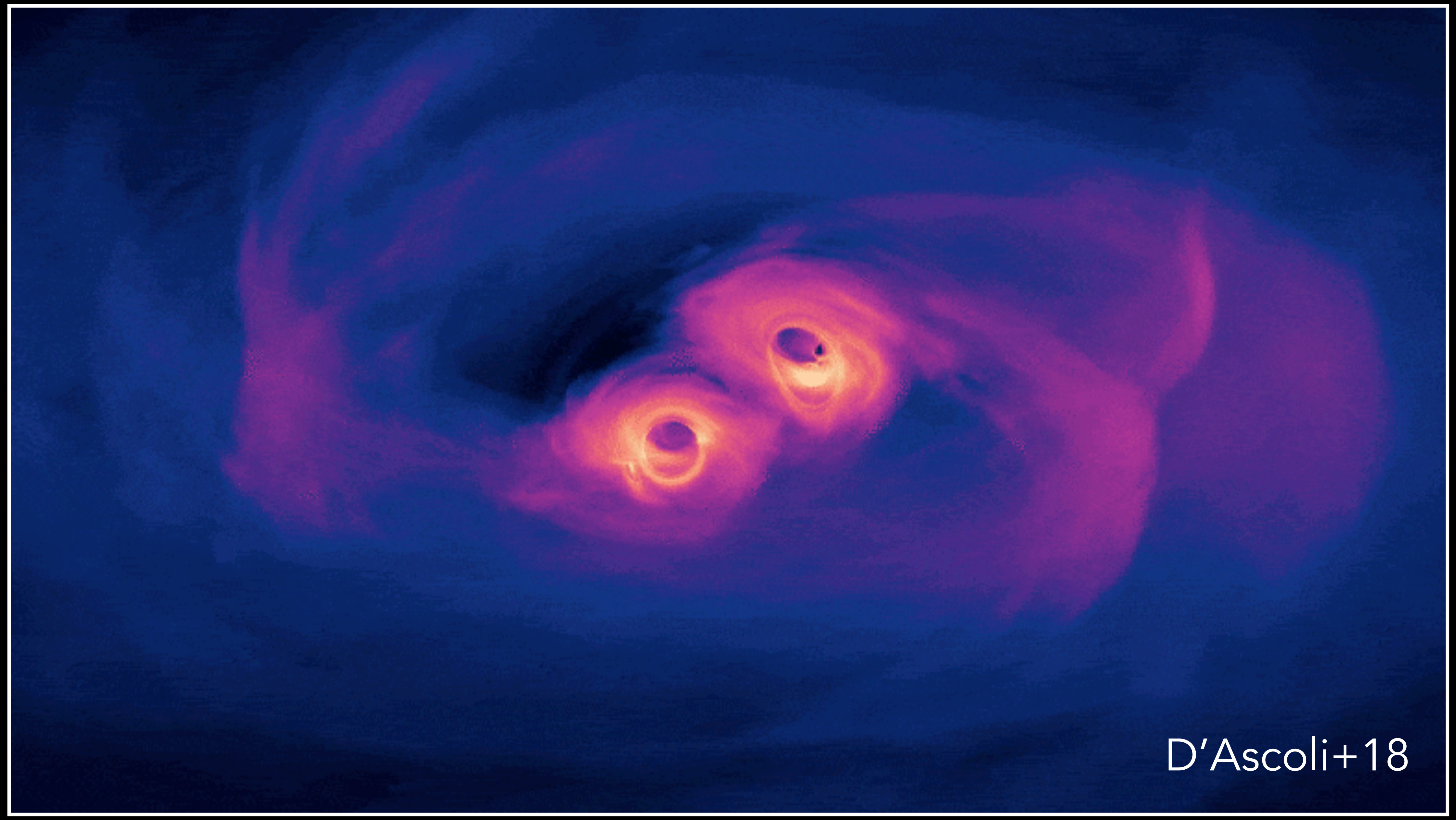
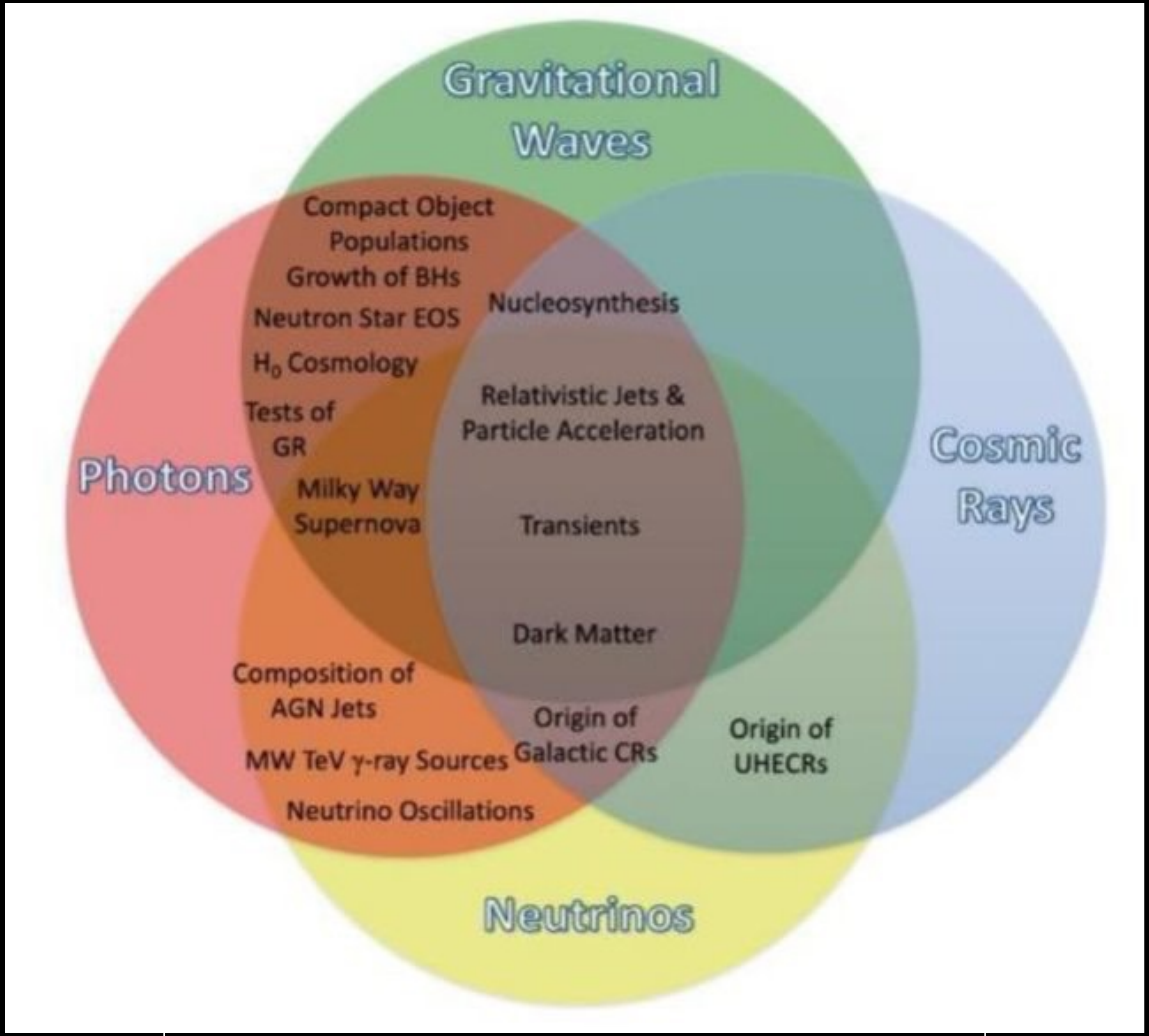


THE DYNAMIC UNIVERSE WITH CMB-S4

Vikram Ravi
Assistant Professor of Astronomy, California Institute of Technology

CMB-S4: physics all the way down



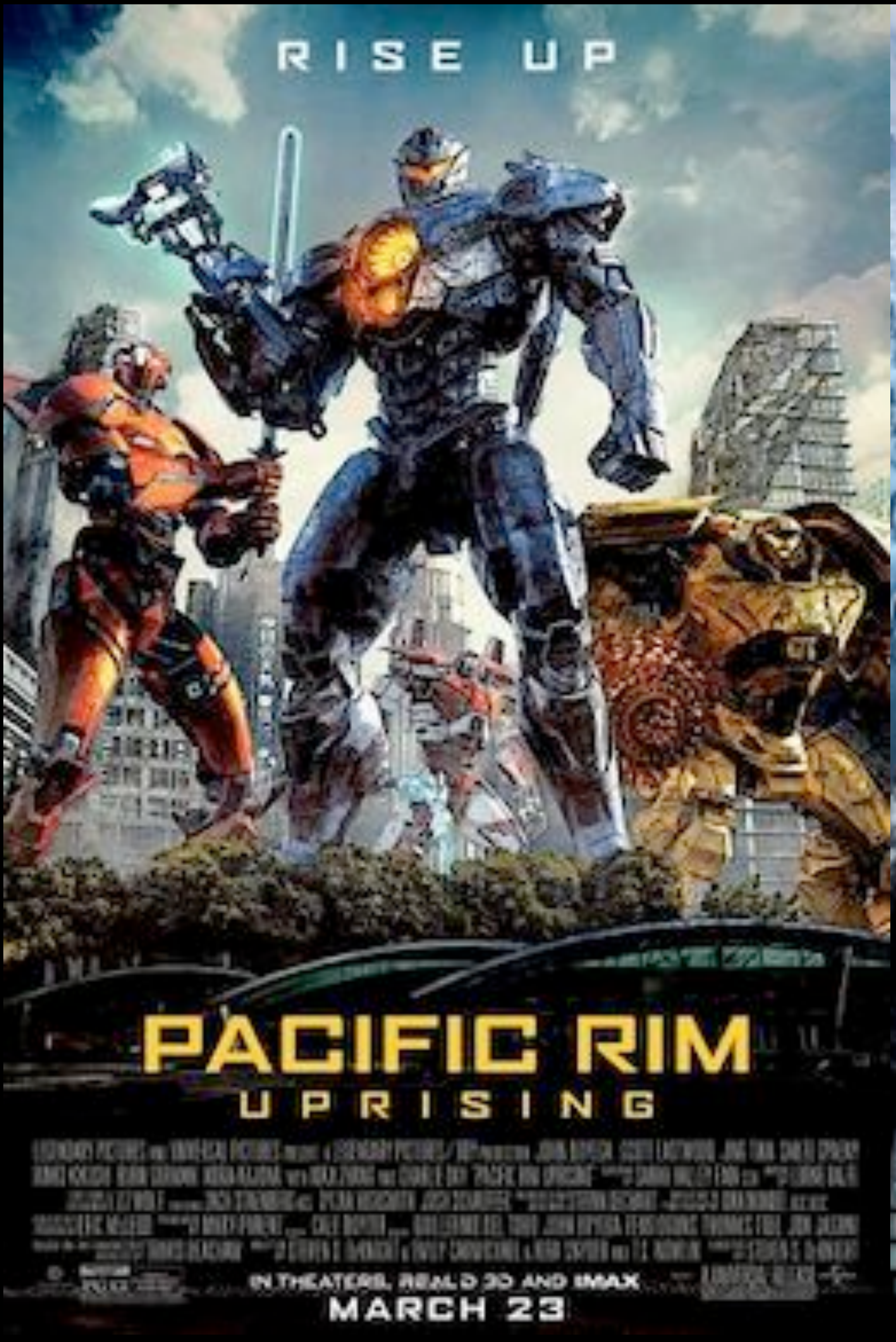
Astro2020 Decadal Survey

Windows on the Universe (multi-messenger astronomy)

Responds to the **New Messengers and New Physics** science theme of Astro2020, together with one of the NSF "10 big ideas". Aspects of the Astro2020 **Cosmic Ecosystems** theme.

What will the world look like in the **mid 2030s and beyond**? *At least, the world of astronomers interested in compact objects, high-energy astrophysical phenomena…*

What will the world look like in the **2030s and beyond**? *At least, the world of astronomers interested in compact objects, high-energy astrophysical phenomena…*

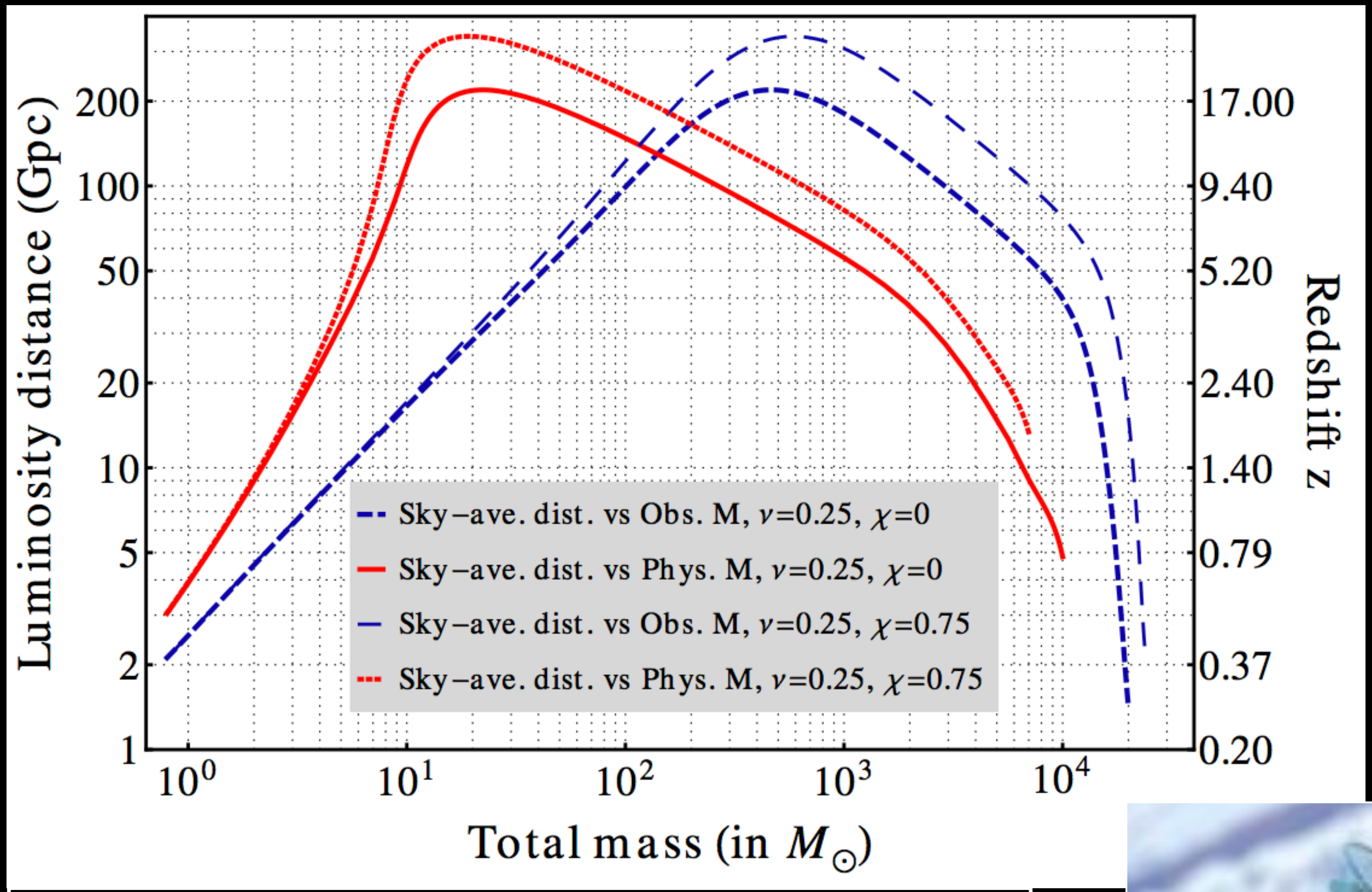


What will the world look like in the **2030s and beyond**? *At least, the world of astronomers interested in compact objects, high-energy astrophysical phenomena…*

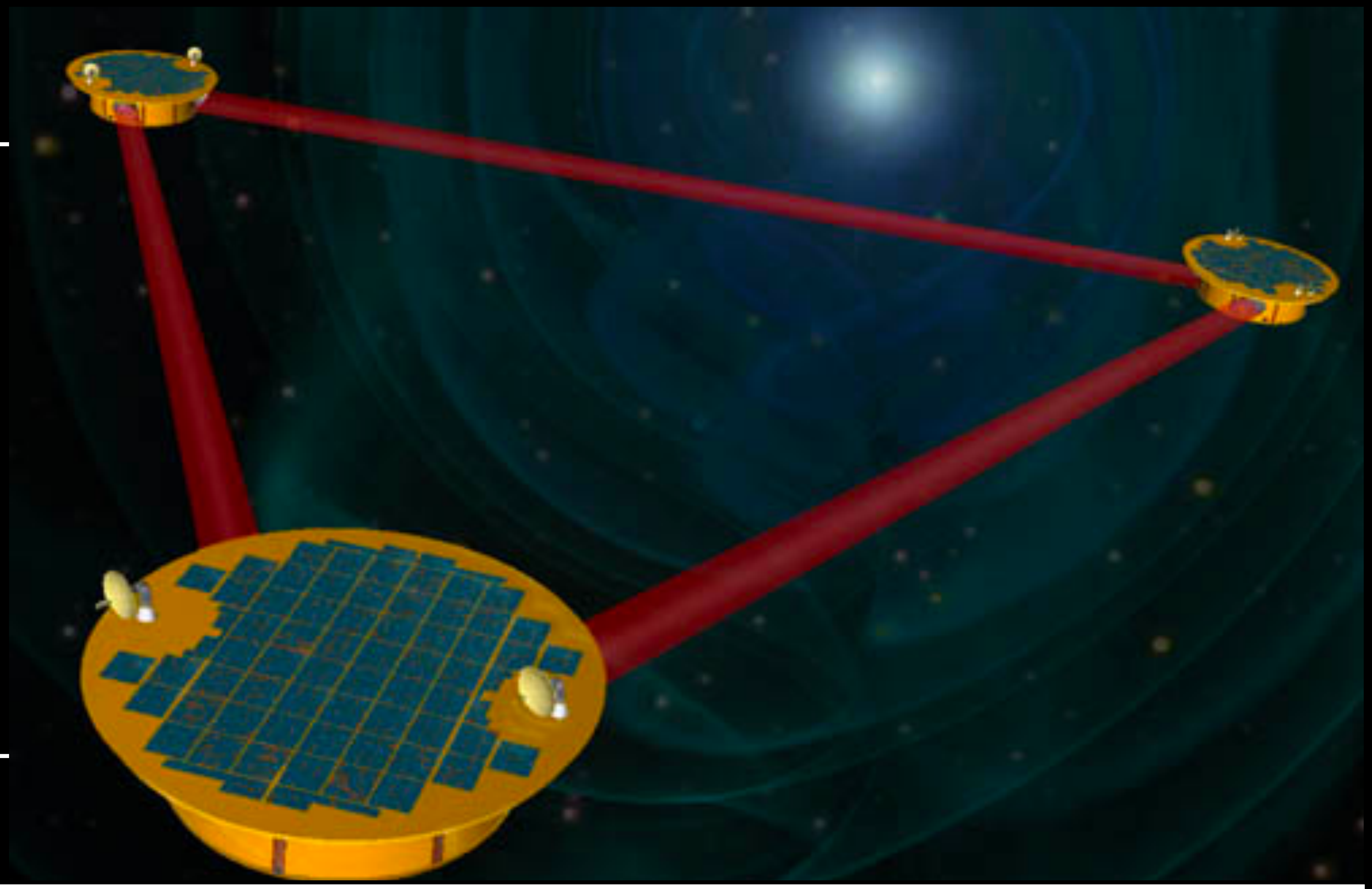
We must plan for the next generation of **multi-messenger facilities**.

We can look forward to a **paradigm shift** in our view of the **dynamic universe**.

We must plan for the next generation of **multi-messenger facilities**.

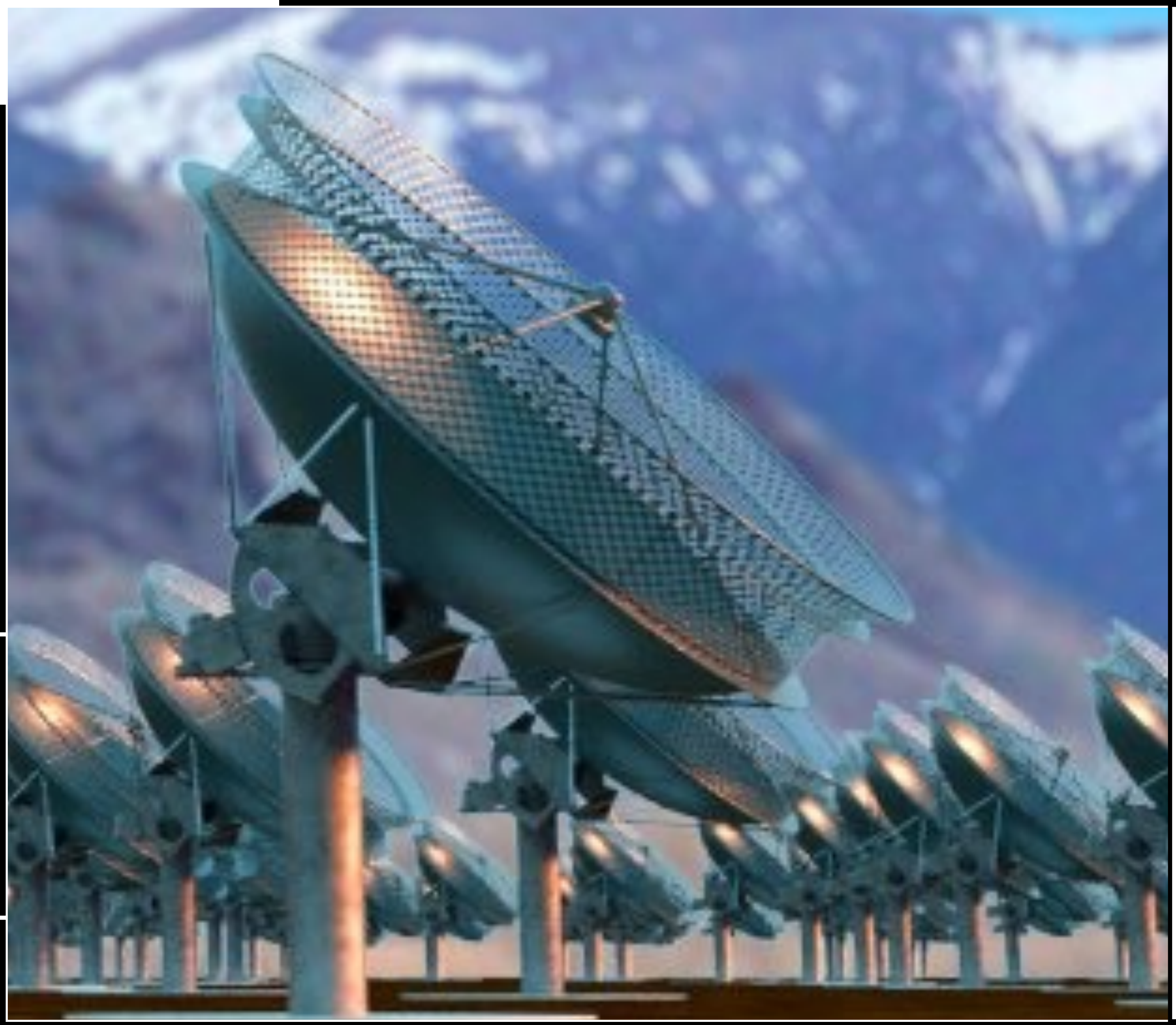


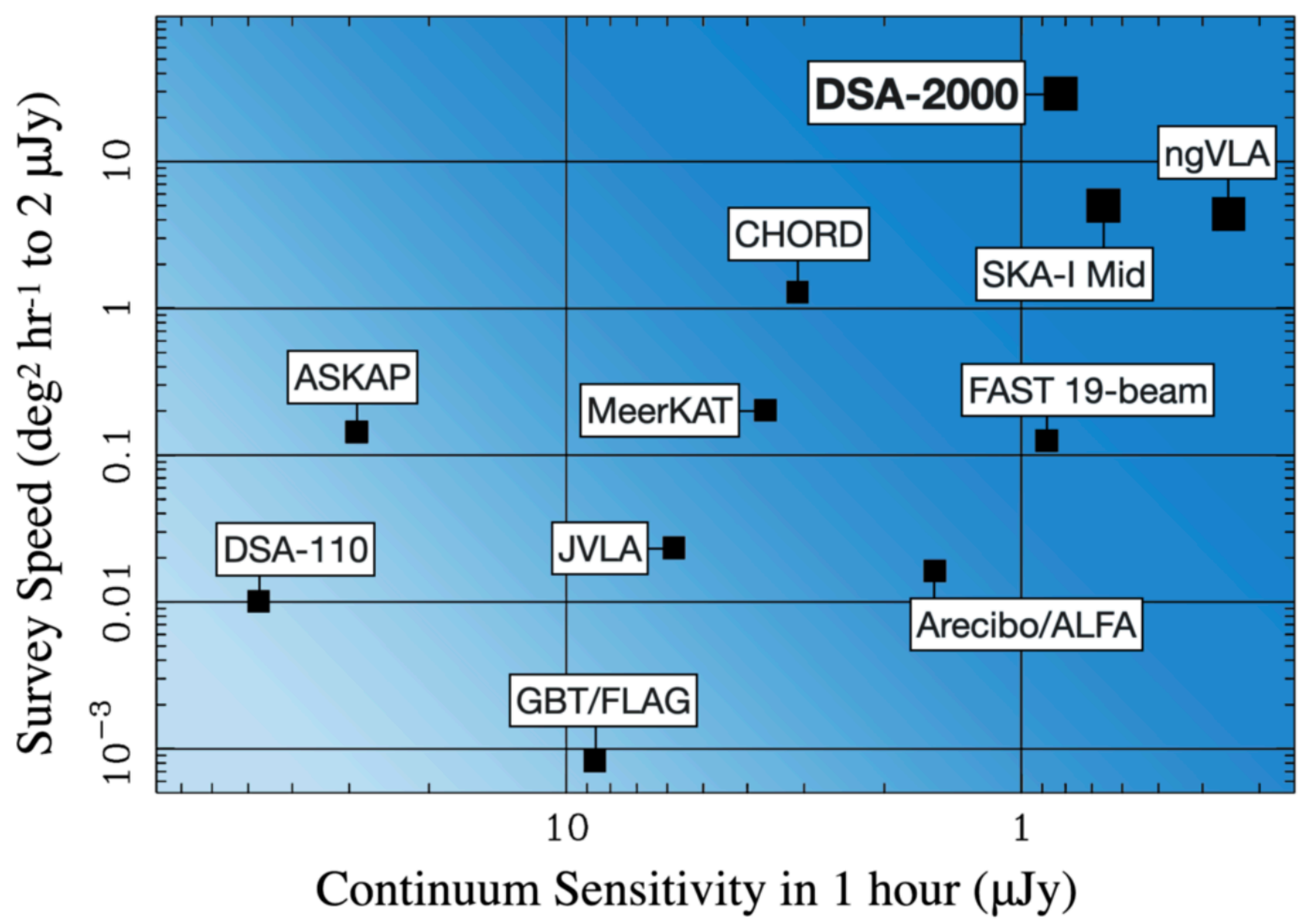
LISA: 2034 launch, with three identical spacecraft. SMBH coalescences [~100], extreme mass-ratio inspirals [~100], compact stellar binaries [~10^6].



2nd gen. aLIGO, VIRGO, KAGRA, INDIGO: up to 10-100 binary NS mergers per yr.
3rd gen. Einstein telescope: 10x better frequency coverage & sensitivity

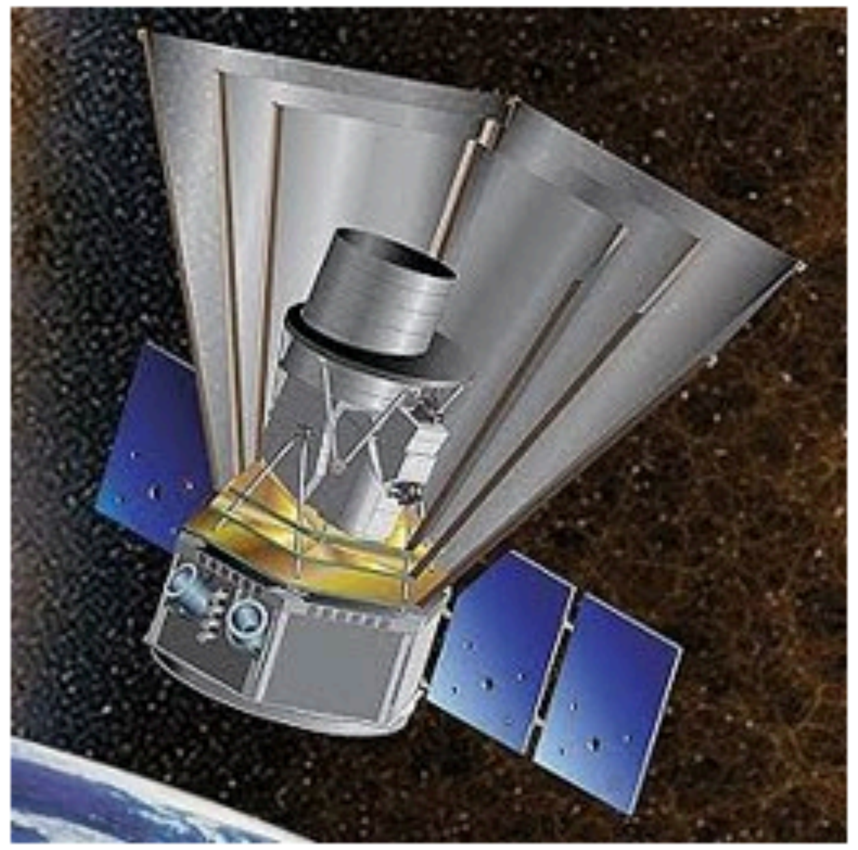
DSA-2000: 25% time for NANOGrav pulsar timing array -> individual binary SMBHs





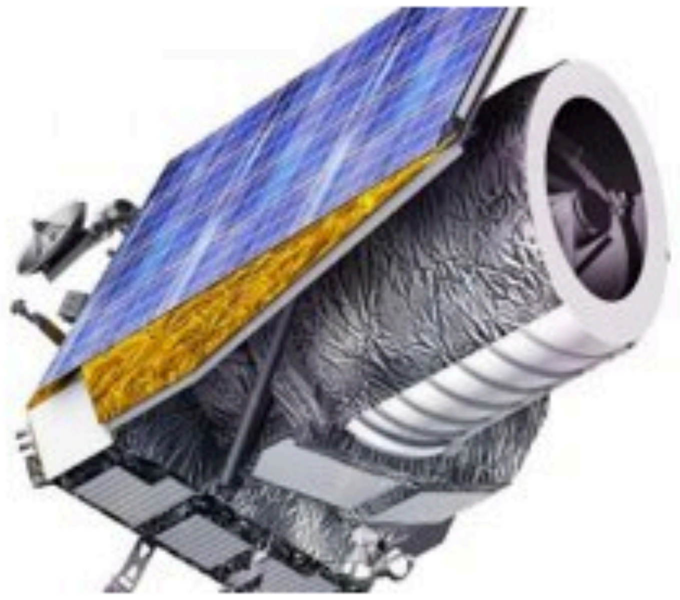
Amaro-Seoane+12, Sathyaprakash+12

We can look forward to a **paradigm shift** in our view of the **dynamic universe**.

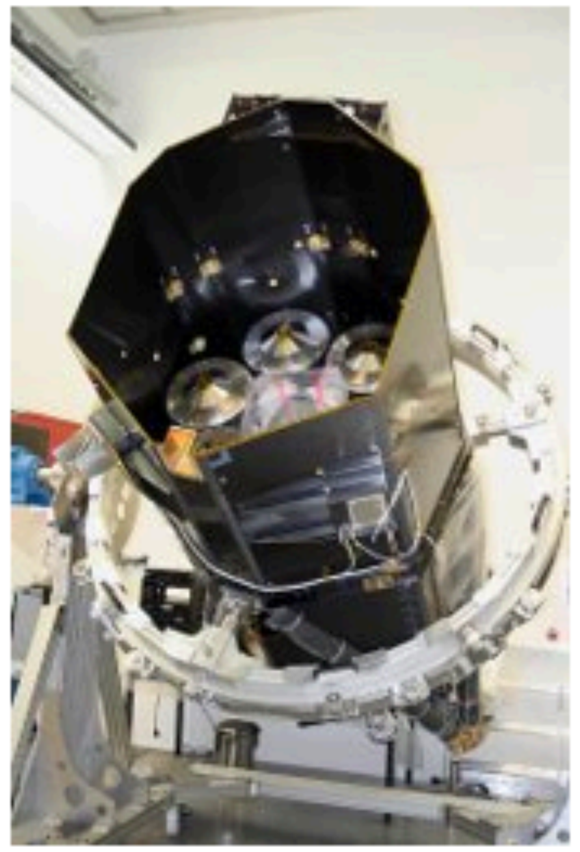


Sphere-X: 2024

WFIRST: 2025

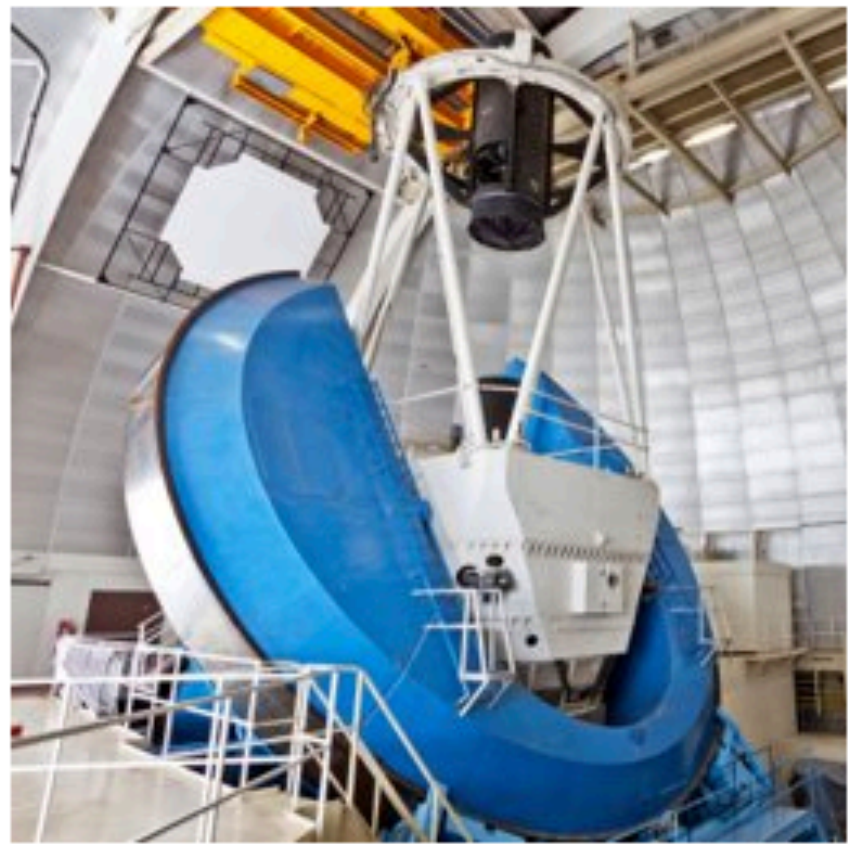


Euclid: 2022

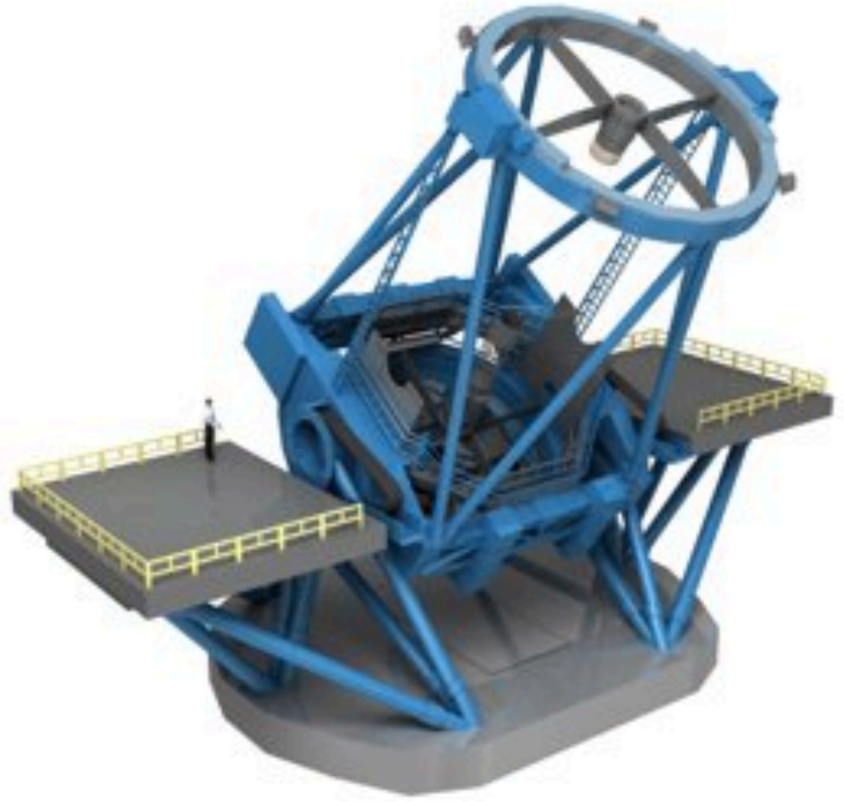


SRG/eROSITA: 2019

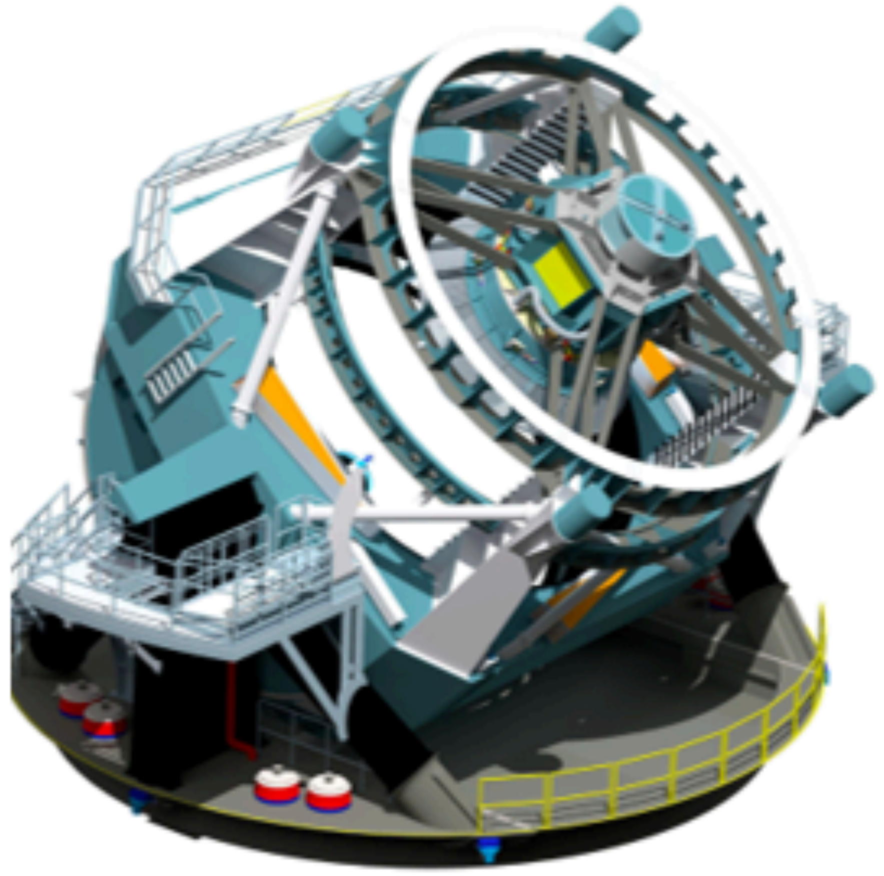
DSA-2000: 2026



DESI: 2019



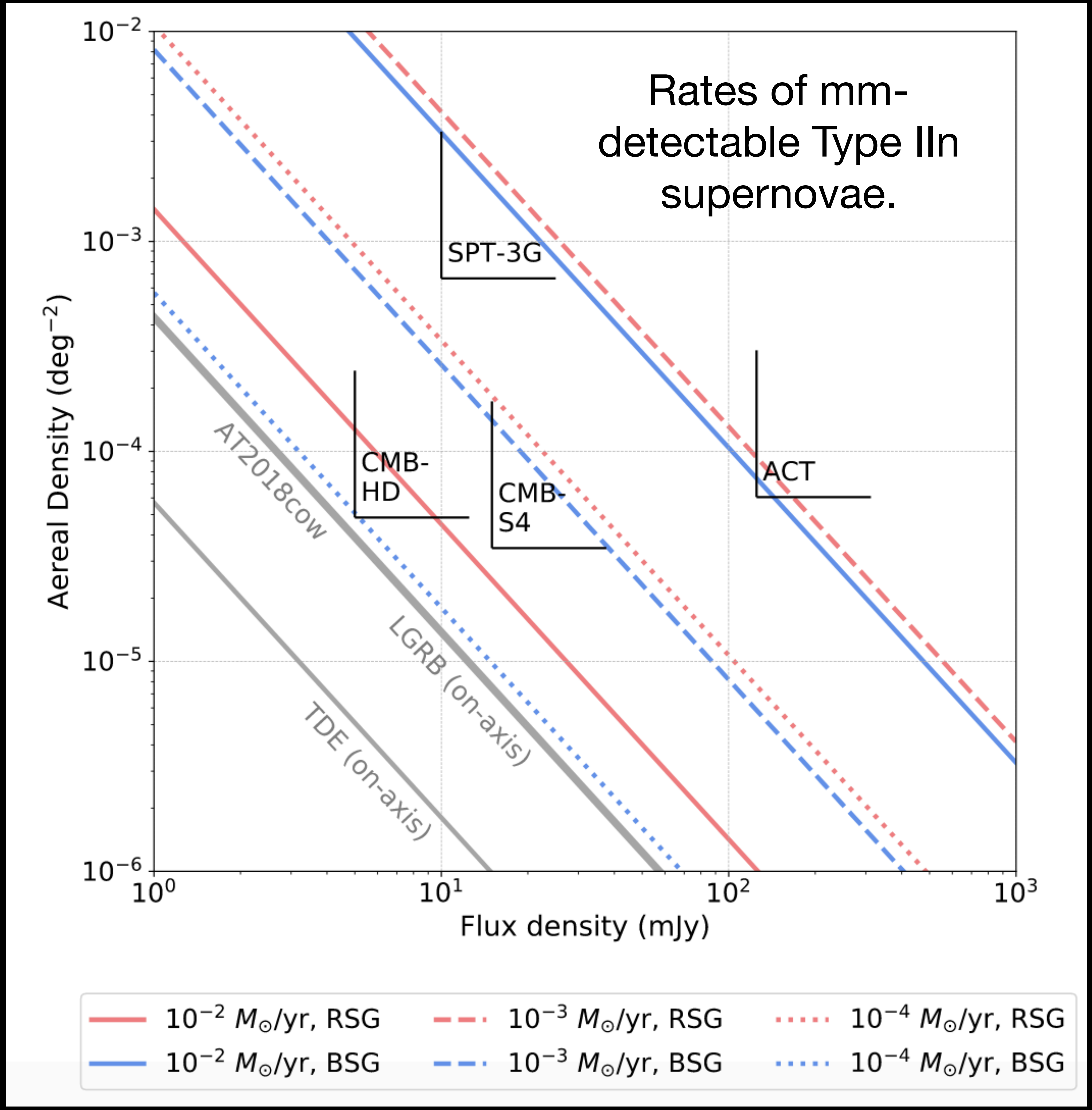
PFS: 2022

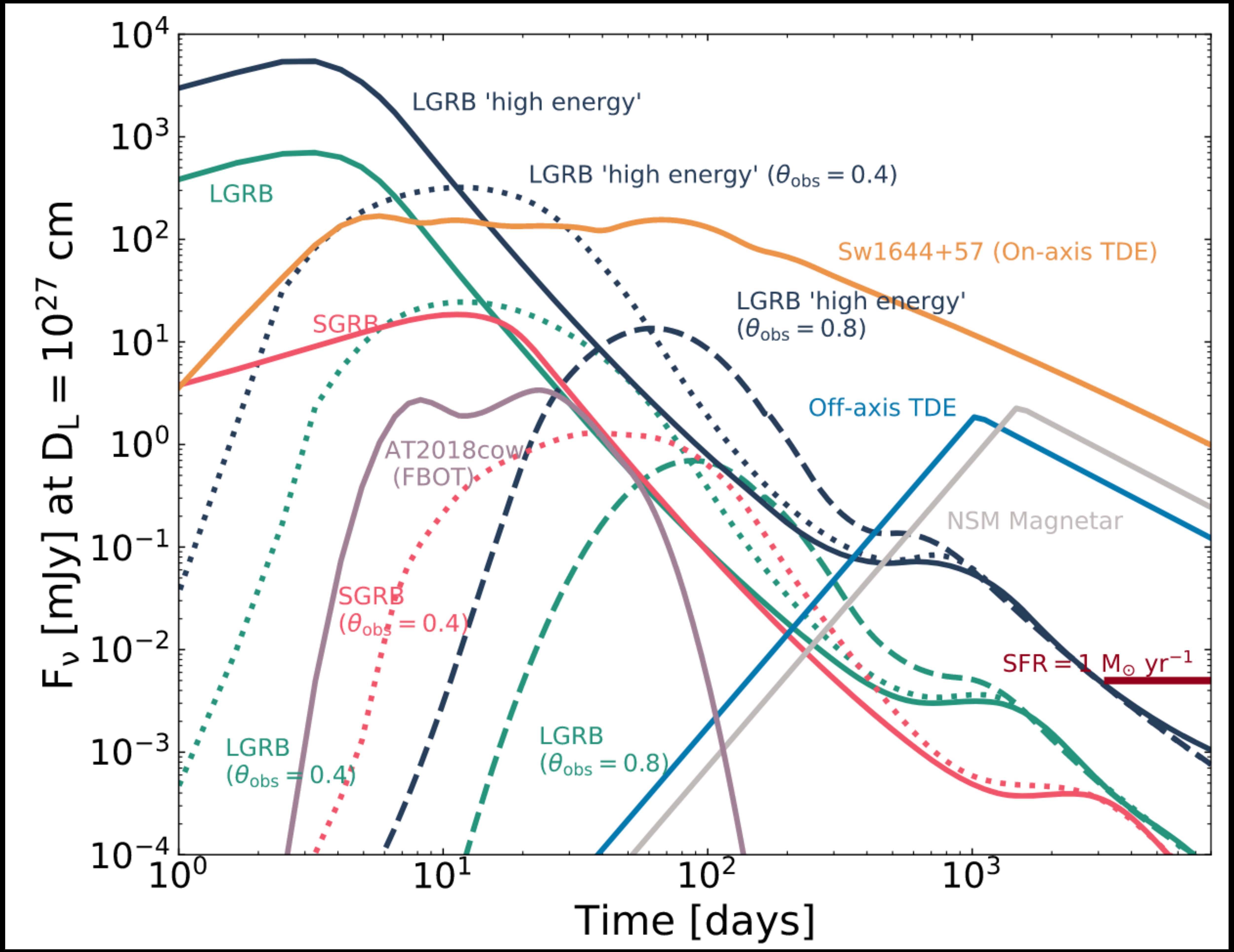


VRO: 2023

WHY MILLIMETER TRANSIENTS

Selects synchrotron emission from more **compact**, more **energetic** sources in **higher-density** environments.





Yadlapalli+22, Eftekhari+22

A. How are different flavors of black holes and neutron stars formed and destroyed?

1. *Watching BH and NS formation in core-collapse supernovae, including GRB-like events.*
2. *What are the outcomes of NS-NS and NS-BH mergers?*

B. What is the full suite of consequences of accretion onto compact objects?

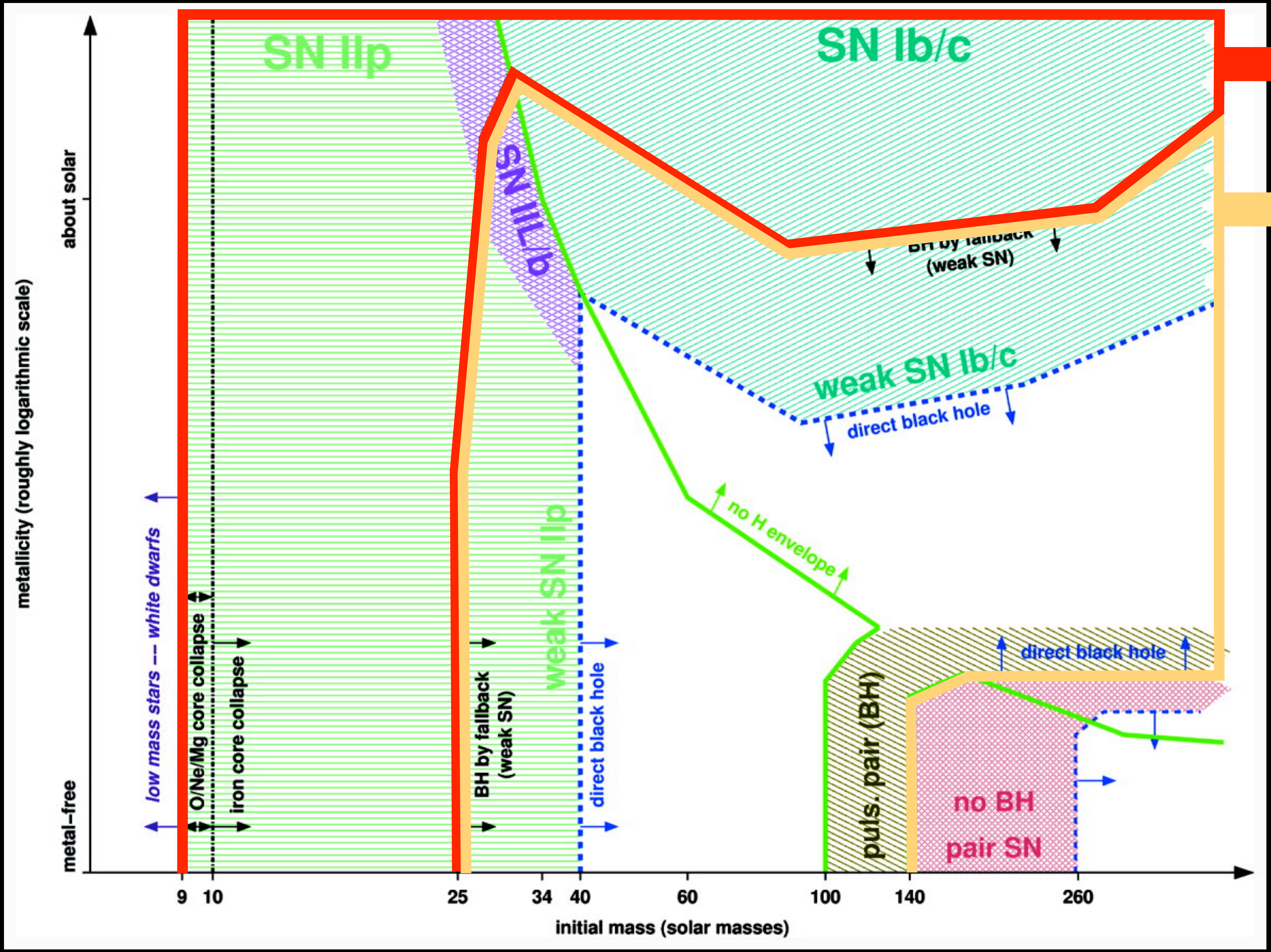
1. *Under what circumstances do SMBHs launch jets / relativistic outflows?*
2. *What are the EM counterparts to SMBH mergers?*

C. What are the origins of ultra-high energy cosmic rays and high-energy neutrinos?

- *Particle acceleration mechanisms and occurrence surrounding [1] active stars, [2] supernovae, [3] tidal disruption events / AGN, [4] GRBs…*

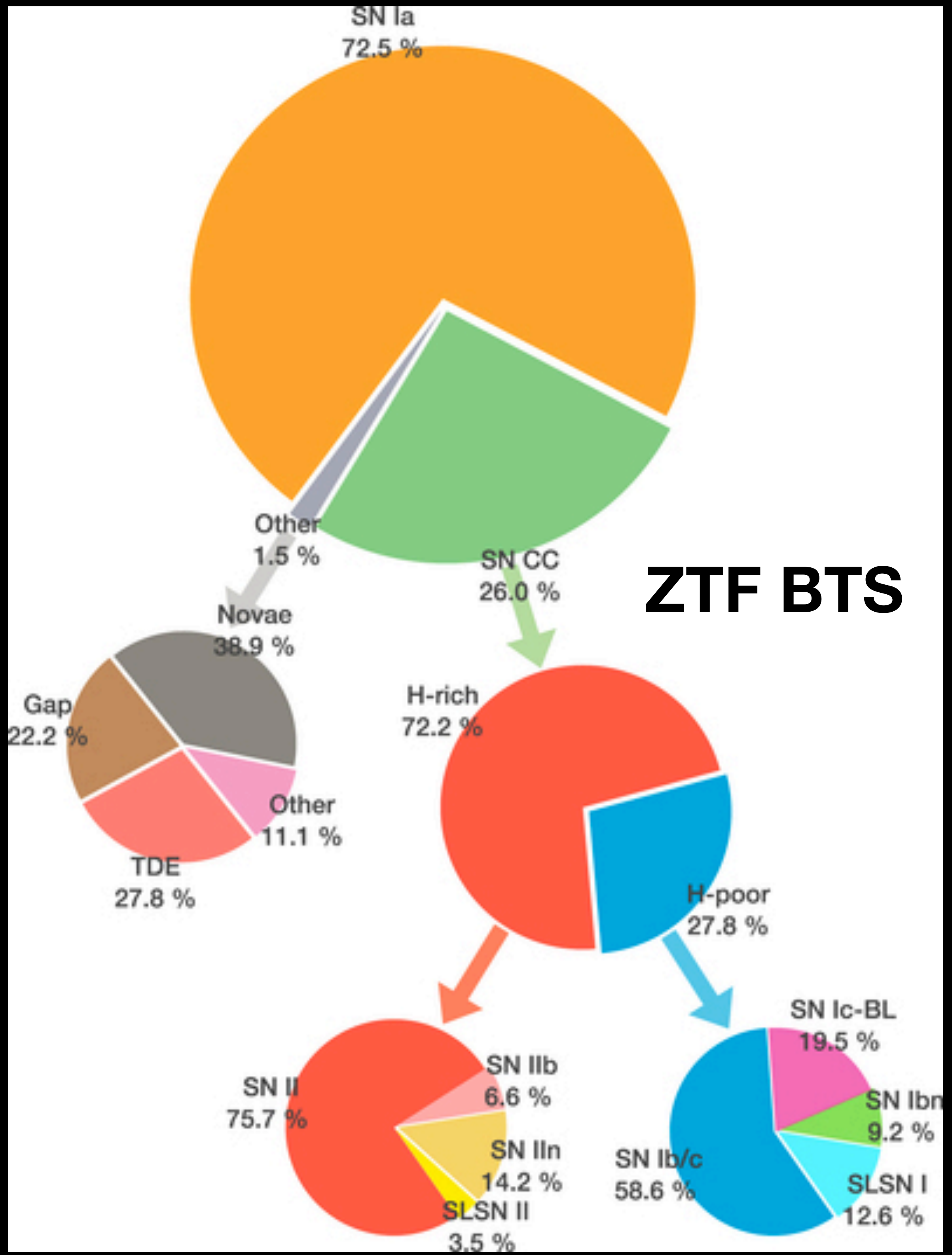
Heger+03, Perley+20

[A1] COMPACT OBJECT FORMATION IN CORE-COLLAPSE SNE

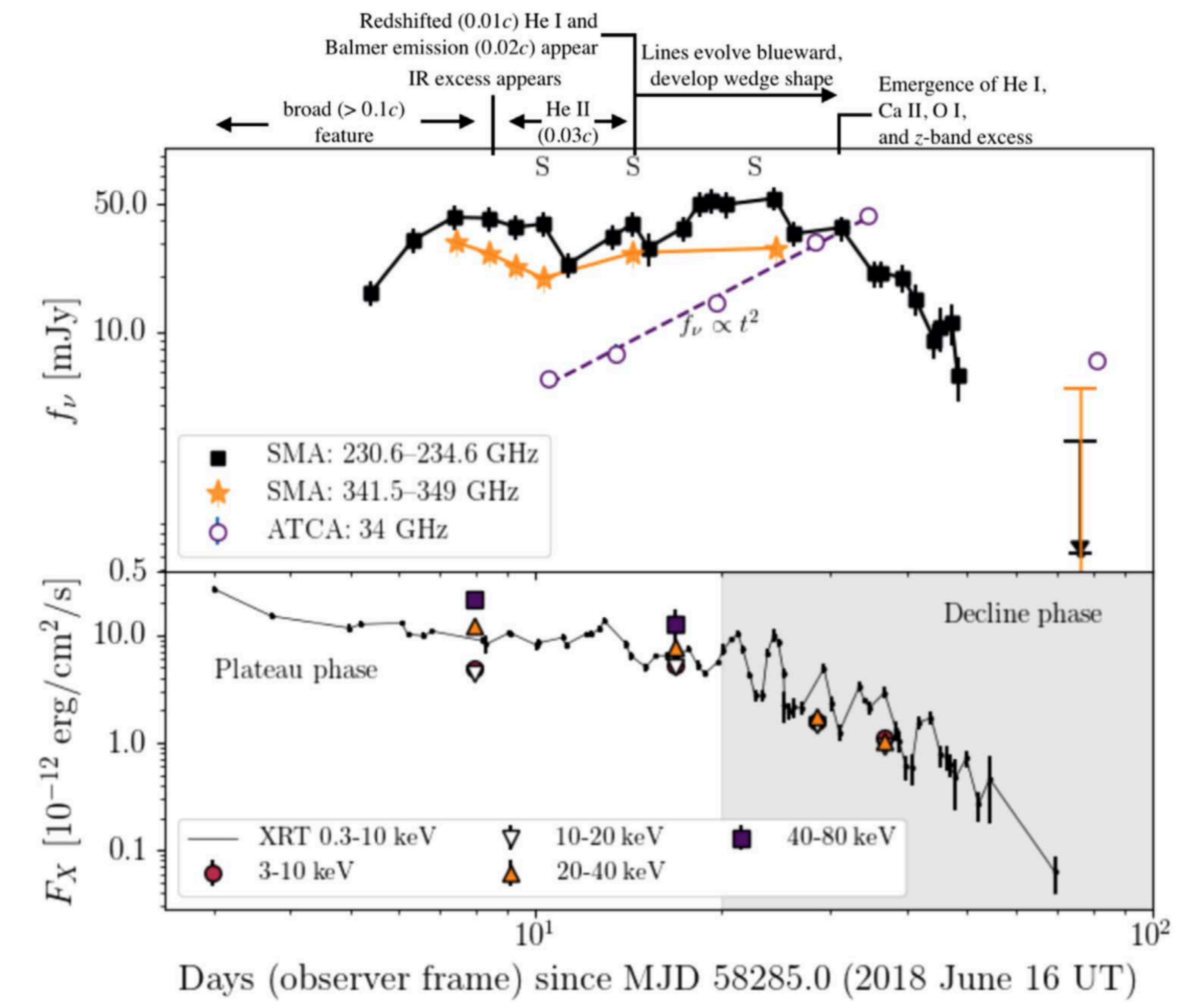


Neutron stars

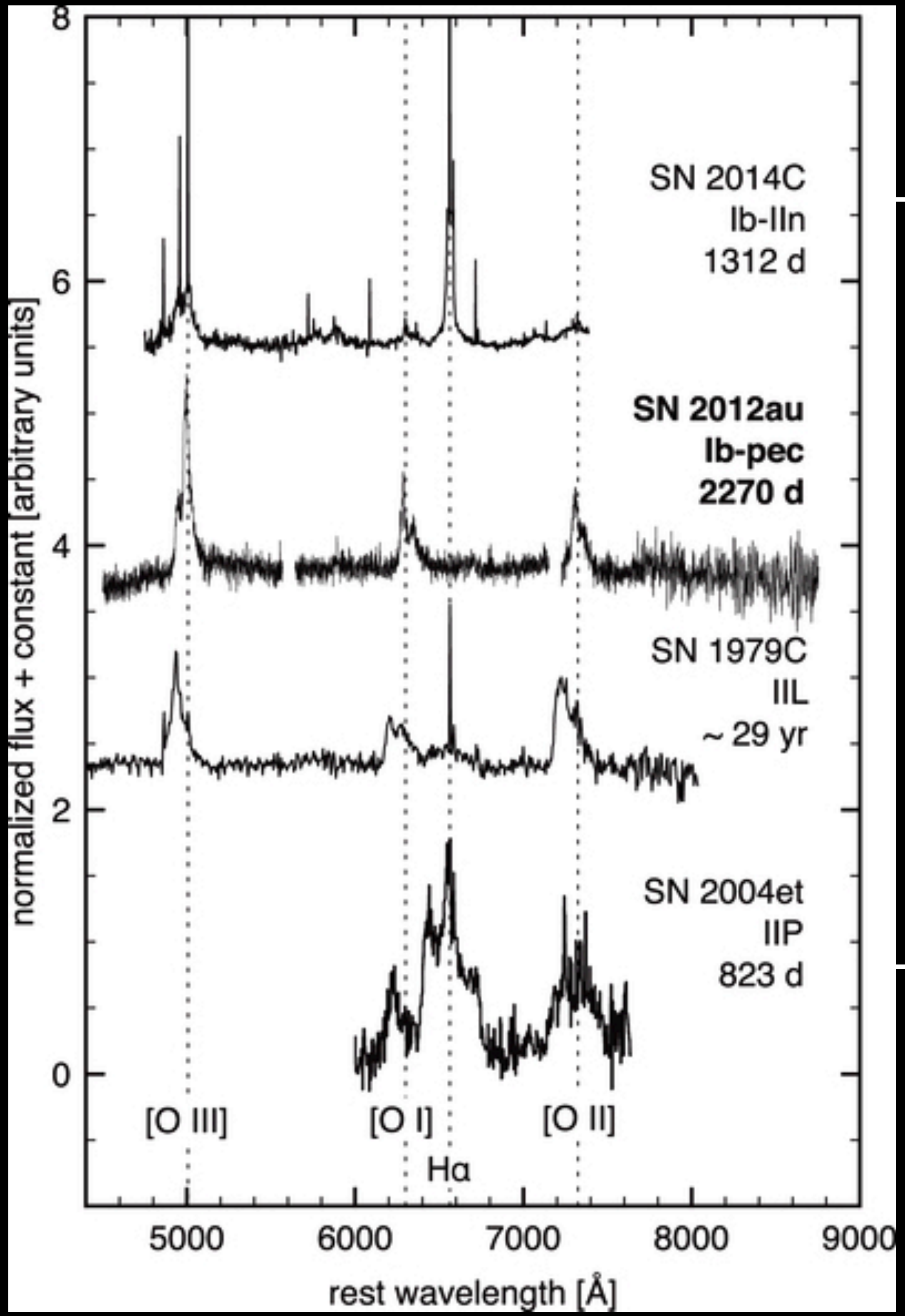
Black holes



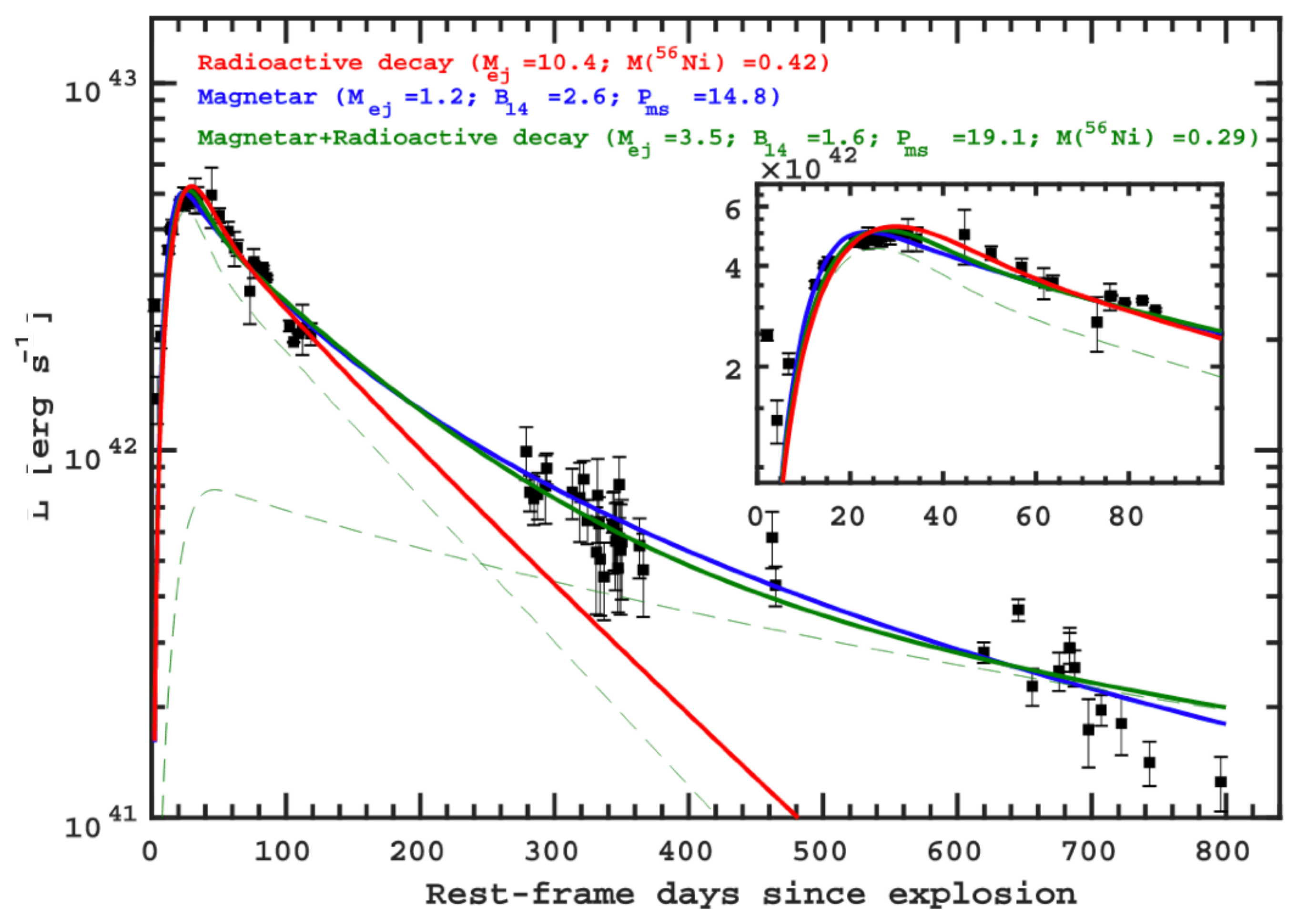
[A1] COMPACT OBJECT FORMATION IN CORE-COLLAPSE SNE



Ho+19: The fast blue optical transient AT2018cow showed evidence of a central engine emerging during its decline phase.

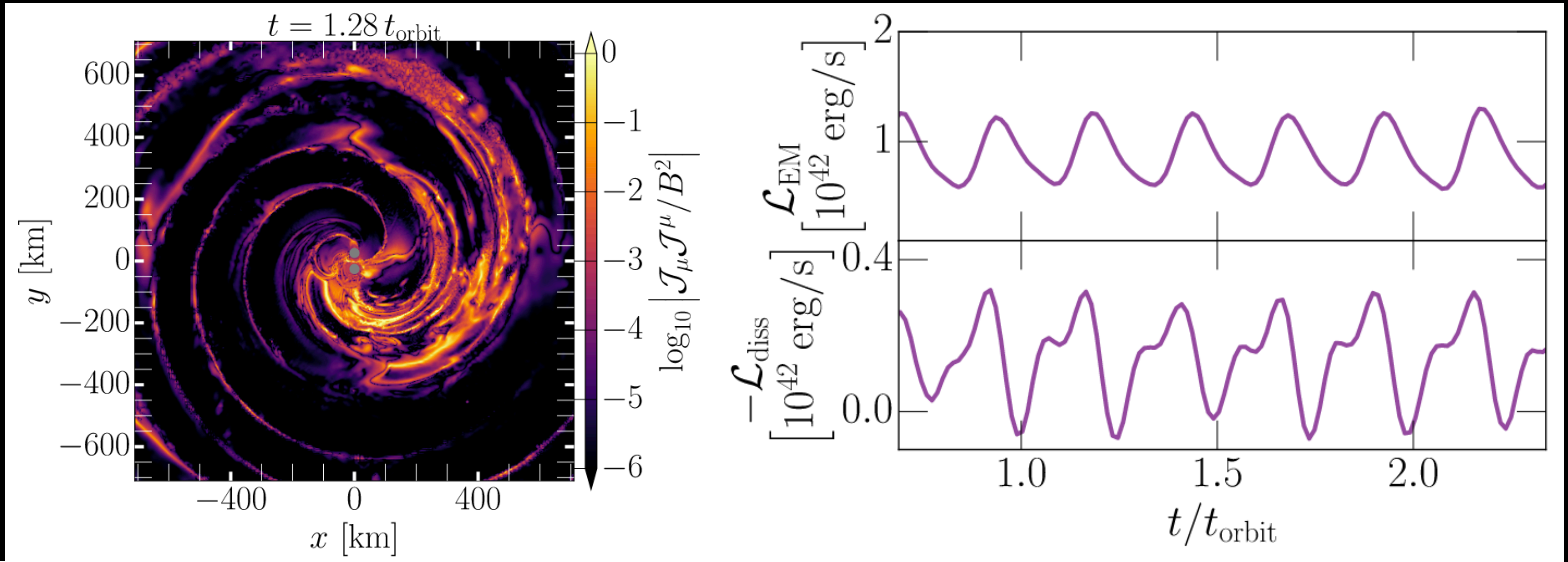


Milisavljevic+17: energetic SN 2012au (Ib) shows broad lines at late times with no interaction signatures. Consistent with expectation from magnetar central engine.



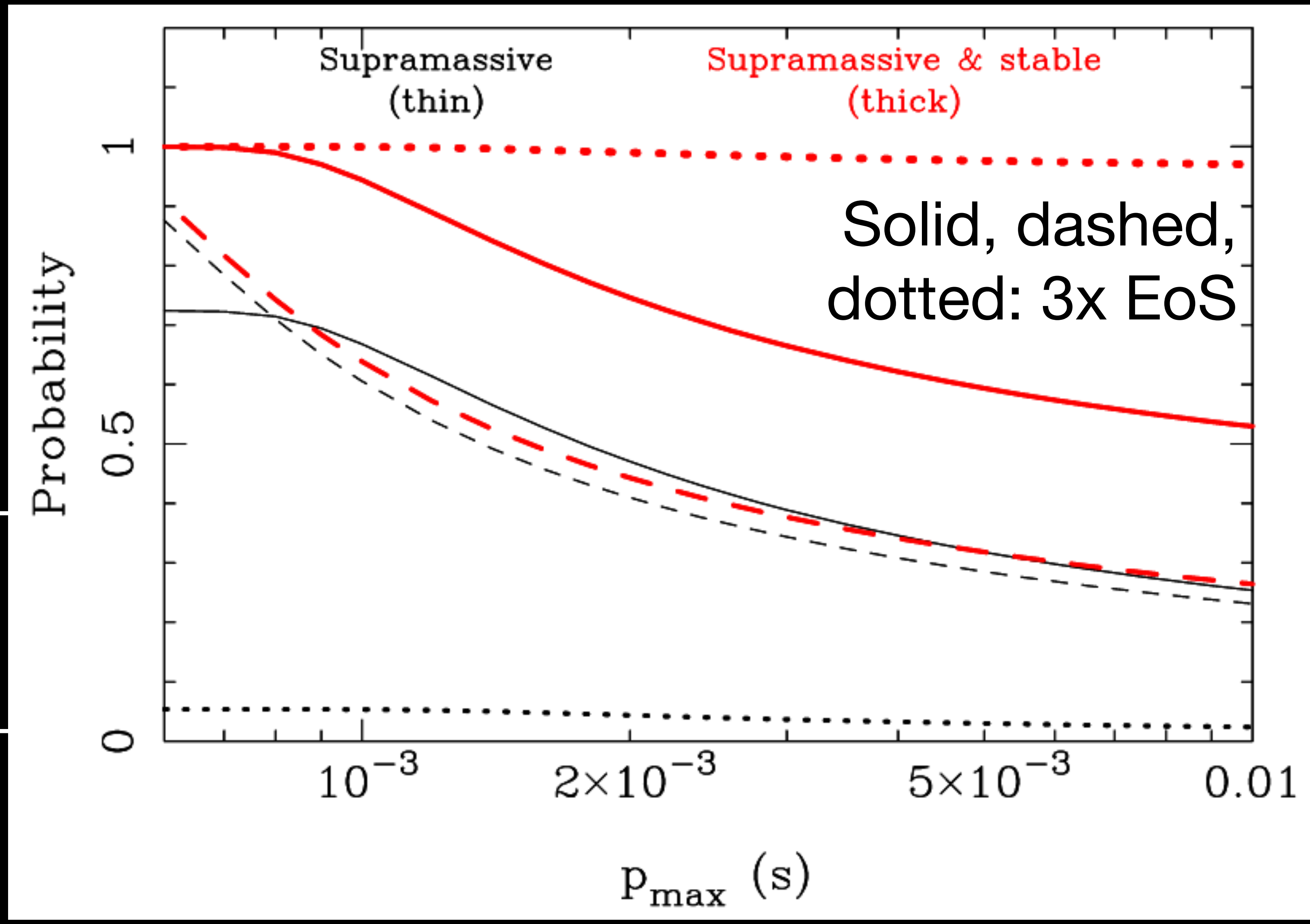
Taddia+19: Ic SN iPTF15dtg lightcurve possibly powered by energy injection from magnetar.

[A2] OUTCOMES OF NS-NS AND NS-BH MERGERS

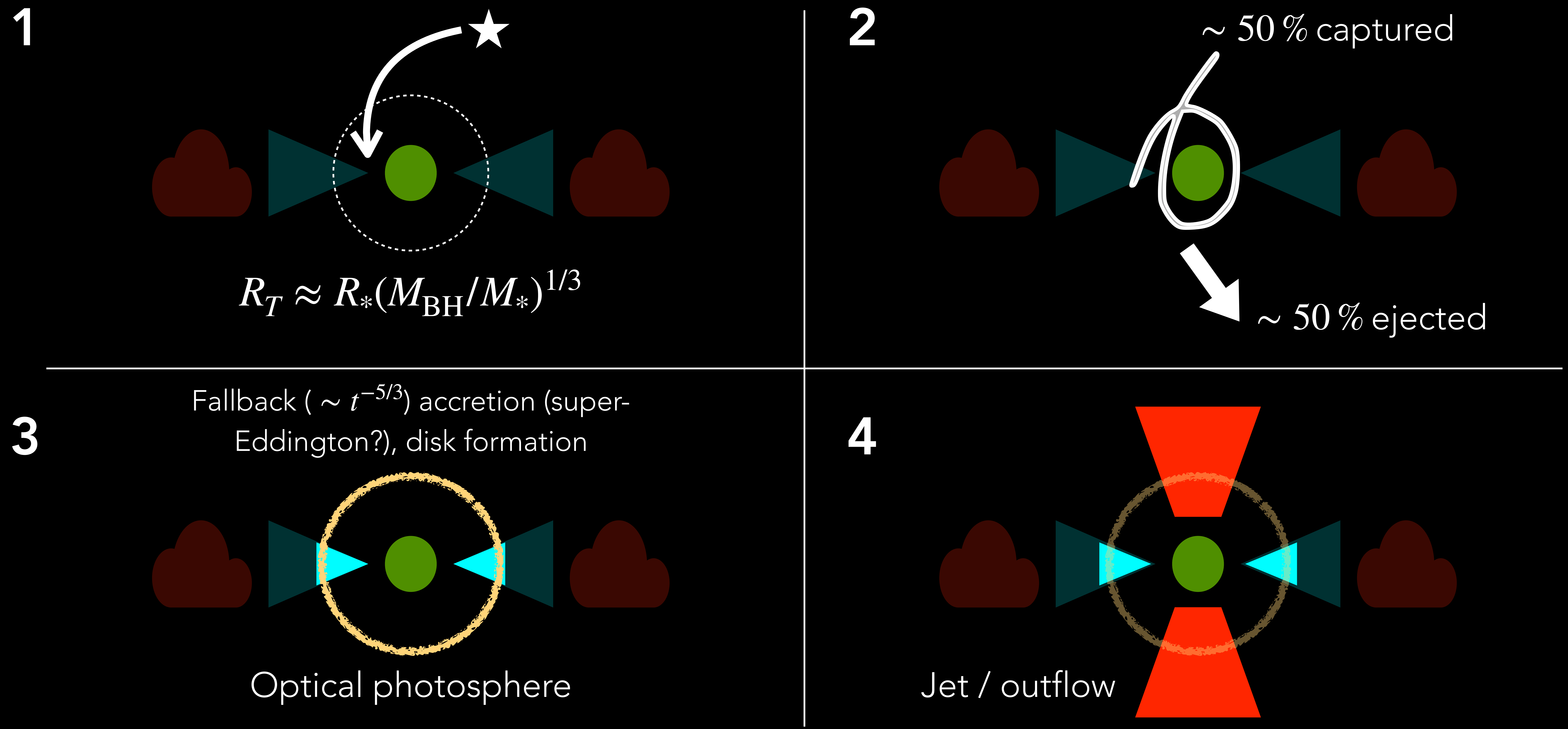


Most & Philippov 22: Reconnection in magnetospheres of NS-NS mergers can give rise to repeated sub-ms transients at frequencies of tens of GHz. Possible cm/mm-wavelength counterpart of NS-NS mergers

Ravi & Lasky 14: Identifying the outcomes of NS-NS mergers is a sensitive probe of the neutron star EoS.



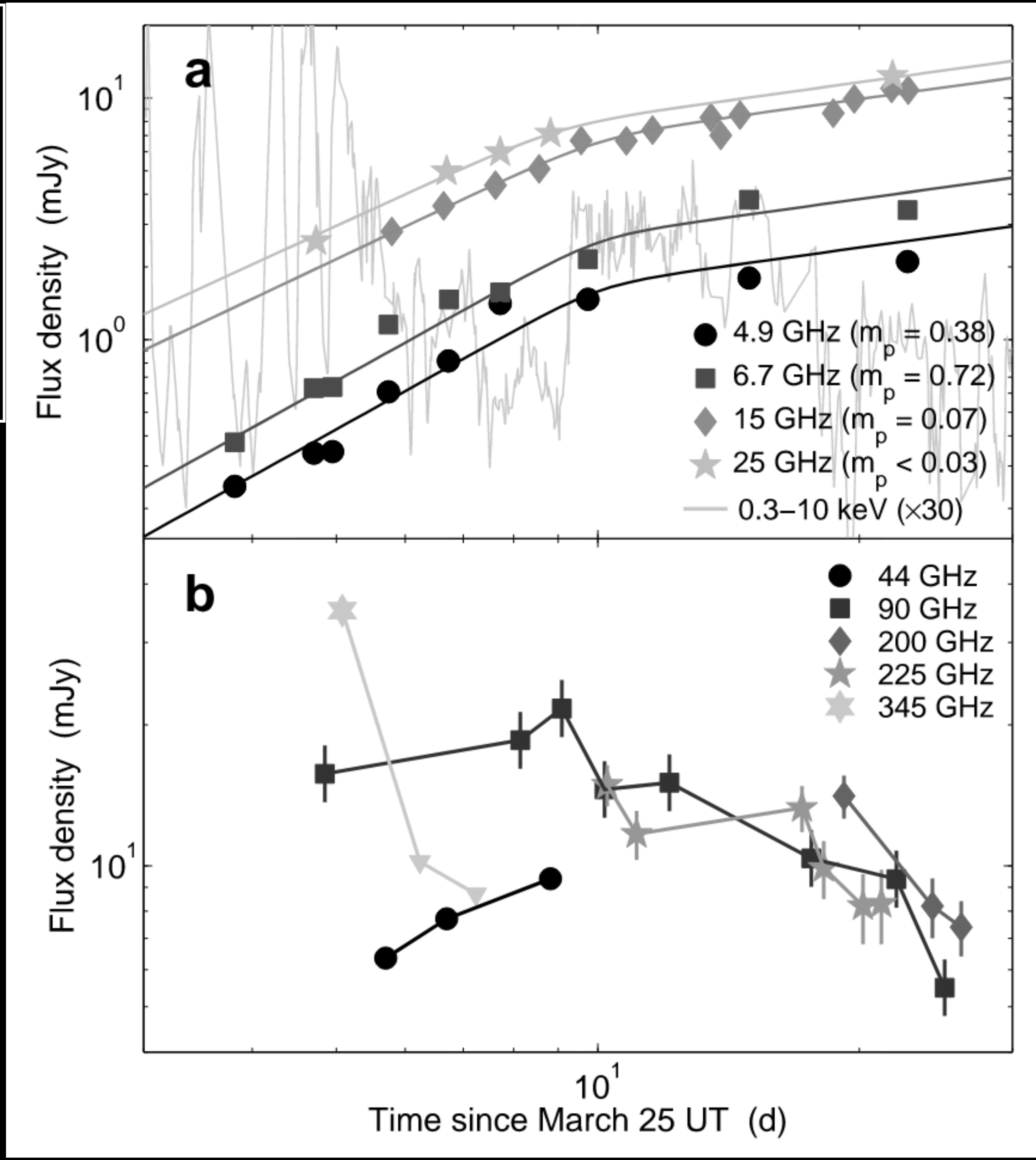
[B1] TRANSIENT JETS AND OUTFLOWS FROM SMBHS

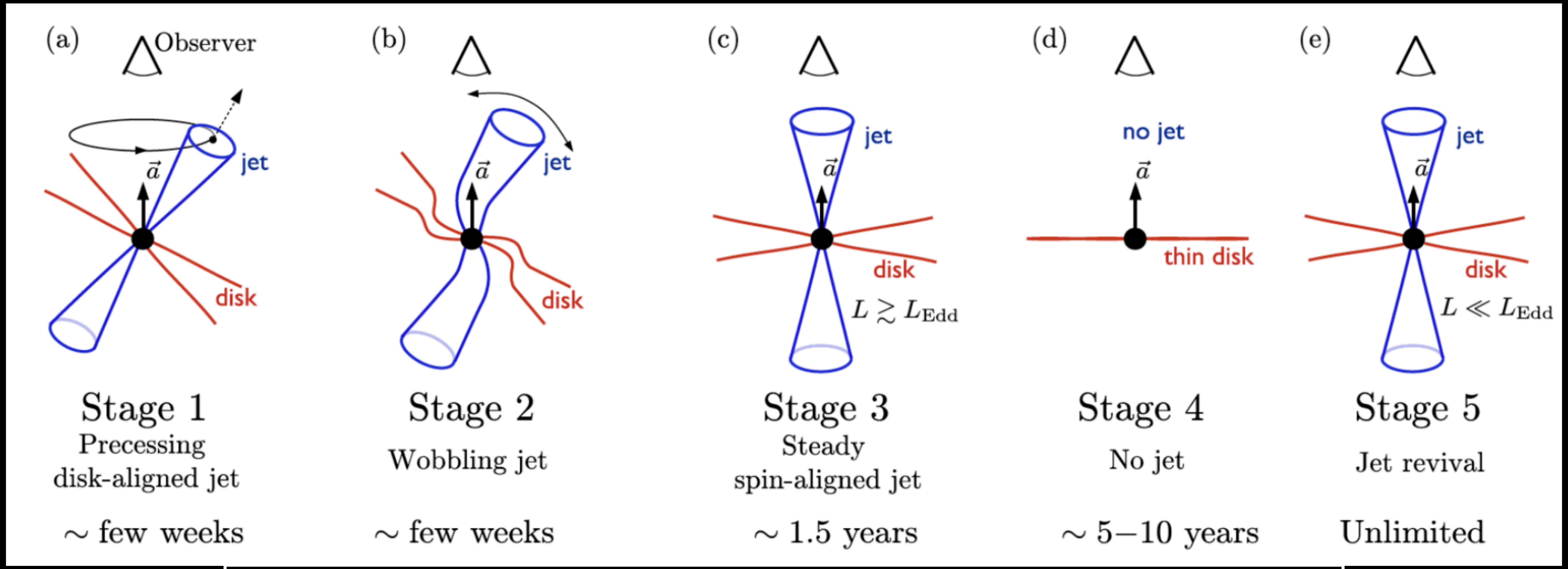


With Jean Somalwar

[B1] TRANSIENT JETS AND OUTFLOWS FROM SMBHS

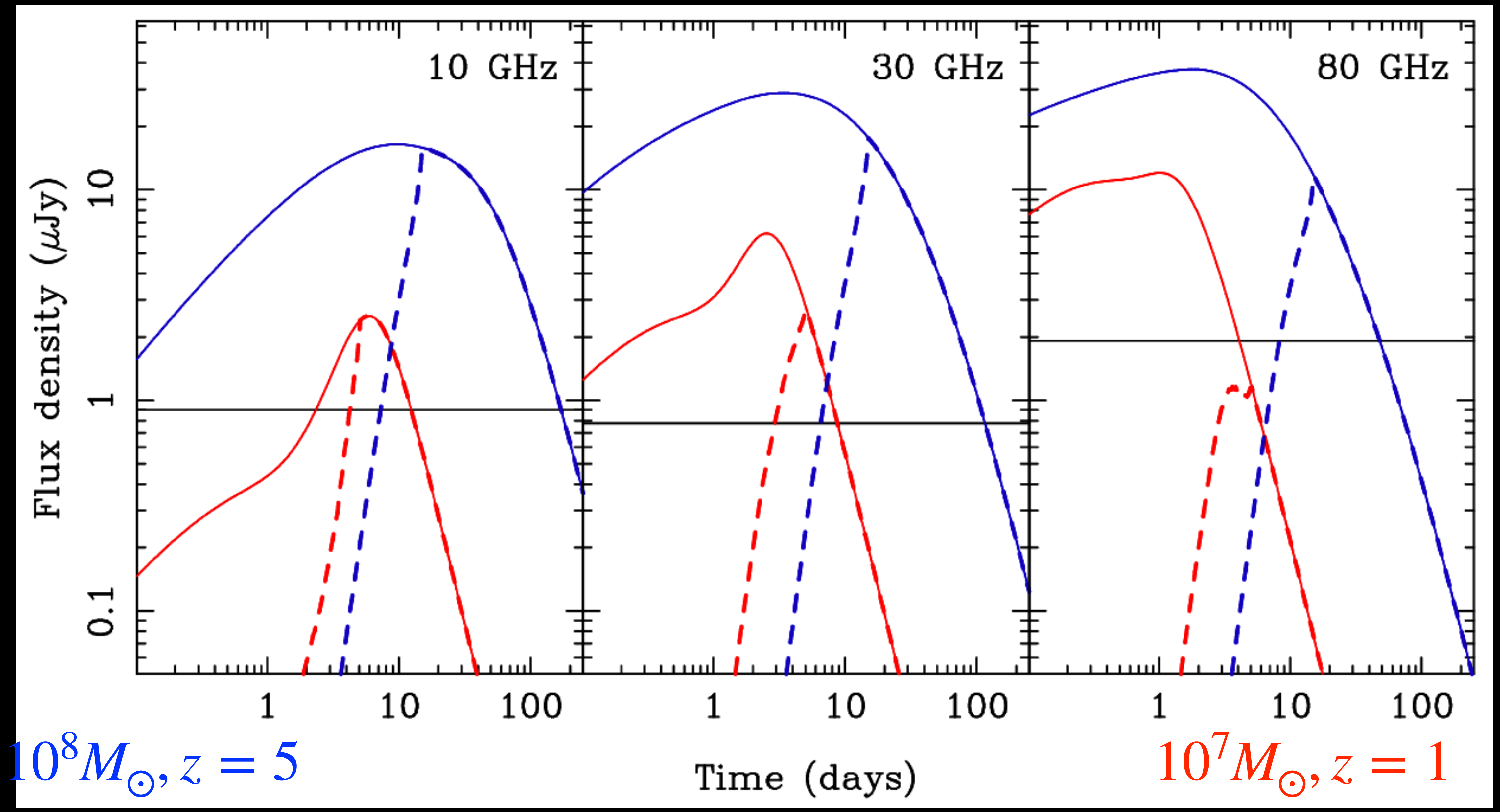
Zauderer+11: cm-mm emission from the relativistic TDE Swift J1644+57. The mm light curves trace the "flickering" of the jet during the early period of apparent super-Eddington accretion. In contrast, the optically thick cm light curves are relatively devoid of information at early times.



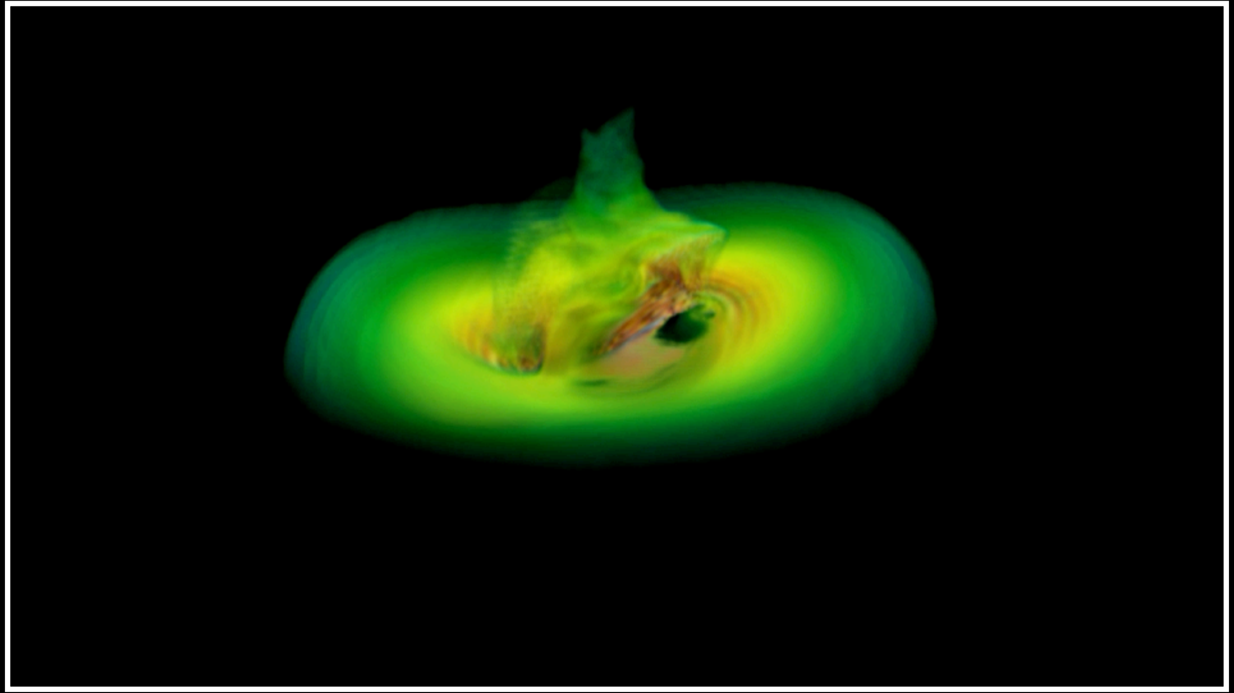


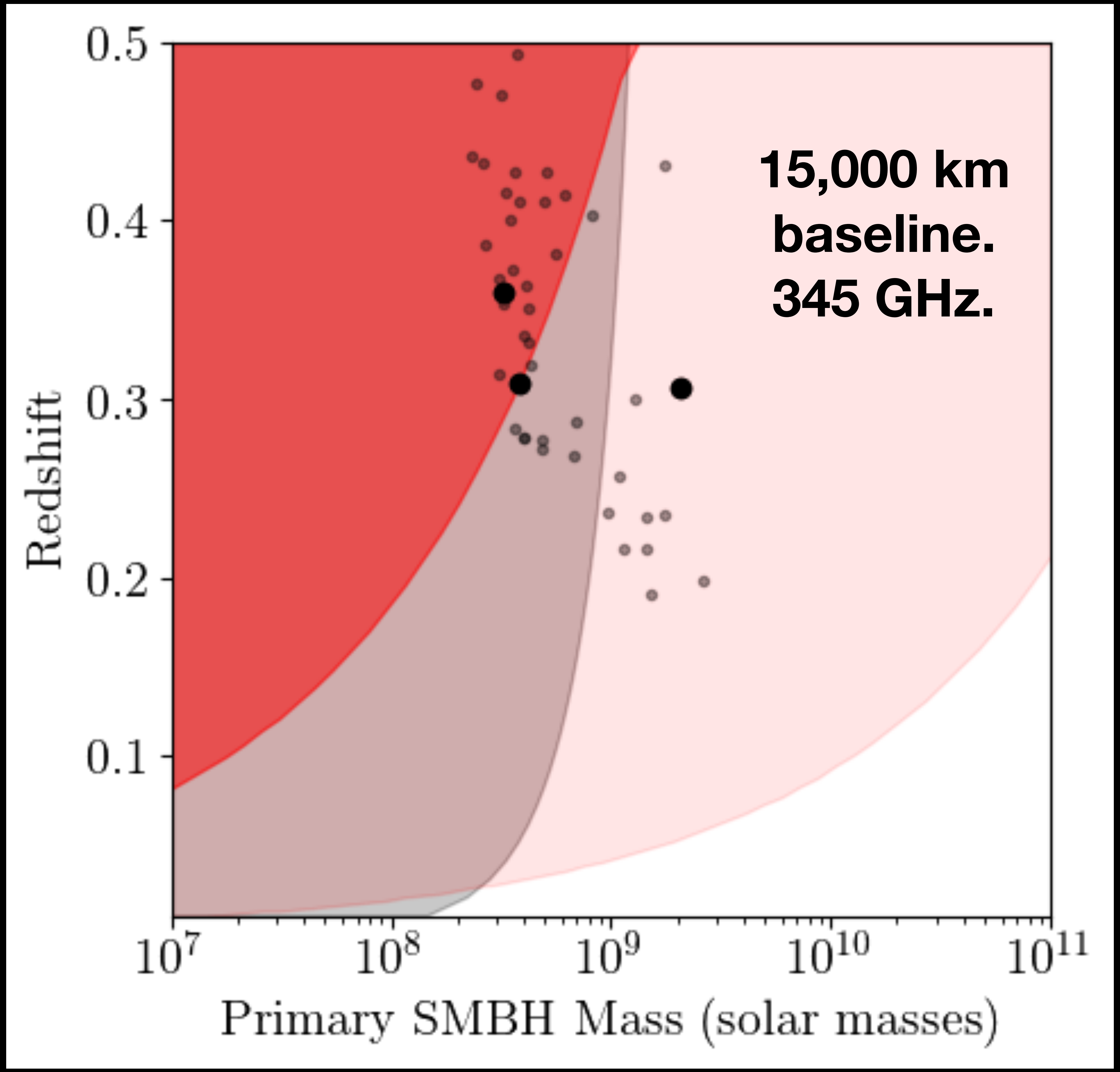
Tchekhovskoy+14: Modeled and predicted jet evolution in Swift J1644+57.

[B2] EM COUNTERPARTS TO SMBH MERGERS



LISA-discovered SMBH-SMBH mergers will be best localized through transient radio emission.

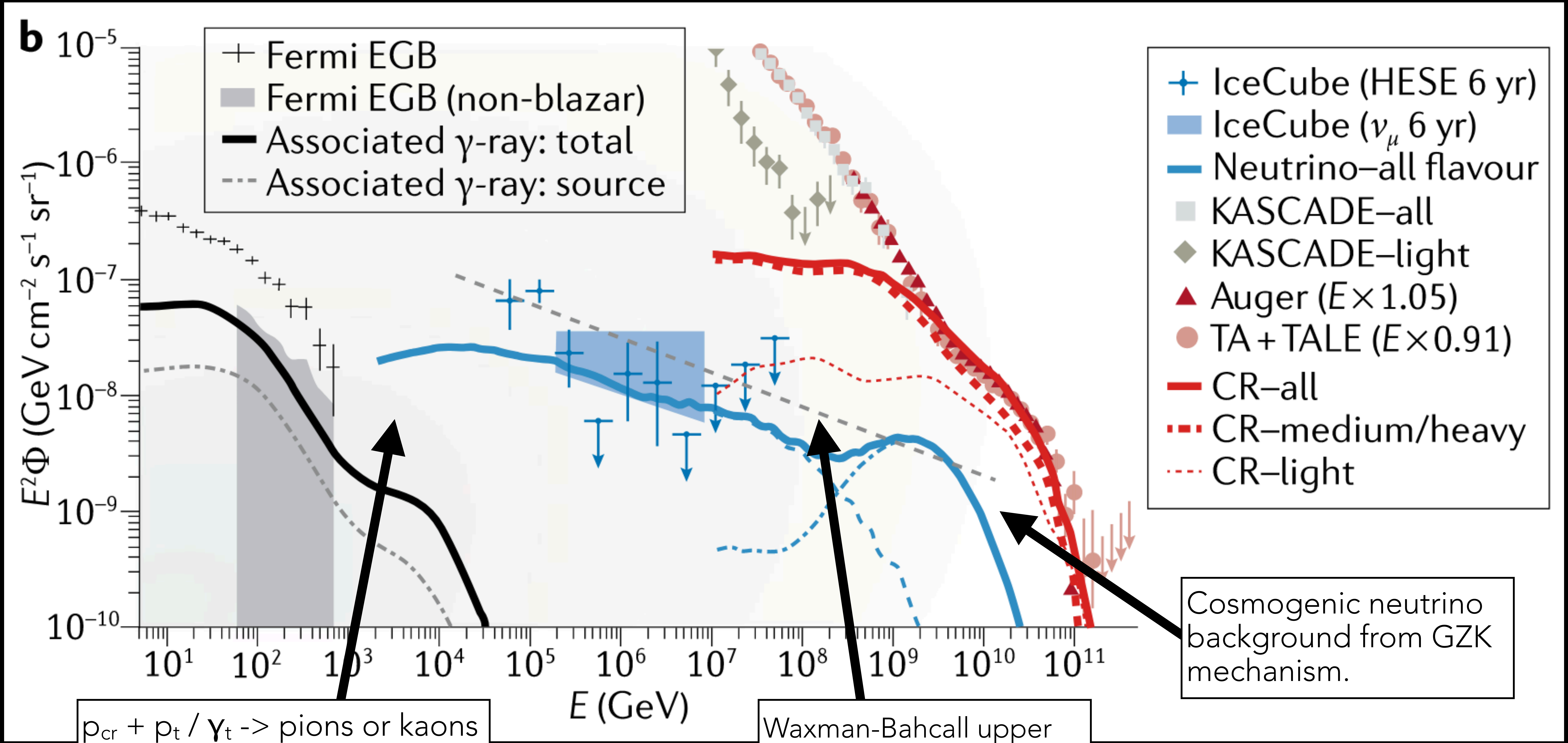




PTA sources can be resolved with mm space-VLBI on lunar baselines.

Giacomazzo+12, Ravi18

[C] PARTICLE ACCELERATION: UNIFICATION?

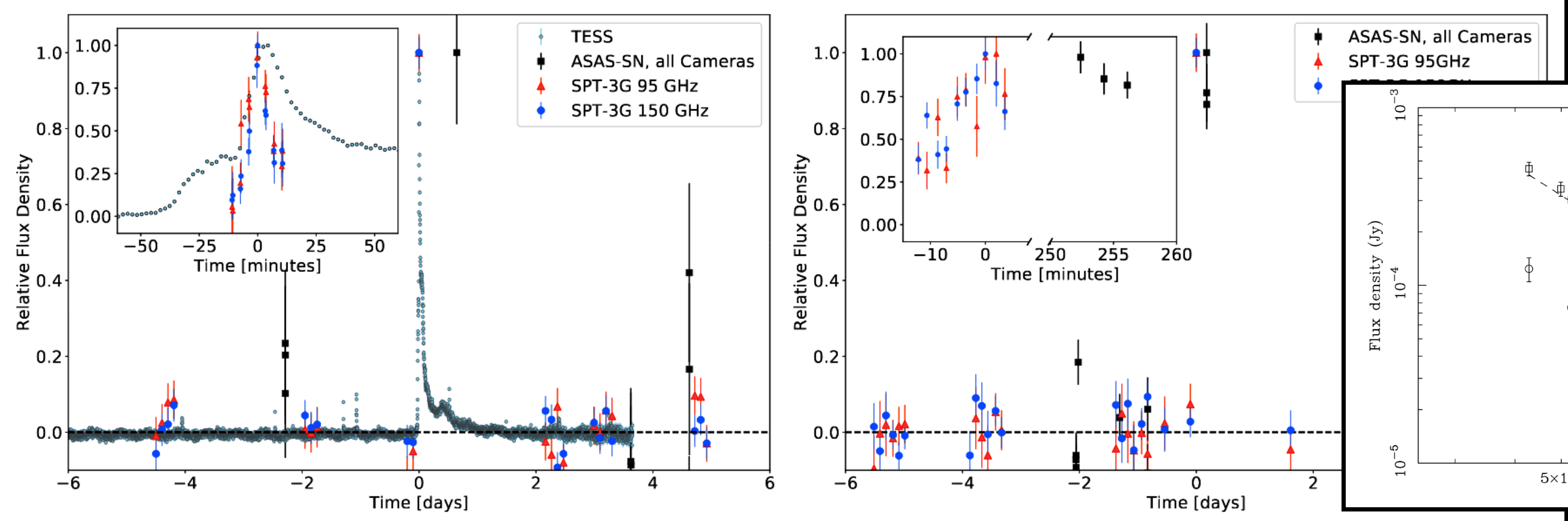


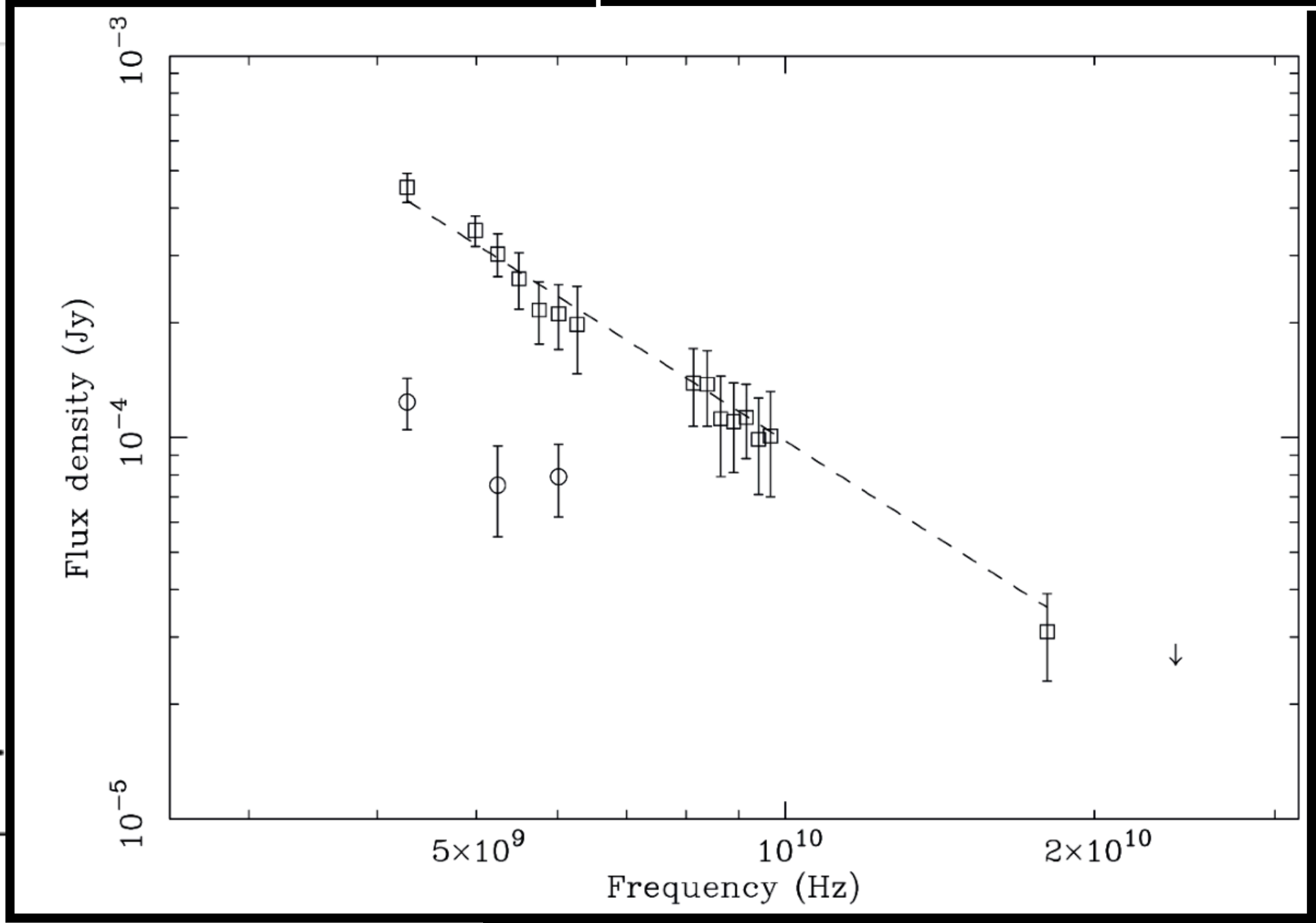
$p_{cr} + p_t$ / γ_t -> pions or kaons -> ~10% of CR energy in neutrinos and gamma-rays.

Meszaros+19

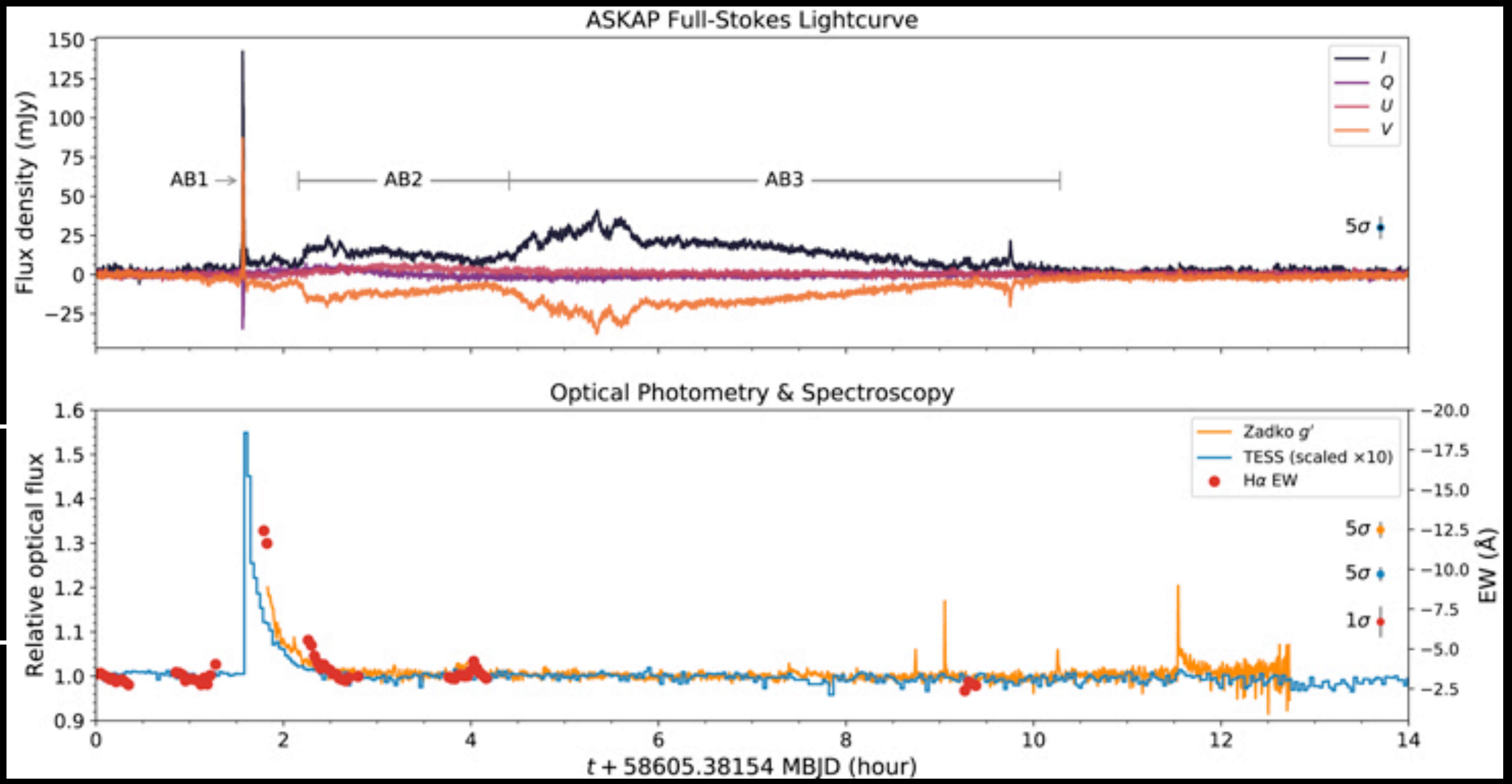
[C1] PARTICLE ACCELERATION: ACTIVE STARS

Ravi+11: Power-law emission from ultra cool dwarf -> particle acceleration at co-rotation breakdown.





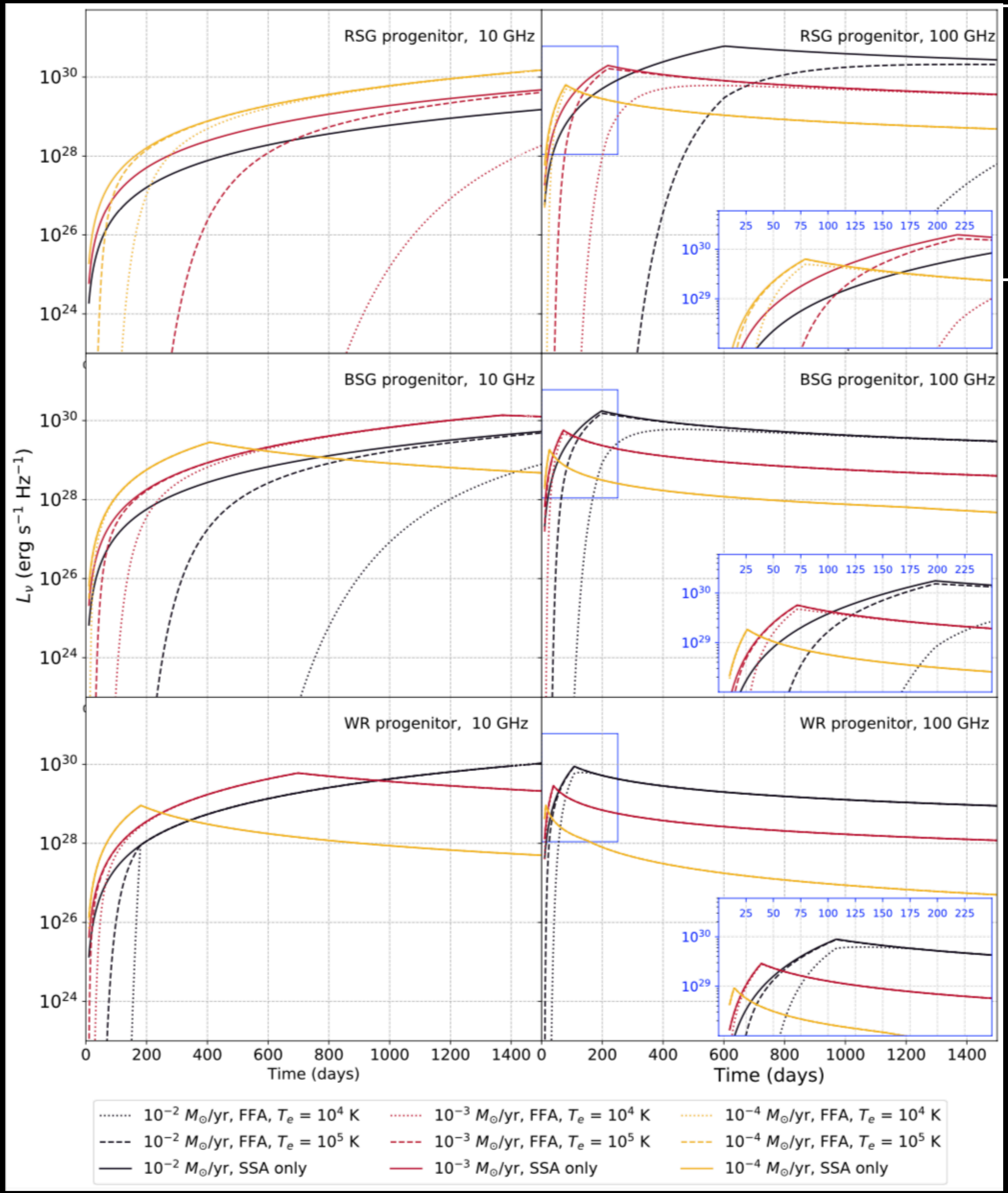
Guns+21: Remarkable sample of 13 millimeter-wavelength flares from 8 stars with luminosities exceeding anything known so far. Emission and particle-acceleration mechanisms are unclear.



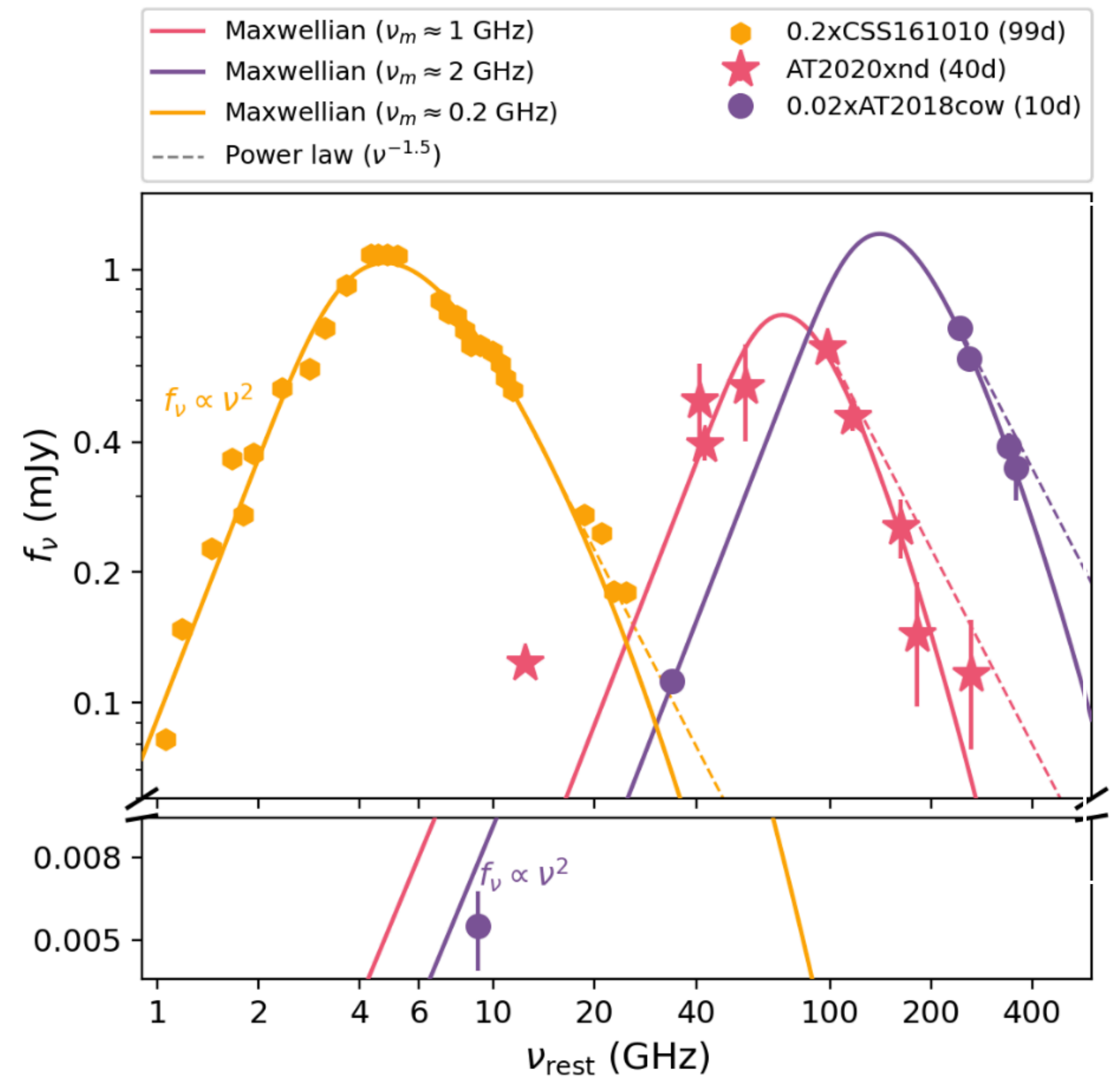
Zic+20: Type IV analog radio burst from Proxima Cen coincident with optical flare, indicative of CME.

With Nitika Yadlapalli

[C2] PARTICLE ACCELERATION: SUPERNOVAE

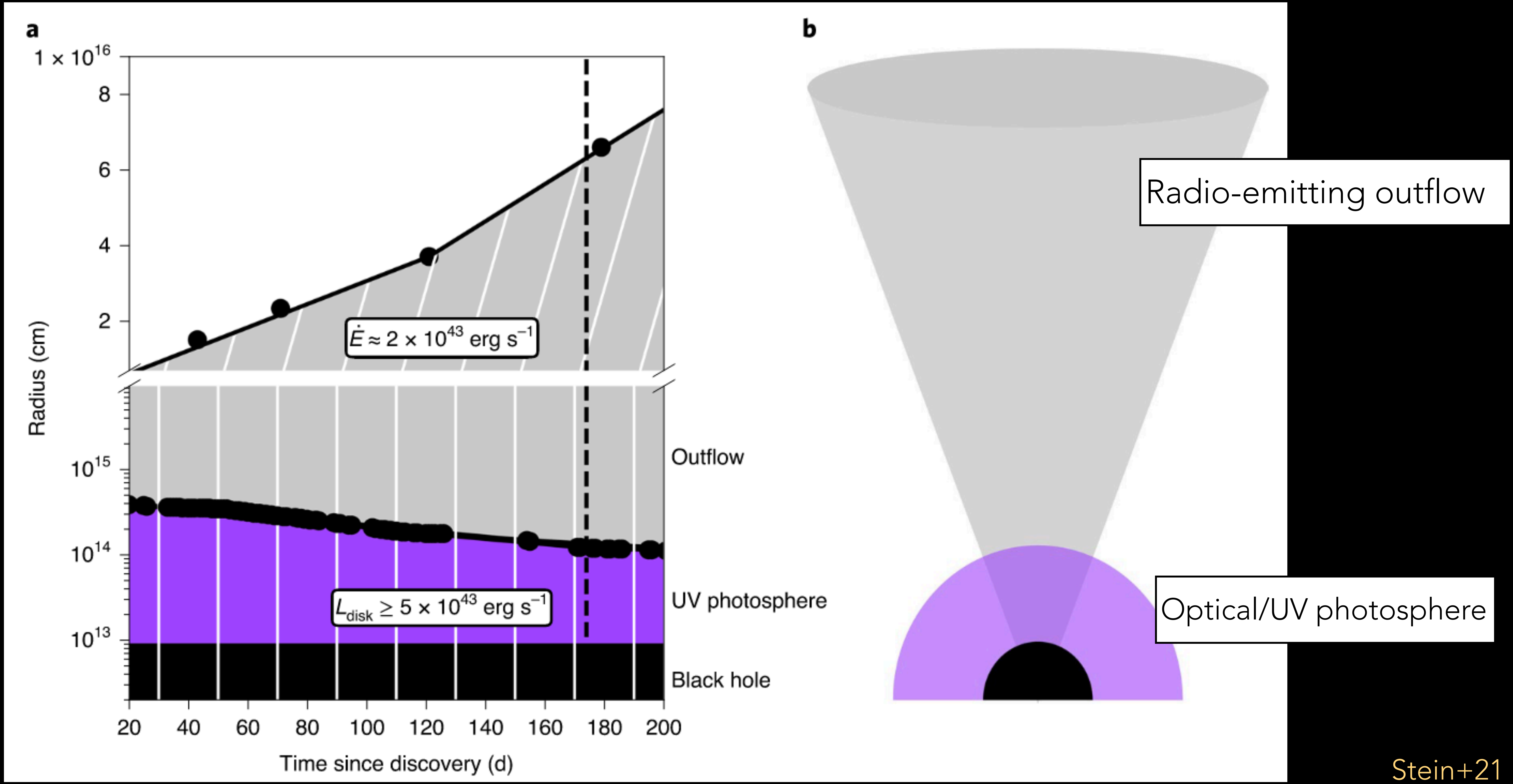


Yadlapalli+22: Ubiquitous detectability of Type IIn supernovae at millimetre wavelengths, despite free-free absorption of cm afterglow emission. Probes shock evolution closest to explosions in dense environments.



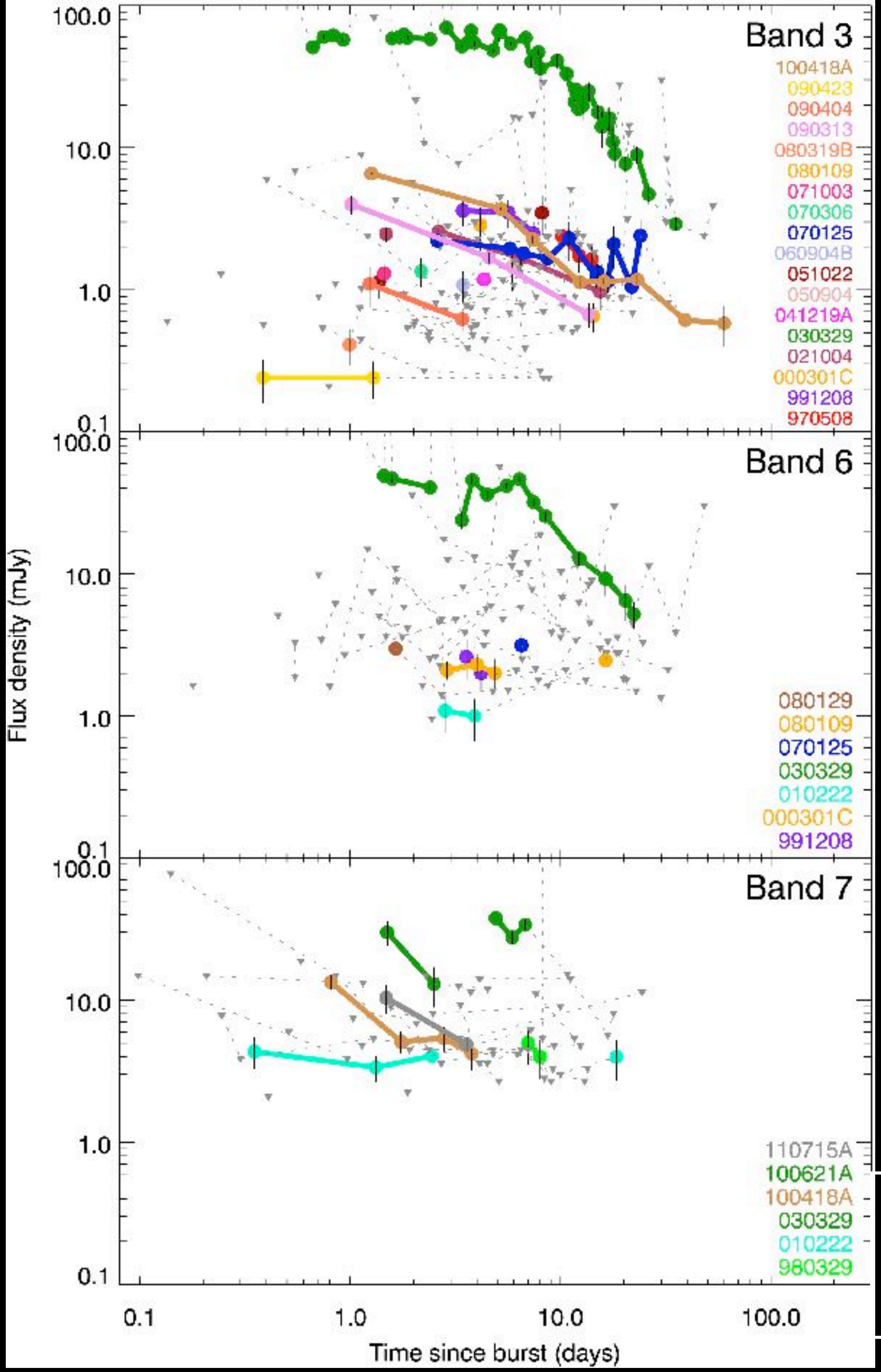
Ho+21: Relativistic Maxwellian electron energy distributions in fast blue optical transients. Why are these events different from normal supernovae?

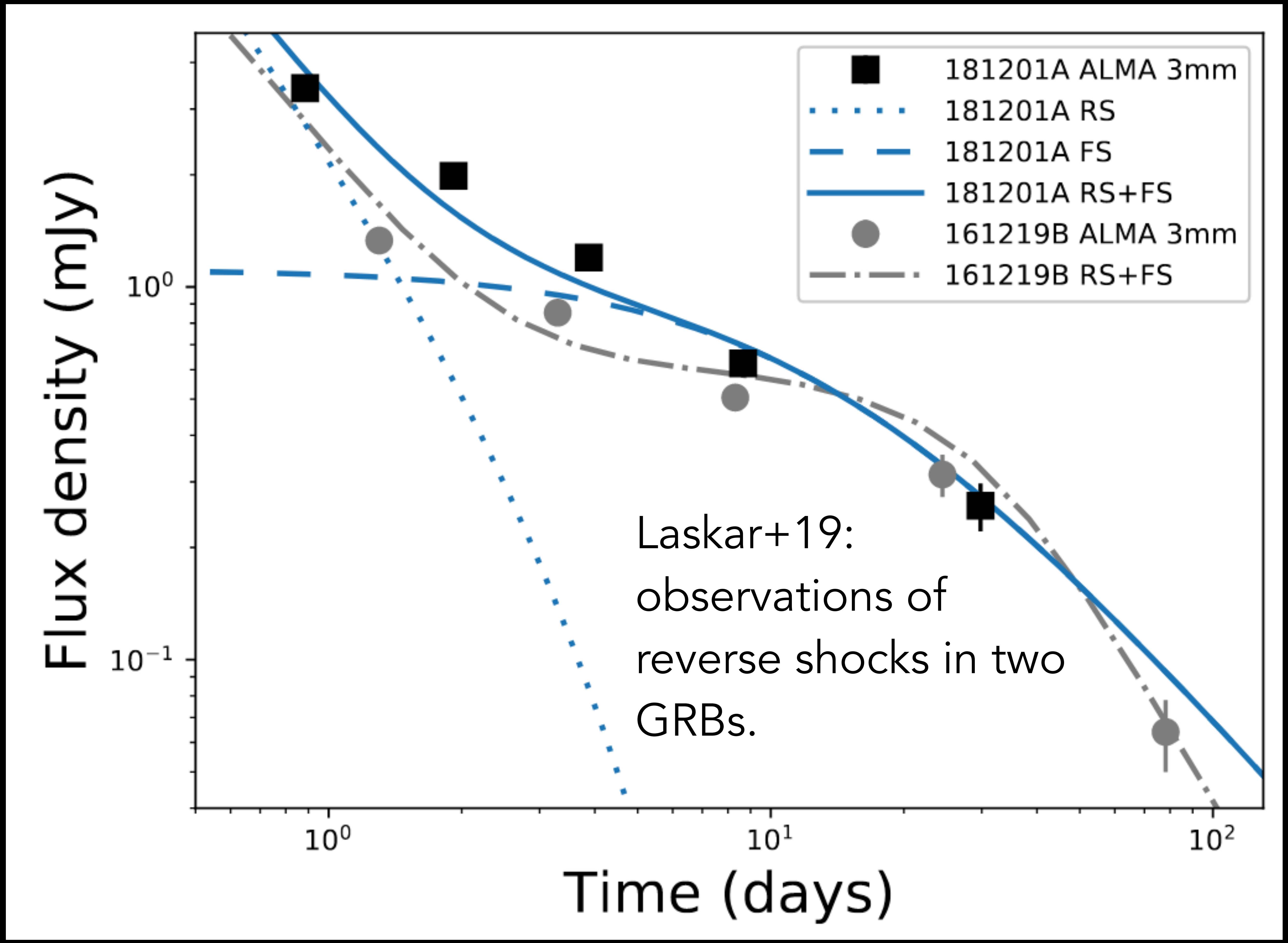
[C3] PARTICLE ACCELERATION: NEUTRINO EMISSION FROM A TDE?



Stein+21

[C4] PARTICLE ACCELERATION: GRB JETS





Laskar+19: observations of reverse shocks in two GRBs.

de Ugarte Postigo +12: Compilation of pre-ALMA mm detections and upper limits on GRBs. Note the large number of upper limits…

THIS IS ALL REALLY HARD!

- **Background transients / variables.**
  - *Is there a gigantic stellar foreground?*
  - *How to place CMB-S4 observations in the context of a transient population?*
  - *Localization accuracy and host identification for a large sample.*
- **Time resolution and cadence.**
  - *There will be no universally acceptable cadence.*
  - *Sensitivity to fast transients.*
- **Frequency, temporal, and spatial agility.**
  - *SEDs peaking anywhere in (and beyond) the CMB-S4 bands.*
  - *ToOs?*

BUT IT IS WORTHWHILE

A. **How are different flavors of black holes and neutron stars formed and destroyed?**
   1. *Watching BH and NS formation in core-collapse supernovae, including GRB-like events.*
   2. *What are the outcomes of NS-NS and NS-BH mergers?*

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   1. *Under what circumstances do SMBHs launch jets / relativistic outflows?*
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