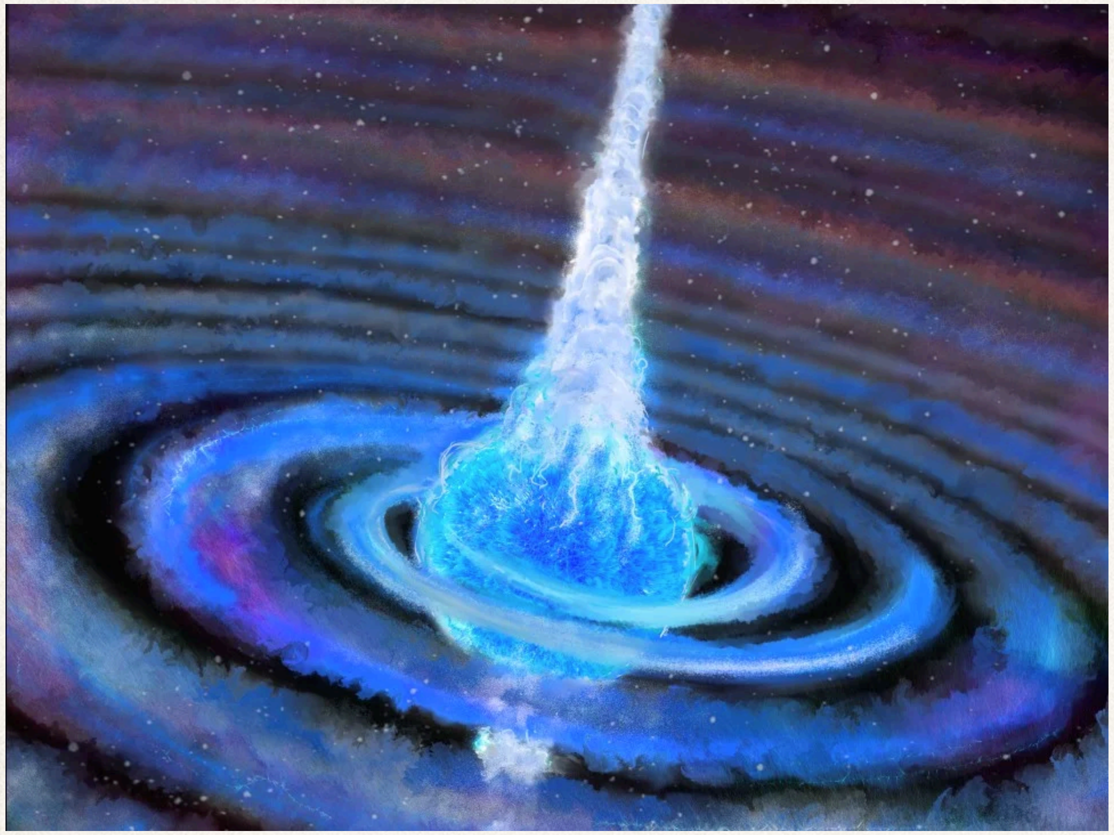



Time-domain science with the VLA Sky Survey

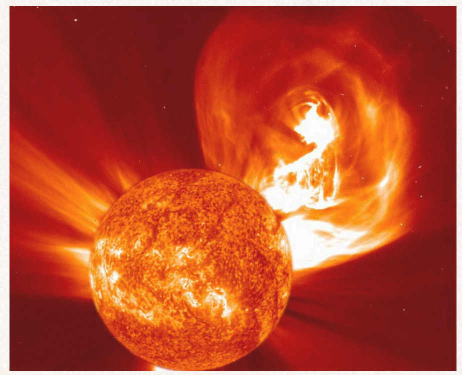
Dillon Dong

Jansky Fellow, NRAO
ddong@nrao.edu

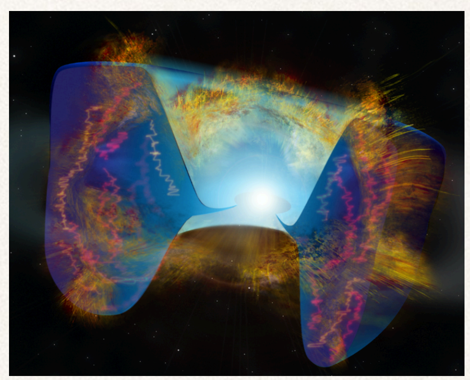
Slow◦ radio transients have been observed from a wide variety of small✳ astronomical objects

◦ where slow = image-domain searches ✳ where small < transient timescale × c

[1] Pre-, post-, and main sequence stars

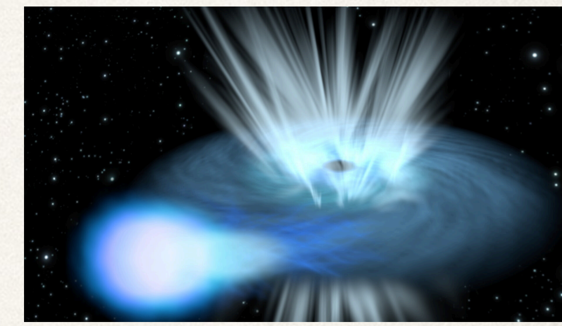


[2] Stellar explosions (supernovae, gamma ray bursts, a compact object/ massive star merger)

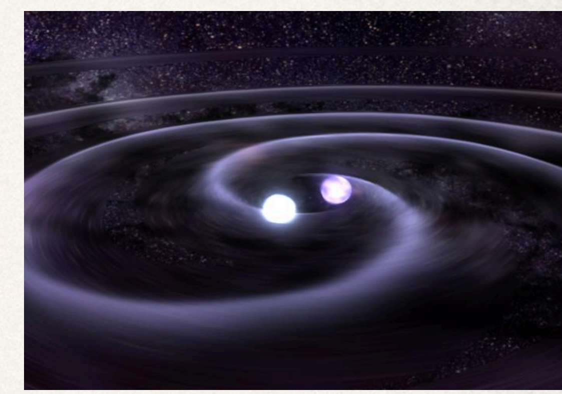


[3] SMBHs: active or quiescent, jetted or low-velocity

[4] Flaring compact objects (white dwarfs, neutron stars, BHs)



[5] Compact object mergers



[6] An emerging pulsar wind nebula

Including (among many other references)

[1] Ayala, Dong, in prep

[2] Dong+21, 23b, in prep

[3] Nyland+20, Somalwar +21, 22, 23

[4] Yao+20, 21, Miller+23, in prep

[5] Hallinan+2017

[6] Dong & Hallinan 2023a, in press

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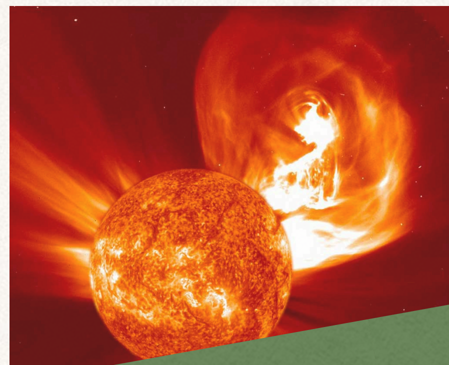
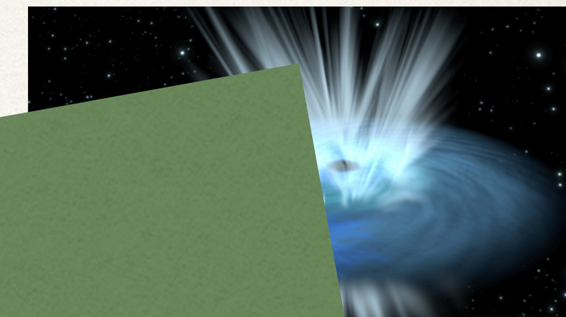
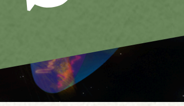


[4] Flaring compact

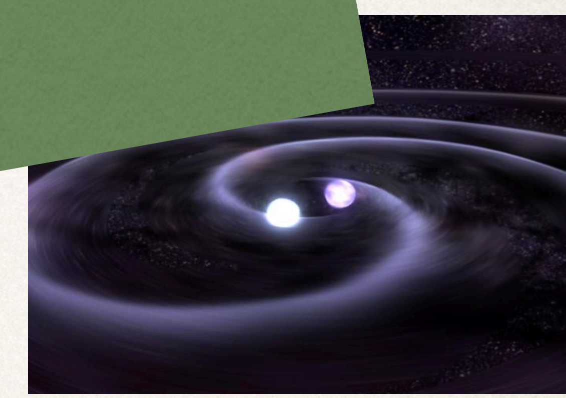


Likely more classes, yet to be discovered

[2]



mergers



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[5] Hallinan+2017

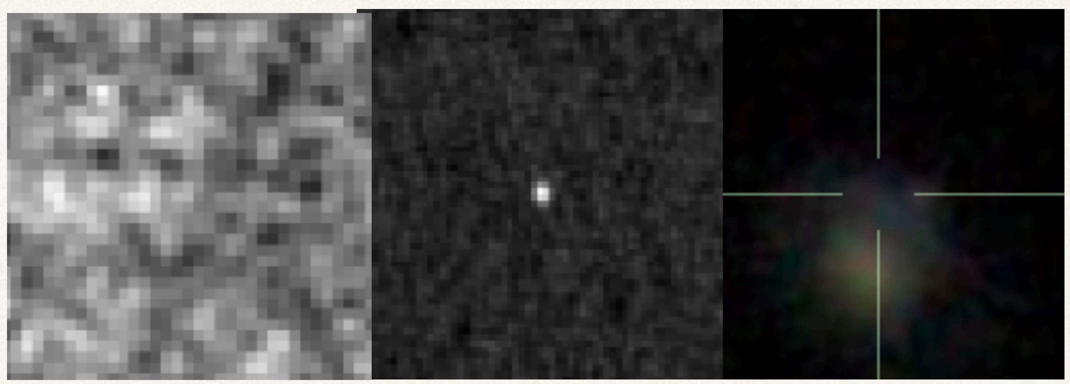
[6] Dong & Hallinan 2023a, in press

But before we can tackle the big questions, there are

Two basic challenges to solve

Detection

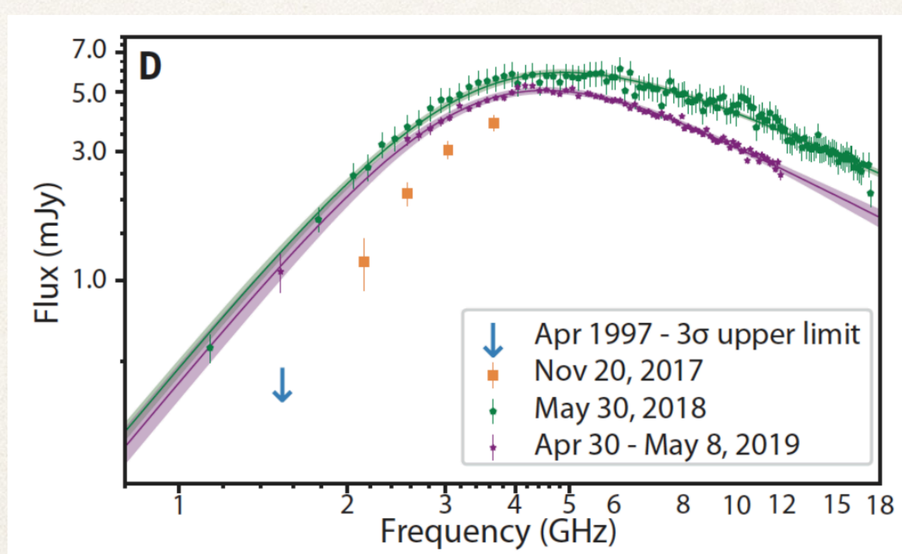
(at scale)



- Assembly of statistical samples
- Achieving the scale required to detect rare classes

Identification

(at scale)



- Characterization of emitting objects / regions
- Identification of new transition populations

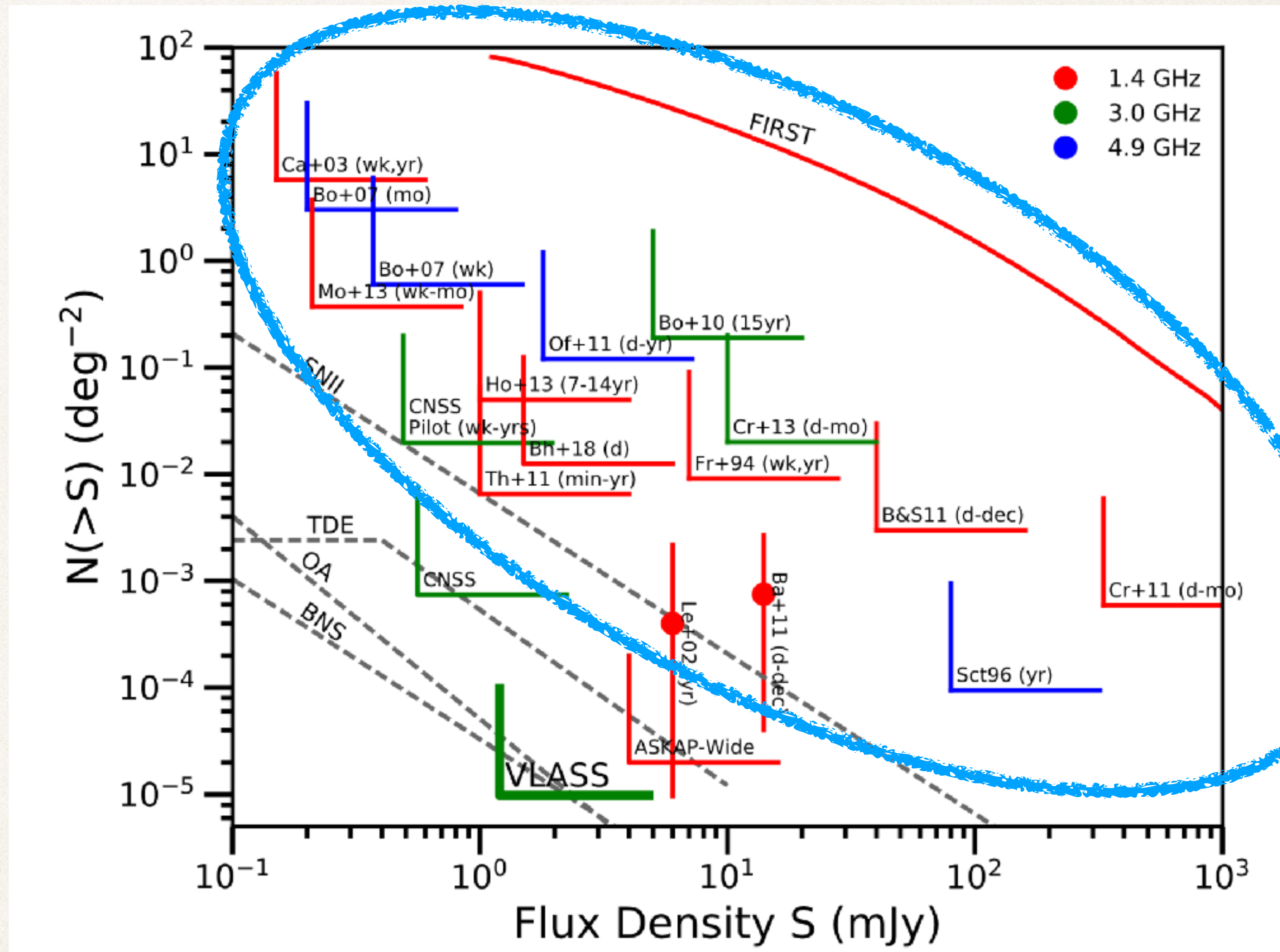
Decades of pioneering surveys doing direct detection of radio transients

Scales probed:

- < 1 deg^2 to ~0.1mJy
- ~10 deg^2 to ~1 mJy
- ~1000 deg^2 to > 10 mJy

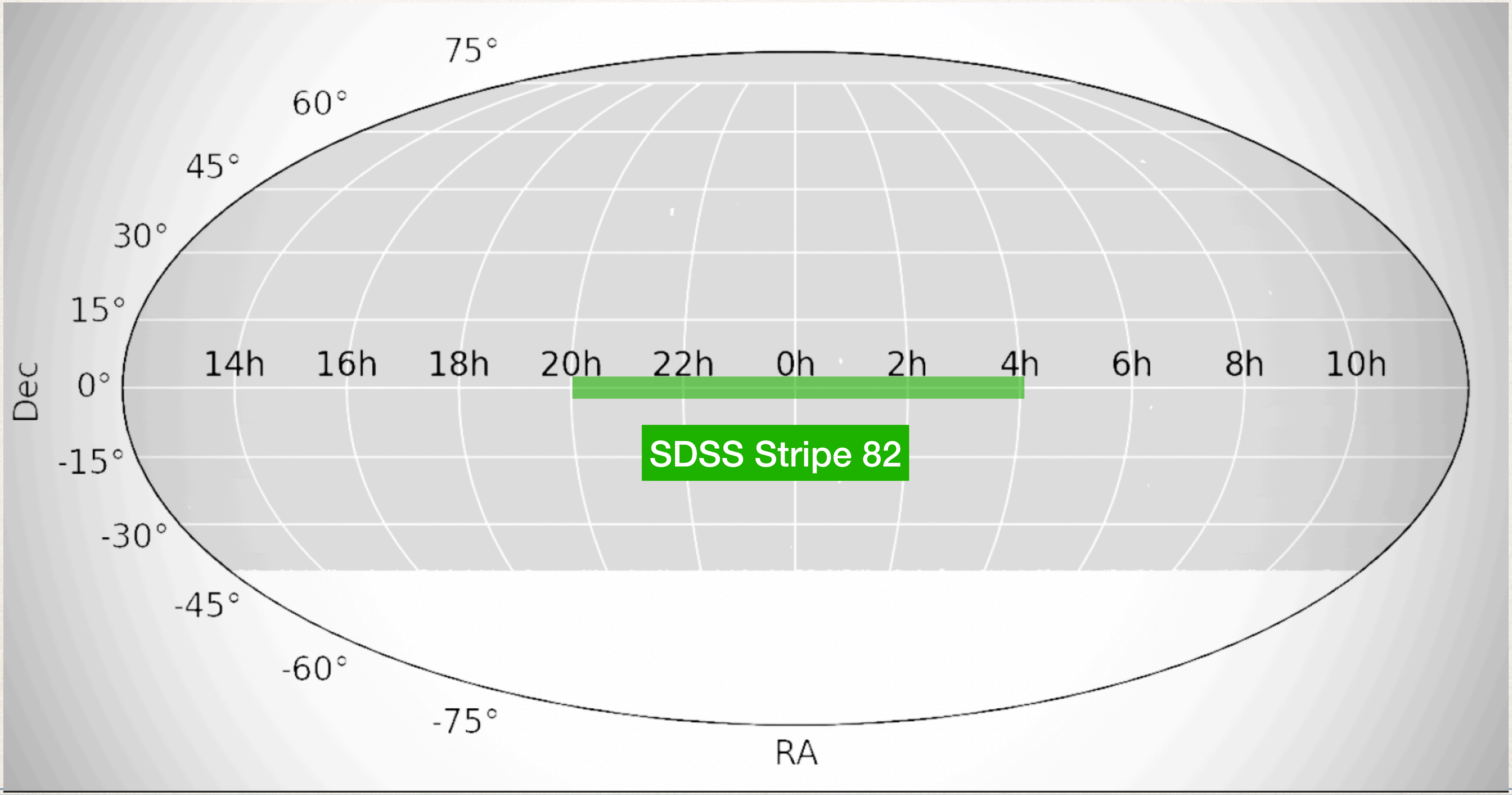
Timescales from days to years

- Mostly upper limits



Frail+12, Lacy+20

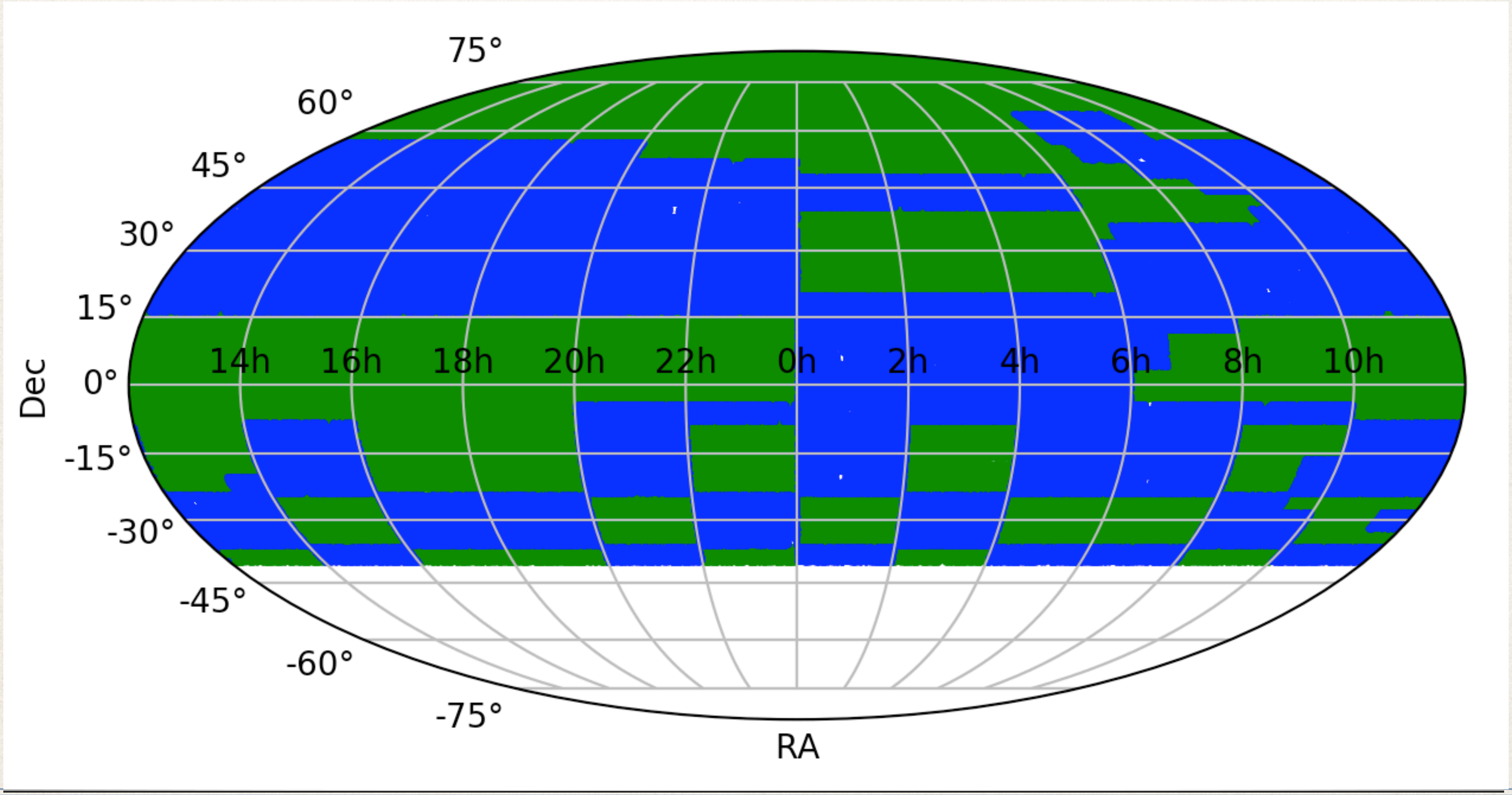
First direct detections in the Caltech-NRAO Stripe 82 Survey (mid 2010s)



O(10) transients found

Mooley+16, Mooley+18, Anderson+19, Kunert-Bajraszewska+20, Wołowska+21

O(1000) transients per epoch in the VLA Sky Survey



Dong+23d, in prep, Chen+23, in prep

Automating transient detection in VLASS

NRAO

- Observations
- Calibration
- Imaging

→

Source extraction

PyBDSF

~10^6 sources per epoch

Dong+23d, in prep

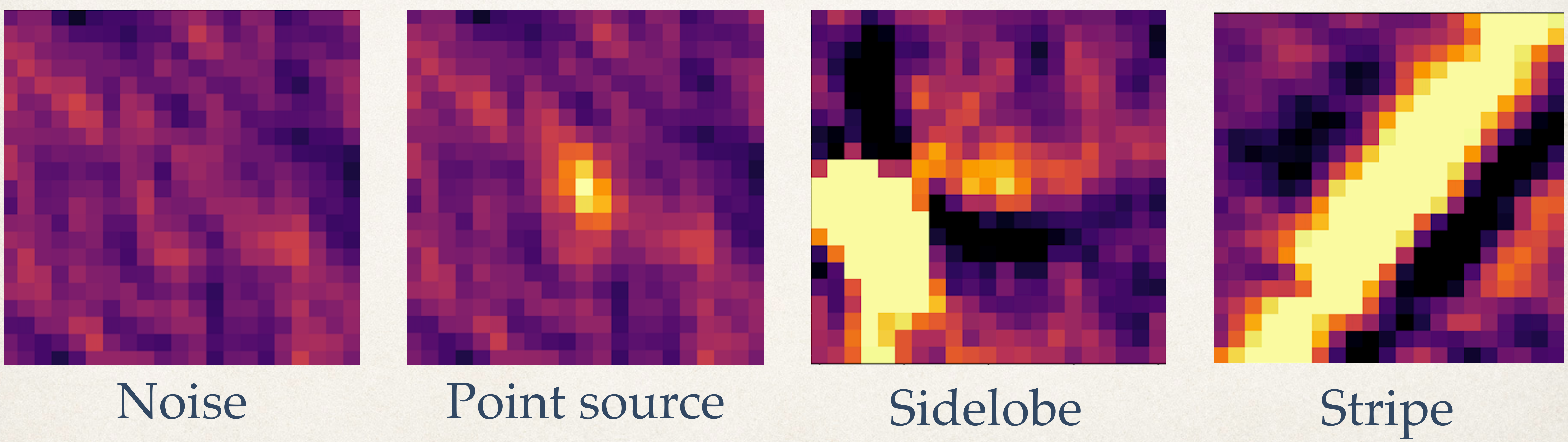
Automating transient detection in VLASS

NRAO [Observations, Calibration, Imaging] → Source extraction

PyBDSF

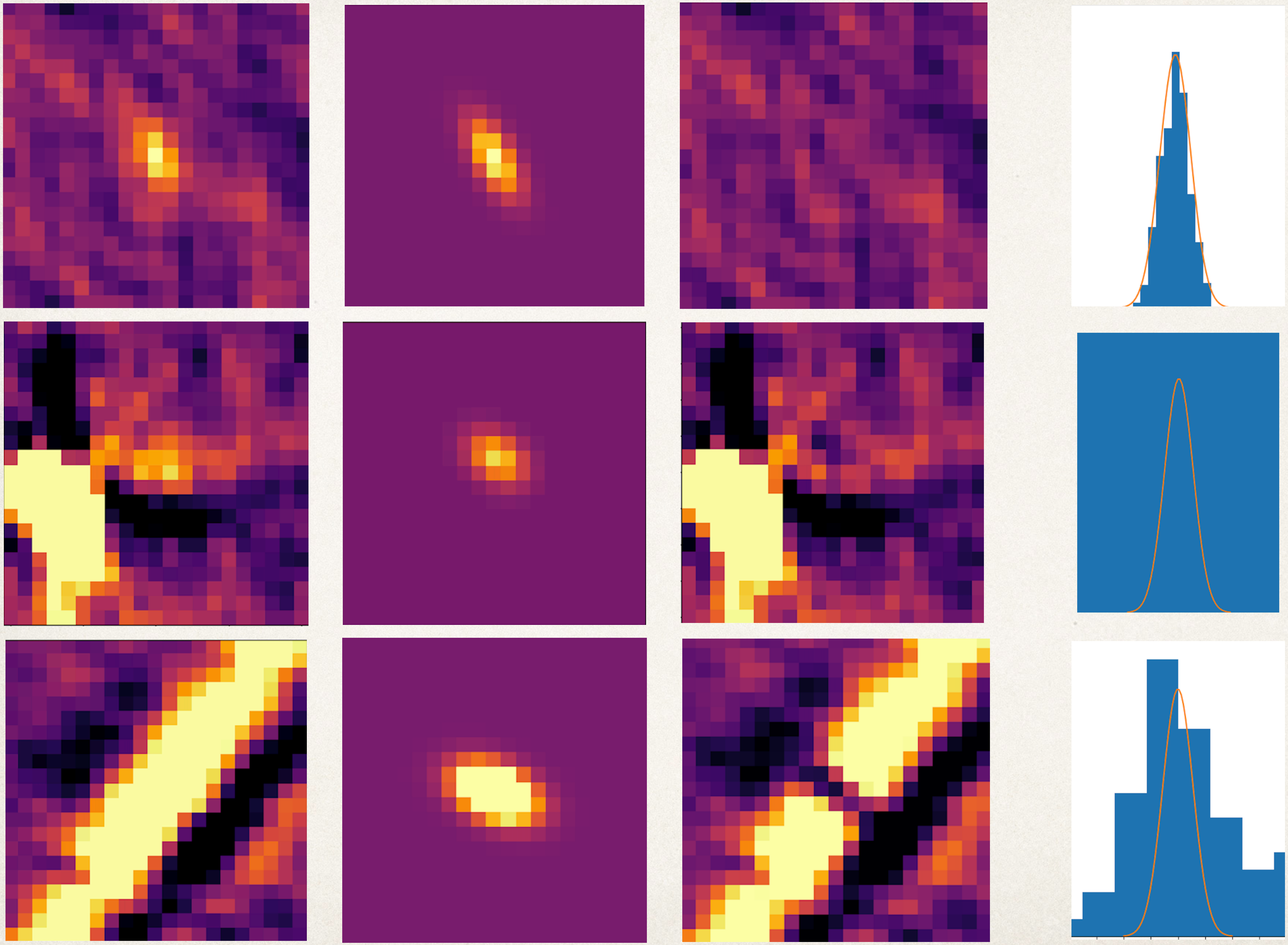
$\sim 10^6$ sources per epoch

→ Artifact filtering

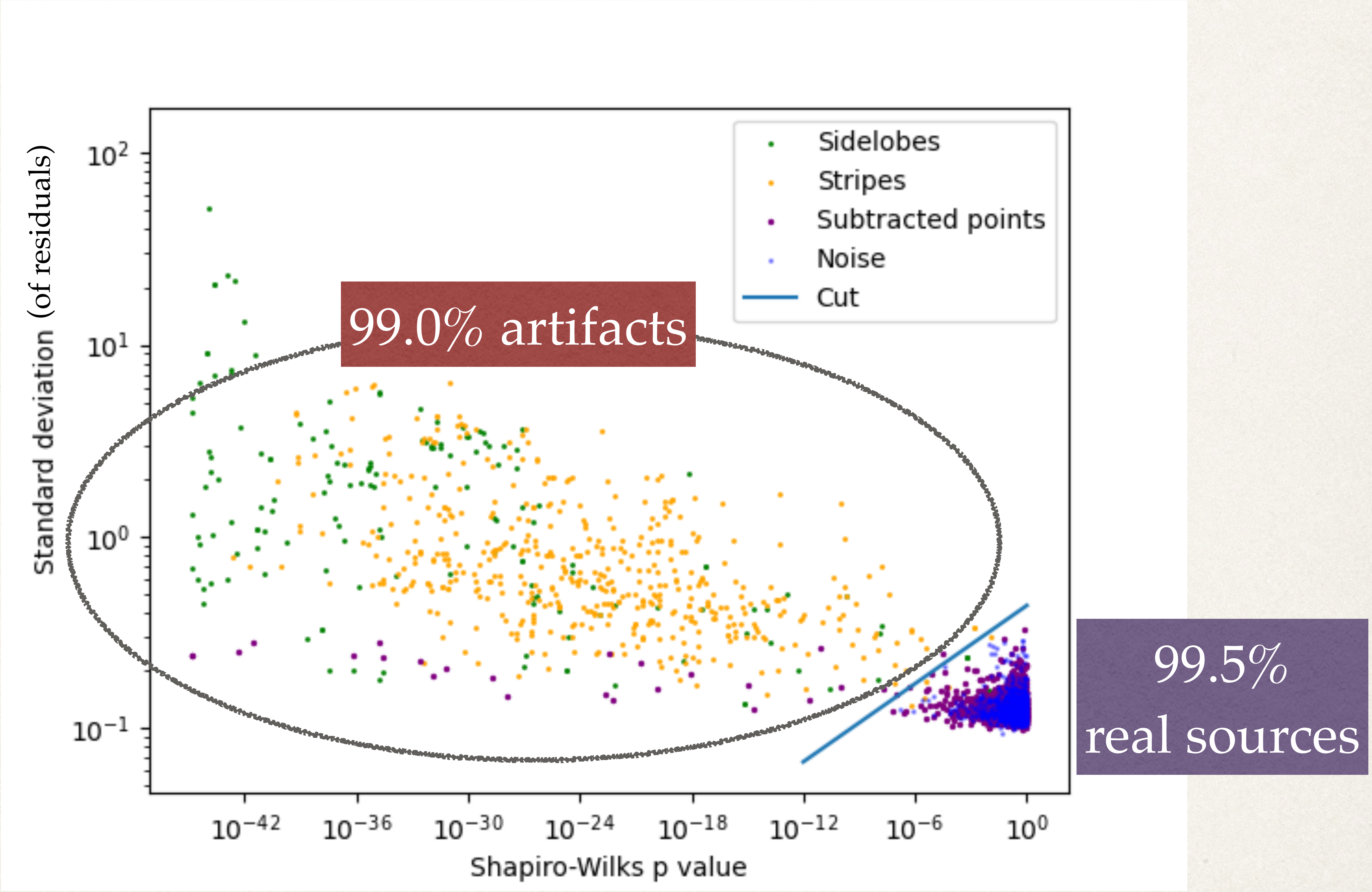


Dong+23d, in prep

Data | Model | Residuals | Residual pixel values



For ~5000 VLASS transient candidates classified by eye, current heuristics have a ~**0.5% false positive rate** and a ~**1% false negative rate**



Dong+23d, in prep

Automating transient detection in VLASS

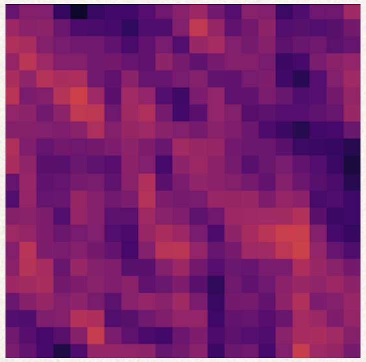
NRAO [Observations / Calibration / Imaging] → Source extraction

PyBDSF

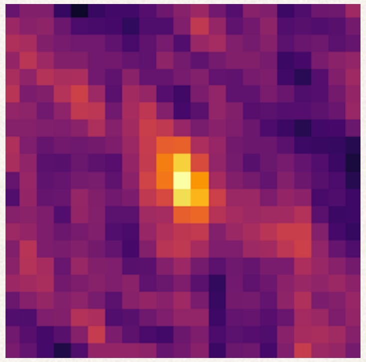
~10^6 sources per epoch

→ Artifact filtering

Noise in one epoch



Point source in another



= transient!

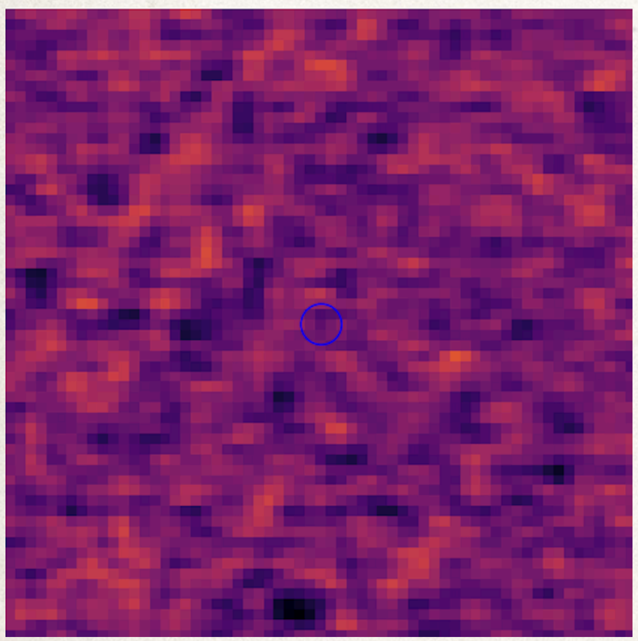
→ Transient catalog

Dong+23d, in prep

Part 2:
Identification

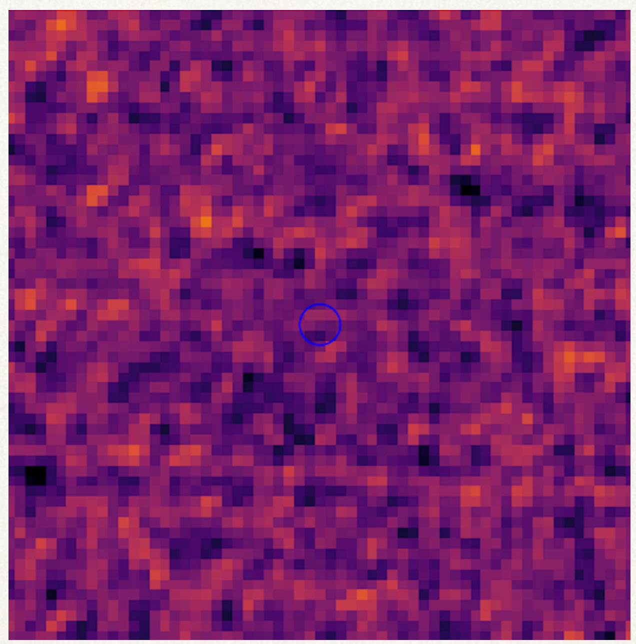
Some sources are immediately identifiable

- Multi-wavelength association ✓
- Observational precedent ✓
- Theoretical expectation ✓



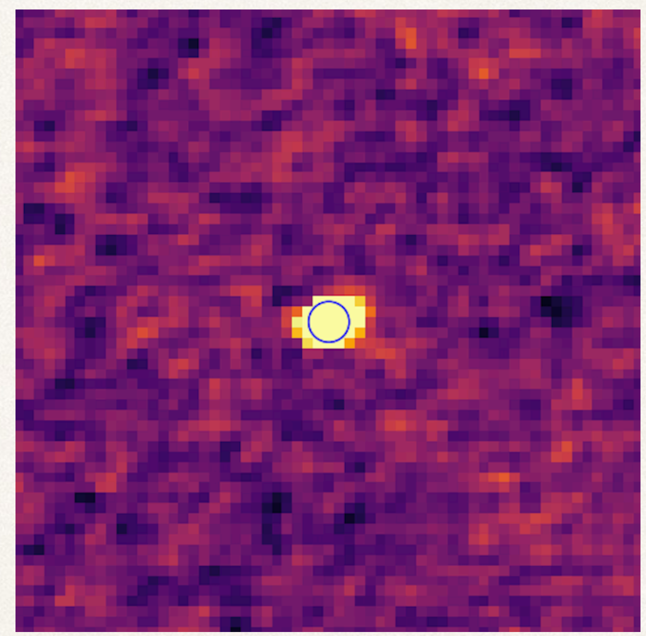
< 0.36 mJy

2017



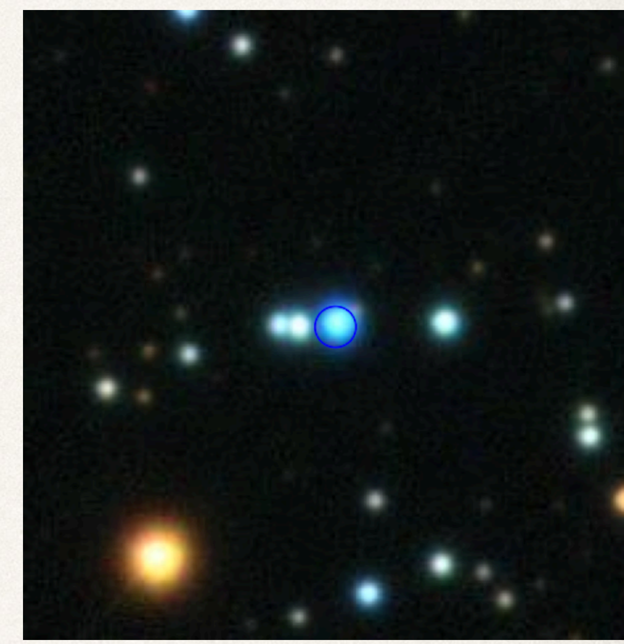
< 0.42 mJy

2020



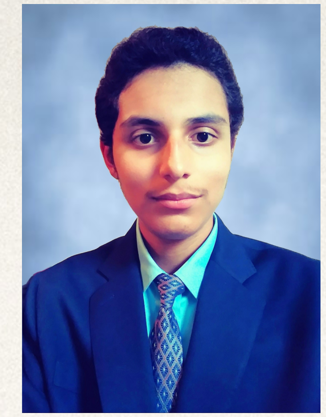
23 mJy

2023



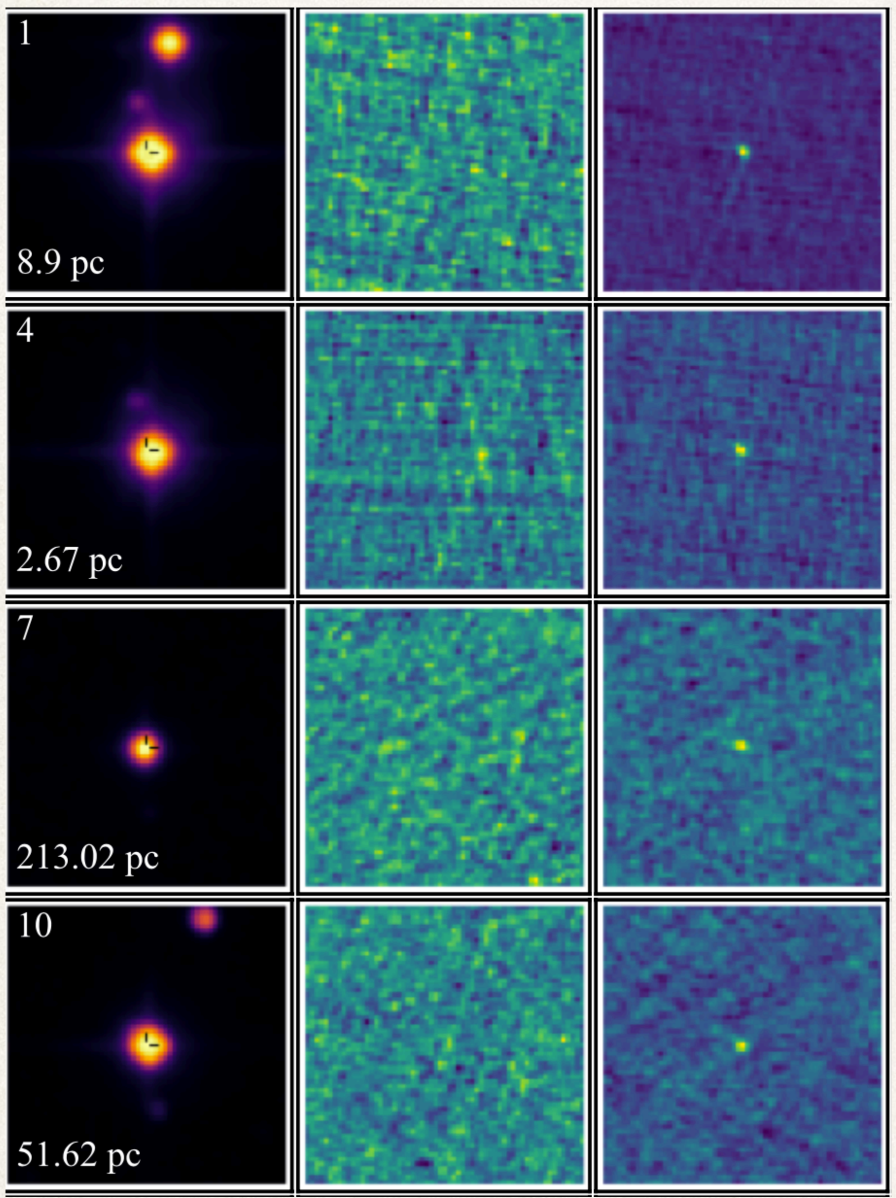
Classical Nova
V1405 Cas
(2021)

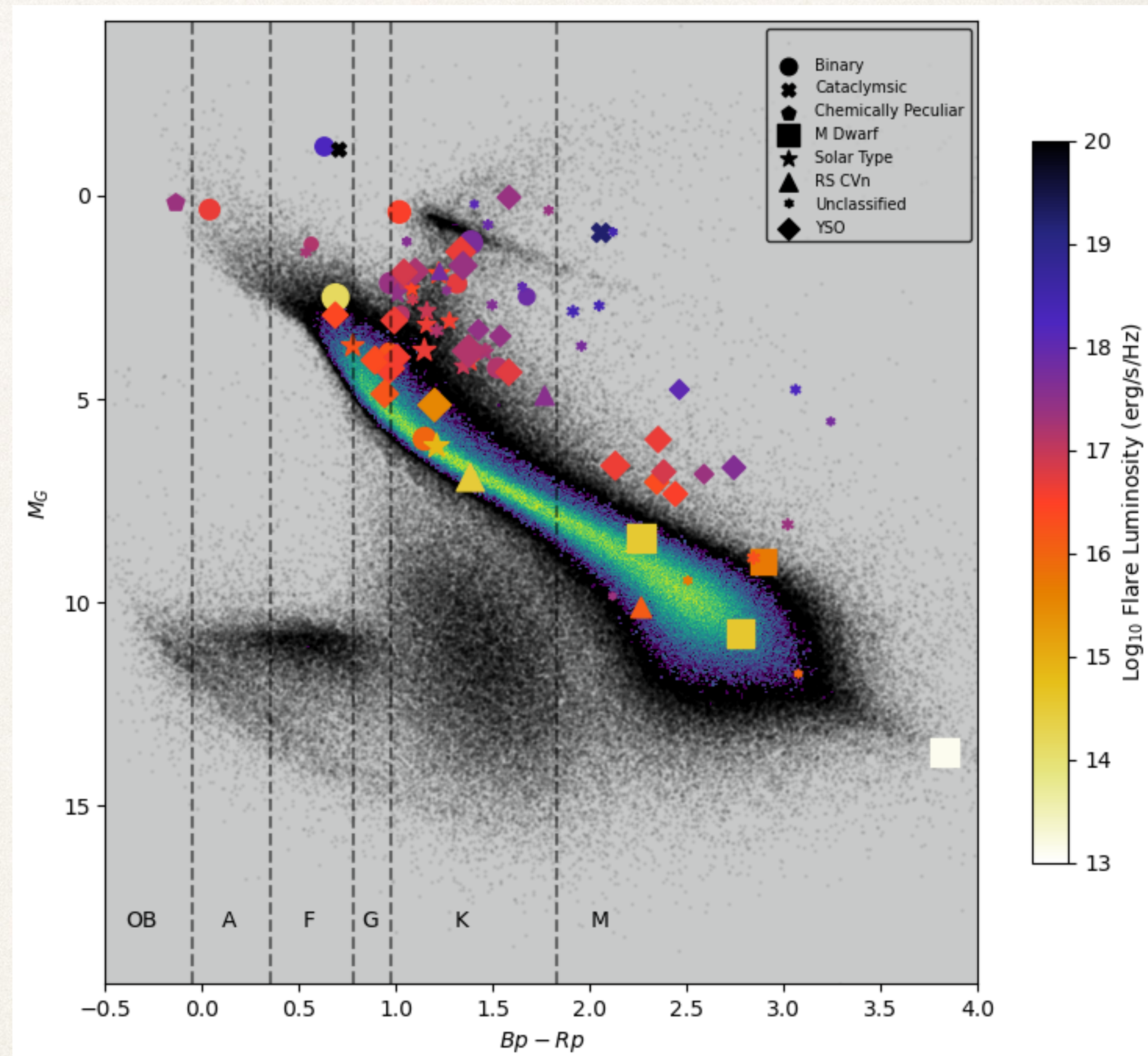
~80 transients in VLASS 2 vs 1 associated with Gaia stars



Carlos Ayala

Incoming senior at Caltech





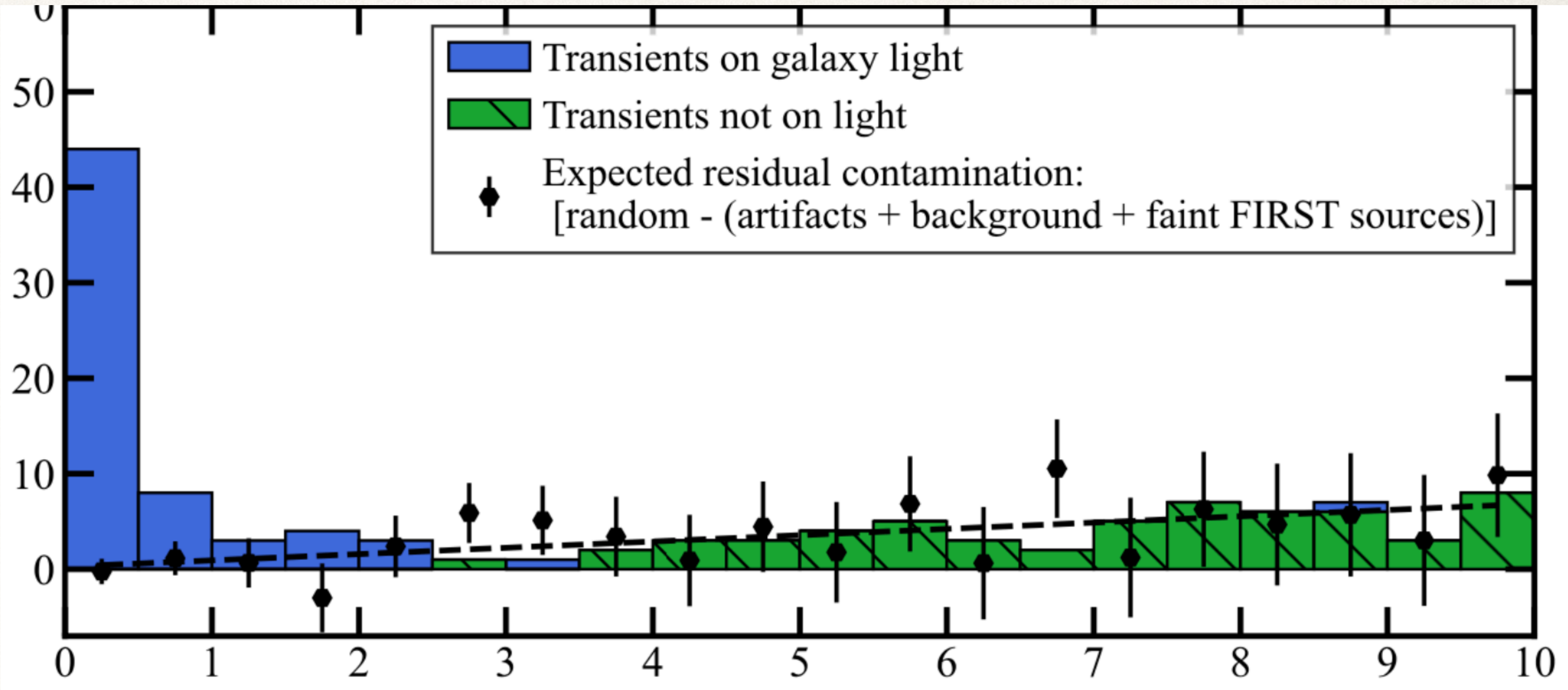
Ayala, Dong et al. 2023 (in prep)

Others are best identified *statistically* in pre-defined experiments

64 transients associated with d < 200 Mpc galaxies in VLASS Epoch 1 vs FIRST

Transient candidates

(automated filters & visual vetting)



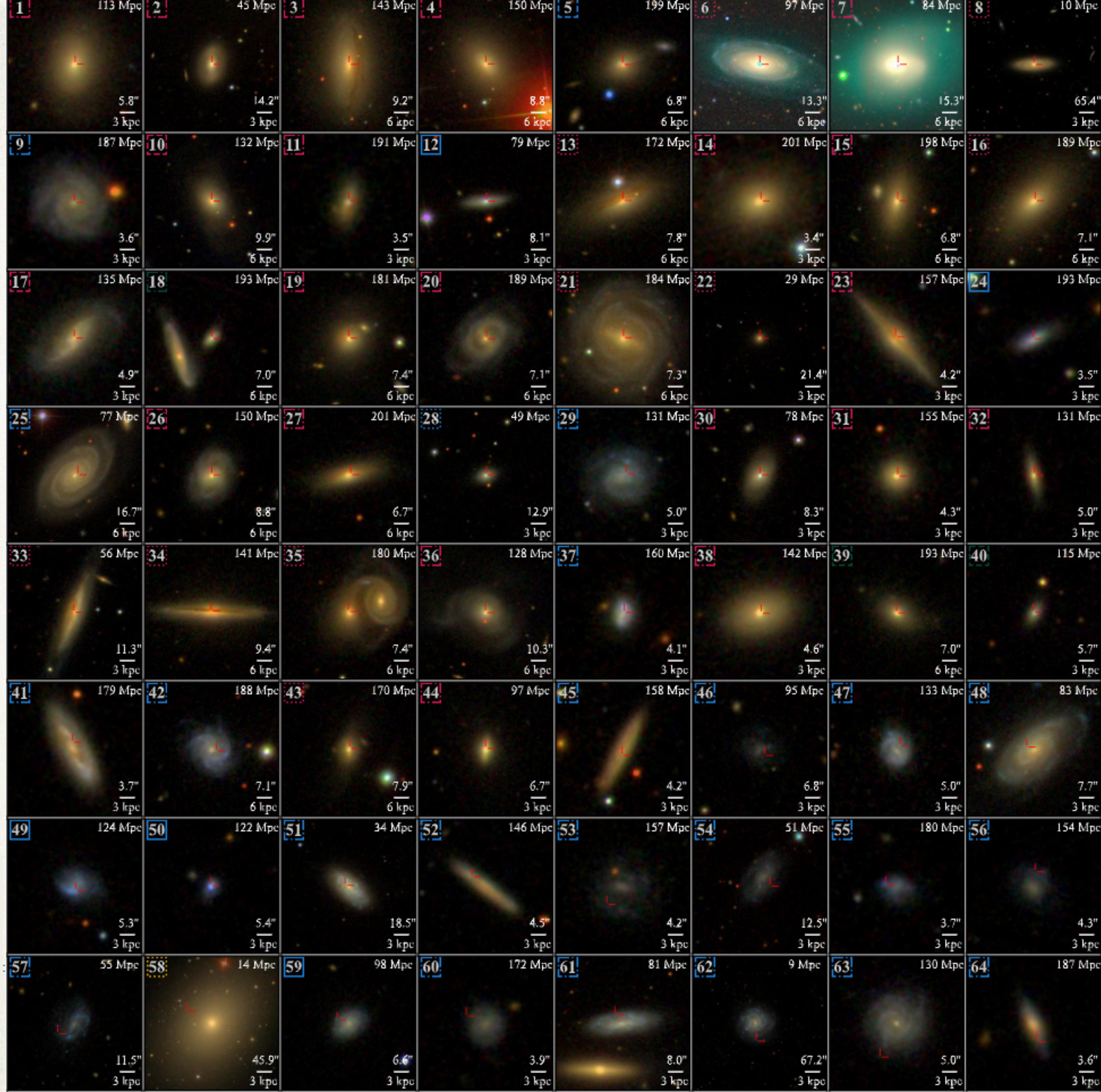
$[r_{norm} = \Delta\theta \, / \, r_{half}(\phi)]$

Offset from nearest d < 200 Mpc galaxy

(normalized by half-light radius)

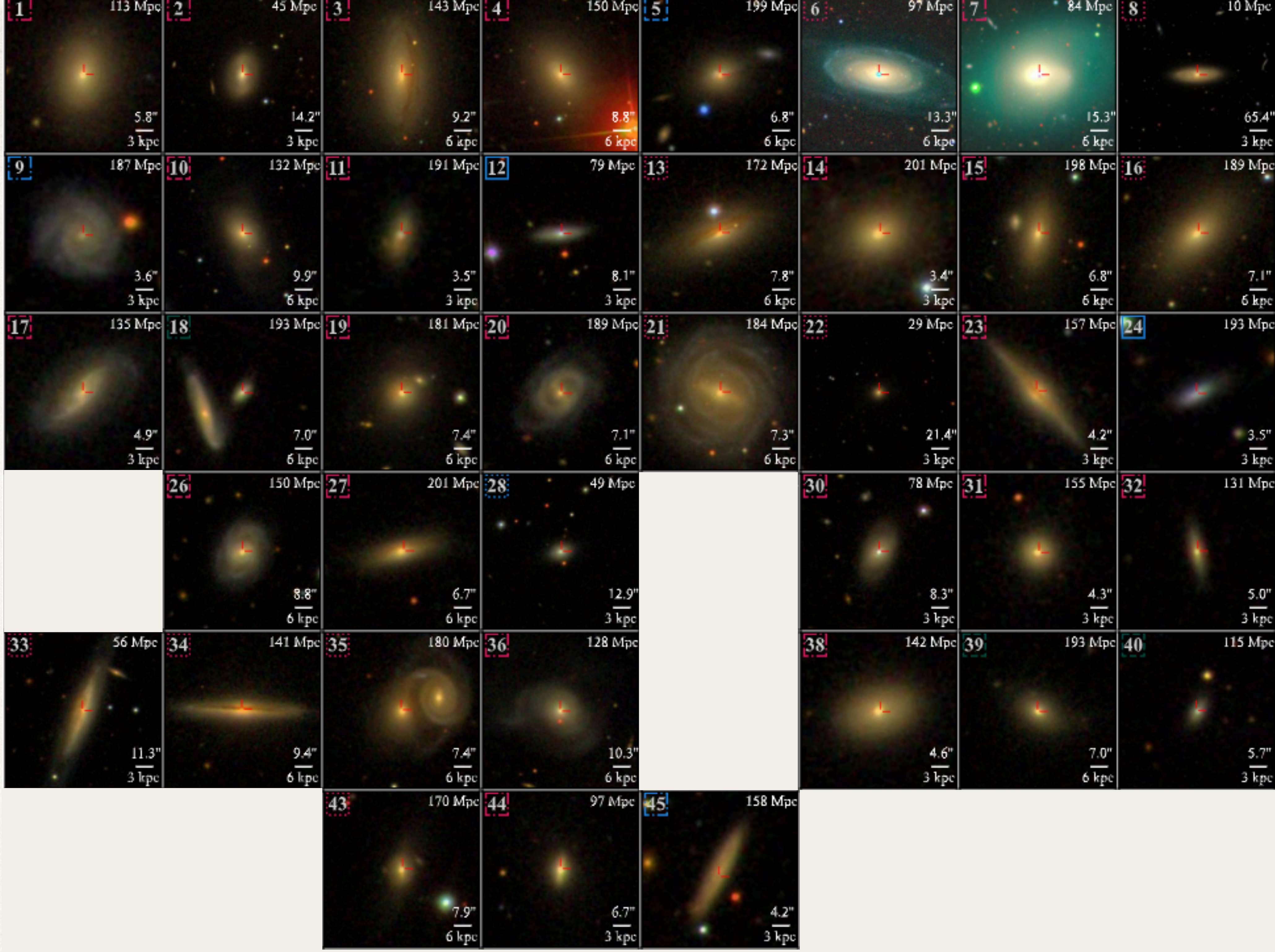
Dong+ 2023b (in prep)

64 transients associated with d < 200 Mpc galaxies in VLASS Epoch 1 vs FIRST



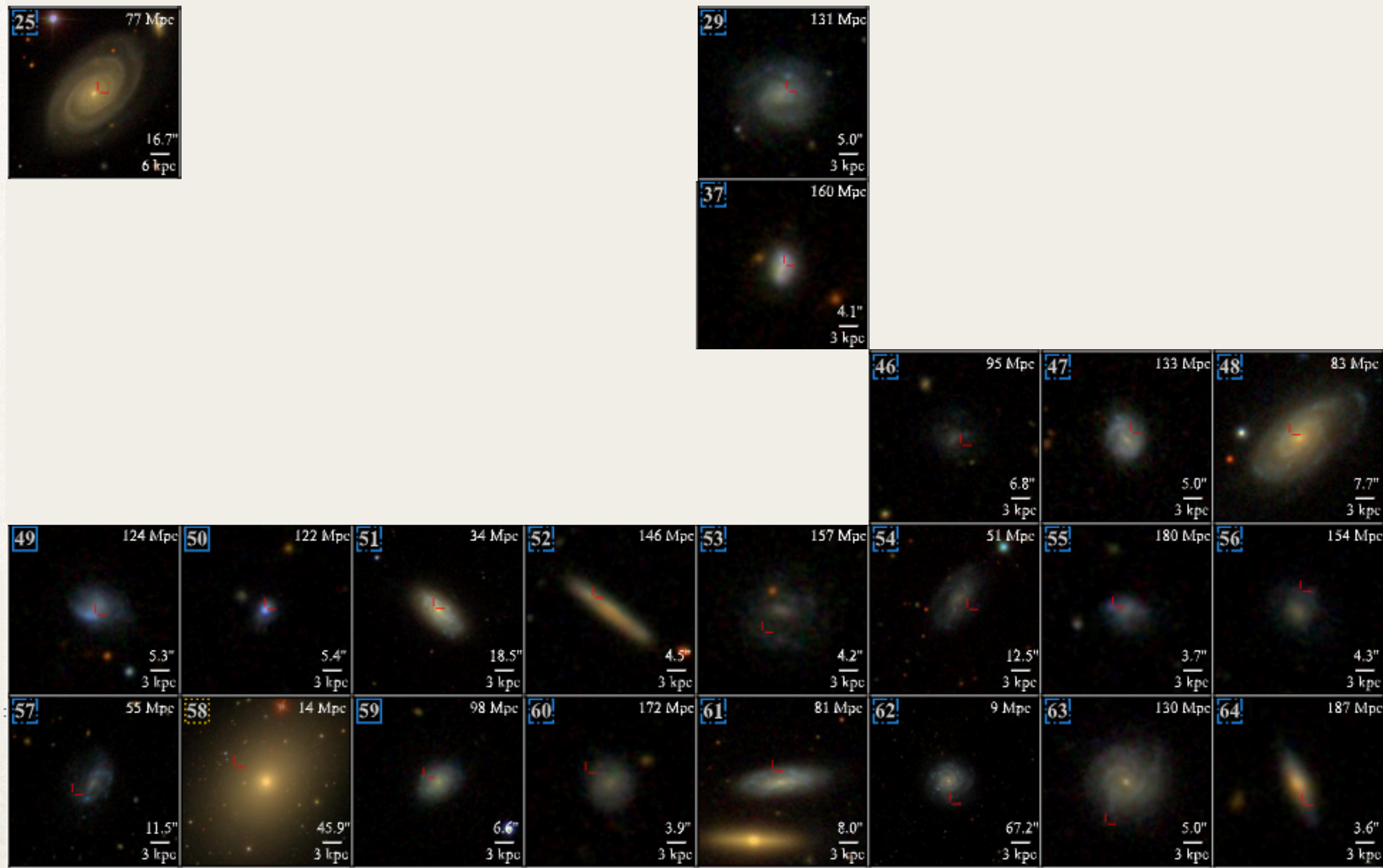
Dong+ 2023b (in prep)

Nuclear transients are primarily located in red and dead galaxies



Dong+ 2023b (in prep)

Off-nuclear transients are primarily located in star forming galaxies

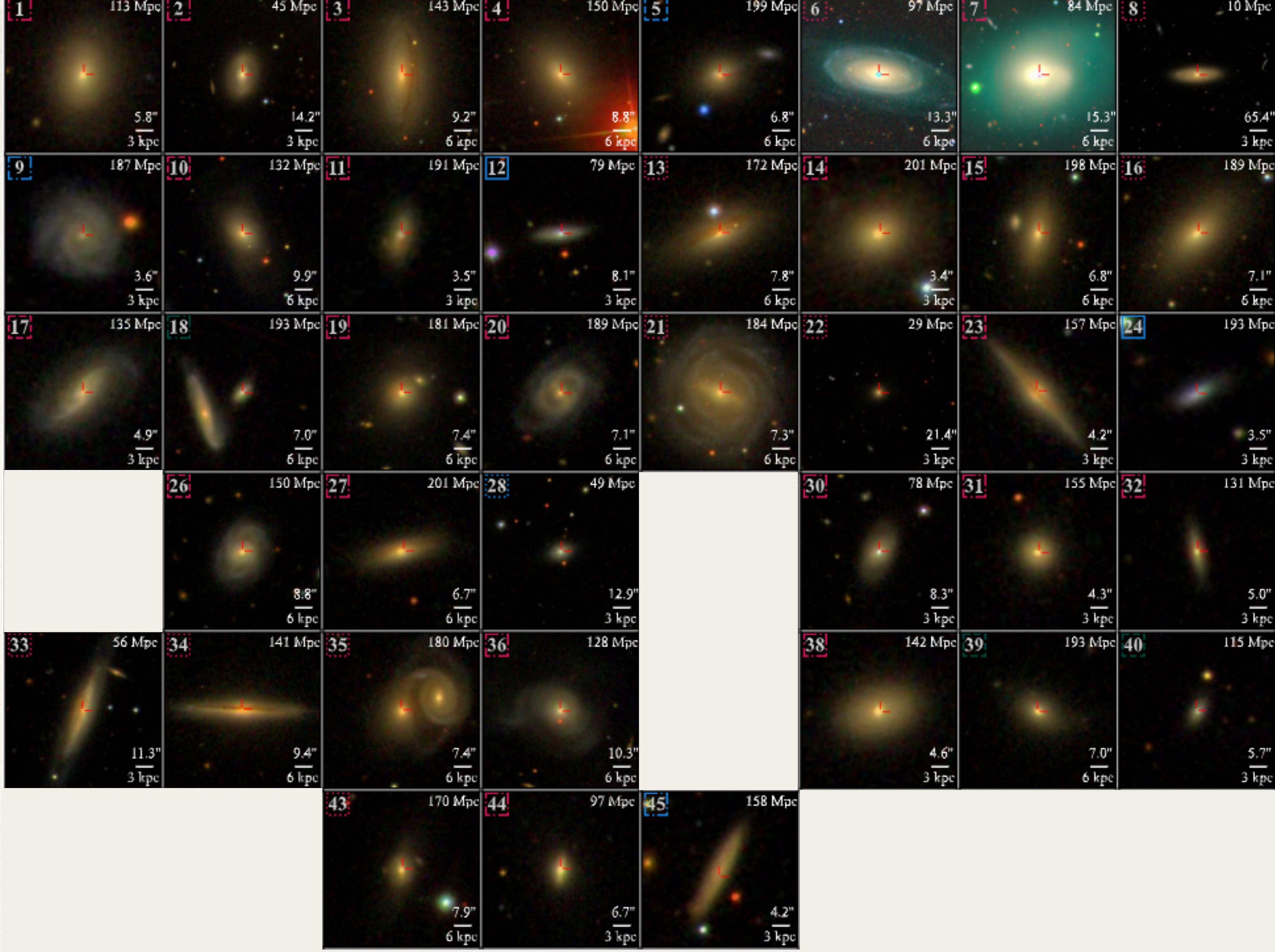


Dong+ 2023b (in prep)

Nuclear transients are primarily located in red and dead galaxies

Many are in AGN:

~1 (non-relativistic) outflow per AGN per century



Dong+ 2023b (in prep)

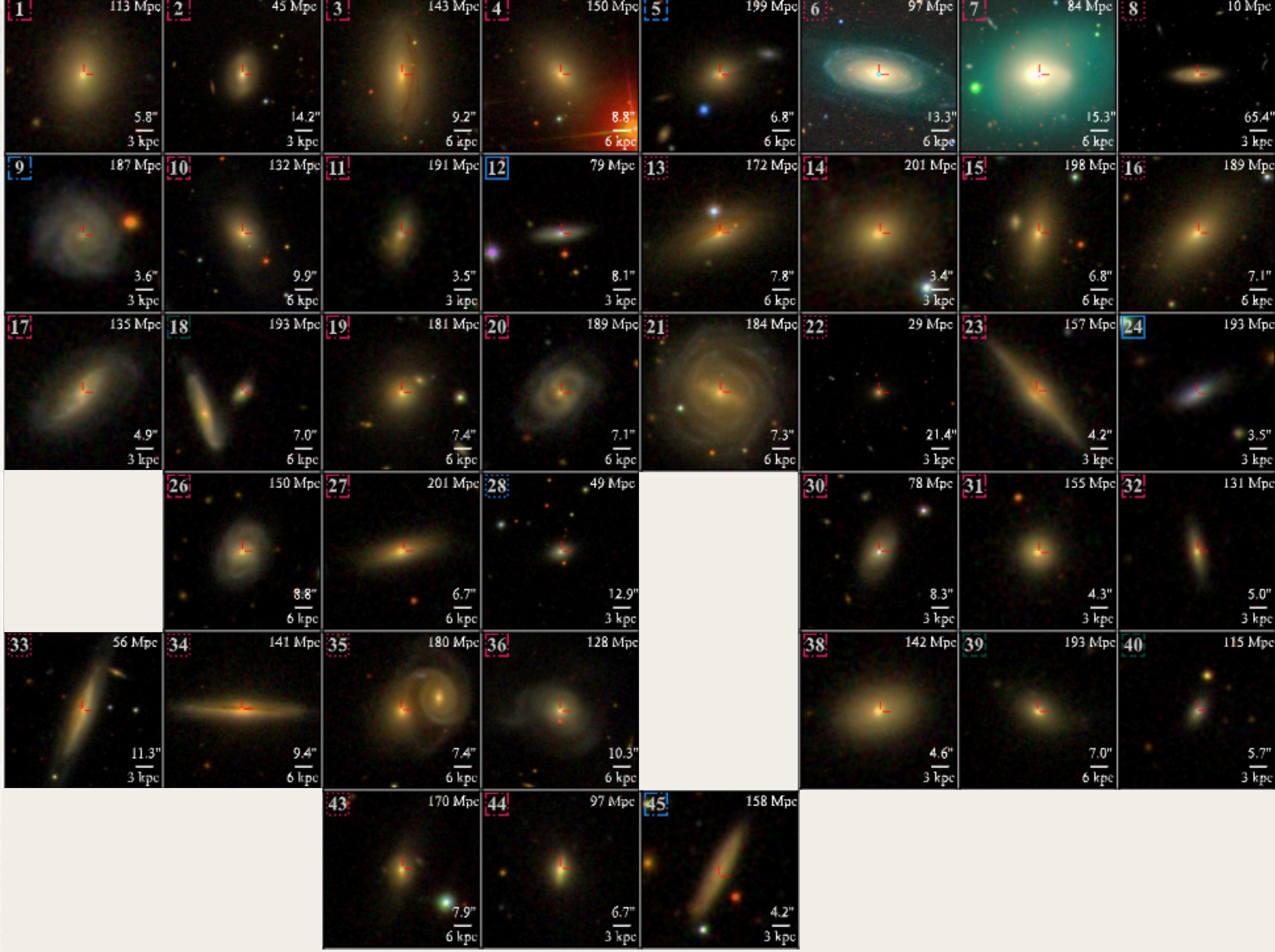
Nuclear transients are primarily located in red and dead galaxies

Many are in AGN:

~1 (non-relativistic) outflow per AGN per century

Some are in completely quiescent galaxies:

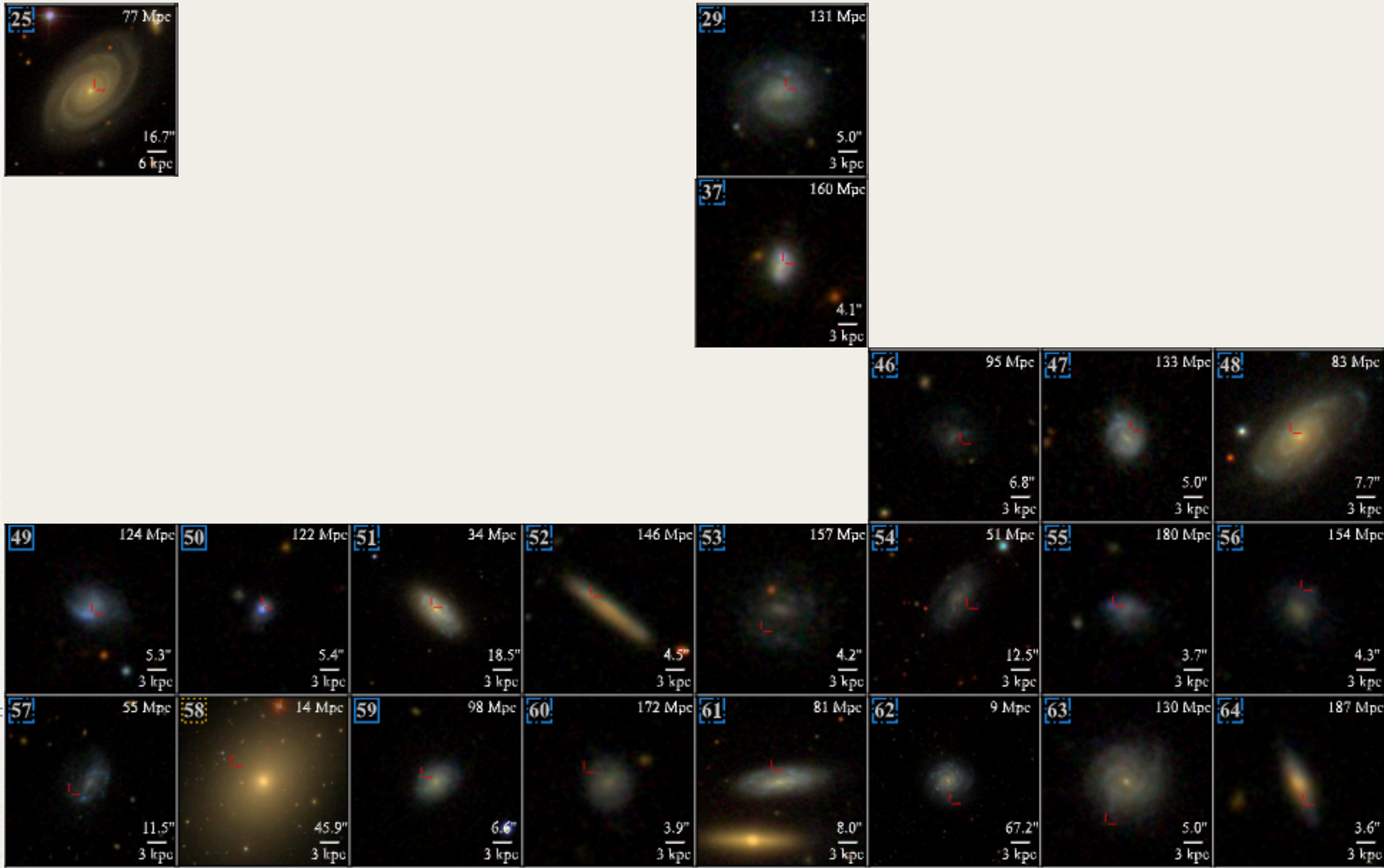
~decade timescale tidal disruption events at ~1-30% of the optical TDE rate



Dong+ 2023b (in prep)

Off-nuclear transients are primarily located in star forming galaxies

Most are consistent with dense shells of gas at ~10^{17} cm around supernovae



Dong+ 2023b (in prep)

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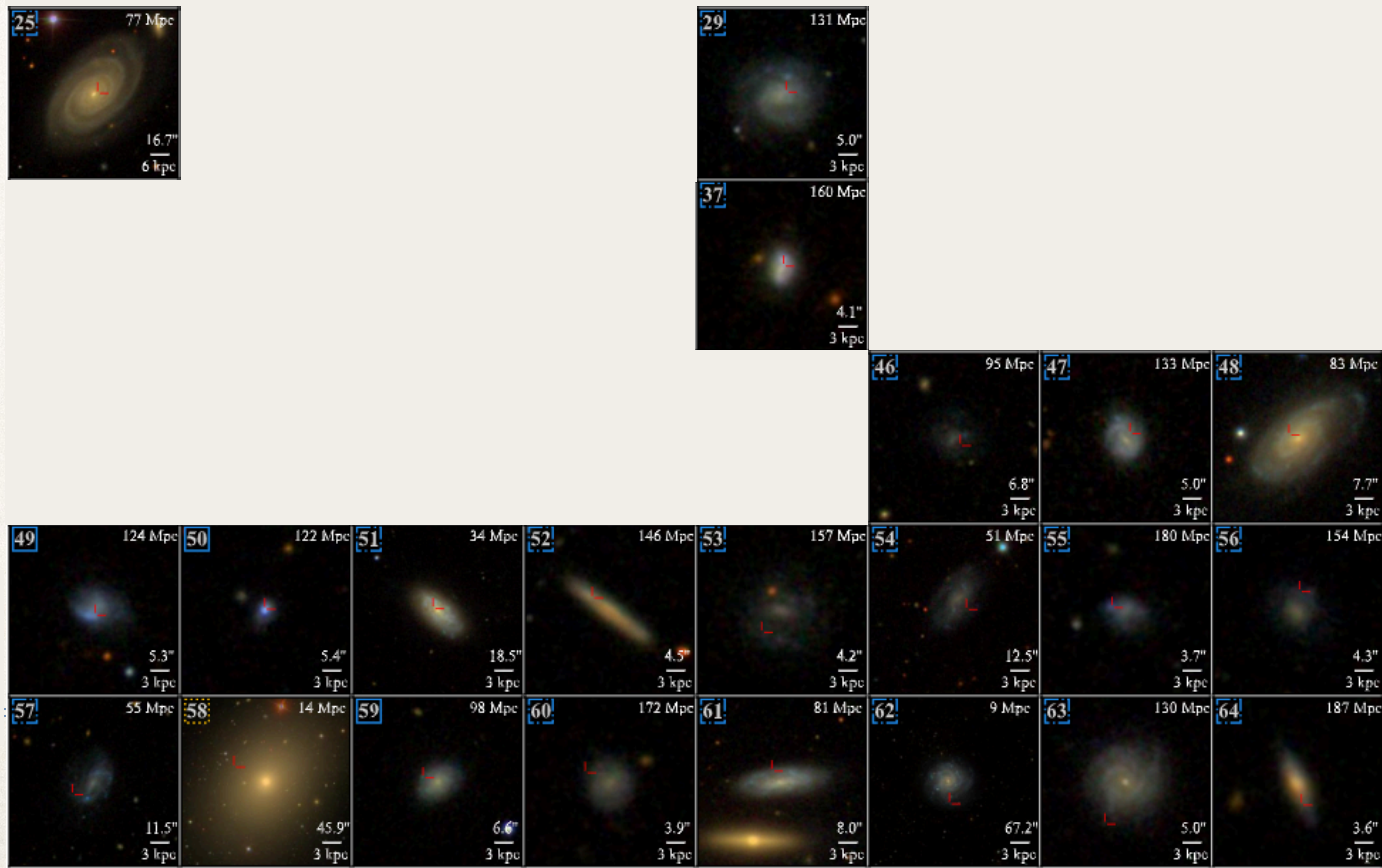
Requires eruptive mass loss ~centuries before supernova



Dong+ 2023b (in prep)

Off-nuclear transients are primarily located in star forming galaxies

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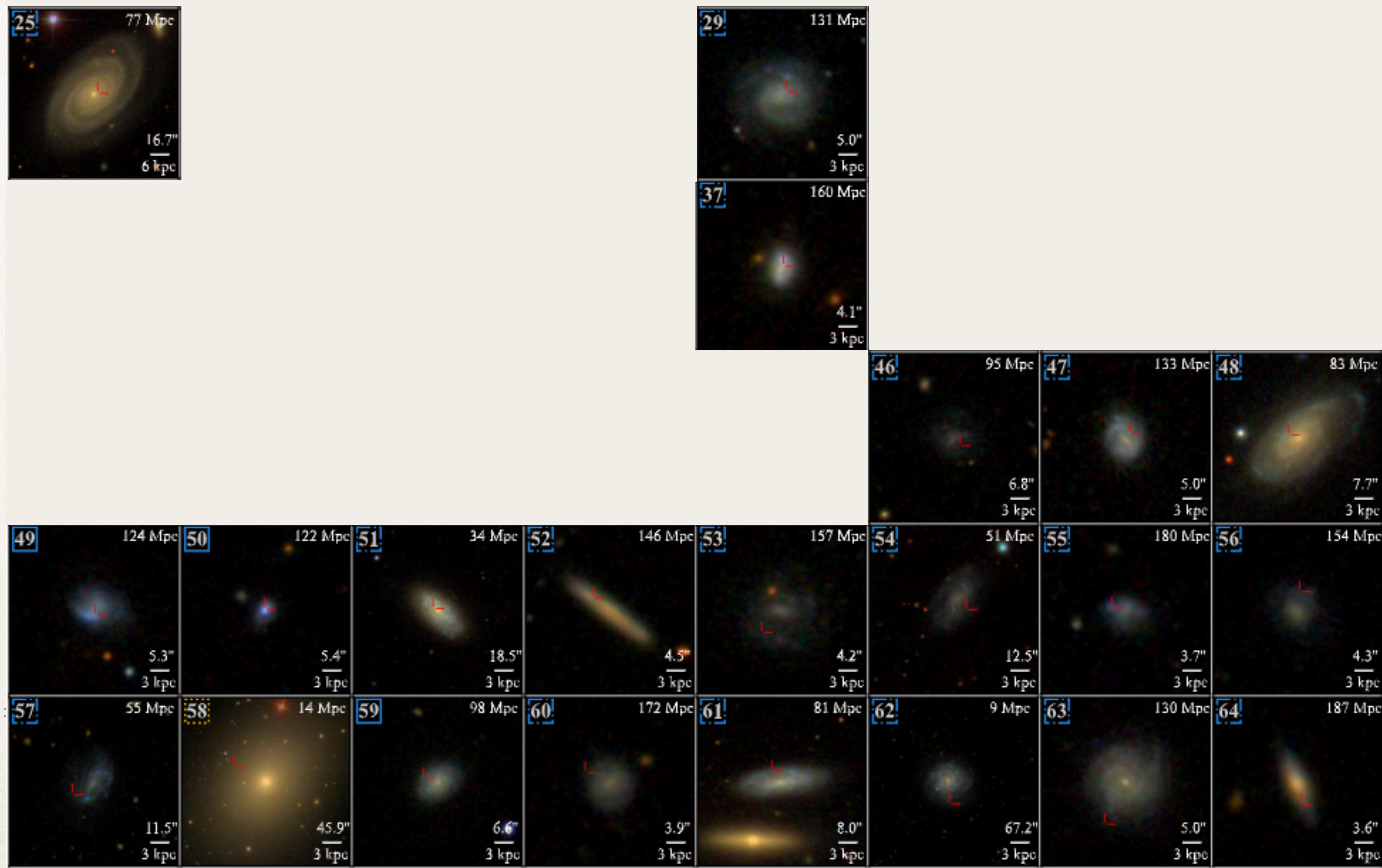
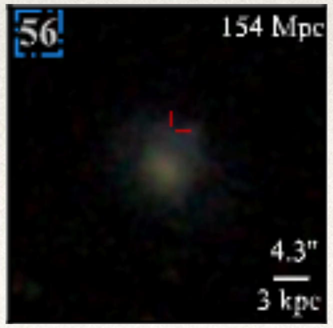
Requires eruptive mass loss ~centuries before supernova

Up to 0.3% of the core collapse SN rate

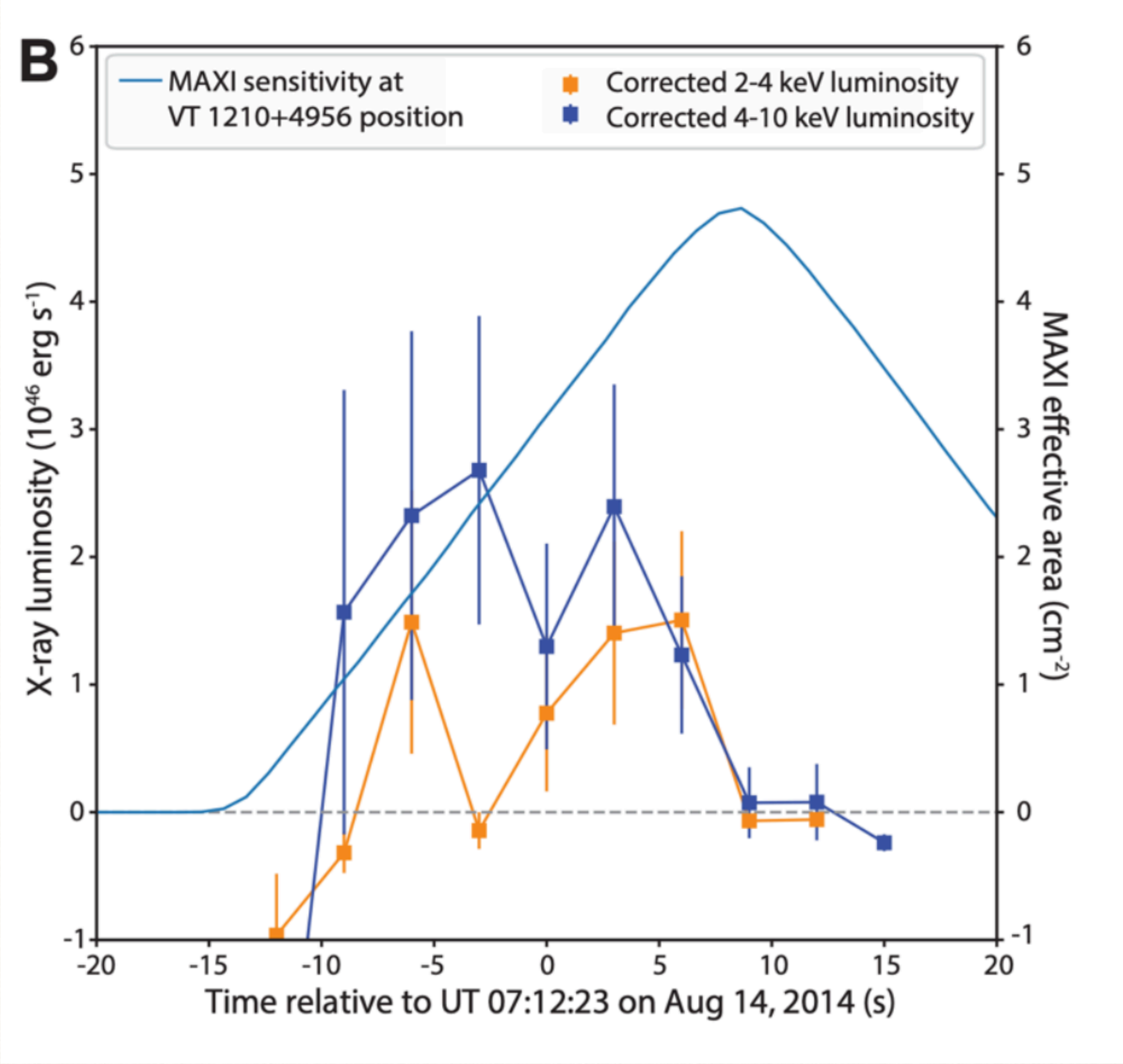


Dong+ 2023b (in prep)

Merger-driven explosion VT 1210+4956

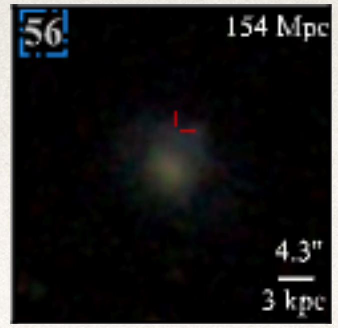


- **Aug 14, 2014:** relativistic ($\Gamma > 2.5$) jet traced by 15s X-ray flash



Dong+2021, Science

Merger-driven explosion
VT 1210+4956



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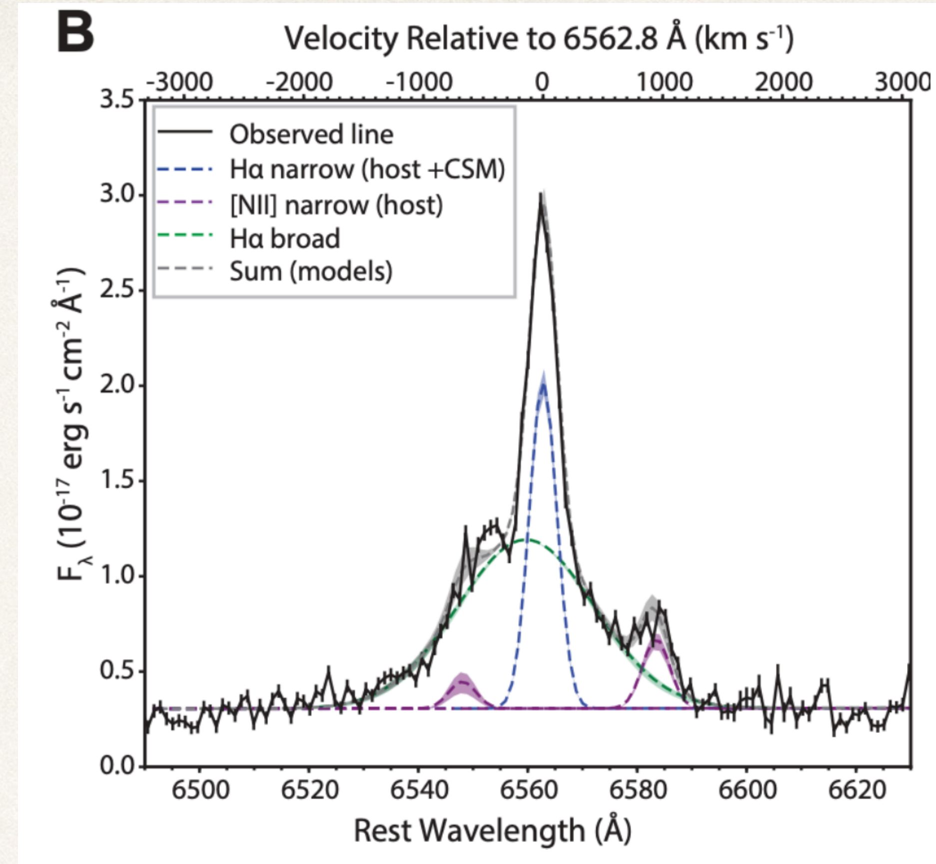
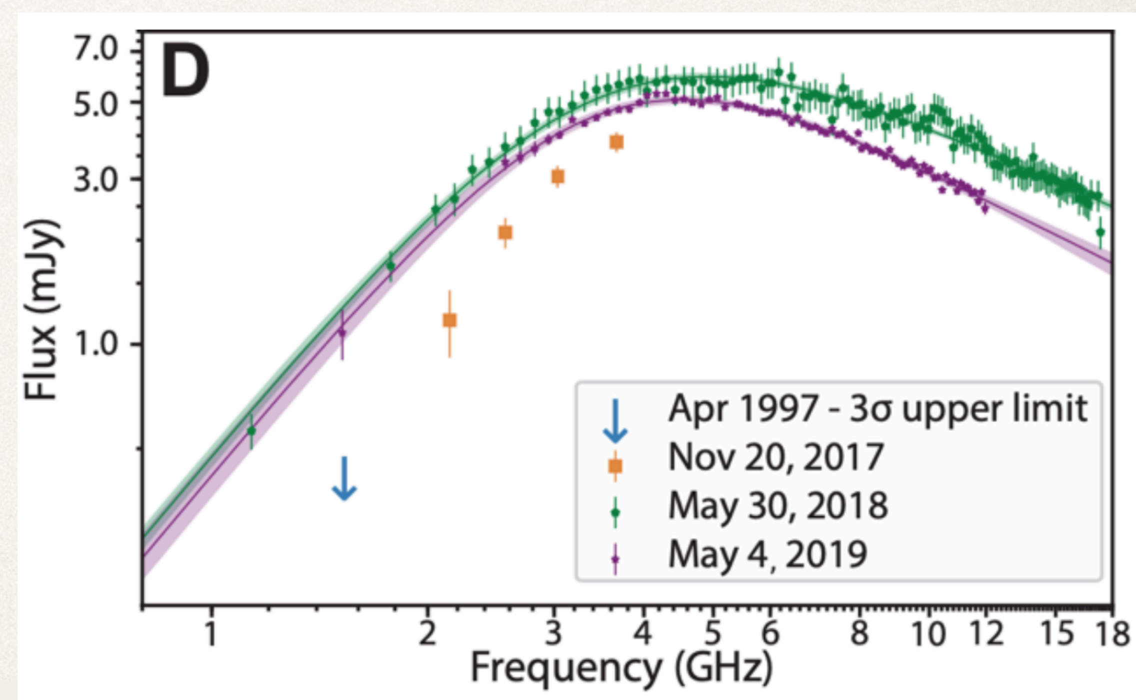
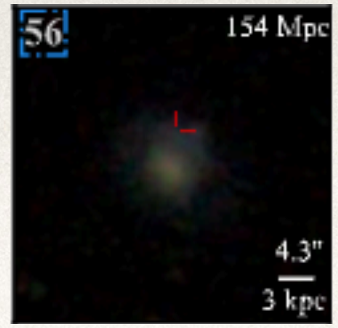




Dong+2021, Science

Merger-driven explosion VT 1210+4956



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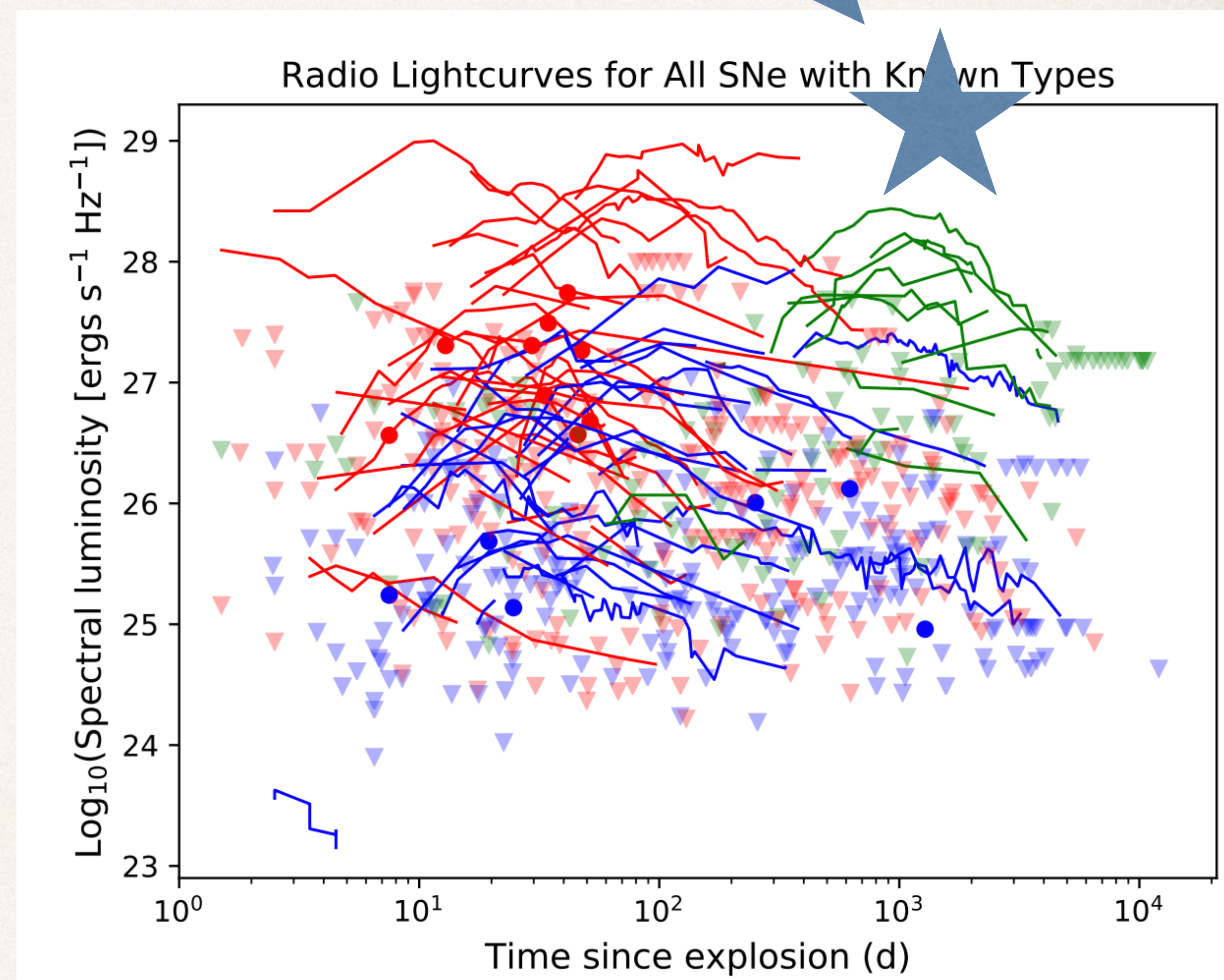
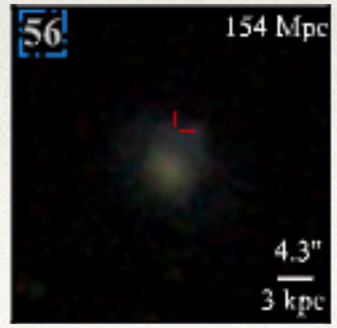
- [tied for] Most luminous radio supernova ever detected

VT 1210



Dong+2021, Science

Merger-driven explosion VT 1210+4956



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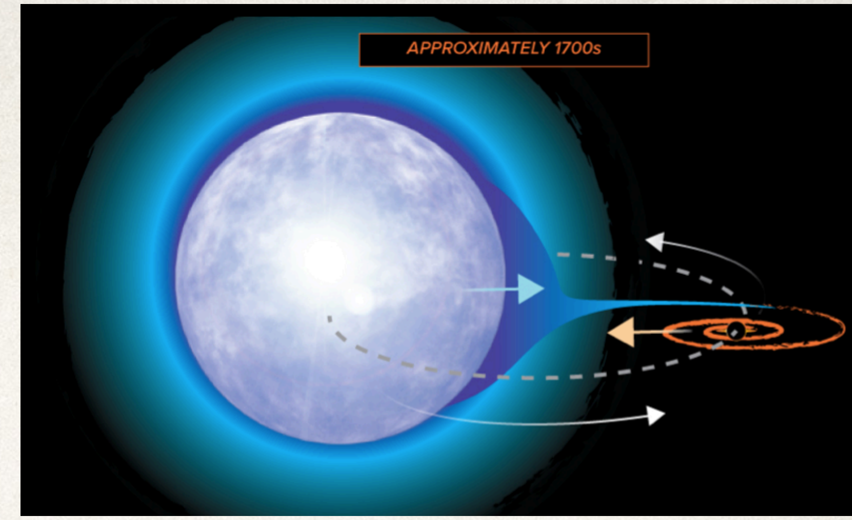
- **2017- present:** supernova ejecta interacting with $> 1\ M_\odot$ aspherical shell, ejected ~centuries before explosion
- [tied for] Most luminous radio supernova ever detected
- Unifying model:
  compact object + massive star merger

  Chevalier+12, Schrøder+19

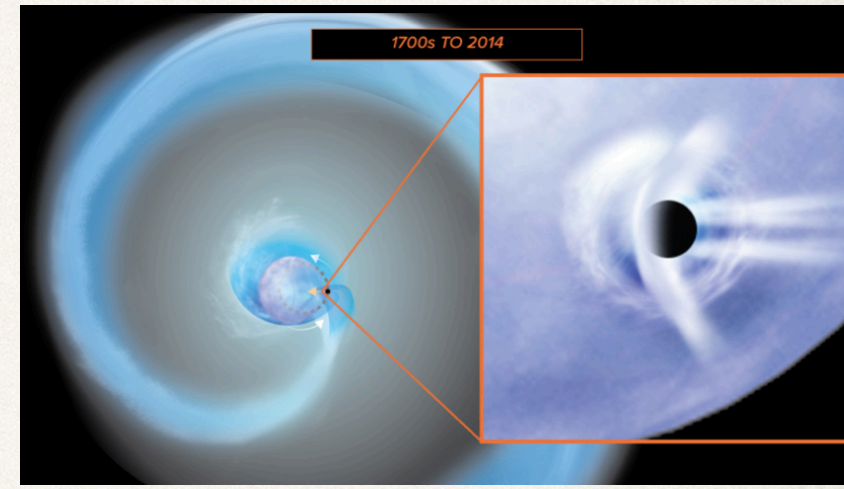
Dong+2021, Science

artists impression: Bill Saxton, Chuck Carter

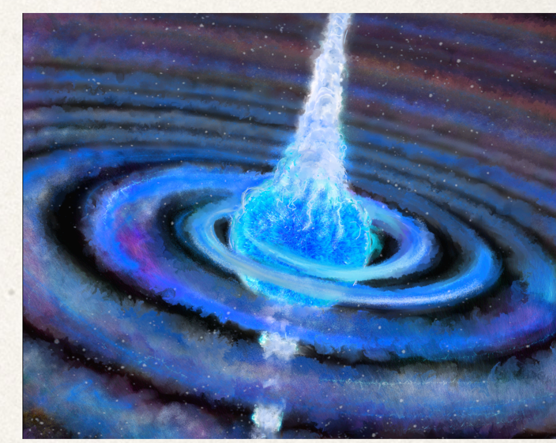
X-ray binary with unstable mass transfer, ejects gas in spiral



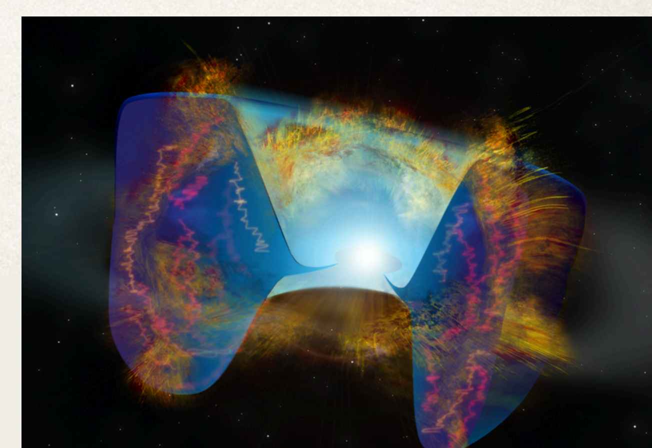
Compact object plunges in



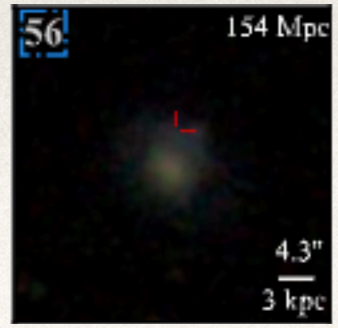
Explosion when object reaches core, launches jet (X-ray)



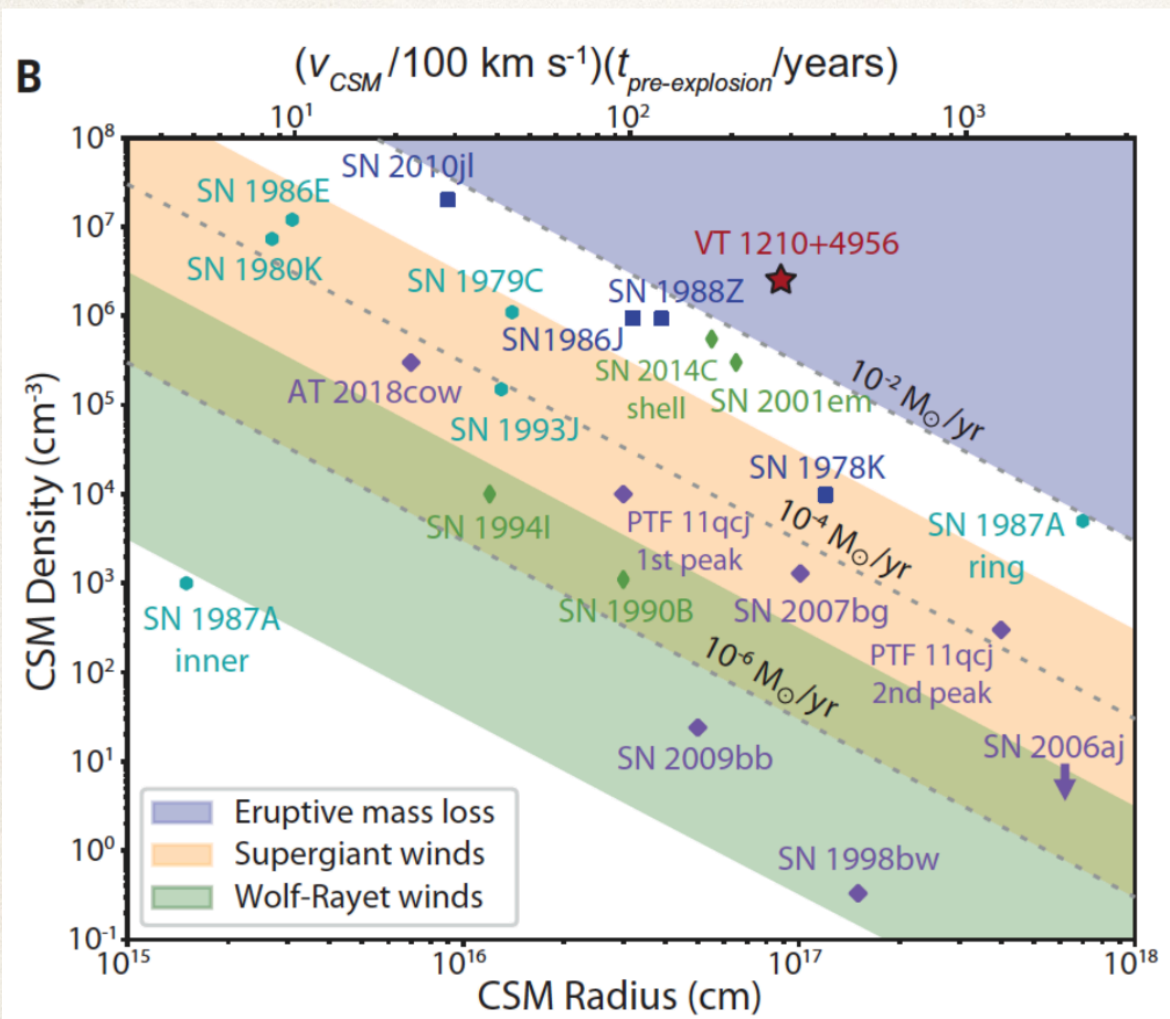
Ejecta hits expanded gas spiral (radio/optical)



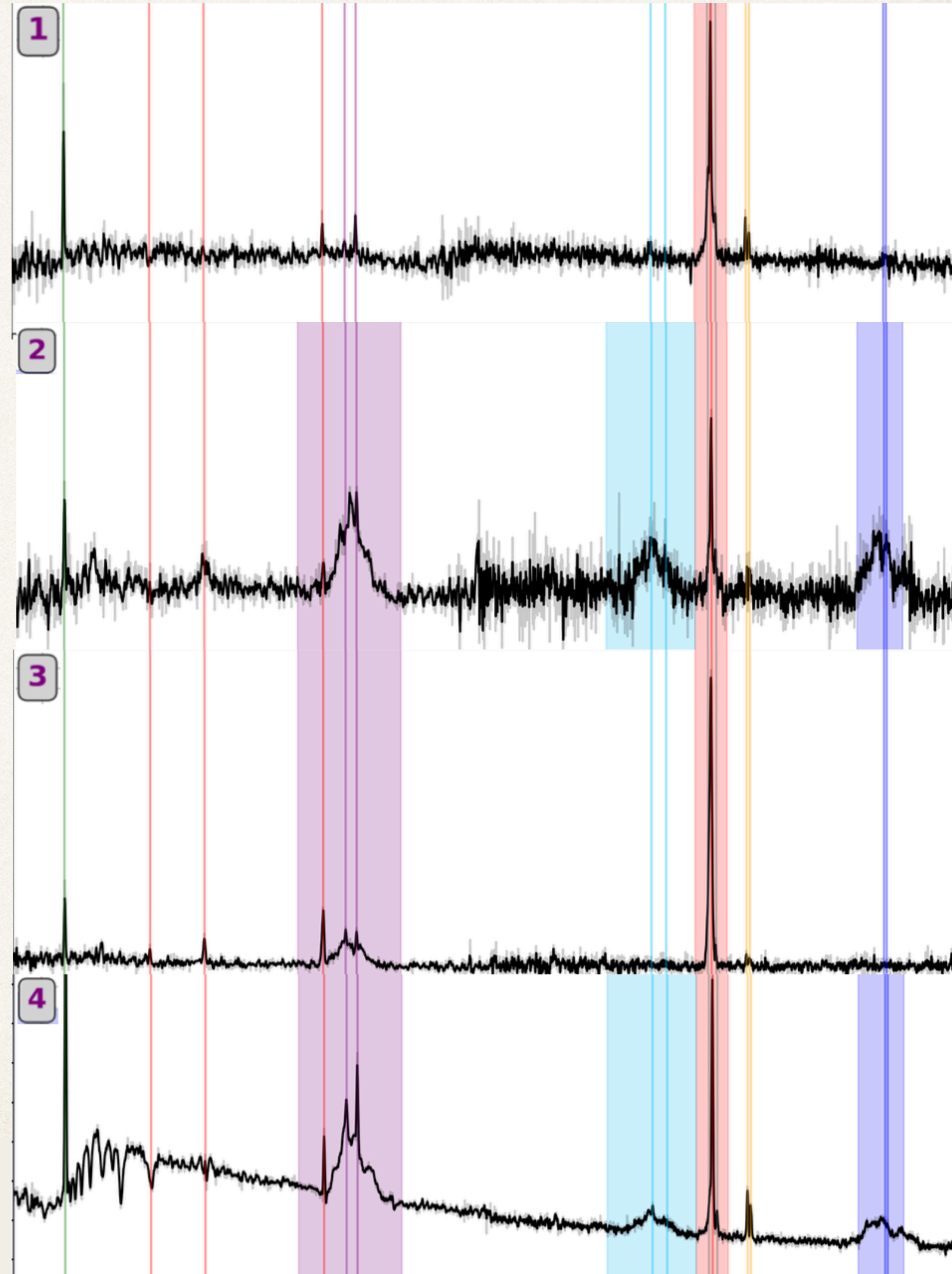
Merger-driven explosion VT 1210+4956



- Broader mystery in stellar evolution:
  What causes mass eruptions centuries before supernova?

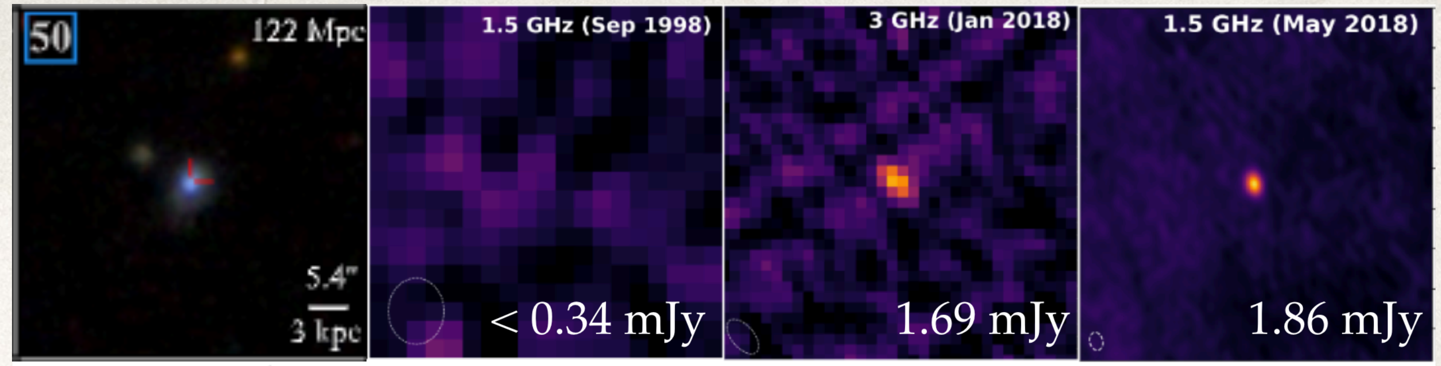


Many more stellar explosions with similar aspherical shells!



Dong+2021, 2023c in prep

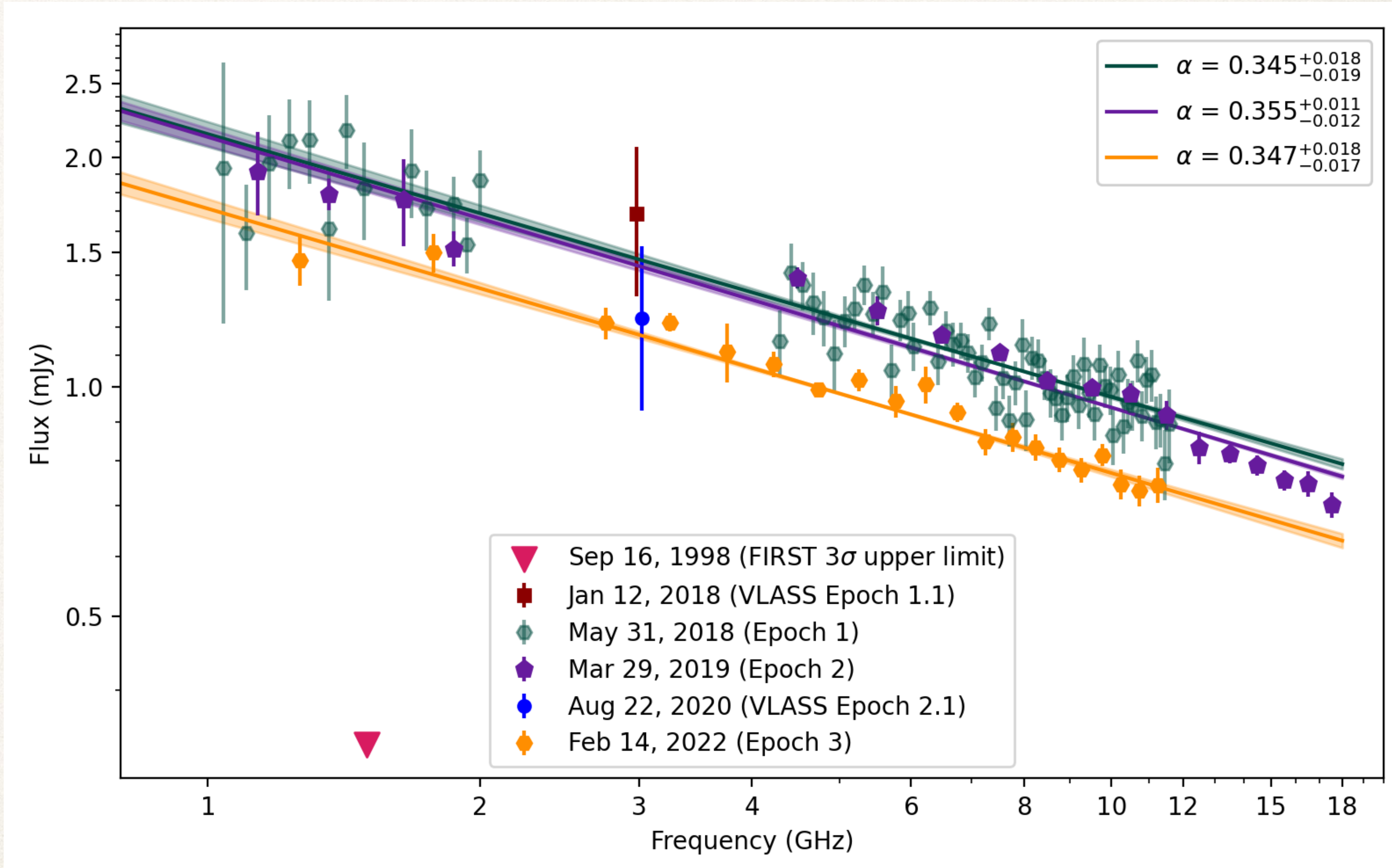
Emerging pulsar wind nebula VT 1137-0337



Radio SED 7σ flatter than theoretical limit for diffusive shock acceleration

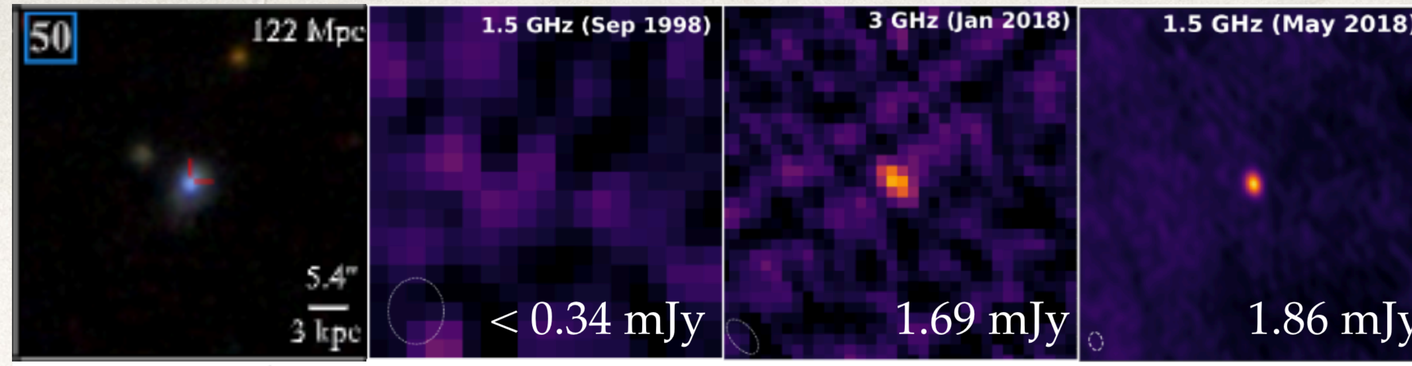
Fading by ~5% per year over 4 years

Too stable to be a jet



Dong & Hallinan 2023a, in press

Emerging pulsar wind nebula VT 1137-0337

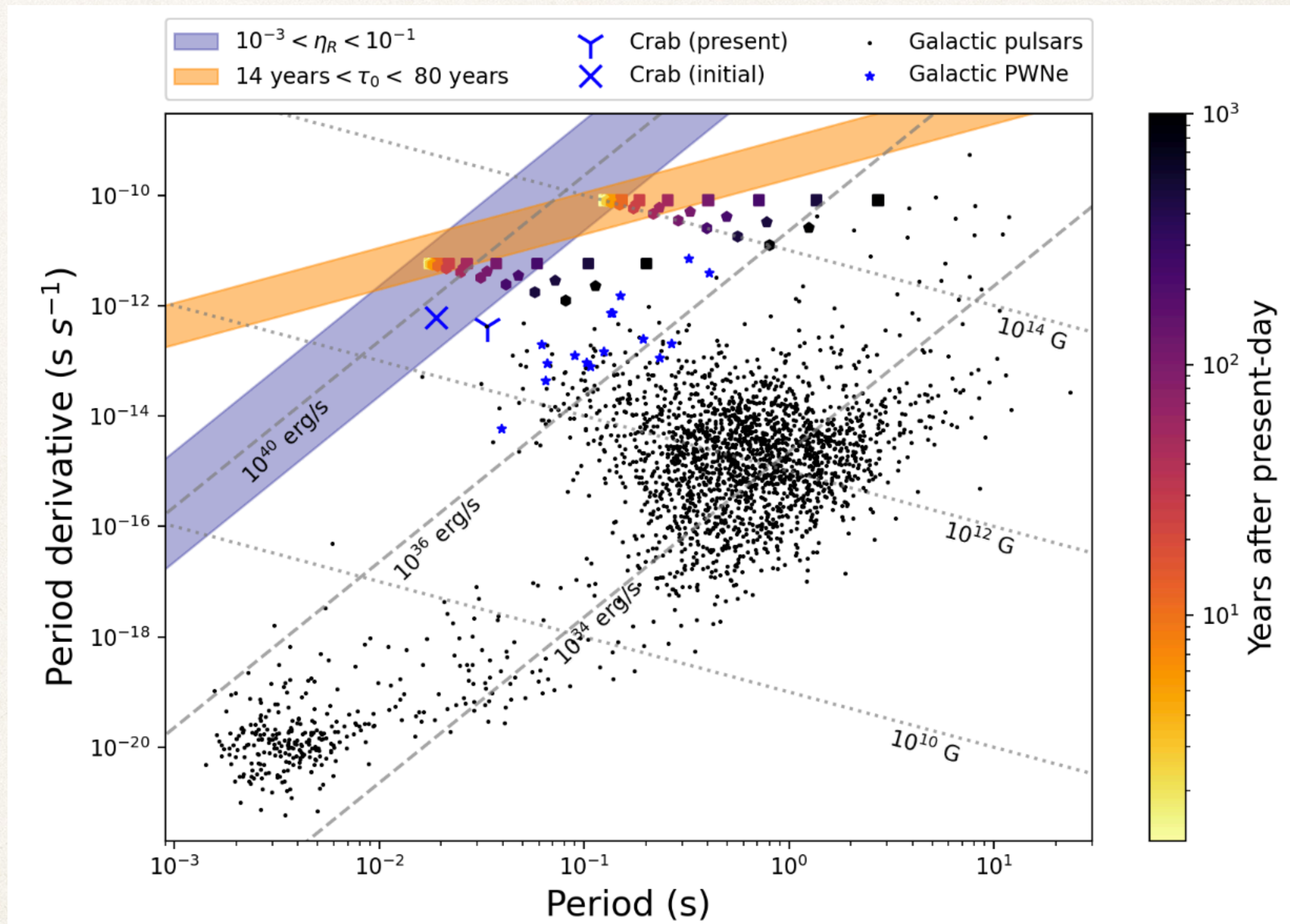


Consistent with an emerging "super-Crab"

Requires initial period ~10 - 100ms
B ~ 10^{13-14} G

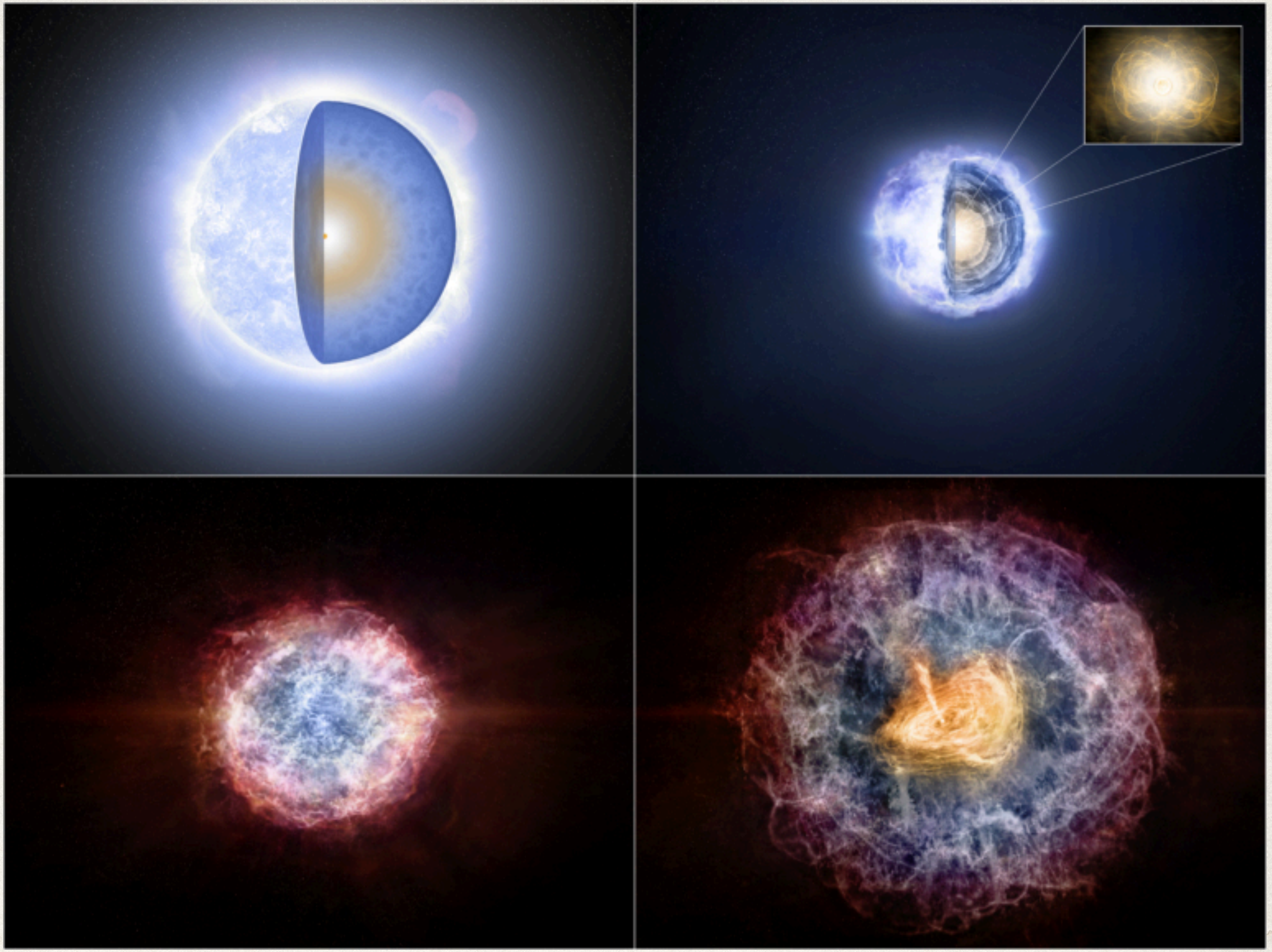
May be analog of FRB persistent sources

(10x less luminous than 121102, 190520B)



Dong & Hallinan 2023a, in press

Emerging pulsar wind nebula VT 1137-0337



Dong & Hallinan 2023a, in press

Artist's credit: Melissa Weiss

Conclusions

Radio transients can be detected at an industrial scale with large datasets & simple automated techniques

Thanks to *radio selection:*

Known transient populations are being found with statistical sample sizes

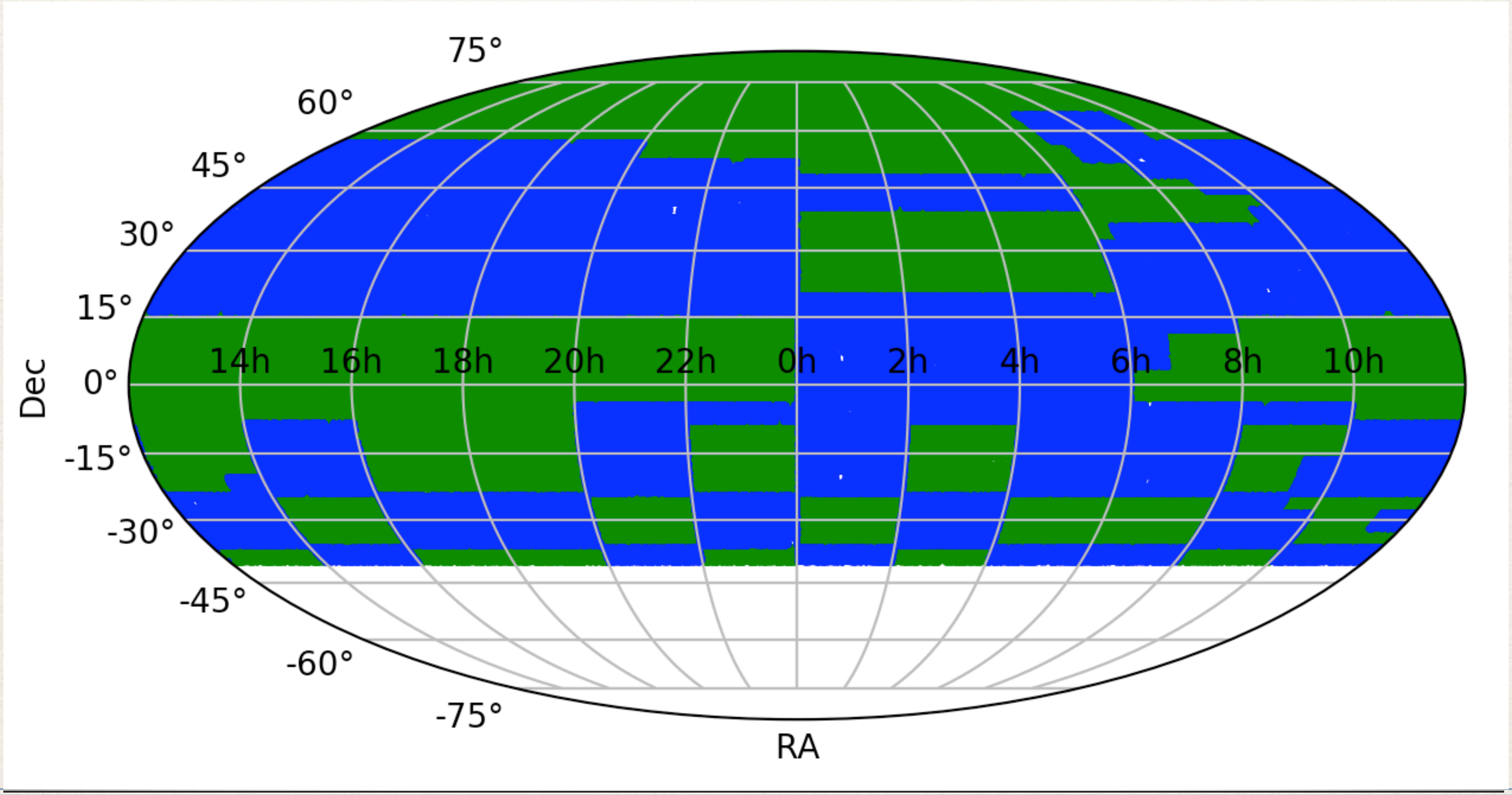
New transient populations are being identified

Merger-driven explosion
VT 1210+4956
(and analogues)

Emerging pulsar wind nebula
VT 1137-0337

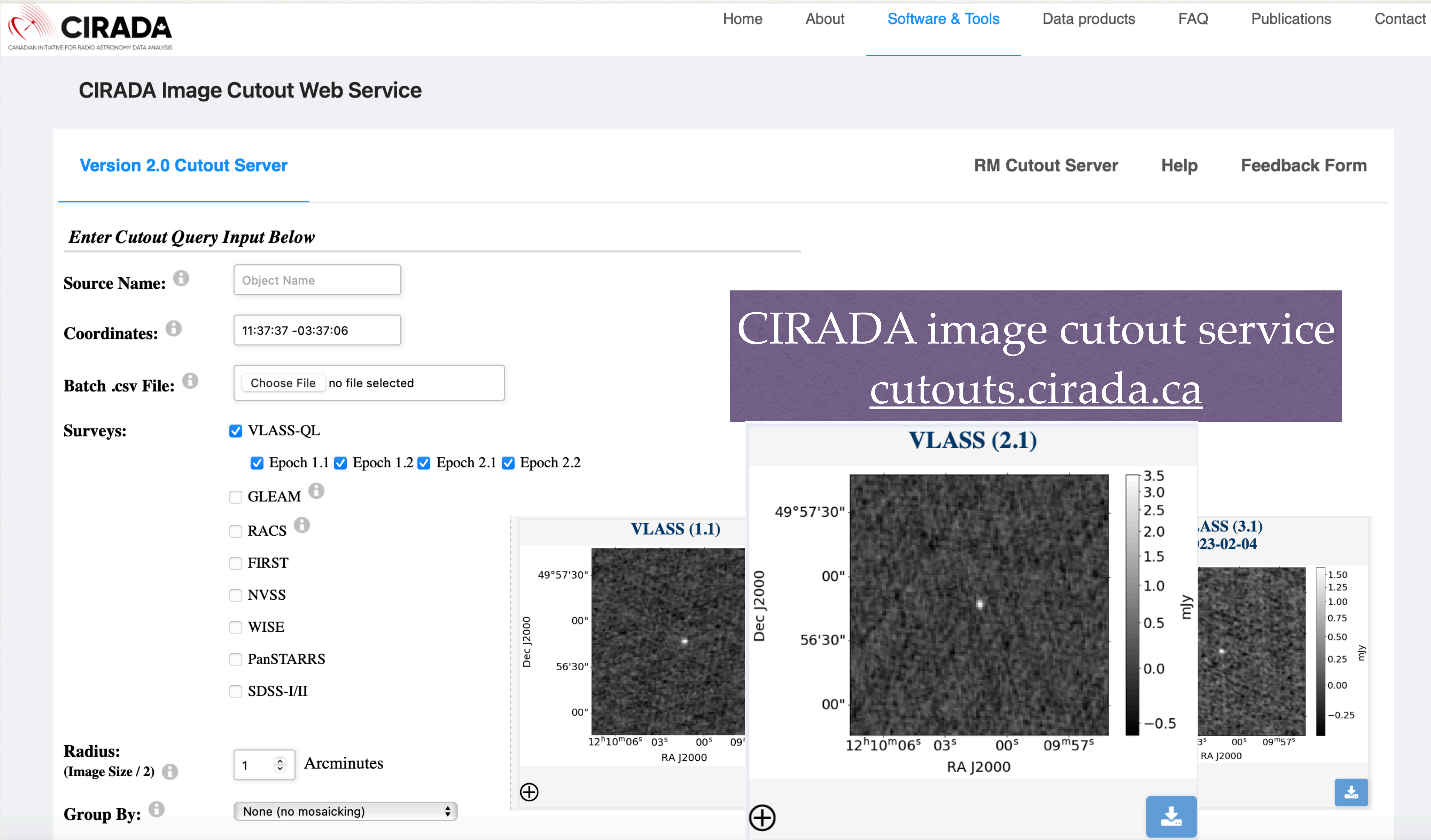
Where do we go from here?

Public transient catalog is in the works!

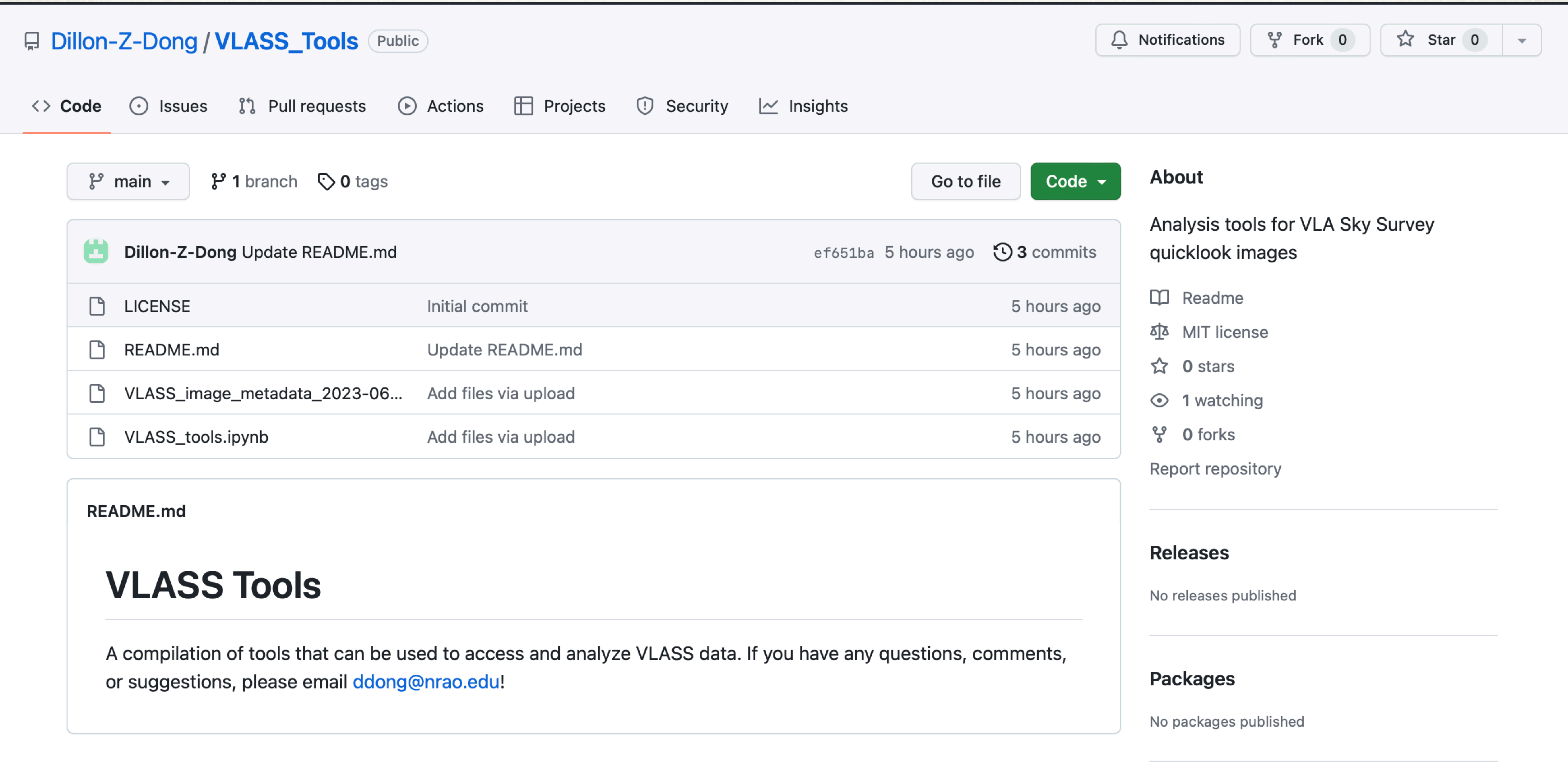


Dong+23d, in prep, Chen+23, in prep

In the meantime, if you have favorite sources you'd like to look at



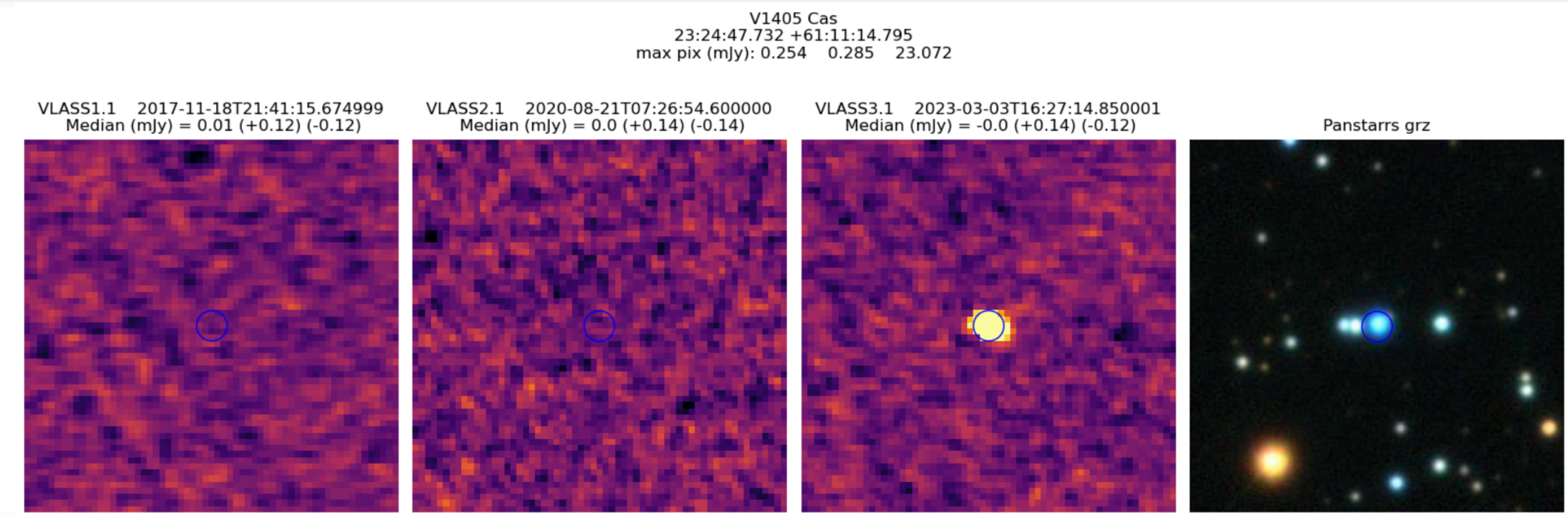
Scripted & customizable VLASS tools (for small batches): https://github.com/dillon-z-dong/VLASS_Tools/tree/main

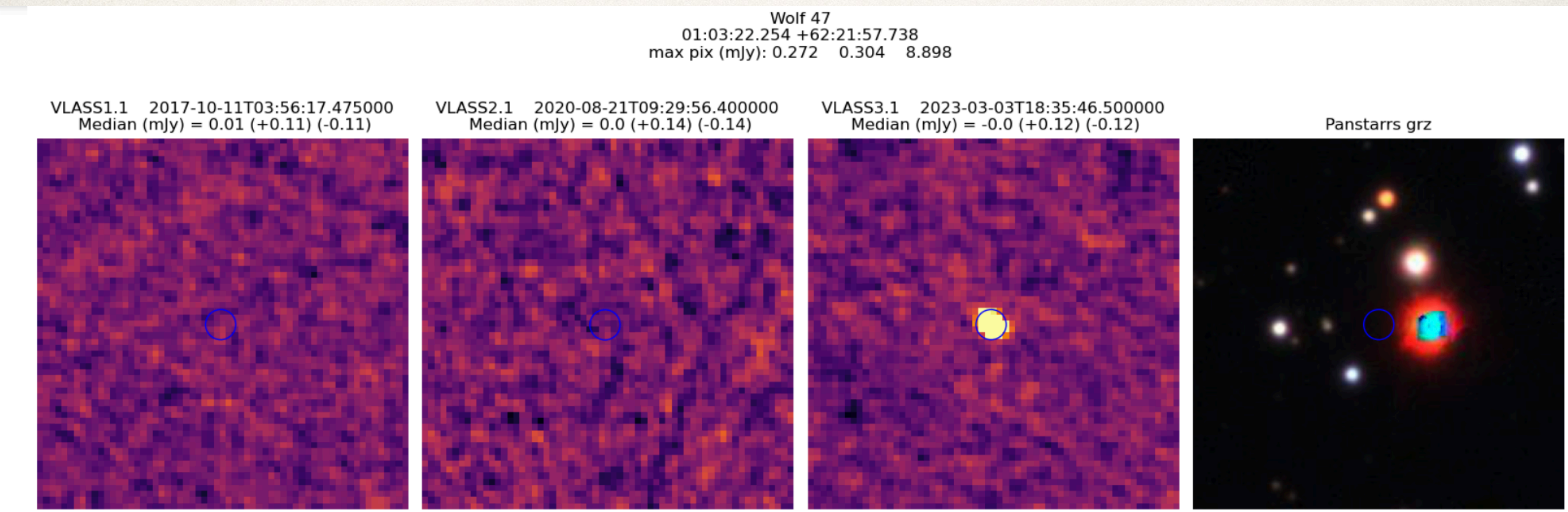


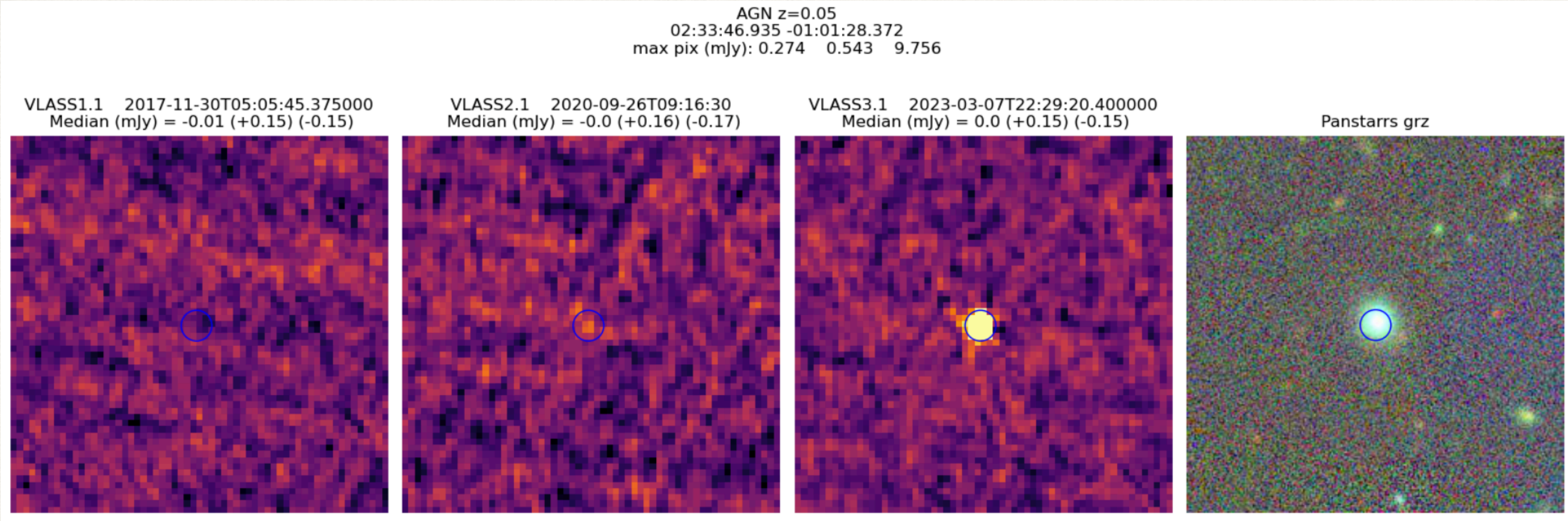
Scripted & customizable VLASS tools (for small batches):
https://github.com/dillon-z-dong/VLASS_Tools/tree/main

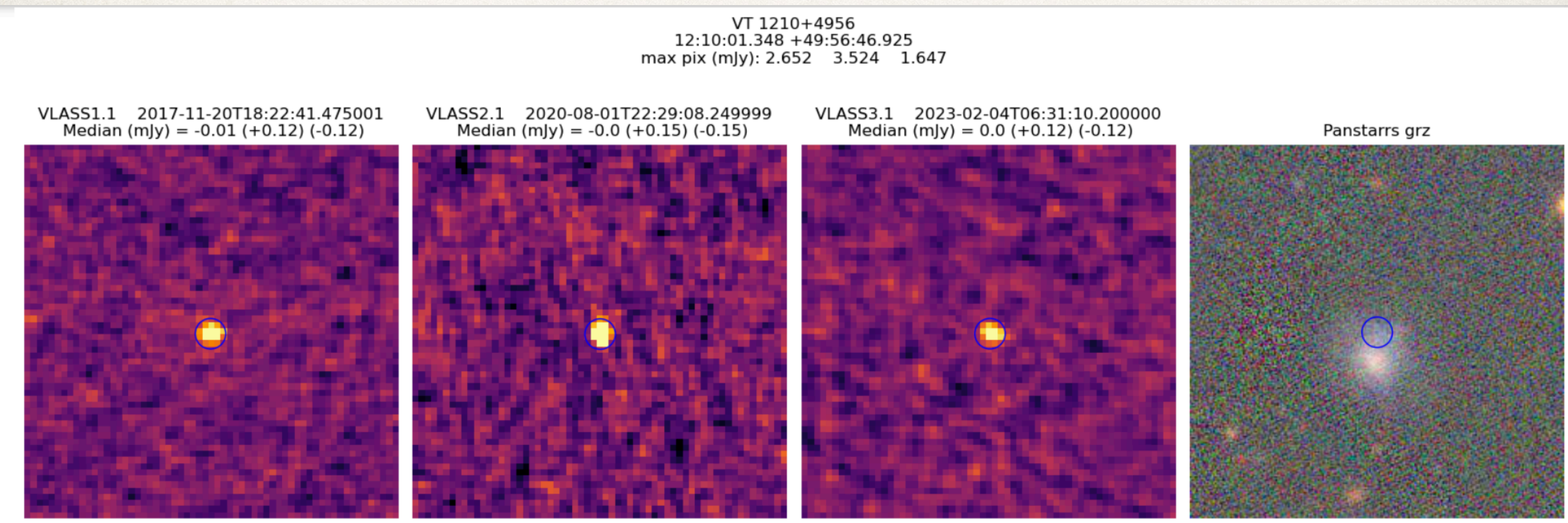
Functions to:

- Figure out which images contain a given ra, dec
- Get metadata from those images (date observed, etc.)
- Automatically download those images
- Make customizable image cutouts
- Run basic forced photometry
  (more sophisticated tools coming soon!)


V1405 Cas
23:24:47.732 +61:11:14.795
max pix (mJy): 0.254 0.285 23.072
VLASS1.1 2017-11-18T21:41:15.674999
Median (mJy) = 0.01 (+0.12) (-0.12)
VLASS2.1 2020-08-21T07:26:54.600000
Median (mJy) = 0.0 (+0.14) (-0.14)
VLASS3.1 2023-03-03T16:27:14.850001
Median (mJy) = -0.0 (+0.14) (-0.12)
Panstarrs grz


Wolf 47
01:03:22.254 +62:21:57.738
max pix (mJy): 0.272 0.304 8.898
VLASS1.1 2017-10-11T03:56:17.475000
Median (mJy) = 0.01 (+0.11) (-0.11)
VLASS2.1 2020-08-21T09:29:56.400000
Median (mJy) = 0.0 (+0.14) (-0.14)
VLASS3.1 2023-03-03T18:35:46.500000
Median (mJy) = -0.0 (+0.12) (-0.12)
Panstarrs grz


AGN z=0.05
02:33:46.935 -01:01:28.372
max pix (mJy): 0.274 0.543 9.756
VLASS1.1 2017-11-30T05:05:45.375000
Median (mJy) = -0.01 (+0.15) (-0.15)
VLASS2.1 2020-09-26T09:16:30
Median (mJy) = -0.0 (+0.16) (-0.17)
VLASS3.1 2023-03-07T22:29:20.400000
Median (mJy) = 0.0 (+0.15) (-0.15)
Panstarrs grz


VT 1210+4956
12:10:01.348 +49:56:46.925
max pix (mJy): 2.652 3.524 1.647
VLASS1.1 2017-11-20T18:22:41.475001
Median (mJy) = -0.01 (+0.12) (-0.12)
VLASS2.1 2020-08-01T22:29:08.249999
Median (mJy) = -0.0 (+0.15) (-0.15)
VLASS3.1 2023-02-04T06:31:10.200000
Median (mJy) = 0.0 (+0.12) (-0.12)
Panstarrs grz