Image credit: DESY

Extra-galatic transients**

synergies with CTAO and KM3NeT

**from massive black holes

September 8, 2025

Sjoert van Velzen, Leiden Observatory

Including collaboration with: Andrew Mummery , Suvi Gezari, James Miller-Jones, Kate Alexander, Adelle Goodwin, Nicholas Stone, Robert Stein, Marek Kowalski, DJ Pasham

Disclaimer

- I have some multi-messenger credentials (GW, PeV neutrinos, cosmic rays)
- But no papers with *real* high-energy photons:
  - Highest detected photon: ~1 keV
  - Highest upper limits: ~100 GeV (Fermi/LAT)

Acronyms in this talk

I’ve tried to avoid them

- BH = Black hole 🤗
- EM, MW, MM, GW = Electro-magnetic, Multi-wavelength, Multi-messenger, Gravitational Wave
- AGN = Active Galactic Nucleus
  - *A massive black hole in the center of a galaxy that is accreting and thus EM visible*
- “Massive”: $\gtrsim 10^5 M_\odot$
- kpc = kilo parsec

Fundamental questions about black holes

Are black holes spinning?

Is accretion physics scale invariant?

Black hole genesis in the early universe

Image credit: Wikimedia

Answers from transient surveys

Are black holes spinning?

Is accretion physics scale invariant?

Black hole genesis in the early universe

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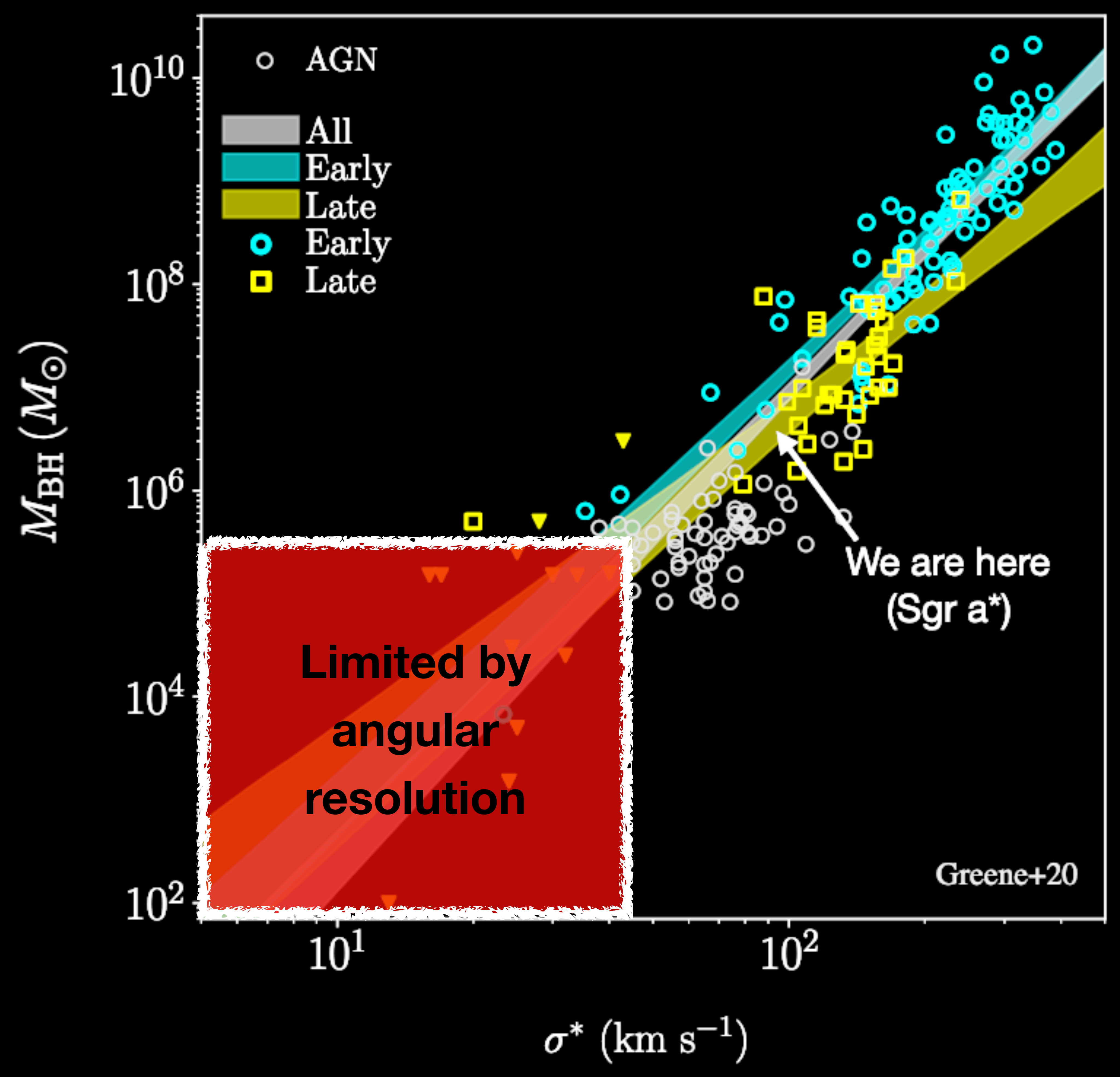
Detailed single source studies (MW, MM)

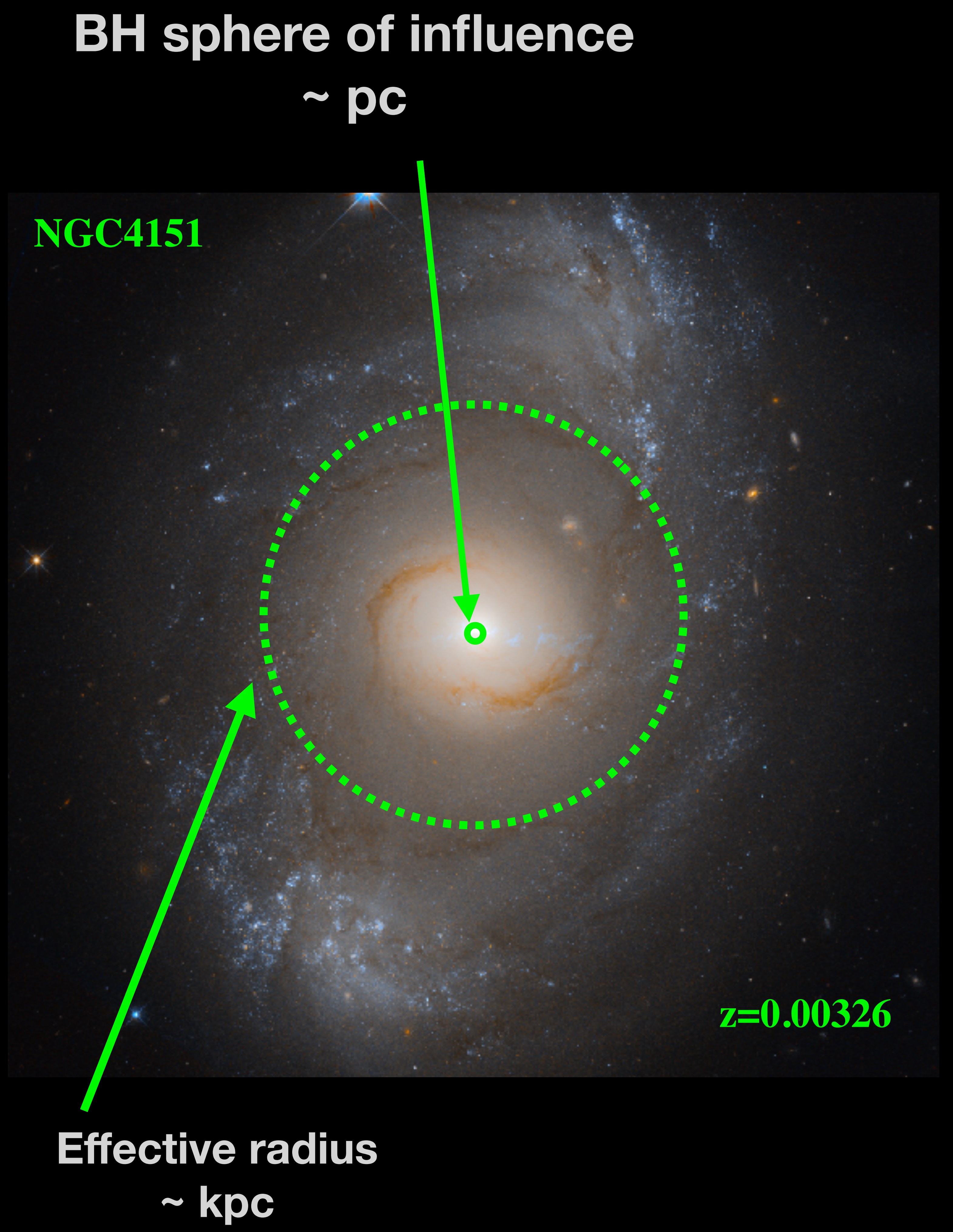
Large samples
(often single wavelength)

Reliable black hole mass estimates

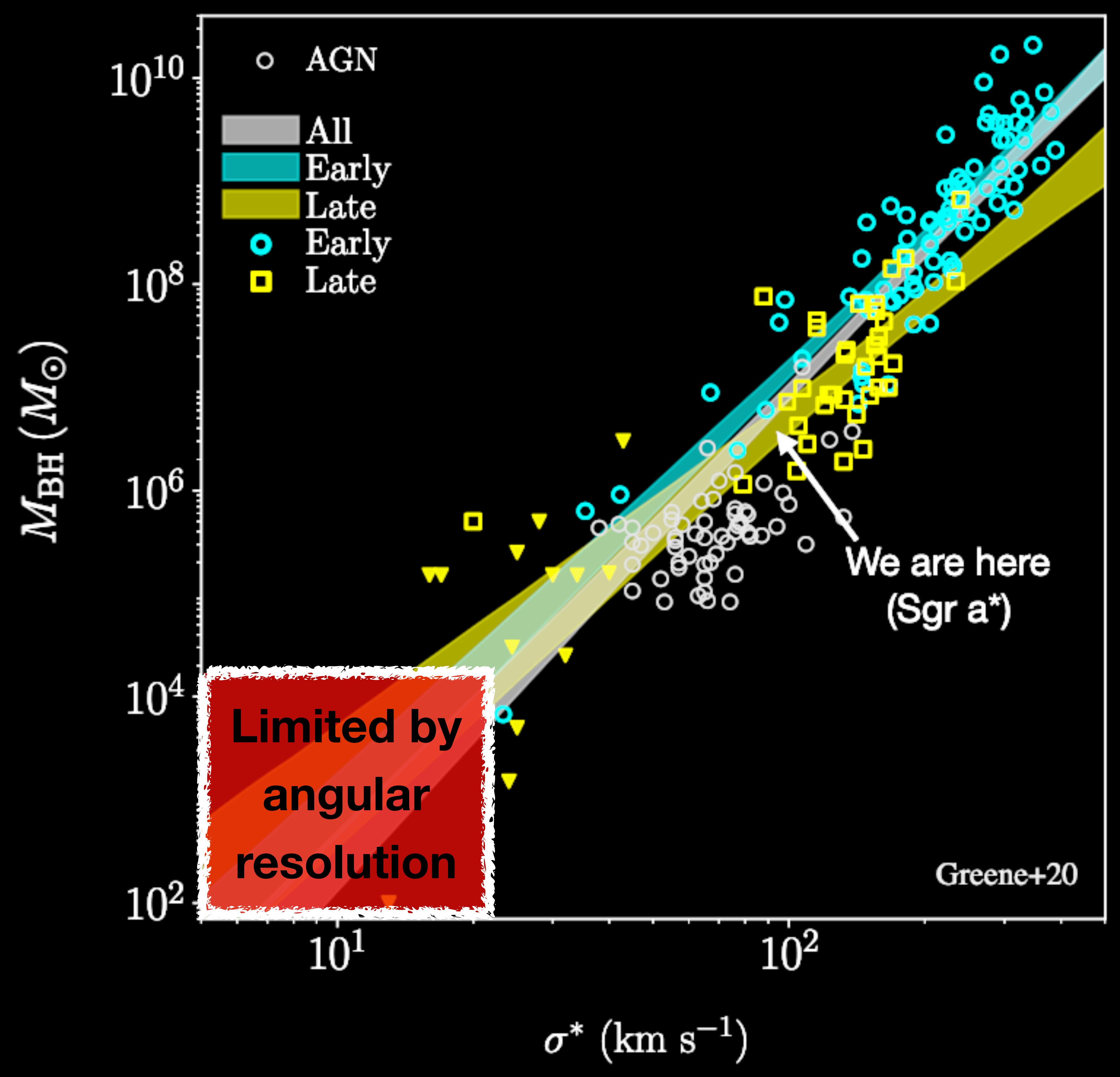
Image credit: Wikimedia

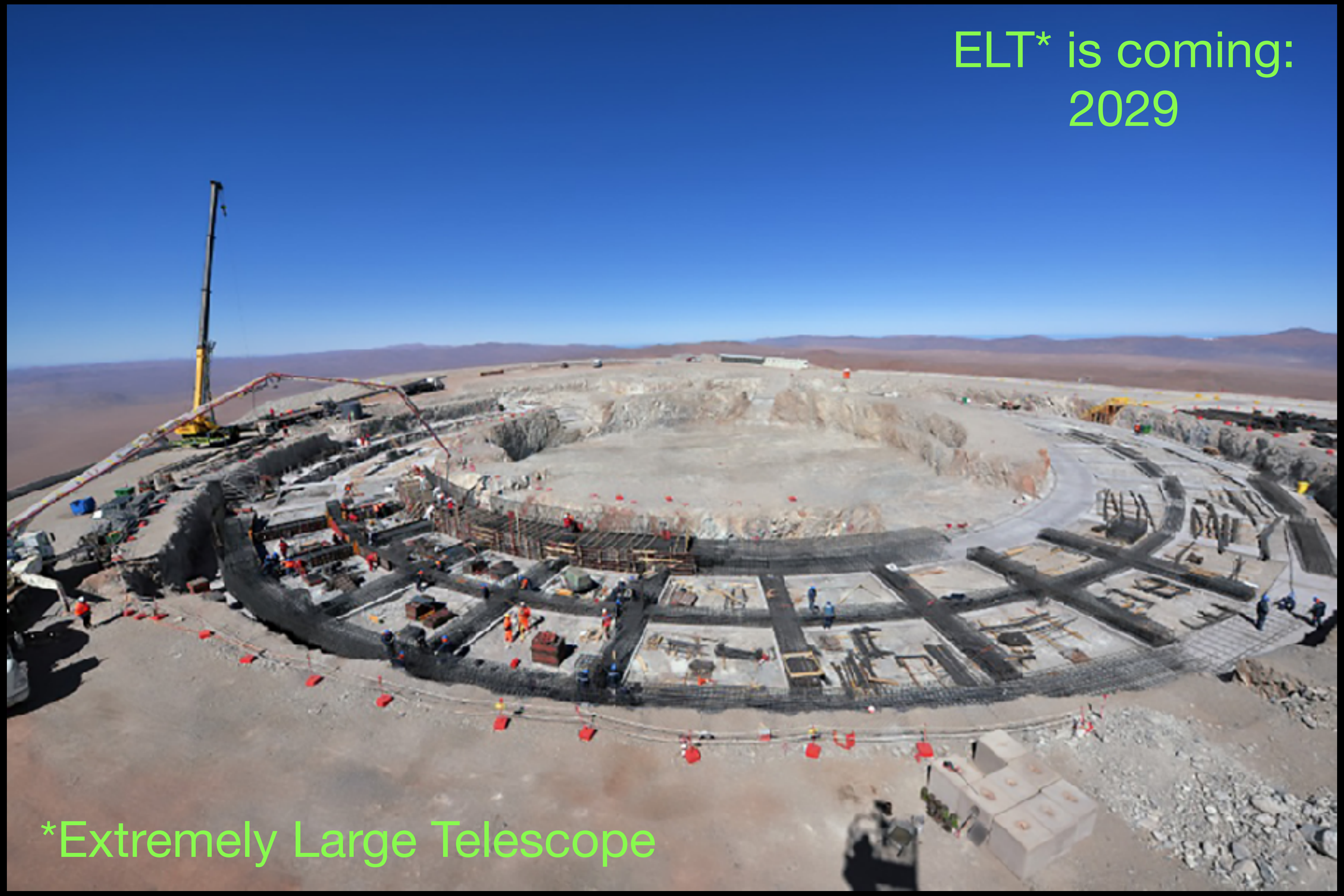
Traditional BH mass measurements are running out of steam



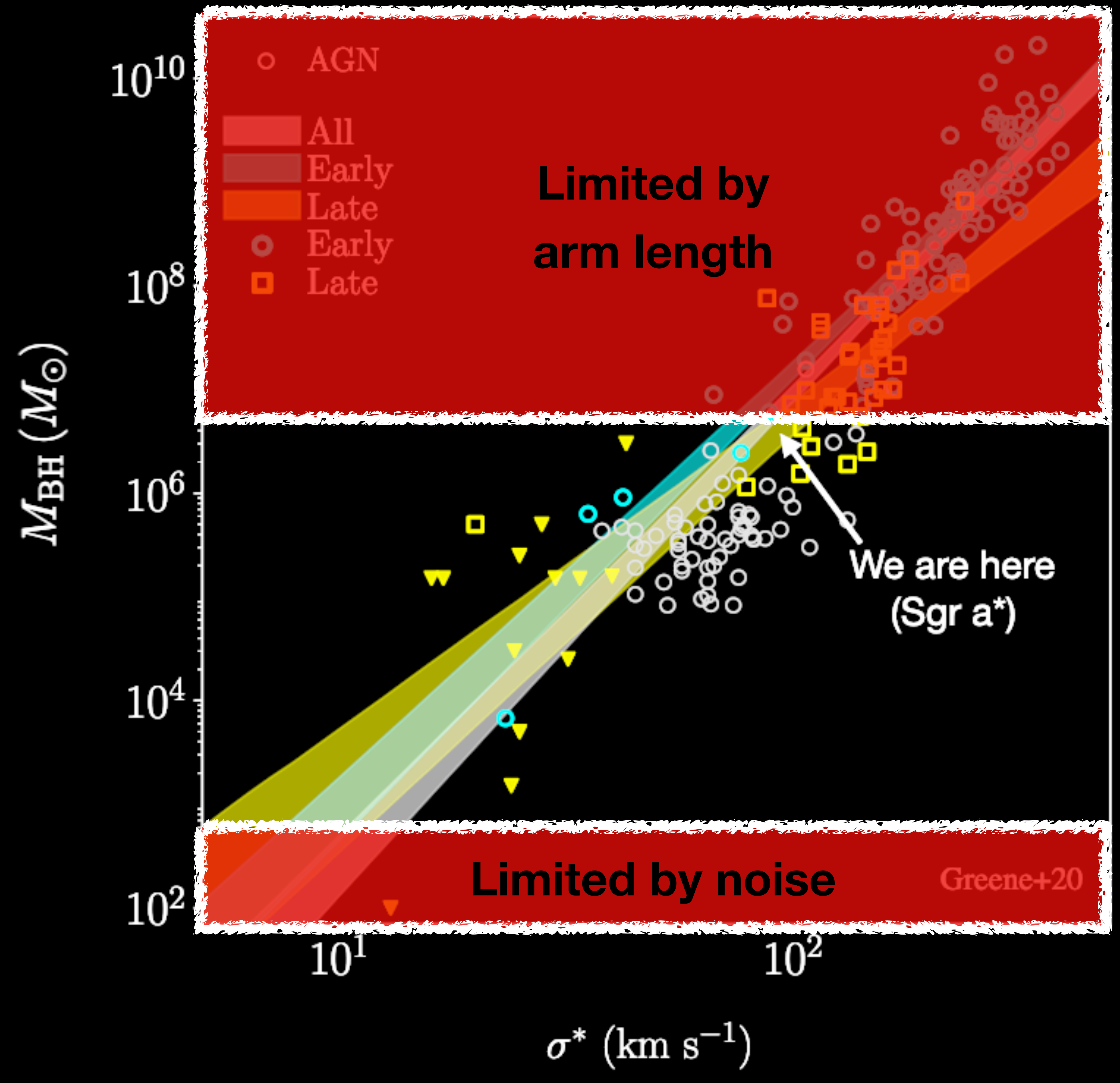


BH mass measurements in the next decae

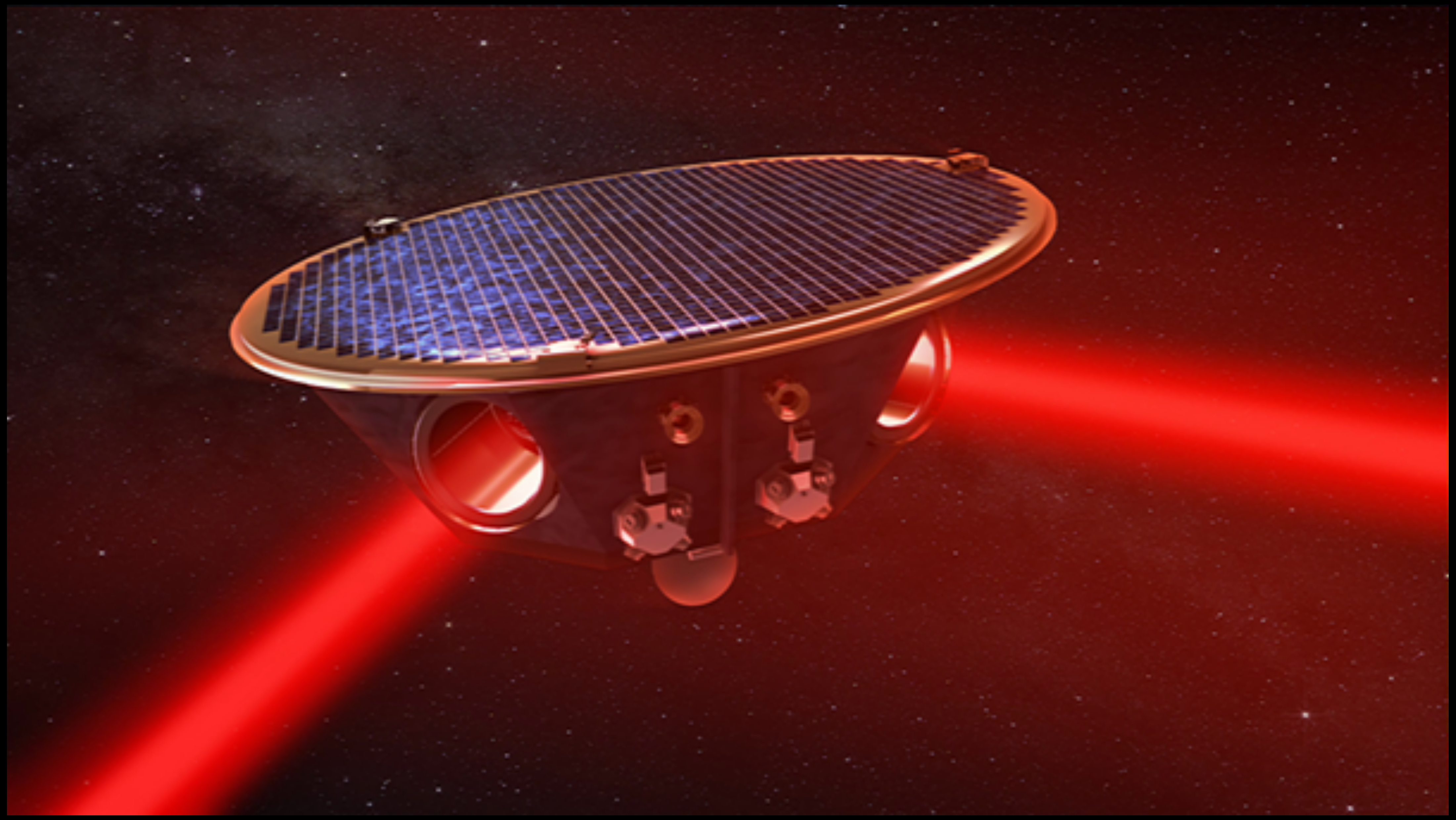




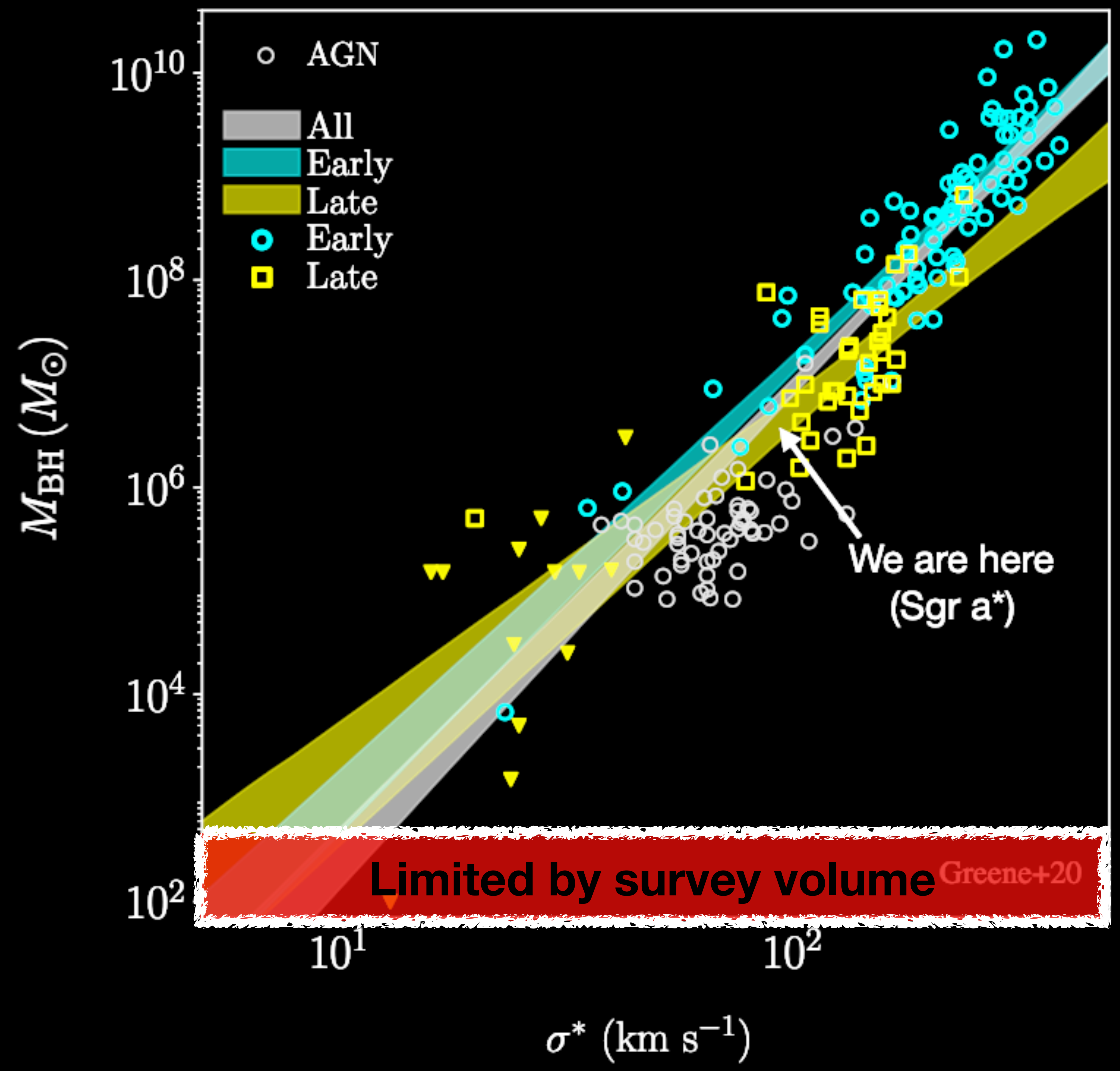
BH mass measurements in the next-next decade



LISA is coming:
2035+



Transient-based BH mass measurements*, starting now



Vera C. Rubin Observatory

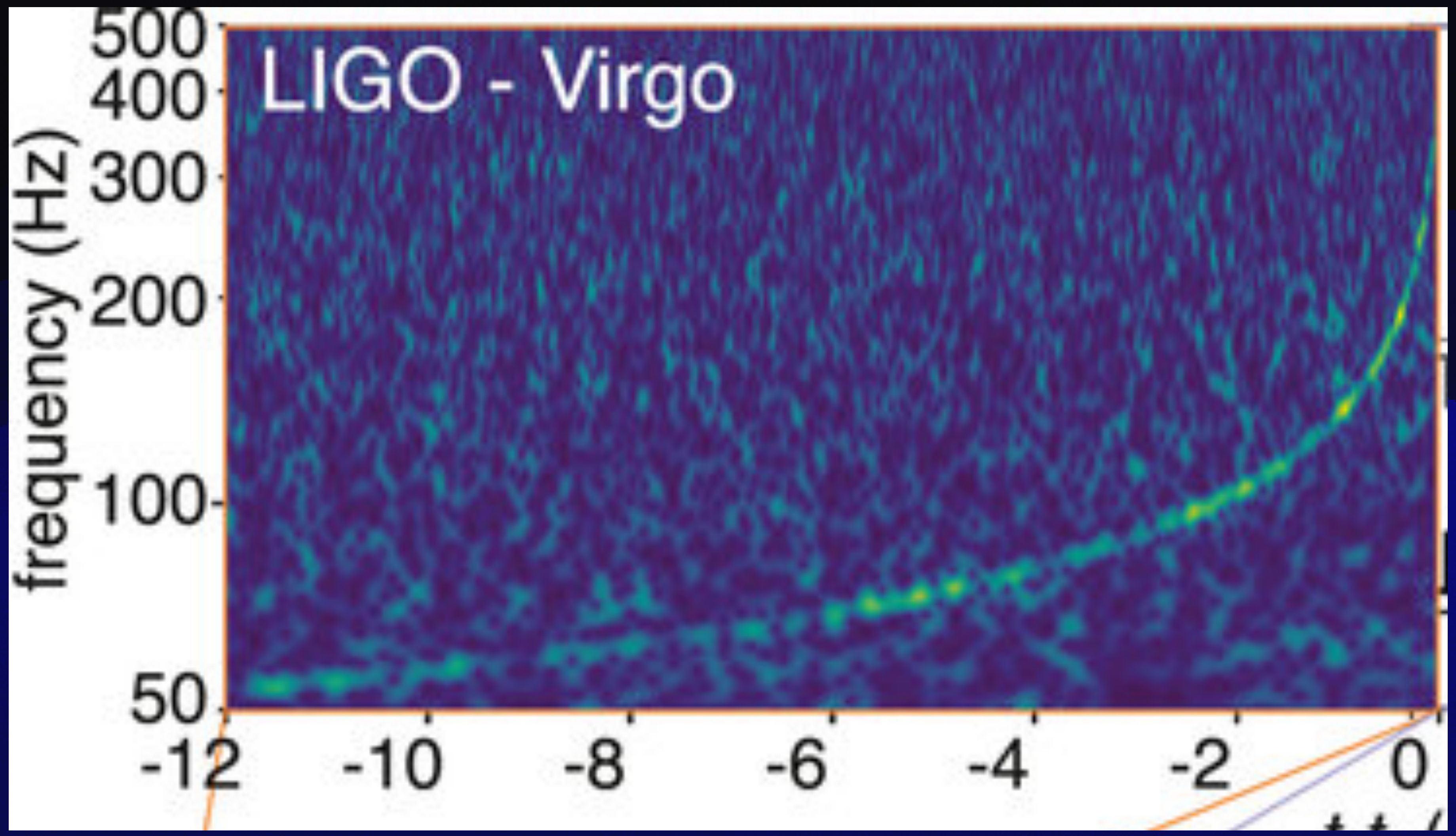
*How? See backup slides

Rest of this talk

- Part 1: Two recent MM results:
  - Examples for future CTAO-KM3NeT synergies?
- Part 2: The landscape observatories in the next decade:
  - A unique place for CTAO+KM3NeT?

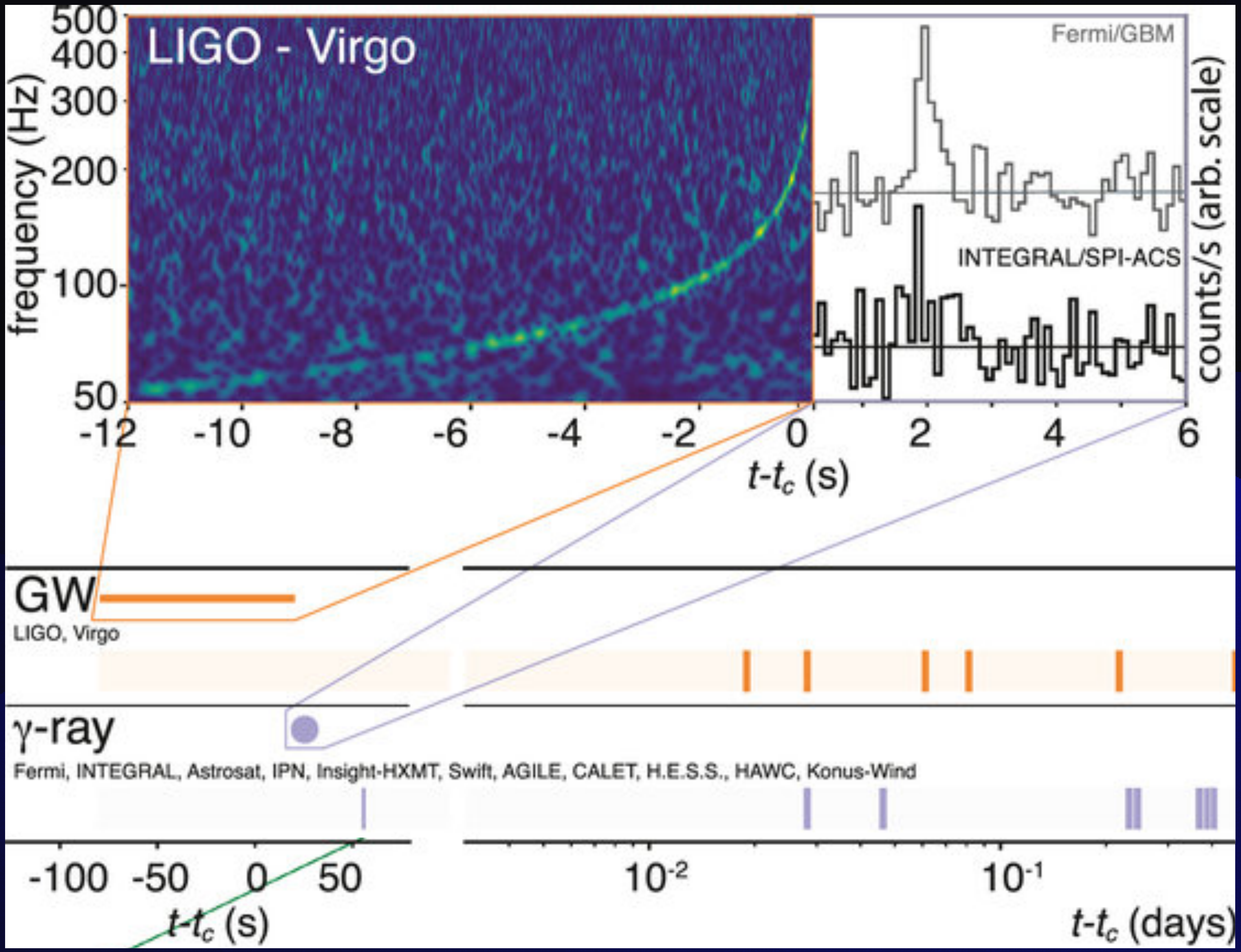
A succes story: kilonova GW170817

Step 1: GW



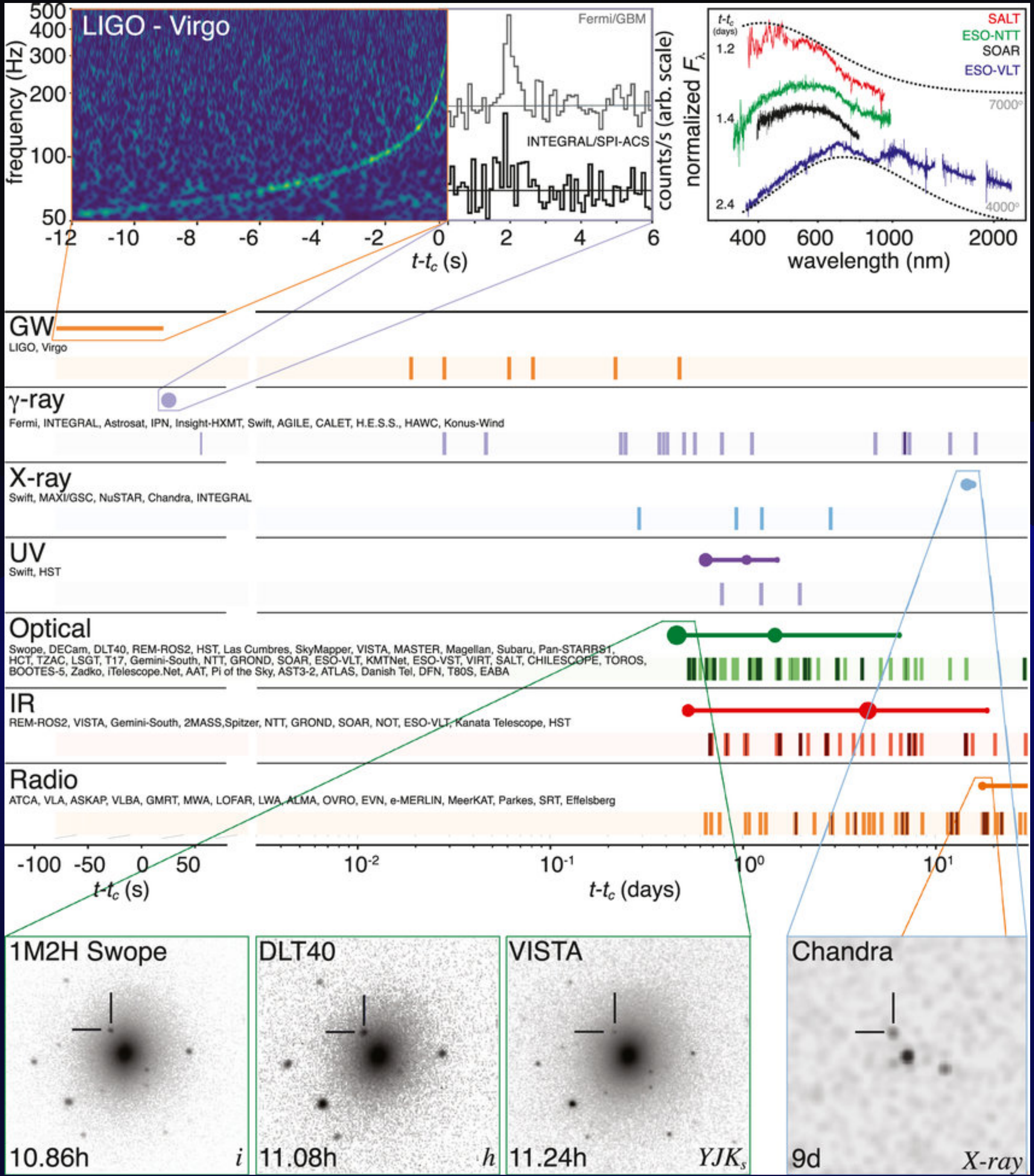
Abbott et al. 2017

Step 2: γ-rays



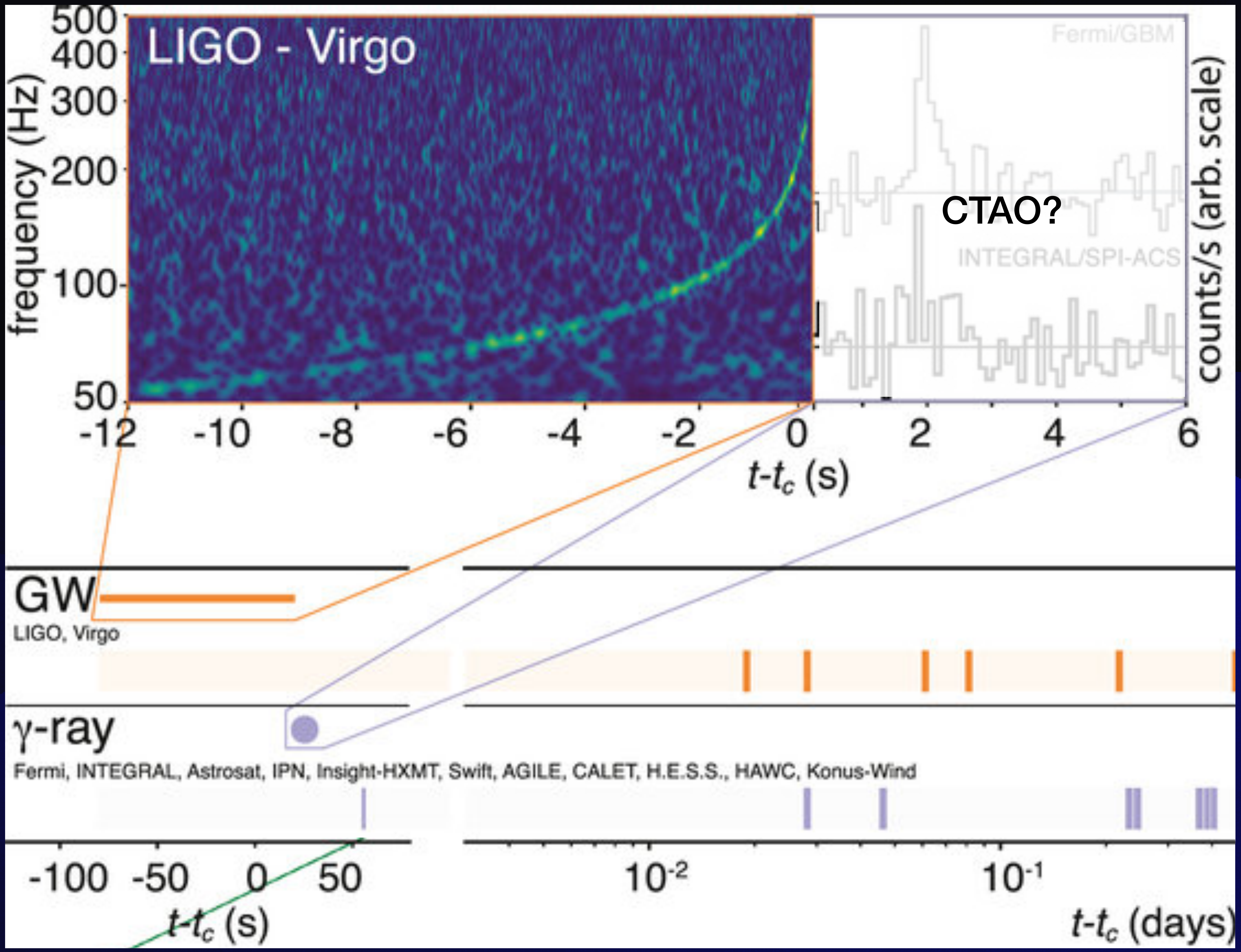
Abbott et al. 2017

Step 3: very MW



GW + CTAO

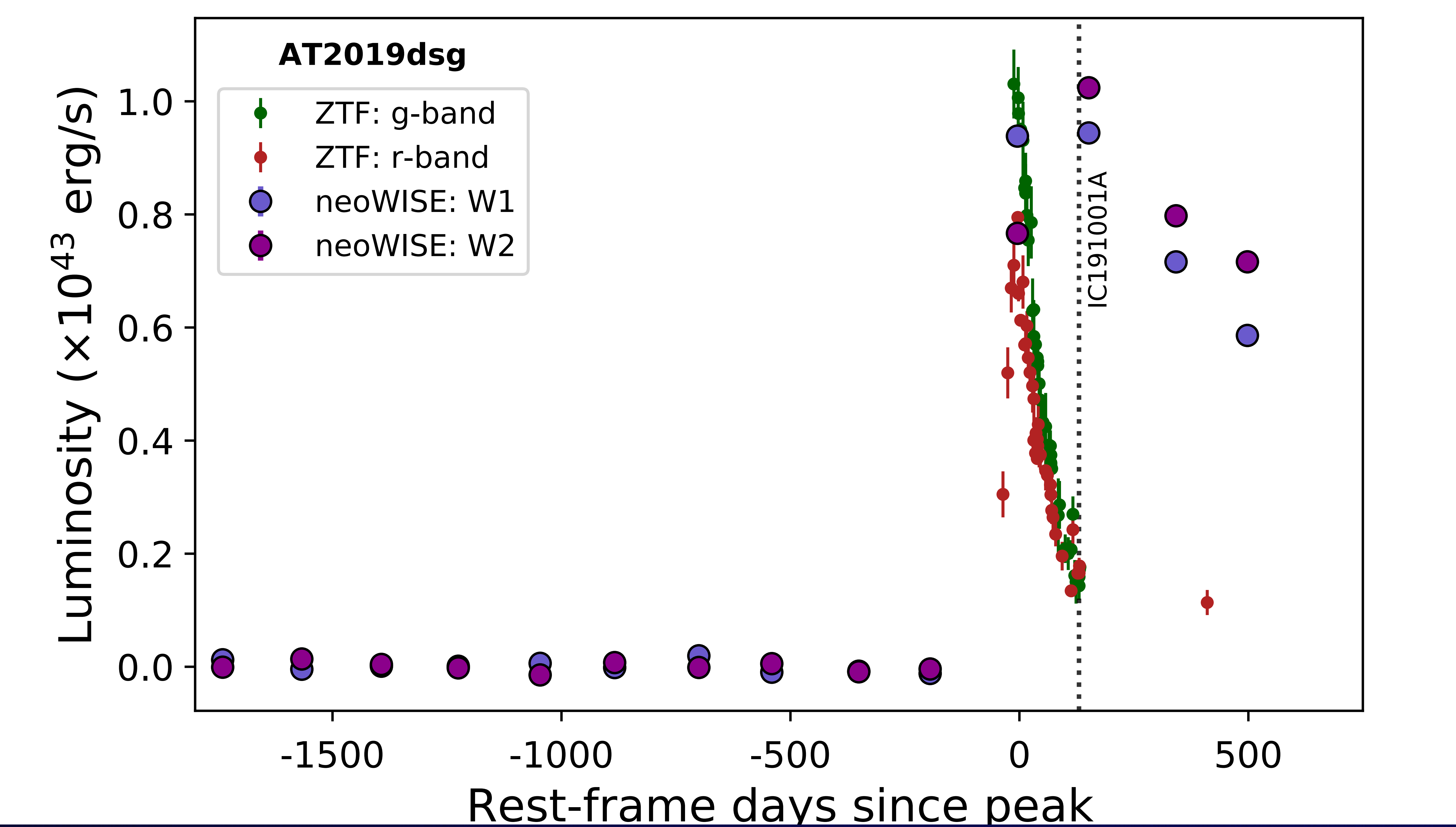
- CTAO operational during next observing run (O5)
- Need dedicated follow-up (e.g., Carosi et al 2024)
- More sensitive to on-axis jets (Mondal et al. 2024)
- ~10% detection rate predicted (Carosi et al. 2024)



A second example: massive BH flares and neutrinos

Let's consider slower transients

- In 2019: high-energy neutrino in coincidence with a transient from a massive black hole (a "TDE"; Stein et al. 2021)
- In 2020, another neutrino found after a peculiar AGN flare (Reusch et al. 2022)
- In 2023: systematic search, another neutrino found together with a flaring AGN (van Velzen et al. 2023)



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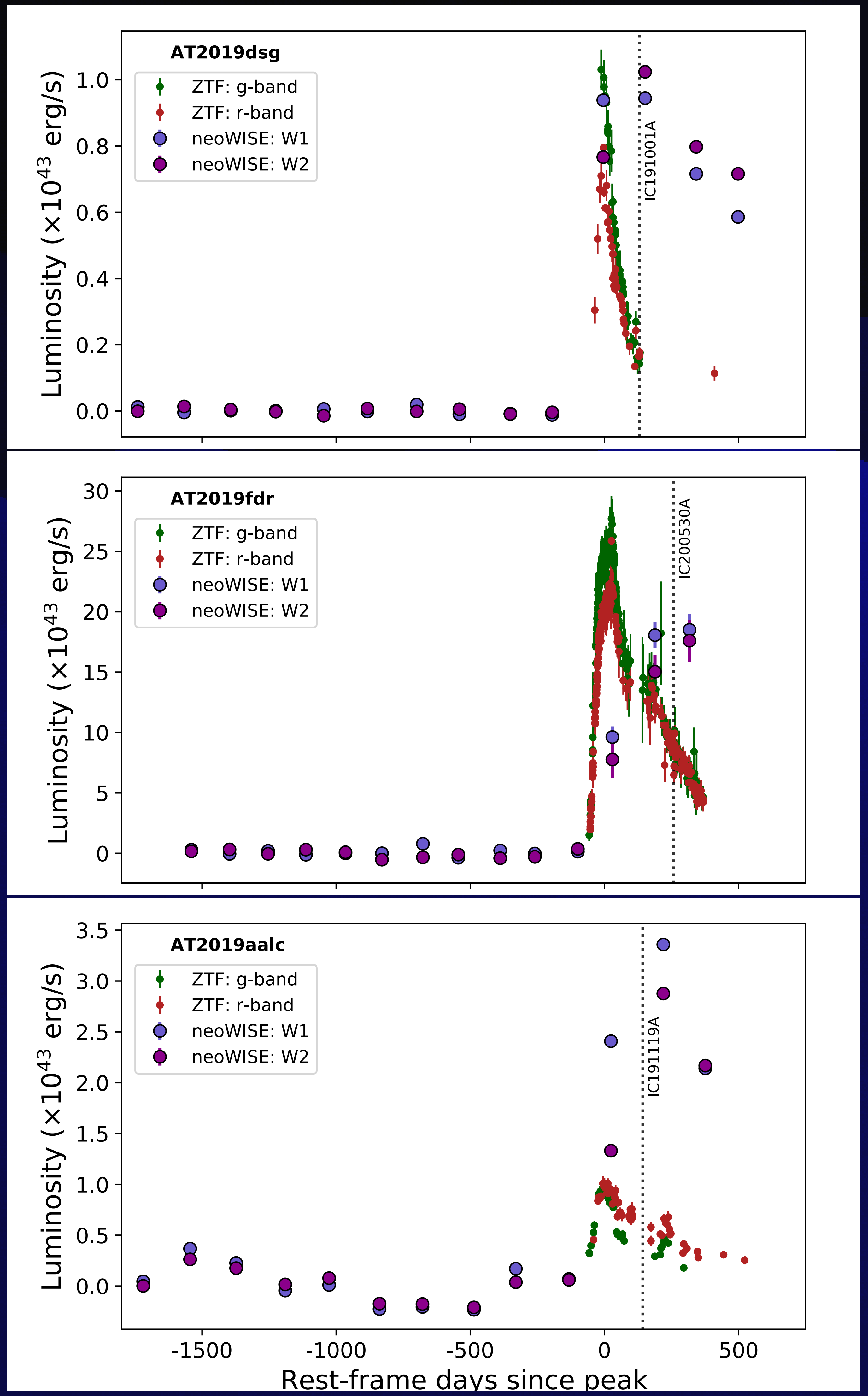
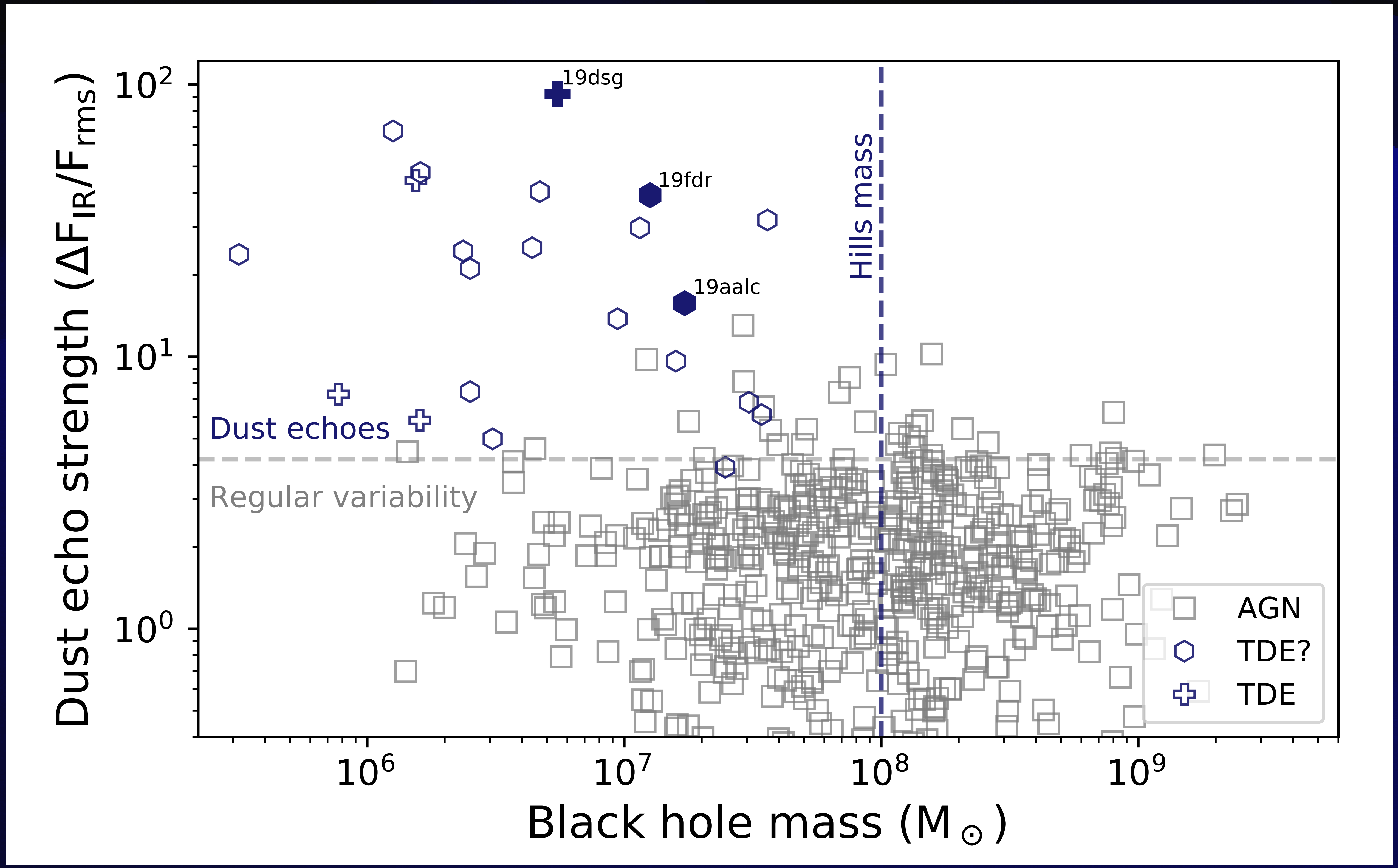


A second example: massive BH flares and neutrinos

Let's consider slower transients

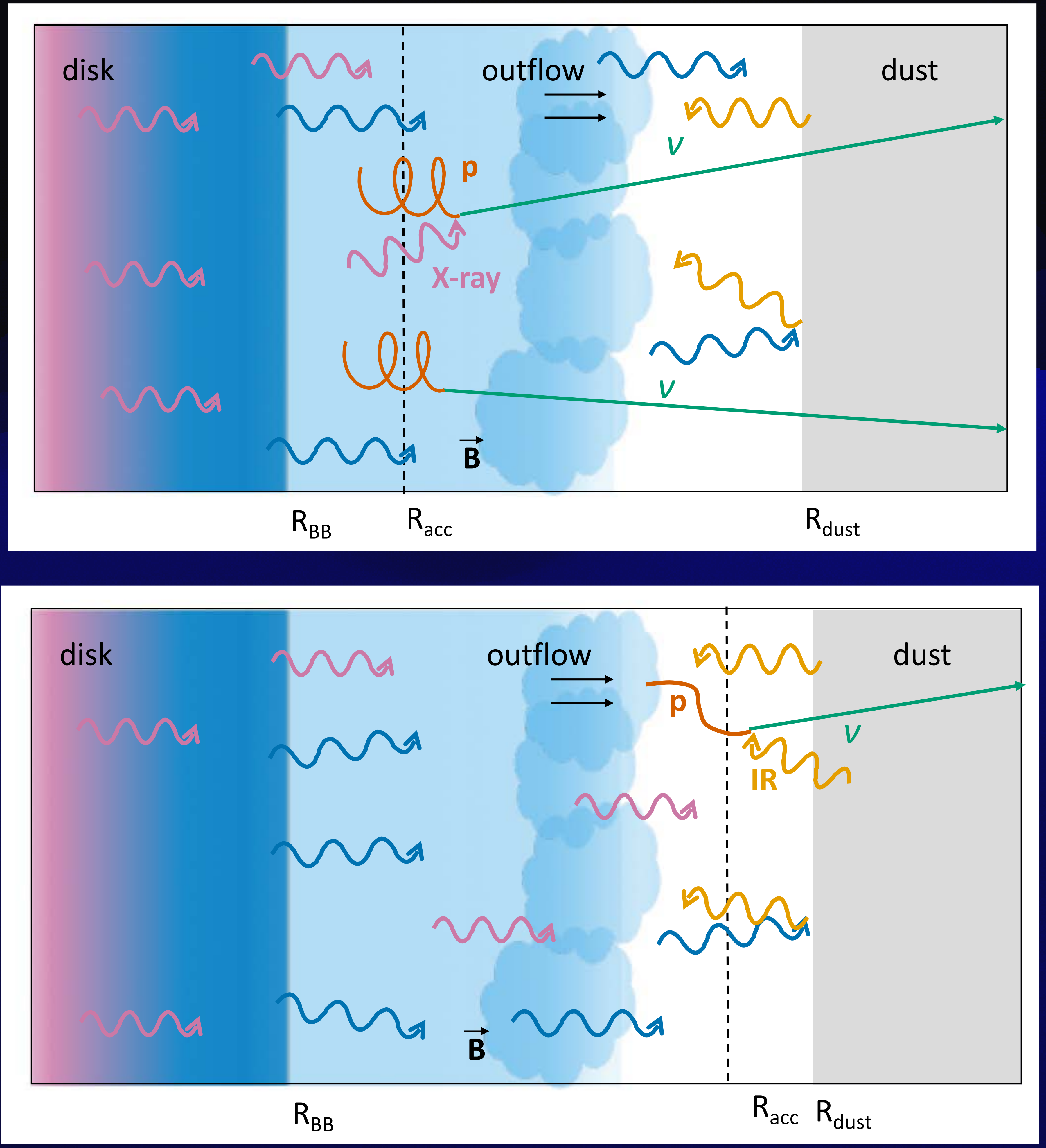
- **All three** neutrino associations:
  - Strong infrared flares (very uncommon for AGN)
  - Detected in the radio (uncommon for AGN)
  - Detected in X-ray, with soft spectra (very uncommon for AGN)
- Each wavelength yields 3σ significance of the neutrino ossociation



A second example: massive BH flares and neutrinos

What if this was 5-sigma?

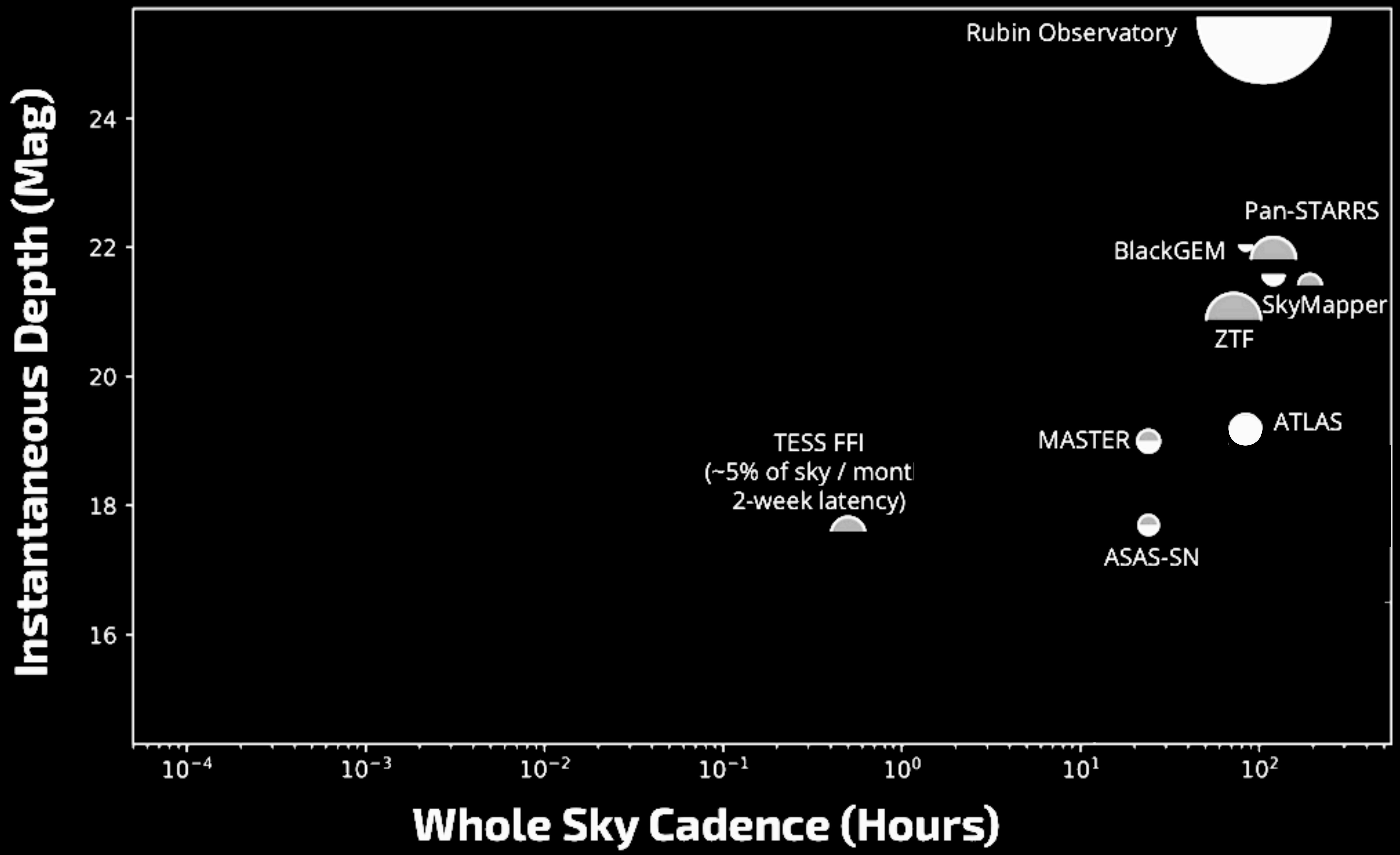
- Flaring AGN are, for some reason, better particle accelerators?
- High density of UV and X-ray photons:
    - Opaque for TeV gamma-rays (due to two-photon annihilation)
    - Similar to some models for NGC 1068 (e.g., Murase 2022)
- CTAO *non-detections* become very important for model testing



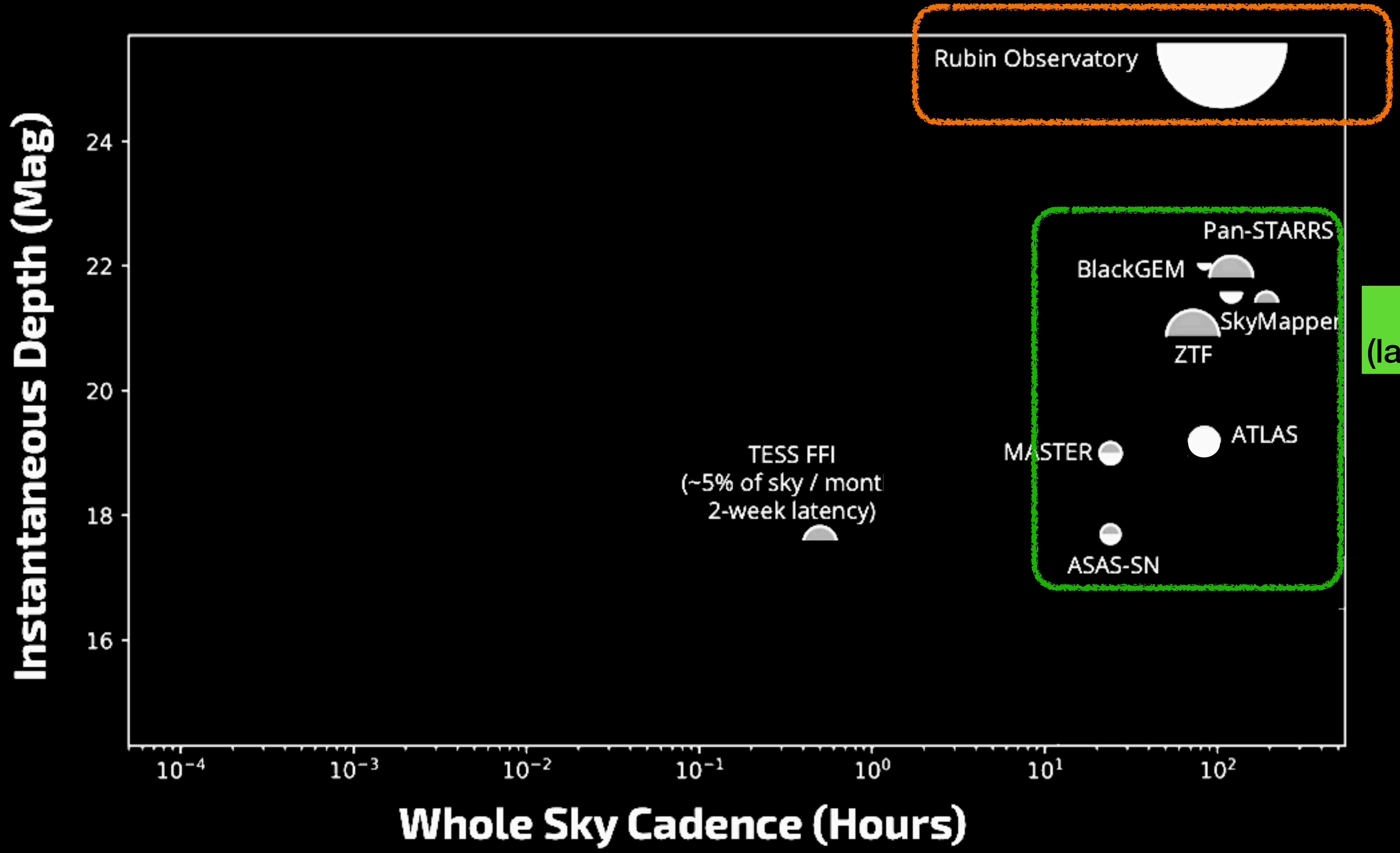
Winter & Lunardini (2023)

Revolution in transient astronomy

Revolution in transient astronomy



Optical transient surveys



Starting ~now

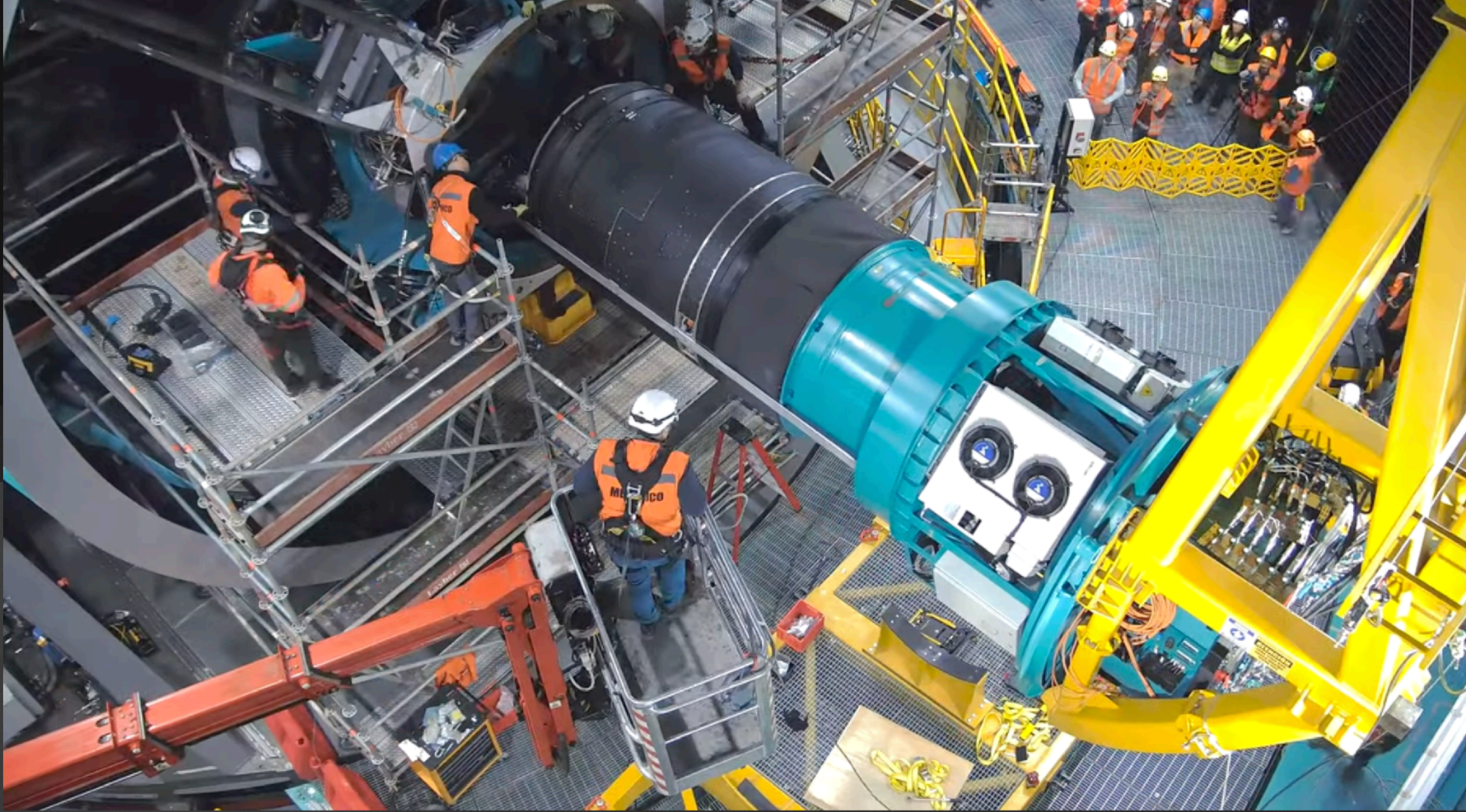
Ongoing (last 10 years)

Vera C. Rubin Observatory

- Mirror: 8.4 m
- FoV: 9.6 deg^2
- 6 bands (u, g, r, i, z, y)
- Limiting m_g=24.5 (= “deep”)
- 20B galaxies; 18B stars
- 10M transient alerts per night

Alert data is **public**, provided via Community Brokers

I lead the TDE group in Rubin



LSST Camera Installation - March 2025

Vera C. Rubin Observatory

Extraordinary detection rates

- Number of detections: $N \propto V \propto \Omega_{\rm sky} R^3 \propto \Omega_{\rm sky} F_{\rm lim}^{3/2}$
- Rubin is about 20 more sensitive than current surveys and $\Omega_{\rm sky}$ is similar…
    - Detection rates increases by a factor 100!

Black hole transients detected since 1990

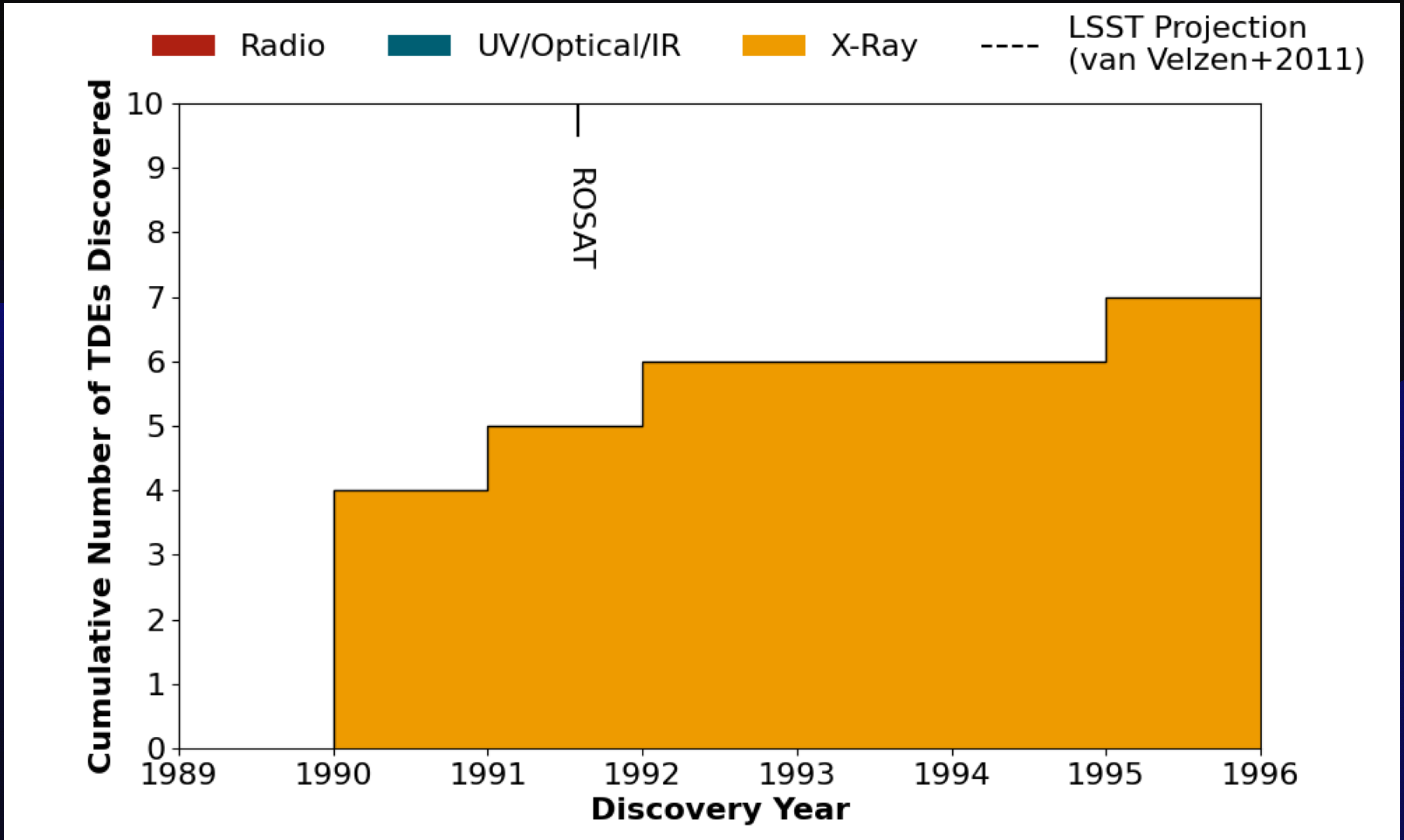


Image credit: N. Franz (https://github.com/astro-otter/examples/blob/main/tde-discovery-histogram-linear.gif)

Black hole transients detected since 1990

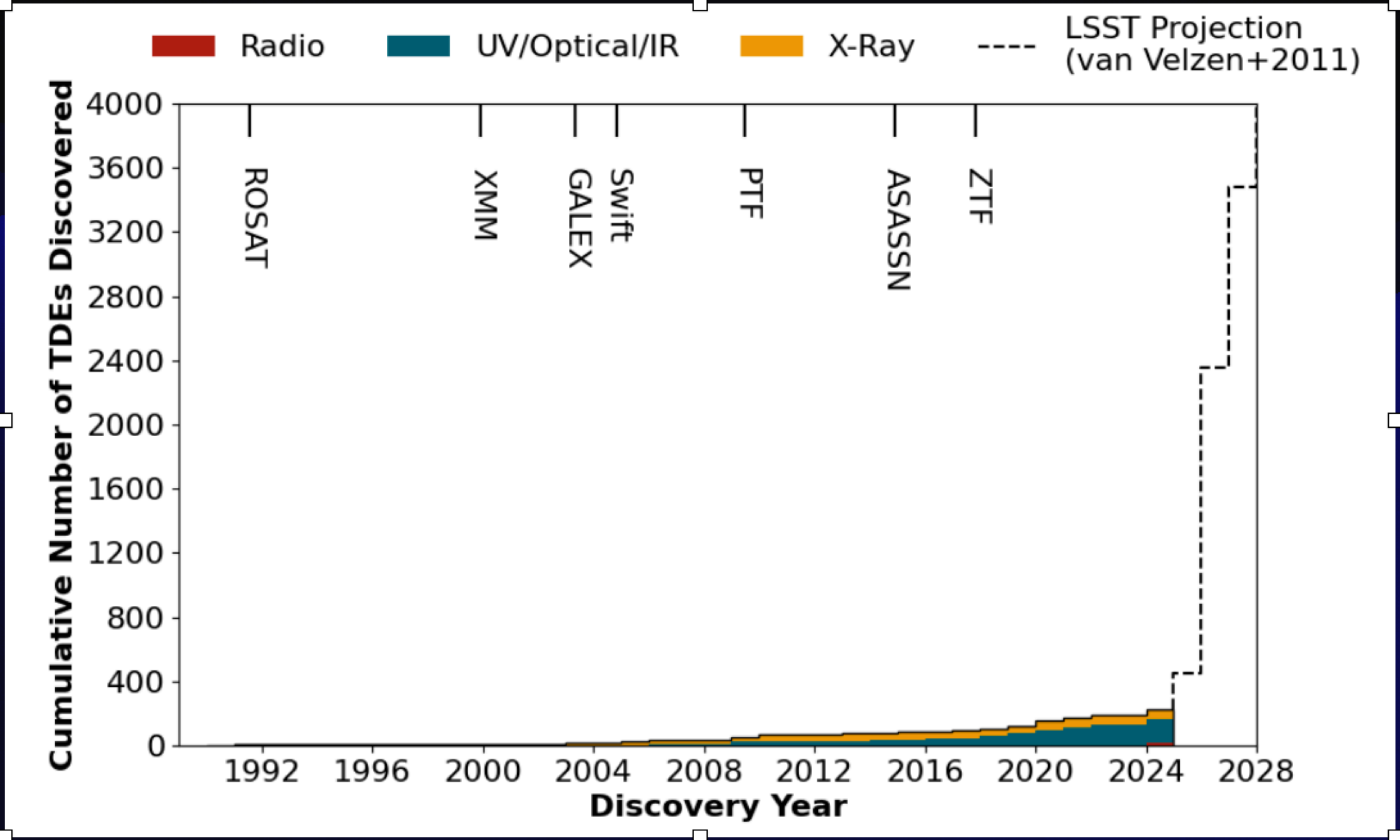


Image credit: N. Franz (https://github.com/astro-otter/examples/blob/main/tde-discovery-histogram-linear.gif)

Who can keep up?

- To keep up with Rubin
  - Factor 10 increase in sensitivity
  - For survey missions: all sky (South)
  - For follow-up: can accept (lots of) triggers

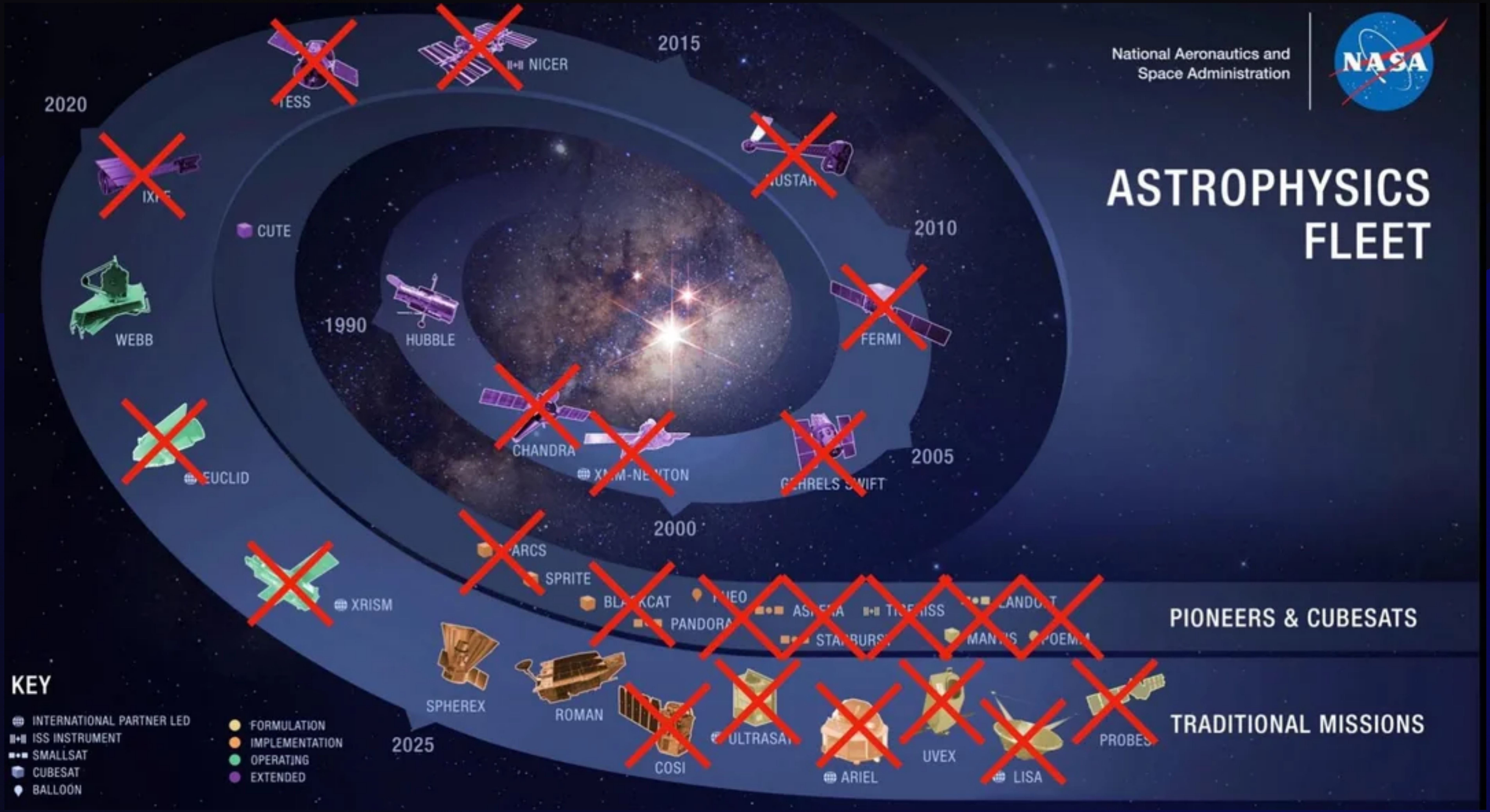
Who can keep up with the Rubin Nuclear Transient rate?

WAVELENGTH	CURRENT	WITHIN 5 YEARS	KEEP UP WITH RUBIN?
UV	Swift, HST, svom	ULTRASAT (2027?)	YES
X-ray	Swift, Chandra, XMM, NUSTAR, NICER, IXPE, XRISM, Fermi, Einstein Probe, SVOM	COSI, **CTAO**	YES/NO
Infrared	NEOWISE, JWST	NEO Surveyor (2027)	NO
Radio	VLA, AMI, ALMA, EVN, ATCA, GMRT		NO

Who can keep up with the Rubin Nuclear Transient rate?

WAVELENGTH	CURRENT	2030-2040	KEEP UP WITH RUBIN?
UV	Swift, HST, svom	UVEX (2030)	YES
X-ray	Swift, Chandra, XMM, NUSTAR, NICER, IXPE, Fermi, Einstein Probe, SVOM	eXTP, CATCH, AXIS, THESEUS, ATHENA	YES
Infrared	NEOWISE, JWST		
Radio	VLA, AMI, ALMA, EVN, ATCA, GMRT	SKA-mid, ngVLA, DSA-2000, FAST-core-array	YES

Budget nightmares



Disclaimer:
image from Reddit

Conclusions

- Both CTAO and Rubin observatory will make a huge leap in sensitivity
- Rubin has ToO capabilities! (for public neutrino alerts, not yet γ-ray)
- While majority of Rubin transients are not TeV sources…
- … Faint/rare optical transients are my best bet for new synergies
  - How to filter for these in the Rubin alert stream?
- CTAO follow-up of potential KM3NeT neutrino sources is key:
  - Non-detections possible for high X-ray photon densities
  - But (unexpected) detections will happen!

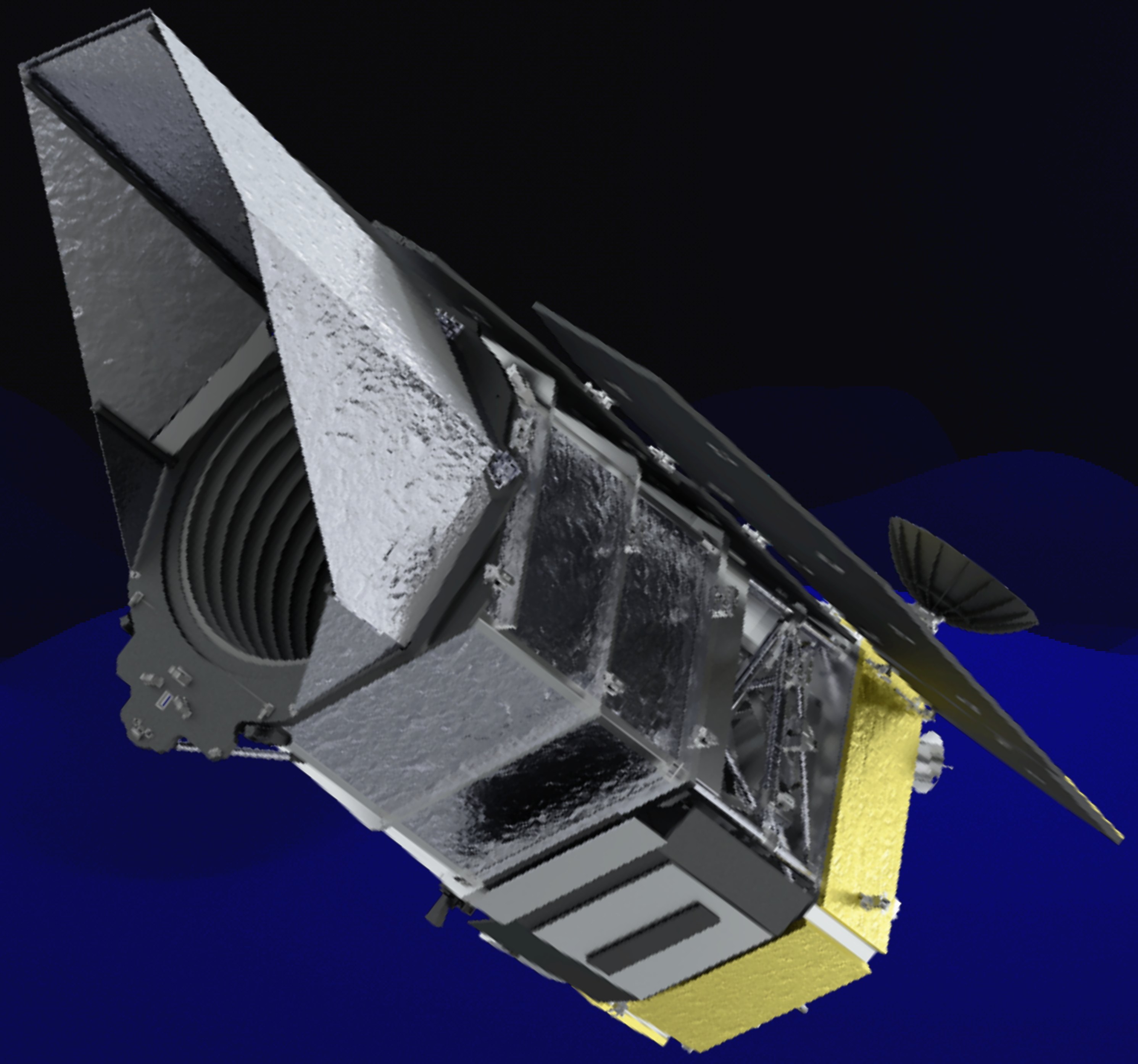
Adding more messengers

WAVELENGTH	CURRENT	within 5 years	WITHIN 15 YEARS
UV	Swift, HST	ULTRASAT (2026)	UVEX (2030)
X-ray	Swift, Chandra, XMM, NUSTAR, NICER, IXPE, Fermi	EP, SVOM, XRISM, COSI, CTA	eXTP? CATCH? AXIS? THESEUS? ATHENA
Infrared	NEOWISE, JWST	NEO Surveyor (2027)	
Radio	VLA, AMI, ALMA, EVN, ATCA, GMRT	SKA-mid	ngVLA, DSA-2000
GW	LIGO/VIRGO/KAGRA	Upgrades	Ligo India, Taiji, LISA, Cosmic Explorer, Einstein Telescope
Neutrinos	IceCube	KM3NET	IceCube Gen2, TRIDENT?

Roman Space Telescope

Launch 2027

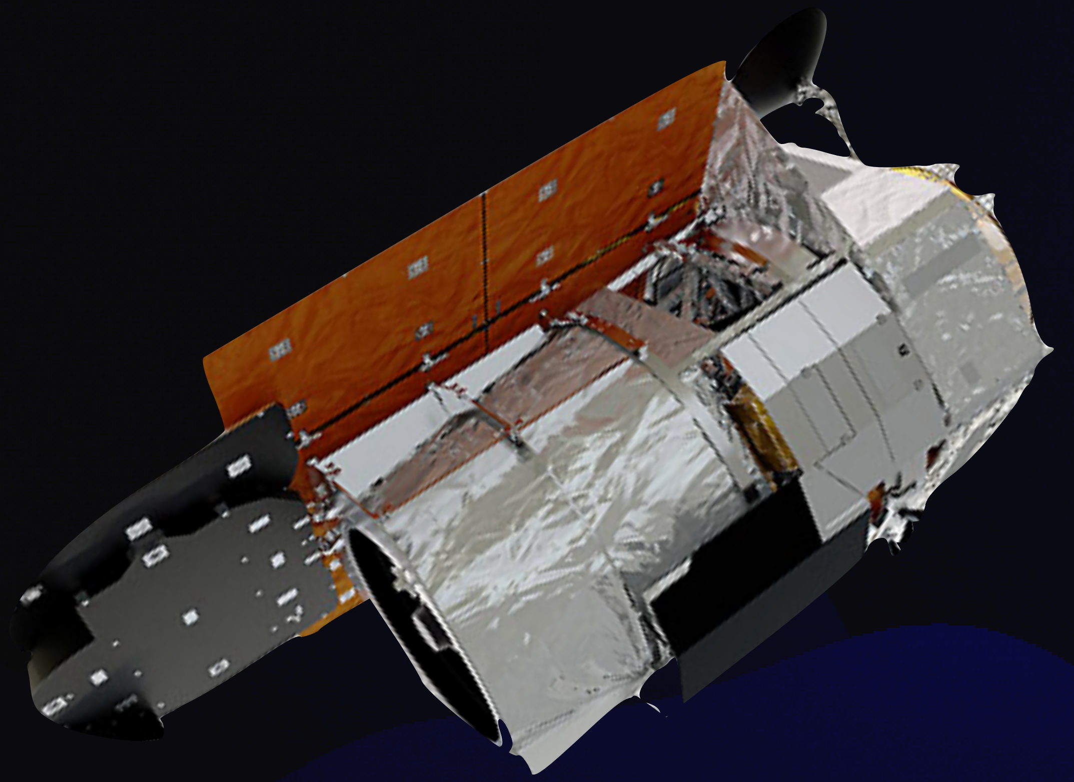
- Conduct two time-domain surveys:
  - Very deep near-IR (m~25);
  - 10-30 sq. deg
  - 150 epochs over 2 years
  - Main science goal: ~10^4 SNe Ia at z~1-2
    - 10^2 TDEs at these redshifts!
    - Again, photometric classification only
  - Lots of hot dust transients!

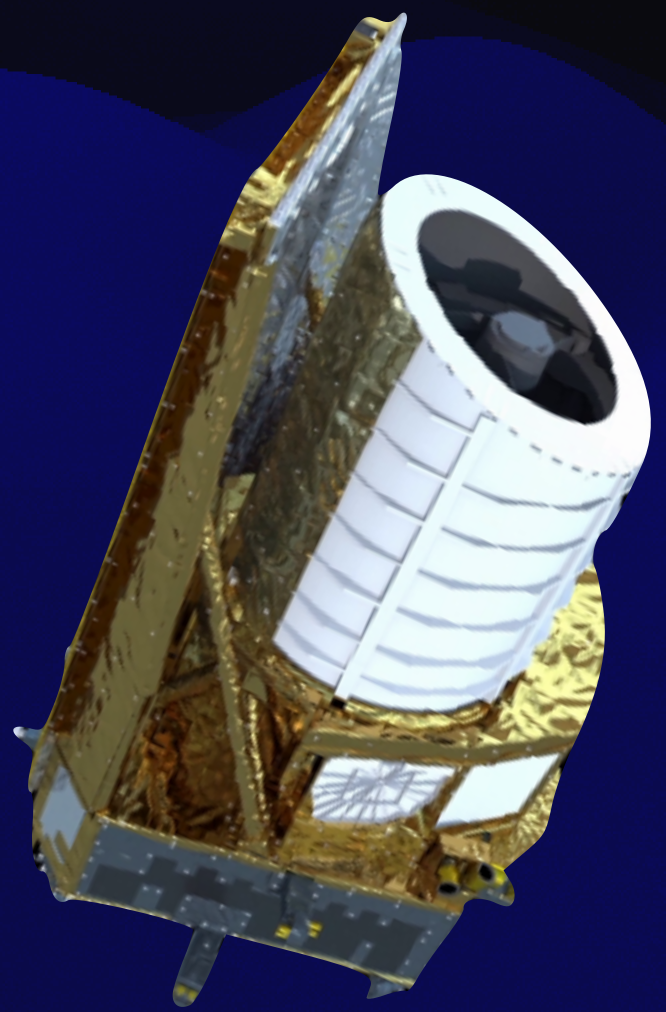


More optical observatories

- EUCLID (NIR imaging, single epoch, but good for host galaxies)
- SPHEREx (all-sky IR spectra)
- Chinese Space Station Telescope (Xuntian; December 2026)

- Plato (2026)
- Roman Space Telescope (2027?)
- Ground-based specialists:
  - Now: ASAS-SN, ZTF, ATLAS, PS1, BlackGEM, WINTER, **LS4**, **WFST** …
  - Future: Argus Array, and more

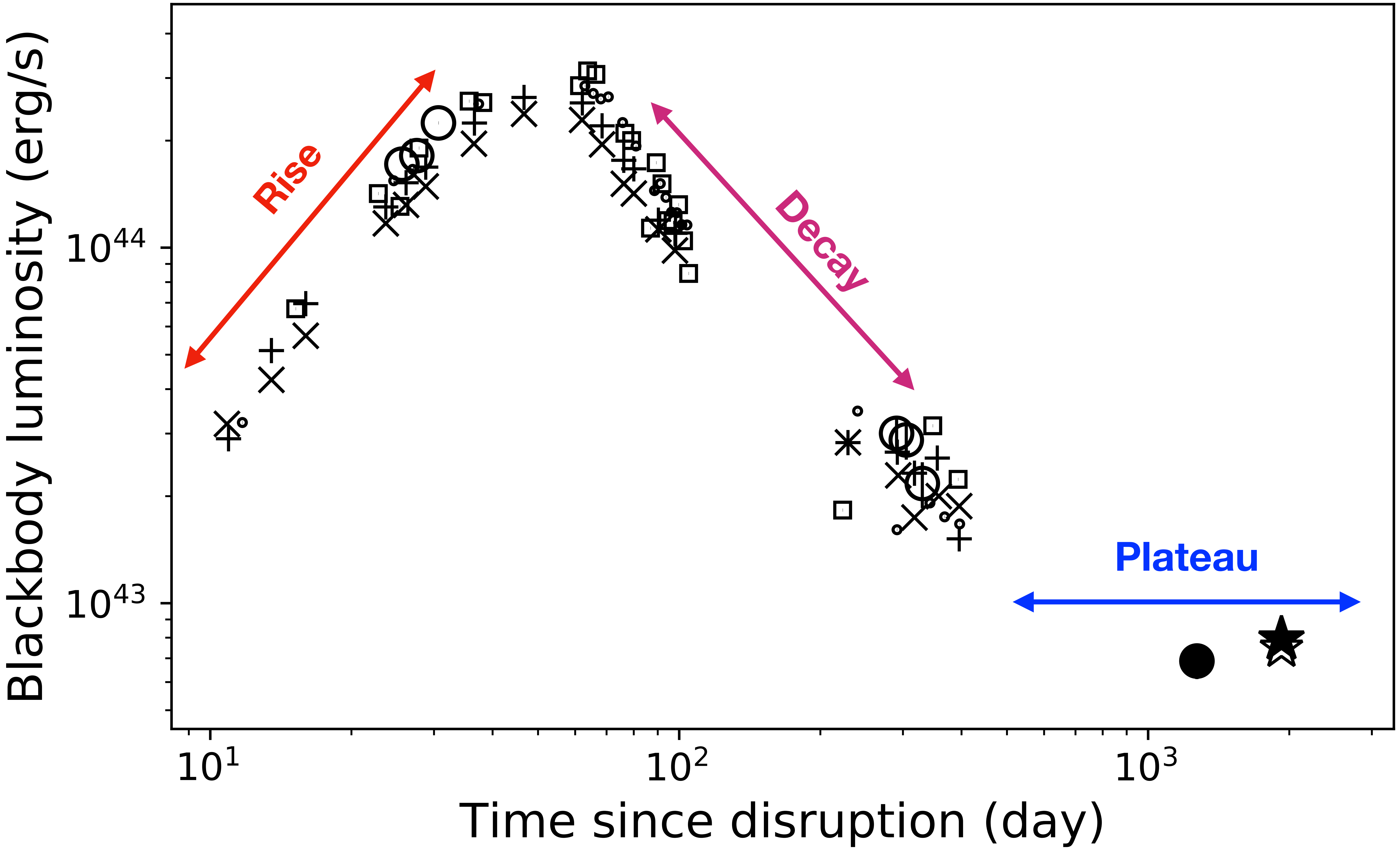




How to measure black hole mass from transient light curves

One example

Optical/UV light curves

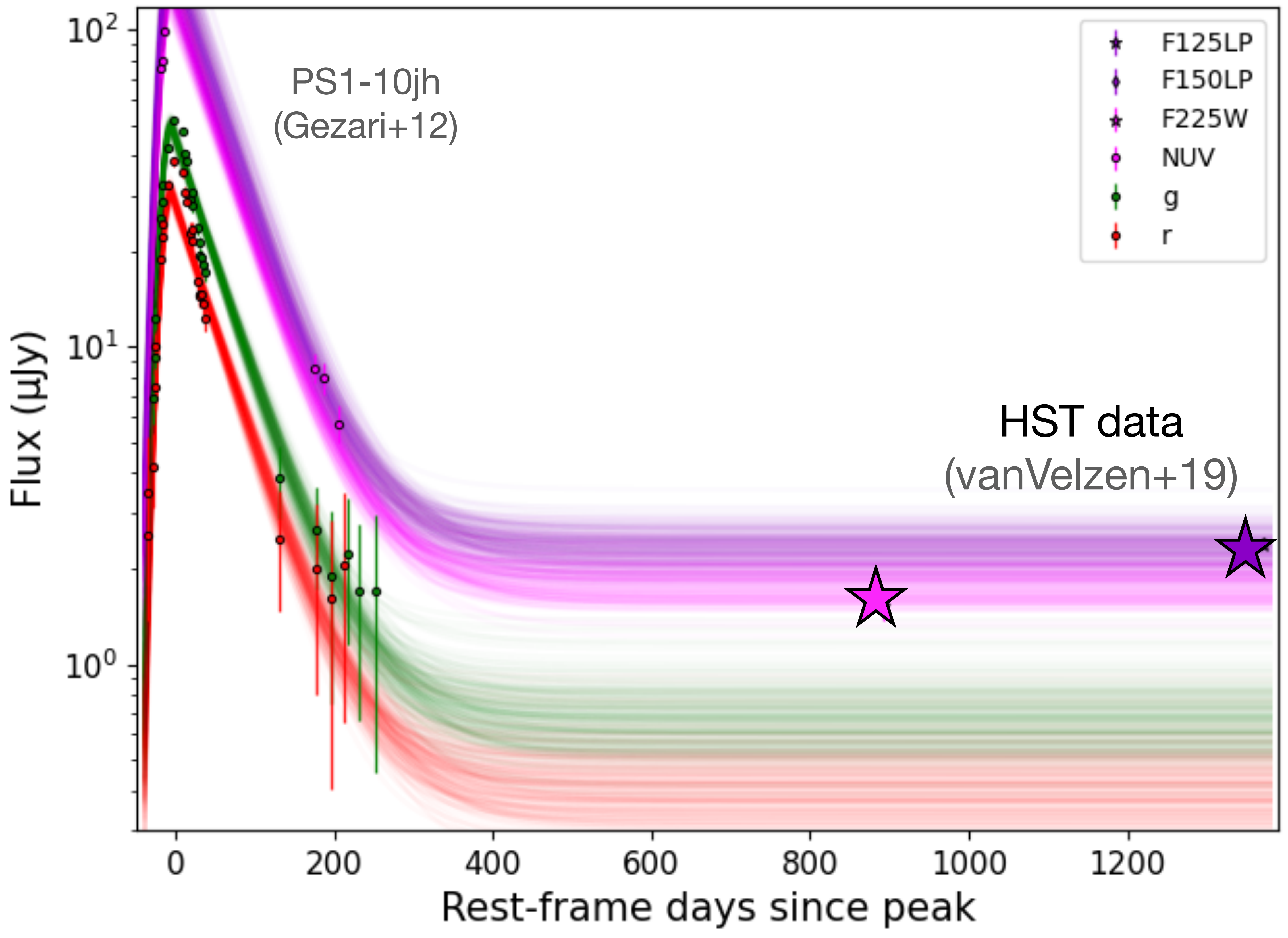


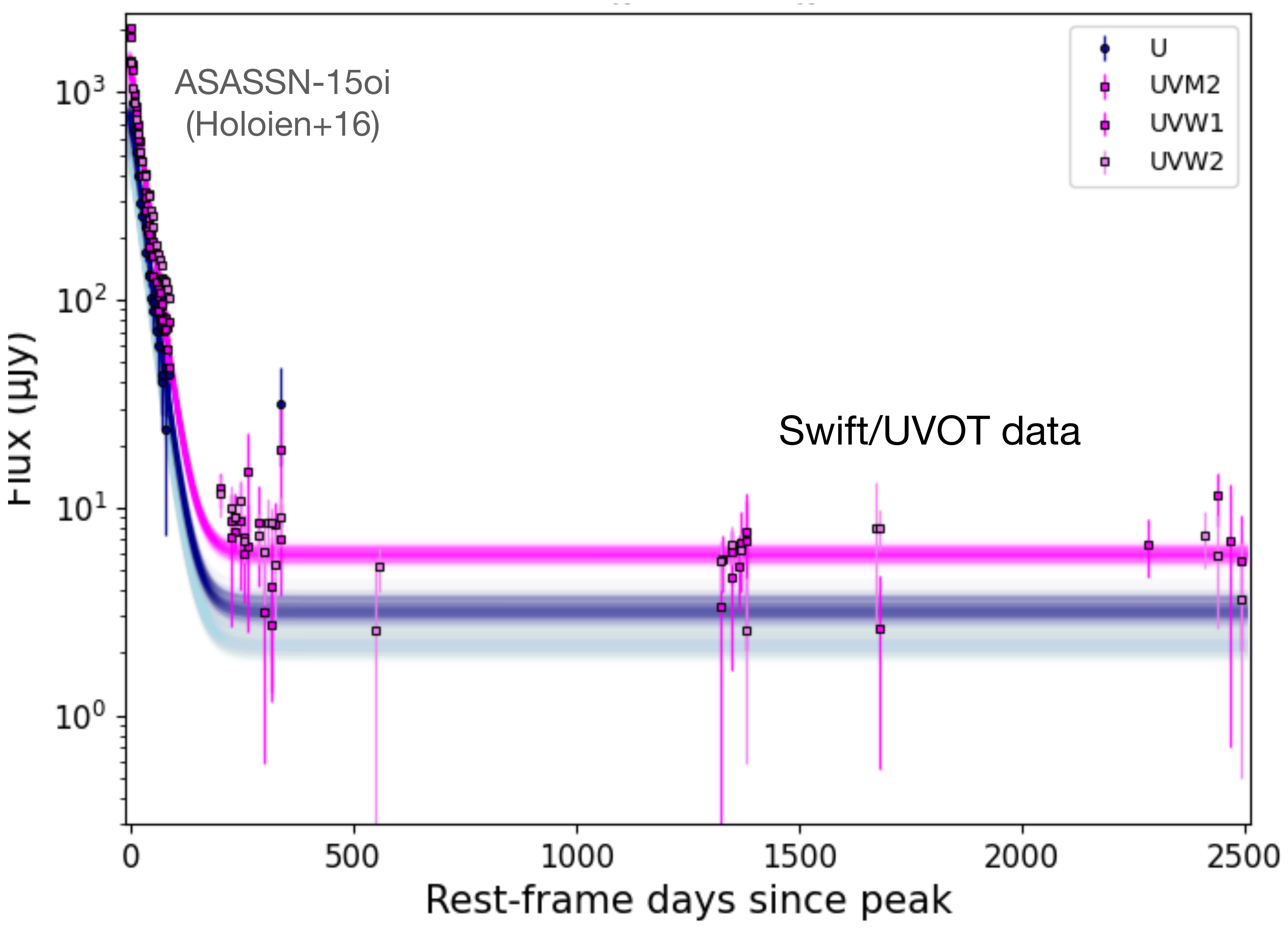
Data of PS-10jh Gezari et al. (2012, 2015);
van Velzen et al. (2019)

Plateau phase

- **Accretion disk (!)**

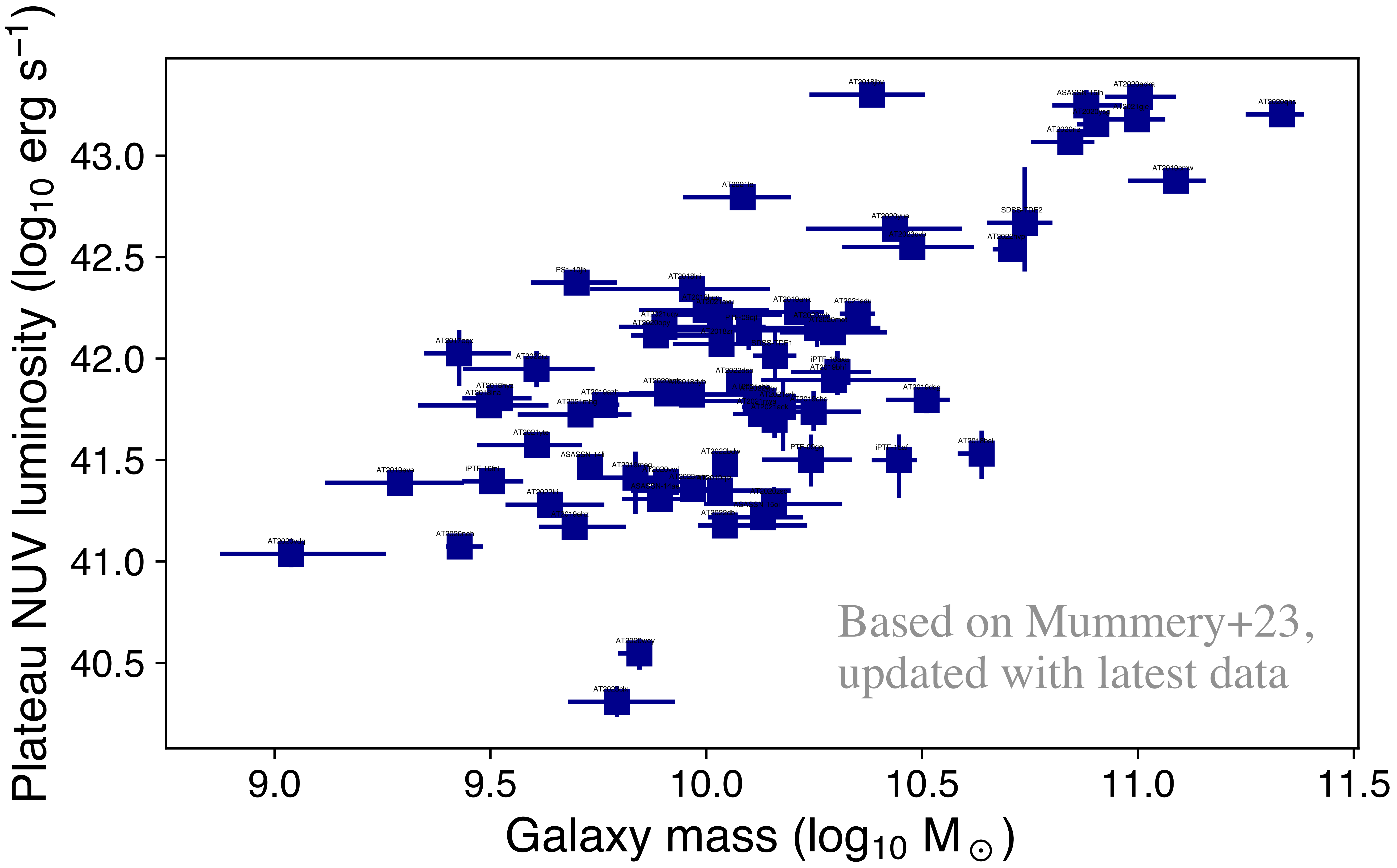
Late-time plateaus are common





Plateau luminosity correlates with host galaxy mass

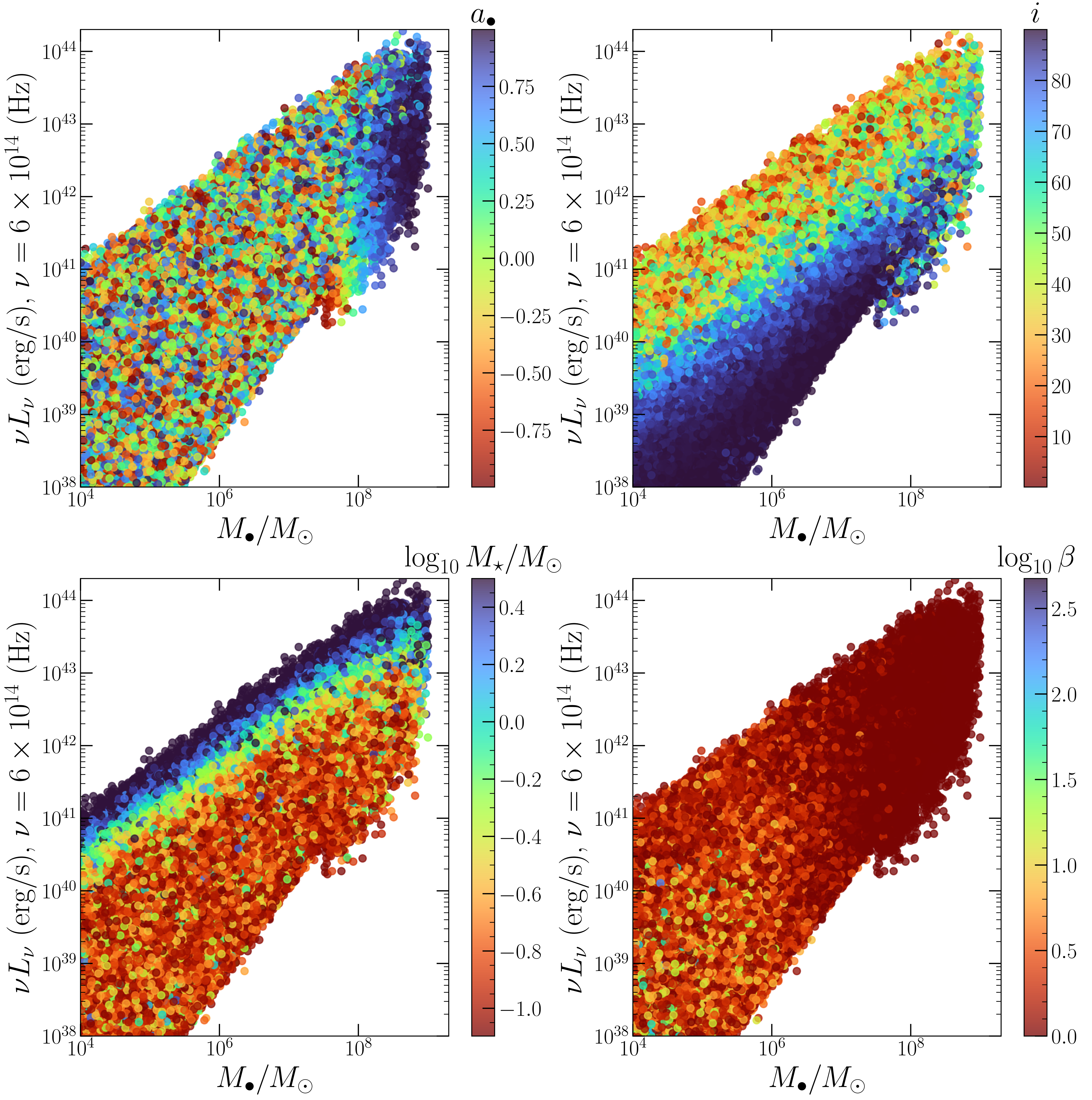
- Strongest correlation of all lightcurve properties
- Significance: $p = 5 \times 10^{-7} \sim 5\sigma$
- 0.33 dex scatter in mass-direction
- Theory predicts black hole mass from plateau (Mummery & Balbus 2020; Mummery 2022)



Accretion disk model

6 free parameters:

$M_\bullet\, M_{\rm star}\, \cos(i)\, a_\bullet\, \beta\, \mathscr{V}$

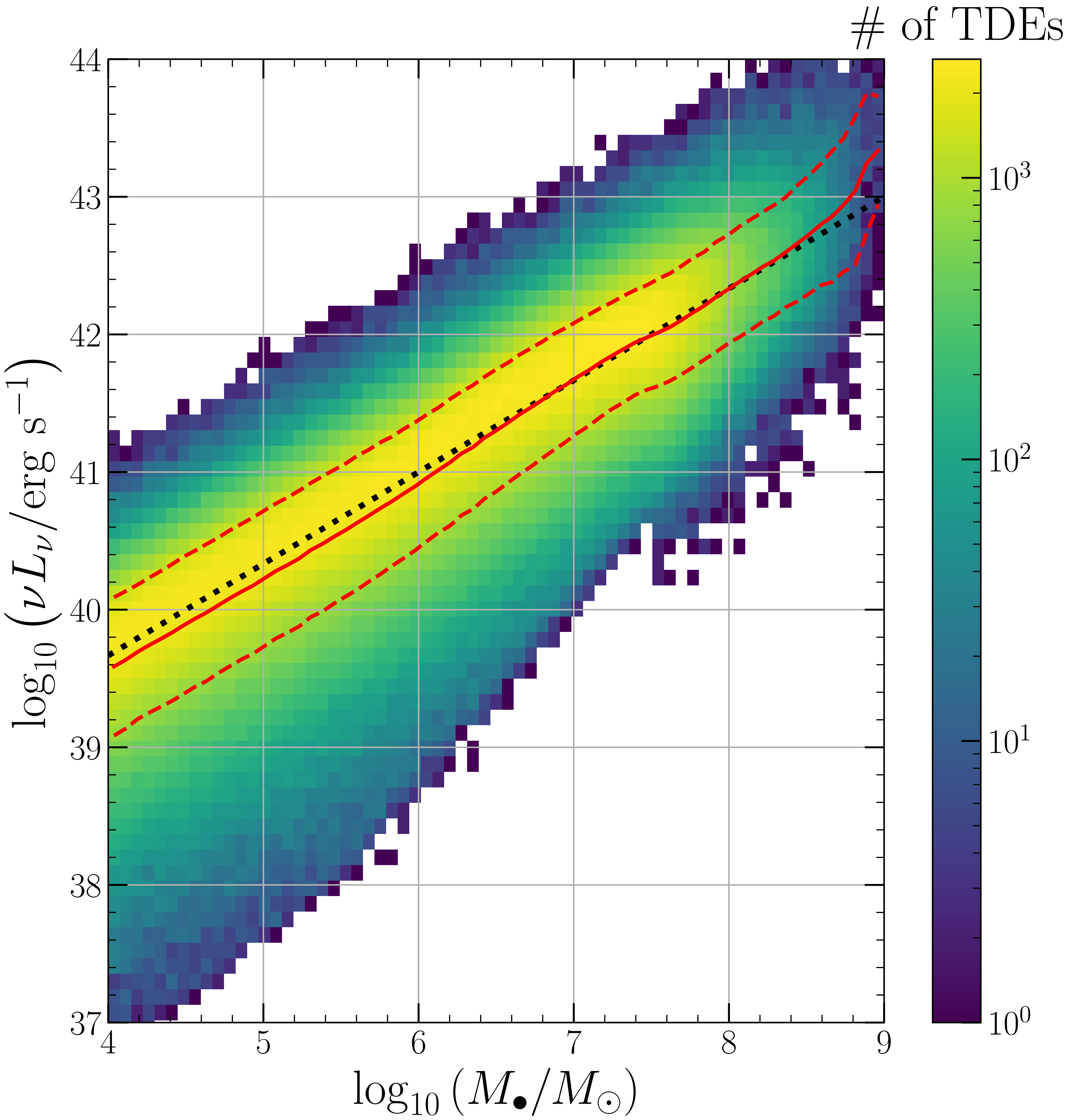


Accretion disk model

After marginalizing:

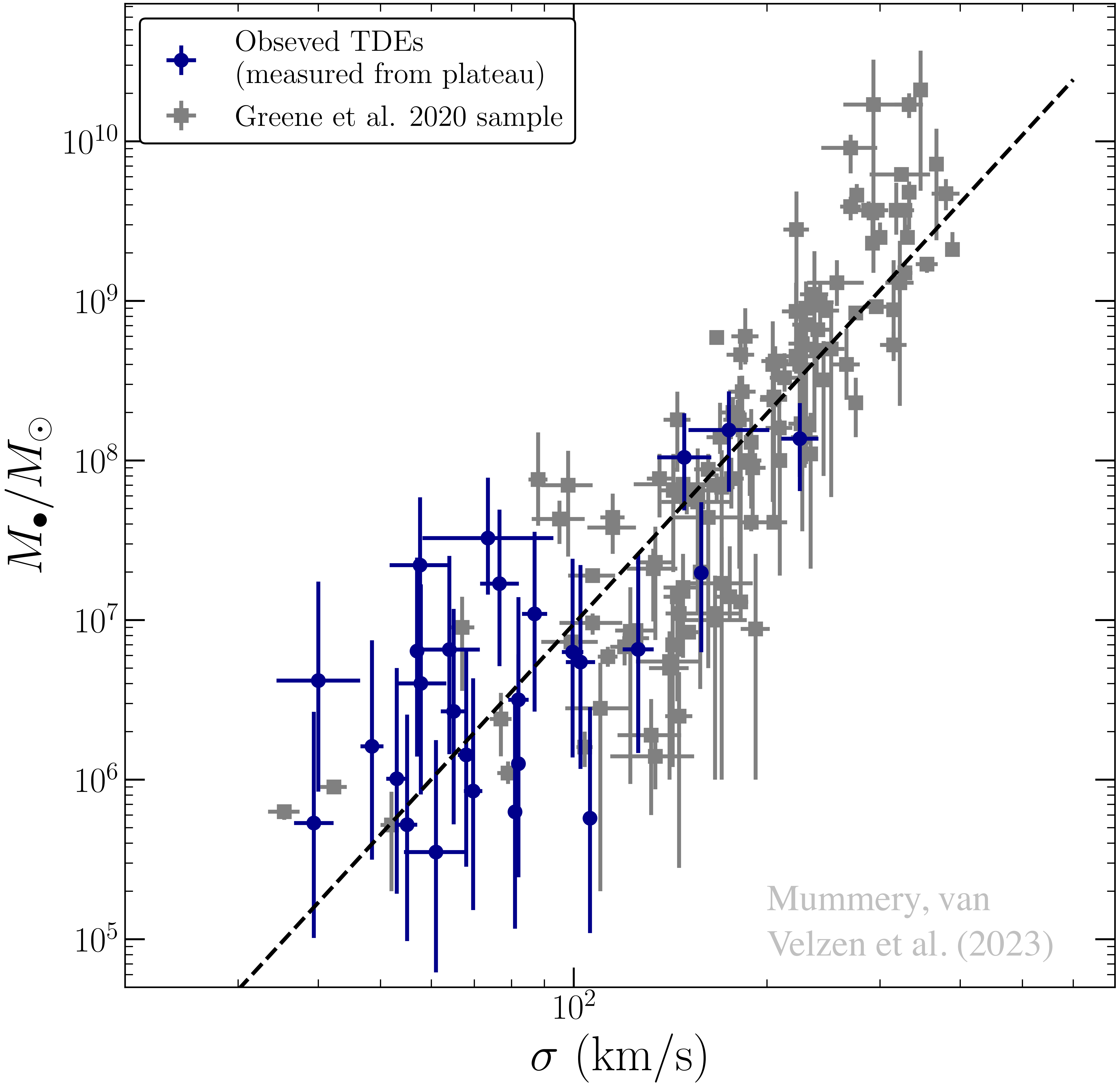
$L_{\rm plateau} \sim M_\bullet^{0.66}$

with $0.4\ {\rm dex}$ **scatter**



Extending the M-sigma relation

Excellent agreement



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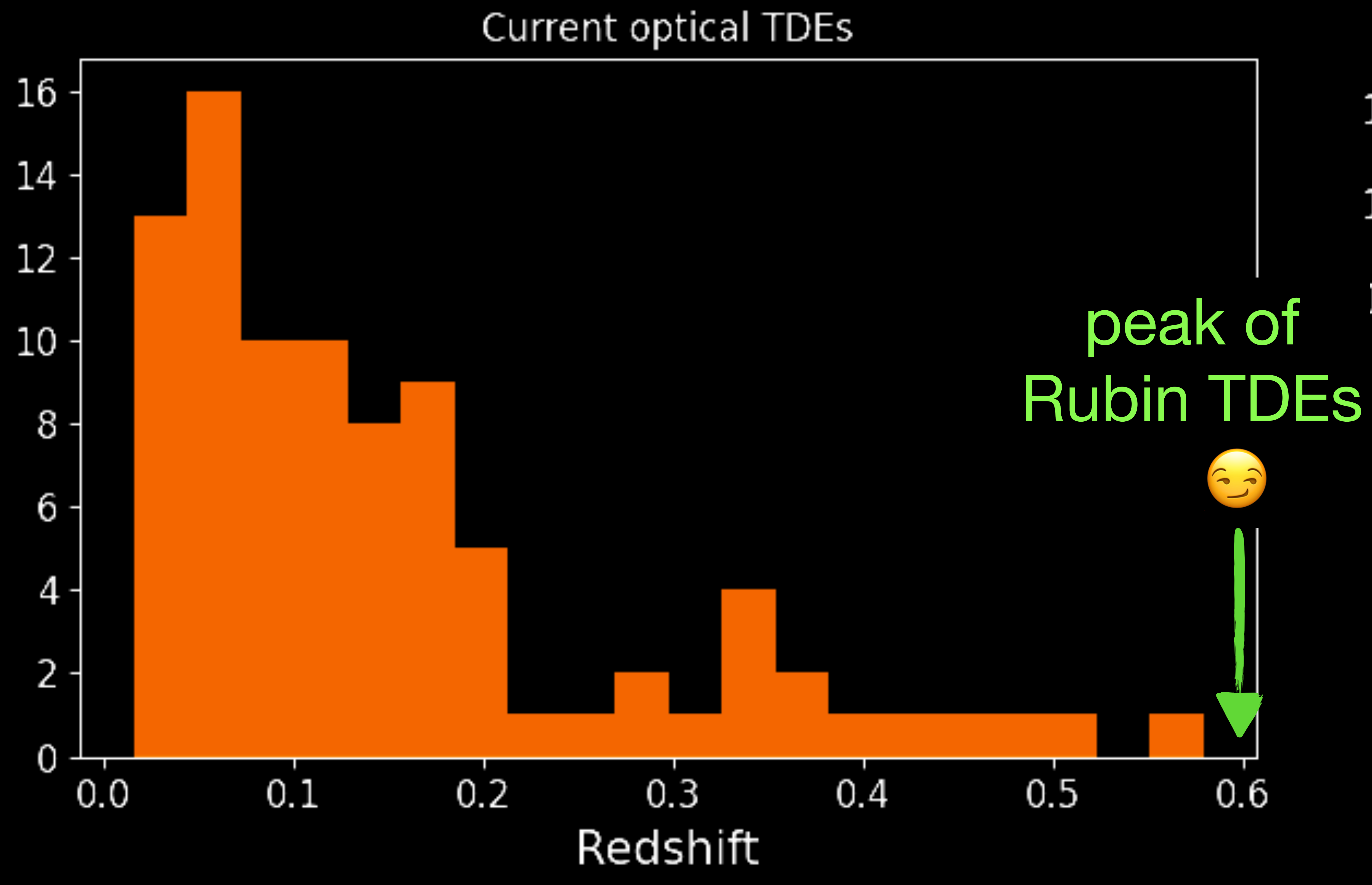
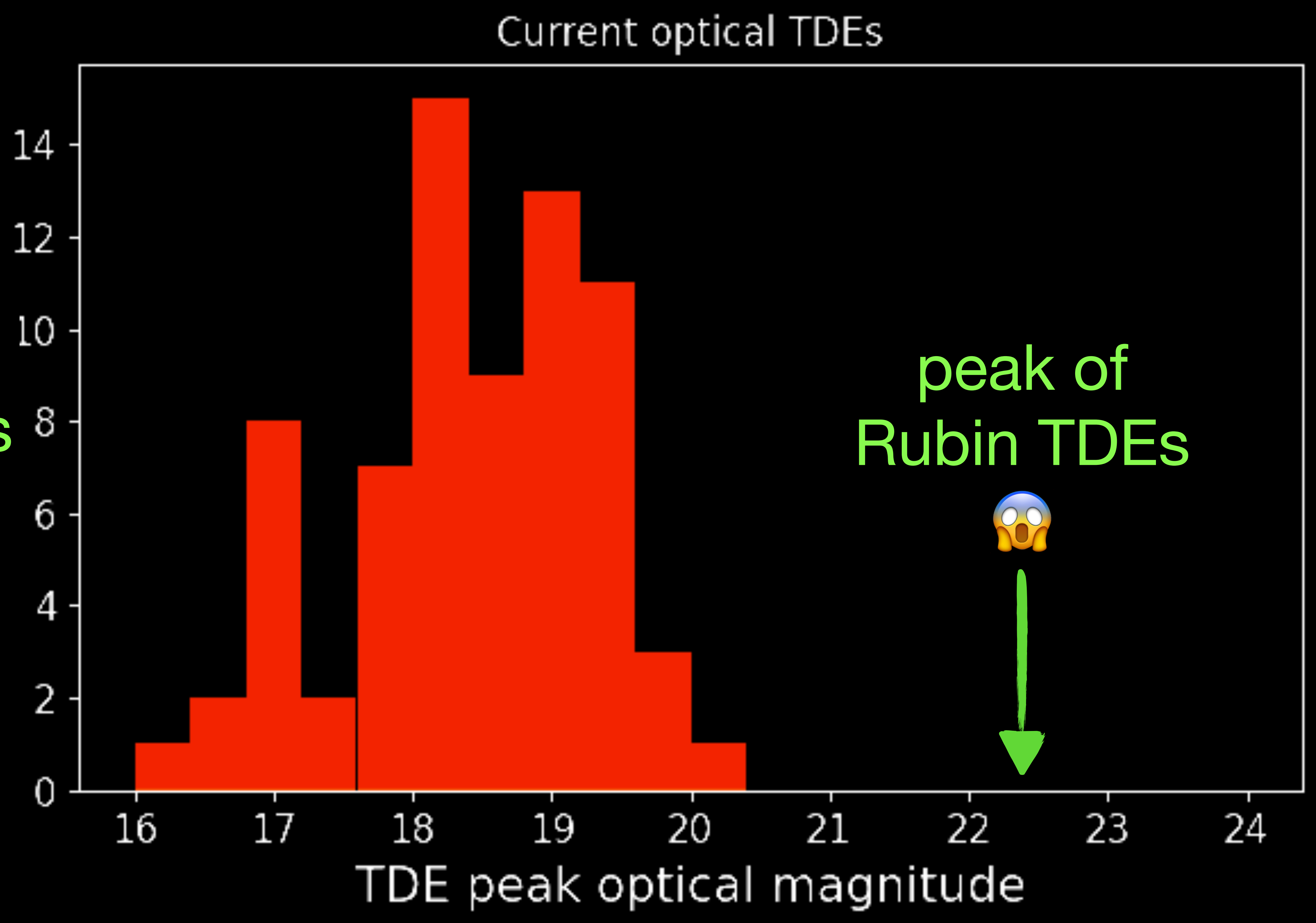
Neutrinos	IceCube	KM3NET	IceCube Gen2, TRIDENT?

Vera C. Rubin Observatory

Extraordinary classification challenge

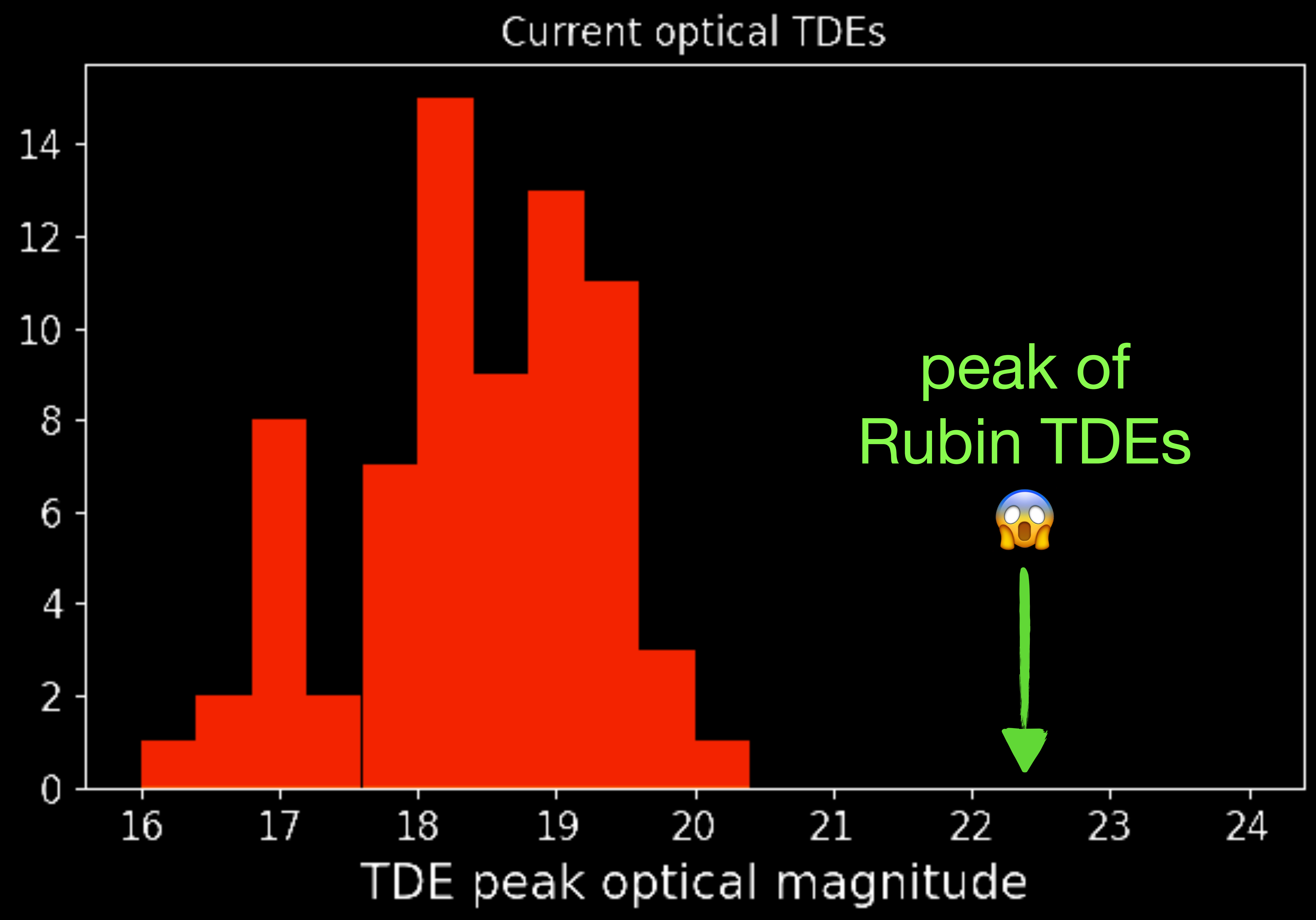




Vera C. Rubin Observatory

Extraordinary classification challenge

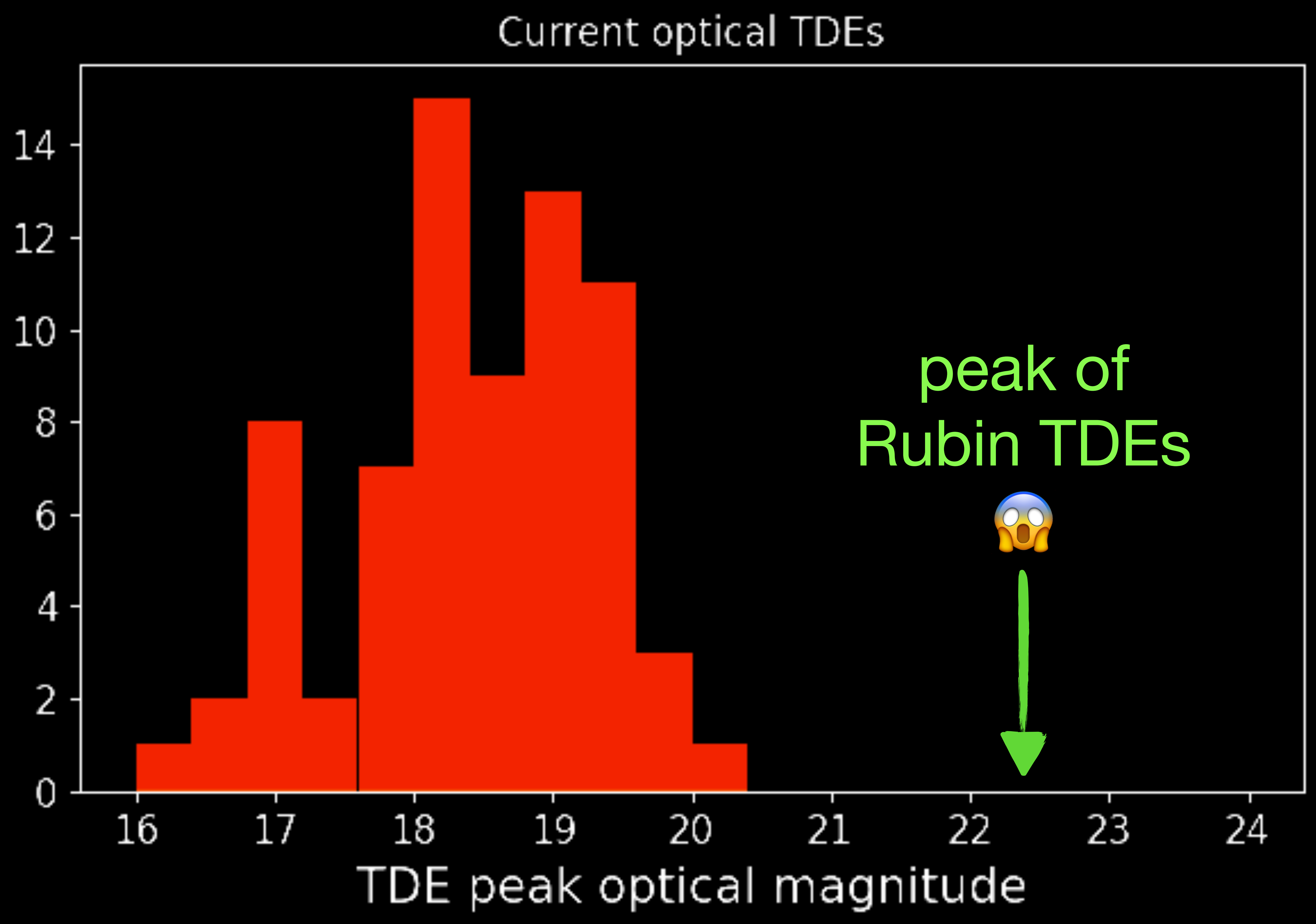
- Photometric classification required
  - Machine learning;
  - Need a training sample:
    - From simulations?
    - Of known TDEs?
    - Subset of Rubin data



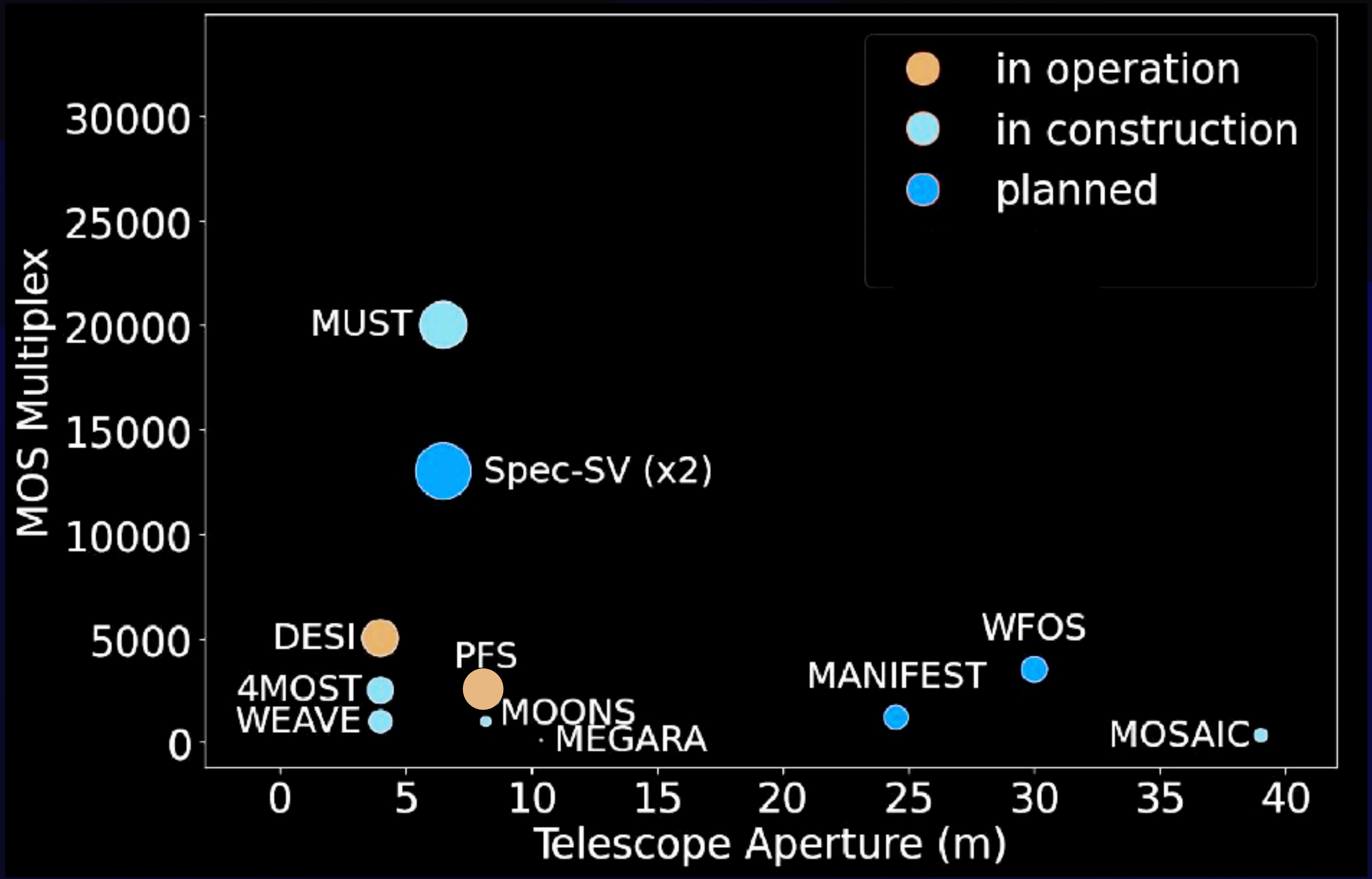
Vera C. Rubin Observatory

Limitations of photometric classification

- ML good at *finding what we already know*
- Most TDE properties (jets, QPEs) were not predicted
  - ML Anomaly detection (eg, self-organizing maps, Isolation forests):
    - ML has yet to detect something truly new
    - How to examine the anomaly if the transient has faded?



Spectroscopic follow-up



Wide field spectroscopic telescope

could become operational in Chile … after 2040

Telescope aperture (M1)	12 m seeing limited		
Telescope FoV	3.1 deg^2		
Telescope Spec. range	0.35-1.6 μm		
Operations	MOS and IFS simultaneous operations ToO implemented at telescope and fibre level		
Modes	MOS-LR	MOS-HR	IFS
FoV	3.1 deg^2	3.1 deg^2	3x3 arcmin^2 (mosaic on 9x9 arcmin^2)
Spectral range (simultaneous)	0.37-0.97 μm	0.37-0.97 μm 3-4 windows	0.37-0.97 μm
Spectral resolution	4000	40000	3500
Multiplexing	30000	2000