Time-domain astronomy

Sylvia J. Zhu
DESY Zeuthen
sylvia.zhu@desy.de
[she/her]

Rough outline

Day 1: Intro + detectors

How are gamma rays produced and how do we detect them?

Day 2: Rapid transients

How do IACTs observe gamma-ray bursts and other rapidly fading transients?

Day 3: Longer duration transients

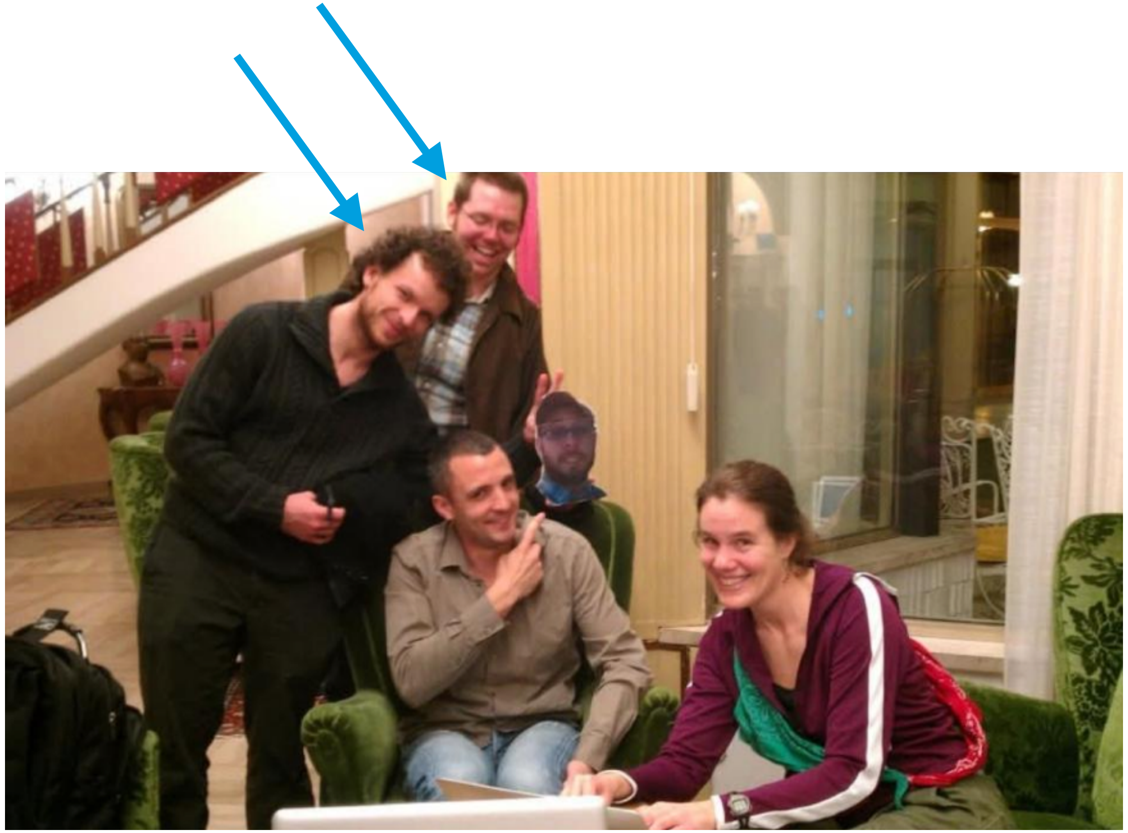
What else must be considered for longer duration transients like supernovae?

core collapse supernovae
flaring AGN as gravitational-wave candidates
maybe other stuff???

before I begin

I found some old pictures of other lecturers ……….

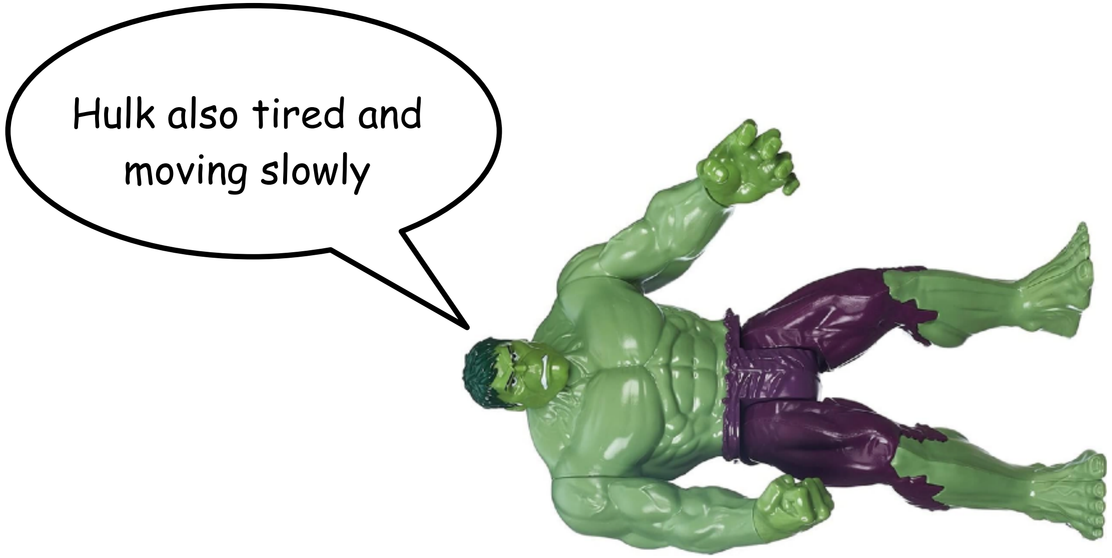
David in 2011



David and Fabio in 2012

Part 3a. Core collapse supernovae

How should we observe slowly evolving transients?

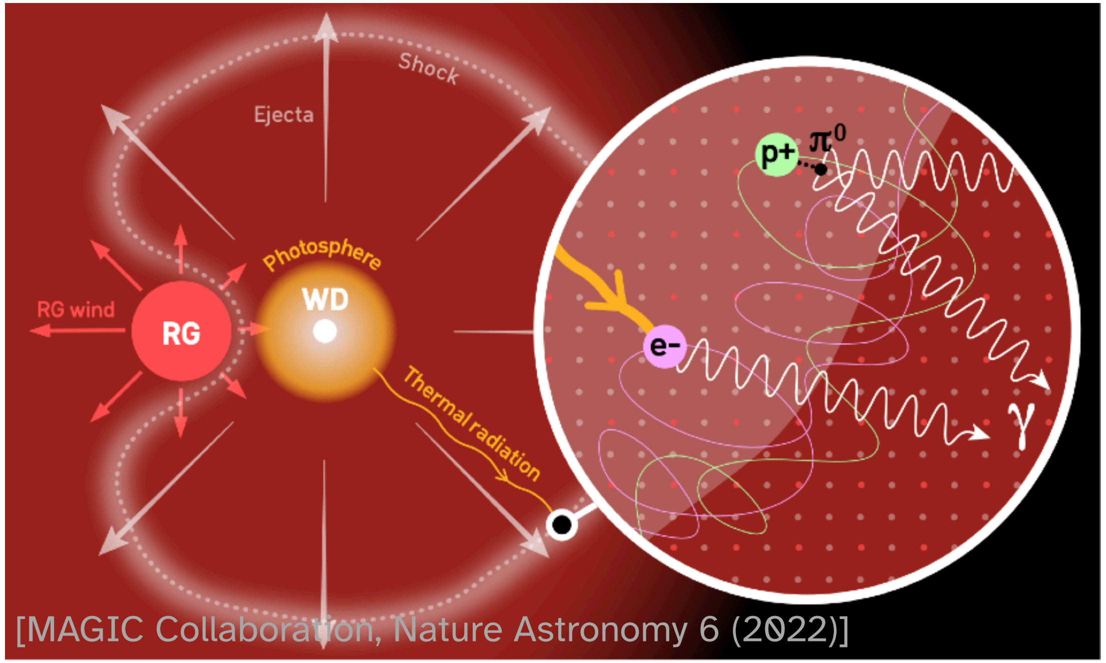


From novae to supernovae?

where are the gamma rays

So, we can get gamma rays from novae

What about supernovae?



[MAGIC Collaboration, Nature Astronomy 6 (2022)]

nova energy release ~1e42 erg
supernova energy release ~ 1e51 erg

side note
"foe" = (10 to the) fifty-one erg

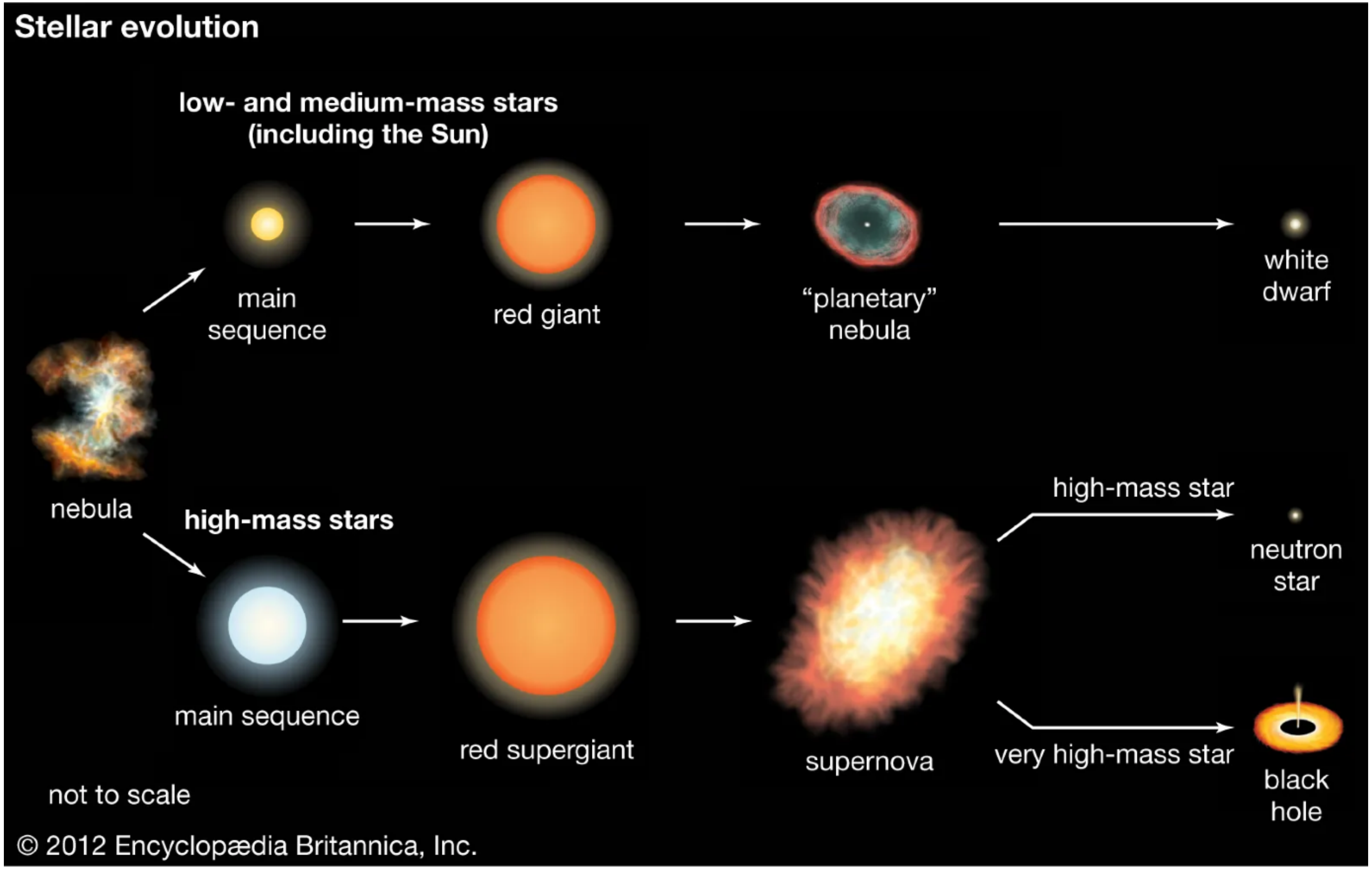
nova distance ~ kpc
supernova distance ~ Mpc

=> from energy arguments, a detection is plausible!

So, are the right ingredients there?

Core-collapse supernovae from astronomy 101

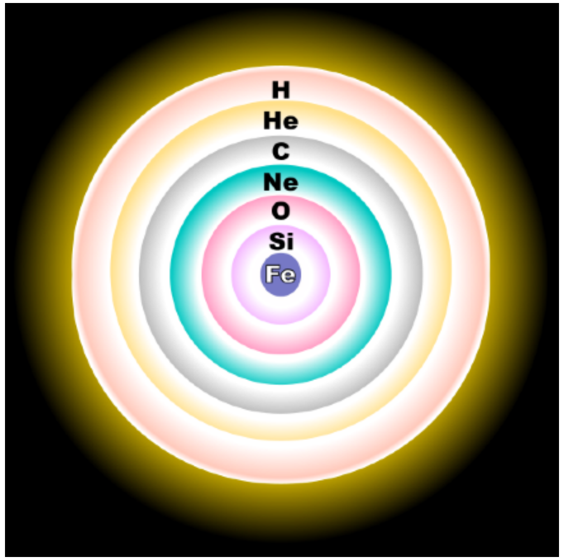
star goes boom



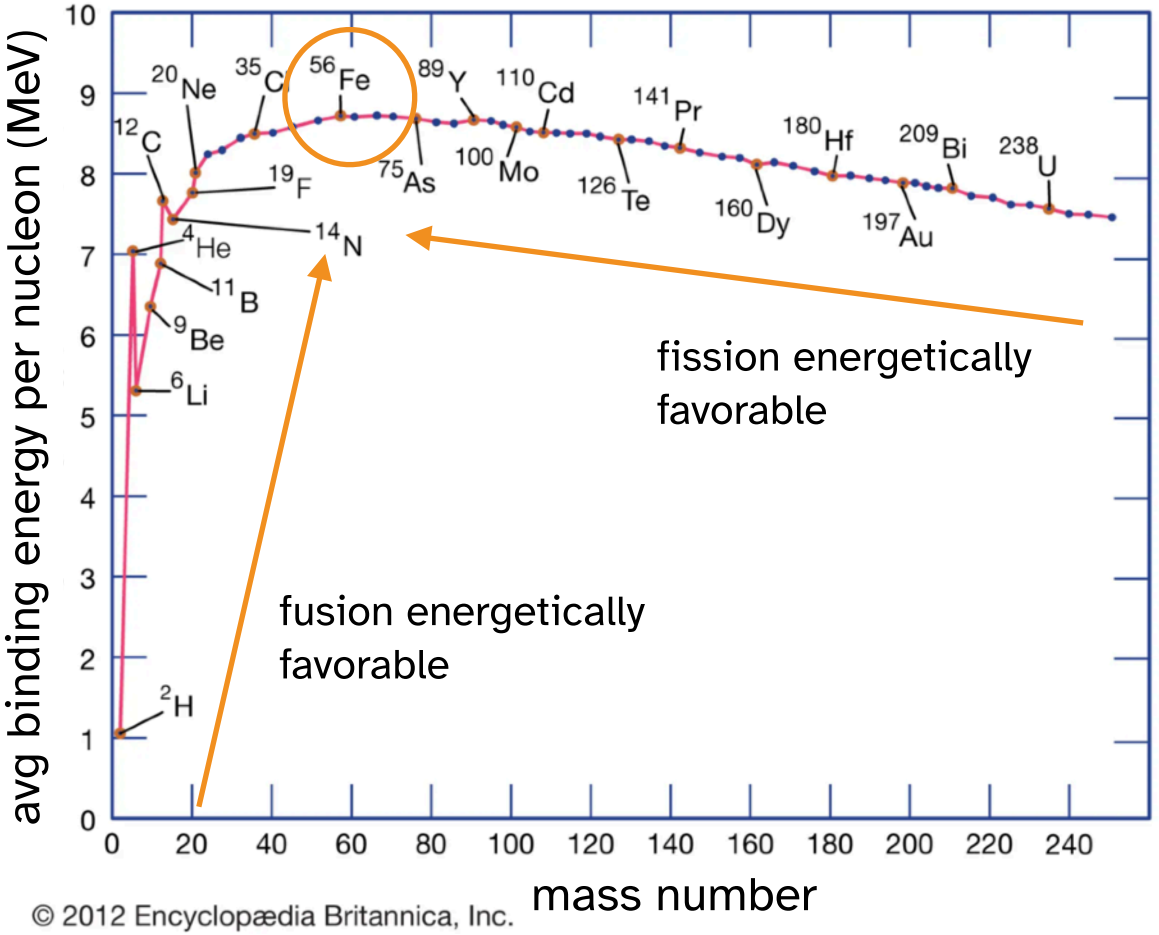
Core-collapse supernovae from astronomy 101

star goes boom

Massive stars fuses successively heavier elements until iron



R. J. Hall



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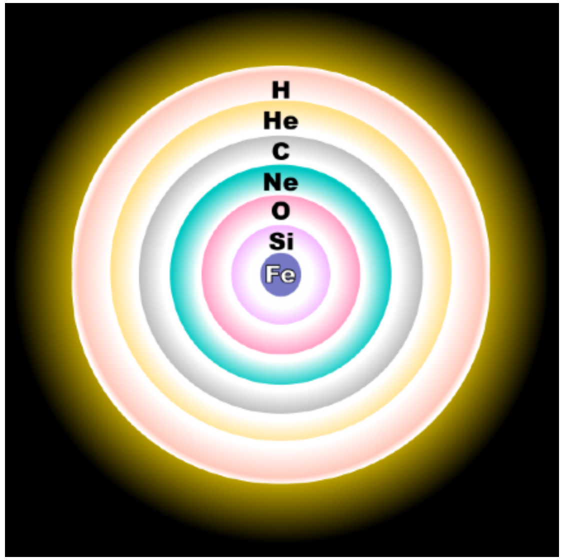

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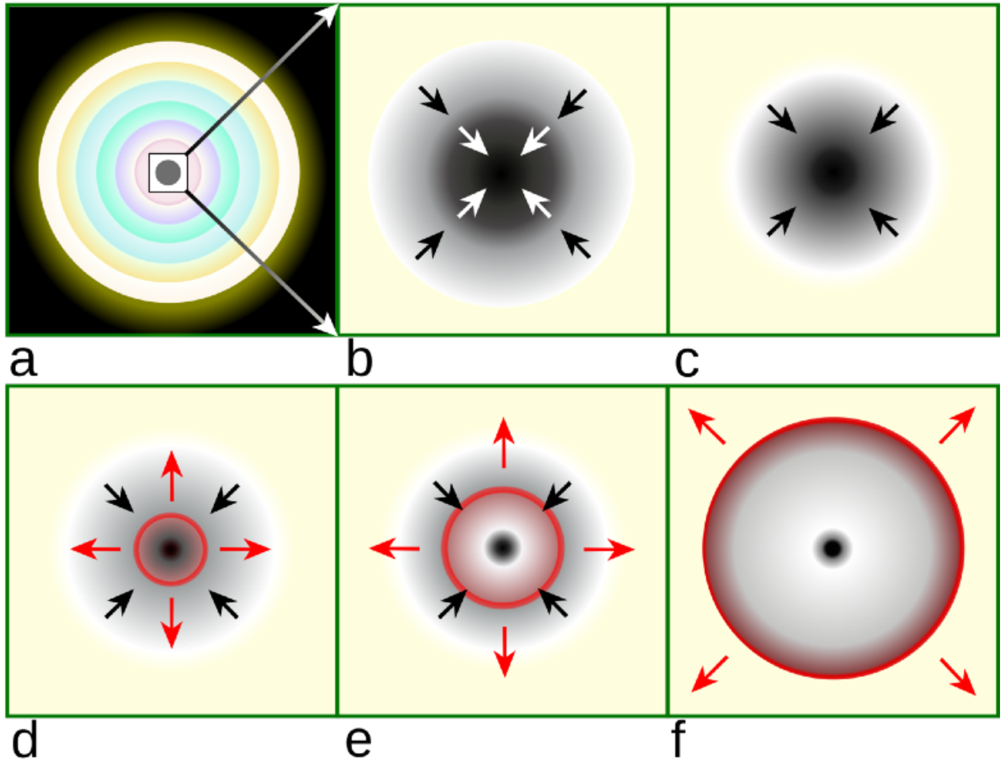


stuff happens*, ultimately a lot of material is ejected at relativistic speeds

*complex, extreme physical conditions, difficult to properly model

Core-collapse supernovae from astronomy 101

star goes boom

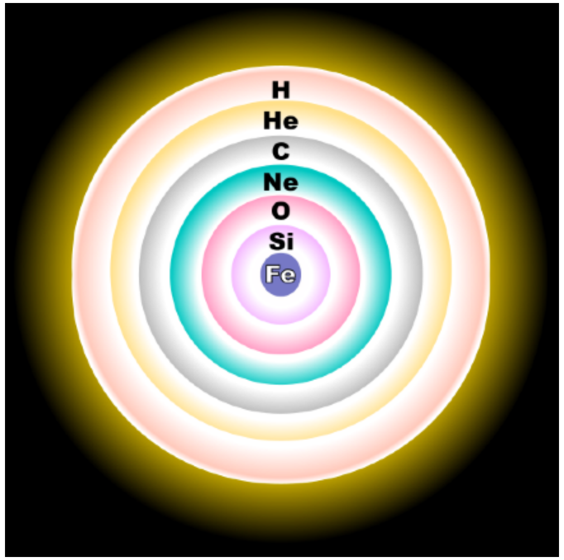
modified from J. Borowska-Naguszewska

Massive star explodes as a supernova, lightcurve is bright at the start and then simply fades?

Core-collapse supernovae from astronomy ~~101~~ 102

star goes boom

Any non-Ia supernova is a core collapse supernova



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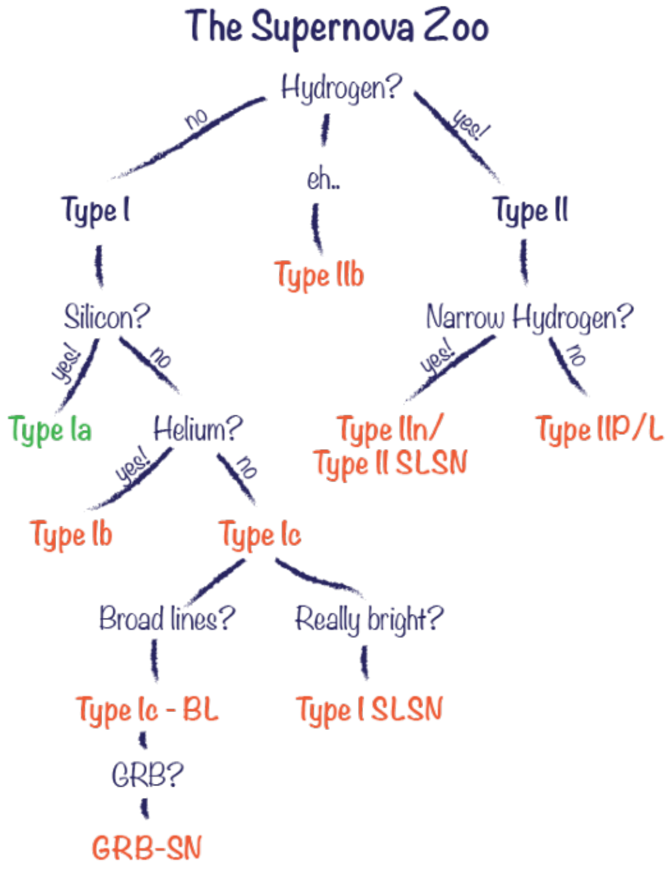

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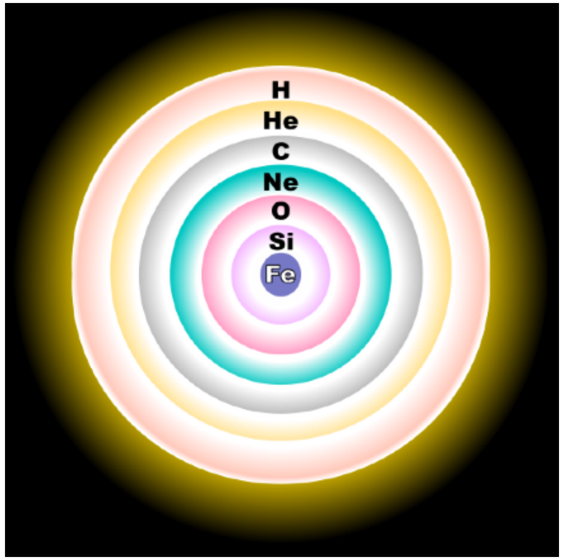

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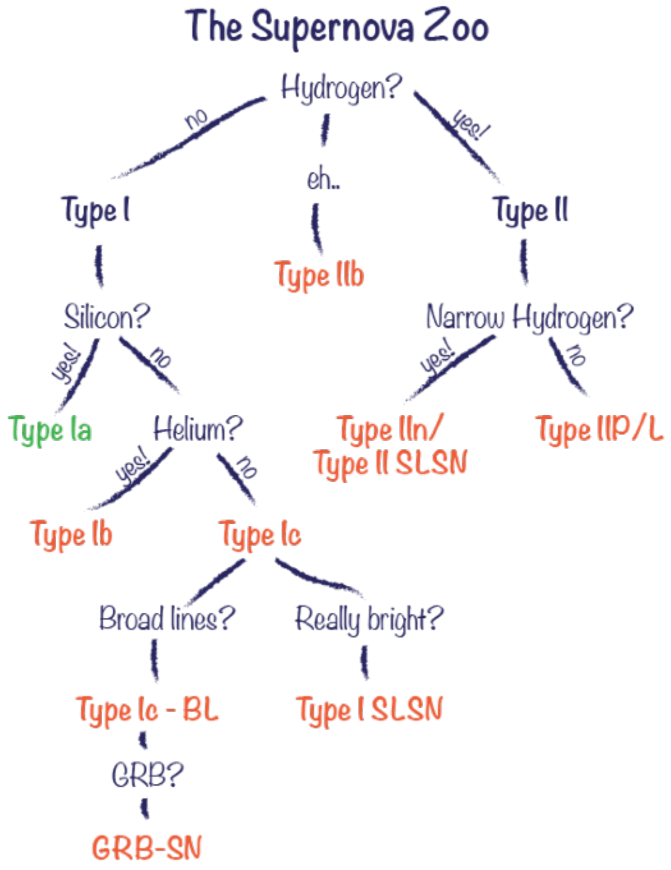

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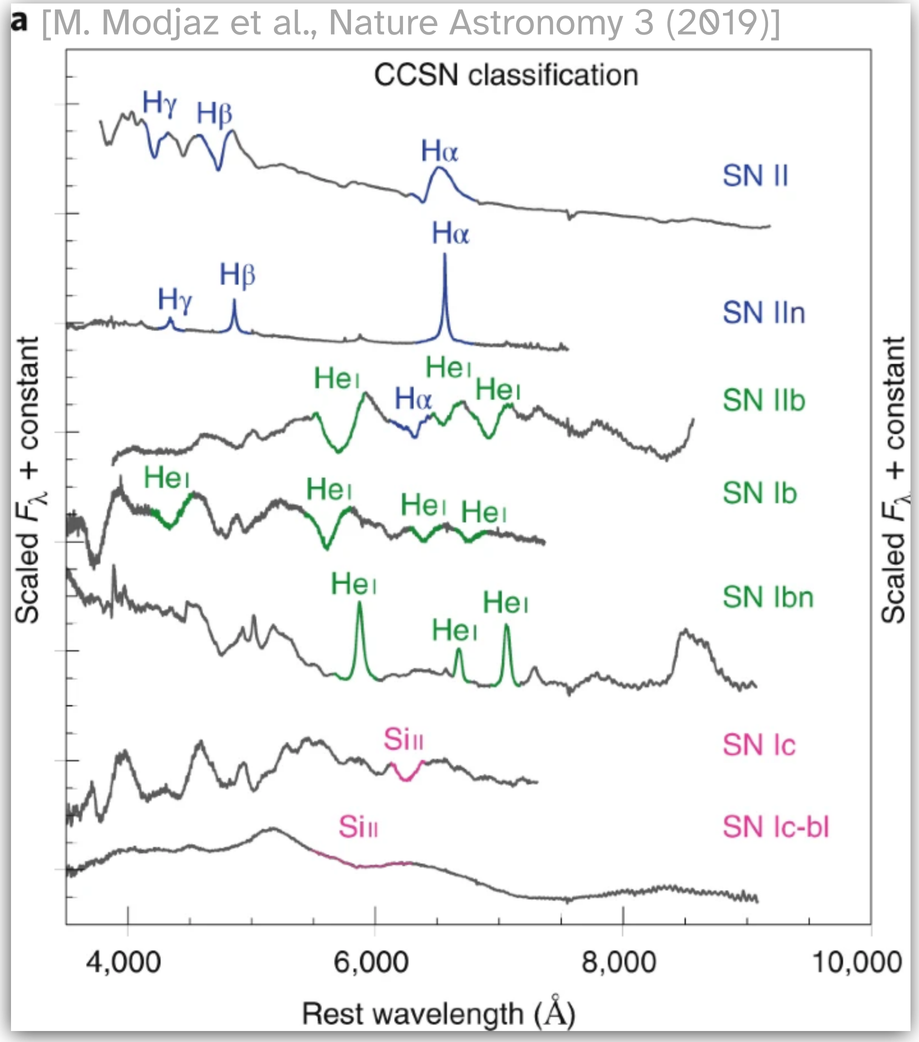

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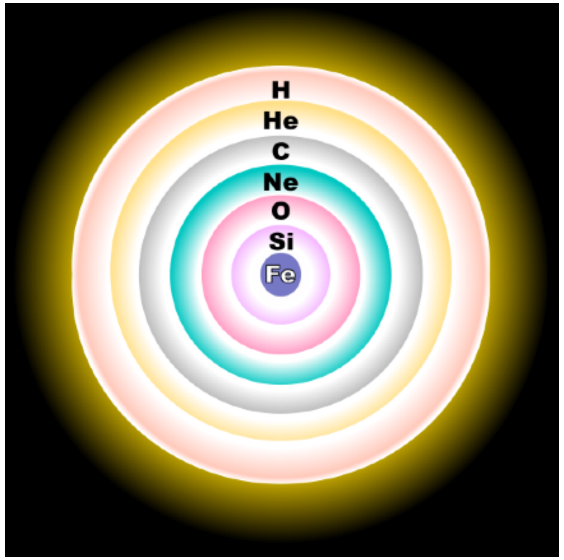

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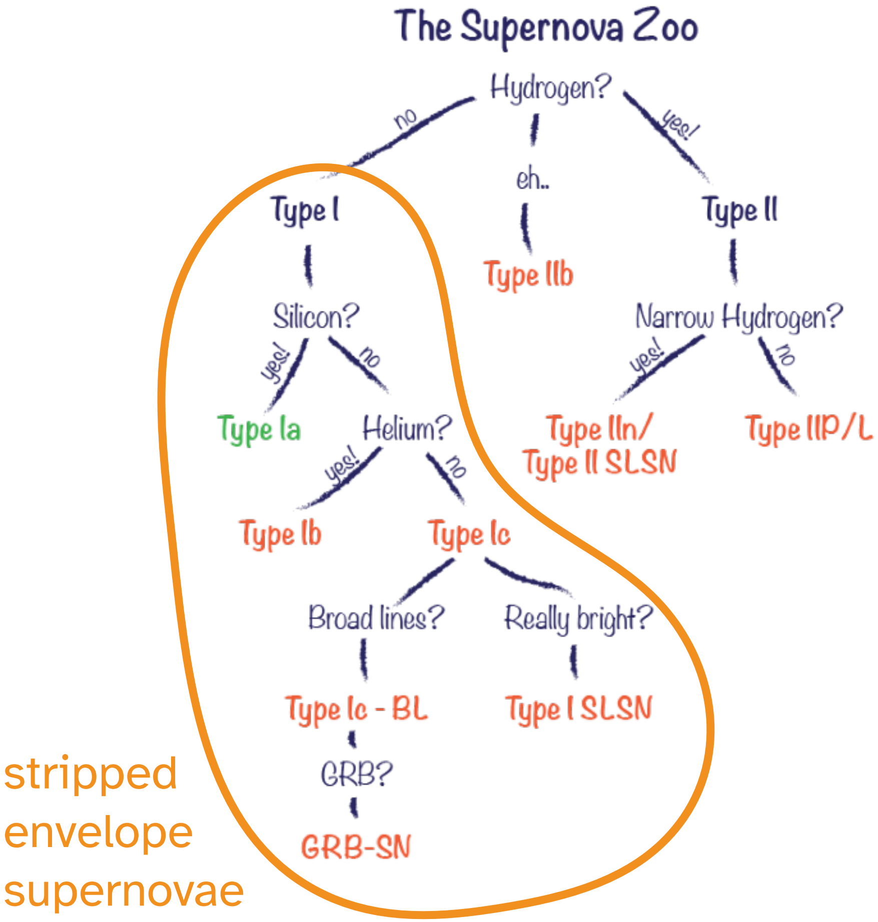

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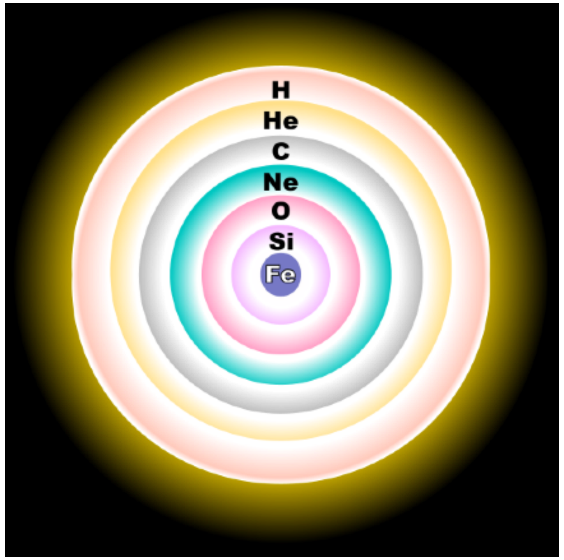

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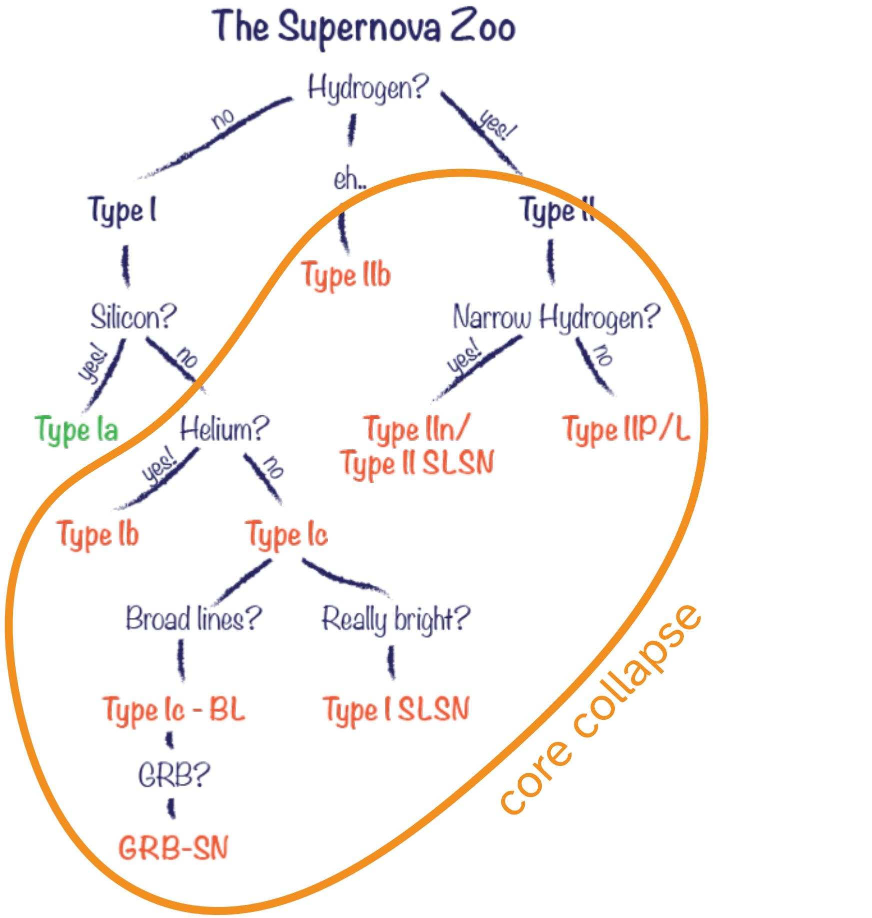

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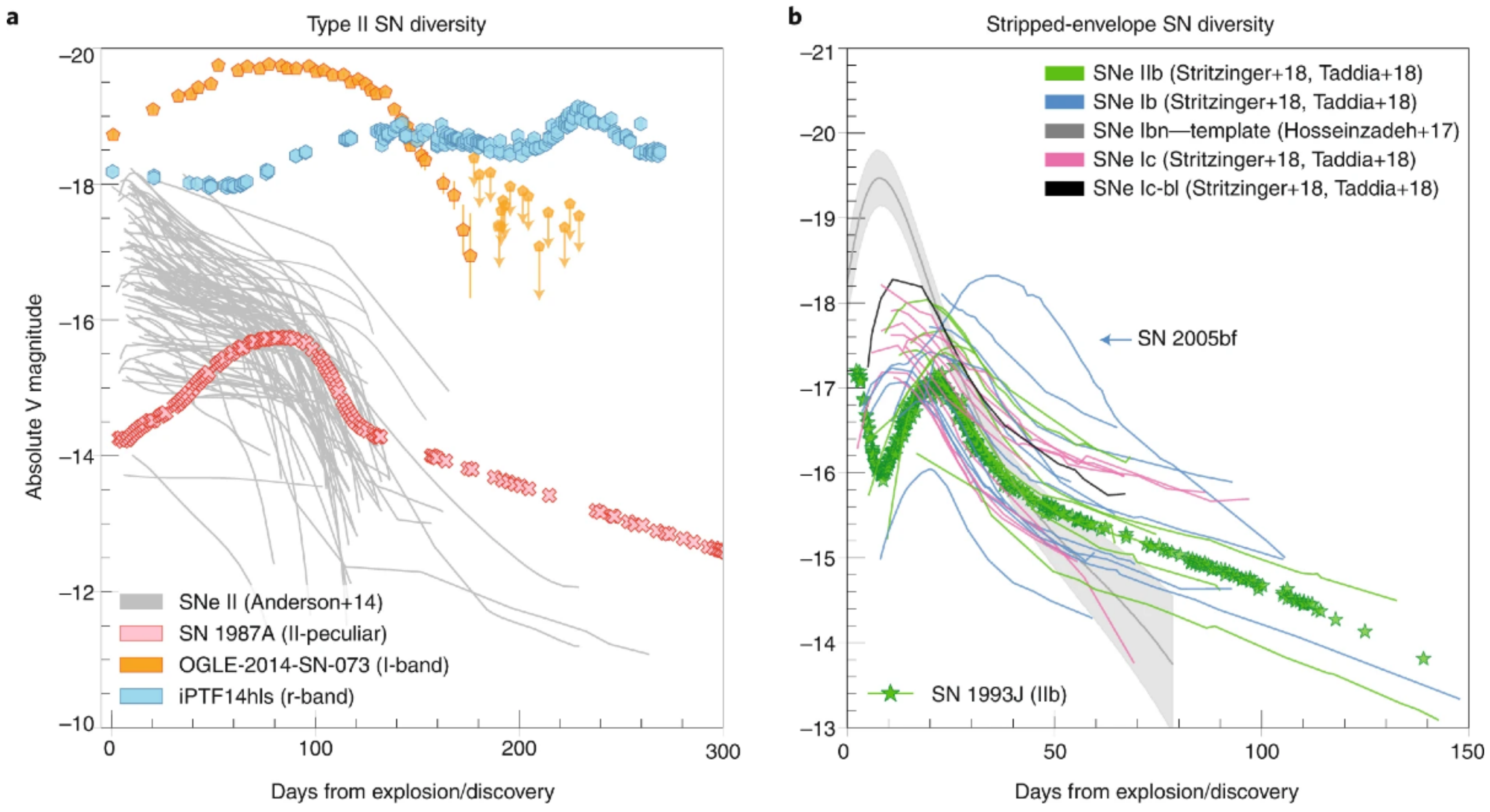


[M. Modjaz et al., Nature Astronomy 3 (2019)]

Supernovae are brightest at ~optical wavelengths

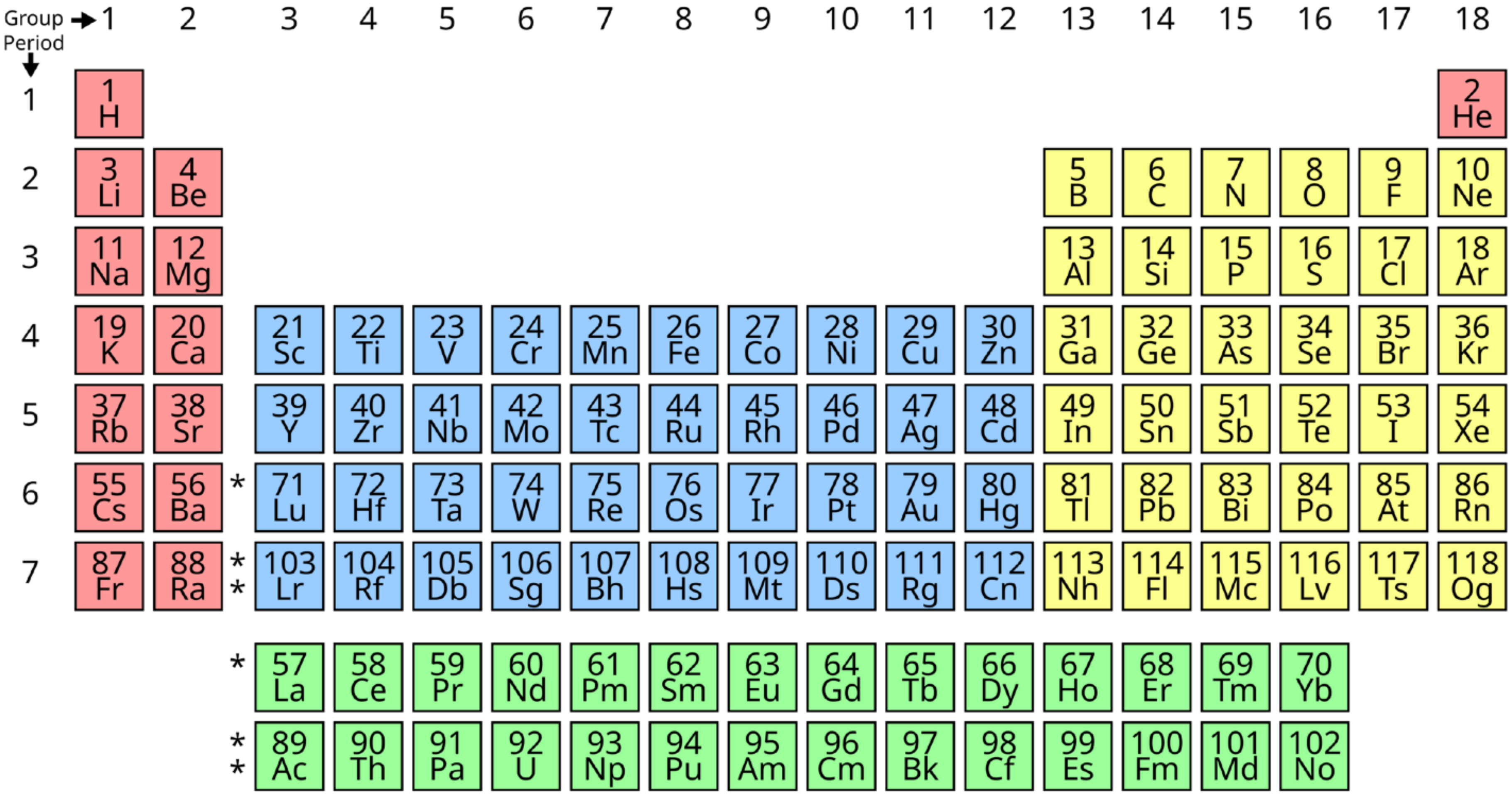
Emission is powered by **radioactive decay**

neutron capture ->
increase mass number *A*

beta decay to a more stable element ->
increase atomic number *Z*
+
nucleus drops to lower energy state ->
release photons

Pause to talk about nucleosynthesis

How do we get elements heavier than helium?



[Double sharp]

Pause to talk about nucleosynthesis

How do we get elements heavier than helium?

????

[Double sharp]

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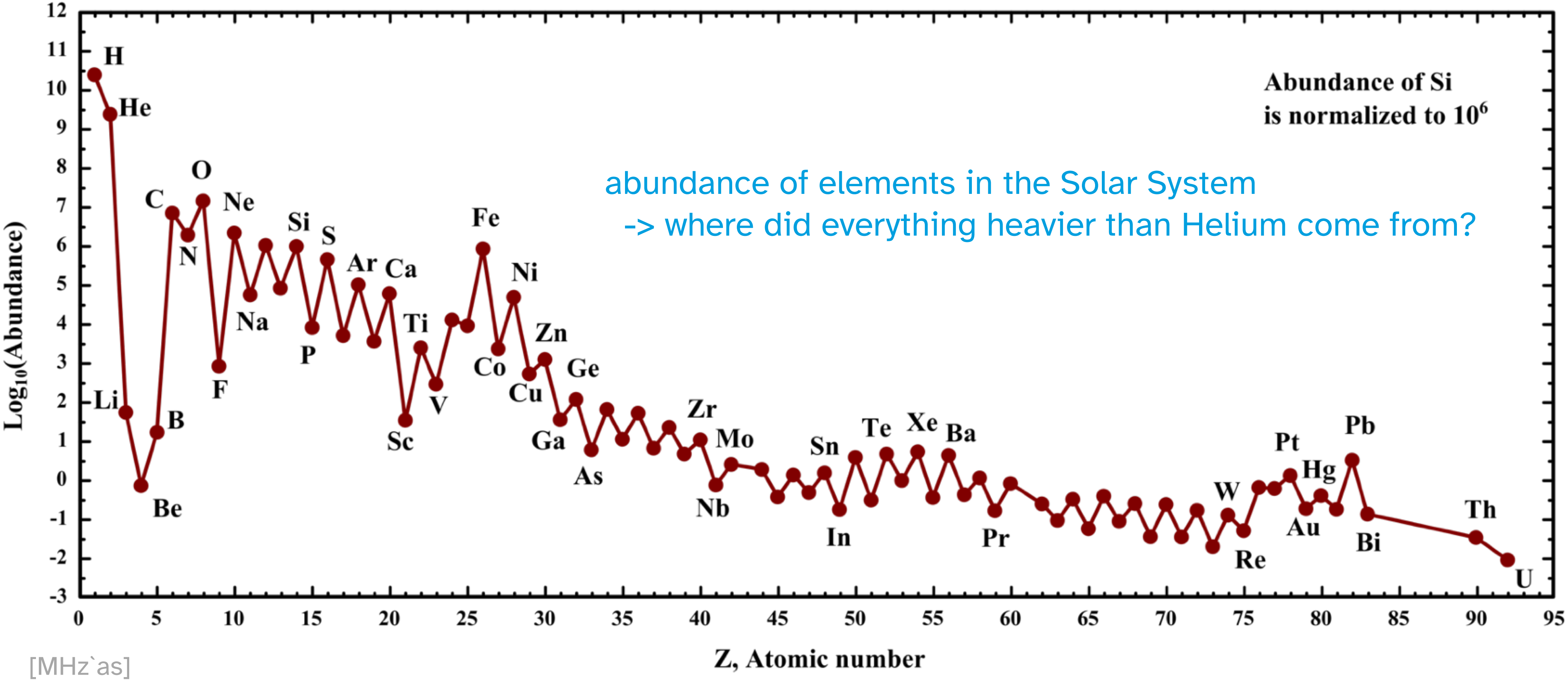
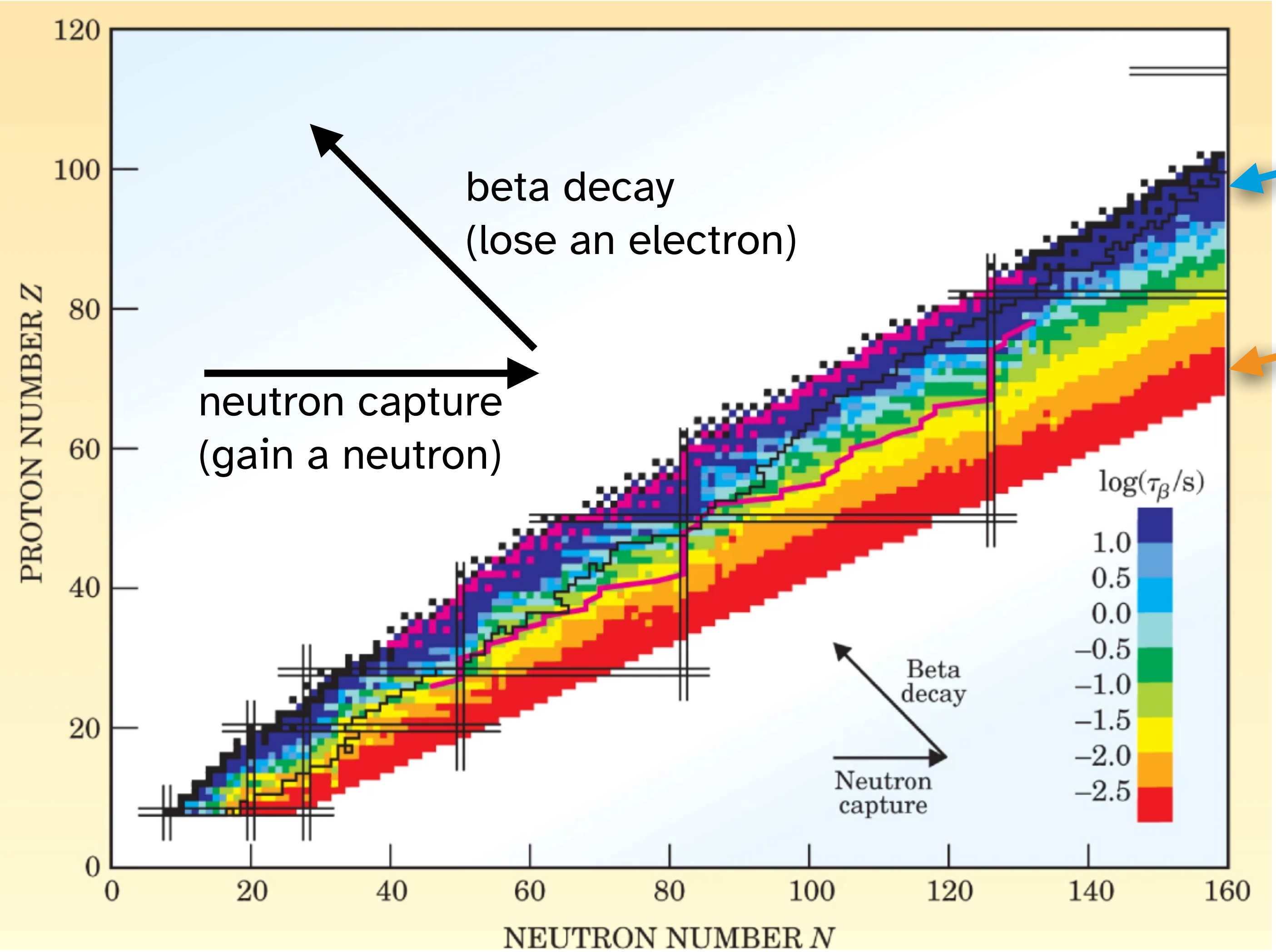


[MHz`as]

Pause to talk about nucleosynthesis

How do we get elements heavier than helium?

key ingredient: free neutrons are captured by nuclei



long lifetime
(stable)

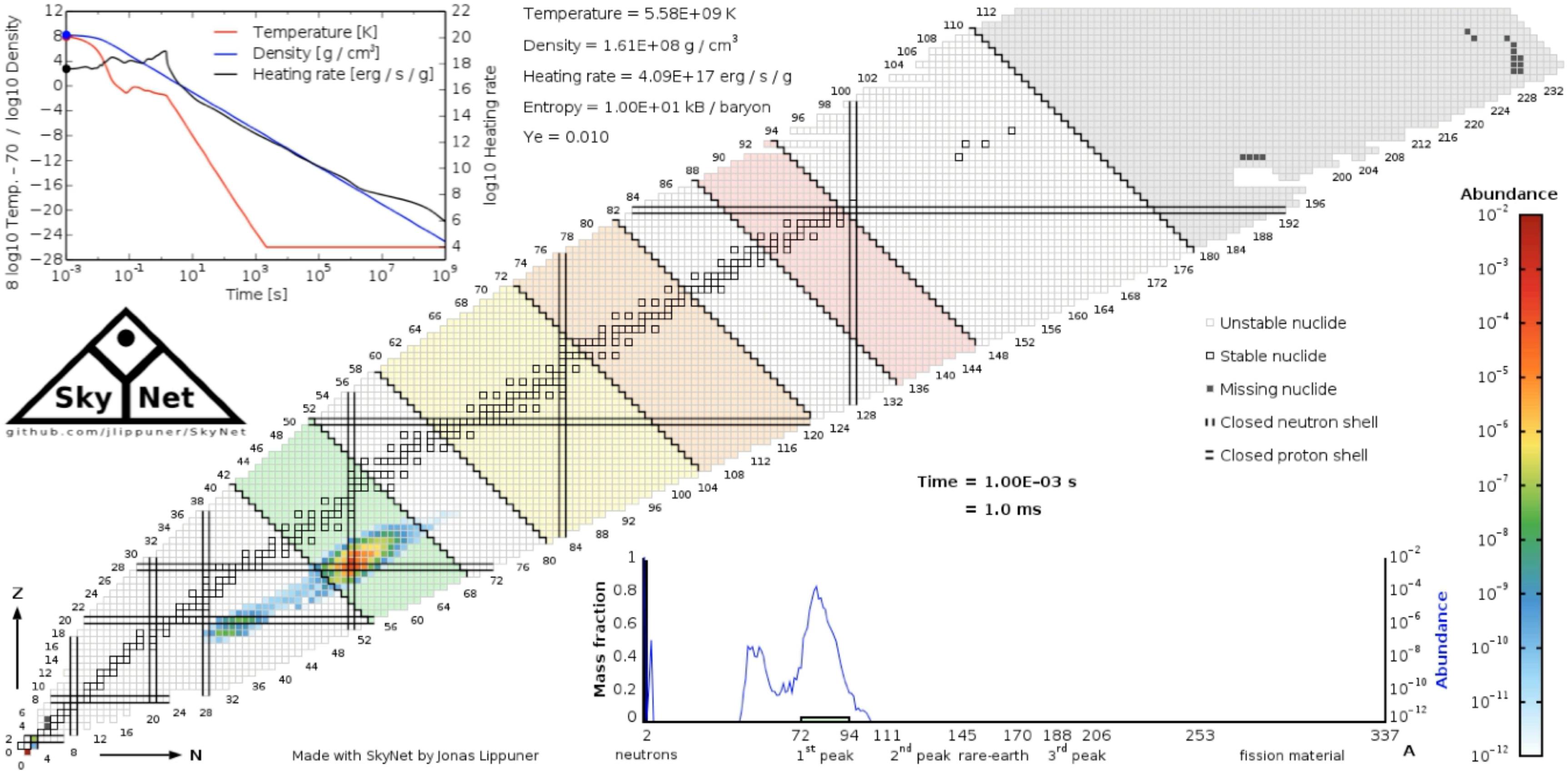
short lifetime
(unstable)

[P. Möller, from J. Cowan and F.-H. Thielemann, Physics Today 57 (2004)]

Pause to talk about nucleosynthesis

How do we get elements heavier than helium?

An example of an r-process nucleosynthesis simulation



[J. Lippuner, SkyNet]

Pause to talk about nucleosynthesis

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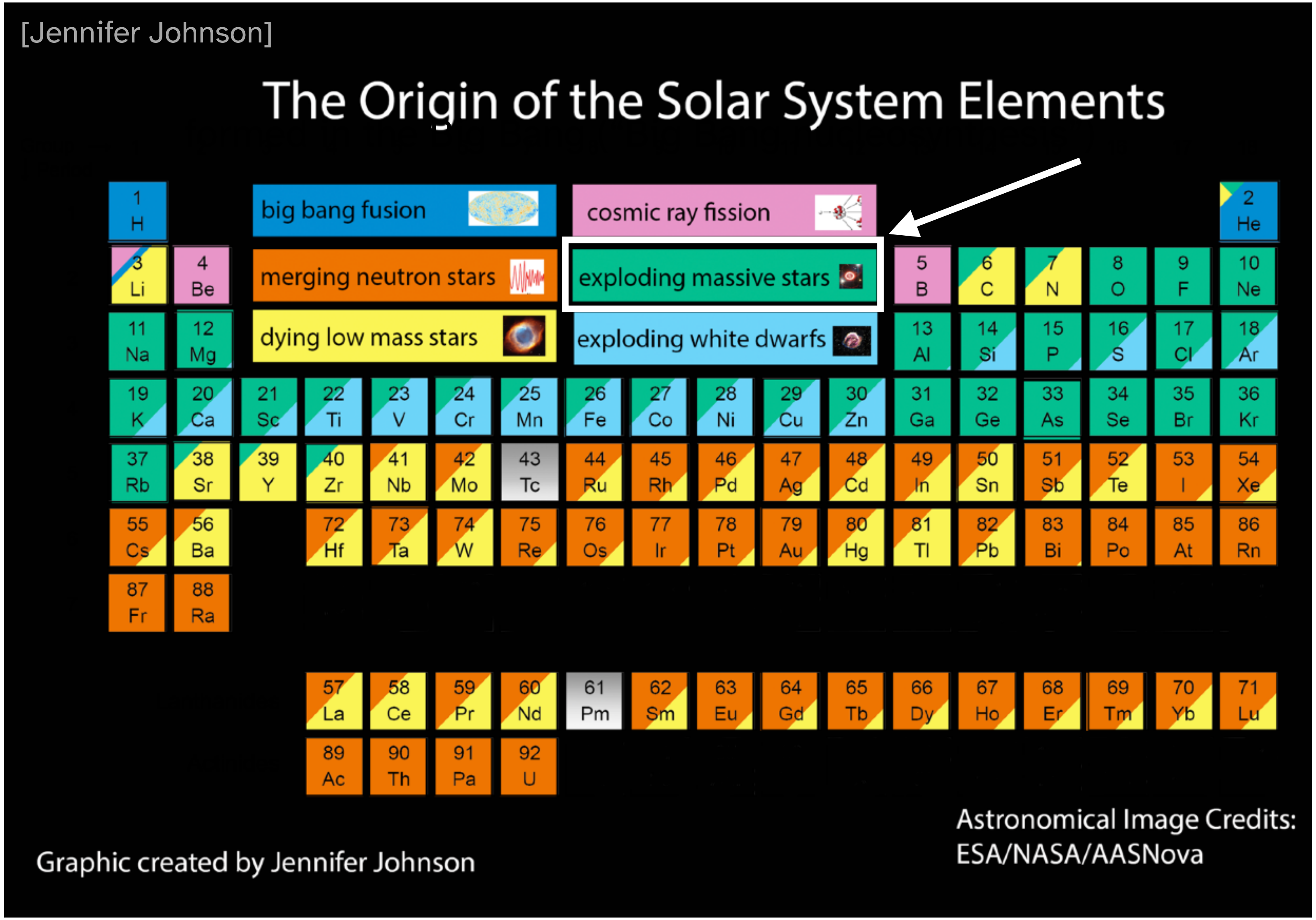

Core-collapse supernovae from astronomy ~~101~~ 102

star goes boom

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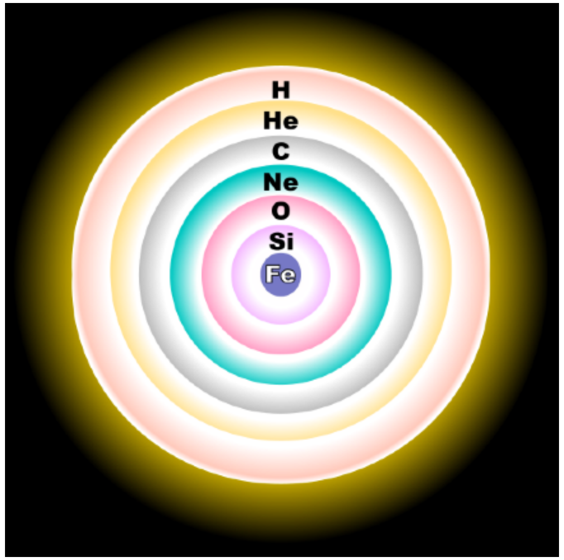

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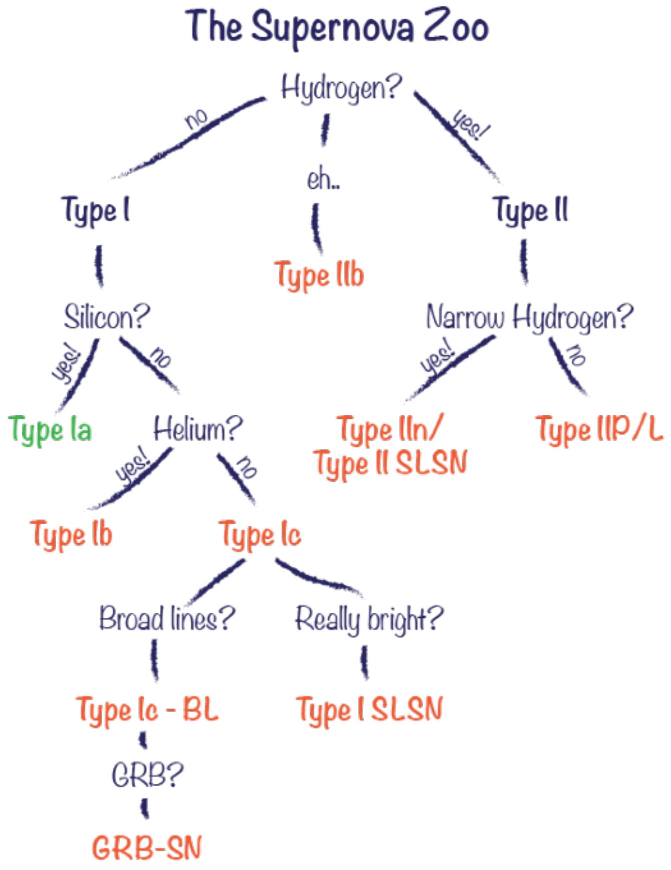

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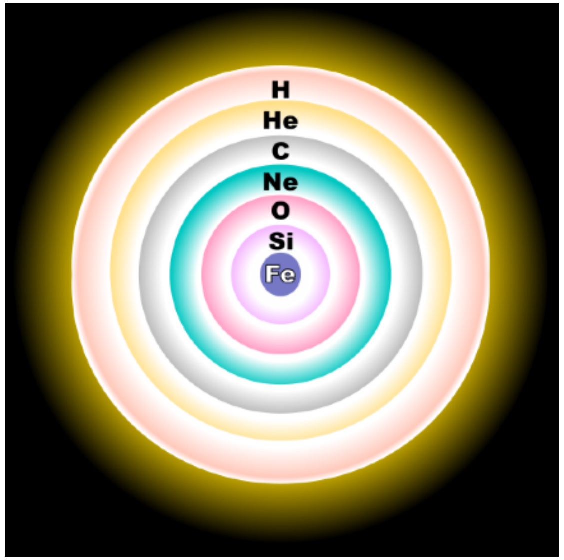

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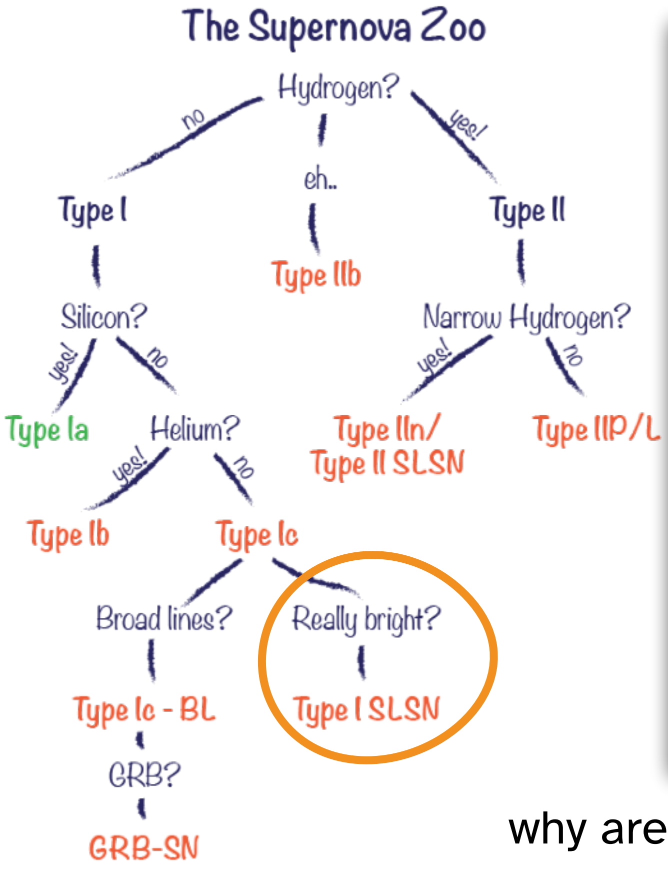

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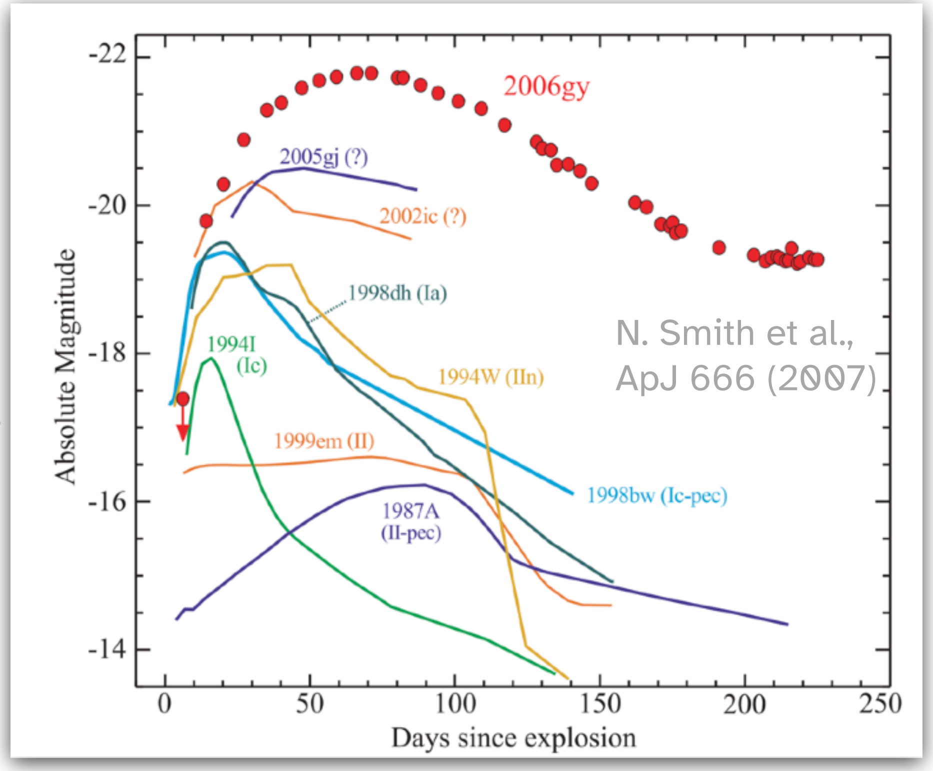

N. Smith et al., ApJ 666 (2007)

why are some SNe so bright / long lasting?
are additional *interactions* providing extra power?

Core-collapse supernovae from astronomy ~~101~~ 102

star goes boom

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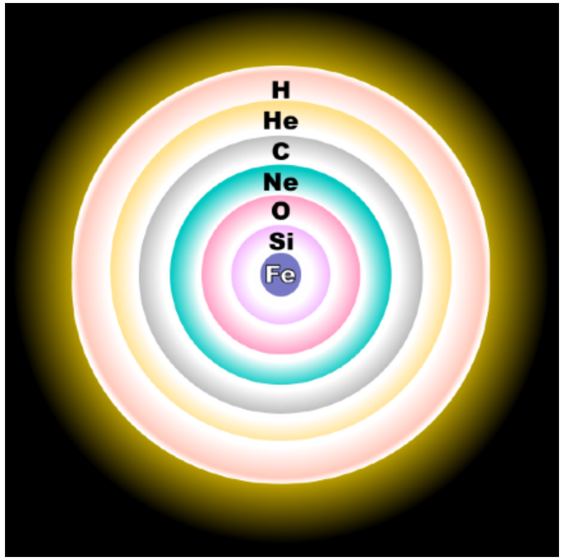

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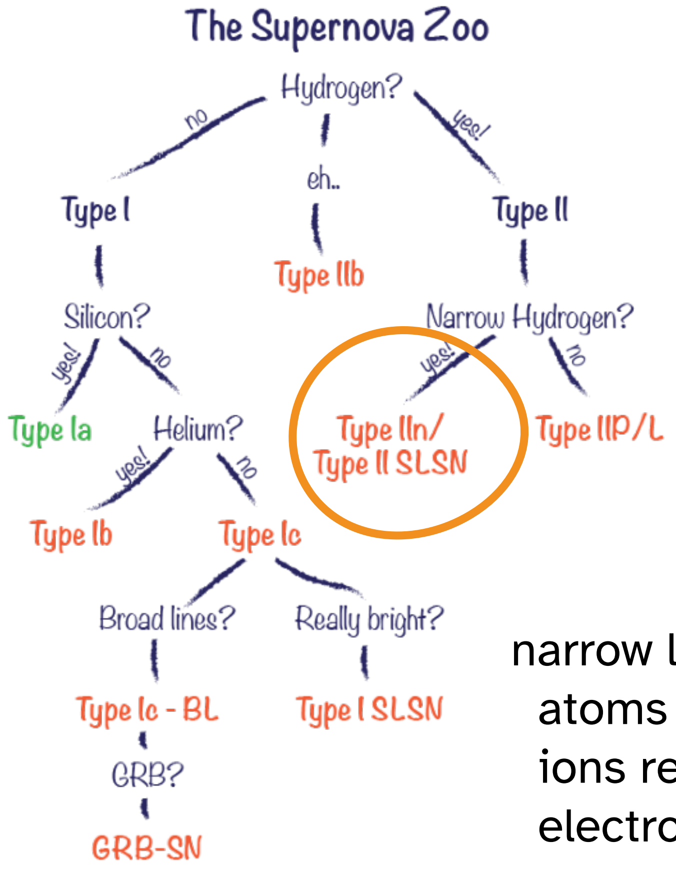

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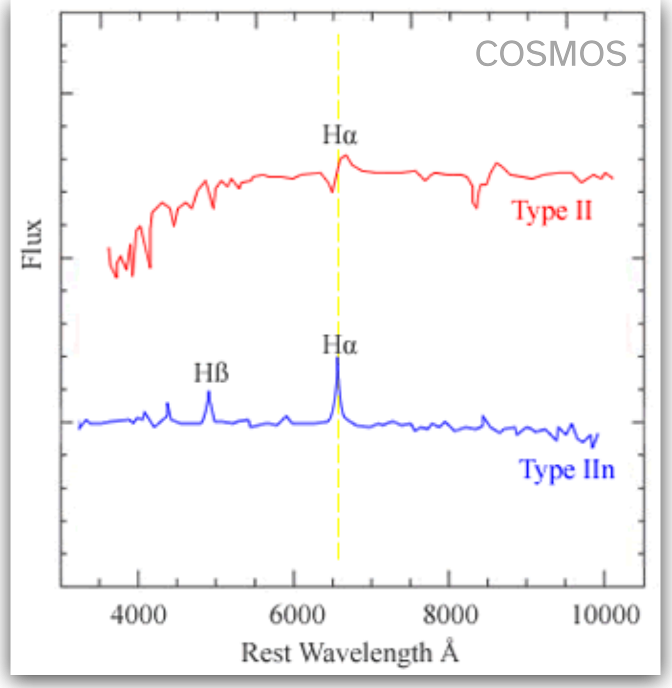

narrow lines indicate slow moving gas:

- atoms are ionized by SN ejecta, lose an electron
- ions recapture electrons (recombination)
- electron cascades down into lower energy levels
  - -> emission at specific wavelengths

Core-collapse supernovae from astronomy ~~101~~ 102

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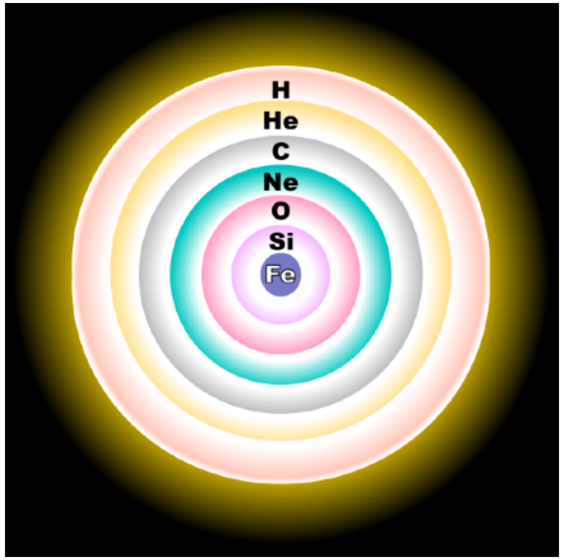

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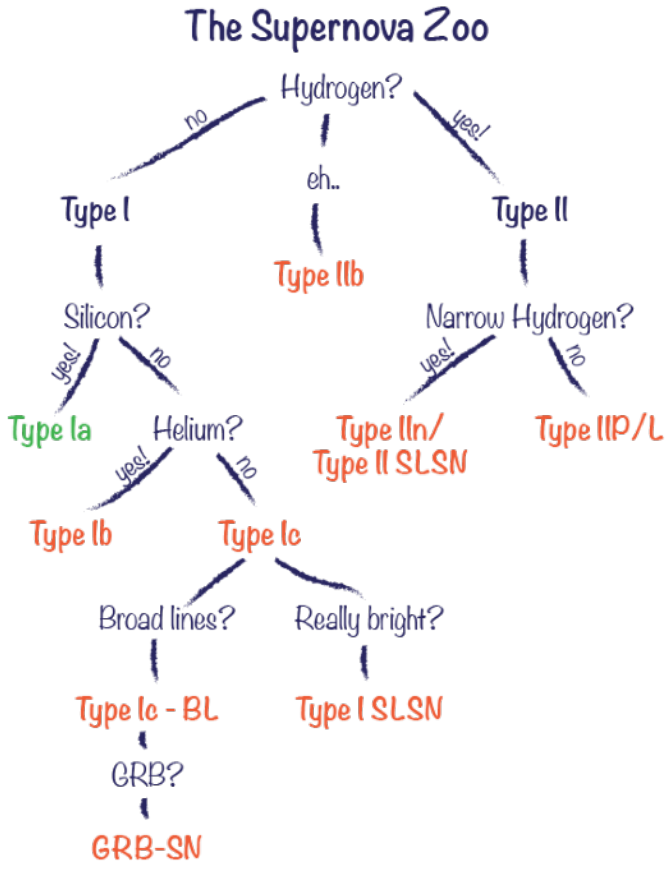


A. Villar

some supernovae show evidence for additional interactions with (slow-moving) external material

=> interacting supernovae

Core-collapse supernovae from astronomy 101

star goes boom

modified from J. Borowska-Naguszewska

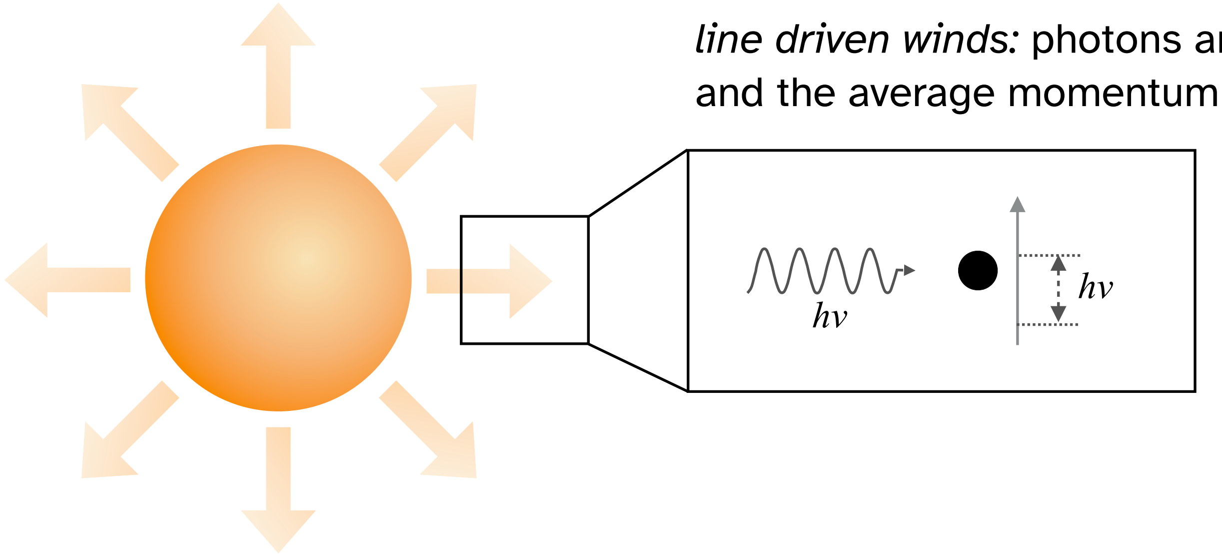
Massive star explodes as a supernova, lightcurve is bright at the start and then simply fades?

Core-collapse supernovae from astronomy 101

star goes boom

Massive stars emit strong stellar winds over their lifetimes

line driven winds: photons are absorbed and the average momentum gain is outward



modi

Massive

These winds create densities in the circumstellar environment

Core-collapse supernovae from astronomy 101

star goes boom

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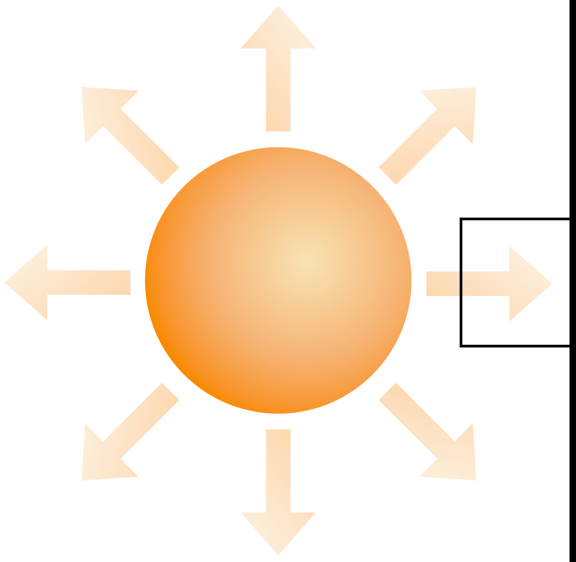

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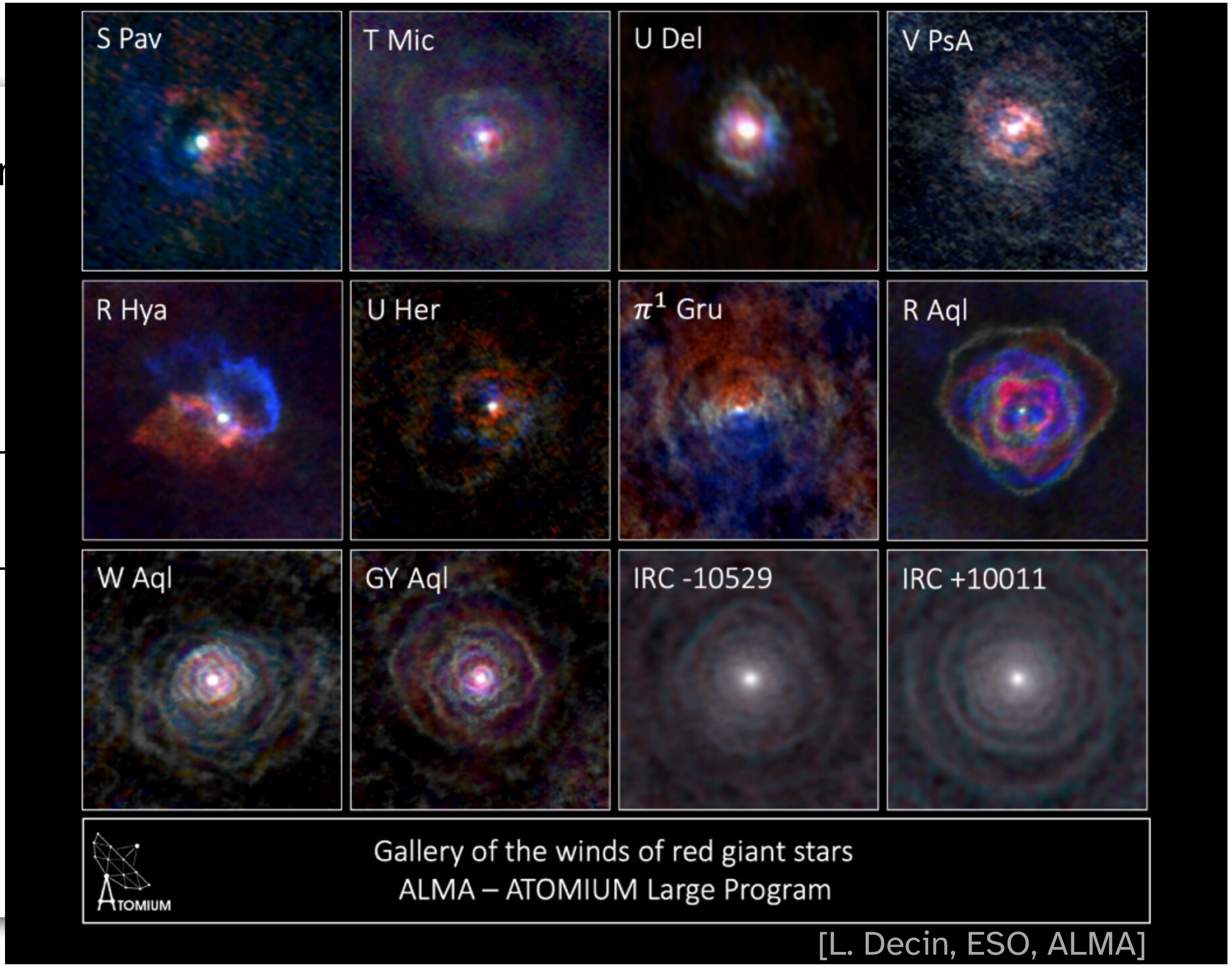

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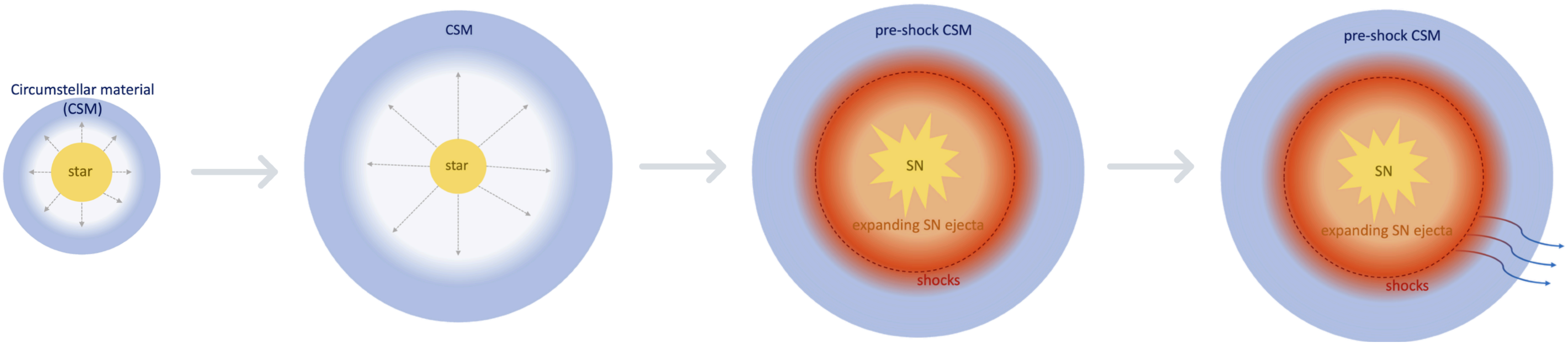

modified from J. Borowska-Naguszewska

Expanding SN ejecta runs into circumstellar material -> shocks -> particle acceleration -> gamma rays????

Core-collapse supernovae from astronomy ~~101~~ 102

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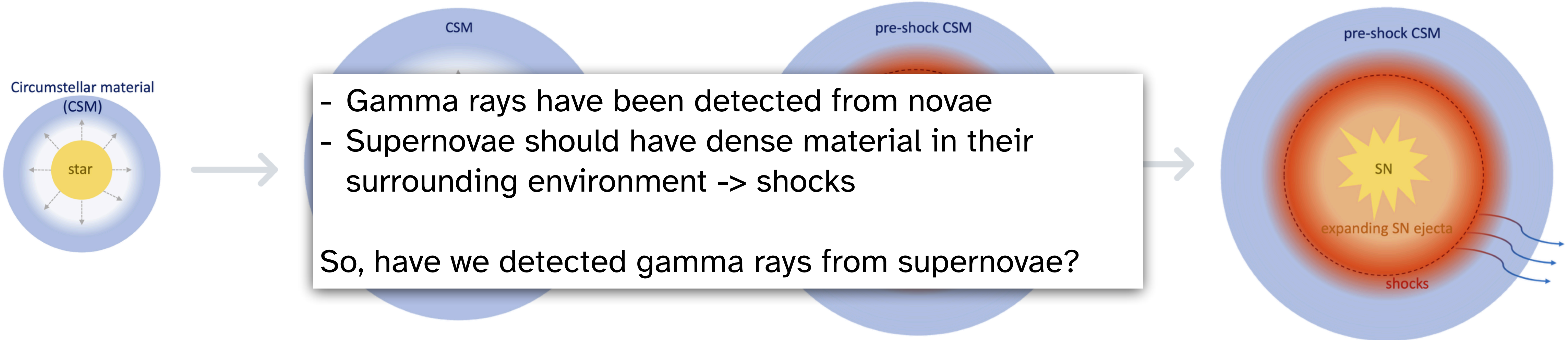


- Gamma rays have been detected from novae
- Supernovae should have dense material in their surrounding environment -> shocks

So, have we detected gamma rays from supernovae?

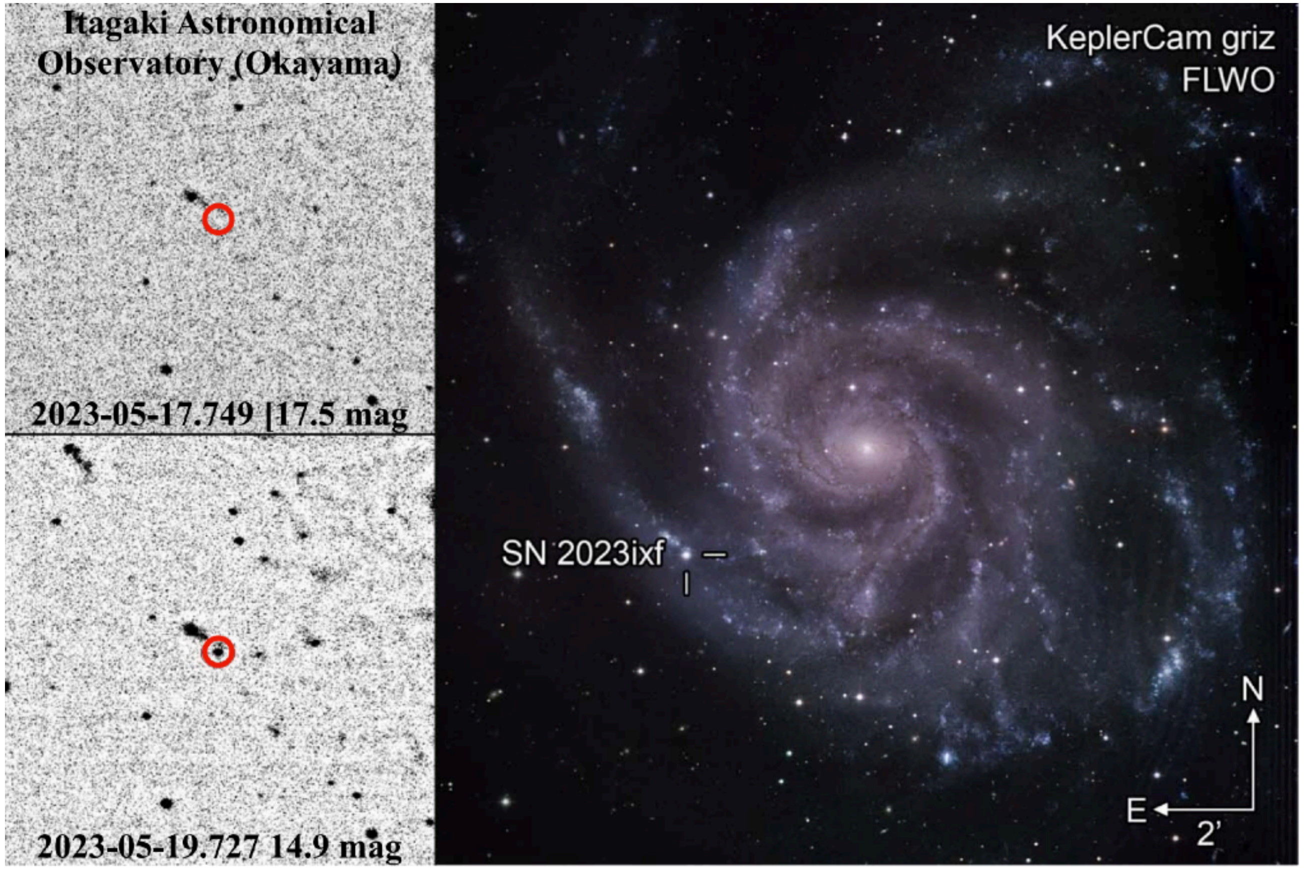
modified from J. Borowska-Naguszewska

Expanding SN ejecta runs into circumstellar material -> shocks -> particle acceleration -> gamma rays????

Searches for gamma-ray emission from CC SNe

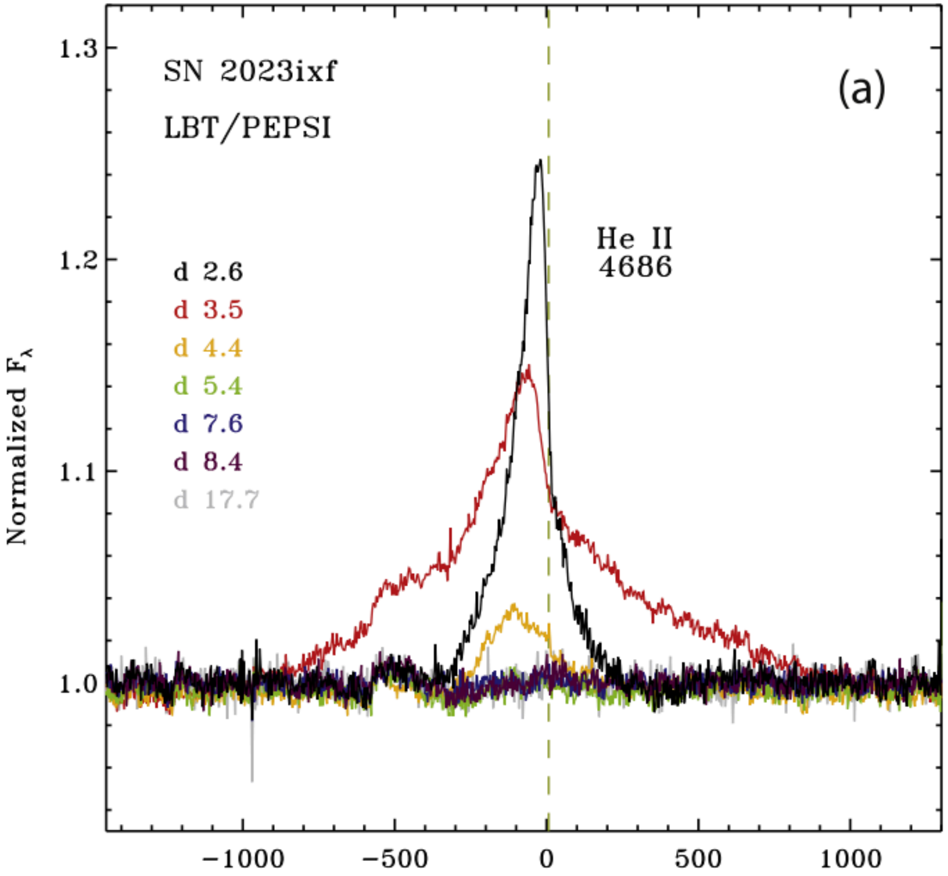
Fermi-LAT observations of SN 2023ixf

A SN II-n just 7 Mpc away (z = 0.0008)



[K. Murase et al., MNRAS 440 (2014)]

strong emission lines that faded over time



[N. Smith et al., ApJ 956 (2023)]

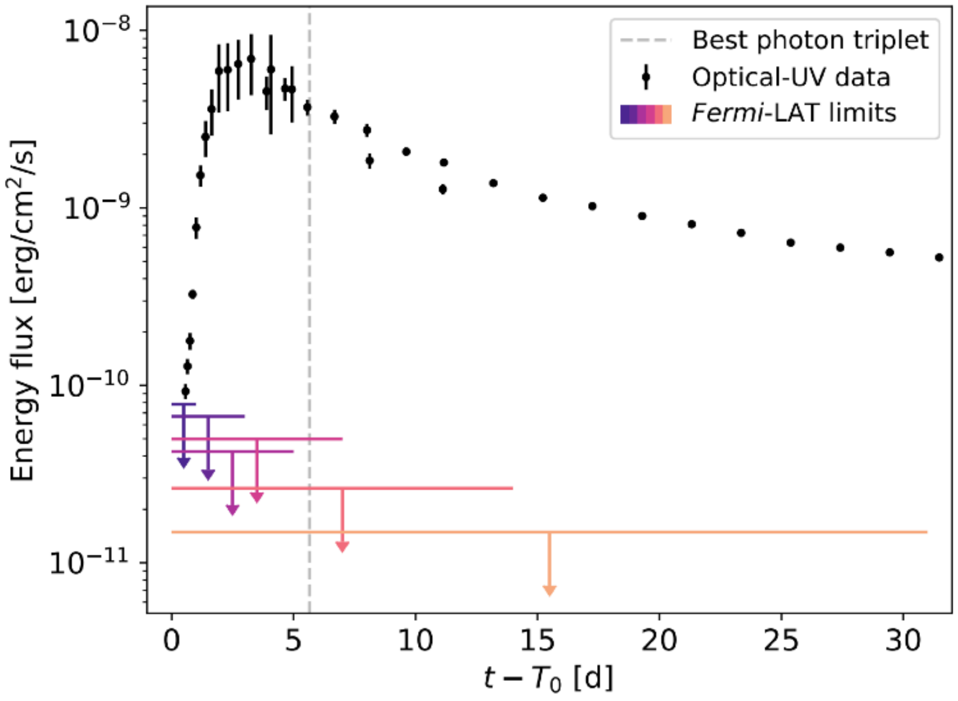
Searches for gamma-ray emission from CC SNe

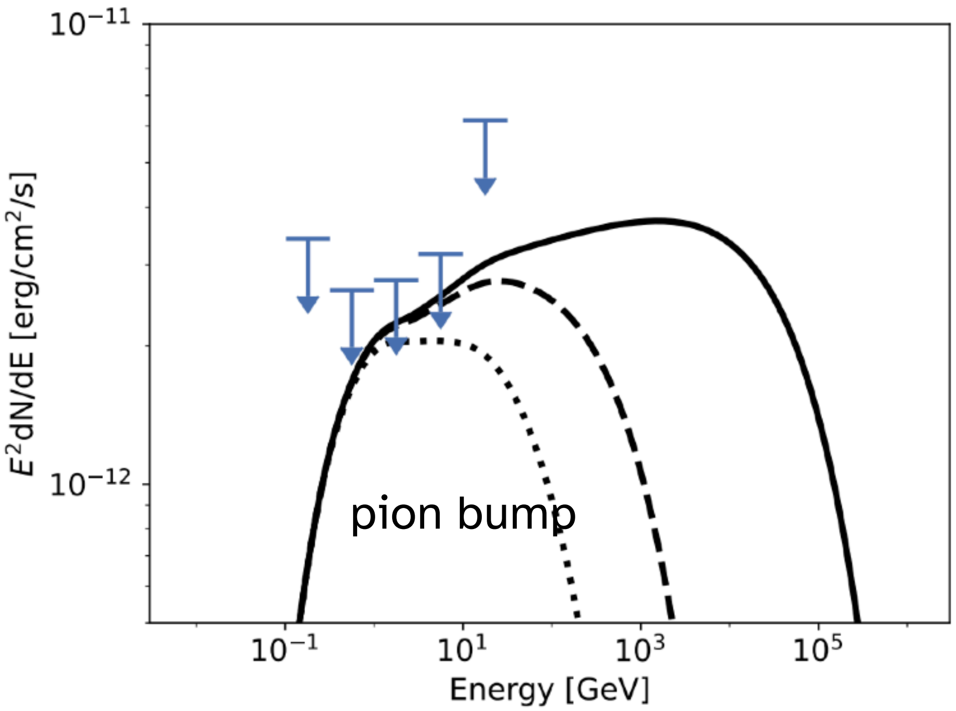
Fermi-LAT observations of SN 2023ixf

LAT upper limits on >100 MeV flux -> upper limits on efficiency of cosmic ray acceleration

how much of the energy goes into accelerating cosmic rays

[G. Martí-Devesa, A&A 686 (2024)]



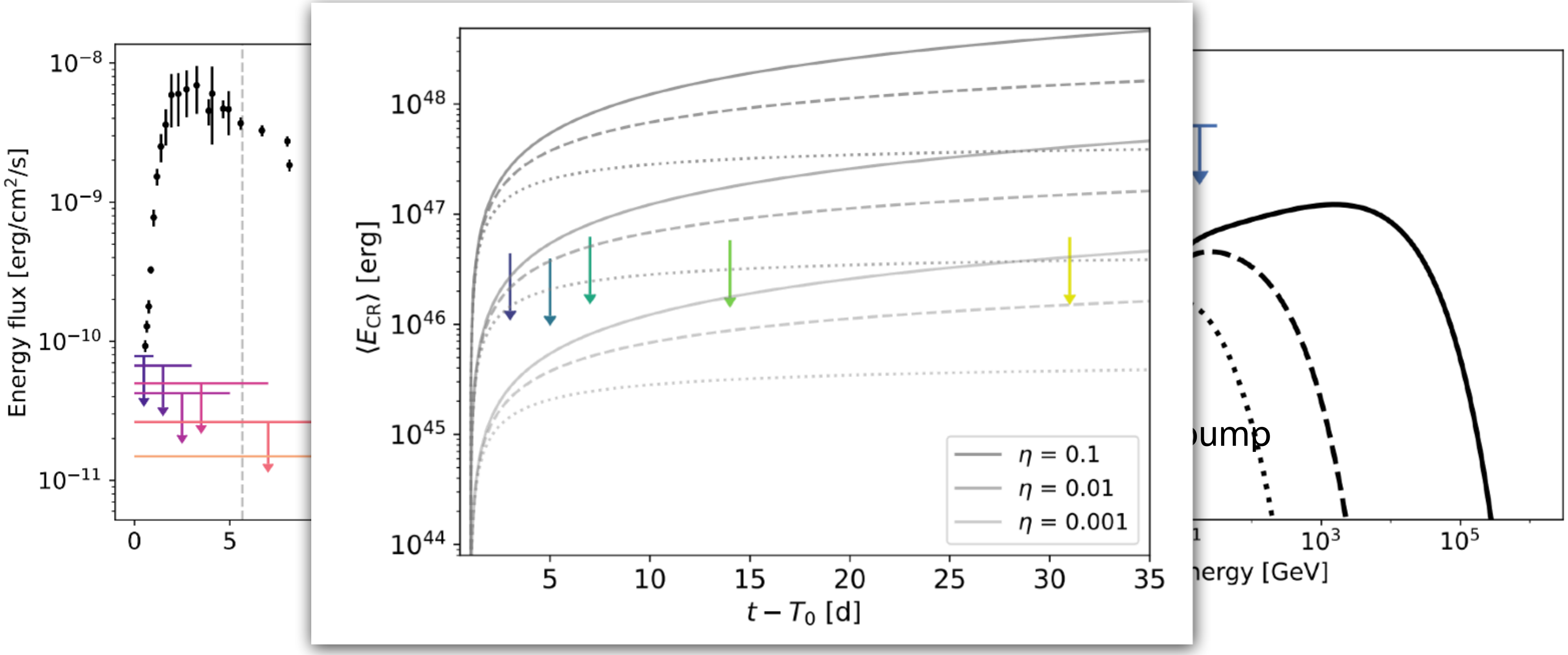


Searches for gamma-ray emission from CC SNe

Fermi-LAT observations of SN 2023ixf

LAT upper limits on >100 MeV flux -> upper limits on efficiency of cosmic ray acceleration of ≲1%

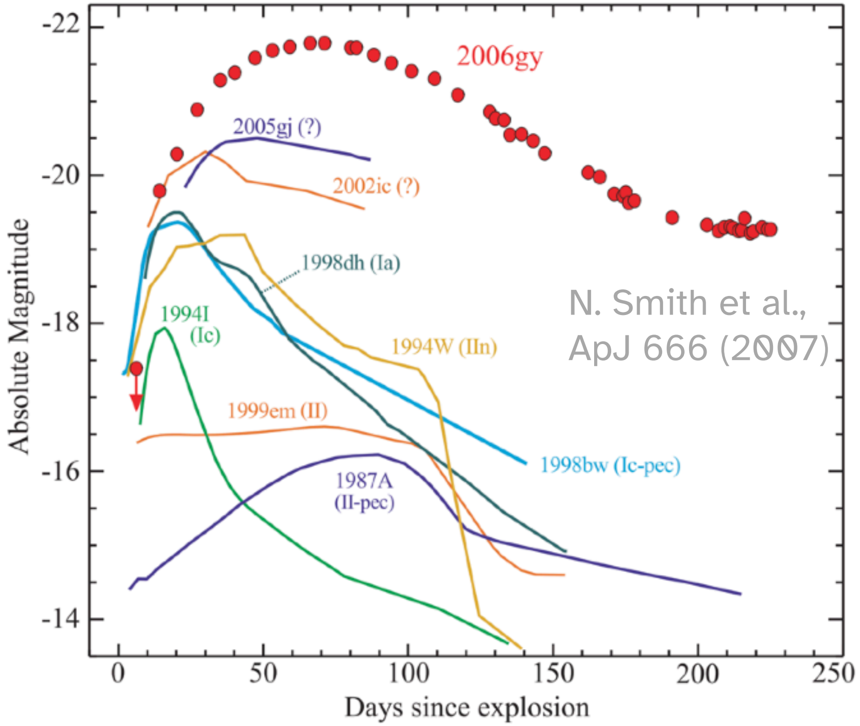
[G. Martí-Devesa, A&A 686 (2024)]



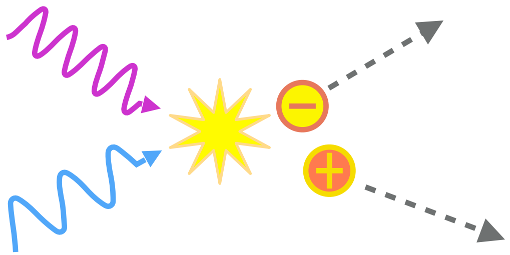
Complication: ɣ-ɣ opacity

When should we look for VHE gamma rays?

The supernova itself is bright in optical-ish photons -> ɣ rays are absorbed initially (~10s to 100s of days?)



N. Smith et al., ApJ 666 (2007)



$\gamma + \gamma \longrightarrow e^+ + e^-$

rule of thumb for γ-γ pair production:

$E_1 E_2 \gtrsim (0.5\ \mathrm{MeV})^2$

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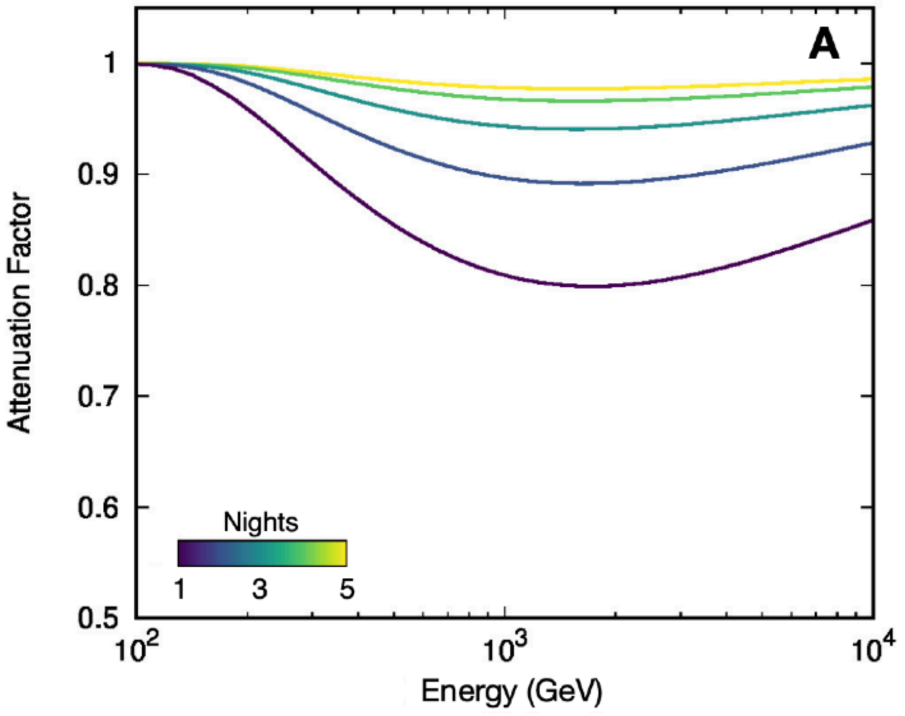
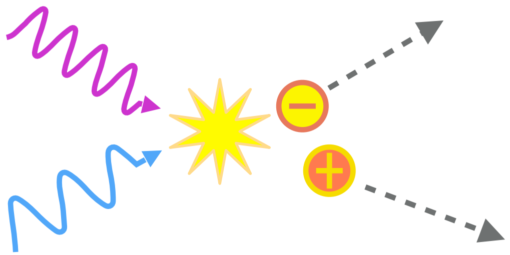
e.g., the recent RS Ophiuchi nova event



[H.E.S.S. Collaboration, Science 376 (2022)]



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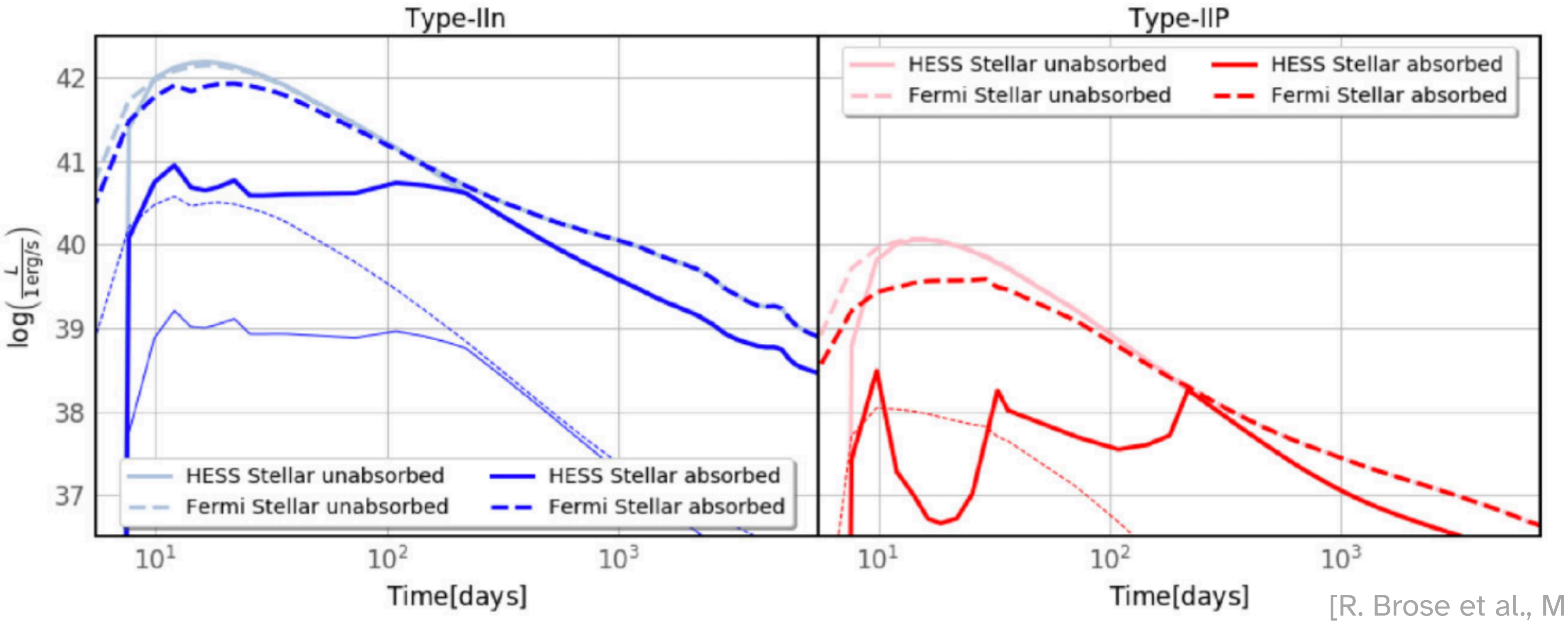


[R. Brose et al., MNRAS 516 (2022)]

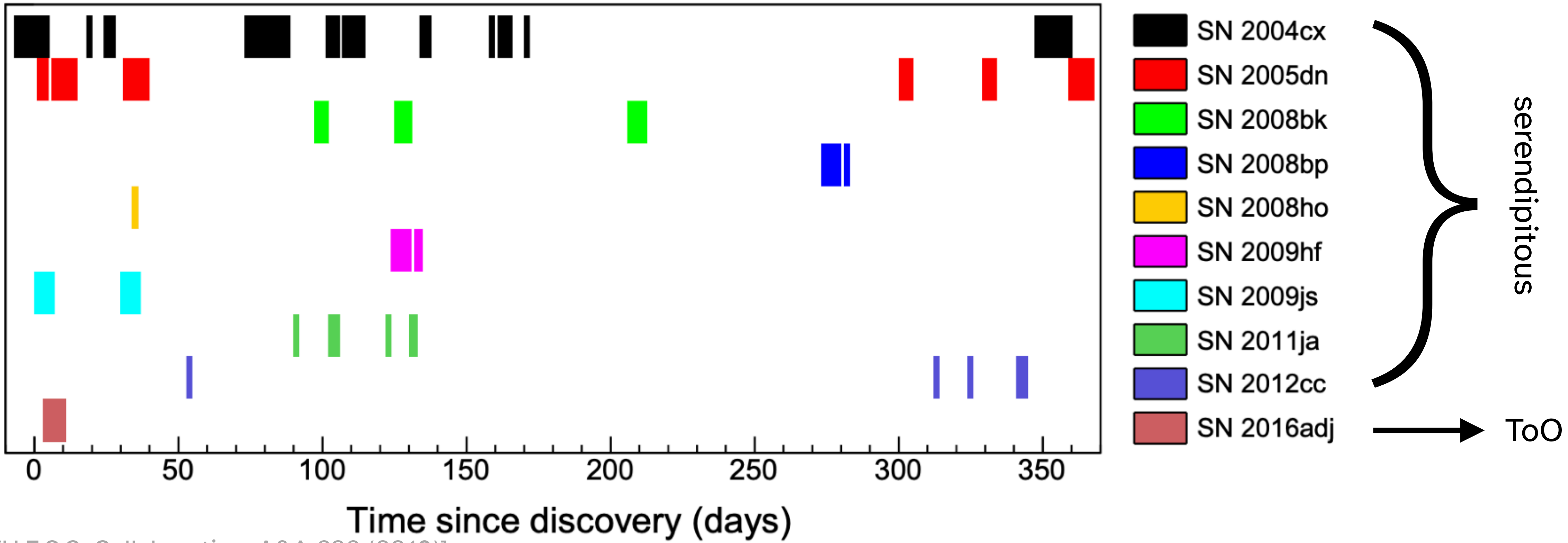
Actual predictions depend strongly on optical SN properties, circumstellar environment, etc.

Searches for gamma-ray emission from CC SNe

H.E.S.S. observations of CC SNe

VHE photons from CC SNe need to wait until the opacity decreases sufficiently (~10s to 100s of days?)

H.E.S.S. observations:



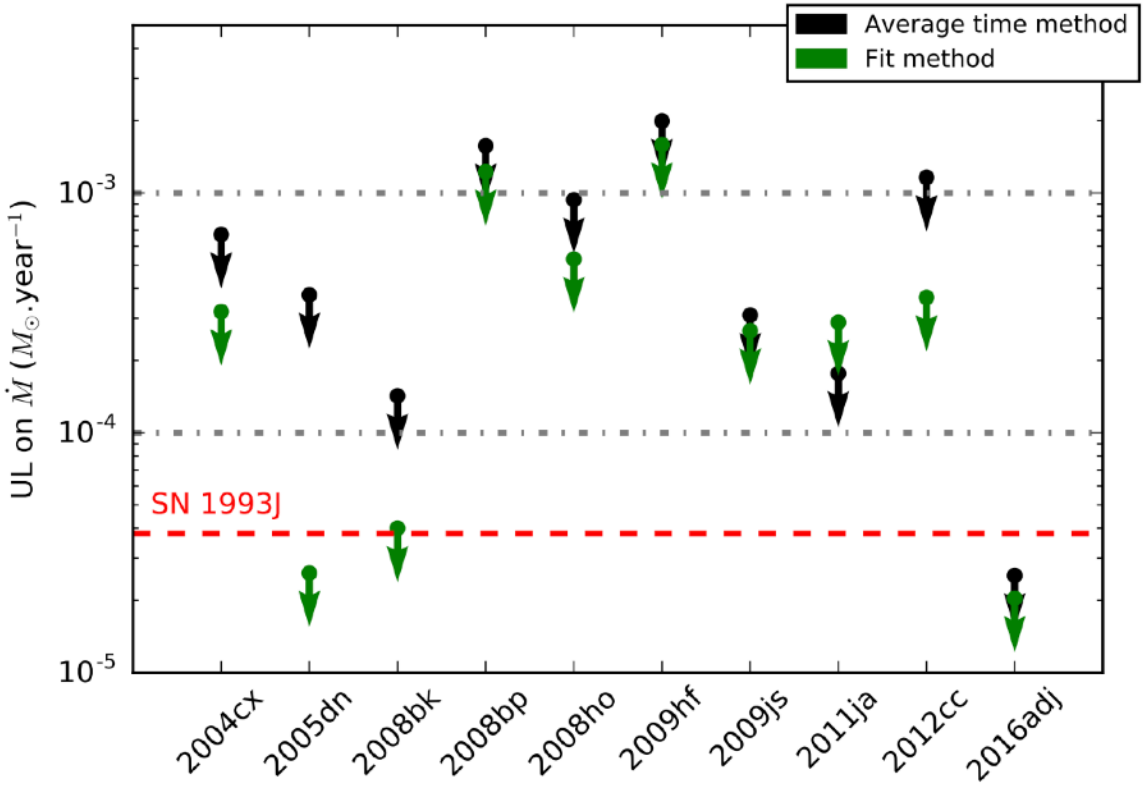
[H.E.S.S. Collaboration, A&A 626 (2019)]

Searches for gamma-ray emission from CC SNe

H.E.S.S. observations of CC SNe

VHE photons from CC SNe need to wait until the opacity decreases sufficiently (~10s to 100s of days?)

H.E.S.S. upper limits on mass loss rate for an efficiency of 10% (+ other assumptions)



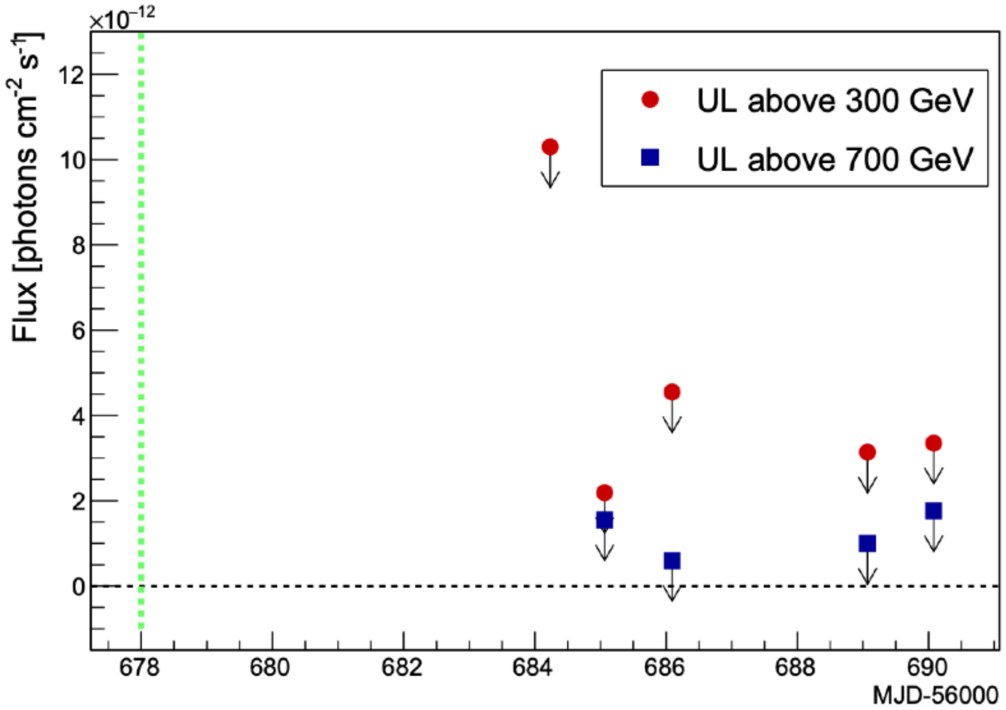
[H.E.S.S. Collaboration, A&A 626 (2019)]

Searches for gamma-ray emission from CC SNe

MAGIC observations of SN 2014J

VHE photons from CC SNe need to wait until the opacity decreases sufficiently (~10s to 100s of days?)

MAGIC observed a very nearby SN Ia (3.6 Mpc):



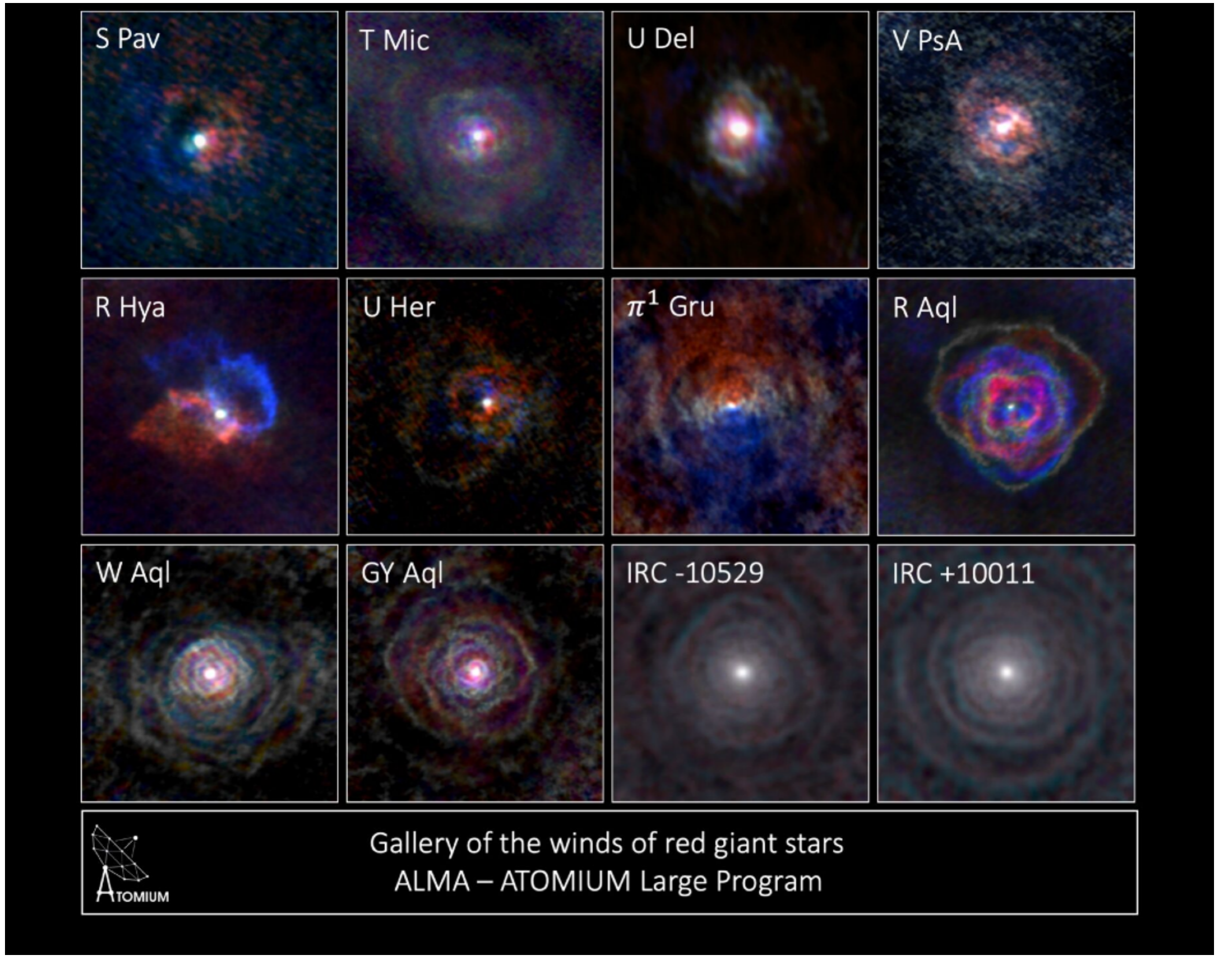
[M. L. Ahnen et al., A&A 602 (2017)]

ally (Dwarkadas & Chevalier 1998). Although the flux keeps increasing with time according to Eq. (1), with this low expansion parameter it will still be about 10^{-21} photons cm^{-2} s^{-1} 100 yr after the SN occurred, which is well below the sensitivity of the current and planned VHE observatories – several orders of magnitude below the sensitivity that the future Cherenkov Telescope Array (CTA[1]) will reach.

No detection -> no VHE detection possible for any SN Ia-CSM?

Circumstellar density profile is complex

Shells from stellar winds of massive stars



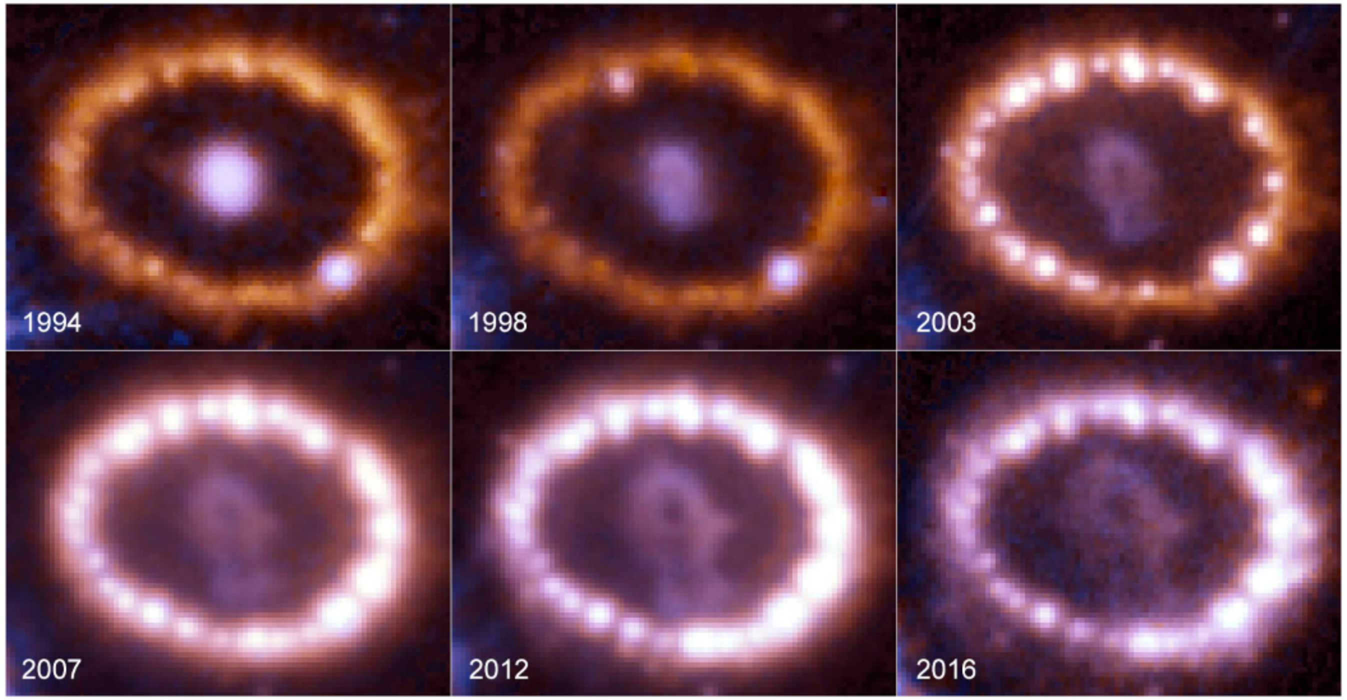
[L. Decin, ESO, ALMA]

- Wind mass loss is episodic, not continuous -> “shells”
- Shape is affected by environment (e.g., stellar companions)

Circumstellar density profile is complex

Interactions with circumstellar shells -> late-time rebrightening

e.g., optical images of SN1987A

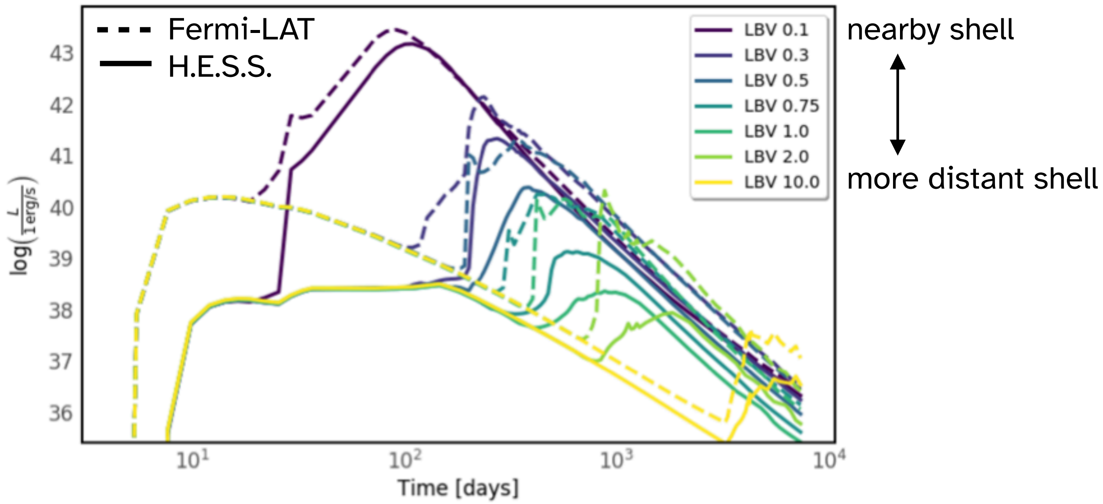


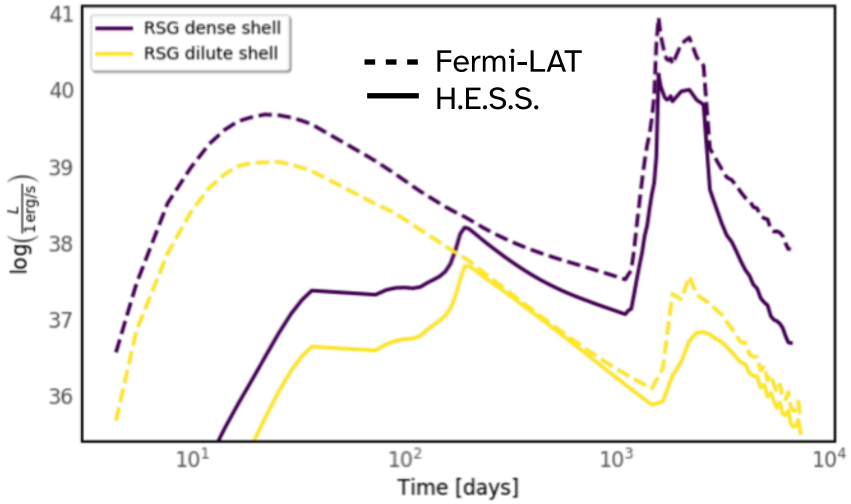
NASA, ESA, R. Kirshner (CfA, Gordon and Betty Moore Foundation), P. Challis (CfA)

SNe can rebrighten after months or years, when the SN shock interacts with a dense circumstellar shell

Prospects for gamma rays from rebrightening supernovae

Interactions with circumstellar shells -> late-time rebrightening

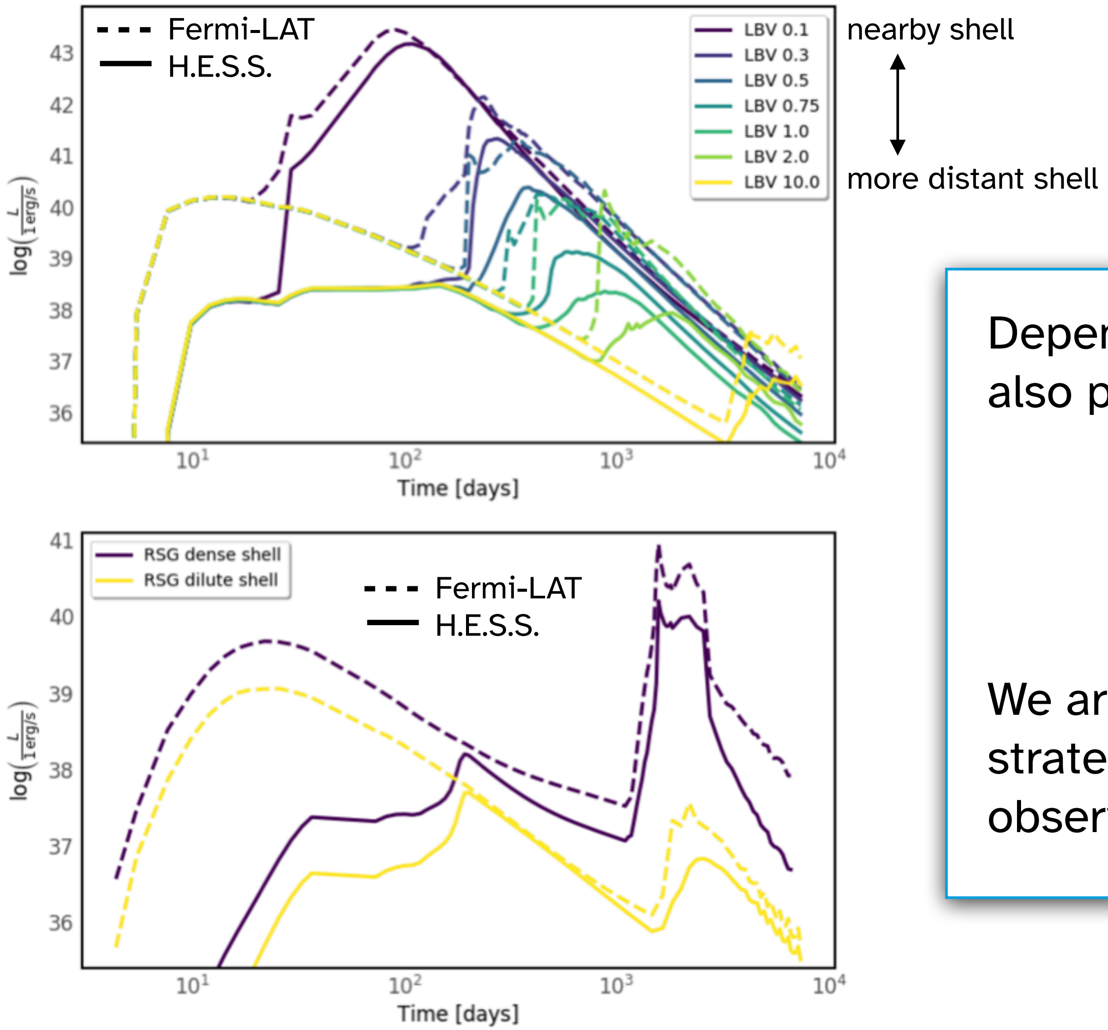




[R. Brose et al., A&A 706 (2026)]

Prospects for gamma rays from rebrightening supernovae

Interactions with circumstellar shells -> late-time rebrightening



[R. Brose et al., A&A 706 (2026)]

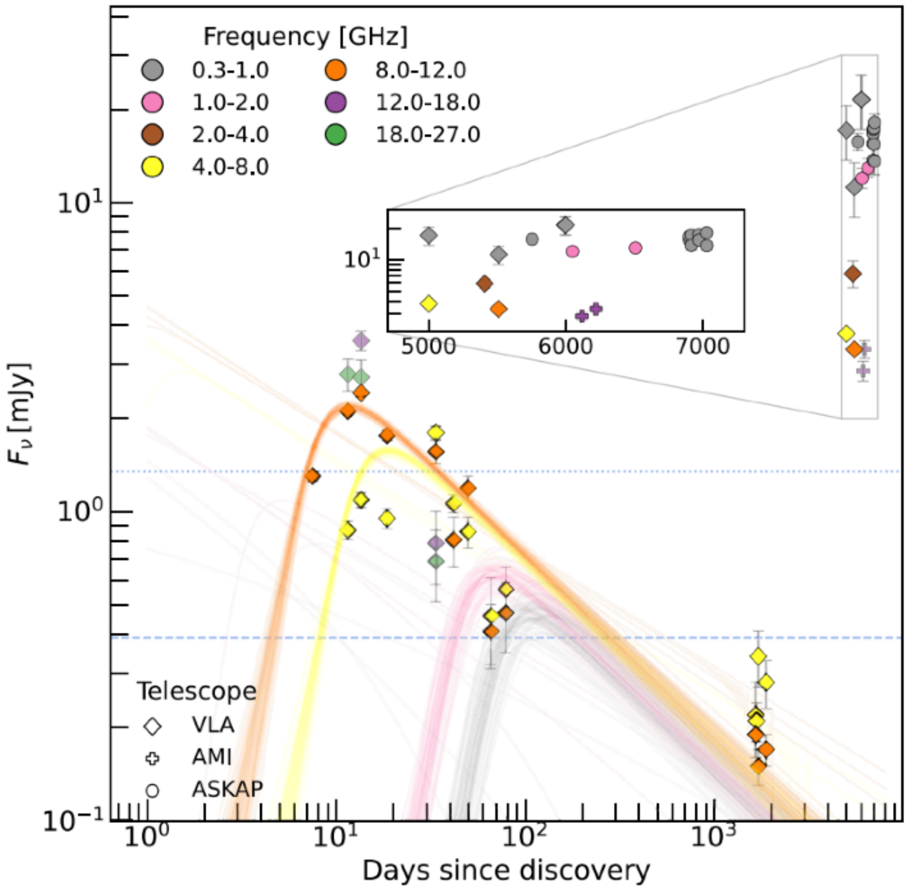
Depending on the shell properties, this could also produce detectable gamma-ray emission

We are starting to explore different observation strategies for SNe (e.g., observe later and/or observe based on MWL rebrightening)

Prospects for gamma rays from rebrightening supernovae

Interactions with circumstellar shells -> late-time rebrightening

[K. Rose et al., MNRAS 534 (2024)]



Some core-collapse supernovae have **rebrightened** after ~years

Rebrightened flux can even be much higher than original SN flux (in radio)

-> interactions with circumstellar shells

"late-time supernova rebrightening"

≈

"very young supernova remnant"

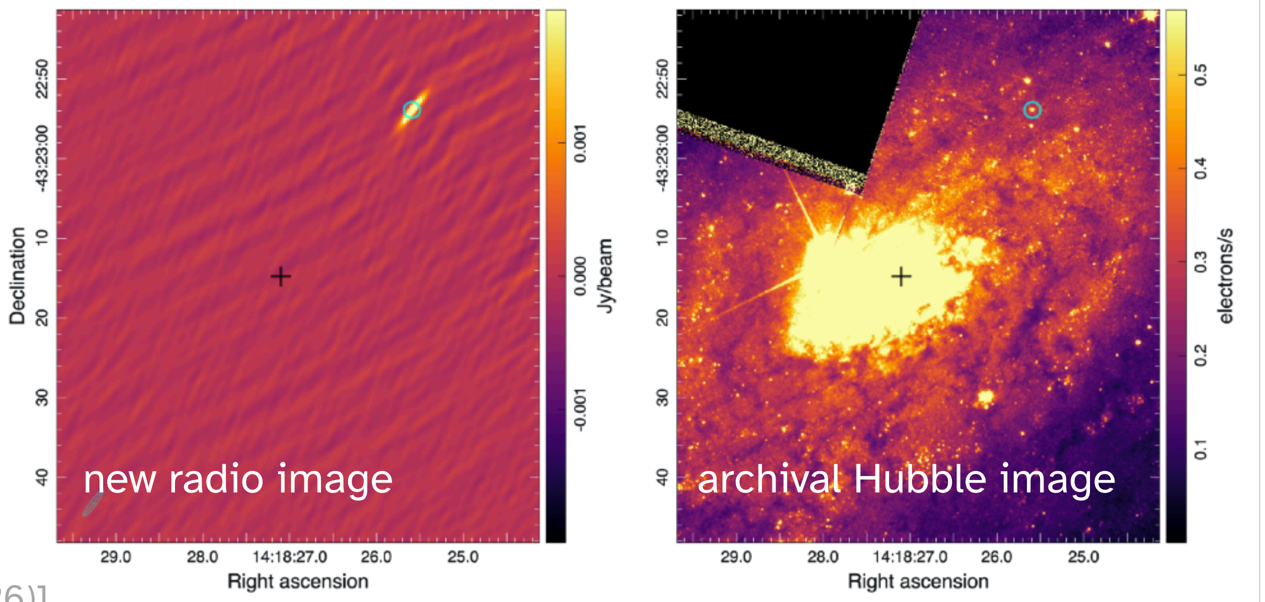
Prospects for gamma rays from rebrightening supernovae

Interactions with circumstellar shells -> late-time rebrightening

SN 2007it on the RISE - a radio detection of an interacting supernova 18 years post-explosion

F. Acero[1] R. Z. E. Alsaberi[2,3] M. Arias[4] J. Borowska-Naguszewska,[5] R. Brose[6,*]
C. Burger-Scheidlin[7,8] P. G. Edwards[9] Q. Feng[10] M. D. Filipović[2] T. Laskar[10]
S. Lazarević[2,9,11,†] J. Mackey[7,8] A. Nucara[12,13] K. Rose[14,9,‡] S. Ryder[15,16] F. Schüssler[17]
A. Simongini[18,13] Z. J. Smeaton[2] I. Sushch[19,20,21] and S. Zhu[22]

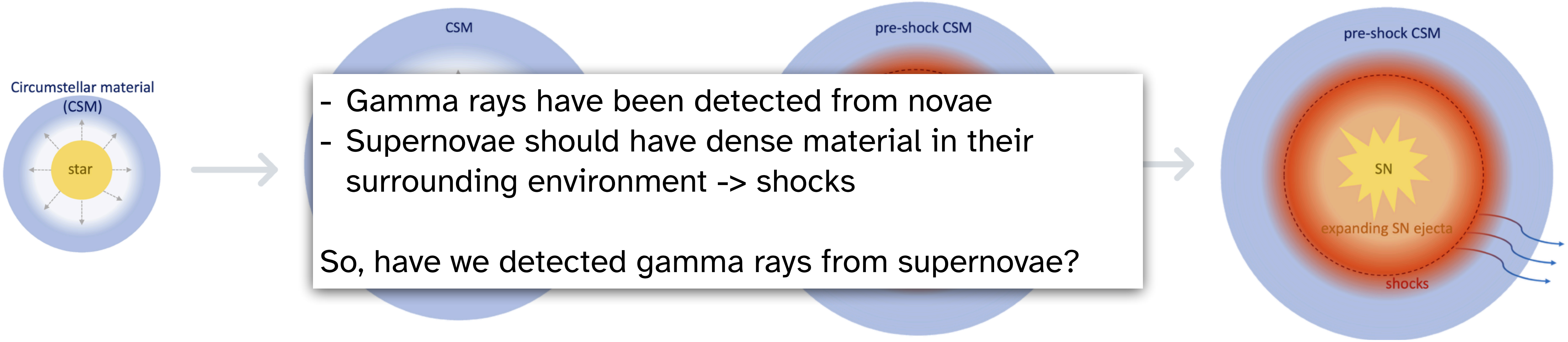
The RISE collaboration



[F. Acero et al., RNAAS 10 (2026)]

Core-collapse supernovae from astronomy ~~101~~ 102

star goes boom



- Gamma rays have been detected from novae
- Supernovae should have dense material in their surrounding environment -> shocks

So, have we detected gamma rays from supernovae?

modified from J. Borowska-Naguszewska

Usually the answer is "No" and I end my SN slides here …

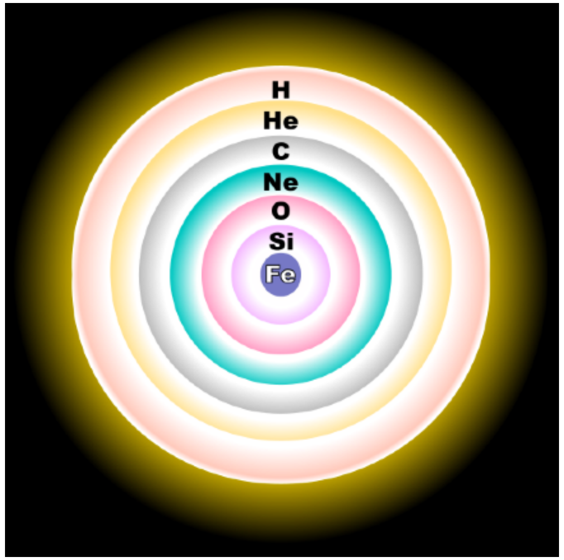
… but WAIT, Fabio has some exciting news going public today …

Expanding SN ejec[…] -> gamma rays????

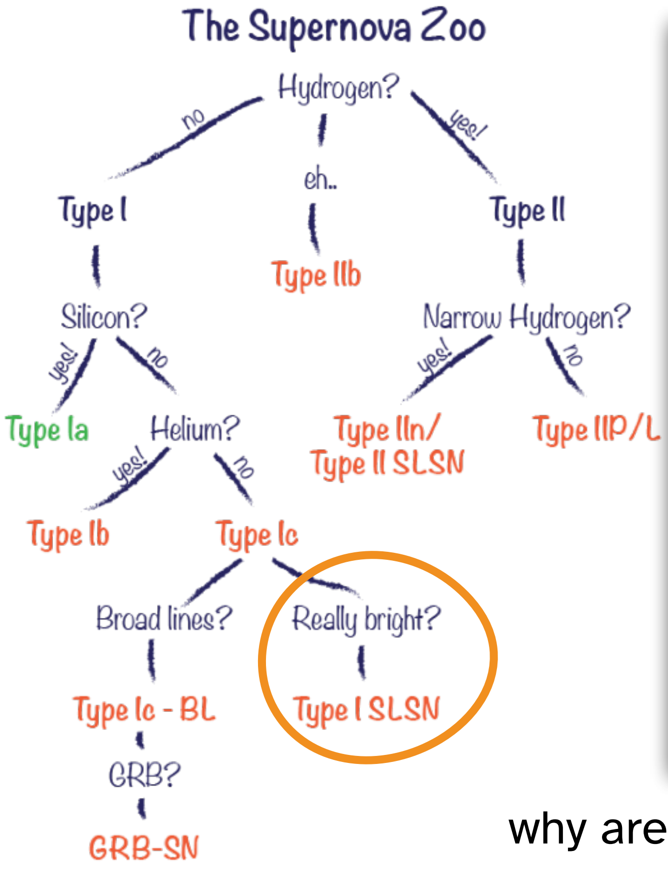
Core-collapse supernovae from astronomy ~~101~~ 102

star goes boom

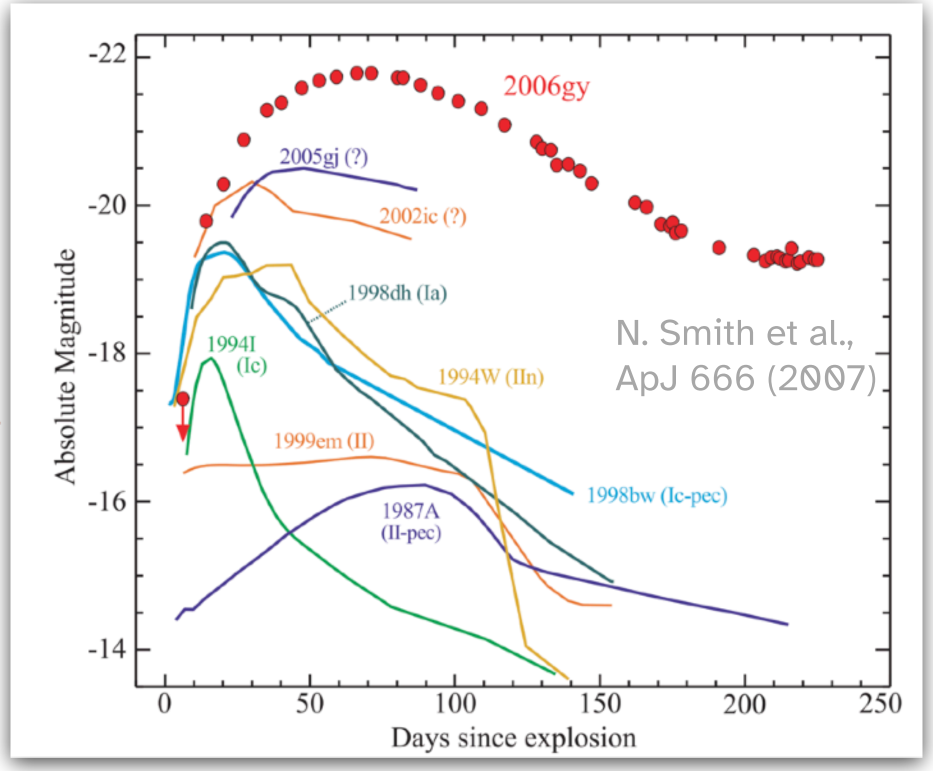
Any non-Ia supernova is a core collapse supernova



R. J. Hall



A. Villar

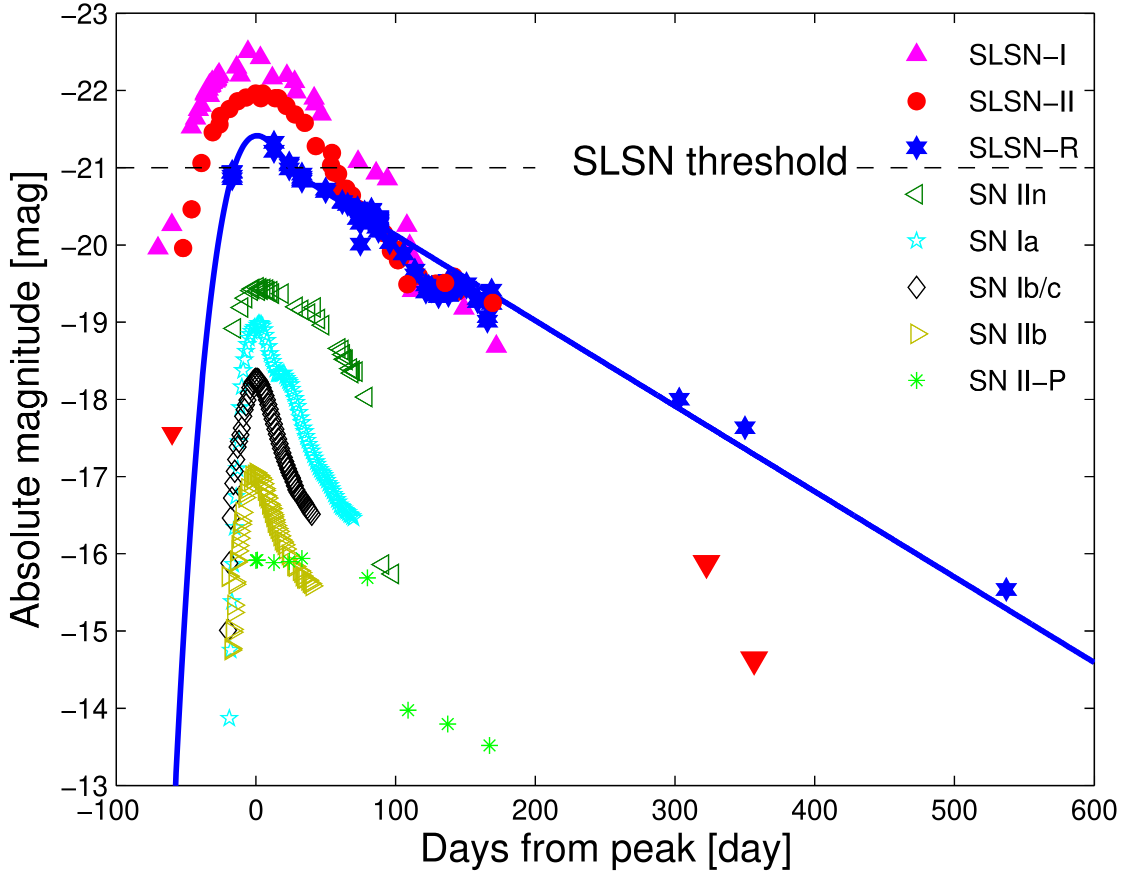


N. Smith et al., ApJ 666 (2007)

why are some SNe so bright / long lasting?
are additional *interactions* providing extra power?

What powers a superluminous supernova?

go ask Fabio



[A. Gal-Yam, Science 337 (2012)]

- circumstellar shell interactions?
- accretion onto the new-born central compact object?
- magnetar central engine?

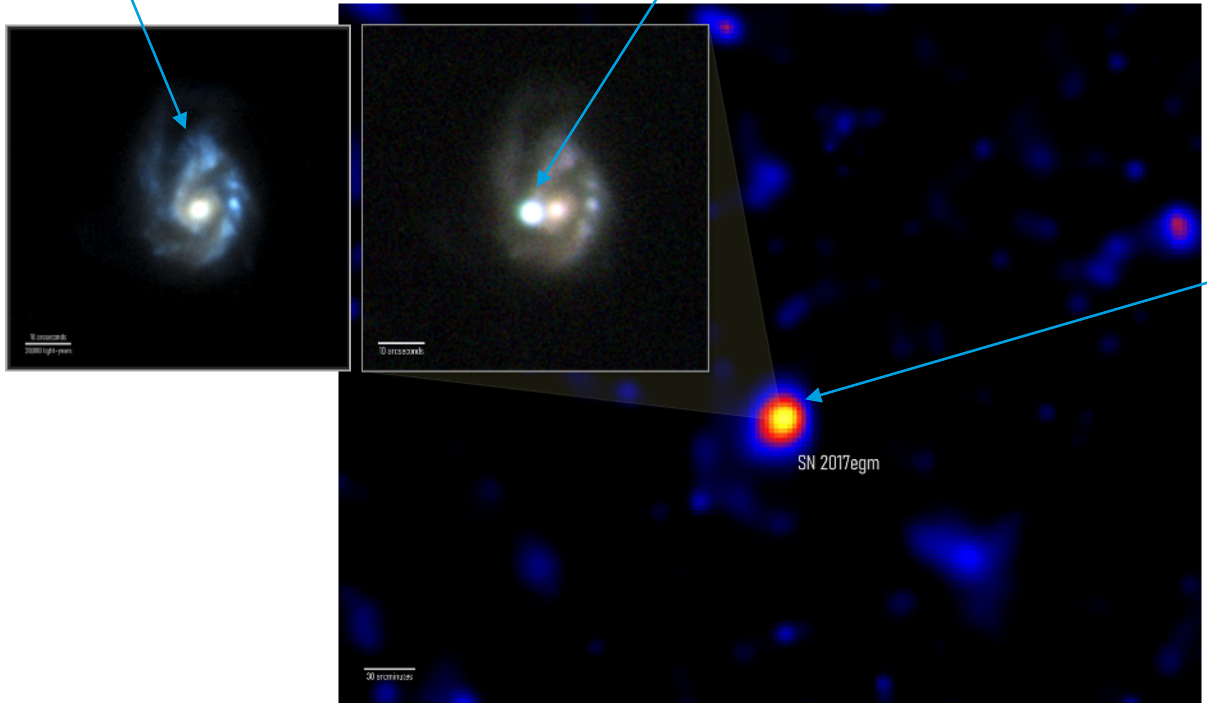
Have we detected gamma rays from a superluminous supernova?

go ask Fabio

the host galaxy normally looks like this

the supernova is clearly visible in optical light

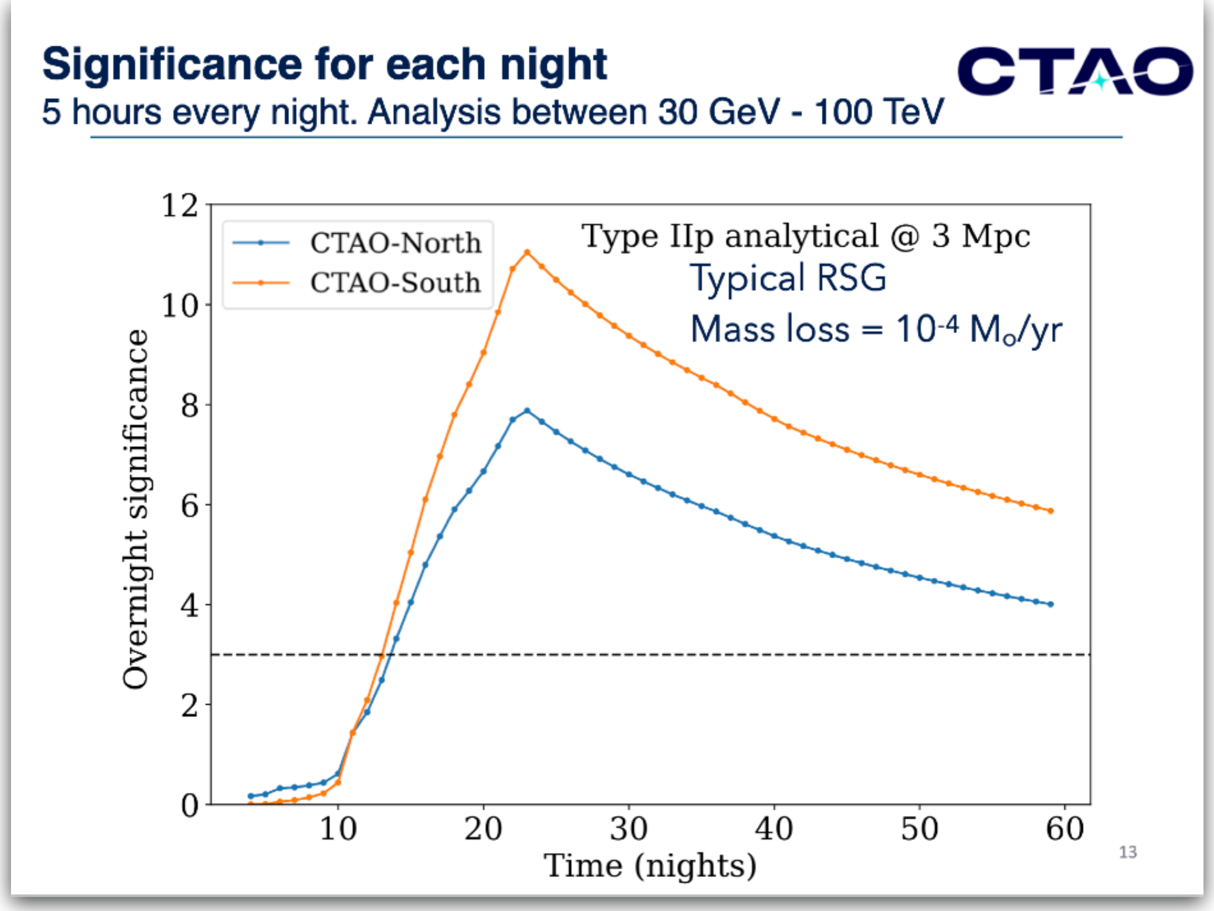
gamma-ray excess 👀

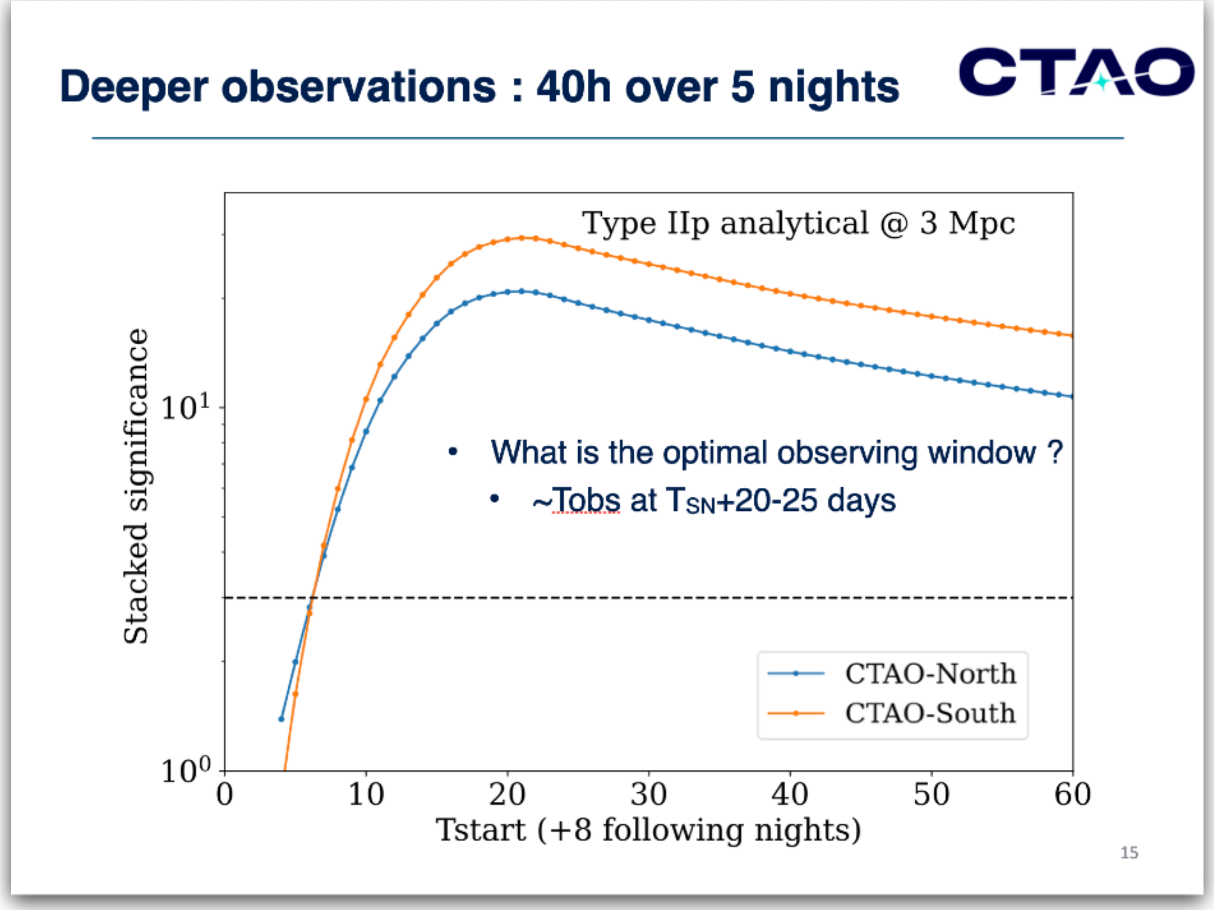


Prospects for CTAO

these slides are by Fabio, ask him for more info

What's the best way to observe a supernova?



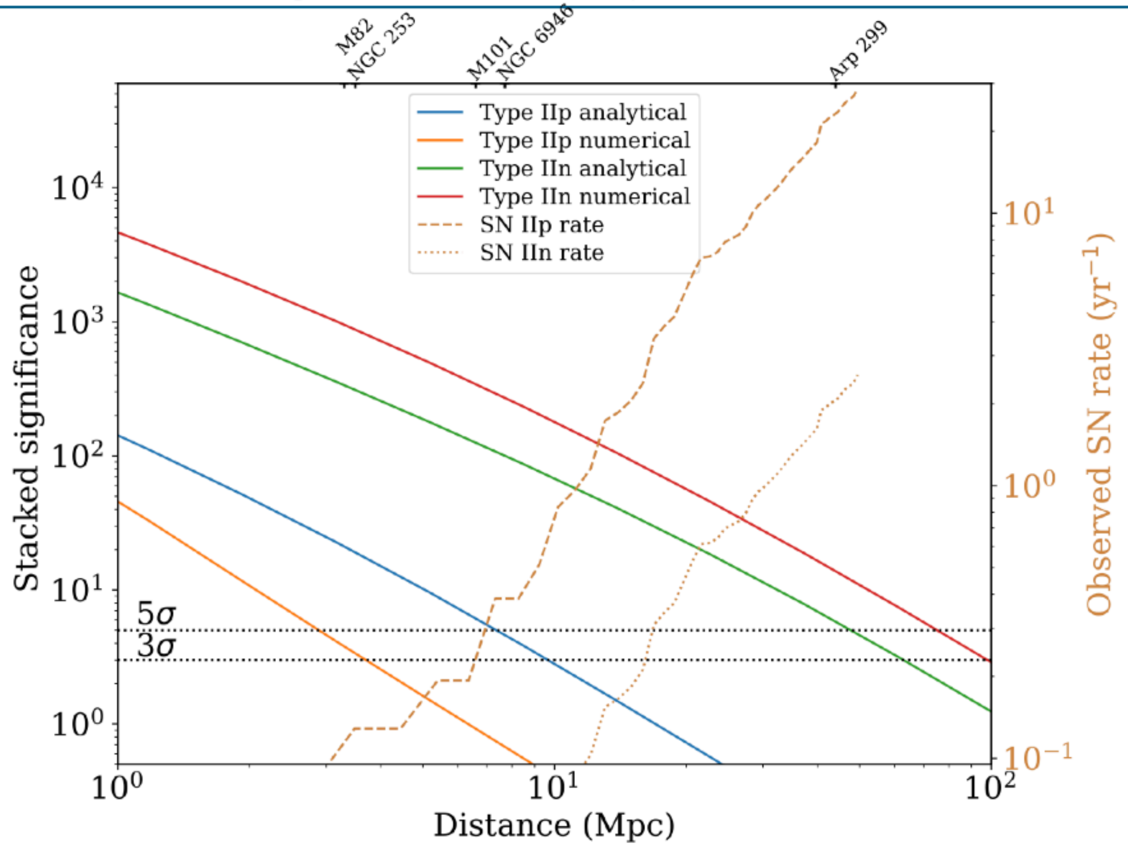


Prospects

these slides ar

Horizon of detectability

40 hours total time. Starting from T=20 days => 28d



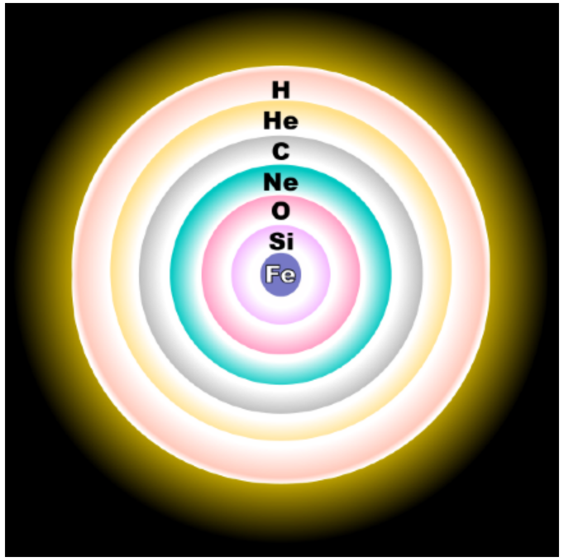
Horizon of 7 Mpc for Type IIp and 70 Mpc for Type IIn

- **Probe the starburst galaxies M82, NGC 253, NGC 6946 @ < 7 Mpc**
- **For cosmological scales this means :**
  - **Probing the local sheet (< 10 Mpc) & core of Laniakea at 70 Mpc**

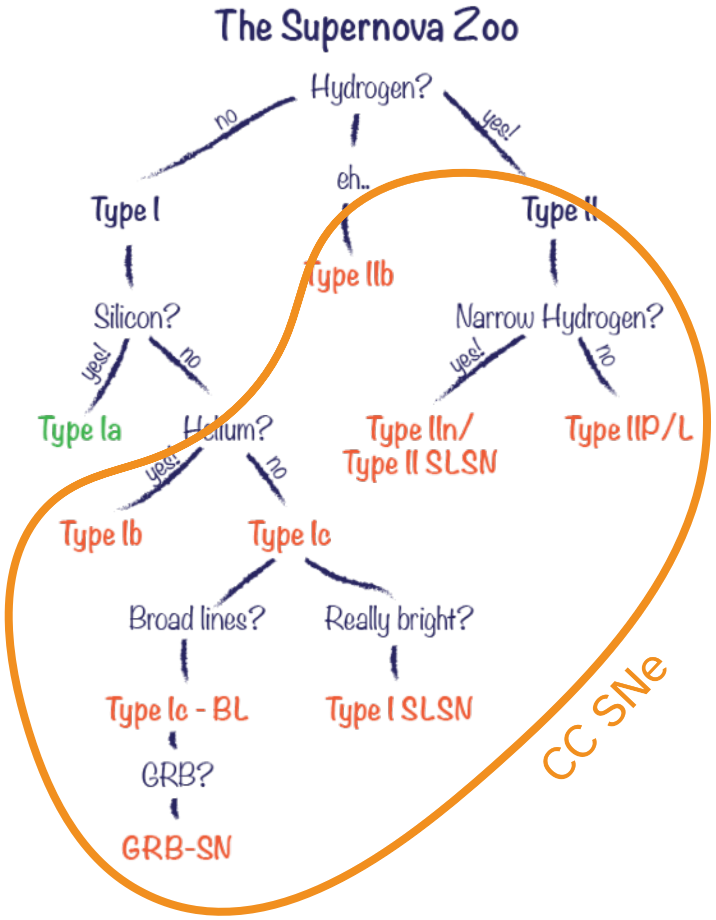
16

Core-collapse supernovae from astronomy ~~101~~ 102

Any non-Ia supernova is a core collapse supernova



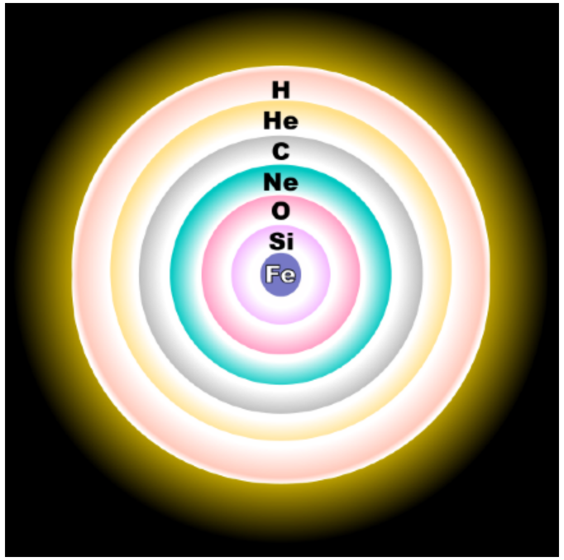
R. J. Hall



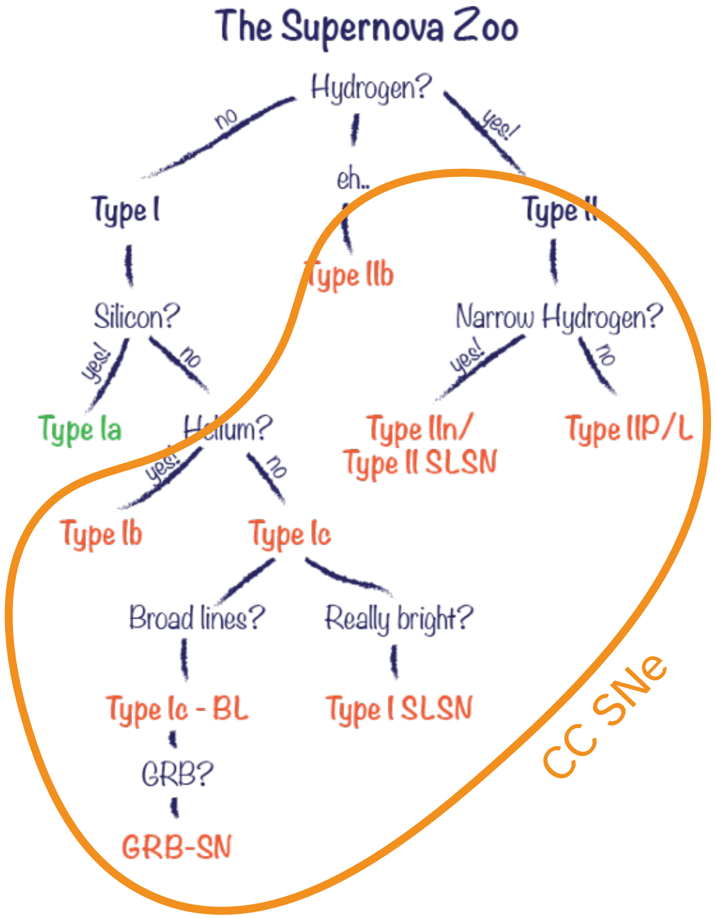
A. Villar

Core-collapse supernovae from astronomy ~~101~~ ~~102~~ 999

Any non-Ia supernova is a core collapse supernova

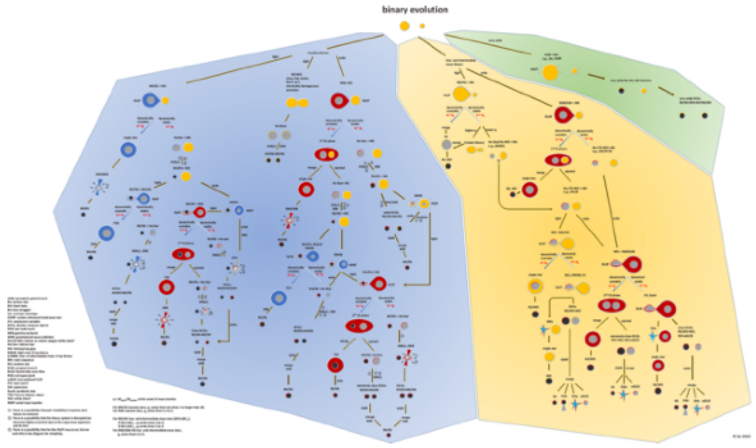


R. J. Hall



A. Villar

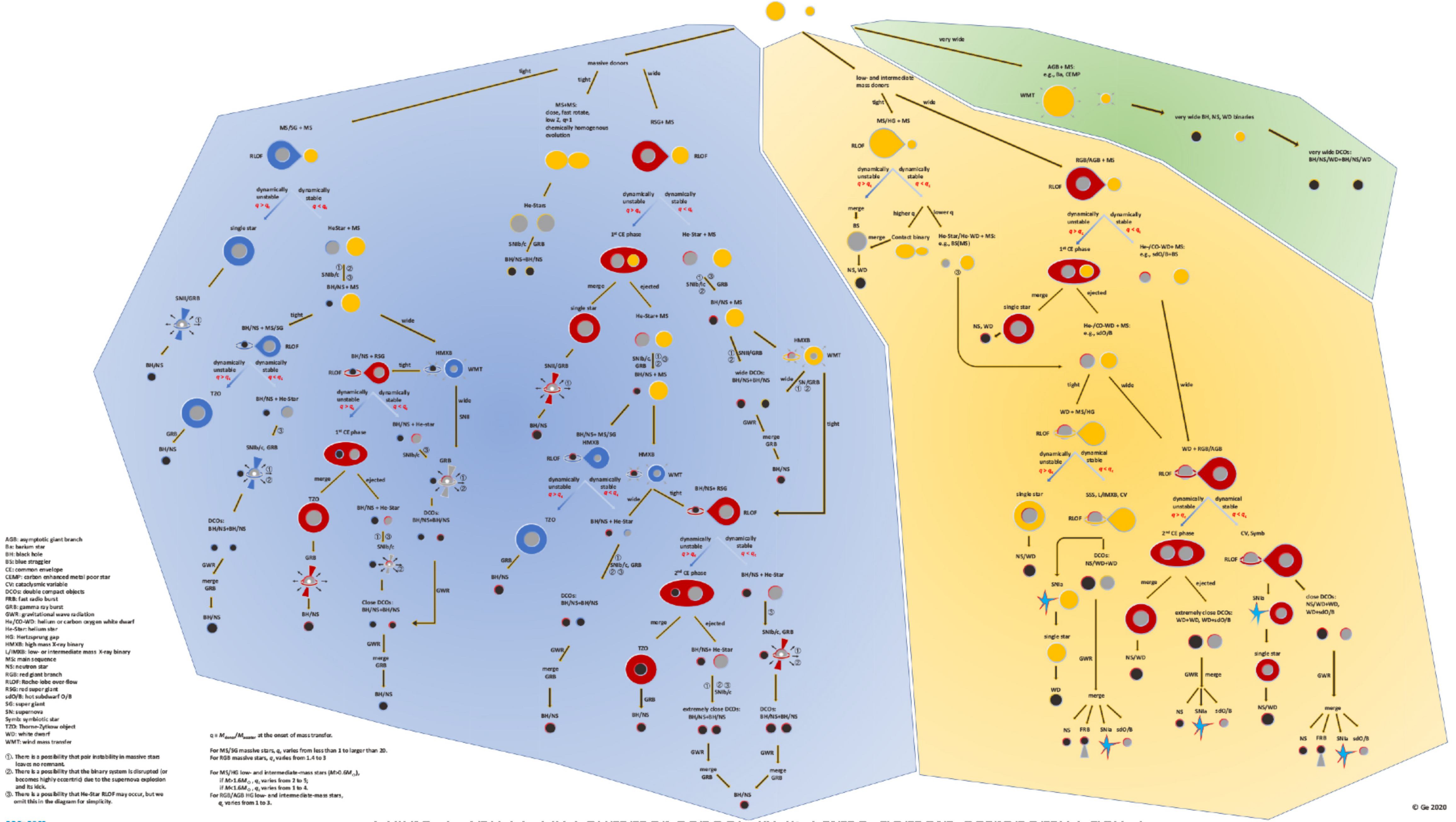
a large fraction of stars are in binaries



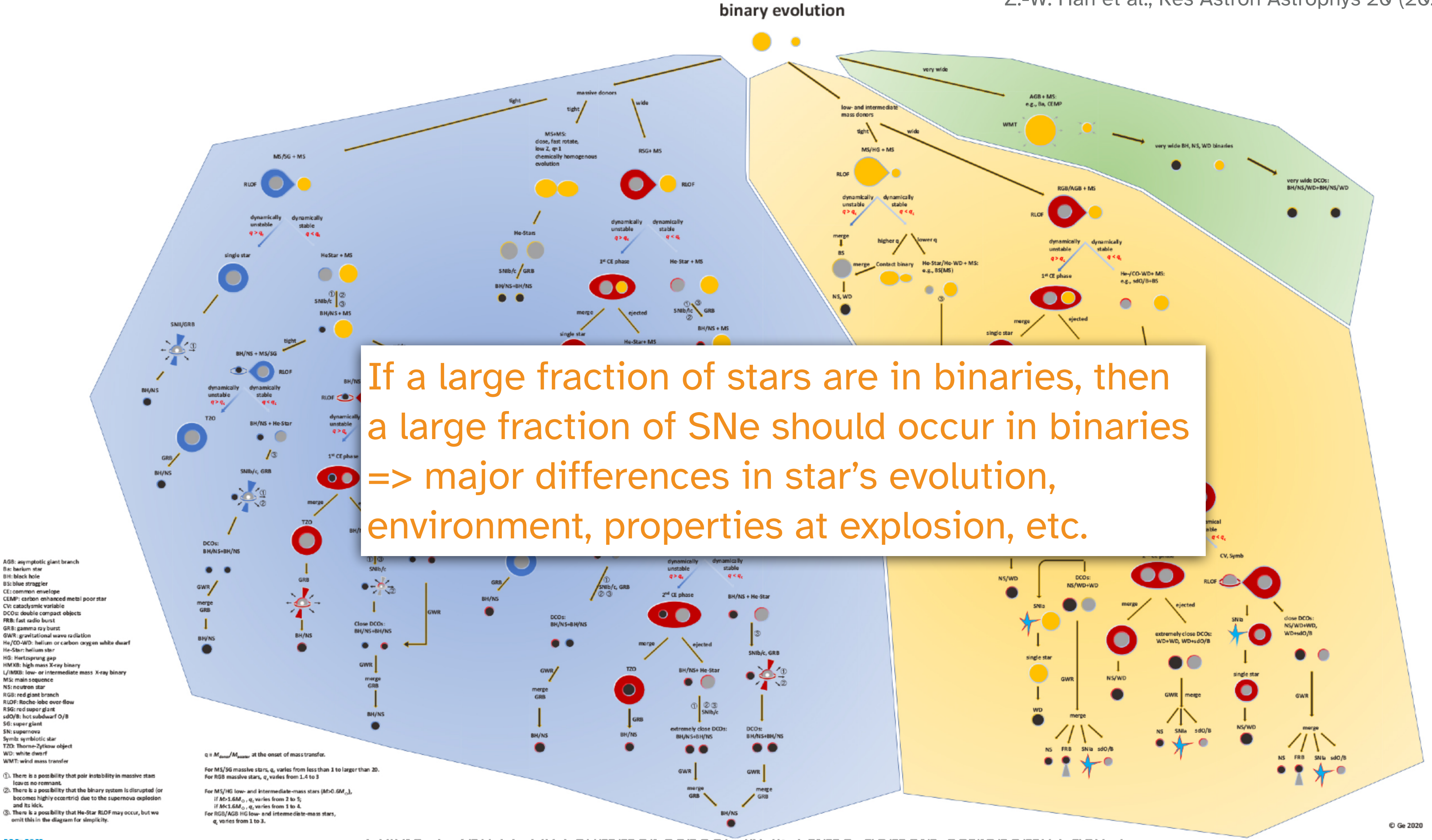
Z.-W. Han et al., Res Astron Astrophys 20 (2020)

Z.-W. Han et al., Res Astron Astrophys 20 (2020)

binary evolution



Z.-W. Han et al., Res Astron Astrophys 20 (2020)

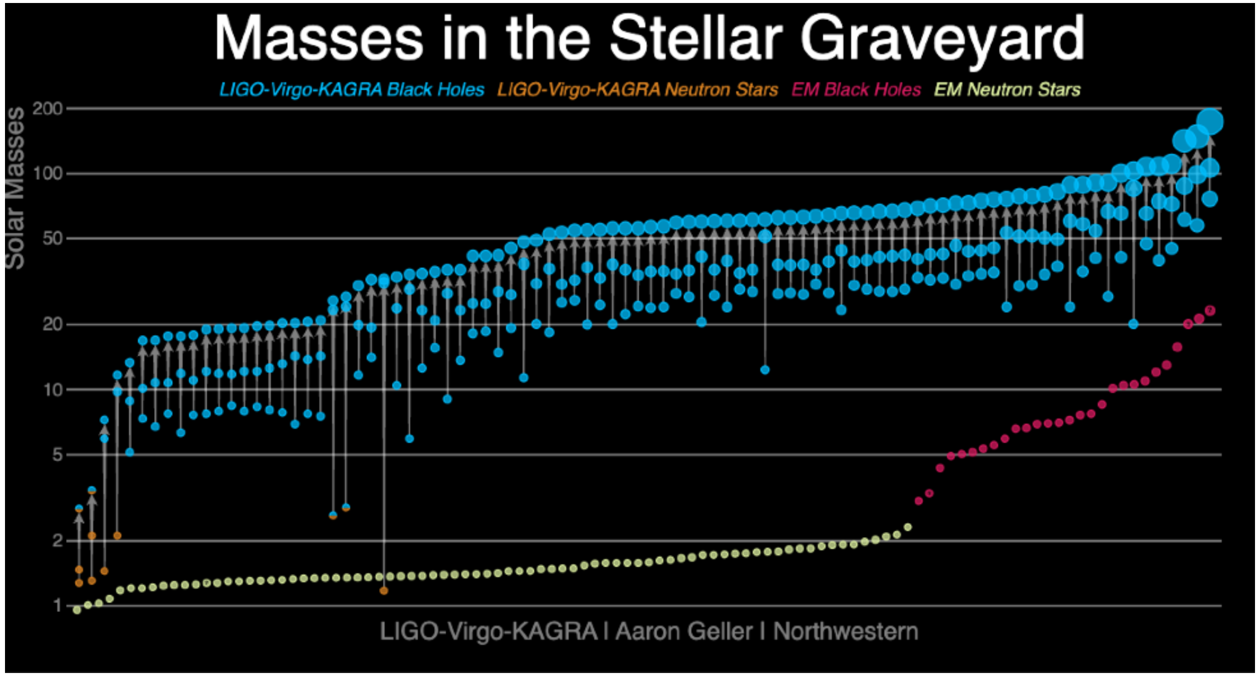


If a large fraction of stars are in binaries, then a large fraction of SNe should occur in binaries => major differences in star's evolution, environment, properties at explosion, etc.

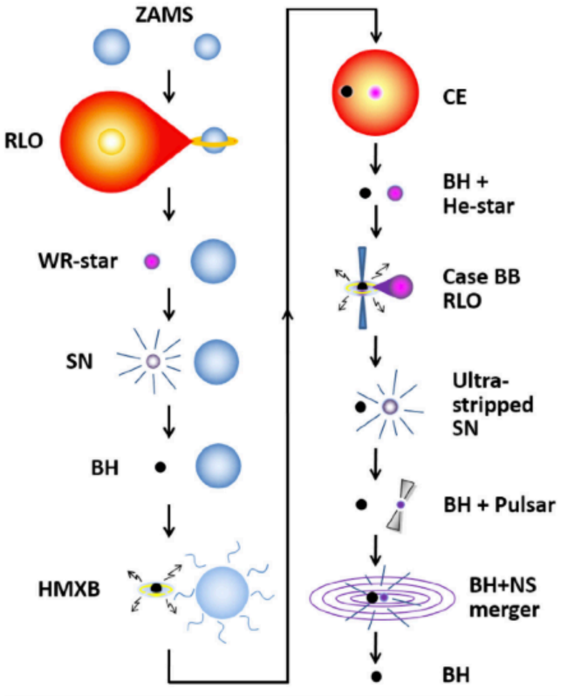
Supernovae in binaries are important

Time-domain astronomy in the era of GW detections

How do the gravitational-wave binaries form and evolve?



LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

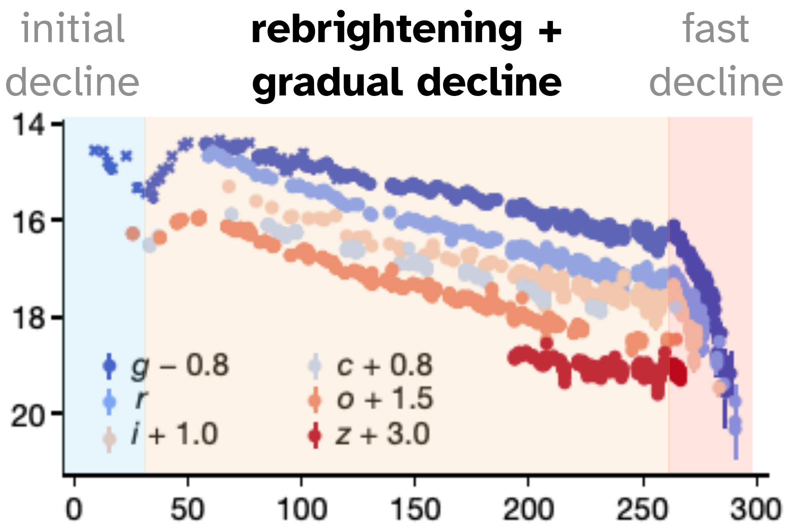


M. U. Kruckow et al., MNRAS 481 (2018)

The curious case of SN2022jli

P. Chen et al., Nature 625 (2024)

CC SNe in a binary system



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P. Chen et al., Nature 625 (2024)

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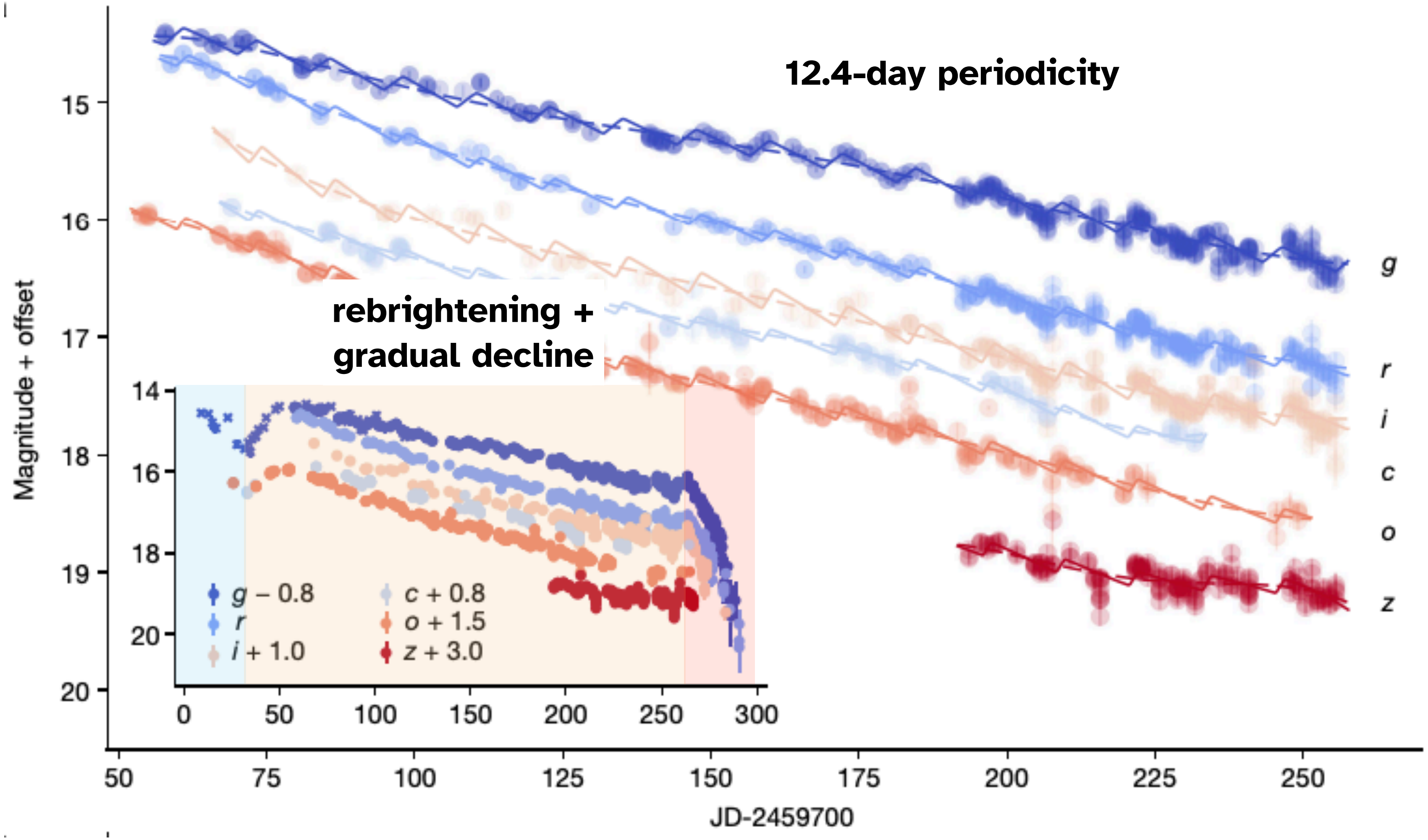
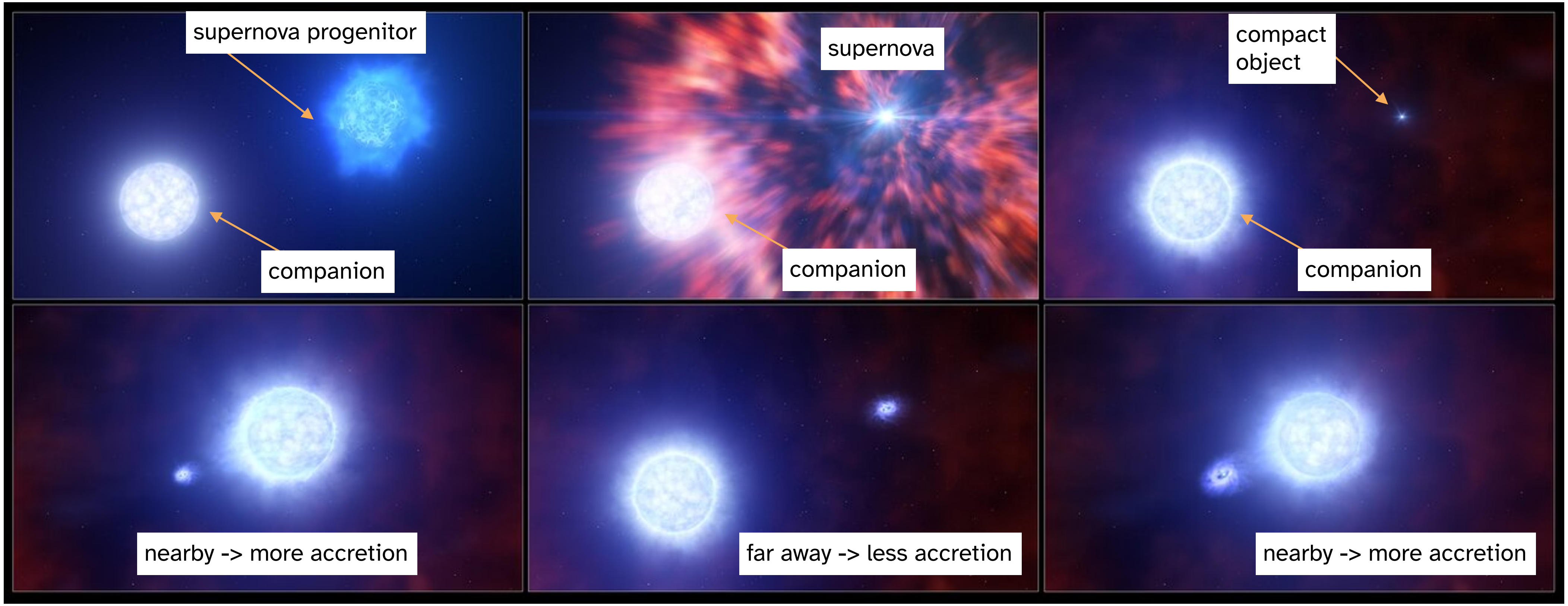


The curious case of SN2022jli

P. Chen et al., Nature 625 (2024)

CC SNe in a binary system

Interpretation: Compact object remnant is accreting from companion in a binary w/ a 12.4-day orbit



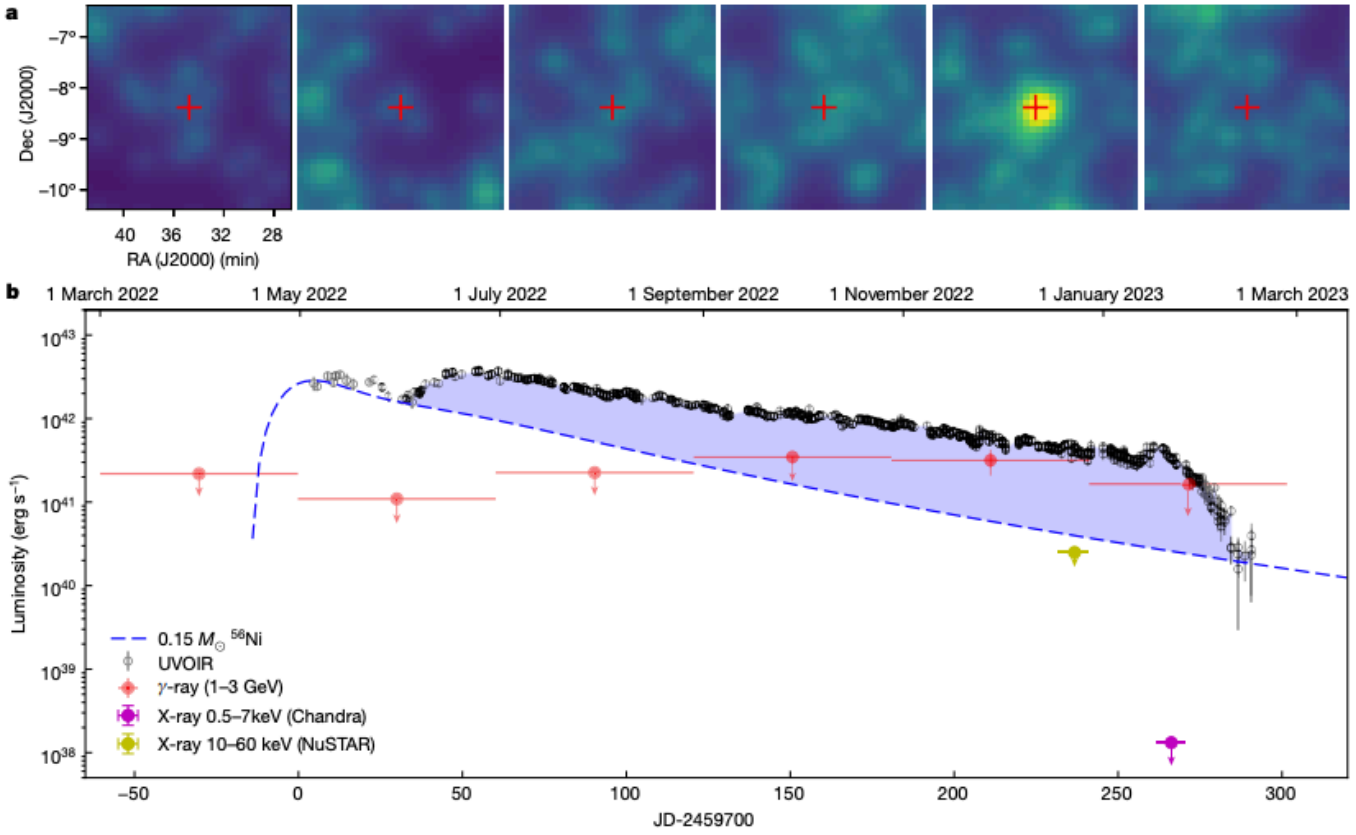
ESO / L. Calçada

The curious case of SN2022jli

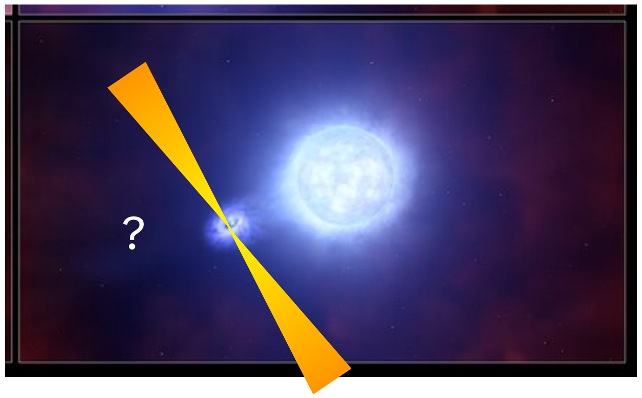
P. Chen et al., Nature 625 (2024)

CC SNe in a binary system

Hint of gamma rays six months after explosion?



Interpretation: jet or shocks
-> particle acceleration
-> gamma rays (once ɣ-ɣ opacity has decreased sufficiently)



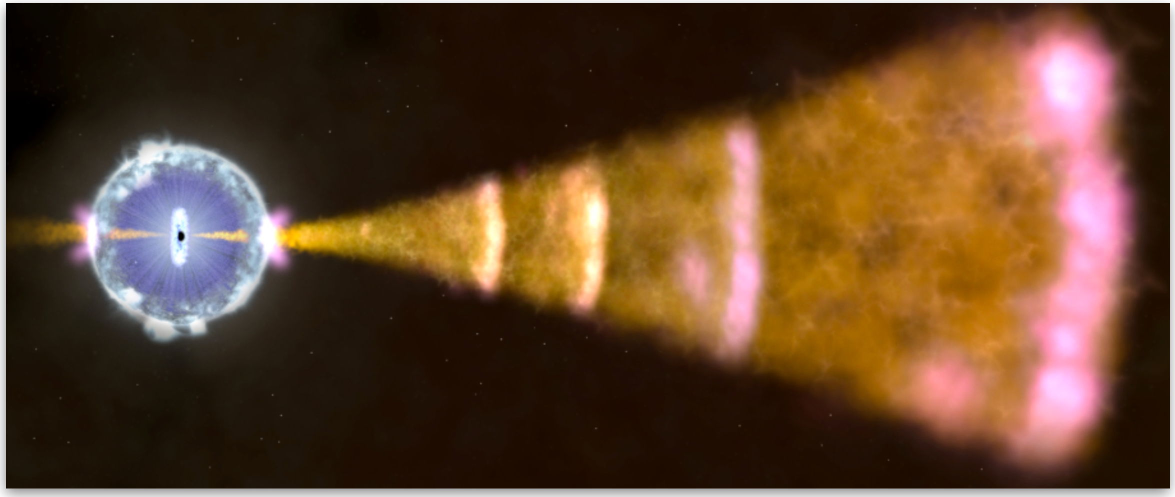
Is this another channel for gamma-ray emission from core collapse SNe?

Pause: return to GRBs

When should we look for VHE gamma rays?

ɣ-ɣ opacity is an issue whenever there are a lot of ambient photons at the “right” energy

q: what about for GRBs?



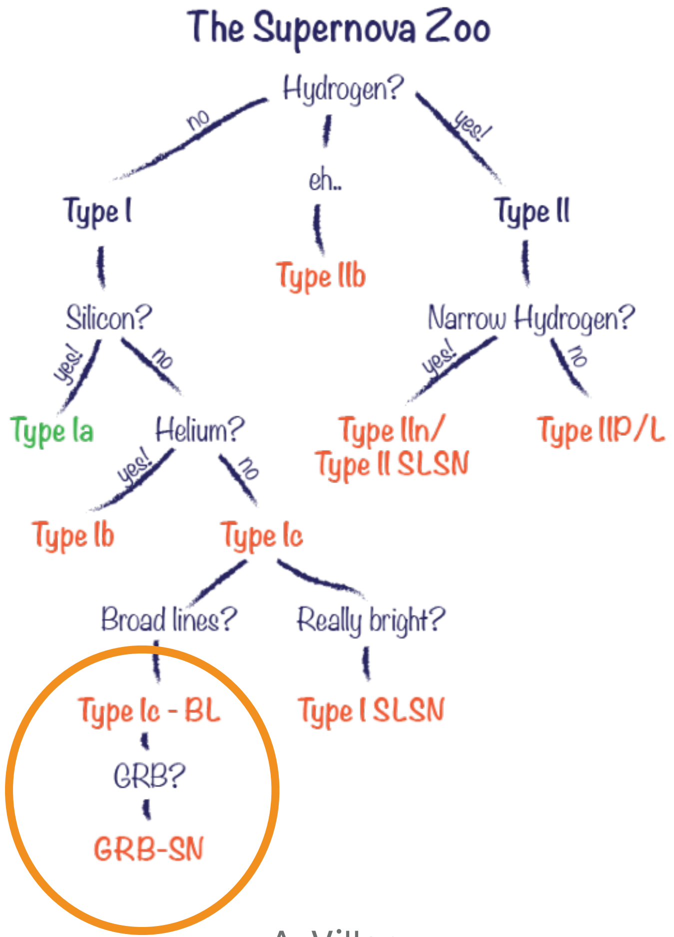
[NASA’s Goddard Space Flight Center]

Indeed, the GRB jet is initially **optically thick**, photons only escape once jet has expanded and density has decreased sufficiently

-> for GRBs, the timescale for sufficiently reduced ɣ-ɣ opacity is <s

Pause: return to GRBs

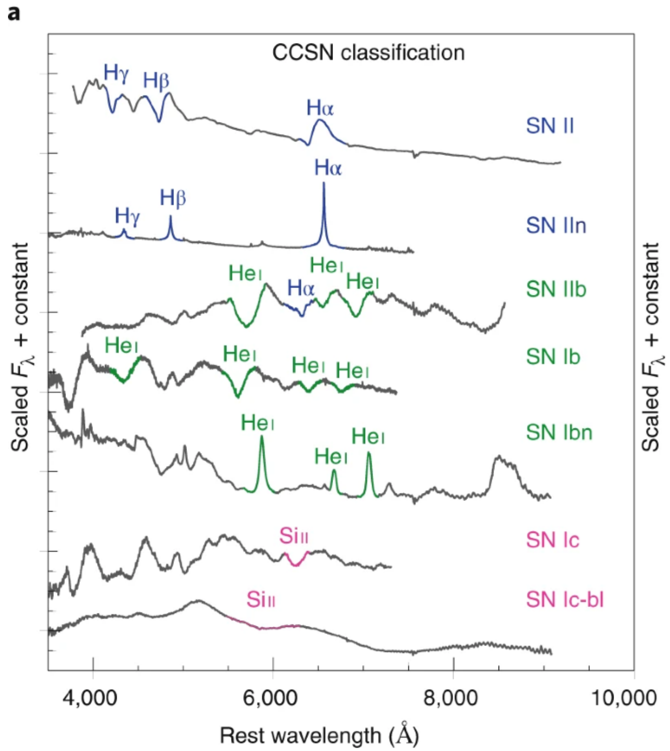
How are long GRBs and core-collapse supernovae related?



A. Villar

The SNe associated with long GRBs tend to be missing both hydrogen and helium lines (“stripped envelope” supernovae)

“BL” = broad lines -> very fast moving material



Pause: return to GRBs

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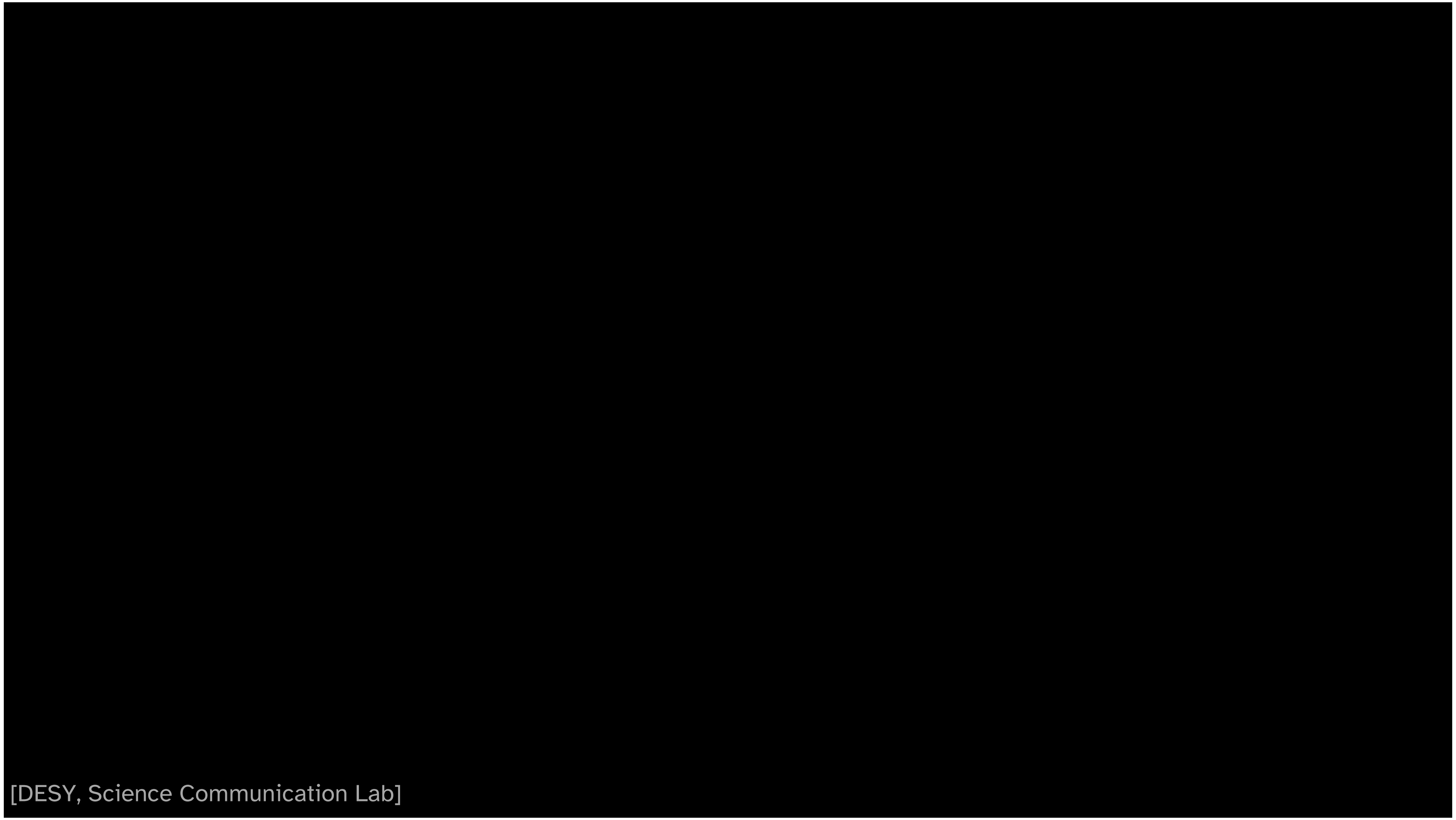


[DESY, Science Communication Lab]

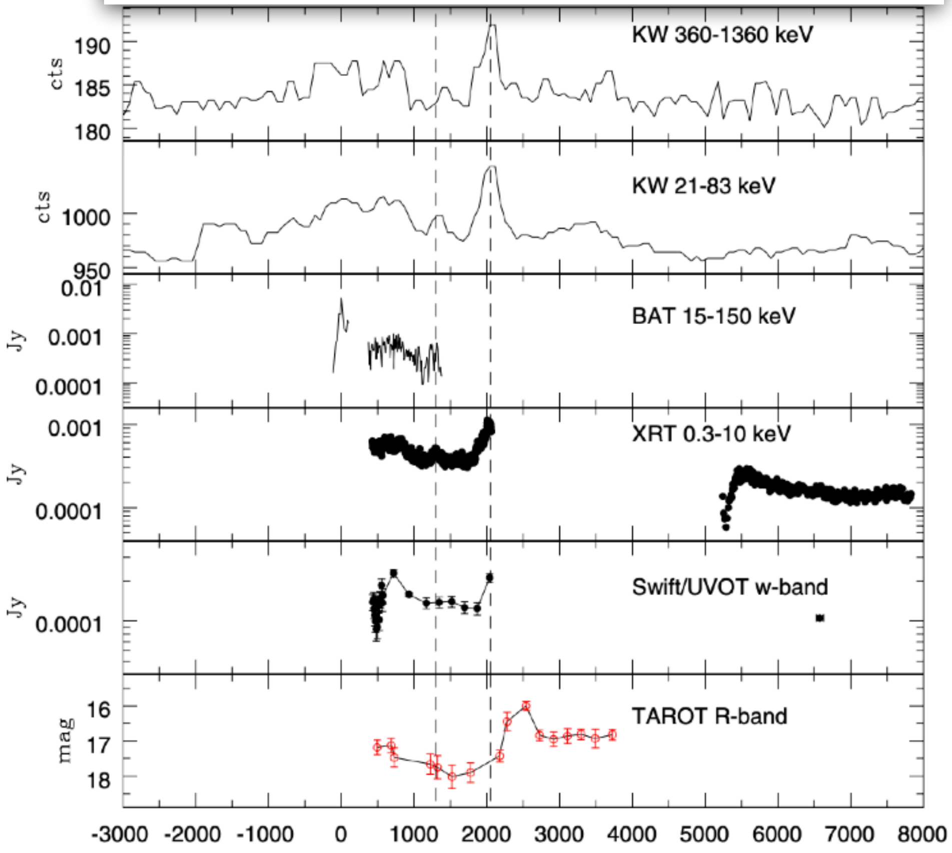
Pause: return to GRBs

How are long GRBs and core-collapse supernovae related?

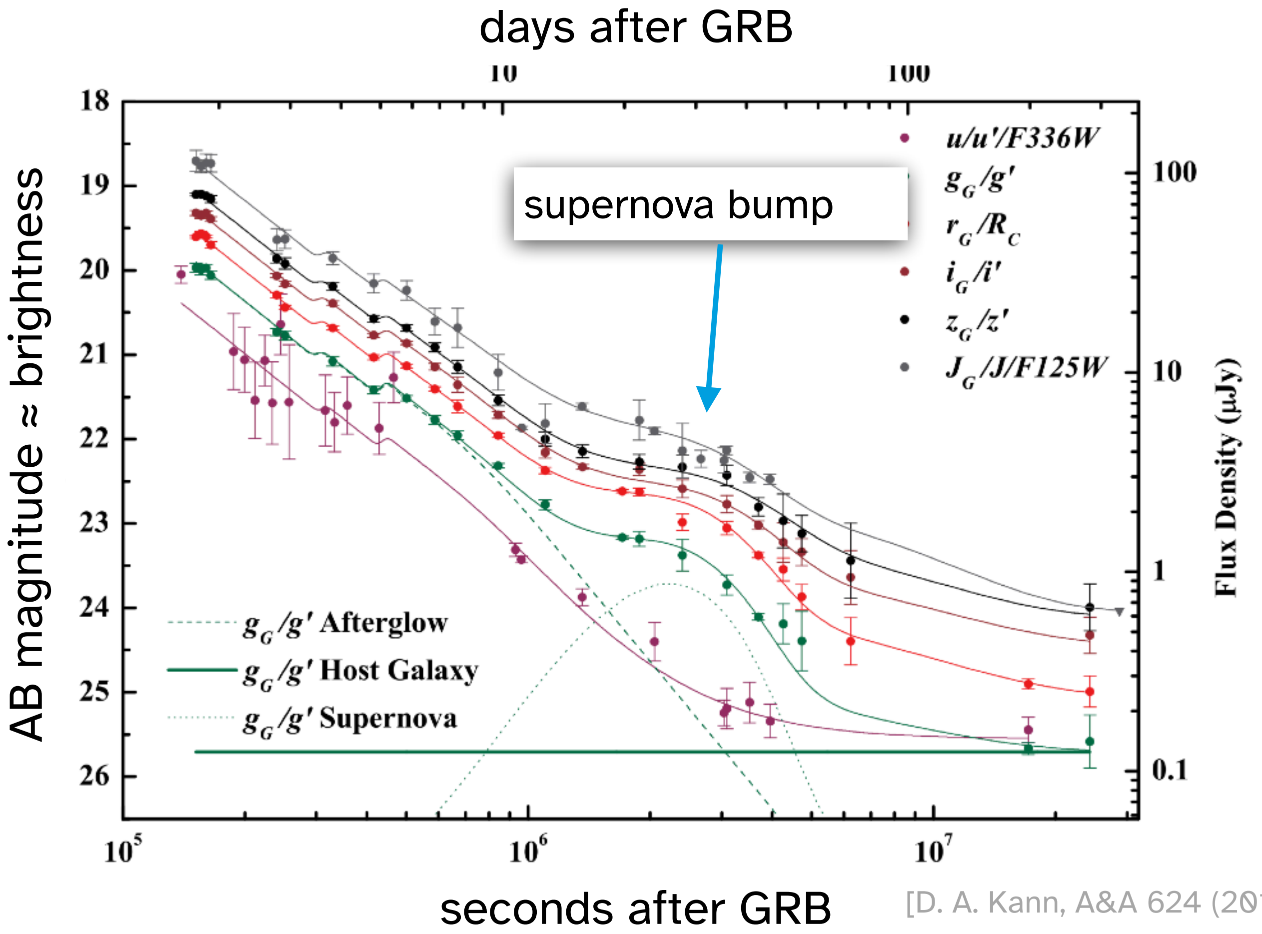
Most GRB-SN are ordinary or even subluminous

Exception: Are superluminous supernovae connected with ultralong GRBs?

“ultralong”: duration ~ 1000s of seconds



[G. Stratta et al., ApJ 779 (2013)]



[D. A. Kann, A&A 624 (2019)]

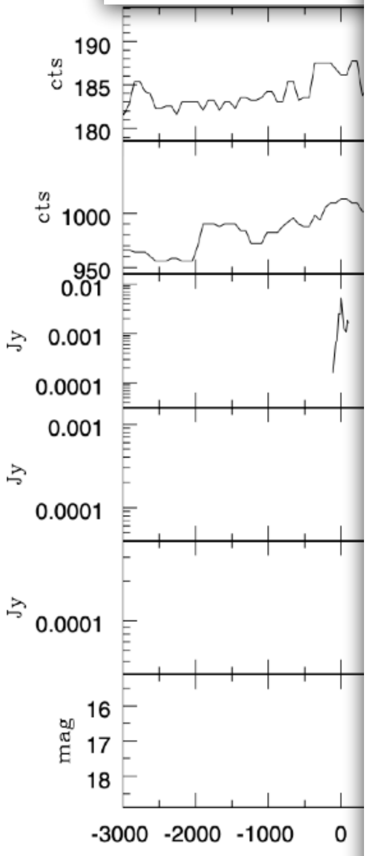
Pause: return to GRBs

How are long GRBs and core-collapse supernovae related?

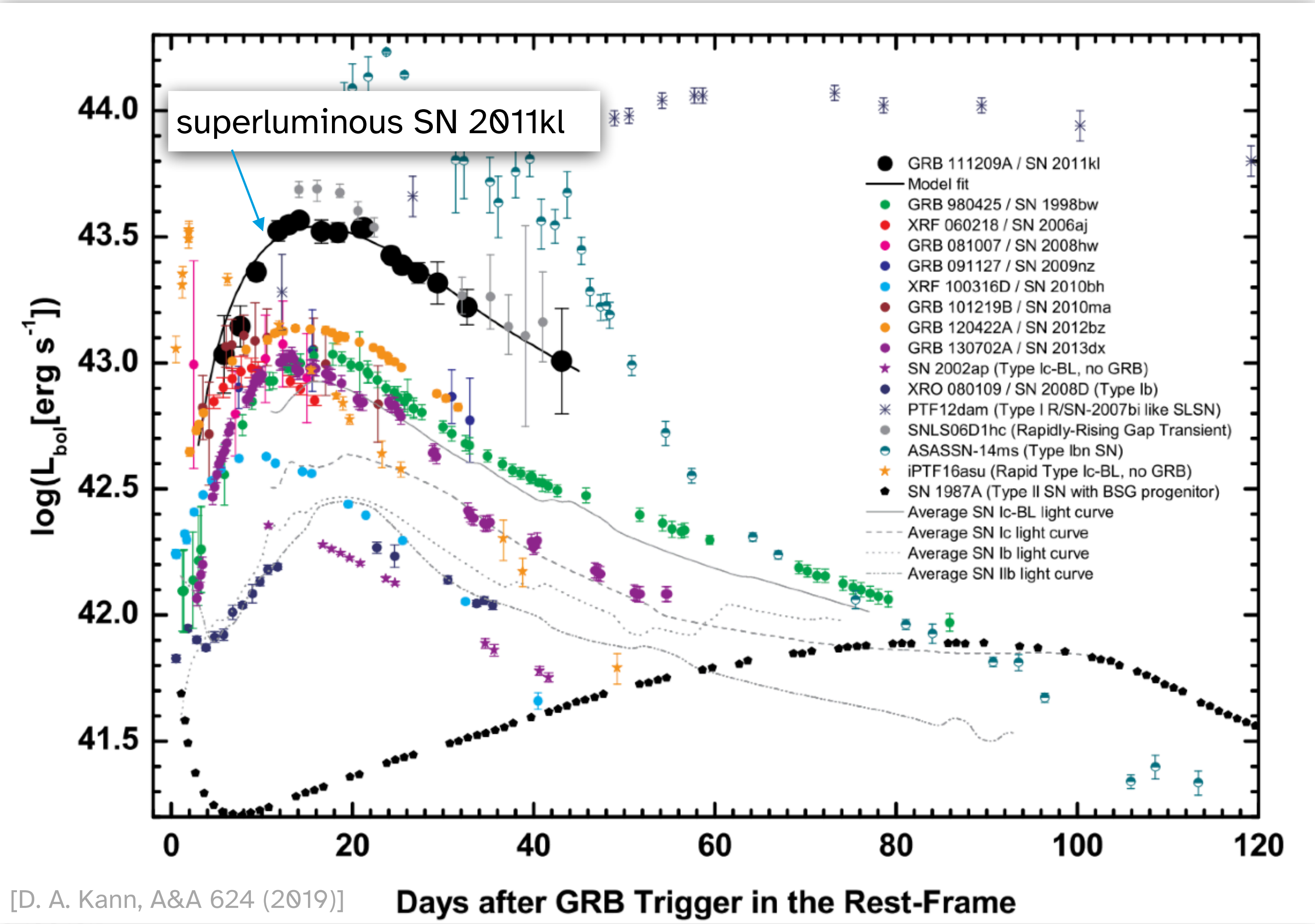
Most GRB-SN ar

Exception: Are s

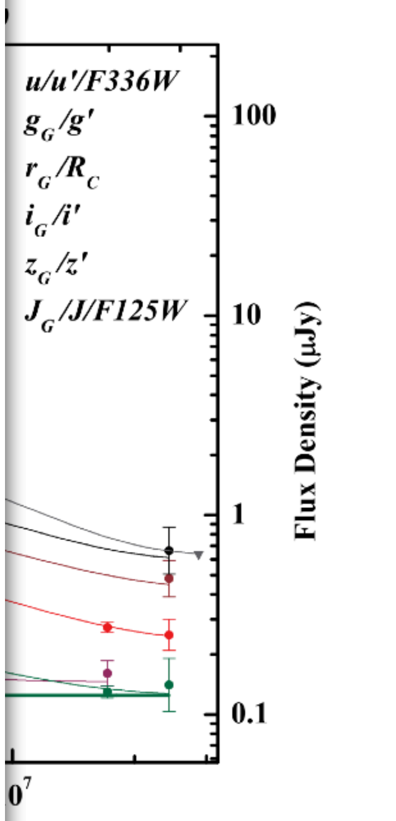
"ultralong": du



[G. Stratta et al., ApJ 779 (2013)]



[D. A. Kann, A&A 624 (2019)]



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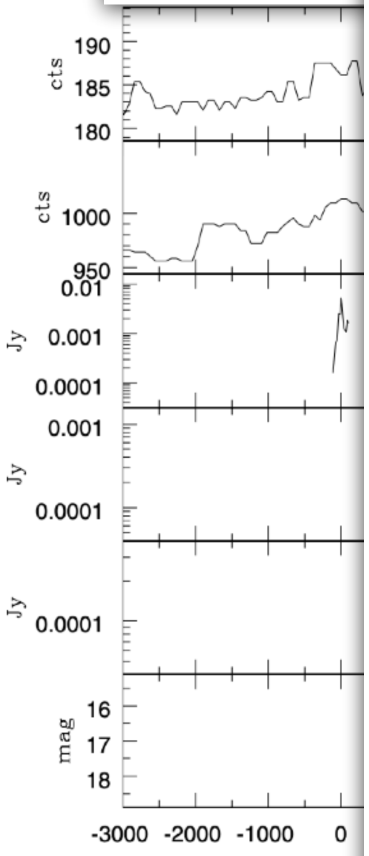
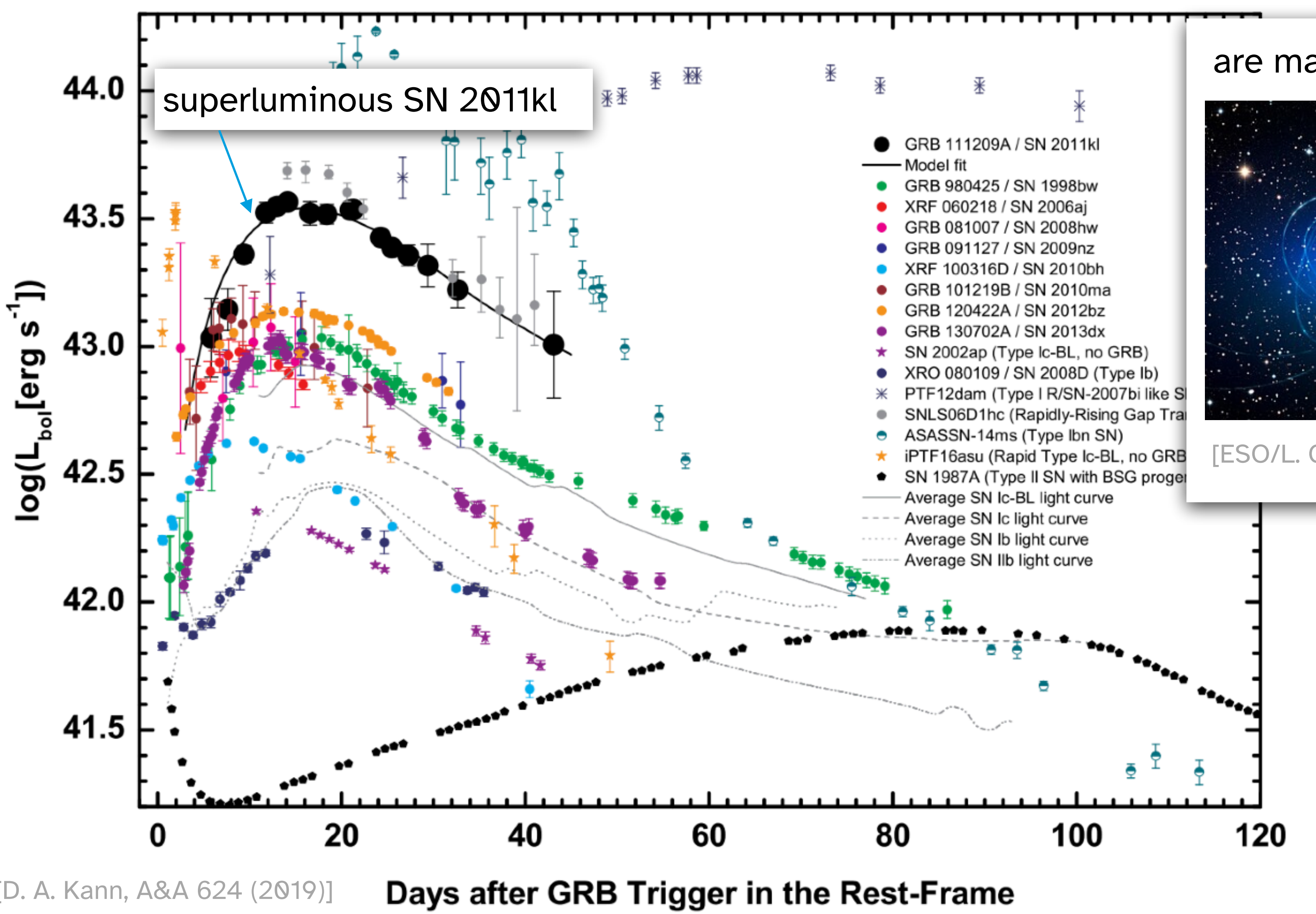
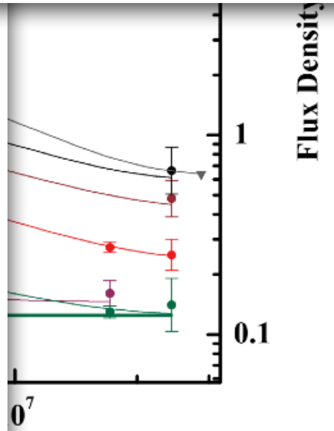


[G. Stratta et al., ApJ 779 (2013)]

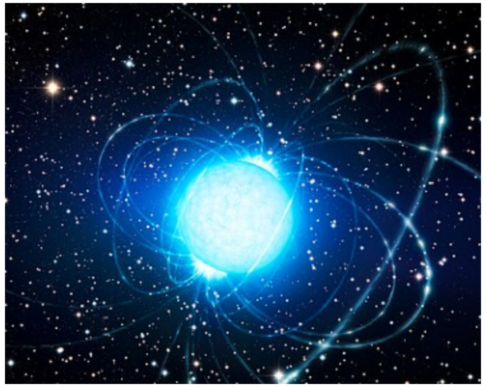


[D. A. Kann, A&A 624 (2019)]



. A. Kann, A&A 624 (2019)]

are magnetars the key?



[ESO/L. Calçada]

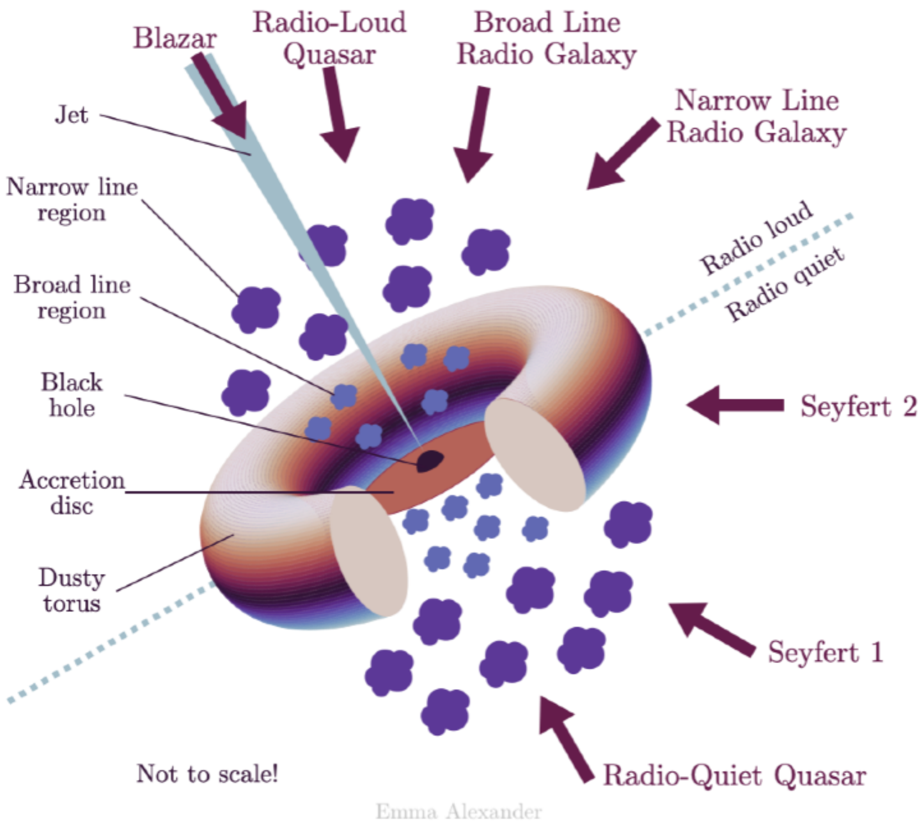
Part 3b. Flaring AGN as gravitational-wave sources

Another messenger related to AGN (maybe)

ok here is my disclaimer that I know very little about AGN

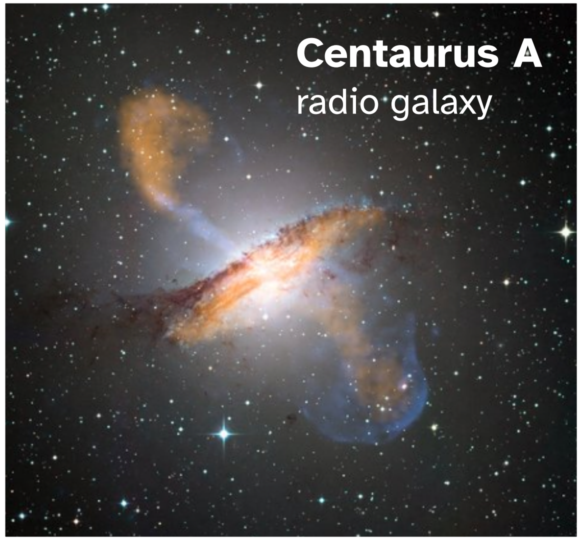
go ask Lea ....

In a nutshell: (super)massive black hole in the middle of a galaxy accretes material and emits photons

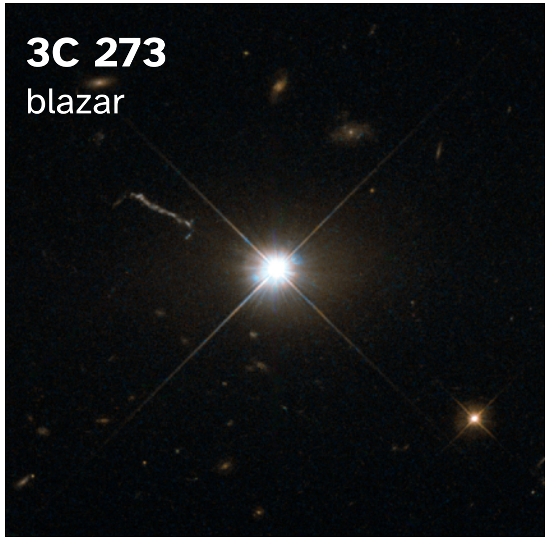


[Emma Alexander]

How we name it depends on the system's properties **and** on our viewing angle



[ESO/WFI; MPIfR/ESO/APEX/A.Weiss et al.; NASA/CXC/CfA/R.Kraft et al.]

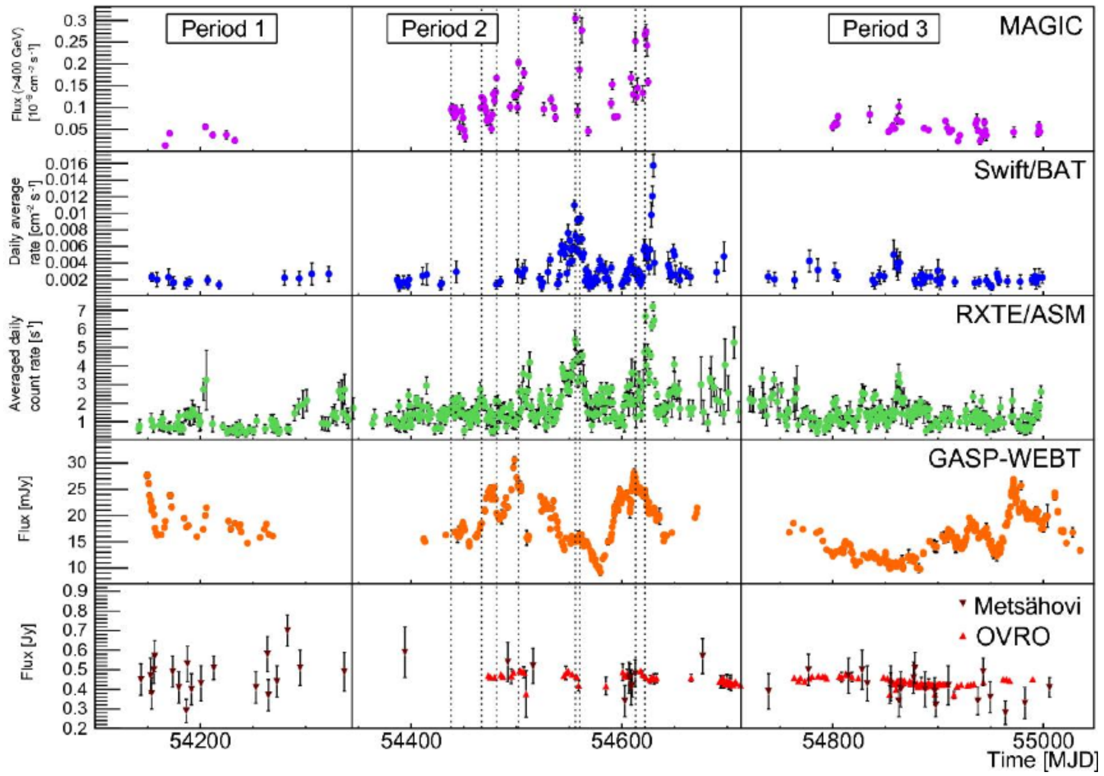


[ESA/Hubble & NASA]

AGN are also major time domain astronomy sources

go ask Lea ....

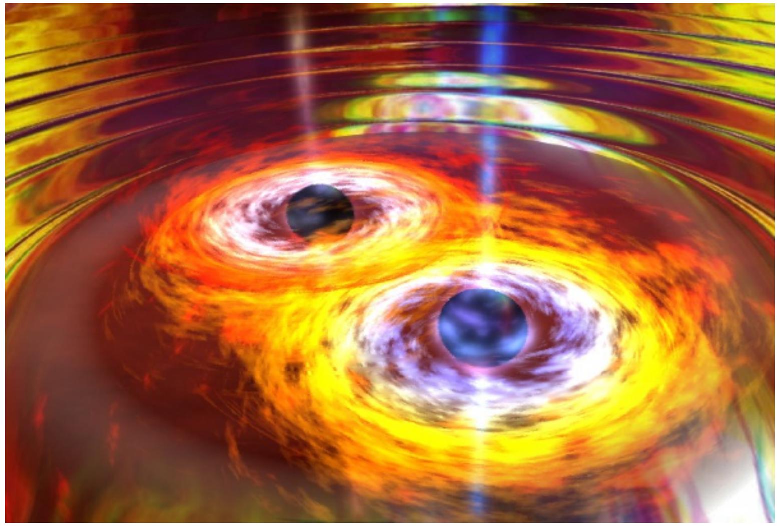
[M. Ahnen et al., A&A 593 (2016)]



AGN often exhibit multiwavelength flaring activity

all the IACTs have active programs for observing AGN (mostly blazars) during flares

- jet precession?
- stochastic processes inside the jet?
- evidence of a binary companion??

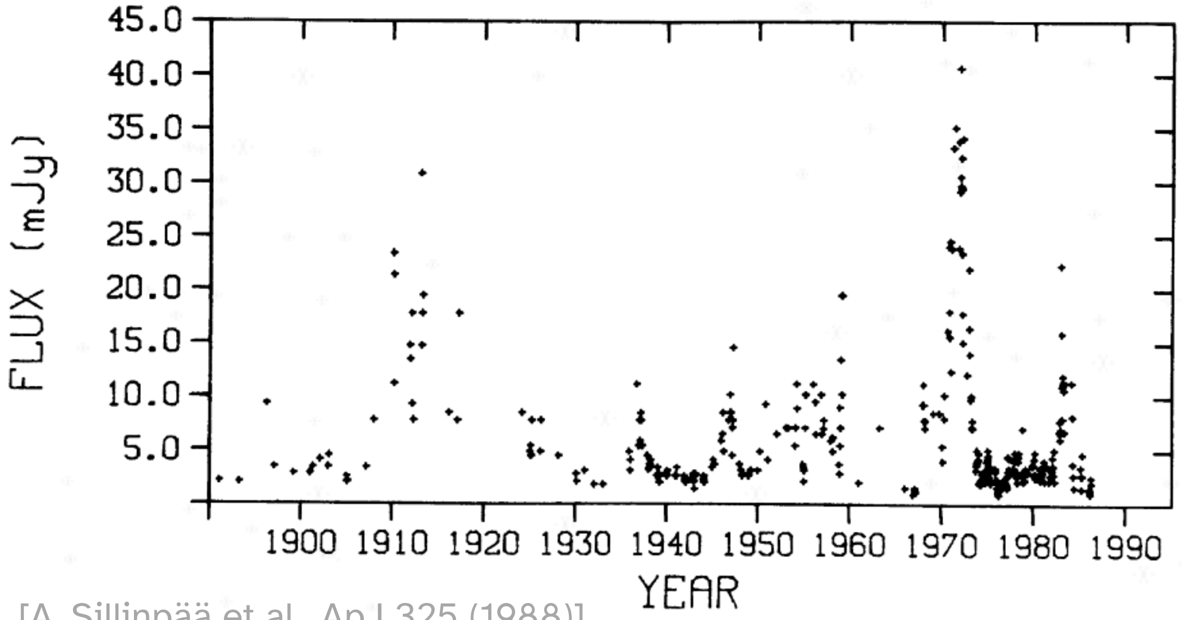


[NASA]

AGN with (quasi)periodic oscillations could become GW sources

(super)massive black hole binaries

OJ 287 is a blazar with quasiperiodic oscillations (~12 year period?)

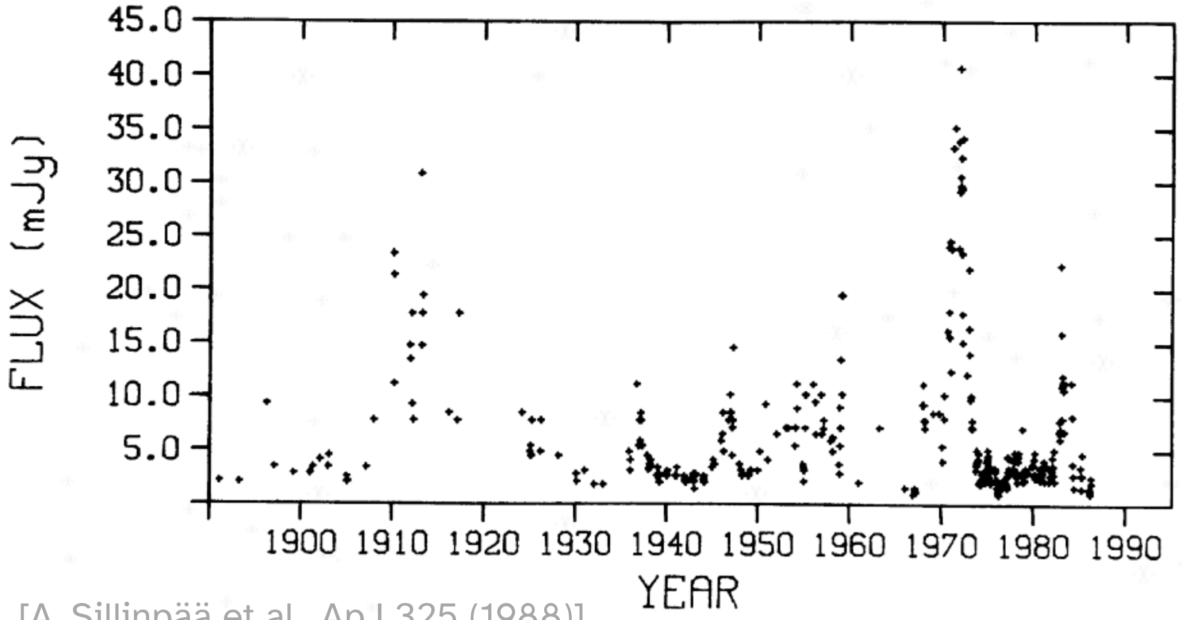


[A. Sillinpää et al., ApJ 325 (1988)]

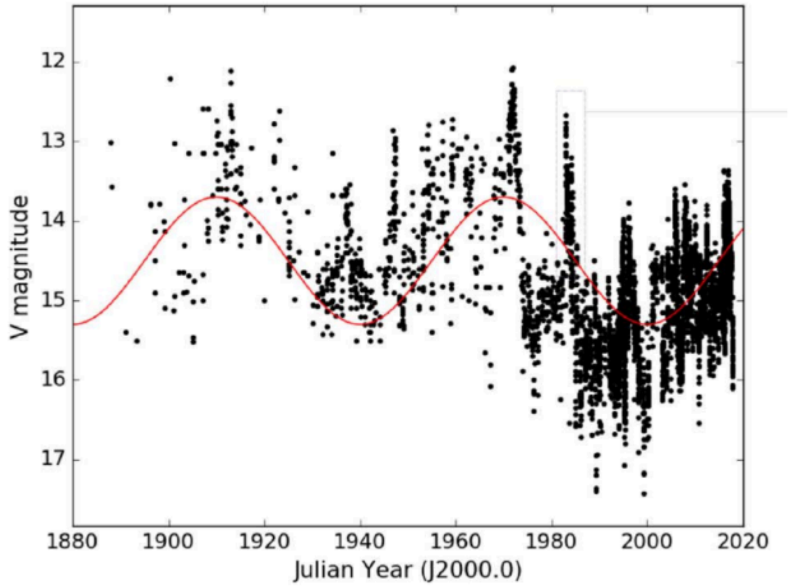
AGN with (quasi)periodic oscillations could become GW sources

(super)massive black hole binaries

OJ 287 is a blazar with quasiperiodic oscillations (~12 year period plus 60-year envelope?)



[A. Sillinpää et al., ApJ 325 (1988)]



[L. Dey et al., ApJ 866 (2018)]

AGN with (quasi)periodic oscillations could become GW sources

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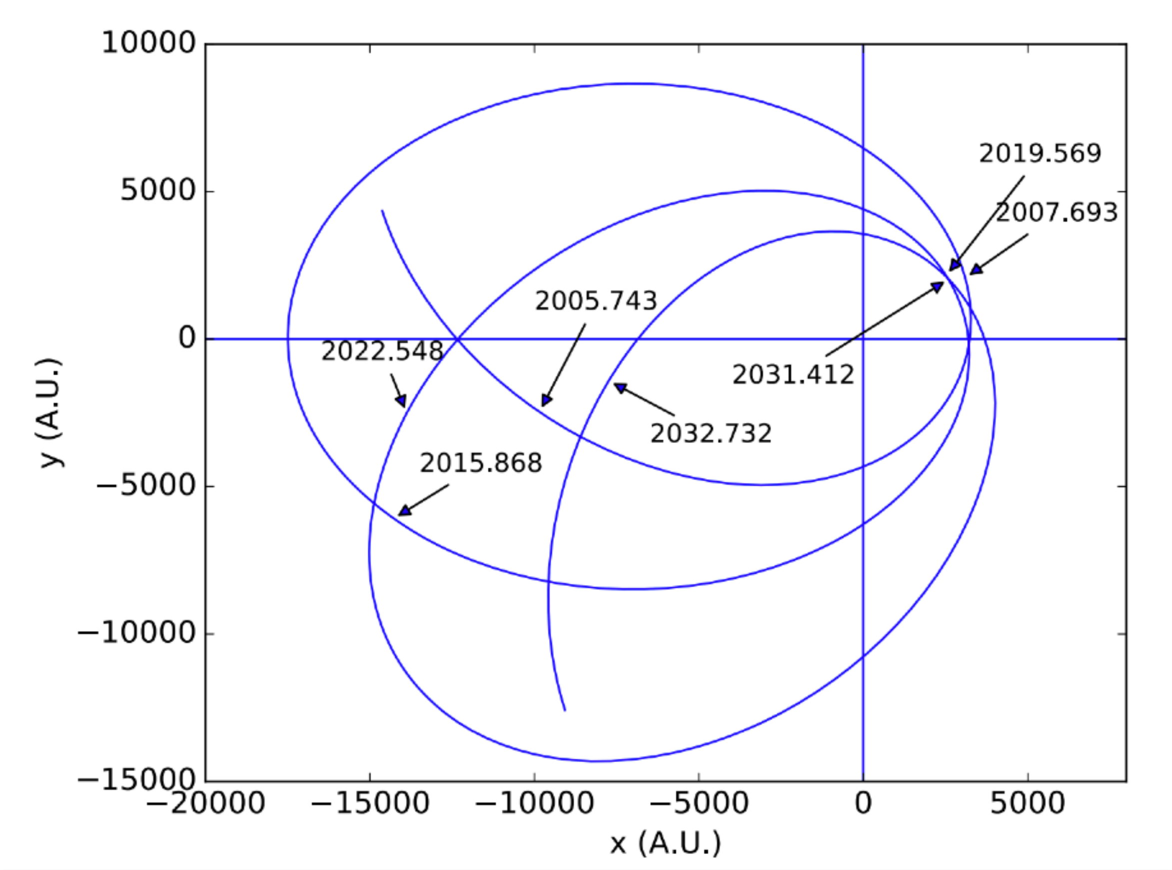

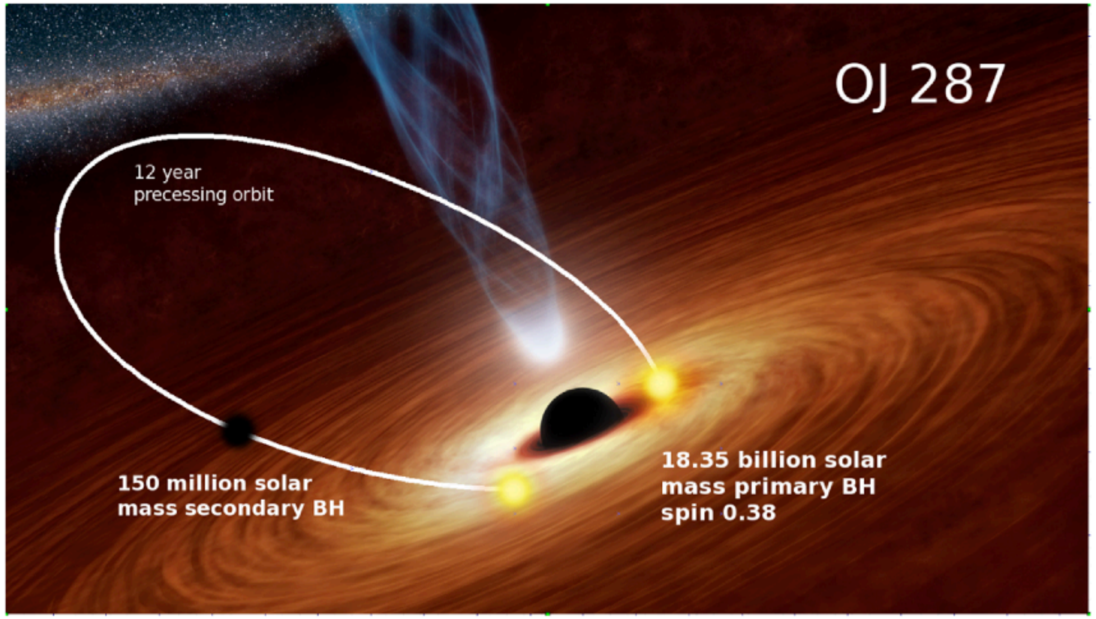

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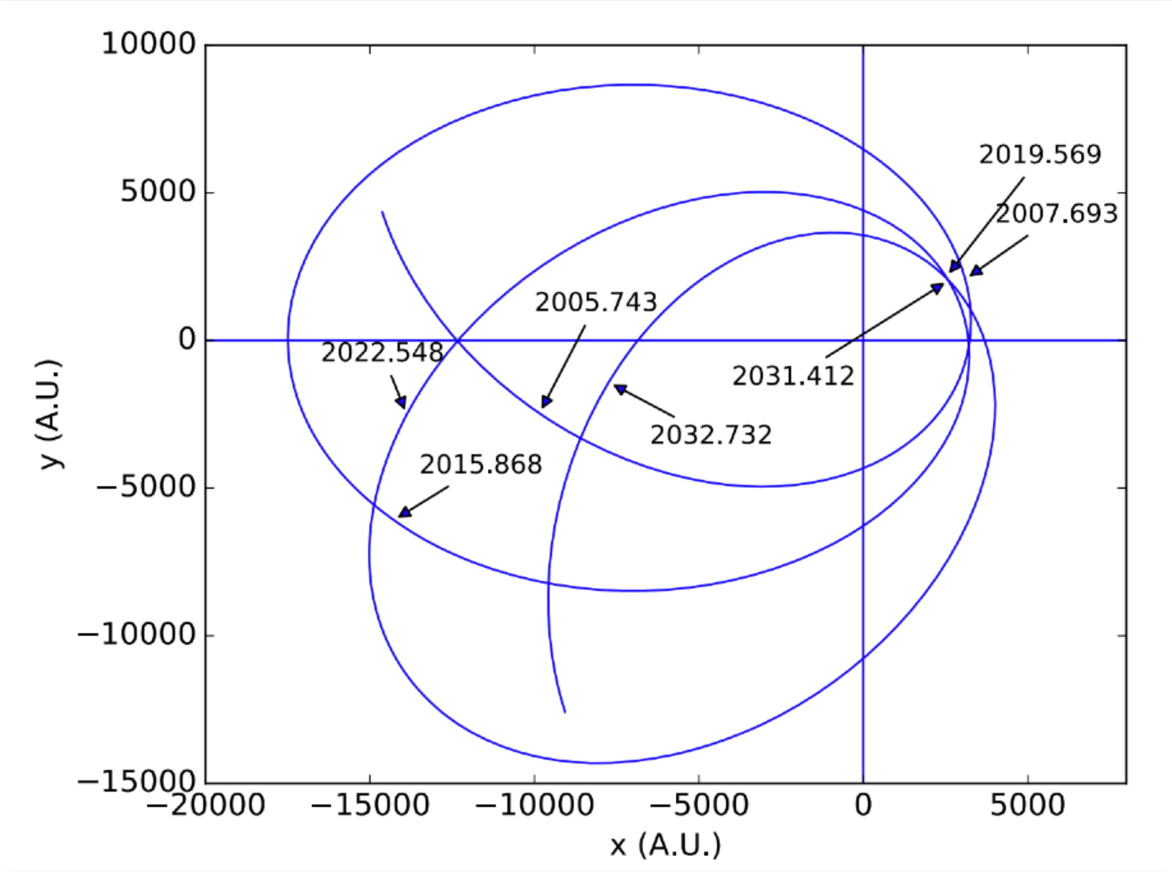
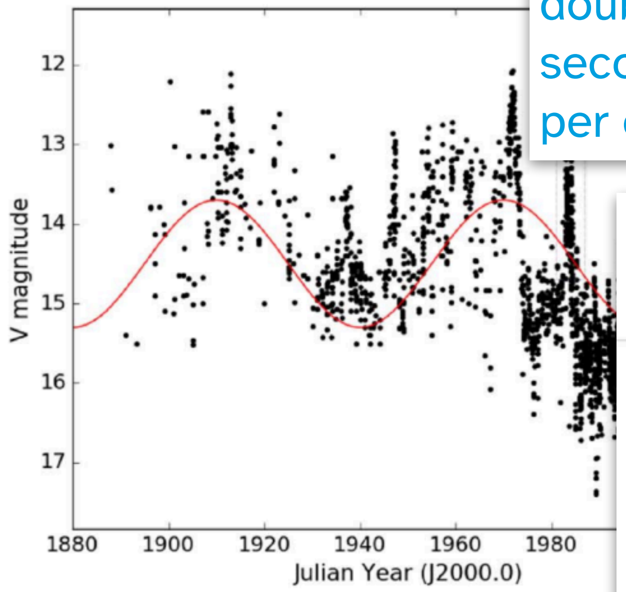
(super)massive black hole binaries

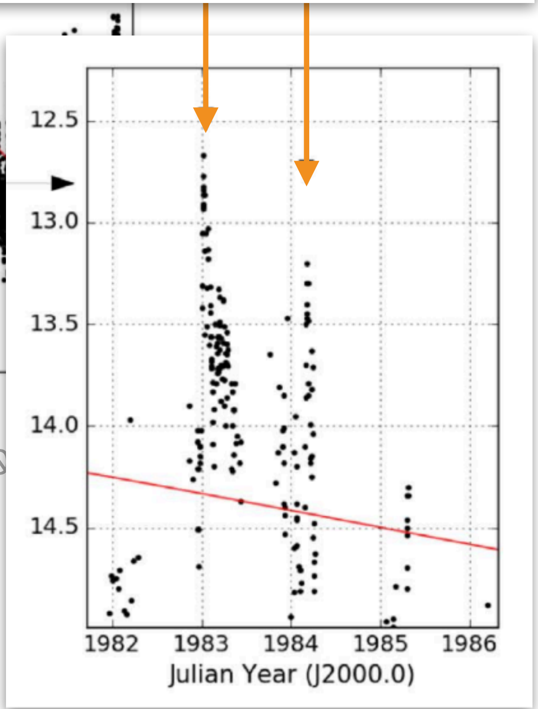
OJ 287 is a blazar with quasiperiodic oscillations (~12 year period plus 60-year envelope?)





[L. Dey et al., ApJ 866 (20

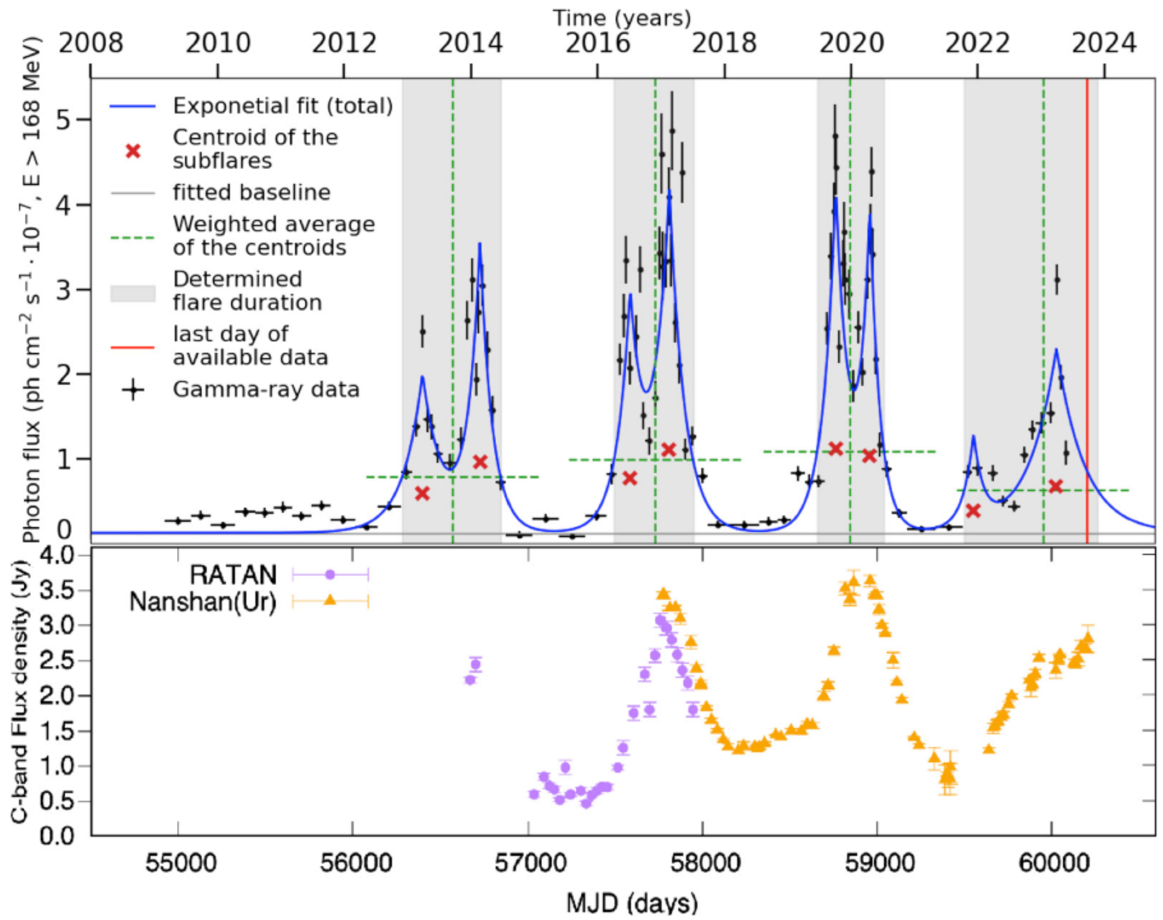
double-peaked structure: secondary SMBH hits twice per orbit



AGN with (quasi)periodic oscillations could become GW sources

(super)massive black hole binaries

A few other candidates have also been found, e.g. J1048+7143



[E. Kun et al., ApJ 940 (2022)]

[E. Kun et al., ApJL 963 (2024)]

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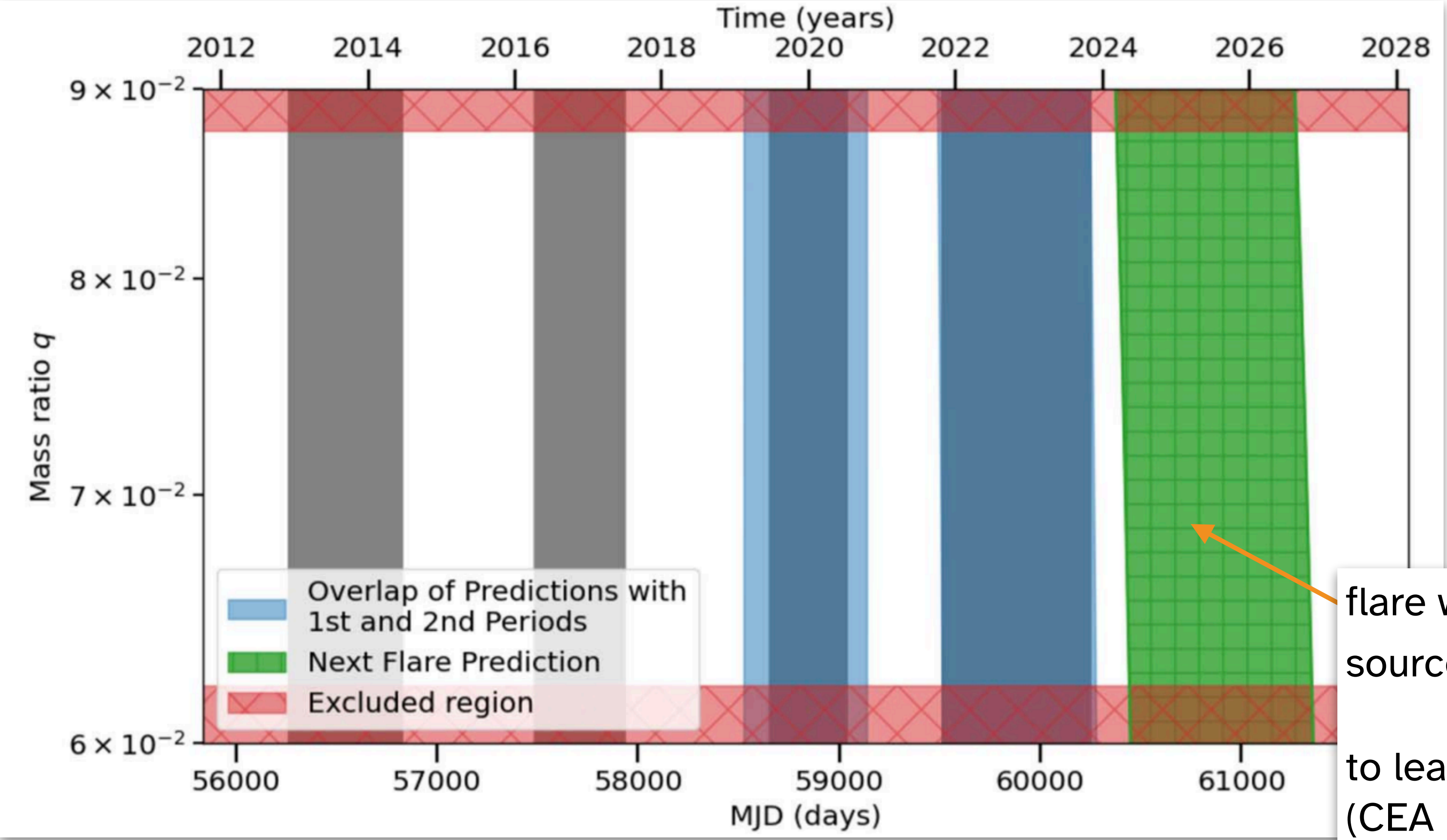


[E. Kun et al., ApJ 940 (2022)]

[E. Kun et al., ApJL 963 (2024)]

flare was predicted here

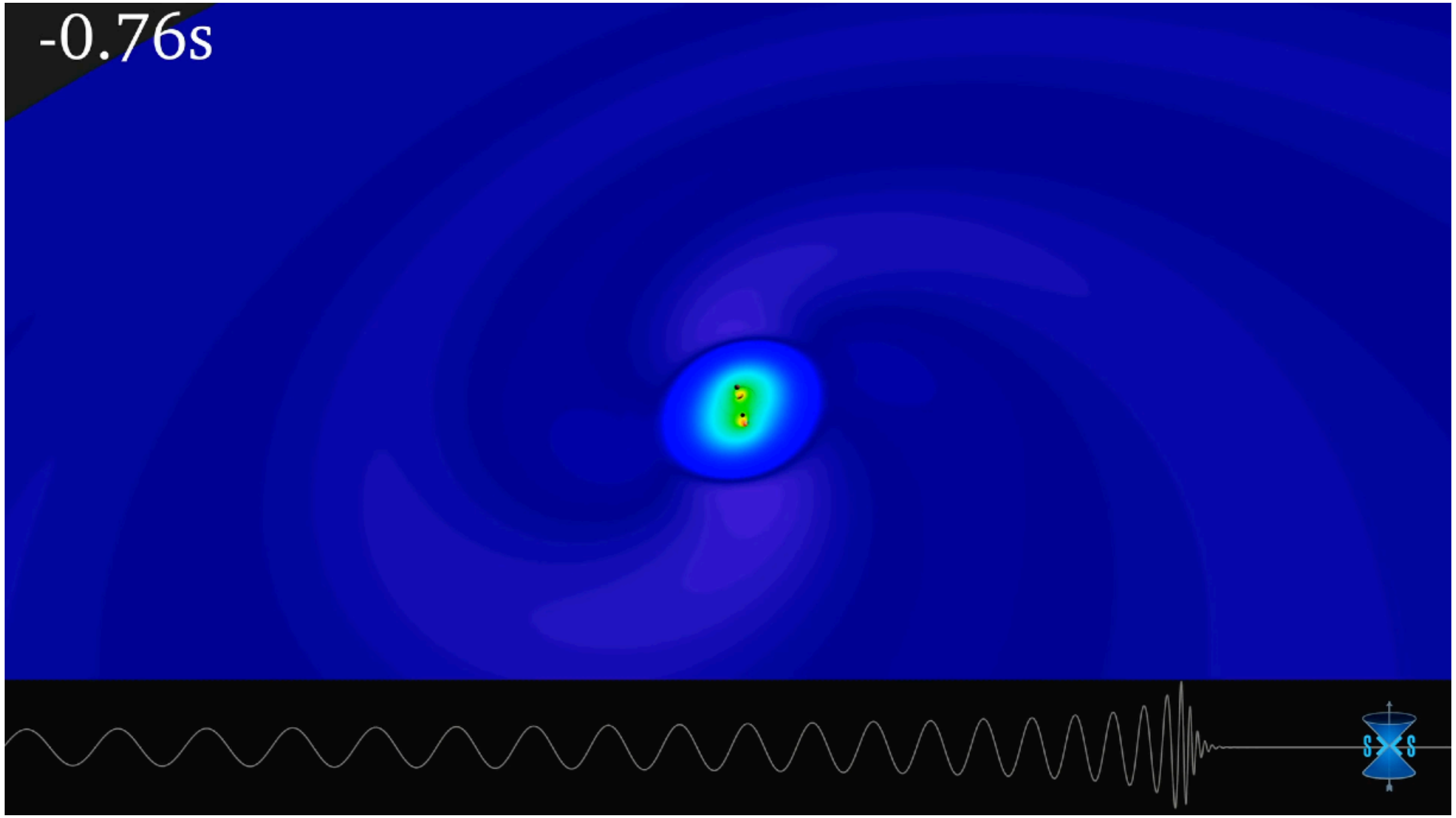
source is indeed flaring right now 👀

to learn more: talk to Ilja Jaroschewski (CEA Saclay)

GWs from (S)MBHBs

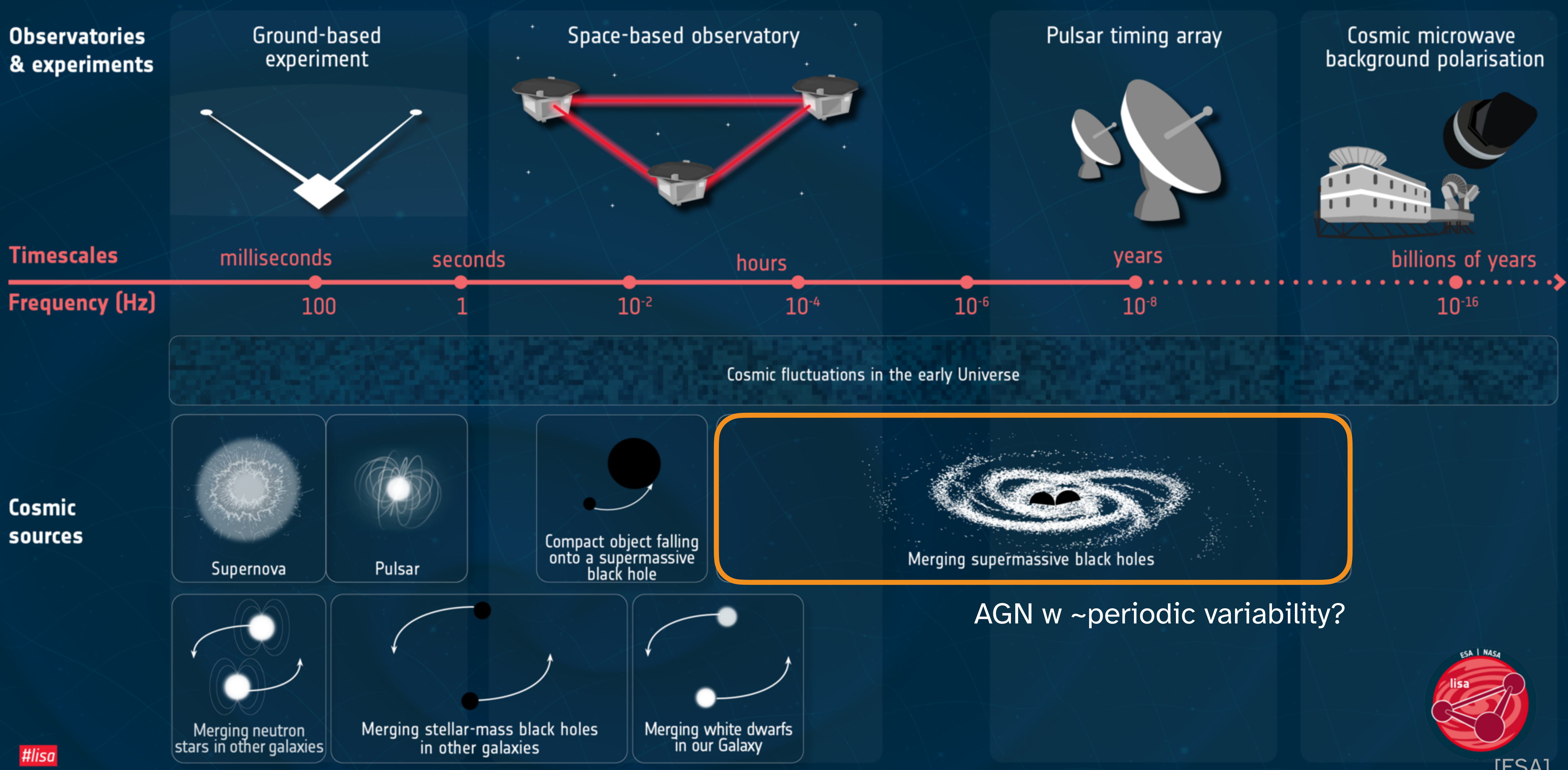
Scaling up the LIGO/Virgo/KAGRA black hole mergers

Reminder: Anything with a changing mass quadrupole moment produces GWs



Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)
Video and explanation: https://www.ligo.caltech.edu/video/ligo20160211v10

THE SPECTRUM OF GRAVITATIONAL WAVES

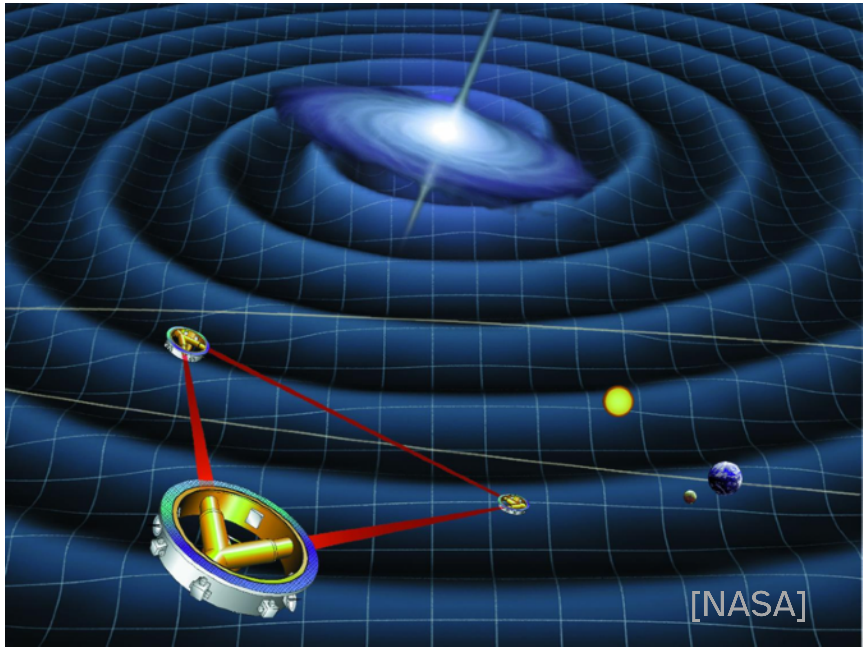


AGN w ~periodic variability?

[ESA]

LISA gravitational-wave observatory

Laser Interferometer Space Antenna



ground-based (LIGO/Virgo/KAGRA)

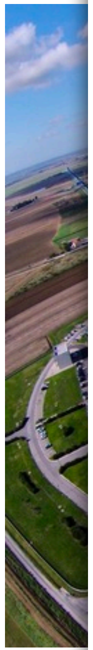
effective arms: O(1000 km)
λ ~ 1000 km -> f_{GW} ~ O(100 Hz)

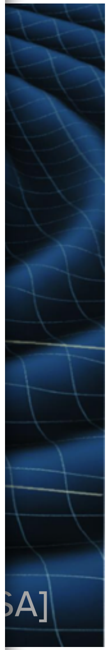
space-based (LISA)

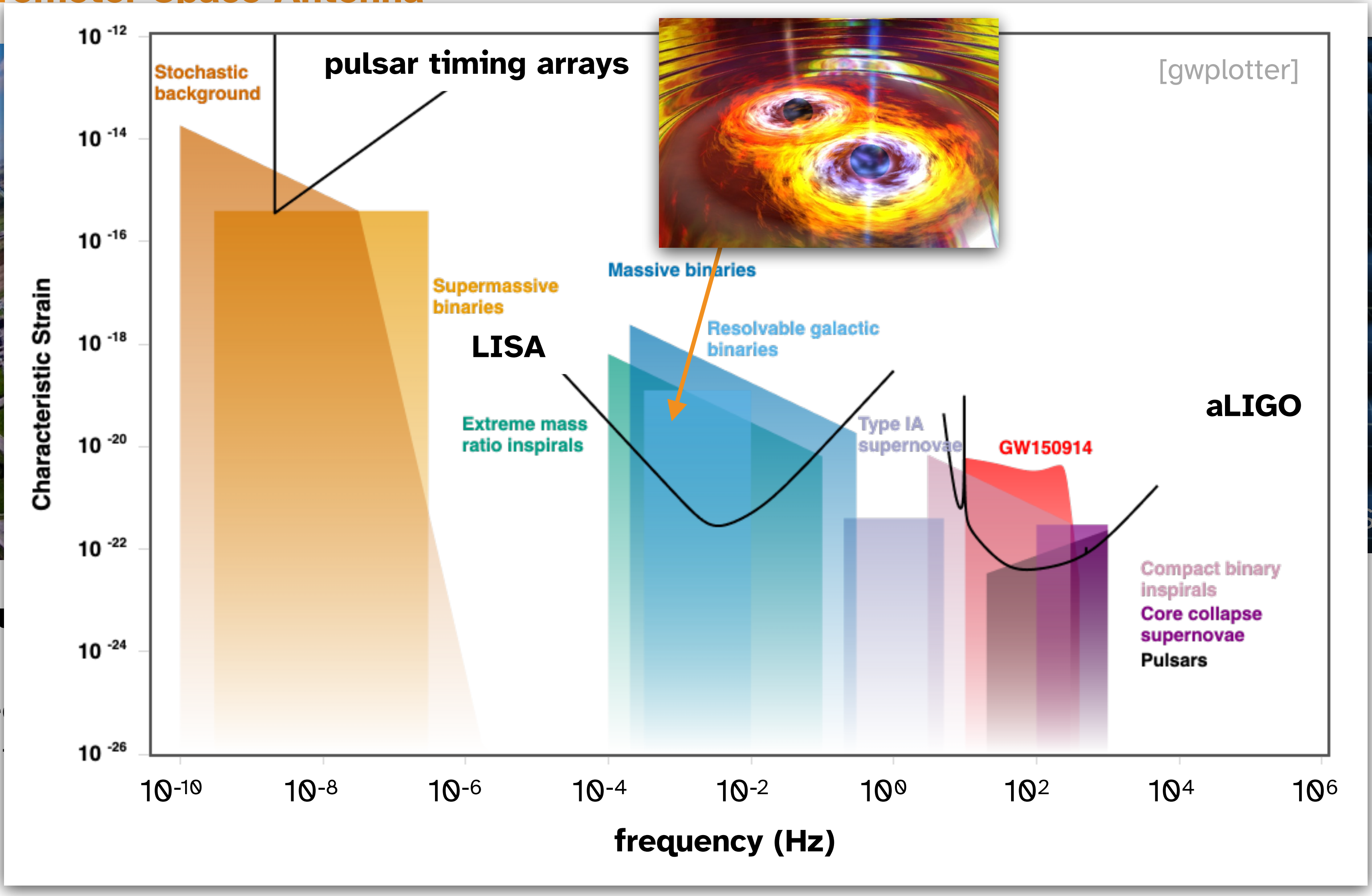
effective arms: O(2.5e6 km)
λ ~ 10^6 km -> f_{GW} ~ O(0.1 Hz)

LISA gravitational-wave observatory

Laser Interferometer Space Antenna







grou

effe

λ ~

finally: some other things

obviously time-domain astronomy in gamma rays is much more than what we've discussed here

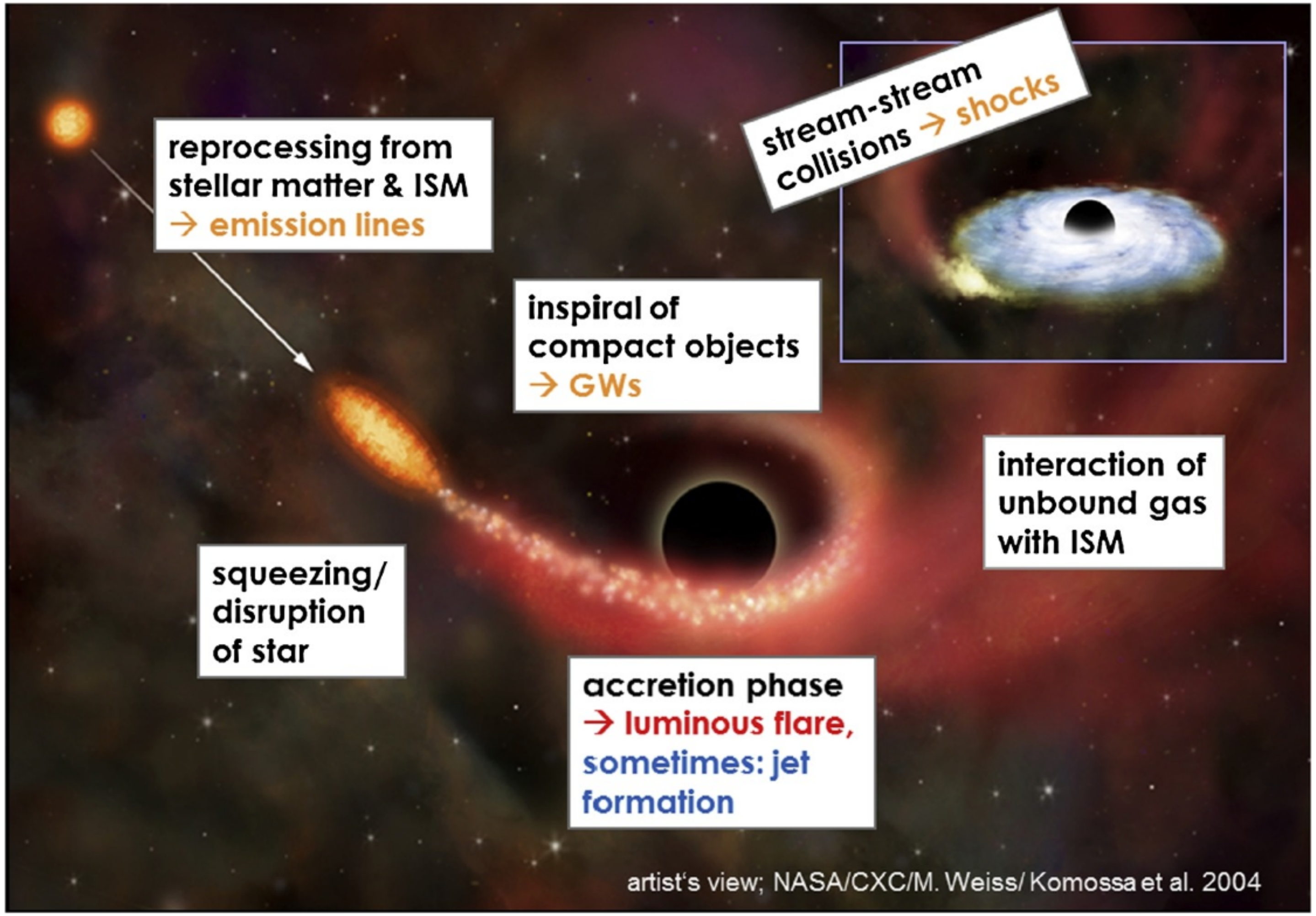
here is a parade of some of those other things

T D E

[DESY, Science Communication Lab]

tidal disruption events (TDEs)

another way to potentially get gamma rays from supermassive black holes

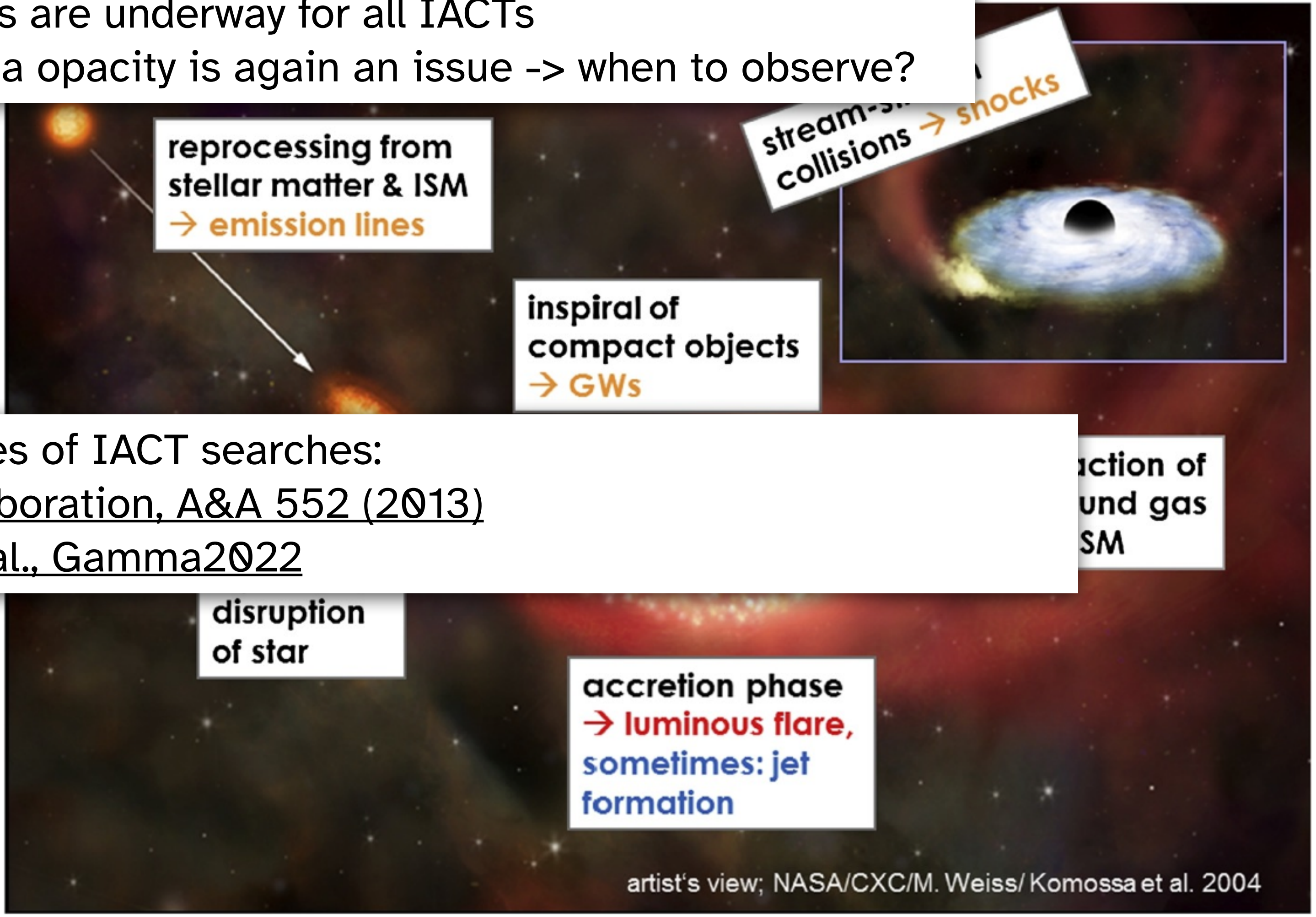


[S. Komossa, JHEAP 7 (2015)]

tidal disruption events (TDEs)

another way to potentially get gamma rays from supermassive black holes

Observing programs are underway for all IACTs
BUT gamma-gamma opacity is again an issue -> when to observe?



A few examples of IACT searches:
- MAGIC collaboration, A&A 552 (2013)
- I. Lypova et al., Gamma2022

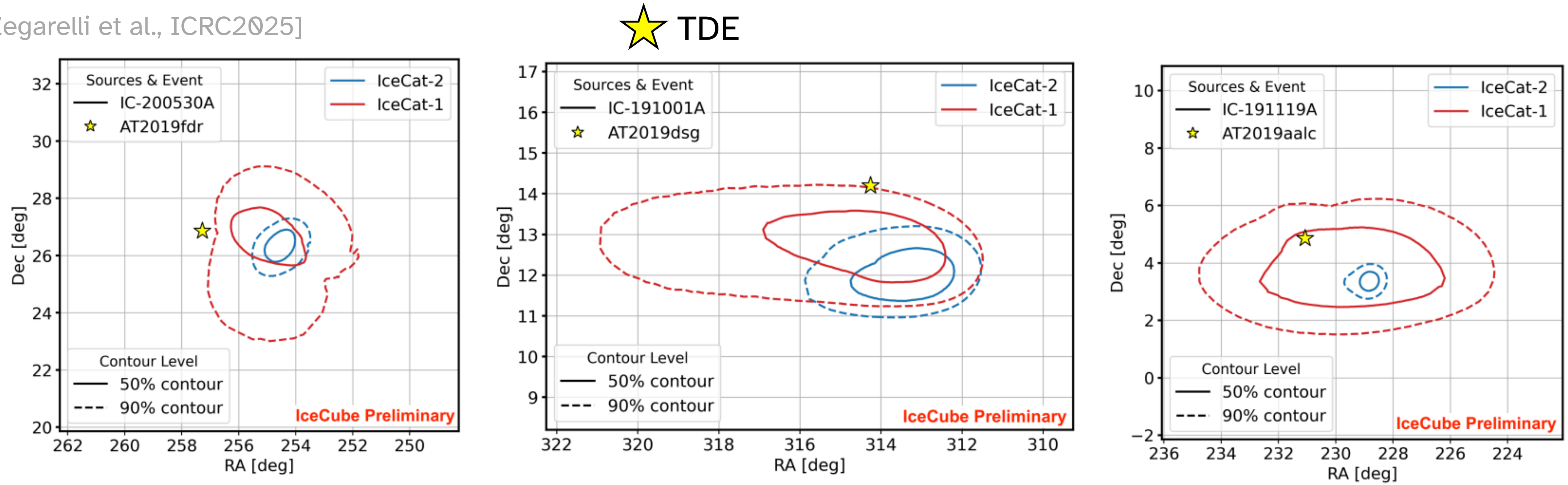
[S. Komossa, JHEAP 7 (2015)]

tidal disruption events (TDEs)

side note on TDEs as potential neutrino sources

Are (some) IceCube-detected neutrinos produced by TDEs? We used to think so, now we don't …

[A. Zegarelli et al., ICRC2025]



(a) AT2019fdr

(b) AT2019dsg

(c) AT2019aalc

In the meantime, the IceCube collaboration improved their localization algorithms …

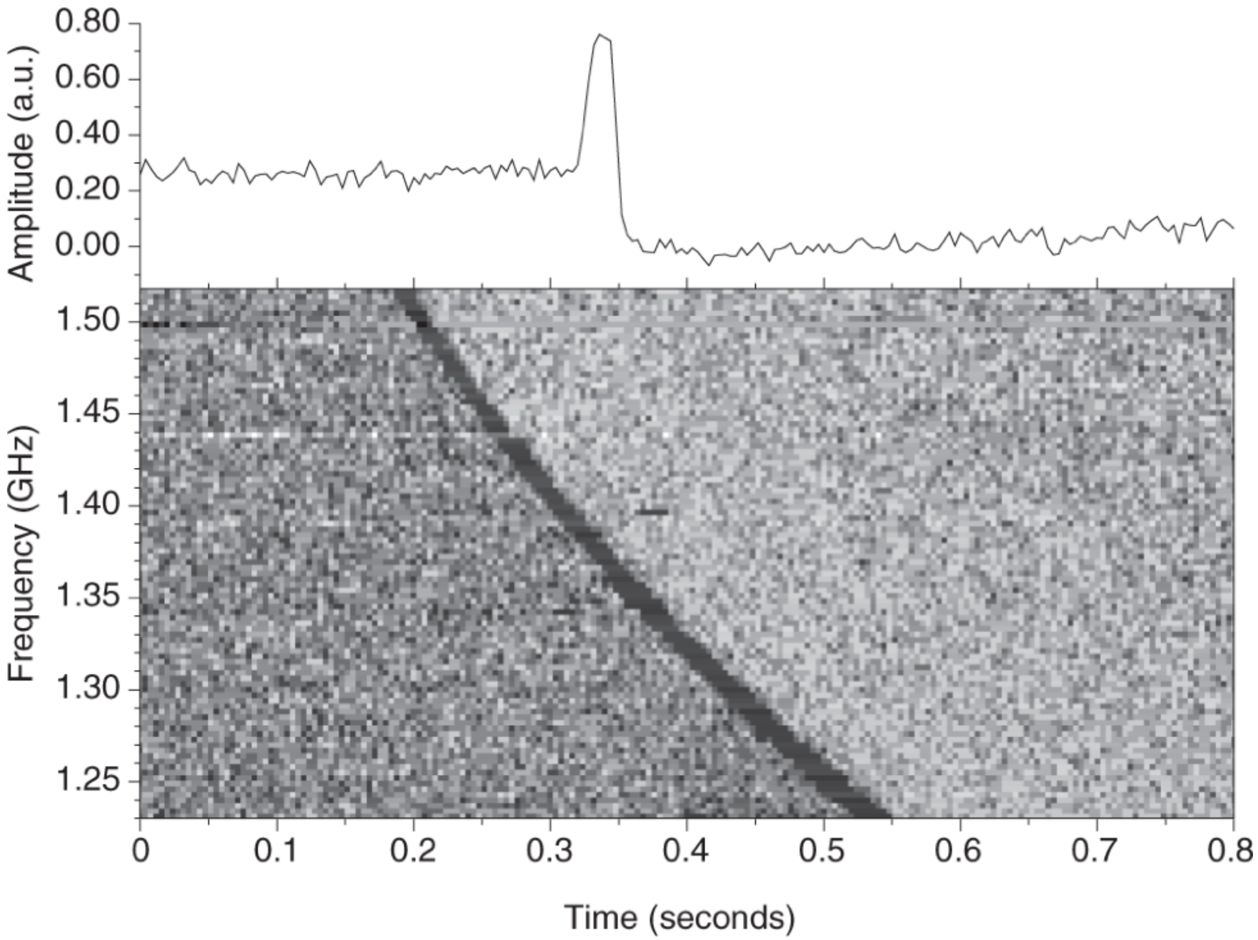
fast radio bursts (FRBs)

we basically have no idea what they are*

* except for the one associated with a soft gamma repeater

a magnetar that produces a burst of (soft) gamma rays

a neutron star with a very high magnetic field



[D. R. Lorimer, Nature Astronomy 2 (2018)]

- very short (<seconds) bursts of radio
- seem to be at cosmological distances
- some fraction of FRB sources are *repeaters* (multiple bursts)

see this review by J. I. Katz for more info

fast radio bursts (FRBs)

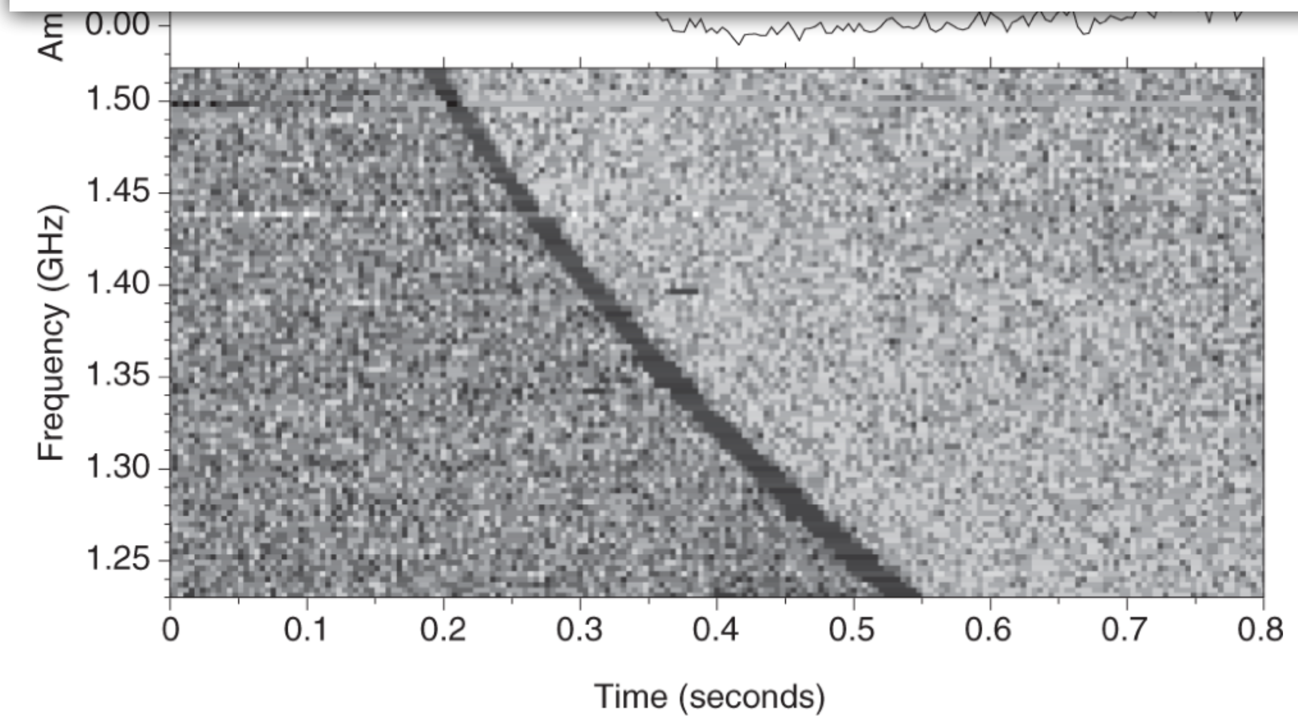
we basically have no idea what they are*

* except for the one associated with a soft gamma repeater

IACTs mostly have to look for some sort of "afterglow" emission

exception: VERITAS can observe ~simultaneously with CHIME

nothing so far ¯_(ツ)_/¯



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