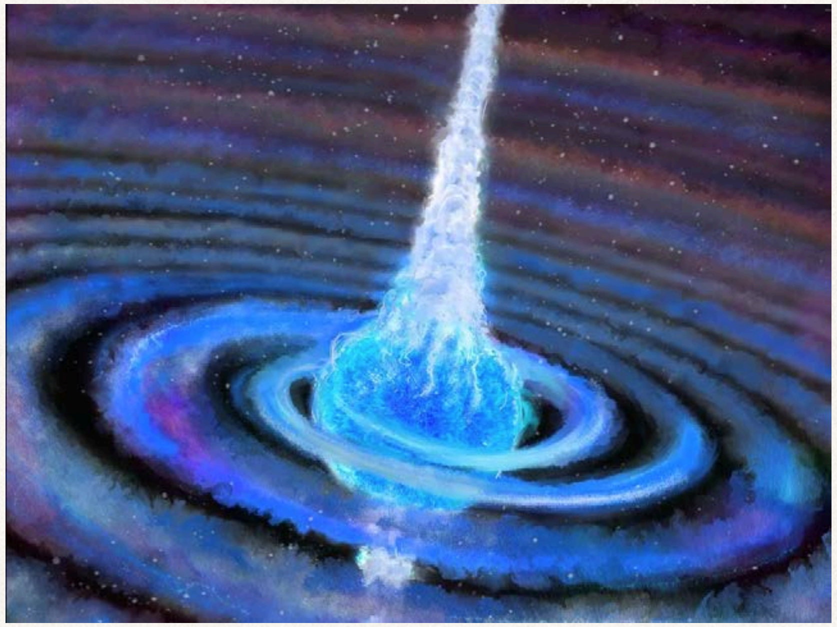
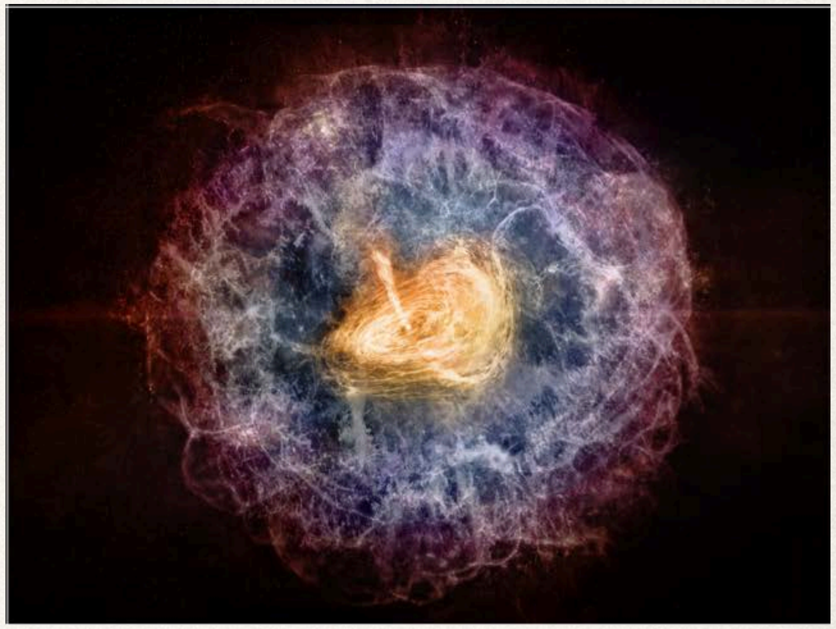
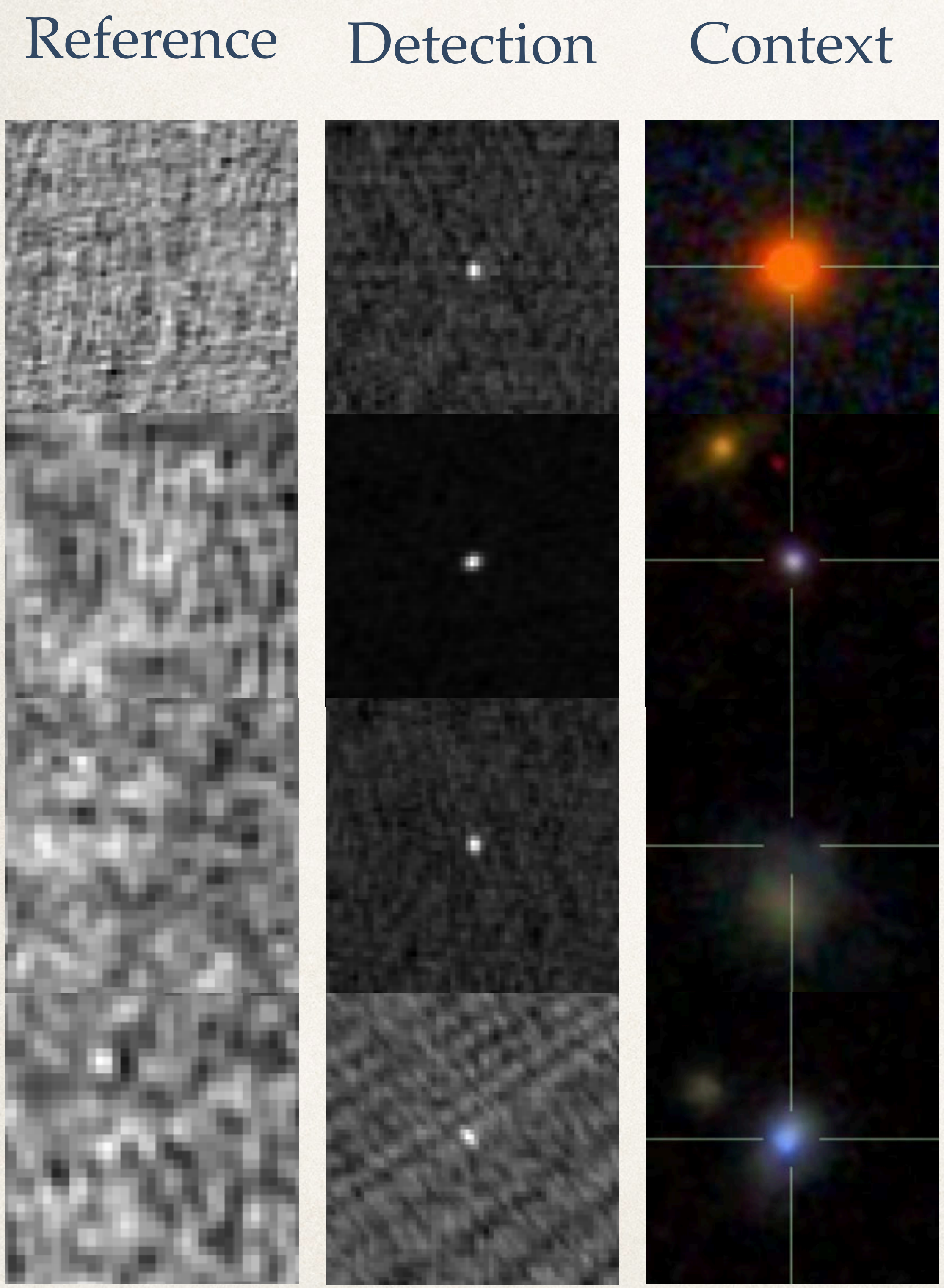
  

A systematic characterization of slow radio transients in d < 200 Mpc galaxies

Dillon Dong

Jansky Fellow, NRAO
ddong@nrao.edu

What do I mean by "slow radio transient"?

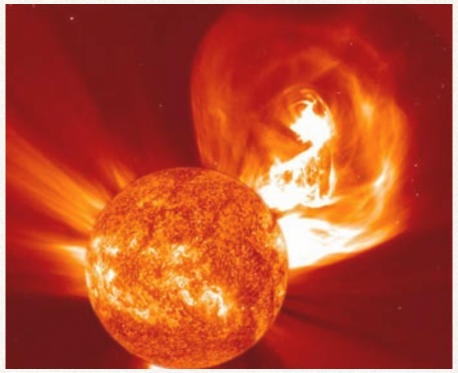


- A sudden increase in radio luminosity (could be over 2 epochs)
- Significantly more luminous than quiescent emission
- Slower than FRBs (searches in images)

- Causality limits emitting region to small size
- In most cases, implies synchrotron emission (new relativistic electrons accelerated, typically by shocks)

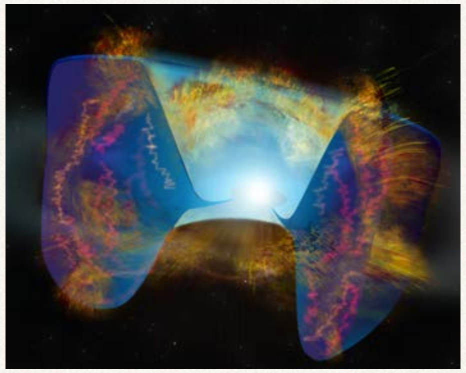
Many astronomical source classes produce slow radio transients

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



[2] Stellar explosions

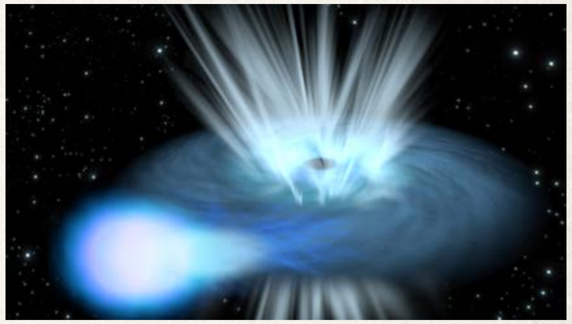
(supernovae, gamma ray bursts, a compact object/ massive star merger)



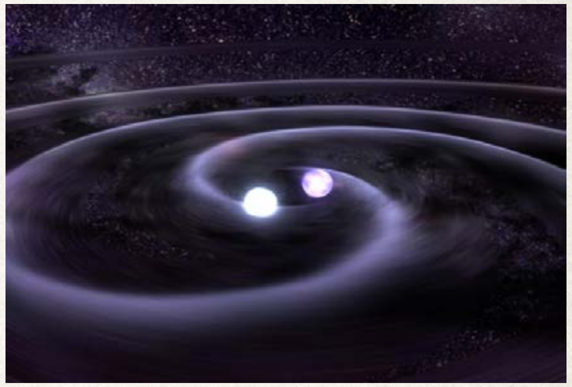
[3] SMBHs: active or quiescent, jetted or low-velocity

[4] Flaring compact objects

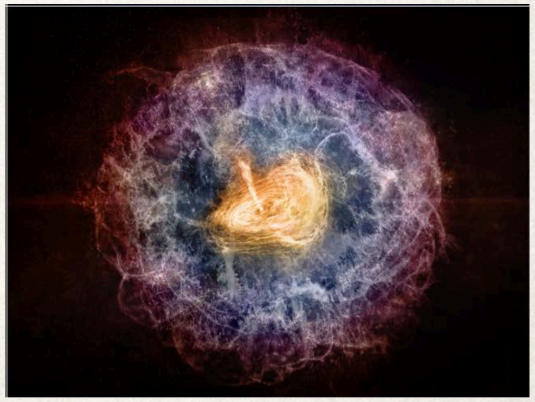
(white dwarfs, neutron stars, BHs)



[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

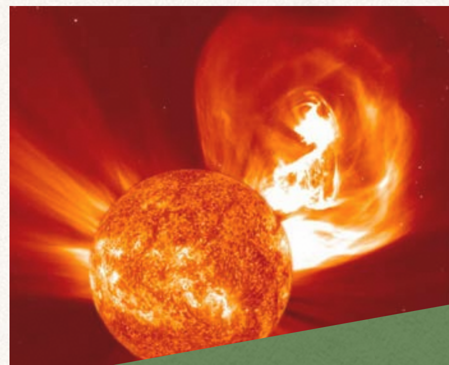
[4] Yao+20, 21, Miller+23, in prep

[5] Hallinan+2017

[6] Dong & Hallinan 2023a

Many astronomical source classes produce slow radio transients

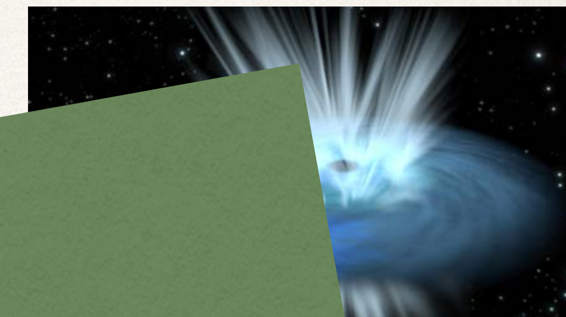
[1] Pre-, post-, and main sequence stars



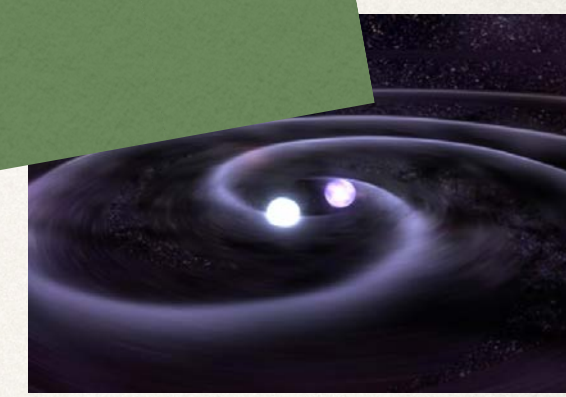
[2]

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

[4] Flaring compact



mergers



[6] An emerging pulsar wind nebula

Likely more classes, yet to be discovered

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

Direct detection of radio transients

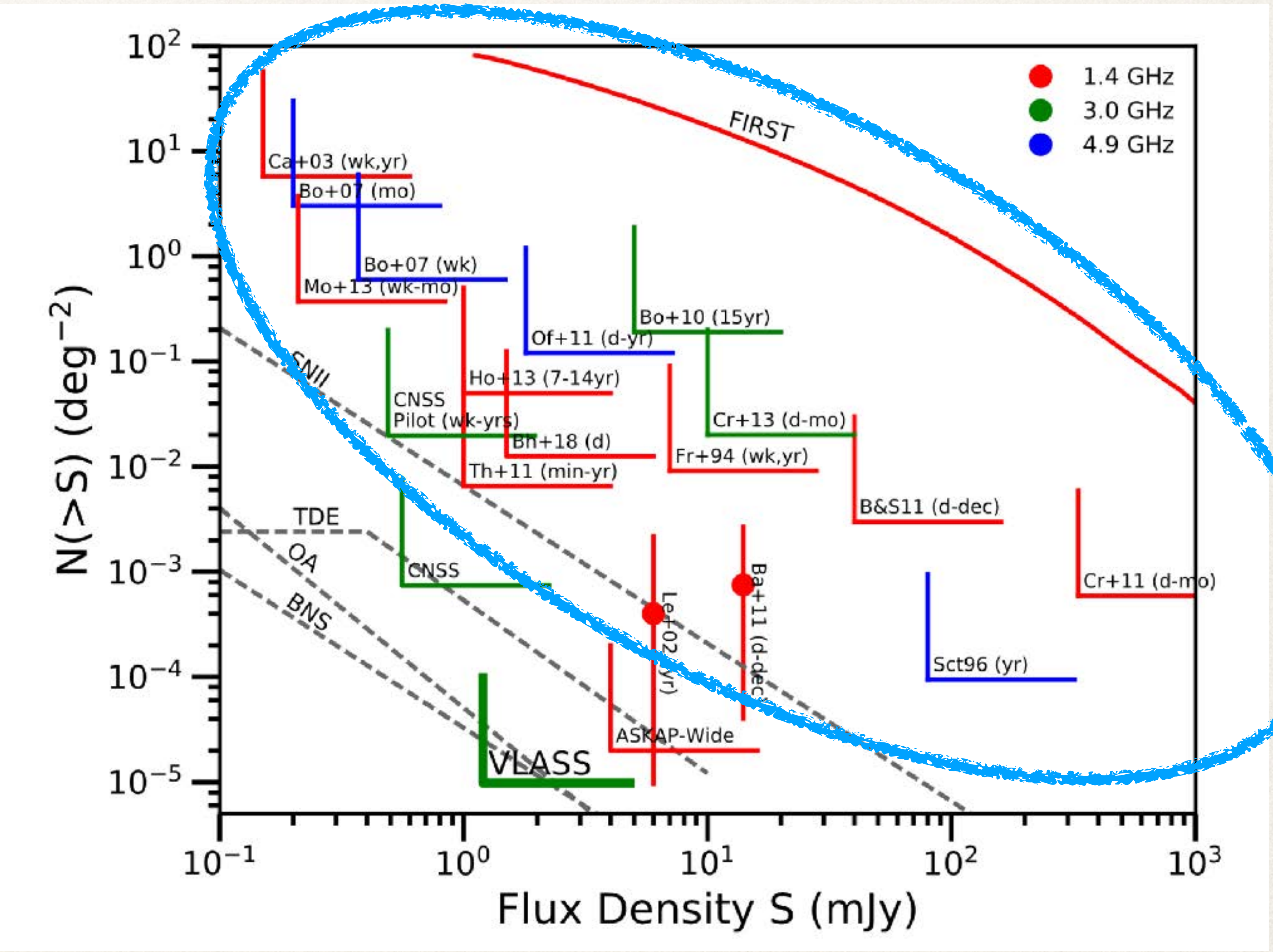
- Decades of pioneering surveys

Scales probed:

- < 1 deg² to ~0.1mJy
- ~10 deg² to ~1 mJy
- ~1000 deg² to > 10 mJy

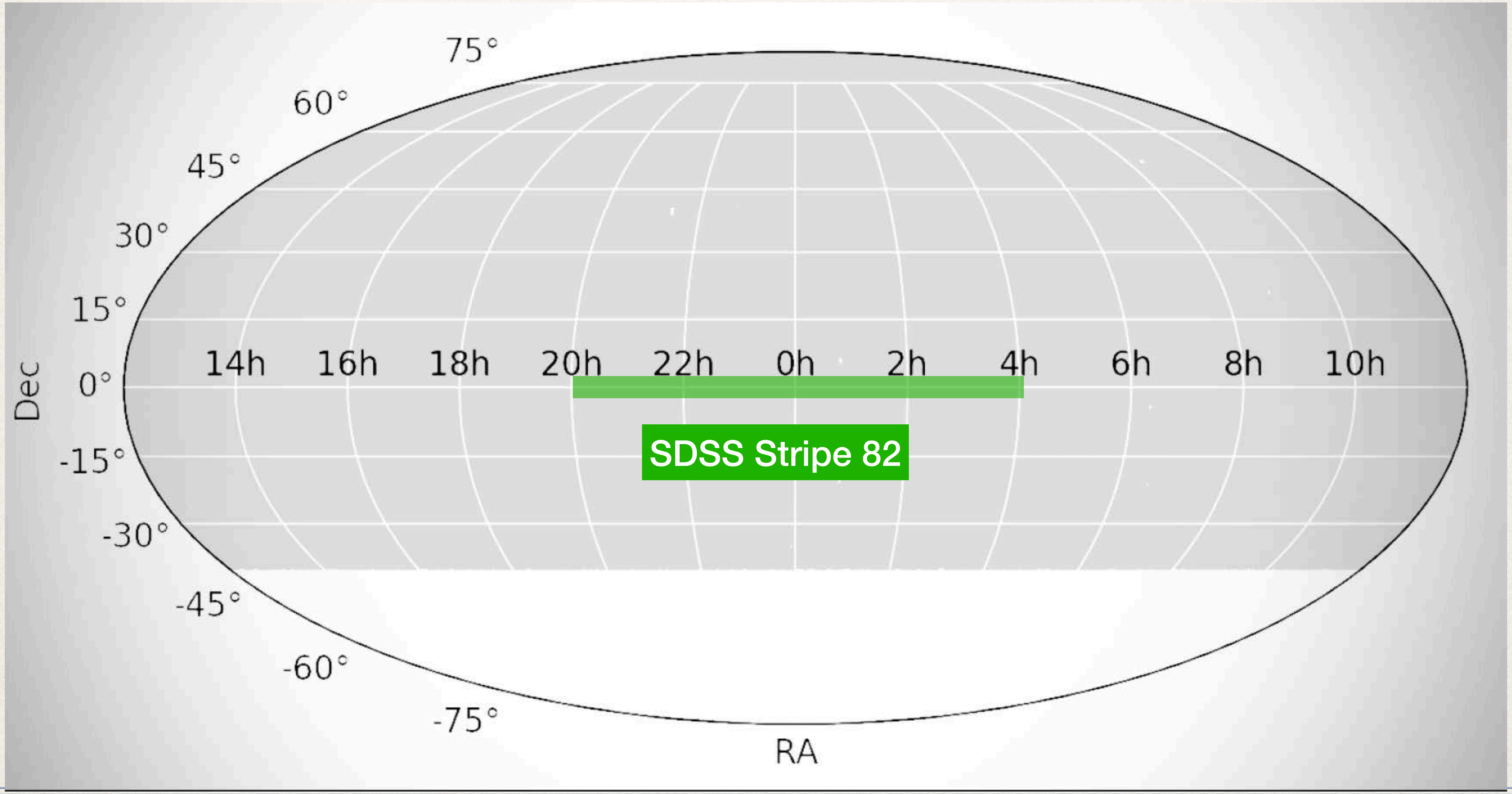
Timescales from days to years

- Mostly upper limits



Frail+12, Lacy+20

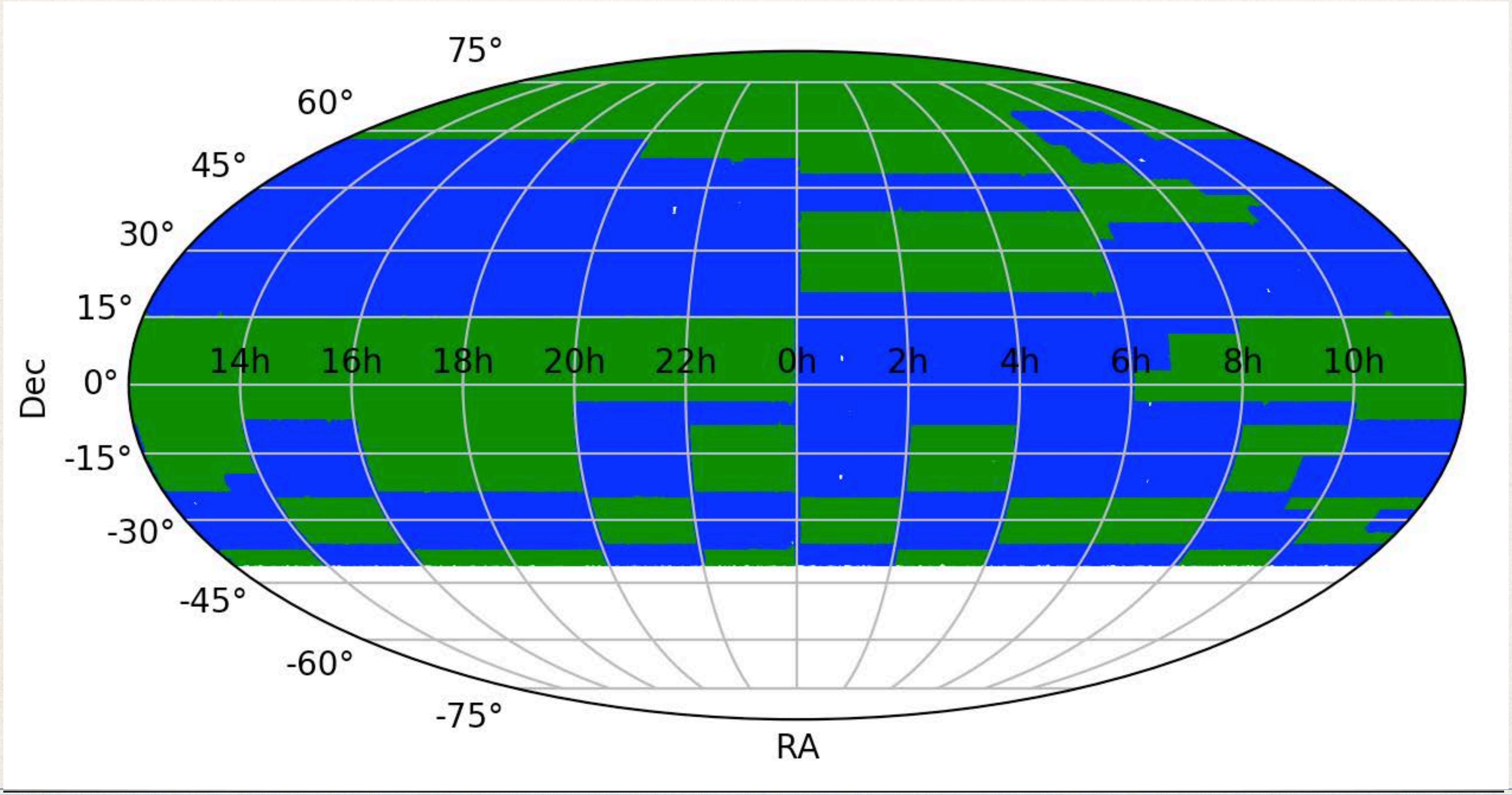
First direct detections in the Caltech-NRAO Stripe 82 Survey (mid 2010s)



O(10) transients found

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

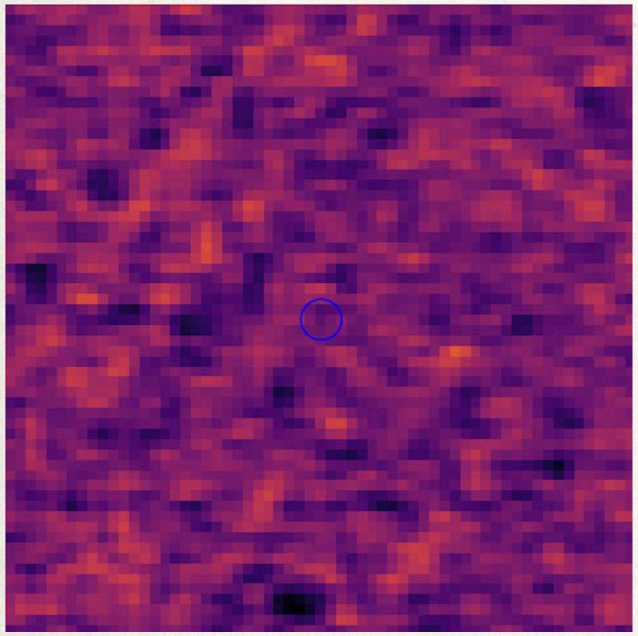
O(1000) transients per epoch in the VLA Sky Survey



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

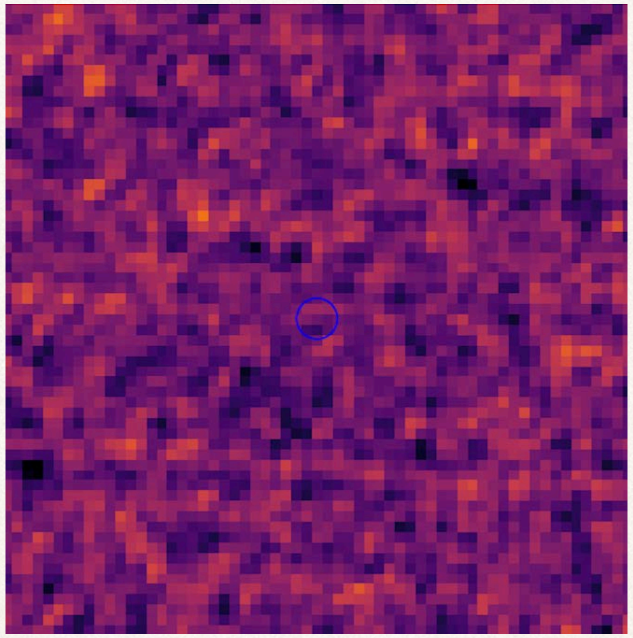
Some transients are immediately identifiable

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



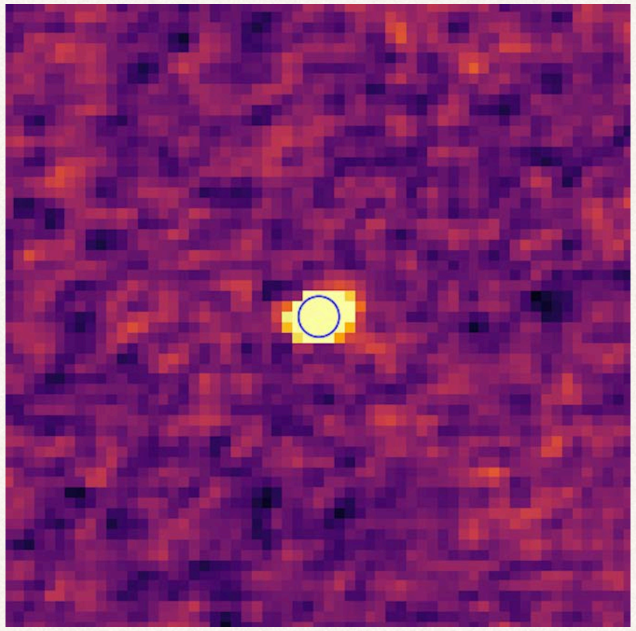
< 0.36 mJy

2017



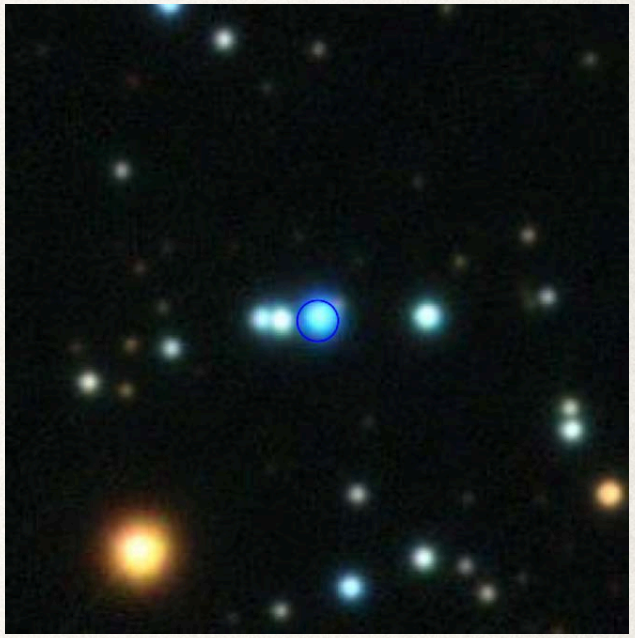
< 0.42 mJy

2020



23 mJy

2023



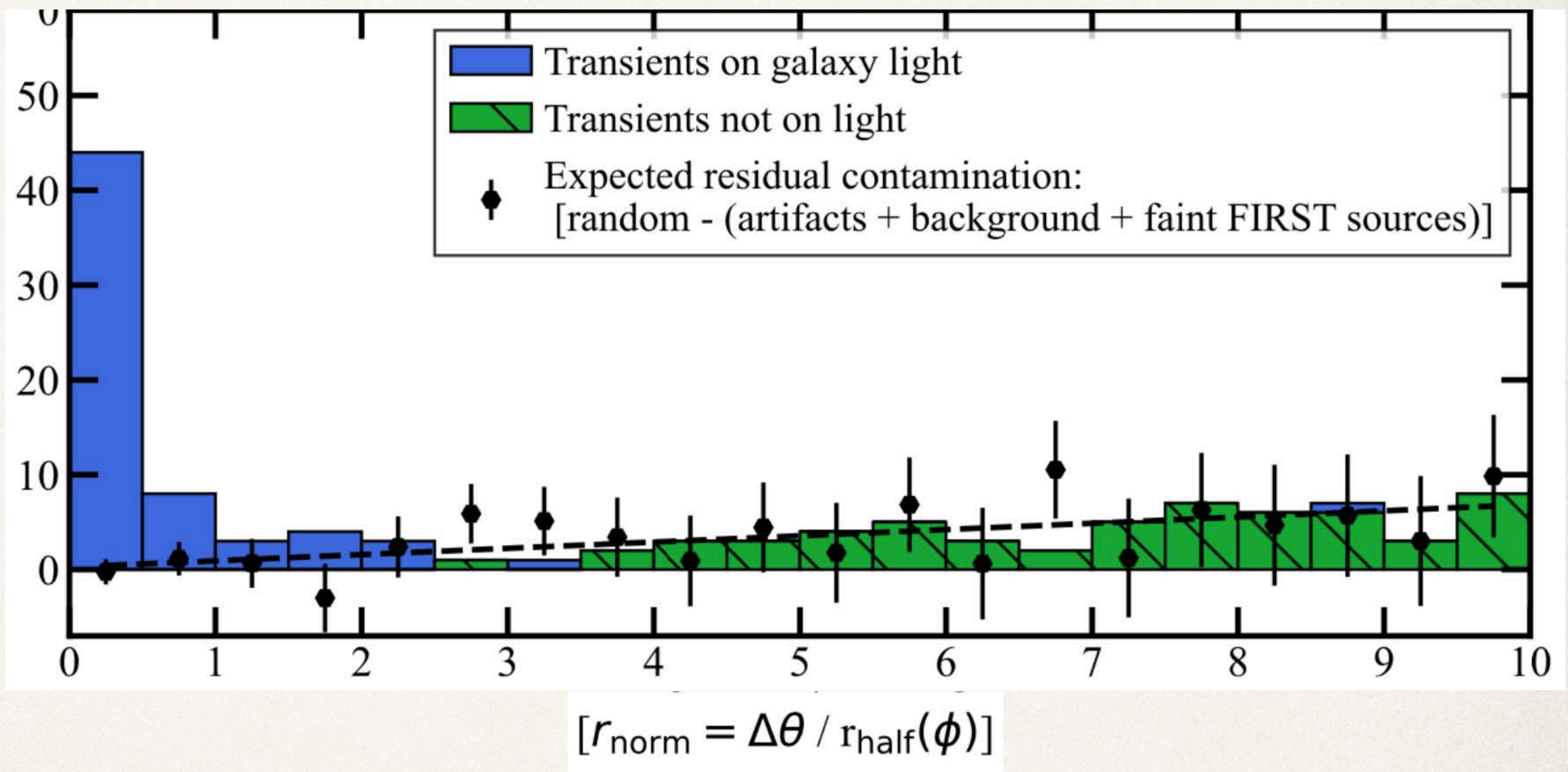
Classical Nova
V1405 Cas
(2021)

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)

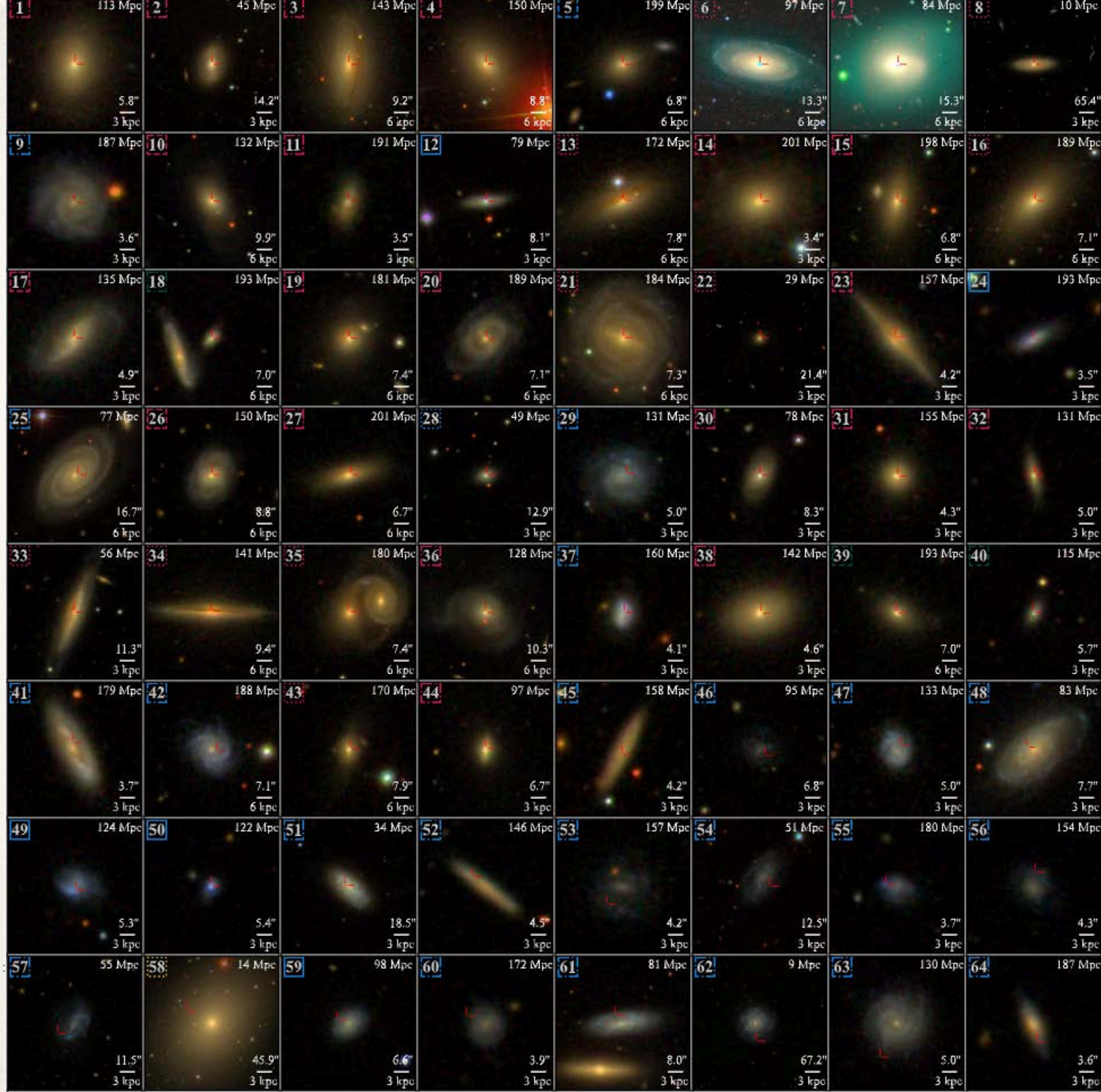


Offset from nearest d < 200 Mpc galaxy

(normalized by half-light radius)

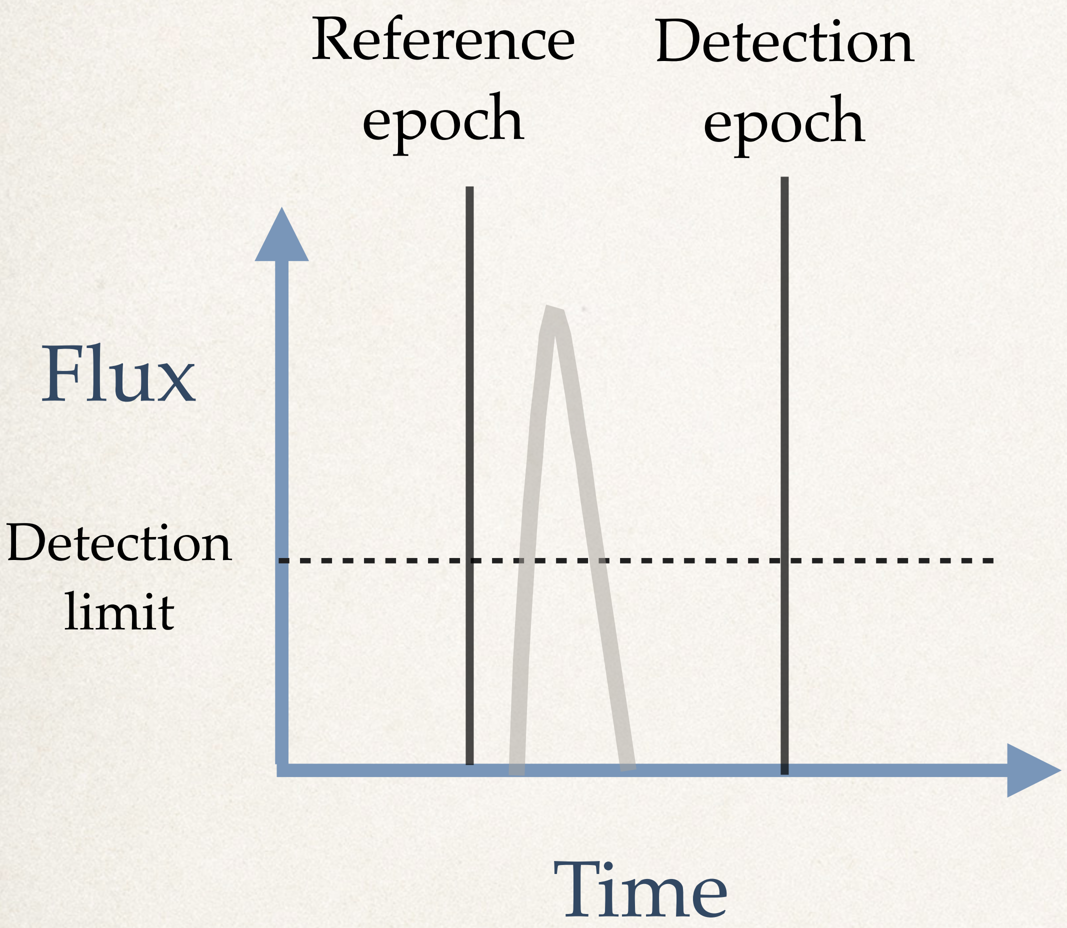
Dong+ 2023b (in prep)

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



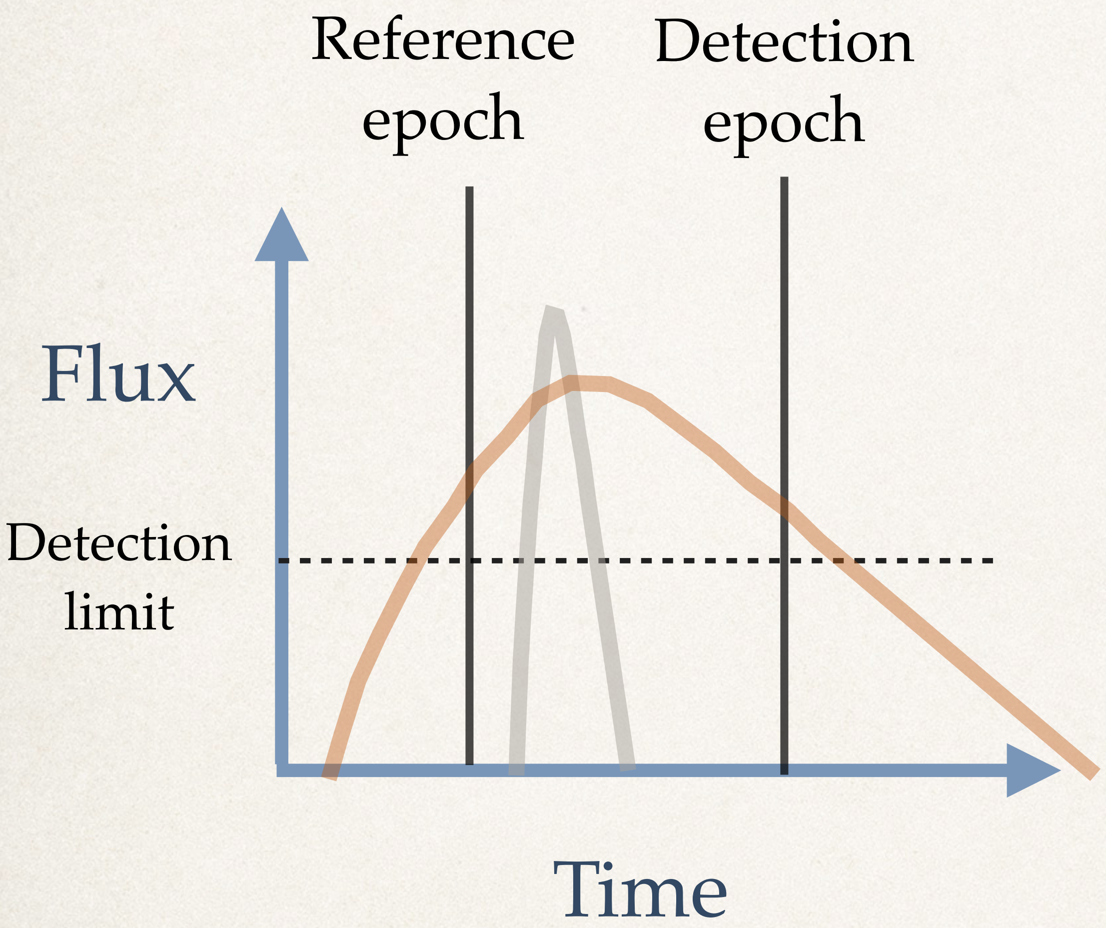
Dong+ 2023b (in prep)

Selection biases as *information*



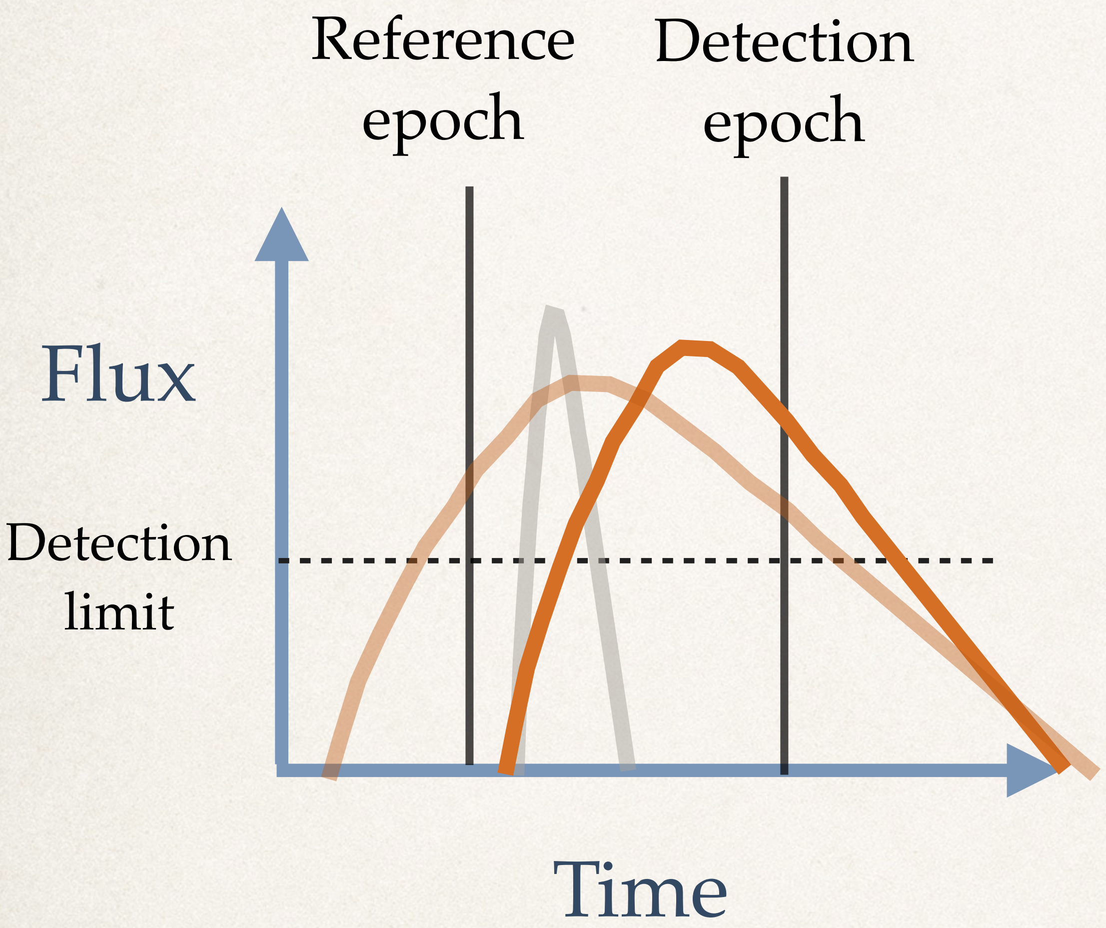
Most transients much faster than the cadence will be missed entirely

Selection biases as *information*



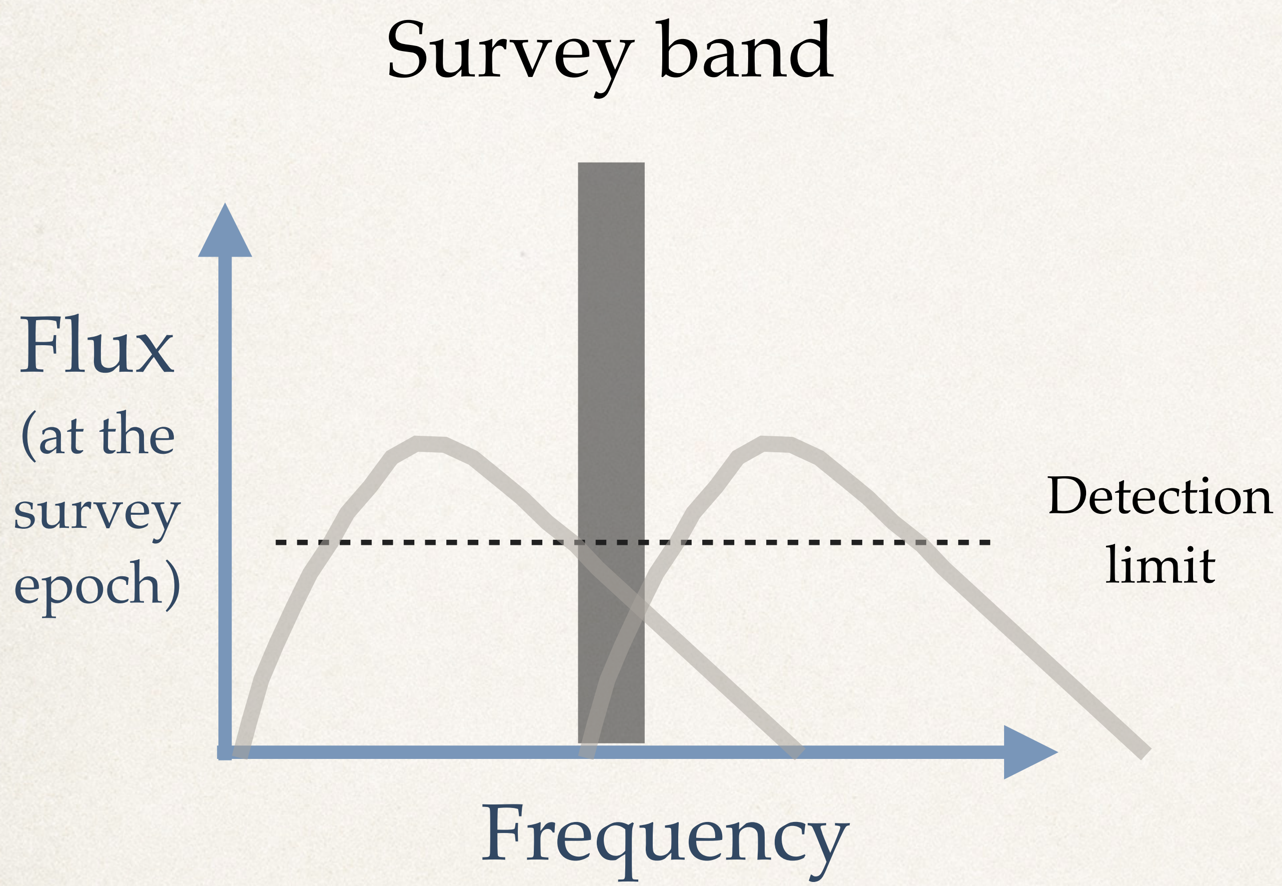
Most transients much slower than the cadence will be picked up as slowly varying sources

Selection biases as *information*



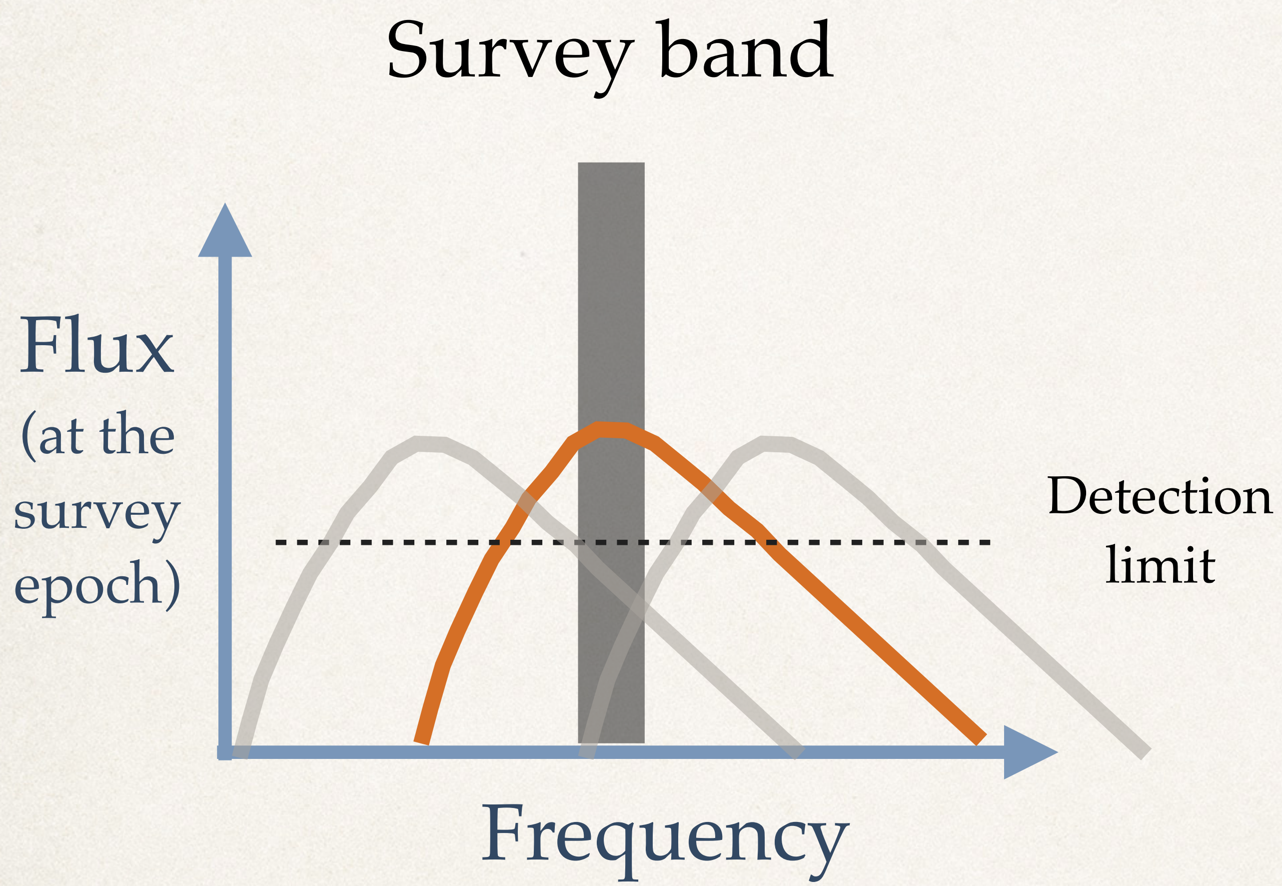
Transients that vary on timescales of order the cadence will be detected most efficiently

Selection biases as *information*



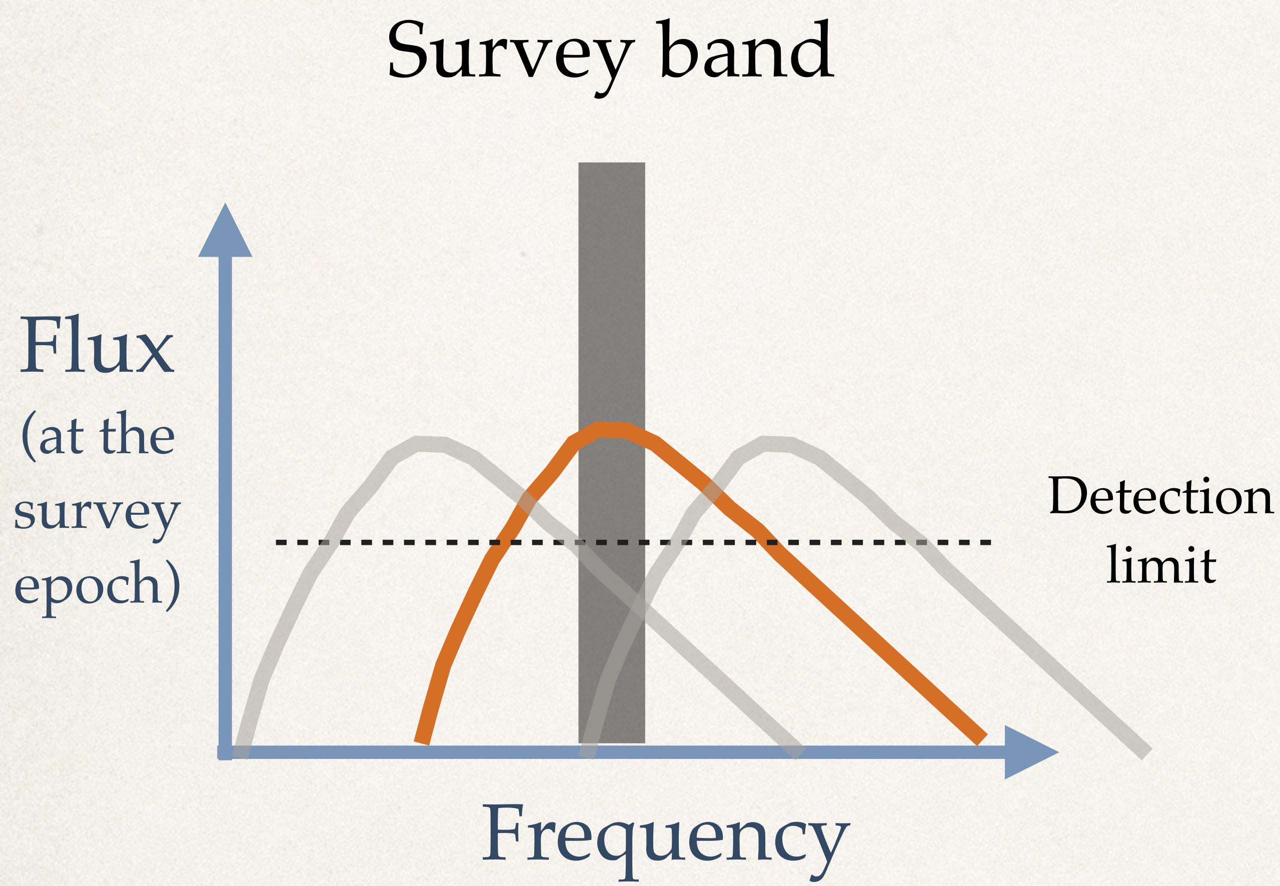
Sources that peak far away from the survey band will have lower flux and need to be closer to be detected

Selection biases as *information*



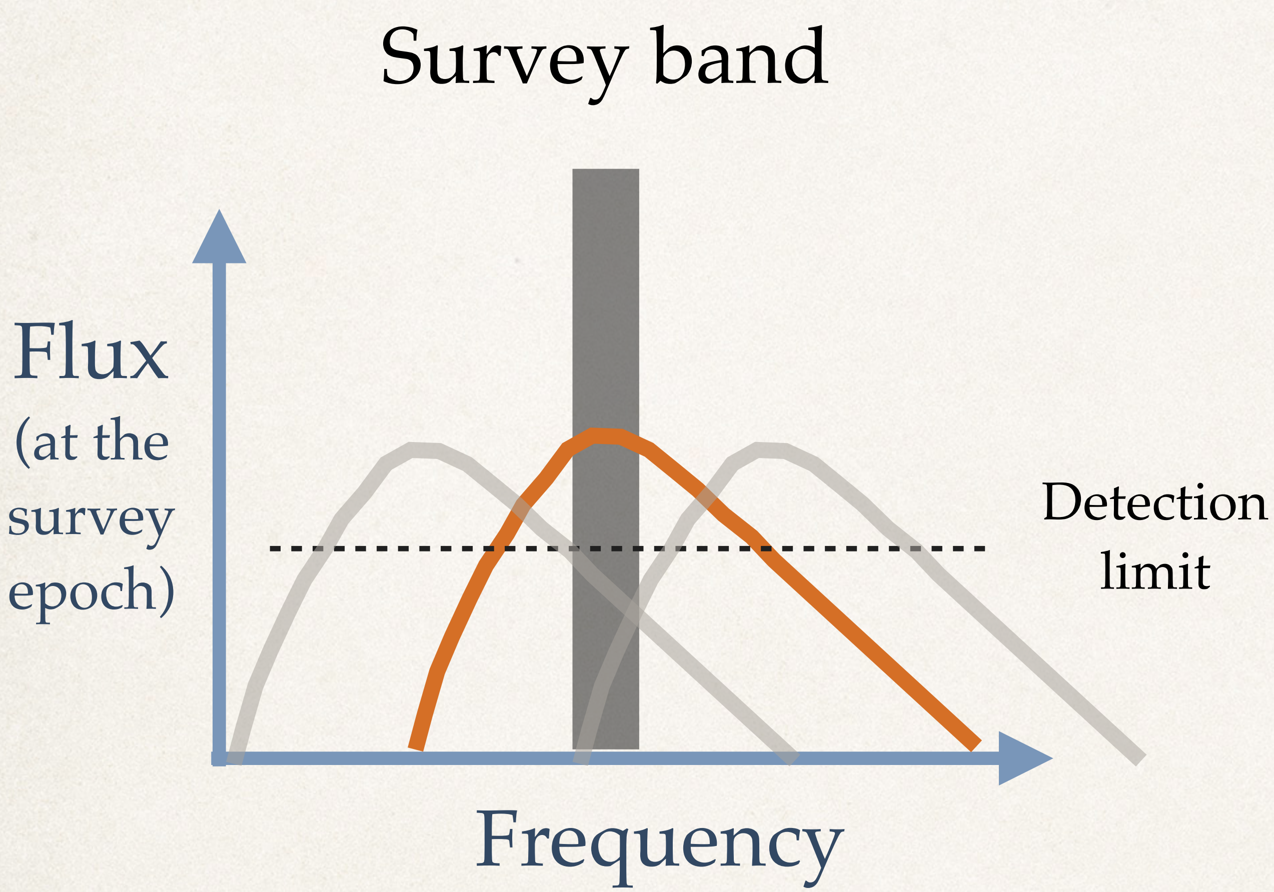
- Surveys are biased towards objects that peak in the survey band

Selection biases as *information*



- Surveys are biased towards objects that peak in the survey band
- Time-domain surveys are biased towards objects that ***spend the right amount of time*** peaking in the survey band

Selection biases as *information*



late 2010s 1990s-2000s

The VLASS - FIRST search is biased towards ~ decade timescale transients peaking at ~3 GHz

- Surveys are biased towards objects that peak in the survey band
- Time-domain surveys are biased towards objects that *spend the right amount of time* peaking in the survey band

The timescale and peak frequency translate to a *physical* scale

Transients peaking at 3GHz in our observed luminosity range have scale radii of ~ 0.1pc (assuming synchrotron self-absorption)

$$R = 7.5 \times 10^{16} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{1}{19}} \left(\frac{f}{0.2}\right)^{-\frac{1}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{\frac{9}{19}} \left(\frac{\nu_p}{5\ \mathrm{GHz}}\right)^{-1}\ \mathrm{cm}$$

e.g., Scott & Readhead 1979, Chevalier 1998

The timescale and peak frequency translate to a *physical* scale

Transients peaking at 3GHz in our observed luminosity range have scale radii of ~ 0.1pc (assuming synchrotron self-absorption)

$$R = 7.5 \times 10^{16} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{1}{19}} \left(\frac{f}{0.2}\right)^{-\frac{1}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{\frac{9}{19}} \left(\frac{\nu_p}{5\ \mathrm{GHz}}\right)^{-1}\ \mathrm{cm}$$

Staying at this radius for ~10 years implies a scale velocity of ~a few thousand km/s

The timescale and peak frequency translate to a *physical* scale

Transients peaking at 3GHz in our observed luminosity range have scale radii of ~ 0.1pc (assuming synchrotron self-absorption)

$$R = 7.5 \times 10^{16} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{1}{19}} \left(\frac{f}{0.2}\right)^{-\frac{1}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{\frac{9}{19}} \left(\frac{\nu_p}{5\ \mathrm{GHz}}\right)^{-1}\ \mathrm{cm}$$

Staying at this radius for ~10 years implies a scale velocity of ~a few thousand km/s

If transient is due to a shock, the corresponding magnetic field & velocity implies a scale pre-shock density of ~10^5 cm^{-3}

$$n_1 = 3.9 \times 10^6 \left(\frac{\epsilon_B}{0.1}\right)^{-1} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{-8}{19}} \left(\frac{f}{0.2}\right)^{\frac{-8}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{-\frac{-4}{19}}$$

e.g., Ho+2019. Dong+21

The timescale and peak frequency translate to a *physical* scale

Transients peaking at 3GHz in our observed luminosity range have scale radii of ~ 0.1pc (assuming synchrotron self-absorption)

$$R = 7.5 \times 10^{16} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{1}{19}} \left(\frac{f}{0.2}\right)^{-\frac{1}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{\frac{9}{19}} \left(\frac{\nu_p}{5\ \mathrm{GHz}}\right)^{-1} \mathrm{cm}$$

Staying at this radius for ~10 years implies a scale velocity of ~a few thousand km/s

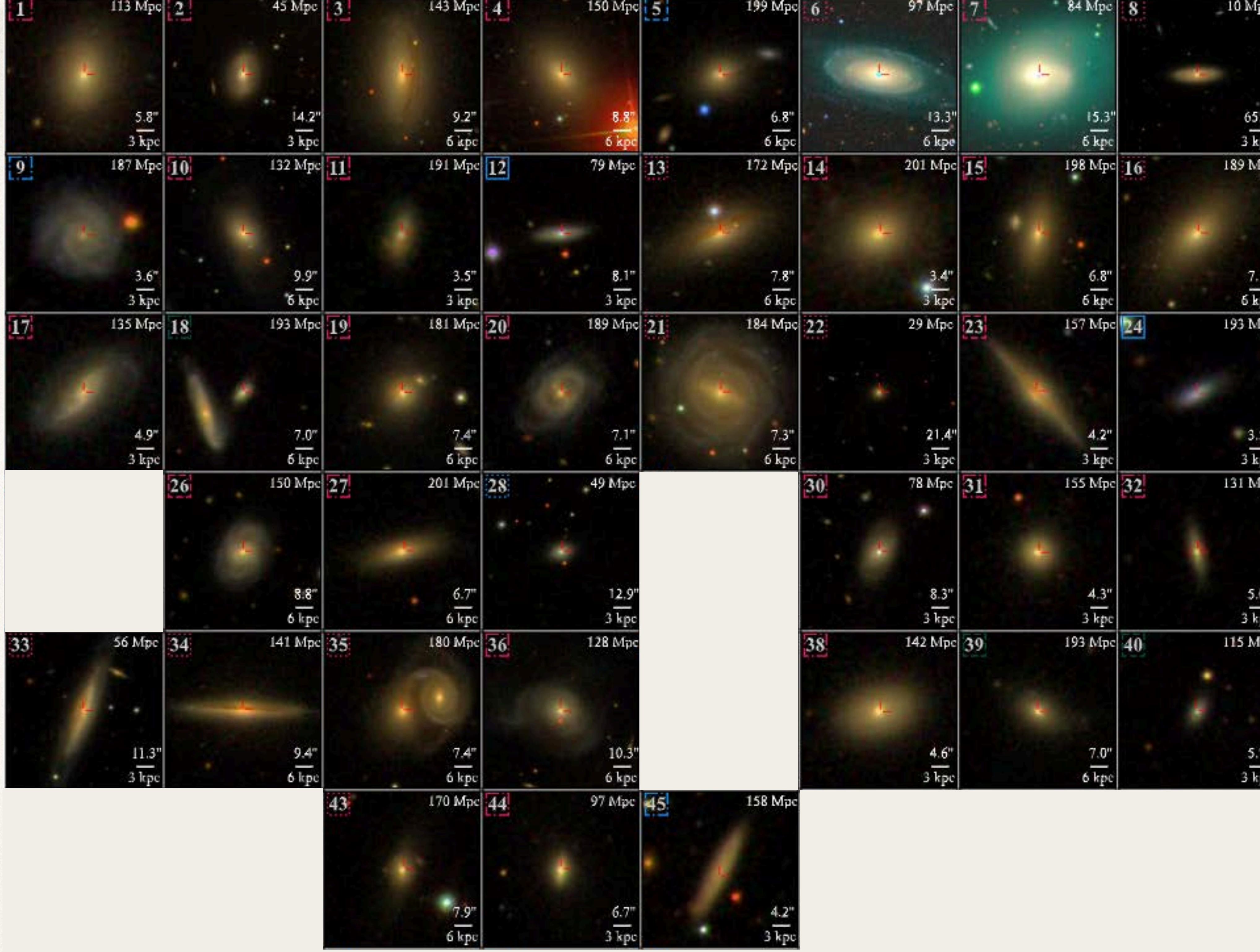
If transient is due to a shock, the corresponding magnetic field & velocity implies a scale pre-shock density of ~10^5 cm^{-3}

$$n_1 = 3.9 \times 10^6 \left(\frac{\epsilon_B}{0.1}\right)^{-1} \left(\frac{\epsilon_e}{\epsilon_B}\right)^{-\frac{-8}{19}} \left(\frac{f}{0.2}\right)^{\frac{-8}{19}} \left(\frac{L_p}{10^{29}\ \mathrm{erg/s/Hz}}\right)^{-\frac{-4}{19}}$$

NOTE: These are *generalizations* (not directly confirmed with more detailed analysis in most cases).

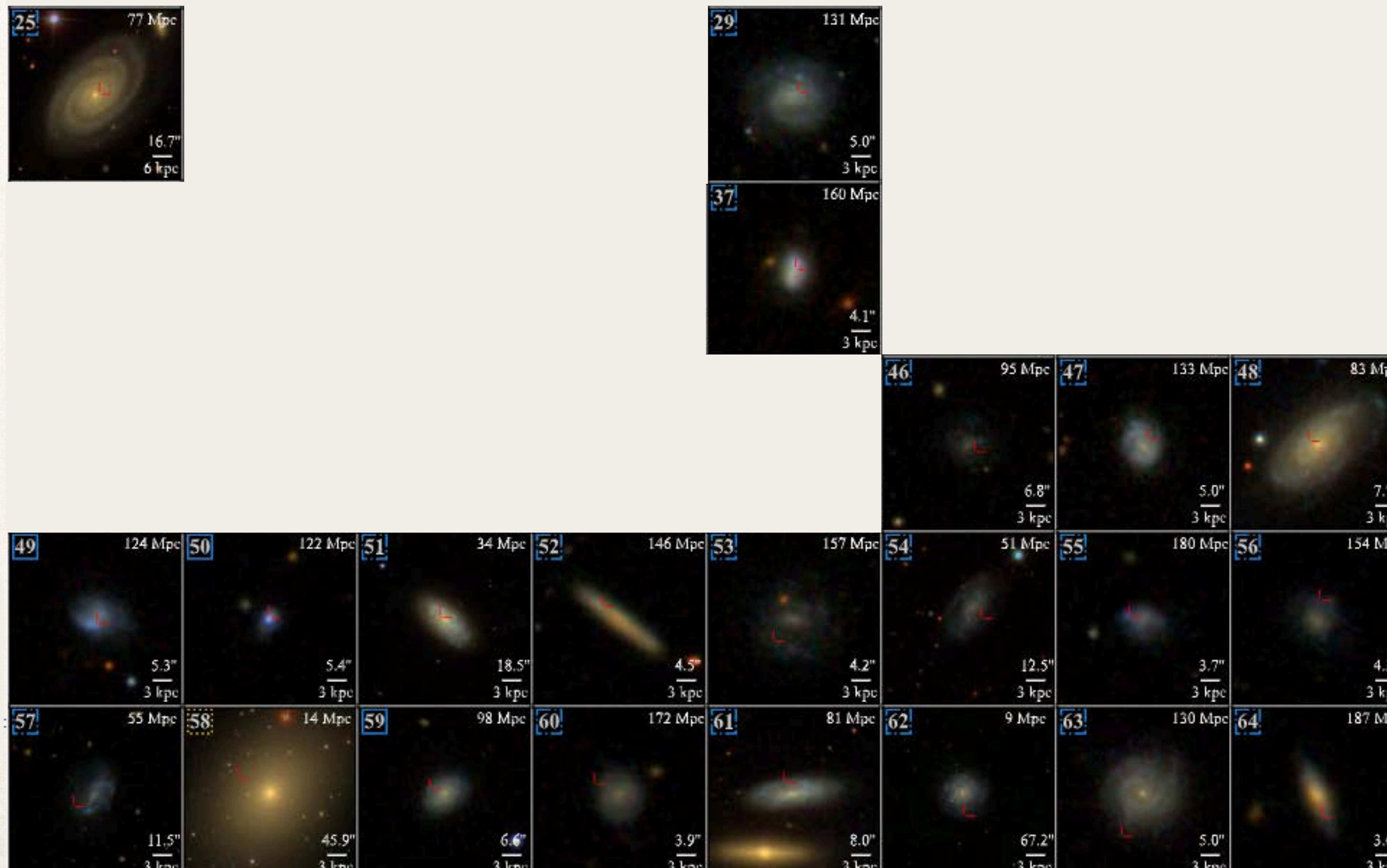
However, they *are consistent* with initial follow-up observations & case studies

Nuclear transients are primarily located in red and dead galaxies



Dong+ 2023b (in prep)

Off-nuclear transients are primarily located in star forming galaxies

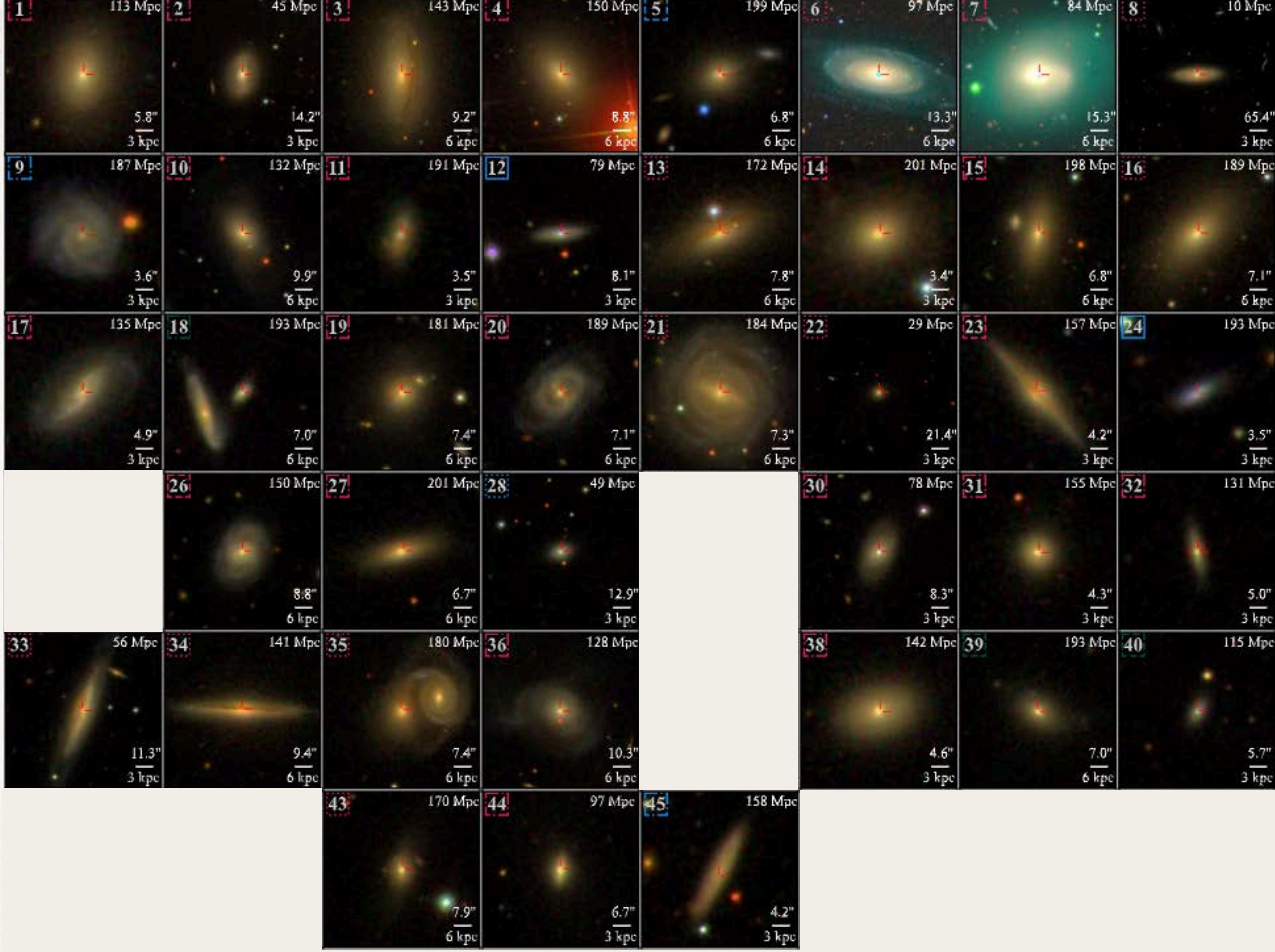


Dong+ 2023b (in prep)

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)

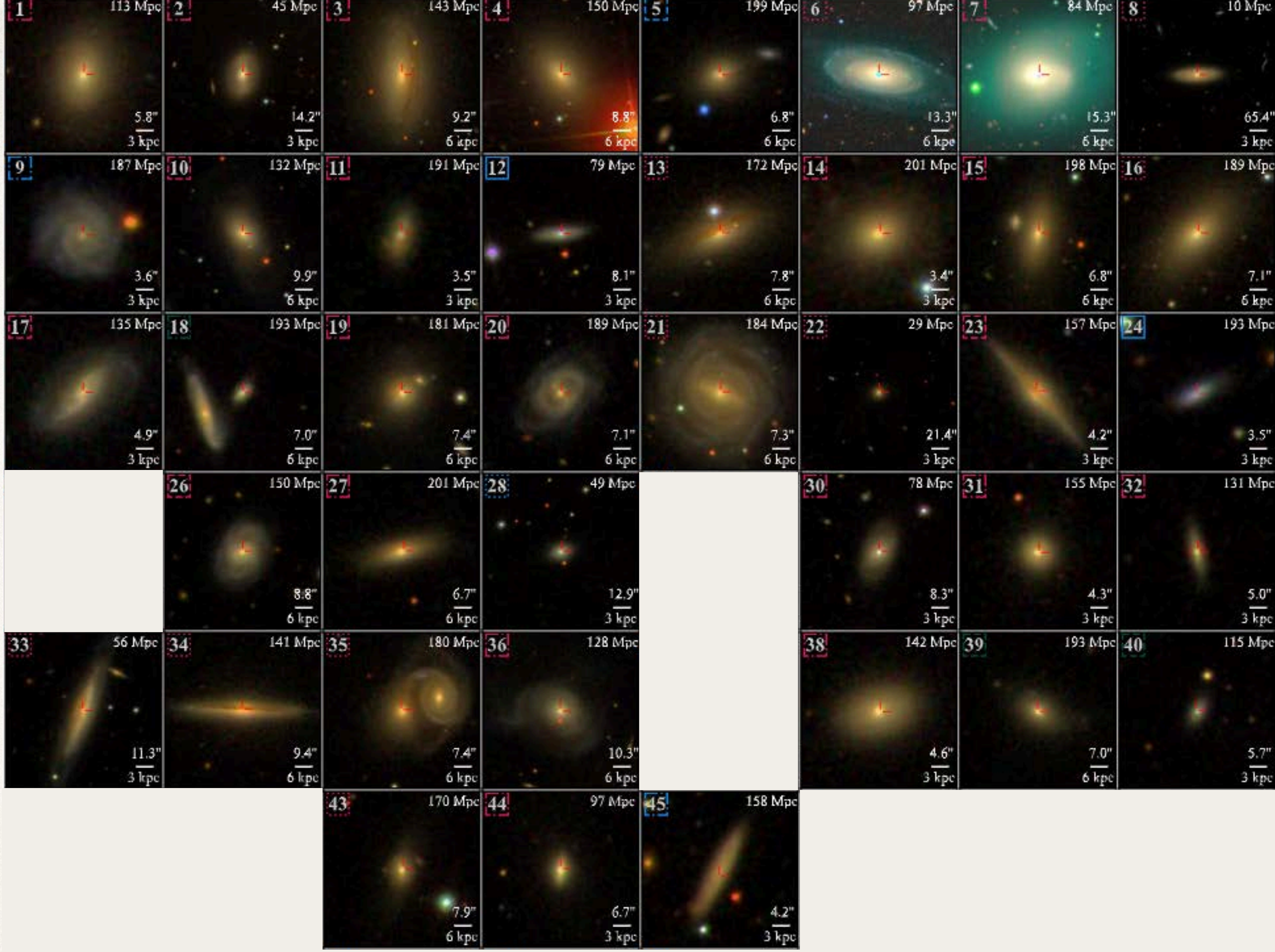
Nuclear transients are primarily located in red and dead galaxies

Many are in AGN:

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

Some are in completely quiescent galaxies:

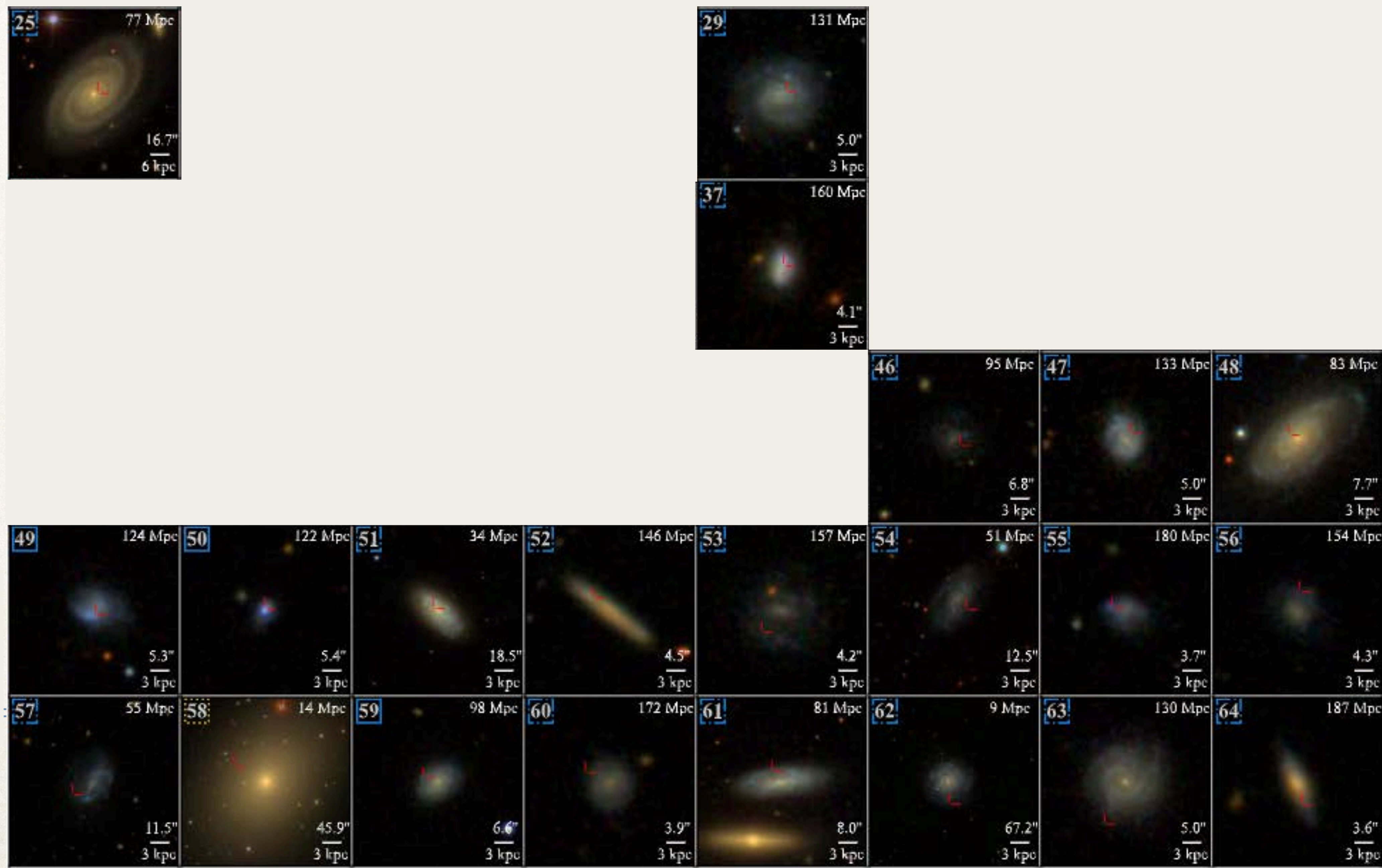
~decade timescale tidal disruption events at ~1-30% of the optical TDE rate



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



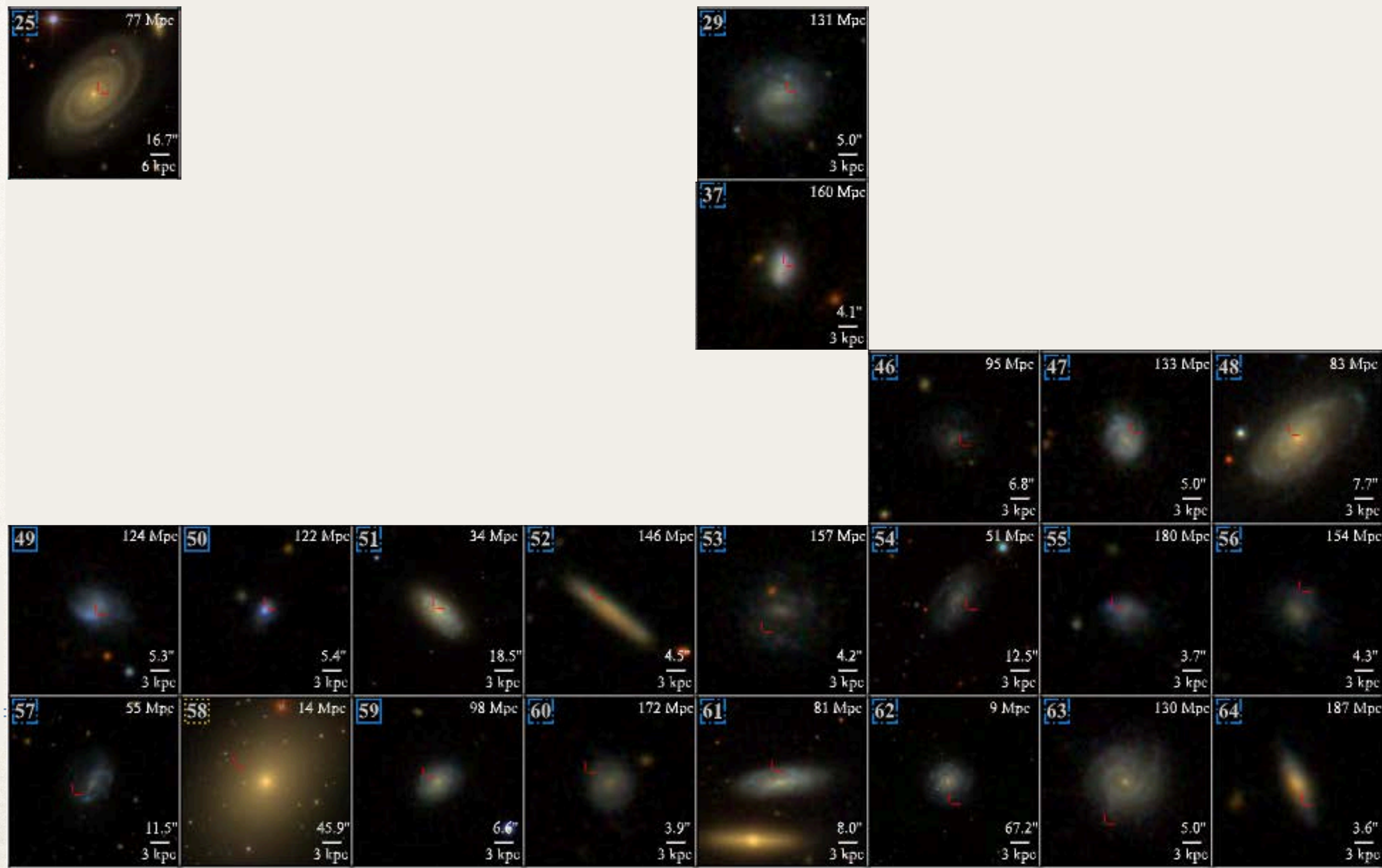
Dong+ 2023b (in prep)

Off-nuclear transients are primarily located in star forming galaxies

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

Requires eruptive mass loss ~centuries before supernova

Dong+ 2023b (in prep)

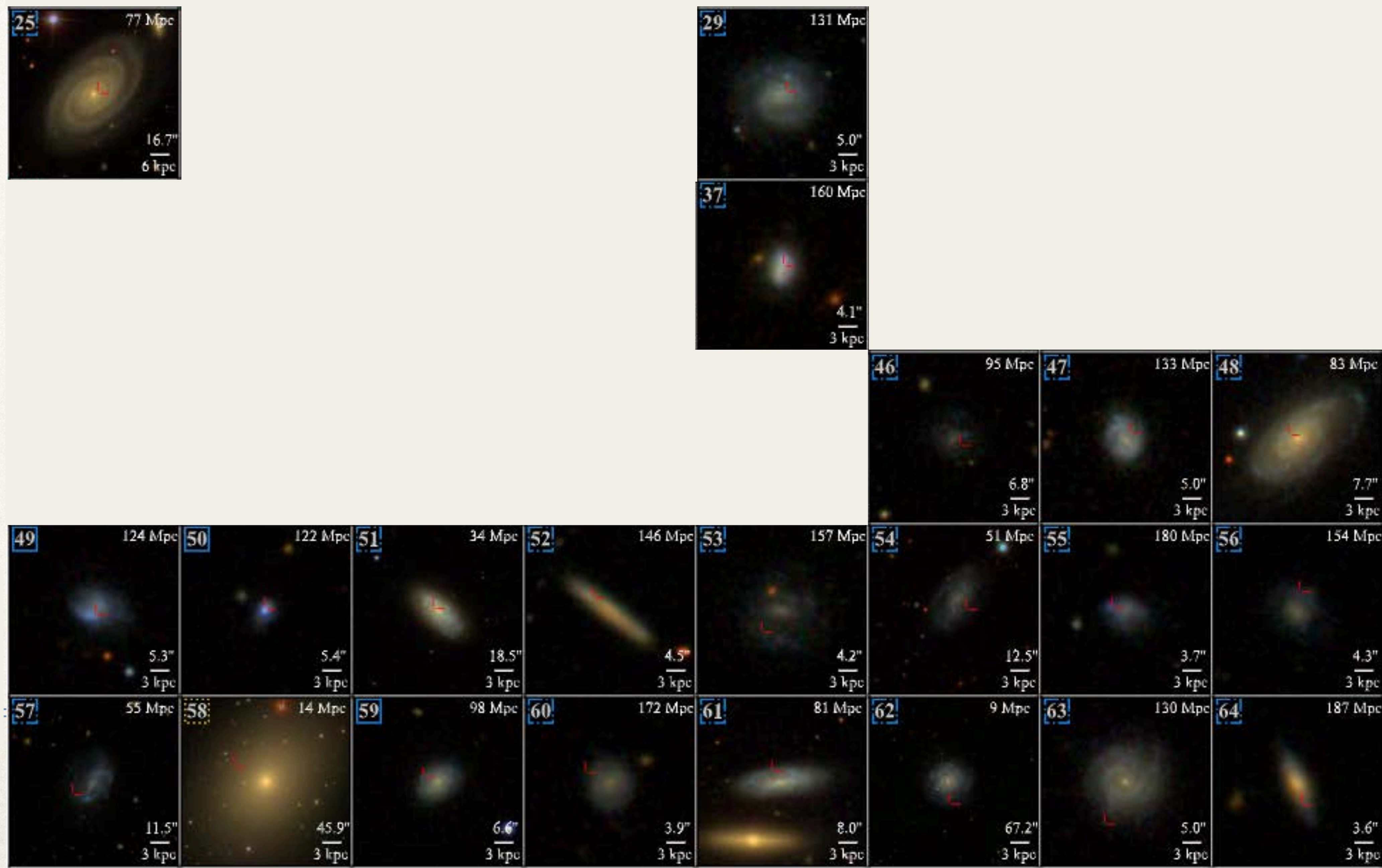


Off-nuclear transients are primarily located in star forming galaxies

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

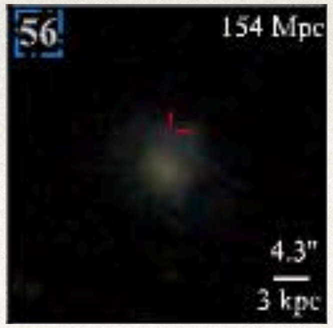
Requires eruptive mass loss ~centuries before supernova

Up to 0.3% of the core collapse SN rate

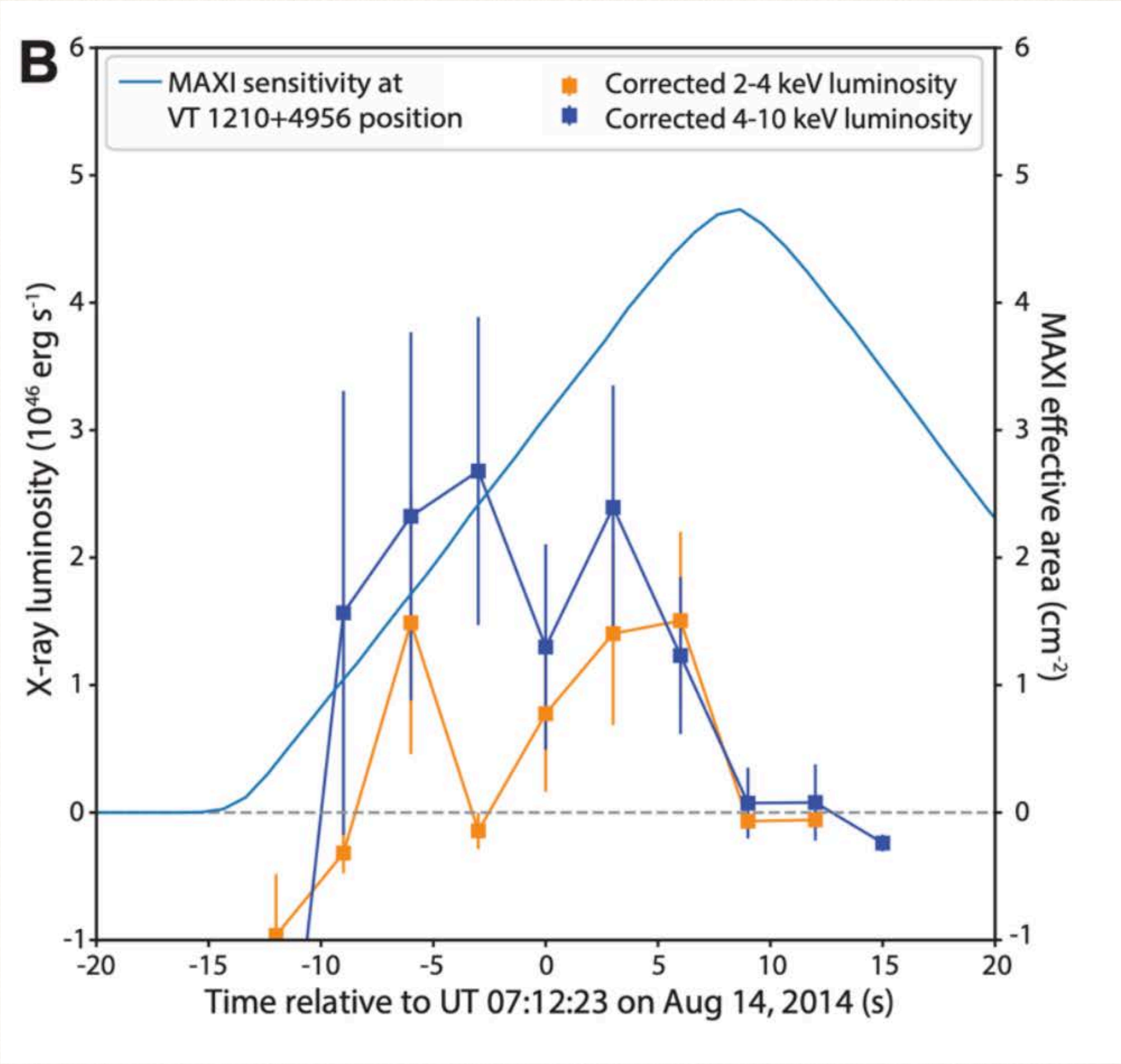


Dong+ 2023b (in prep)

Merger-driven explosion VT 1210+4956

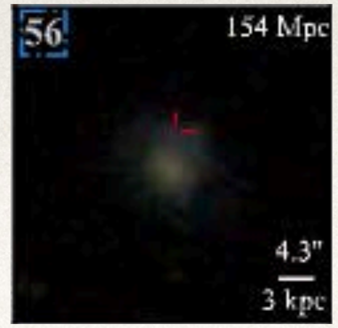


- **Aug 14, 2014:** relativistic ($\Gamma > 2.5$) jet traced by 15s X-ray flash

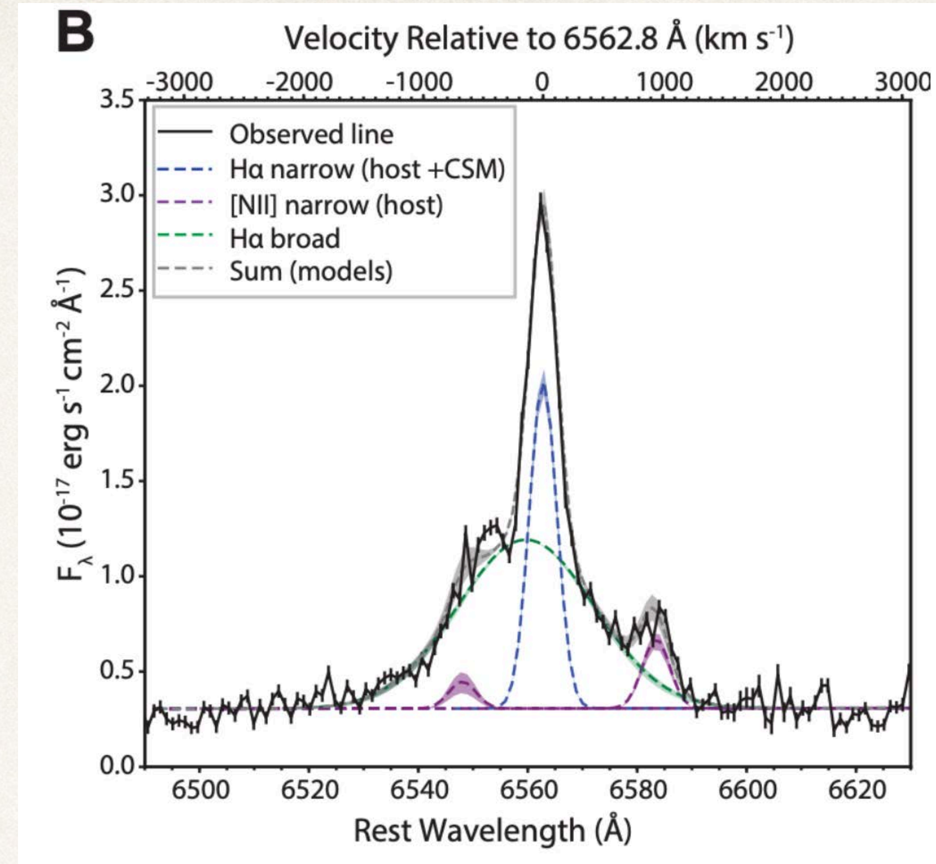


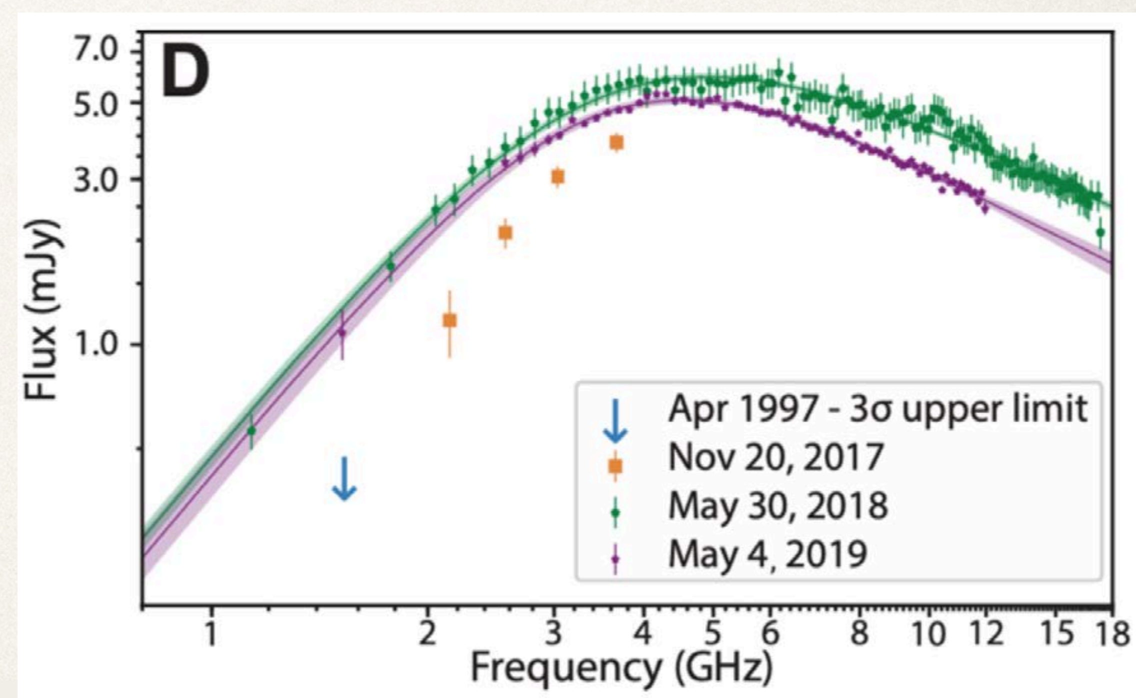
Dong+2021, Science

Merger-driven explosion VT 1210+4956



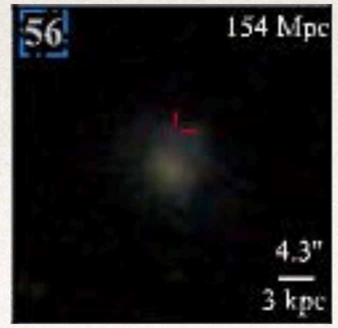
- **Aug 14, 2014:** relativistic ($\Gamma > 2.5$) jet traced by 15s X-ray flash
- **2017- present:** supernova ejecta interacting with $> 1\ M_\odot$ aspherical shell, ejected ~centuries before explosion





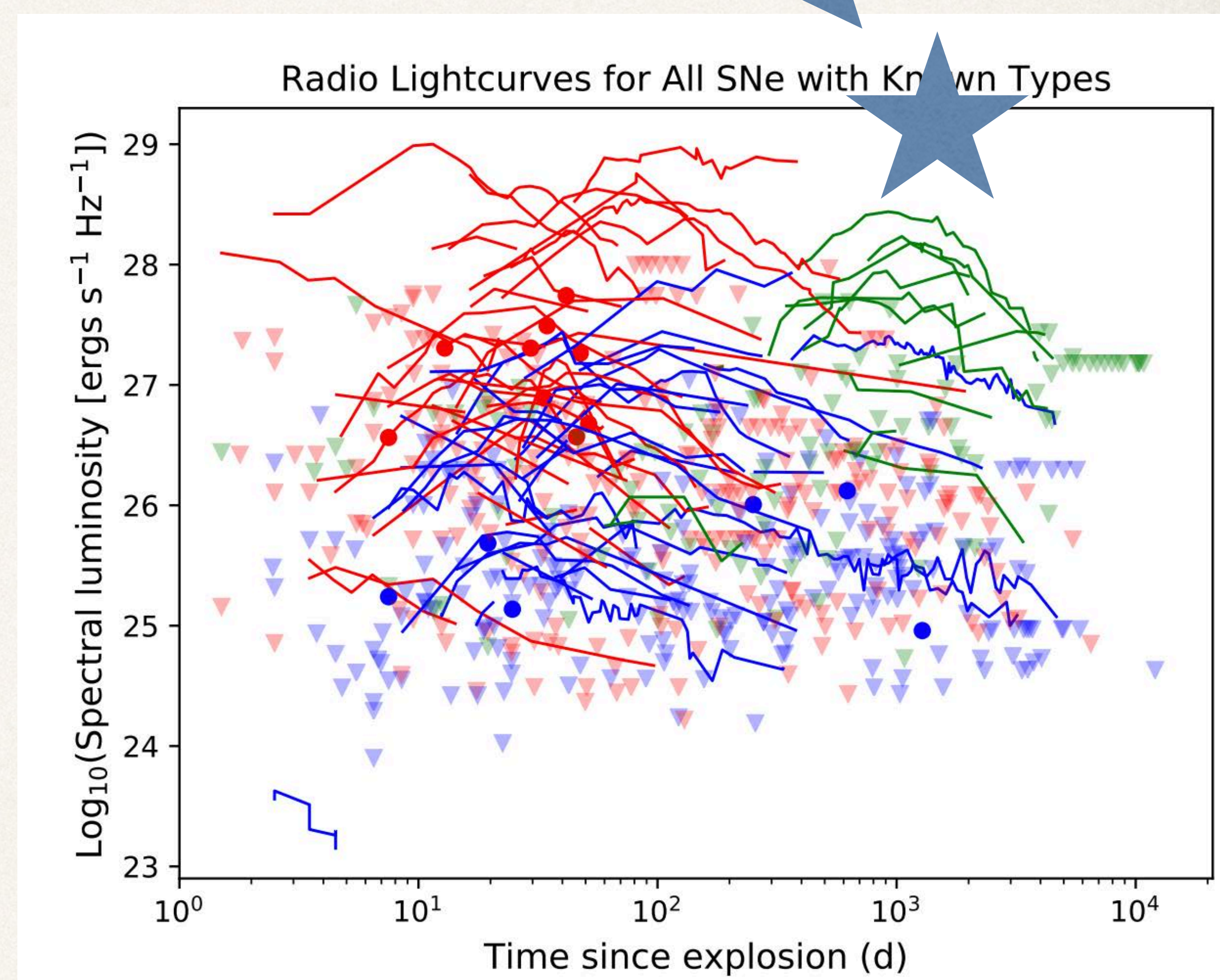
Dong+2021, Science

Merger-driven explosion VT 1210+4956



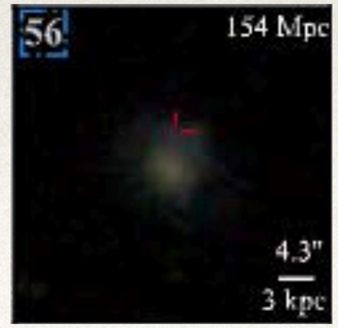
- **Aug 14, 2014:** relativistic ($\Gamma > 2.5$) jet traced by 15s X-ray flash
- **2017- present:** supernova ejecta interacting with $> 1\ M_\odot$ aspherical shell, ejected ~centuries before explosion
- [tied for] Most luminous radio supernova ever detected

VT 1210



Dong+2021, Science

Merger-driven explosion VT 1210+4956



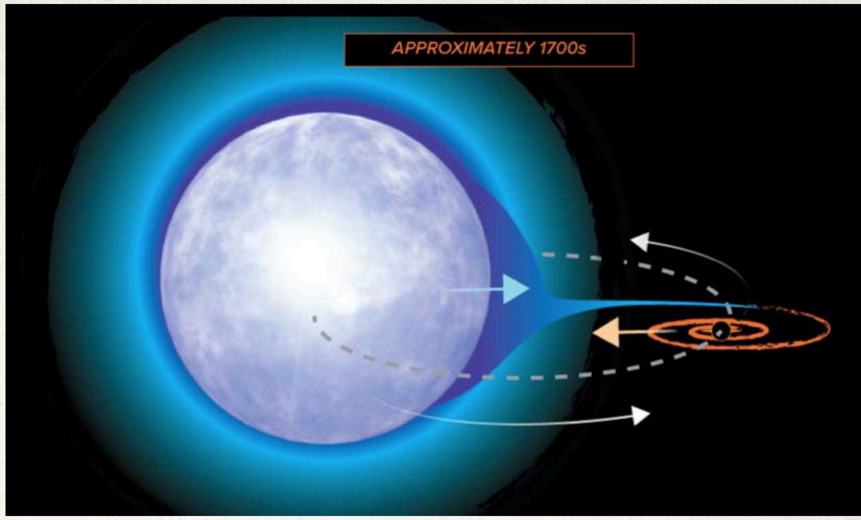
- **Aug 14, 2014:** relativistic ($\Gamma > 2.5$) jet traced by 15s X-ray flash
- **2017- present:** supernova ejecta interacting with $> 1\ M_\odot$ aspherical shell, ejected ~centuries before explosion
- [tied for] Most luminous radio supernova ever detected
- Unifying model:
  compact object + massive star merger

  Chevalier+12, Schrøder+19

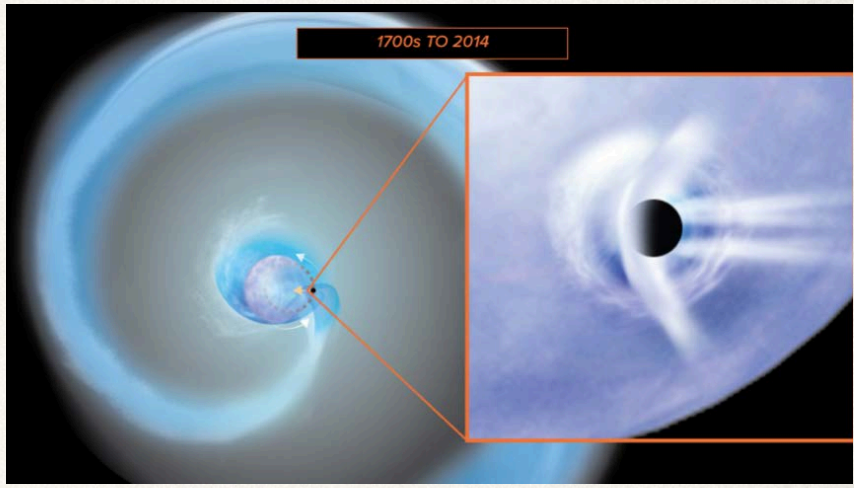
Dong+2021, Science

artists impression: Bill Saxton, Chuck Carter

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

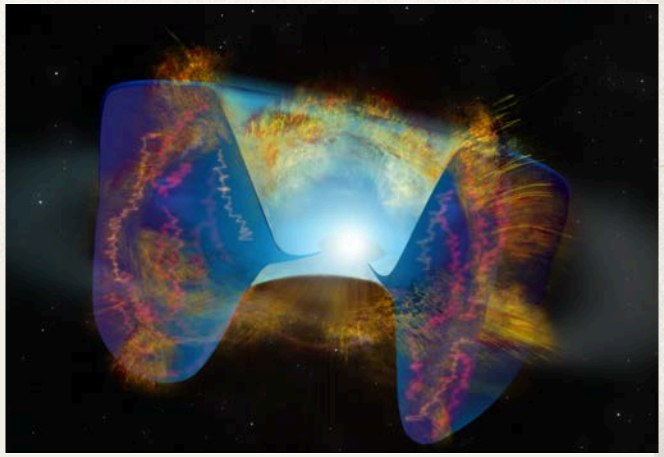


Compact object plunges in

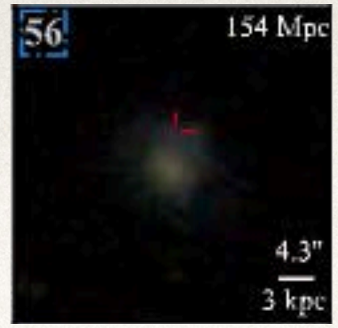


Explosion when object reaches core, launches jet (X-ray)

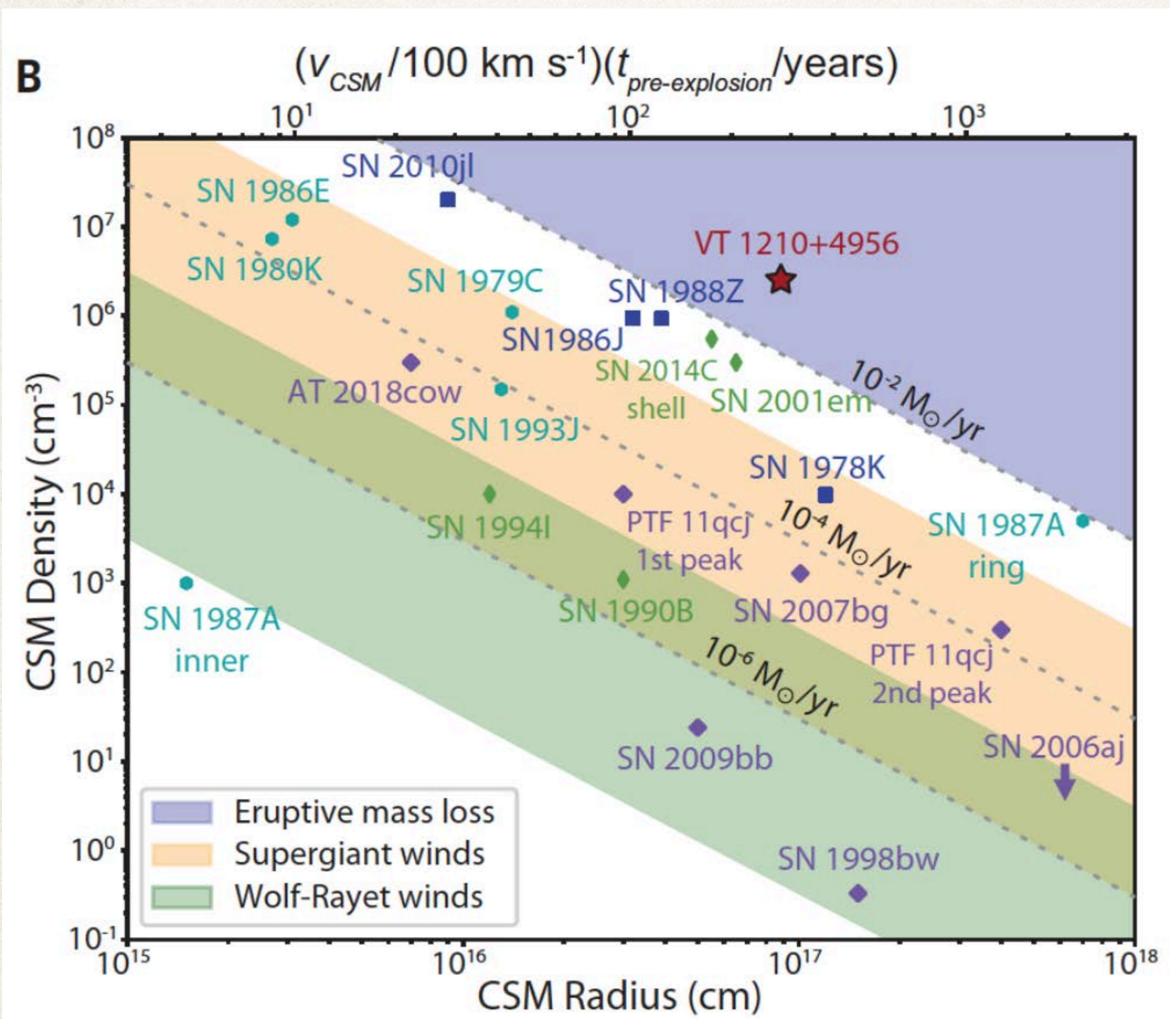
Ejecta hits expanded gas spiral (radio/optical)



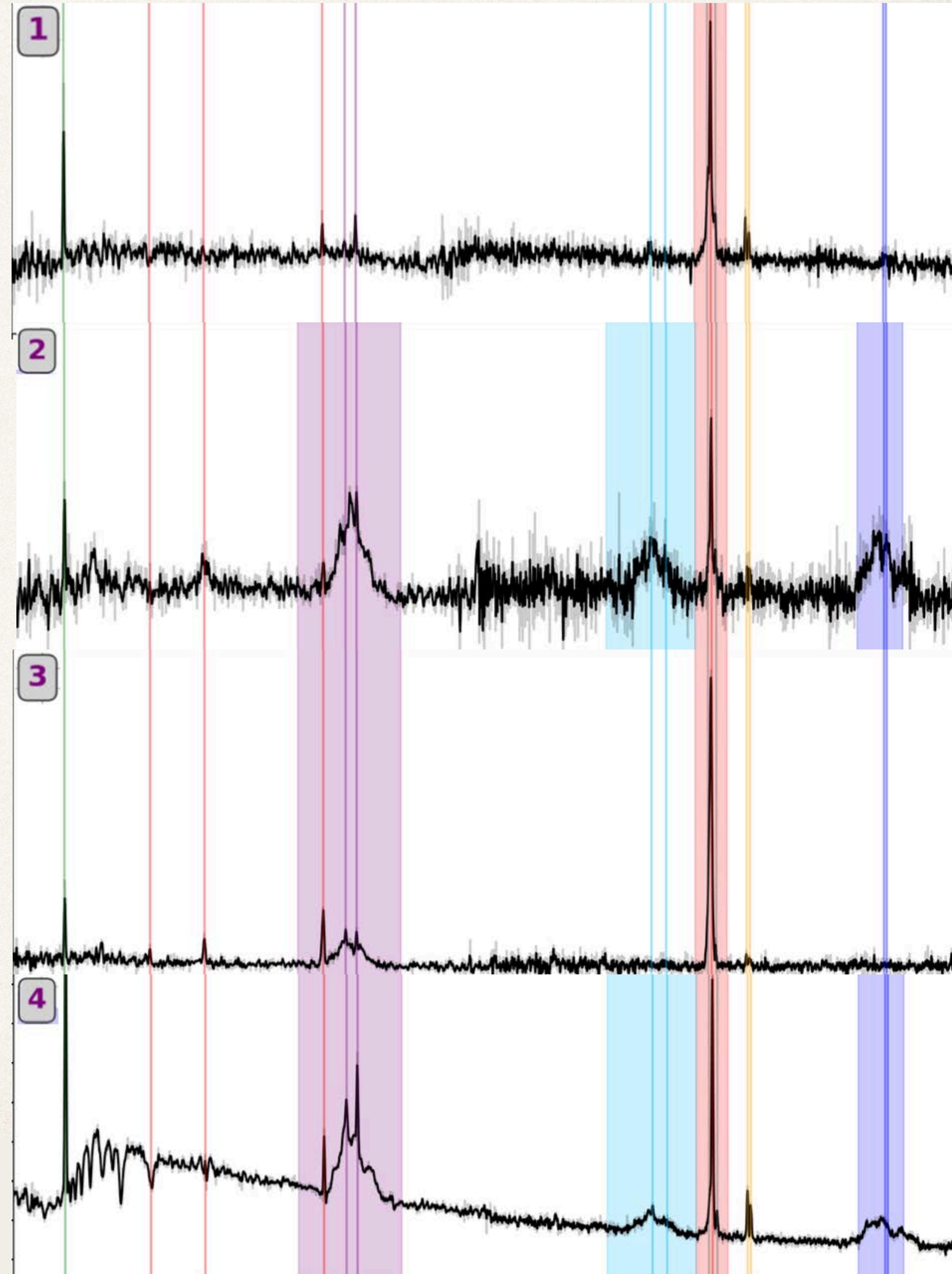
Merger-driven explosion VT 1210+4956



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

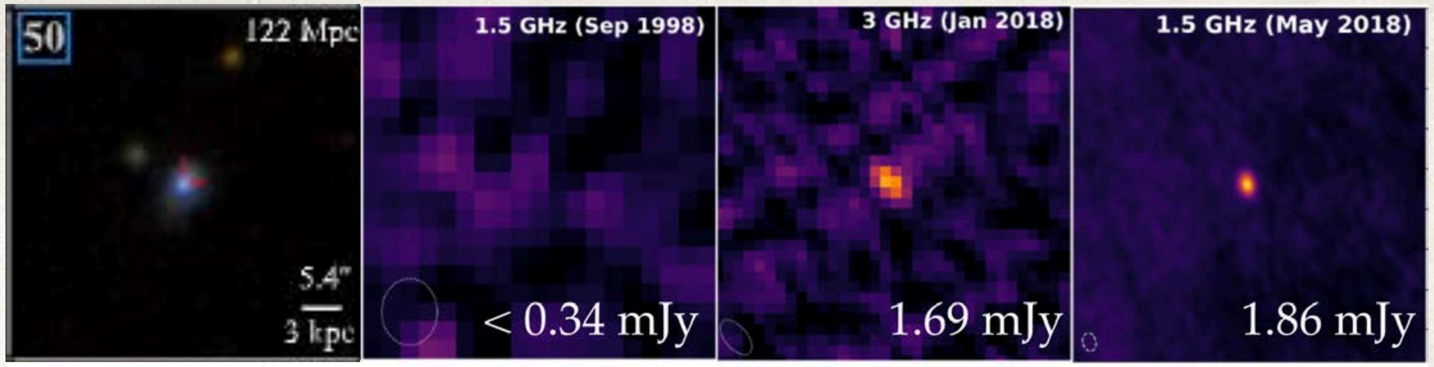


Many more stellar explosions with similar aspherical shells!



Dong+2021, 2023c in prep

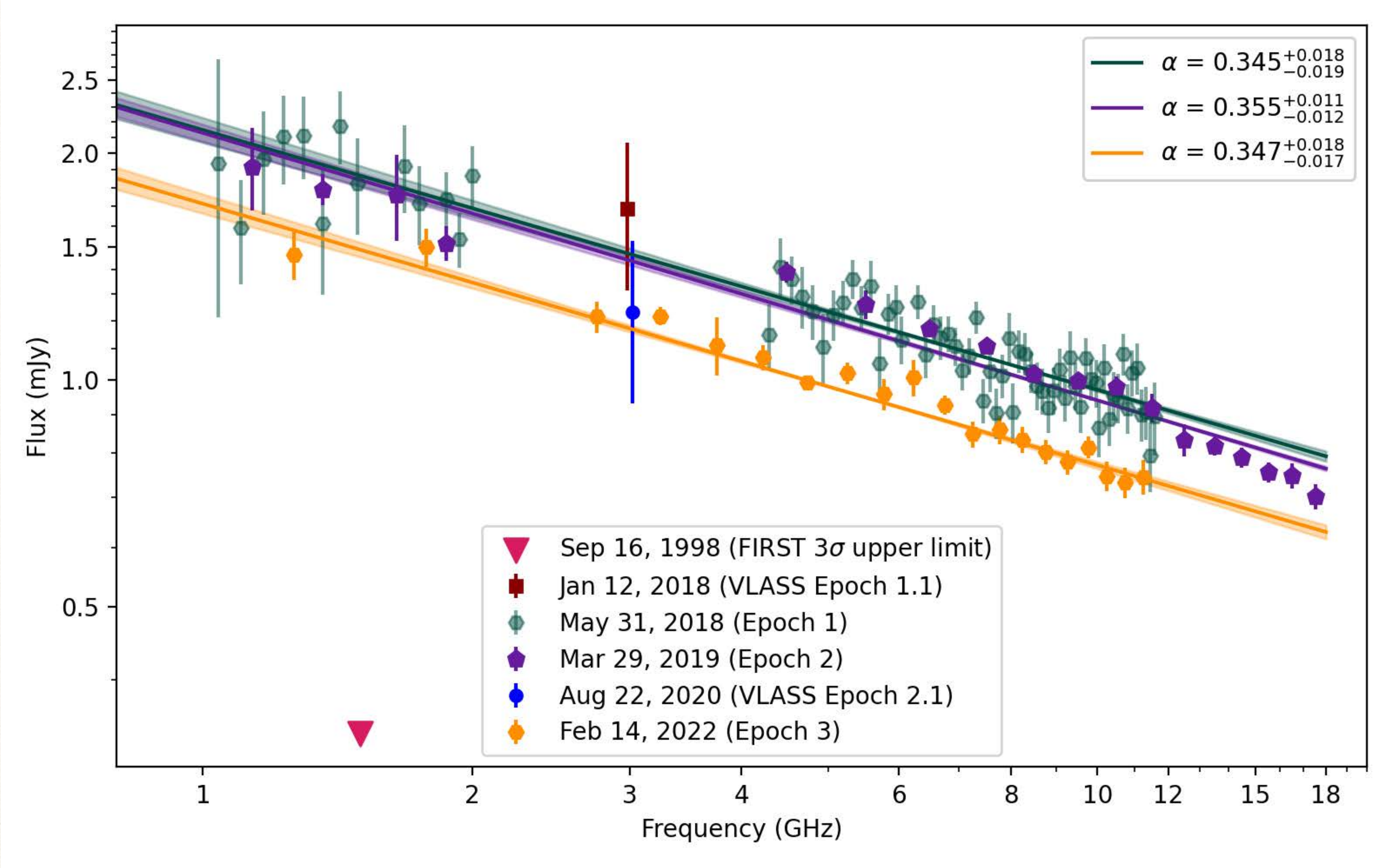
Emerging pulsar wind nebula VT 1137-0337



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

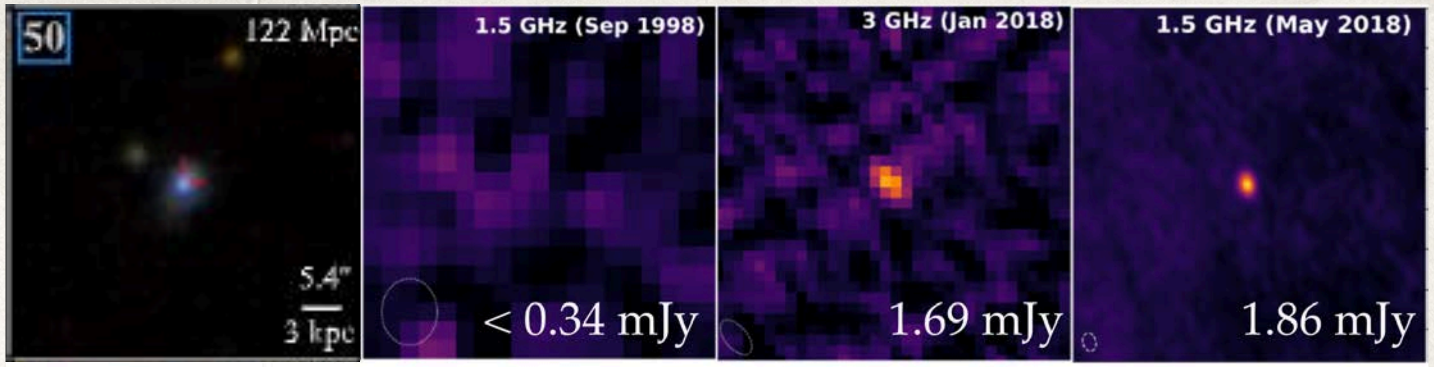
Fading by ~5% per year over 4 years

Too stable to be a jet



Dong & Hallinan 2023a

Emerging pulsar wind nebula VT 1137-0337

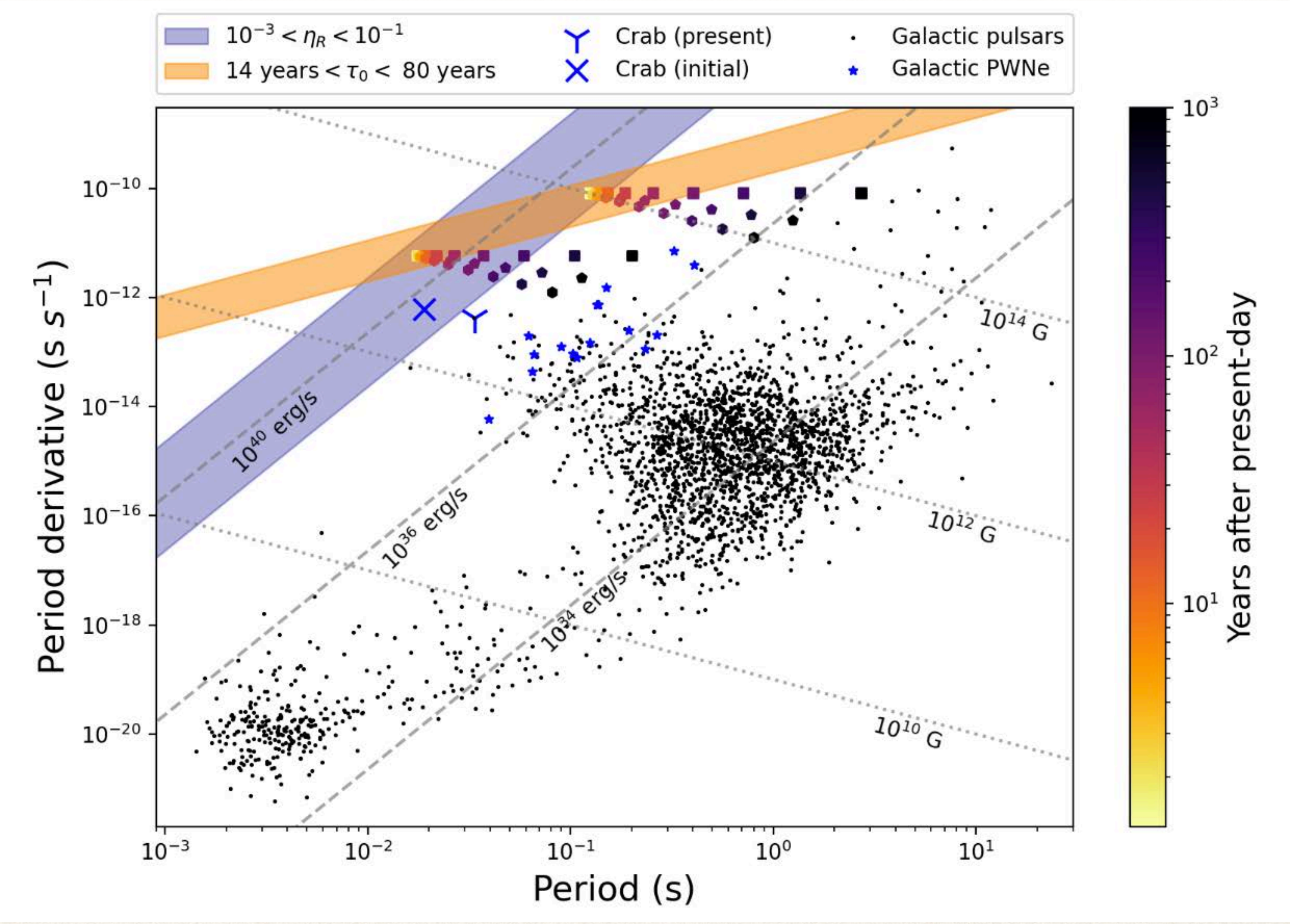


Consistent with an emerging "super-Crab"

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

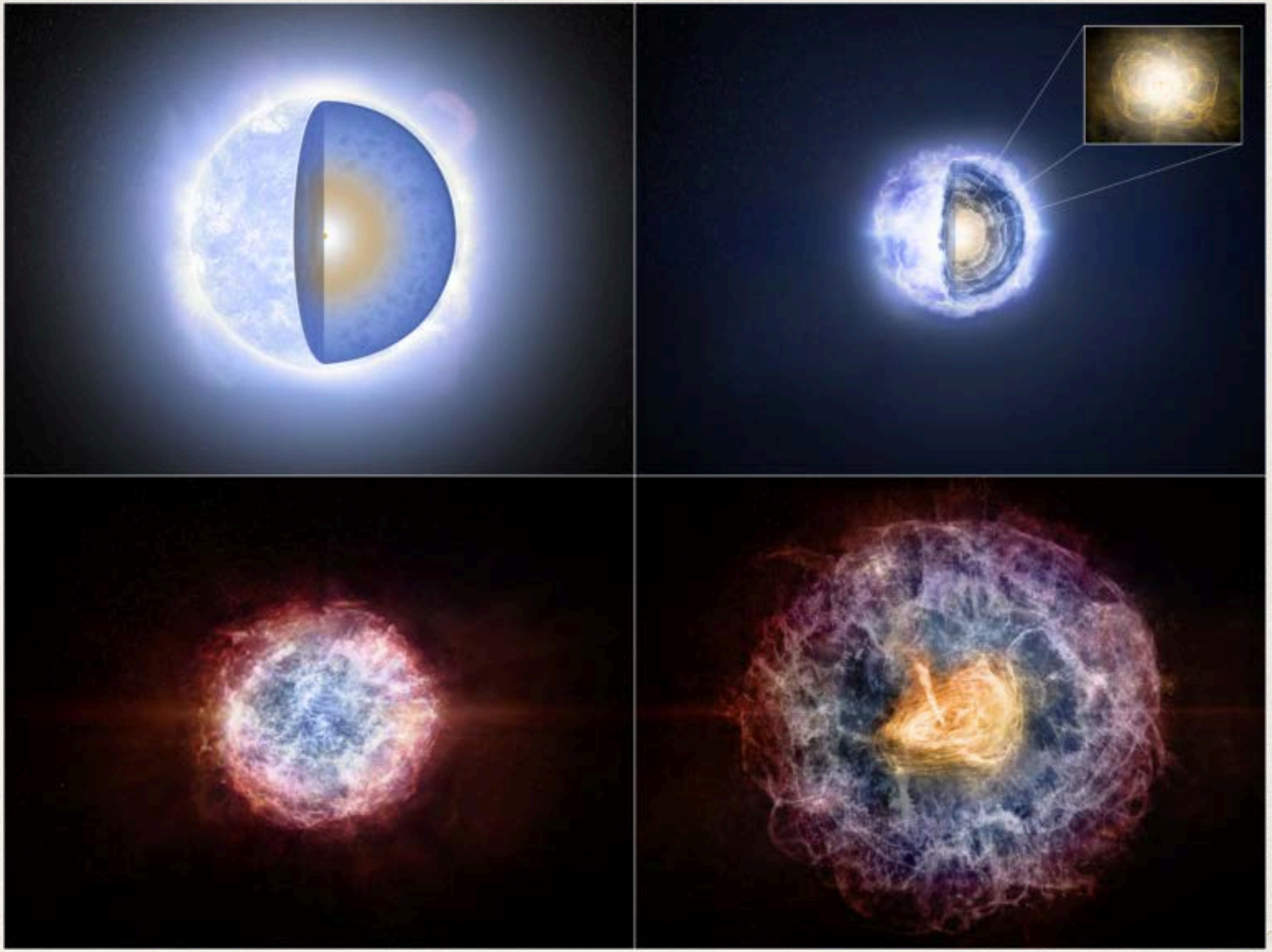
May be analog of FRB persistent sources

(10x less luminous than 121102, 190520B)



Dong & Hallinan 2023a

Emerging pulsar wind nebula VT 1137-0337



Dong & Hallinan 2023a

Artist's credit: Melissa Weiss

Conclusions

- Slow radio transients trace the launch of new relativistic electrons (usually from shocks, but not always)

Conclusions

- Slow radio transients trace the launch of new relativistic electrons (usually from shocks, but not always)
- In a **volume limited survey**, the extragalactic population is split ~50/50 between **SMBH flares** and **stellar explosions**

Conclusions

- Slow radio transients trace the launch of new relativistic electrons (usually from shocks, but not always)
- In a **volume limited survey**, the extragalactic population is split ~50/50 between **SMBH flares** and **stellar explosions**

On year to decade timescales:

- SMBH flares are due to **non-relativistic** outflows from both quiescent BHs (TDEs) and AGN (disk winds? stellar explosions?)

Conclusions

- Slow radio transients trace the launch of new relativistic electrons (usually from shocks, but not always)
- In a **volume limited survey**, the extragalactic population is split ~50/50 between **SMBH flares** and **stellar explosions**

On year to decade timescales:

- SMBH flares are due to **non-relativistic** outflows from both quiescent BHs (TDEs) and AGN (disk winds? stellar explosions?)
- **Stellar explosions** are mostly **dense CSM interaction** (likely aspherical), but some are **extreme pulsar wind nebulae** (analogous to FRB persistent sources)

Conclusions

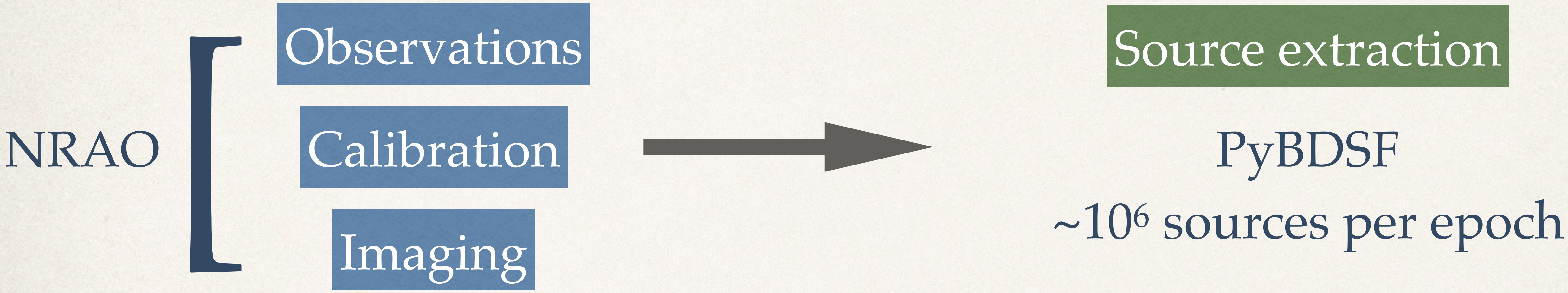
- Slow radio transients trace the launch of new relativistic electrons (usually from shocks, but not always)
- In a **volume limited survey**, the extragalactic population is split ~50/50 between **SMBH flares** and **stellar explosions**

On year to decade timescales:

- SMBH flares are due to **non-relativistic** outflows from both quiescent BHs (TDEs) and AGN (disk winds? stellar explosions?)
- **Stellar explosions** are mostly **dense CSM interaction** (likely aspherical), but some are **extreme pulsar wind nebulae** (analogous to FRB persistent sources)

Extra slides

Automating transient detection in VLASS



Dong+23d, in prep

Automating transient detection in VLASS

NRAO

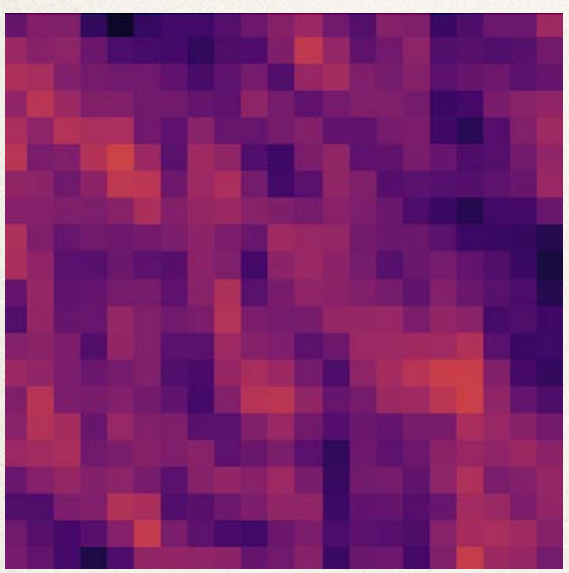
- Observations
- Calibration
- Imaging

→ Source extraction

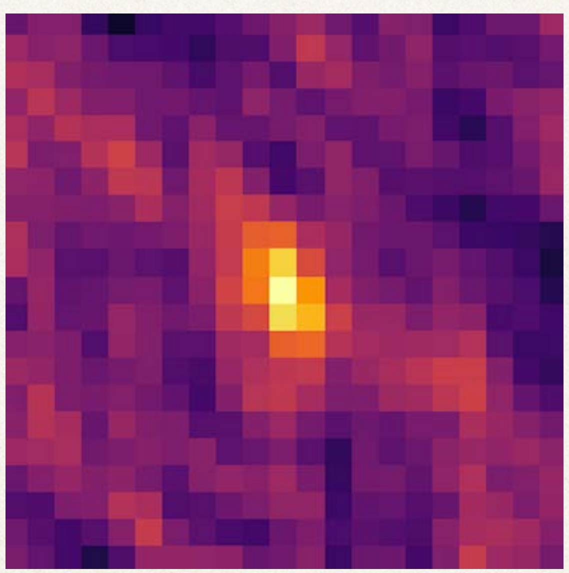
PyBDSF

~10^6 sources per epoch

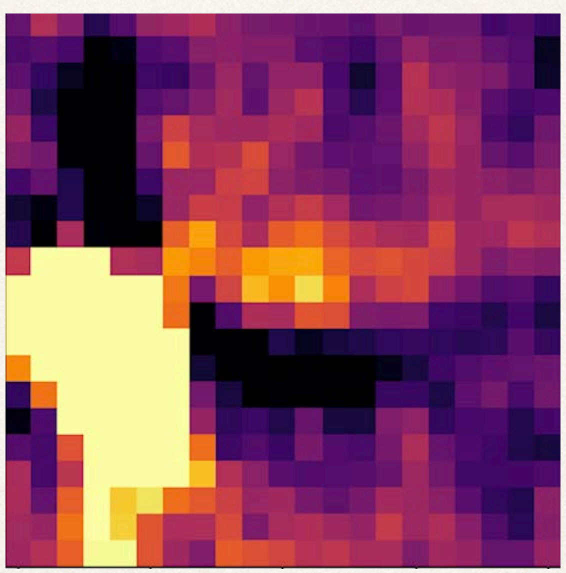
→ Artifact filtering



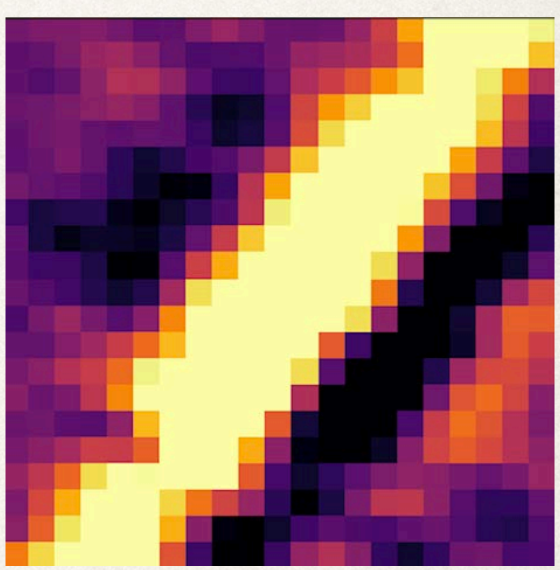
Noise



Point source



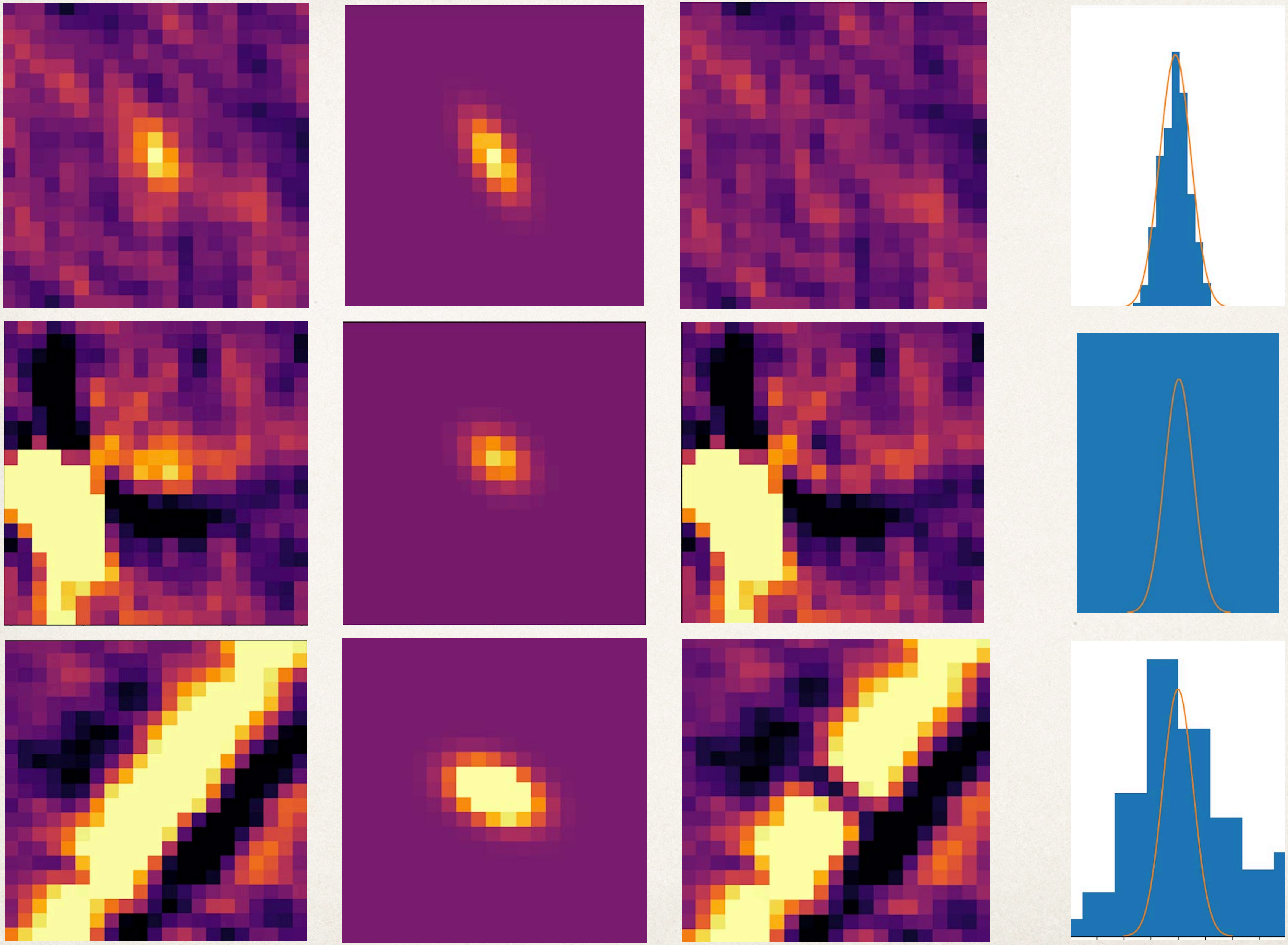
Sidelobe



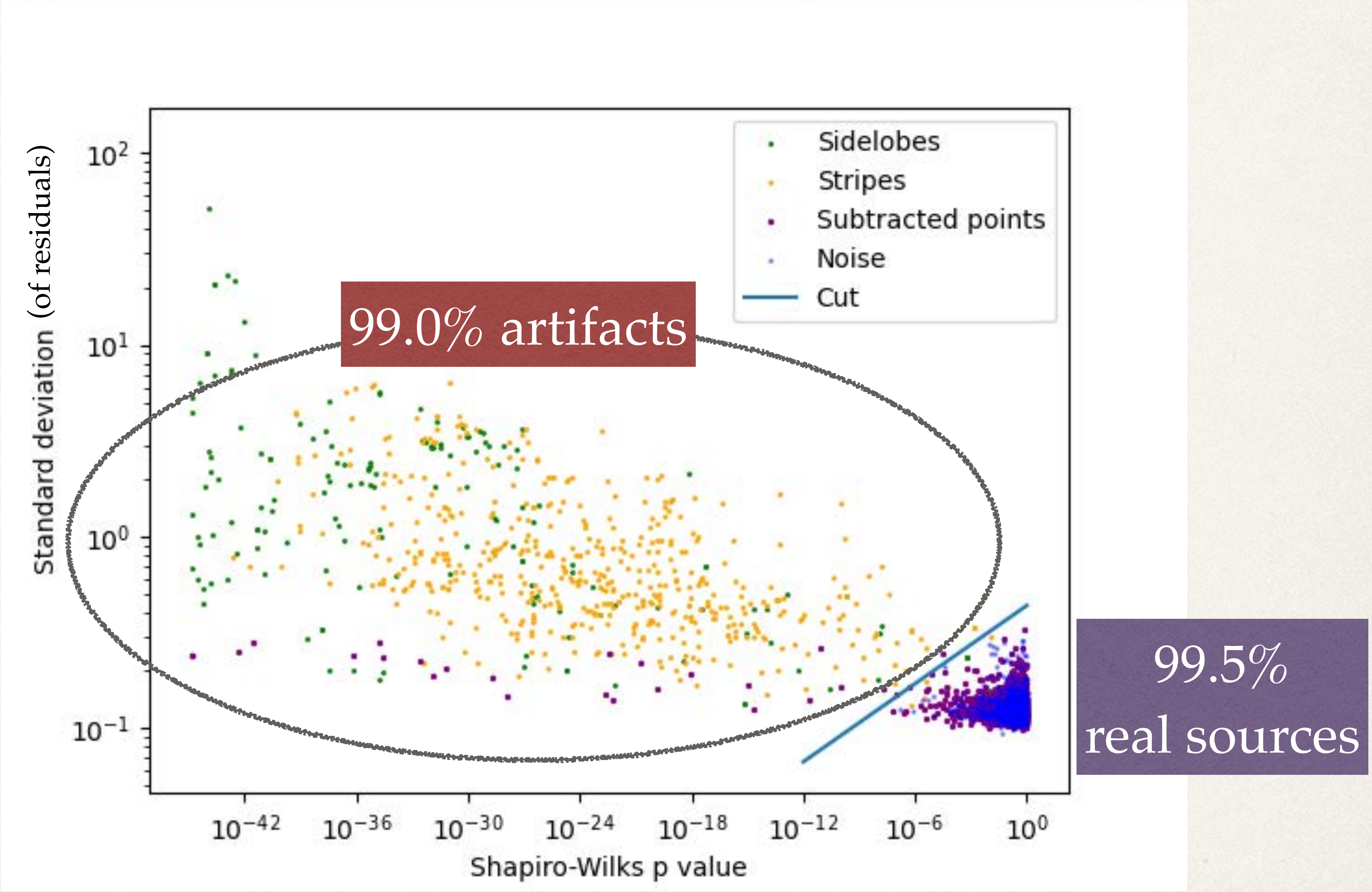
Stripe

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

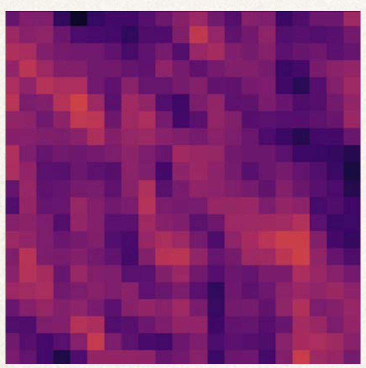
→ Source extraction

PyBDSF

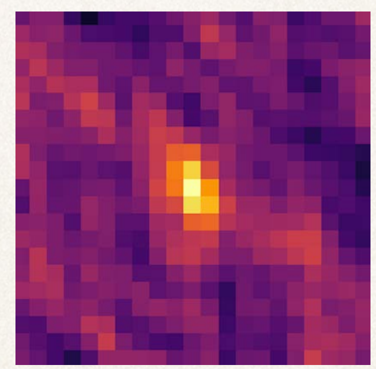
~10^6 sources per epoch

→ Artifact filtering

Noise in one epoch



Point source in another

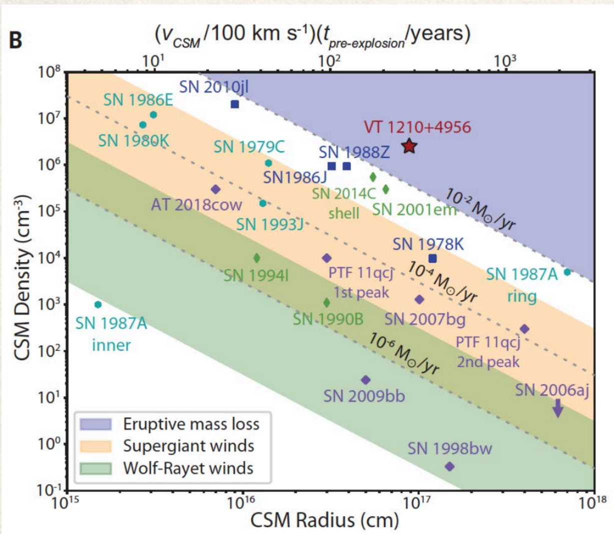


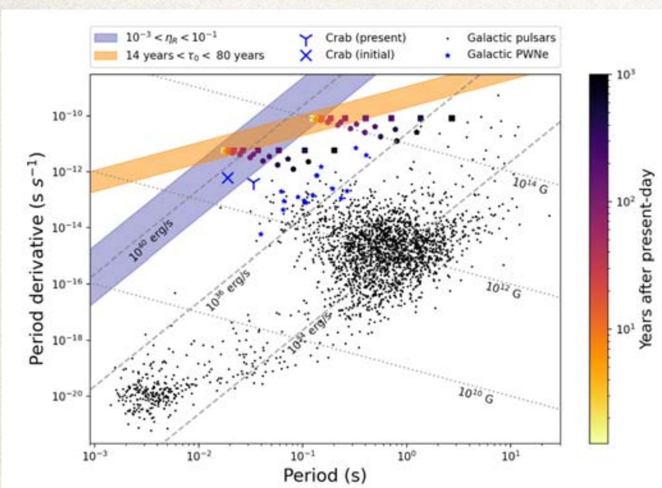
= transient!

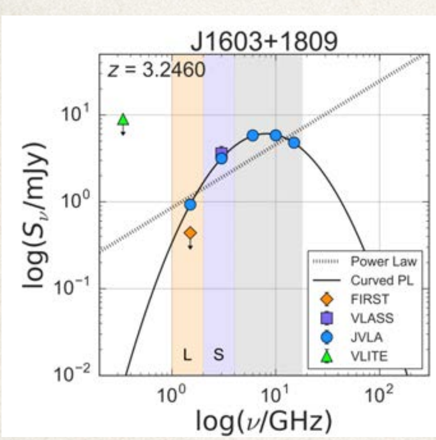
→ Transient catalog

Dong+23d, in prep

These transients open up new windows on short-lived phases of their evolution



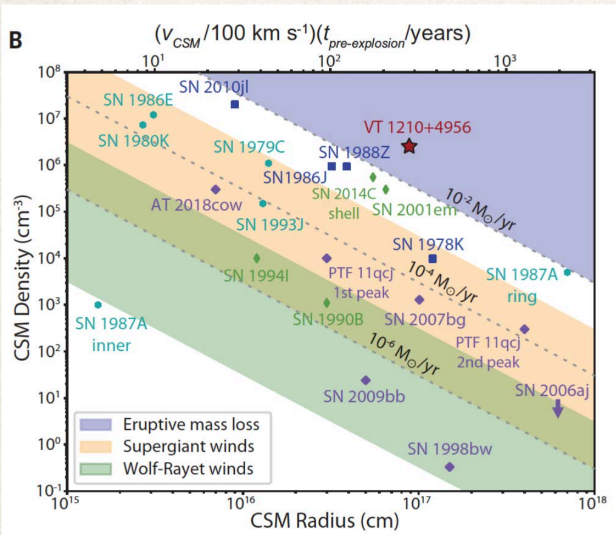


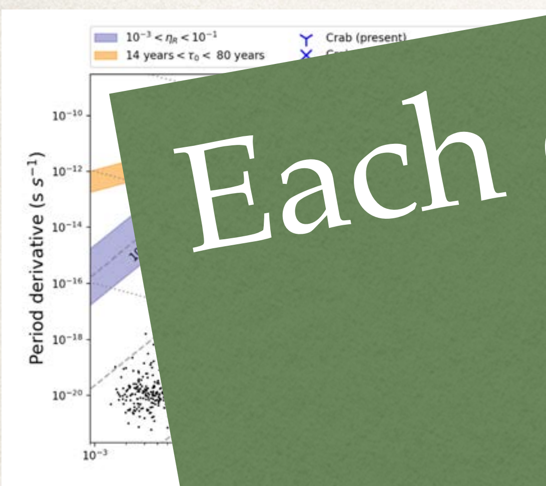


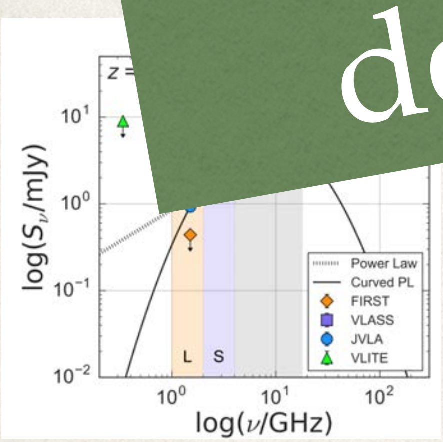
Objects	Transient	Phase	
Massive stars	Luminous (non-relativistic) radio supernovae	Binary mass transfer (Roche-lobe overflow, common envelope)	[1]
Neutron stars	Flat-spectrum radio transients (non-jetted)	Emerging wind-nebulae	[2]
(Super)massive black holes	AGN flares & tidal disruption events	New jets & non-relativistic outflows	[3]

e.g., [1] Dong+21, 23bc in prep [2] Dong & Hallinan 2023 [3] Nyland +20, Somalwar+22, Dong+23b, in prep

These transients trace short-lived but often influential phases of evolution







Objects	Transient	Phase	
Massive stars	Luminous (non-relativistic ...	Binary mass ...er ...erflow, ...ope)	[1]
		...nebulae	[2]
(Super)massive black holes	AGN flares & tidal disruption events	New jets & non-relativistic outflows	[3]

Each class has its own questions that arise when detections are made at scale

e.g., [1] Dong+21, 23bc in prep [2] Dong & Hallinan 2023 [3] Nyland +20, Somalwar+22, Dong+23b, in prep