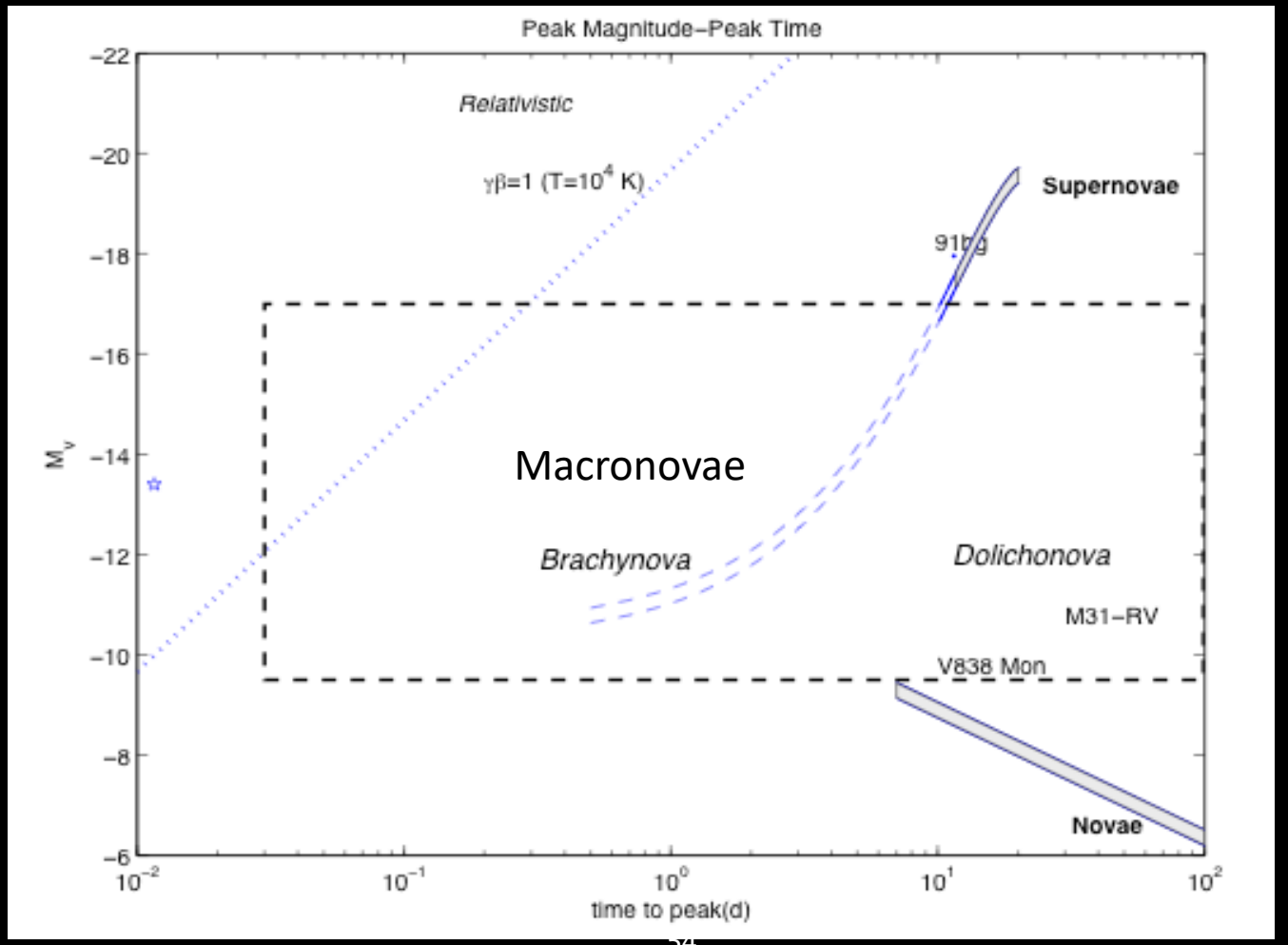
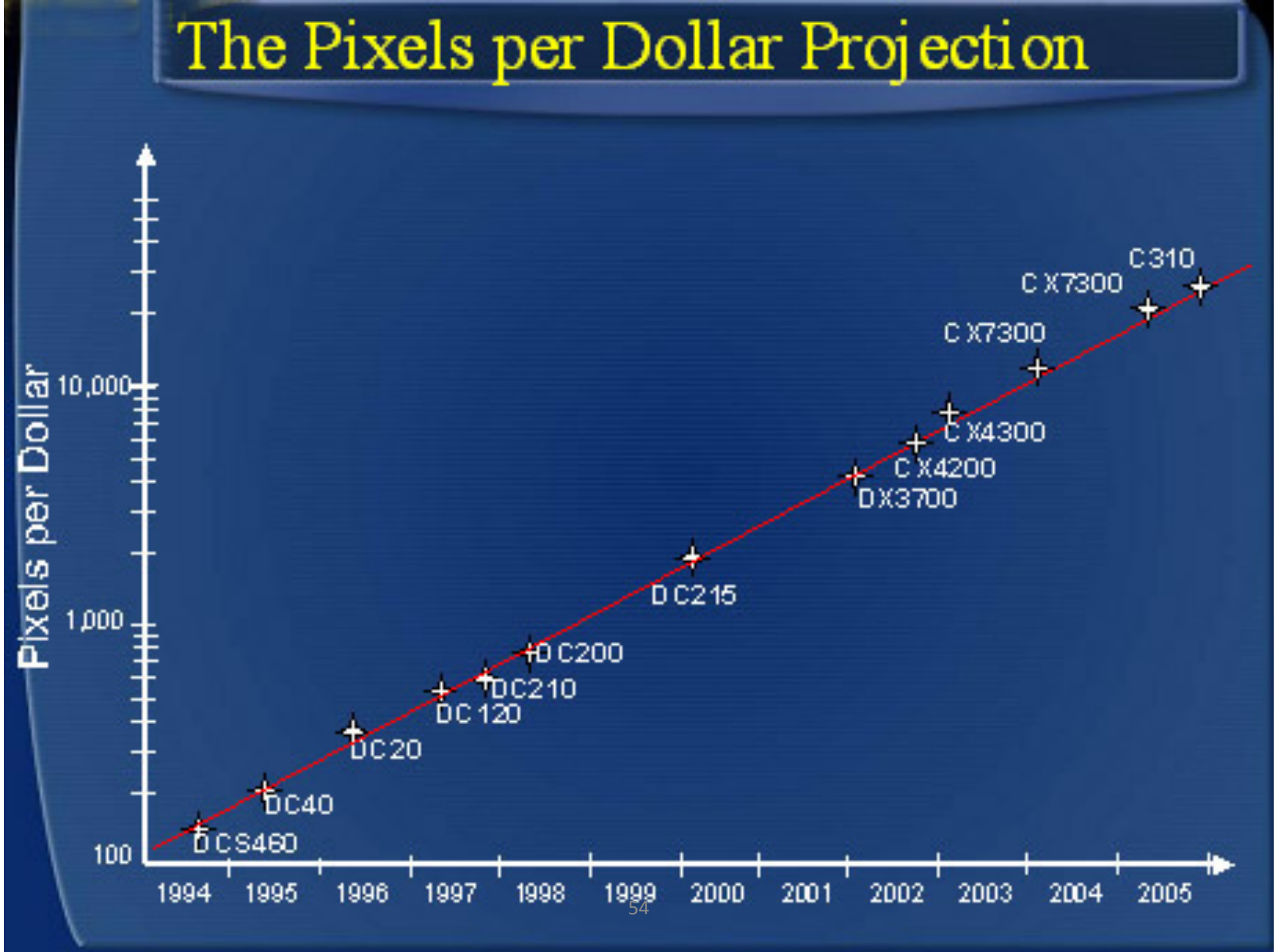
From PTF to ZTF

S. R. Kulkarni

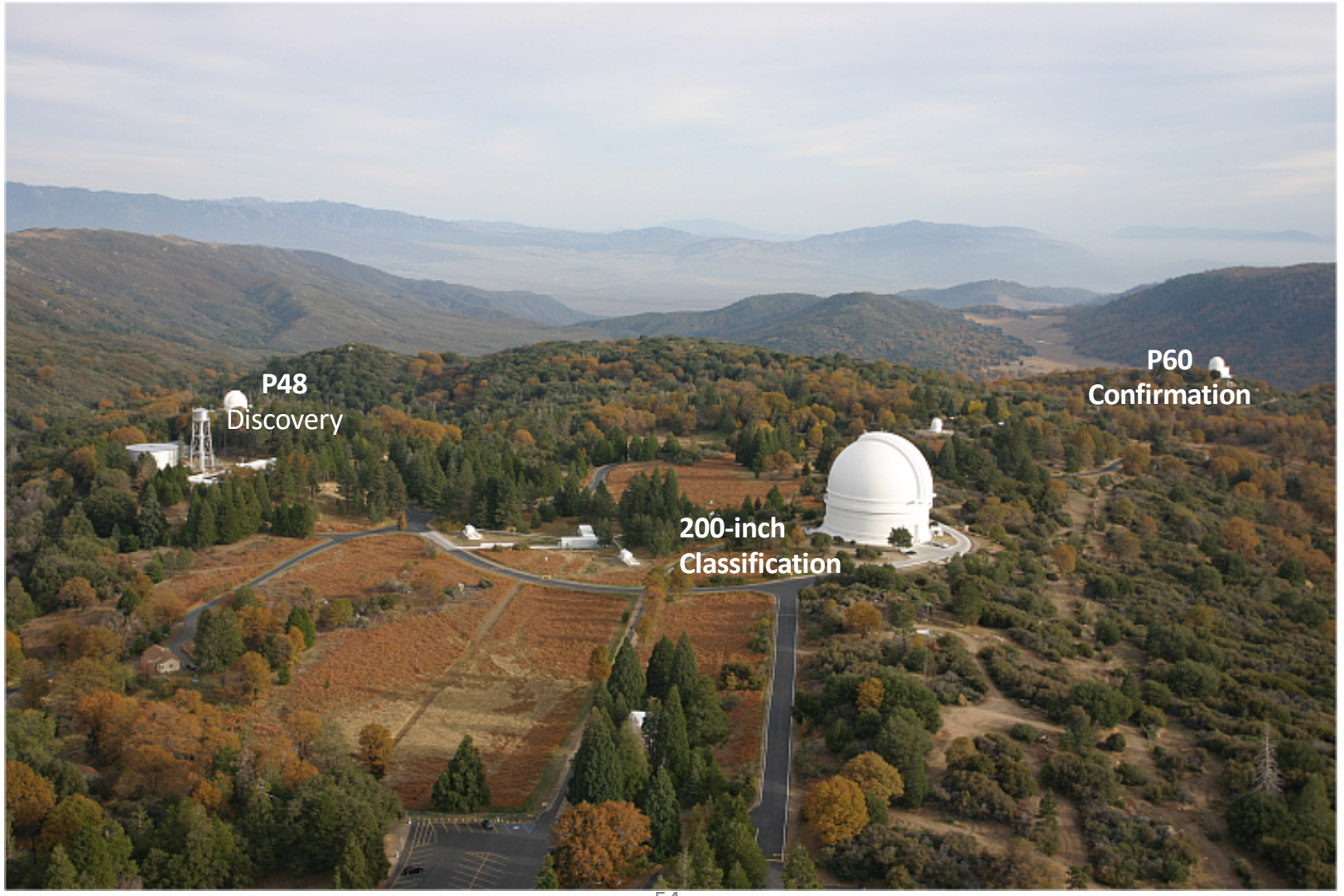
Phase space of explosions is likely very rich



A factory to systematically study cosmic explosions


The Pixels per Dollar Projection
Pixels per Dollar
10,000
1,000
100
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
DCS460
DC40
DC20
DC120
DC210
DC200
DC215
DX3700
CX4200
CX4300
CX7300
CX7300
CX7300
C310

Palomar Transient *Factory*



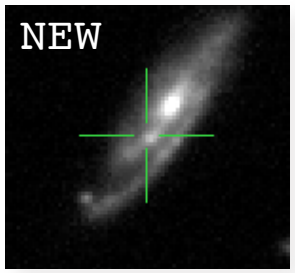
Paul Wellman

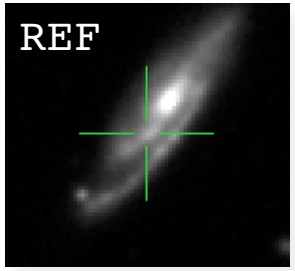
Wayne Rosing at Las Cumbres Observatory Global Telescope Network.

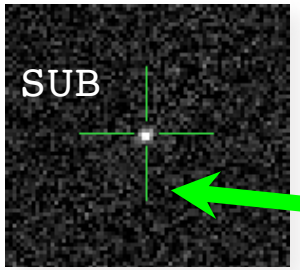
Google Mastermind Turns to the Stars

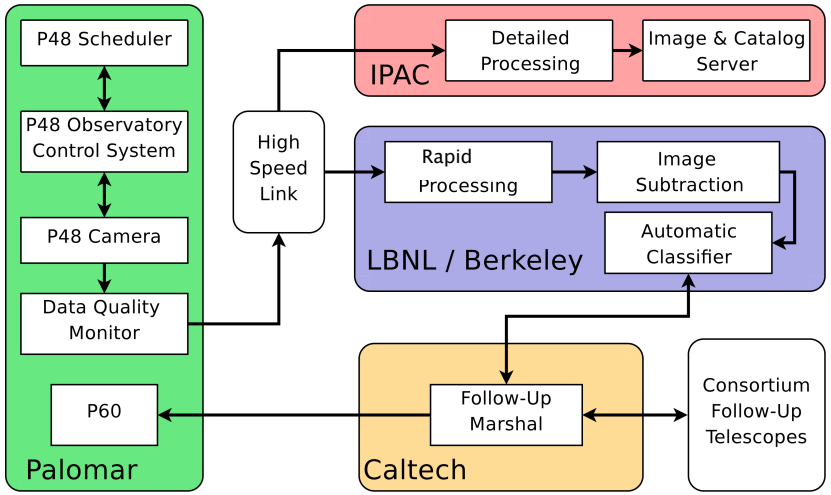
Wayne Rosing on Revolutionizing Astronomy from Goleta

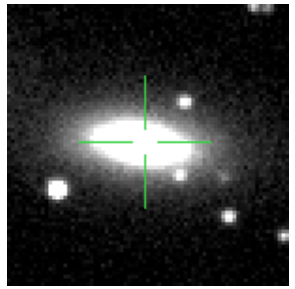
Software, software & more software

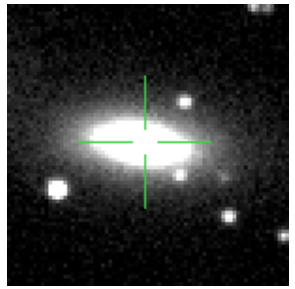


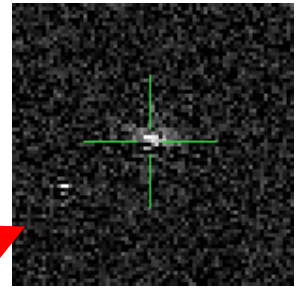












Time from exposure to candidates in the subtraction database: **20 - 40 minutes**

Supernova, good!

Subtraction artifacts, bad!

Hardware, Software & *Grayware!*

Methodology & Technological Developments

- Phase I (Palomar Transient Factory): 2009-2012
  - Machine Learning (ML) for classification
  - Same night classification & follow up
- Phase II (intermediate Transient Factory): 2013-2016
  - Mixed cadence observing
  - Multi-band observing
  - Robotic IFU spectroscopy (SEDM on P60)
  - Demonstration of a Needle in a haystack Search (robust & rapid ML)
- Phase III (Zwicky Transient Factory): 2018-2020
  - Pre-cursor to LSST for Time Domain Astronomy
  - Industrialization of alert distribution

Innovations

- Real-time data transmission (microwave link)
- Robust (fault-tolerant) & real-time pipelines
- Telescope sequencing not done daily but weekly via a sophisticated algorithm
- Application of Machine Learning (ML) for quantitative assessment of candidates
- Devised tools for “follow up”
  - “Marshal” (aggregator of information)
  - “Broker” (help take decision on potential value of candidates using contextual data, past data and other catalogs)

Astronomy can make you rich also!

Courtesy of General Electric

Wise.io

GLOBAL 500

General Electric Acquired These 2 Artificial Intelligence Startups

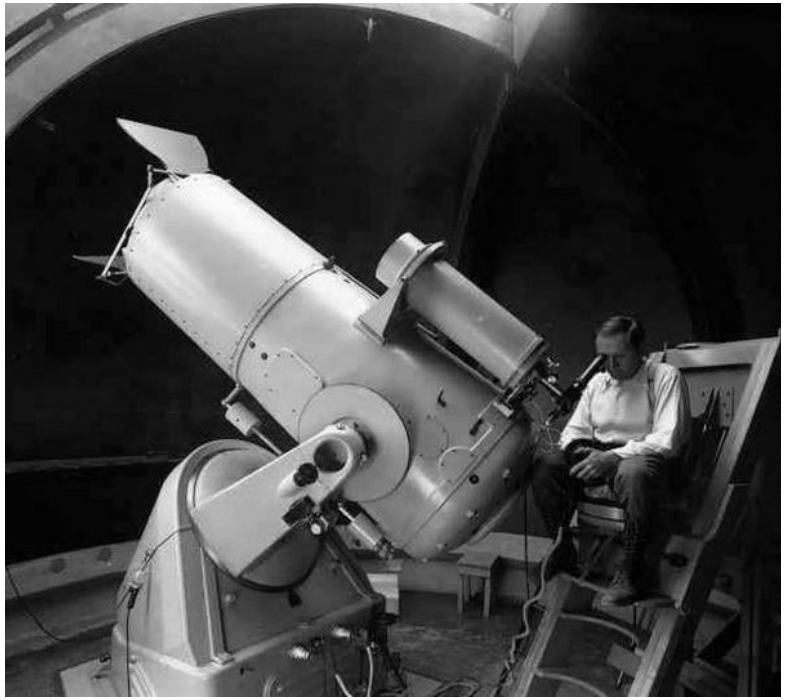
Reuters
Updated: Nov 15, 2016 3:12 PM IST

General Electric said on Tuesday it has acquired two tech startups to build its artificial

Towards An Automated Discovery of the Universe

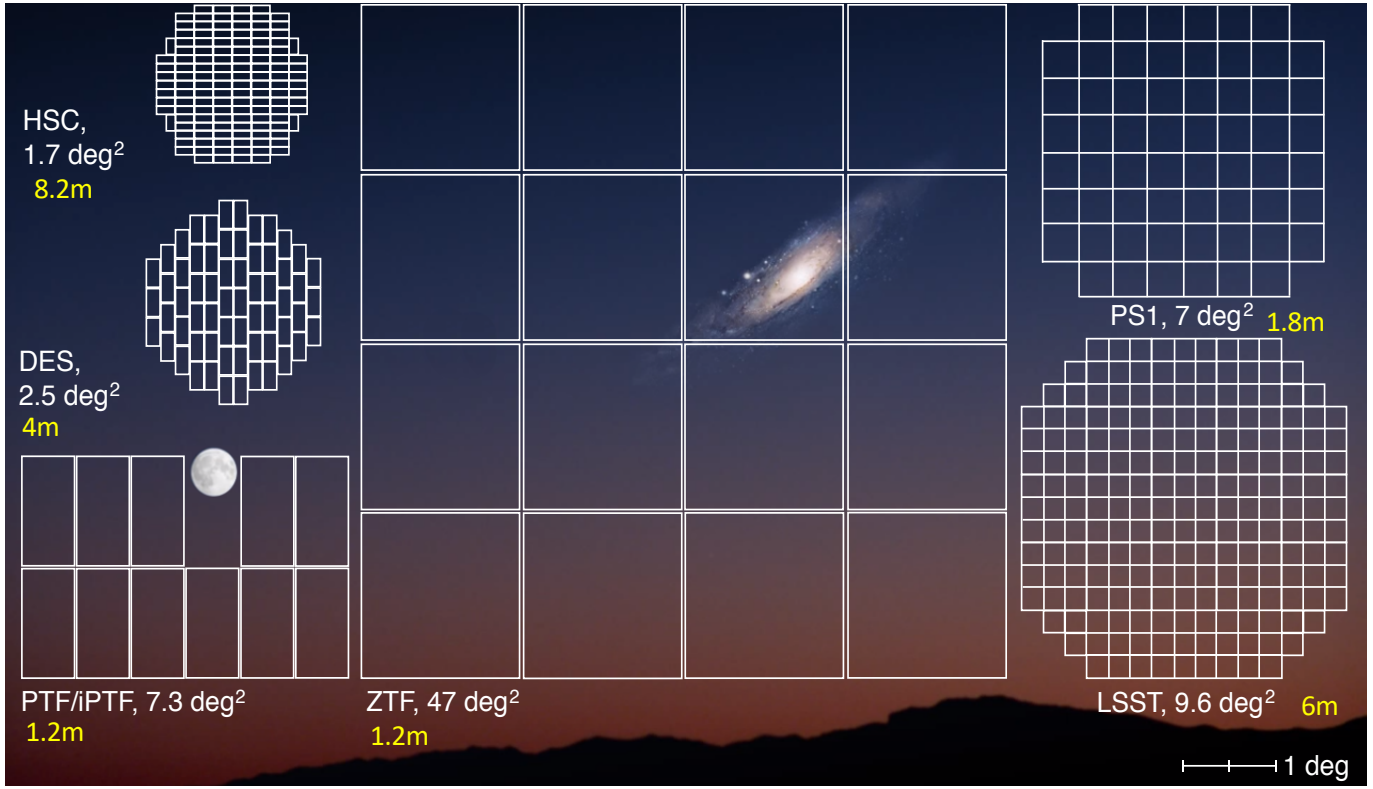
Zwicky Transient Facility

S. Kulkarni
Principal Investigator
M. Graham
Project Scientist
E. Bellm
Survey Scientist



Caltech · Oskar Klein centre · University of Maryland · UW · NSF
Humboldt-Universität zu Berlin · DESY · UWM · UST · Los Alamos National Laboratory EST. 1943 · Berkeley Lab Lawrence Berkeley National Laboratory · Pomona College 1887

Field of view & aperture comparison (ZTF: wide & shallow)



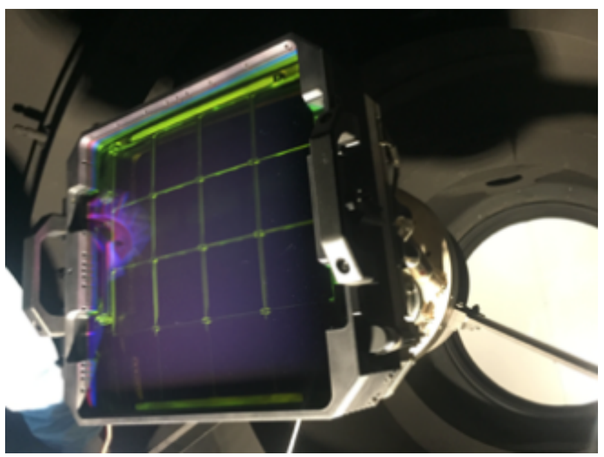
The Workflow of ZTF
&
Highlights of Early-time Transient Observations

Yuhan Yao
20200805

Background: ZTF image of SN2019yvq
Credit: ZTF, A. Miller, D. Golstein

From the Detection to the Discovery

P48 Detection

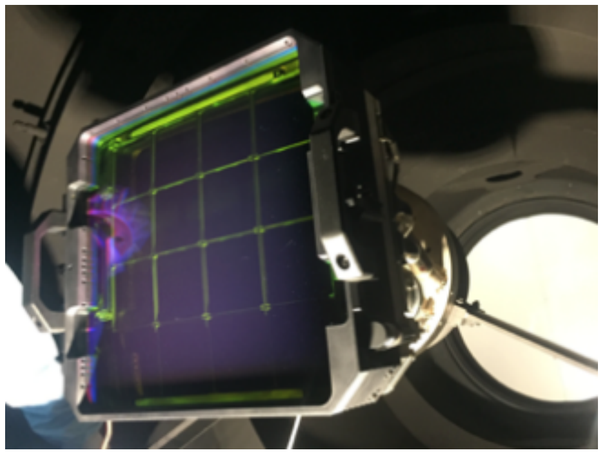


Raw data

Real-time Image subtraction

From the Detection to the Discovery

P48 Detection

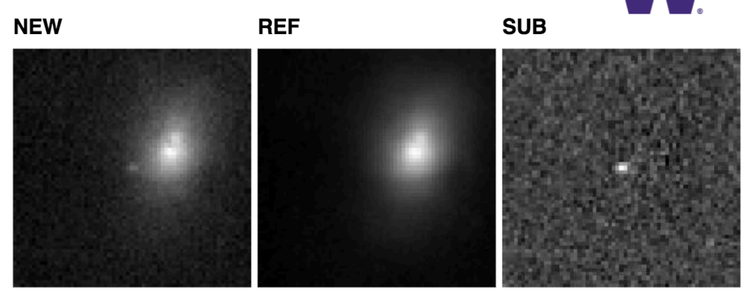


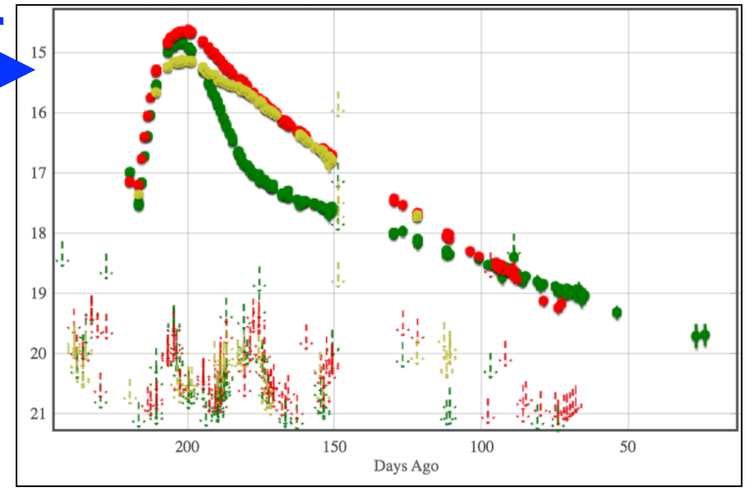
Raw data

Real-time
Image subtraction

ML Classifier

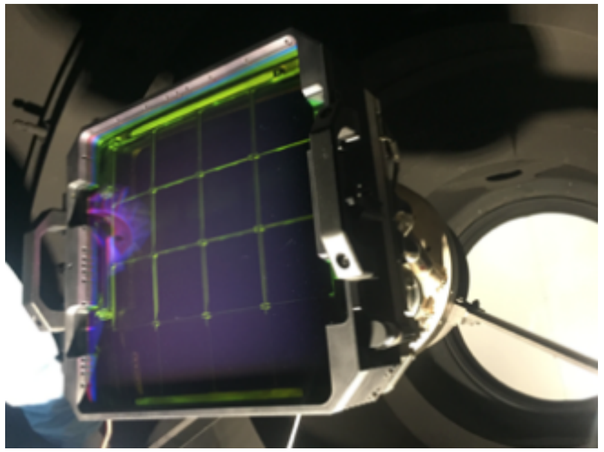
Alert Generation





From the Detection to the Discovery

P48 Detection

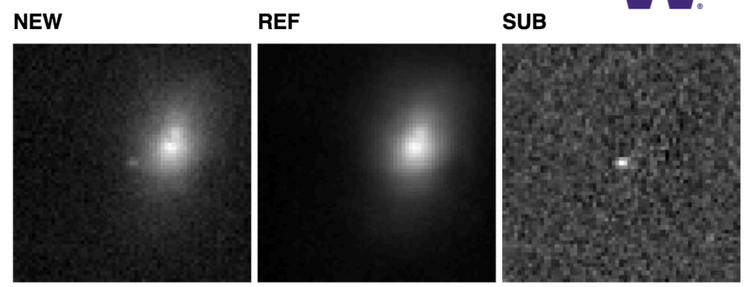


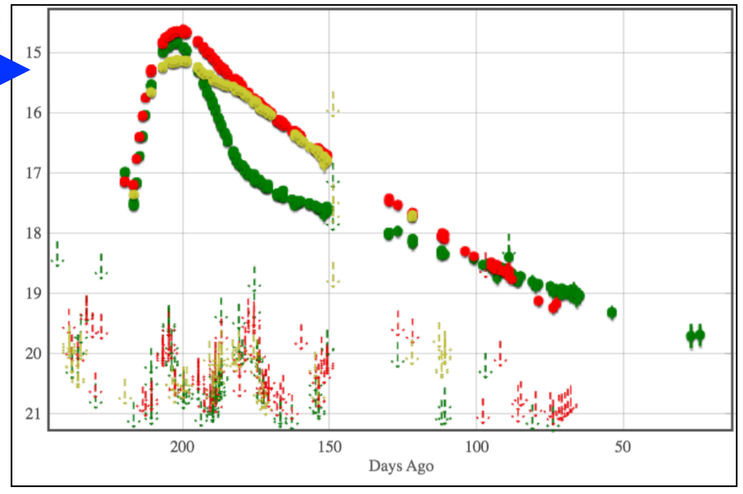
Raw data

Real-time Image subtraction

ML Classifier

Alert Generation





Broker Systems

LCO

Lasair

ALeRCE
Automatic Learning for the Rapid Classification of Events

GROWTH
Followup Marshal

BERKELEY LAB
Lawrence Berkeley National Laboratory

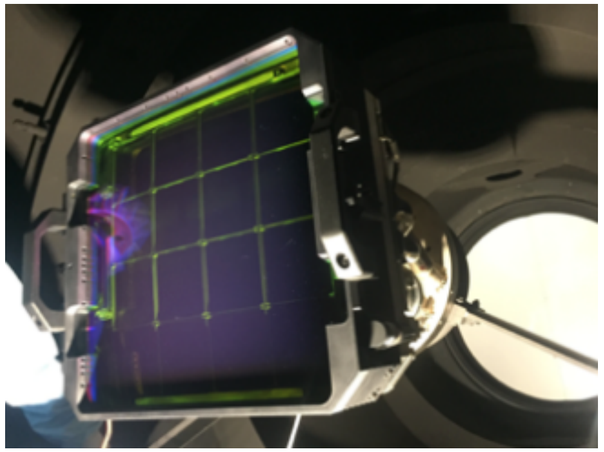
aws

APACHE kafka
A distributed streaming platform

DESY

From the Detection to the Discovery

P48 Detection



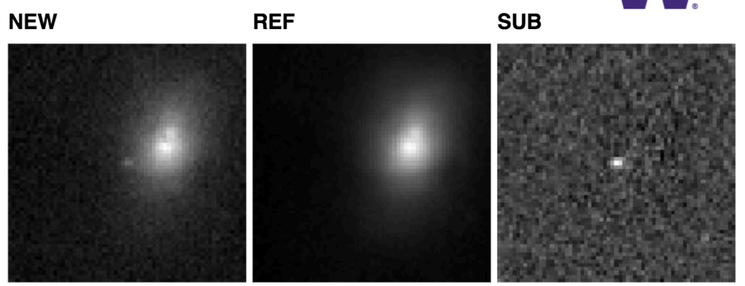
Raw data

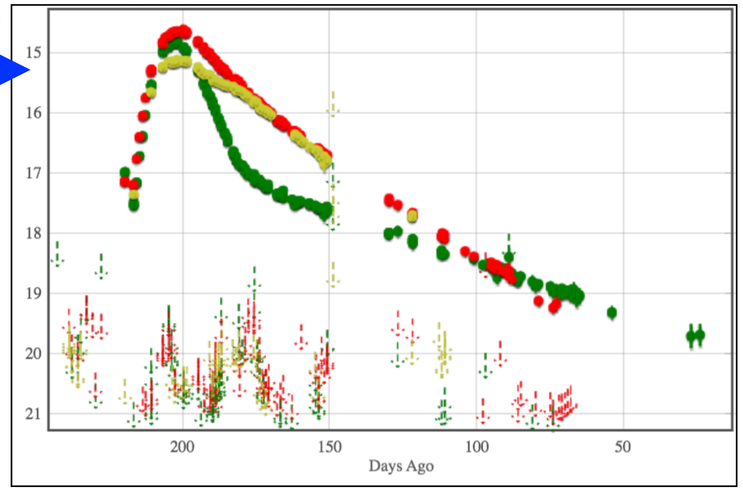
Real-time
Image subtraction

ipac

ML Classifier

Alert Generation





Broker Systems

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ALeRCE
Automatic Learning for the Rapid Classification of Events

GROWTH
Followup Marshal

BERKELEY LAB
Lawrence Berkeley National Laboratory

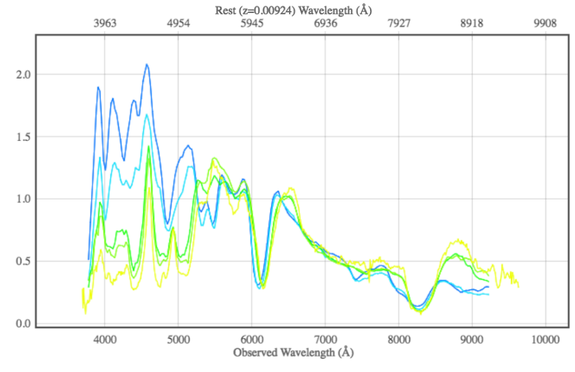
aws

APACHE kafka
A distributed streaming platform

DESY

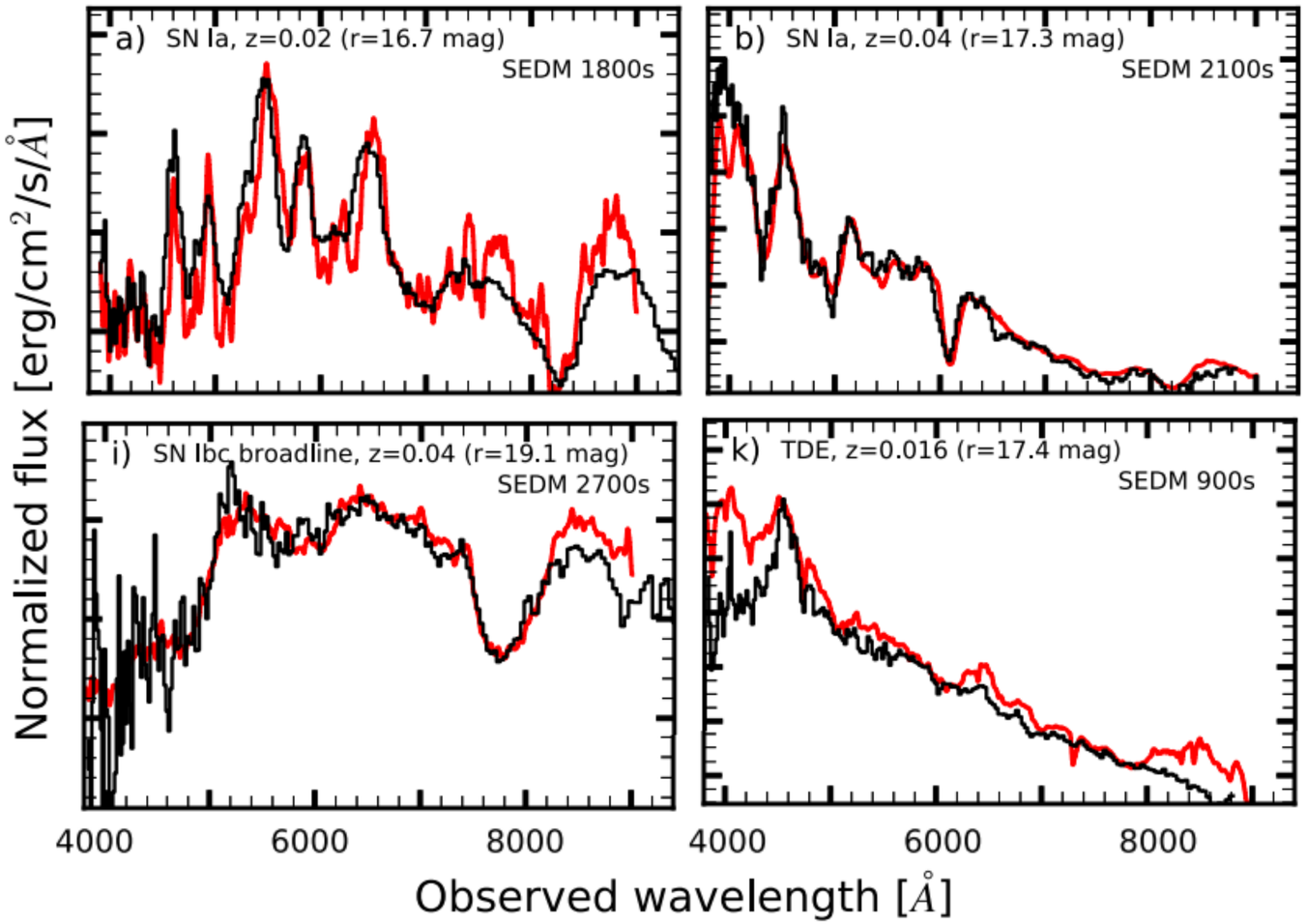
Examine Transients
Assign Follow-up

Spectral Classification

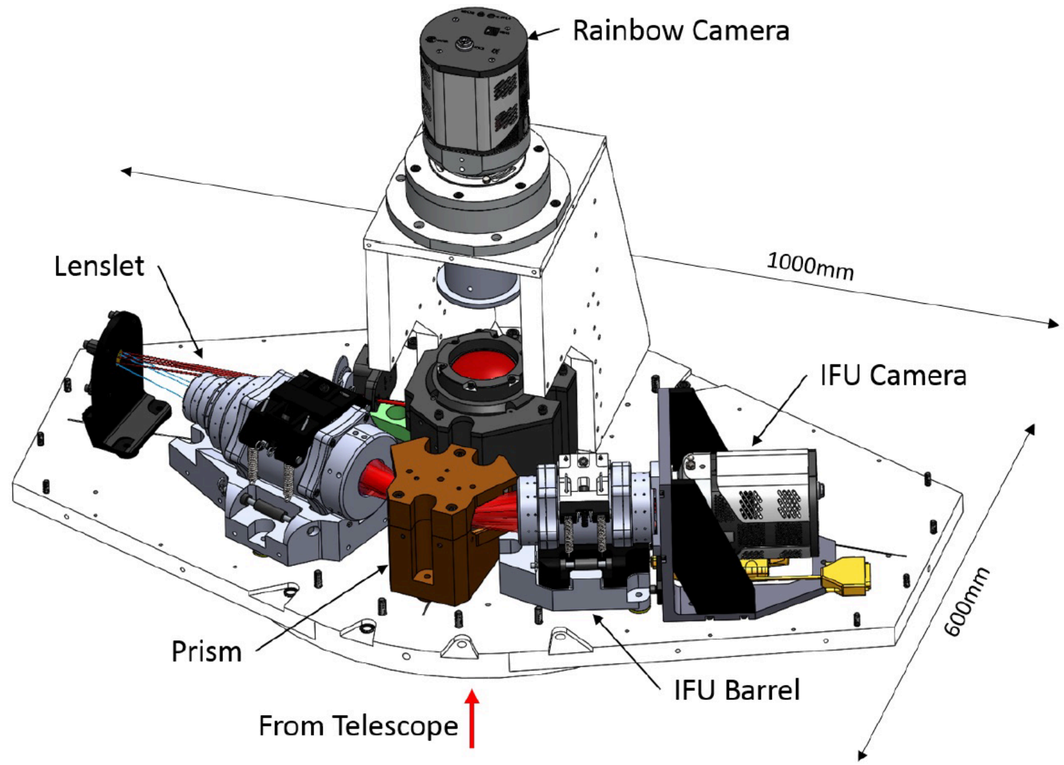


Major Follow up Facility: the Spectral Energy Distribution Machine (SEDM)

On Palomar 60-inch
Classify Transients in Real-time

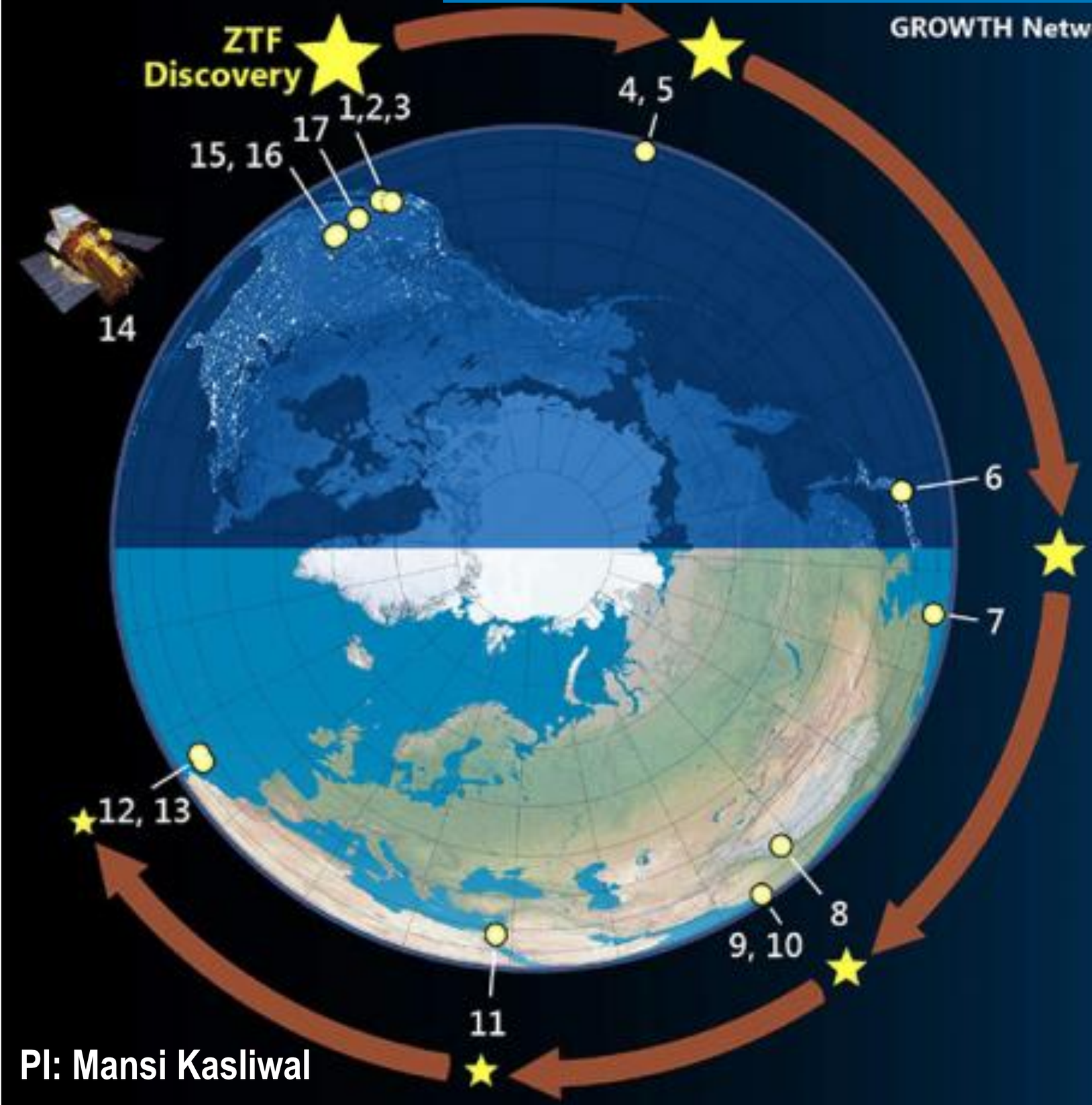


IFU spectrograph (R~100)
"Rainbow Camera" (RC): ugri



Blagorodnova+2018
Rigault+2019

GROWTH: Global Relay of Observatories Watching Transients Happen



GROWTH Network:

1. **Palomar Observatory**
   Caltech (USA)
2. **Table Mountain Observatory**
   Pomona College (USA)
3. **Mount Laguna Observatory**
   San Diego State University (USA)
4. **Gemini North Observatory**
   NOAO (USA) - Mauna Kea
5. **W. M. Keck Observatory**
   Caltech (USA)
6. **Murikabushi Observatory**
   Tokyo Tech University (Japan)
7. **Lulin One-meter Telescope**
   National Central University (Taiwan)
8. **Himalayan Chandra Telescope**
   Indian Institute of Astrophysics (India)
9. **Giant Metrewave Radio Telescope**
   NCRA (India)
10. **IUCAA Girawali Observatory**
    IUCAA (India)
11. **WISE Observatory**
    Weizmann Institute (Israel)
12. **Stella Observatory**
    Humboldt University (Germany)
13. **Nordic Optical Telescope**
    Oskar Klein Centre (Sweden)
14. **Swift Satellite (Ultraviolet and X-ray)**
    NASA (USA)
15. **Expanded Very Large Array (Radio)**
    NRAO (USA)
16. **Fenton Hill Observatory**
    Los Alamos National Laboratory (USA)
17. **Discovery Channel Telescope**
    University of Maryland/JSI (USA)

\+ **University of Wisconsin-Milwaukee**

PI: Mansi Kasliwal

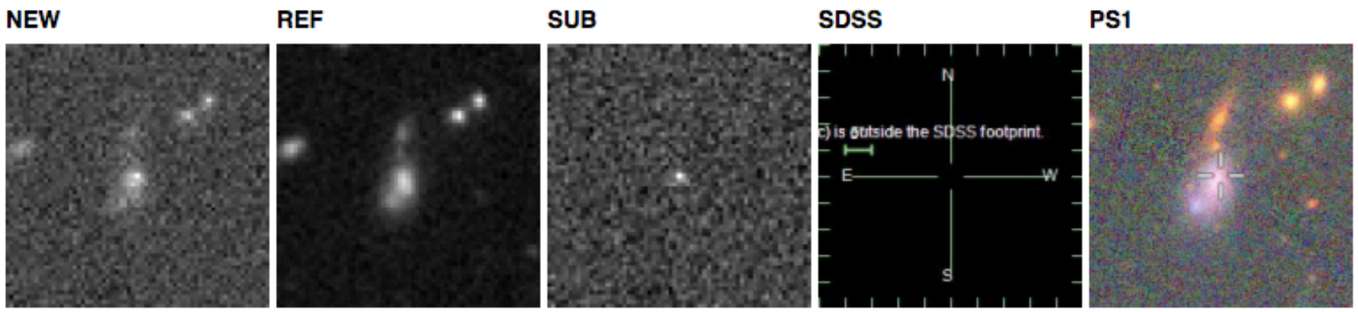
ZTF Team Science Portal

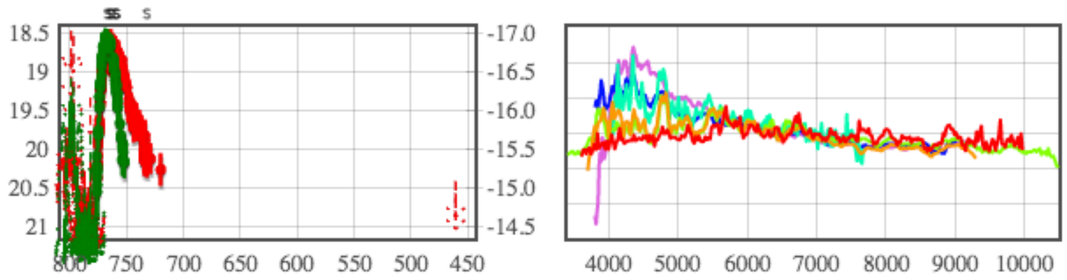
ZTF18abclfee SN Ia 02cx-like

17:14:22.21 +48:15:51.8
258.592528 +48.264377

View another

OVERVIEW | PHOTOMETRY | SPECTROSCOPY | OBSERVABILITY | EXAMINE | FINDING CHART





i = 20.5 (9.8 d) | Upload New Photometry

z = 0.029 | Upload New Spectroscopy
DM (approximate) = 35.46

First saved in partnership data.

ADDITIONAL INFO

NED | TNS | SNEx | SIMBAD | VizieR | HEASARC | SkyView | MPChecker | Extinction
CFHT | IPAC | DSS | WISE | Subaru | VLT | FIRST | CRTS · ADS
iPTF Marshal | LegacySurvey | Avro Packets

CURRENT FOLLOWUP REQUEST

Requester	Instrument	Start Date	End Date	Program	Priority	Status
ysharma	SEDM	2018-06-29	2018-07-06	Redshift Completeness Factor	3	Completed
ysharma	SEDM	2018-07-01	2018-07-08	Redshift Completeness Factor	3	Completed
ysharma	SEDM	2018-07-02	2018-07-09	Redshift Completeness Factor	2	Completed

ADD FOLLOWUP

Instrument: <-- Select Instrument -->

AUTO ANNOTATIONS

2018 Oct 03 oyaron [transfer]: From: Infant Supernovae, To: Garbage Dump
2018 Jul 27 jjencson [transfer]: From: Red Transients, To: Garbage Dump
2018 Jul 09 annayqho [passed_filter]: Red Transients
2018 Jul 09 ysharma [TNS_upload_date]: 2018-07-09
2018 Jul 09 Ariel [transfer]: From: ZTF Science Validation, To: Cosmology
2018 Jun 30 fremling [IAU name]: SN2018cxk
2018 Jun 29 ysharma [Saved_date]: 2018-06-28 RCF
2018 Jun 28 KTaggart [passed_filter]: Superluminous Supernovae II
2018 Jun 28 KTaggart [passed_filter]: Redshift Completeness Factor
2018 Jun 28 rlunnan [passed_filter]: ZTF Science Validation
2018 Jun 21 steveschulze [passed_filter]: Infant Supernovae
Auto Annotation Submission Form

COMMENTS

2019 Apr 12 yyao [redshift]: 0.029
2018 Aug 04 kde [comment]: looks nebular
2018 Jul 08 nblago [info]: Attached SNID fit. [view attachment]
2018 Jul 08 nblago [redshift]: 0.03
2018 Jul 08 nblago [classification]: SN Ia 02cx-like
2018 Jul 08 rsw [comment]: From new pipeline
2018 Jul 02 mbulla [redshift]: 0.05
2018 Jul 02 mbulla [info]: Good match to a Ic at +1 [view attachment]

Add a Comment:

Attach File: Choose File No file chosen
Type: info Save Comment

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'Cosmology'
Soft Alert (email)
Hard Alert (email + SMS)
Send Alert

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Subscribe to this Target (immediate alerts)

ZTF Team Science Portal

Examination of Transient Light curve and Spectra

Useful links at source position

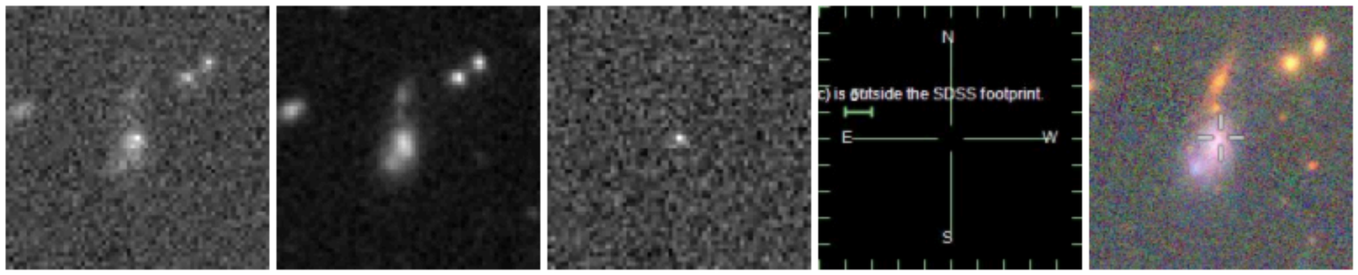
ZTF18abclfee SN Ia 02cx-like

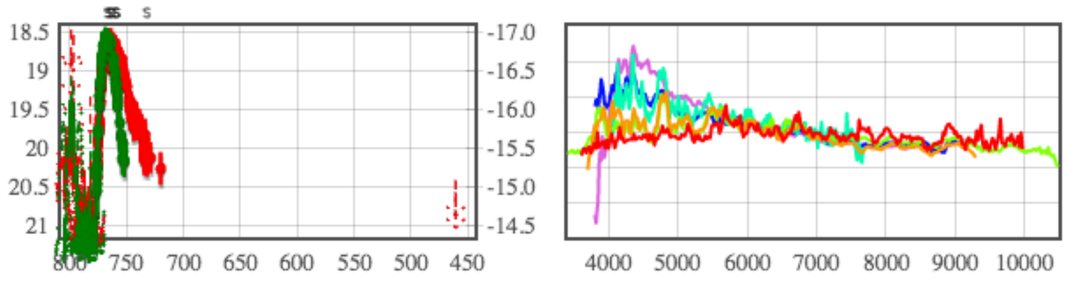
17:14:22.21 +48:15:51.8
258.592528 +48.264377

View another

OVERVIEW | PHOTOMETRY | SPECTROSCOPY | OBSERVABILITY | EXAMINE | FINDING CHART

NEW REF SUB SDSS PS1





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ADD FOLLOWUP

Instrument: <-- Select Instrument -->

Easily Assign Follow-up

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2018 Jul 09 annayqho [passed_filter]: Red Transients
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Auto Annotation Submission Form

Auto-annotations

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2018 Jul 08 rsw [comment]: From new pipeline
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2018 Jul 02 mbulla [info]: Good match to a Ic at +1 [view attachment]

Leave a comment

Add a Comment:

Attach File: Choose File No file chosen
Type: info Save Comment

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Soft Alert (email)

Alert Team Members

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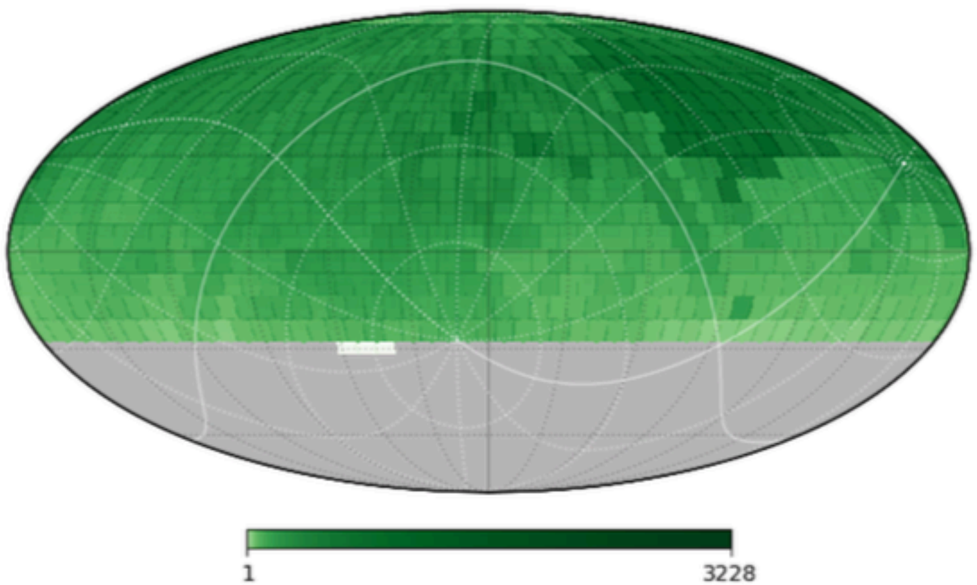
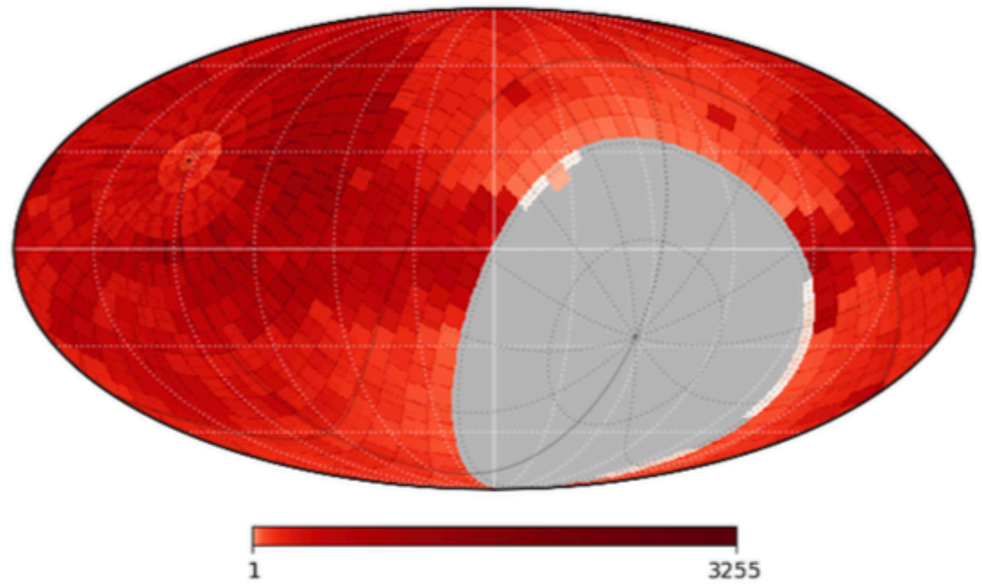
Subscribe to this Target (daily digest)
Subscribe to this Target (immediate alerts)

Where does ZTF look at?



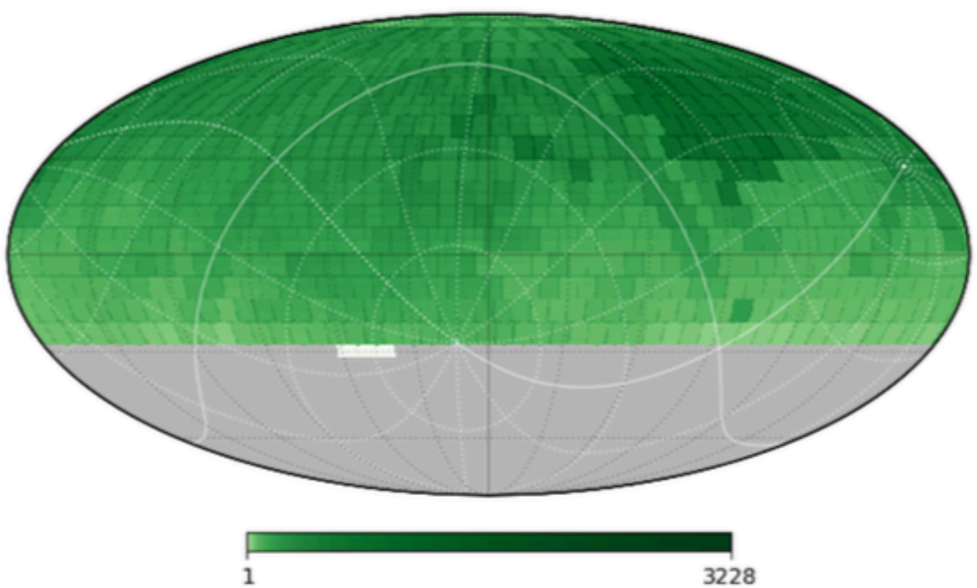
Equatorial frame g-band

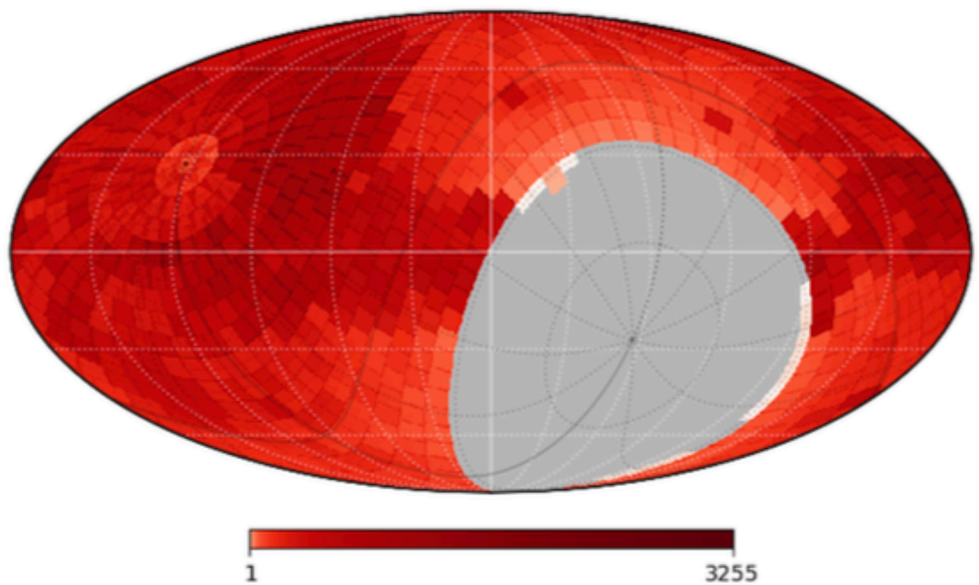


Galactic frame r-band

ZTF Exposure Map from Mar 2018 to Apr 2020

Where does ZTF look at?





Public Surveys

- g+r 3-d cadence: 25% of time. (Fremling & De's talk)
- g+r 1-d cadence: 15% of time. Galactic Plane —> TESS sectors —> SRG fields

Partnership Surveys

Uniform Depth Survey (g, r, i-band to reach same depth), high-cadence survey (3g + 3r nightly)
Galactic Plane Survey (Burdge's talk), Twilight survey (r-band), etc

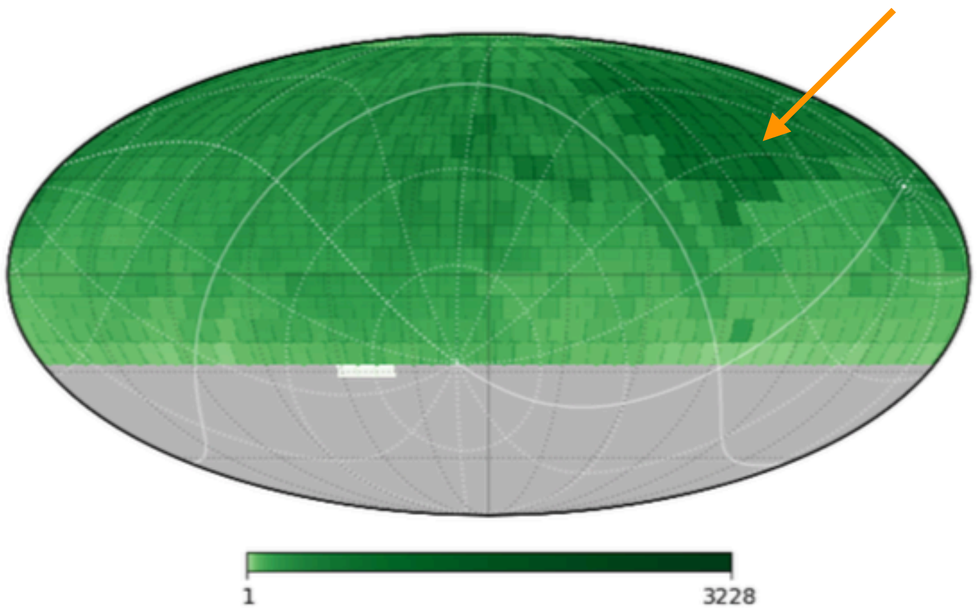
Caltech Surveys

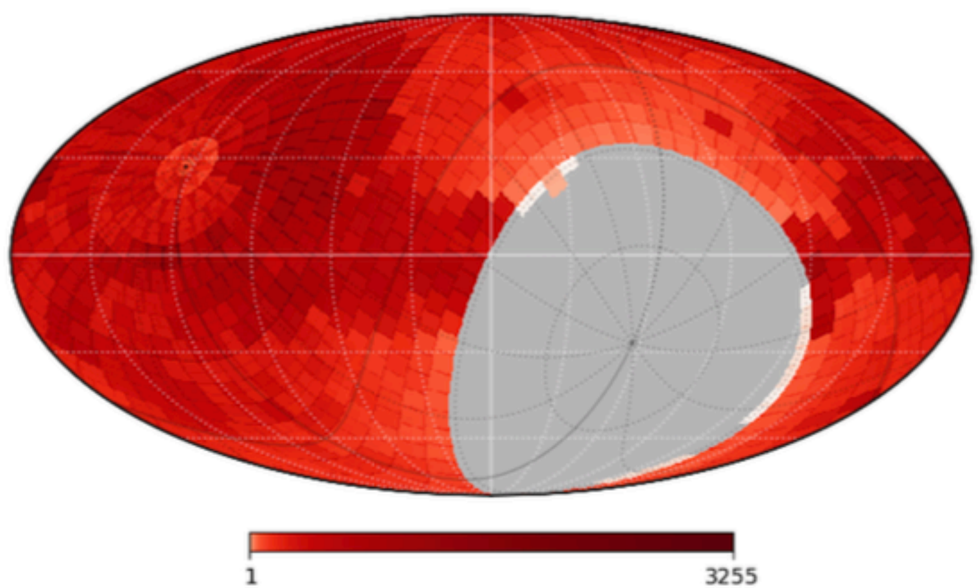
1g + 1r nightly 2000 sq^2

ToO Observations

MMA (Anand's talk)

Where does ZTF look at?





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- g+r 1-d cadence: 15% of time. Galactic Plane —> TESS sectors —> SRG fields

Partnership Surveys

Uniform Depth Survey (g, r, i-band to reach same depth), **high-cadence survey (3g + 3r nightly)**
Galactic Plane Survey (Burdge's talk), Twilight survey (r-band), etc

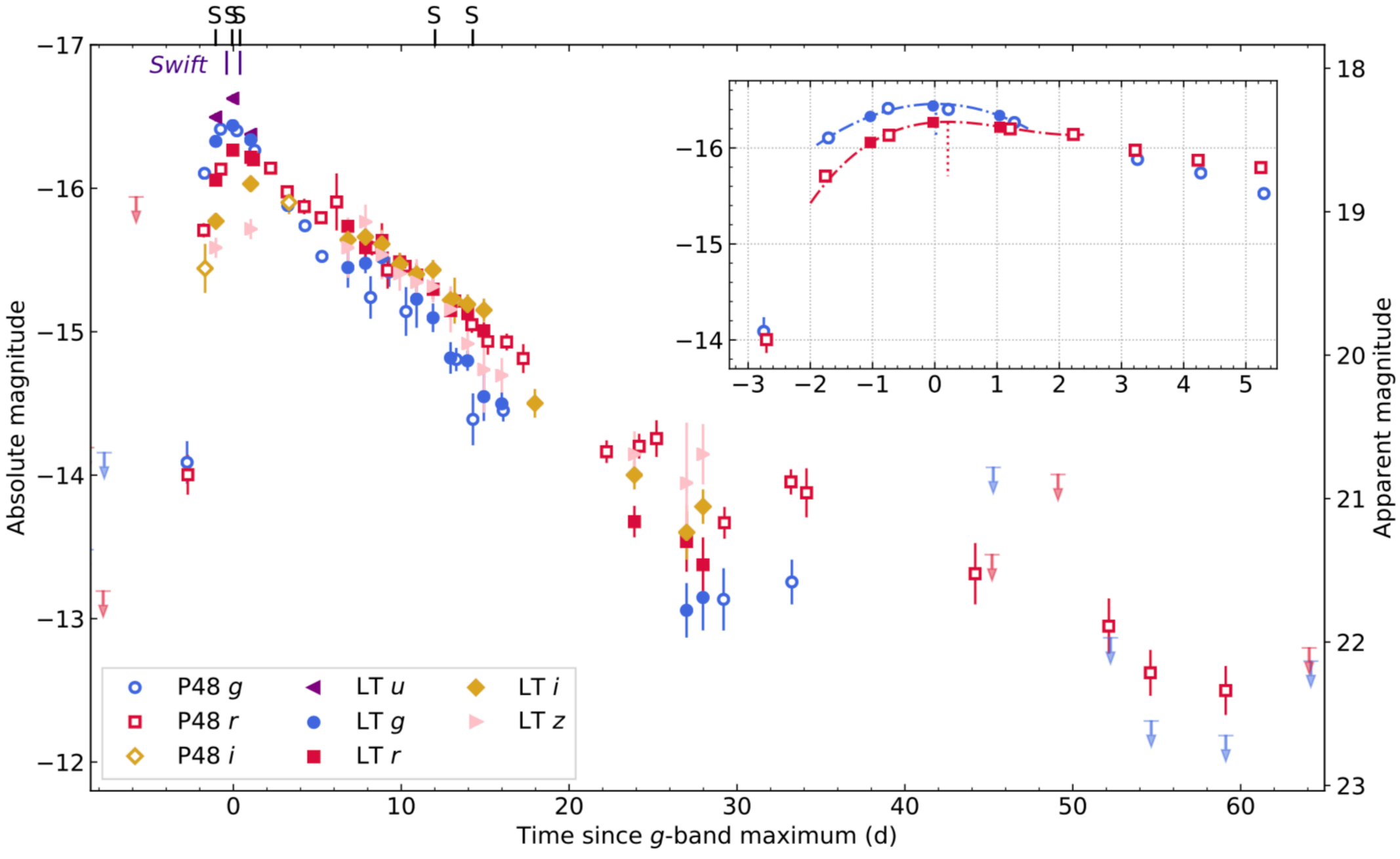
Caltech Surveys

1g + 1r nightly 2000 sq^2

ToO Observations

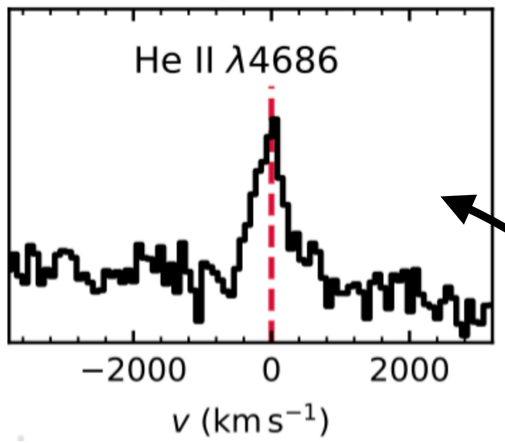
MMA (Anand's talk)

Catch Infant Core-collapse Supernovae!

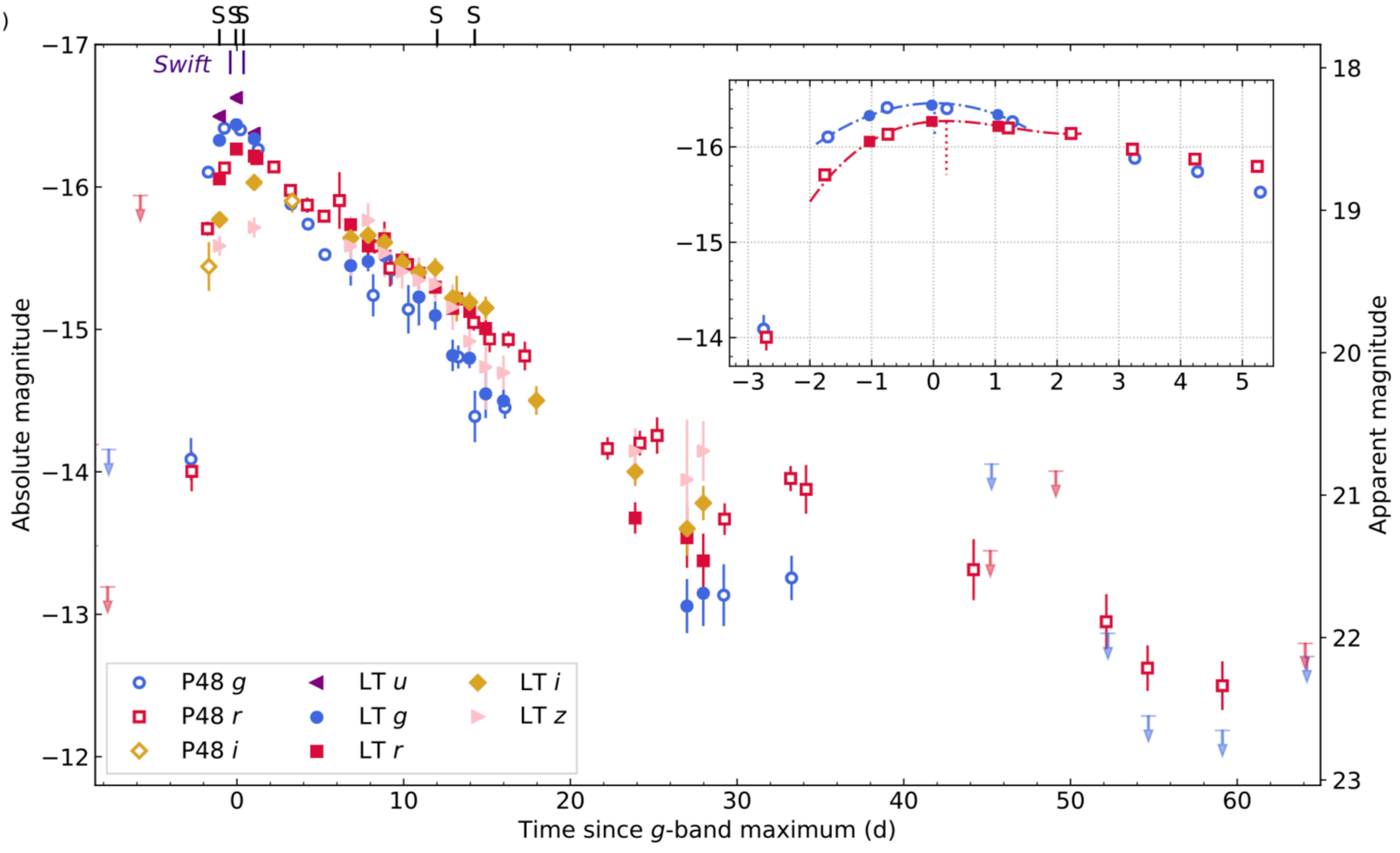


Yao+2020

Catch Infant Core-collapse Supernovae!

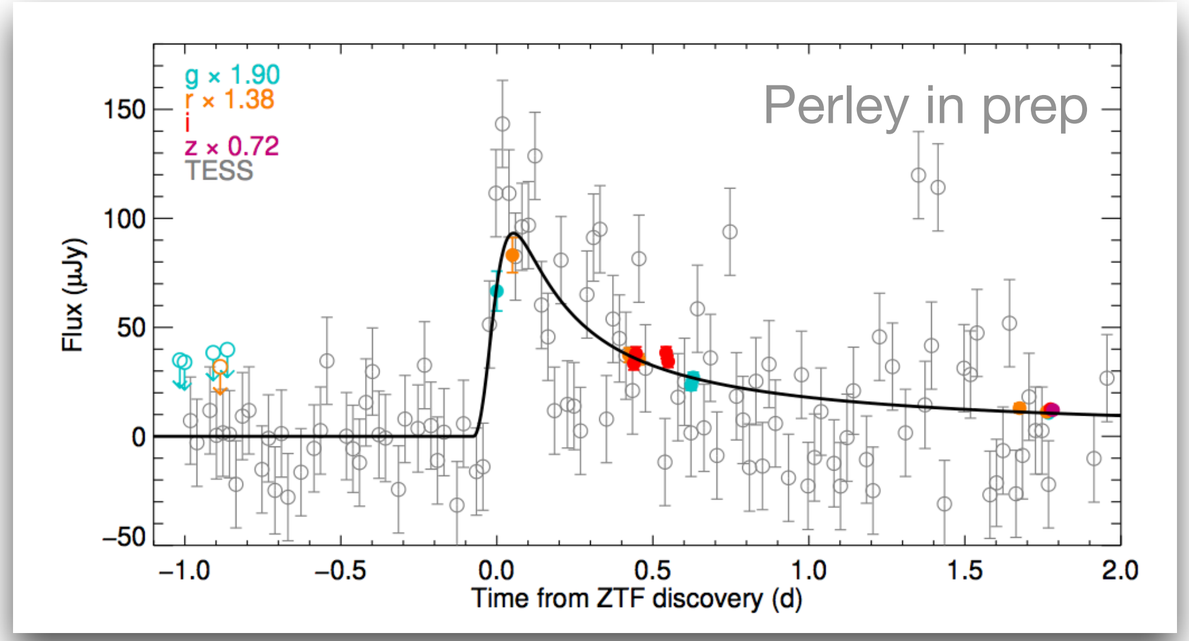


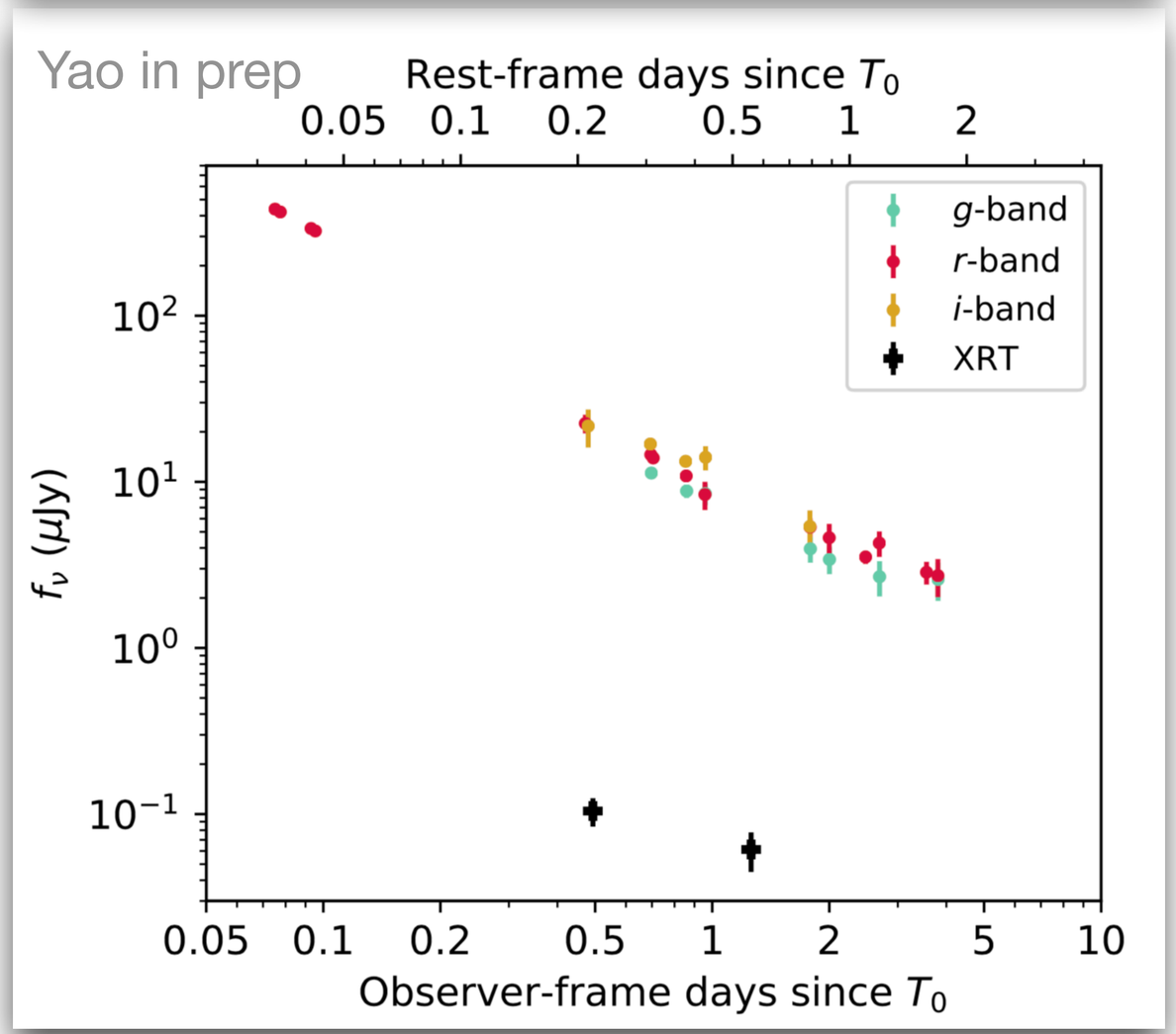
Circumstellar material being ionized by shock breakout

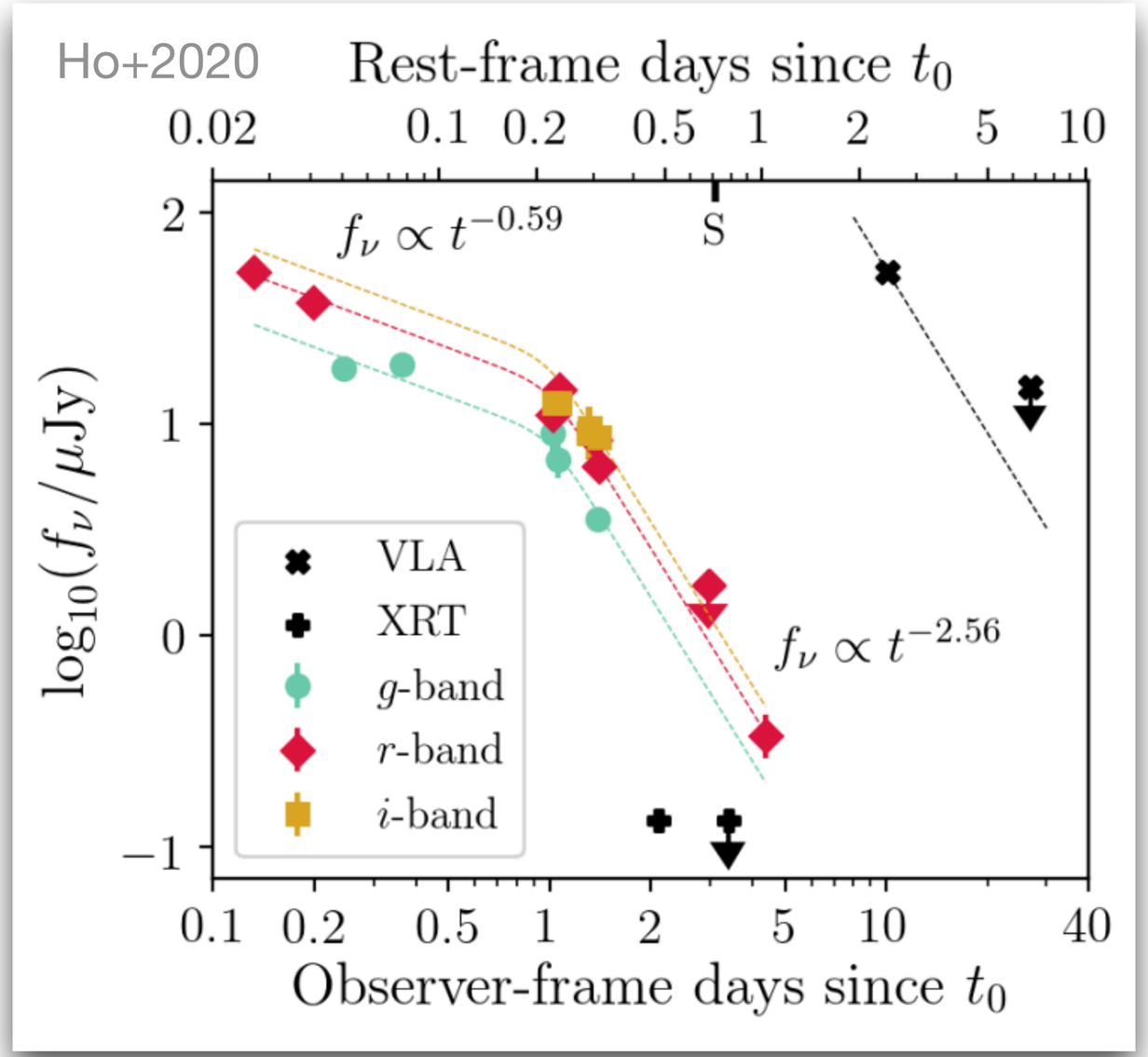


Yao+2020

Blindly Find Afterglows
With or without detected GRBs

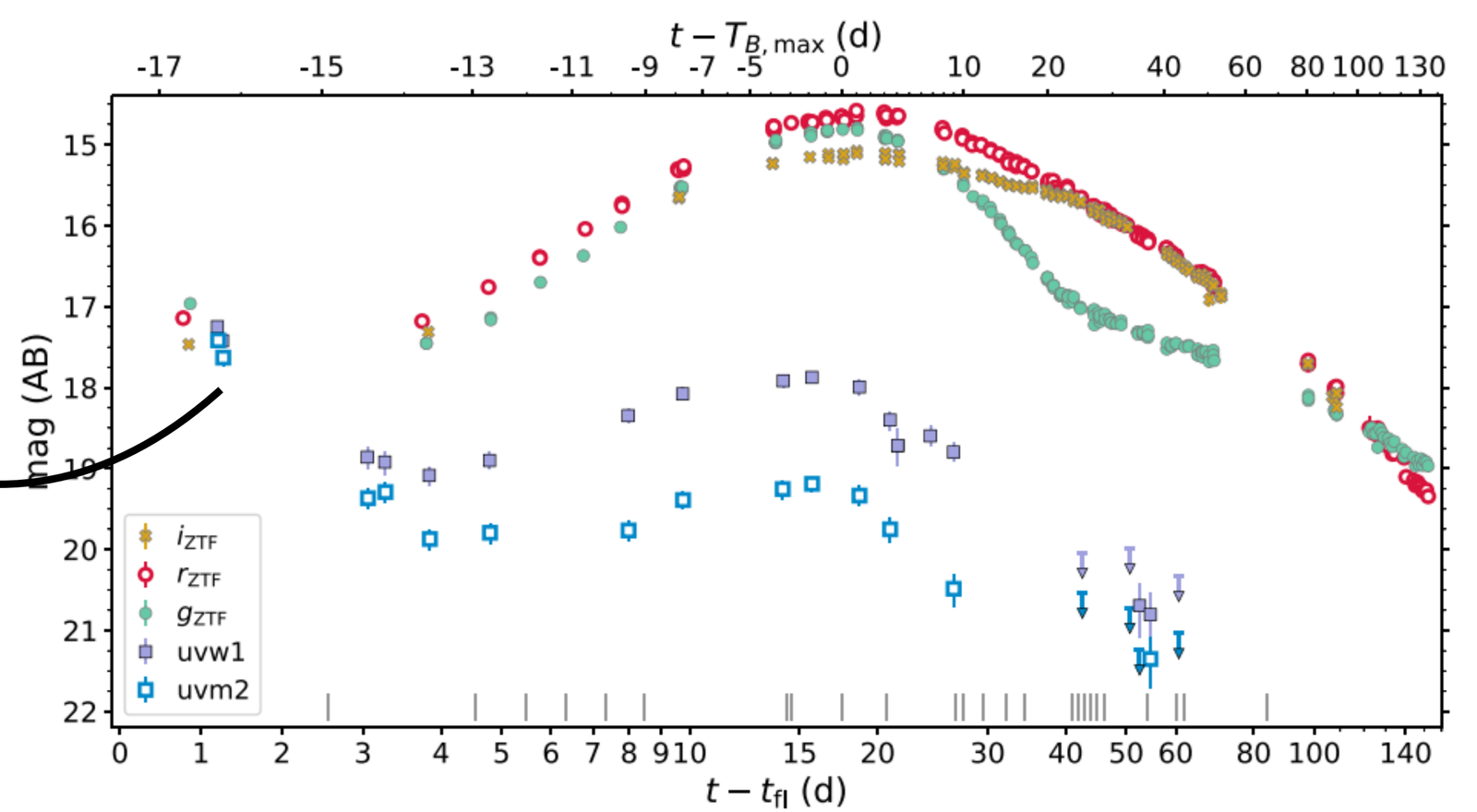


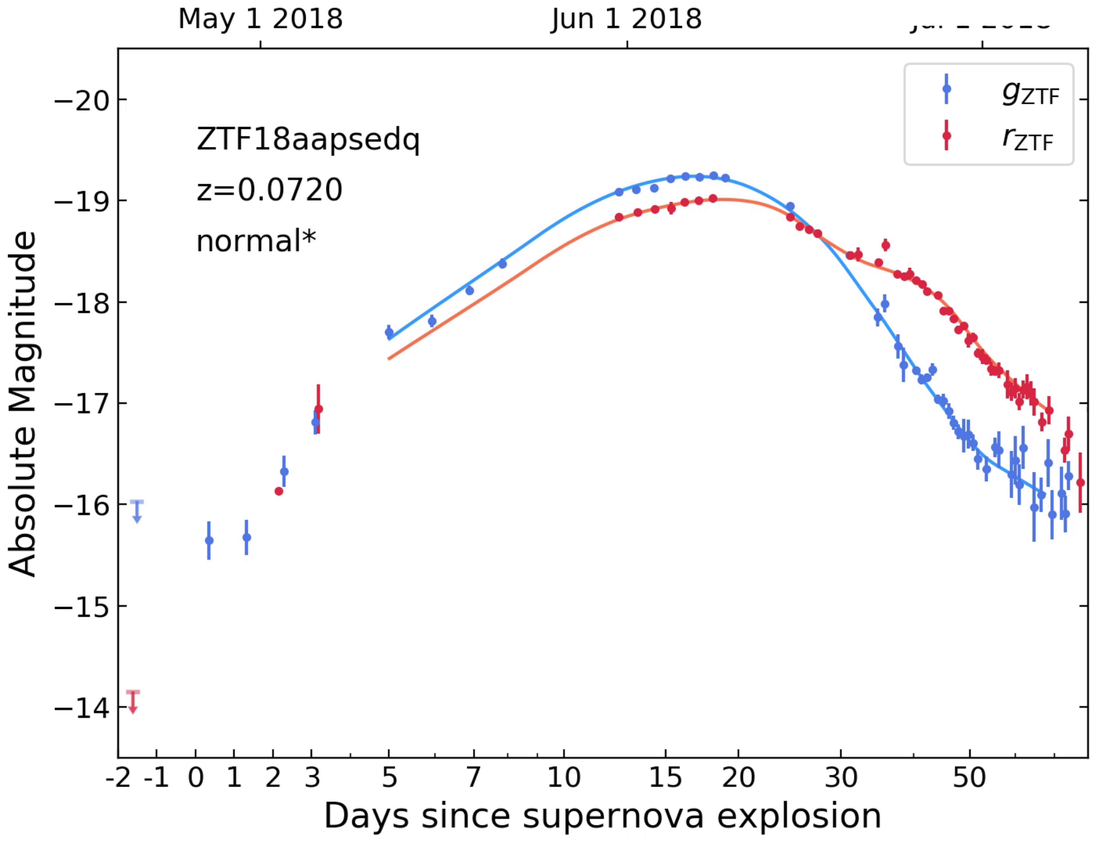




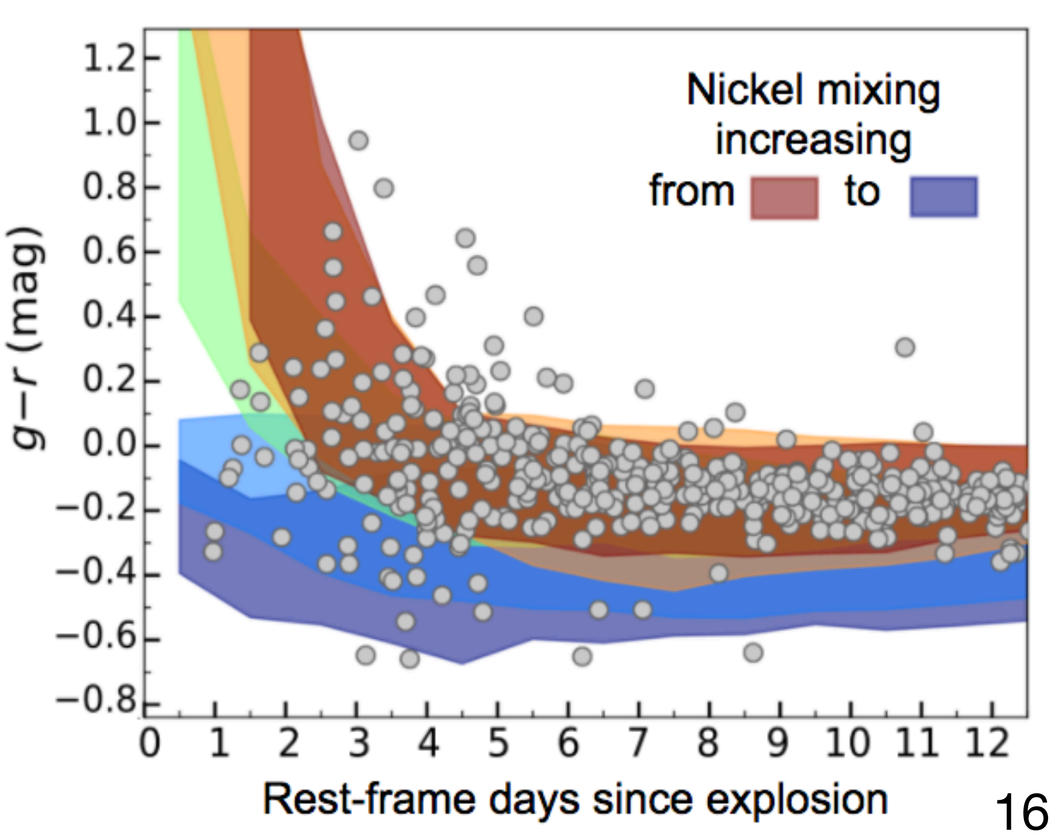
Early Observation of Type Ia Supernovae

Ultraviolet Flash



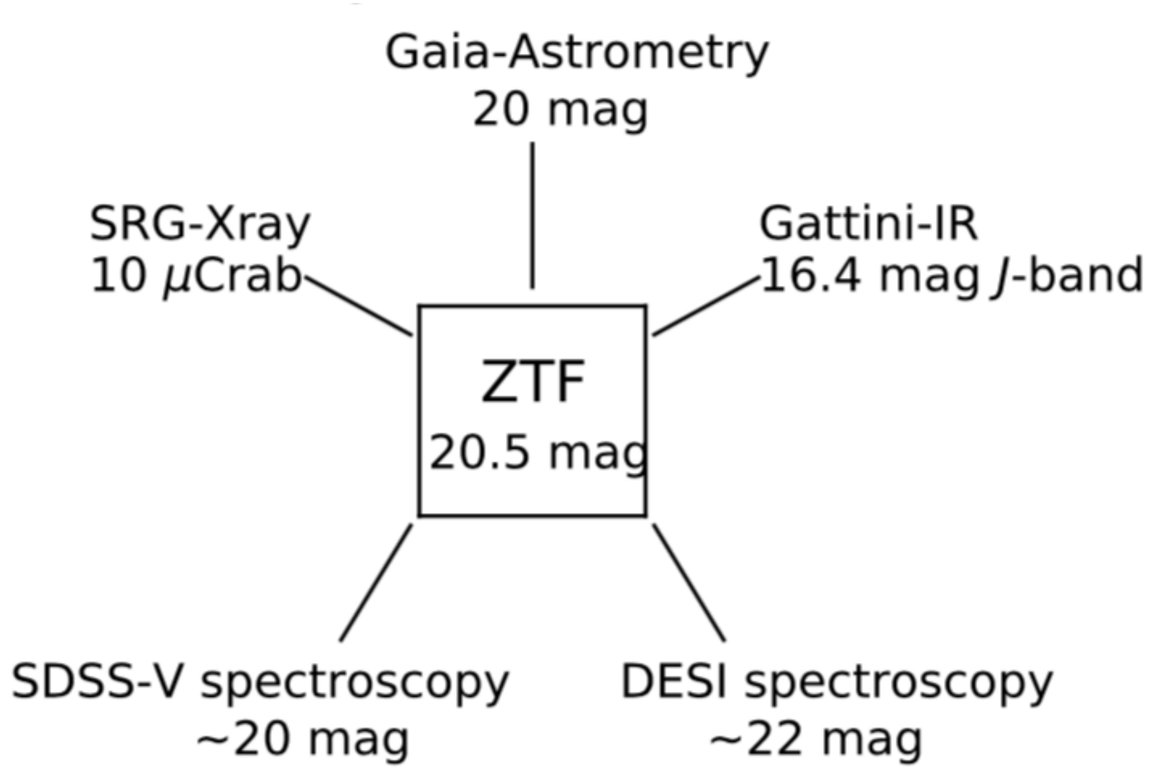


Yao+2019
Bulla+2020
Miller+2020a



How long will ZTF last?

ZTF Phase-I (Mar 2018 — Sep 2020)
ZTF Phase-II (Oct 2020 — Sep 2023)



2d Cadence all sky public survey

Class	Rate (yr^{-1})	Notes
SN Ia (<18.5)	1200	Redshift Completeness Factor
SN Ia (z<0.1)	2900	Peculiar velocities
Infant SN II	100	Flash spectroscopy
Infant Ia	400	Progenitor Study
<200 Mpc SNe	700	Demographics
SLSN	78	Demographics
TDE	20	Demographics

The Zwicky Transient Facility Bright Transient Survey:

An Unbiased View of the Transient Sky

Christoffer Fremling (Caltech)

Shri Kulkarni (Caltech), Adam Miller (Northwestern), Daniel Perley (LJMU)
Aishwarya Dahiwale, Yashvi Sharma, Don Neill (Caltech),
Jesper Sollerman, Suhail Dhawan, Ariel Goobar, Rahul Biswas (Stockholm),
Kirsty Taggart (LJMU), Melissa Graham (Washington), Jakob Nordin (Humboldt), Alison Dugas (Hawaii), Rachel Bruch, Steve Schulze, Ido Irani, Erez Zimmerman (Weizmann),
Kishore Patra, Shaunak Modak, Andrew Hoffman, Alex Filippenko (UCB),
Jannis Necker, Ludwig Rauch, Samantha Goldwasser (DESY)

Caltech

P48

P60, SEDM

P200

Christoffer Fremling, Shri Kulkarni (Caltech), Adam Miller (Northwestern), Daniel Perley (LJMU)
Aishwarya Dahiwale, Yashvi Sharma, Don Neill (Caltech),
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Kishore Patra, Shaunak Modak, Andrew Hoffman, Alex Filippenko (UCB),
Jannis Necker, Ludwig Rauch, Samantha Goldwasser (DESY)

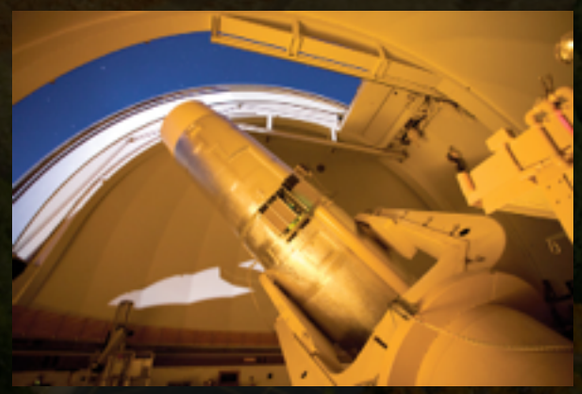
The ZTF Bright Transient Survey **BTS**

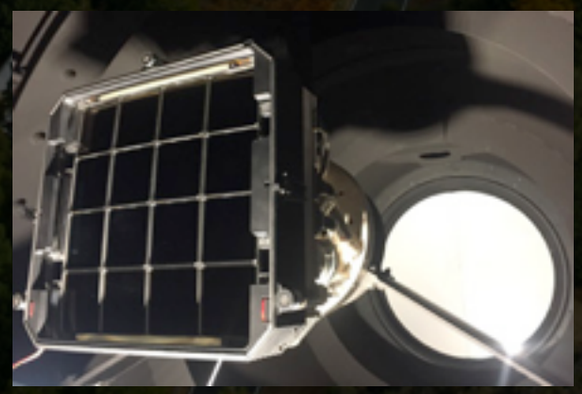
Magnitude limited survey, spectroscopically complete to 18.5 mag.

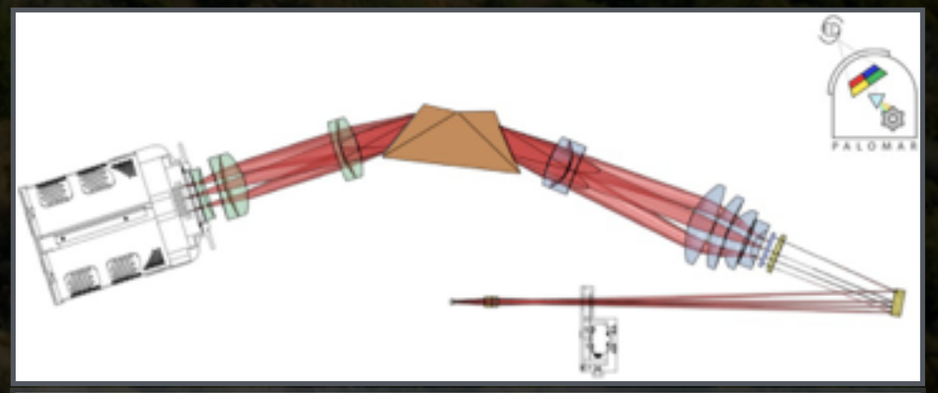
1. Catalog all SN candidates < 19 mag and send to the Transient Name Server
2. Classify all <18.5 mag SNe using mainly Palomar 60 inch with SEDM
3. Classify 19 to 18.5 mag sources selectively

Data from the public ZTF Northern Sky Survey

("Celestial Cinematography"; Bellm & Kulkarni, 2017, Nature Astronomy 1, 71)

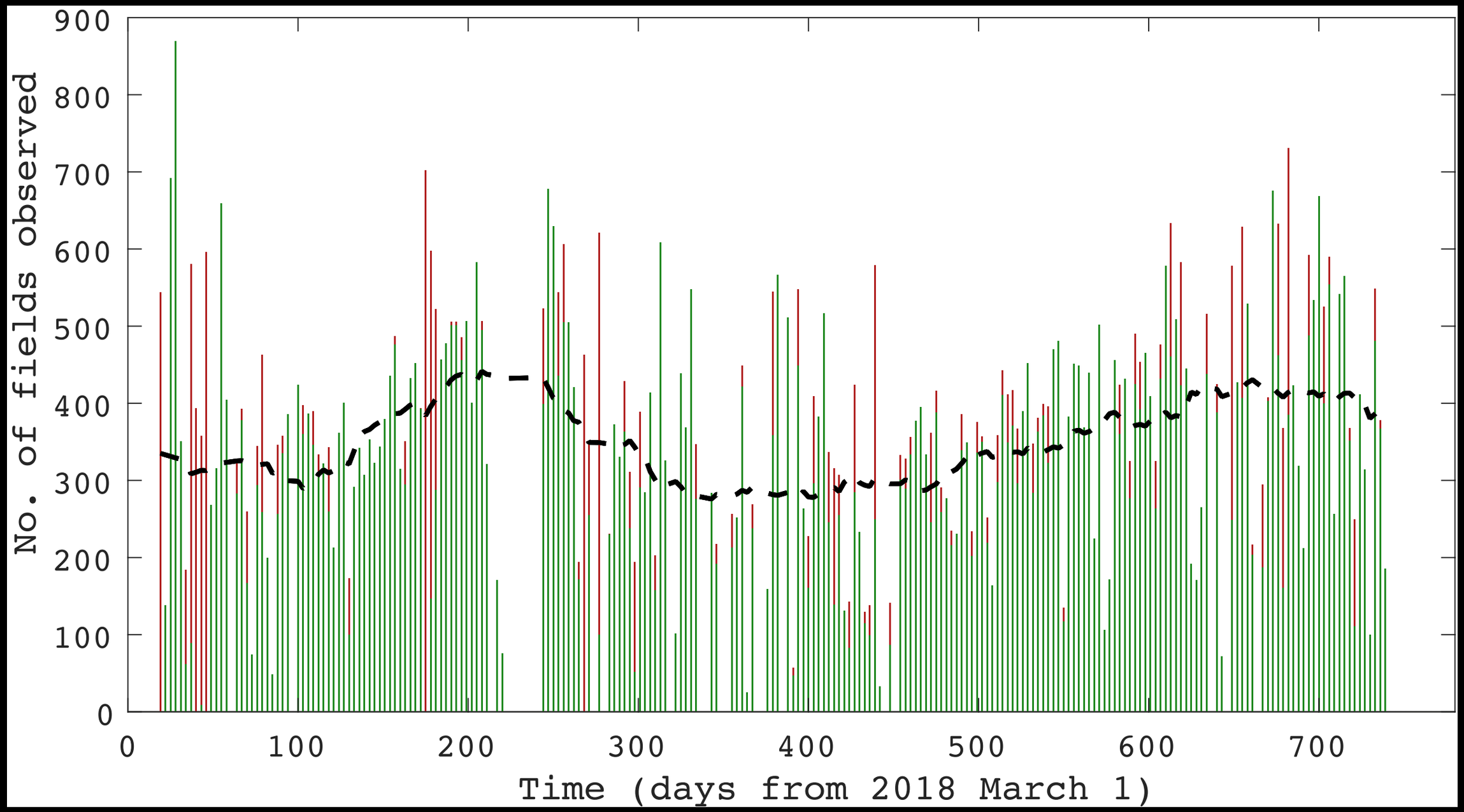




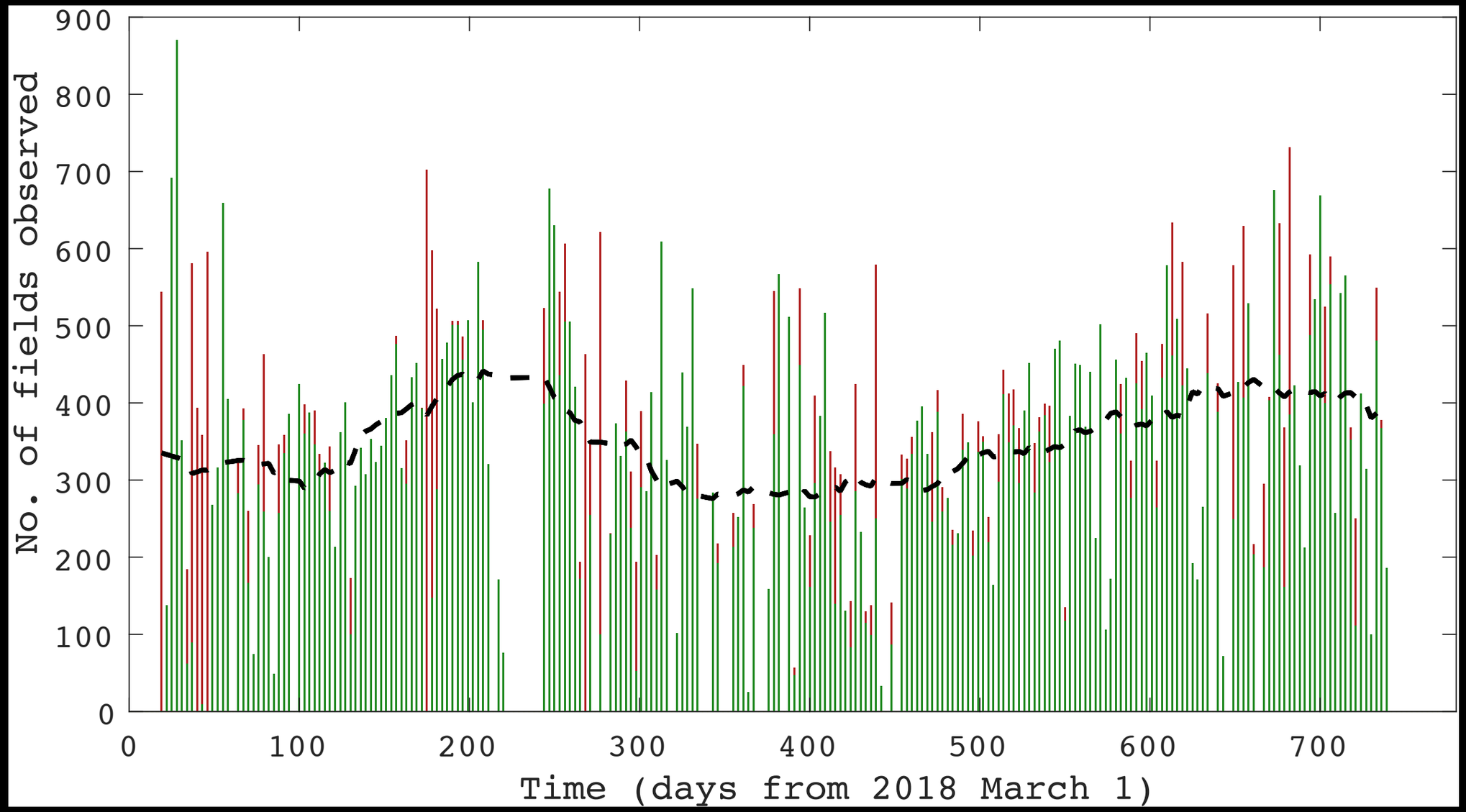


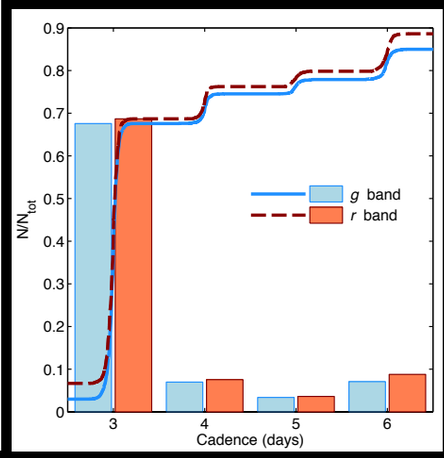
3 day cadence, Northern Sky in g & r filters

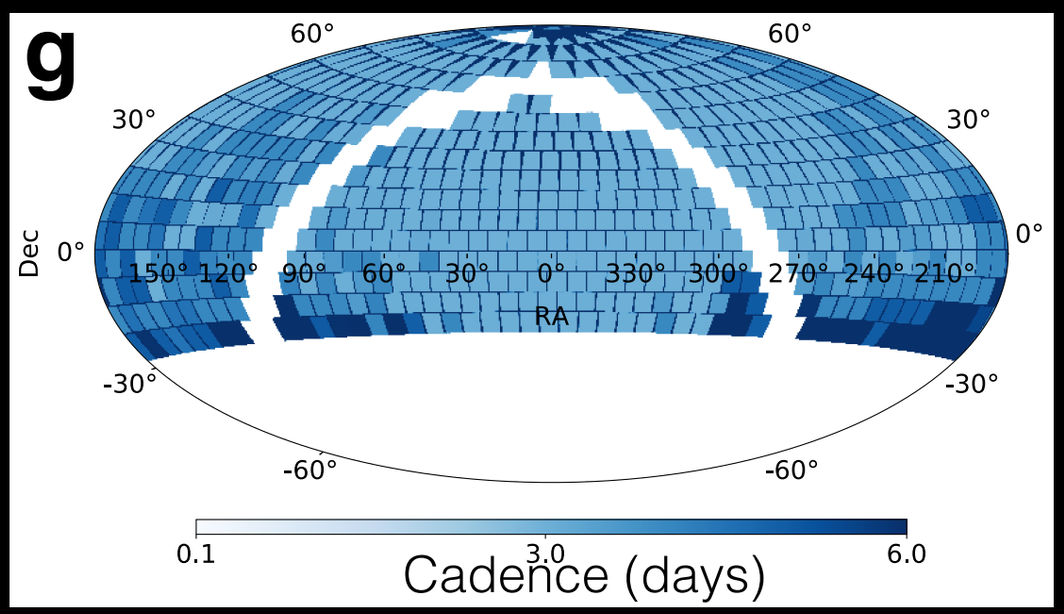
3d-cadence coverage of the ZTF NSS

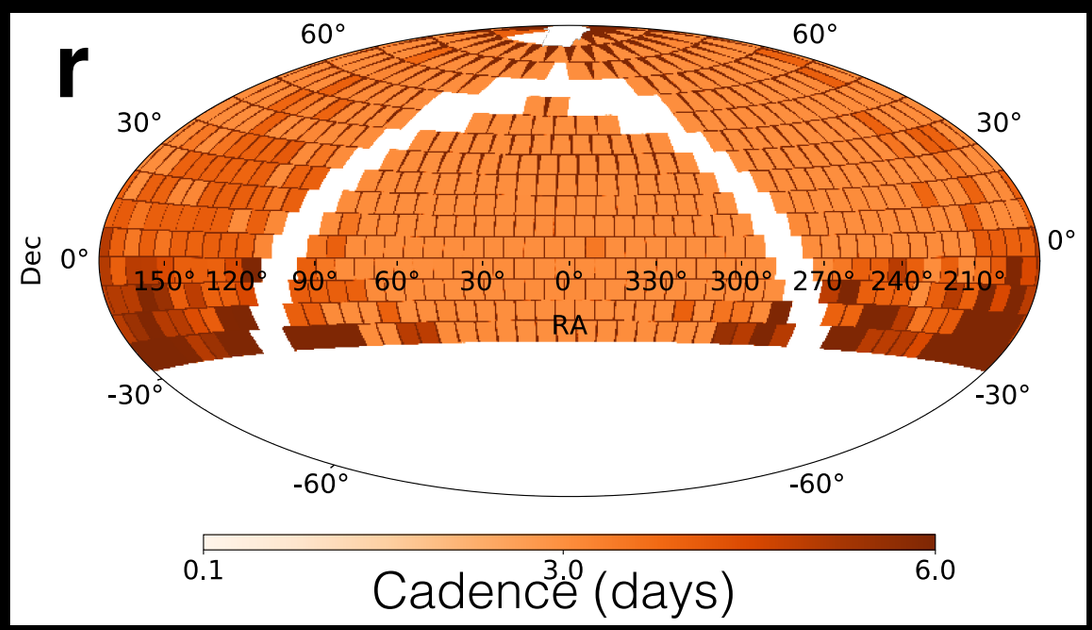


3d-cadence coverage of the ZTF NSS









BTS in Practice

ZTF public alert stream
(10^5 alerts/night)

Real, not moving, no long-term history,
not by a bright star, <19 mag, |b|>7

Candidates list
(~50 alerts/night)

Not obviously stellar/AGN

Saved event list
(~10/night sent to TNS)

m < 18.5,
or rising/
notable

SEDM queue
(~5 requests/night)

Successful classification

Classified SN
(~3/day sent to TNS)

Other
spectrographs
(LT, P200, etc.)

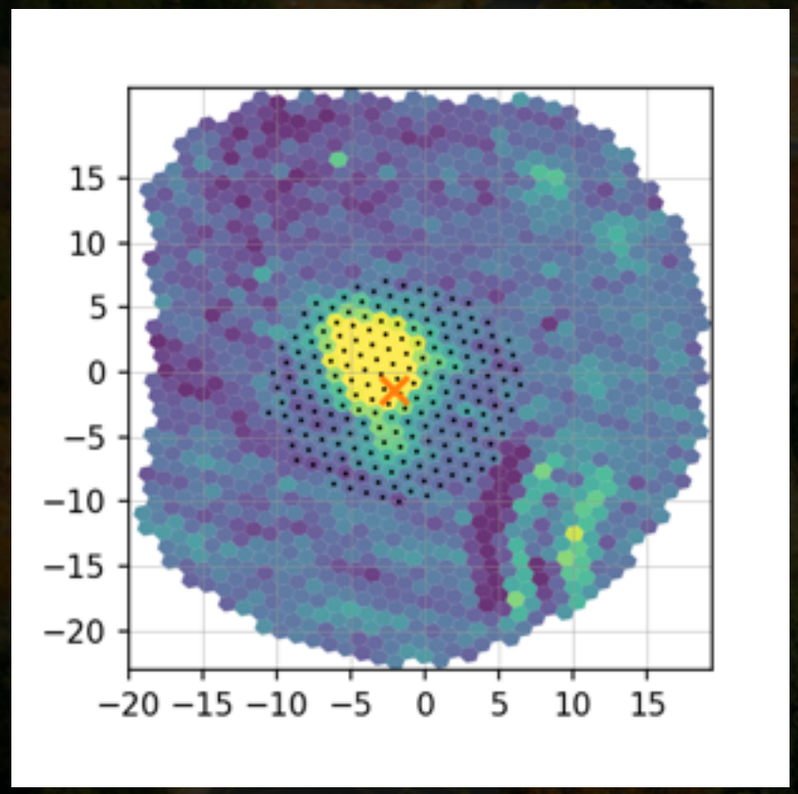
Ambiguous classification, m_{peak} < 18.5, and fading?

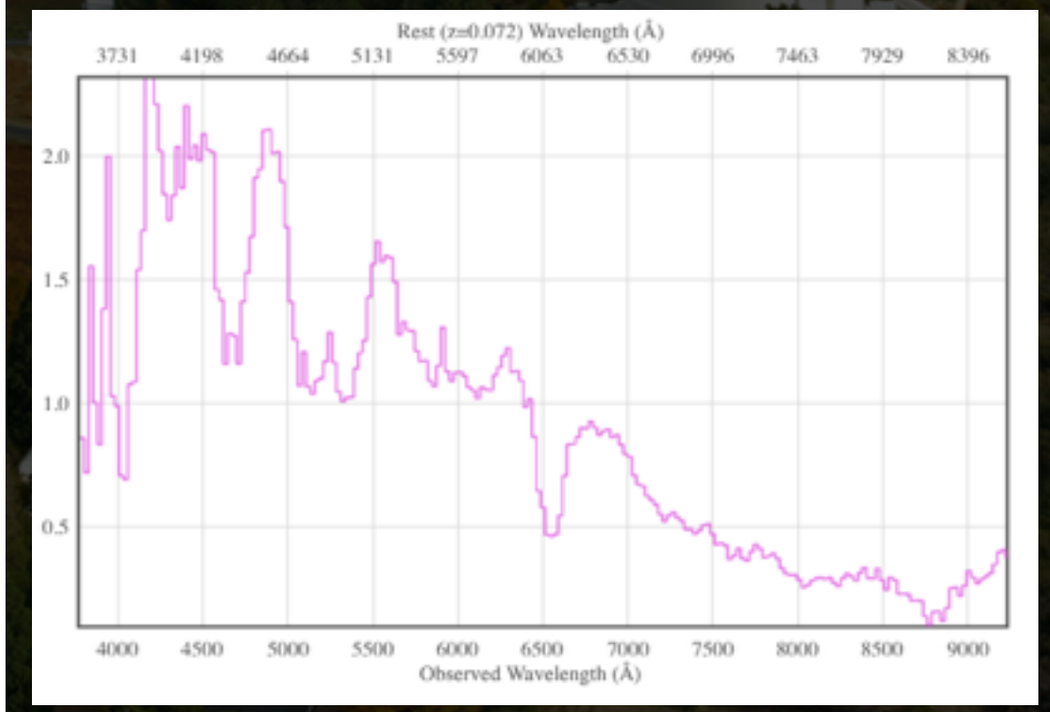
Ambiguous classification and m<18.5?

The ZTF Bright Transient Survey (BTS)

BTS classifications

Goal is to spectroscopically classify all transients brighter than 18.5 mag, using mainly SEDM. Currently we trigger all SN candidates at ~19 mag, with rising priority towards <18.5 mag.



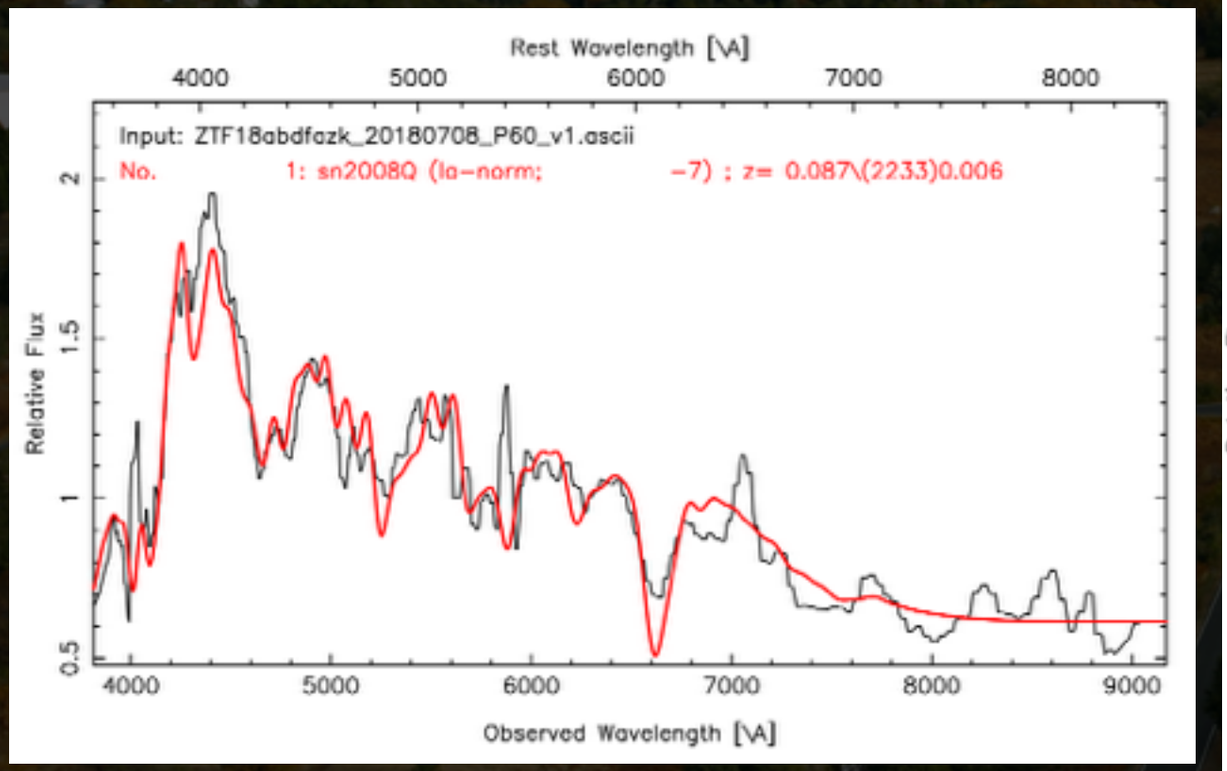


SEDM, 18.5 mag
25 min exp

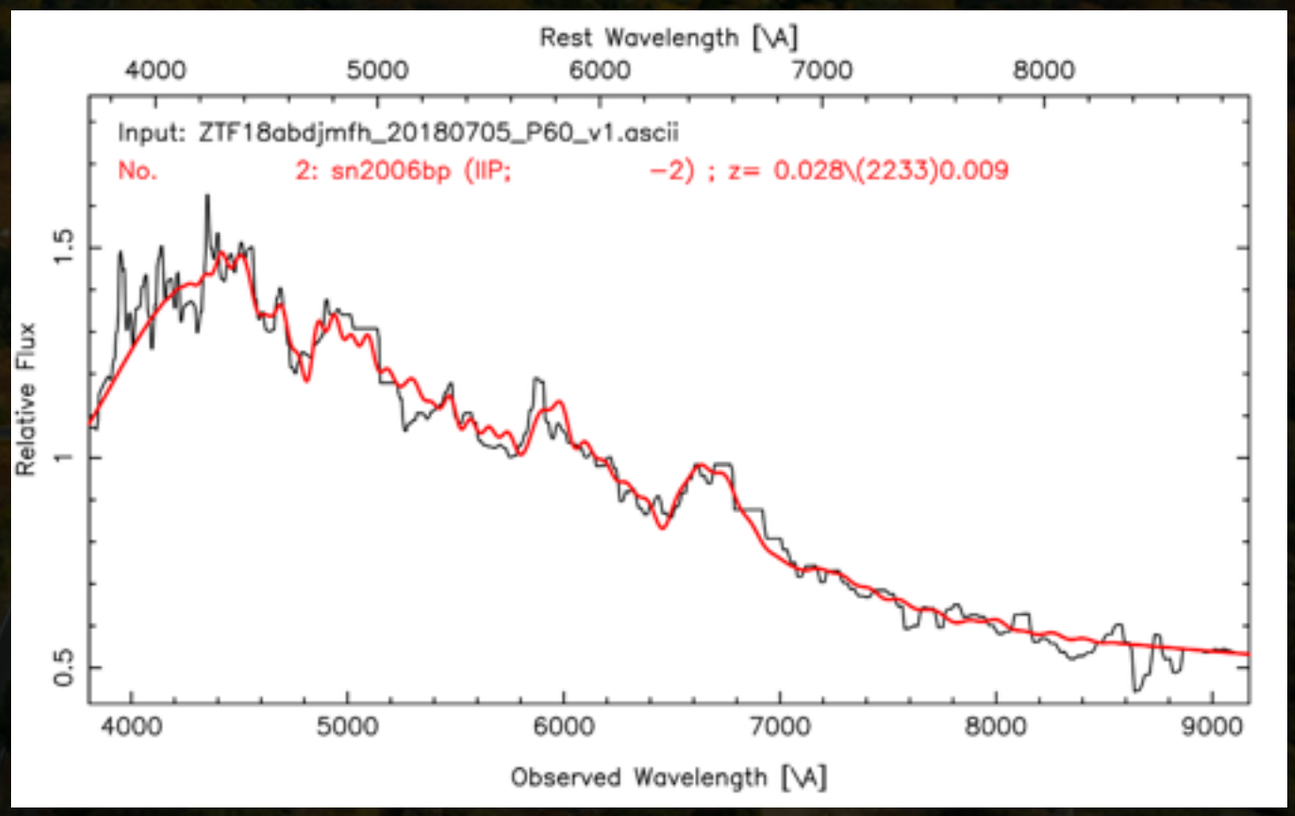
The ZTF Bright Transient Survey (BTS)

SEDM classifications

Based on template matching (e.g., SNID)



SN Ia



SN II

Daily, we publish successful classifications to TNS

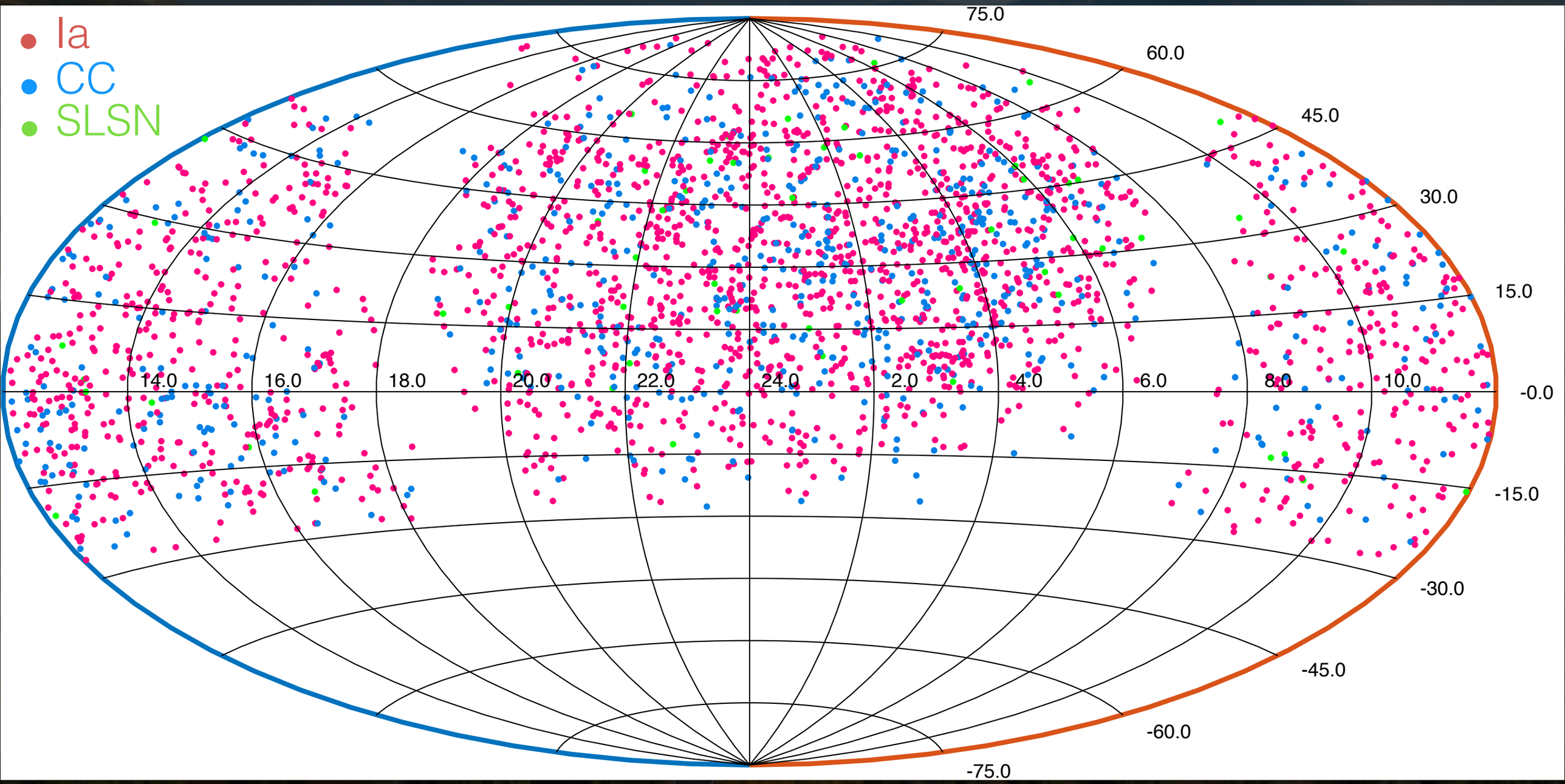
The ZTF Bright Transient Survey (BTS)

BTS classifications

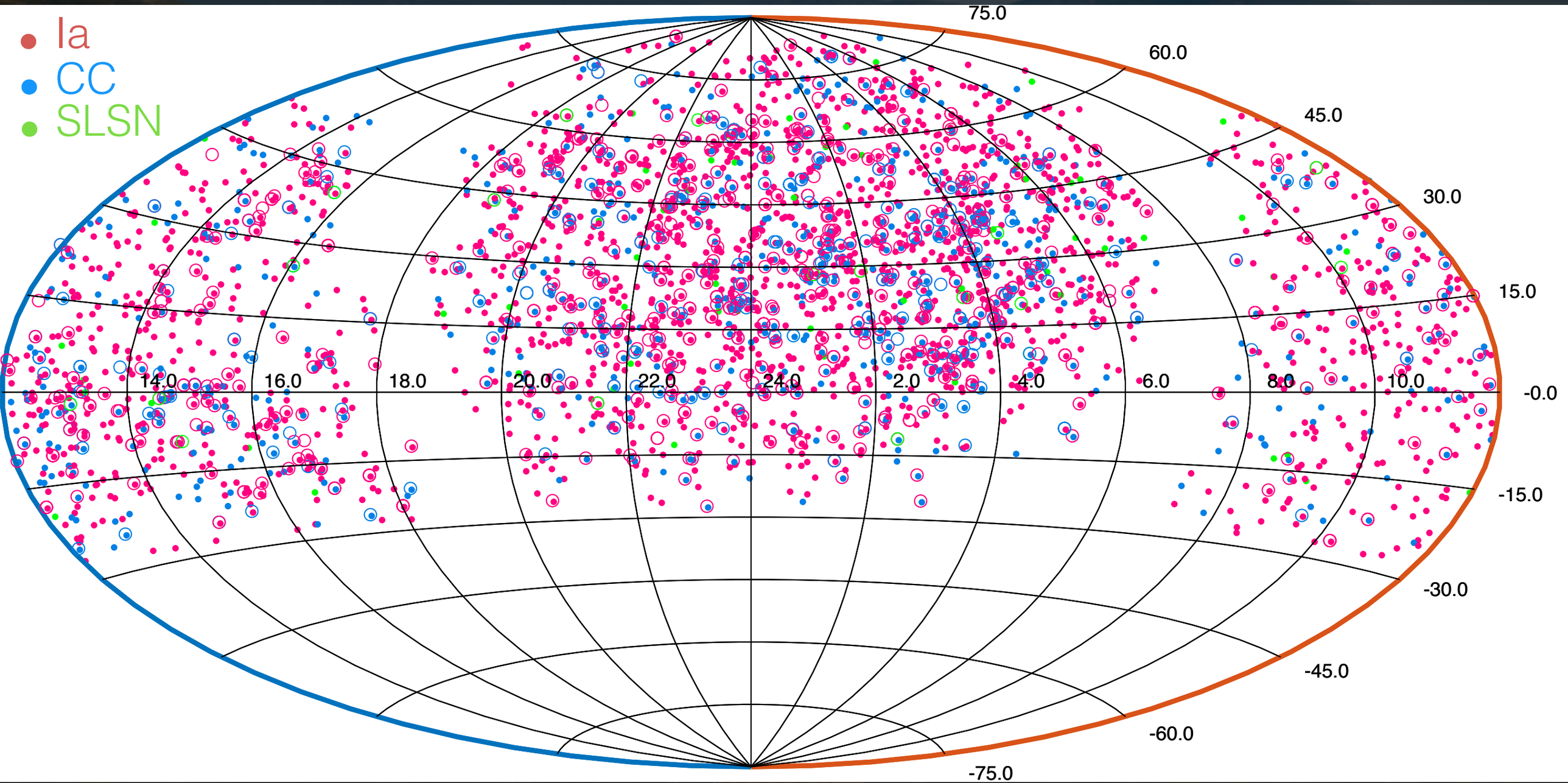
When SEDM fails, we use other facilities — Mainly Palomar 200 inch.

Lick 3m, NOT, LT, APO, Keck, … + community, via TNS.

BTS SN sky positions



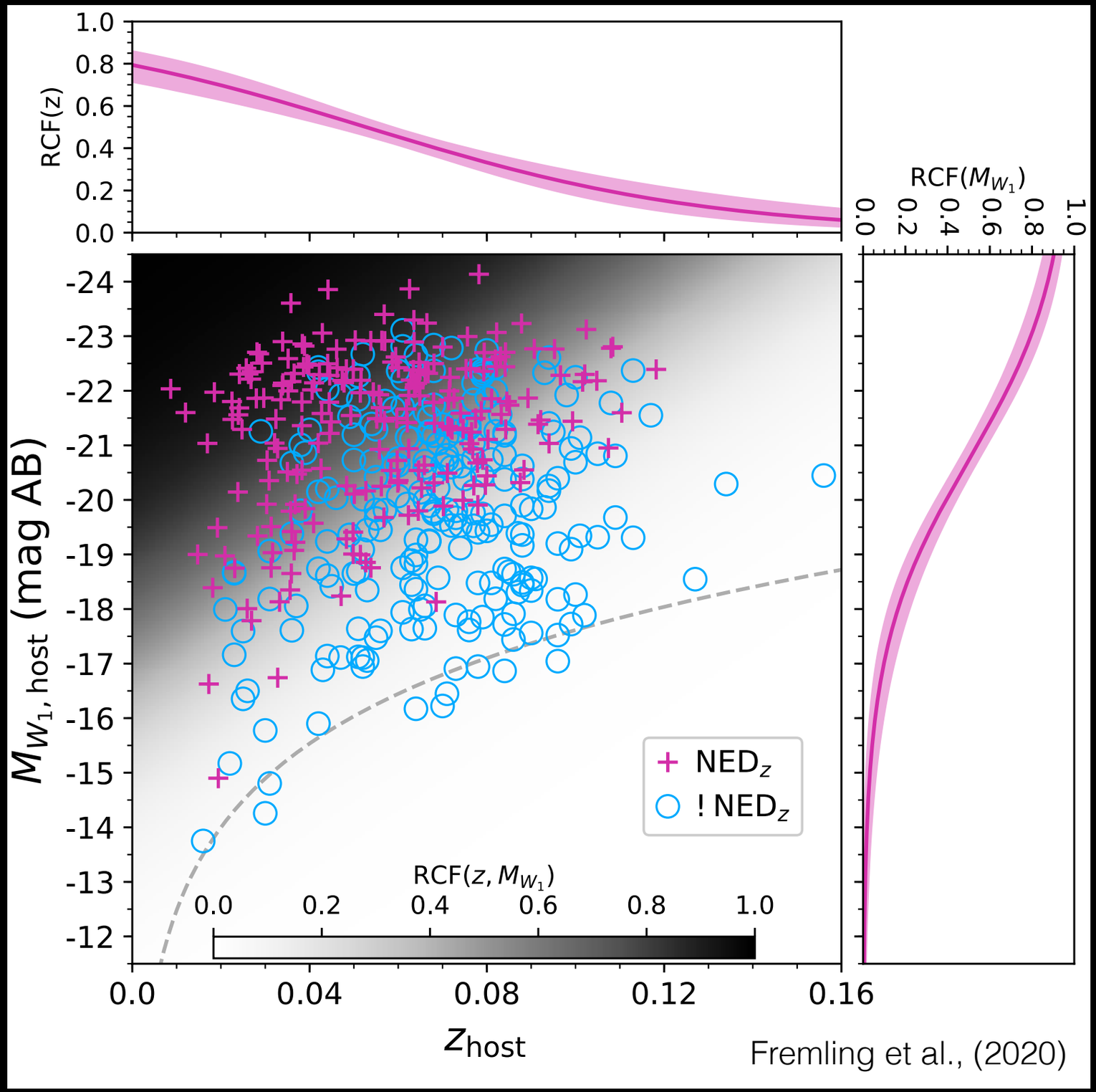
BTS SN sky positions



SNe in galaxies with known redshift circled.
This is why an untargeted survey is needed!

Redshift completeness of current local galaxy catalogs

RCF ~ 0.6 at 200 Mpc



Fremling et al., (2020)

Classified Extragalactic Transient Count (2020 August)

m < 19 (incomplete)

3132 ex.gal. transients

2230 SN Ia
incl. 5 Iax

204 SN Ib/c
incl. 11 Ibn, 27 Ic-BL, 28 SLSN-I

666 SN II
incl. 45 IIb, 84 IIn, 21 SLSN-II

+ 12 TDEs

+ 20 "other" (Novae, ILRTs, FBOTs, LBVs)

m < 18.5 (complete)

1206 ex.gal. transients

879 Ia
incl. 3 Iax

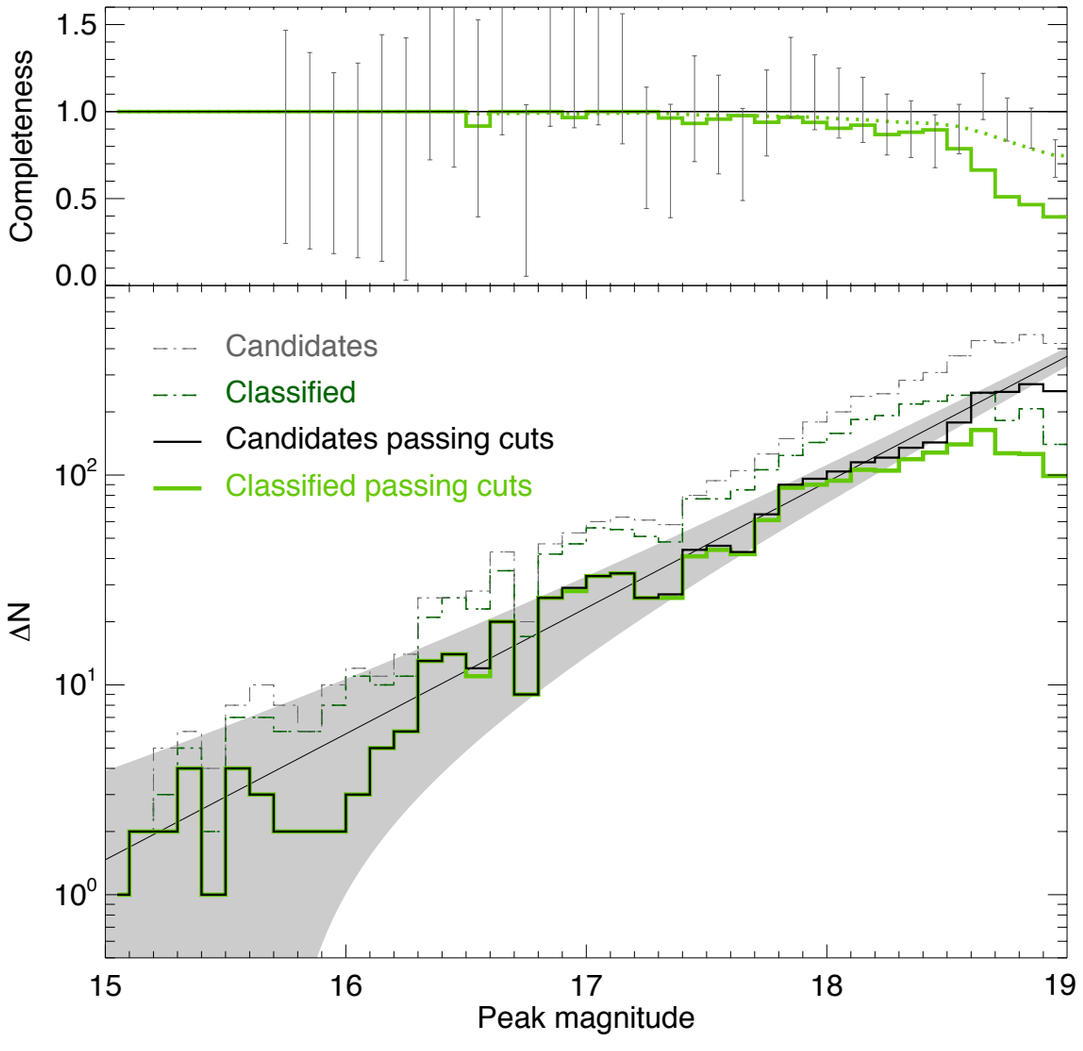
85 Ib/c
incl. 8 Ibn, 17 Ic-BL, 11 SLSN-I

226 II
incl. 28 IIb, 53 IIn, 14 SLSN-II

+ 5 TDEs

+ 11 "other"

Classified Extragalactic Transient Count



m < 18.5 (complete)

1206 ex.gal. transients

879 Ia

incl. 3 Iax

85 Ib/c

incl. 8 Ibn, 17 Ic-BL, 11 SLSN-I

226 II

incl. 28 IIb, 53 IIn, 14 SLSN-II

+ 5 TDEs

+ 11 "other"

https://www.astro.caltech.edu/ztf/bts/bts.php

Sample explorer: https://www.astro.caltech.edu/ztf/bts/explorer.php

ZTF Bright Transient Survey Sample Explorer Table

Some basic documentation is available here.

P48 coverage quality: Any

Classification: SESN Custom filter: Exclude:

Require SN-like light curve

Show P48 images:

New Ref Sub PS1

Show light curves

Filters (mouseover for info):

	Saved:	Peaked:	Last Obs:	RA:	Dec:	z:	Rise:	Fade:	Peak mag:	Last mag:	Abs mag:	Save vis:	Late vis:	Curr vis:	b:	A_g:	
Start:						0	.										
End:						0.03	15	15									
Sort:																	Reverse

Submit Display as: Grid Table

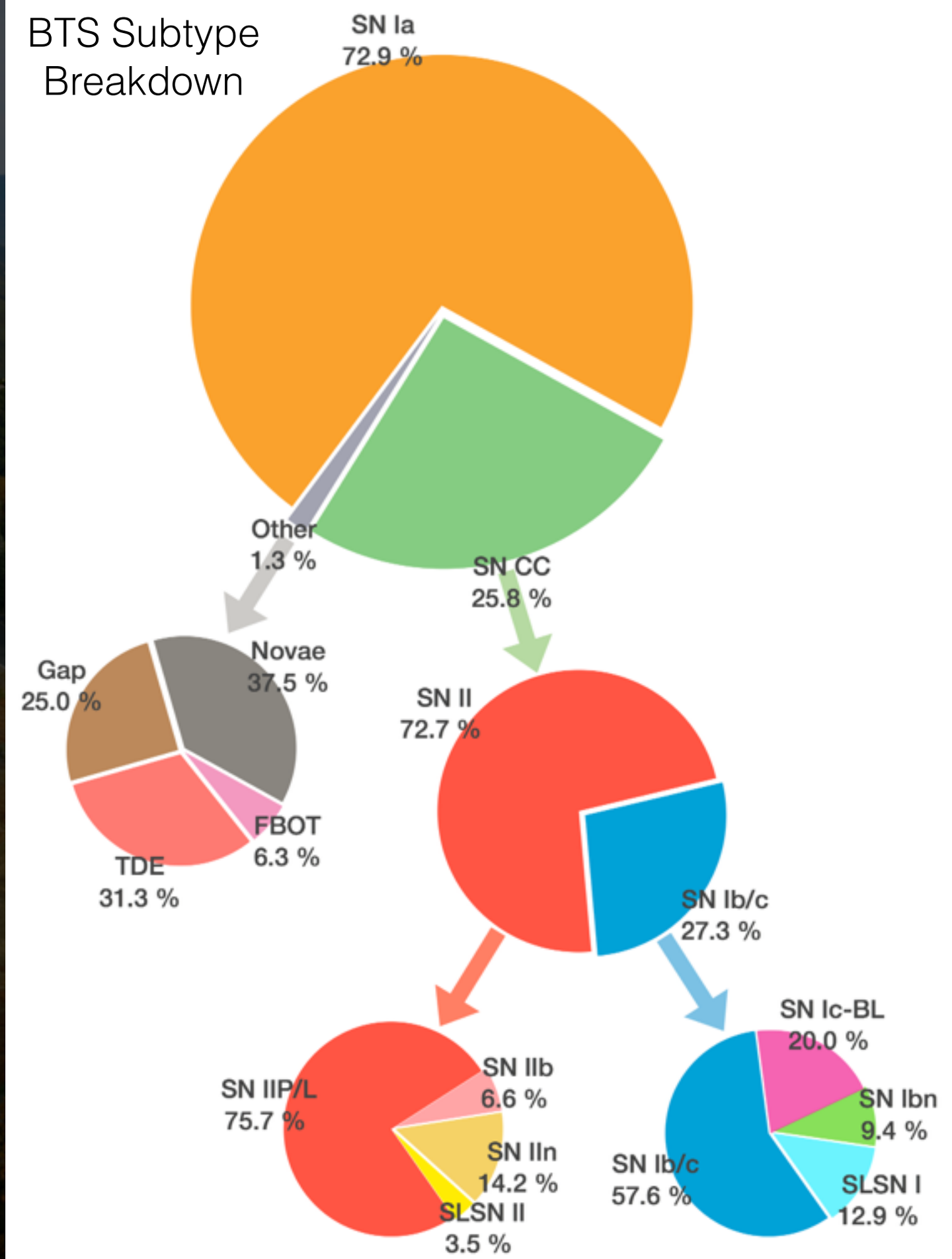
32 candidates returned by query.

ZTF ID	TNS ID	saved	RA	Dec	Peak mag	Last mag	Rise	Fade	Type	Redshift	M_abs	Coverage	Visibility	b	A_g
ZTF19aaxdzqt	SN2019fxo	2019-06-04	11:03:52.60	-03:20:13.2	r = 17.49 (-294.40)	r = 17.84 (-284.41)	>0	>10	SNIb/c	0.024	-17.70	00100	1.5 0.0 6.7	+50.0	.165
ZTF19acoknir	SN2019uda	2019-11-13	13:12:37.14	+46:48:55.8	r = 18.68 (-141.10)	r = 18.98 (-132.08)	>0	>9	SNIb/c	0.028	-16.76	00011	1.1 2.8 9.3	+69.9	.039
ZTF19accjfgv	SN2019rta	2019-10-03	08:28:49.32	+75:19:41.1	g = 17.96 (-173.18)	r = 19.59 (-154.15)	>0	5.68	SNIIb	0.027	-17.46	00110	3.9 6.2 7.8	+32.3	.083
ZTF18abcyhju	SN2018cup	2018-06-28	12:35:22.96	+29:29:31.8	r = 17.50 (-638.38)	r = 17.69 (-626.44)	2.31	>11.9	SNIIb	0.01524	-16.64	11110	2.7 1.1 9.4	+85.7	.076
ZTF18abwkrbl	SN2018gjx	2018-09-17	02:16:15.58	+28:35:28.6	g = 15.96 (-553.17)	r = 19.58 (-468.35)	2.37	5.17	SNIIb	0.00999	-17.50	11111	7.0 9.4 0.0	-30.7	.291
ZTF19aadpoik	SN2019yc	2019-01-22	00:39:35.00	+00:52:04.1	g = 16.43 (-427.45)	r = 17.99 (-410.50)	3.14	3.05	SNIIb	0.0145	-17.61	10100	1.9 0.0 0.0	-61.9	.067
ZTF19acxmpnz	SN2019wfy	2019-12-16	07:23:00.55	+26:37:22.6	r = 18.30 (-105.31)	r = 20.26 (-58.37)	3.6	5.76	SNIb/c	0.0265	-17.19	11111	8.9 9.4 4.8	+18.3	.291
ZTF19ackjszs	SN2019tsf	2019-11-02	11:08:32.80	-10:28:54.4	r = 17.32 (-143.08)	g = 18.40 (-118.09)	>4	>11	SNIb	0.021	-17.61	01010	0.0 2.2 5.7	+44.9	.214
ZTF18acceaem	SN2018hnw	2018-11-09	20:14:37.54	-19:21:01.8	r = 17.58 (-501.48)	r = 17.58 (-501.48)	>4	>0	SNIb/c	0.028	-18.08	00000	1.1 0.0 0.0	-26.7	.363
ZTF19aadnxbh	SN2019uo	2019-01-20	12:02:36.61	+41:03:42.0	g = 16.85 (-425.13)	g = 20.62 (-385.29)	6.11	7.7	SNIbn	0.02045	-17.92	11111	7.1 9.0 9.9	+72.8	.043
ZTF20aaskdhj	SN2020eai	2020-03-05	04:59:08.05	+04:58:21.9	g = 18.08 (-15.41)	g = 18.08 (-15.41)	6.55	>0	SNIb	0.01562	-16.33	11000	3.0 0.4 1.5	-22.2	.275
ZTF19acjtpqd	SN2019tqb	2019-11-05	16:21:53.89	+38:55:47.2	g = 17.01 (-134.51)	g = 17.01 (-134.51)	6.84	>0	SNIc	0.01717	-17.36	11000	0.5 0.0 5.9	+45.0	.028
ZTF19aatmkll	SN2016dqt	2019-05-03	18:30:29.04	+74:07:15.8	g = 17.25 (-315.22)	g = 20.08 (-258.29)	7.09	6.69	SNIbn	0.02475	-18.10	10011	6.9 7.5 5.2	+27.4	.211
ZTF20aaelulu	SN2020oi	2020-01-08	12:22:54.93	+15:49:25.1	r = 13.83 (-66.09)	g = 17.22 (-17.16)	7.23	8.31	SNIc	0.0052	-17.97	11111	5.2 7.5 8.6	+76.9	.086
ZTF20aajcdad	SN2020bcq	2020-01-27	13:26:29.65	+36:00:31.0	r = 17.05 (-45.10)	g = 19.49 (-17.16)	8.43	12.82	SNIb	0.01861	-17.51	11110	6.0 8.1 8.8	+78.4	.052
ZTF19aamsetj	SN2019cad	2019-03-20	09:08:42.95	+44:48:46.0	r = 17.37 (-339.28)	r = 19.77 (-299.43)	8.96	13.73	SNIc	0.02751	-18.04	11111	7.5 2.7 7.1	+42.6	.058
ZTF18abgrbjb	SN2018efd	2018-07-15	18:19:59.68	+51:47:47.6	r = 18.90 (-607.33)	g = 20.29 (-600.40)	9.14	>5.1	SNIIb	0.03	-16.74	11100	7.7 6.1 4.4	+25.7	.114
ZTF19aadwtoe	SN2019abb	2019-01-22	07:54:17.27	+14:16:22.4	r = 17.32 (-418.26)	r = 19.84 (-324.44)	9.43	11.87	SNIc	0.0153	-16.86	11011	8.4 6.7 4.8	+20.2	.126

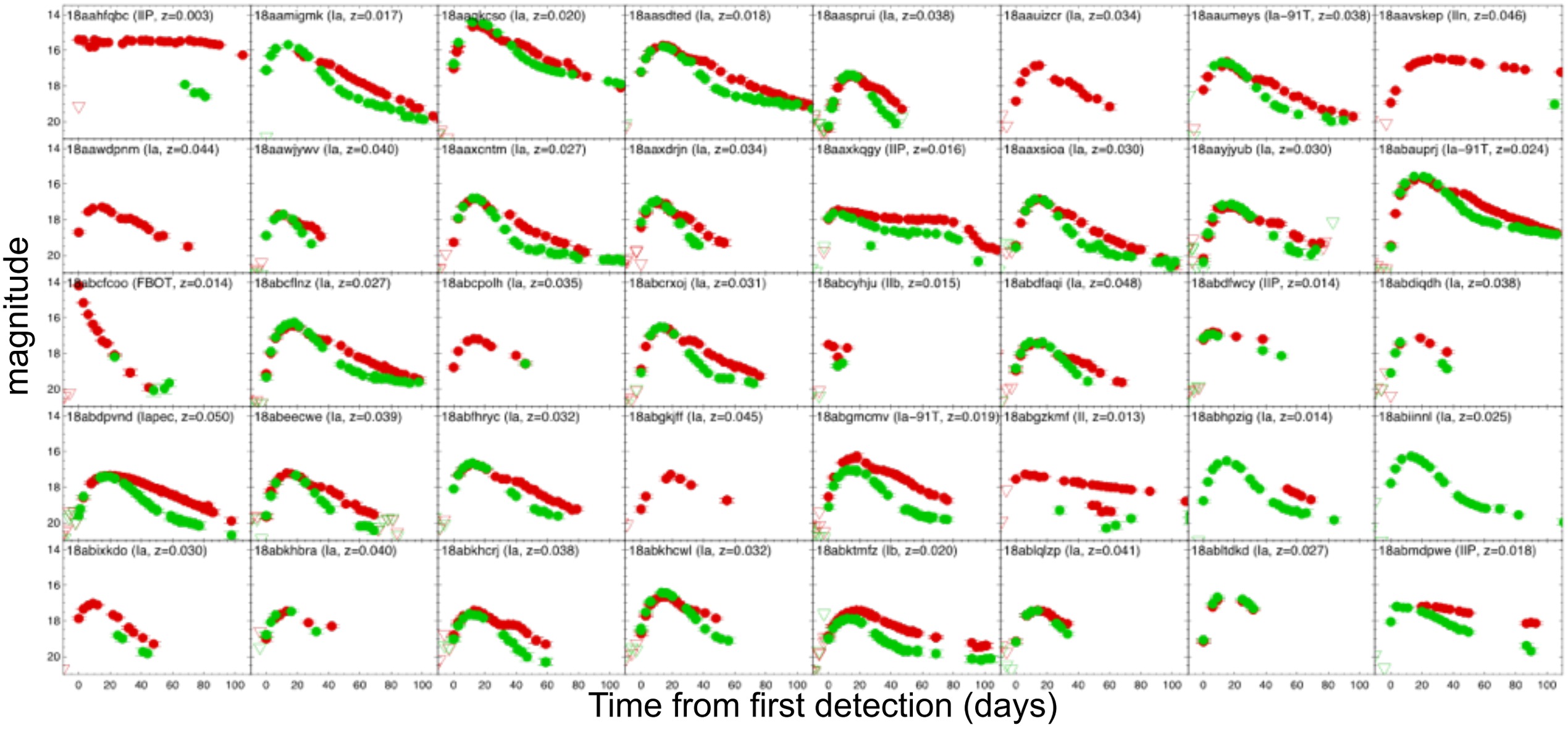
BTS/RCF
Ongoing analysis and results:

- Redshift completeness of local galaxy catalogs
- Demographics: lightcurves and luminosity functions
- Rates
- Demographics: Host galaxies

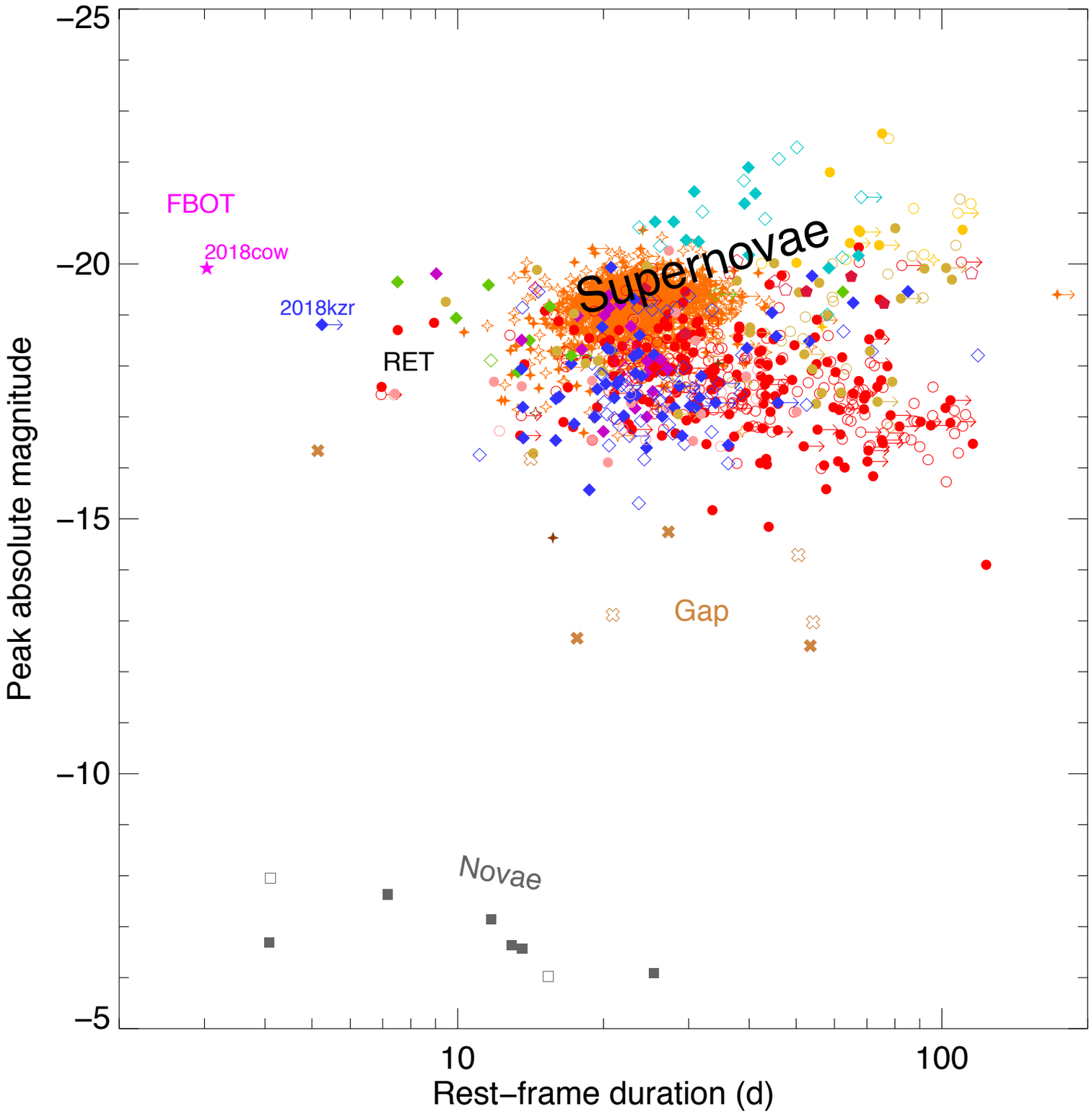
BTS Subtype Breakdown

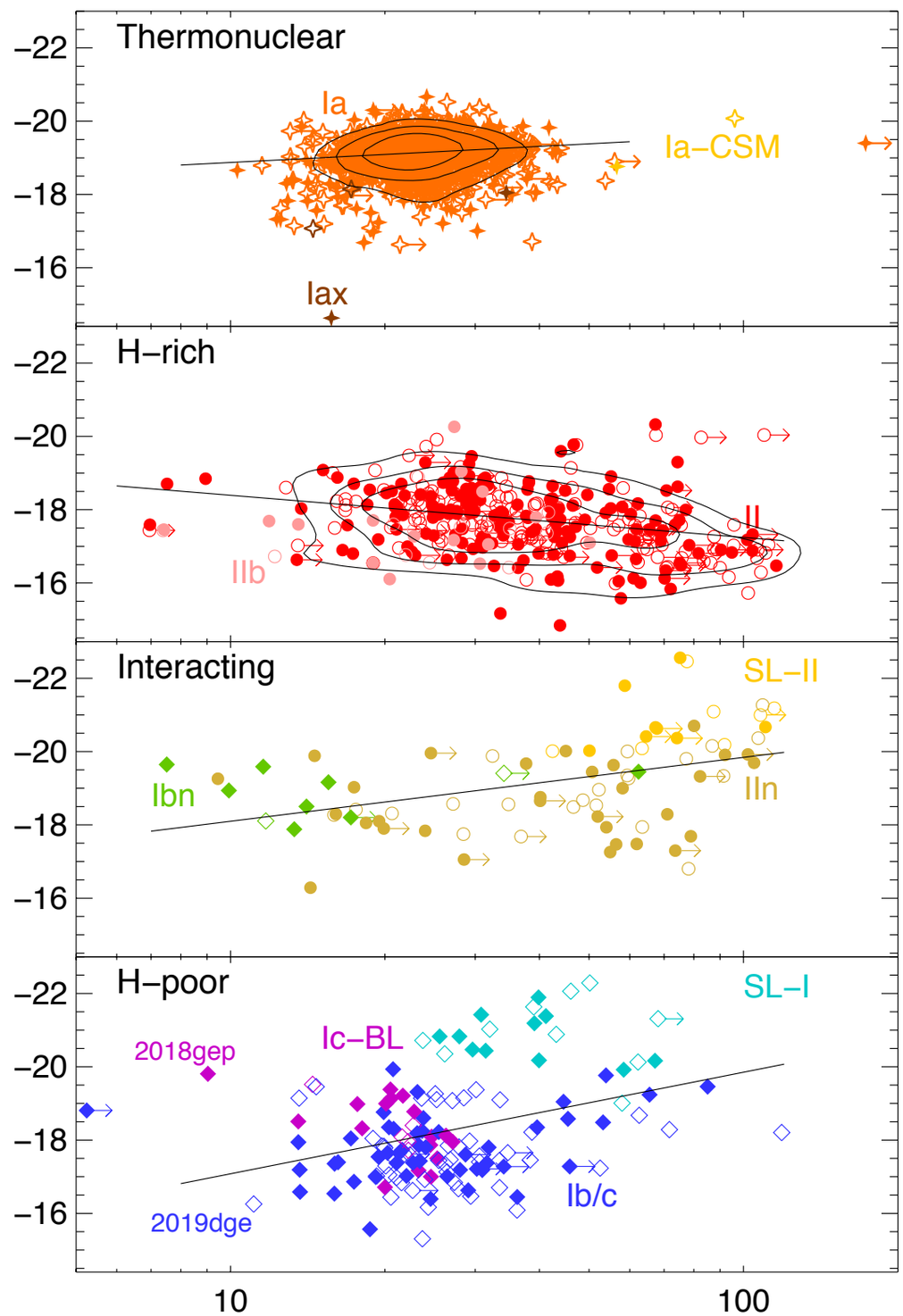


BTS Example Light Curves

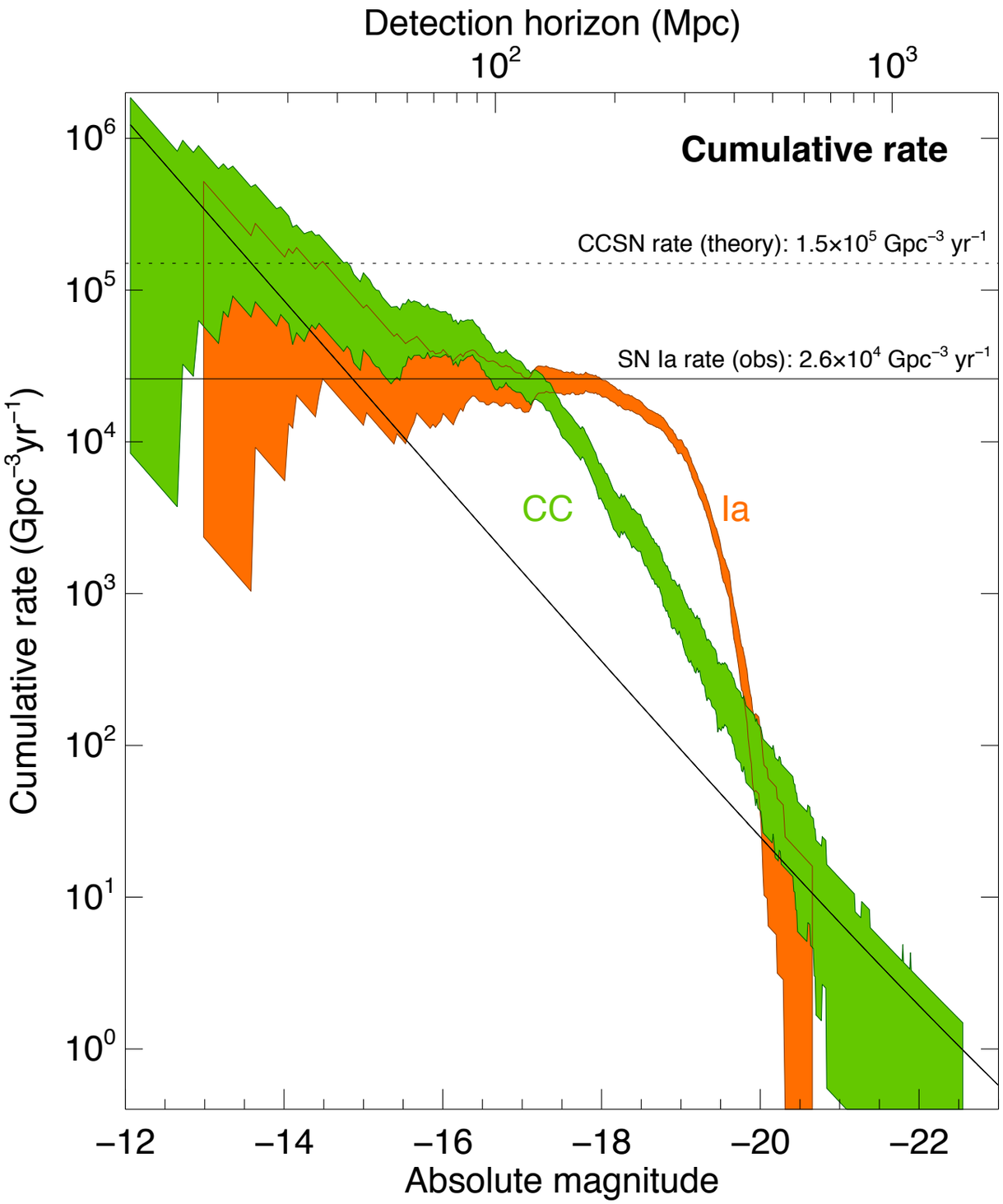


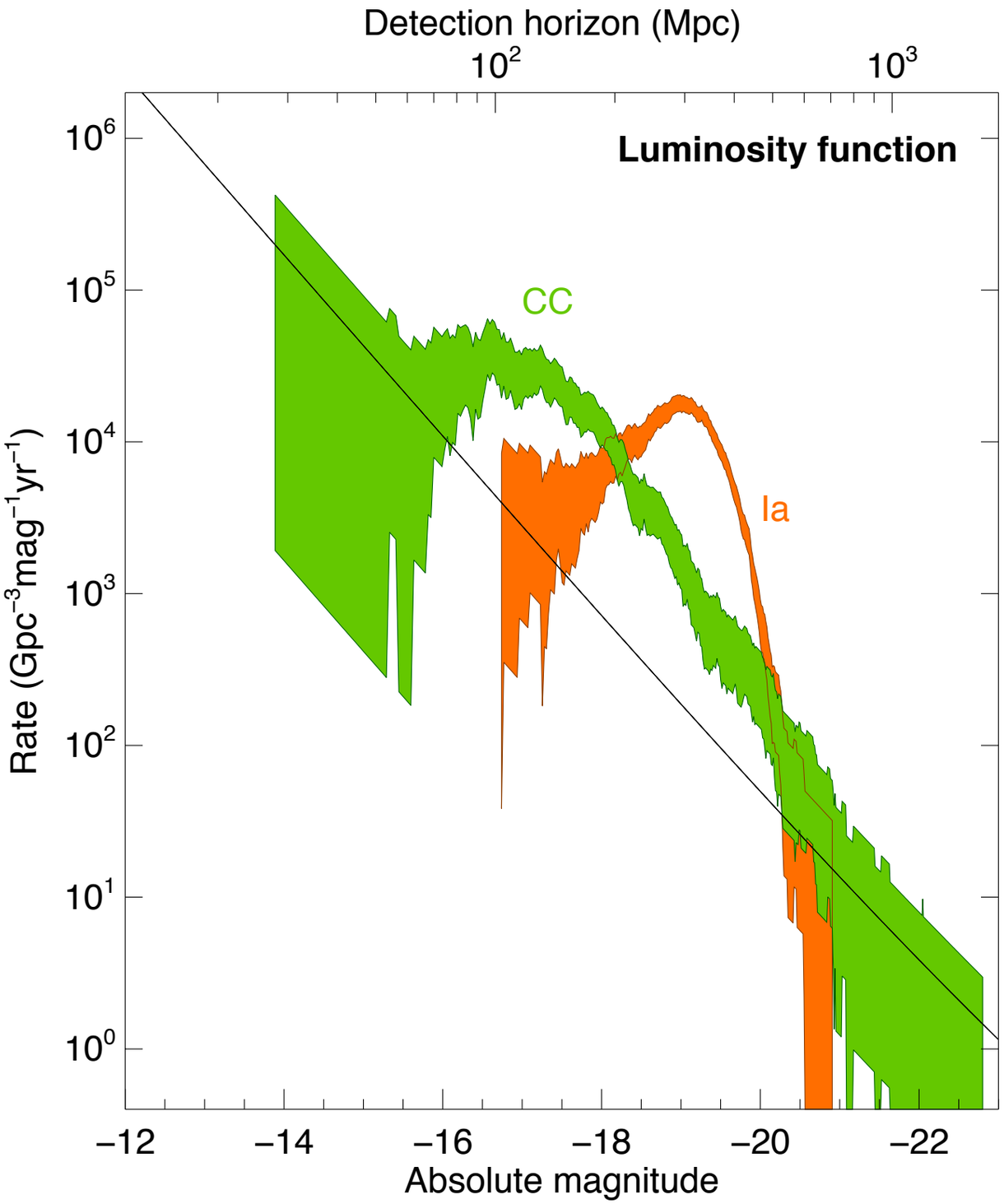
Supernova Lightcurve Parameter Space



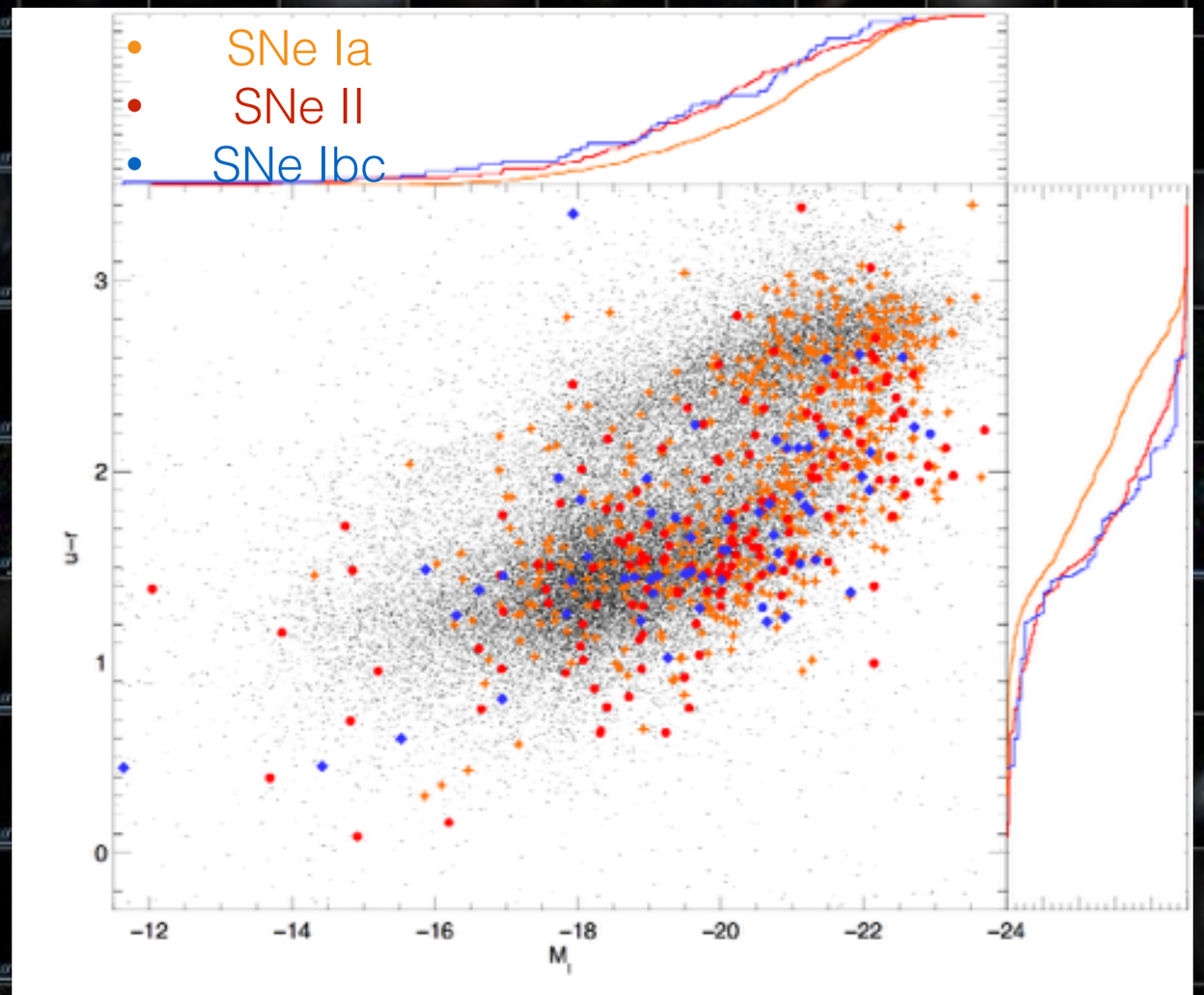


Supernova Lightcurve Parameter Space



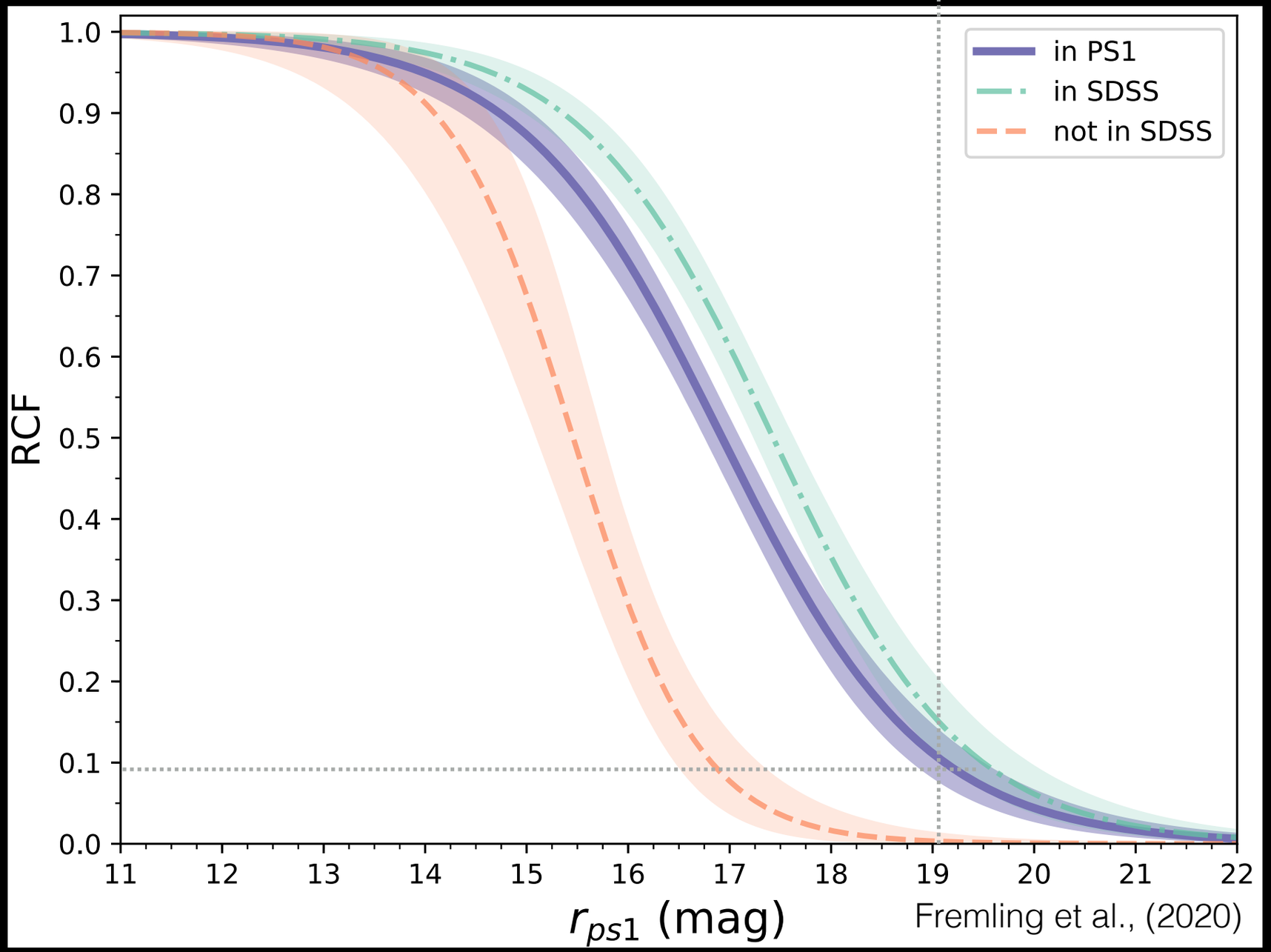


Host Galaxies

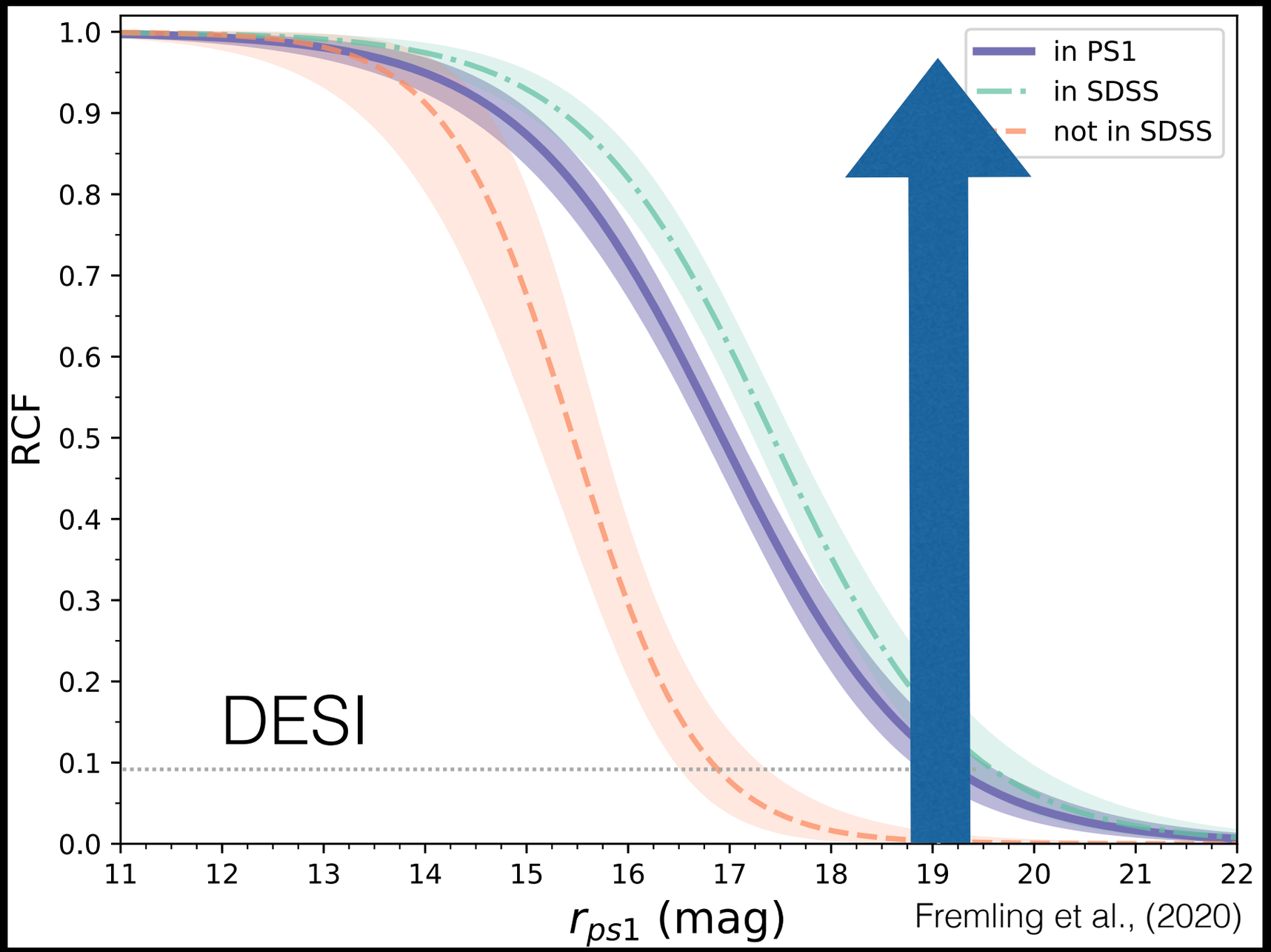


CCSN host collage from Kirsty Taggart

Redshift completeness of current local galaxy catalogs



Redshift completeness of current local galaxy catalogs



Transients in the local universe with ZTF and Palomar Gattini-IR

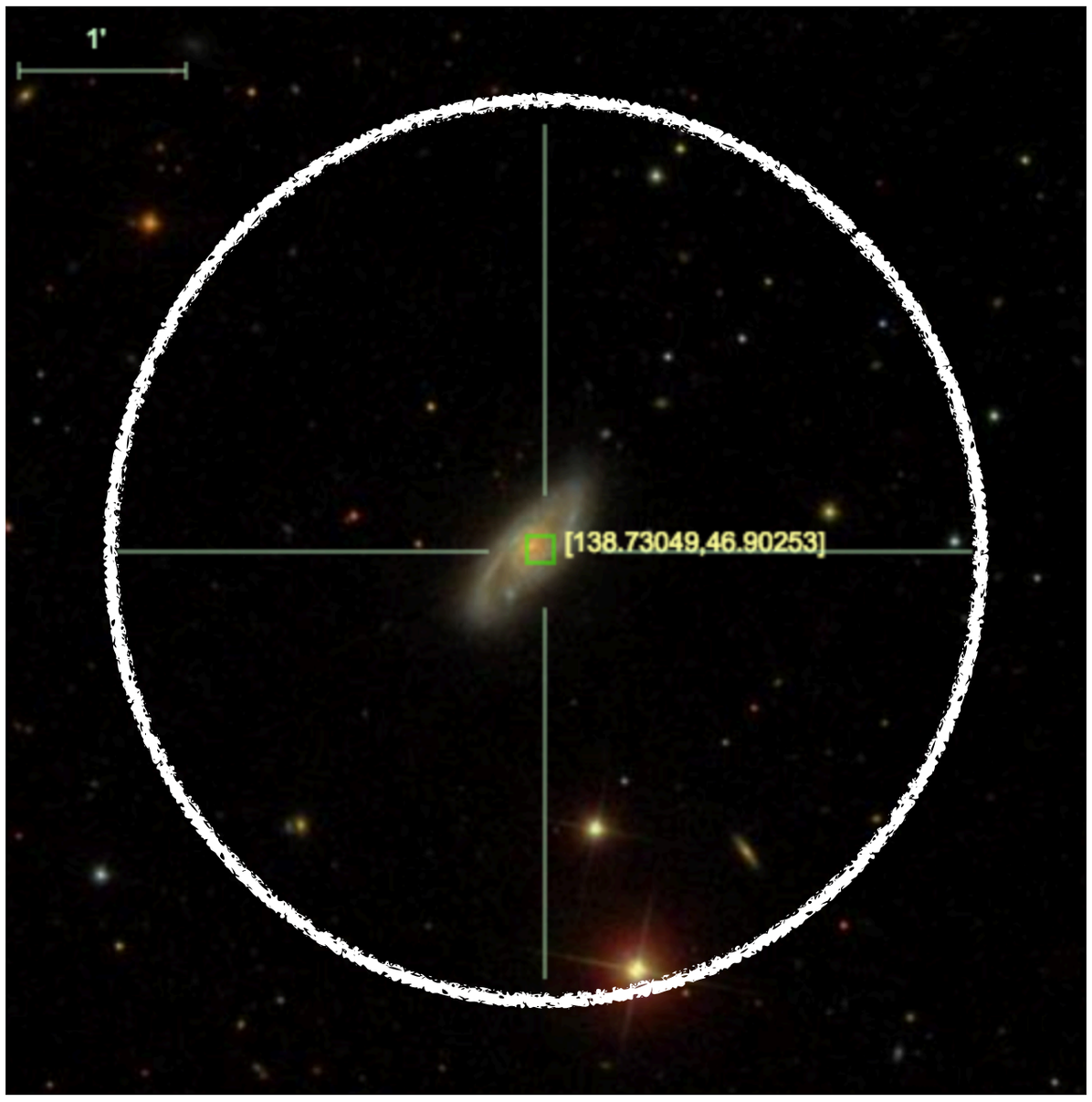
Searching for elusive thermonuclear explosions

Kishalay De

Caltech

Local universe transients with ZTF

Census of the Local Universe experiment (< 200 Mpc)

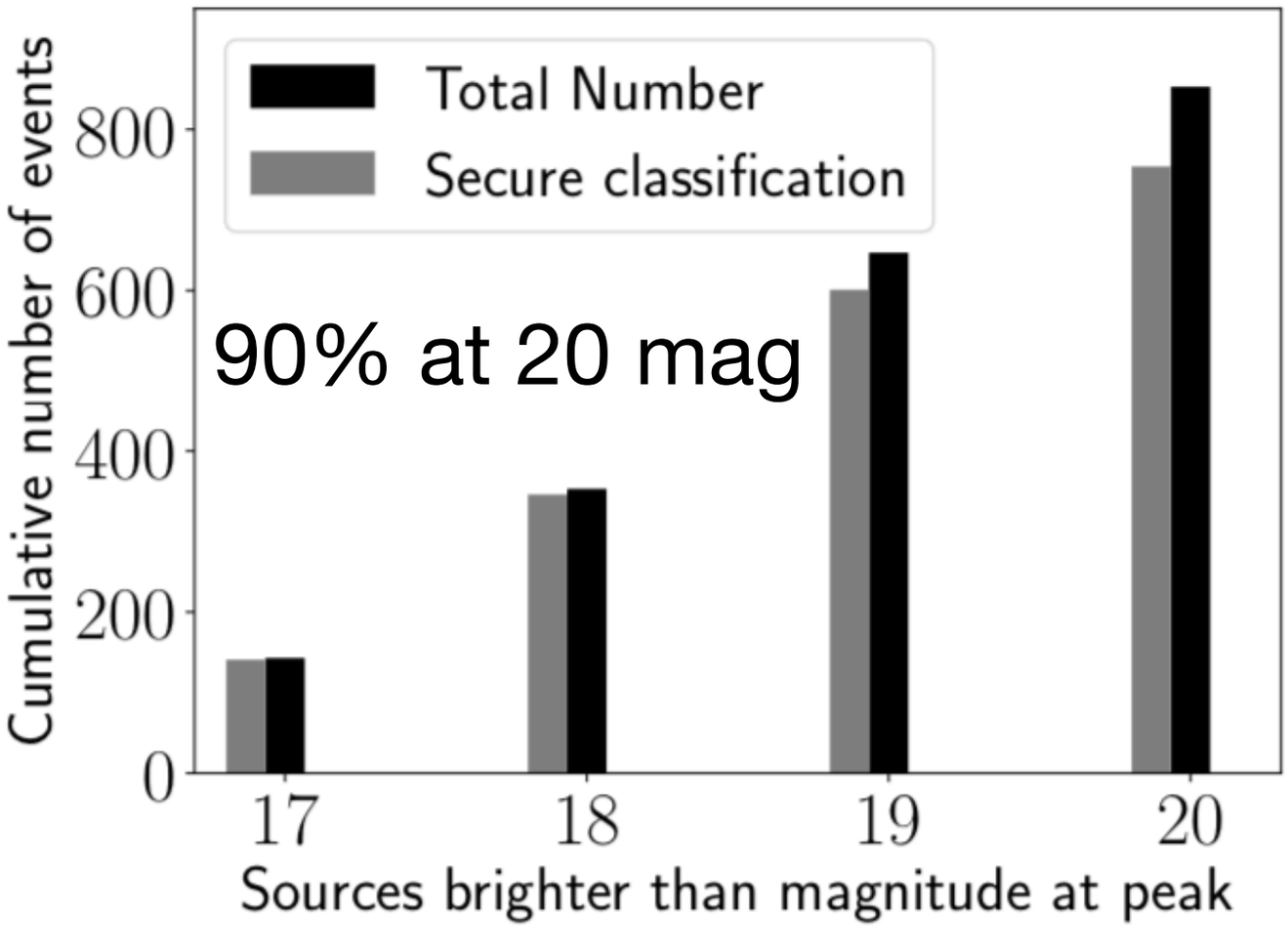


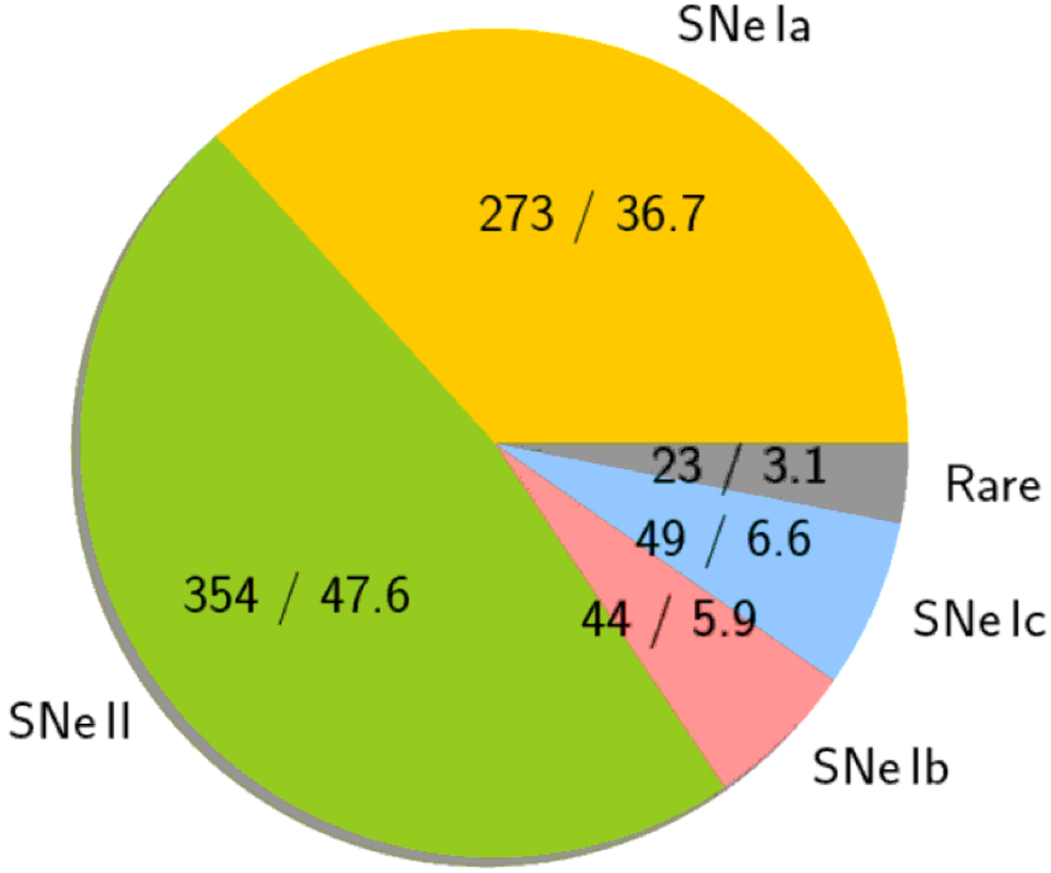
De+ 2020b

Spectroscopic classification of all transients brighter than 20 mag, within 100” of host galaxy

Local universe supernova demographics

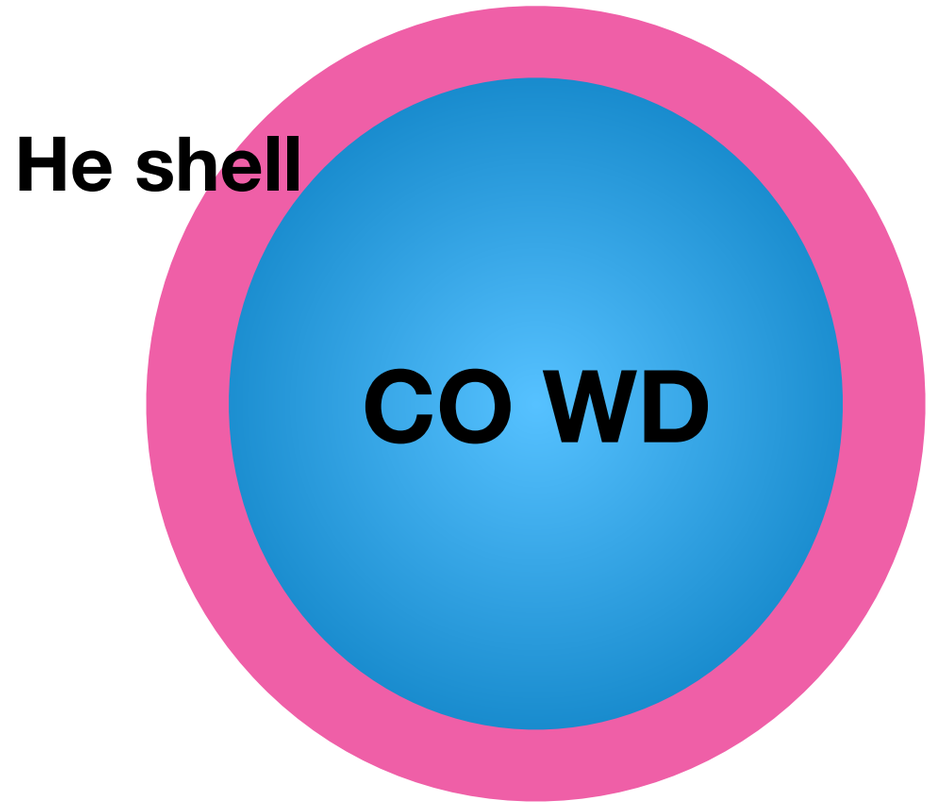
754 spectroscopically classified SNe in 16 months
(~ 1200 classified as of April 2020)





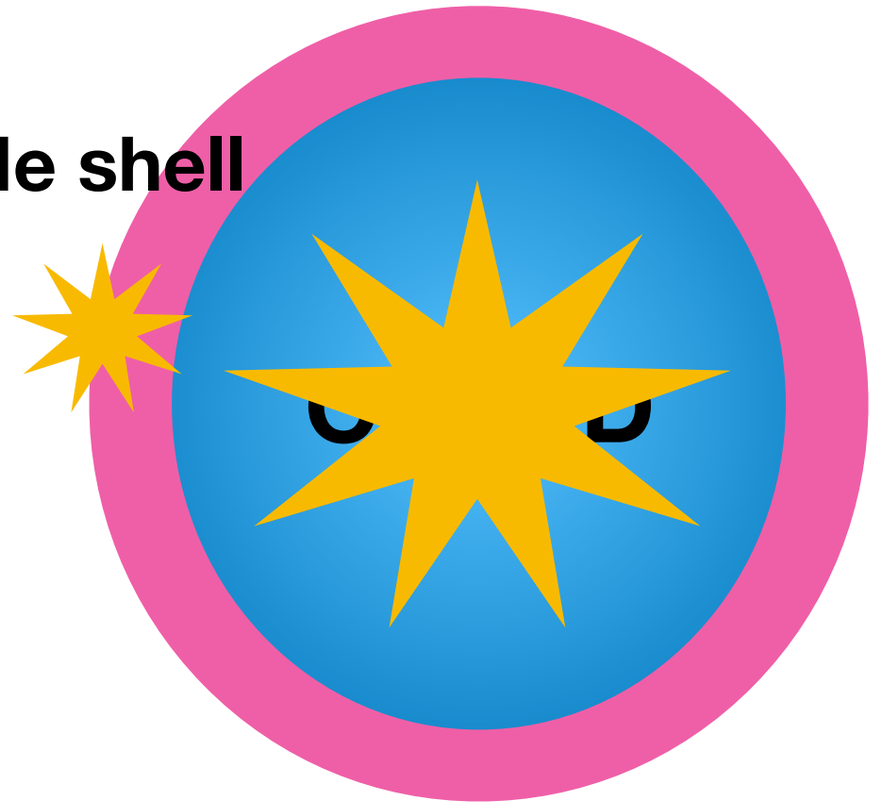
De+ 2020b

Thermonuclear shell explosions on white dwarfs



Nomoto 1982; Woosley+ 1986; Nugent+ 1997; Fink+ 2010; Sim+ 2012; Shen & Moore 2014; Polin+ 2019a,b

Thermonuclear shell explosions on white dwarfs



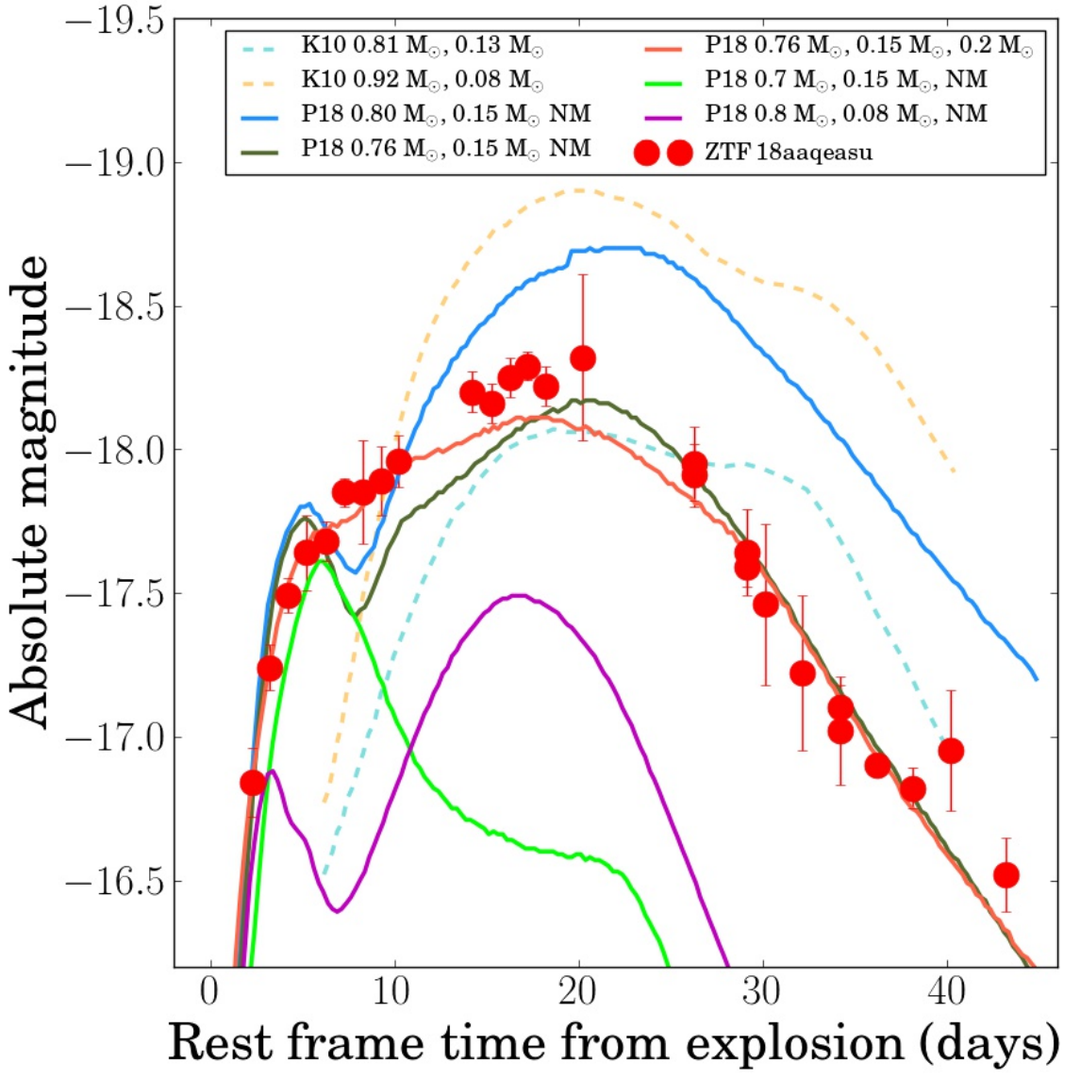
Nomoto 1982; Woosley+ 1986; Nugent+ 1997; Fink+ 2010; Sim+ 2012; Shen & Moore 2014; Polin+ 2019a,b

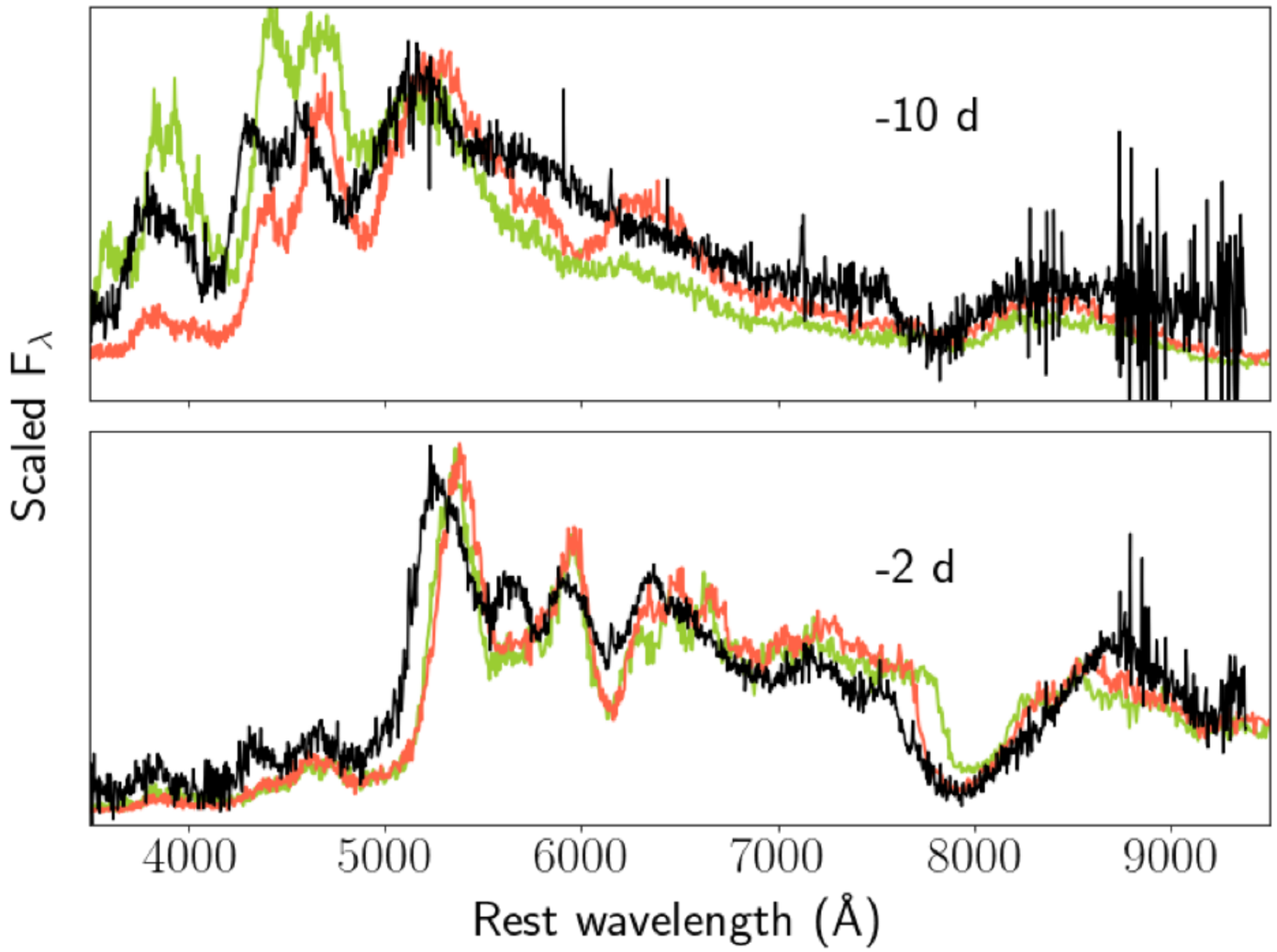
- Does the He burn in a detonation/deflagration?
- Does the shell detonation trigger a detonation in the underlying core? For what shell and core masses?
- Implications for the progenitors of Type Ia supernovae and the fate of He accreting white dwarfs

ZTF 18aaqeasu (SN 2018byg)

Fast rise + strong line blanketing = Smoking gun signature of shell detonation

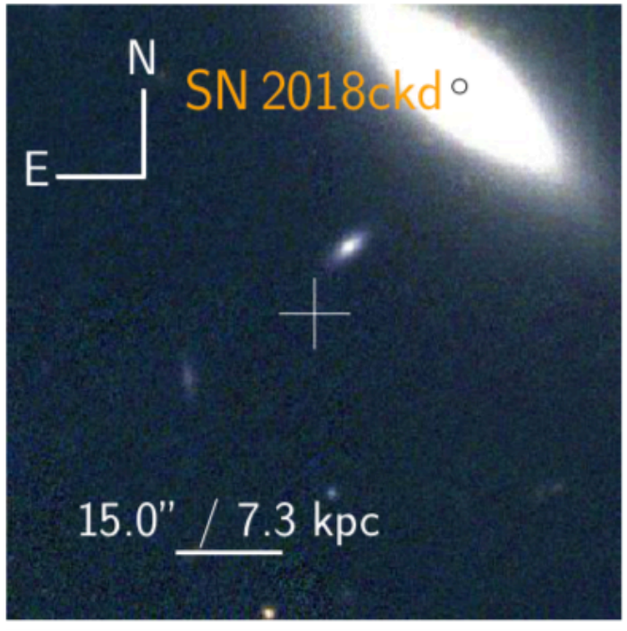
De+ 2019a

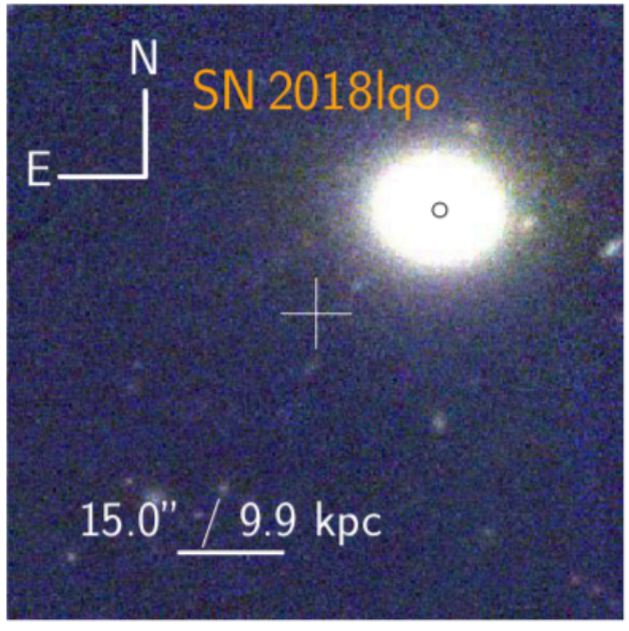


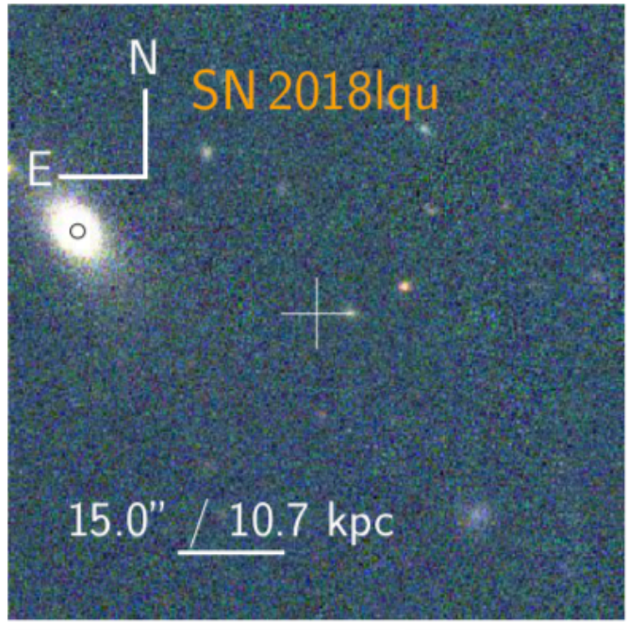


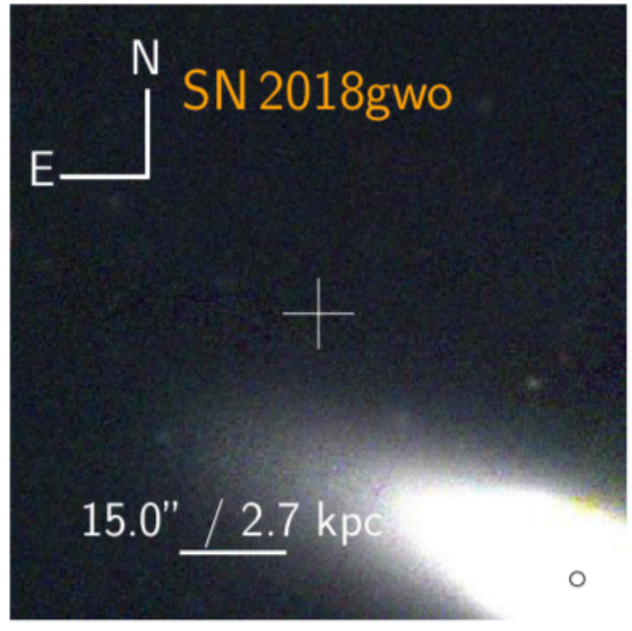
Massive shell detonations exist but rare in the universe (~ 1% of all SNe Ia)

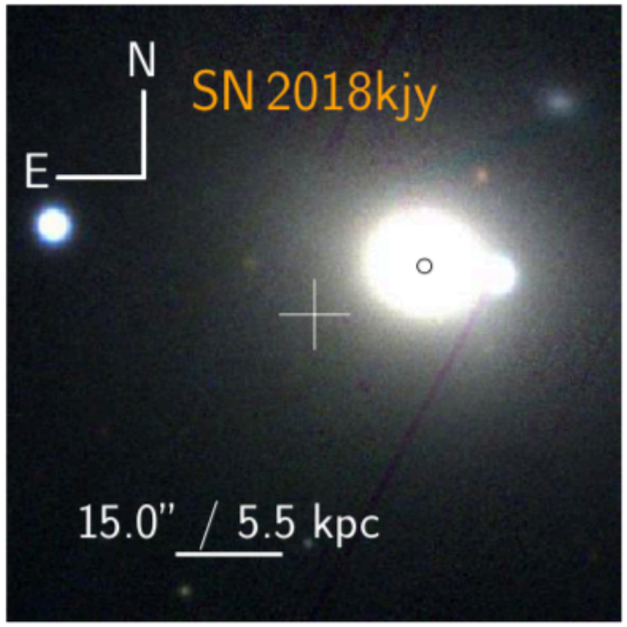
Search for faint thermonuclear supernovae

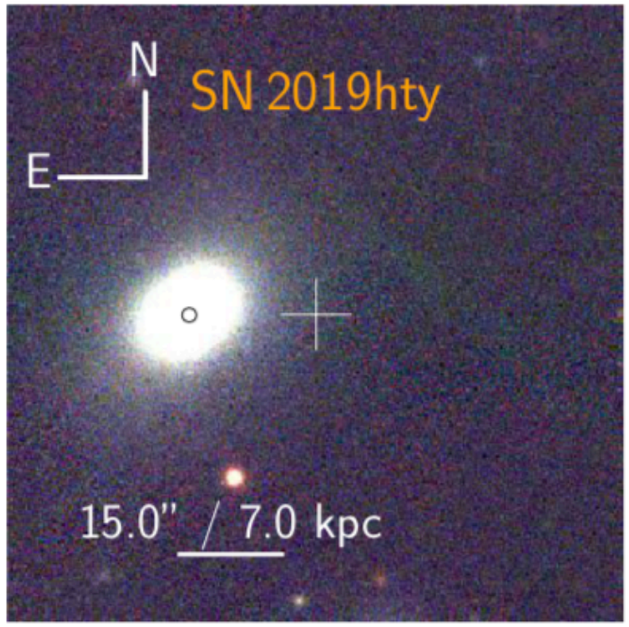


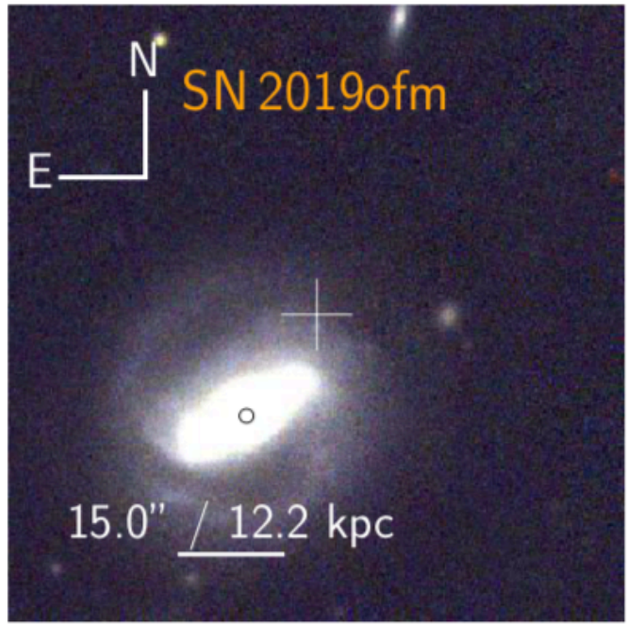


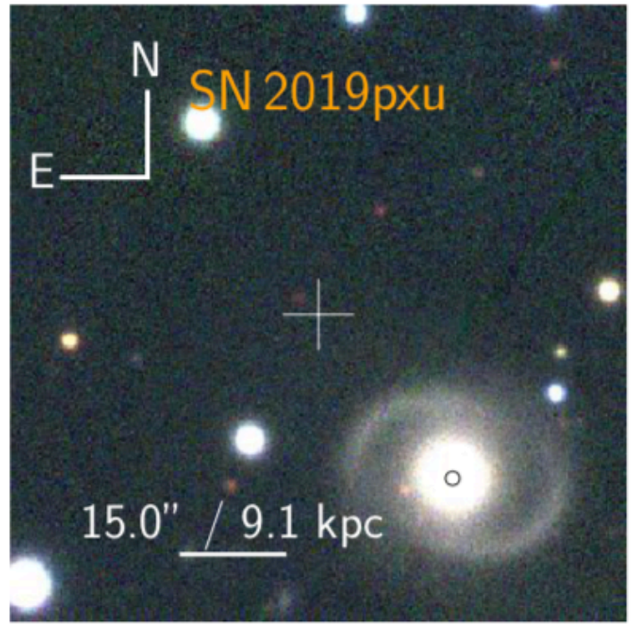








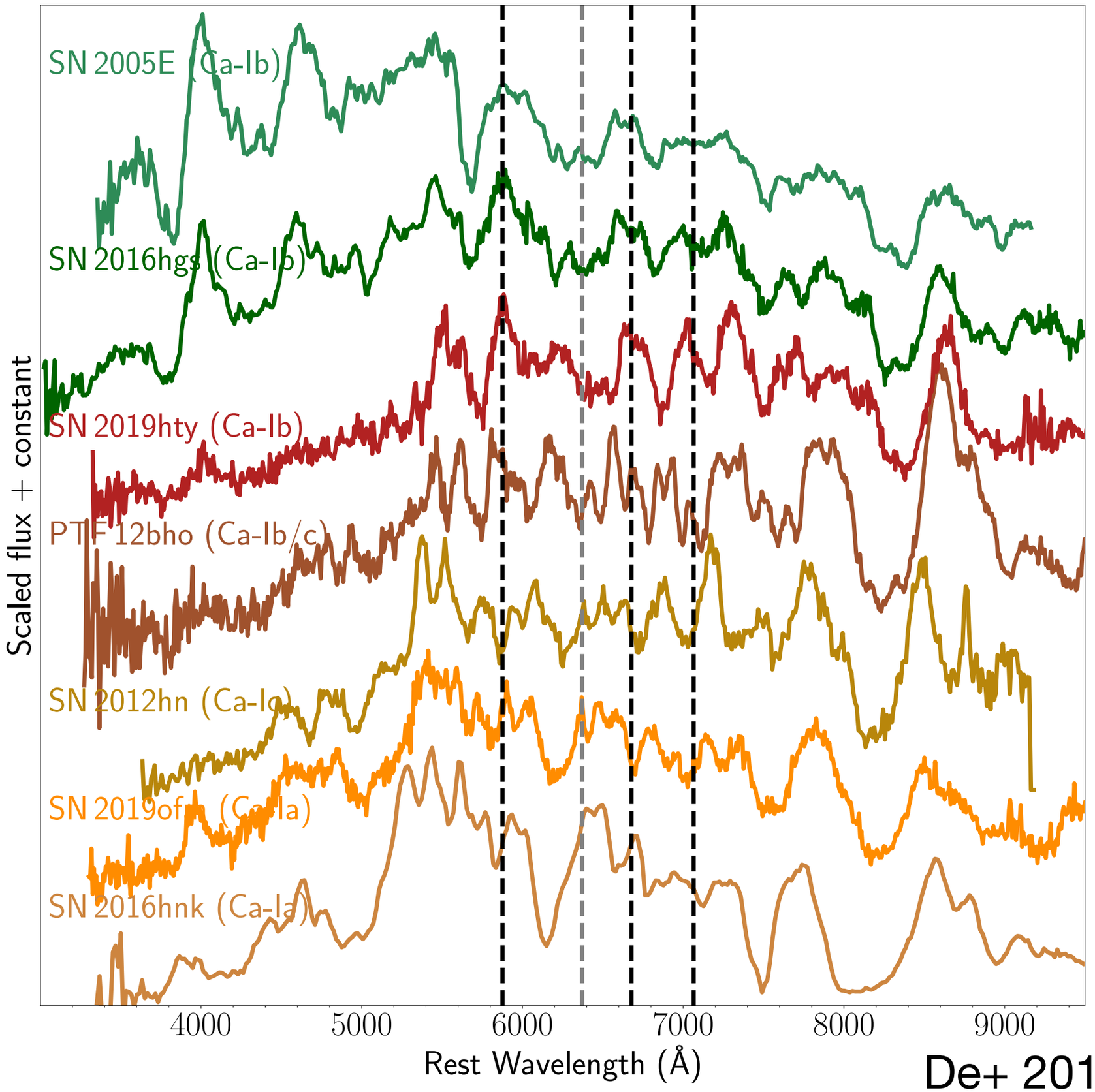




Largest homogeneous sample of ‘Ca-rich’ thermonuclear SNe — 15% of SN Ia rate

De+ 2020b

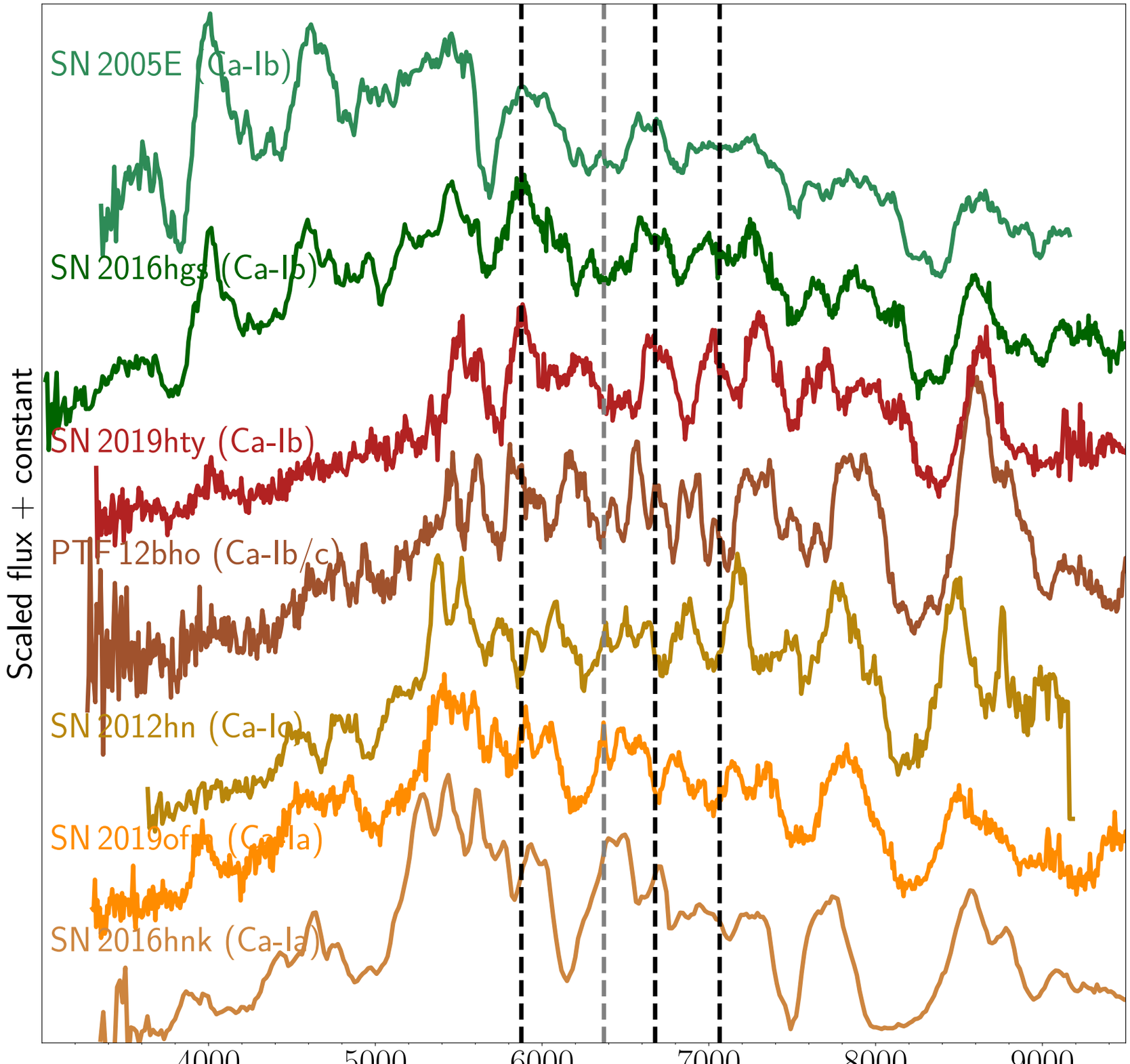
A photometric + spectroscopic continuum



De+ 2018, De+ 2020b

A photometric + spectroscopic continuum

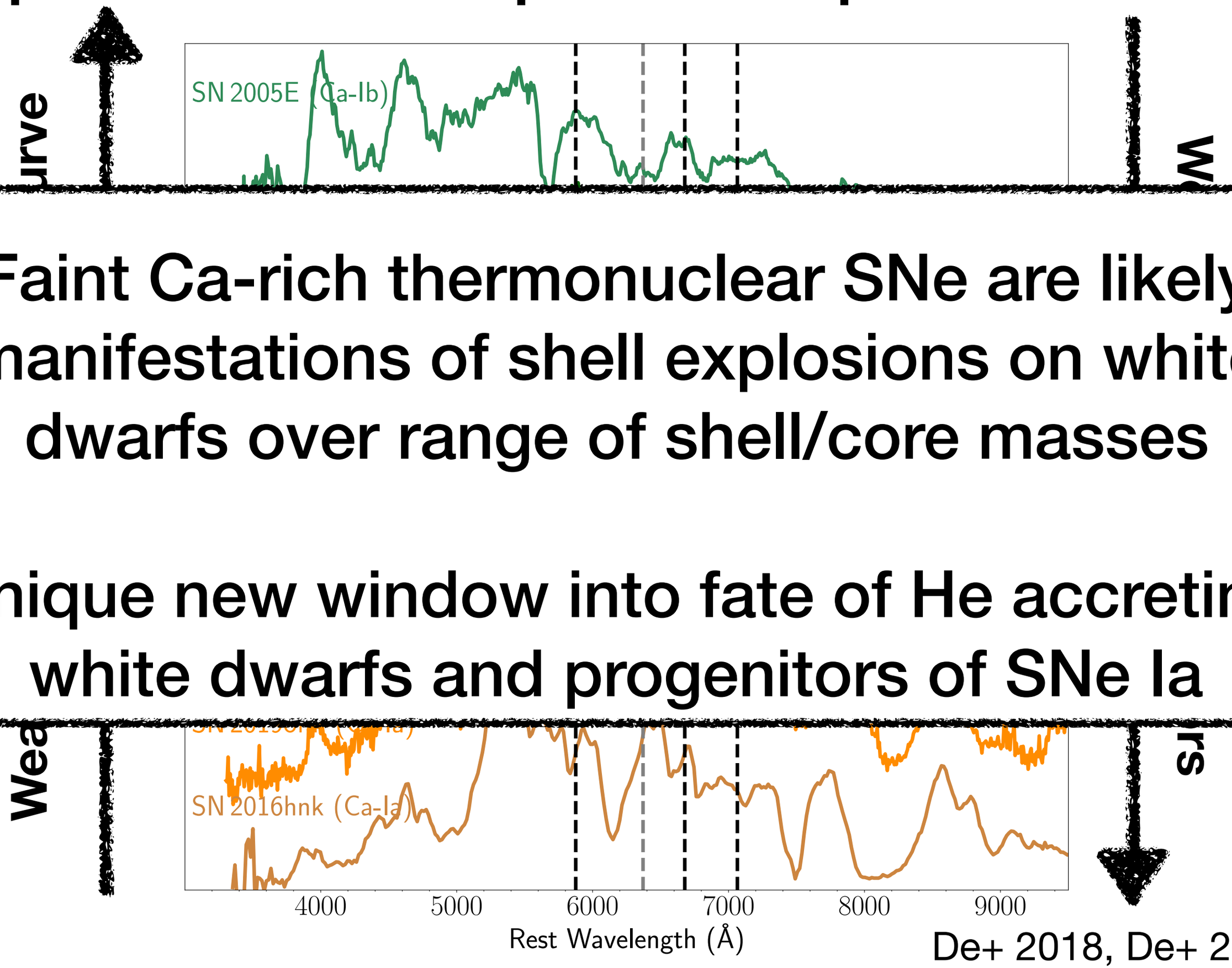
Weaker Si II / faster light curve



Weaker He / Redder colors

De+ 2018, De+ 2020b

A photometric + spectroscopic continuum

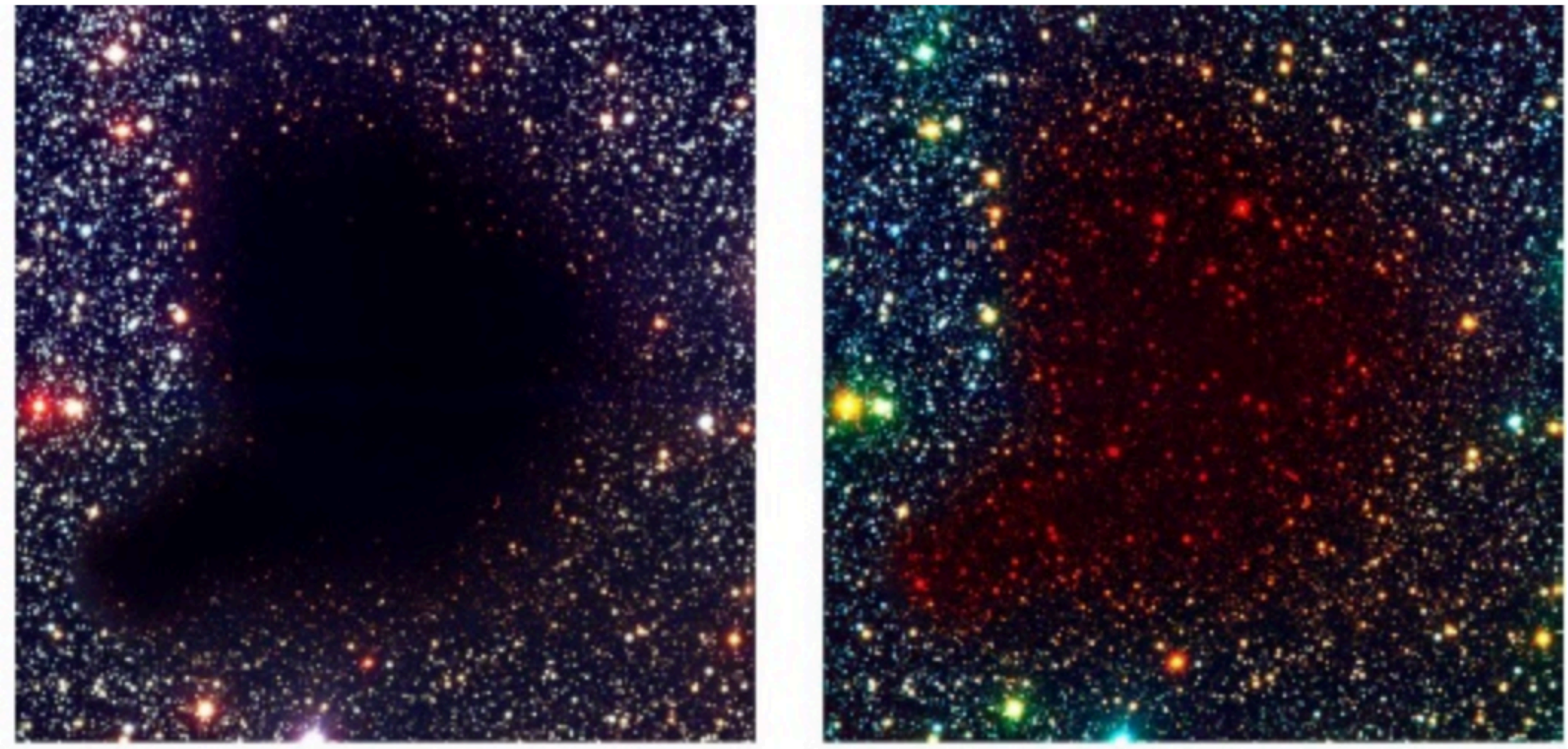


Faint Ca-rich thermonuclear SNe are likely manifestations of shell explosions on white dwarfs over range of shell/core masses

Unique new window into fate of He accreting white dwarfs and progenitors of SNe Ia

De+ 2018, De+ 2020b

Time domain sky in the near-infrared



The NIR is sensitive to the temporal phenomena obscured by dust or intrinsically red

Challenging due to atmospheric foreground

30 cm telescope, 25 square degree field of view

J band camera: 2K x 2K with **8.7 arcsec** pixels

De+ 2020a, Moore & Kasliwal 2019

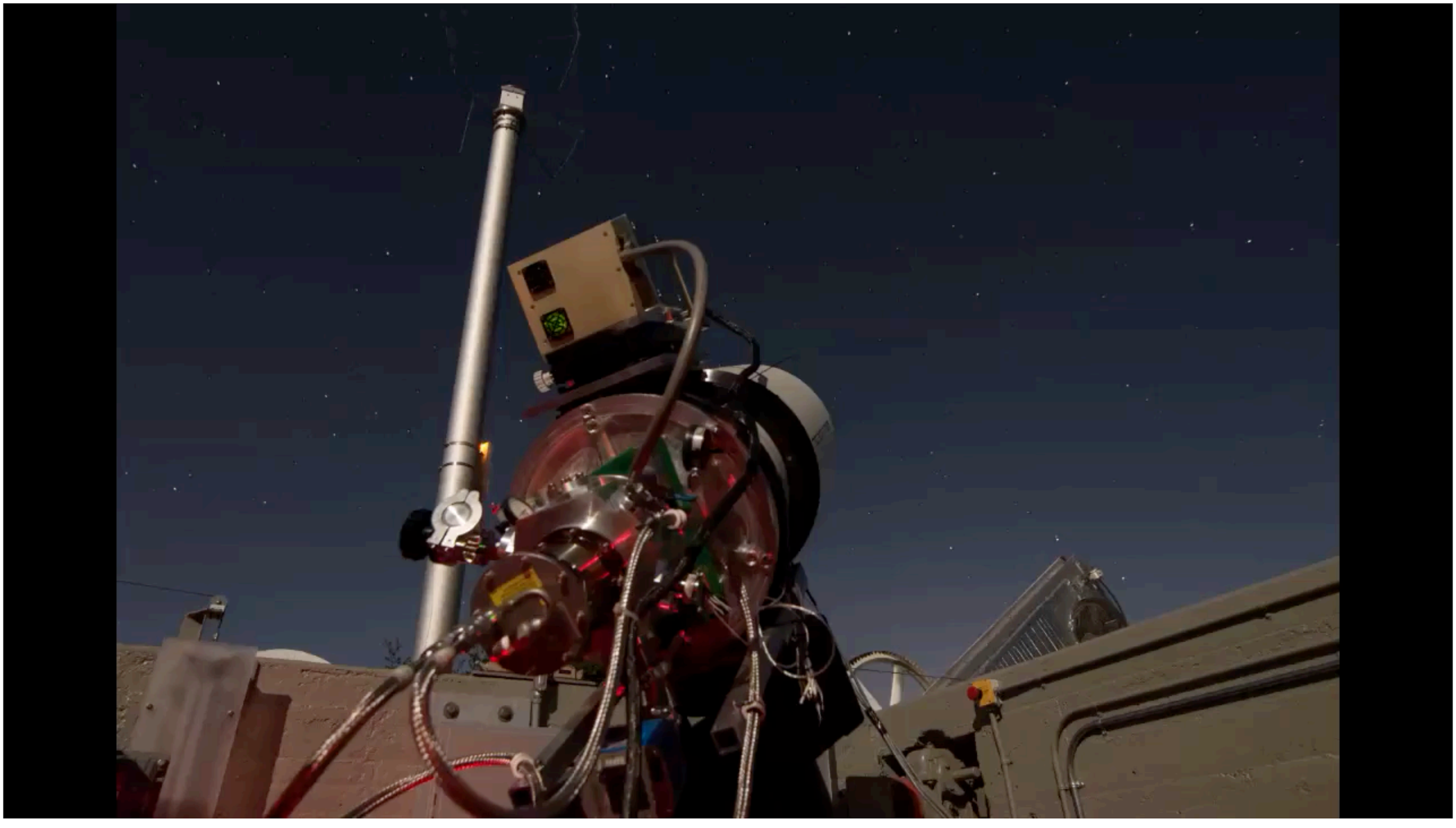
First light in September 2018

30 c

J ba

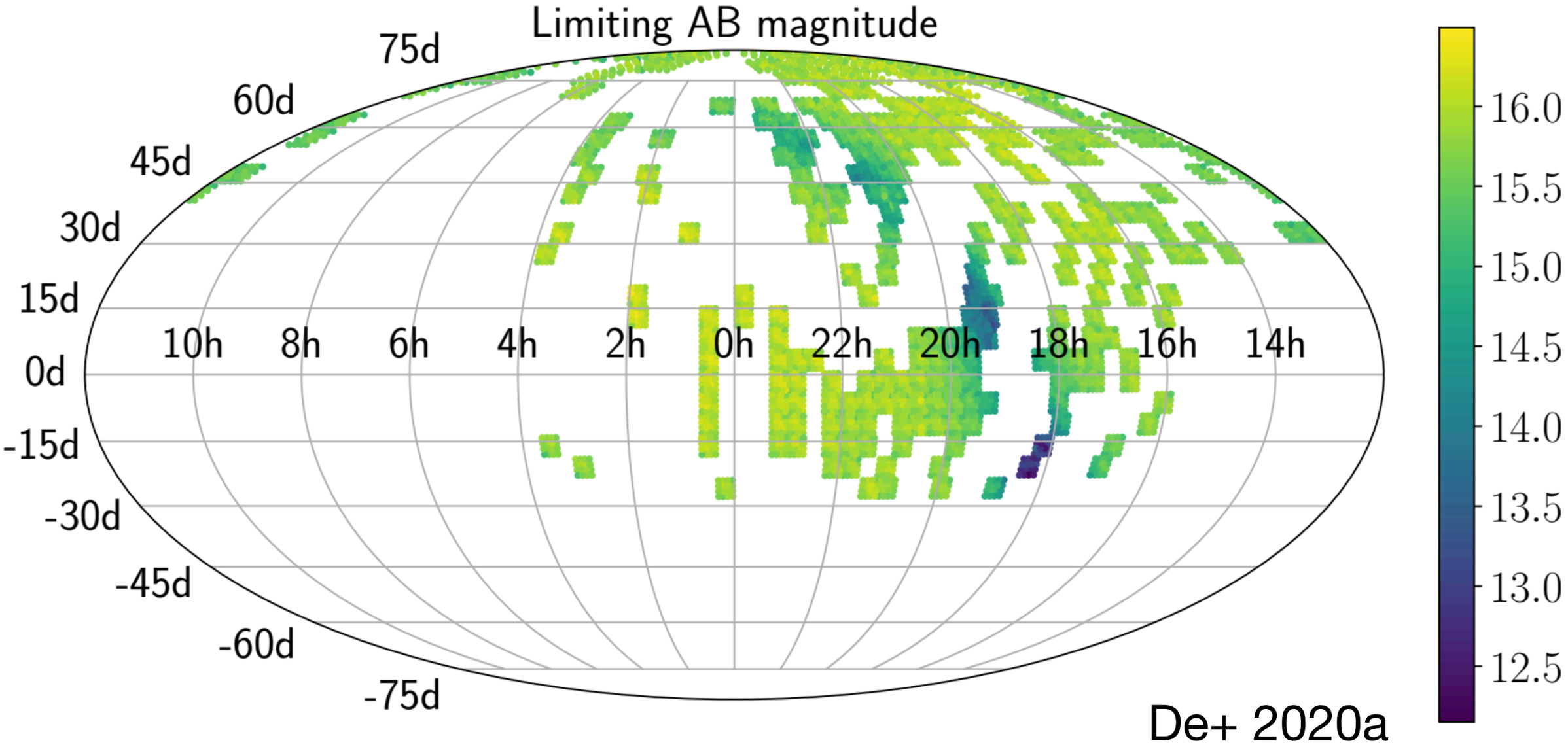
De+ 2020a, Moore & Kasliwal 2019

Robotic eyes on the infrared sky



Credit: Scott Adams

Nightly sky coverage



Areal coverage of ~ **7500 square degrees**.

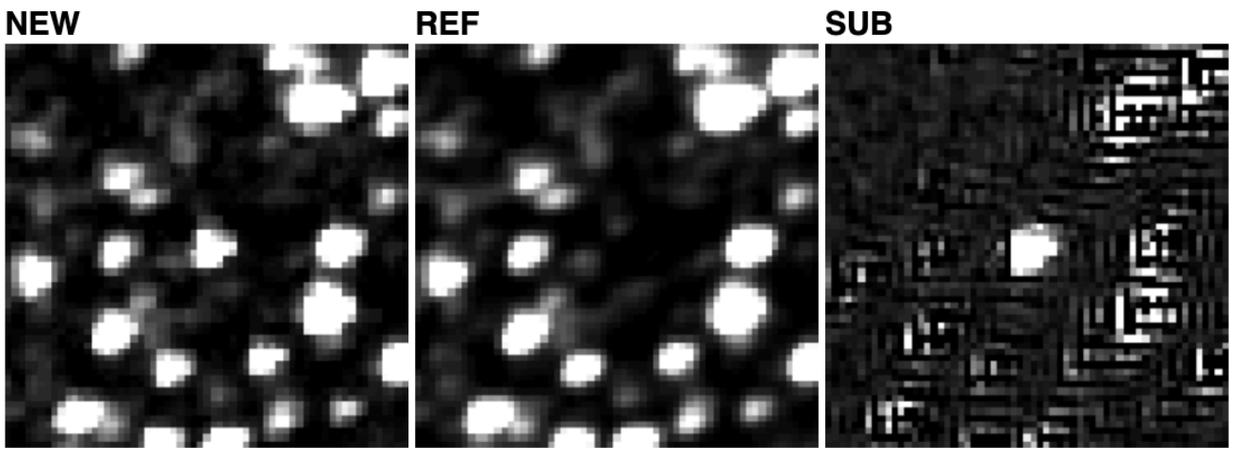
Summer 2020: 1-day cadence survey of Galactic plane + 2-day cadence rest of the sky

Searching for Galactic classical novae in the NIR

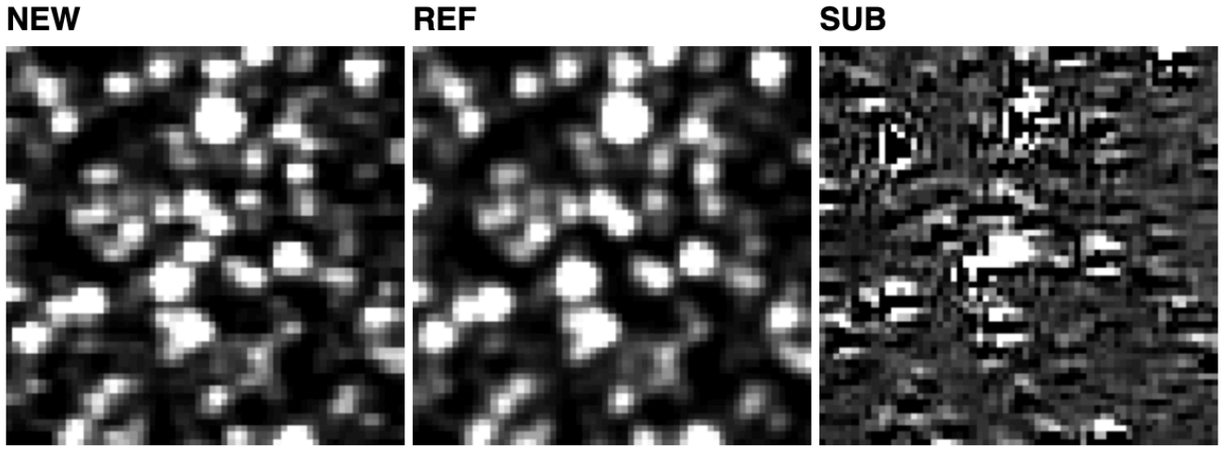
Observed optical nova rates ~4x lower than expected.

How many novae are missed to extinction?

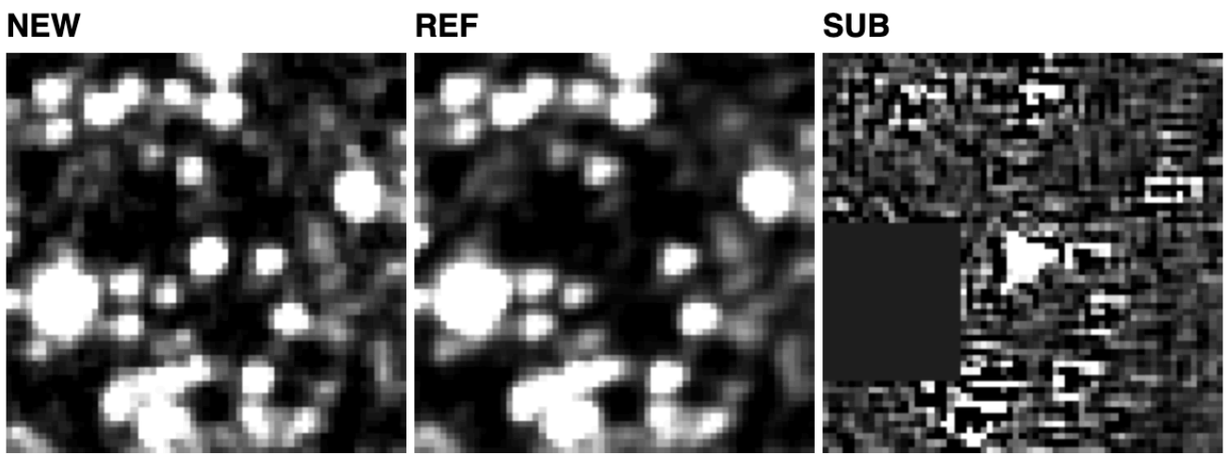
PGIR19brv



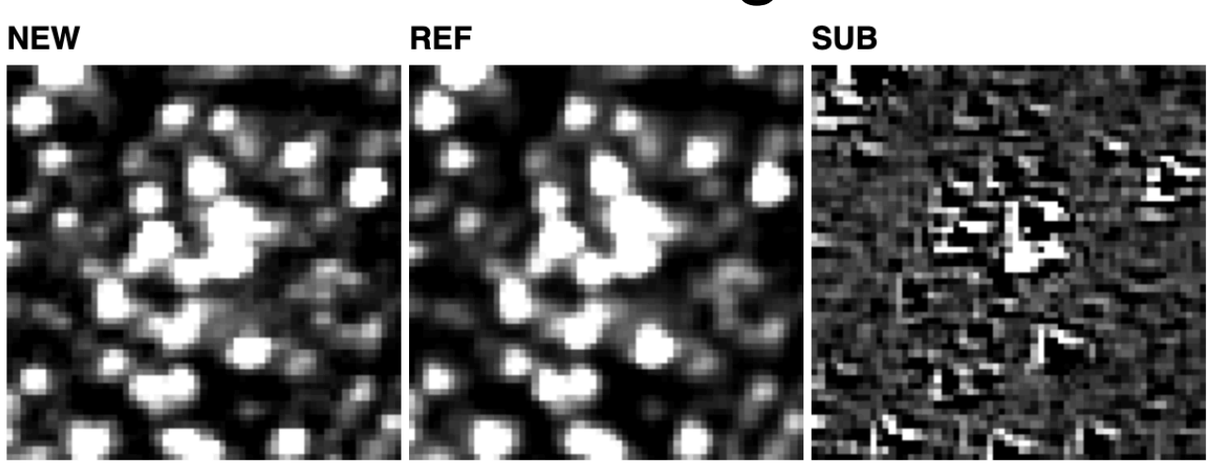
PGIR20dsv



PGIR20duo

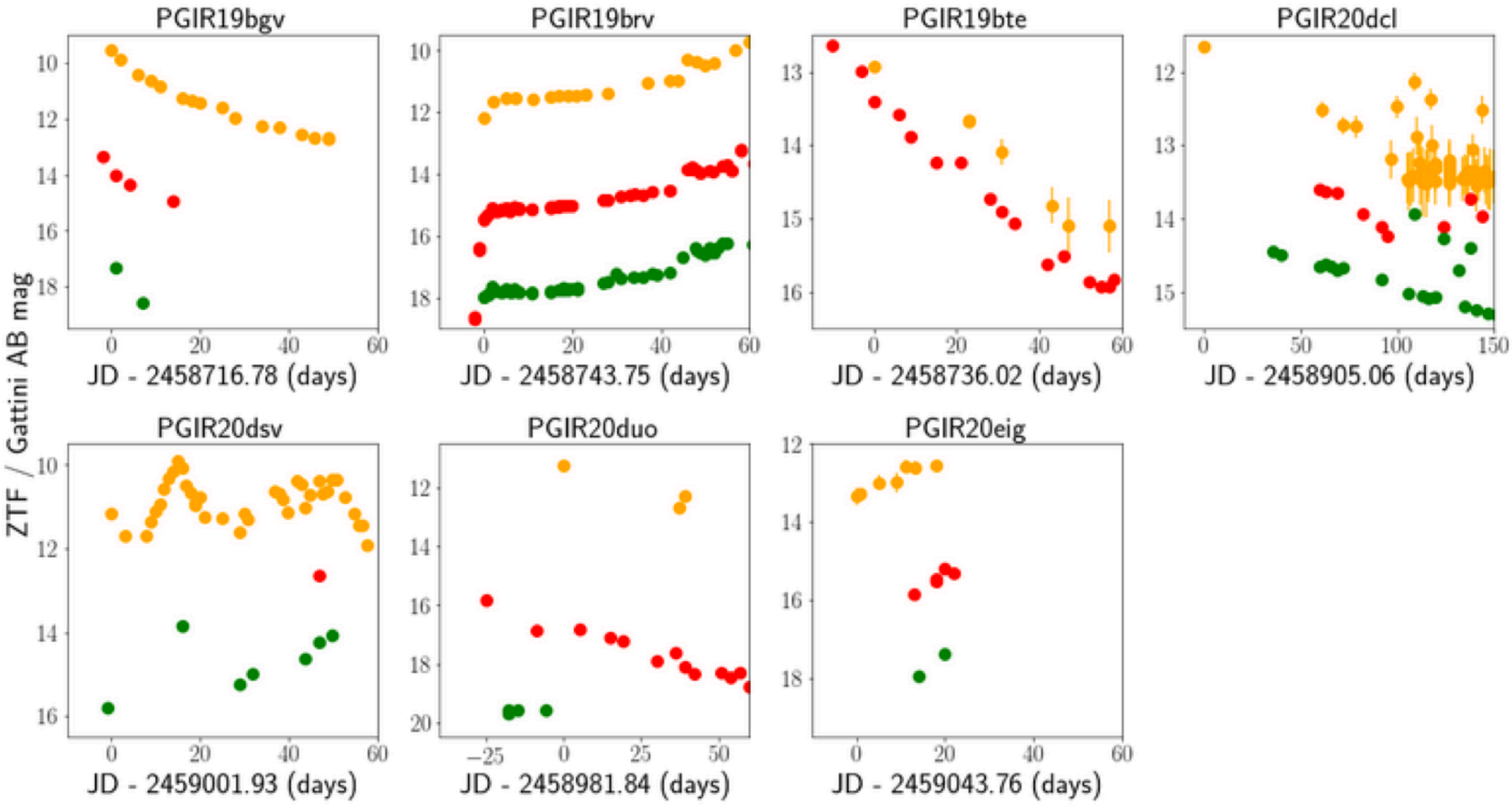


PGIR20eig

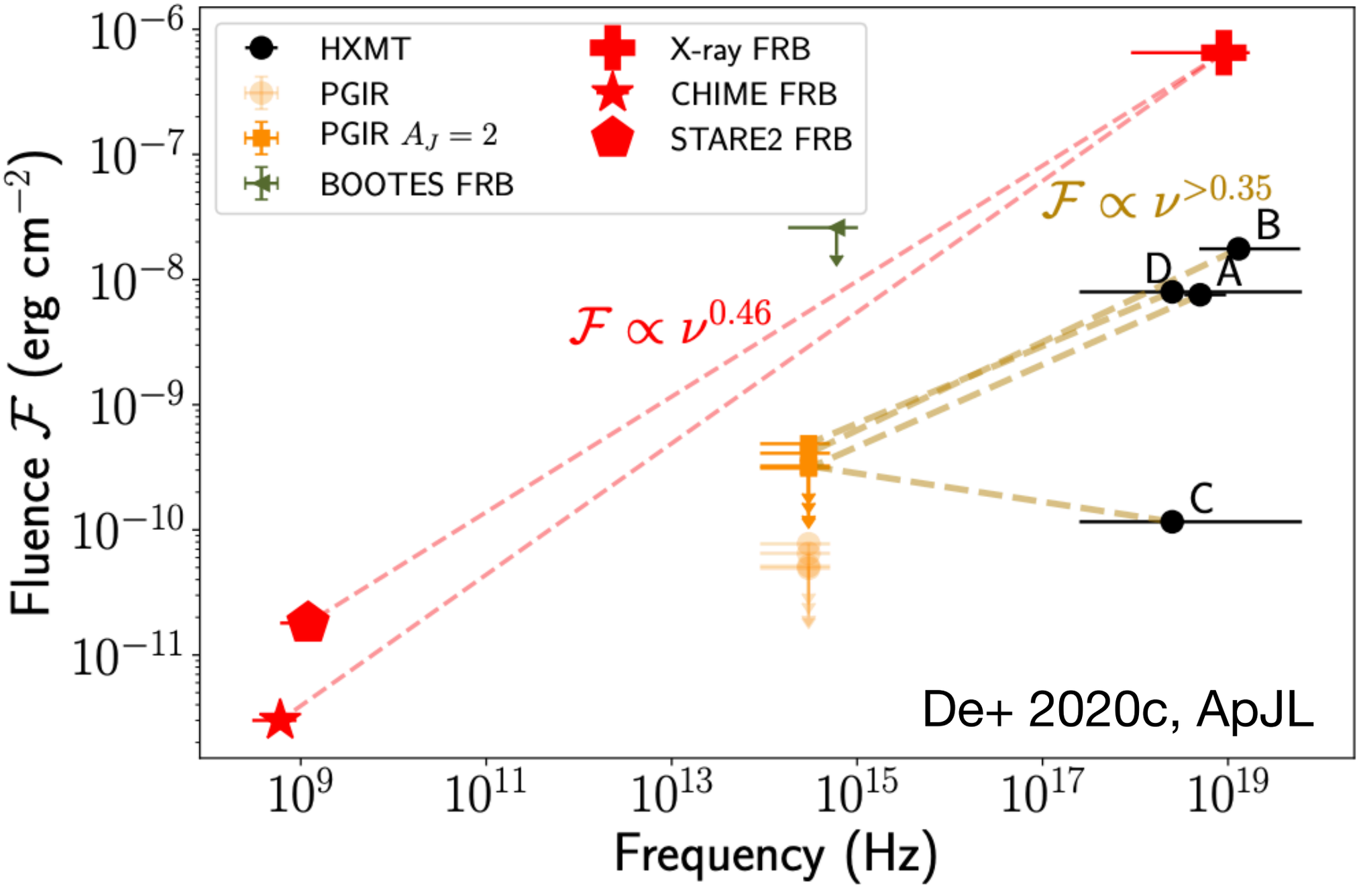


PGIR has discovered more than half of Northern Galactic novae in 2020

A_V ~ 0 to 10 mag. Most classical novae could be missed or misclassified as dwarf novae in the optical

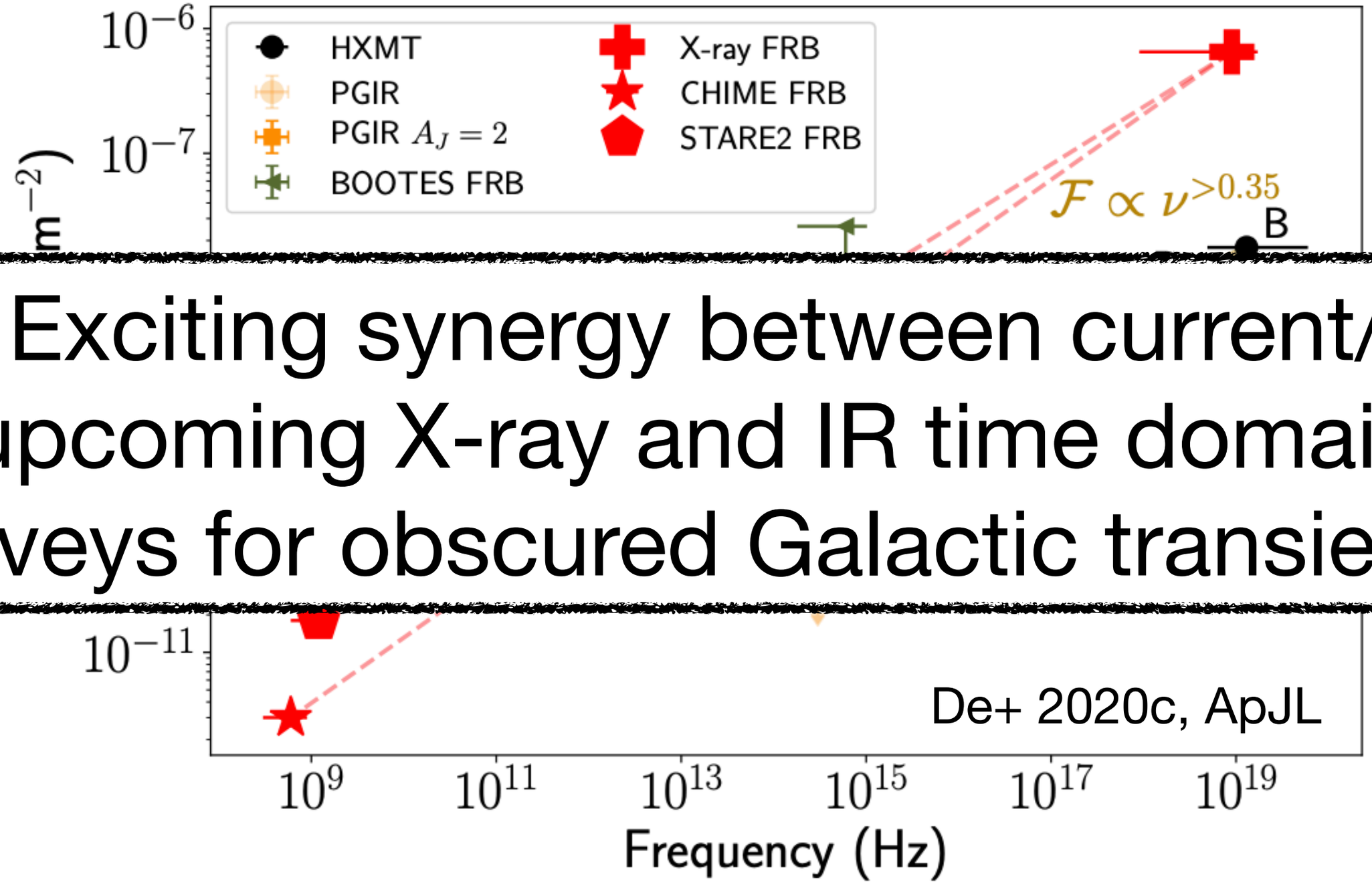


Simultaneous NIR constraints on X-ray bursts from SGR 1935+2154 with targeted follow-up



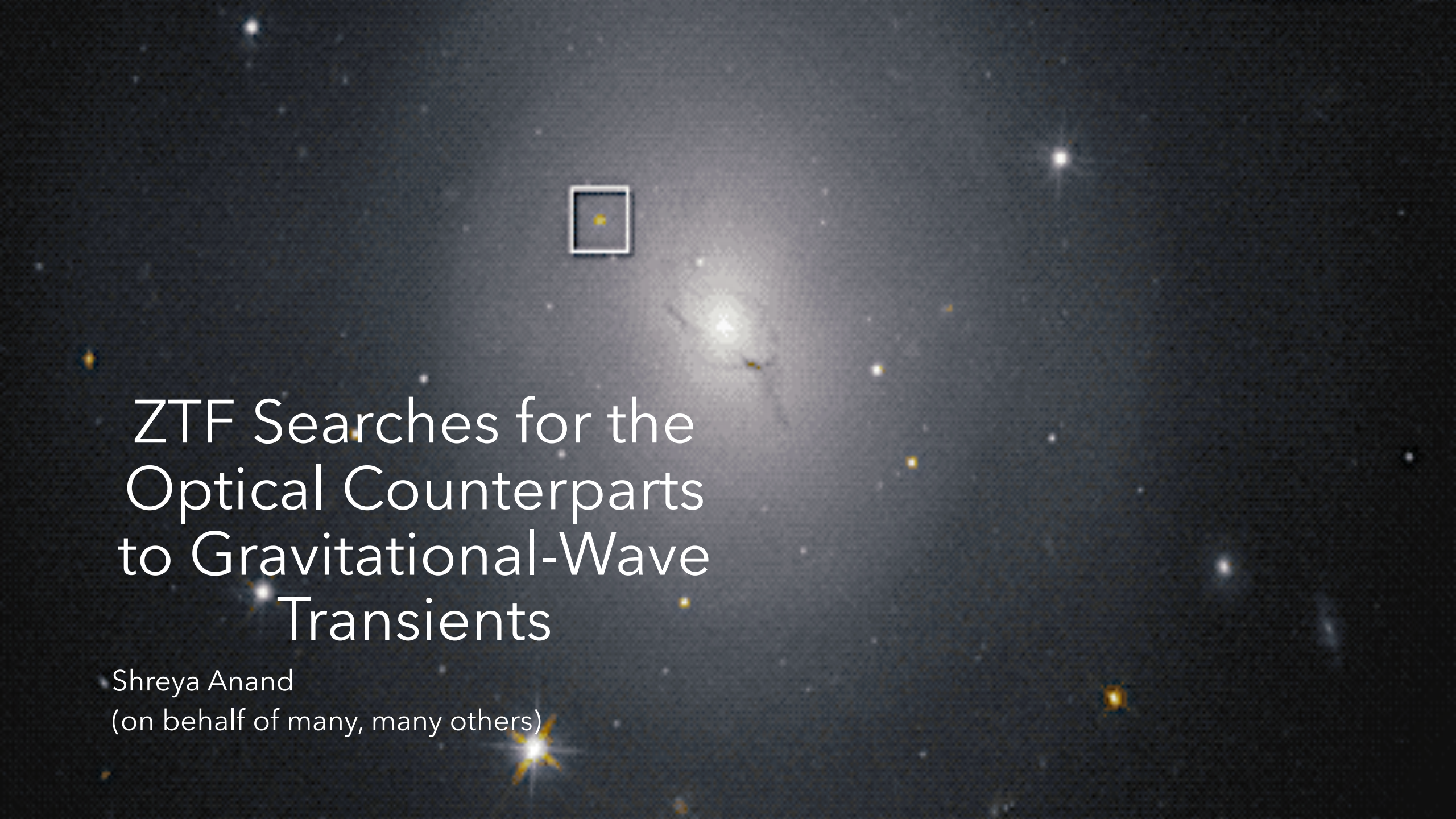
Novel readout mode **(100% efficiency)** + low extinction results in deepest limits on second-timescale flares

Simultaneous NIR constraints on X-ray bursts from SGR 1935+2154 with targeted follow-up



Exciting synergy between current/ upcoming X-ray and IR time domain surveys for obscured Galactic transients!

Novel readout mode **(100% efficiency)** + low extinction results in deepest limits on second-timescale flares



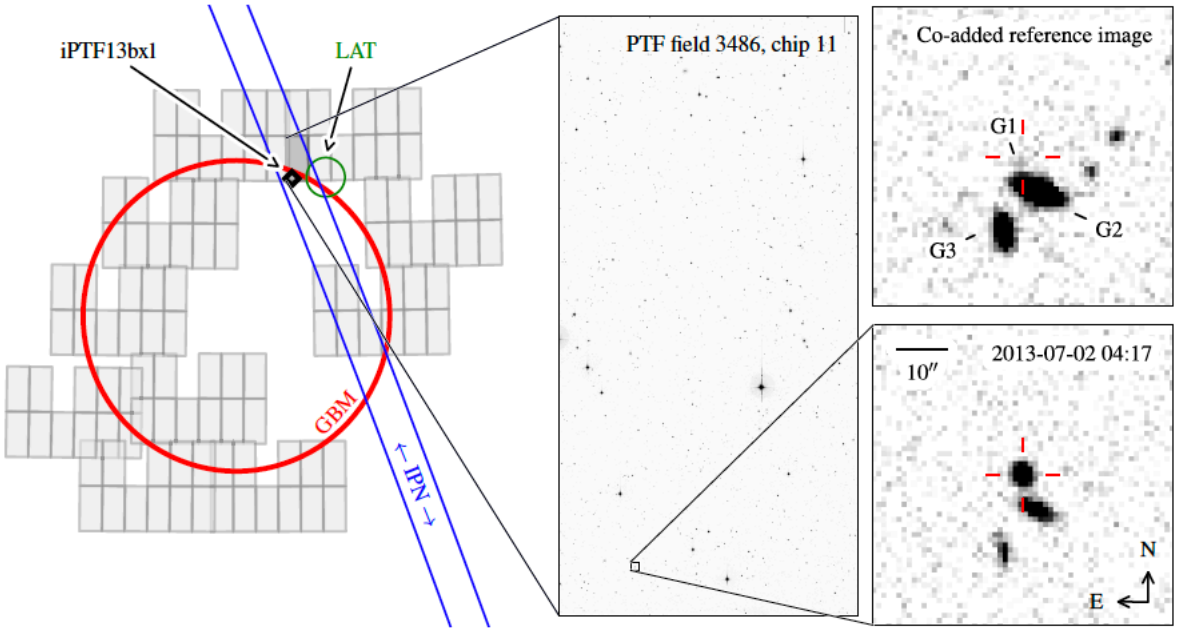
ZTF Searches for the Optical Counterparts to Gravitational-Wave Transients

Shreya Anand
(on behalf of many, many others)

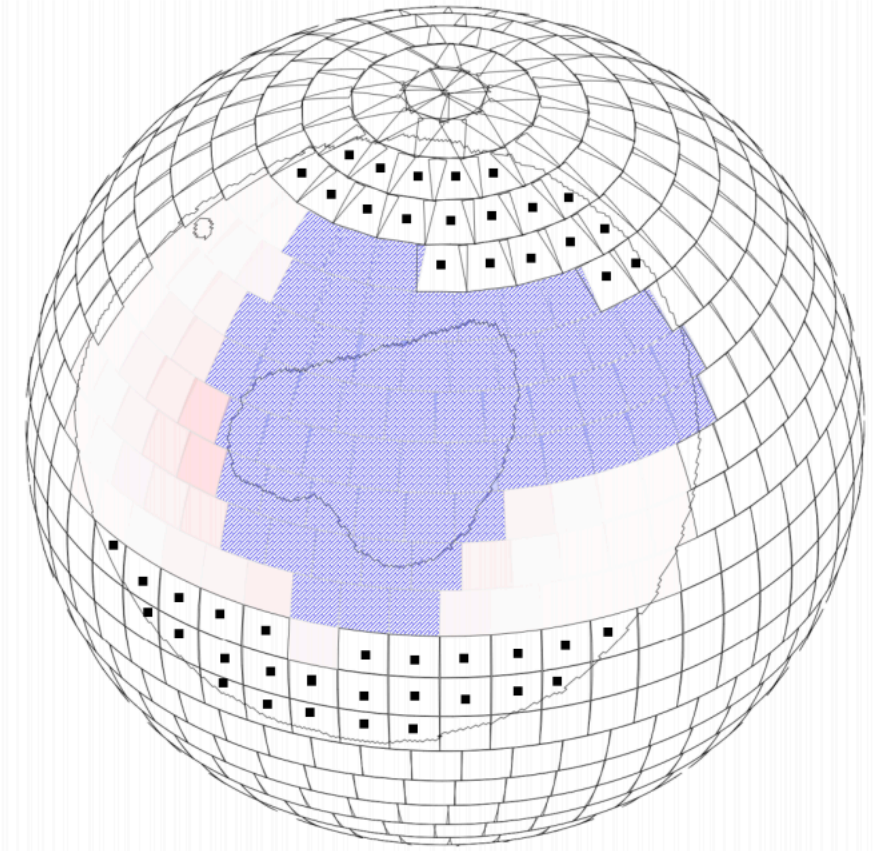
Wide-field targeted searches with ZTF

2900 sq. deg. search for an SGRB counterpart

71 sq. deg. search for a LGRB afterglow

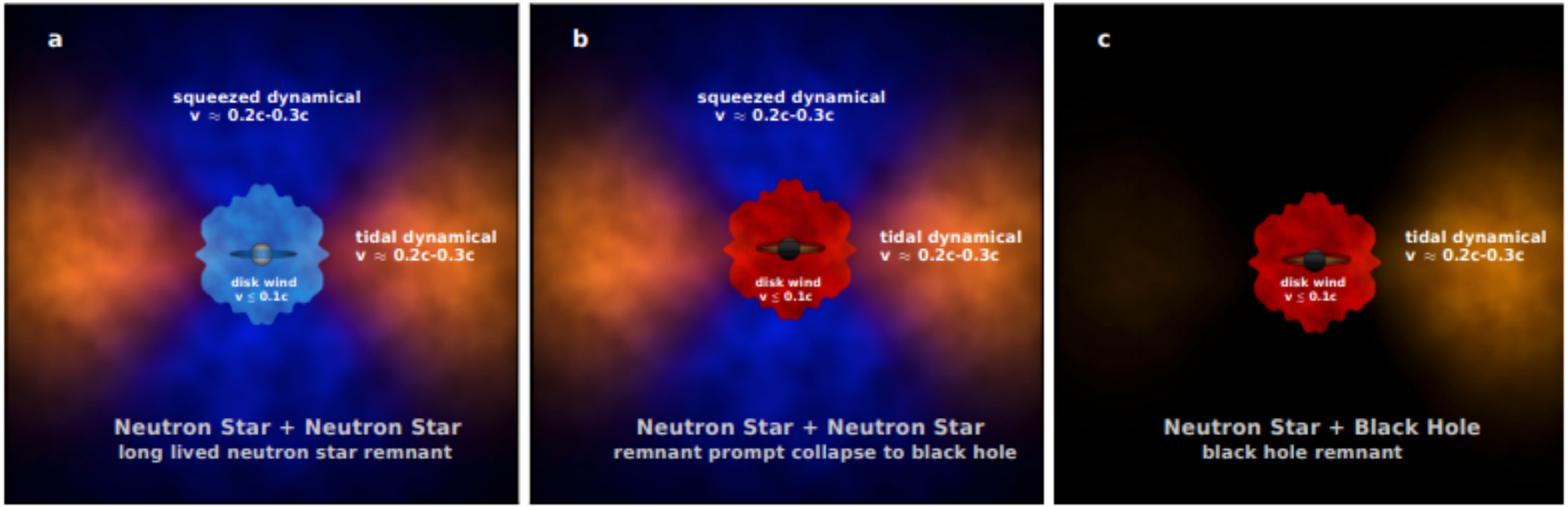


Singer+2013



Coughlin+2019

Optical Counterparts to Gravitational Waves

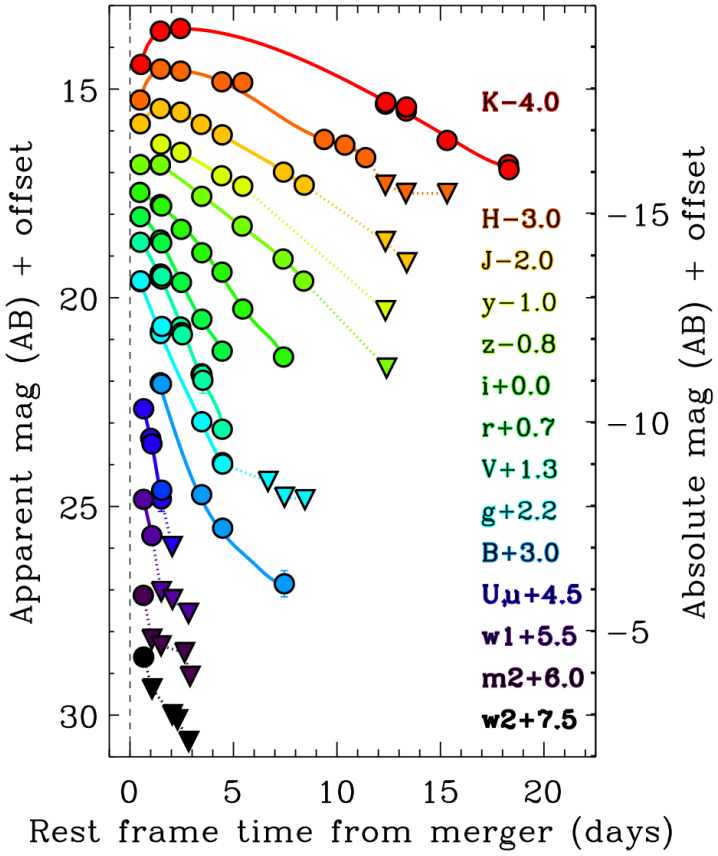


- BNS: either long-lived NS remnant (blue wind) or prompt collapse to a black hole (red wind)

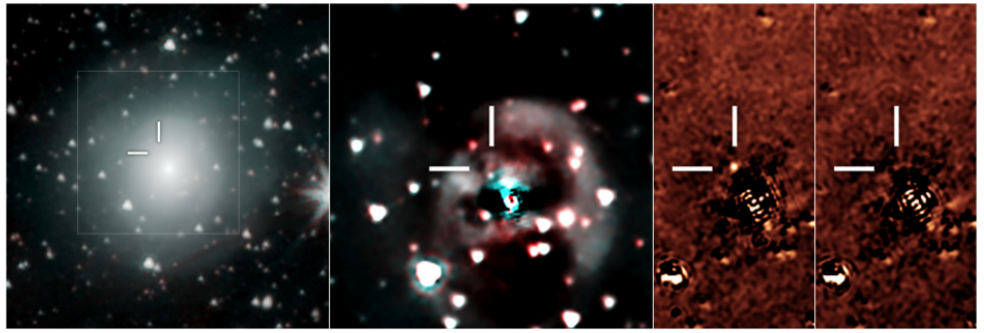
- NSBH: black hole remnant (red wind)

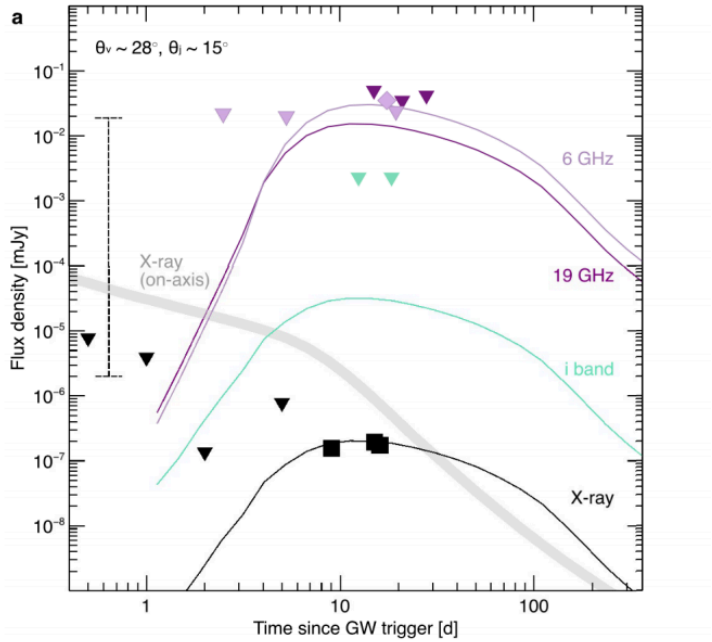
Kasen+2017

GW170817: hallmark of multi-messenger astronomy



Drout+2017





Troja+2017, Kasliwal+2019

Kilonova Models: BNS vs. NSBH

- NSBH KN models predict:
  - Longer lasting emission
  - Redder wavelengths
  - Brighter → more ejecta

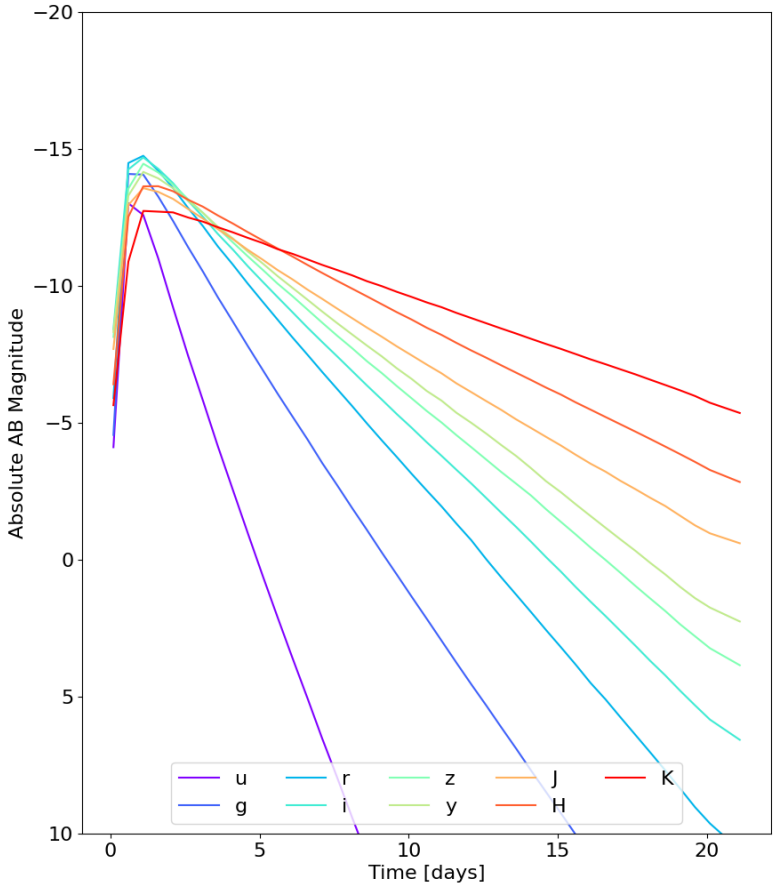
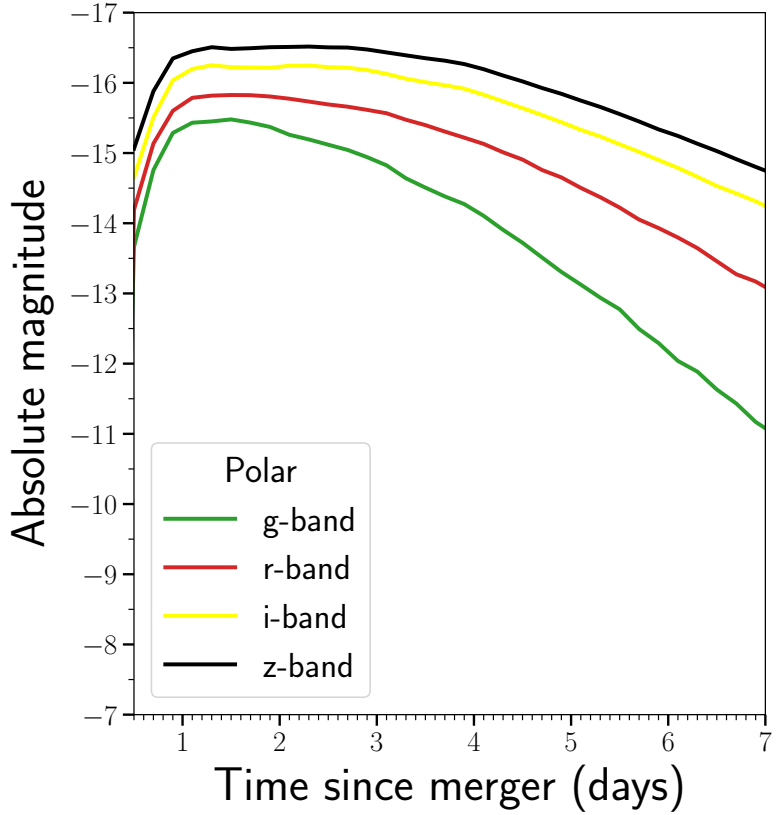


Figure Courtesy: P. Rajkumar



Anand & Coughlin+2020, in press.

ZTF EMGW follow-ups during LIGO's 3rd observing run

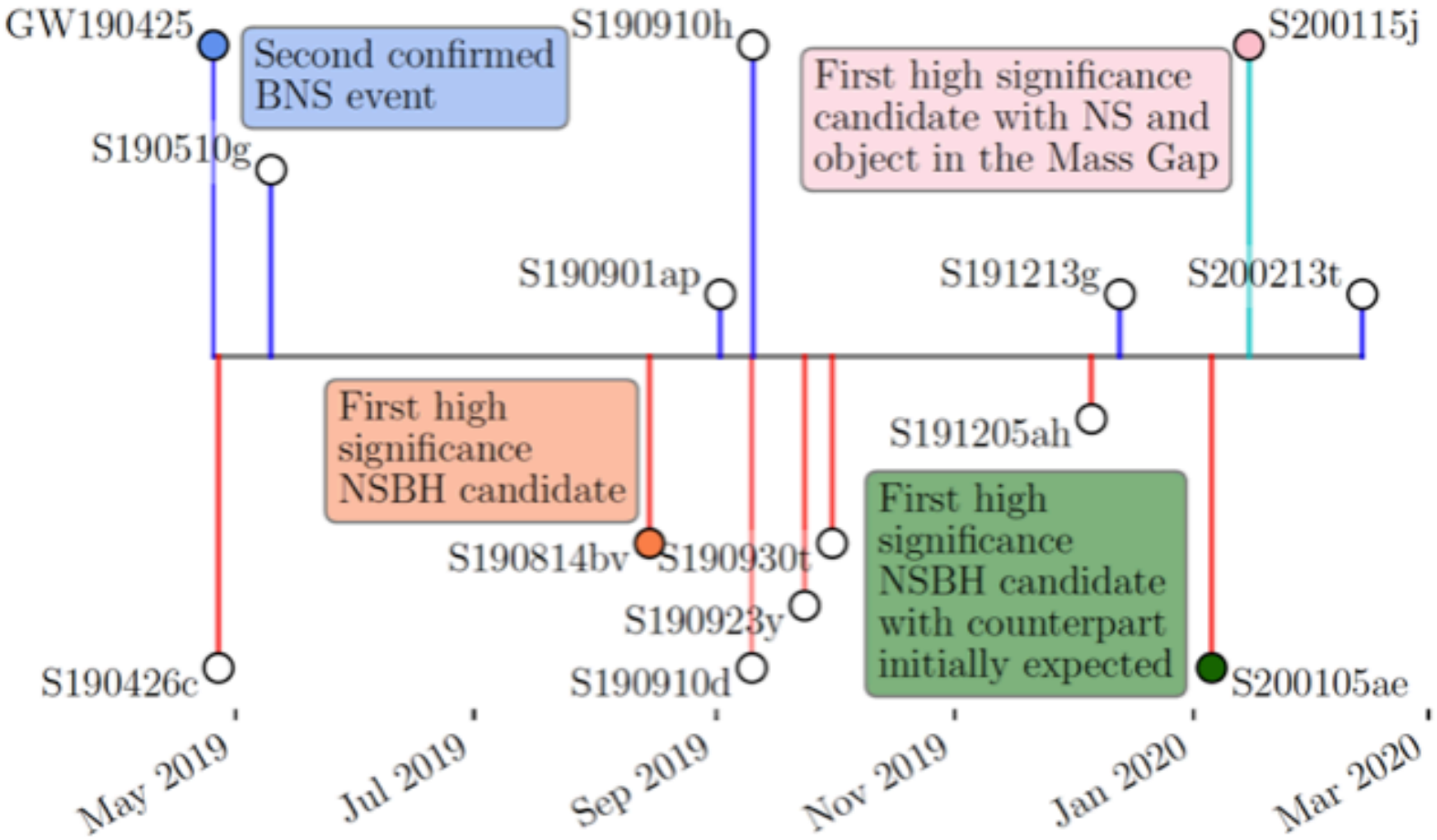
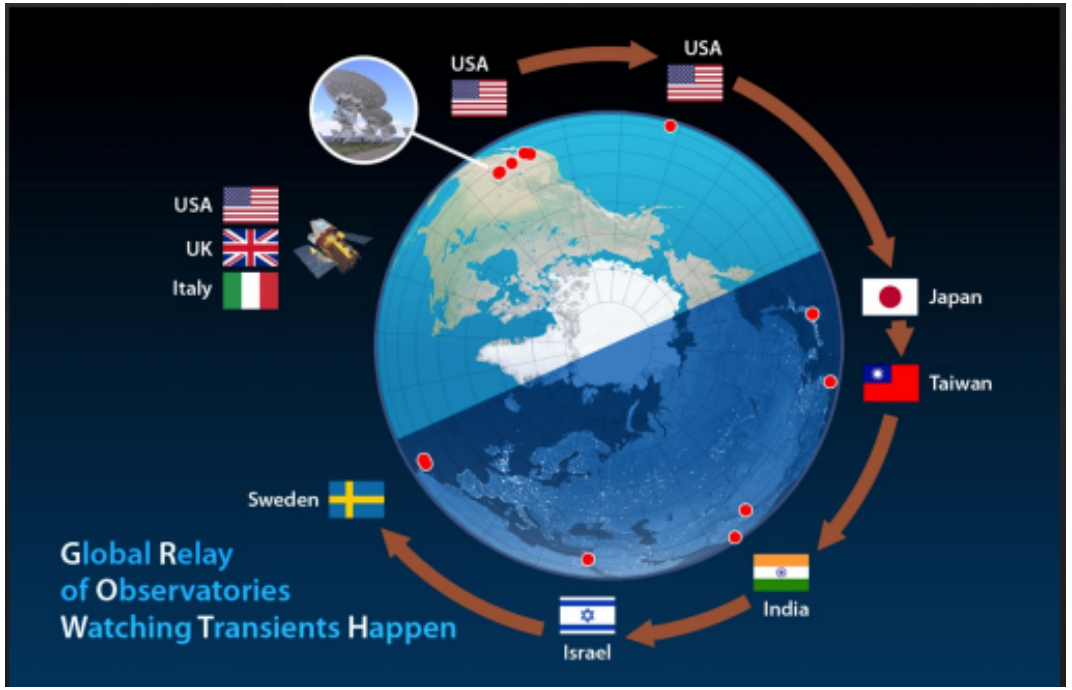


Figure courtesy: M. W. Coughlin

GROWTH Target-of-Opportunity Observations

Global collaboration of astronomers….

Figure courtesy: GROWTH



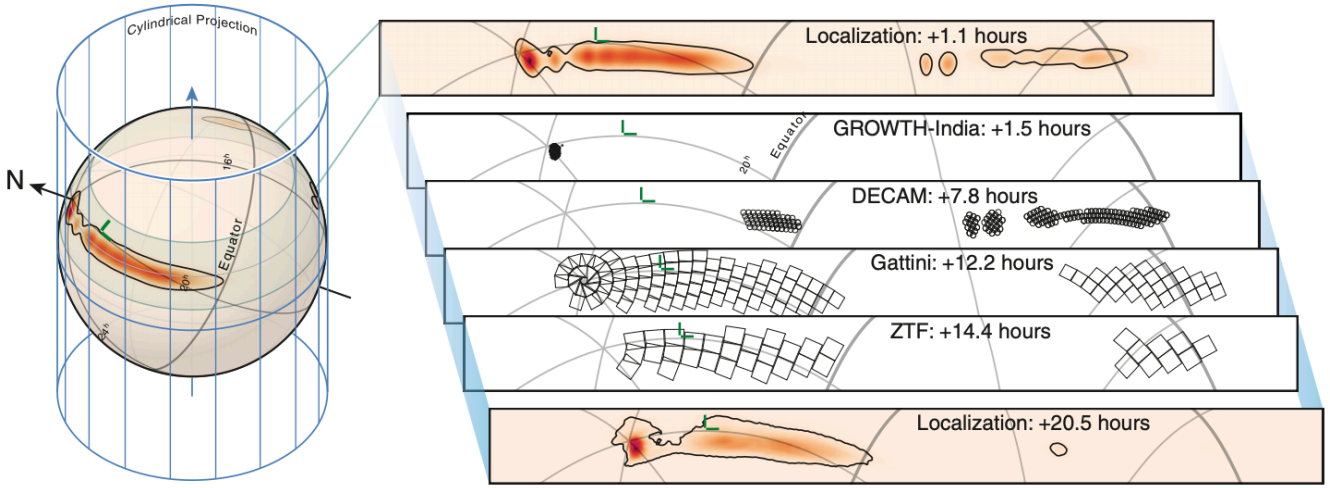
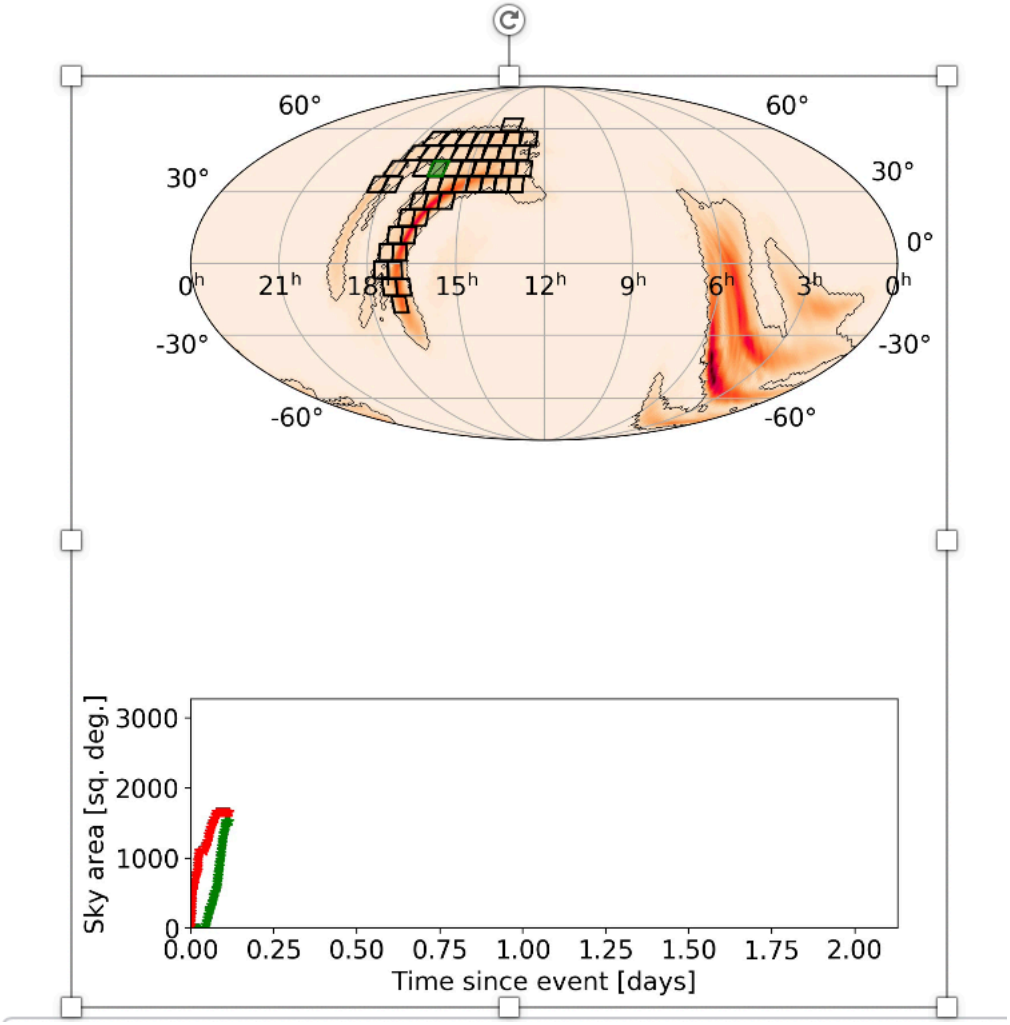
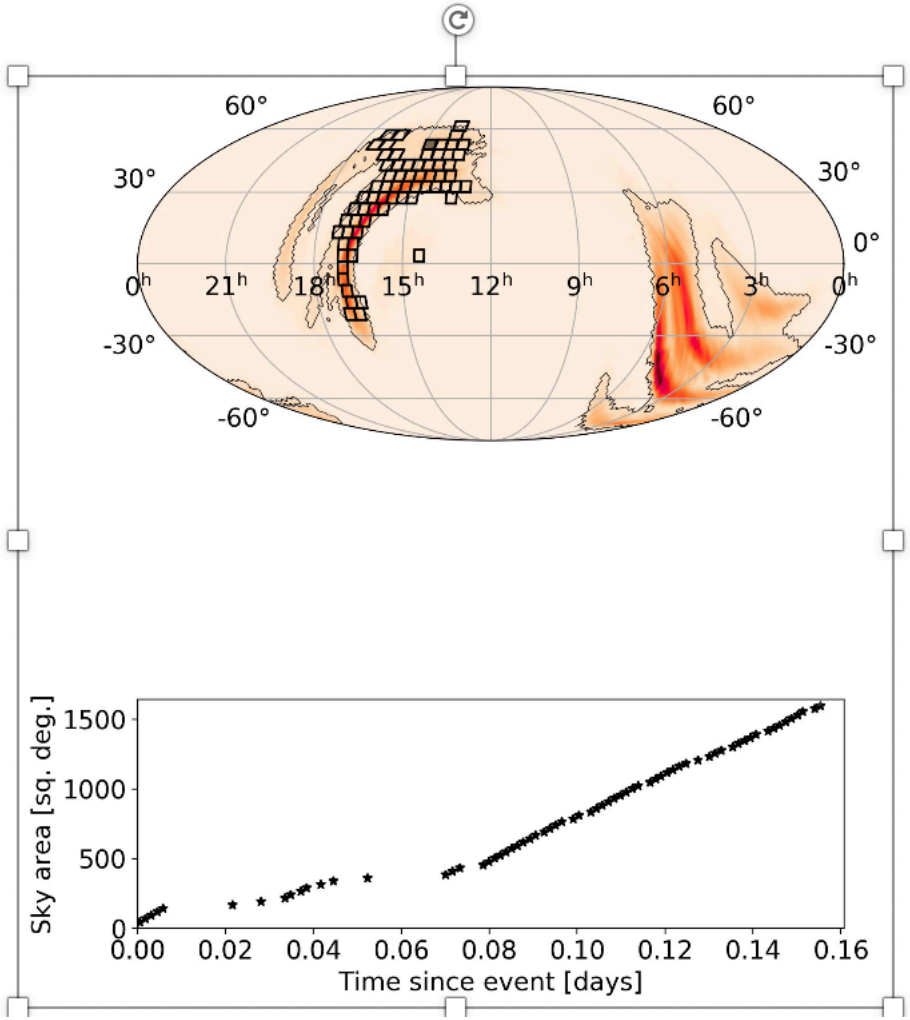


Figure courtesy: L. P. Singer

…and global coordination of observatories!

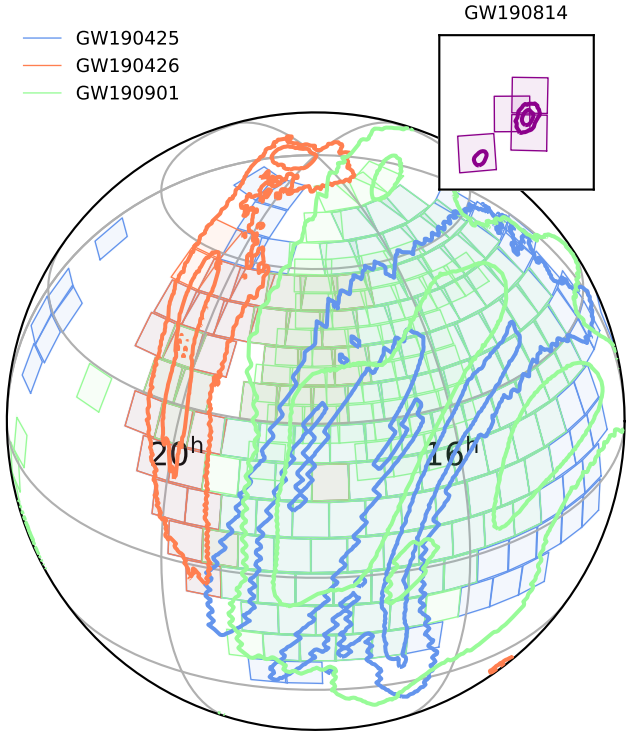
Example: tiling the skymap of GW190425

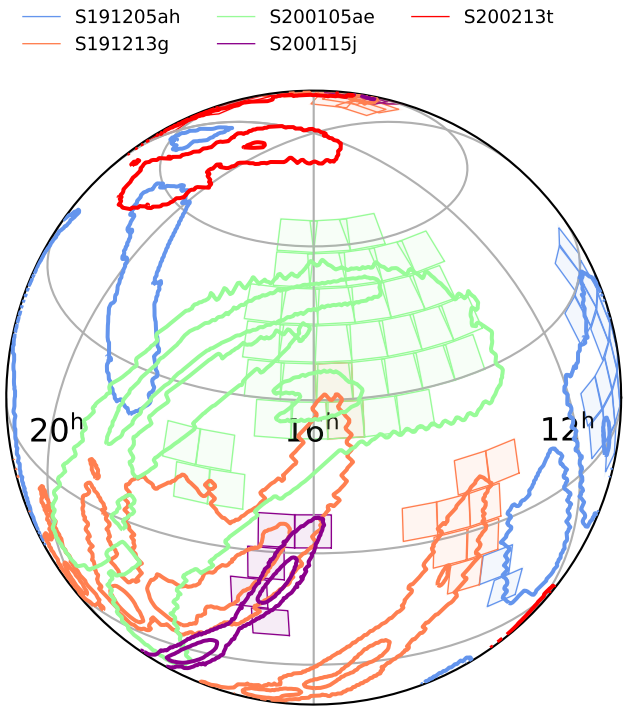


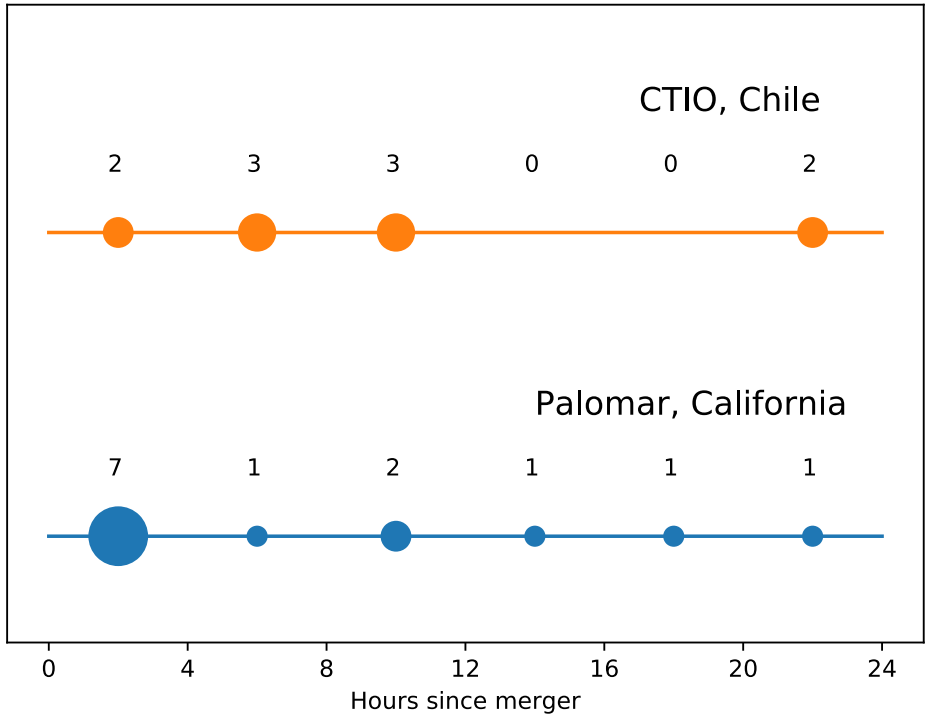


Coughlin+2019

ZTF follow-ups of LIGO O3 events

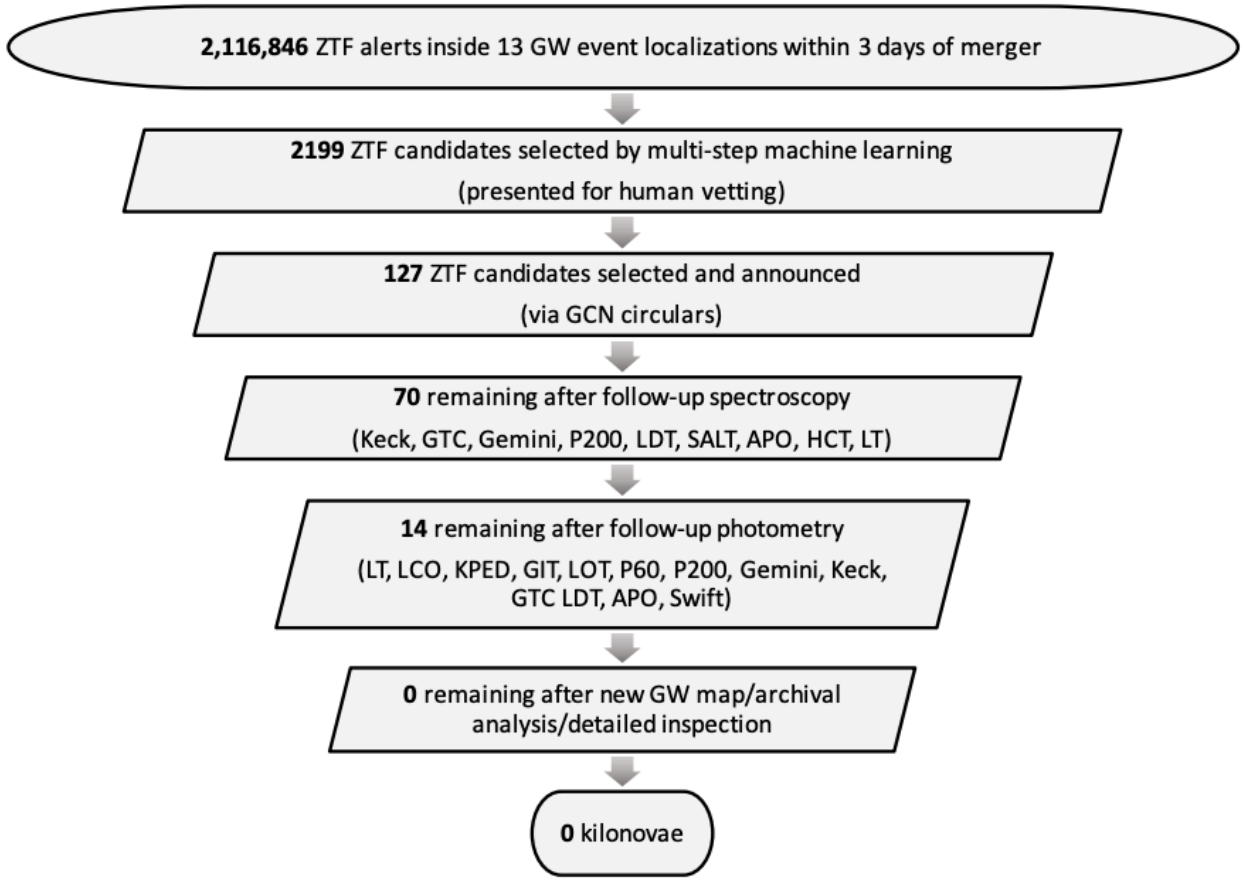


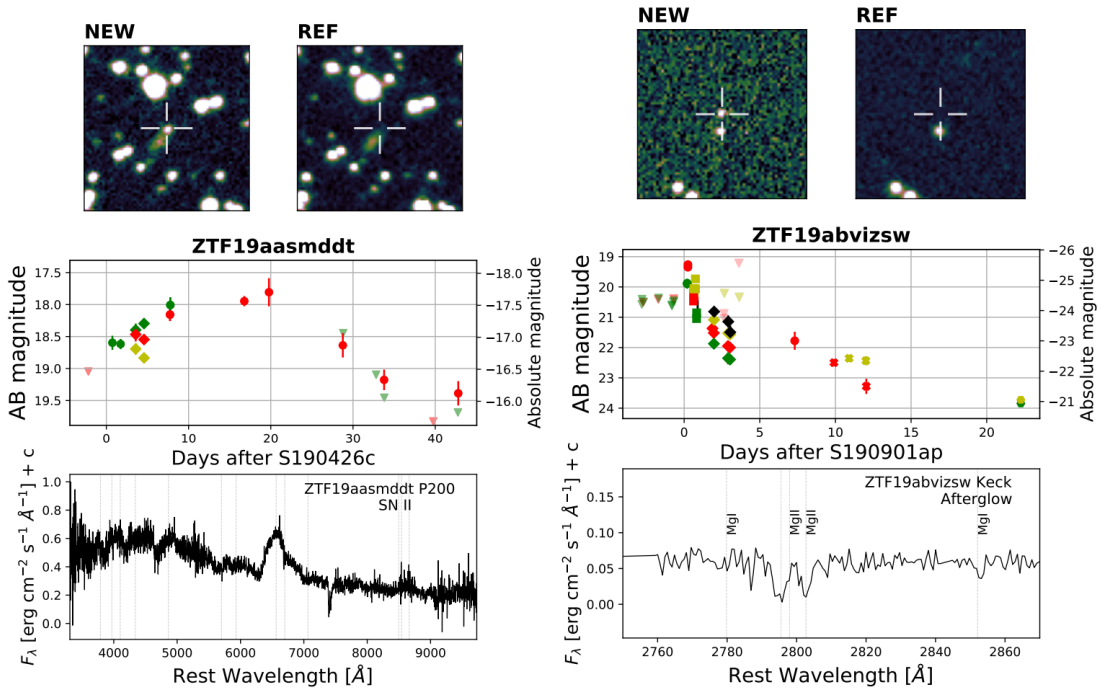




Kasliwal+2020

Candidate Selection flowchart

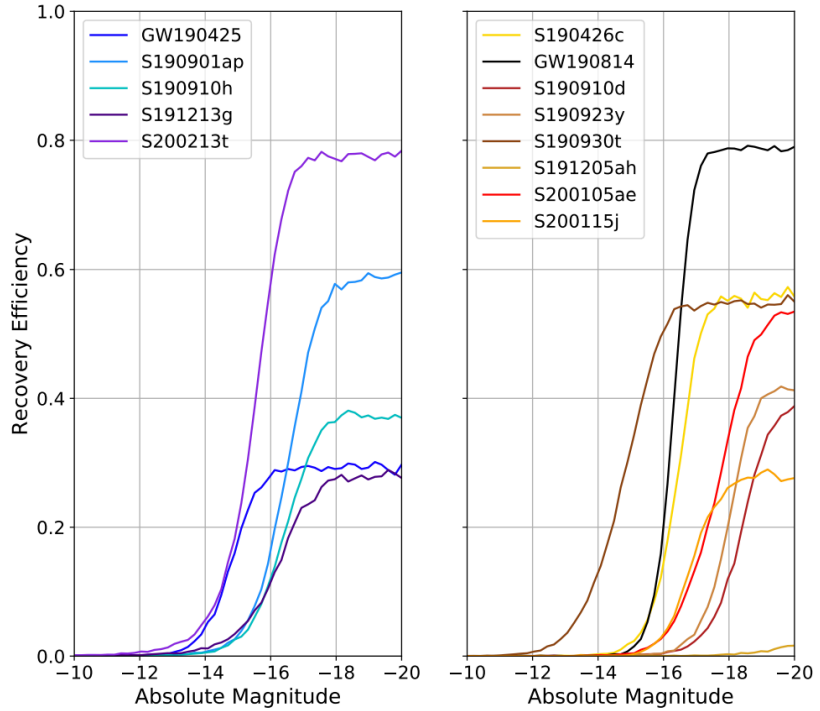




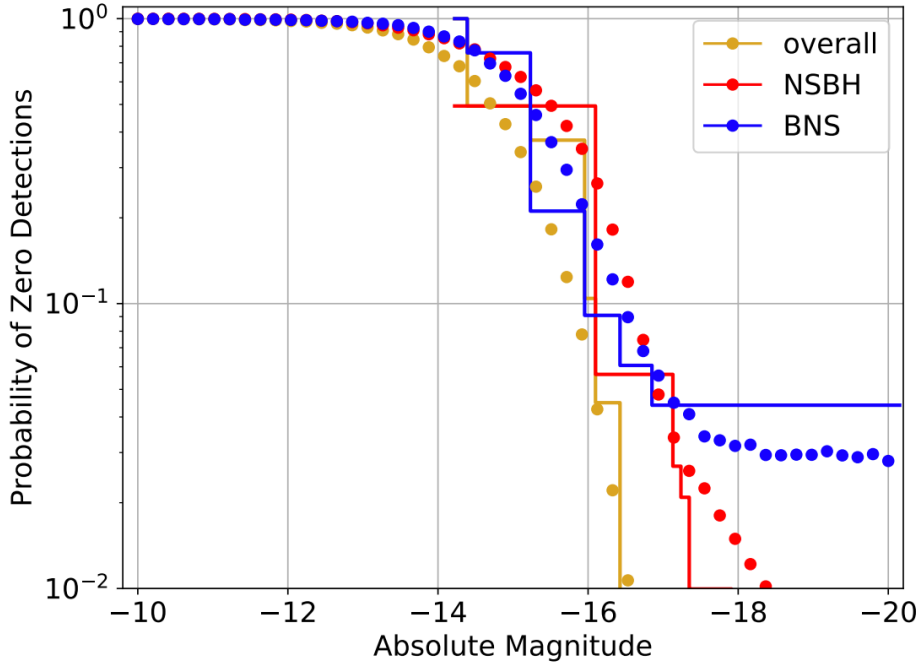
SN II (left) and untriggered GRB afterglow (right)
Kasliwal+2020

What can we do in the face of non-detection?

Detection Efficiency



Non-detection Probability



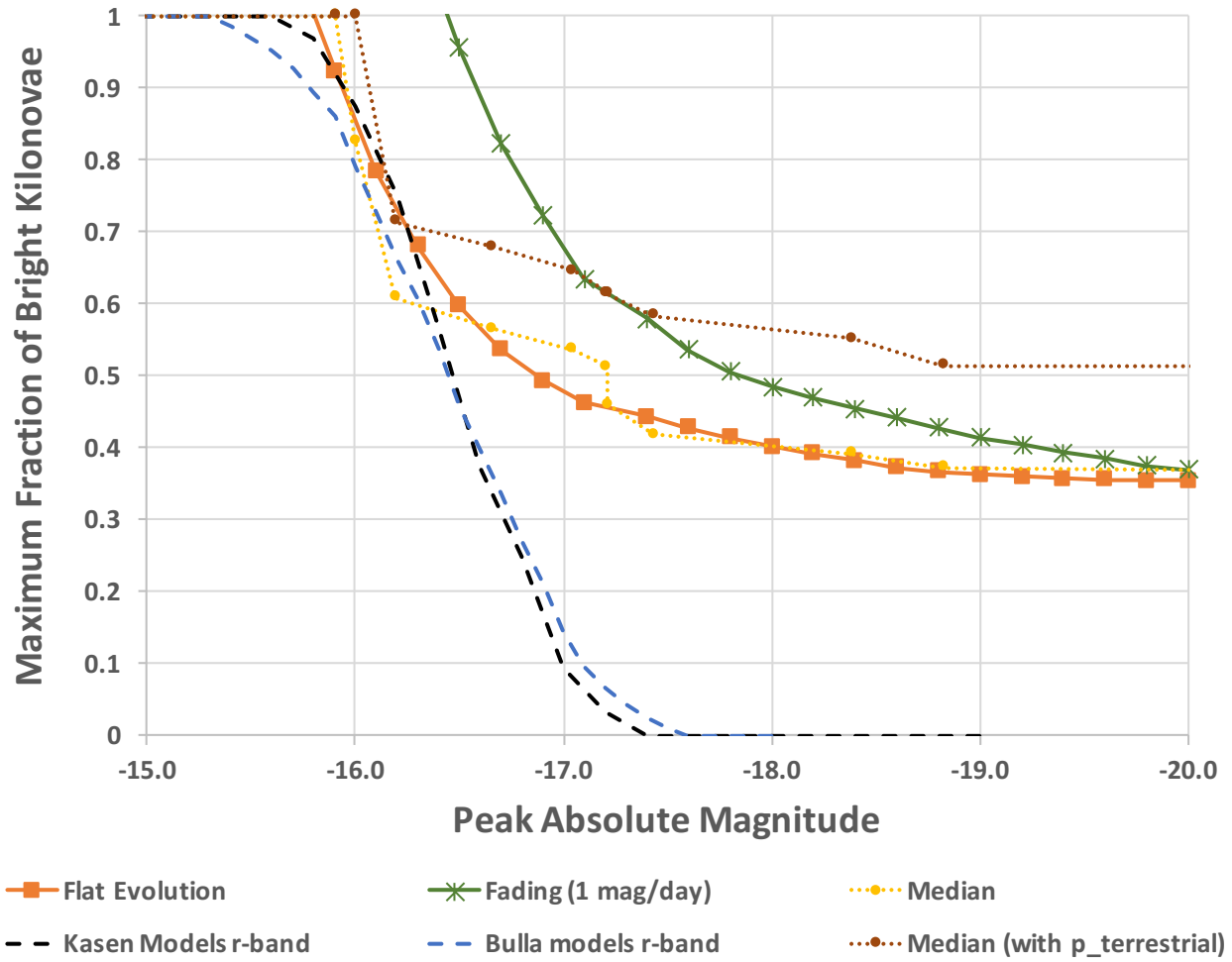
If all KNe peaked at an absolute magnitude of -16.1, our joint non-detection probability is 4.2% (Kasliwal+2020).

Kilonova Luminosity Function Constraints

$$(1 - \mathrm{CL}) = \prod_{i=1}^{N} (1 - f_b * p_i)$$

$$(1 - \mathrm{CL}) = \prod_{i=1}^{N} (1 - f_b * p_i * (1 - t_i))$$

No more than 57% (89%) of kilonovae could be brighter than -16.6 mag assuming flat (fading at 1 mag/day) evolution (Kasliwal+2020)



Increasing our chances of kilonova detection…

- Scheduling
  - Tailor to BNS or NSBH
  - Survey cadence optimization
  - Dynamical exposure times

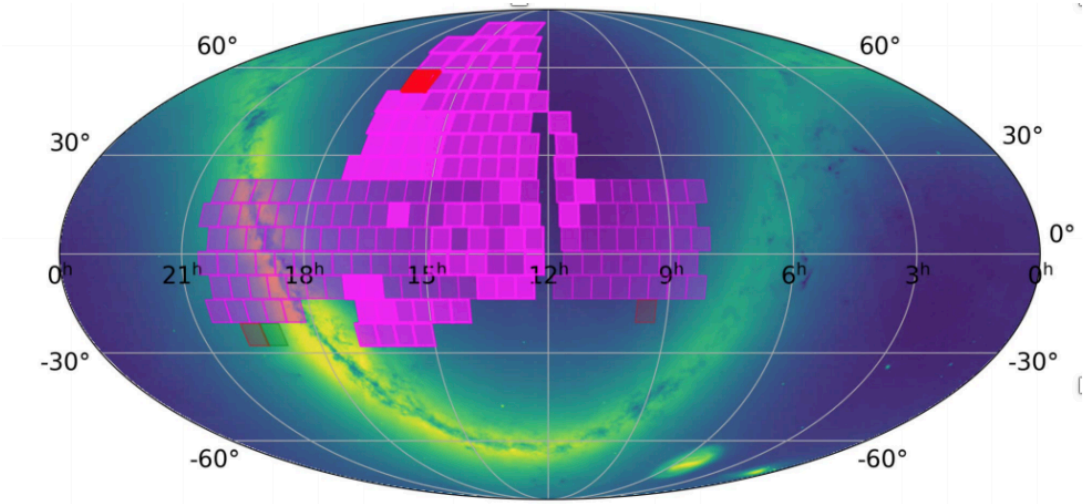


Figure Courtesy: M. AlMualla

- Model analysis
  - Creation of surrogate models
  - Analyzing effect of geometry on lightcurve prediction
  - GW parameter estimation to inform lightcurves

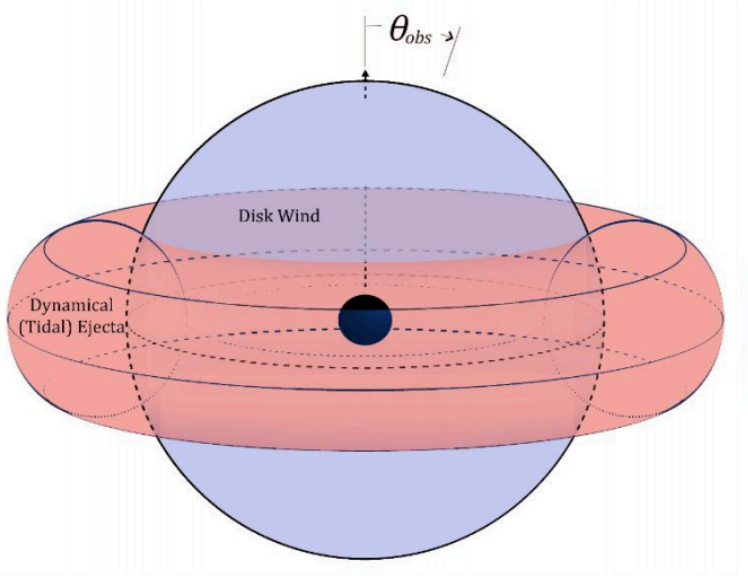
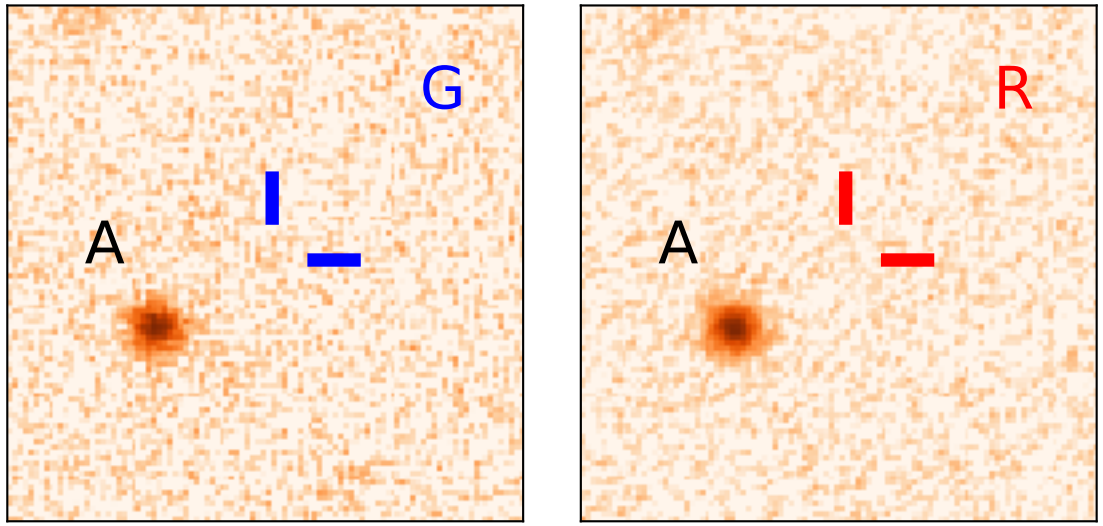


Figure Courtesy: J. Heinzel

Increasing our chances of kilonova detection…

- Transient searches and vetting
  - Deep, late-time ZTF queries
  - Filters for kilonova evolution



Andreoni+2020, in press.

- Luminosity function/Rates
  - Bayesian formalism for kilonova detection probability
  - Mapping model predictions to observables
  - KN Simulation and recovery

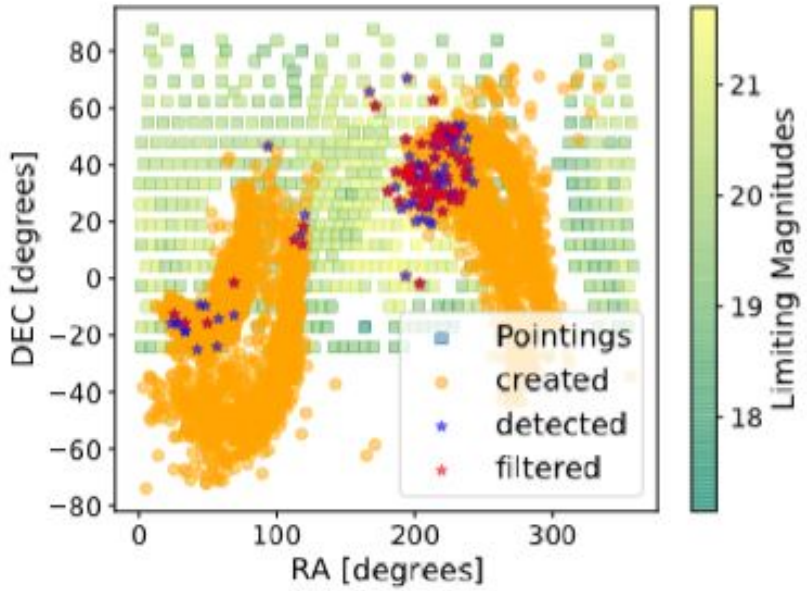
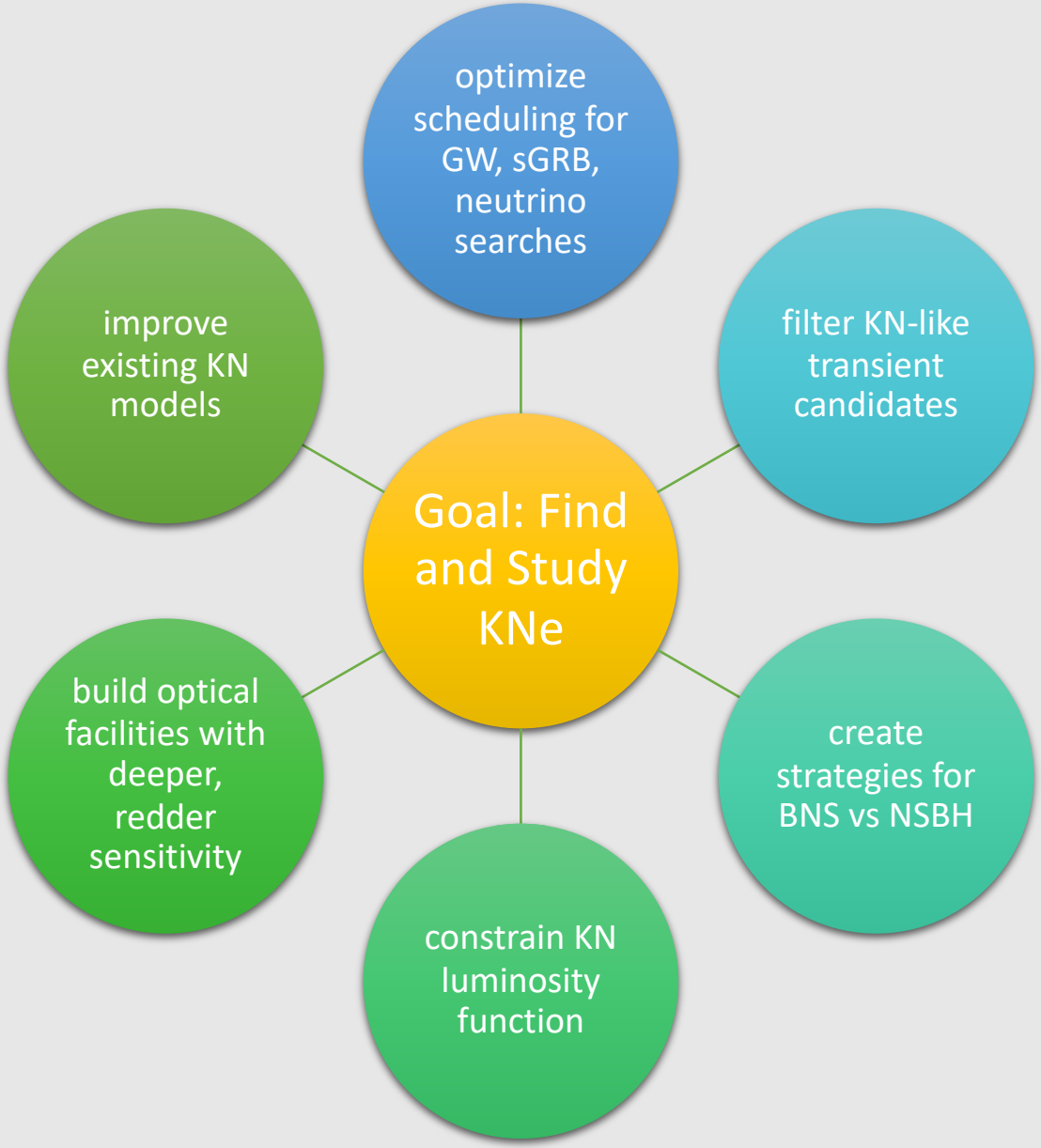


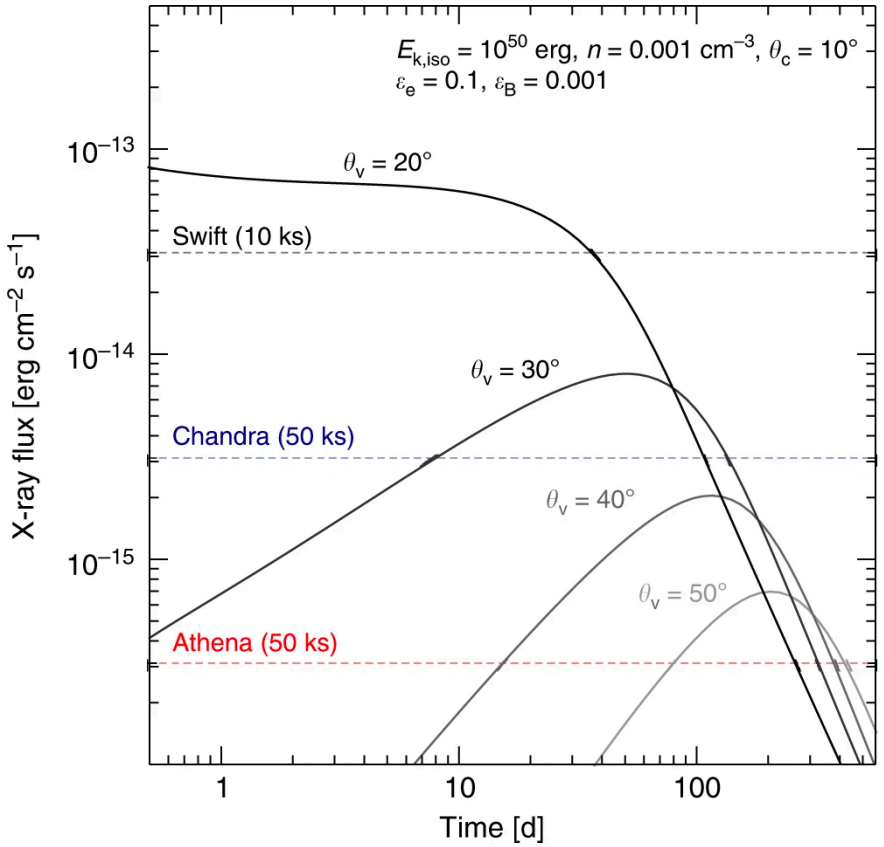
Figure Courtesy: P. Rajkumar

Synergies for kilonova identification and analysis



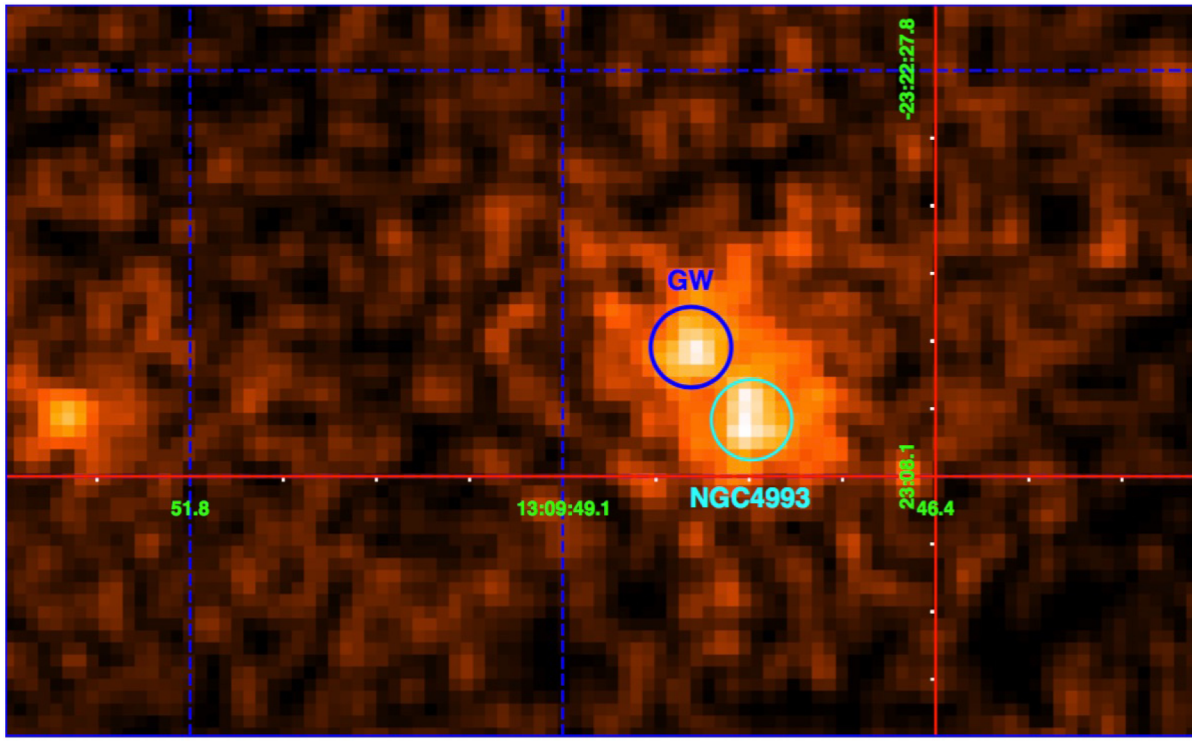
The Future is Bright!

Simulated X-ray lightcurves of GW counterparts at different viewing angles. (Troja+2018)



We look forward to…

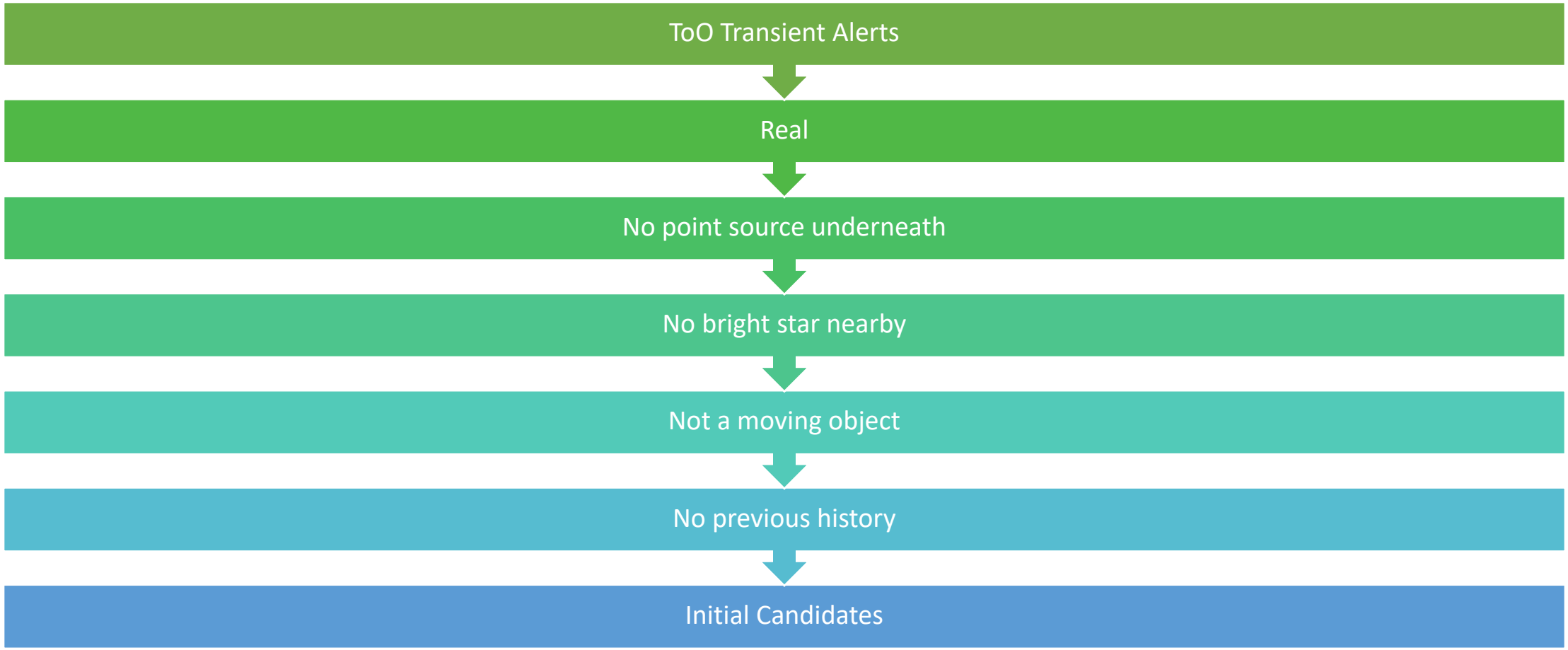
- Kilonova identification with ZTF, and
- Collaboration with NICER and other x-ray missions for targeted follow-up!



XMM-Newton and MOS data co-added for GW170817 (D'Avanzo+2018)

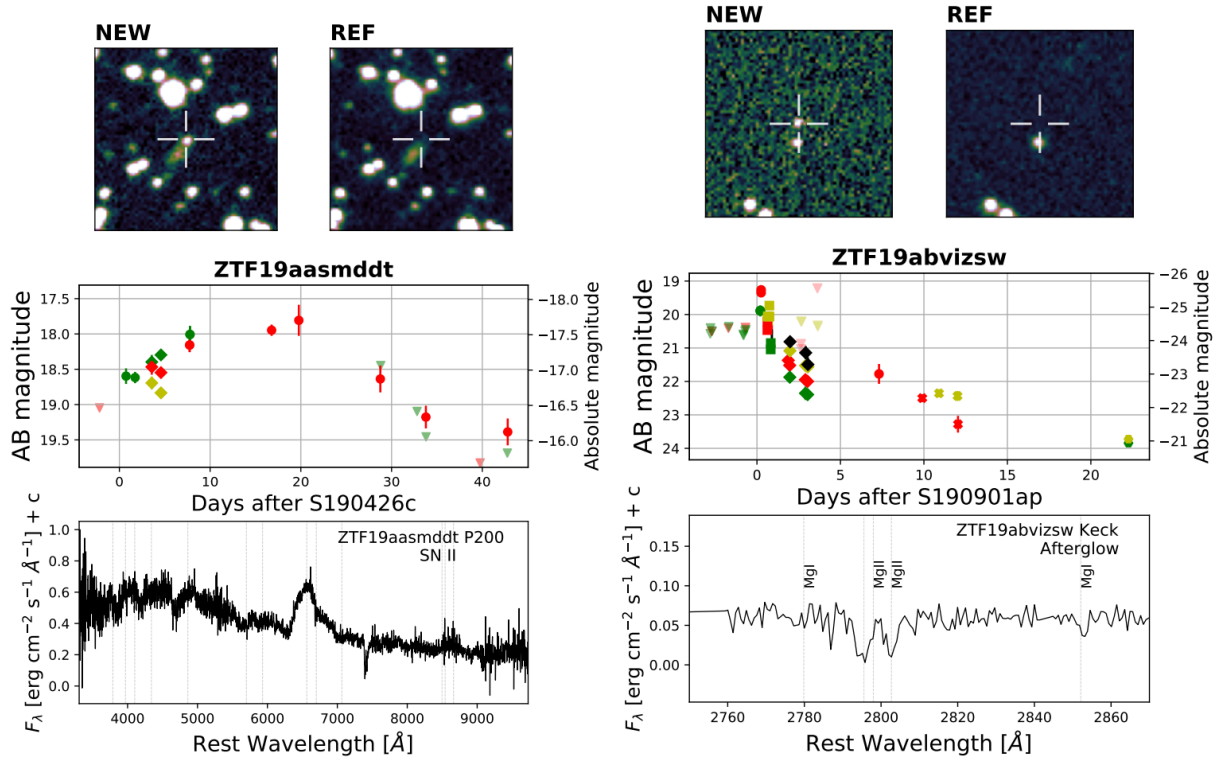
Thank you for your attention!

Initial Transient Filtering



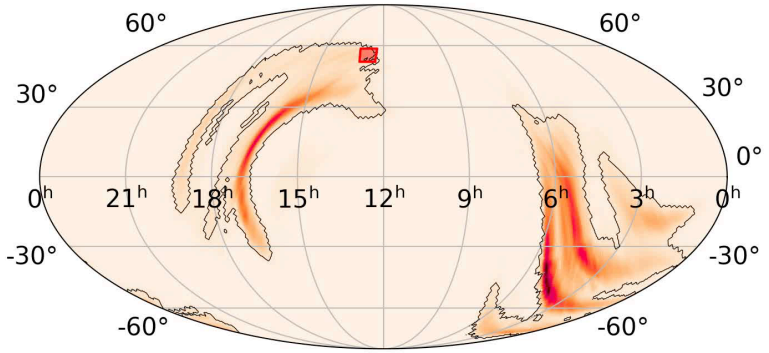
Candidate Rejection Criteria

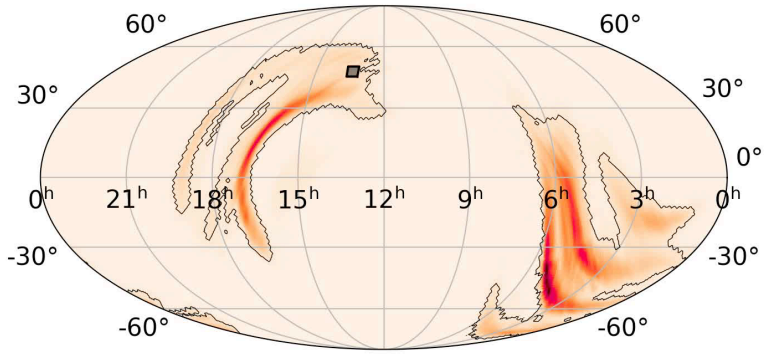
- Inconsistent spectroscopic classification
- Inconsistent Redshift
- Slow photometric evolution
- Outside of LALInference skymap
- Artifacts
- Asteroids
- Previous activity

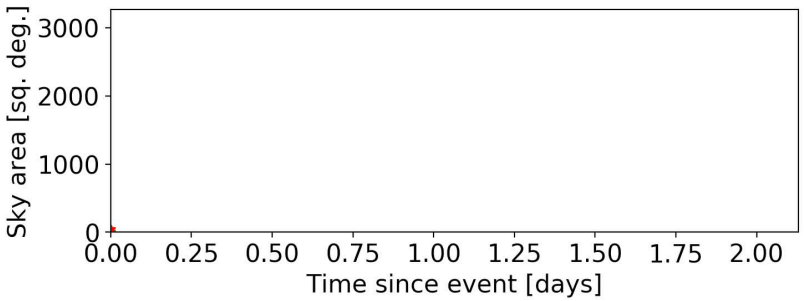


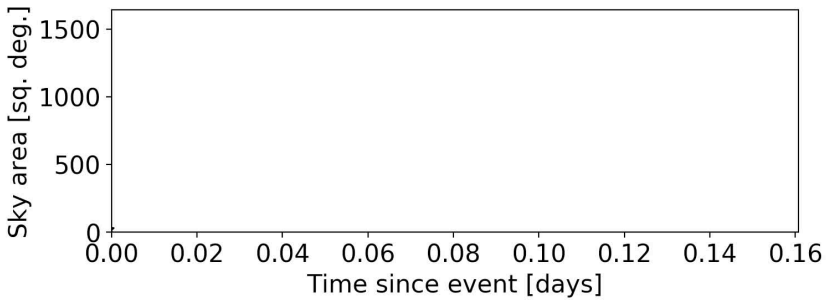
SN II (left) and untriggered GRB afterglow (right)
Kasliwal+2020

Example: tiling the skymap of GW190425









The optically detectable *LISA* source survey

Kevin Burdge

California Institute of Technology

Division of Physics, Mathematics, and Astronomy

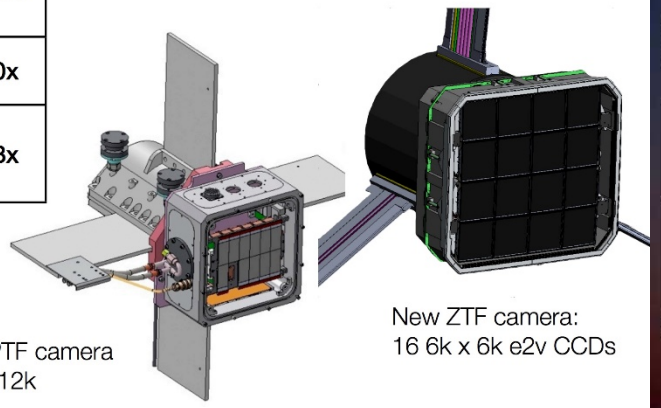
Discovery: using the Zwicky Transient Facility

ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**15.0x**
Relative Volumetric Survey Rate	1x	**12.3x**

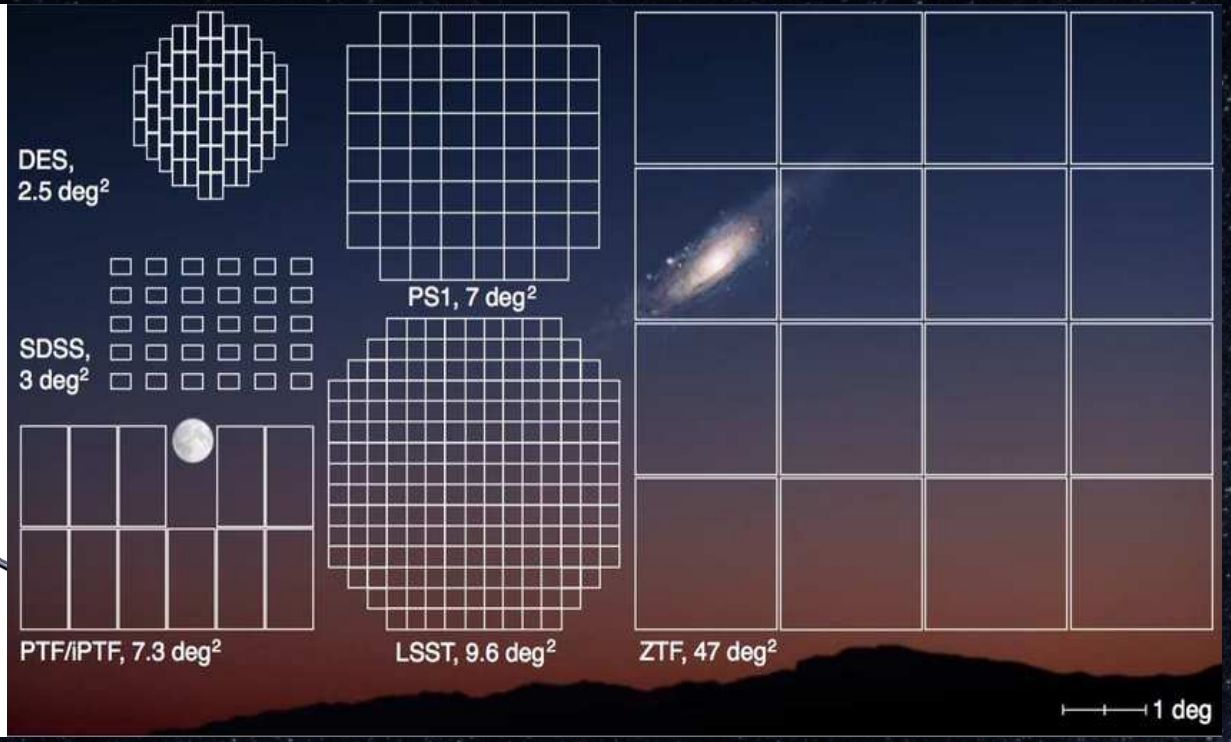
3750 deg^2/hour
⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey



Existing PTF camera
MOSAIC 12k

New ZTF camera:
16 6k x 6k e2v CCDs



The crucial element: ZTF has a large field of view, and accumulates many epochs quickly

But it’s not trivial to find these objects…

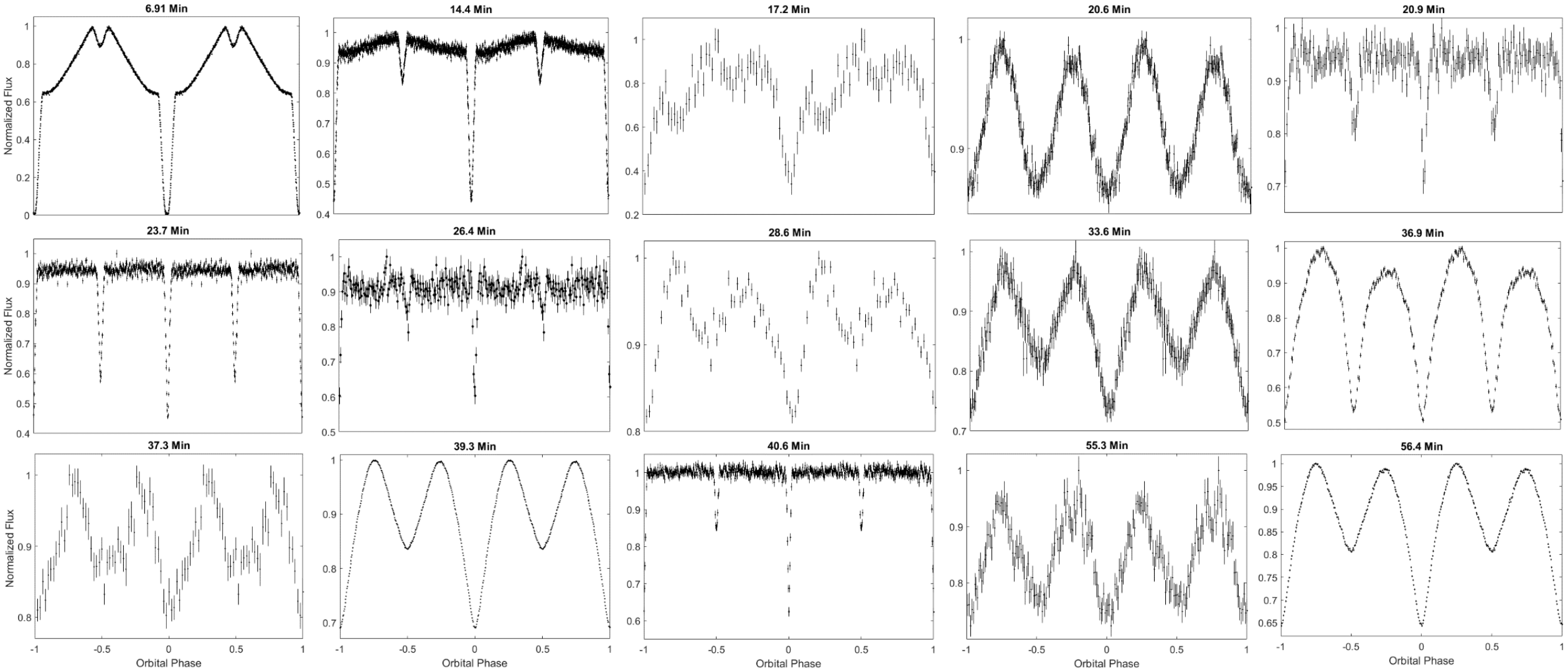
Searching for minute periods in data sampled over months to years->enormous frequency grids

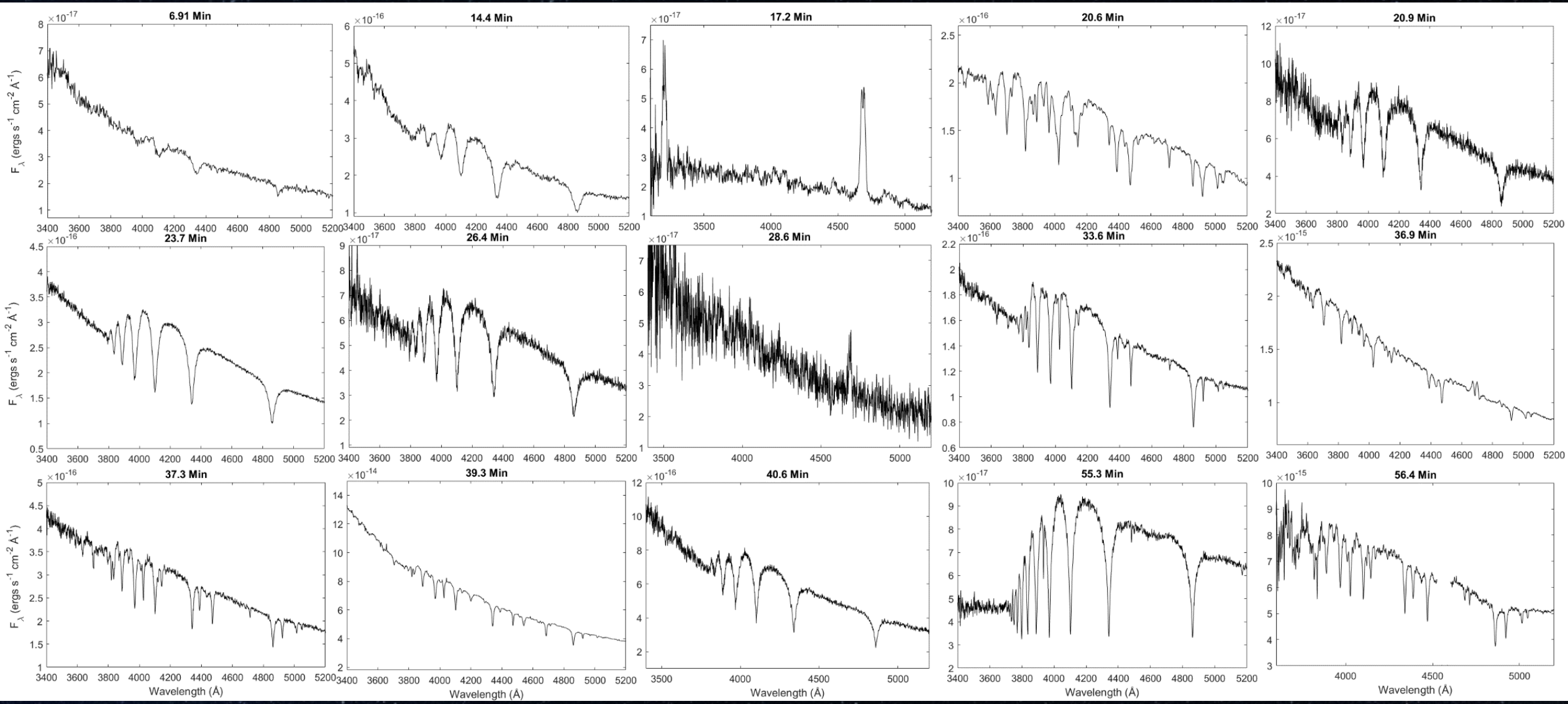
Graphics processing units help a lot with this

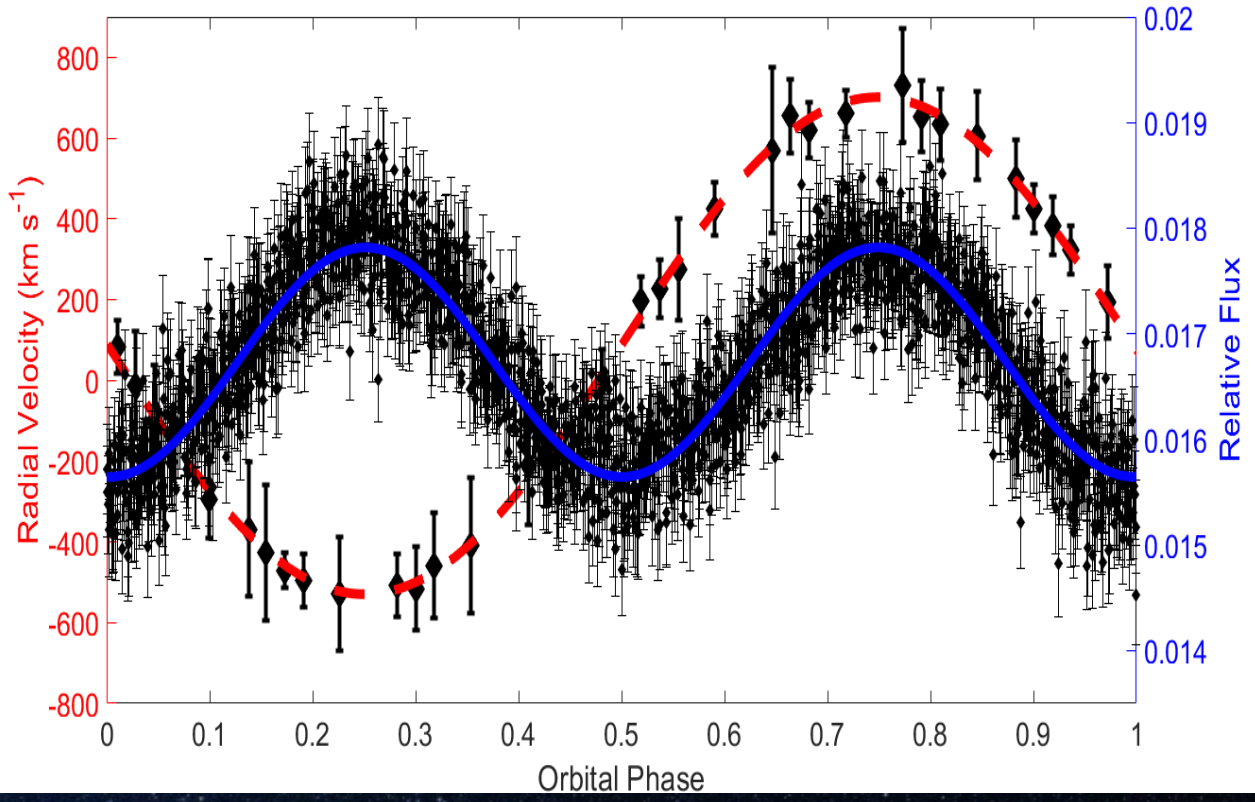
The time domain revolution

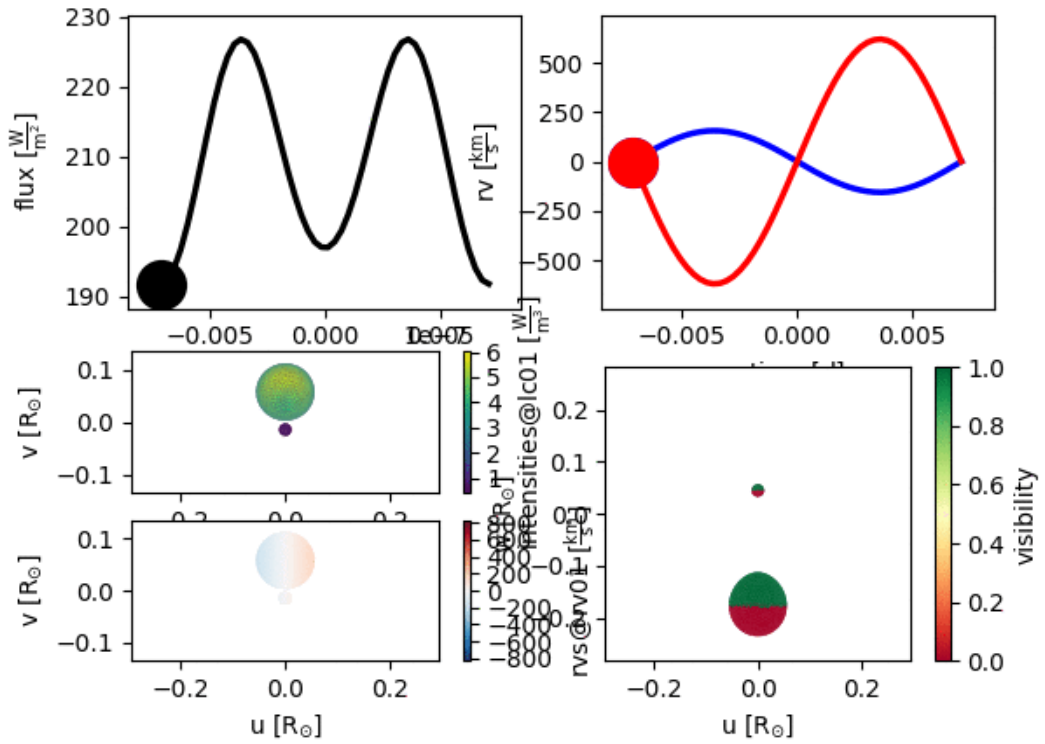
- >300 objects exhibiting periods under 30 minutes
- Several new detached and accreting double degenerates
- Many other classes of sources, including intermediate polars, ZZ Cetis, DB WD pulsators, sdB pulsators, rapidly rotating isolated magnetic WDs, etc

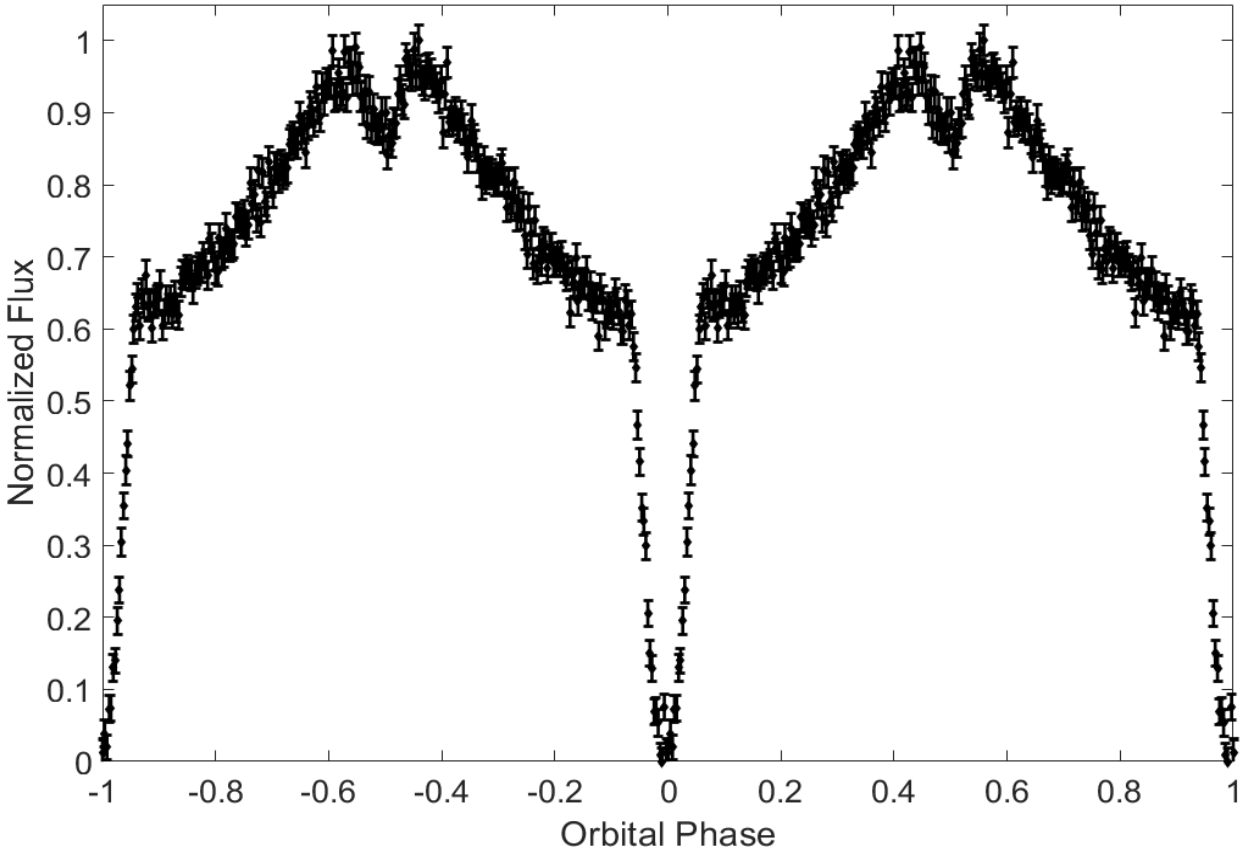
Okay, now let’s get to the good stuff

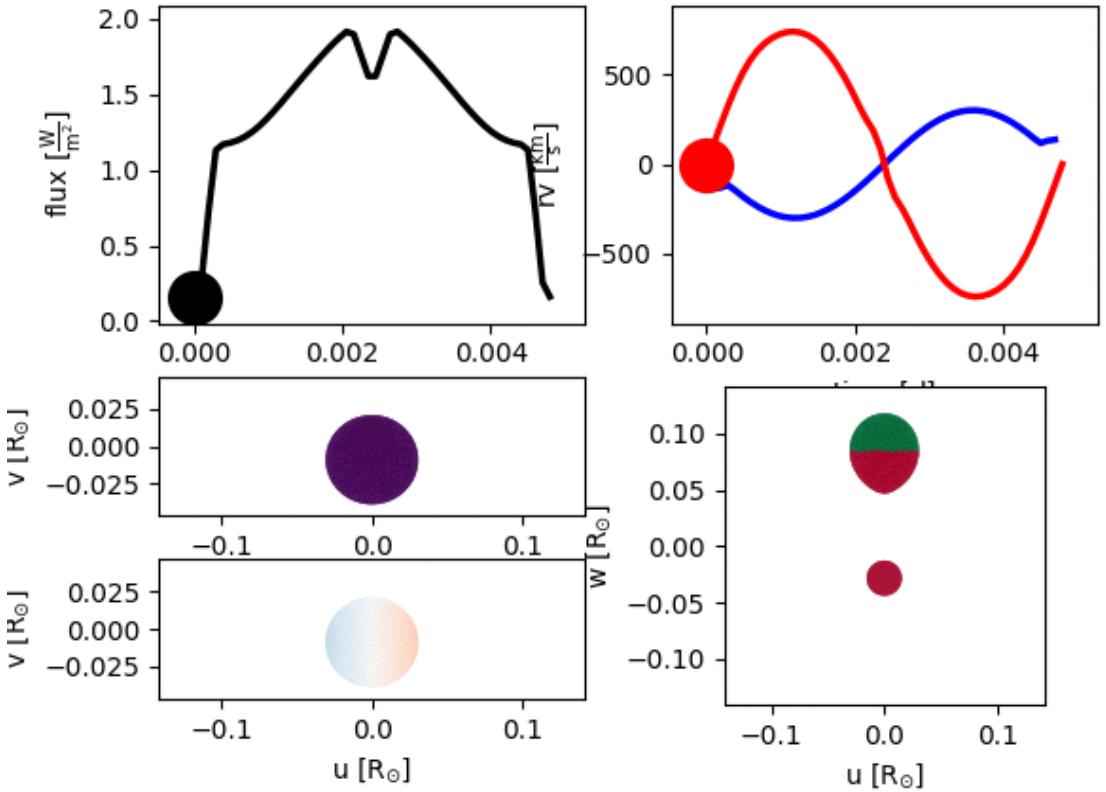

6.91 Min
14.4 Min
17.2 Min
20.6 Min
20.9 Min
23.7 Min
26.4 Min
28.6 Min
33.6 Min
36.9 Min
37.3 Min
39.3 Min
40.6 Min
55.3 Min
56.4 Min
Normalized Flux
Orbital Phase

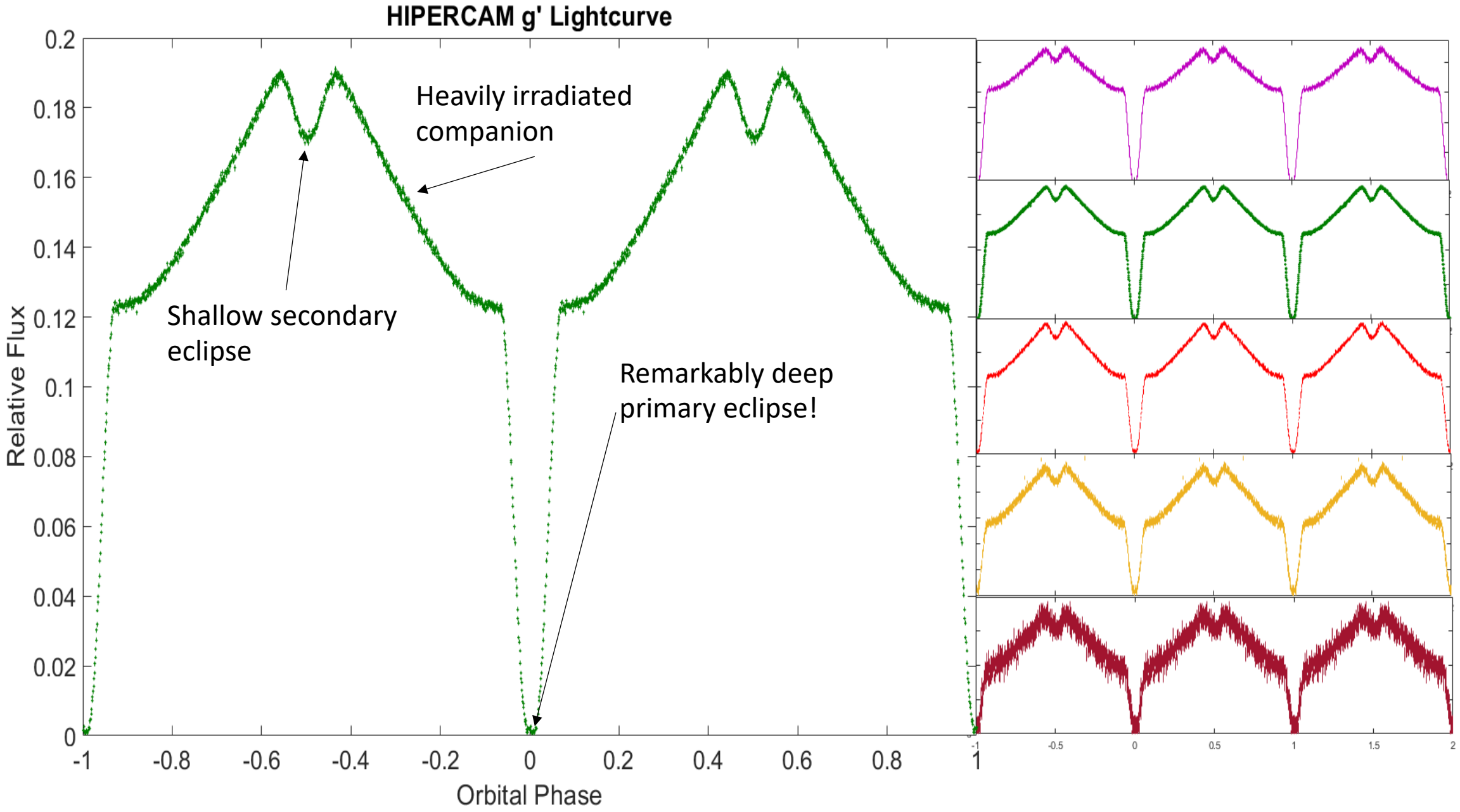

6.91 Min
14.4 Min
17.2 Min
20.6 Min
20.9 Min
23.7 Min
26.4 Min
28.6 Min
33.6 Min
36.9 Min
37.3 Min
39.3 Min
40.6 Min
55.3 Min
56.4 Min
F_λ (ergs s^-1 cm^-2 Å^-1)
Wavelength (Å)

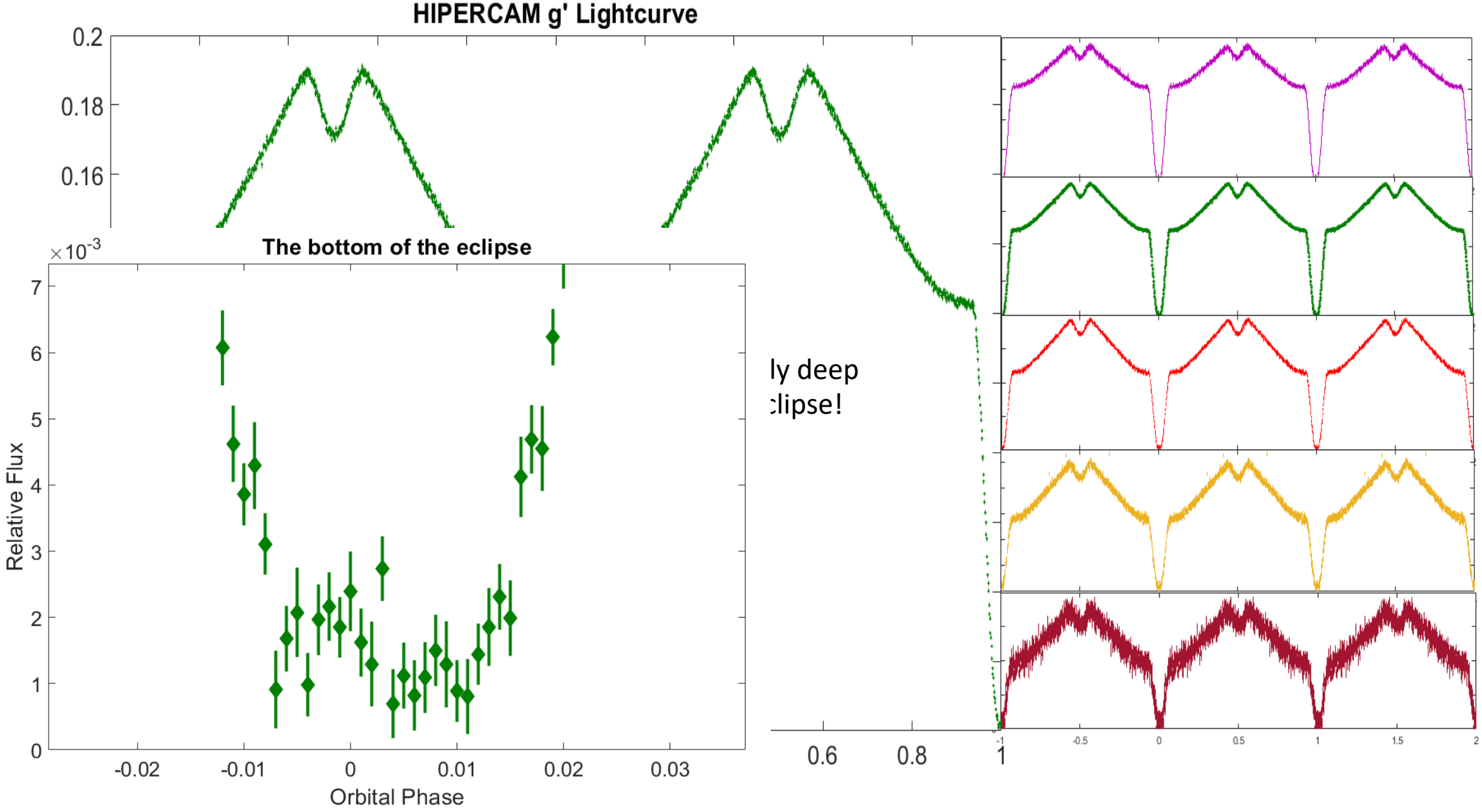

Radial Velocity (km s^{-1})
Relative Flux
Orbital Phase
800
600
400
200
0
-200
-400
-600
-800
0.02
0.019
0.018
0.017
0.016
0.015
0.014
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

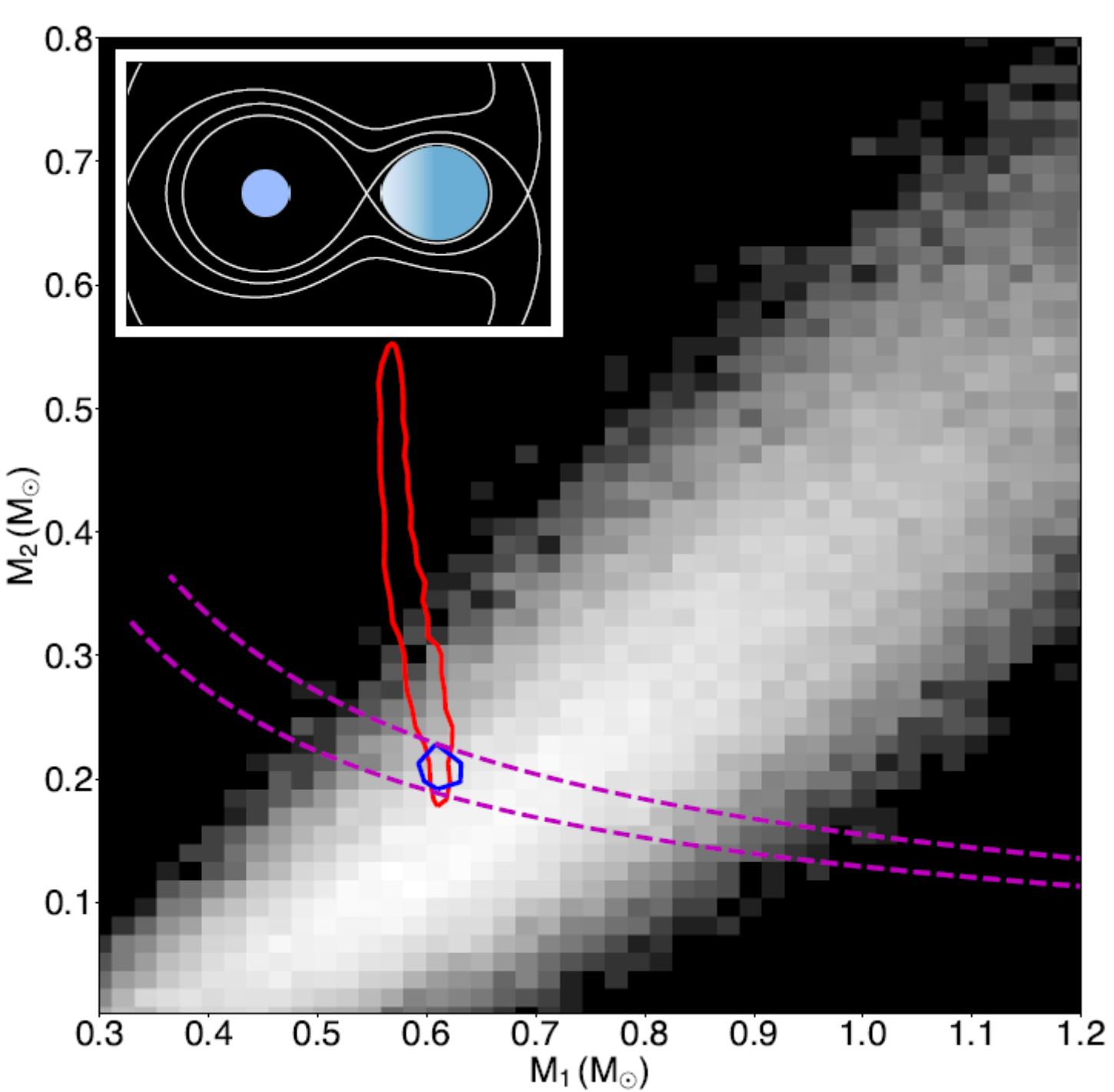

flux [$\frac{W}{m^2}$]
rv [$\frac{km}{s}$]
v [R$_\odot$]
u [R$_\odot$]
visibility
230
220
210
200
190
500
250
0
-250
-500
0.1
0.0
-0.1
0.2
-0.2
1.0
0.8
0.6
0.4
0.2
0.0


Normalized Flux
Orbital Phase
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

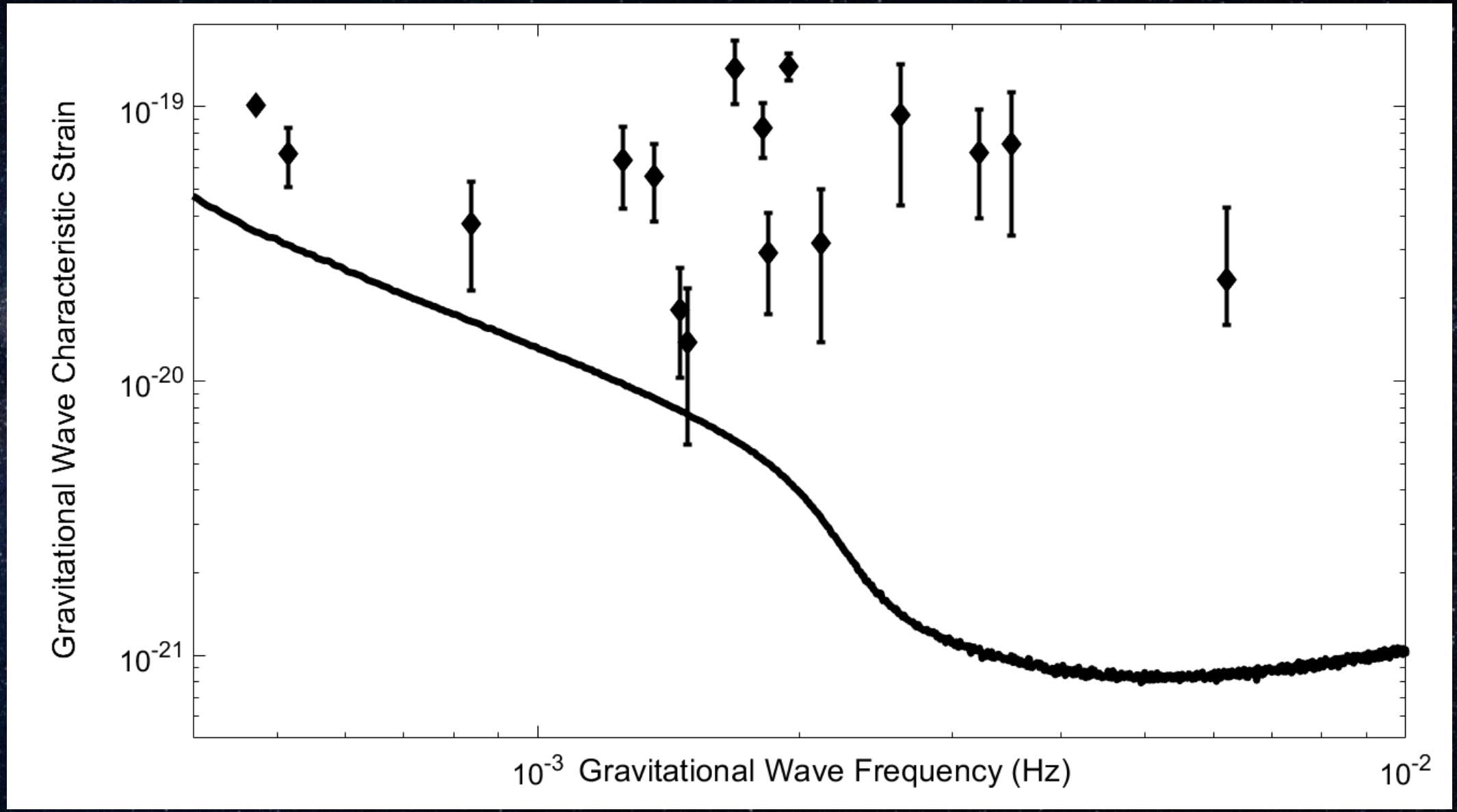

flux [W/m²]
rv [km/s]
v [R⊙]
w [R⊙]
u [R⊙]
2.0
1.5
1.0
0.5
0.0
500
0
−500
0.000
0.002
0.004
0.025
0.000
−0.025
−0.1
0.0
0.1
0.10
0.05
0.00
−0.05
−0.10

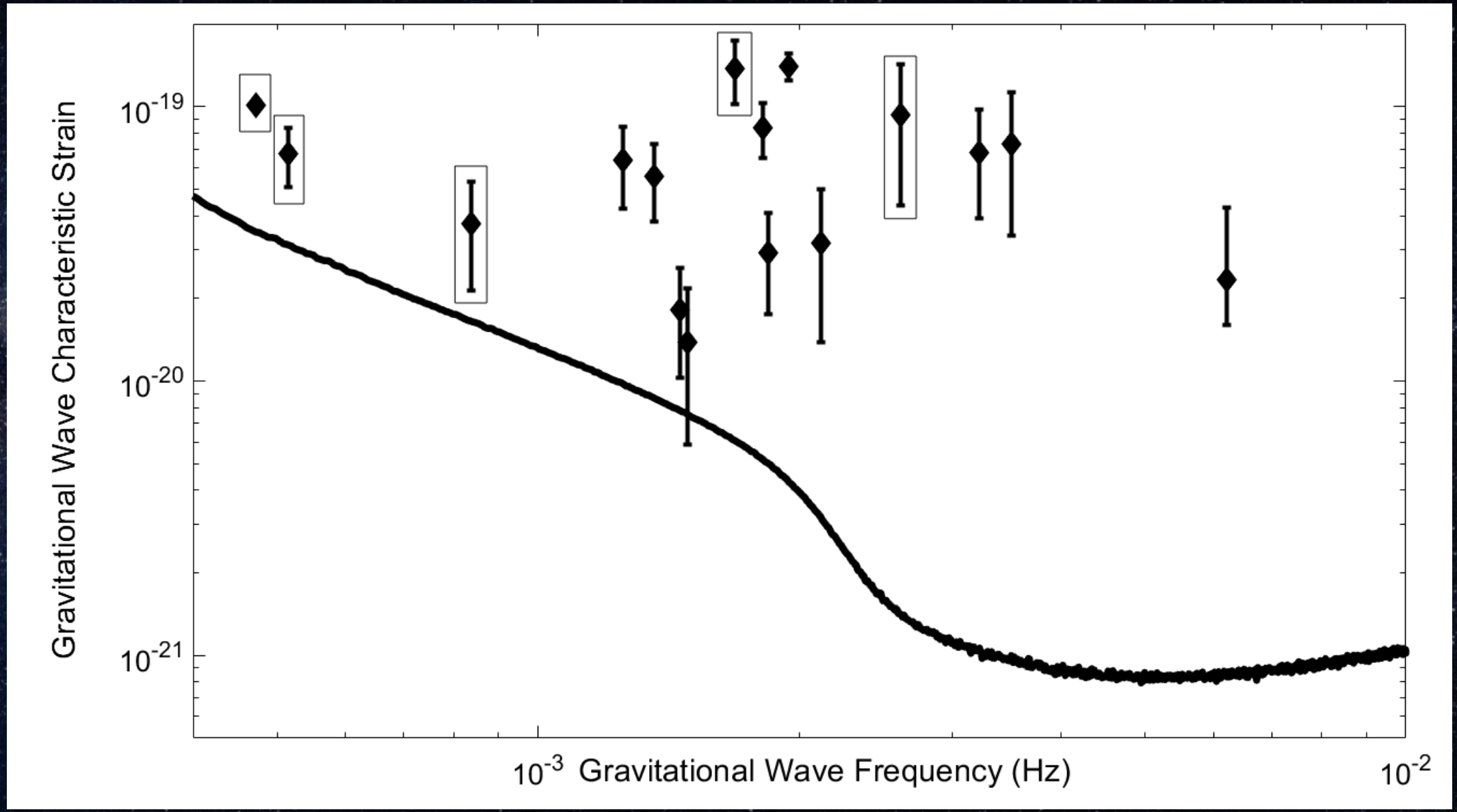

HIPERCAM g' Lightcurve
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
Relative Flux
Orbital Phase
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
-0.5
0
0.5
1
1.5
2

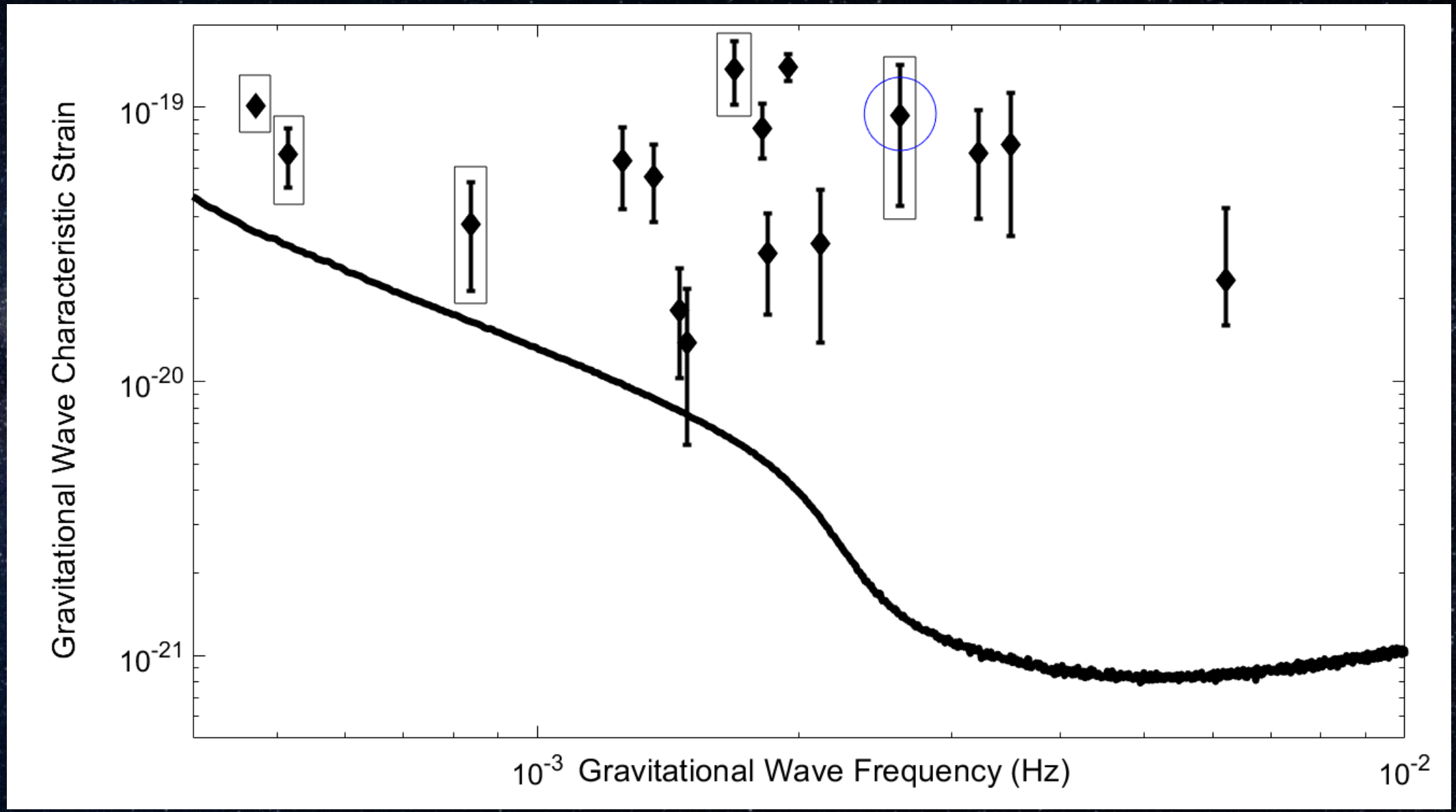

HIPERCAM g' Lightcurve
0.2
0.18
0.16
The bottom of the eclipse
×10^-3
7
6
5
4
3
2
1
0
Relative Flux
-0.02
-0.01
0
0.01
0.02
0.03
Orbital Phase
ly deep
clipse!
0.6
0.8
1
-1
-0.5
0
0.5
1
1.5
2

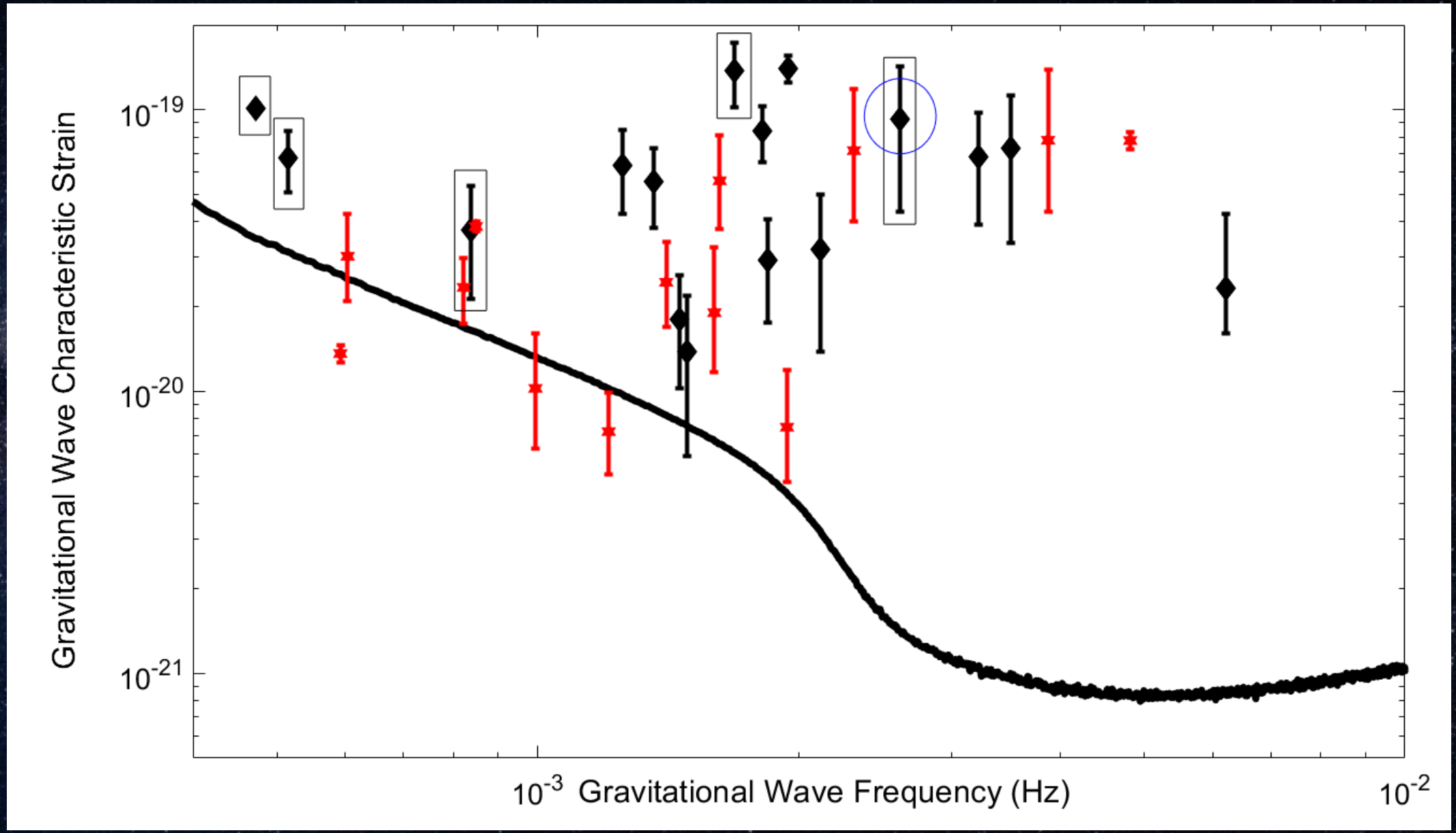

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$M_2\,(M_\odot)$
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
$M_1\,(M_\odot)$

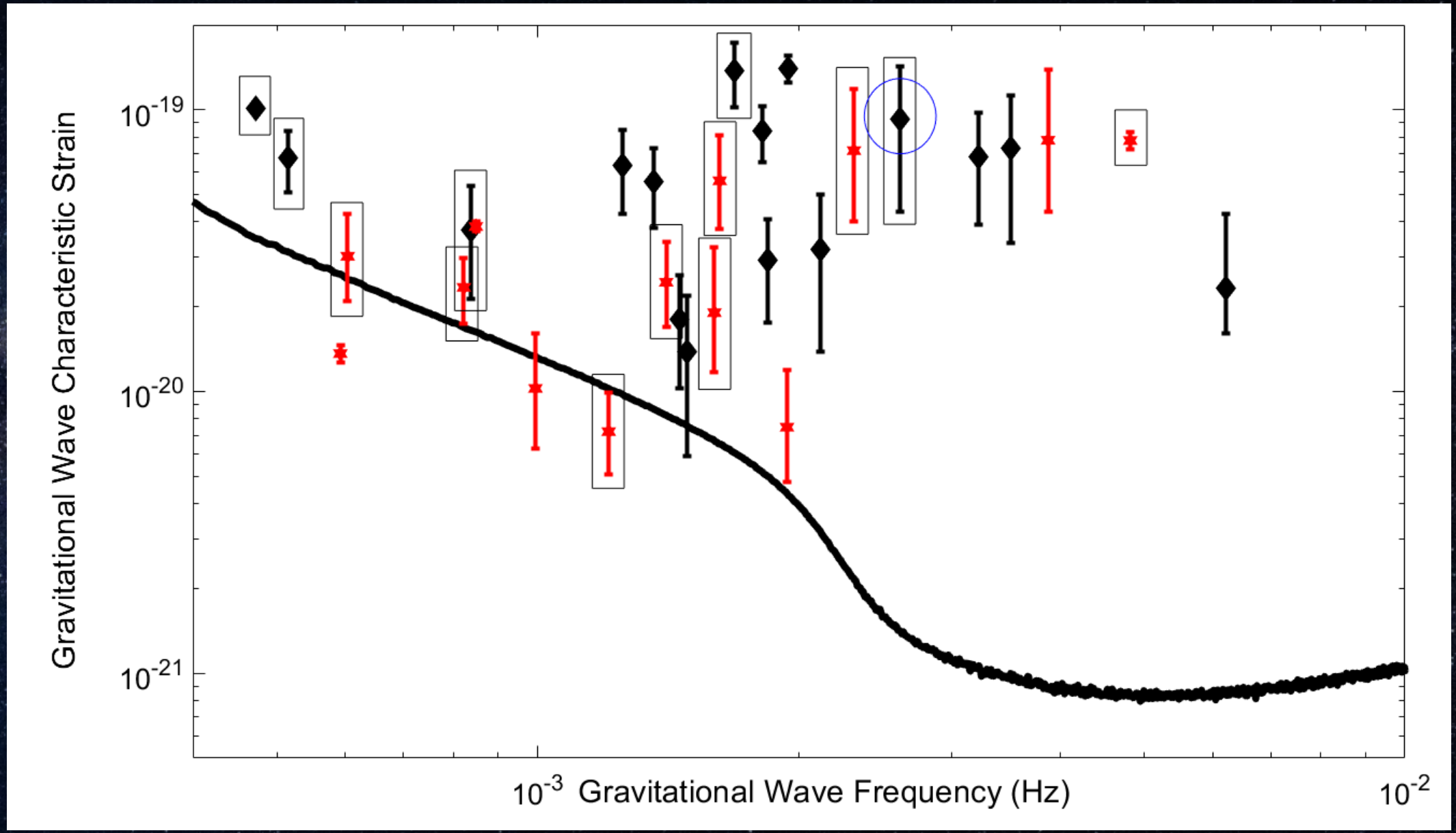
Deep pr

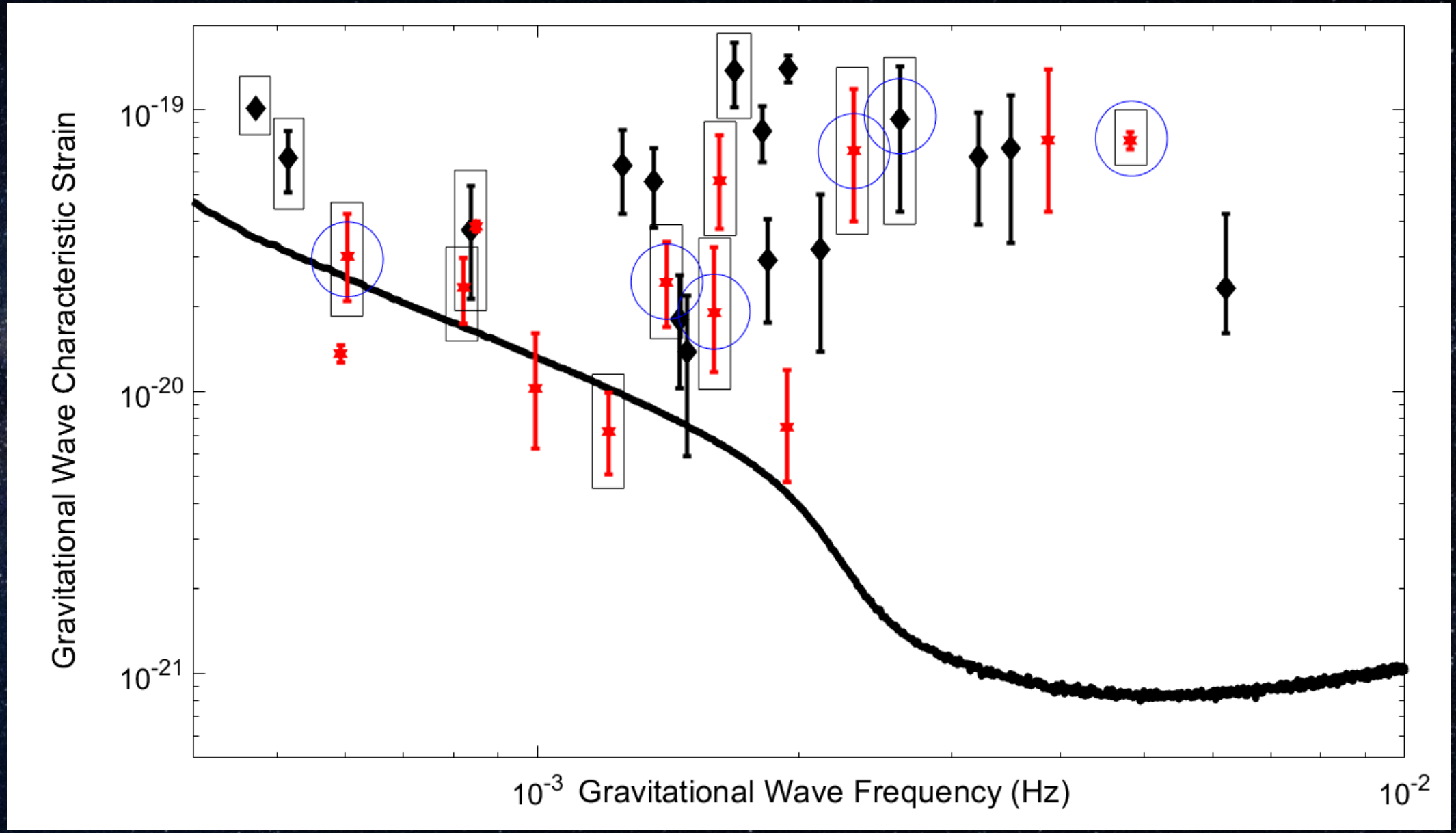

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}

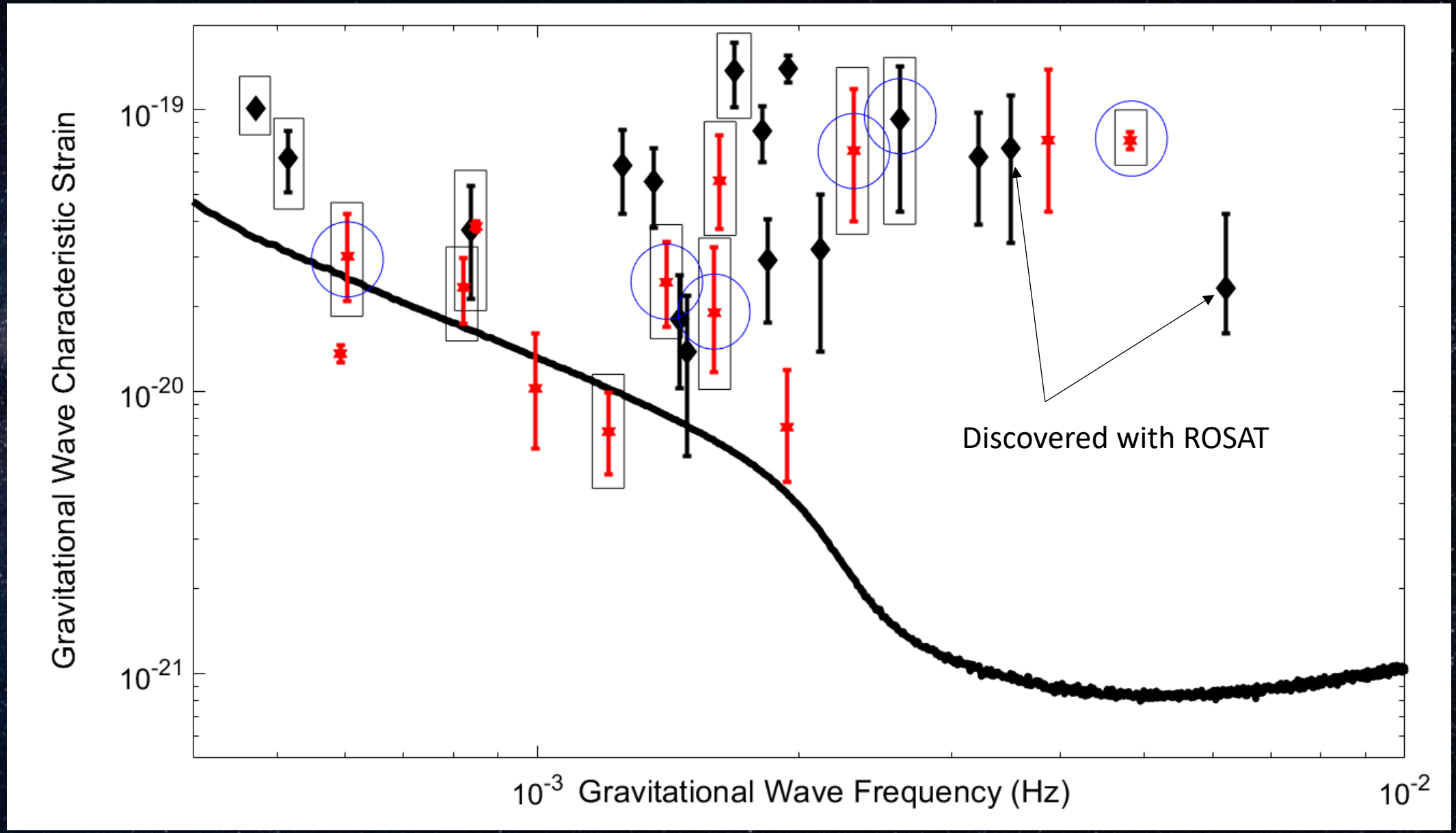

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}

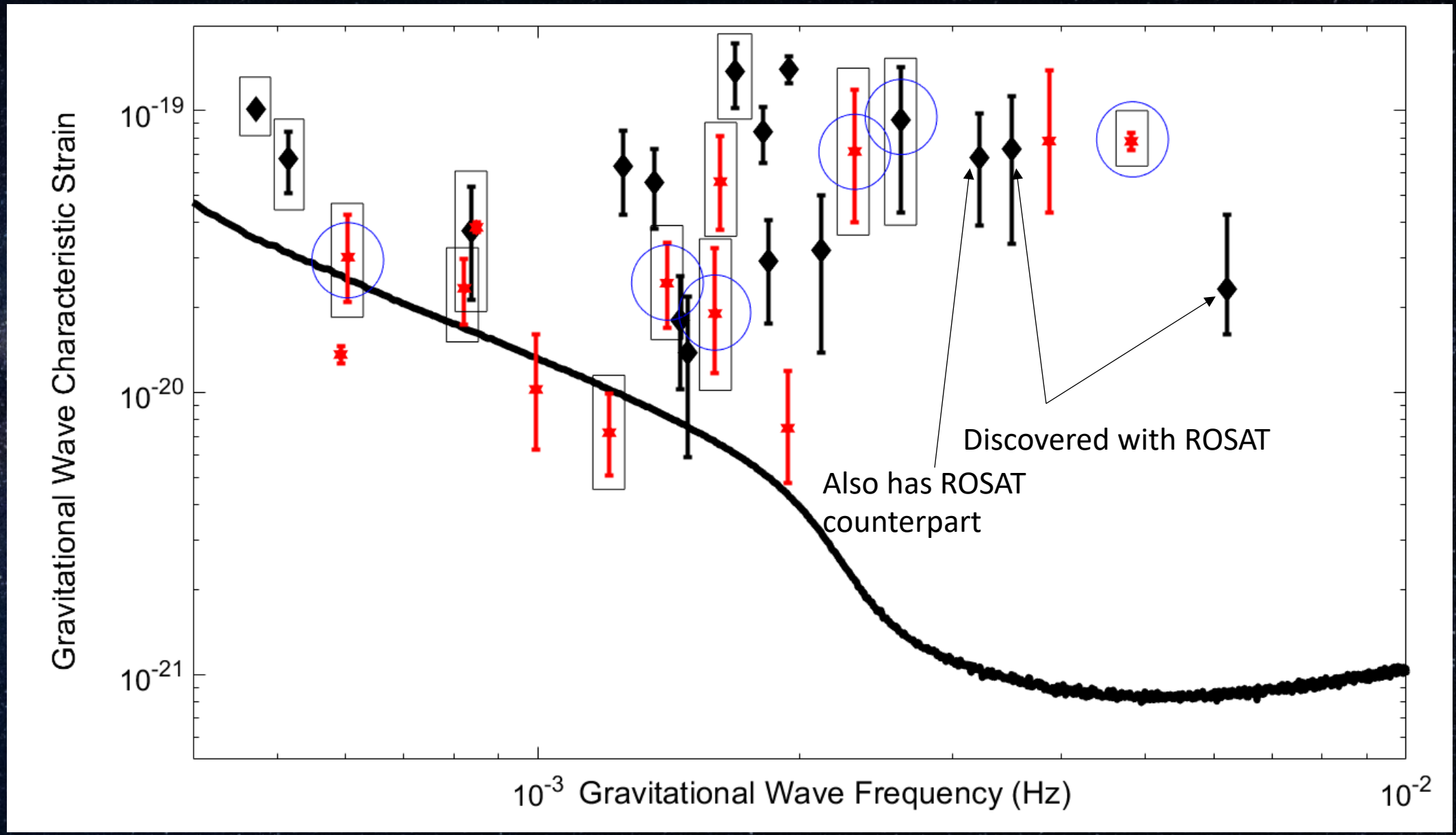

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}

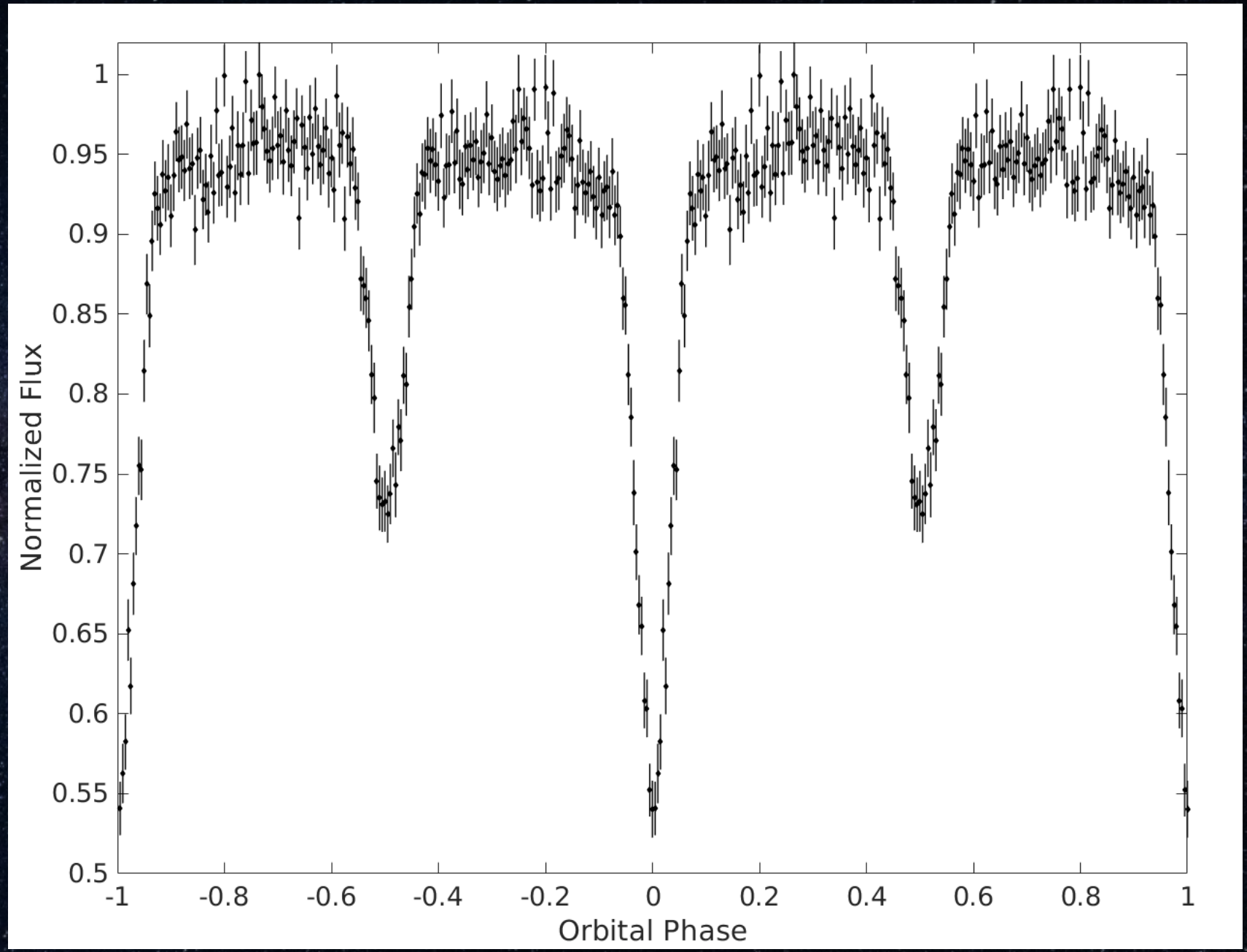

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}


Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}


Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}

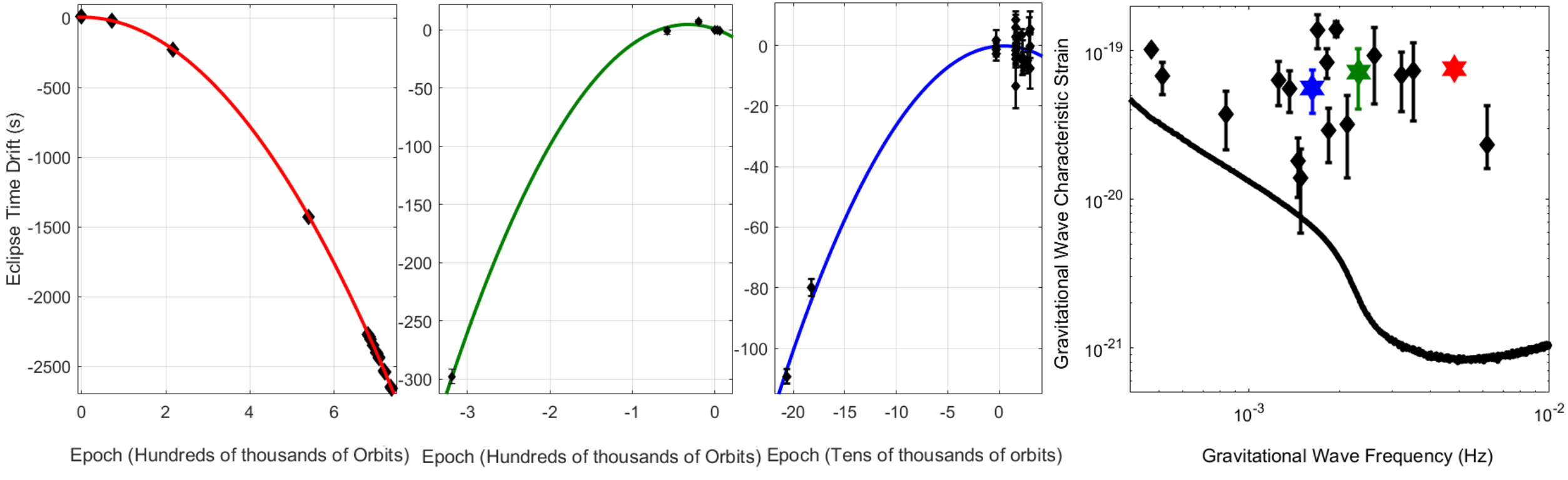

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}
Discovered with ROSAT

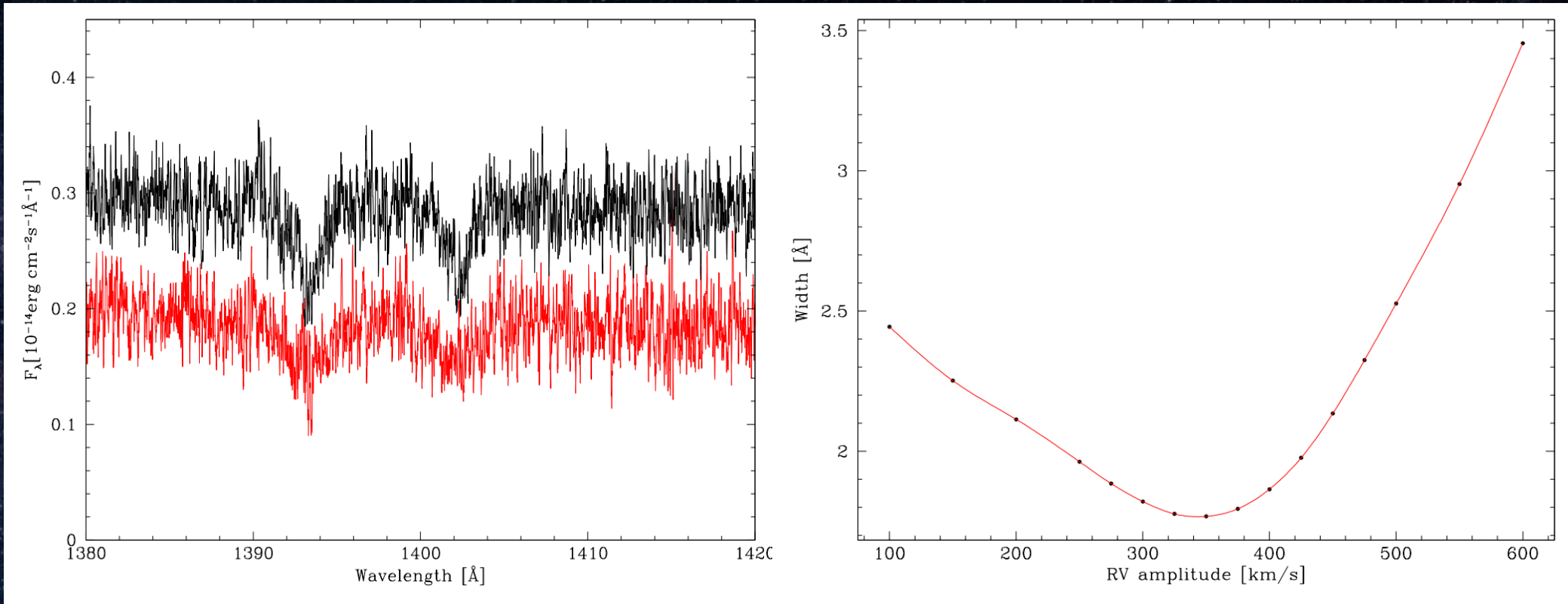

Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3} Gravitational Wave Frequency (Hz)
10^{-2}
Discovered with ROSAT
Also has ROSAT counterpart

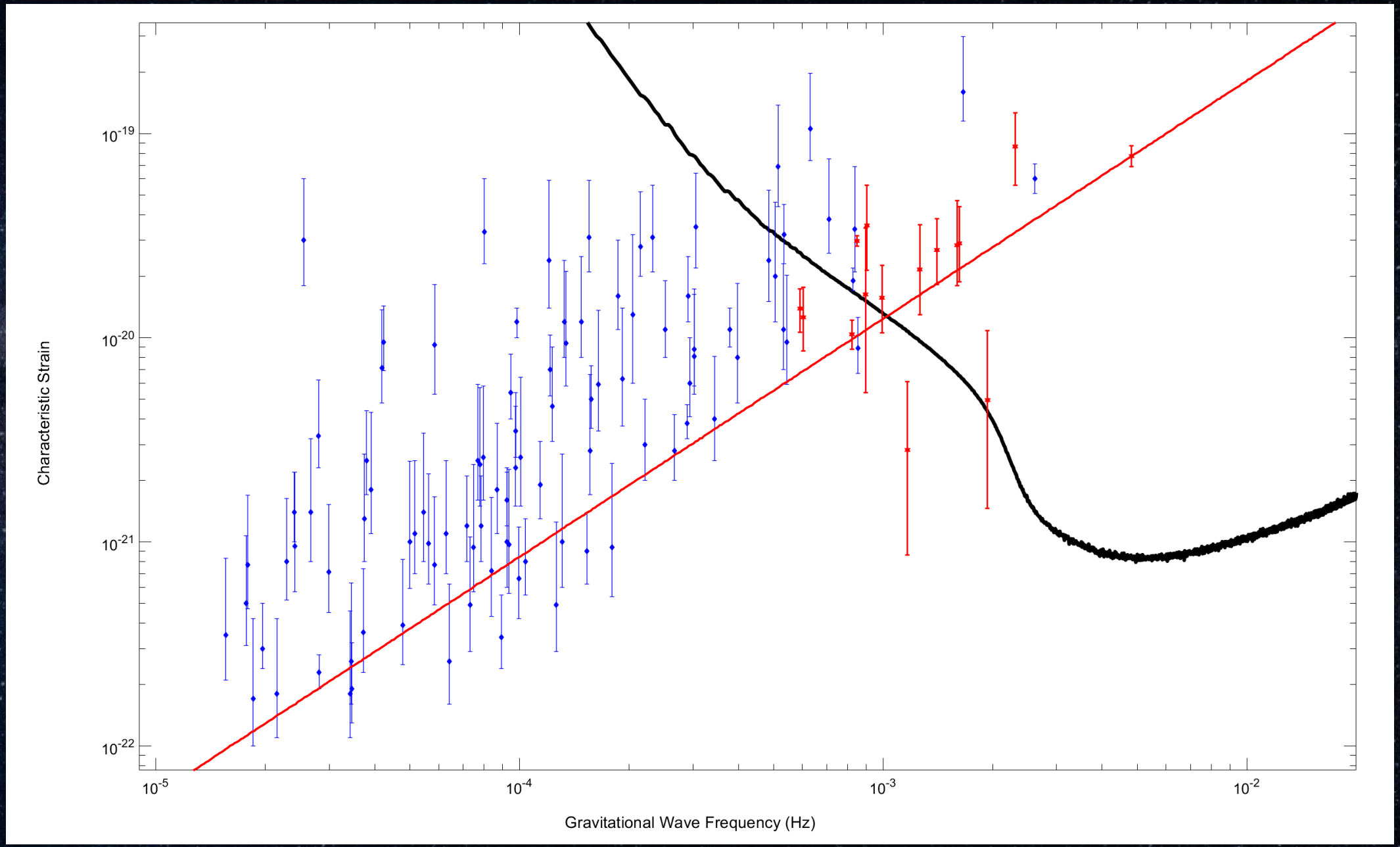

Normalized Flux
Orbital Phase
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

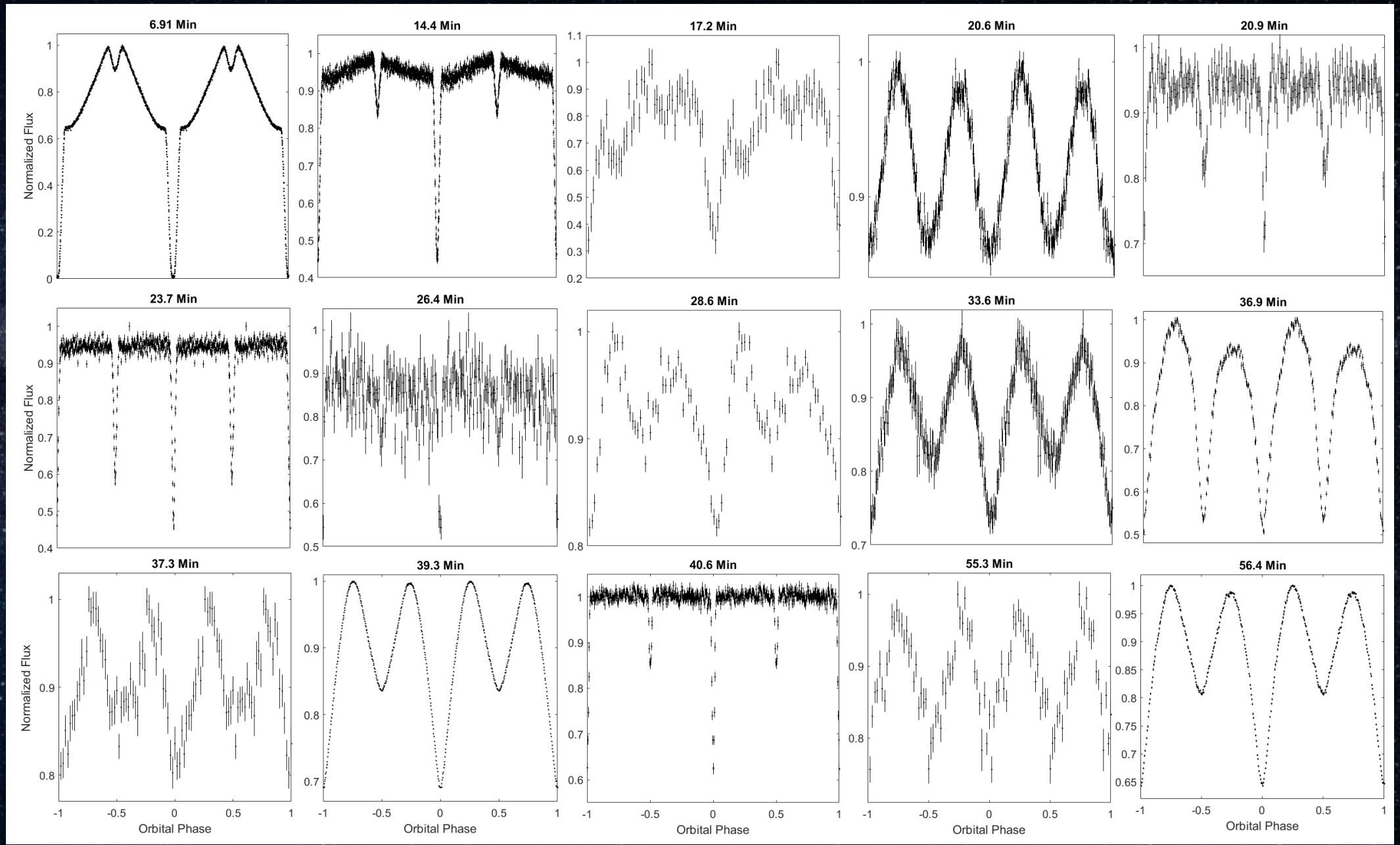
Looking to the future

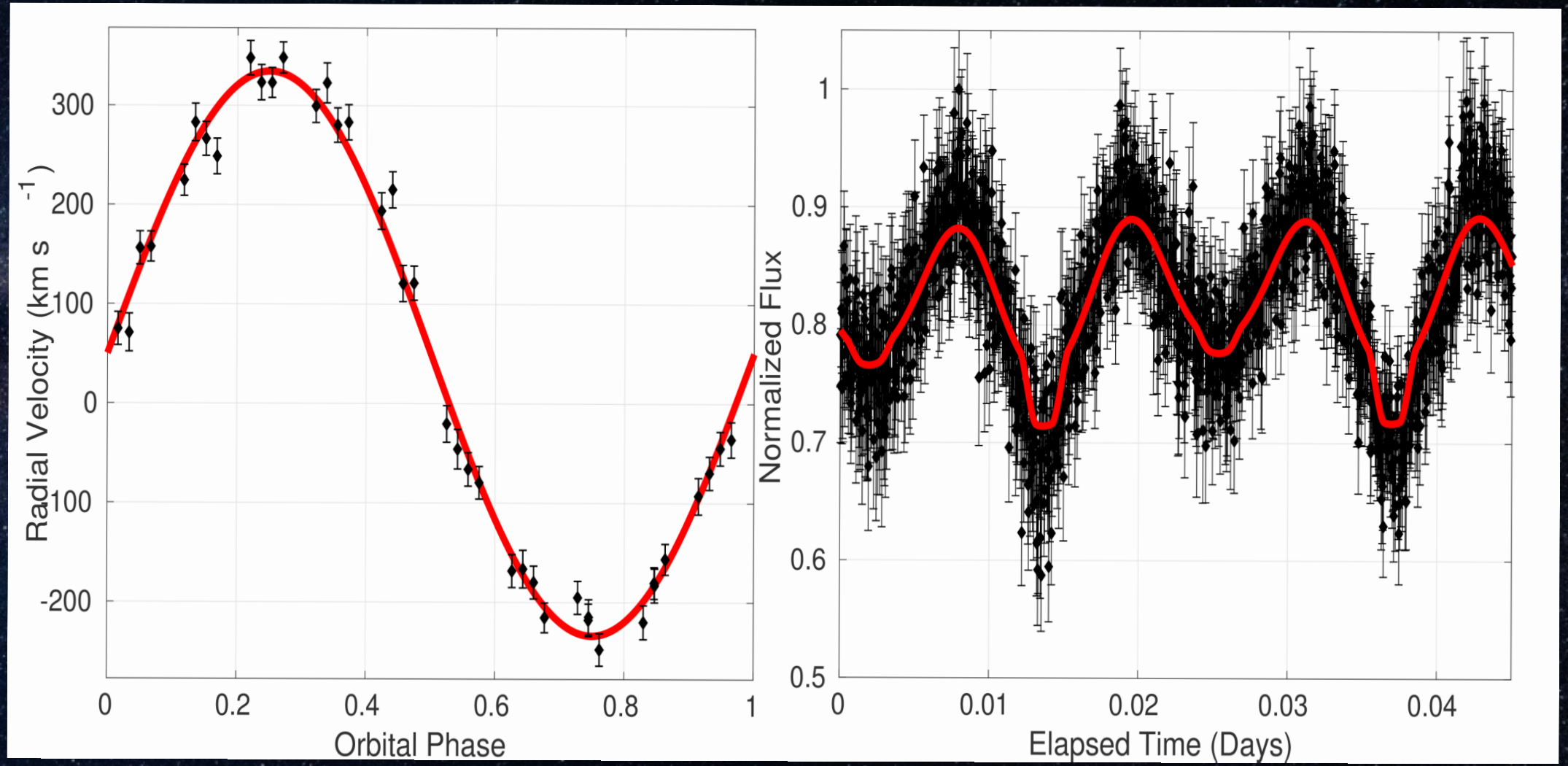
- In the LSST+LISA era, relying on phase-resolved spectroscopy will not be feasible
- Some of the most exciting gravitational wave sources in the LISA band should be strong X-ray sources detectable in all sky surveys, like the 5.4 minute binary, HM Cancri (aka RX J0806.3+1527)
- Timing of short period x-ray sources is important in confirming their nature, and also measuring physical effects such as orbital evolution

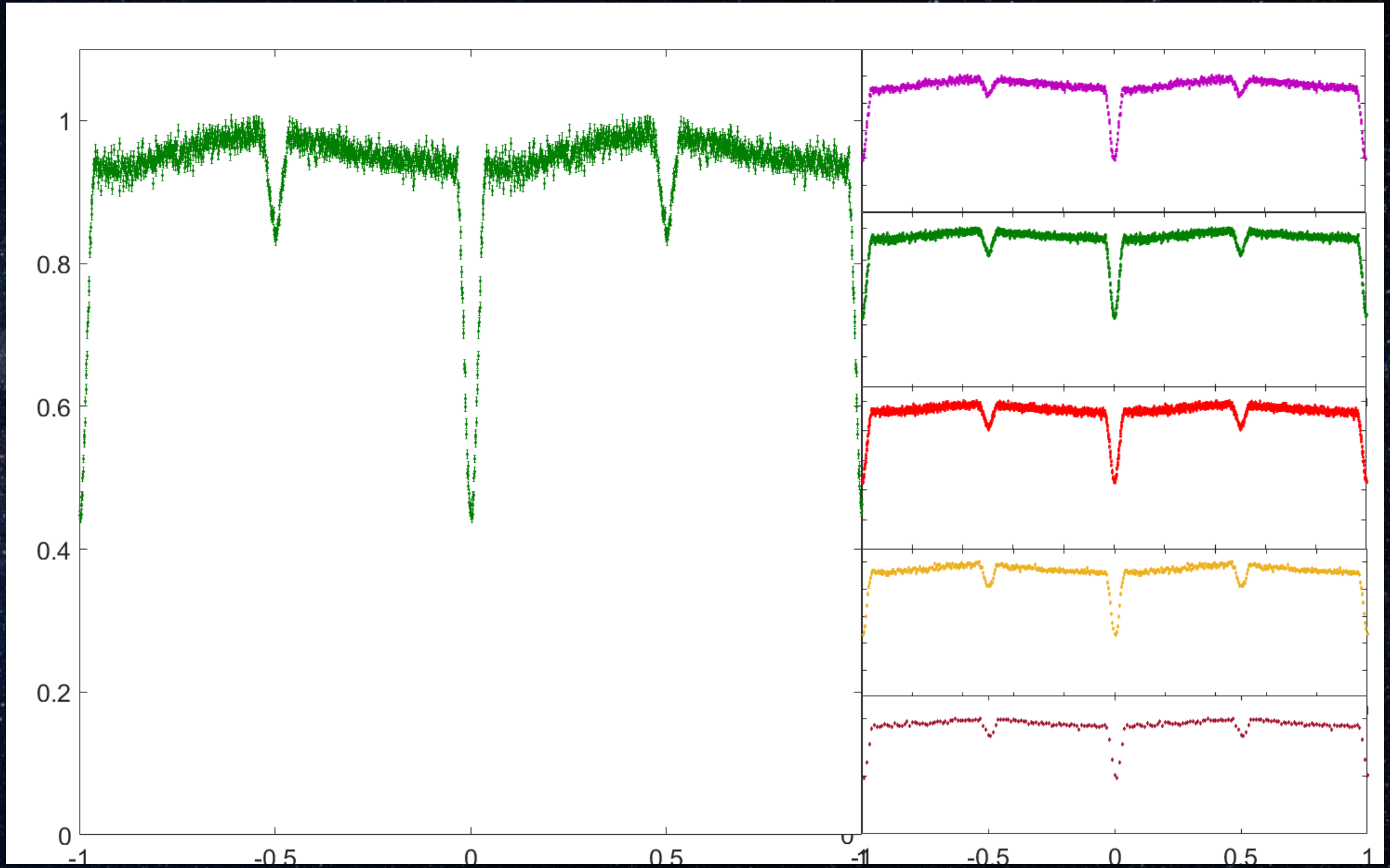

Eclipse Time Drift (s)
0
-500
-1000
-1500
-2000
-2500
0
2
4
6
Epoch (Hundreds of thousands of Orbits)
0
-50
-100
-150
-200
-250
-300
-3
-2
-1
0
Epoch (Hundreds of thousands of Orbits)
0
-20
-40
-60
-80
-100
-20
-15
-10
-5
0
Epoch (Tens of thousands of orbits)
Gravitational Wave Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-3}
10^{-2}
Gravitational Wave Frequency (Hz)

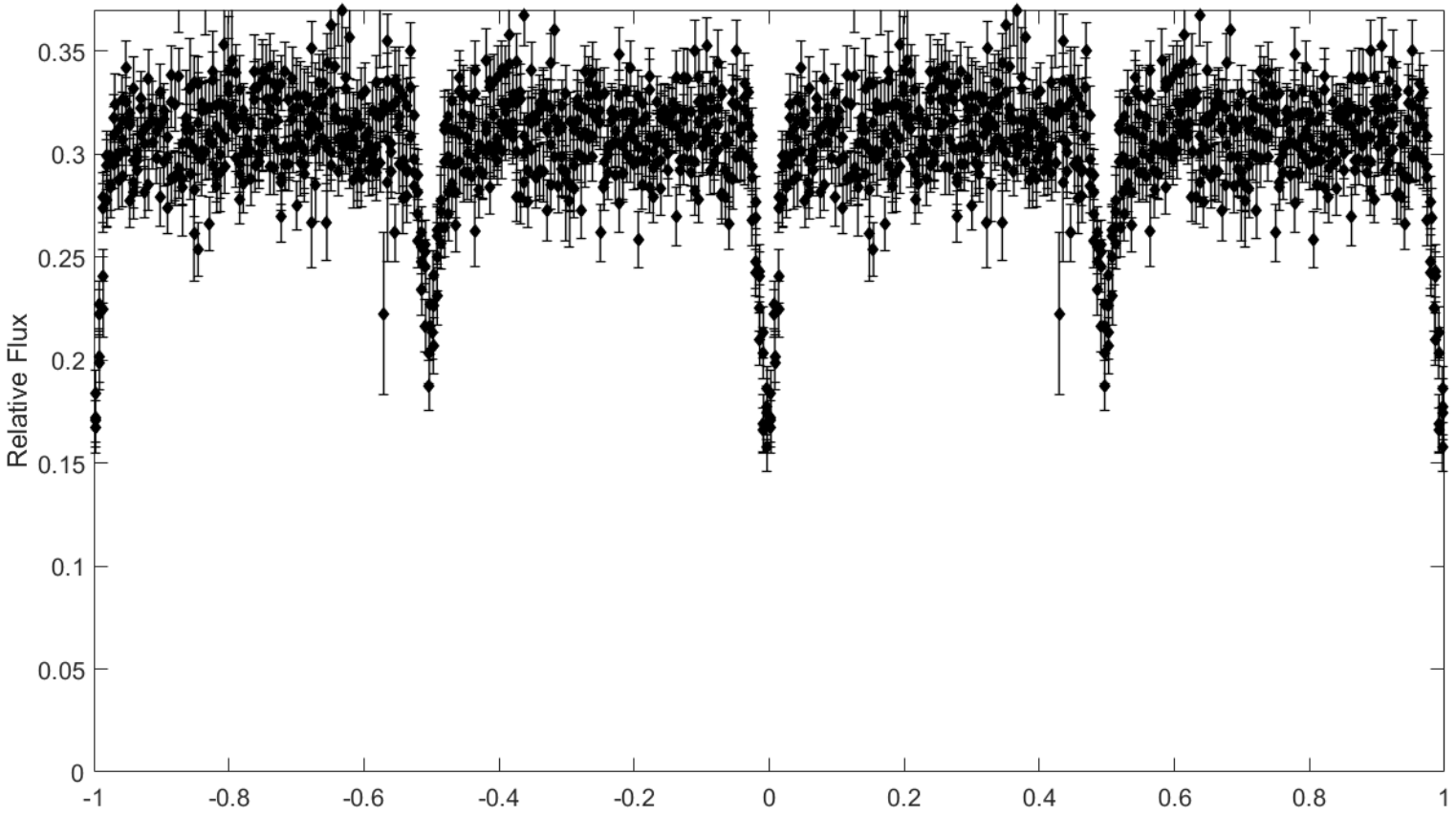

0.4
0.3
0.2
0.1
0
$F_\lambda[10^{-14}$erg cm^{-2}s^{-1}Å$^{-1}]$
1380
1390
1400
1410
1420
Wavelength [Å]
3.5
3
2.5
2
Width [Å]
100
200
300
400
500
600
RV amplitude [km/s]

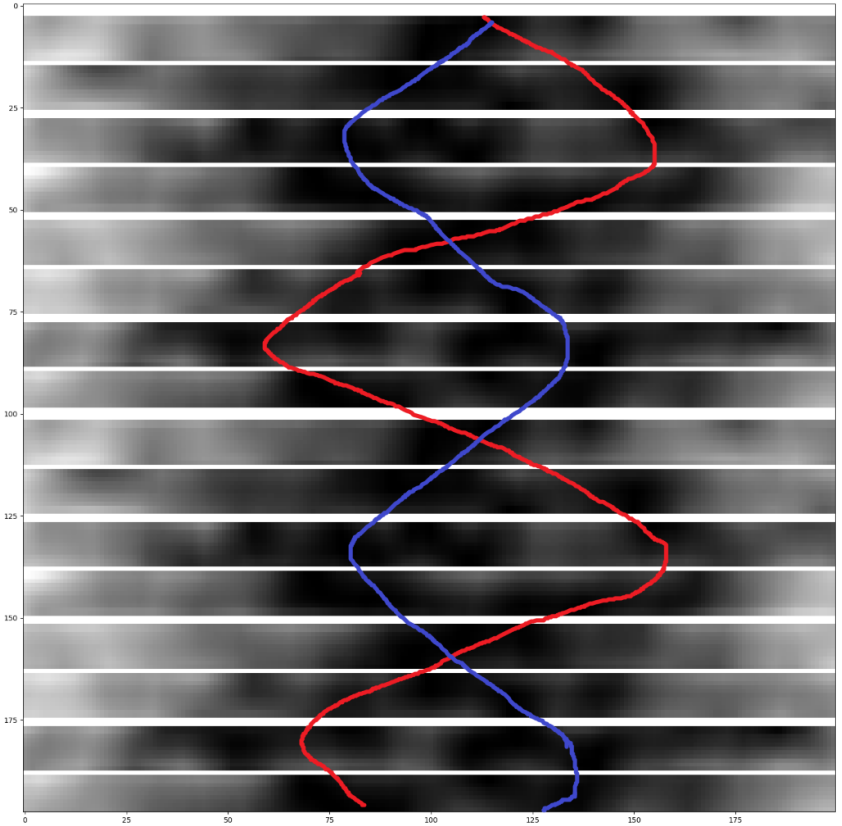

Characteristic Strain
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Gravitational Wave Frequency (Hz)

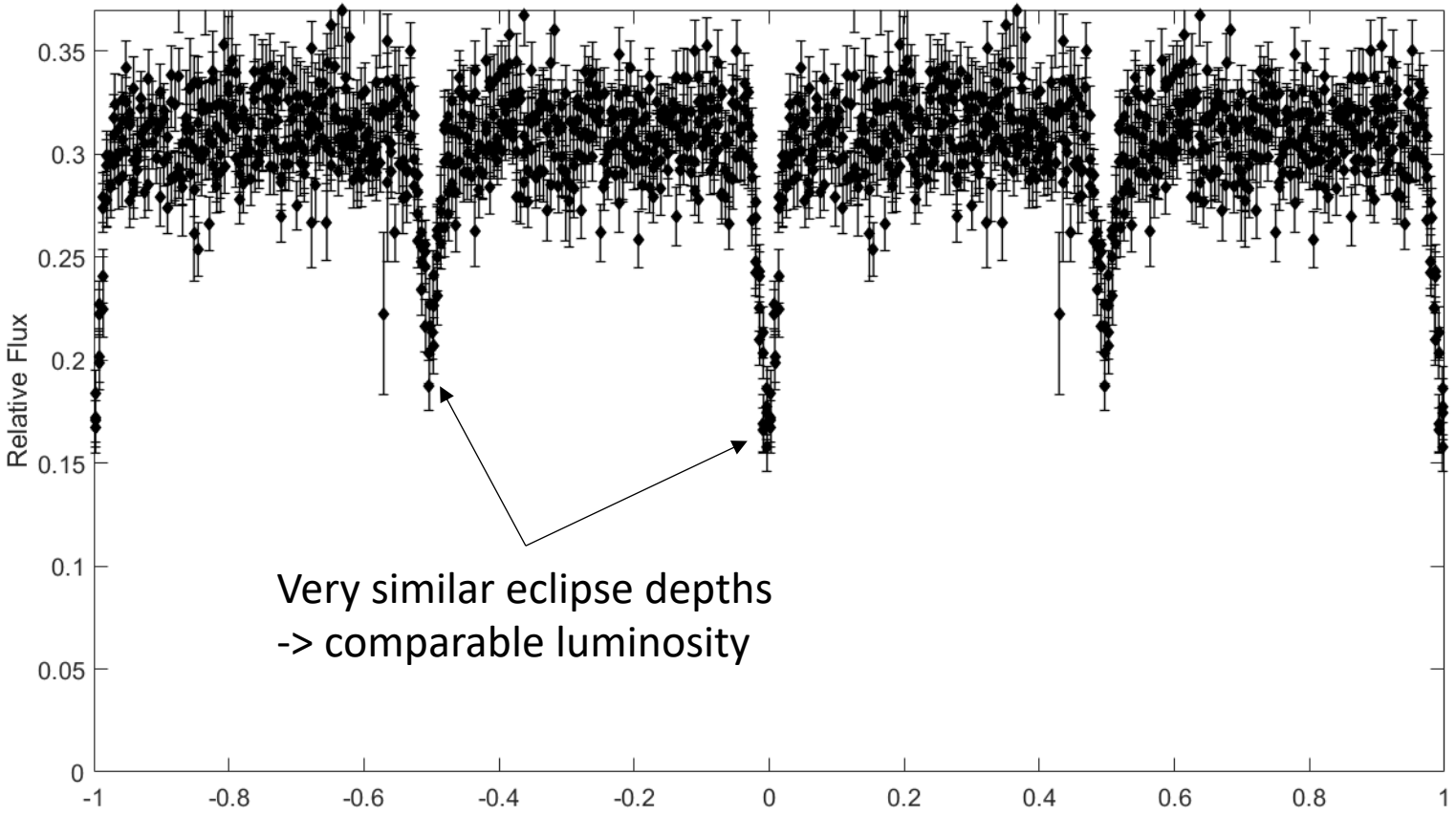

6.91 Min
14.4 Min
17.2 Min
20.6 Min
20.9 Min
23.7 Min
26.4 Min
28.6 Min
33.6 Min
36.9 Min
37.3 Min
39.3 Min
40.6 Min
55.3 Min
56.4 Min
Normalized Flux
Orbital Phase

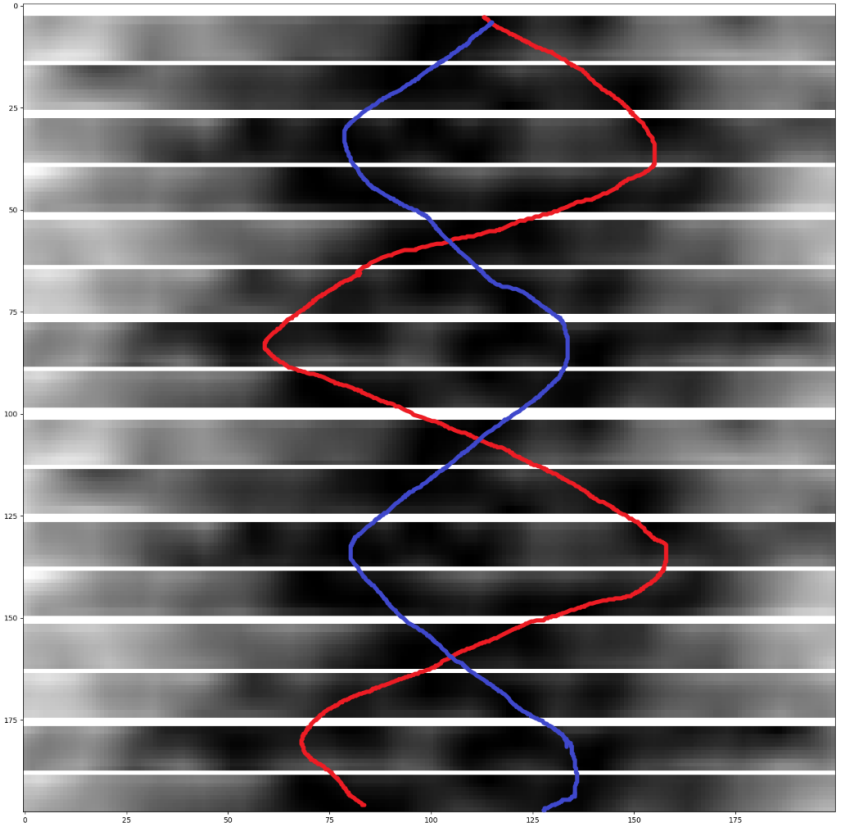

Radial Velocity (km s^{-1})
300
200
100
0
-100
-200
0
0.2
0.4
0.6
0.8
1
Orbital Phase
Normalized Flux
1
0.9
0.8
0.7
0.6
0.5
0
0.01
0.02
0.03
0.04
Elapsed Time (Days)

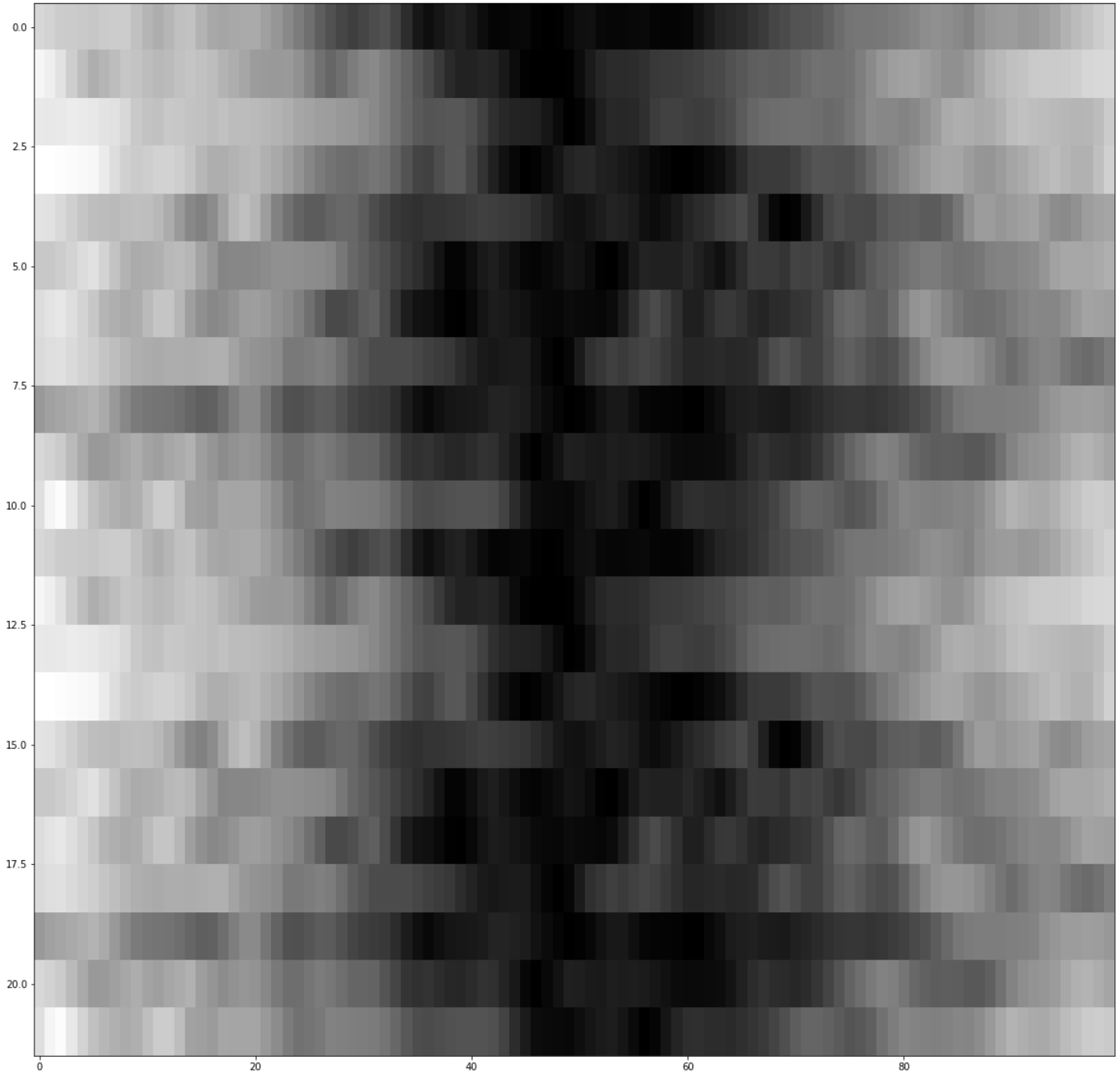

1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1


Relative Flux
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1




Relative Flux
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Very similar eclipse depths
-> comparable luminosity




0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
0
20
40
60
80