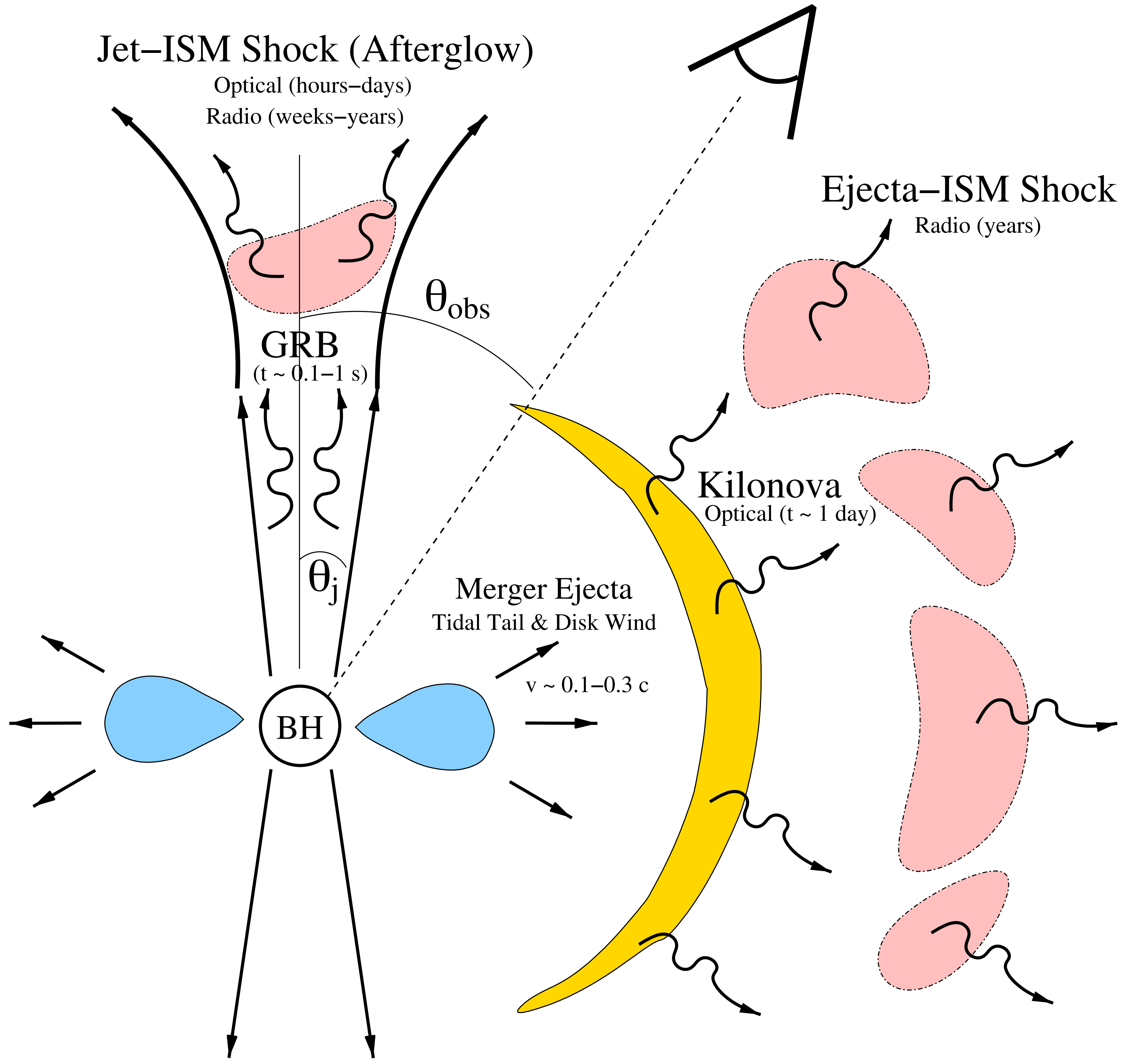
X-ray and UV follow-up of gravitational wave events

Phil Evans

University of Leicester

What are we looking for?

- **Binary Neutron Star mergers.**
  - Jets (short? GRBs)
    - Off-axis?
  - Kilonova.



Metzger & Berger 2012
ApJ, 746, 48

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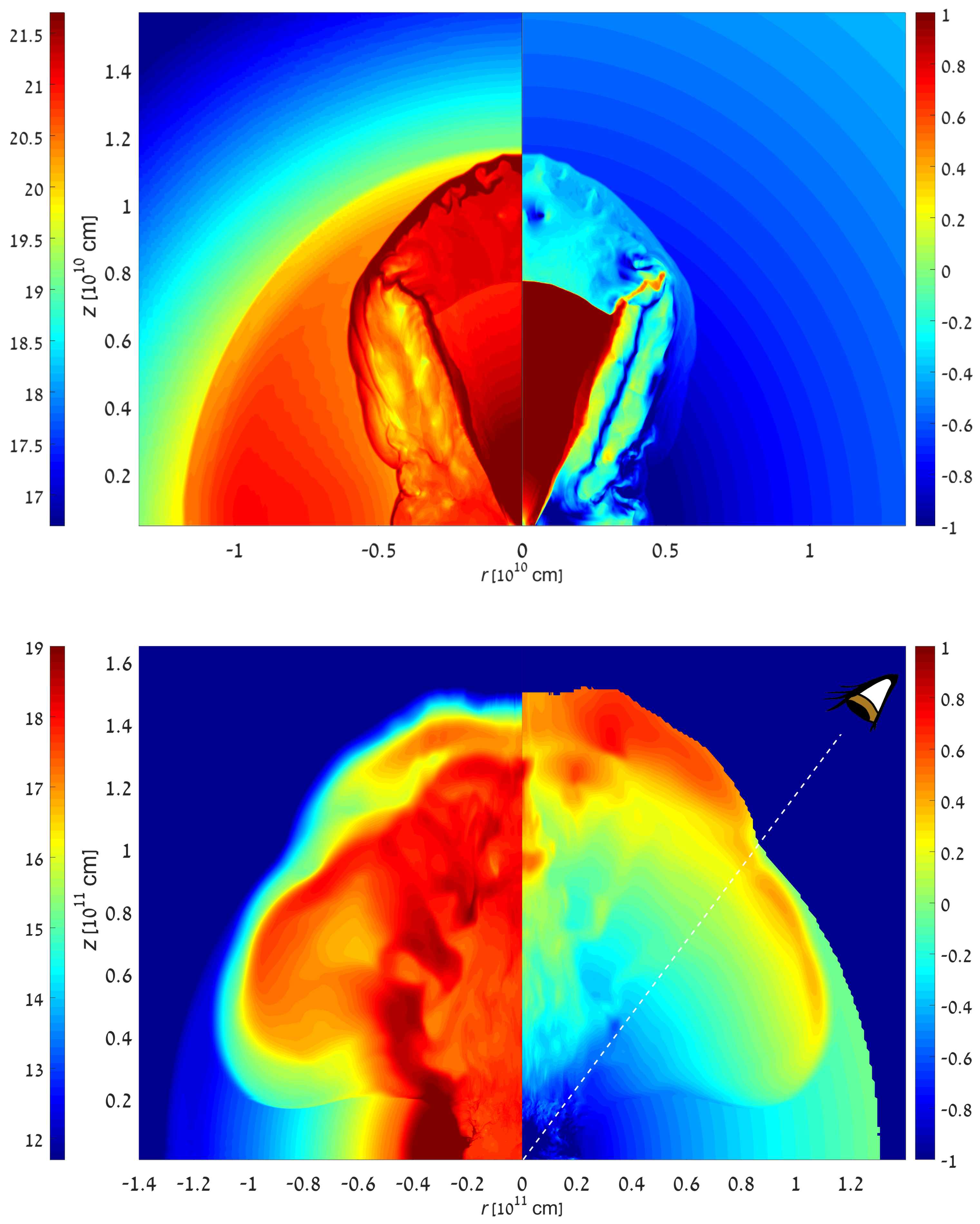
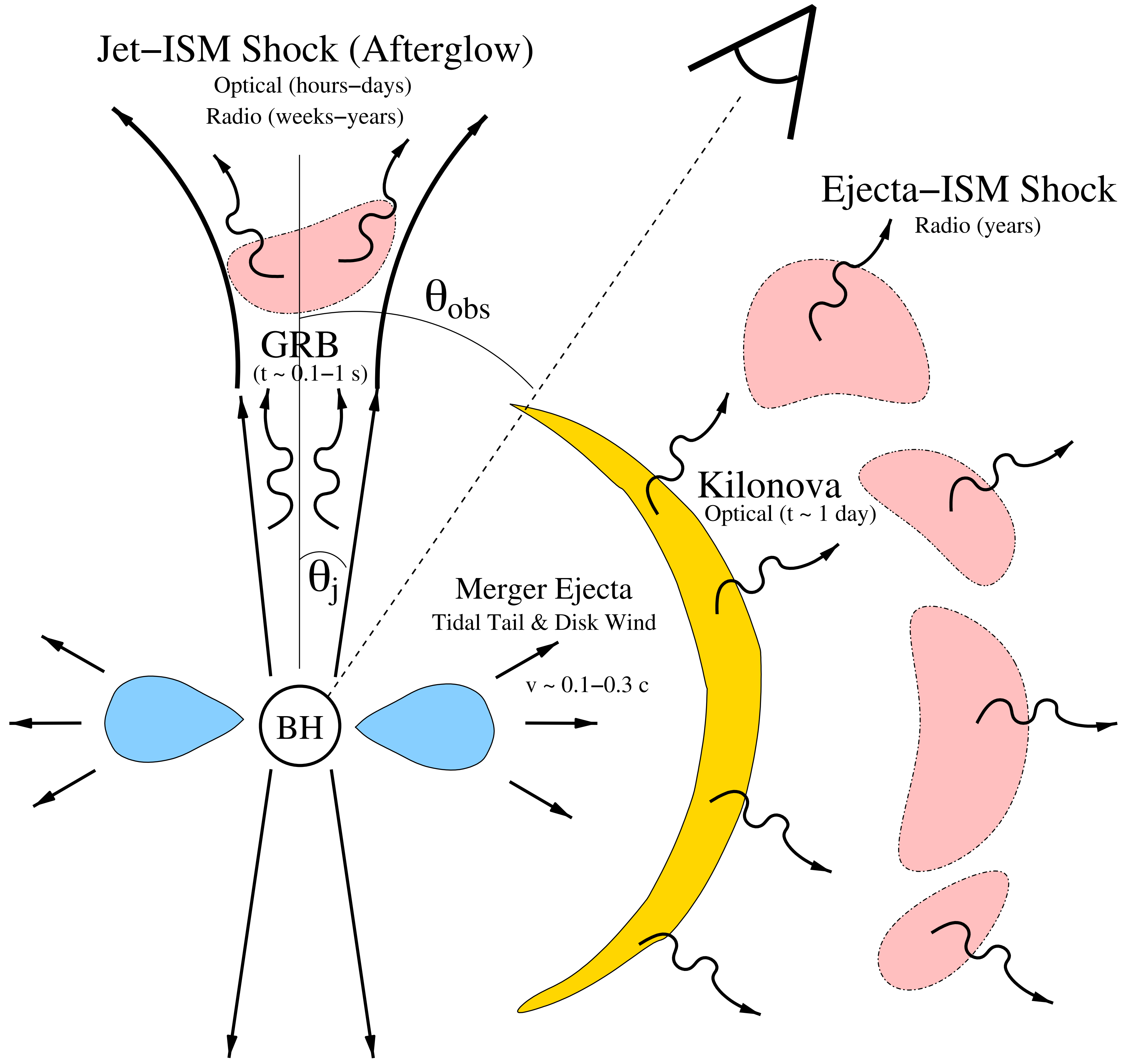


Gottlieb+ 2018
MNRAS, 479, 588



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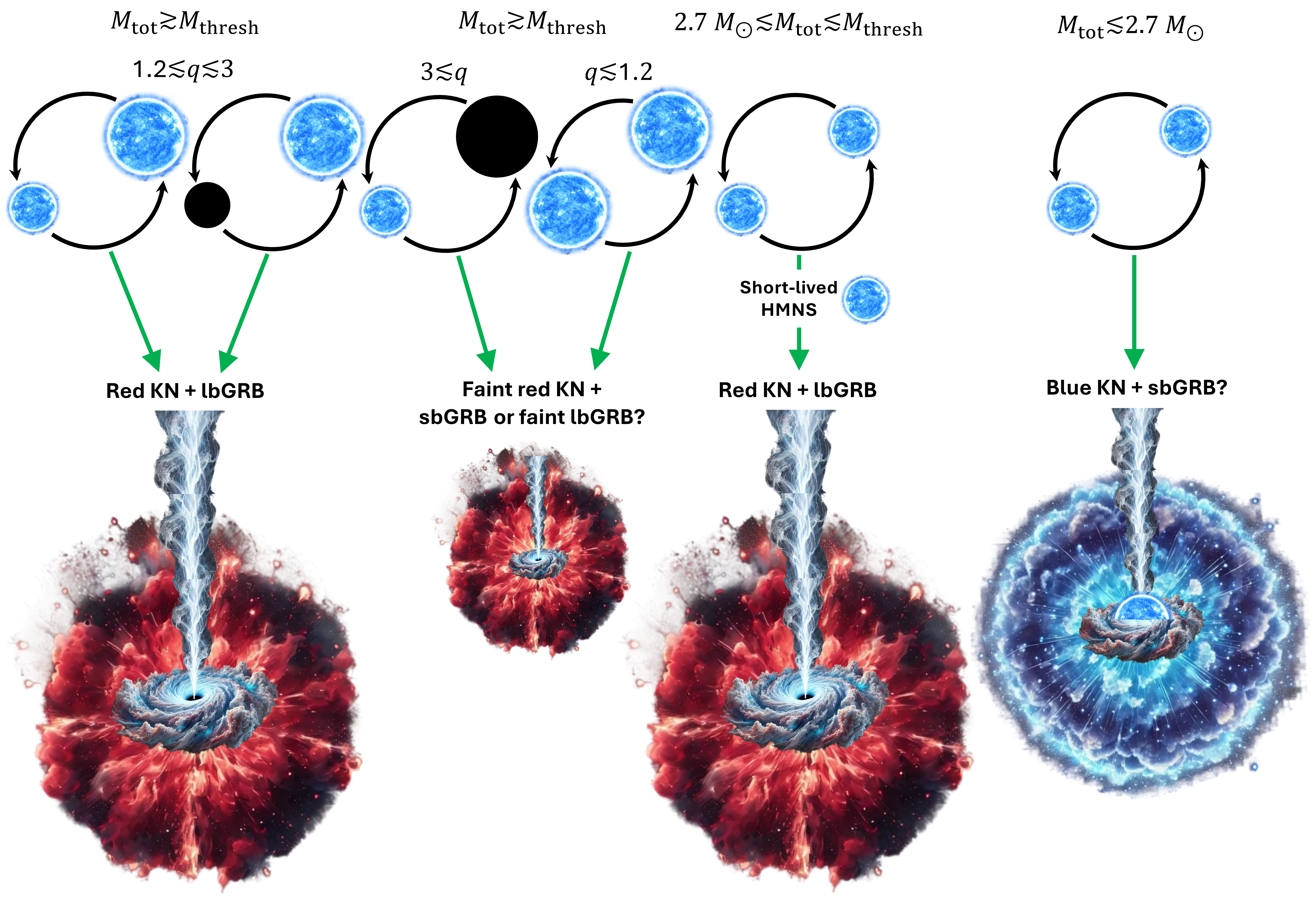

Gottlieb+ 2024
arXiv: 2411.13657

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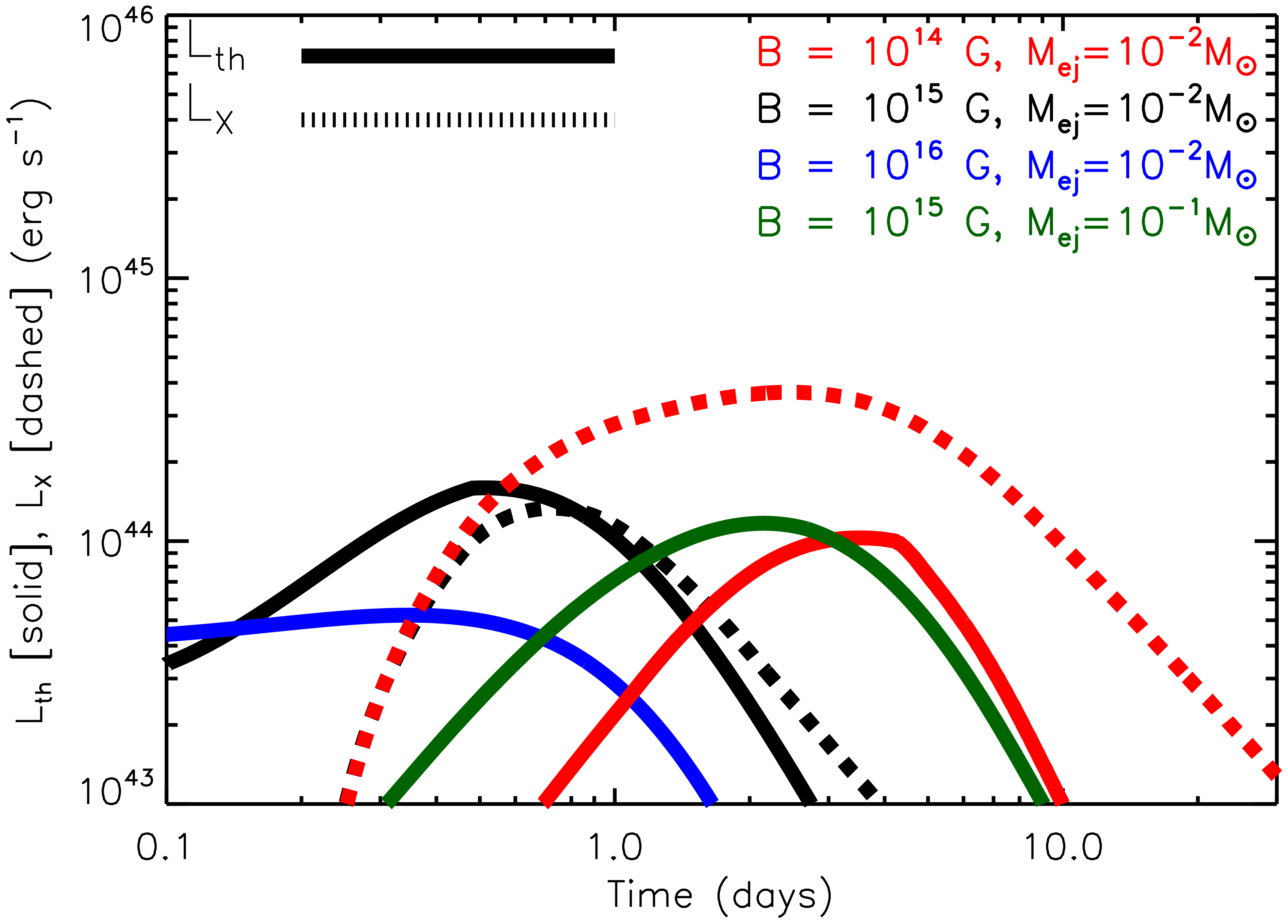

Solid = optical/UV (thermal)
Dashed = X-ray (non-thermal)

Metzger & Piro, 2014
MNRAS, 439, 3916

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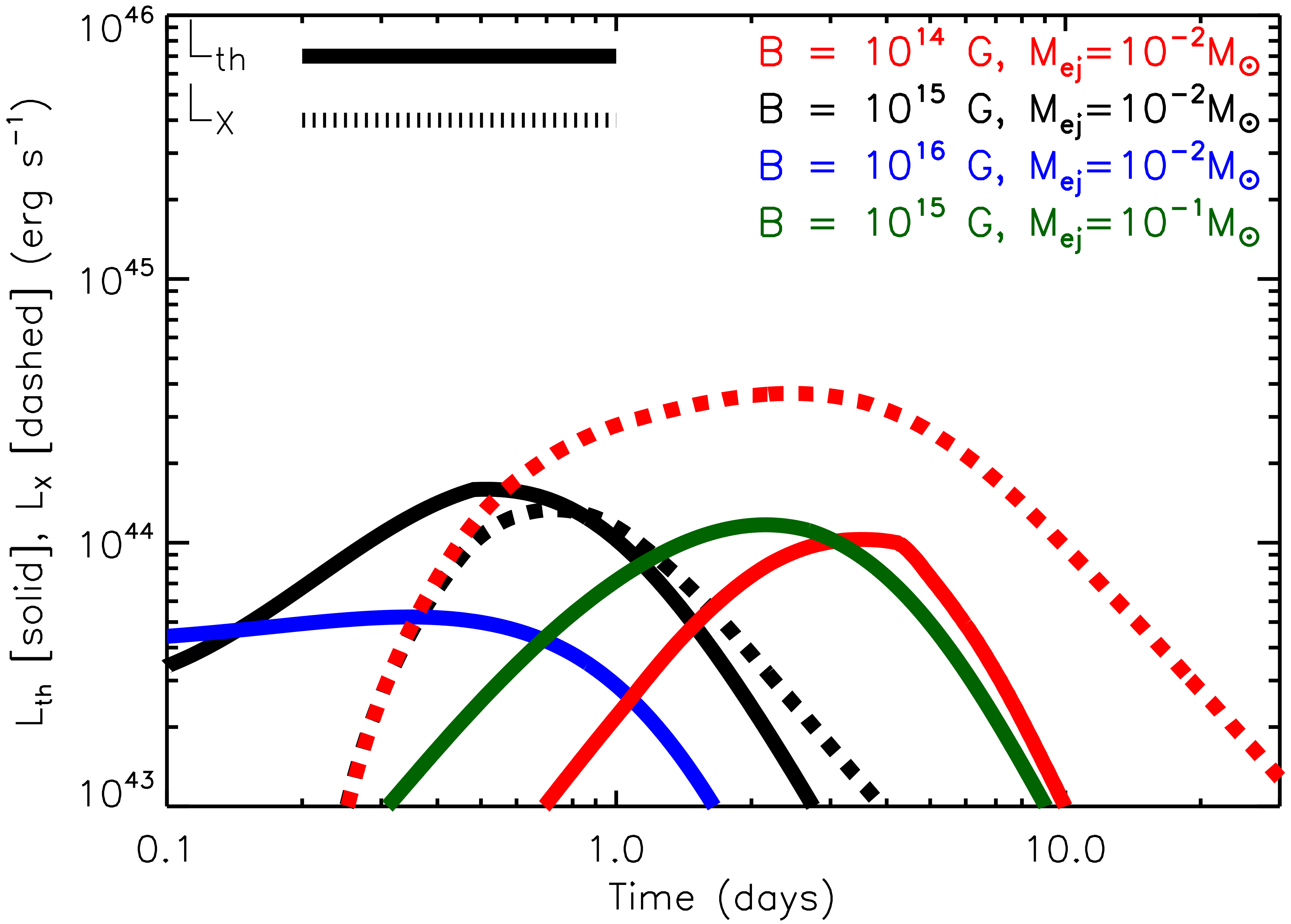
- **NH-BH mergers**
  - *Maybe* a GRB / KN.
- **BBH mergers**
  - 🤷‍♂️



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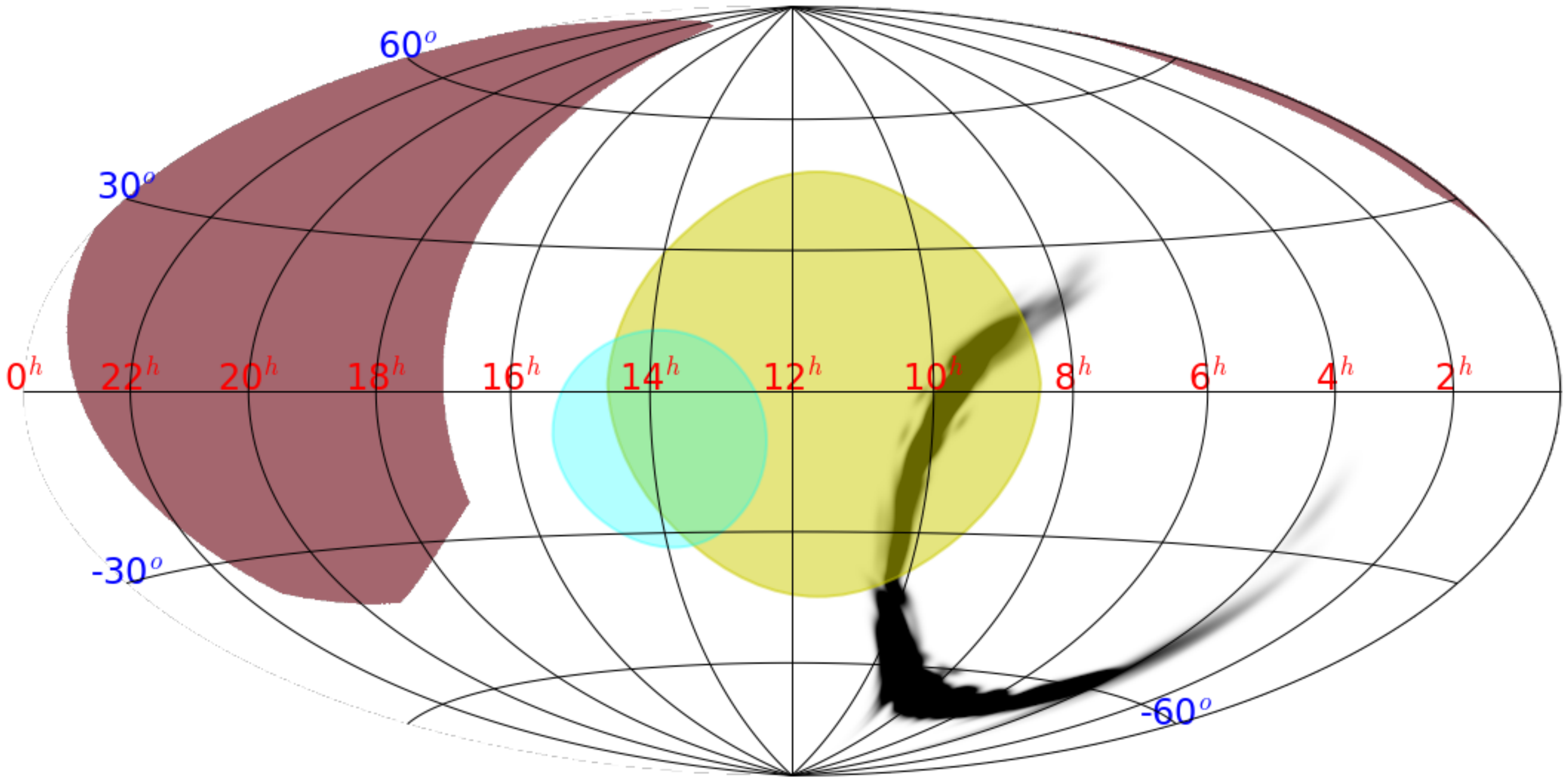
And how do you search?

- GW are hard to localise!
  - But we can optimise…



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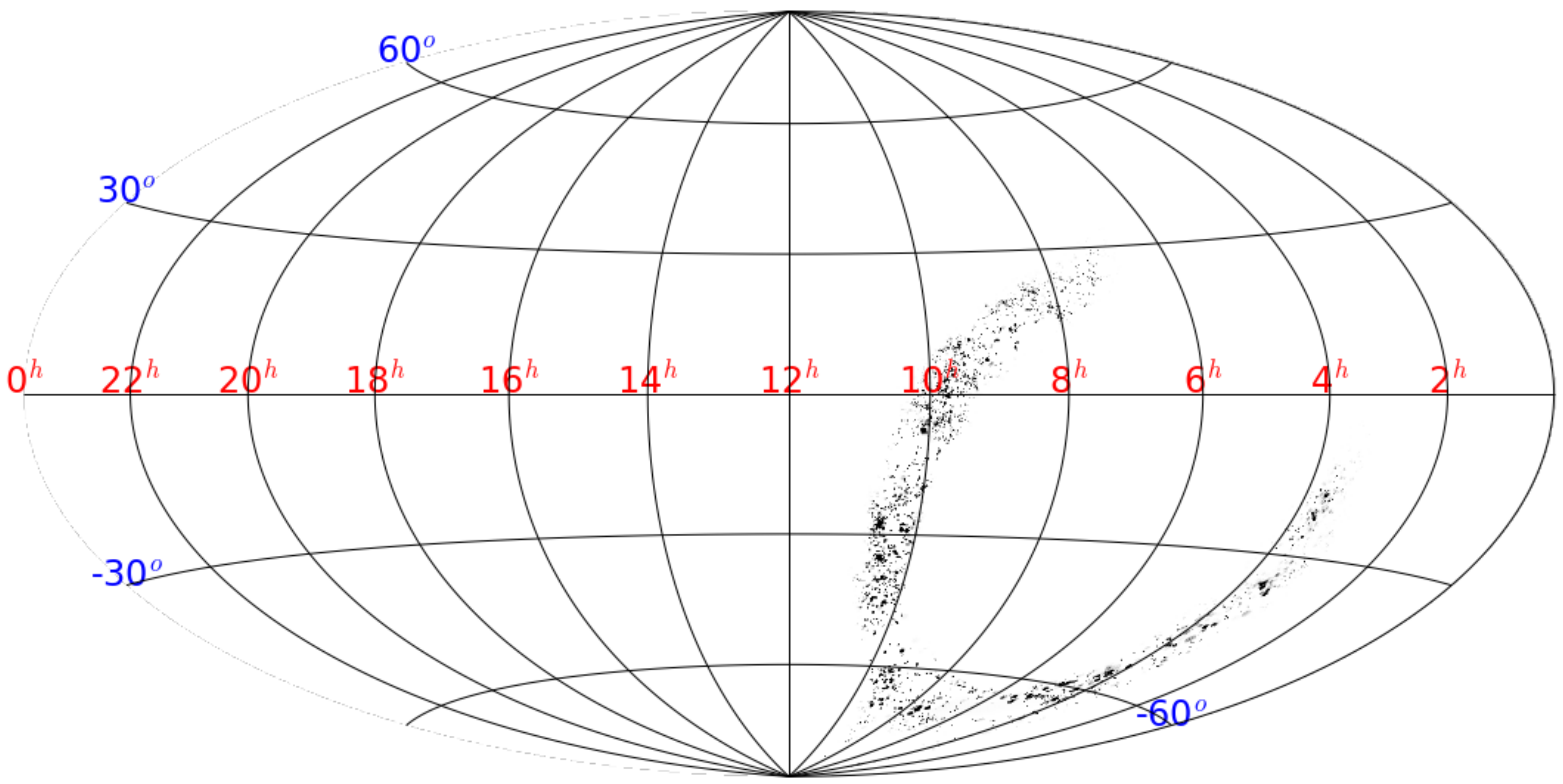

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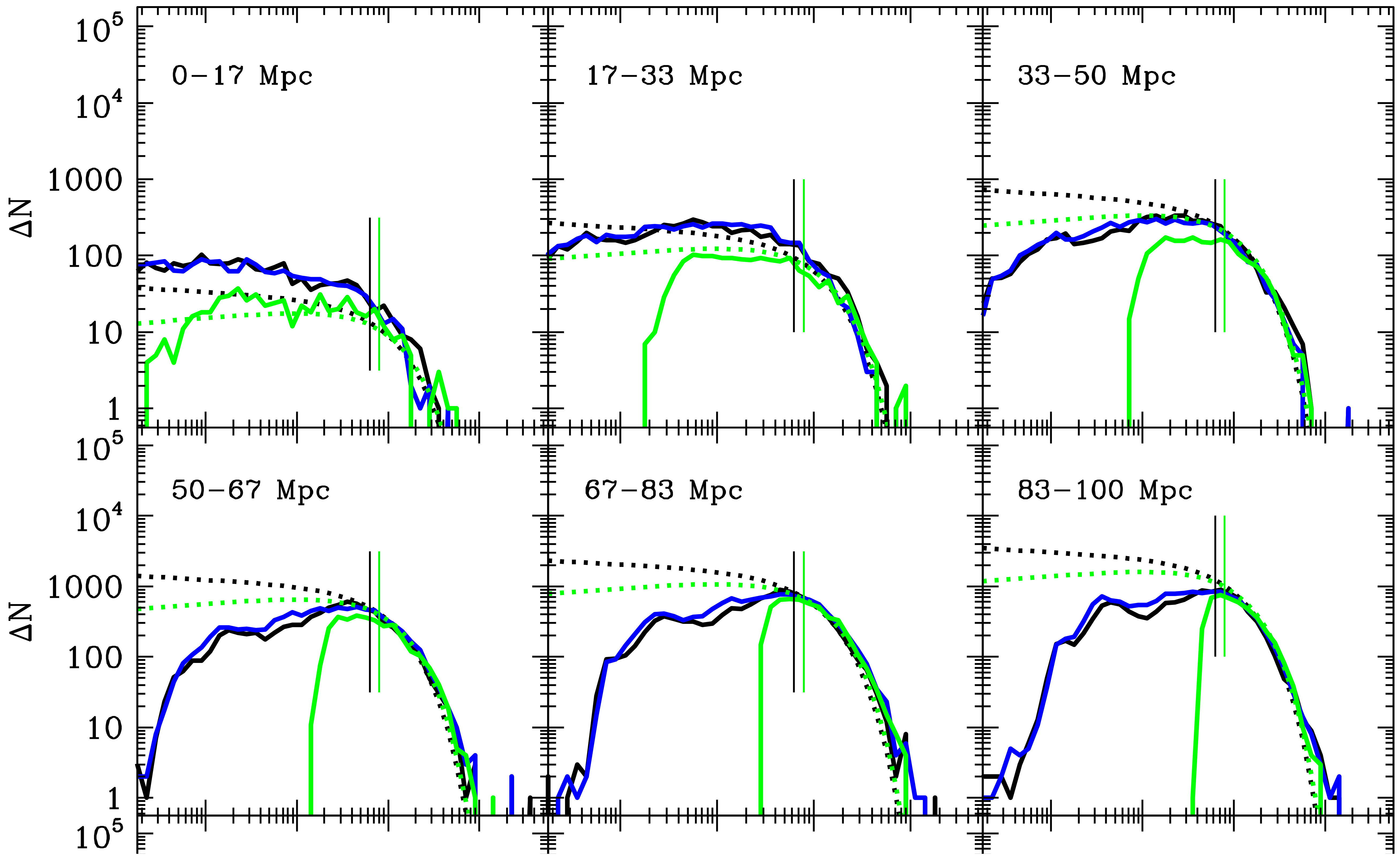

Gehrels+ 2016
ApJ, 820, 136

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$$\mathcal{P}_{\mathrm{gal},p} = \mathcal{P}_{\mathrm{GW},p} C_p N \sum_g \left(\mathcal{P}(g|P_p(D)) \frac{L_g}{L_{\mathrm{tot}}} \right)$$

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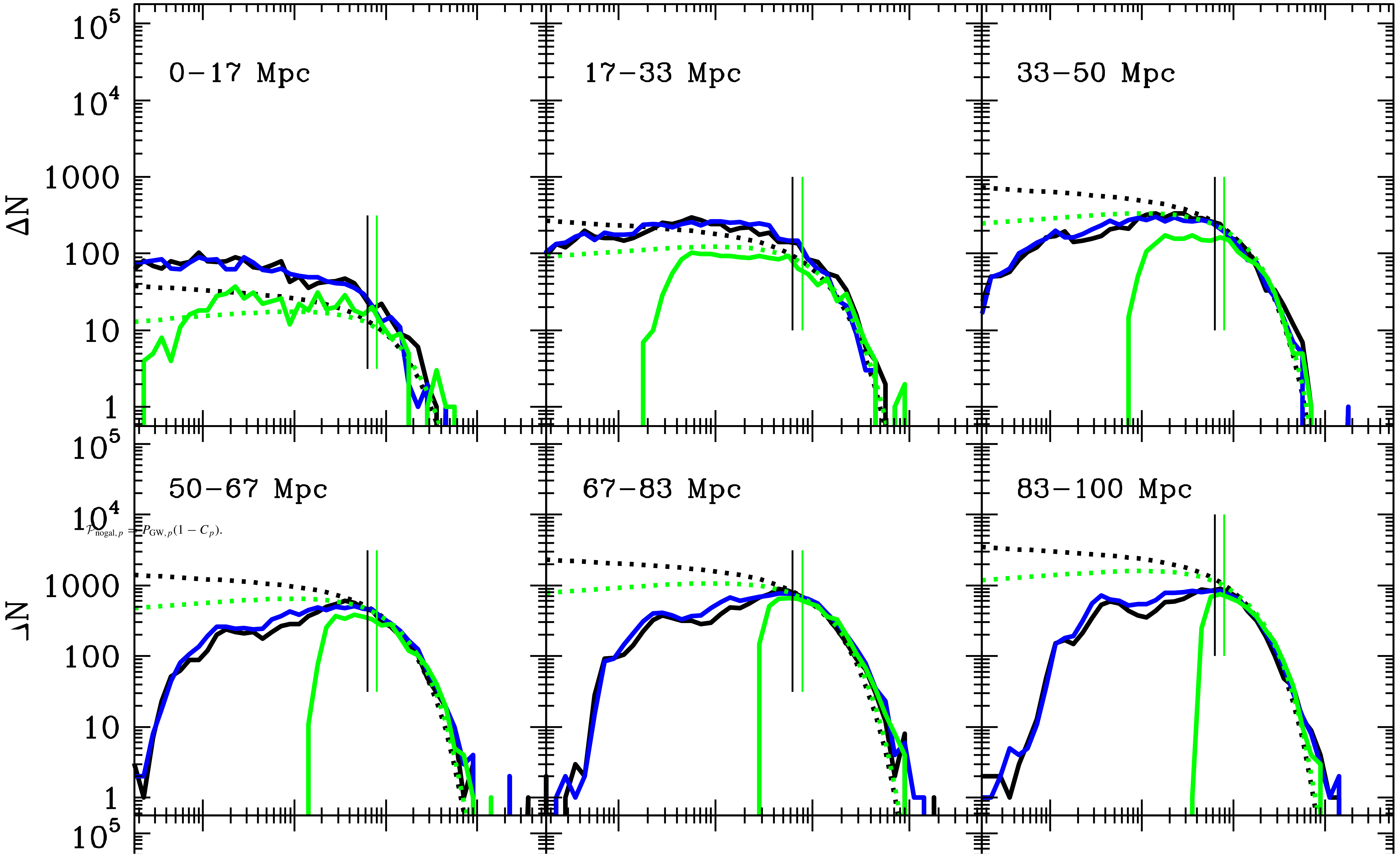

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MNRAS, 462, 1591

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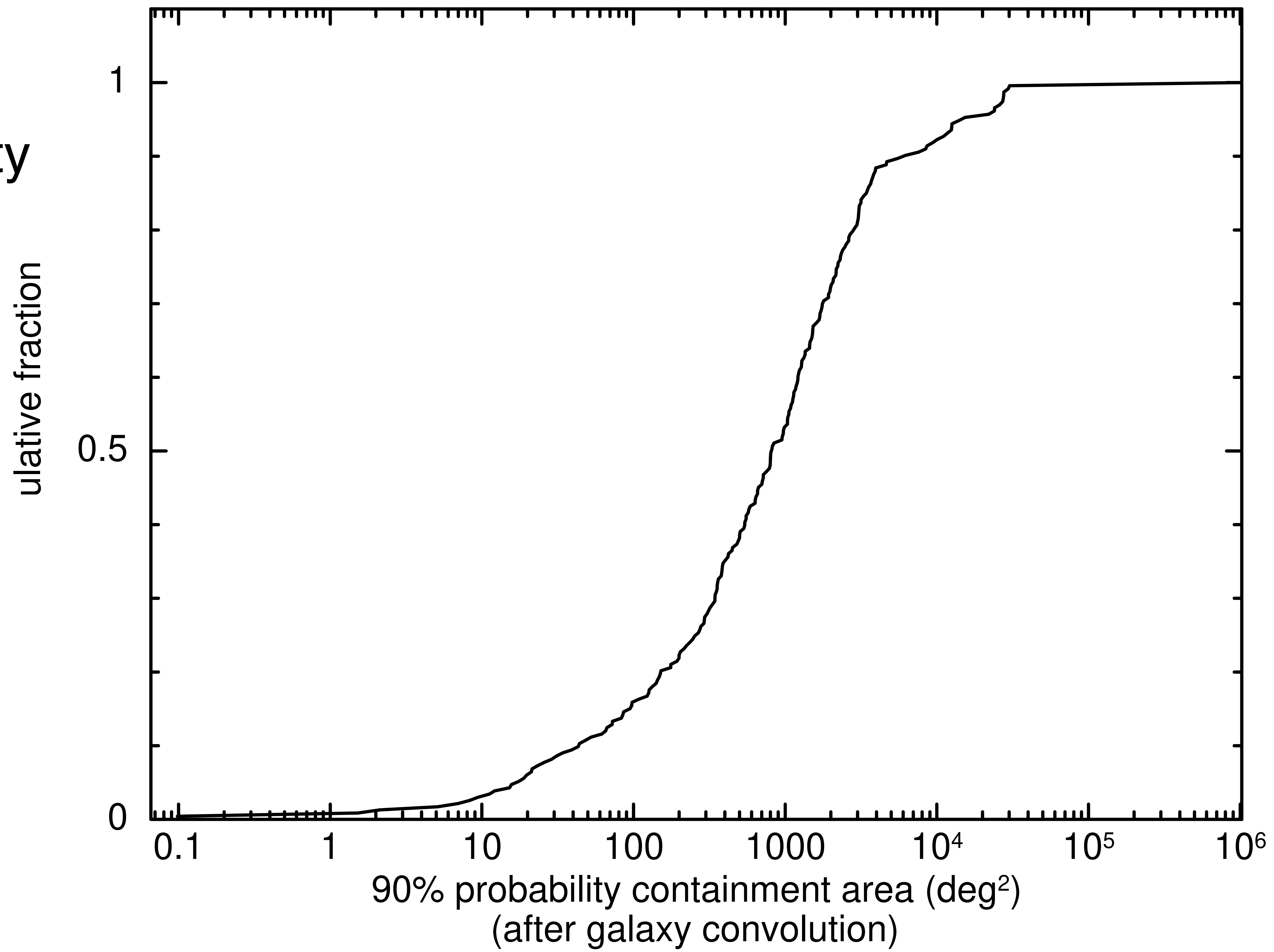
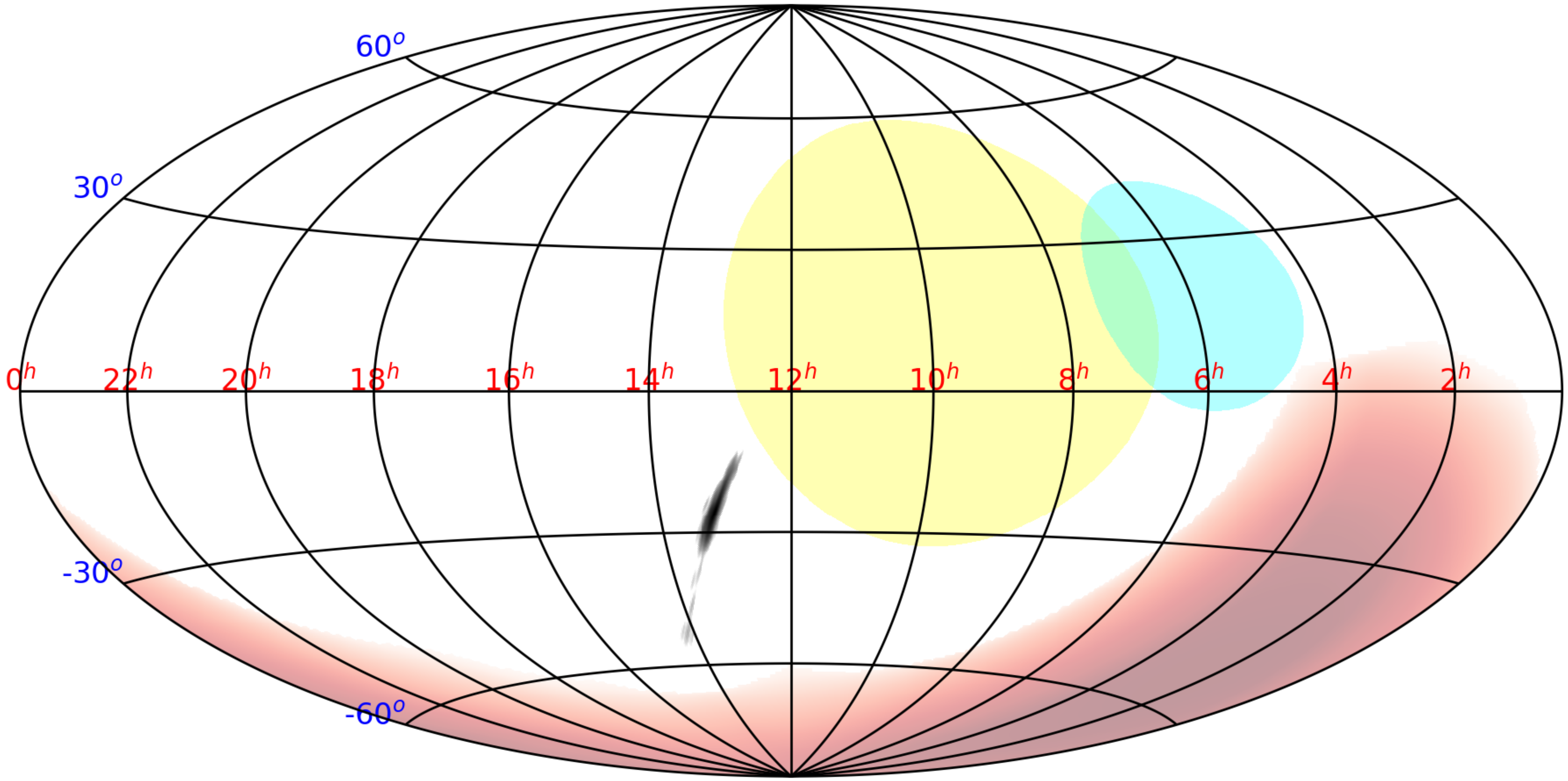


Evans+ 2016
MNRAS, 462, 1591

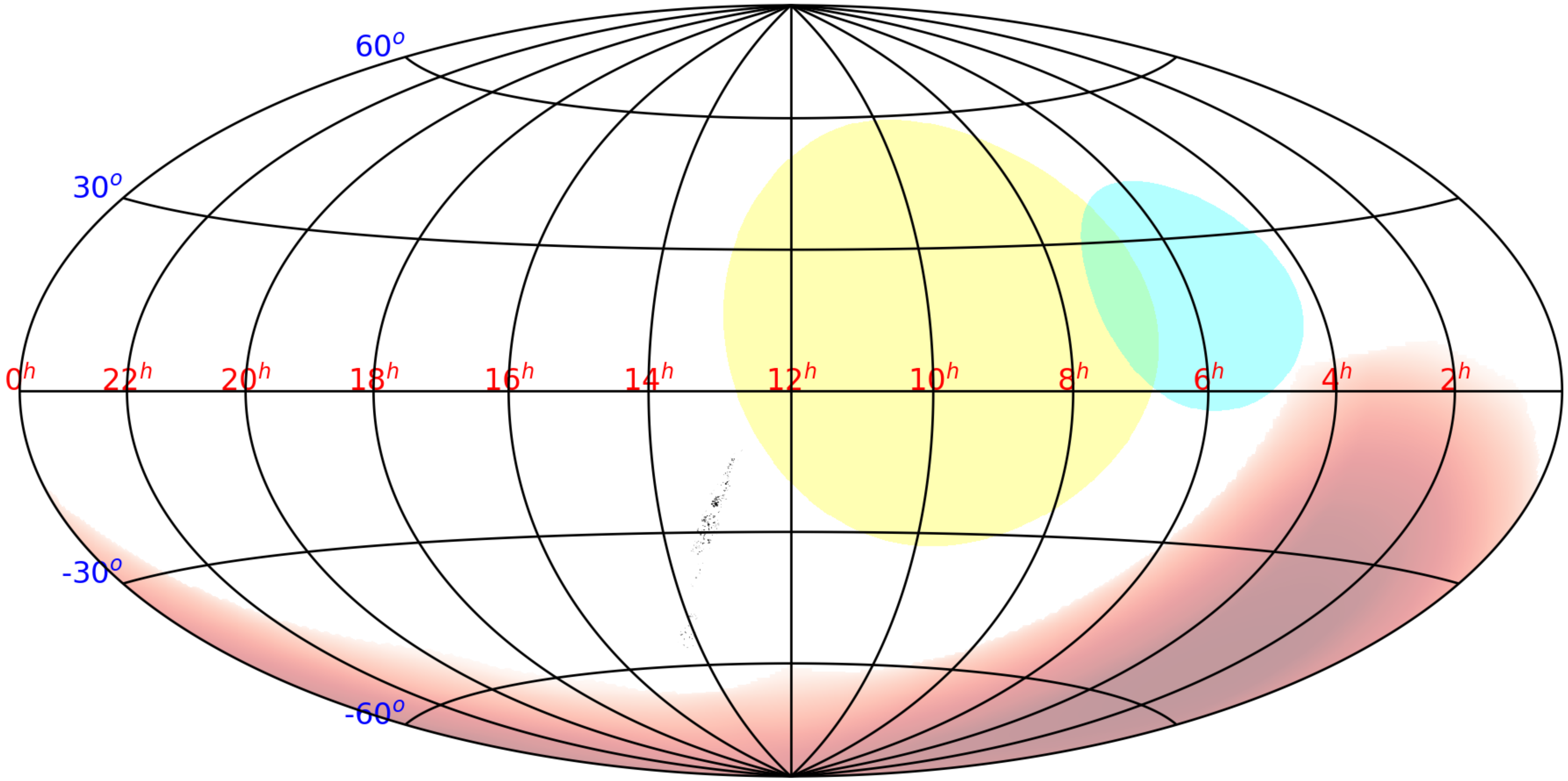
Yeah, but what have you seen?

- To date: two BNS triggers
  - GW 170817
  - GW 190425
- A likely NS-BH
  - GW 230529

GW 170817

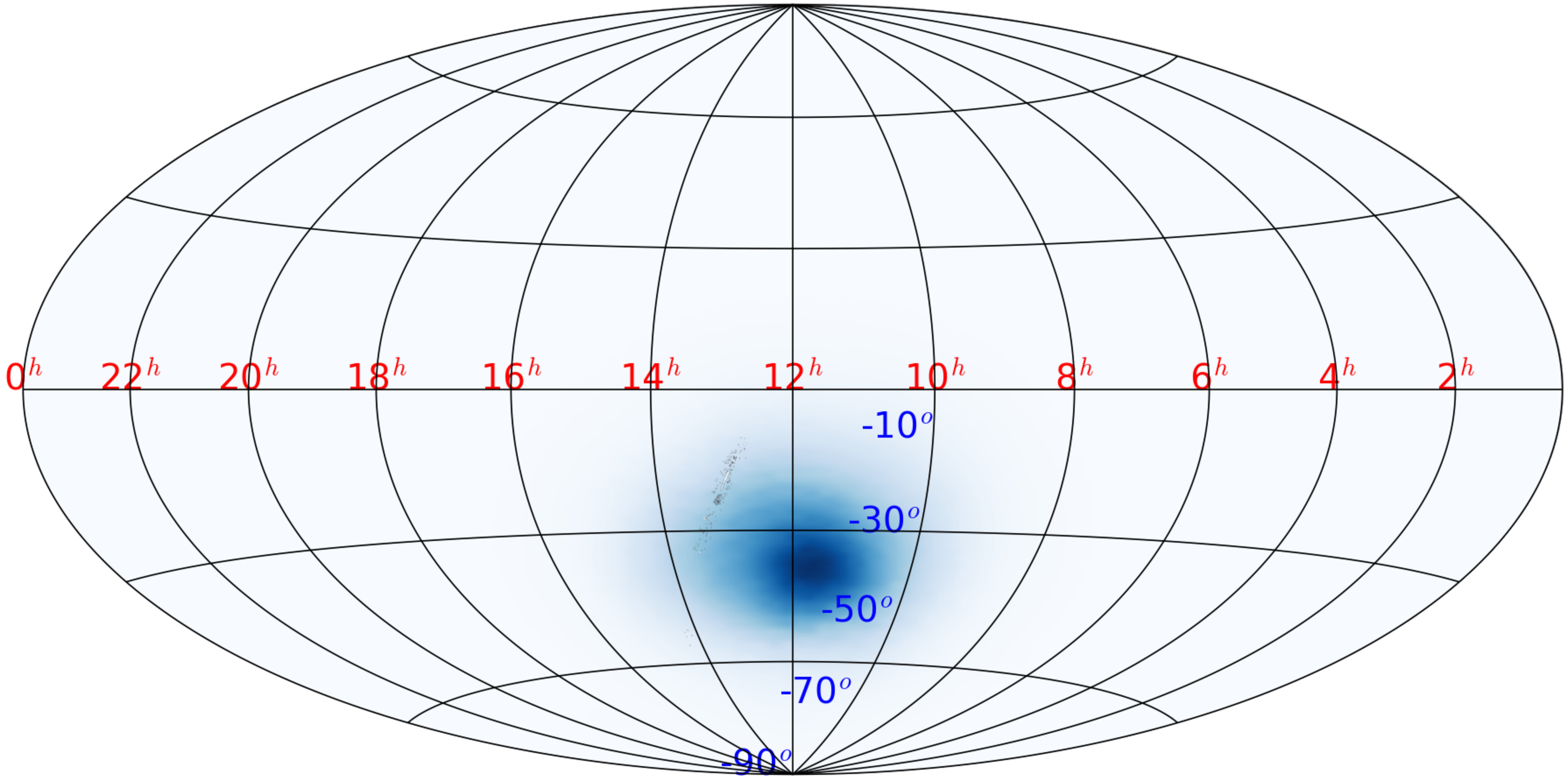


GW 170817



$A_{90} < 1$ deg^2.

GW 170817



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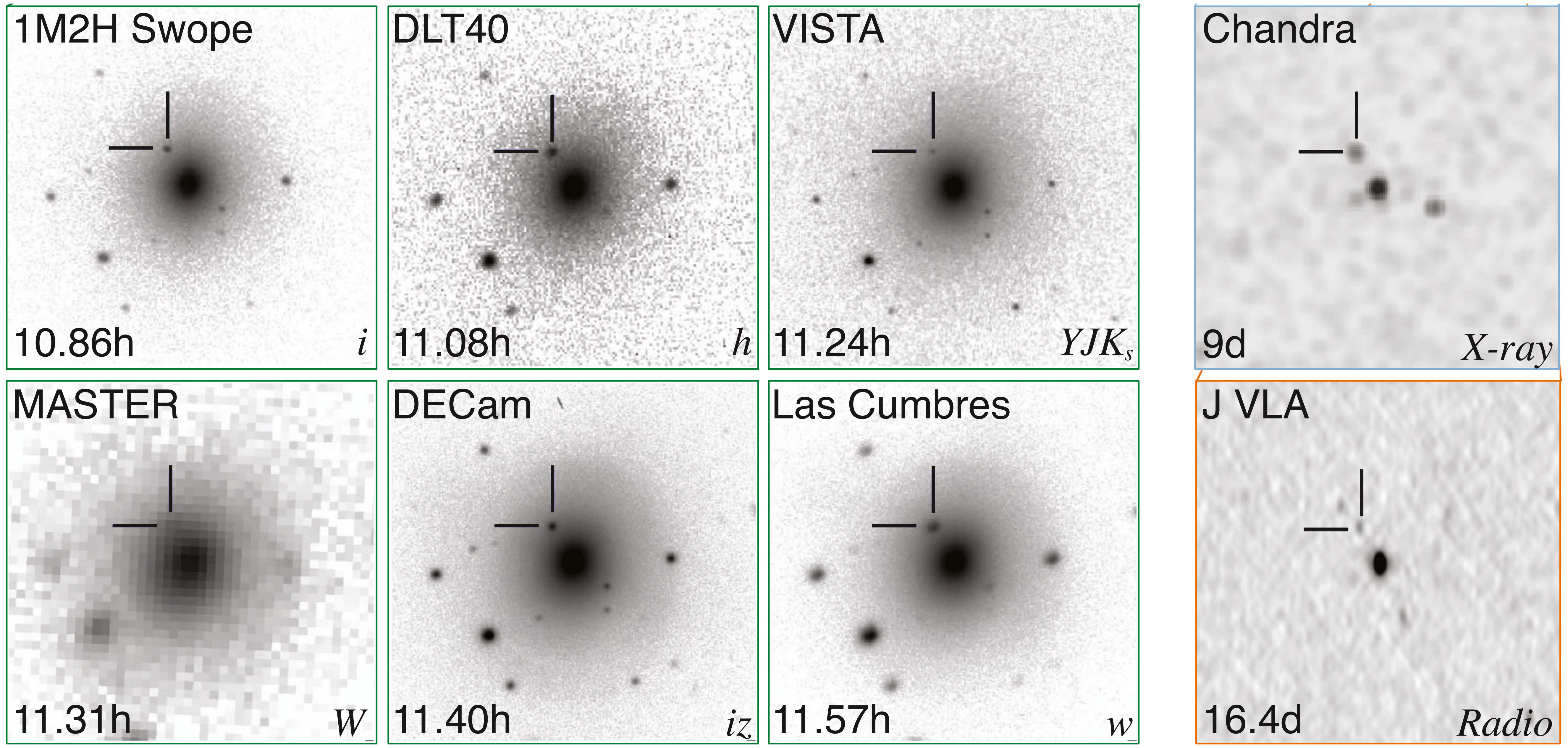
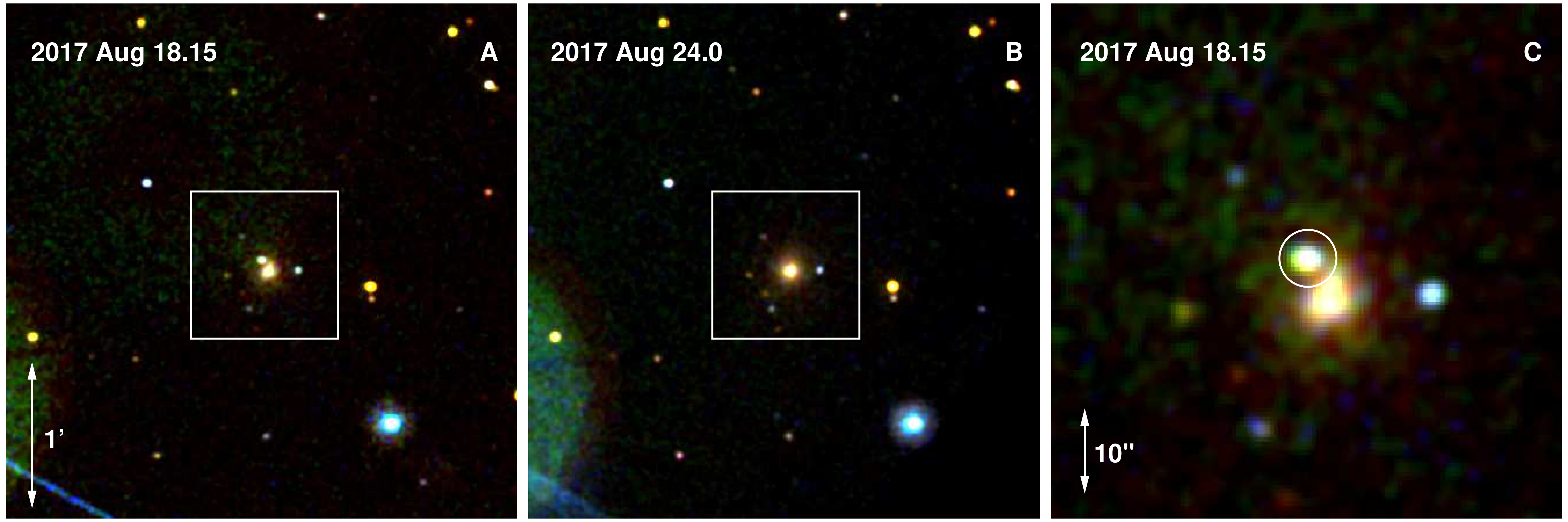


Abbott+++ 2017

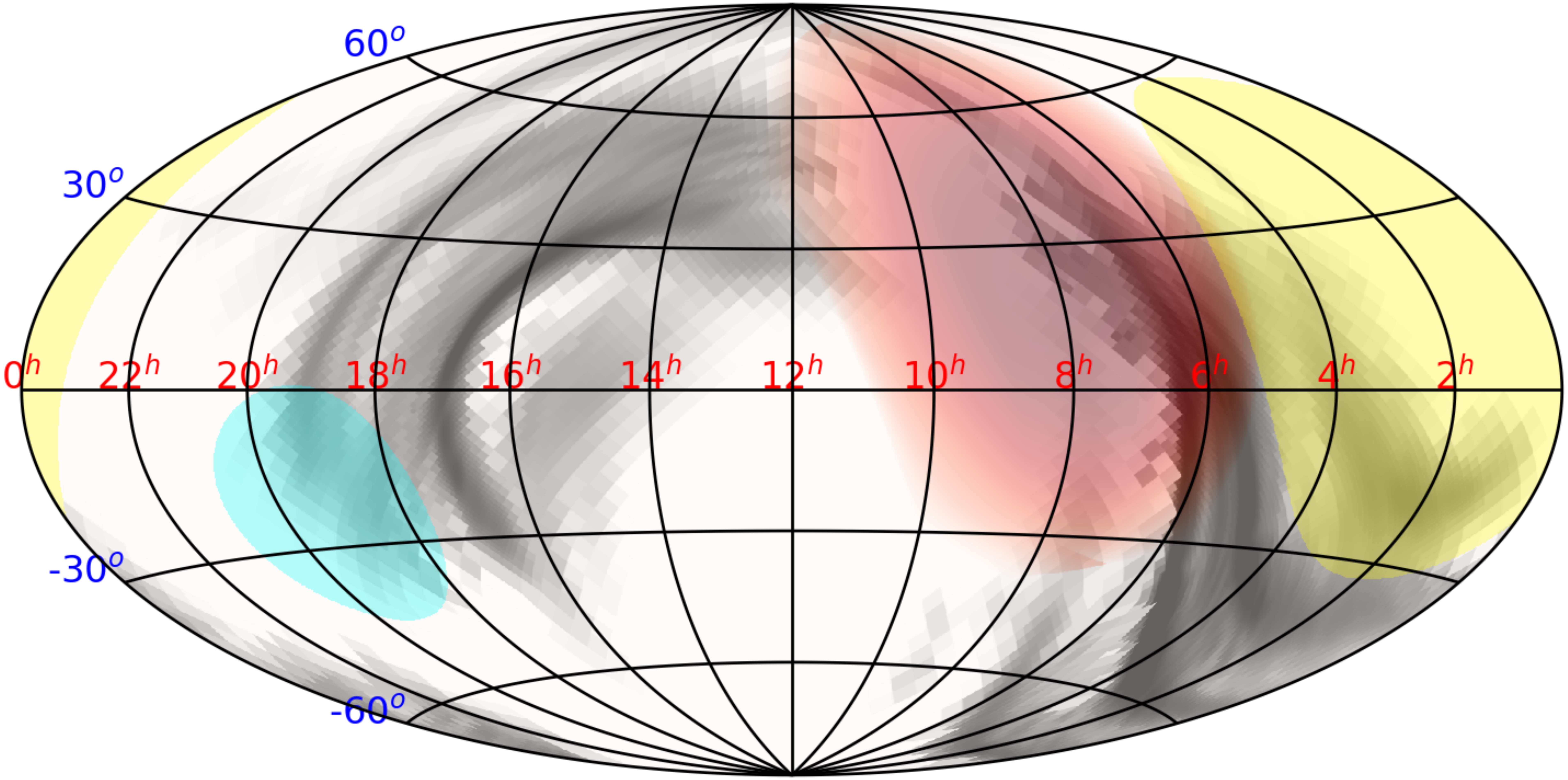
ApJL, 848, L12

Evans+ 2017

Science, 358, 1565



GW 190425



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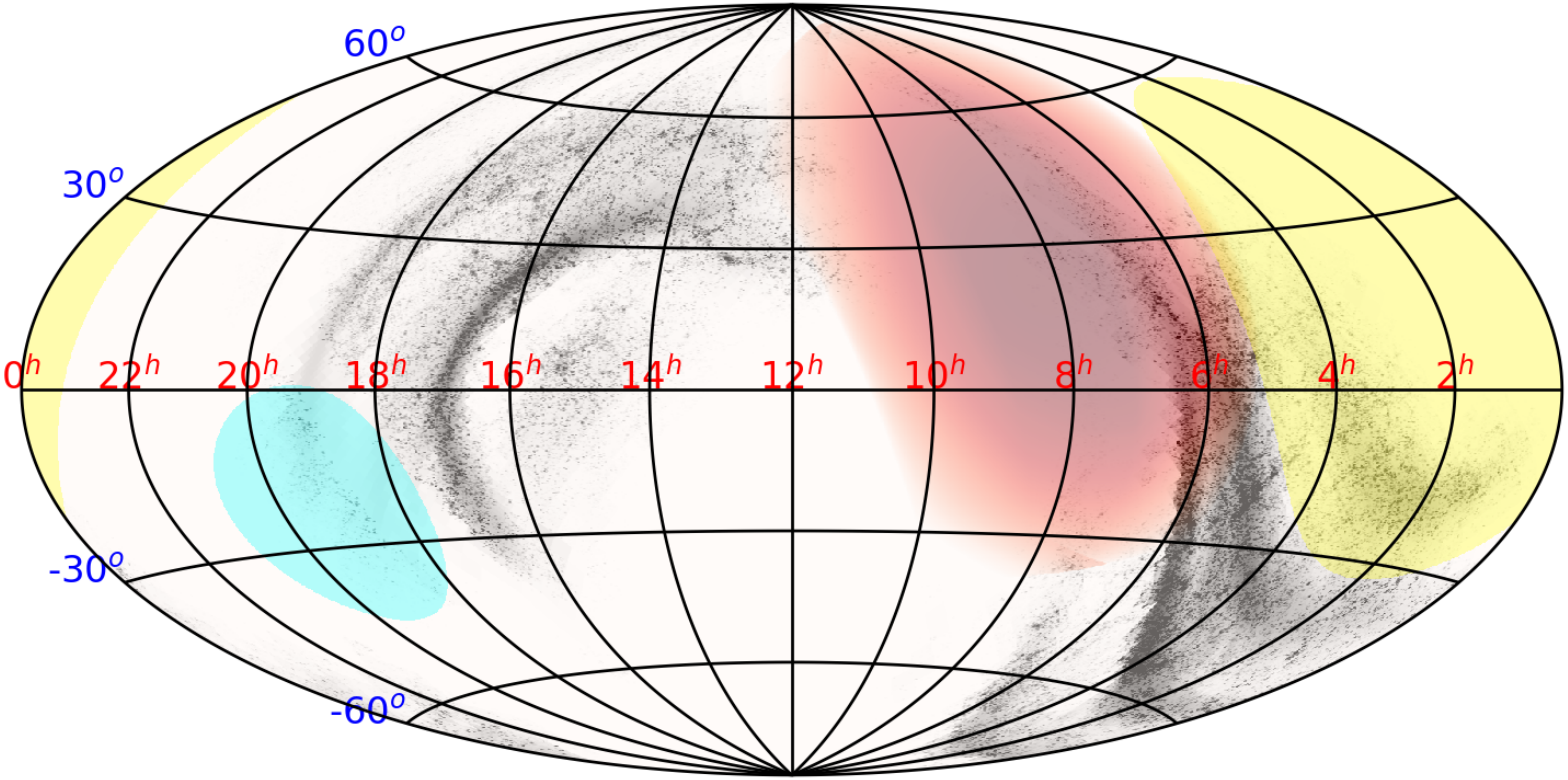
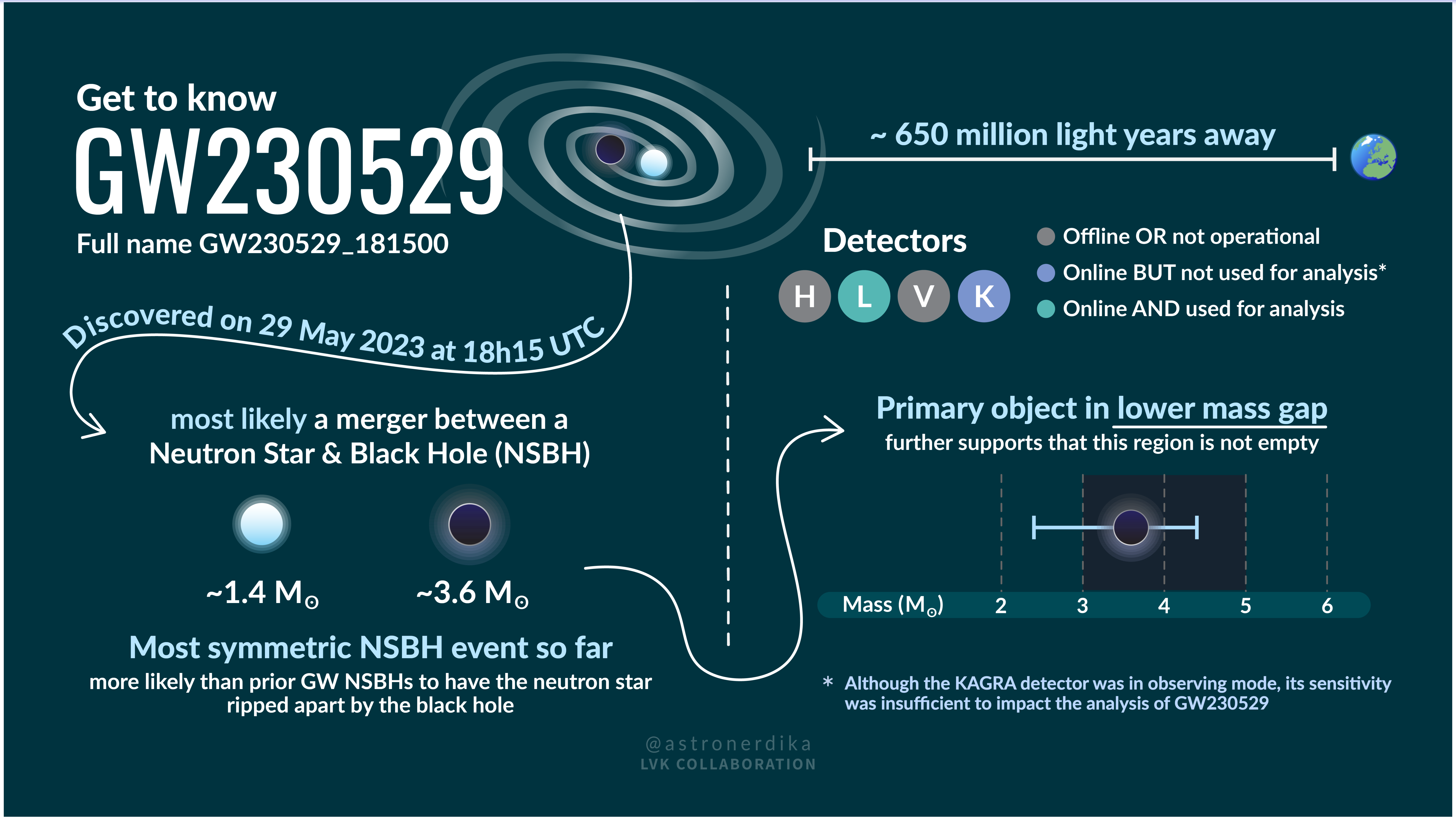


A_{90} = 3,833 deg^2.

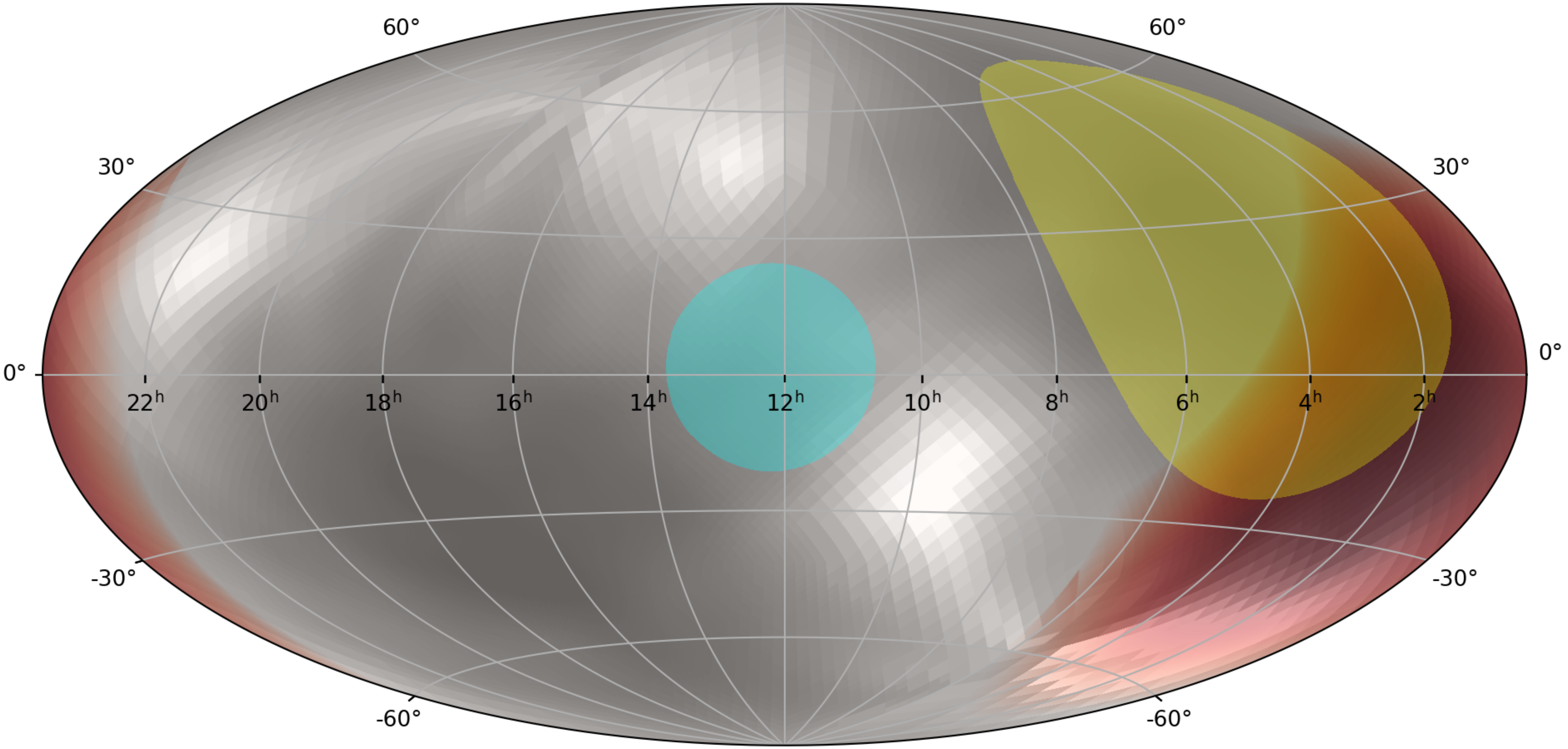
GW 230529



https://gwosc.org/eventapi/html/O4_Discovery_Papers/GW230529_181500/v1/

Credit: Shanika Galaudage / Observatoire de la Côte d'Azur

GW 230529



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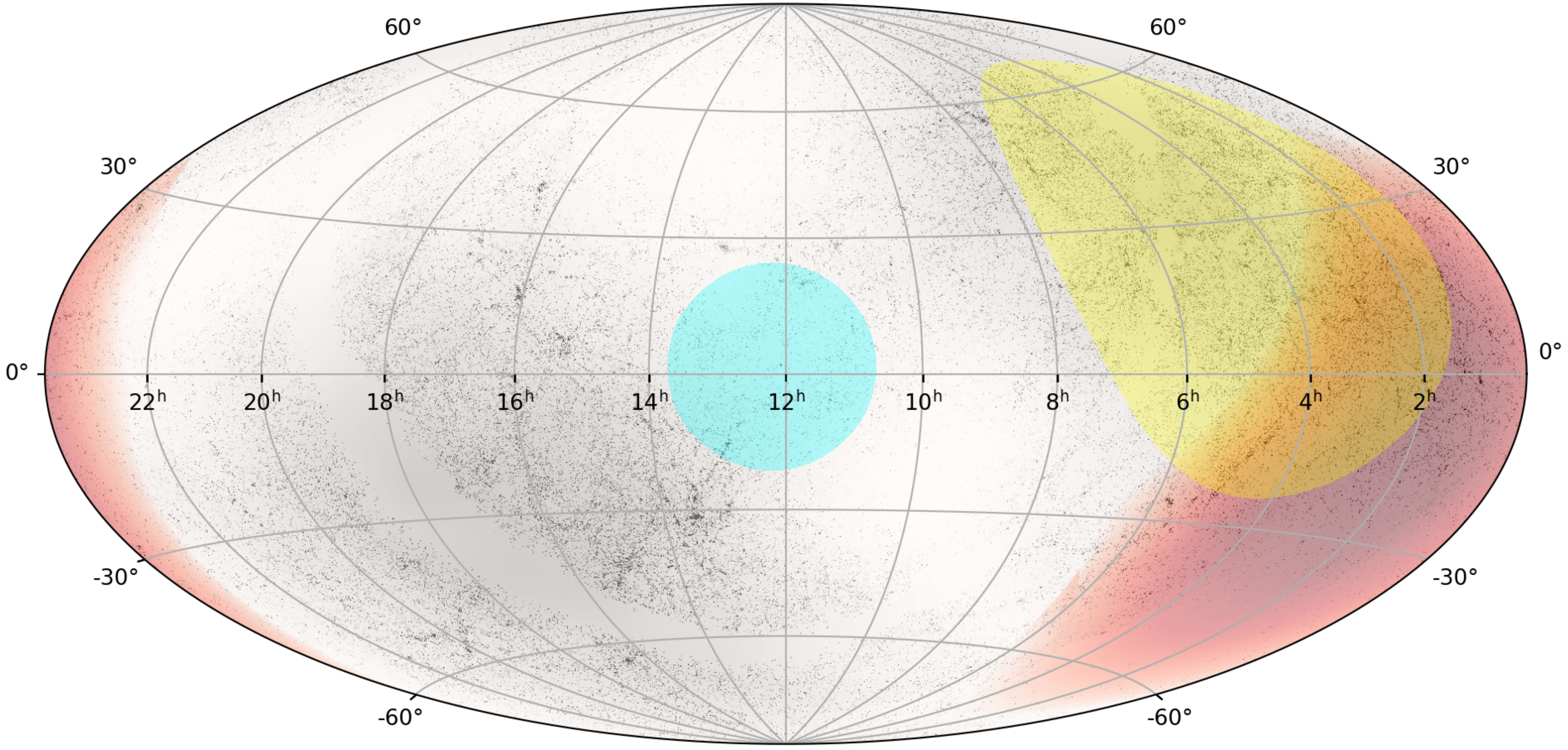
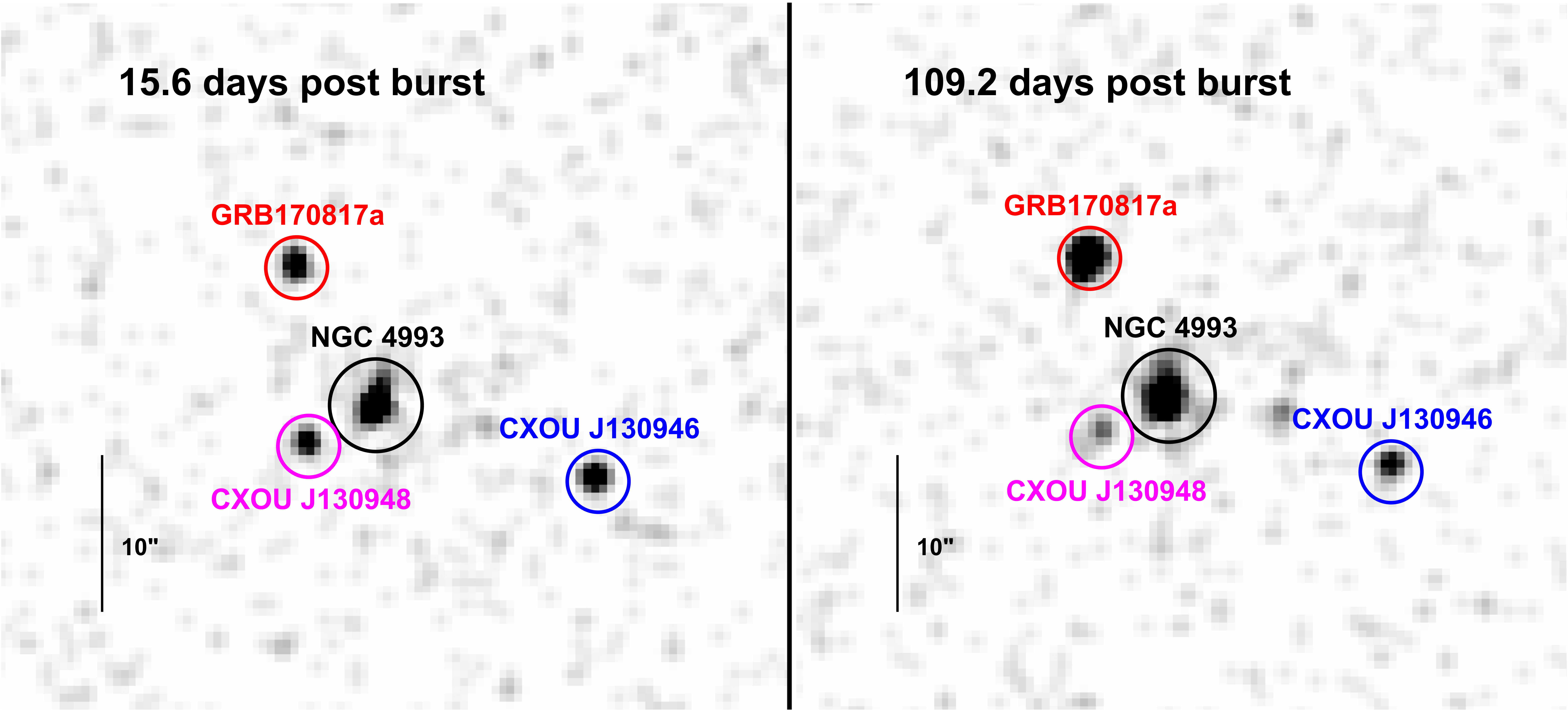


A_{90} = 12,545 deg^2.

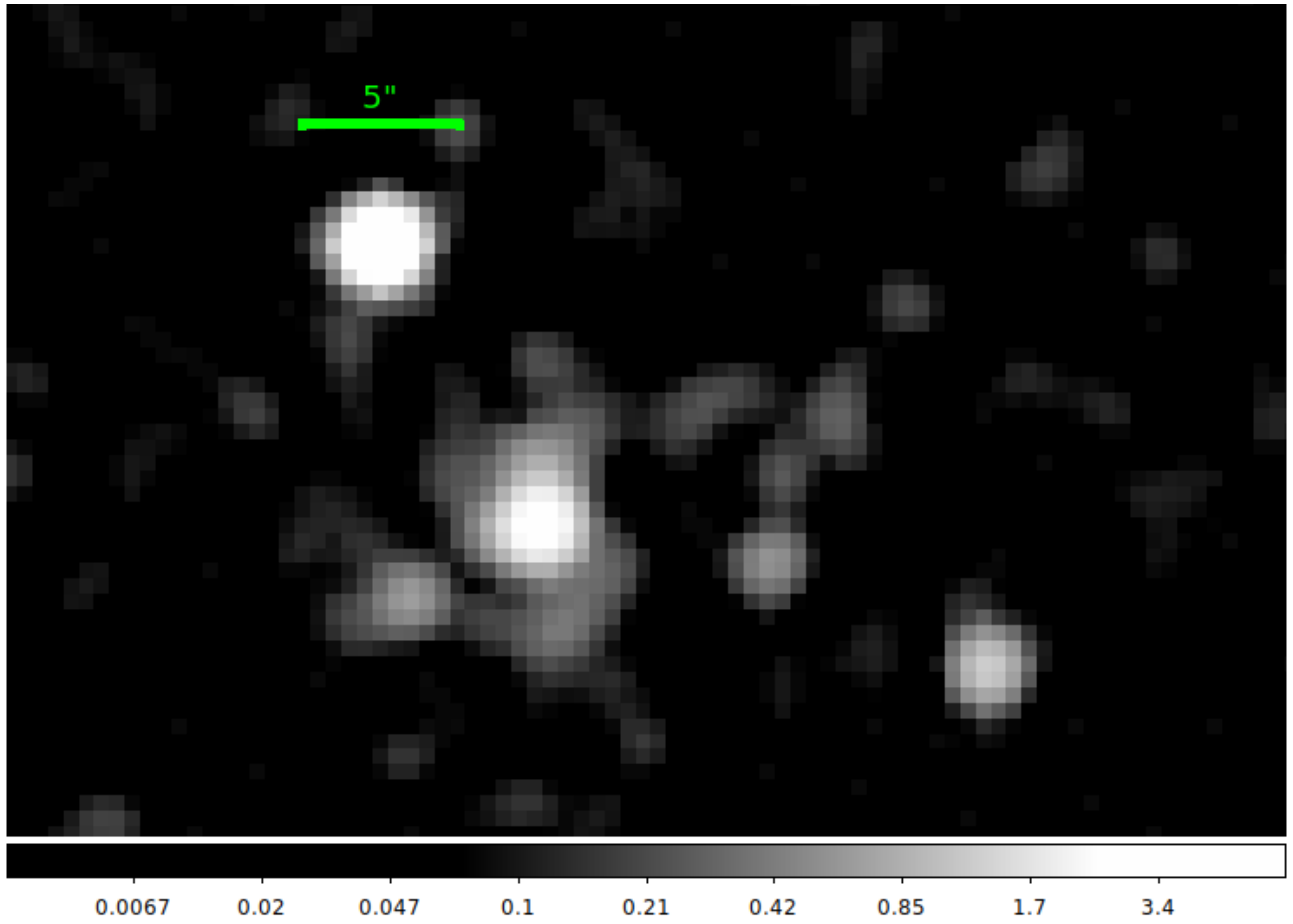
Back to 170817



Ruan… PE+ (2018)
ApJL, 853, L14

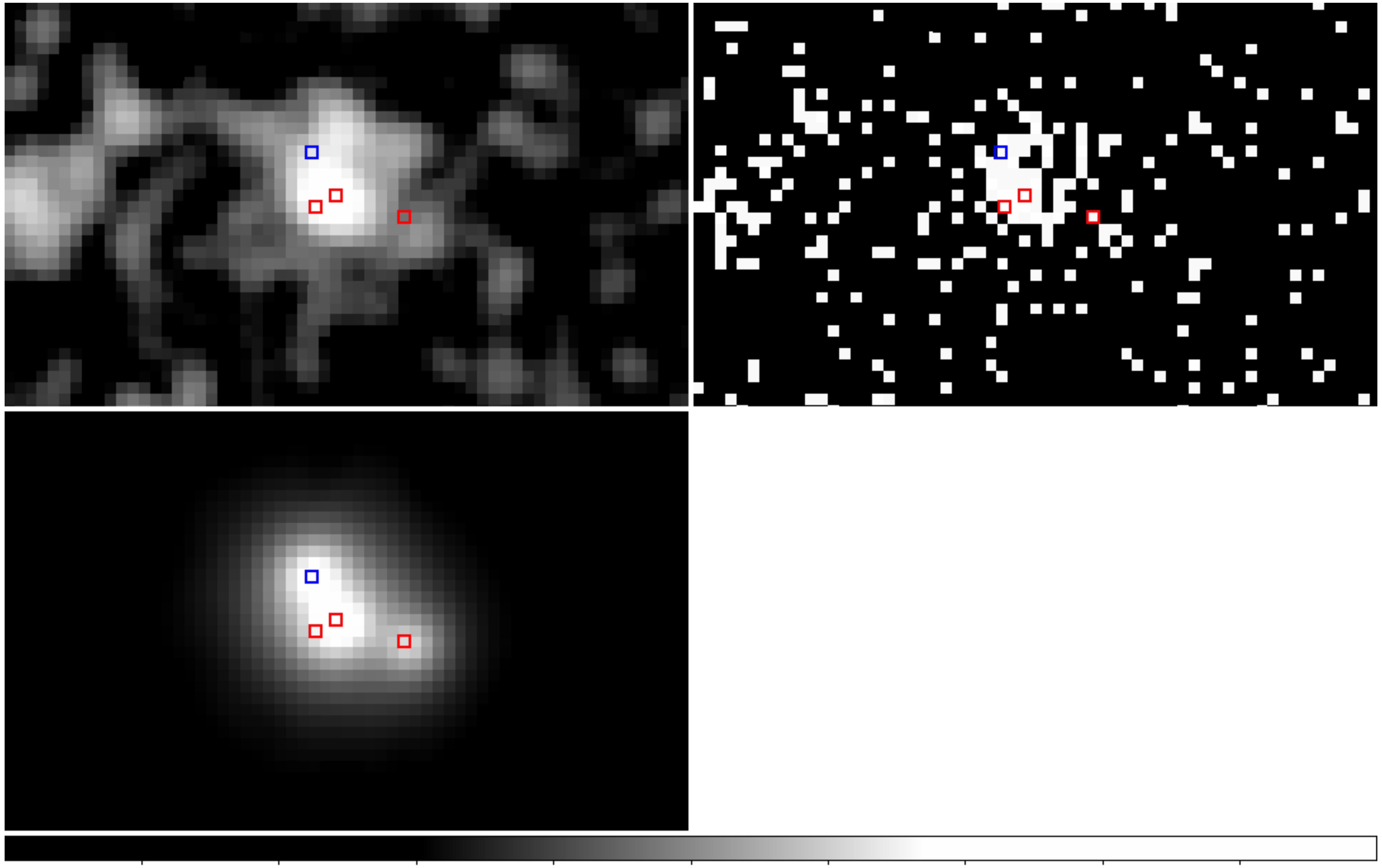
See also Troja+ (2017)
Nature, 554, 71

Back to 170817



Chandra image (smoothed).

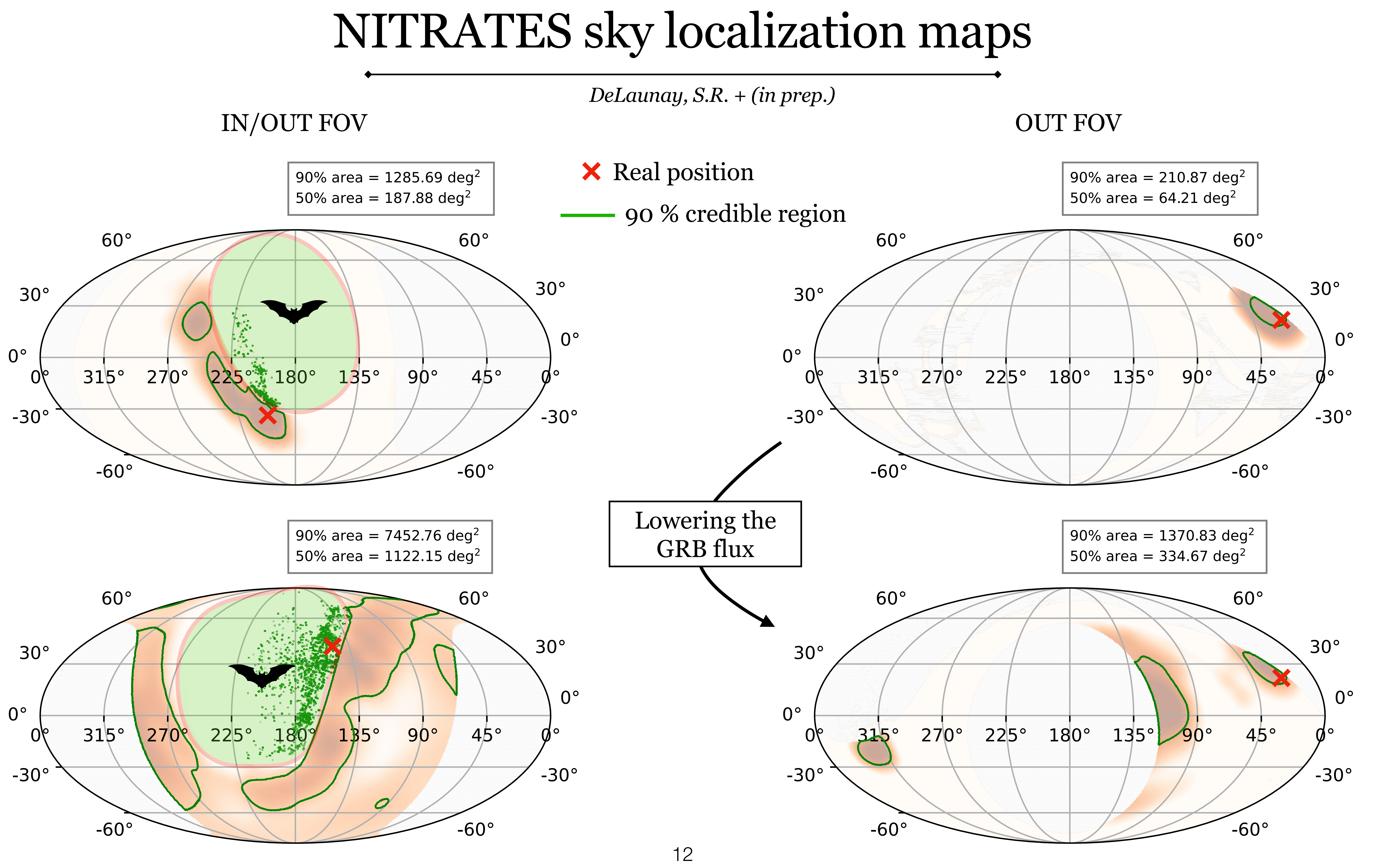
XRT = 2.357”/pix



Top: XRT data (smooth/orig)

Bottom: Chandra image convolved with XRT PSF.

Can we do better? NITRATES



Slide courtesy Samuele Ronchini

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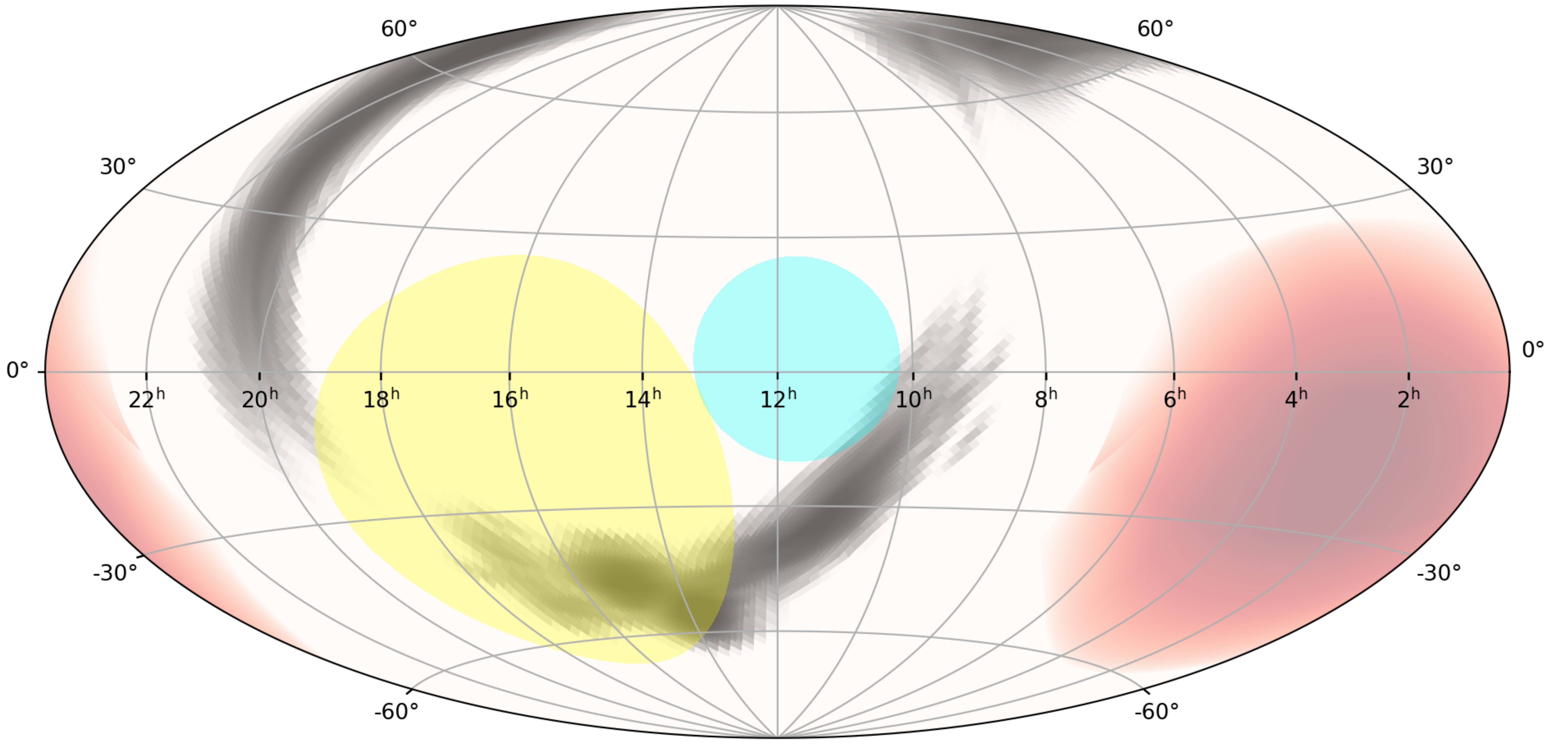

GW 241125 - BBH

A_{90} = 2,153 deg^2.

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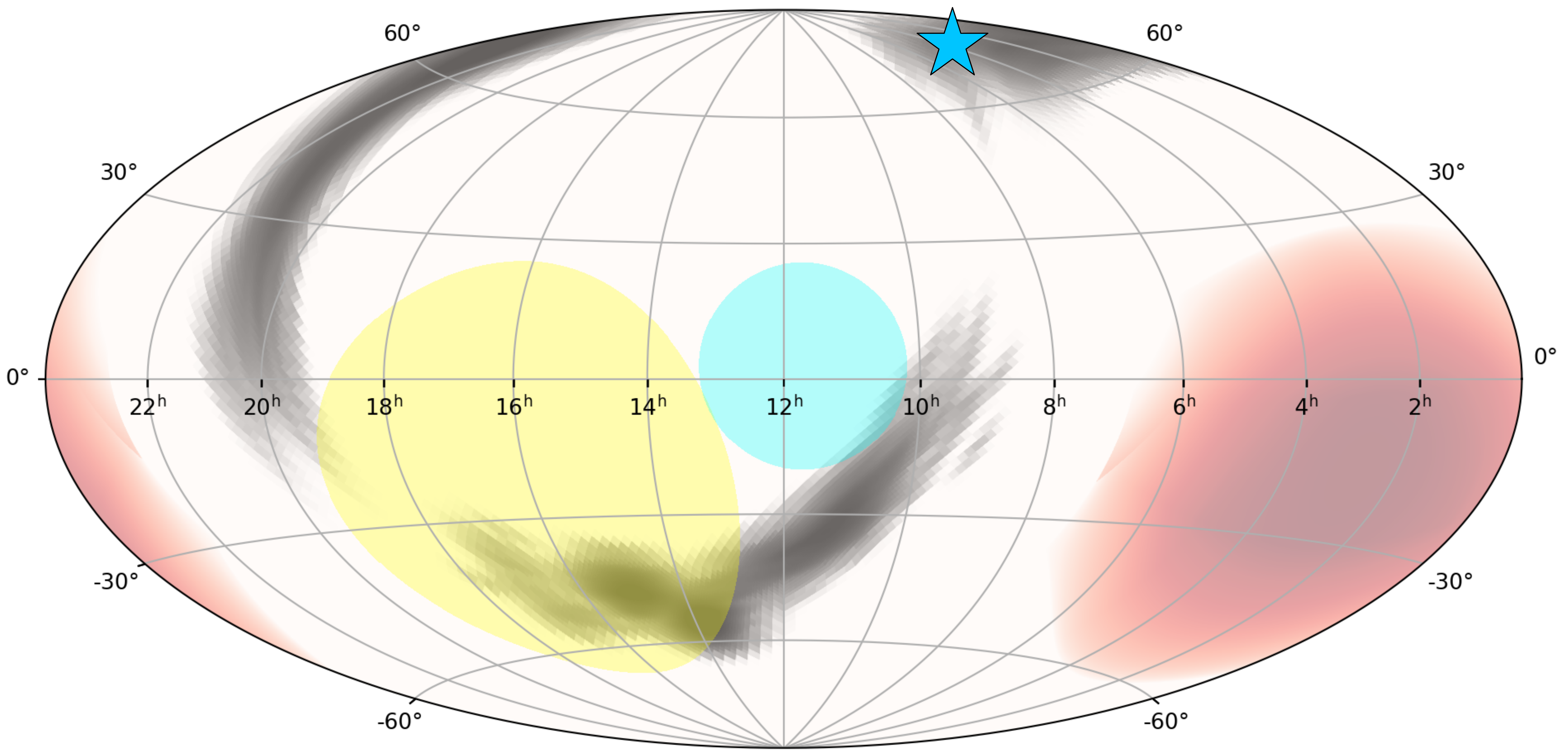


GW 241125 - BBH

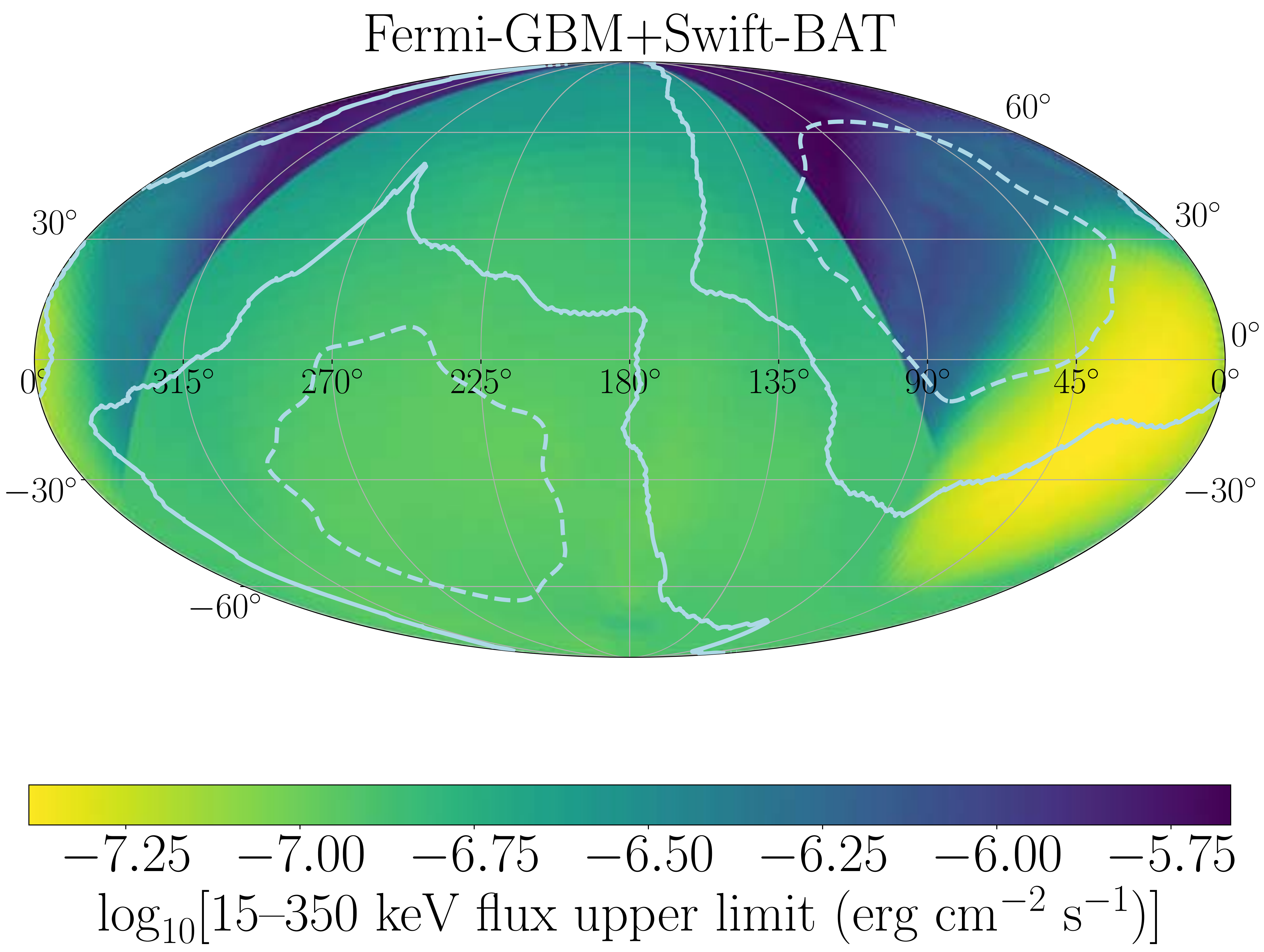
A_{90} = 2,153 deg².

NITRATES:

- 11 s post-merger
- Subthreshold
- R_{84} = 5' (!)

Back to GW 230529

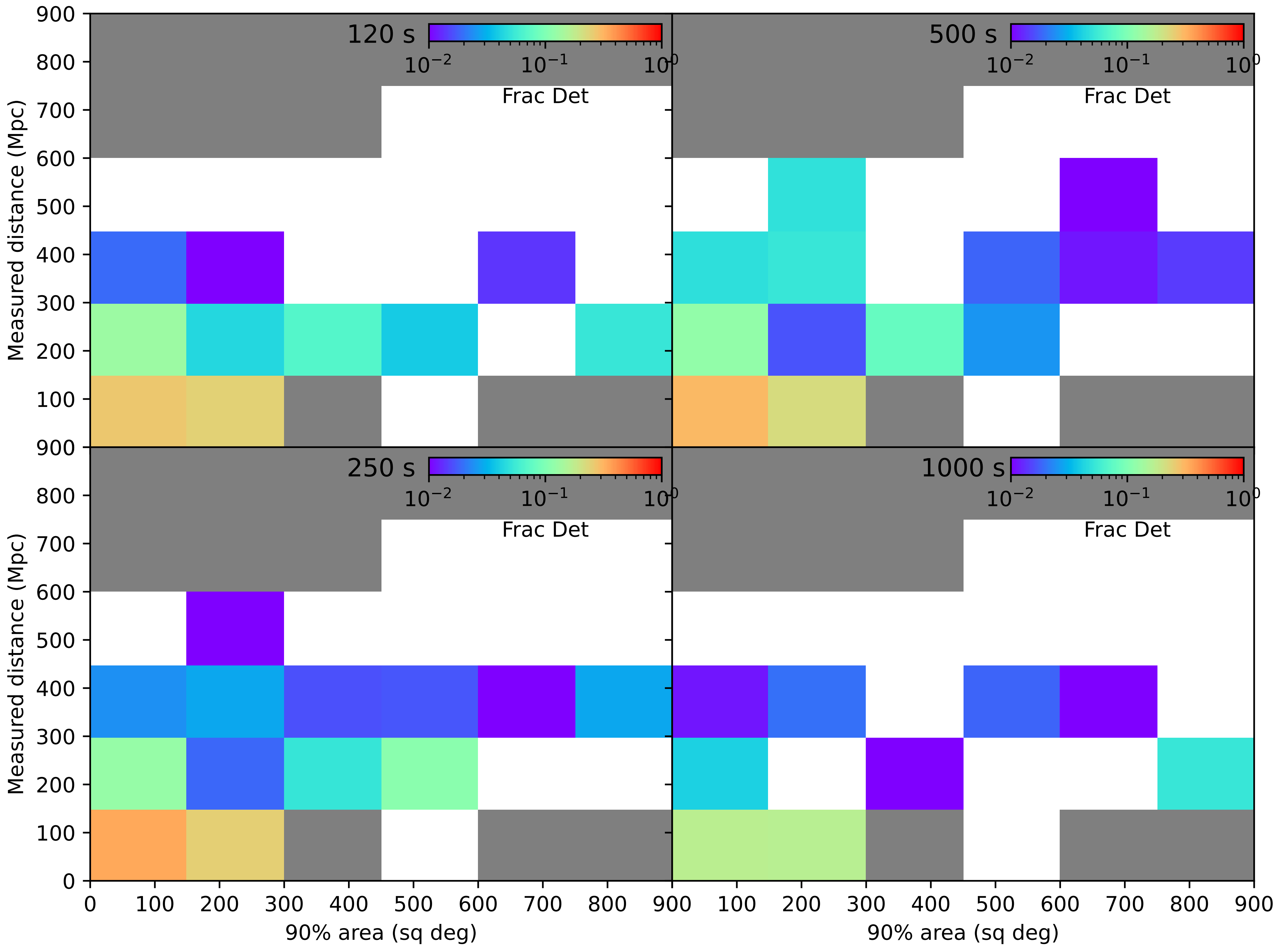
- A NS-BH merger (probably).
  - $M_1 \sim 3.6\ M_\odot$
  - $M_2 \sim 1.4\ M_\odot$
  - *Fermi*-GBM and *Swift*-BAT covered the whole sky!
  - No GRB at $>10^{48}$ erg/s.

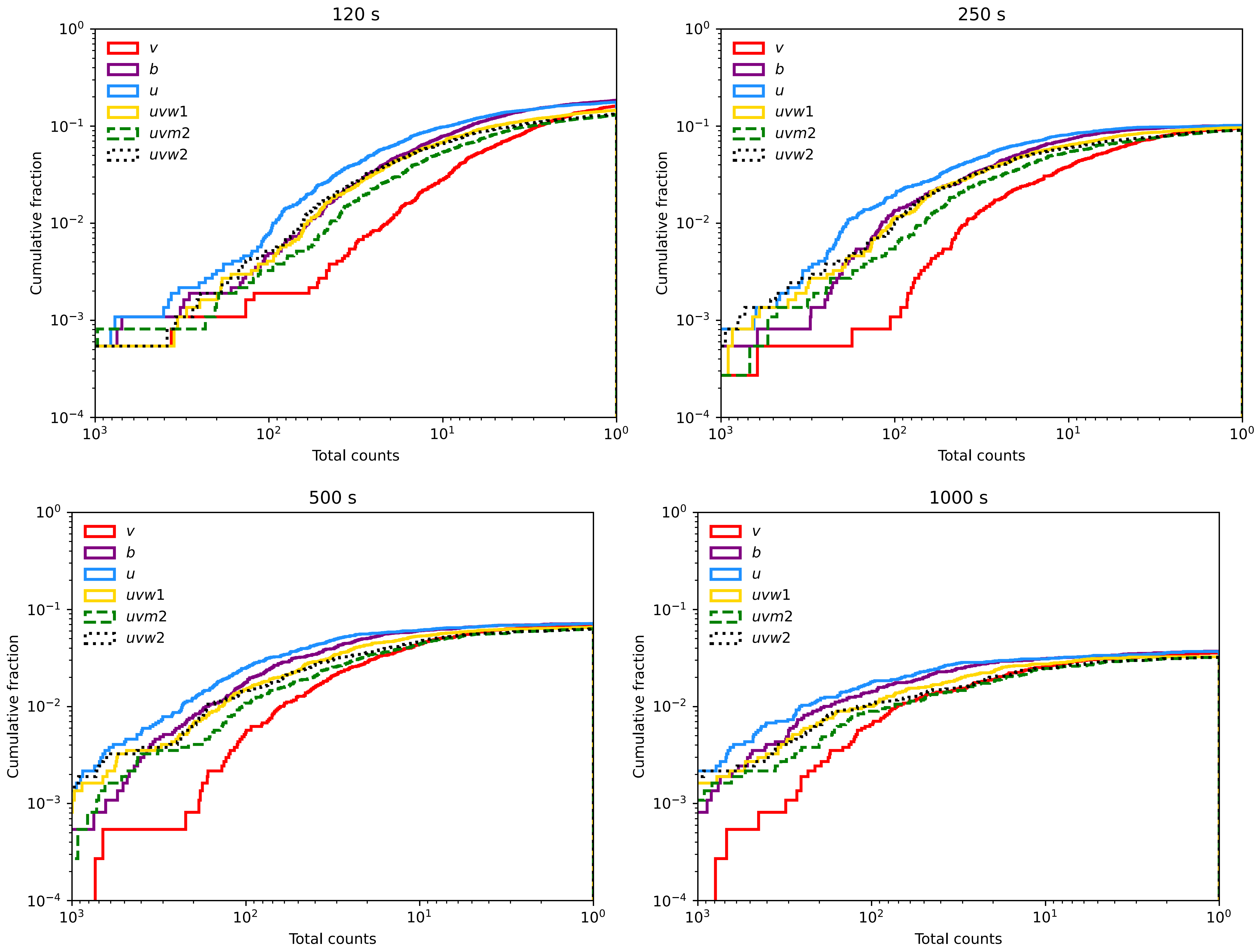


Ronchini+ (2024)
ApJL, 970, L20

Follow up approach

- Simulations show that the UV KN is best counterpart for *Swift*.
- Exploring optimal exposure time (sensitivity vs arrival time).





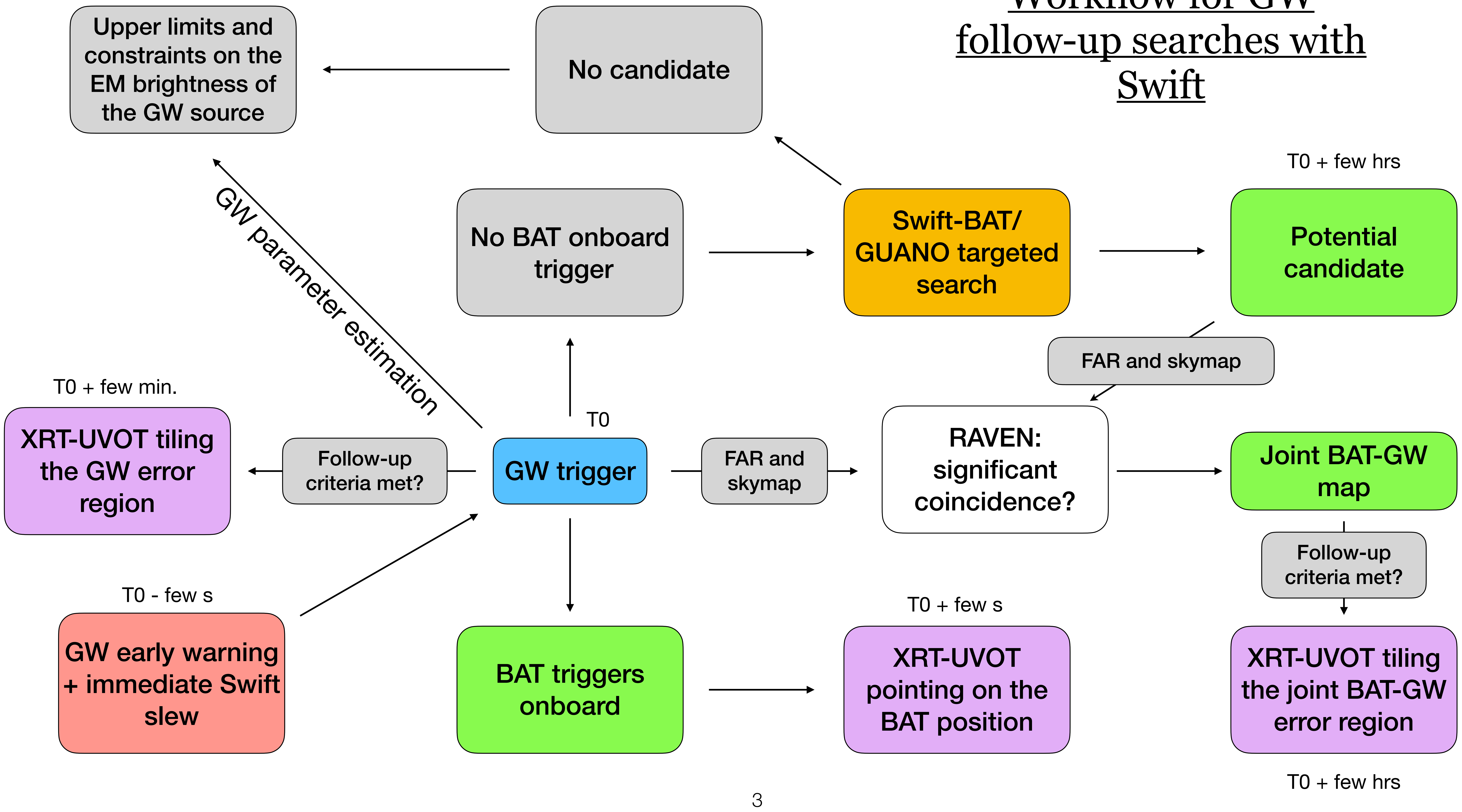
Eyles-Ferris, PE+ (2025)

MNRAS, 536, 2857

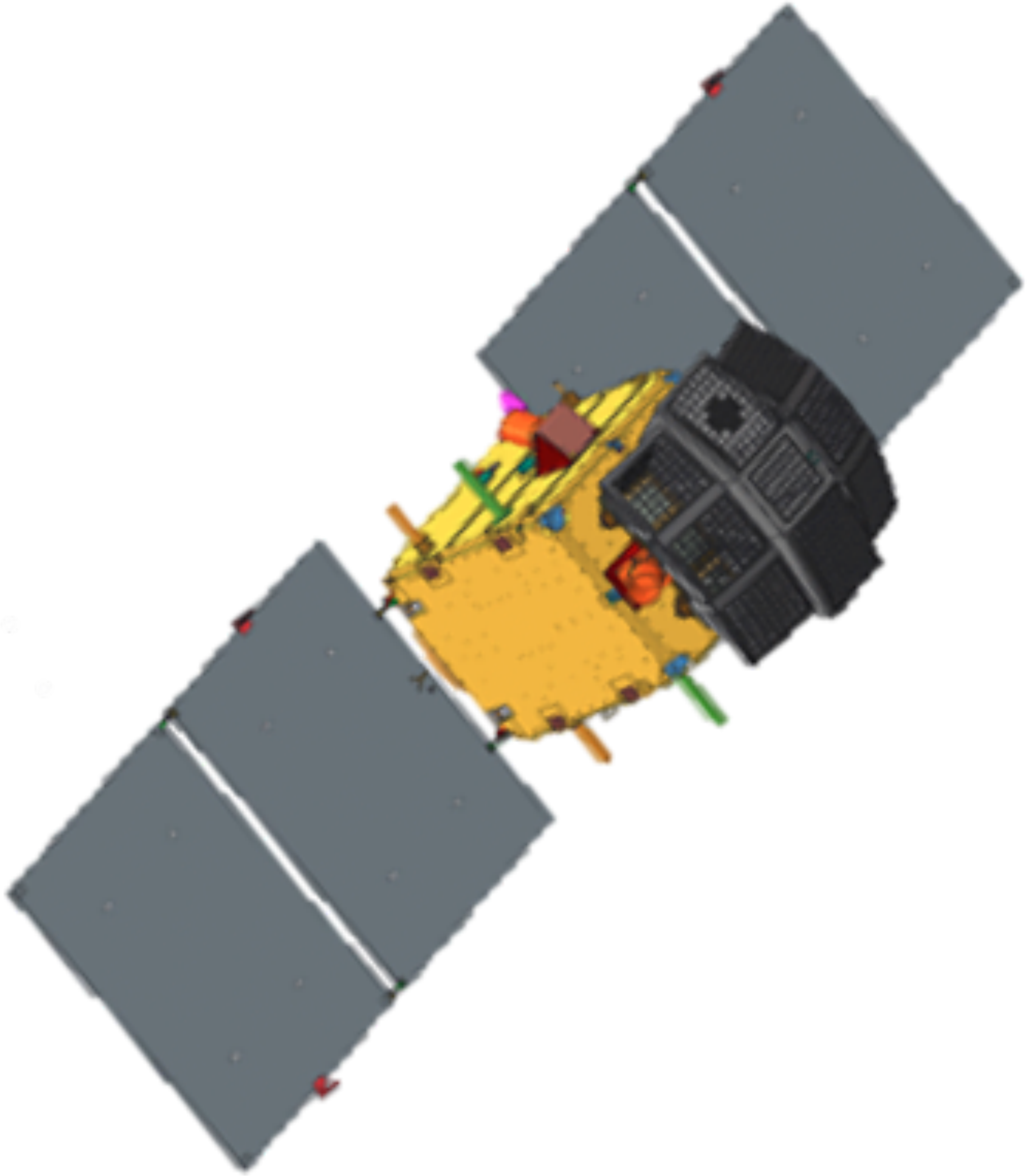
Follow up approach

Workflow for GW follow-up searches with Swift

Slide courtesy Samuele Ronchini

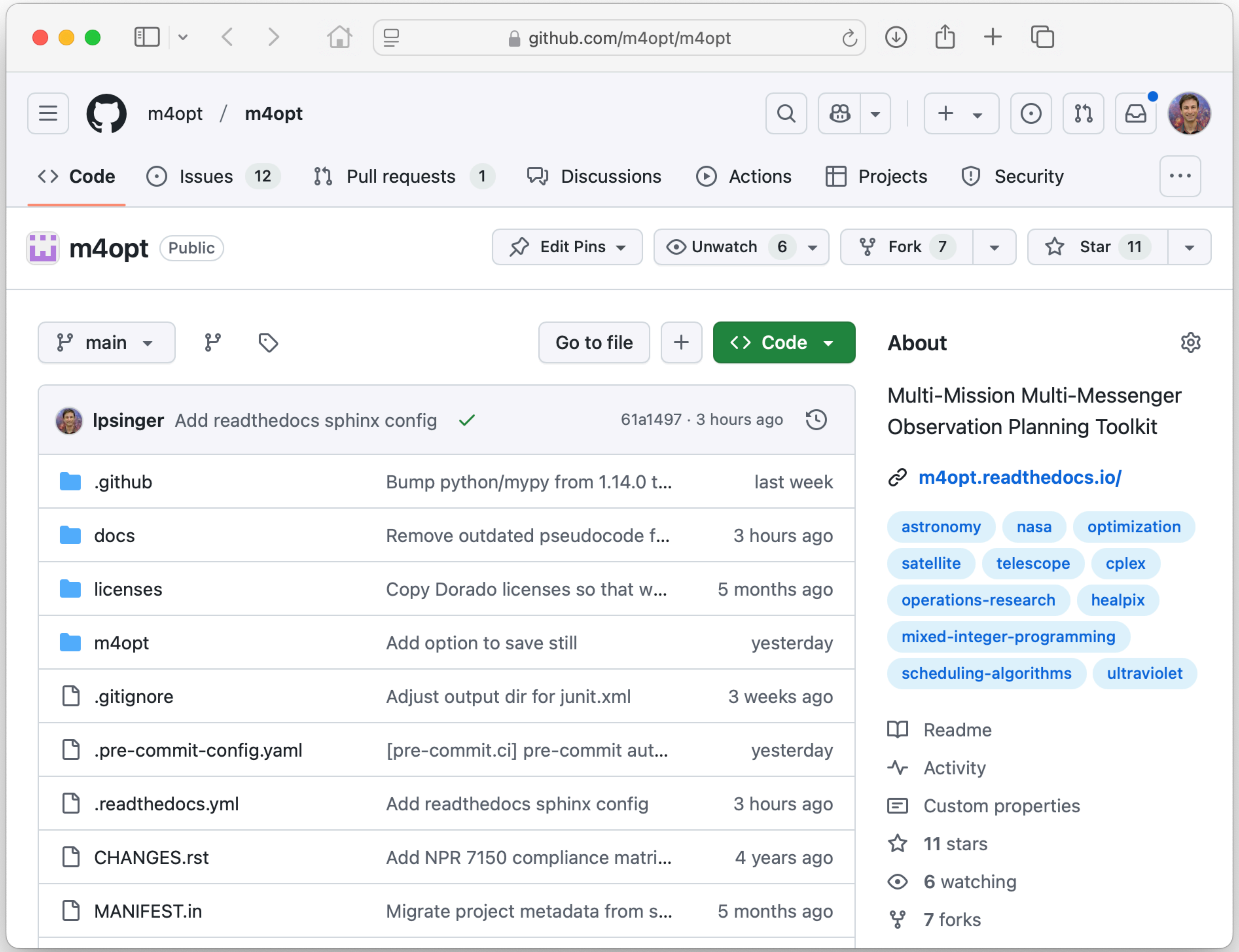


The future — SVOM and EP



M⁴OPT: Multi-Mission Multi-Messenger Observation Planning Toolkit

UNIVERSITY OF LEICESTER



- Mixed integer linear programming scheduler for targets of opportunity
- Deeply integrated with the Astropy ecosystem
- Vector-accelerated synthetic photometry for larger parameter sweeps than are practical with synphot
- Observing constraint modeling framework inspired by astroplan
- Free and open source

https://github.com/m4opt/m4opt

Conclusions

- GW follow up is hard!
  - but worth it!
- A lot of theory… very little data.
- This is a good era to work in the field.
  - Swift
  - SVOM
  - Einstein Probe
  - (UVEX)
  - Kagra
  - LIGO-India?
- … we just need some blasted BNS mergers!