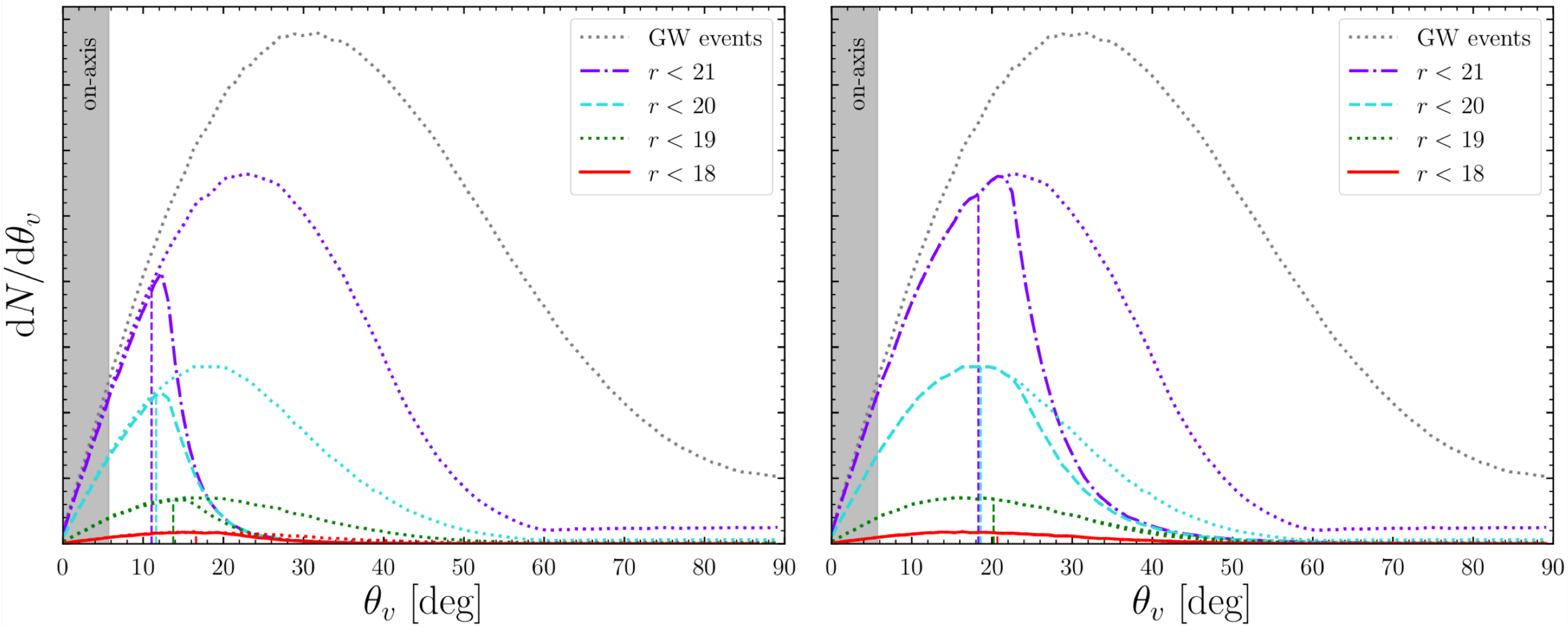


- GW detection: viewing angle cannot be too large
- No KN detection: viewing angle cannot be too small
- Most constraining = i band : viewing angle = 50±10°
- Caveats: (1) only ~30% of the error box (7500 deg^2) was covered by these deep searches; (2) High chirp mass: if no blue KN, no constraint.

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: radio afterglow associated to GW+KN events

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)

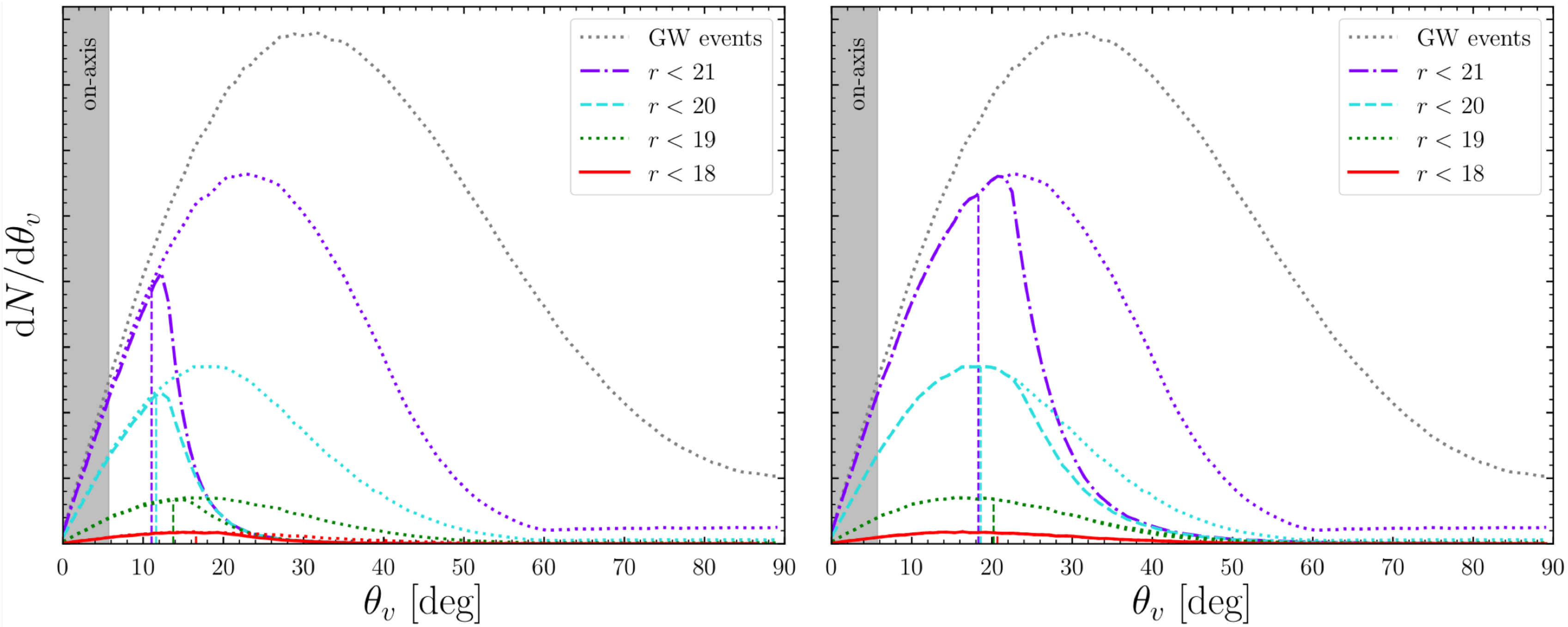
Brighter afterglows: dense environments	
rlim	detectable AG
19	97% (0.5 per year)
20	81% (1.5 per year)
21	59% (2.9 per year)

More details on the properties of detectable afterglows (peak time, VLBI?, …): see Duque, Daigne & Mochkovitch 2019 (includes AG w/o KN)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: radio afterglow associated to GW+KN events

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



Standard prescription

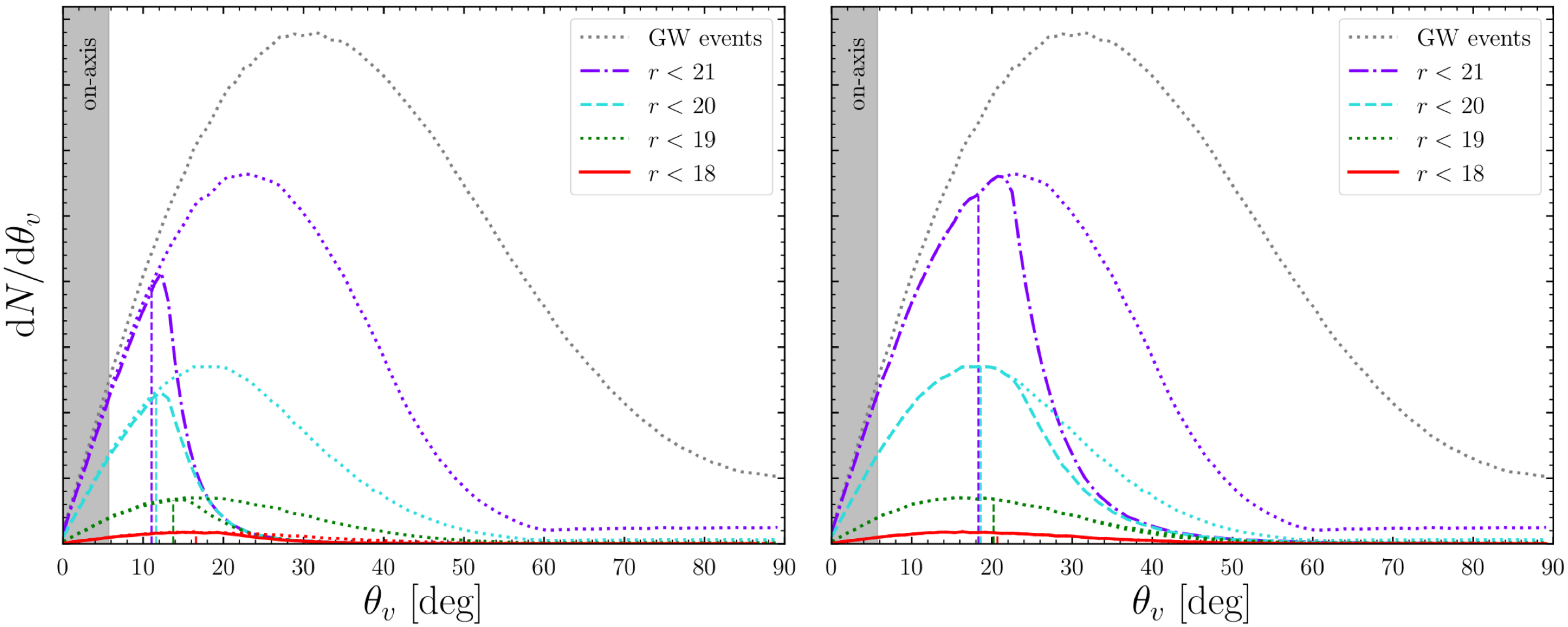
Brighter afterglows: dense environments

- Dense environments are expected for fast merging systems
- Several arguments for a population of short merger times
  (e.g. early enrichment in r-elements, see Vangioni, Goriely, Daigne, François & Belcynski 2017 and Dvorkin, Daigne, Goriely, Vangioni & Silk 2021)
- Afterglow statistics can reveal this population!
  (see discussion in Duque, Beniamini, Daigne & Mochkovitch 2020)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: radio afterglow associated to GW+KN events

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



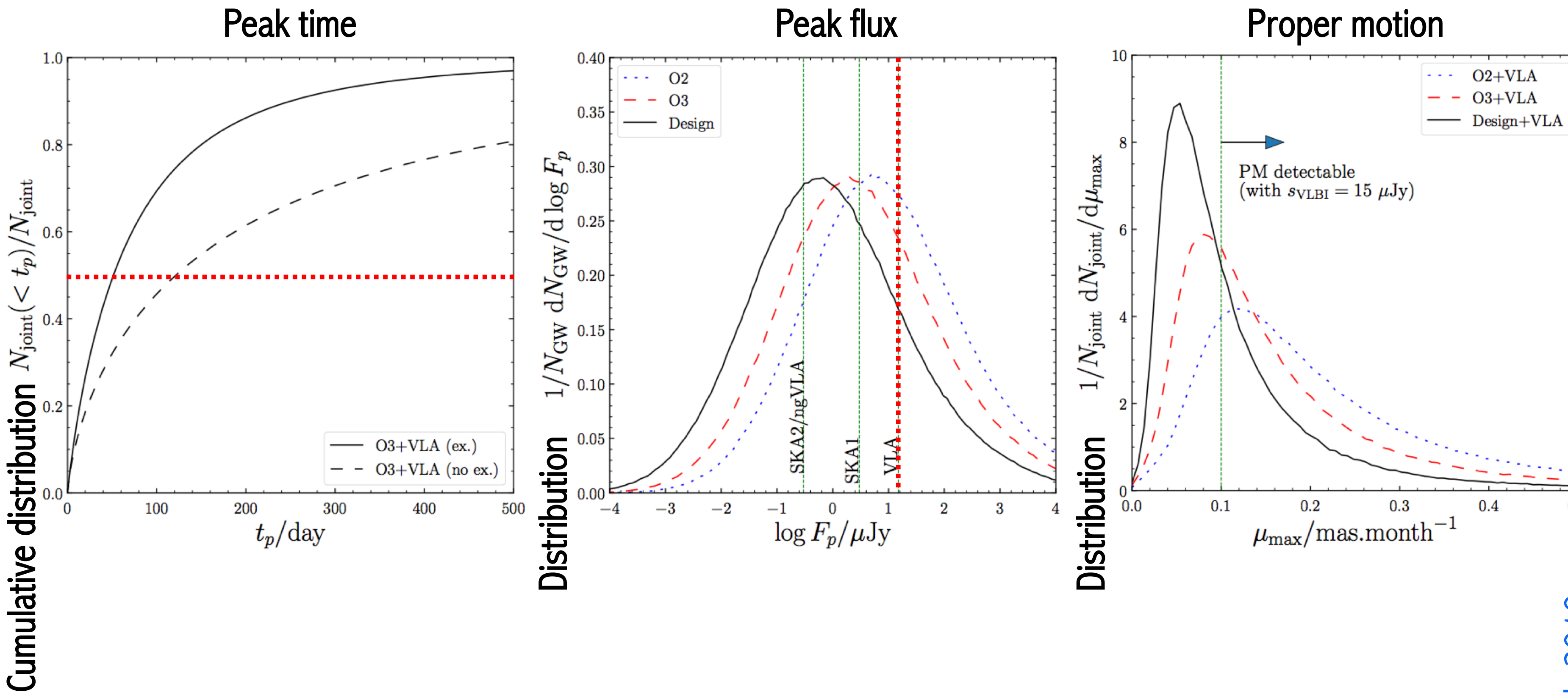
Standard prescription

Brighter afterglows: dense environments

- Even a small sample of afterglows would be fruitful to study the jet physics.
- On the other hand, afterglows are too rare to have a strong impact on GW-cosmology (even if they allow a good measurement of the viewing angle). (see discussion in Mastrogiovanni, Duque, Chassande-Mottin, Daigne & Mochkovitch 21)

Mochkovitch, Daigne, Duque & Zitouni, 2021

Results: radio afterglow following GW triggers



- (Very) late peak times ; Uncertainty: lateral expansion of the jet?
- VLBI is rapidly lost with increasing GW sensitivity
- VLA sensitivity is above the mean peak flux in O2-O3-O4-design configuration. SKA2/ngVLA sensitivity would be below.
- How to search radio afterglows without a KN?

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
  - GW trigger + no KN detection can bring some constraints.
- **Afterglows are more rare**
  - 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?**
- Possible extensions: add NSBH, improve model for BNS population (mass, rate (z), etc.), connect KN/AG parameters with BNS properties, simulate lightcurves, etc.