

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





Binary Neutron Star mergers. 0

Jets (short? GRBs)

- Off-axis?
- Kilonova.







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





Binary Neutron Star mergers. 0

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







Gottlieb+ 2024 arXiv: 2411.13657







Binary Neutron Star mergers.

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

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

- 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 | MAX 90% ARE |
|----------------|-----------|--------------|----------------------|
| P_disrupt =0 | 1/10 yr | / | 30 deg ² |
| P_disrupt <0.5 | 1/90 days | 150 Mpc | 300 deg ² |
| P_disrupt >0.5 | 1/90 days | 400 Mpc | 300 deg ² |
| Bursts | 1/yr | / | / |
| Sub-Solar Mass | 1/2yr | 400 Mpc | 300 deg ² |
| 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

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

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

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

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

 For potentially bright GW sources, exposure optimized₀ to maximize detection chance for Kilonova Evans+ 2016

MNRAS, 462, 1591

ulative frac

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

11

12

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

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

Abbott+++ 2017

ApJL, 848, L12

! !

GW 170817

Evans+ 2017

Science, 358, 1565

14

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

oiscovered on 29 May 2023 at 18h15 UT

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

~3.6 M_o

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

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

GW 230529

16

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

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

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

Back to 170817

17

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

Back to 170817

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

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

Can we do better? NITRATES

Slide courtesy Samuele Ronchini

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

Can we do better? NITRATES

GW 241125 - BBH

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

Can we do better? NITRATES

GW 241125 - BBH

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

NITRATES:

- 11 s post-merger
- Subthreshold 0

•
$$R_{84} = 5'(!)$$

- 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

-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

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

Follow up approach

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

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

З

The future — SVOM and EP

M⁴OPT: 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> ² m4opt.readthedocs.io/ |
| docs | Remove outdated pseudocode f | 3 hours ago | astronomy nasa optimization |
| 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 |
| .pre-commit-config.yaml | [pre-commit.ci] pre-commit aut | yesterday | Readme |
| .readthedocs.yml | Add readthedocs sphinx config | 3 hours ago | Custom properties |
| CHANGES.rst | Add NPR 7150 compliance matri | 4 years ago | ☆ 11 stars |
| | Migrate project metadata from s | 5 months ago | 6 watching |

- 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

- 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

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

