Current + upcoming radio surveys
& what they can teach us about

The wide diversity of stellar explosions

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A long long time ago in a galaxy far, far away…

A (kind of) long time ago in a galaxy (not so) far away…

There was a massive star

A (kind of) long time ago in a galaxy (not so) far away…

Betelgeuse

Red supergiant

$M \sim 17\ M_\odot$

$\dot{M} \sim 5 \times 10^{-6}\ M_\odot\ yr^{-1}$

$\sim 10^{8}\ \dot{M}_\odot$

There was a massive star

Blowing the wind of ~100 million suns

Humphreys & Jones 2021

No wait, it was that *other* massive star…

Zoomed out
~4000x

VY CMa

Red supergiant

$M \sim 17\ M_\odot$

$\sim 1 M_{Betelgeuse}$

$\dot{M} \sim 6 \times 10^{-4}\ M_\odot\ yr^{-1}$

$\sim 100\ \dot{M}_{Betelgeuse}$

Blowing the wind of ~~~100 million~~ ~10 billion suns

Humphreys & Jones 2021

Or actually, there were two massive stars…

…whose winds collided as they orbited

$M \sim 8.4\ M_{\odot}$ (Wolf Rayet) + $20.5\ M_{\odot}$ (O5 giant)

$\dot{M} \sim 3\ \dot{M}_{Betelgeuse} + 0.1\dot{M}_{Betelgeuse}$

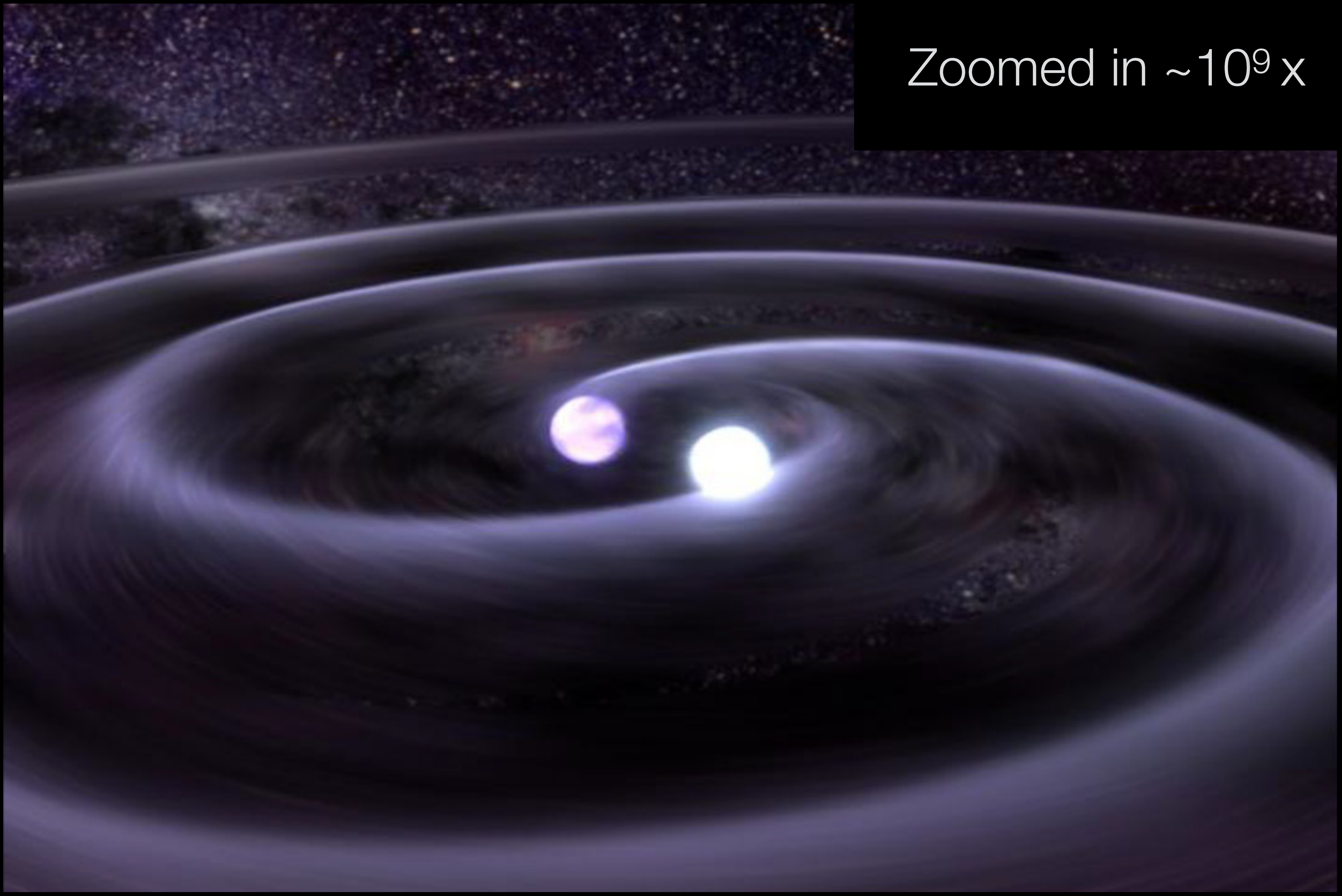
Anguita-Aguero+2022

Or maybe it was an eruption not a wind…

…that *ejected* several times the mass of the sun
in just a few years (~10^{4-5} $\dot{M}_{Betelgeuse}$)

Smith+2018

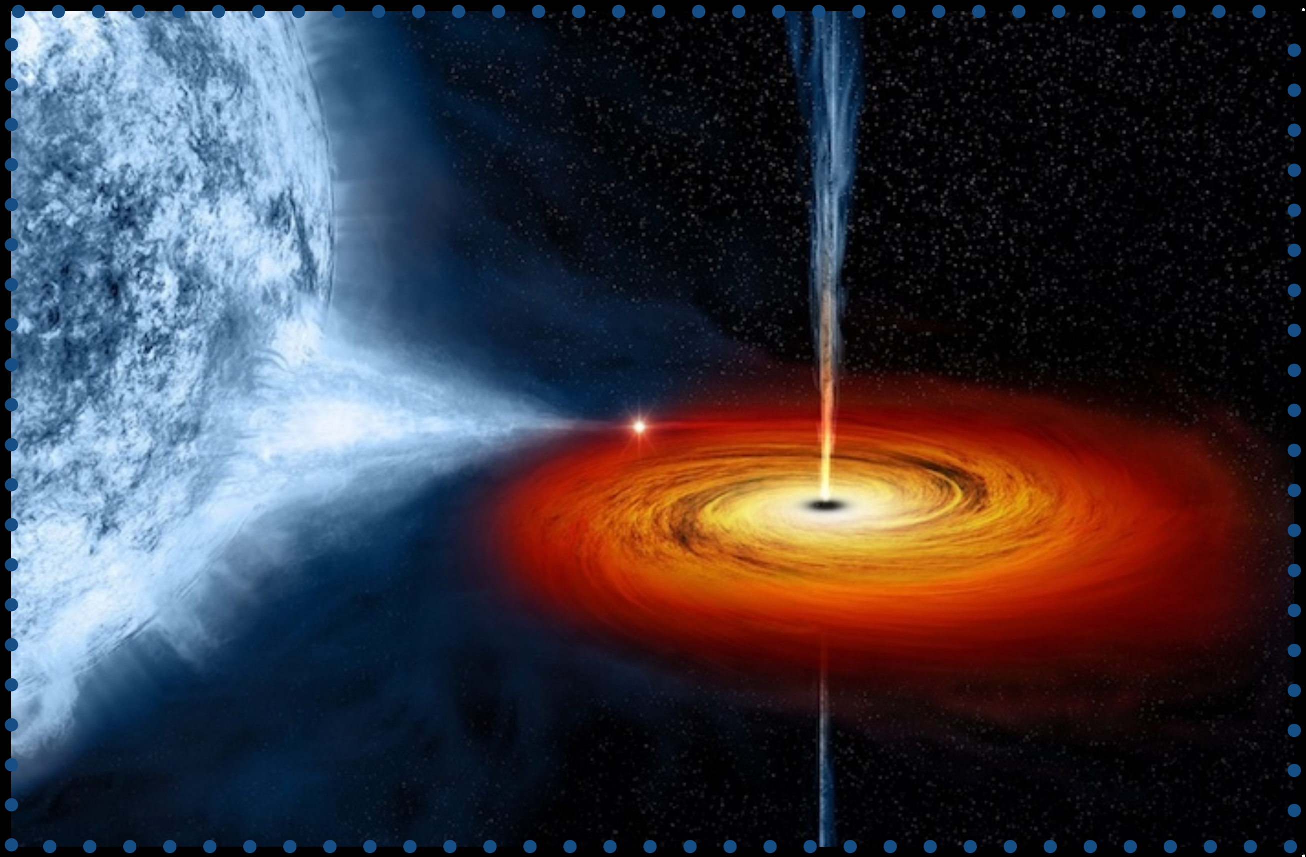
Or… it could have been two [not so] massive [not quite] stars

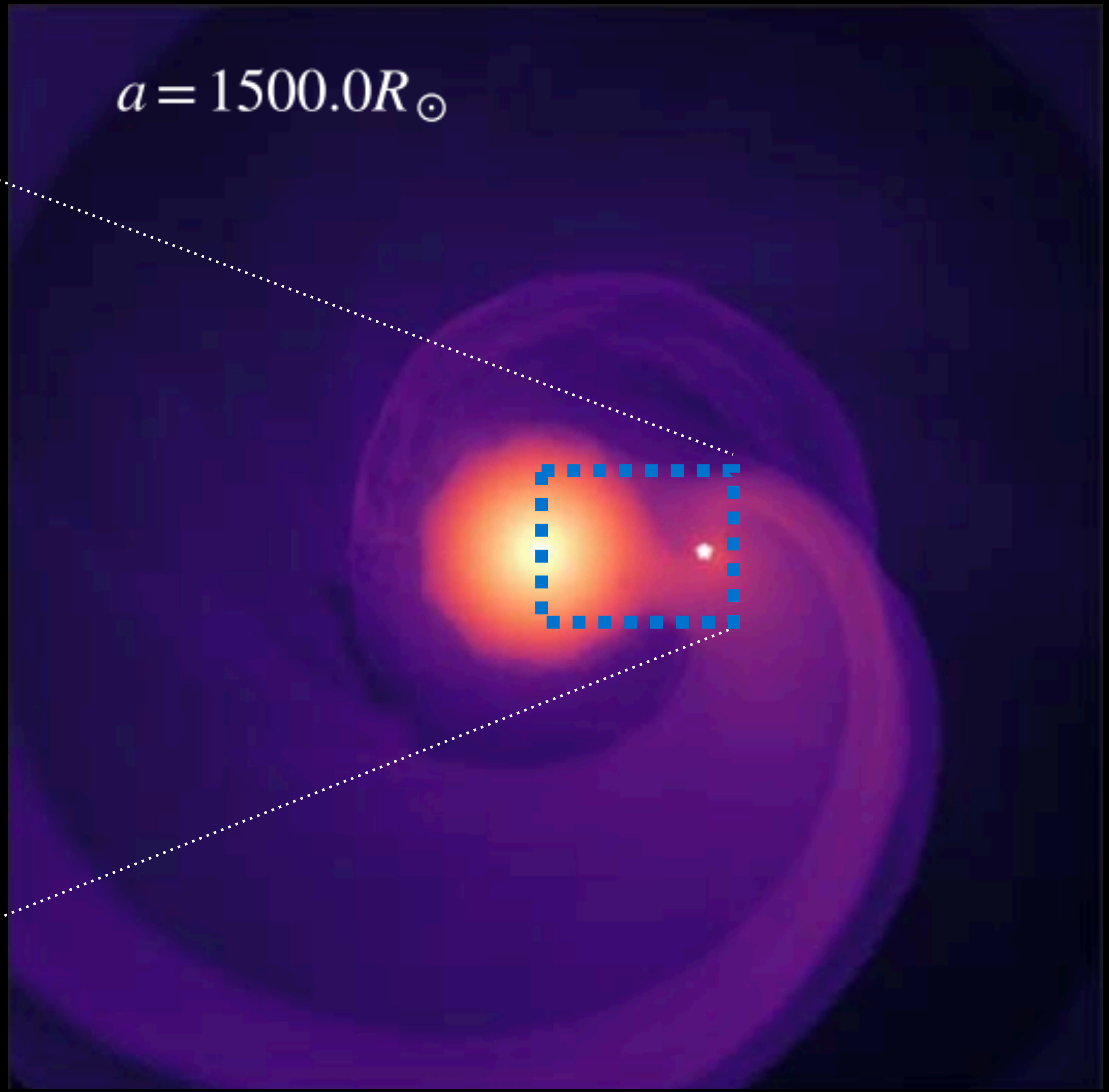


Zoomed in ~10^9 x

That really didn't have much of a wind at all

Or, perhaps even
one massive star + one compact object

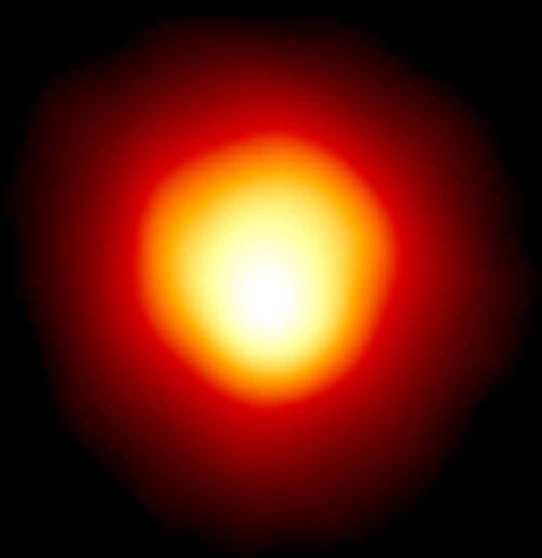


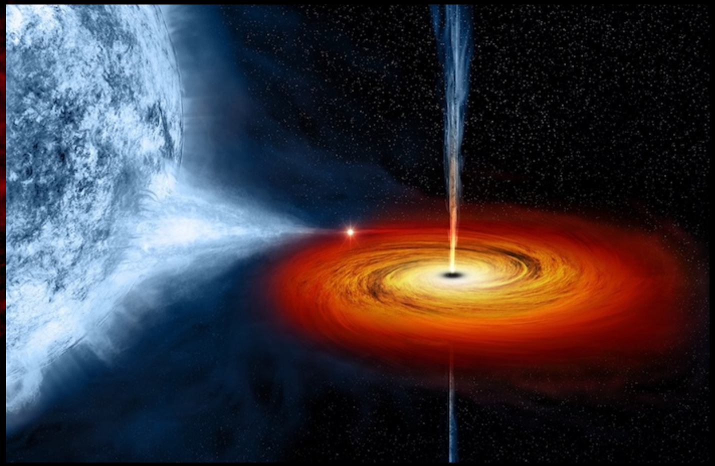


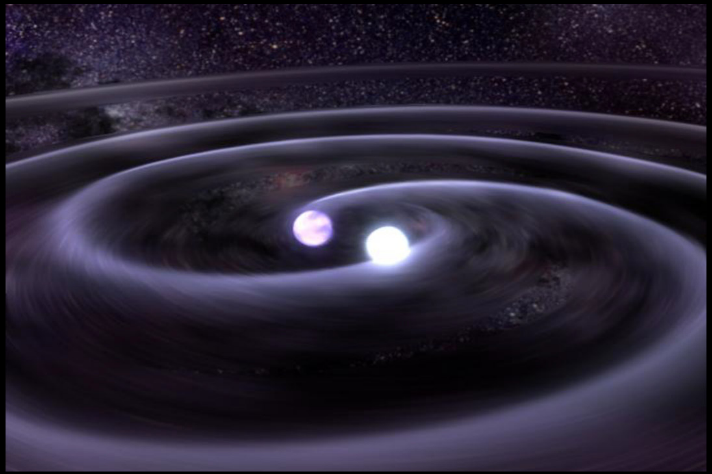
Creating a spiral from Roche lobe overflow at a rate up to ~$10^4\ \dot{M}_{Betelgeuse}$

Schroder+2020, Dong+2021, see also Mohamed+07

These incredibly diverse systems are all thought to be stellar explosion progenitors

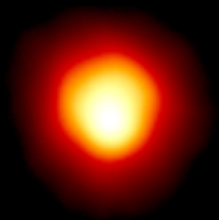


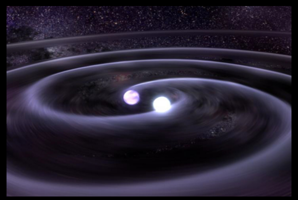


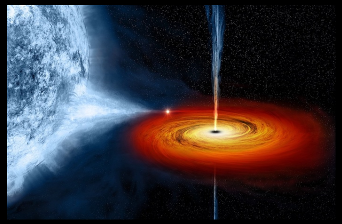


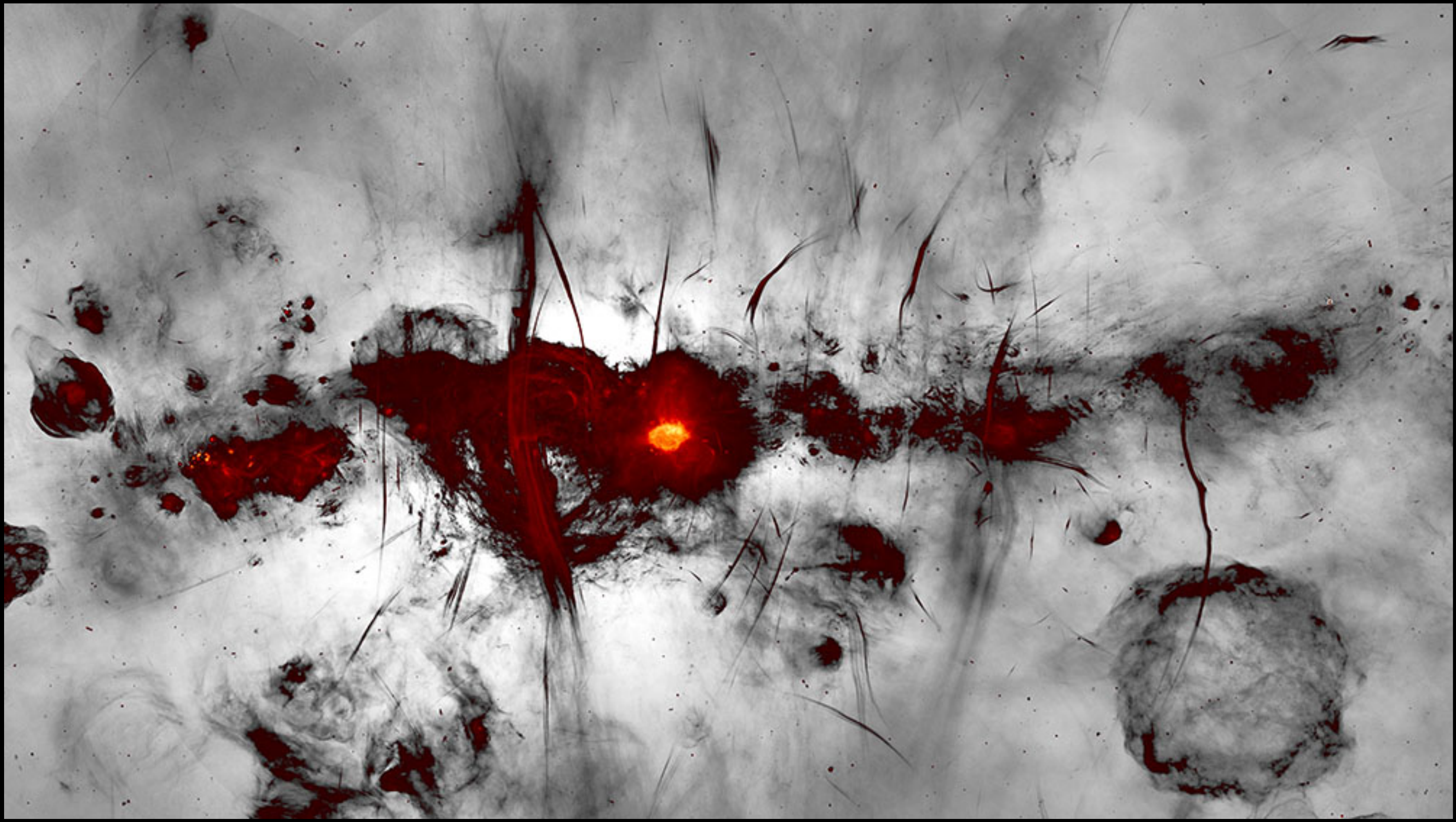
How can we connect explosions to progenitors?

How do these explosions influence their environment & future generations of stars?



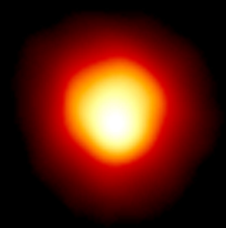


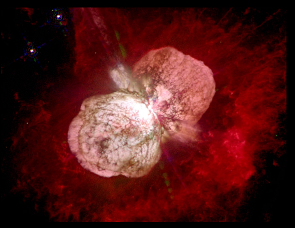


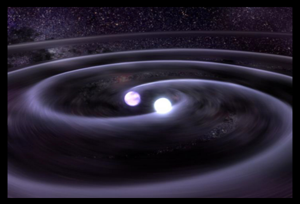


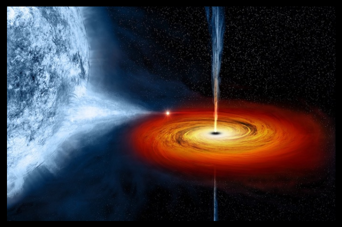
Heywood+22

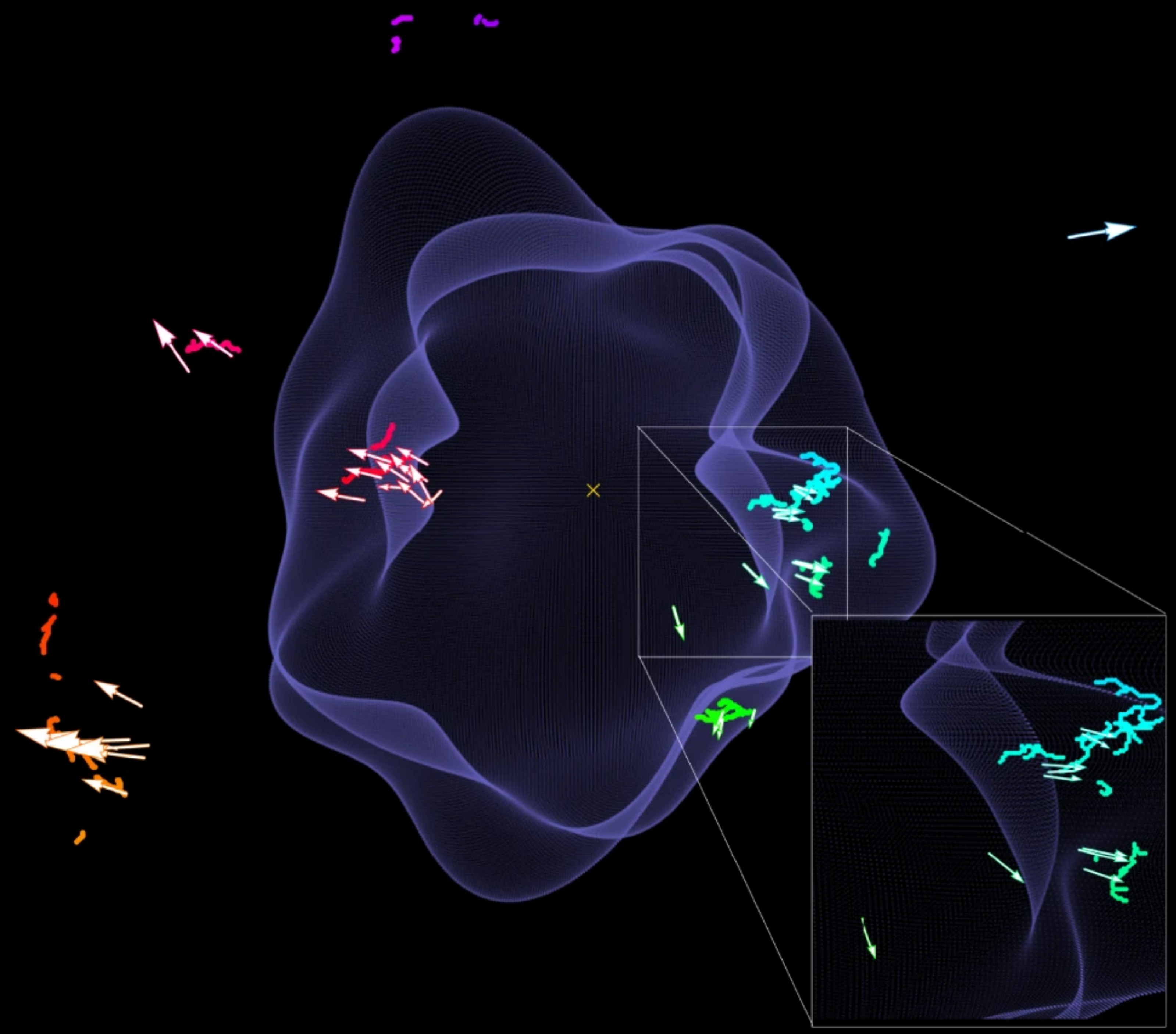
How do these explosions influence their environment & future generations of stars?











Zucker+22

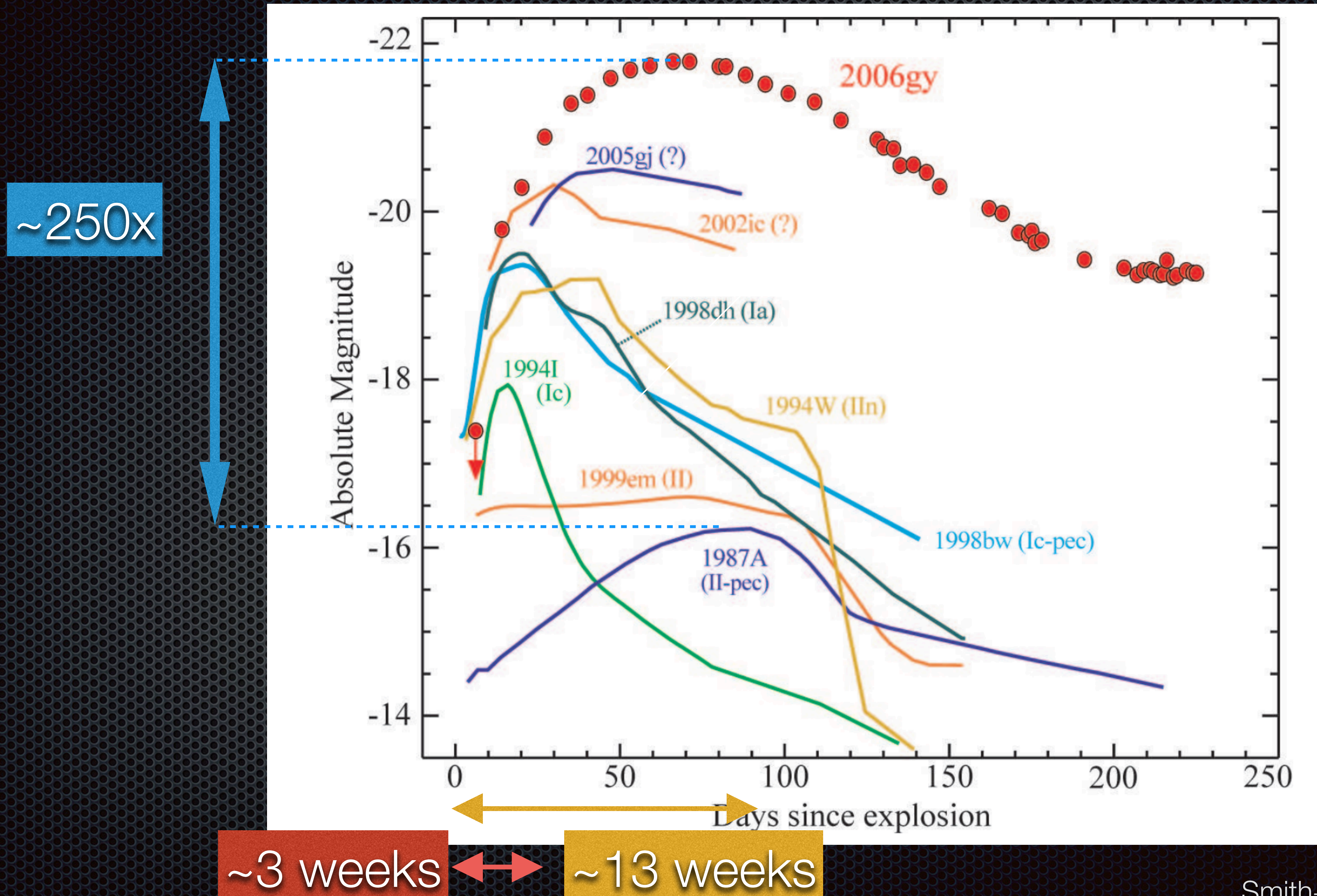
Most of what we historically know
about supernovae
is based on optical observations

In the optical, we've detected ~10^4 supernovae

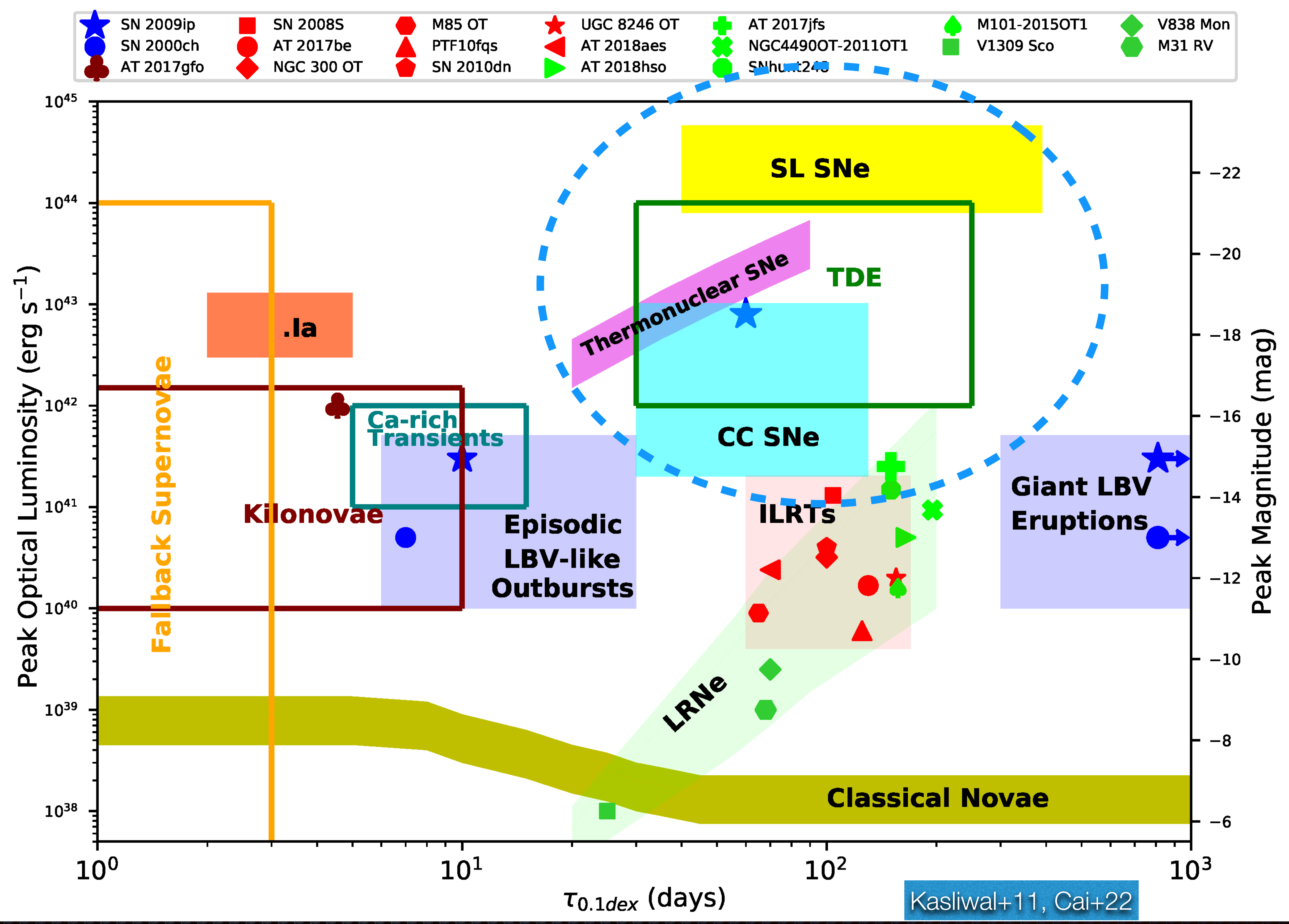
So we're sensitive to explosions as rare as ~1 in 10,000

[aside from systematic sample bias]

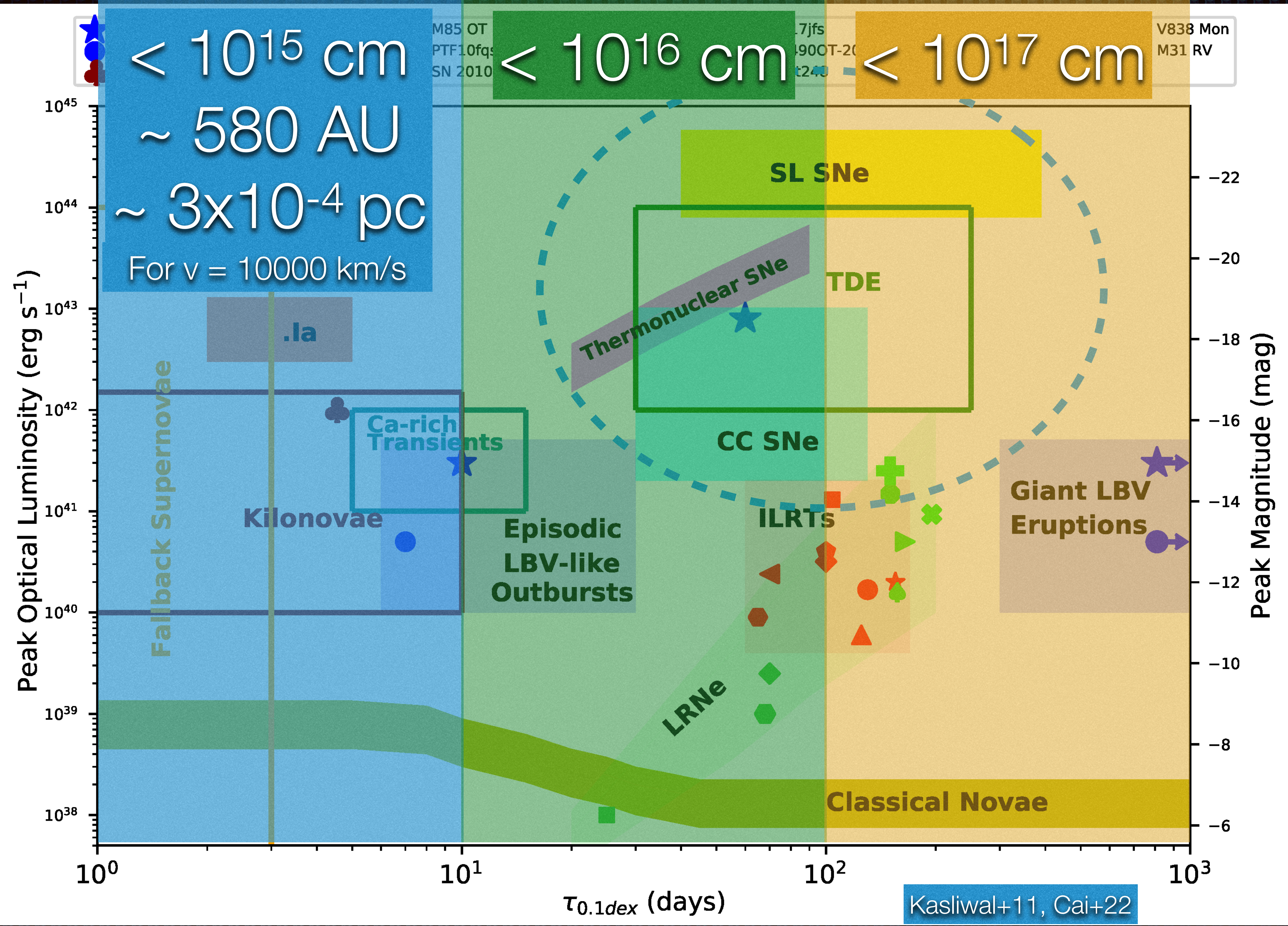
“Regular” optical supernovae peak at ~weeks to months; their peak luminosities span ~2-3 orders of magnitude



Smith+2007



SN 2009ip
SN 2000ch
AT 2017gfo
SN 2008S
AT 2017be
NGC 300 OT
M85 OT
PTF10fqs
SN 2010dn
UGC 8246 OT
AT 2018aes
AT 2018hso
AT 2017jfs
NGC4490OT-2011OT1
SNhunt248
M101-2015OT1
V1309 Sco
V838 Mon
M31 RV
SL SNe
TDE
Thermonuclear SNe
.Ia
CC SNe
Ca-rich Transients
Kilonovae
Fallback Supernovae
Episodic LBV-like Outbursts
ILRTs
Giant LBV Eruptions
LRNe
Classical Novae
Peak Optical Luminosity (erg s^{-1})
Peak Magnitude (mag)
$\tau_{0.1dex}$ (days)
Kasliwal+11, Cai+22



< 10^15 cm
~ 580 AU
~ 3x10^-4 pc
For v = 10000 km/s
< 10^16 cm
< 10^17 cm
M85 OT
PTF10fqs
V838 Mon
M31 RV
SL SNe
TDE
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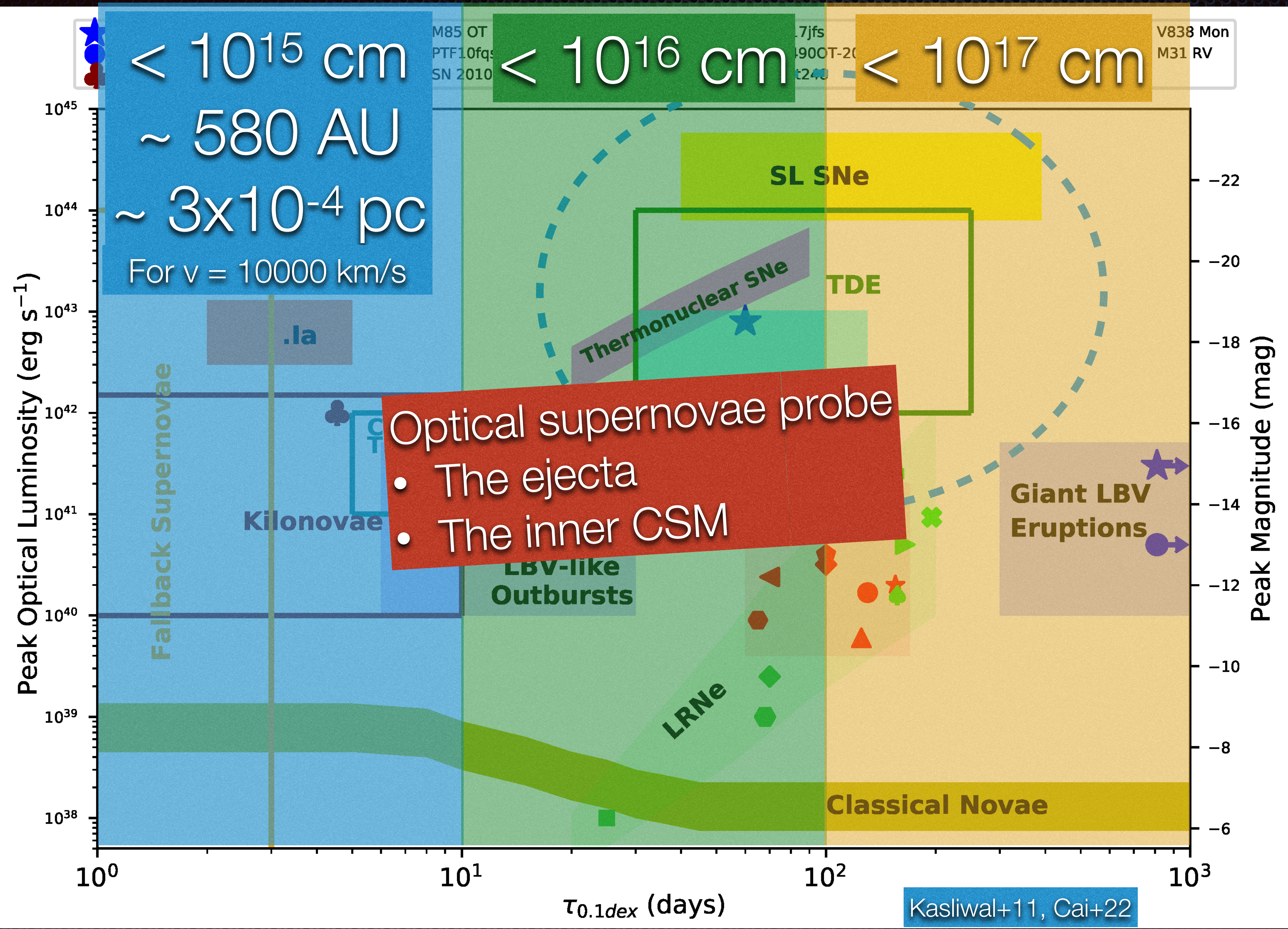

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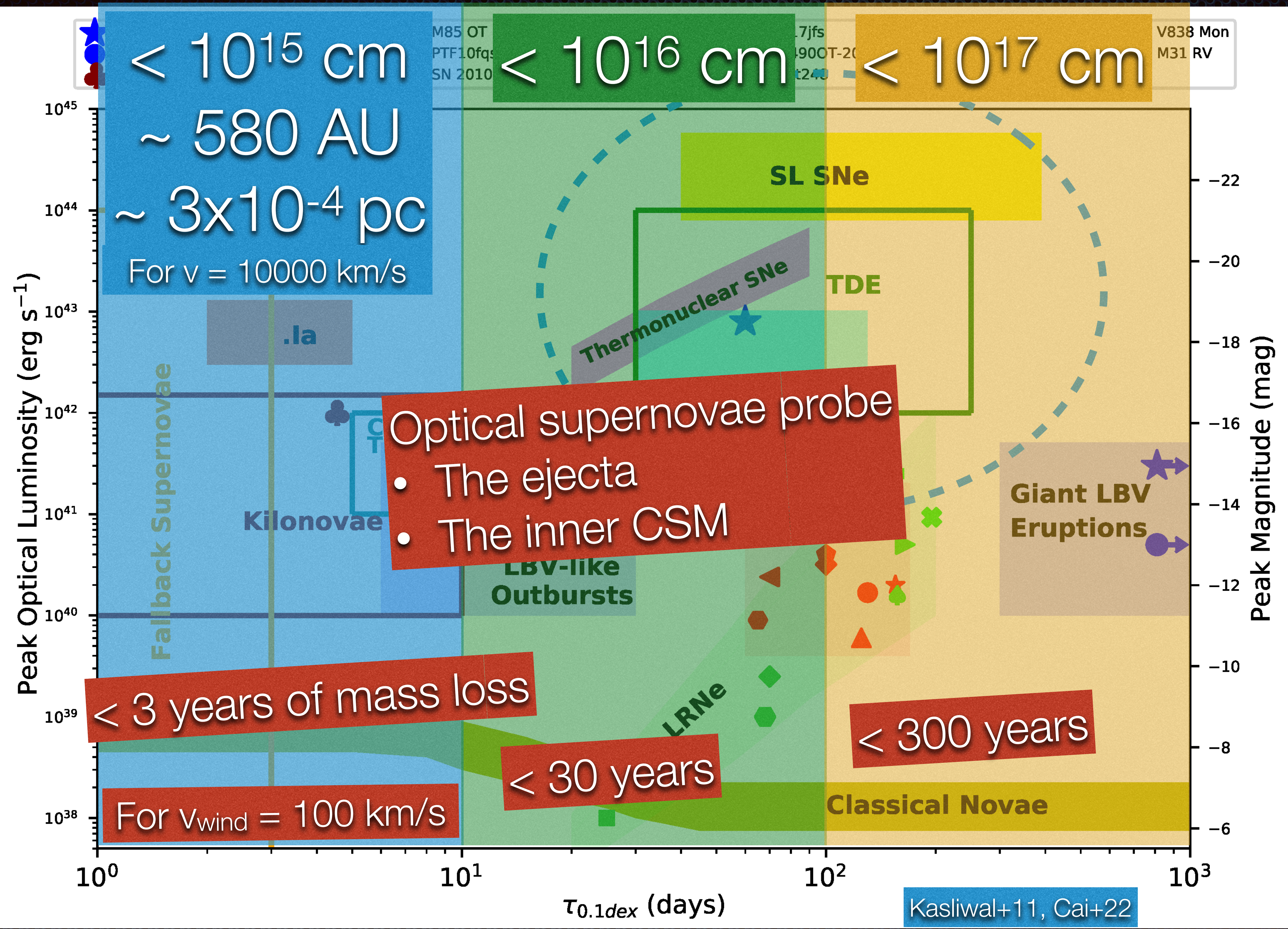
Classical Novae
Optical supernovae probe
• The ejecta
• The inner CSM
Peak Optical Luminosity (erg s^-1)
Peak Magnitude (mag)
τ0.1dex (days)
Kasliwal+11, Cai+22



< 10^15 cm
~ 580 AU
~ 3x10^-4 pc
For v = 10000 km/s
< 10^16 cm
< 10^17 cm
M85 OT
PTF10fqs
SN 2010
V838 Mon
M31 RV
SL SNe
TDE
Thermonuclear SNe
.Ia
Fallback Supernovae
Kilonovae
Optical supernovae probe
• The ejecta
• The inner CSM
LBV-like Outbursts
Giant LBV Eruptions
LRNe
Classical Novae
< 3 years of mass loss
< 30 years
< 300 years
For vwind = 100 km/s
Peak Optical Luminosity (erg s^-1)
Peak Magnitude (mag)
τ0.1dex (days)
Kasliwal+11, Cai+22

Radio observations are ramping up quickly

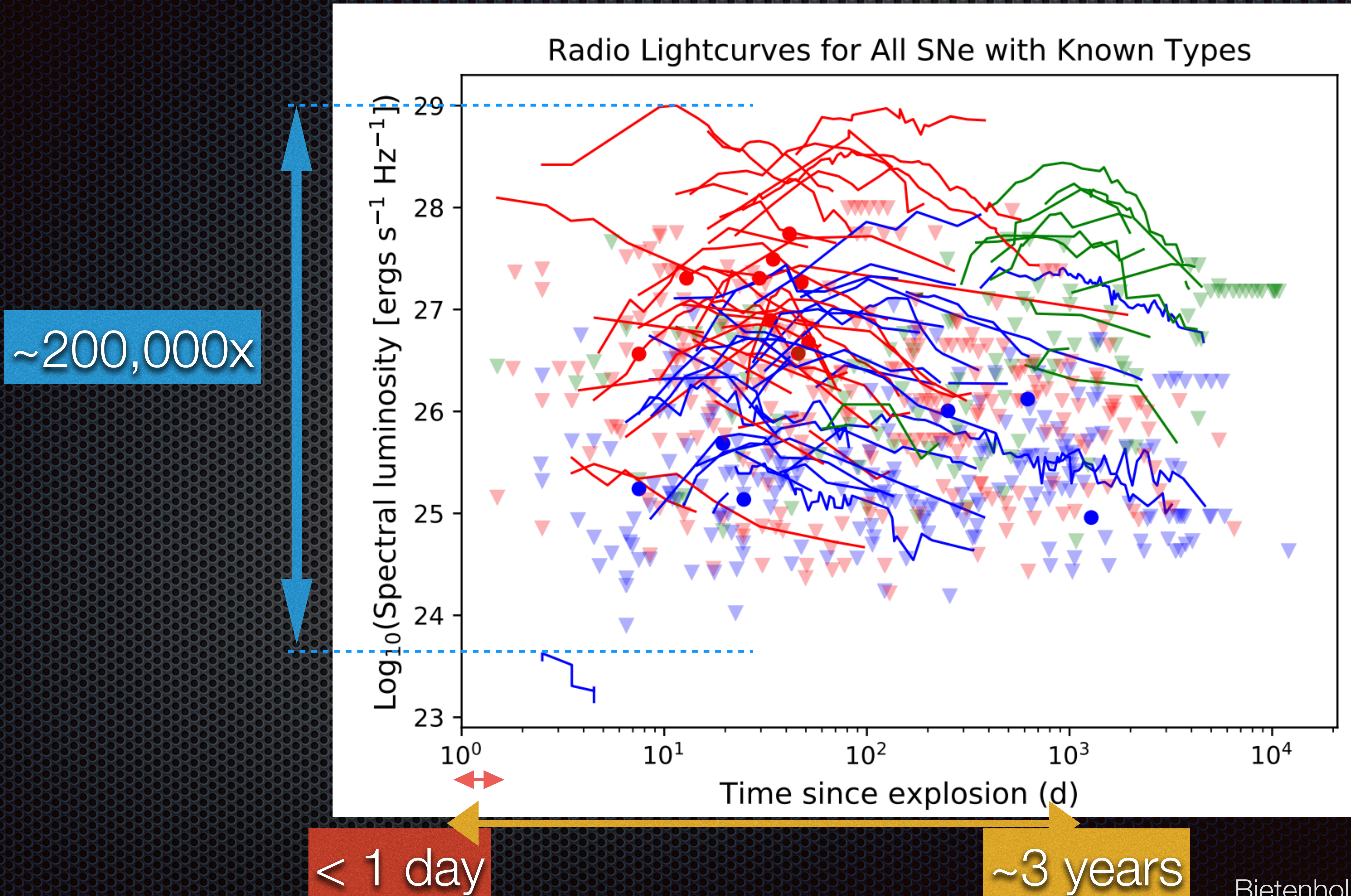
In the radio we've detected O(10^2) supernovae

Follow up observations

91 detections
234 observations

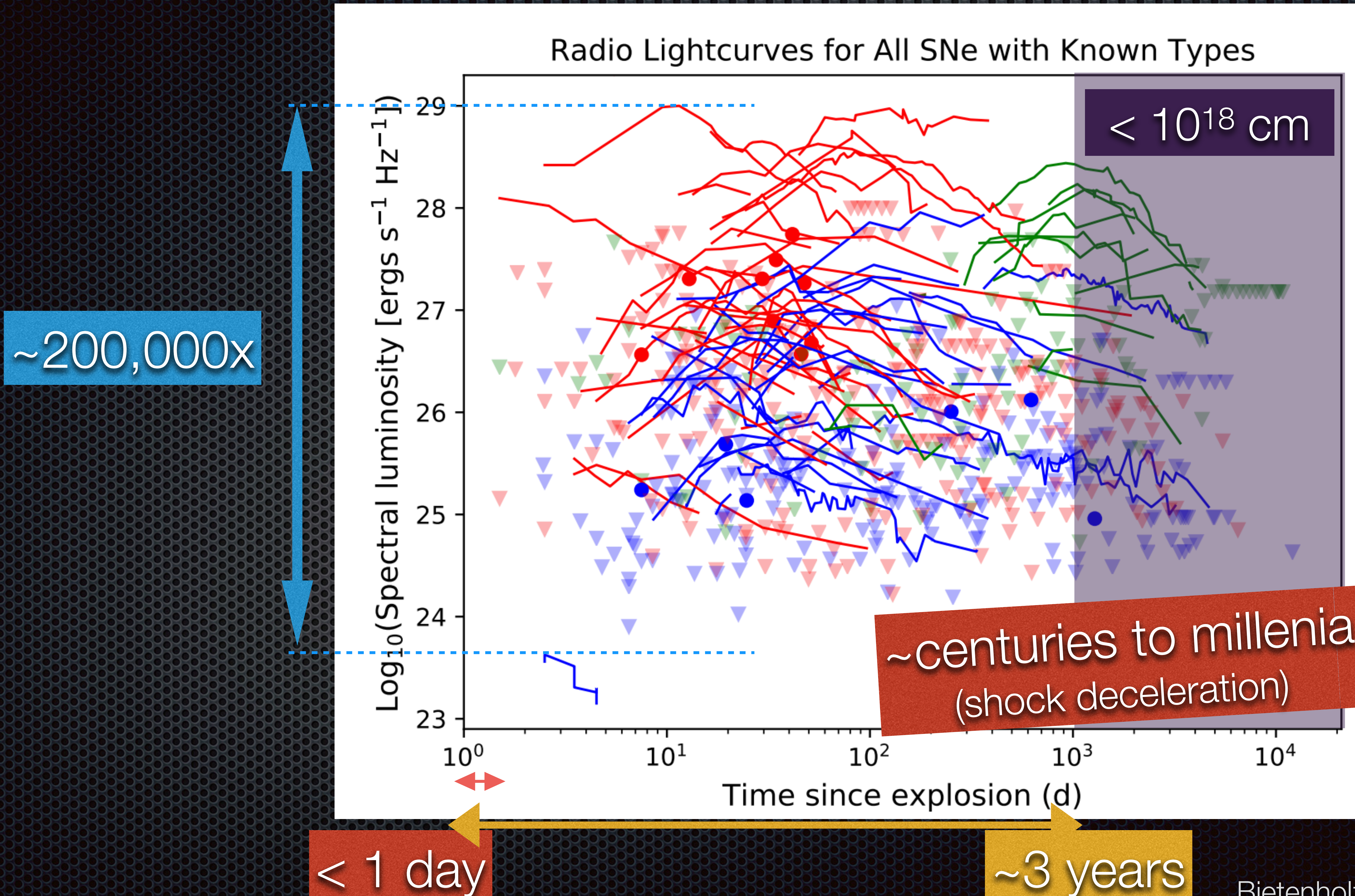
Bietenholz+20

Follow-up radio supernovae peak at ~days to years; their peak luminosities span >5 orders of magnitude



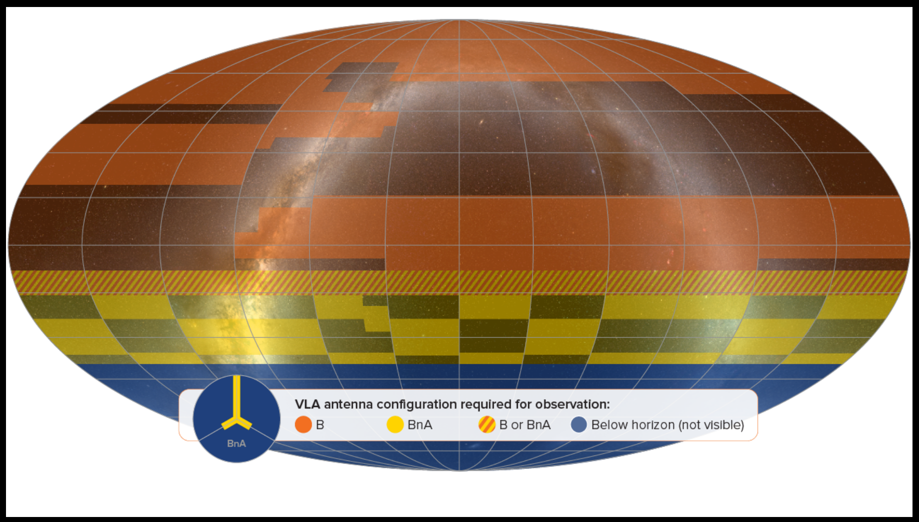
Bietenholz+20

The late peaks probe mass loss up to ~an order of magnitude earlier



Bietenholz+20

A growing number of radio supernovae detected in all-sky surveys



Follow up observations

Serendipitous detections in surveys

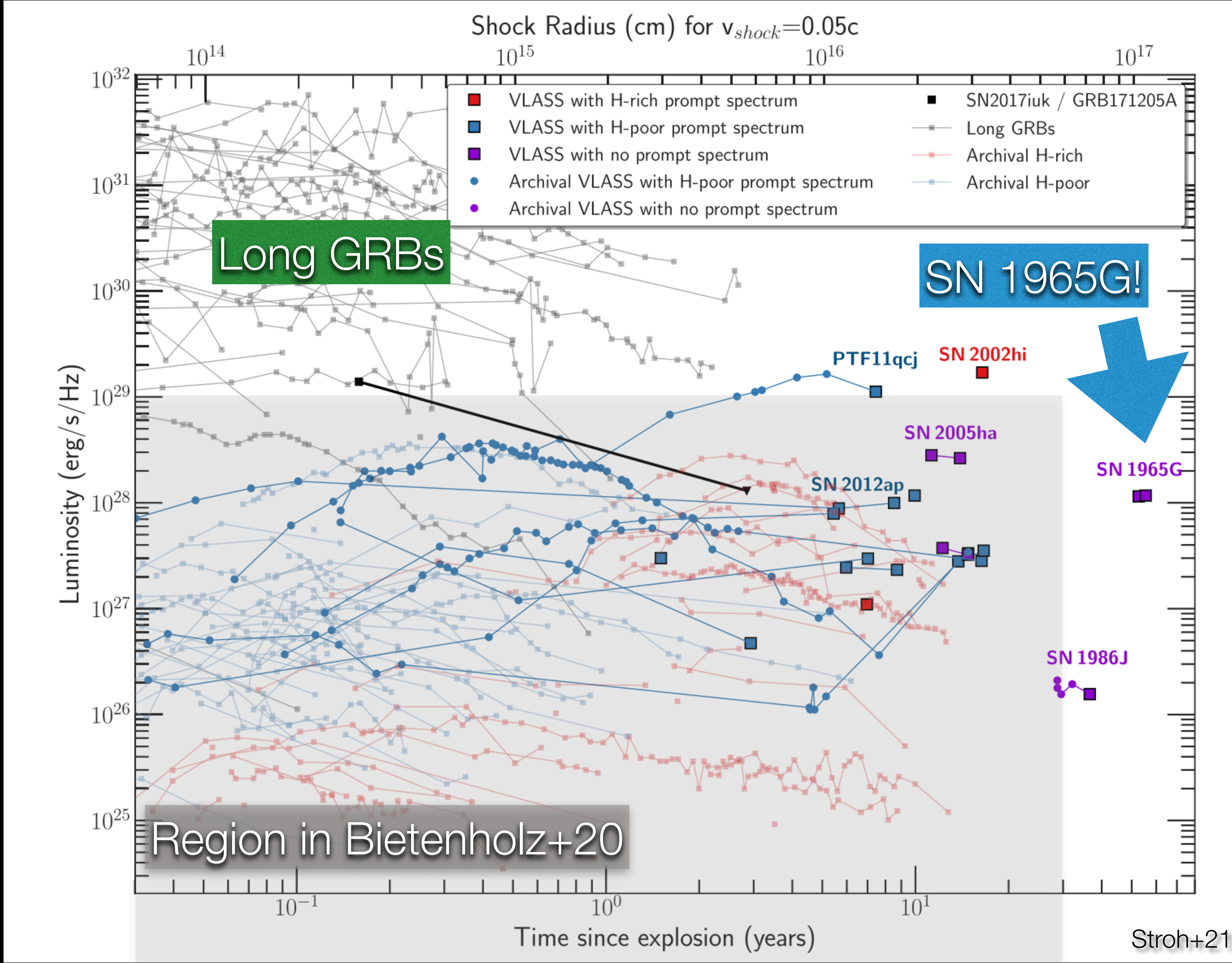
91 detections
234 observations

19 detections in VLASS

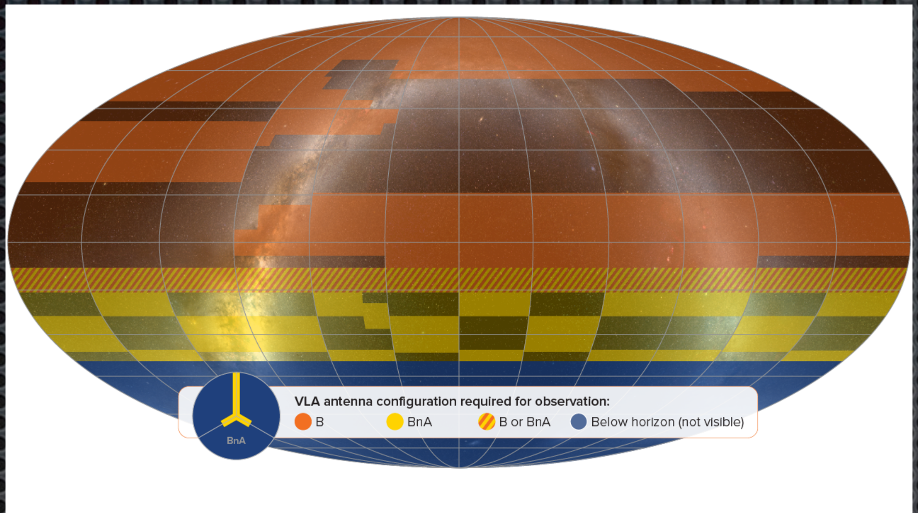
Bietenholz+20

Stroh+21

More in other surveys?


Shock Radius (cm) for v_{shock}=0.05c
VLASS with H-rich prompt spectrum
VLASS with H-poor prompt spectrum
VLASS with no prompt spectrum
Archival VLASS with H-poor prompt spectrum
Archival VLASS with no prompt spectrum
SN2017iuk / GRB171205A
Long GRBs
Archival H-rich
Archival H-poor
Long GRBs
SN 1965G!
PTF11qcj
SN 2002hi
SN 2005ha
SN 2012ap
SN 1965G
SN 1986J
Region in Bietenholz+20
Luminosity (erg/s/Hz)
Time since explosion (years)
Stroh+21

In the radio we've detected $O(10^2)$ supernovae



VLA SKY SURVEY

Follow up observations

91 detections
234 observations

Bietenholz+20

Serendipitous detections in surveys

+19 detections in VLASS

Stroh+21

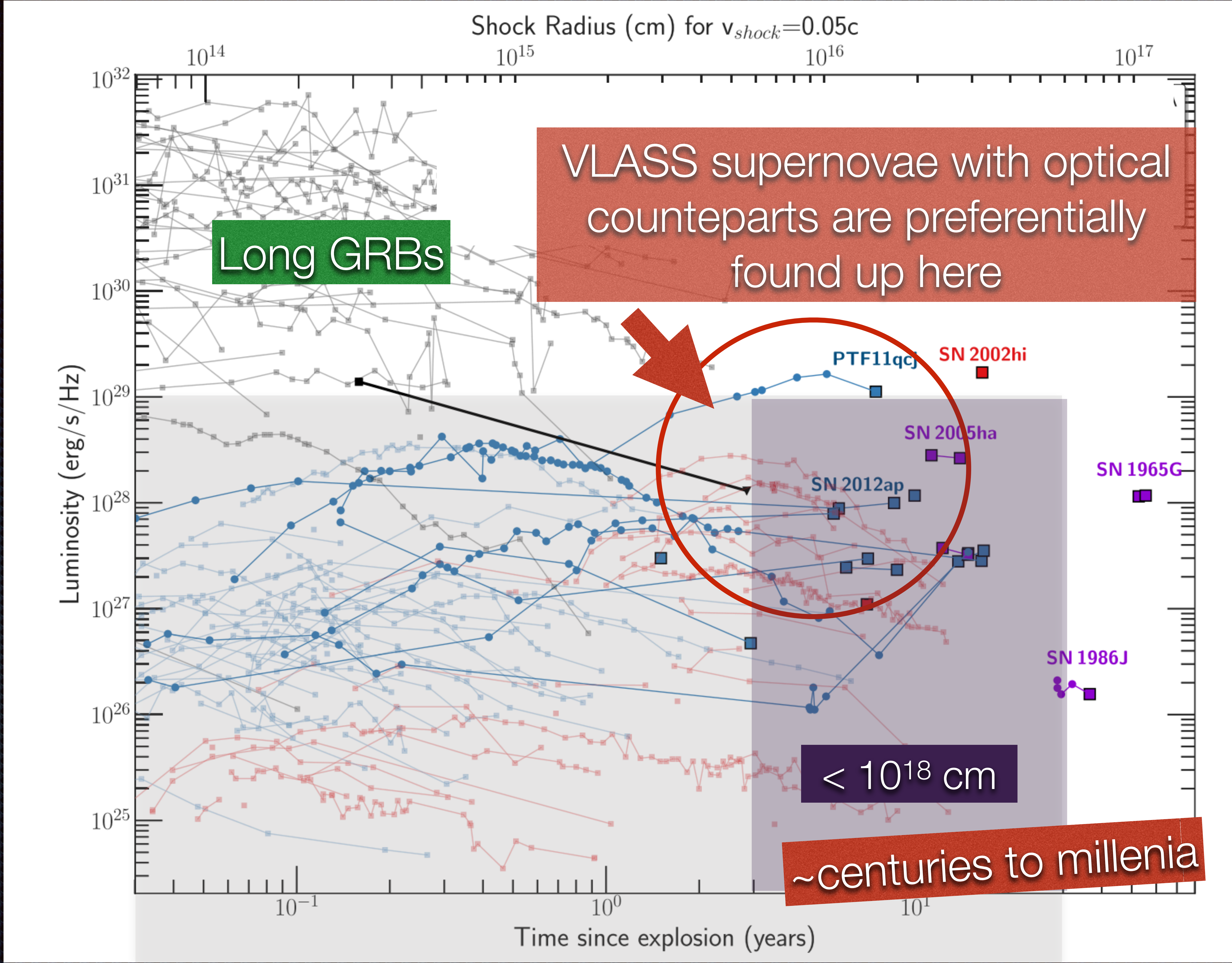
More in other surveys?

Direct detection in surveys

~a few dozen to 100 in VLASS

Dong et al. in prep

More in other surveys?


Shock Radius (cm) for v_{shock}=0.05c
10^{14}
10^{15}
10^{16}
10^{17}
VLASS supernovae with optical counteparts are preferentially found up here
Long GRBs
PTF11qcj
SN 2002hi
SN 2005ha
SN 1965G
SN 2012ap
SN 1986J
< 10^{18} cm
~centuries to millenia
Luminosity (erg/s/Hz)
10^{32}
10^{31}
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{-1}
10^{0}
10^{1}
Time since explosion (years)

Radio supernovae probe
1-2 orders of magnitude later
timescales than optical supernovae

This extends our probe of pre-supernova mass loss to earlier times

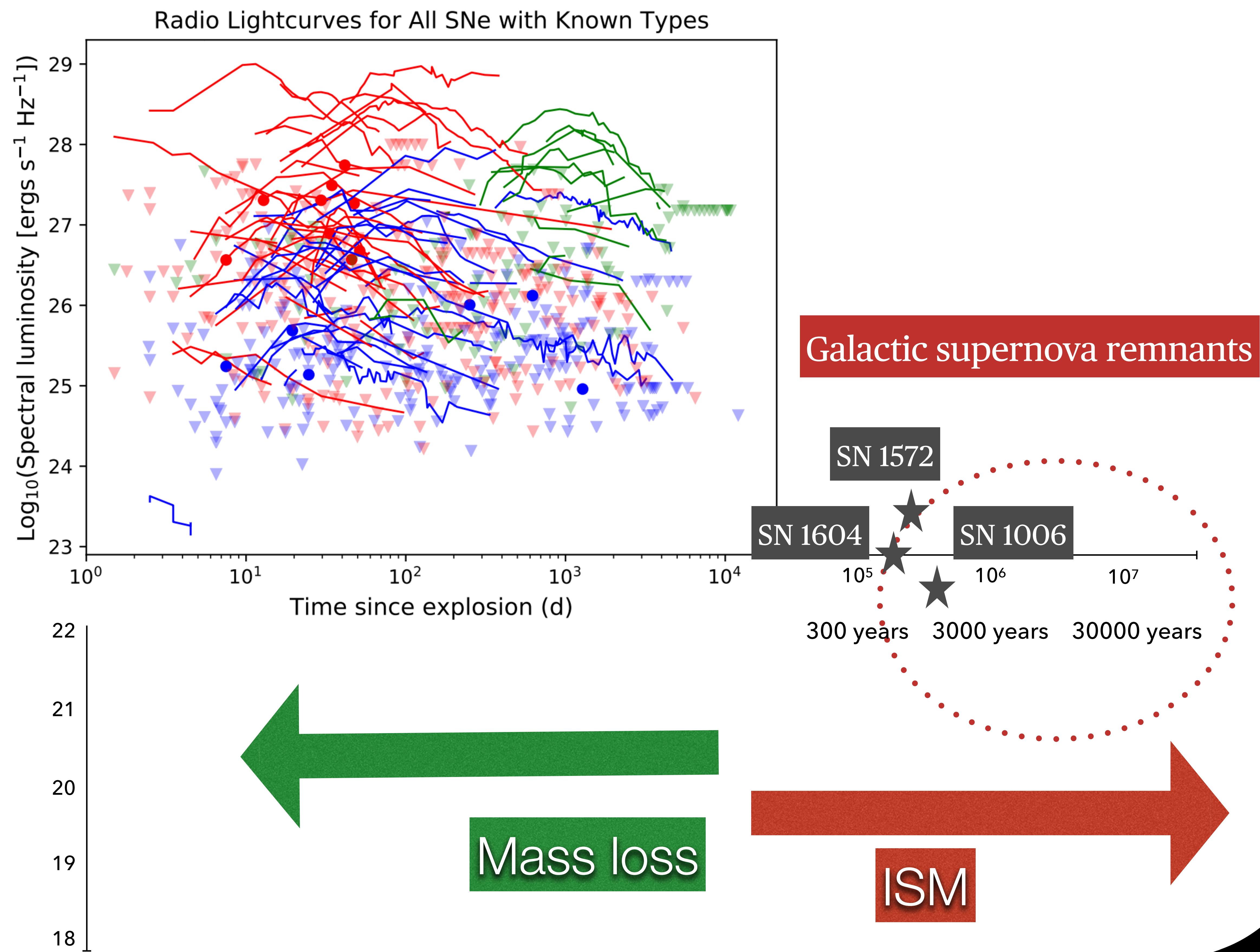
Radio supernovae probe
1-2 orders of magnitude later
timescales than optical supernovae

This extends our probe of pre-supernova mass loss by a similar factor

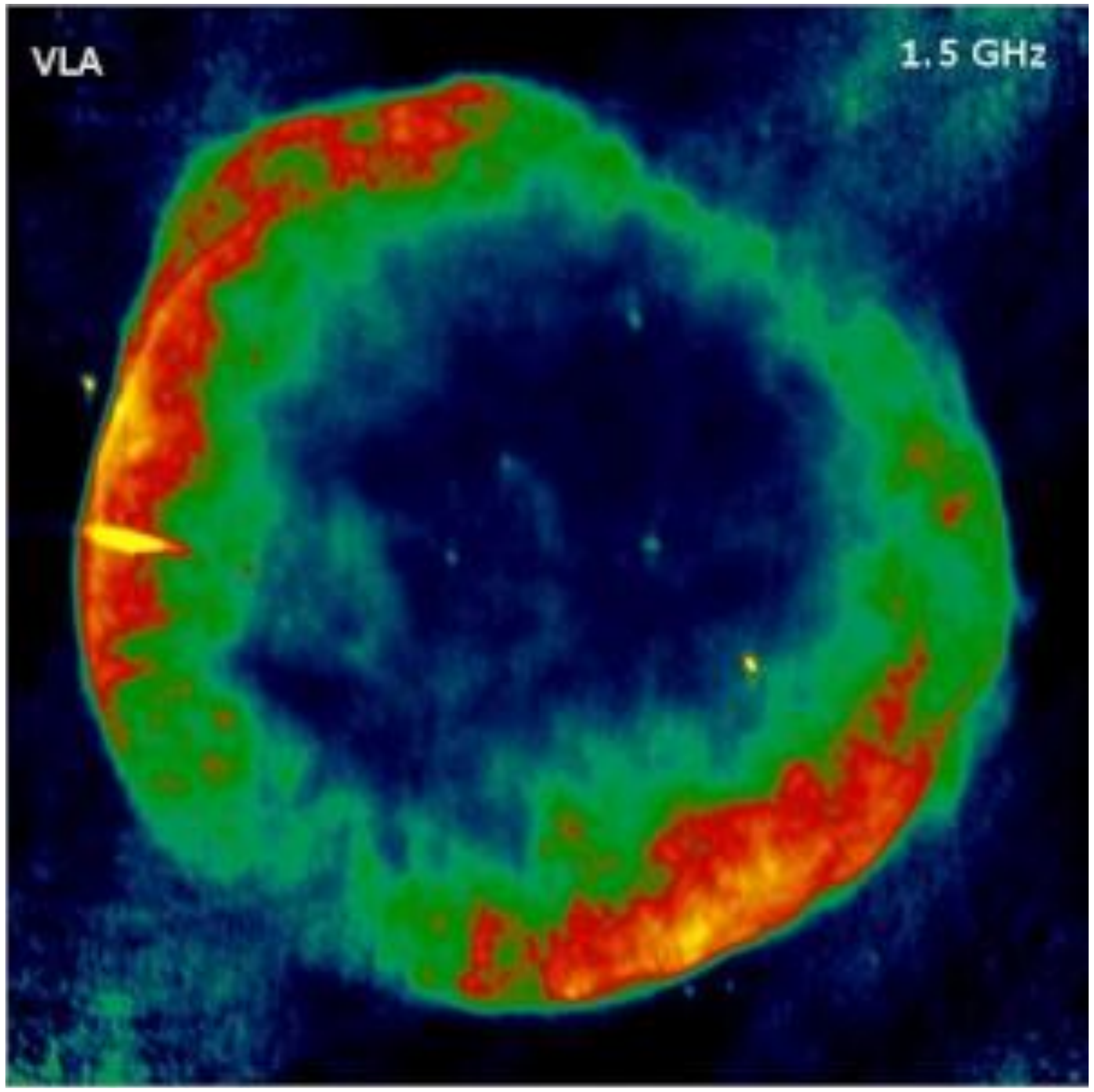
But what about the other axis?

What determines a supernova's radio luminosity?

This might be best illustrated with supernova *remnants*


Radio Lightcurves for All SNe with Known Types
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
26
25
24
23
Time since explosion (d)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
22
21
20
19
18
Galactic supernova remnants
SN 1572
SN 1604
SN 1006
300 years
3000 years
30000 years
Mass loss
ISM

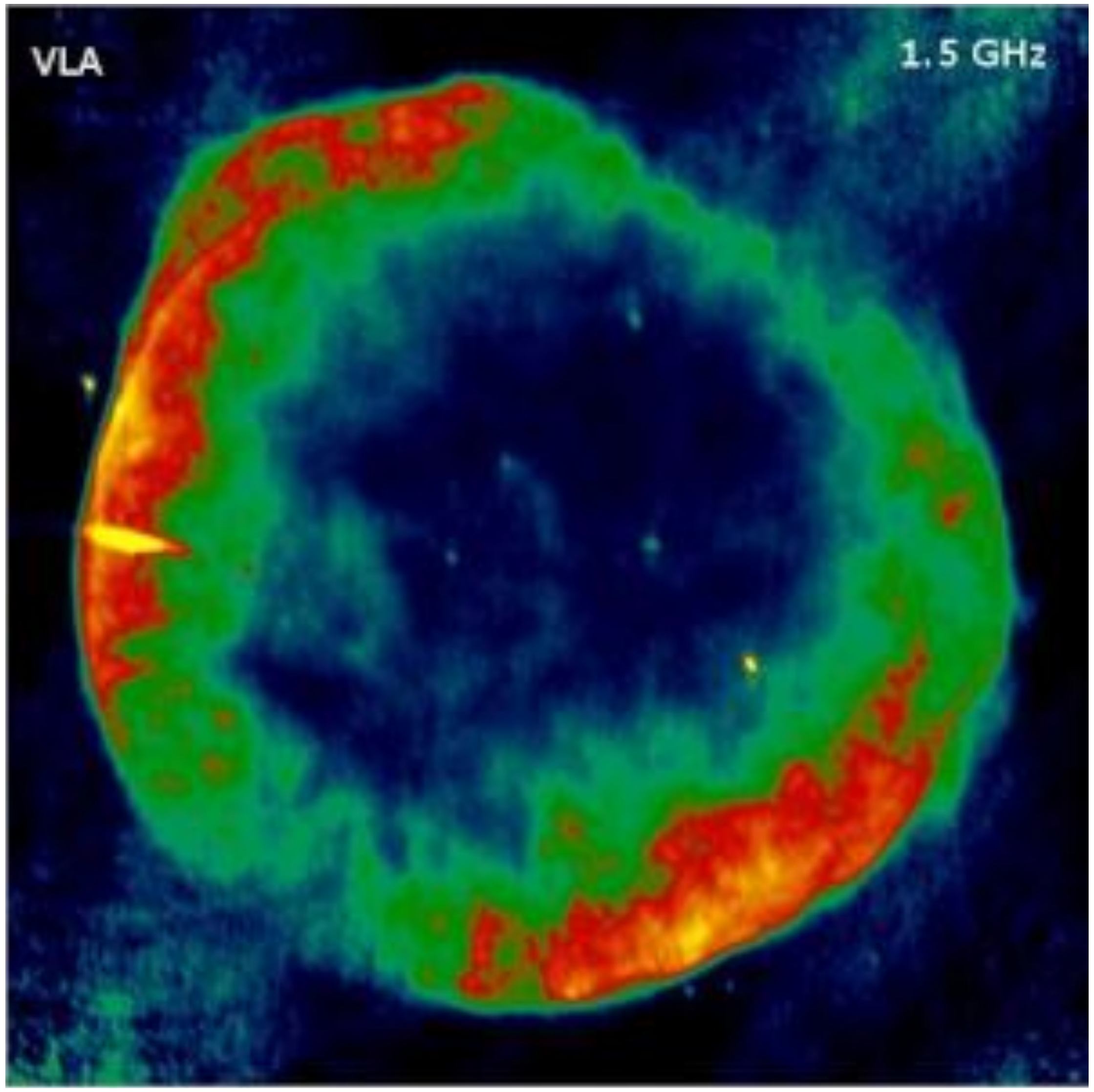
Rothenflug+04



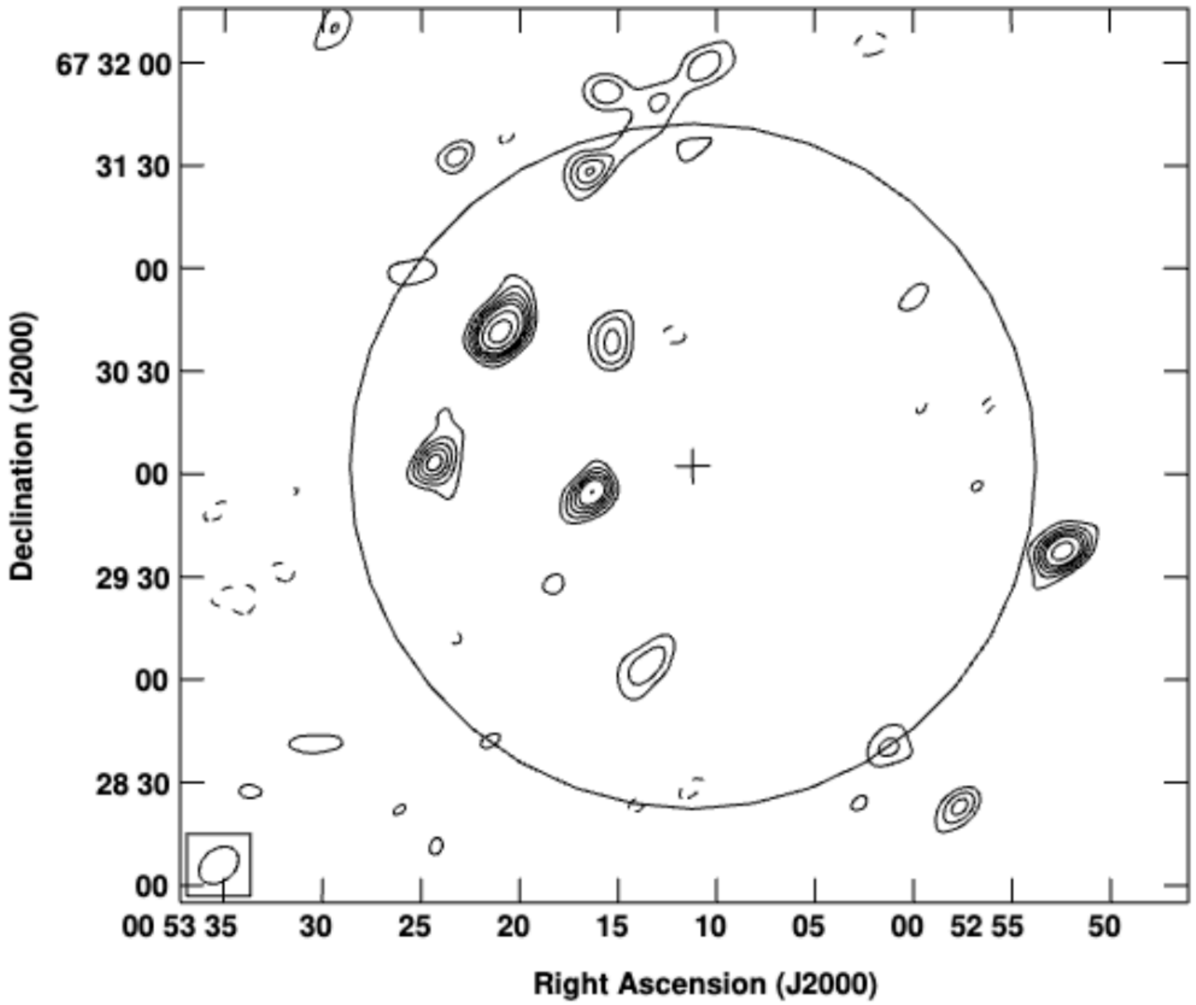
Type Ia SN 1006 (d = 1.9 kpc)

Integrated flux 19 Jy

Rothenflug+04



Dong, Frail et al. in prep



Type Ia SN 1006 (d = 1.9 kpc)

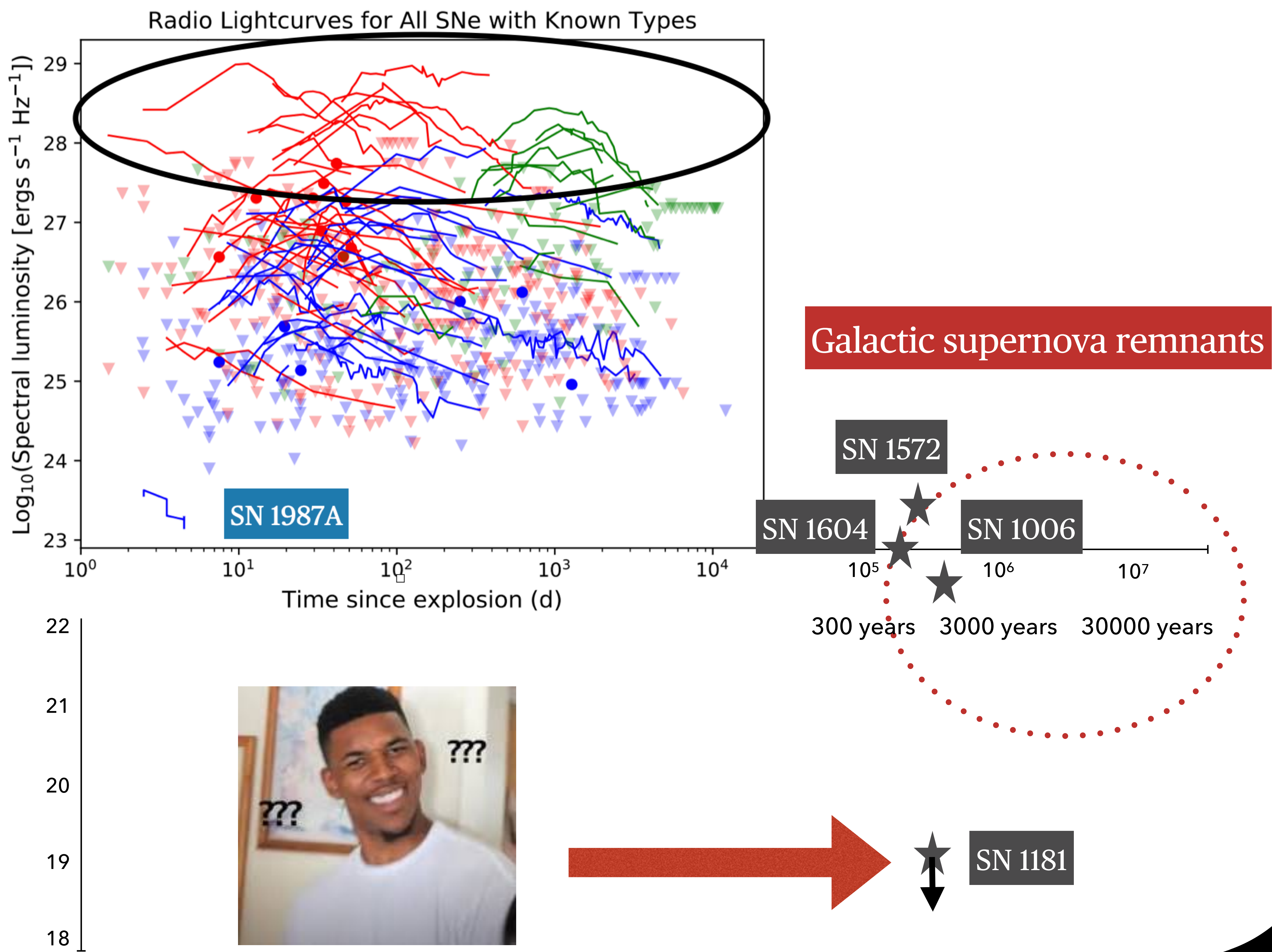
Integrated flux 19 Jy

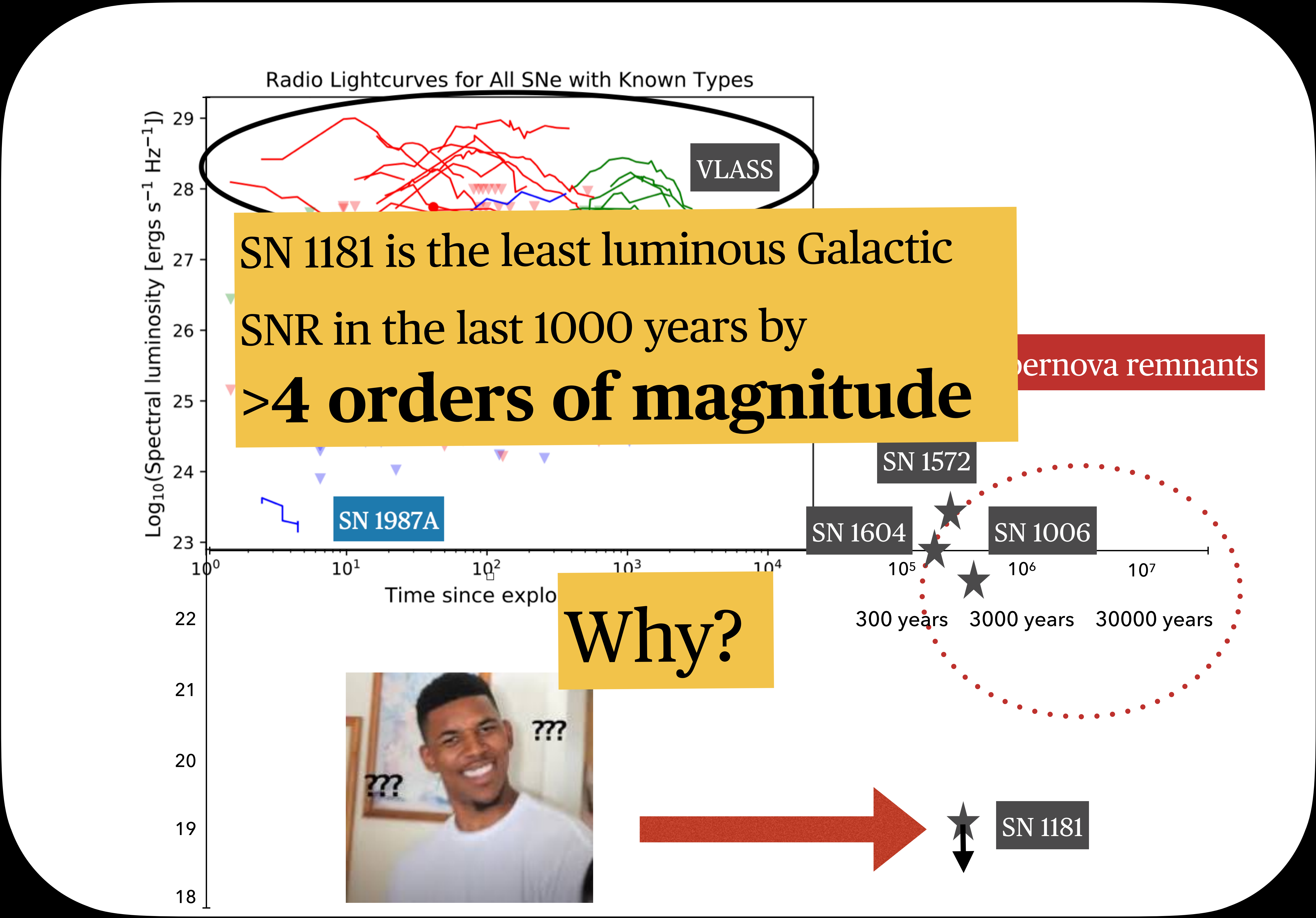
Equivalent to 1.7mJy/beam

Type Iax SN 1181 (d = 2.3 kpc)

Integrated flux < 0.6mJy

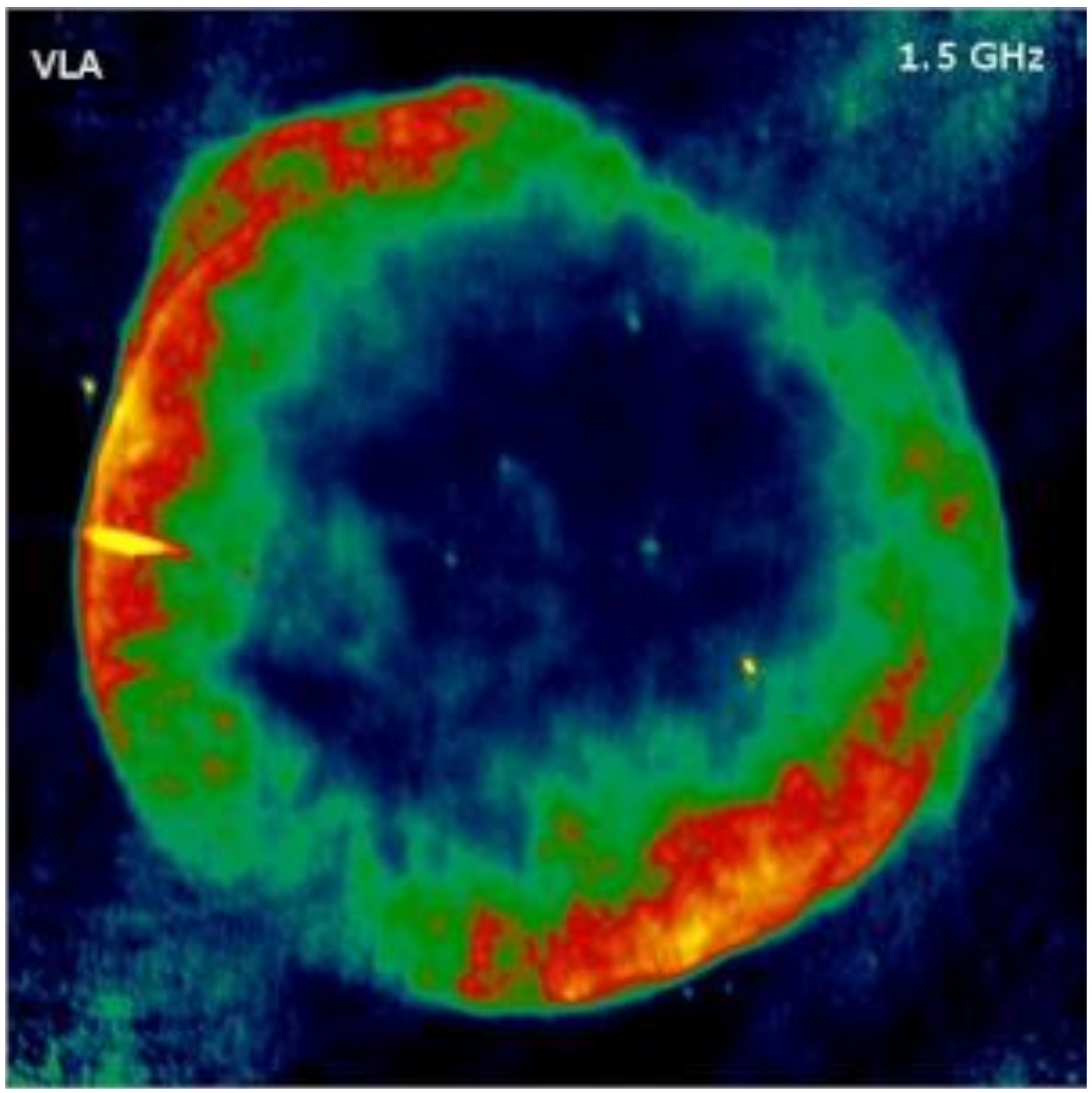
< 14uJy / beam


Radio Lightcurves for All SNe with Known Types
Log10(Spectral luminosity [ergs s^-1 Hz^-1])
29
28
27
26
25
24
23
22
21
20
19
18
10^0
10^1
10^2
10^3
10^4
Time since explosion (d)
SN 1987A
Galactic supernova remnants
SN 1572
SN 1604
SN 1006
10^5
10^6
10^7
300 years
3000 years
30000 years
???
???
SN 1181

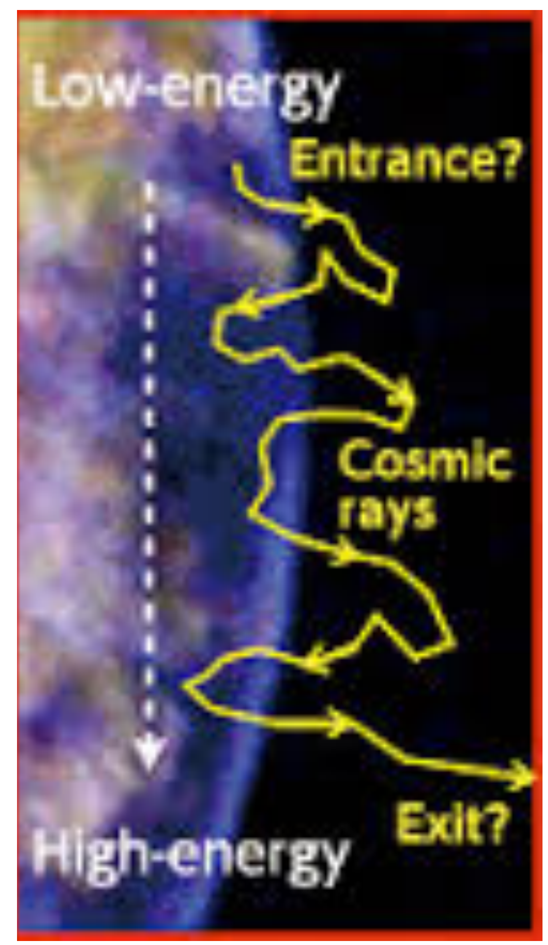

Radio Lightcurves for All SNe with Known Types
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
26
25
24
23
22
21
20
19
18
VLASS
SN 1987A
Time since explo
SN 1181 is the least luminous Galactic
SNR in the last 1000 years by
>4 orders of magnitude
pernova remnants
SN 1572
SN 1604
SN 1006
300 years
3000 years
30000 years
Why?
???
???
SN 1181

What determines a SNR’s radio luminosity?

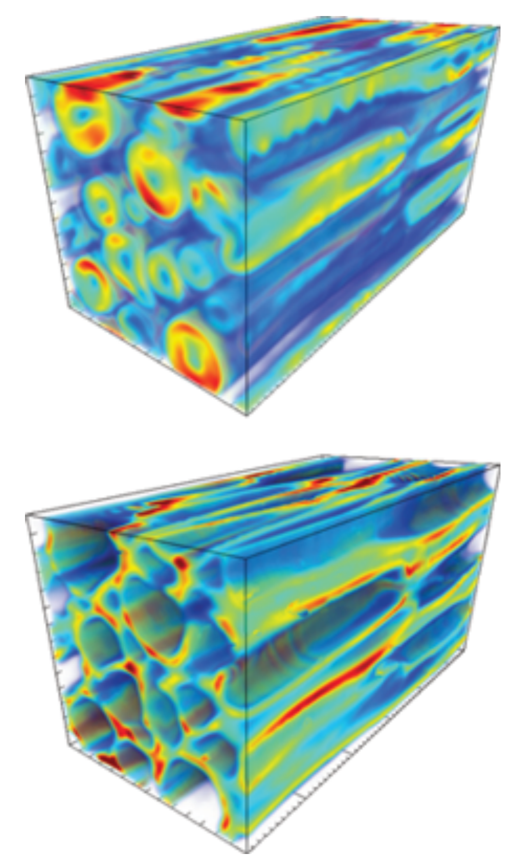
Radio emission from supernovae is mostly synchrotron emission from the forward shock



DIFFUSIVE SHOCK ACCELERATION



MAGNETIC FIELD AMPLIFICATION



The radio luminosity is directly determined by (1) emitting region volume, (2) electron density, (3) magnetic field strength

Constants

Rel. electron density (ingredient 2)

$$L_\nu = 2\pi^2 c_5 r_s^3 N_0 B^{\alpha+1} \left(\frac{\nu}{2c_1}\right)^{-\alpha}$$

Shock radius (ingredient 1)

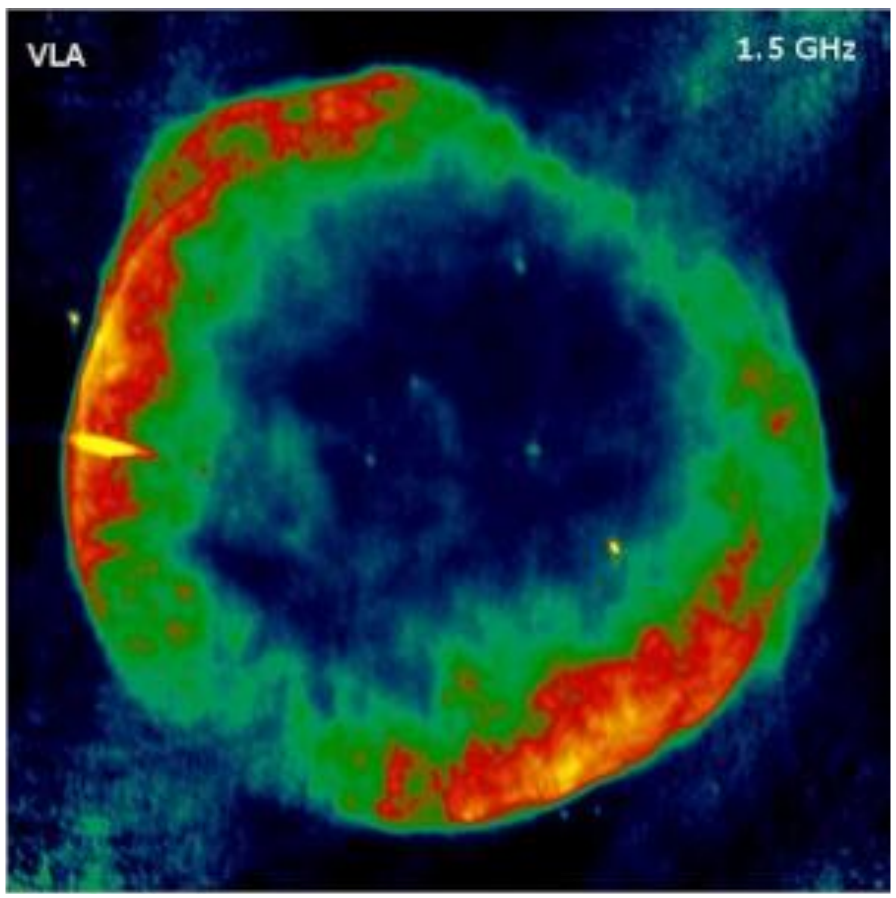
B field strength (ingredient 3)

Slightly modified from Chevalier (1998)

In the optically thin limit for a simplified geometry

See Sarbadhicary+17 for a more general equation that includes synchrotron self-absorption

The supernova remnant's size/velocity is determined by the energy, ejecta mass (profile), and CSM density



Ingredient #1:

the volume of the emitting region

$$r_s(t) = (1.3\,\mathrm{pc})\ t_{100}^{0.7}\ n_\circ^{-0.1}\ \mathrm{E}_{51}^{0.35}\ \mathrm{M}_{ej}^{-0.25}$$

$$v_s(t) = (8800\,\mathrm{km\,s^{-1}})\ t_{100}^{-0.3}\ n_\circ^{-0.1}\ \mathrm{E}_{51}^{0.35}\ \mathrm{M}_{ej}^{-0.25}$$

The particles are accelerated in a power law energy distribution

$$N(E) = N_0 E^{-p}$$

p is related to the radio spectral index α by

α = (p-1)/2

Number density per energy of relativistic electrons

[erg/cm^3]

Ingredient #2:

the number density (and spectral index) of relativistic electrons

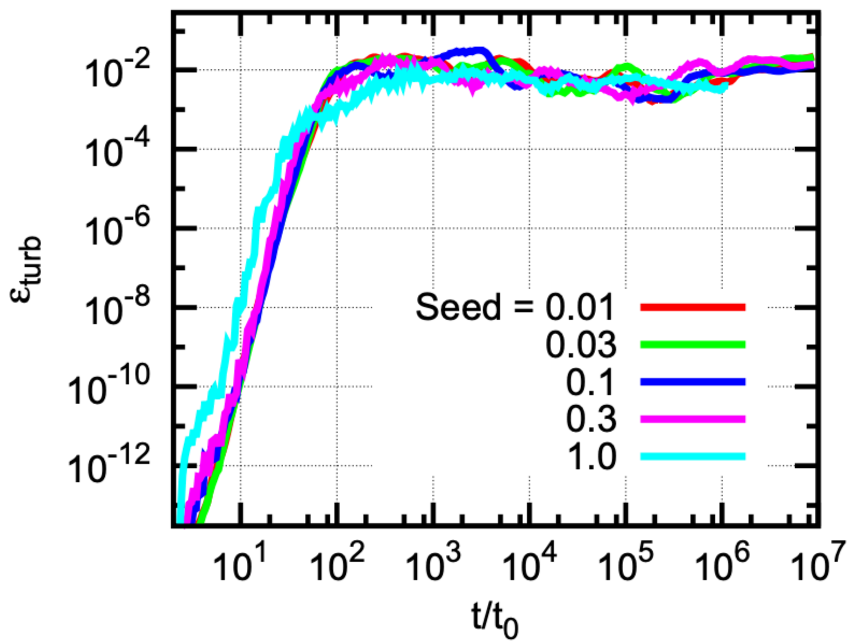
$$N_0 = (p-2)\ \epsilon_e\ \rho_0 v_s^2\ E_m^{p-2}$$

The relativistic particles create streaming instabilities ahead of the shock.

This accelerates the magnetic field to a saturation level that depends on the shock's energy, velocity, particle acceleration efficiency & (sometimes) initial magnetic field

Ingredient #3:

the strength of the magnetic field



Duffell +18

Fraction of shock energy in B field

Particle acceleration efficiency

The amplification is uncertain, but a reasonable analytic description is:

Sarbadhicary+17

$$\epsilon_B = \frac{\xi_{cr}}{2}\left(\frac{v_s}{c} + \frac{1}{M_A}\right)$$

Shock velocity

Alfven Mach number

$$M_A = v_s/v_A \quad v_A = B_0/\sqrt{4\pi\rho_0}$$

Can use the above to create lightcurves for SNRs

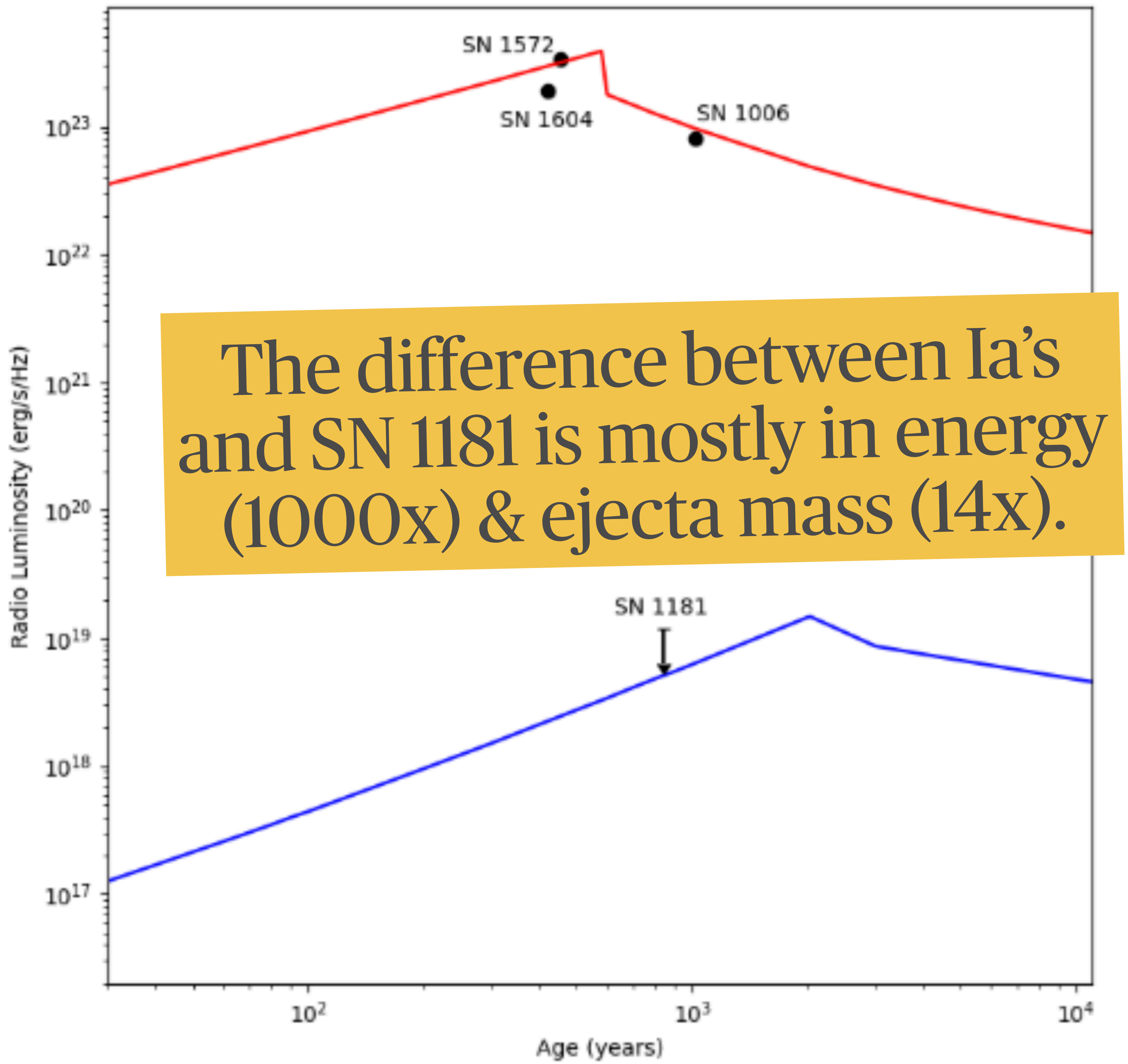
Fiducial model for regular Type Ias

- n= 0.1 cm^{-3}
- E = 1e51 erg
- M = 1.4 solar masses

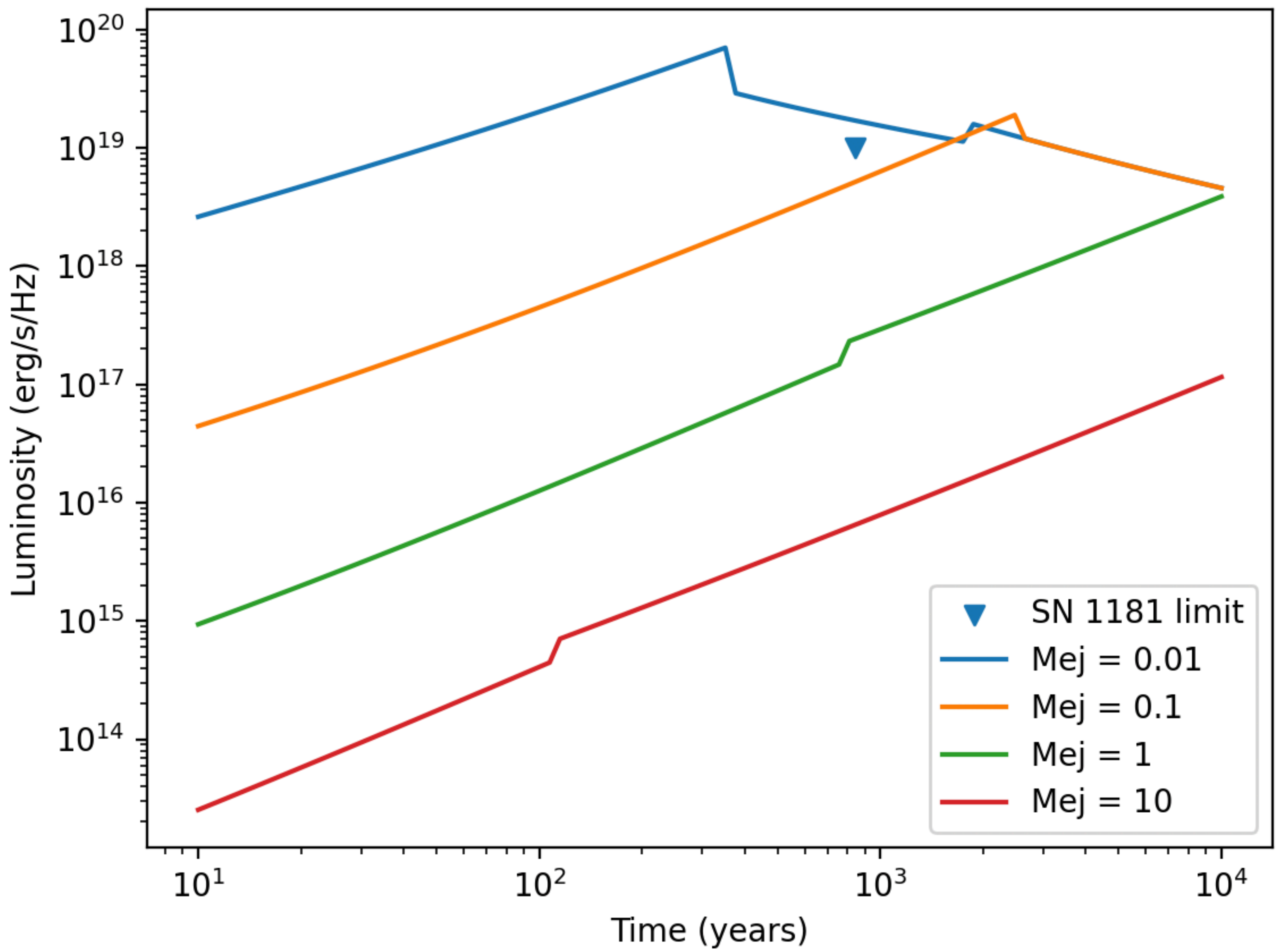
Fiducial model for SN 1181

- n= 0.1 cm^{-3}
- E = 1e48 erg
- M = 0.1 solar masses

Parameters based on X-ray analysis (Ko+23,24)



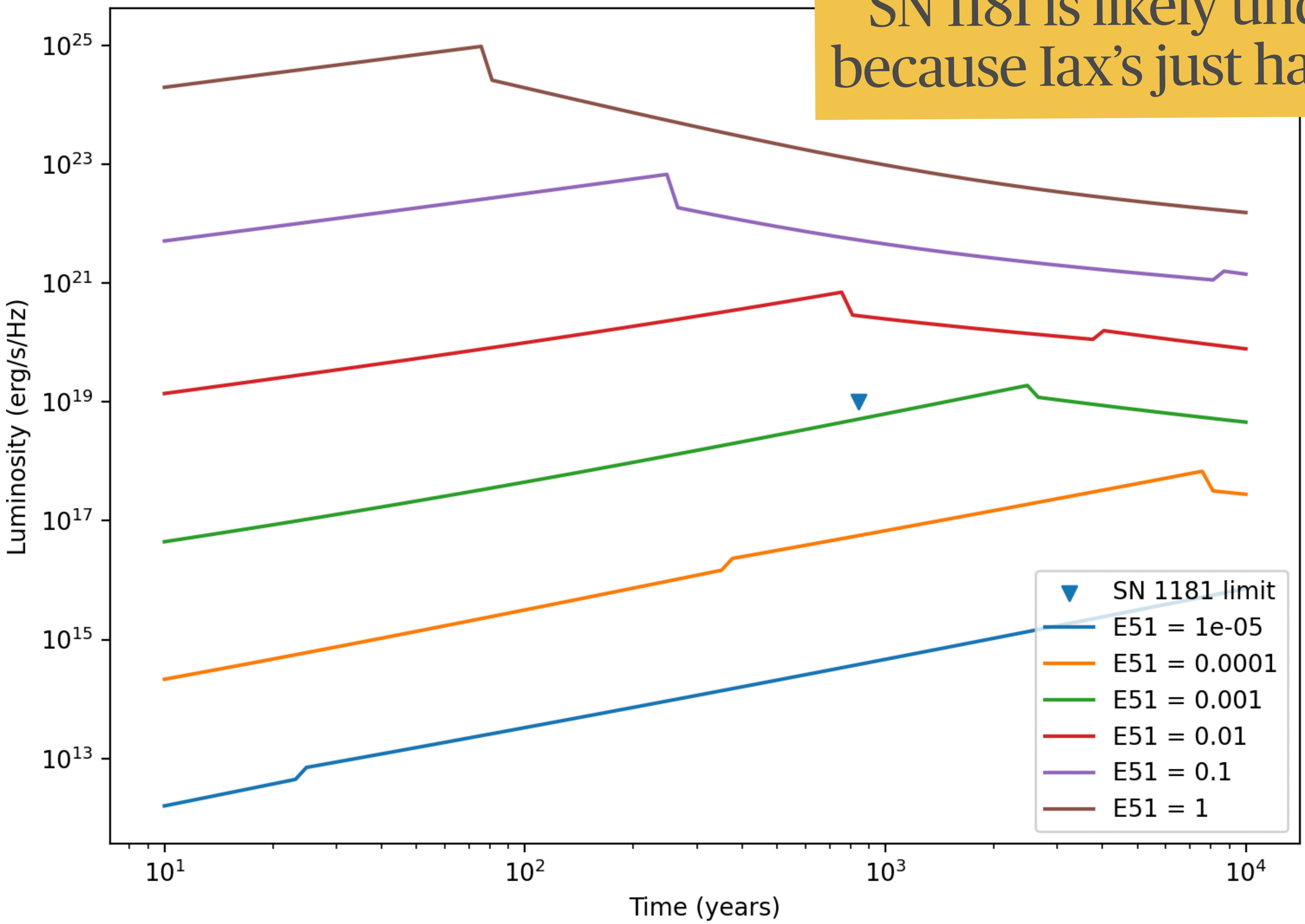
Lowering ejecta mass *increases* the radio luminosity



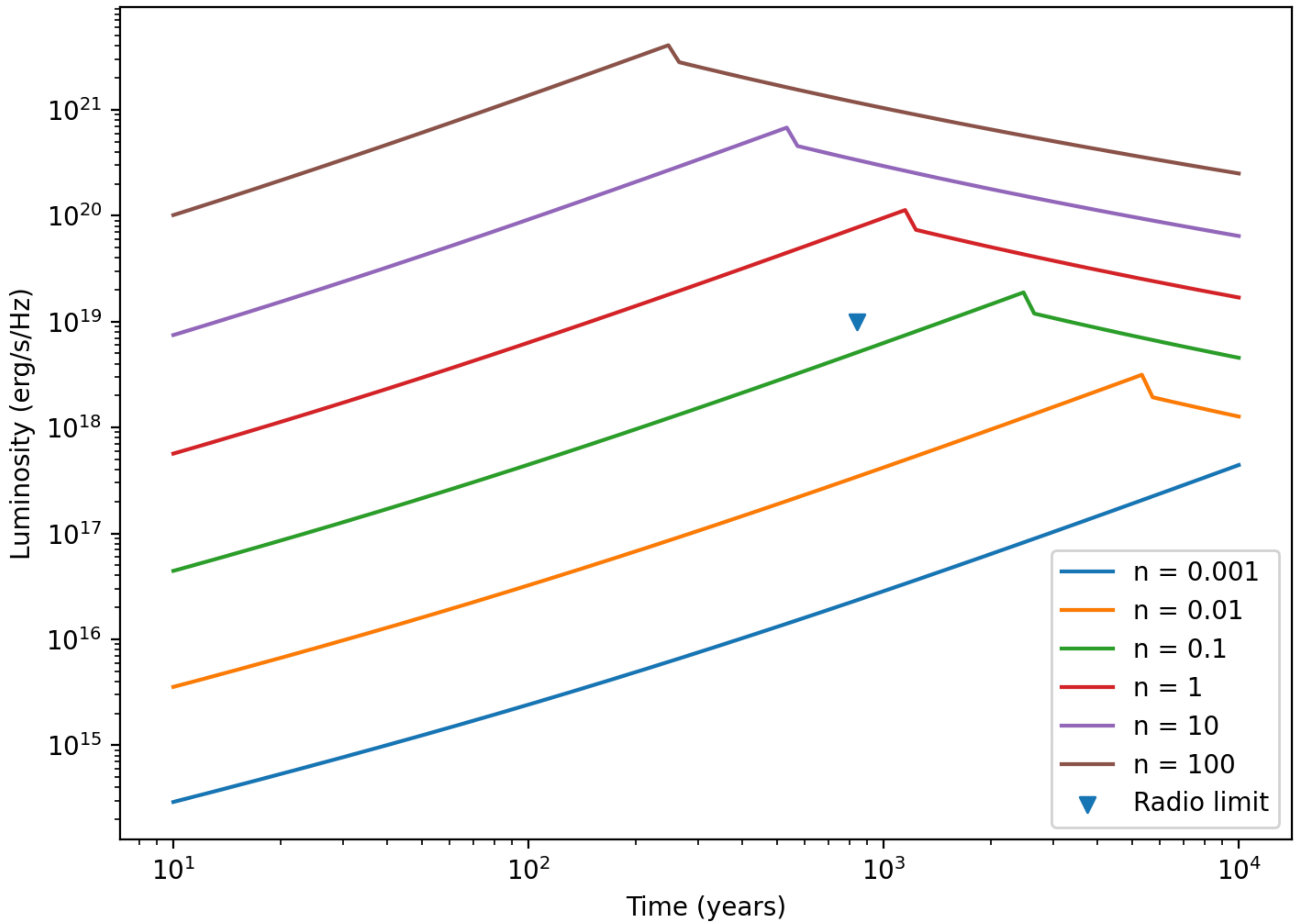
So that's not the reason…

Decreasing the energy *sharply* decreases the luminosity

SN 1181 is likely underluminous because Iax's just have low energy



Decreasing density also significantly lowers luminosity



A supernova / SNR's *unabsorbed* luminosity is set by

Volume

B field

Relativistic electron density + spectral index

↔

Ejecta energy

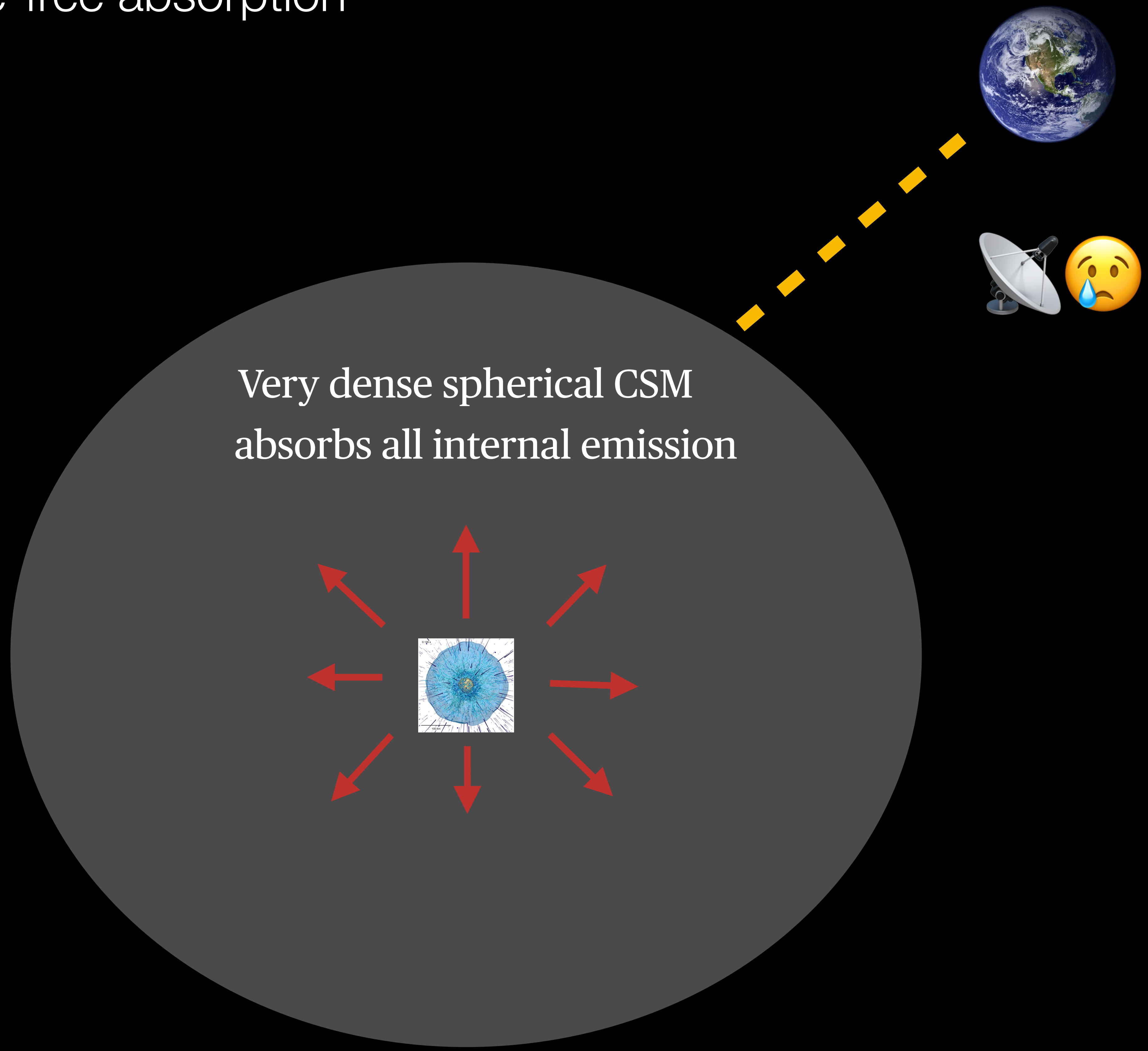
Ejecta mass

Mass loss (SNe)
ISM density (remants)

When you include absorption, there is also

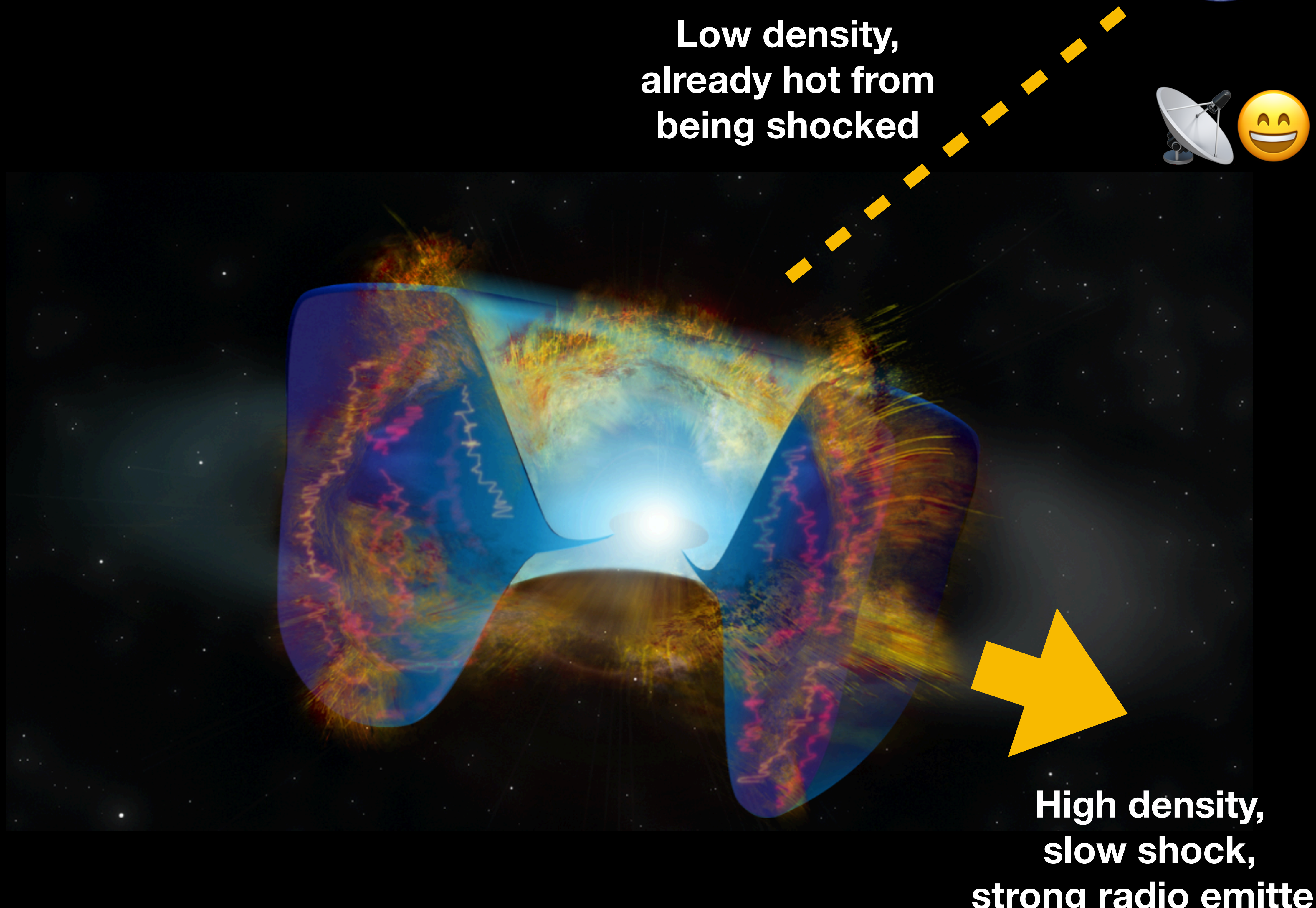
Emitting region geometry

Example: free-free absorption



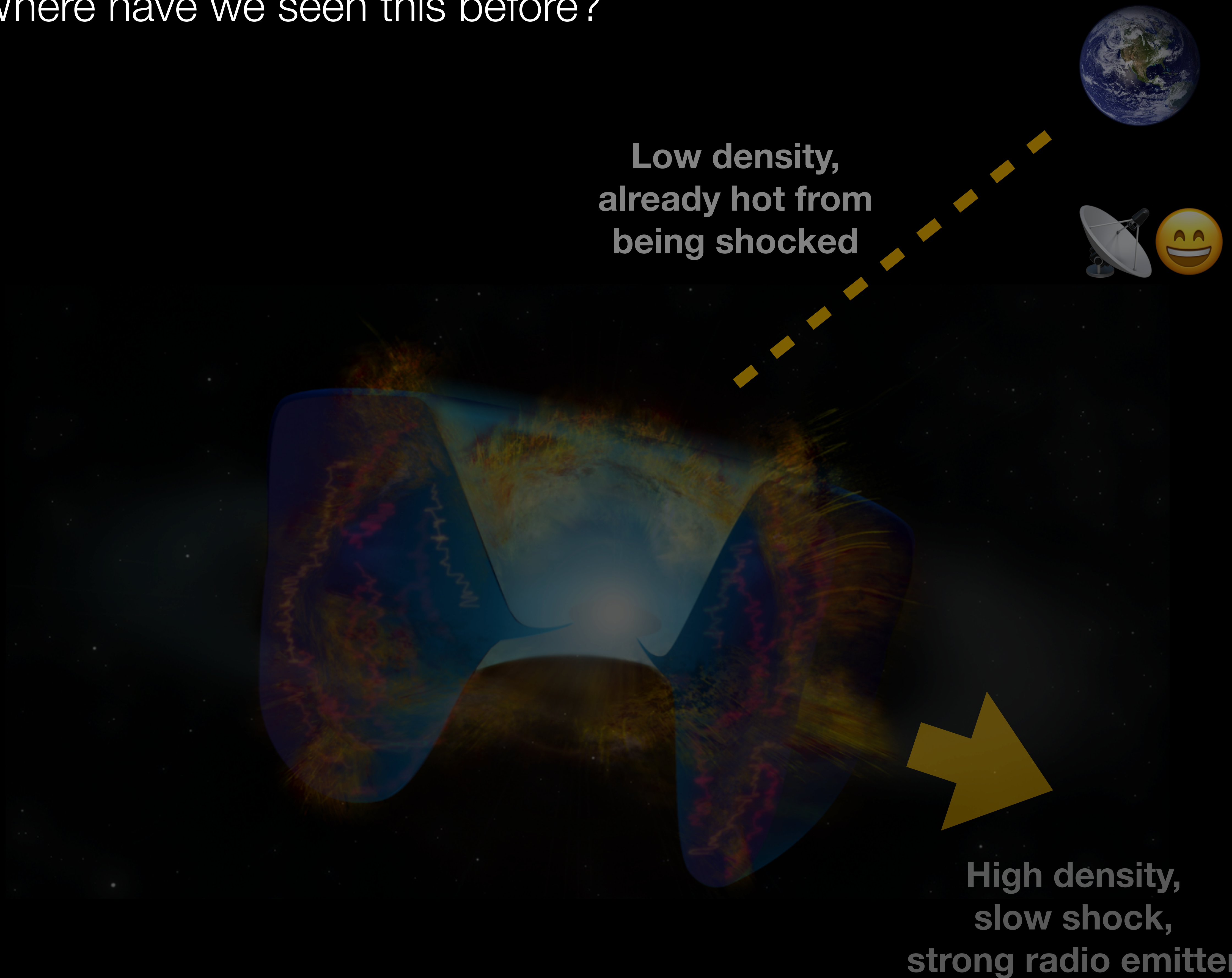
Dong+21

But you can get around this with the power of geometry!



Dong+21

Where have we seen this before?



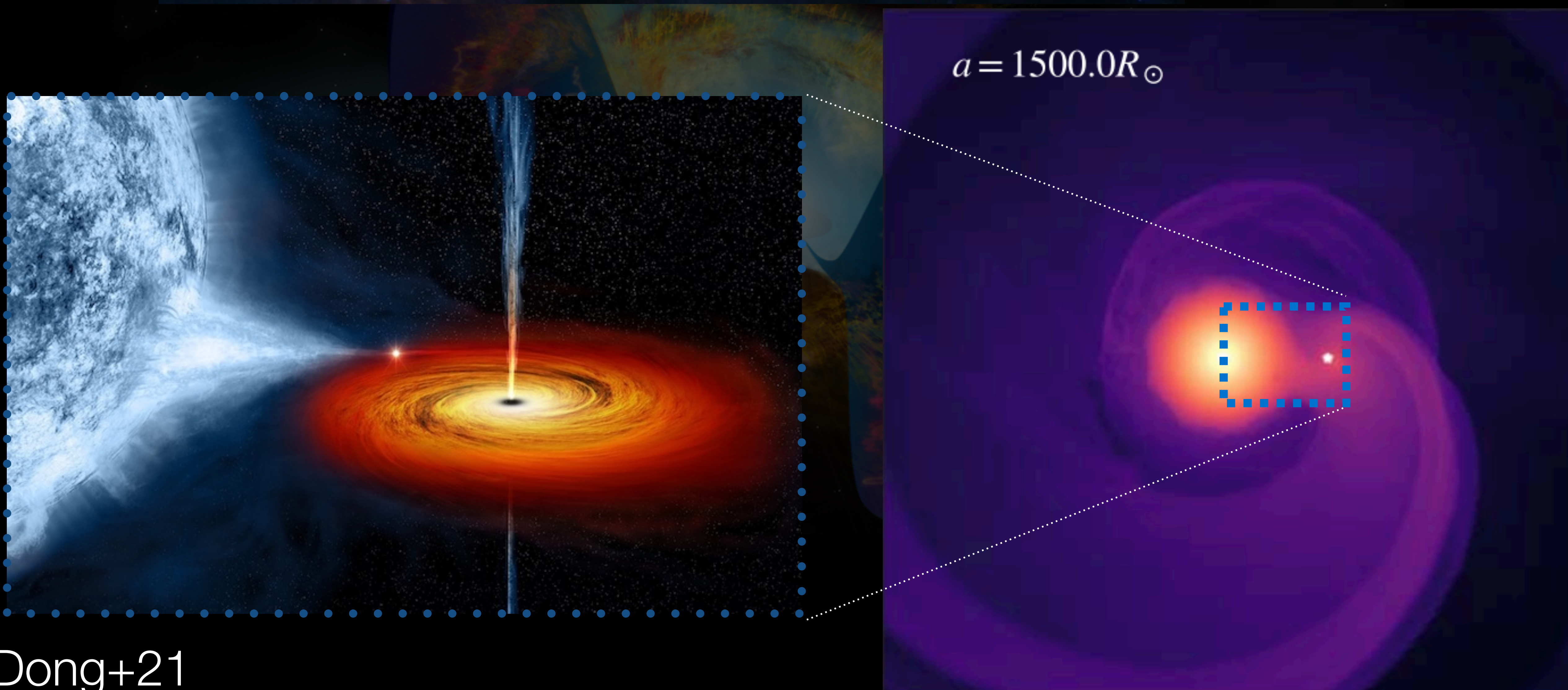
Dong+21

Where have we seen this before?

High density,
slow shock,
strong radio emitter

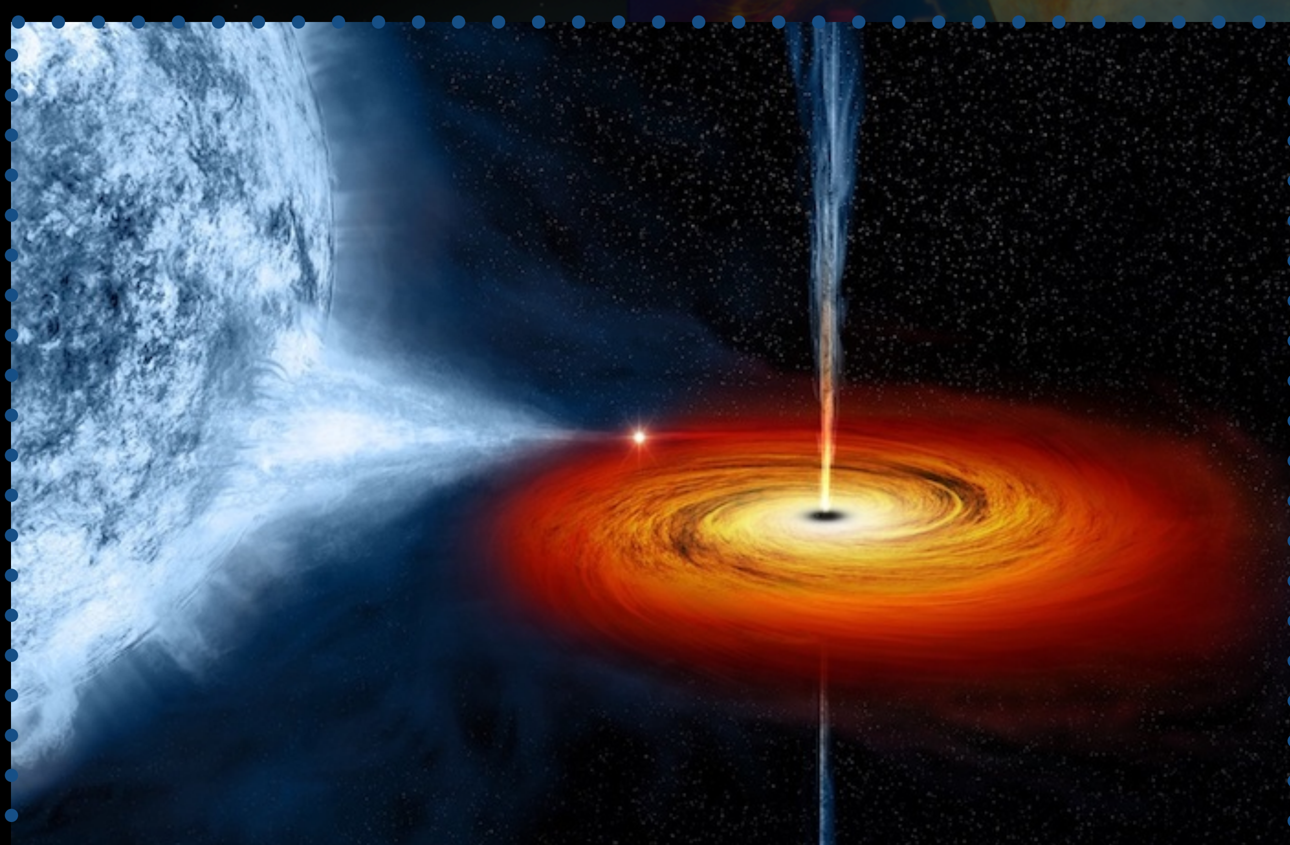
Dong+21

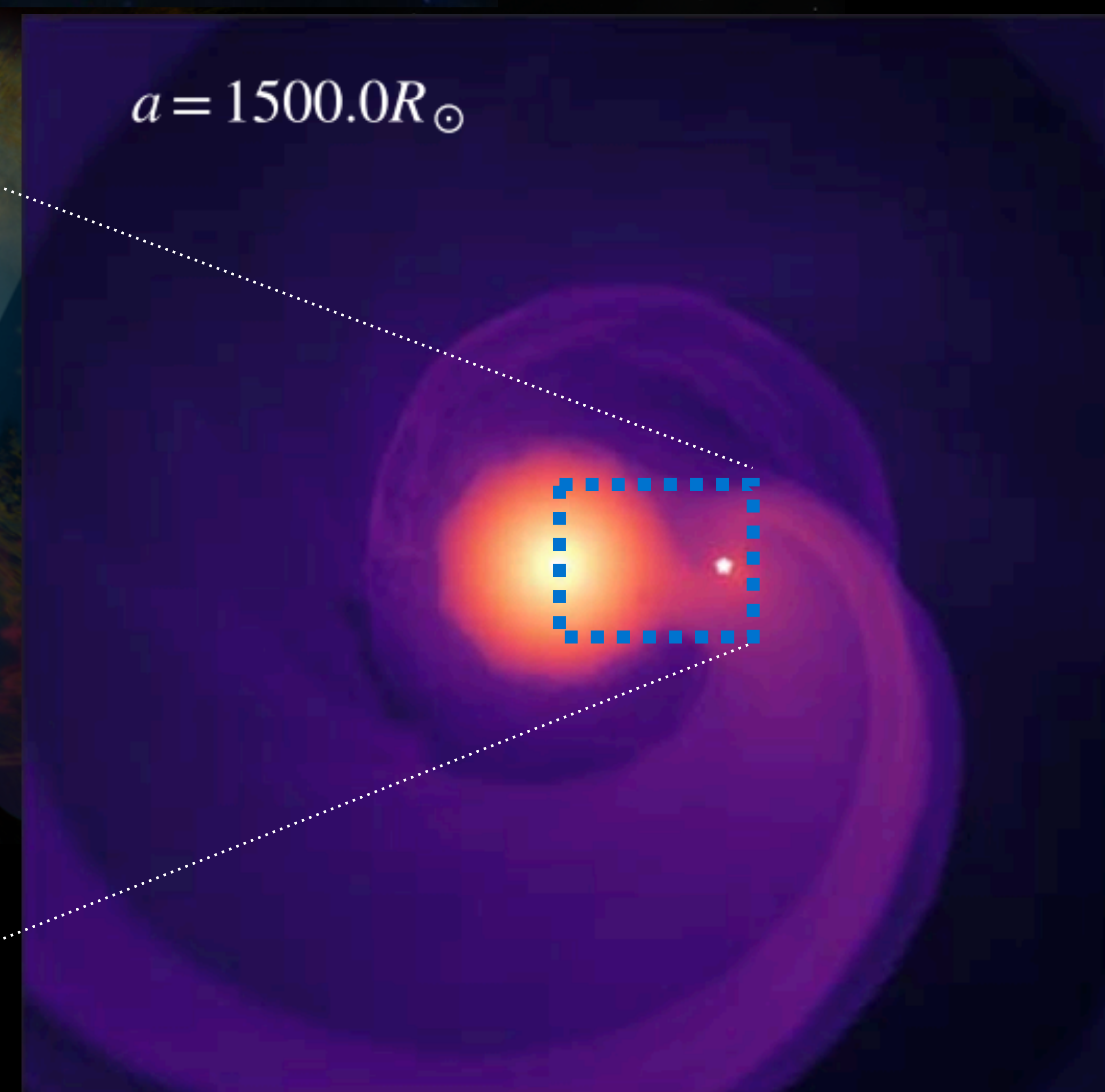
Where have we seen this before?



Dong+21

Where have we seen this before?





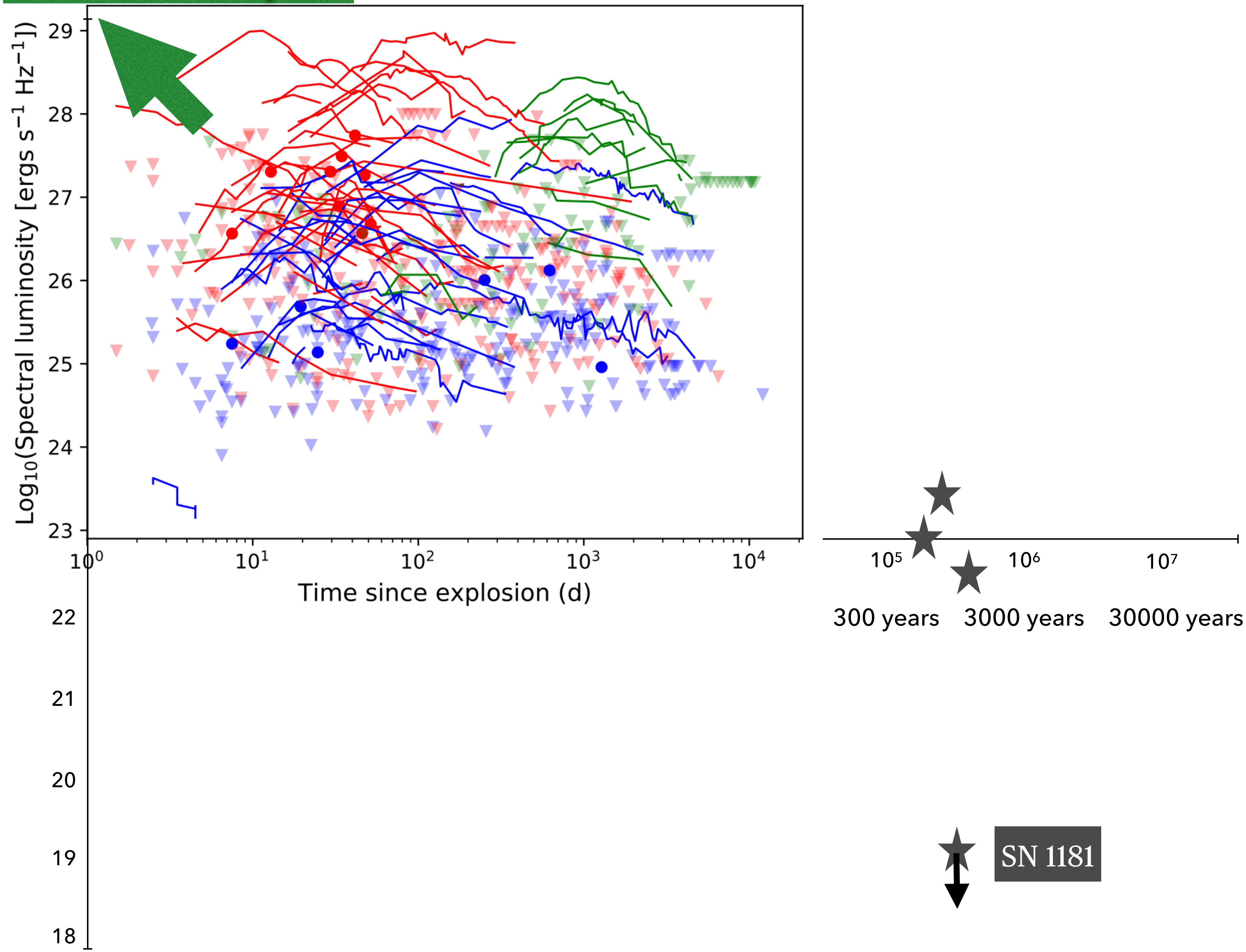
Dong+21

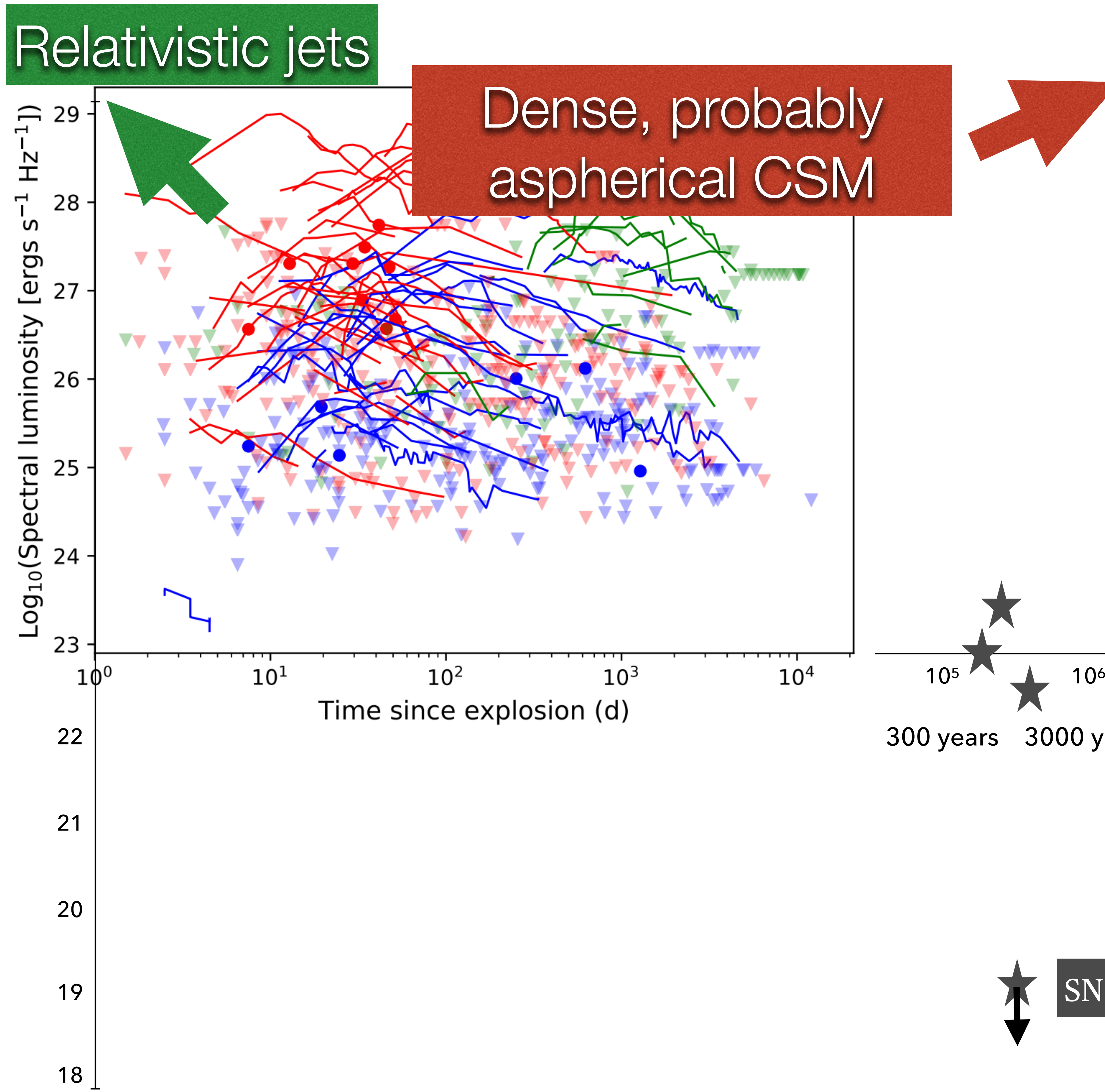
Let’s go back to the parameter space now

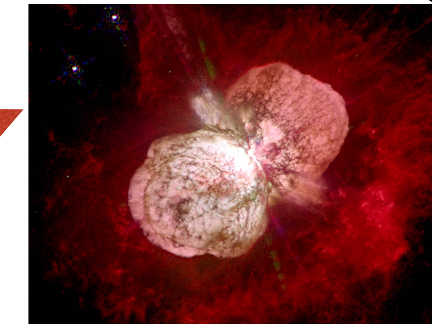
Where do different types of stellar explosions live?

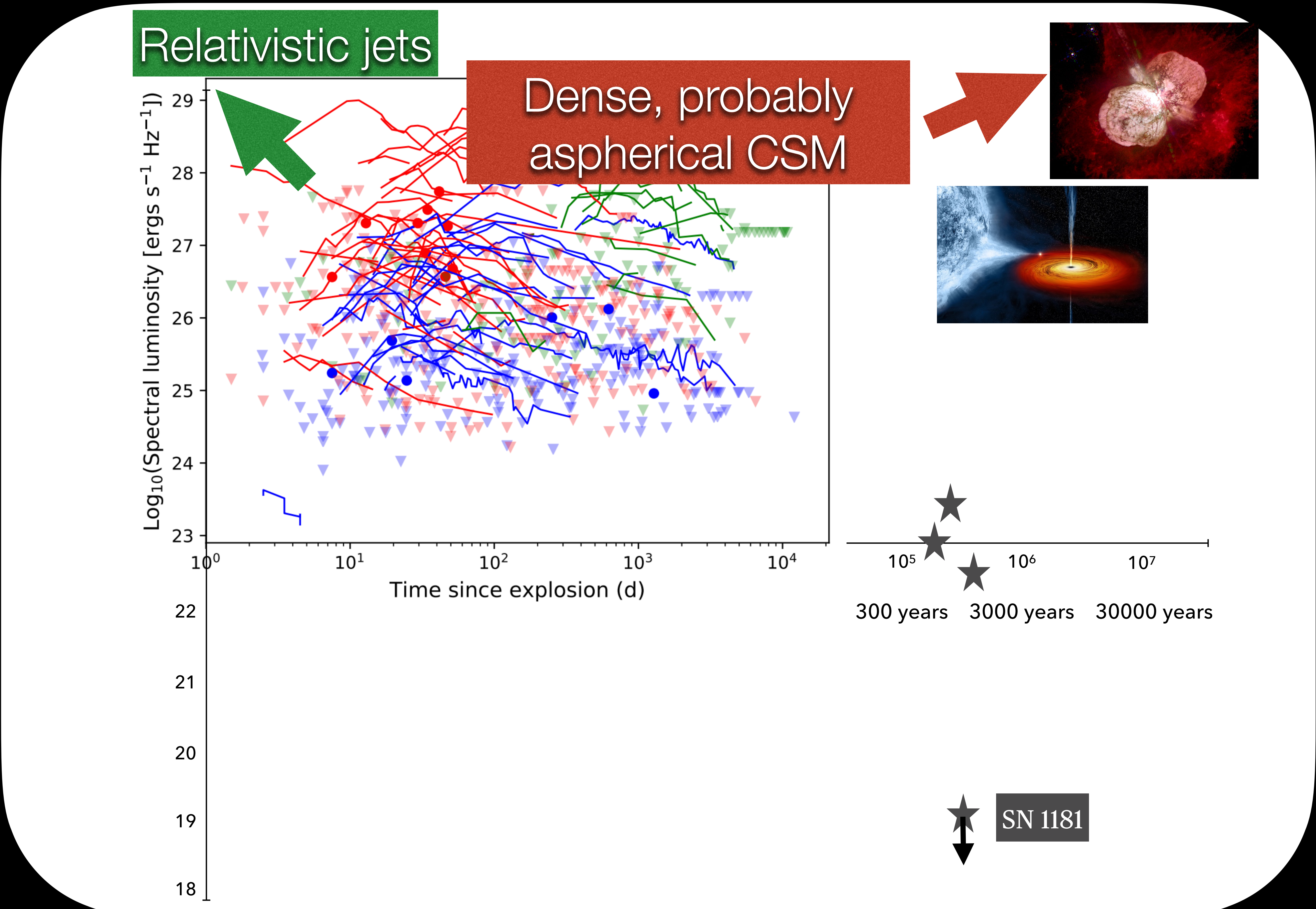
How can we find them with present+future observations?

Relativistic jets




Relativistic jets
Dense, probably aspherical CSM
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
26
25
24
23
22
21
20
19
18
Time since explosion (d)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
300 years
3000 years
30000 years
SN 1181




Relativistic jets
Dense, probably aspherical CSM
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
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20
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Time since explosion (d)
10^0
10^1
10^2
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10^4
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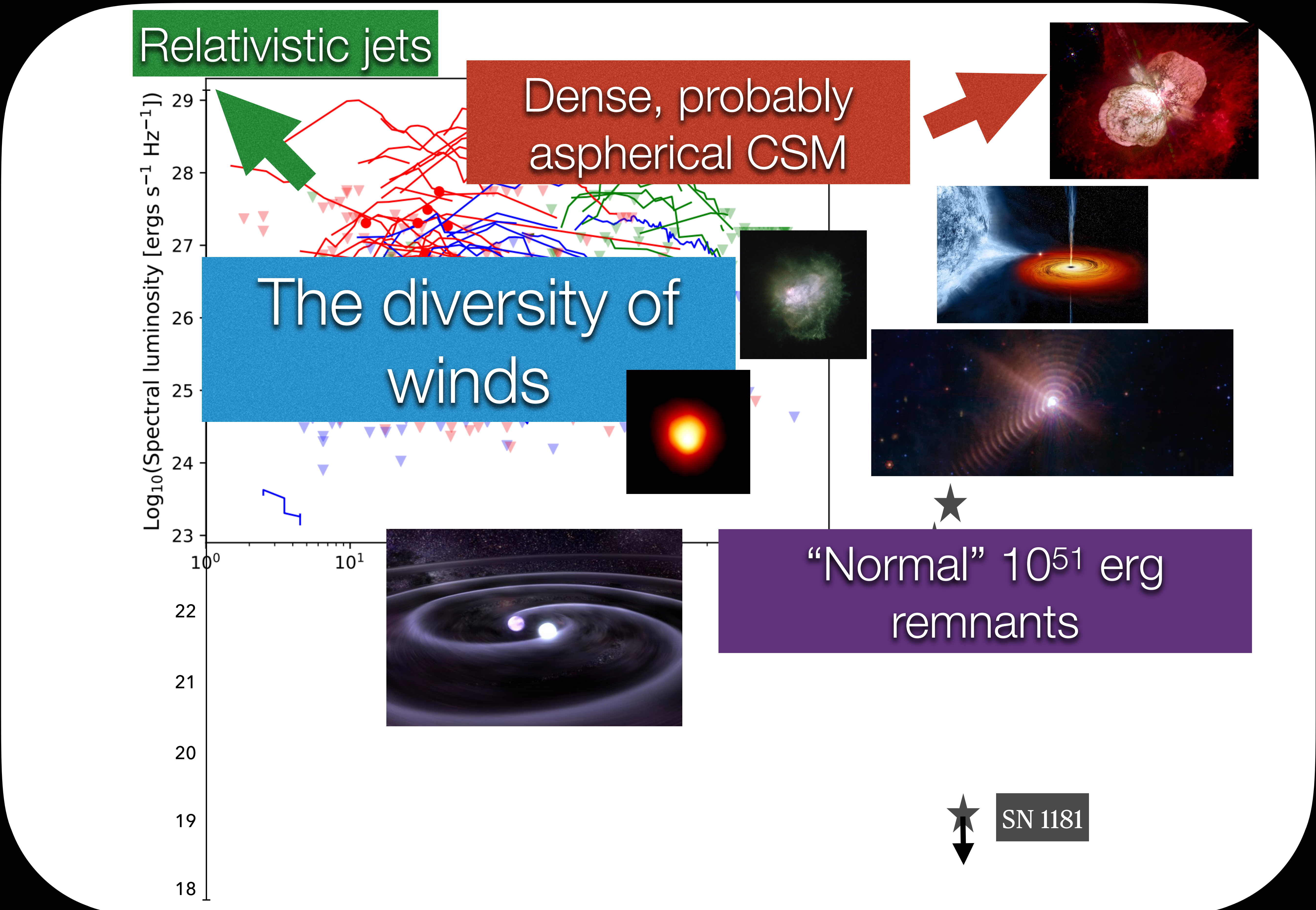
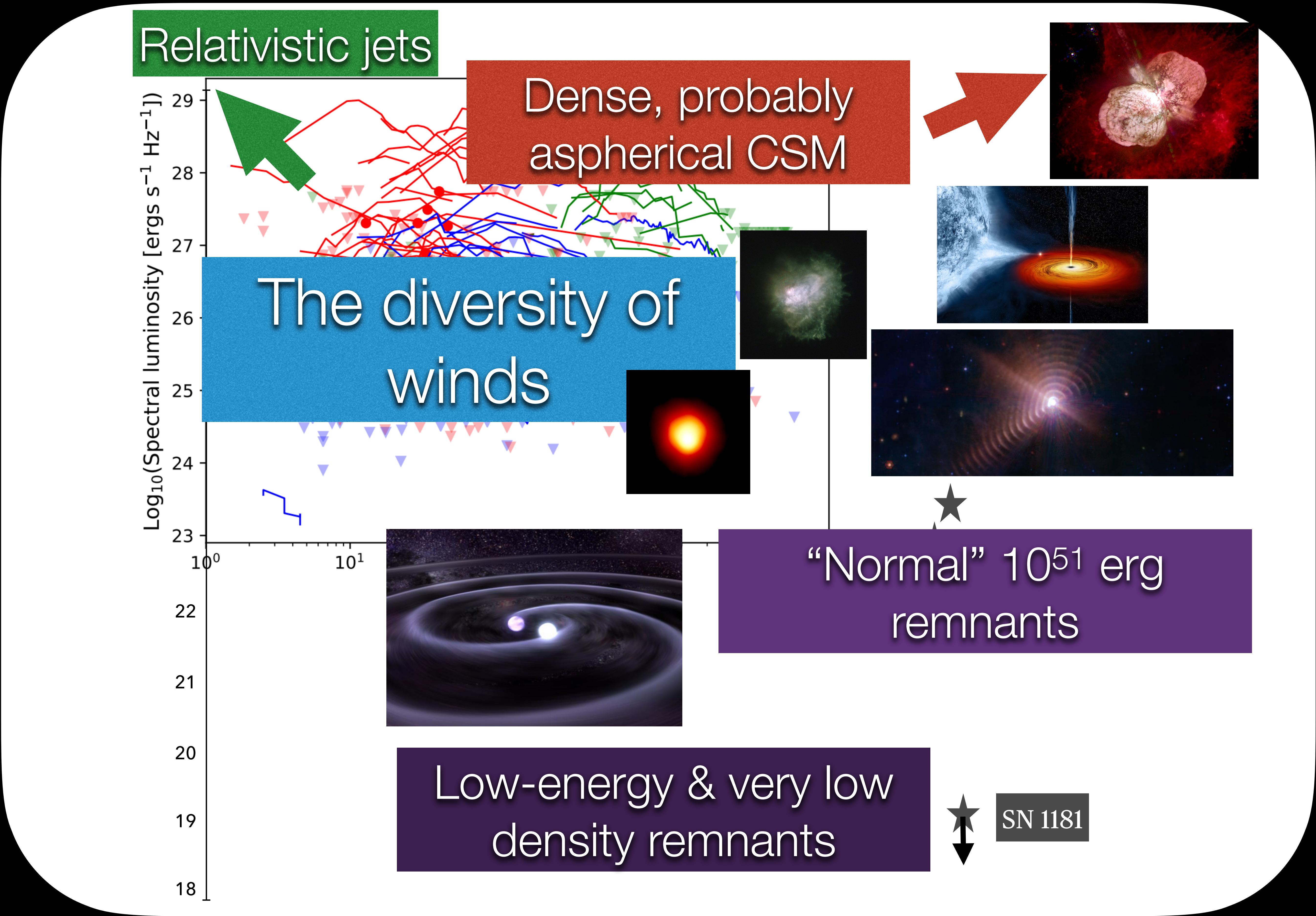
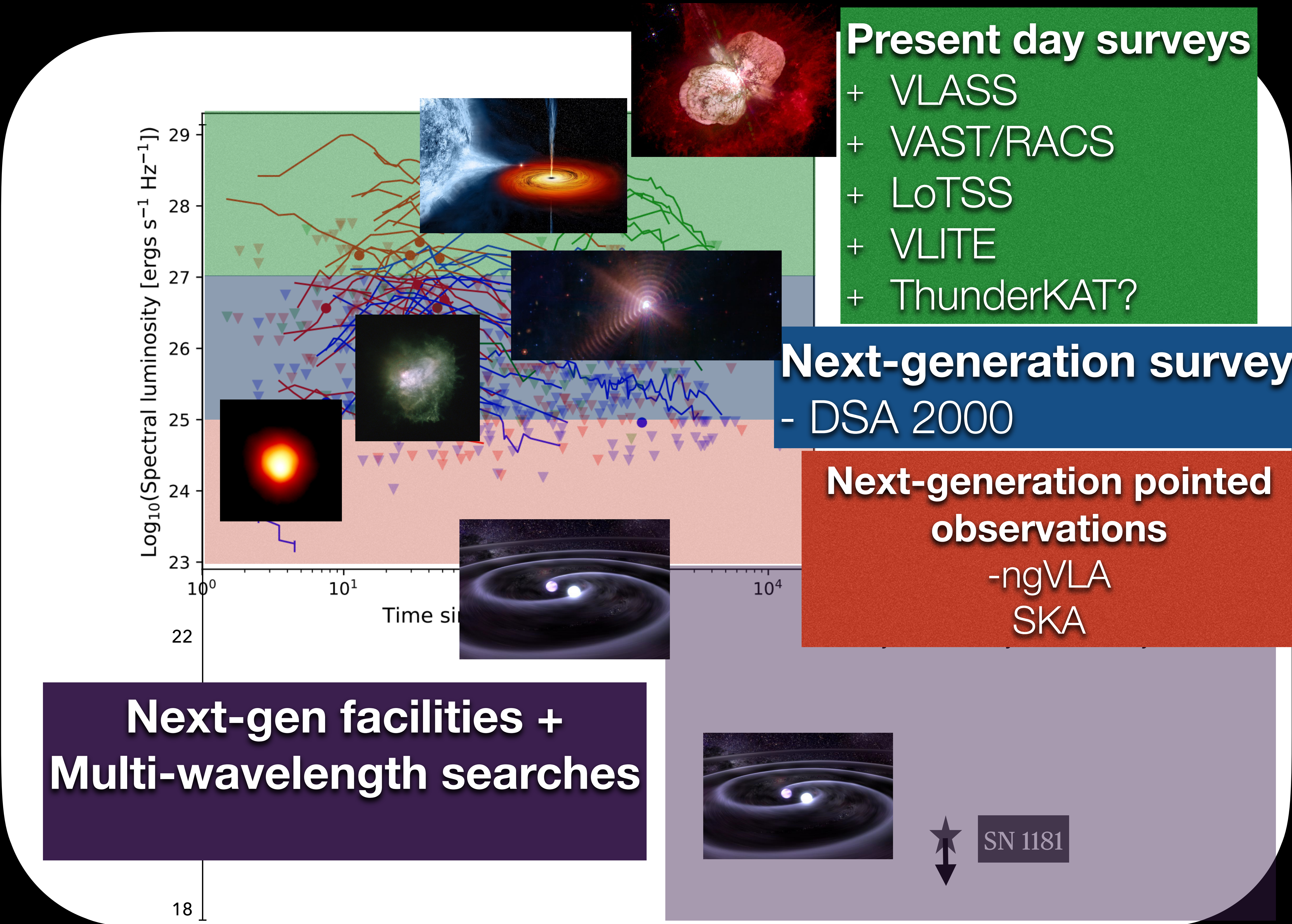
300 years
3000 years
30000 years
SN 1181


Relativistic jets
Dense, probably aspherical CSM
The diversity of winds
“Normal” 10⁵¹ erg remnants
SN 1181
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
26
25
24
23
22
21
20
19
18
10^0
10^1


Relativistic jets
Dense, probably aspherical CSM
The diversity of winds
"Normal" 10^51 erg remnants
Low-energy & very low density remnants
SN 1181
Log10(Spectral luminosity [ergs s^-1 Hz^-1])
29
28
27
26
25
24
23
22
21
20
19
18
10^0
10^1



Present day surveys
+ VLASS
+ VAST/RACS
+ LoTSS
+ VLITE
+ ThunderKAT?
Next-generation surveys
- DSA 2000
Next-generation pointed observations
-ngVLA
SKA
Next-gen facilities + Multi-wavelength searches
SN 1181
Log10(Spectral luminosity [ergs s−1 Hz−1])
29
28
27
26
25
24
23
22
18
10^0
10^1
10^4