



Of Needles in Haystacks



Lessons from the GW-MMADS follow-up campaign during the fourth LIGO/Virgo/KAGRA observing run

Tomás Cabrera | Carnegie Mellon University
Throughput Computing Week 2026 | Madison, WI



MMA Research



Researcher



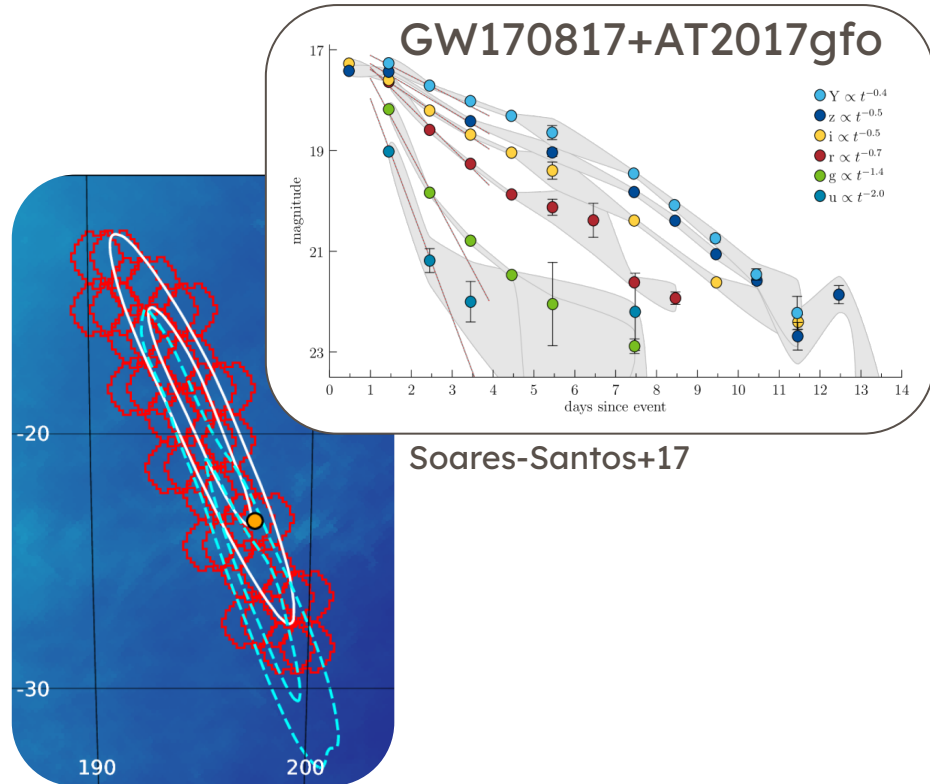
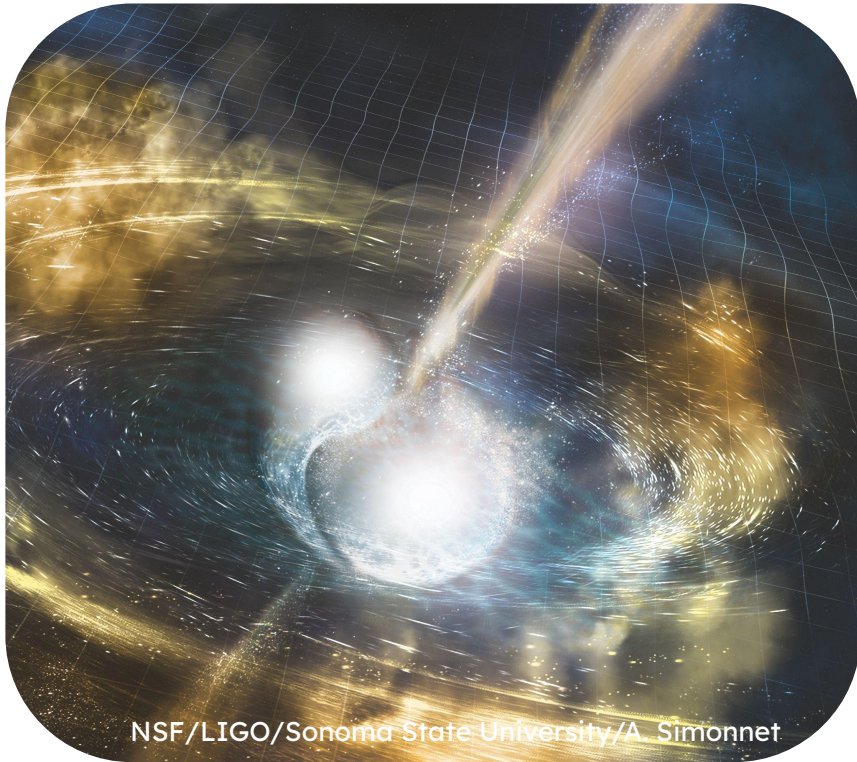
New Attendee



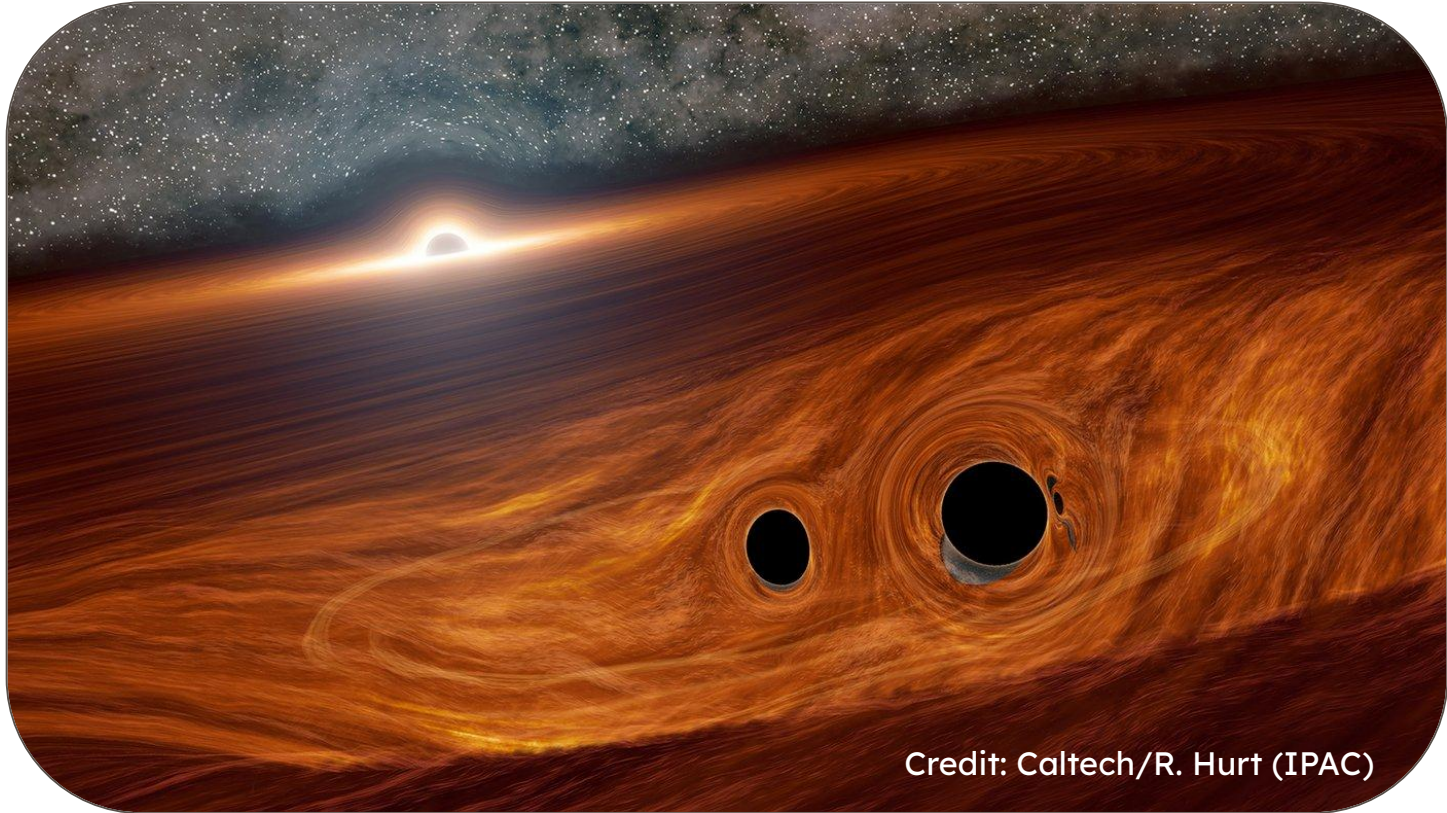
Outline

- Background on GW multimessengers
- Walkthrough of GW follow-up
- Lessons learned

EM+GW: Binary neutron stars mergers + kilonovae

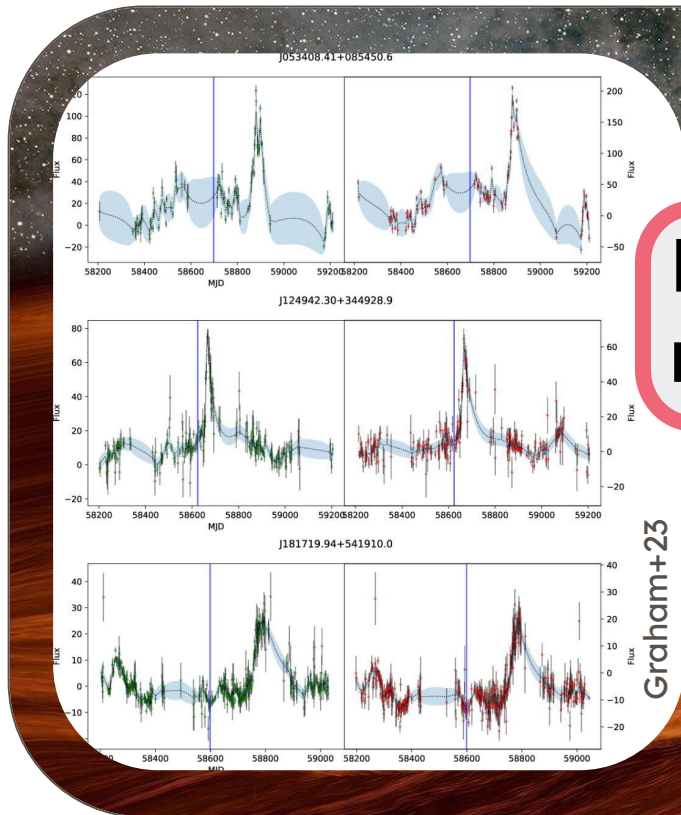


EM+GW: Binary black holes + AGN flares



Credit: Caltech/R. Hurt (IPAC)

EM+GW: Binary black holes + AGN flares



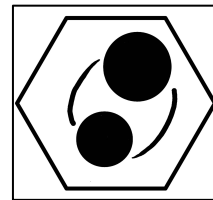
**BBHs are
multimessengers too!**

Graham+23

Caltech/R. Hurt (IPAC)

The GW-MMADS O4 team

(Gravitational Wave Multi-Messenger Astronomy DECam Survey; PIs: Andreoni + Palmese)



Igor Andreoni

(UNC-Chapel Hill)

Brendan O'Connor

Keerthi Kunnumkai

Antonella Palmese

(advisor)

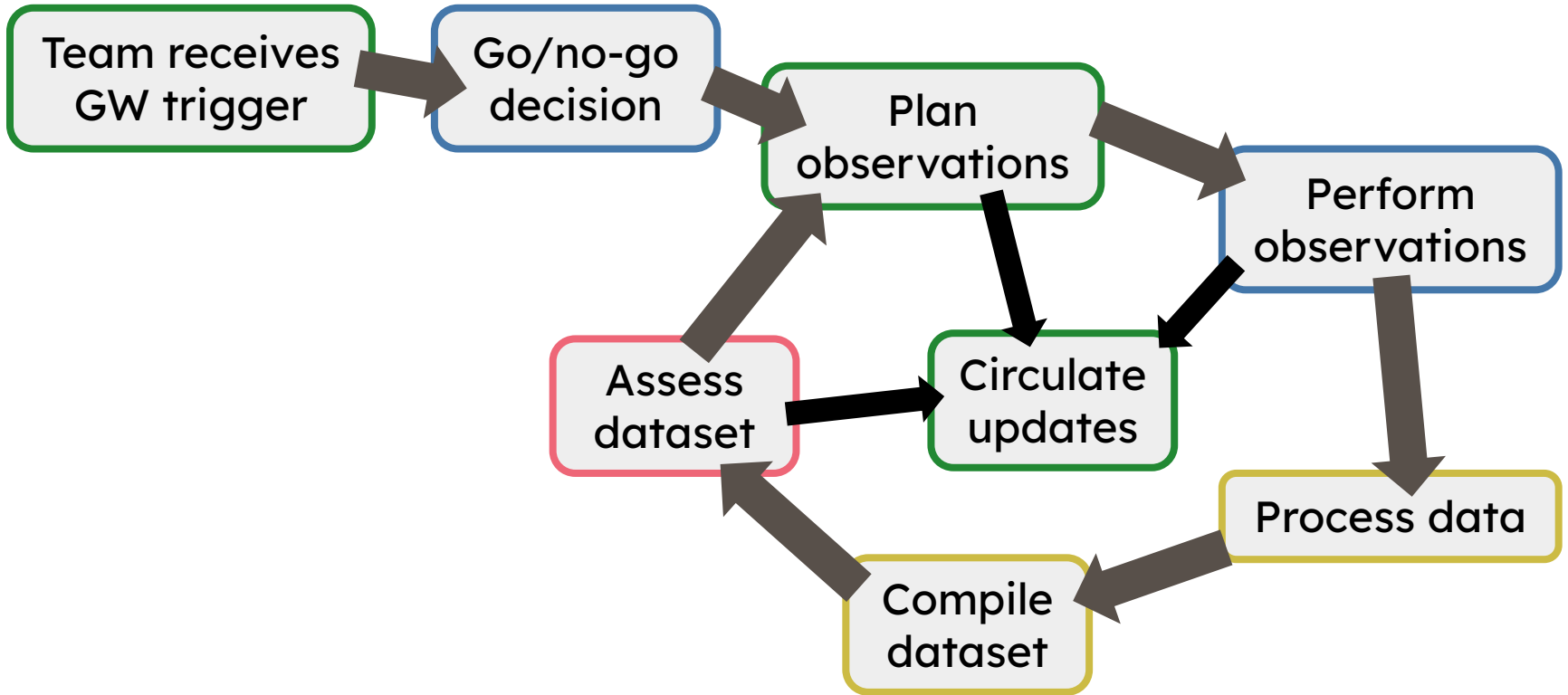
Also:

- Barry McKernan (CUNY)
- Saavik Ford (CUNY)
- Matthew Graham (Caltech)
- Tomás Ahumada (NOIRLab)
- Michael Coughlin (UMN)
- Daniel Gruen (LMU)
- Frank Valdes (NOIRLab)
- and many more!

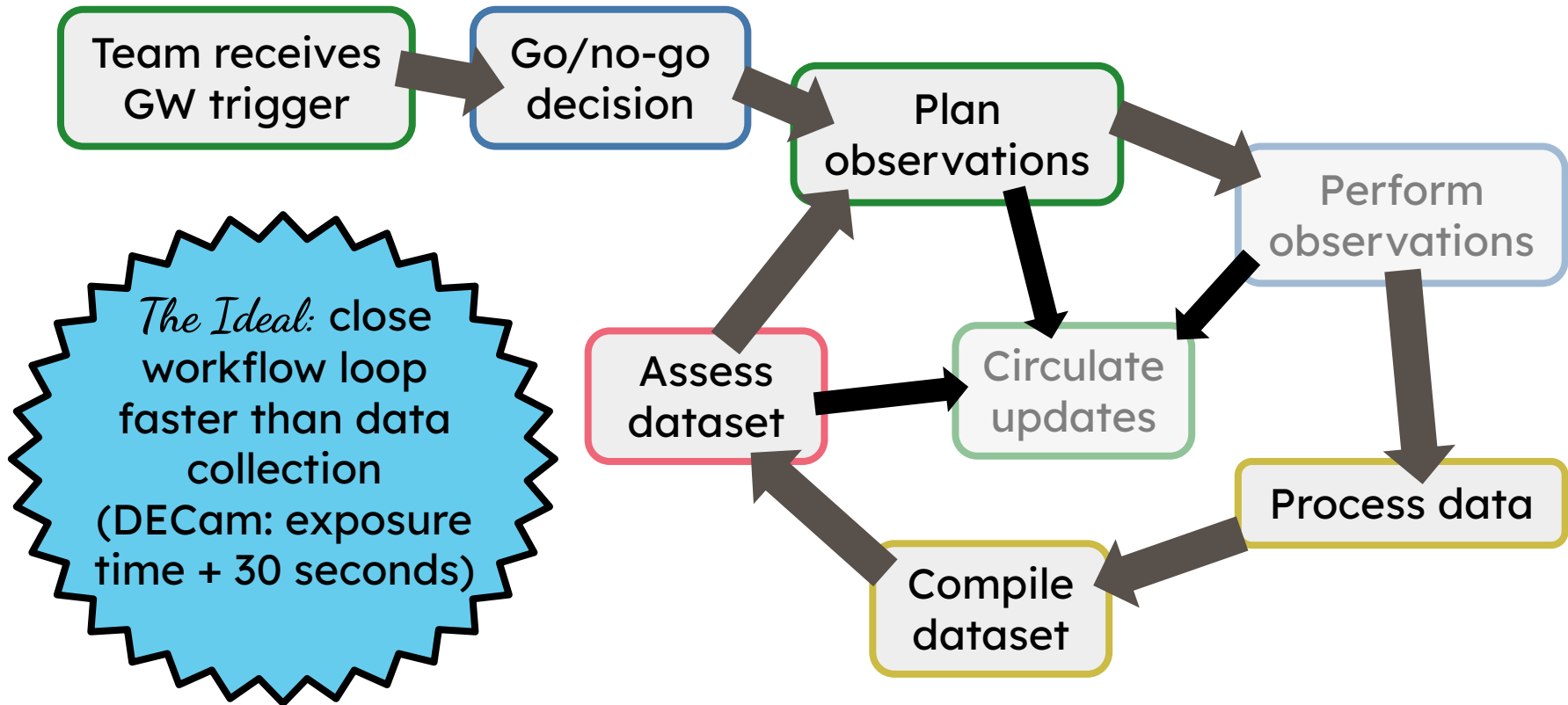
Lei Hu

Xander Hall

The counterpart search workflow



The counterpart search workflow

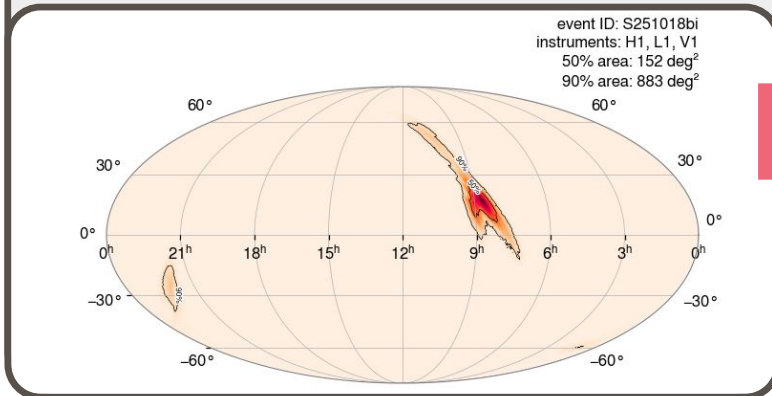


Team receives
GW trigger

100% solved

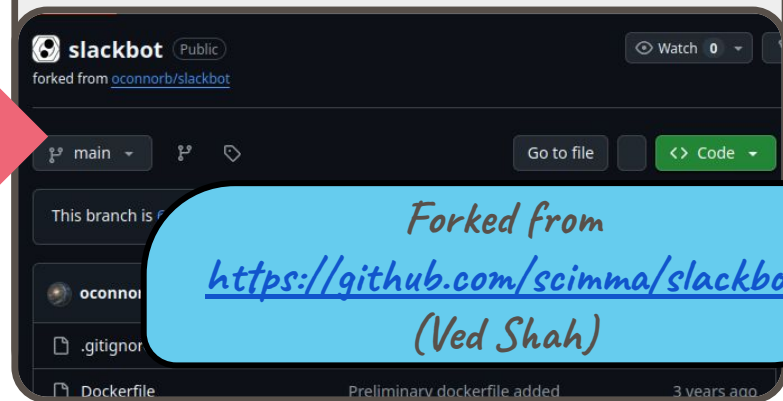
LVK Public Alerts User Guide

<https://emfollow.docs.ligo.org/userguide/>



Slackbot

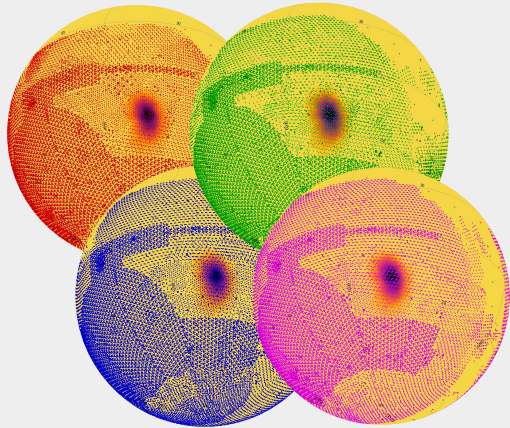
<https://github.com/CMU-MMA/slackbot>



Go/no-go
decision

Depends on science case

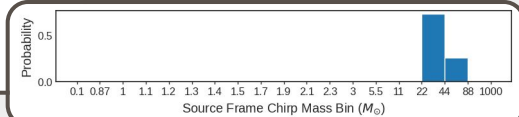
Archival coverage?



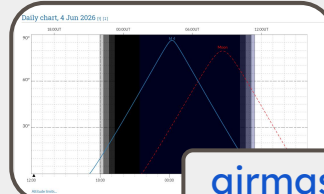
Event parameters?

HasMassGap 0%
HasNS 0%
HasRemnant 0%

BBH 100%
NSBH <1%
BNS <1%
Terrestrial 0%



Observability?



airmass.org

Weather?

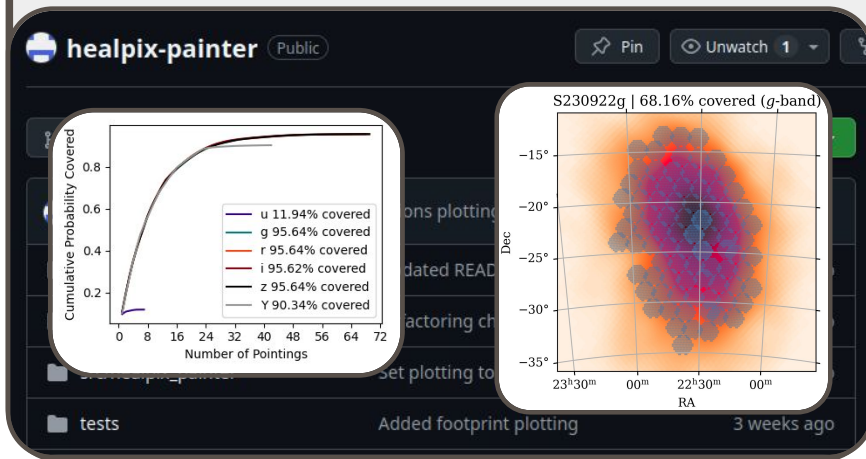


Plan observations

80% solved

healpix-painter

<https://github.com/tomas-cabrera/healpix-painter>



- What does the archival coverage look like?
- What filters are available?
- How deep is the coverage?
- How much time is available?
- What photometric catalogs are available?

See also:
gwemopt

(Coughlin+18,19, Almualla+20)

<https://github.com/skyportal/gwemopt>

Process data

75% solved

GW-MMADS DECam pipeline

Hu, Cabrera+26 ([arXiv:2603.08593](https://arxiv.org/abs/2603.08593))

A GPU-Accelerated Transient Detection Pipeline for DECam Time-Domain Surveys

LEI HU ^{1,2} TOMÁS CABRERA ¹ ANTONELLA PALMESE ¹ LIFAN WANG ³ IGOR ANDREONI ⁴ XANDER J. HALL ¹
XINGZHUO CHEN ^{3,5} JIAWEN YANG ³ FRANK VALDES ⁶ BRENDAN O'CONNOR ¹ AND YUHAN CHEN ⁷

¹ *McWilliams Center for Cosmology and Astrophysics, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213*

² *Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, 209 South 33rd Street, PA 19104, USA*

³ *George P. and Cynthia Woods Mitchell Institute for Fundamental Physics & Astronomy,*

Texas A. & M. University, Department of Physics and Astronomy, 4242 TAMU, College Station, TX 77843, USA

⁴ *Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA*

⁵ *Texas A&M Institute of Data Science John R. Blocker Building, Suite 227 155 Ireland Street, TAMU 3156 College Station, TX 77843-3156*

⁶ *NSF NOIRLab, 950 N Cherry Ave, Tucson, AZ 85719, USA*

⁷ *Department of Physics, University of California, Berkeley, CA 94720, USA*

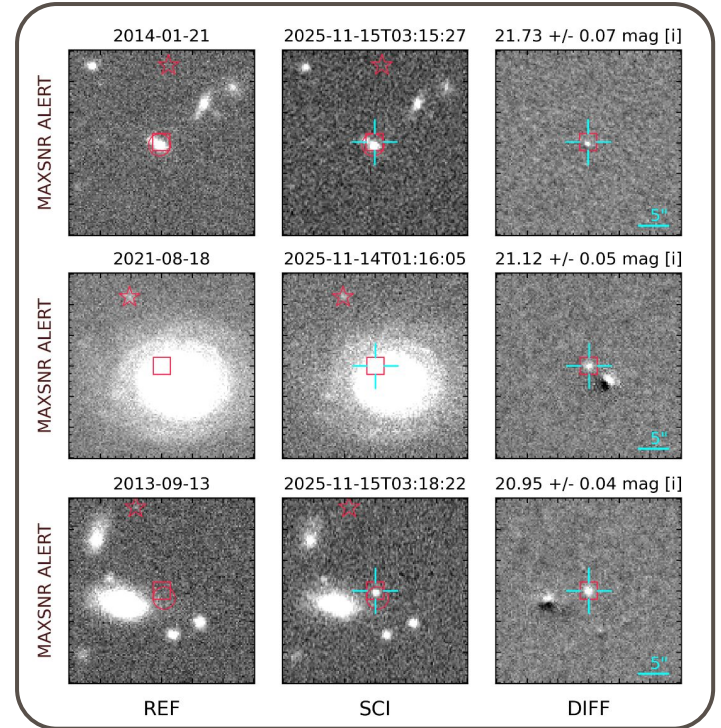
Process data

75% solved

GW-MMADS DECam pipeline

Hu, Cabrera+26 ([arXiv:2603.08593](https://arxiv.org/abs/2603.08593))

- GPU image differencing w/ SFFT (Hu+22)



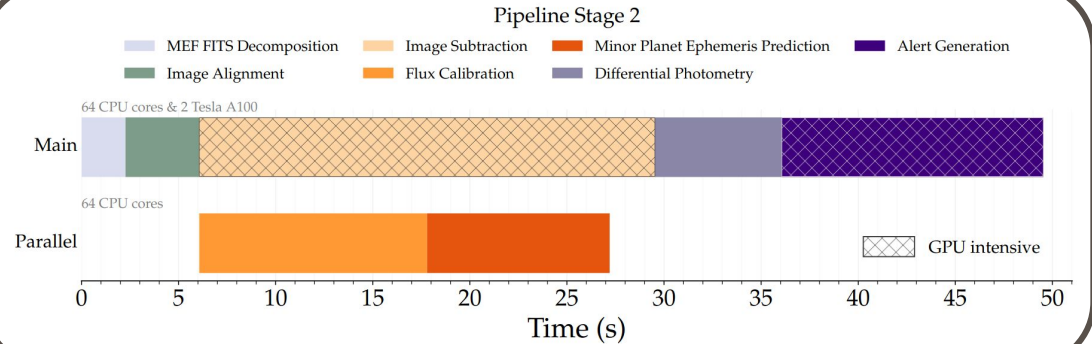
Process data

75% solved

GW-MMADS DECam pipeline

Hu, Cabrera+26 ([arXiv:2603.08593](https://arxiv.org/abs/2603.08593))

- GPU image differencing w/ SFFT (Hu+22)
- **~50s/DECam exposure**



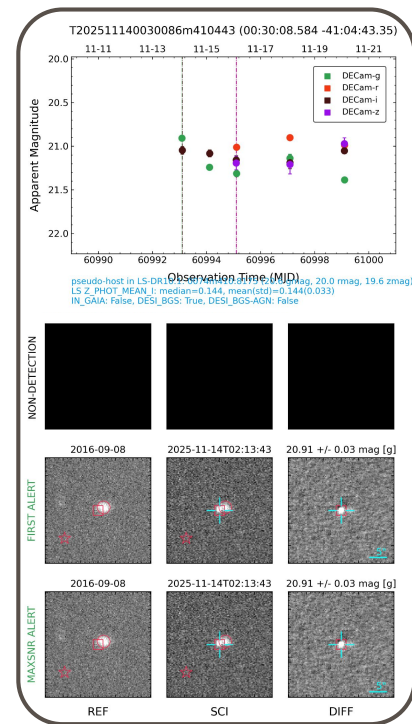
Compile dataset

40%

GW-MMADS DECam pipeline

Hu, **Cabrera+26** ([arXiv:2603.08593](https://arxiv.org/abs/2603.08593))

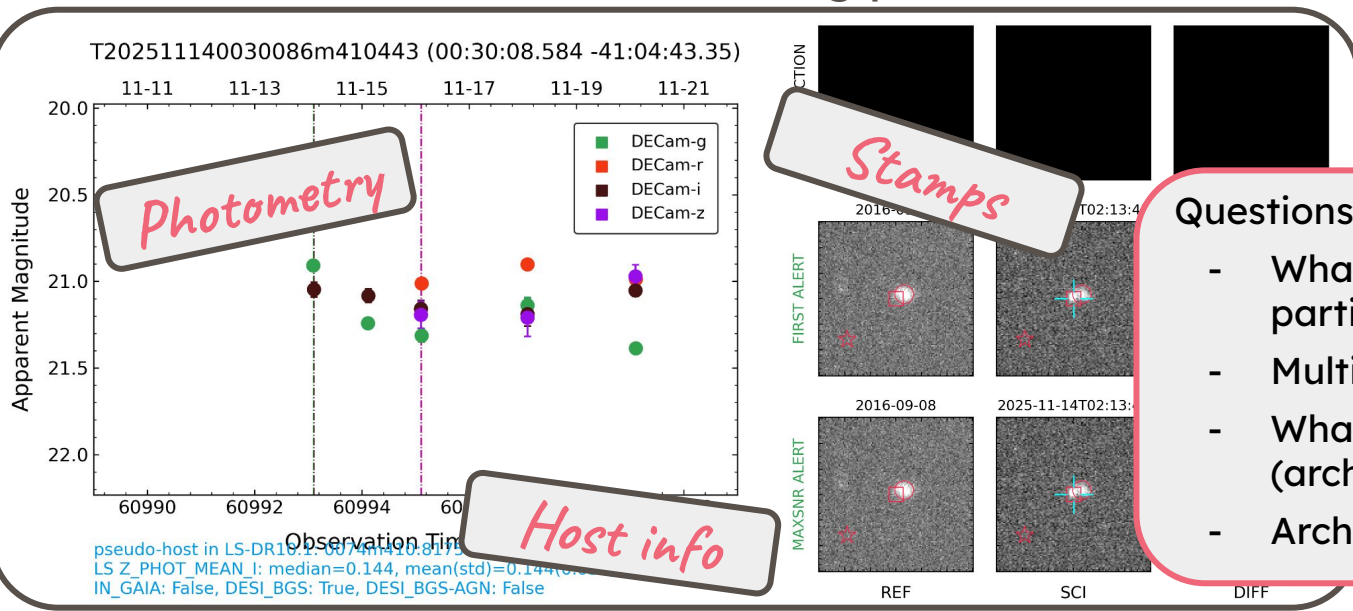
- GPU image differencing w/ SFFT (Hu+22)
- ~50s/DECam exposure
- Crossmatch with galaxy catalogs (redshifts?)
- Generate summary plots



Assess
dataset

25%

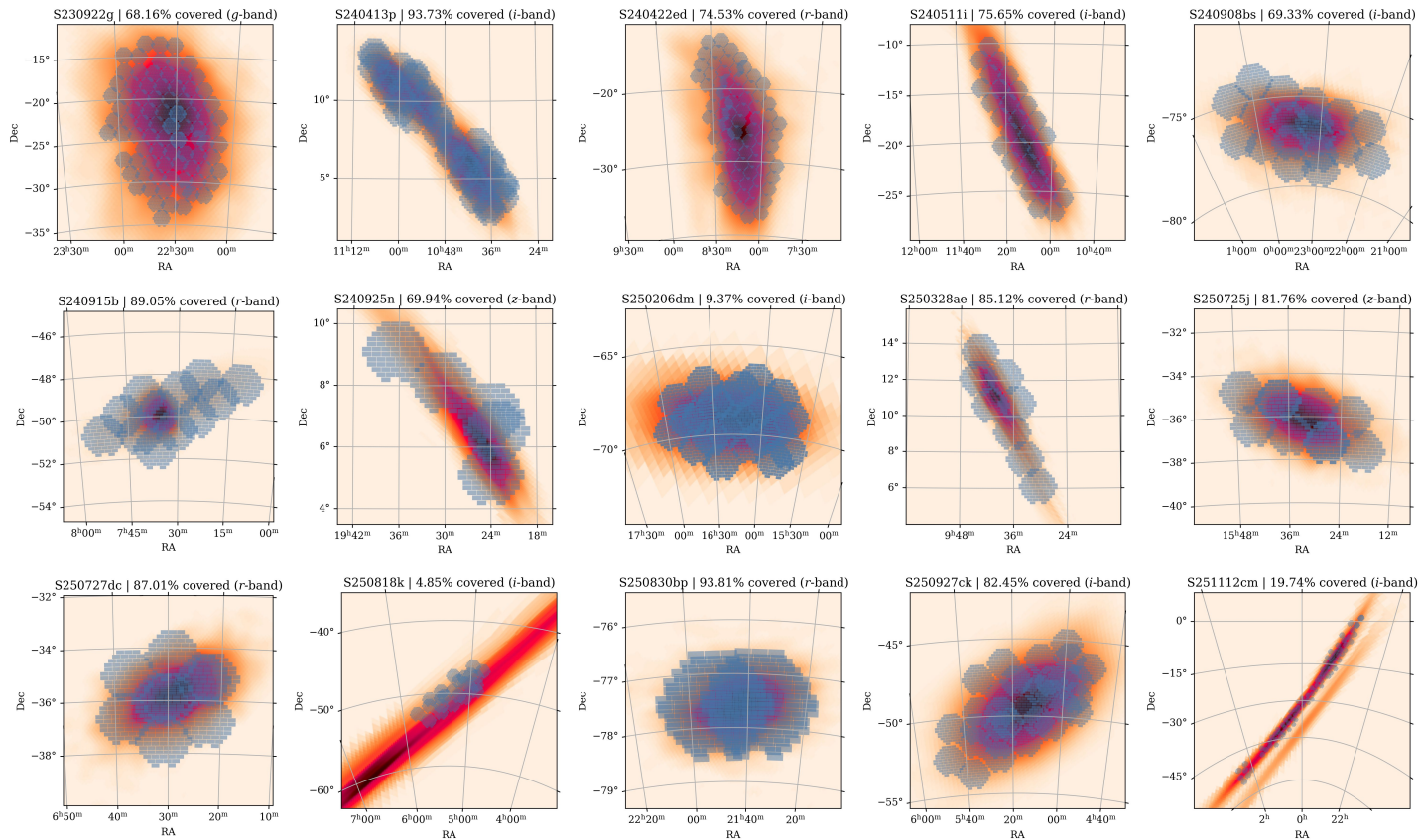
GW-MMADS vetting plot



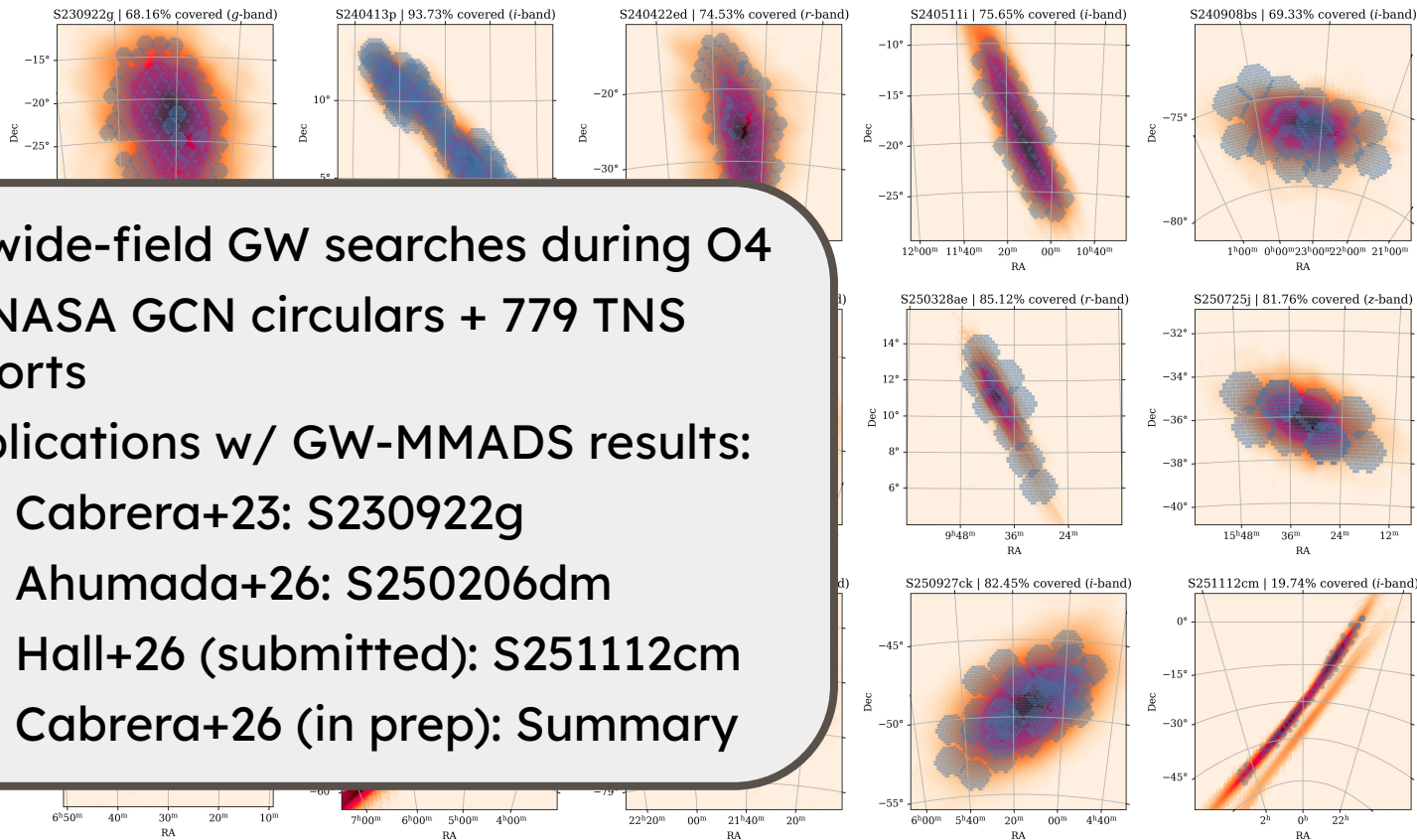
Questions not answered by plot:

- What does the stamp for a particular exposure look like?
- Multiband photometry?
- What spectra are available (archival or otherwise?)
- Archival lightcurves for host?

GW-MMADS O4 results



GW-MMADS O4 results



- 15 wide-field GW searches during O4
- 16 NASA GCN circulars + 779 TNS reports
- Publications w/ GW-MMADS results:
 - Cabrera+23: S230922g
 - Ahumada+26: S250206dm
 - Hall+26 (submitted): S251112cm
 - Cabrera+26 (in prep): Summary

Lessons learned + future prospects

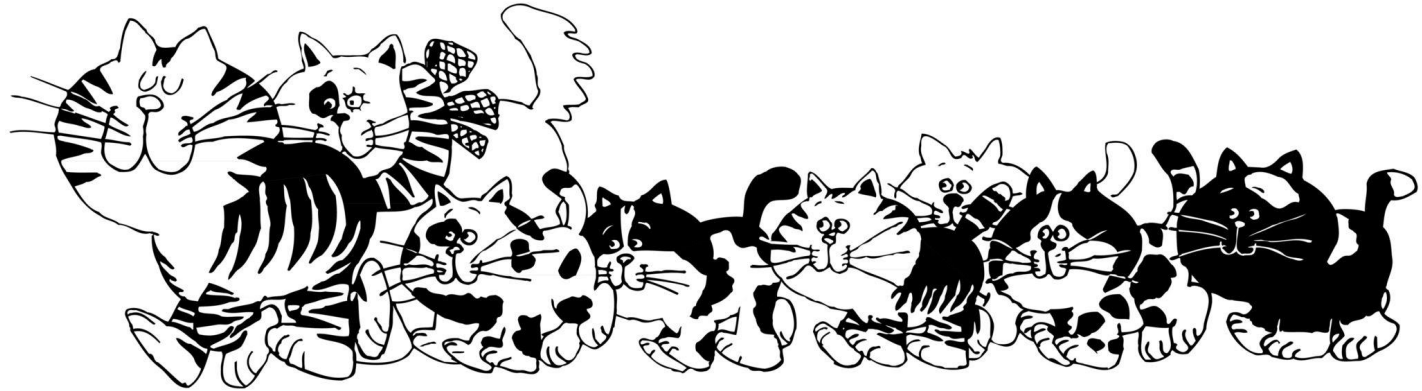
If Rubin wants to test its capabilities during IR1, it will need to trigger on a BBH.

Observing run	Network	Source class		
		BNS	NSBH	BBH
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HL	1_{-1}^{+4}	3_{-3}^{+7}	210_{-120}^{+250}
O4	HLV	2_{-2}^{+4}	4_{-4}^{+9}	240_{-140}^{+290}
O5a	HLV	5_{-5}^{+9}	11_{-8}^{+17}	520_{-290}^{+620}
O5b	HLV	10_{-8}^{+15}	21_{-14}^{+28}	760_{-420}^{+910}
O5c	HLV	15_{-11}^{+20}	25_{-16}^{+33}	890_{-490}^{+1060}

GW follow-up is not compute-limited..

GW follow-up is not compute-limited..

...but someone needs to herd the cats.



Only a human can say “**Eureka!**”

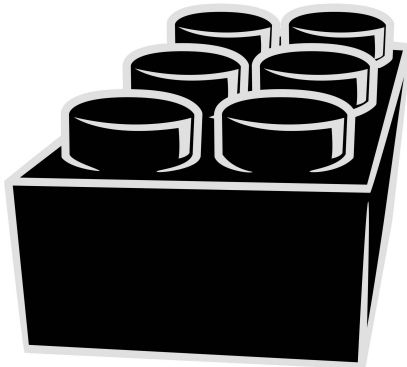
Only a human can say **“Eureka!”**



How can we learn to
“drink from the firehose”
of large data streams?

Many scientists want (or need)
bespoke solutions.

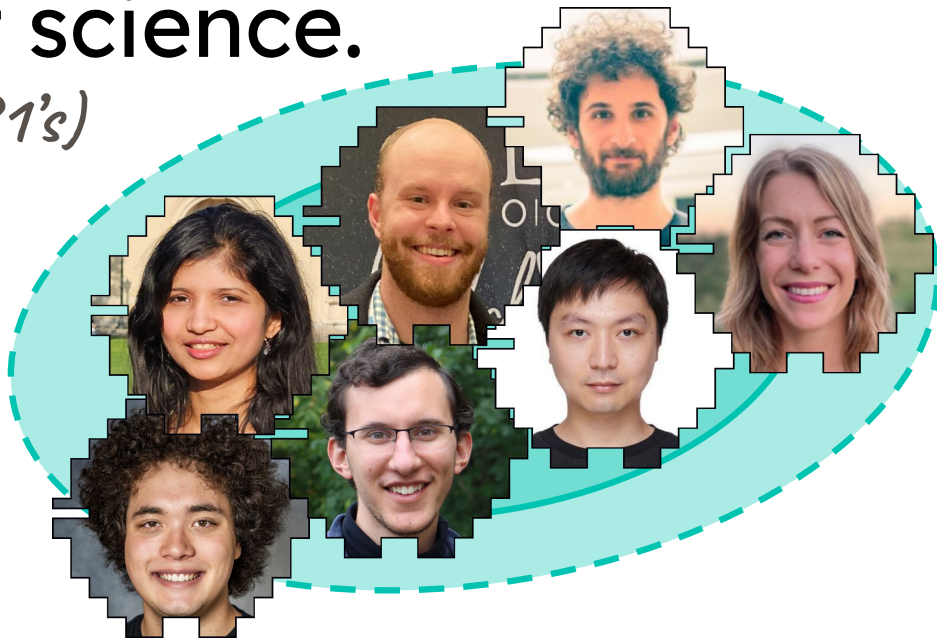
Many scientists want (or need)
bespoke solutions.



How can we design solutions to
be at least **modular?**

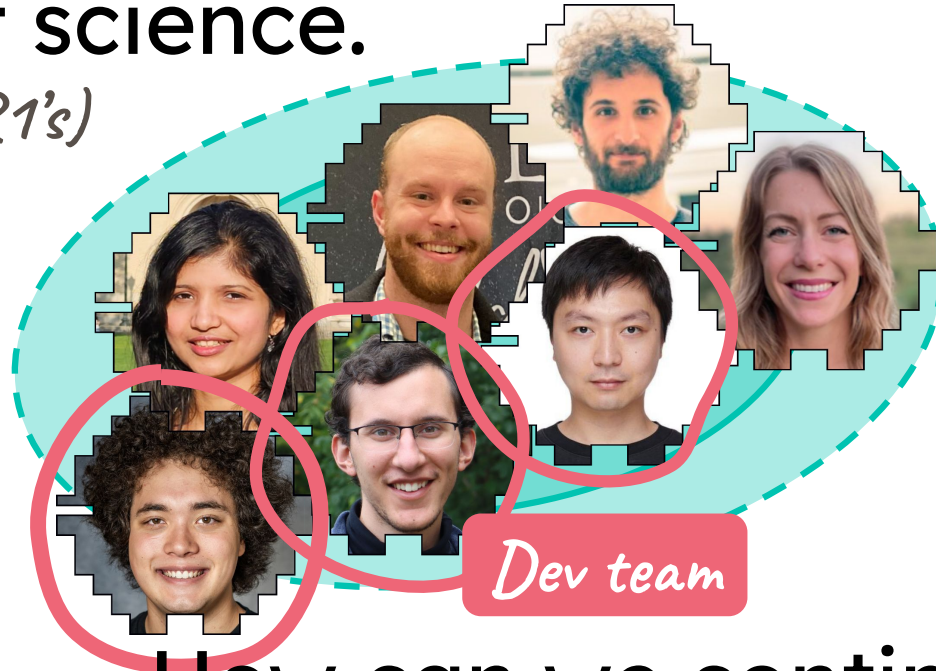
There will always be small teams doing important science.

(even at R1's)



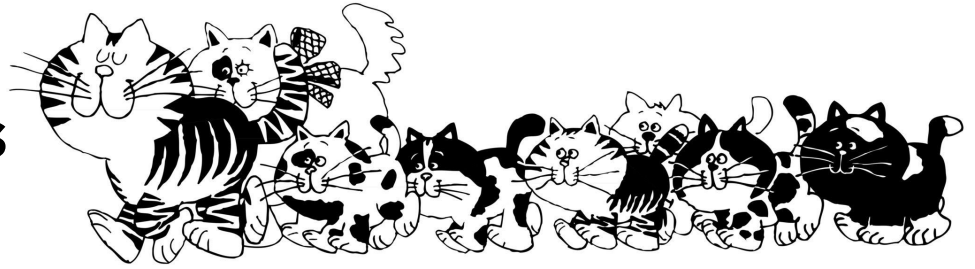
There will always be small teams doing important science.

(even at R1's)

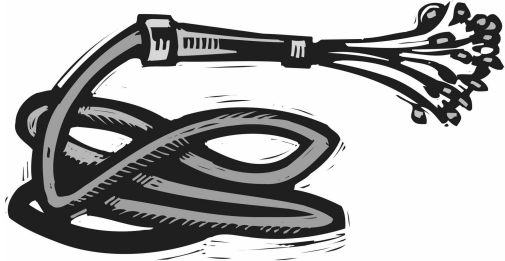


How can we continue to make best practices **accessible**?

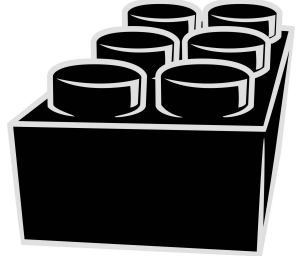
Herd cats



Learn to drink from the firehose



Design modular solutions



Promote accessible computing

