AST3100 Astrophysical transients

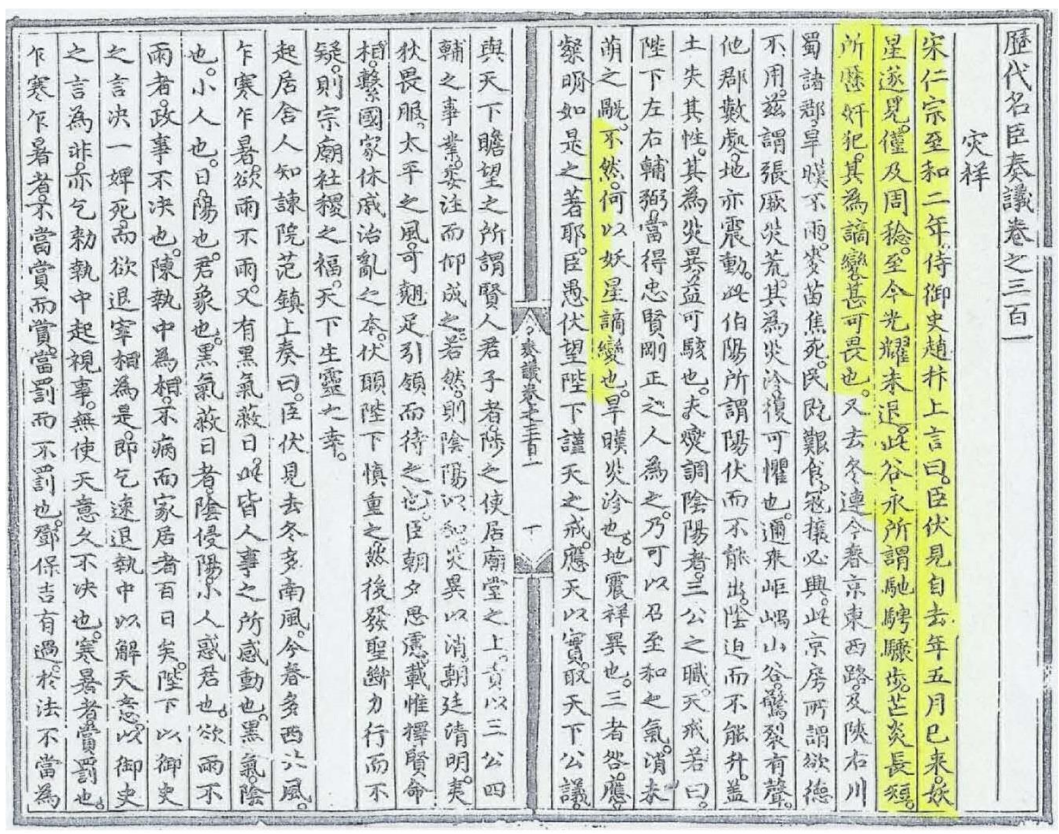
"You don't observe the same Universe twice!"

Ziggy Pleunis
Meeting 1 Week 1
2022 September 12

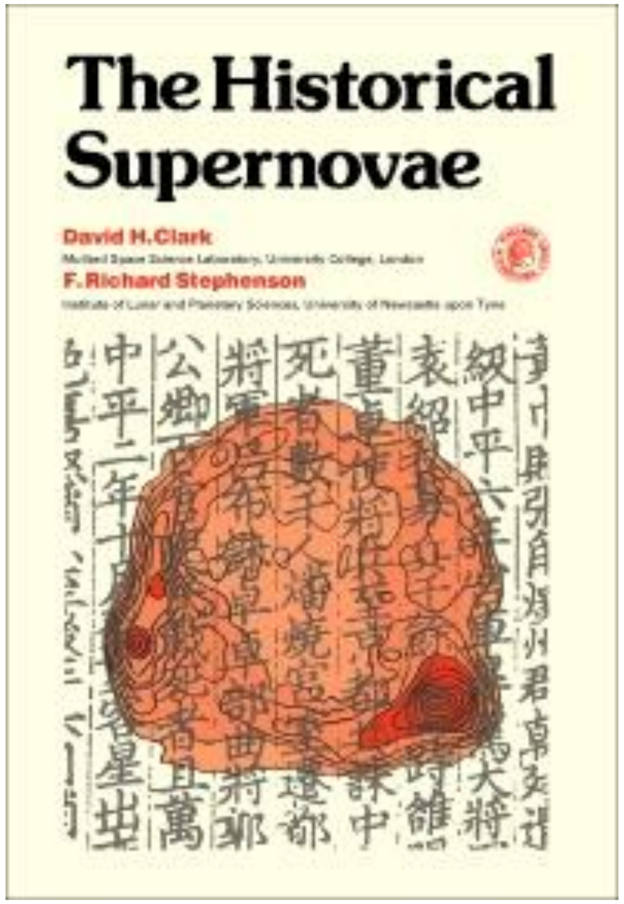
📷 X-ray: NASA/CXC/GSFC/ B.Williams et al; Optical: DSS

“Guest stars” or “new stars”

Records from Egypt, Iraq, Korea, Japan and other places exist of sightings of supernovae in 1006, 1054, 1572 and 1604 and Chinese recordings of similar events go back to at least the 2nd century

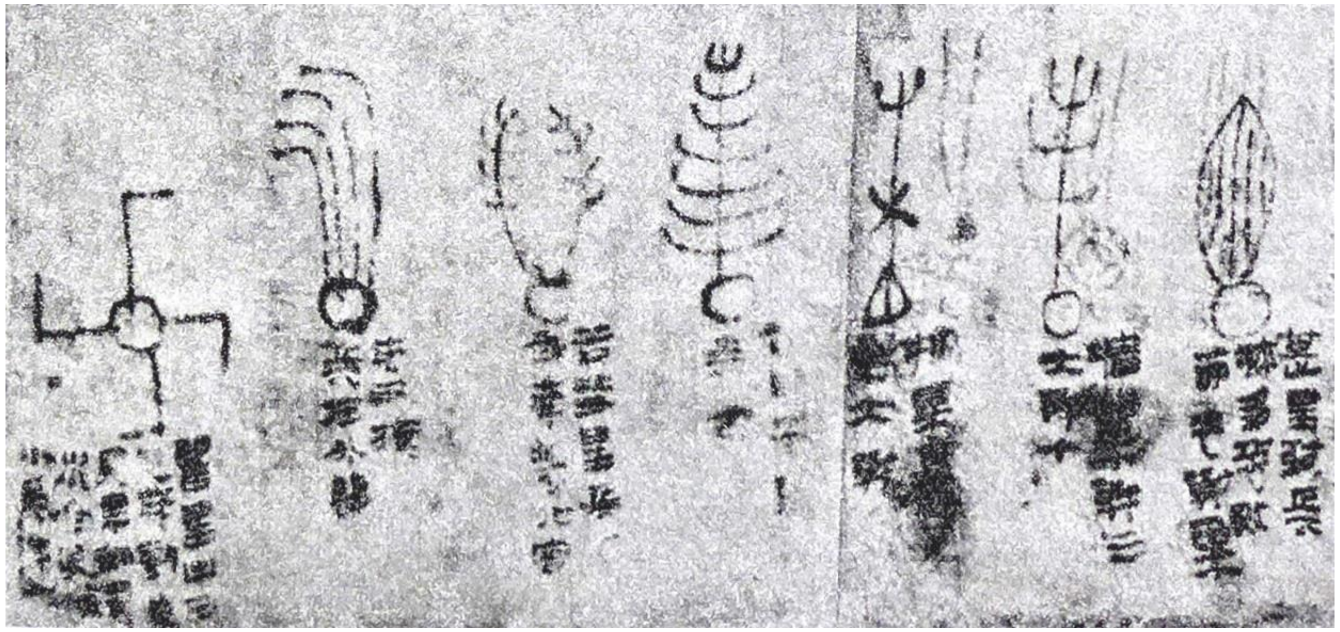


Chinese astronomers reporting Supernova 1054



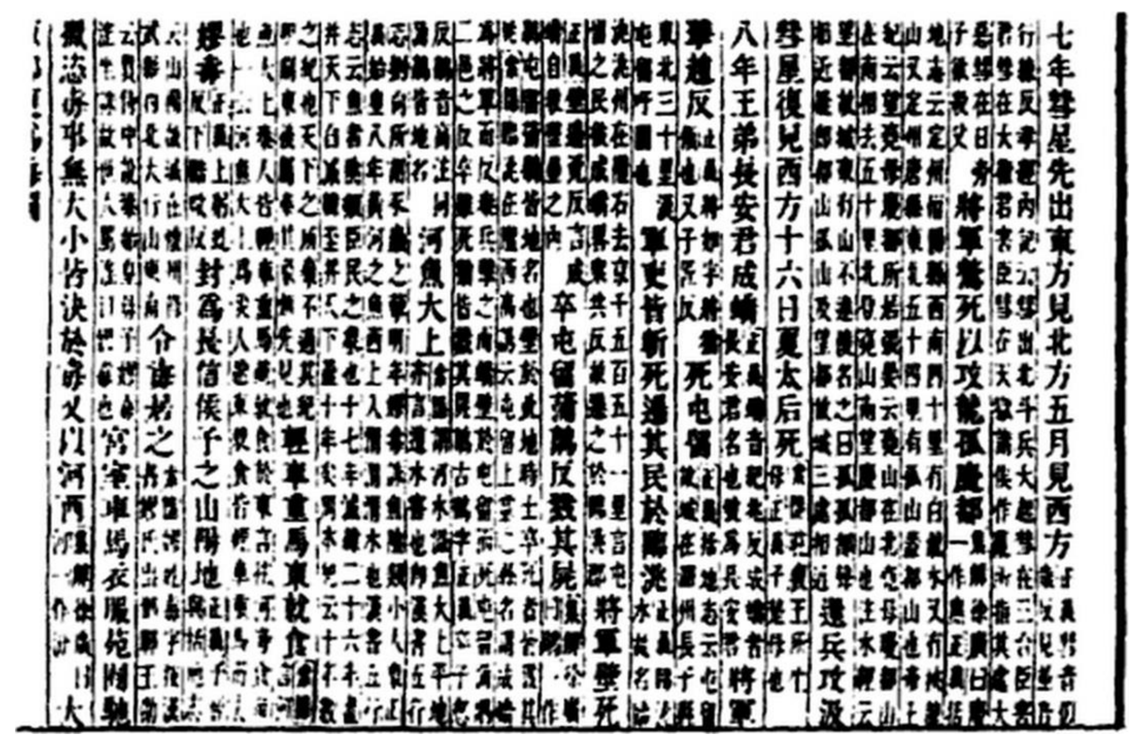
e.g., 📖 Clark & Stephenson, 1977

Comets



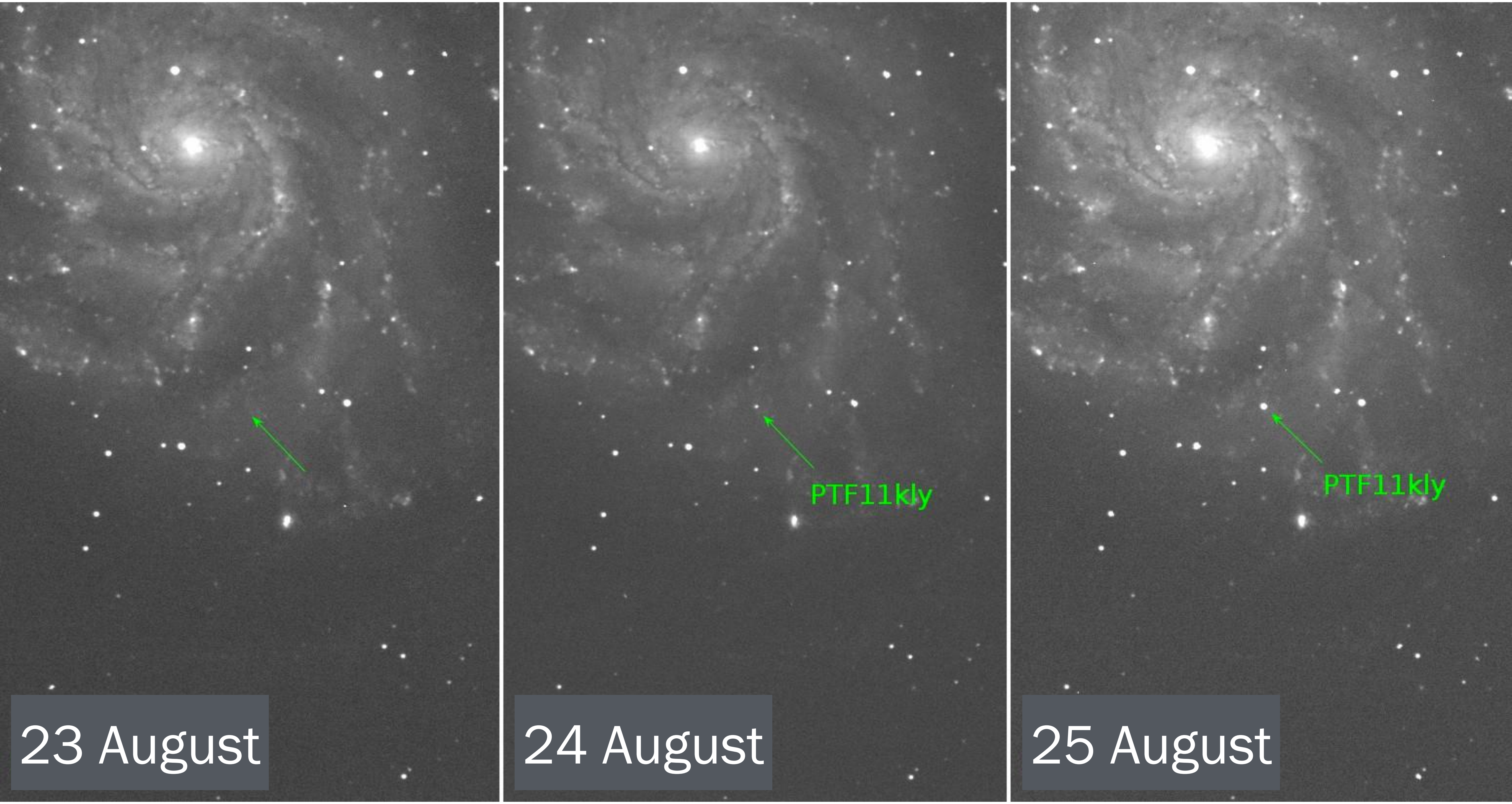
2nd century BC, Han dynasty, unearthed from Mawangdui tomb

Earliest confirmed Chinese comet observation is from 613 BC



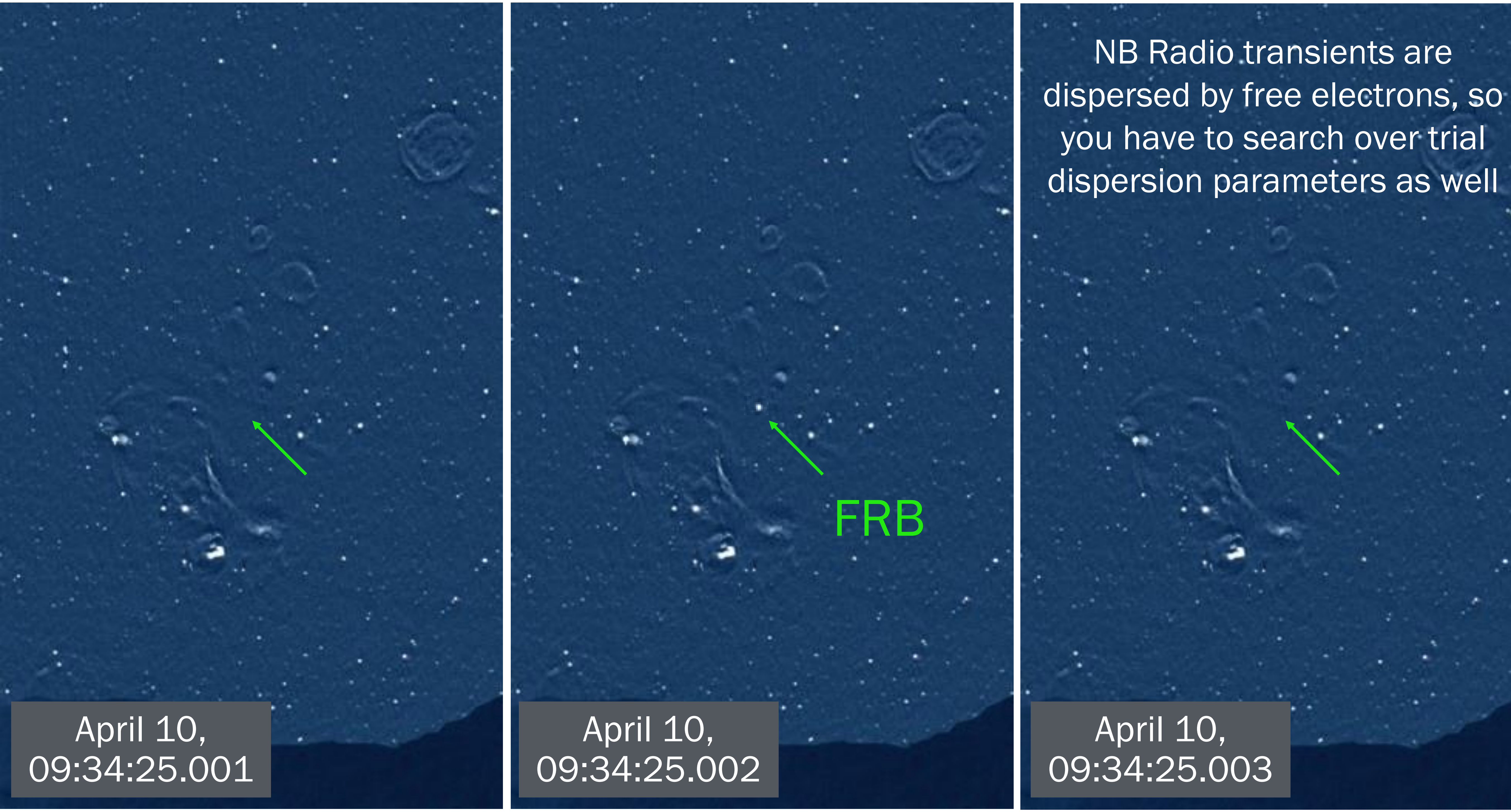
Report of the 240 BC apparition of Halley's [sic] comet from the Shiji (史記)

Spotting a supernova



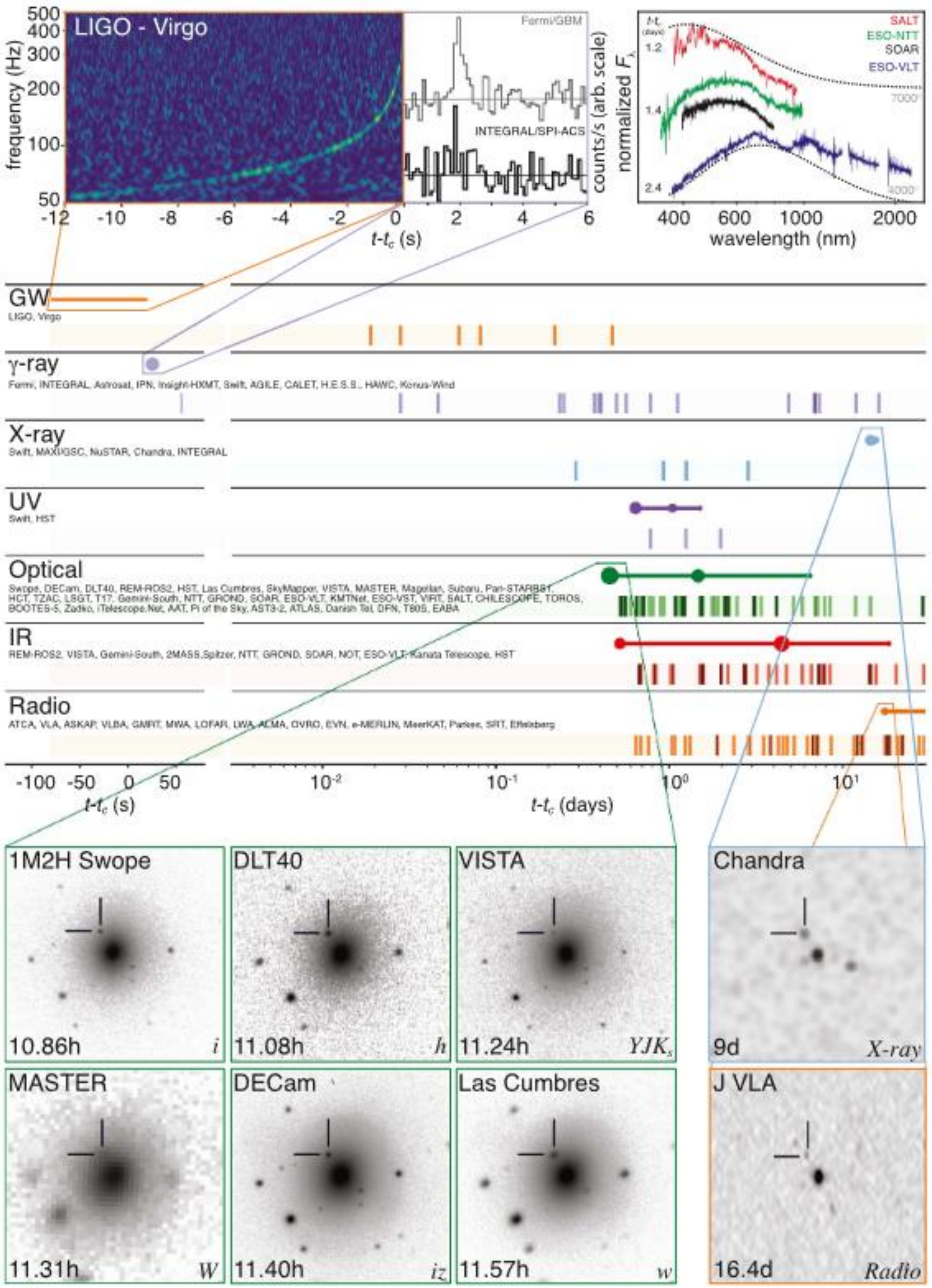
Spotting a fast radio burst (FRB)

$\nu = 4.85$ GHz
$\lambda = 62$ mm



NRAO/AUI

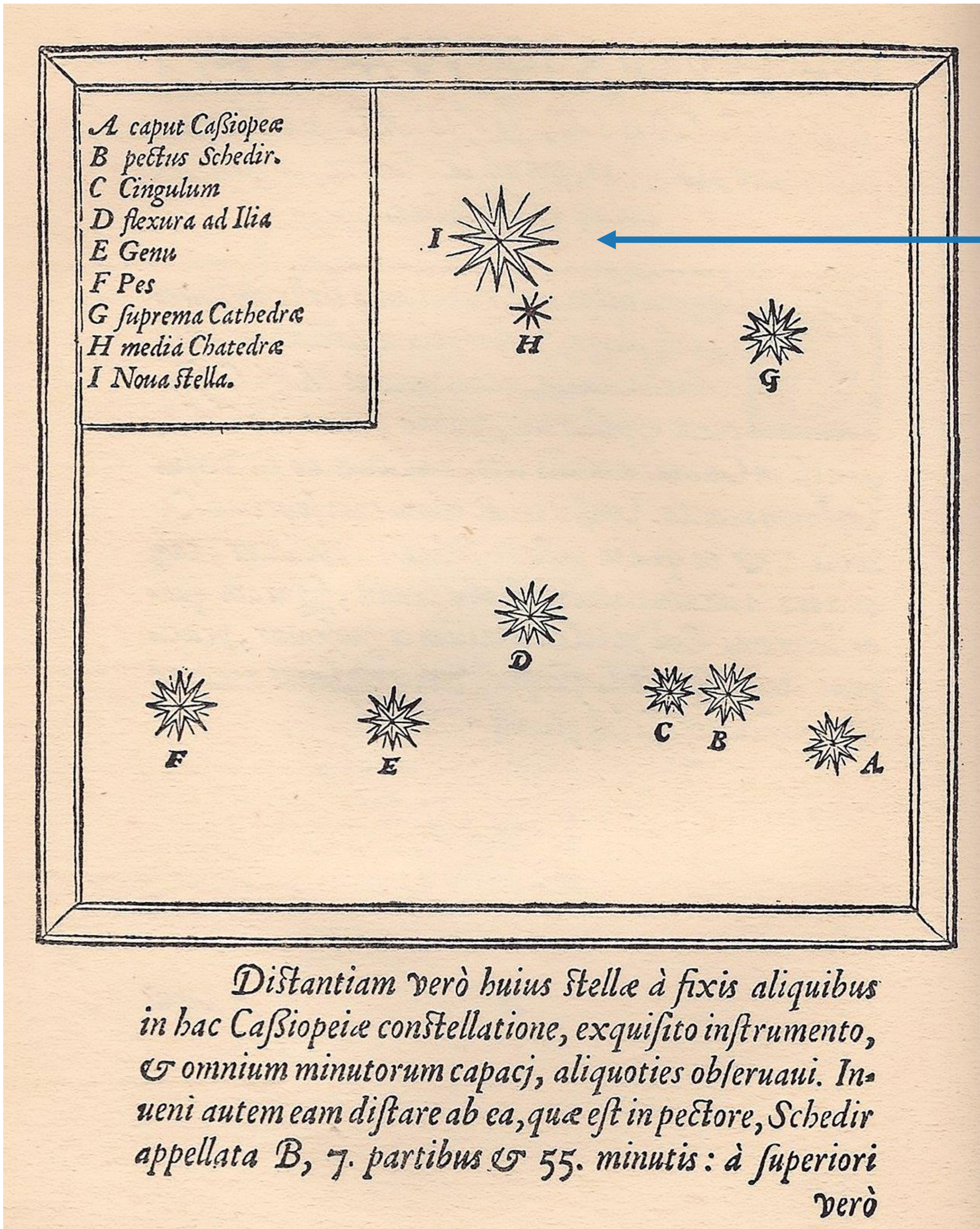
Understanding an astrophysical transient



Outline

1. A little bit of history
2. Phase space of astrophysical transients
3. Solving the mystery
4. How to go about discovering new phenomena

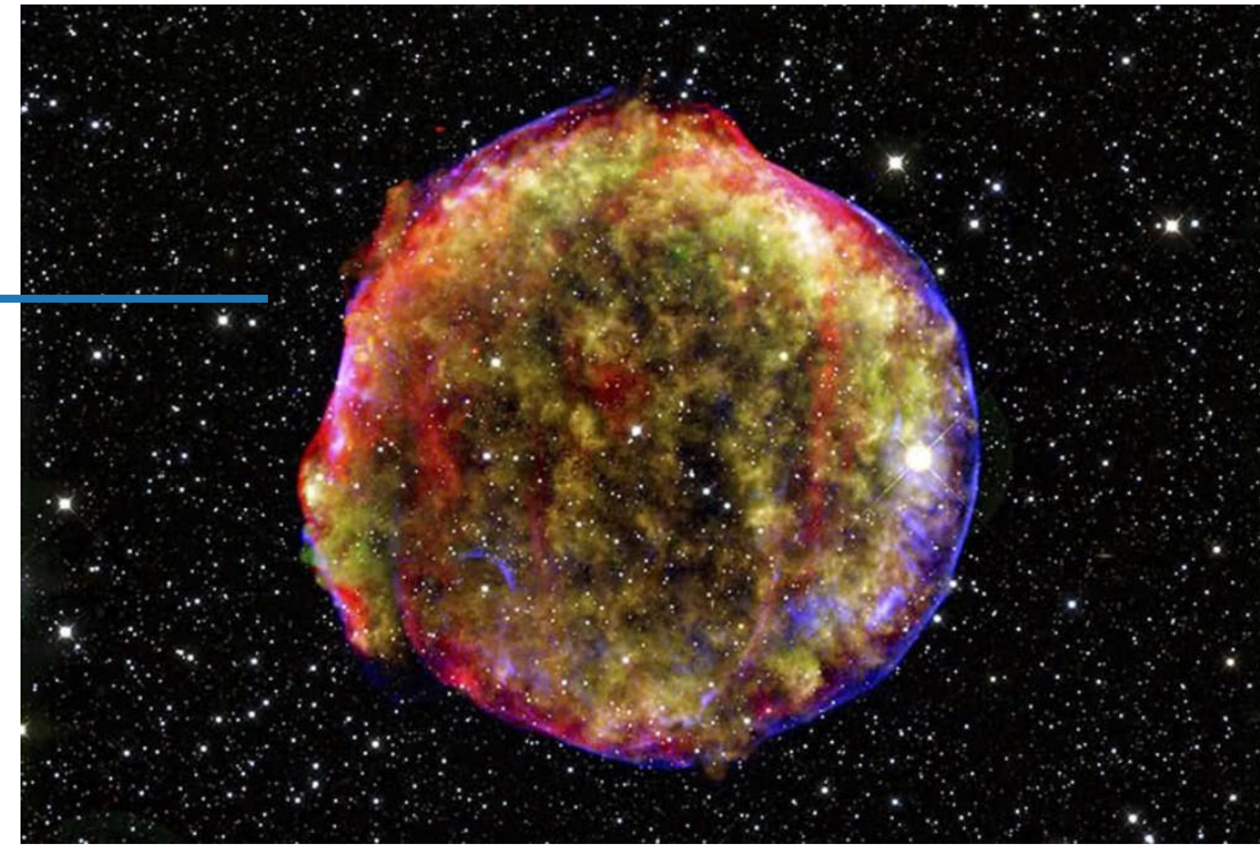
De nova stella (On the New Star)



A caput Caßiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G suprema Cathedræ
H media Chatedræ
I Noua stella.

Distantiam verò huius stellæ à fixis aliquibus in hac Caßiopeiæ constellatione, exquisito instrumento, & omnium minutorum capacj, aliquoties obseruaui. Inueni autem eam distare ab ea, quæ est in pectore, Schedir appellata B, 7. partibus & 55. minutis: à superiori verò

Brahe 1573



X-ray: NASA/CXC/SAO; Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O. Krause et al.

Novae and supernovae

"The extensive investigations of extragalactic systems during recent years have brought to light the remarkable fact that there exist two well-defined types of new stars or novae which might be distinguished as *common novae* and *super-novae*. No intermediate objects have so far been observed."

Current understanding is that both novae and Type Ia supernovae are powered by nuclear fusion, for novae in accreted matter on a white dwarf (more or less stable), for type Ia supernovae in the white dwarf itself (explosively)

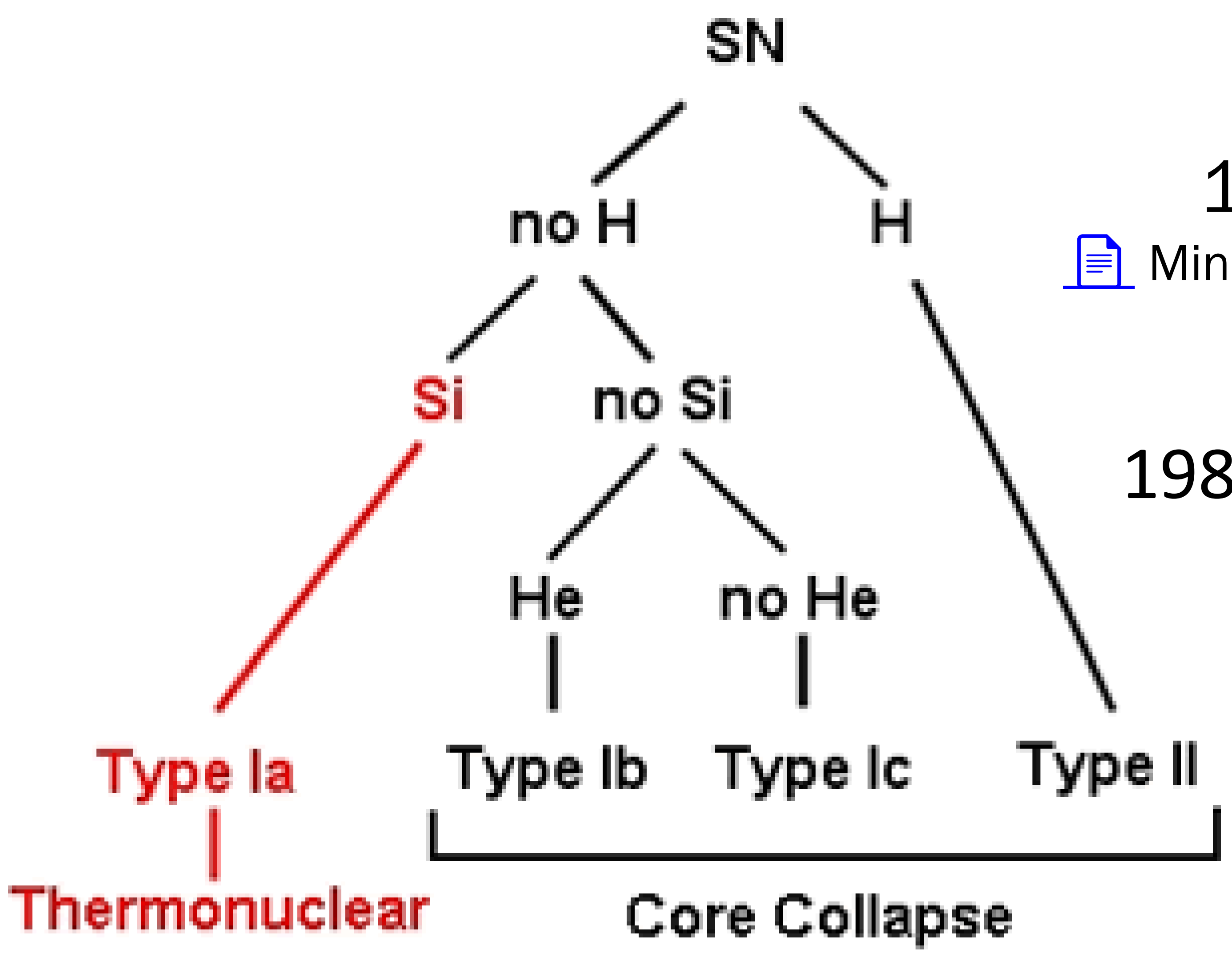
Novae ejecta mass: 10^{-4} – 10^{-5} M_{sun}

Type 1a supernovae ejecta mass: 10^{-1} – 1 M_{sun}

Baade & Zwicky 1934

Supernovae

See Week 5



1941

Minkowski 1941

1980s

Can find these anywhere

Associated with massive stars

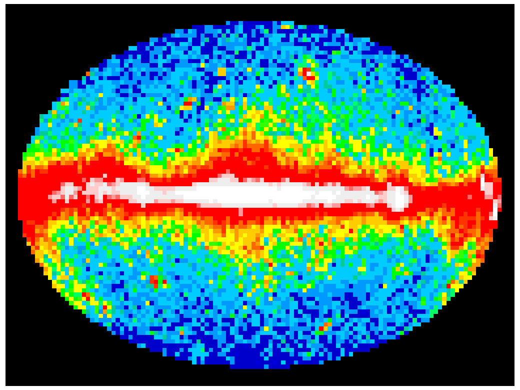
Gamma-ray bursts

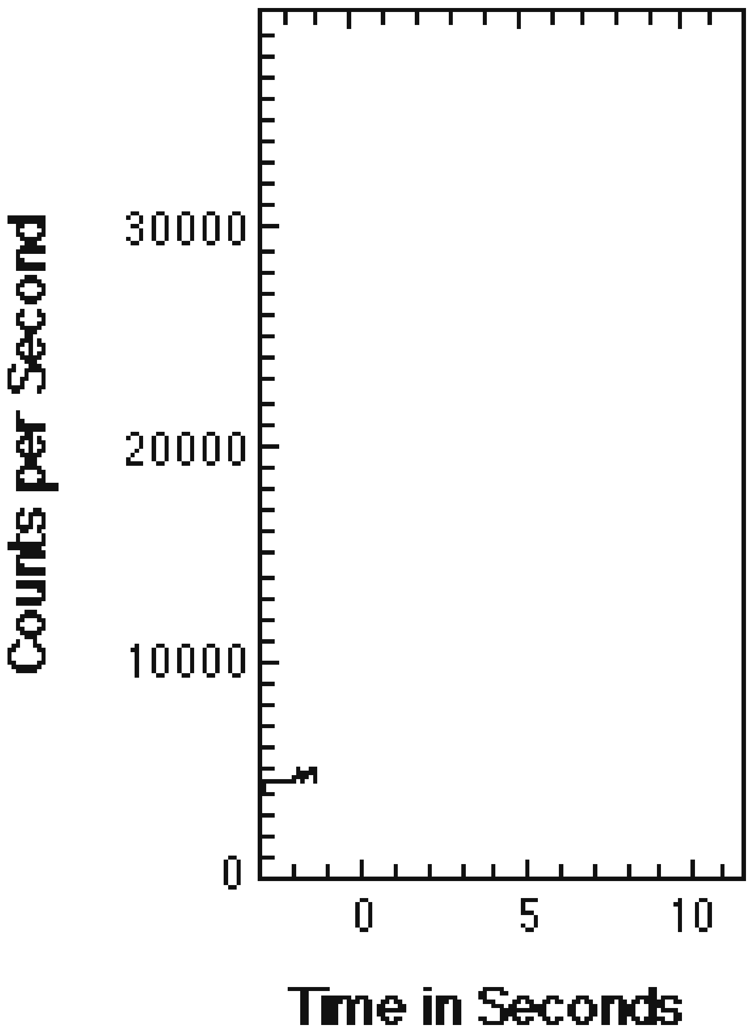
See Week 6

Testing of nuclear weapons banned in 1963, but Vela satellites were put up in late 1960s to watch for nuclear explosions – discovered gamma-ray bursts by accident

Klebesadel, Strong & Olson 1973

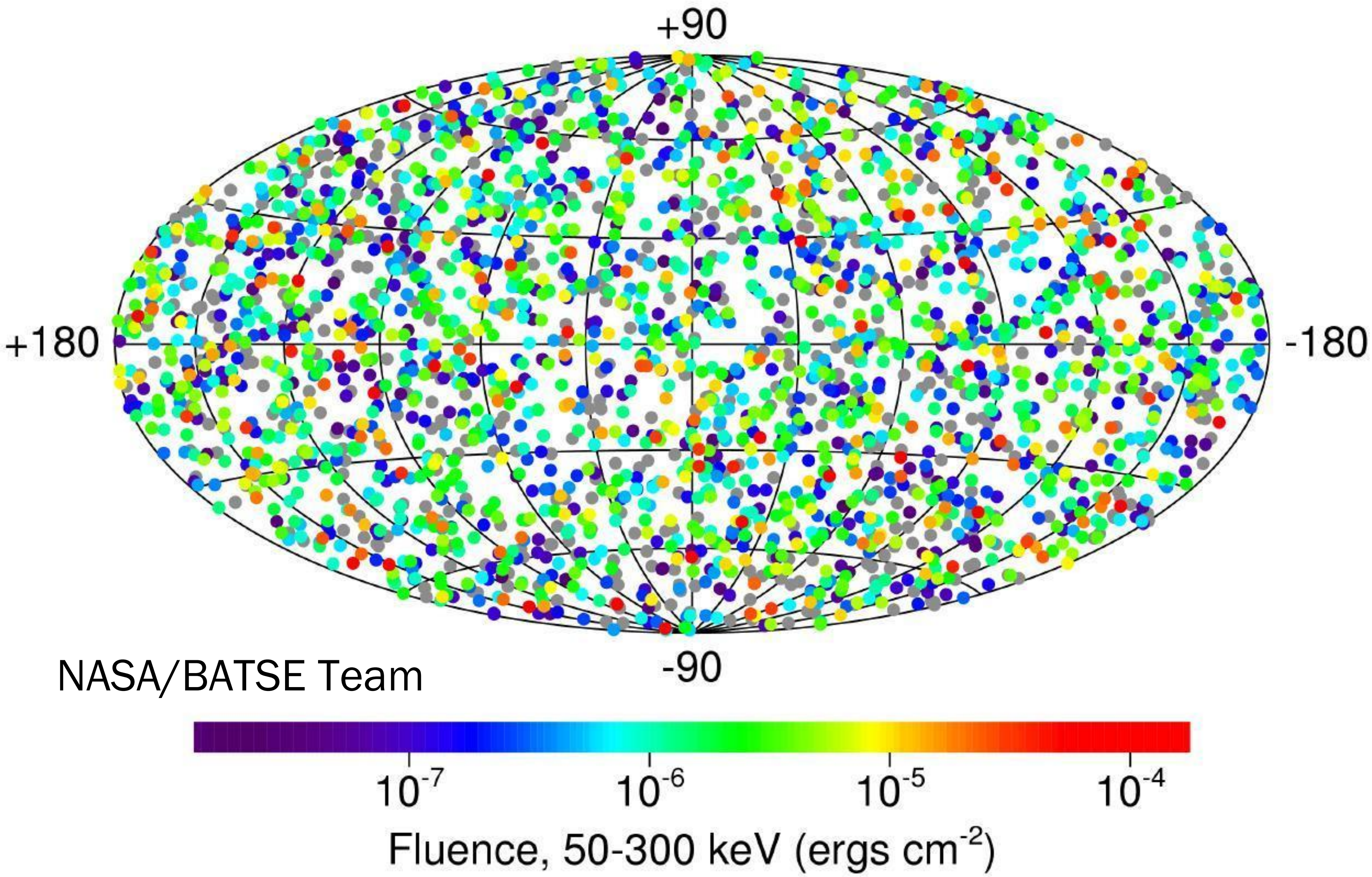
GRB detected with BATSE on board the Compton Gamma-Ray Observatory





Gamma-ray bursts sky distribution (from BATSE)

See Week 6



NASA/BATSE Team

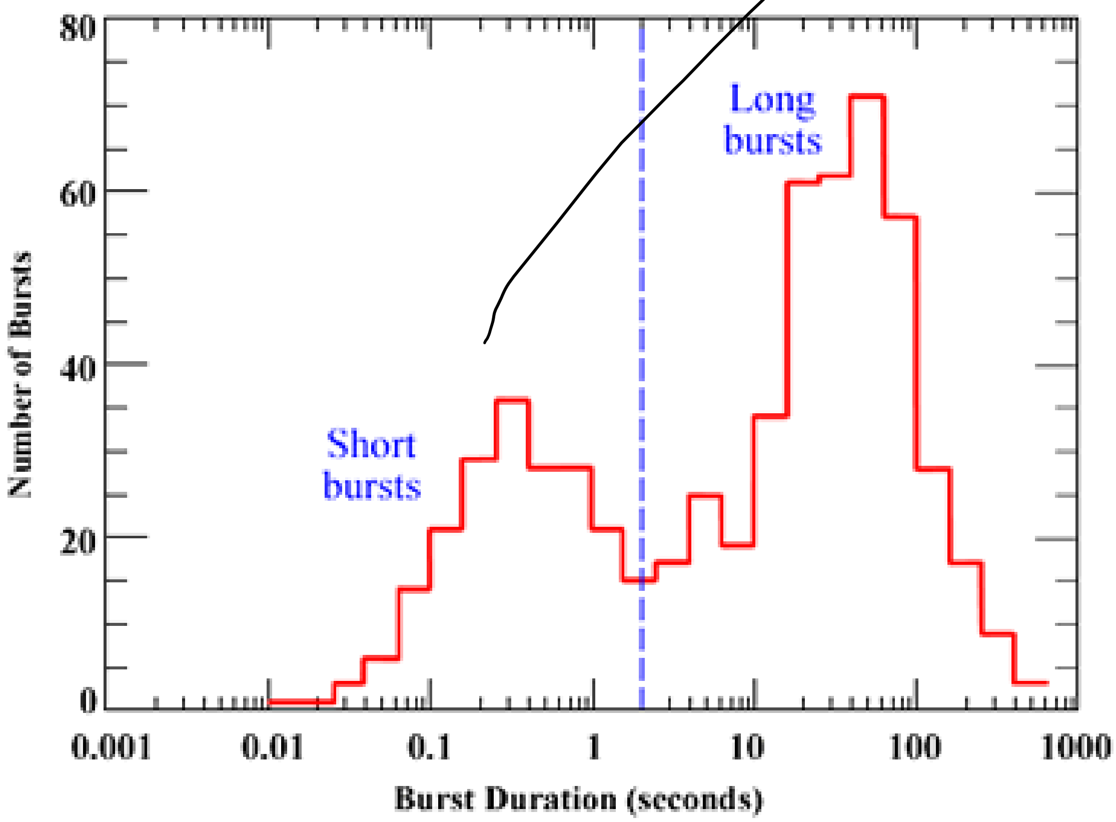
Badges for the great debate of 1995

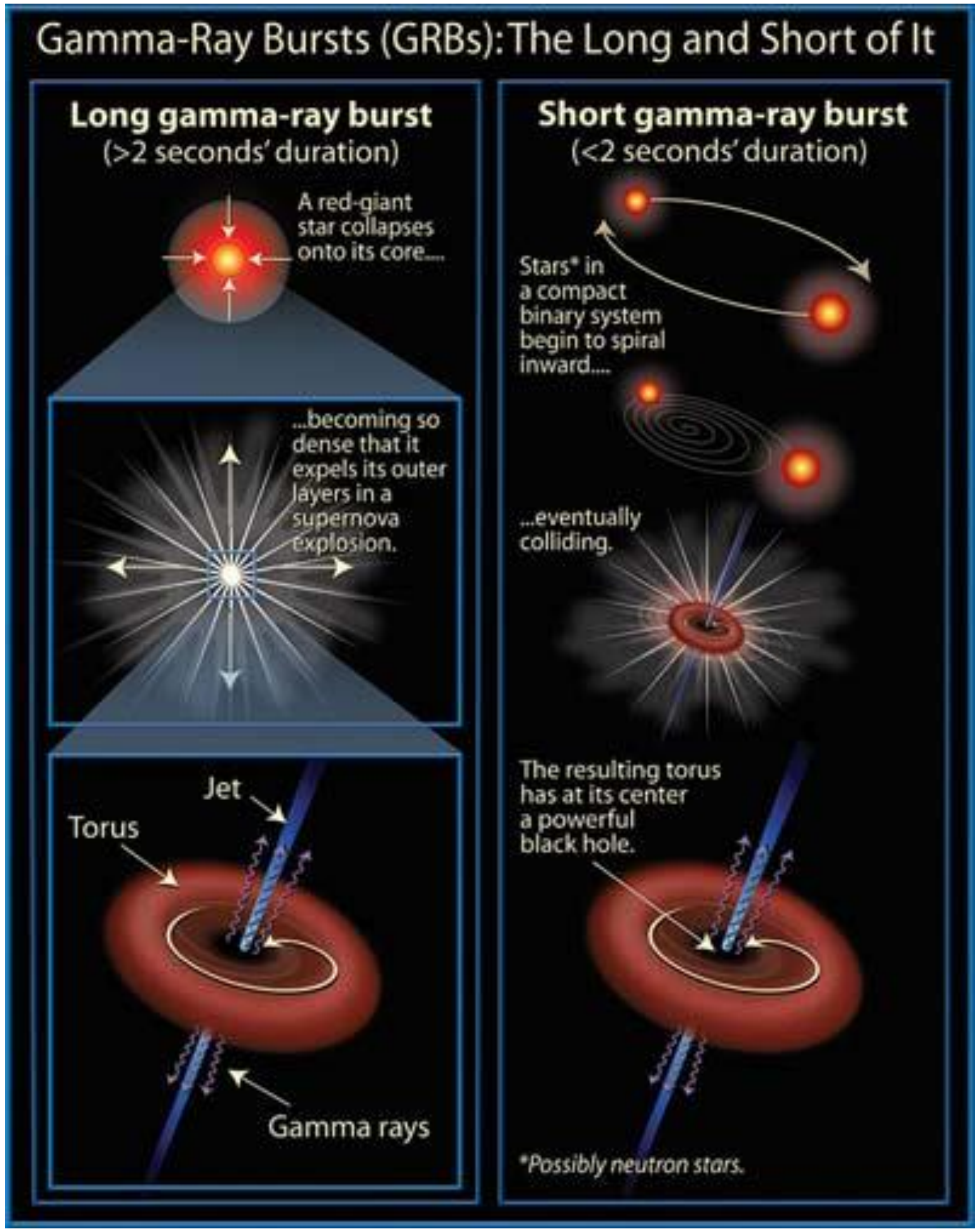
First measured afterglow at $0.835 \leq z \leq 2.3$ confirmed extragalactic origin, needed precise enough localization

Metzger+ 1997

Gamma-ray bursts

See Week 6

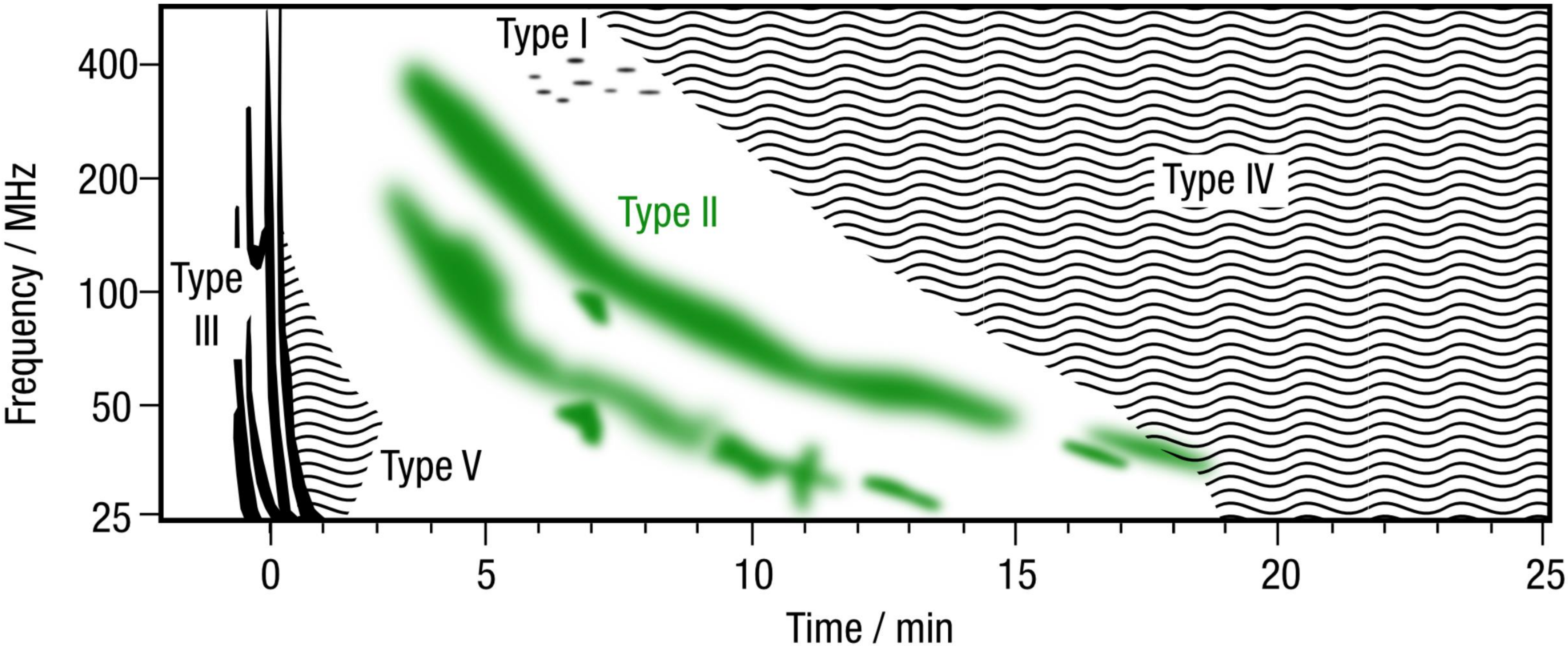


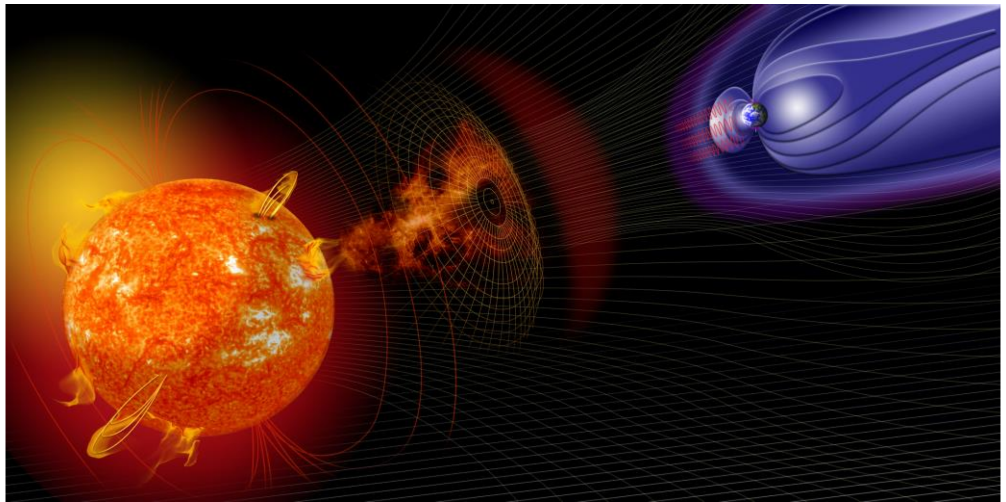


Kouveliotou+ 1993

Solar radio bursts

Ganse+ 2012





Other examples

X-ray bursts

Accretion outbursts (in young stars, cataclysmic variables, X-ray binaries)

Tidal disruption events

Superluminous supernovae

Kilonovae

Jovian bursts

Flare stars

Pulsar giant pulses

Magnetar flares

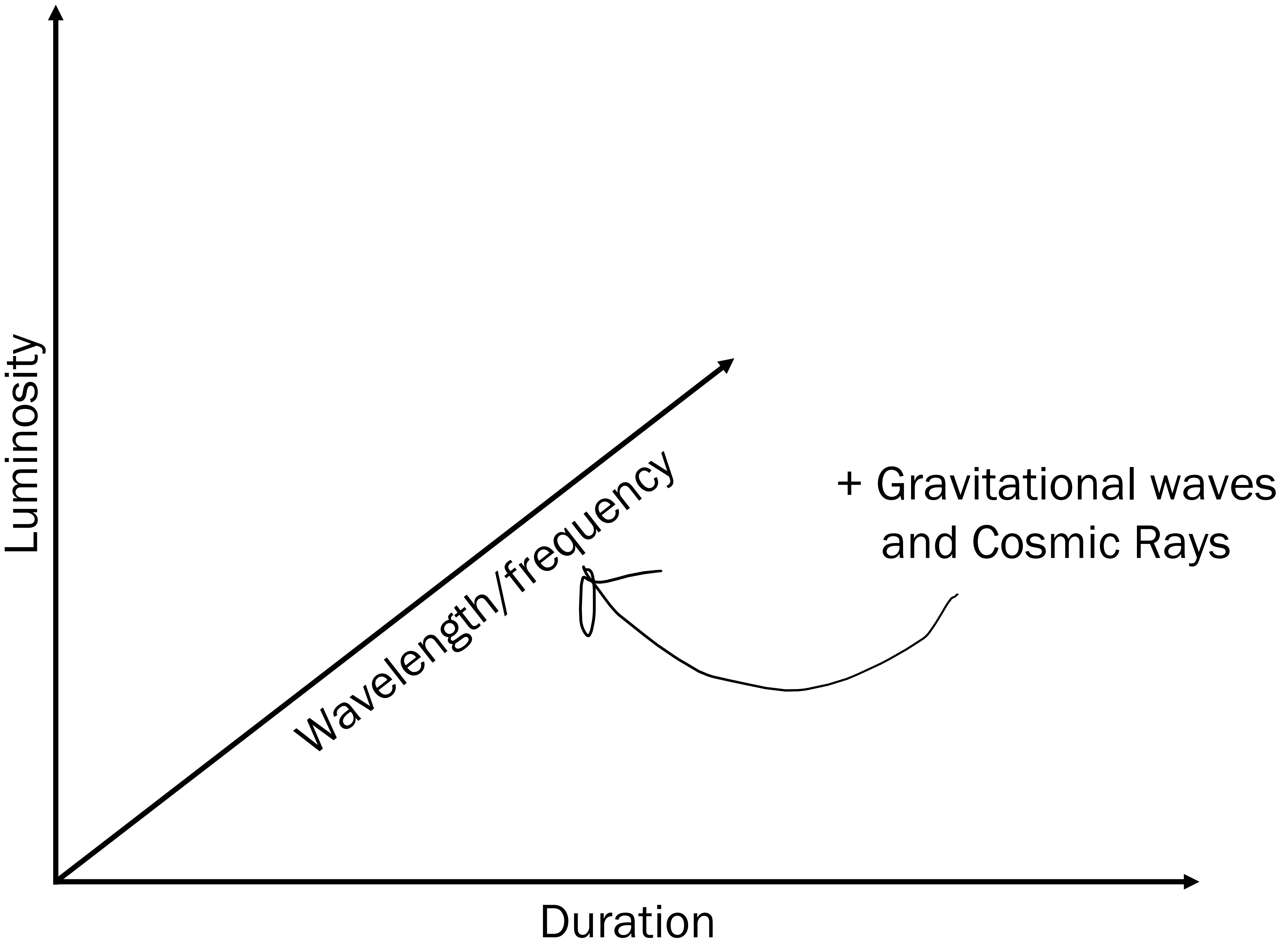
Astrophysical transients: a general definition

Something that brightens or dims significantly (> 100x?) on a human timescale

Something that is able to release a significant (> 1%?) amount of energy on a short timescale

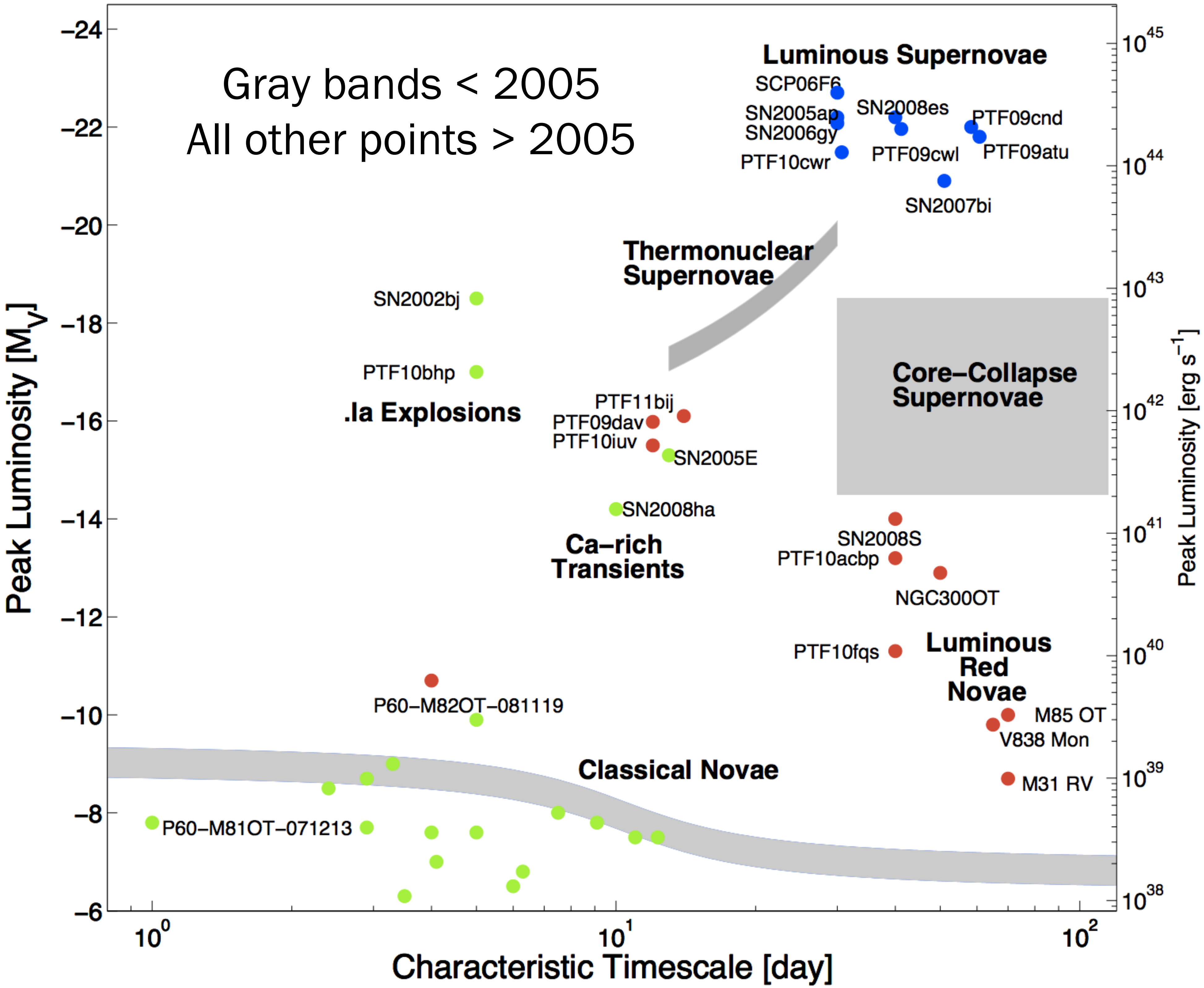
Difference between disruption (one-off) and eruption (can repeat)

Astrophysical transients phase space



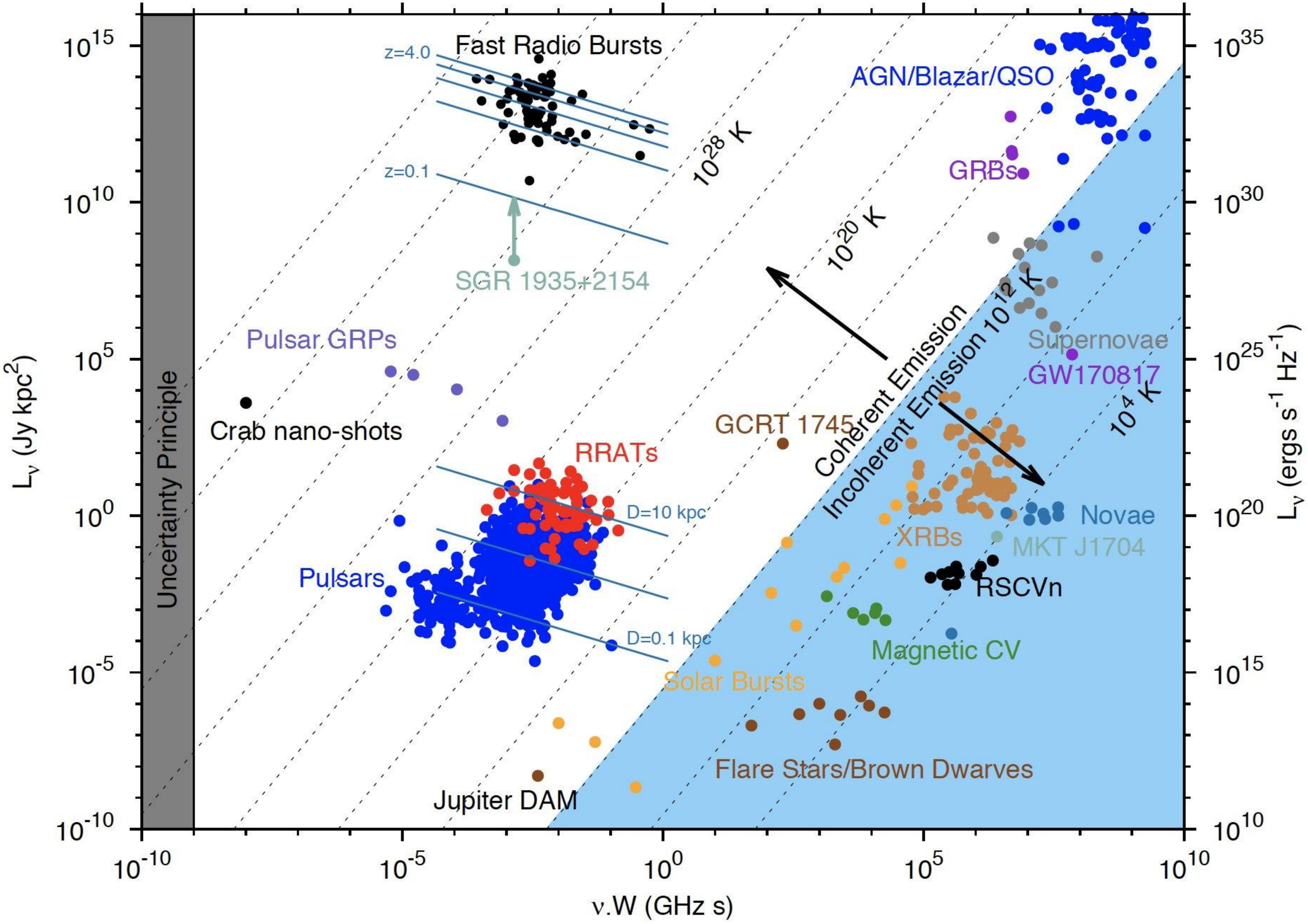
Astrophysical transients phase space: optical

See Week 2



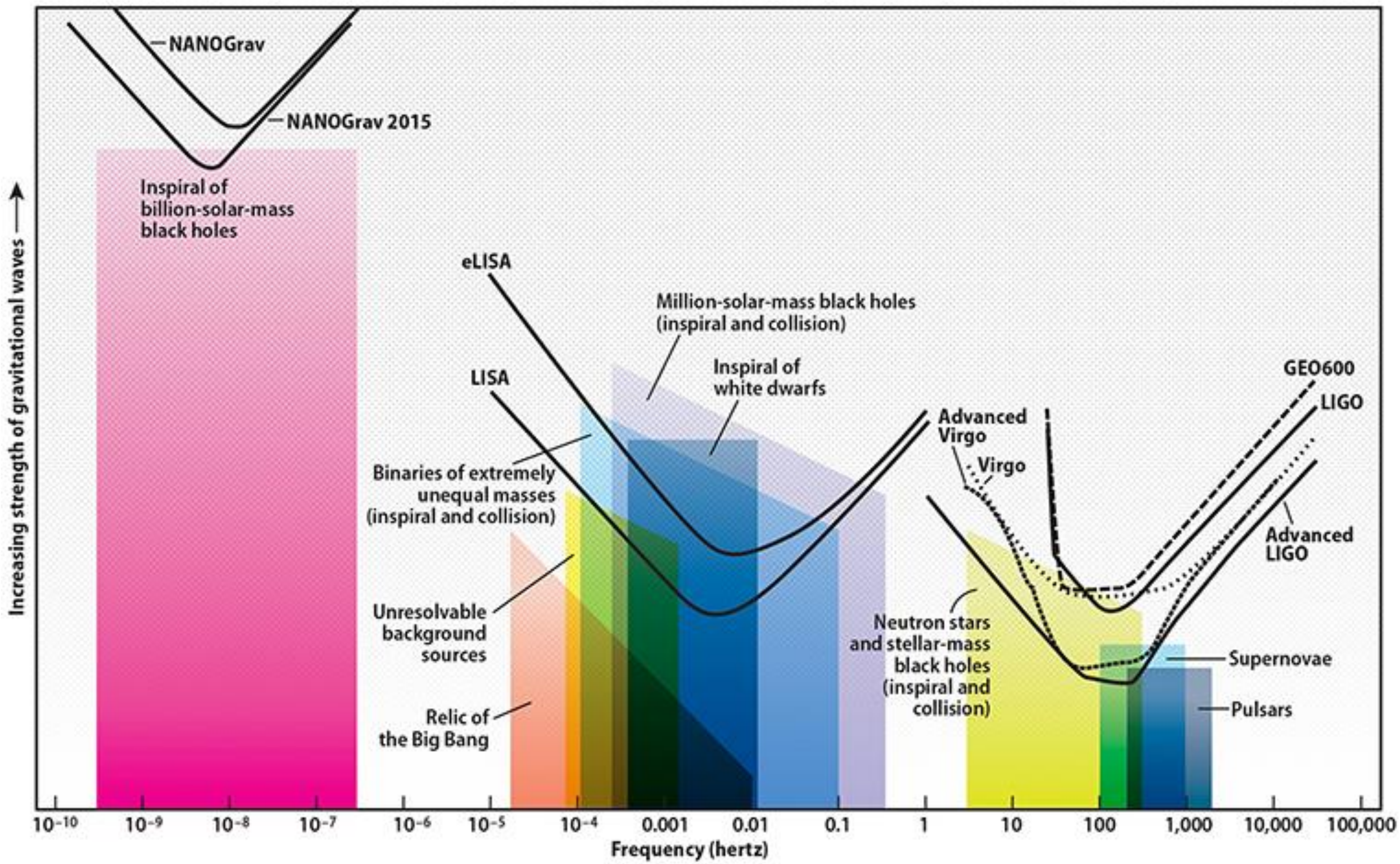
Astrophysical transients phase space: radio

See Week 2



Astrophysical transients phase space: multi-messenger

See Week 2



Roen Kelly, after C. Moore, R. Cole, and C. Berry

Linking timescales to physics

Star radiating away:

Thermal timescale

$$\tau_{th} = \frac{\text{total kinetic energy}}{\text{rate of energy loss}} \approx \frac{GM^2}{2RL}$$

set by opacity

e.g. §3.3 in 📖 Kippenhahn+ 2012

Accretion disk:

Viscous timescale

$$t_{\rm vis} \sim \rho R^2/\overline{\eta},$$

typically much longer than the free-fall timescale

e.g. 📖 King+ 2002

Stellar collapse or accretion:

Free-fall time

$$t_{\rm ff} \sim (R^3/GM)^{1/2}$$

set by gravity

~0.1 ms for neutron star of black hole, but ~10 s for white dwarf

Causality links emitting region to the minimum burst duration by the light crossing time

$$R/c \sim 30(R/10^9 \ \mathrm{cm}) \ \mathrm{ms}$$

Linking spectra to physics

Radiative processes:

- Bremsstrahlung
- Blackbody
- Synchrotron (thermal and non-thermal)
- Compton scattering

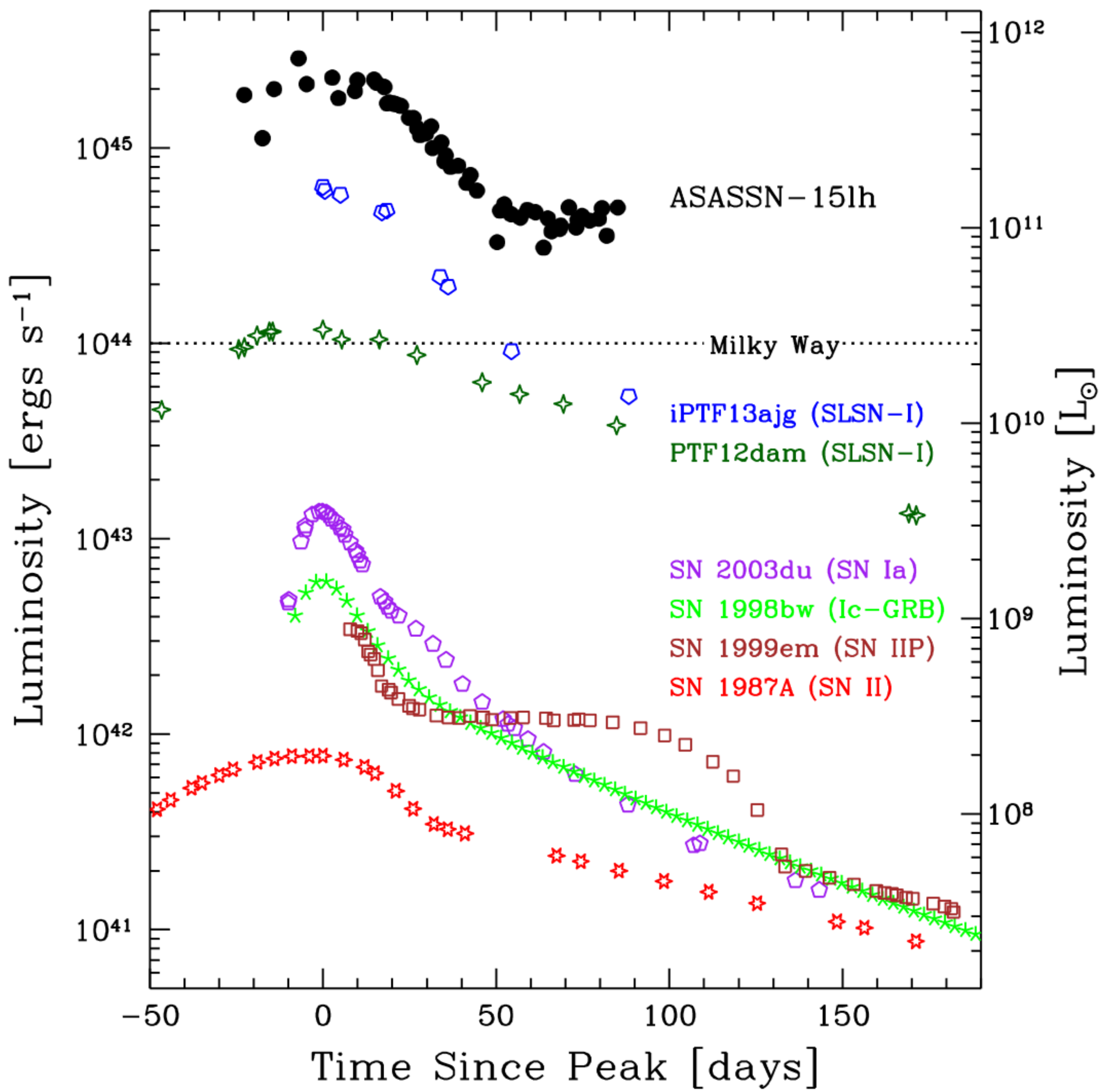
Need to match observed spectral energy distribution of transient

Many books cover radiative processes;
📖 Rybicki & Lightman 2004 is a classic

The physics of explosions

See Weeks 3--4

Energy of explosion, mass of ejecta, velocity of ejecta, rise time of explosion, **peak luminosity** and **decay time of explosion**



Dong+ 2016

Linking transients to possible progenitors

Q How would you go about this?

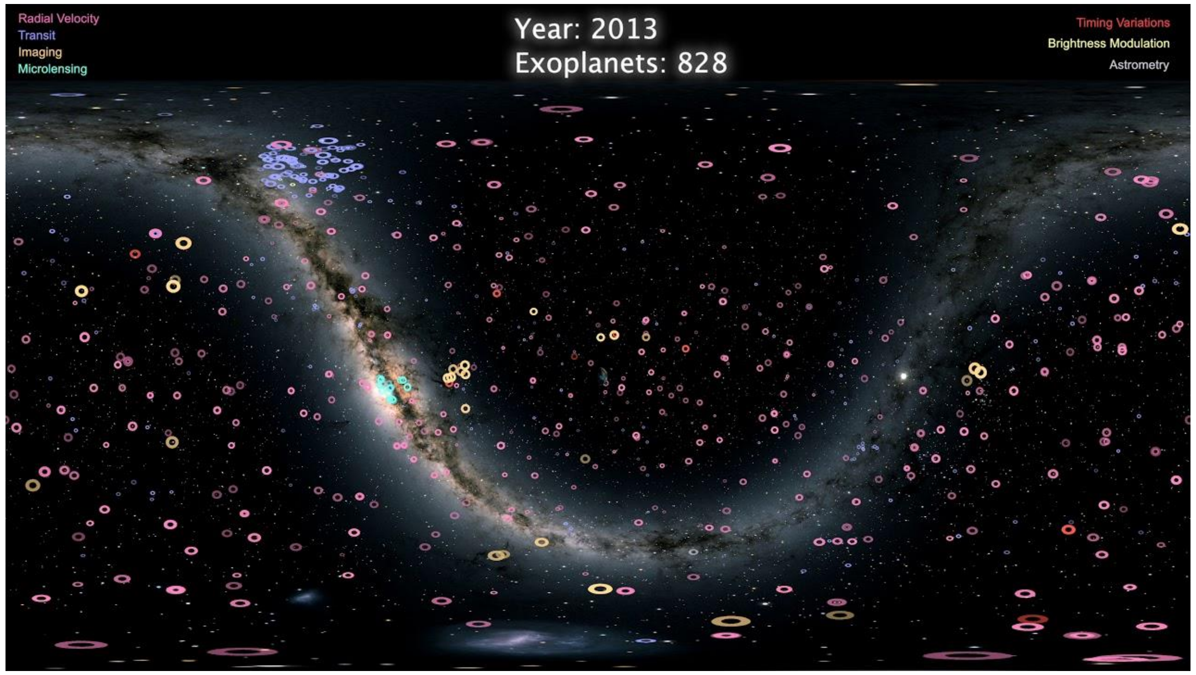
Think, pair, share

Sky distributions

What does the sky distribution of a transient tell us about its origin?

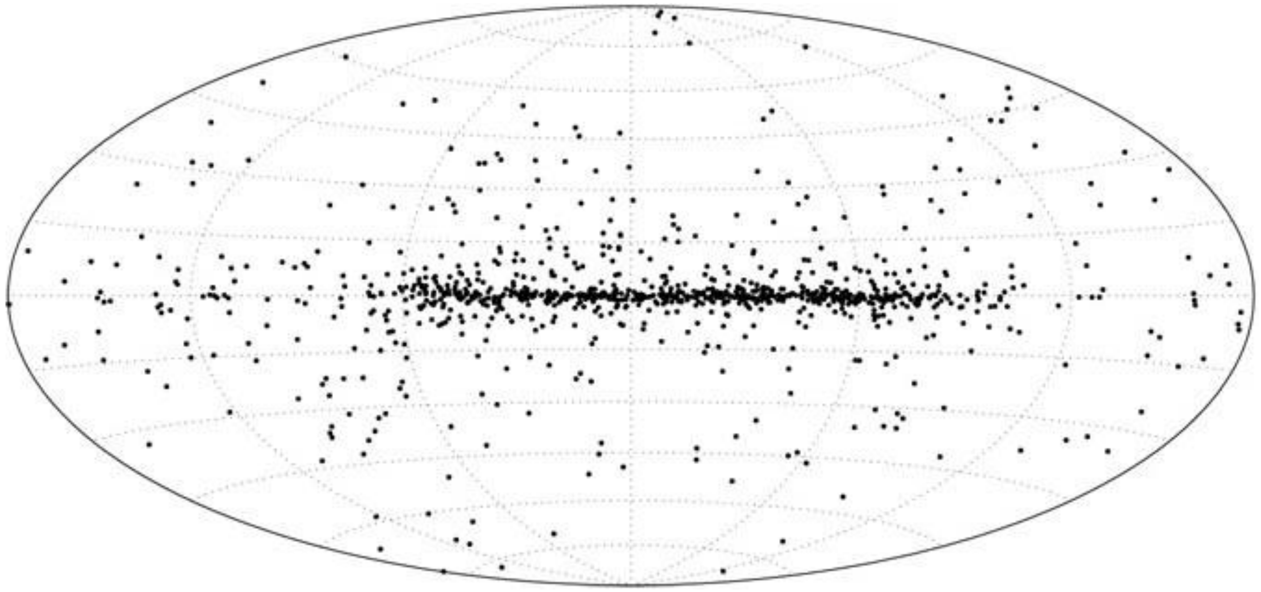
Nearby: e.g., exoplanets

Video credit: SYSTEM Sounds (M. Russo, A. Santaguida); Data: NASA Exoplanet Archive



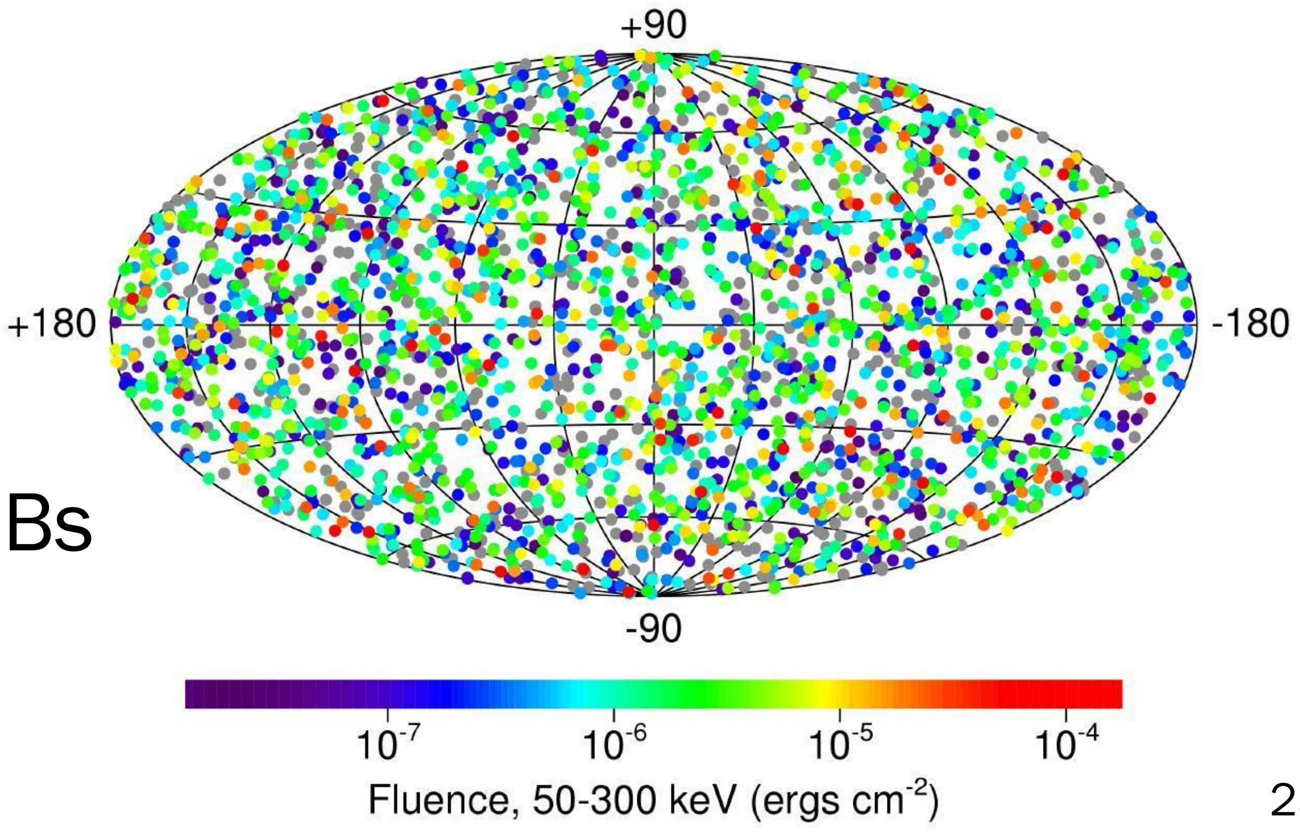
Galactic: e.g, pulsars

Lorimer 2001



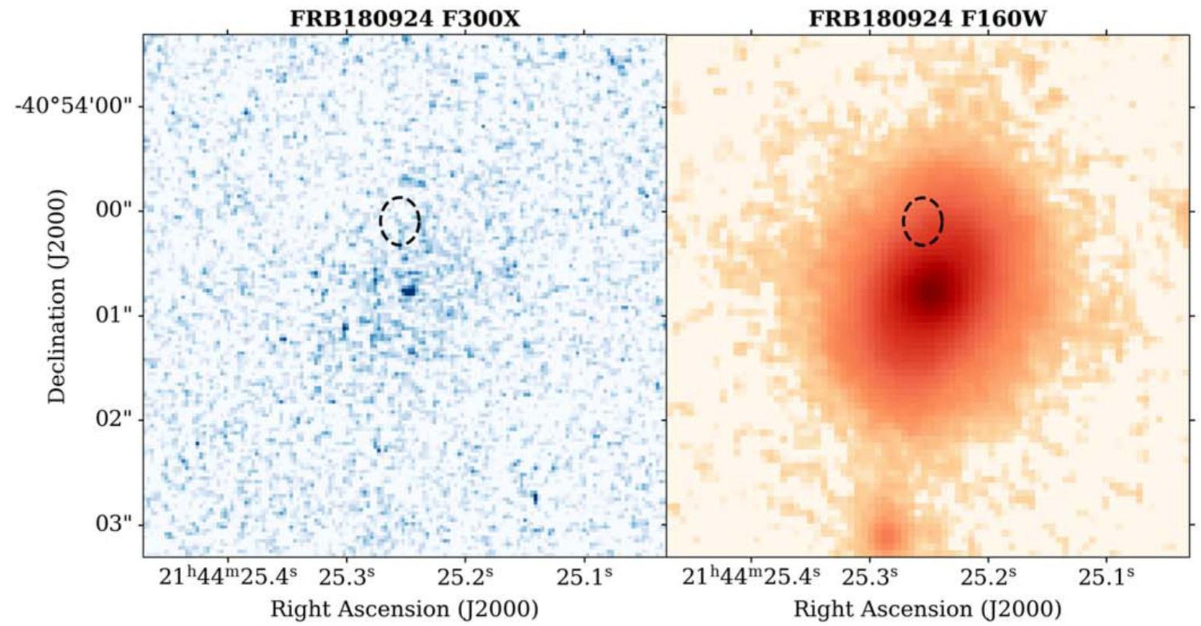
Extragalactic: e.g., GRBs

NASA/BATSE Team



Galaxy offsets

What does the Galactic offset distribution of a transient tell us about its origin?



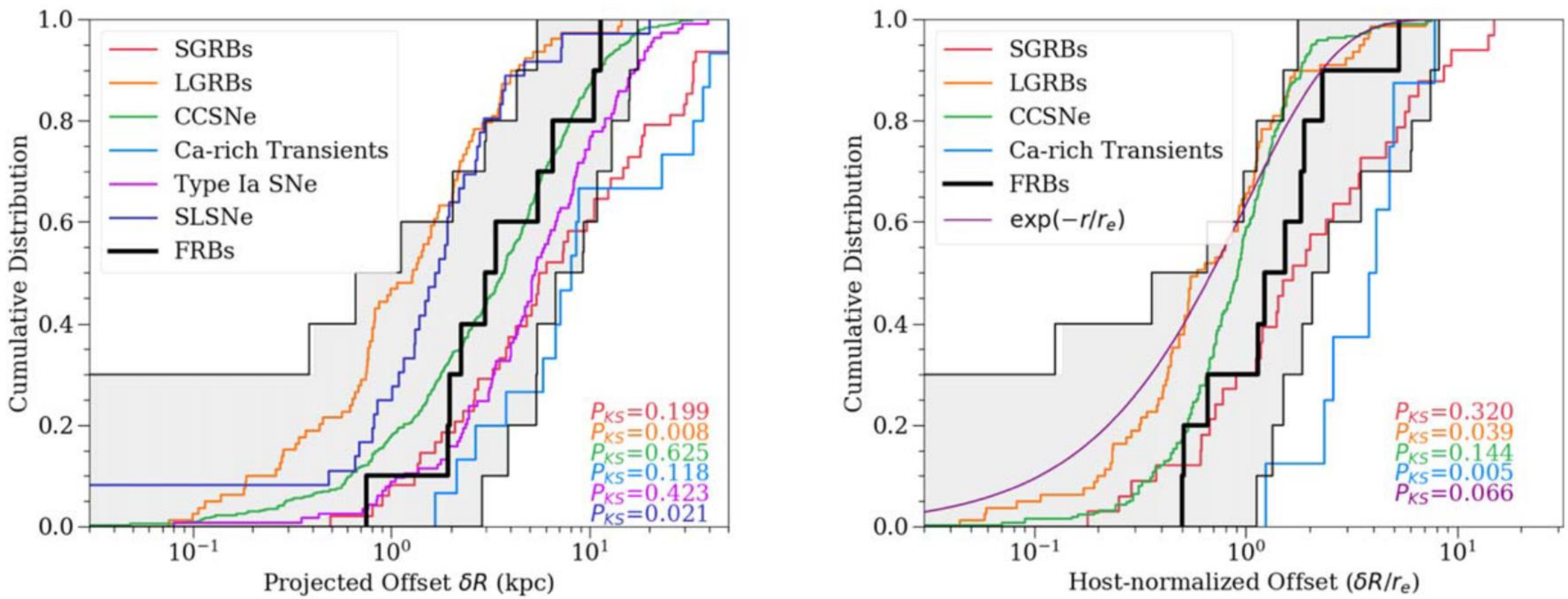
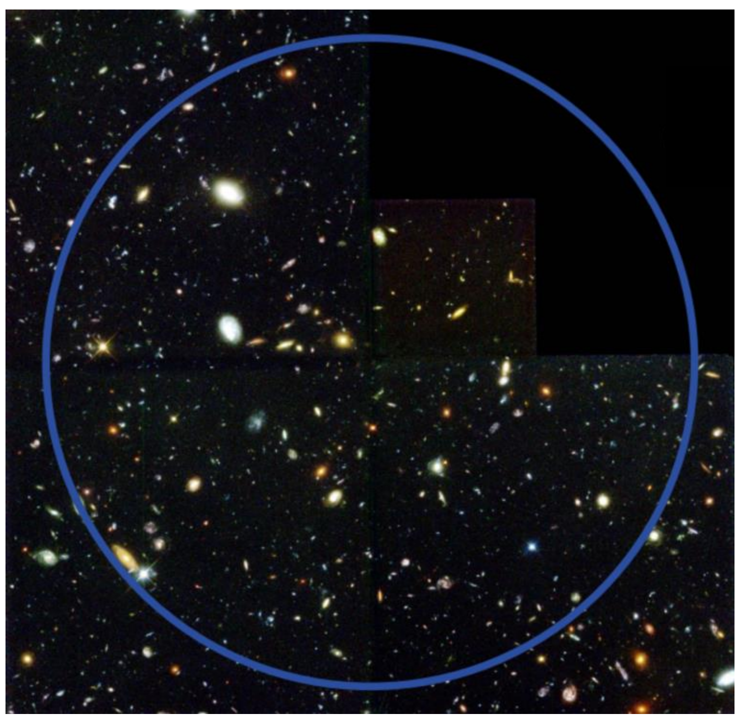


Figure 4. Left: cumulative distribution of projected physical offsets, δR, for the 10 FRBs in the HST and ground-based samples (black line). The gray shaded region is a bootstrap estimate of the rms of the distribution, which accounts for both uncertainties on individual measurements and statistical uncertainties due to the sample size. Comparison samples are included for SGRBs (Fong et al. 2010; Fong & Berger 2013), LGRBs (Blanchard et al. 2016), Ca-rich transients (Lunnan et al. 2017; De et al. 2020), Type Ia SNe (Uddin et al. 2020), CCSNe (Schulze et al. 2020), and SLSNe (Lunnan et al. 2015; Schulze et al. 2020) for events at $z < 1$. The computed p-values from a two-sided K-S test are listed for each population relative to the FRB sample. Right: same as the left panel but for the host-normalized offsets ($\delta R/r_e$). This plot also shows the profile of an exponential disk.

Mannings+ 2020

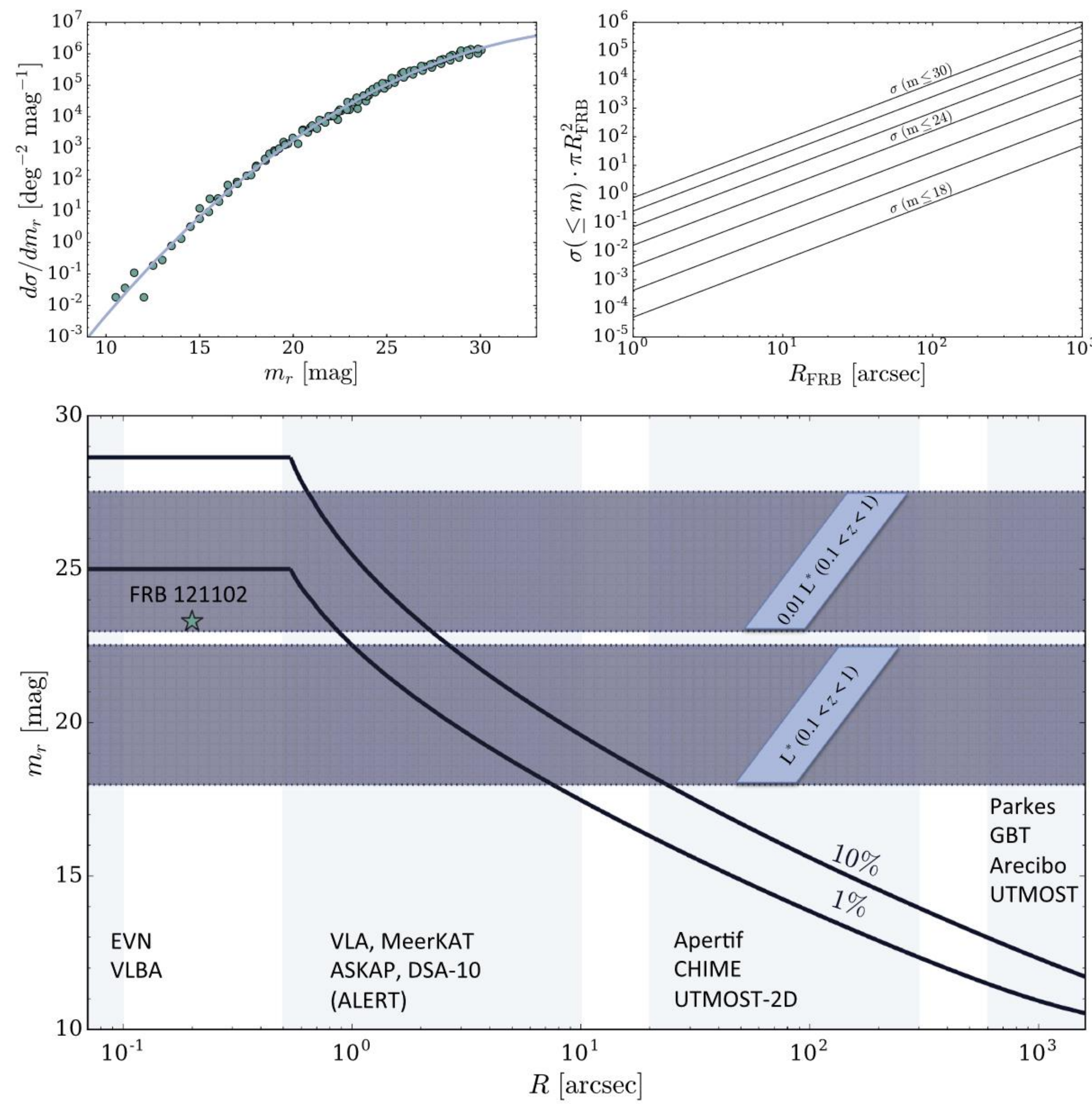
Chance coincidence probabilities

How likely is it to find a galaxy at the position of a transient?



Typical uncertainty for lots of fast radio bursts is only ~ 1 arcmin

How likely is it to find another transient at the position of a transient?



Eftekhari & Berger 2017

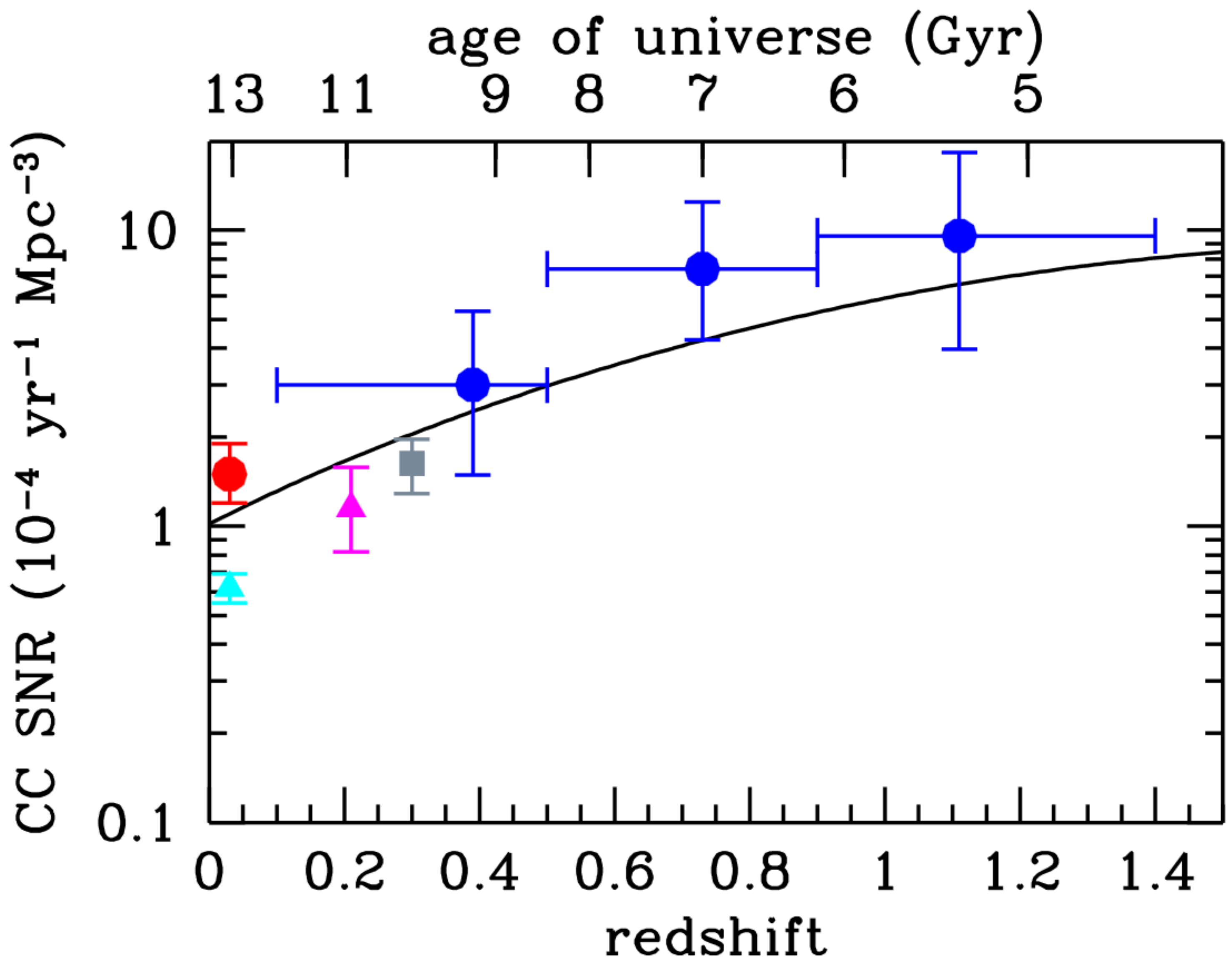
Rates

What does the (volumetric) rate of a transient tell us about its origin?

Important concepts:
- Sensitivity
- Selection effects
- Completeness
- Star formation history

Star-formation history from cosmic core-collapse supernova rate (from massive, short-lived stars)

Madau & Dickinson 2014



The ideal telescope

Q What variables to optimize when designing a telescope?

Field of view

Collecting area/sensitivity

Frequency coverage/bandwidth

Spatial resolution

Time resolution (readout speed)

Cost

Technical challenges

Filling in transients phase space: the experimentalist approach

Expect the unexpected

Can I find an optimum in possible telescope phase space that works well with current technology?

For example: supernovae, pulsars, GRBs and FRBs

Filling in transients phase space: the theorist approach

Known eruptions: failure of hydrostatic equilibrium, run-away fusion, magnetic reconnection, accretion instability, ?

Known disruptions: run-away pressure loss, run-away fusion, mergers, ?

For all possible single stars, compact remnants and binaries made out of combinations of those, what to expect?

For all of those what are expected light curves and where do they land in our transient phase space?

For example: tidal disruption events

See Weeks 9--10

Astrophysical transients

Disruptions and eruptions of single stars, compact remnants and binaries produce celestial transients that brighten and dim significantly on timescales from a few nanoseconds to a few years

Transients provide mystery and opportunity*

We can define a phase space for discoveries

The last decade has seen an explosion of new explosions

Technological improvements and new instruments coming online will likely lead to more surprises in the next decade

*Unfortunately, we did not have time today to discuss using transients as probes much today