

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

University of Leicester

P. Evans – First ACME workshop – Toulouse: 9/04/2025



Phil Evans



### **Binary Neutron Star mergers.** 0

- Jets (short? GRBs)
  - Off-axis?
- Kilonova.





ApJ, 746, 48





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  - What colour?







Gottlieb+ 2024 arXiv: 2411.13657







### Binary Neutron Star mergers.

- Jets (short? GRBs)
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- Kilonova.
  - What colour?
- Magnetar spin-down.









### Binary Neutron Star mergers.

- Jets (short? GRBs)
  - Off-axis?
- Kilonova.
  - What colour?
- Magnetar spin-down.
- NH-BH mergers
  - Maybe a GRB / KN.
- BBH mergers











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













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- GW are hard to localise! 0
  - But we can optimise...
  - Gehrels: 50% of galaxy luminosity (hence mass) is in «50% of galaxies.
    - Target bright galaxies.

ΔN

ΔN





Gehrels+ 2016 ApJ, 820, 136











Z

	MAX FAR	MAX DISTANCE	<b>MAX 90% ARE</b>
P_disrupt =0	1/10 yr	/	30 deg <sup>2</sup>
P_disrupt <0.5	1/90 days	150 Mpc	300 deg <sup>2</sup>
P_disrupt >0.5	1/90 days	400 Mpc	300 deg <sup>2</sup>
Bursts	1/yr	/	/
Sub-Solar Mass	1/2yr	400 Mpc	300 deg <sup>2</sup>
galax	ies.		

- Target bright galaxies.
- Evans+: calculate probability per dalaxv.

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

$$\mathcal{P}_{\operatorname{nogal},p} = P_{\operatorname{GW},p}(1-C_p).$$

• For potentially bright GW sources, exposure optimized to maximize detection chance for Kilonova

MNRAS, 462, 1591





Gehrels+ 2016 ApJ, 820, 136











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MNRAS, 462, 1591

ulative frac









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



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













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









### Abbott+++ 2017

ApJL, 848, L12



! !

## GW 170817



### Evans+ 2017

Science, 358, 1565













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













oiscovered on 29 May 2023 at 18h15 UT

most likely a merger between a Neutron Star & Black Hole (NSBH)



~3.6 M<sub>o</sub>

### Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

https://gwosc.org/eventapi/html/O4\_Discovery\_Papers/GW230529\_181500/v1/ Credit: Shanika Galaudage / Observatoire de la Côte d'Azur

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**GW 230529** 



















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### $A_{90} = 12,545 \text{ deg}^2$ .









### Ruan... PE+ (2018) ApJL, 853, L14

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

# Back to 170817



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### Chandra image (smoothed). XRT = 2.357"/pix

# Back to 170817





### Top: XRT data (smooth/orig) Bottom: Chandra image convolved with XRT PSF.

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# **Can we do better? NITRATES**







### Slide courtesy Samuele Ronchini

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### **Can we do better? NITRATES**



### GW 241125 - BBH

![](_page_24_Picture_5.jpeg)

### $A_{90} = 2,153 \text{ deg}^2$ .

![](_page_24_Picture_7.jpeg)

![](_page_24_Picture_8.jpeg)

![](_page_25_Picture_0.jpeg)

## **Can we do better? NITRATES**

![](_page_25_Figure_2.jpeg)

### GW 241125 - BBH

![](_page_25_Picture_5.jpeg)

### $A_{90} = 2,153 \text{ deg}^2$ .

### NITRATES:

- 11 s post-merger
- Subthreshold 0

• 
$$R_{84} = 5'(!)$$

![](_page_25_Picture_12.jpeg)

- 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.

# **Back to GW 230529**

![](_page_26_Picture_9.jpeg)

![](_page_26_Figure_10.jpeg)

### -7.25 -7.00 -6.75 -6.50 -6.25 -6.00 -5.75 $\log_{10}[15-350 \text{ keV flux upper limit (erg cm}^{-2} \text{ s}^{-1})]$

Ronchini+ (2024) ApJL, 970, L20

![](_page_26_Picture_13.jpeg)

![](_page_27_Picture_0.jpeg)

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

![](_page_27_Figure_4.jpeg)

### **Follow up approach**

![](_page_27_Picture_7.jpeg)

![](_page_27_Figure_8.jpeg)

Eyles-Ferris, PE+ (2025) MNRAS, 536, 2857

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![](_page_27_Picture_11.jpeg)

![](_page_27_Picture_12.jpeg)

![](_page_28_Figure_0.jpeg)

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![](_page_28_Picture_4.jpeg)

![](_page_28_Figure_5.jpeg)

![](_page_28_Picture_6.jpeg)

![](_page_29_Picture_0.jpeg)

![](_page_29_Picture_2.jpeg)

### The future — SVOM and EP

![](_page_29_Picture_5.jpeg)

![](_page_29_Picture_6.jpeg)

![](_page_29_Picture_7.jpeg)

![](_page_30_Picture_0.jpeg)

### M<sup>4</sup>OPT: Multi-Mission Multi-Messenger Observation Planning Toolkit

	G ☐ github.com/m4opt/m	4opt උ	
m4opt / m4opt		QB	-   + - O II 🗗 🎯
Code 🕢 Issues 12 12	Pull requests 1 🖓 Discussions	➢ Actions	Projects 🕑 Security \cdots
m4opt Public	S Edit Pins ▼	Jnwatch 6 🗸	양 Fork 7 ▼ ☆ Star 11 ▼
ド main ▾ ♡	Go to file +	<> Code -	About 🕸
Ipsinger Add readthedocs s	sphinx config 🗸 61a1497 ·	3 hours ago 🕚	Multi-Mission Multi-Messenger Observation Planning Toolkit
github	Bump python/mypy from 1.14.0 t	last week	<i>c</i> <sup>2</sup> m4opt.readthedocs.io/
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licenses	Copy Dorado licenses so that w	5 months ago	operations-research healpix
m4opt	Add option to save still	yesterday	mixed-integer-programming
🗋 .gitignore	Adjust output dir for junit.xml	3 weeks ago	scheduling-algorithms ultraviolet
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CHANGES.rst	Add NPR 7150 compliance matri	4 years ago	☆ 11 stars
	Migrate project metadata from s	5 months ago	6 watching

![](_page_30_Picture_5.jpeg)

- 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

![](_page_30_Picture_11.jpeg)

![](_page_30_Picture_12.jpeg)

- GW follow up is hard! 0
  - 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  $\bigcirc$
  - LIGO-India?
- ... we just need some blasted BNS mergers!

## Conclusions

![](_page_31_Picture_15.jpeg)

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![](_page_31_Picture_18.jpeg)