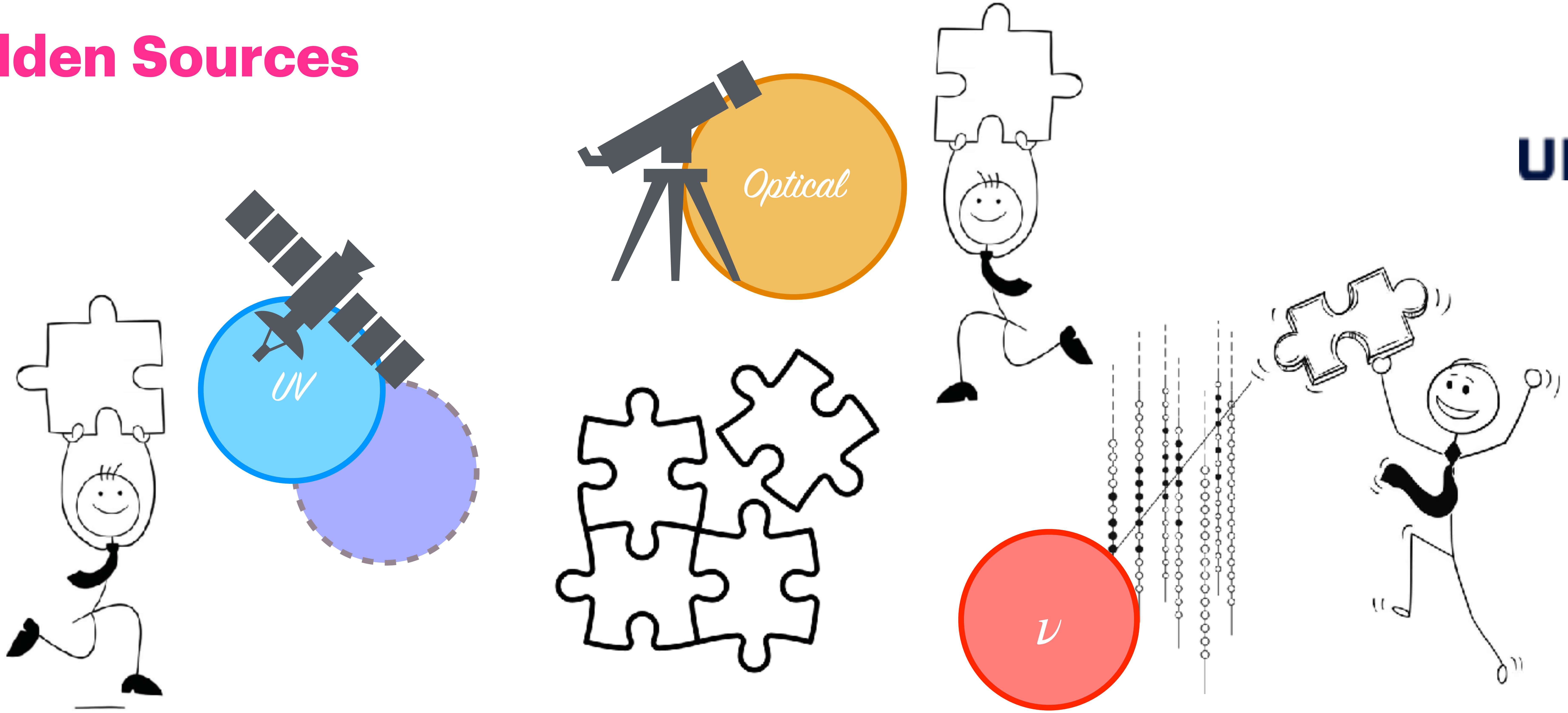
Hidden Sources



ARIEL UNIVERSITY

Towards future multi-messenger detections of core-collapse supernovae harbouring choked jets

Dafne Guetta **RICAP2024**

Based on A. Zegarelli, Guetta et al., accepted in A&A, arXiv:2403.16234

Look at our work here!

Outline

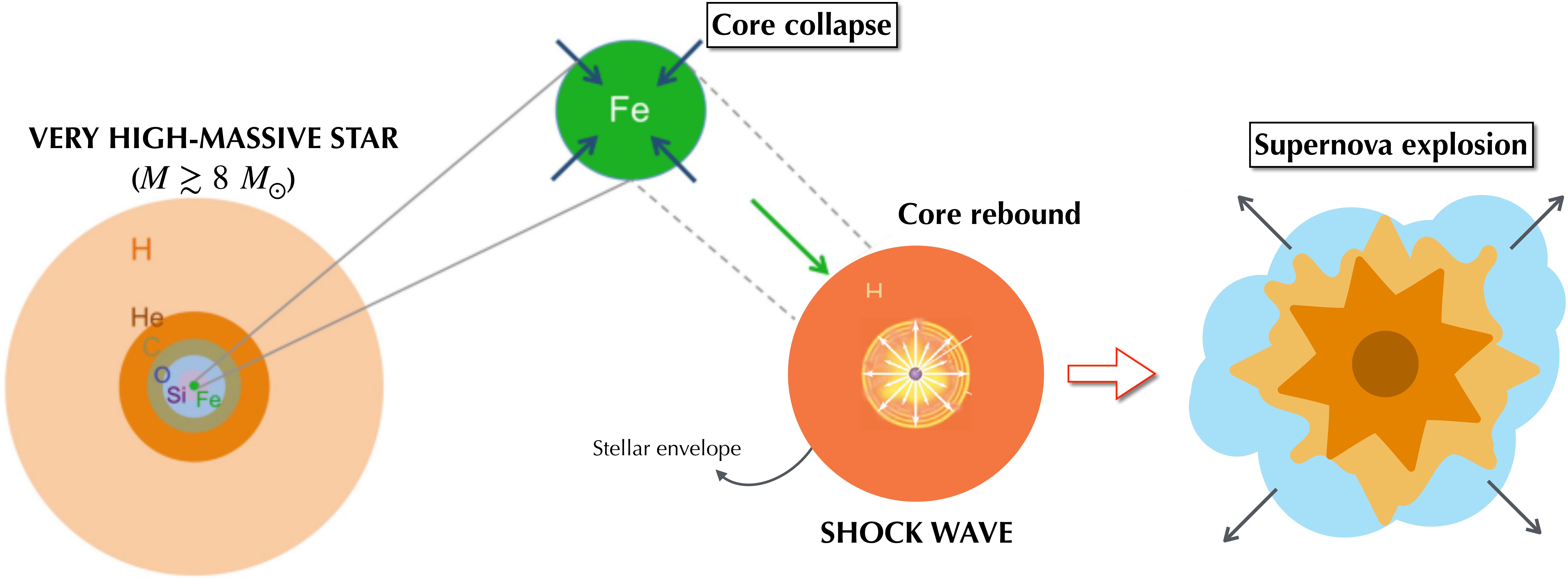
CHOKED JETS FROM CORE-COLLAPSE SUPERNOVAE

- Modelling and possible progenitors
- Why choked jets are important in the multi-messenger field
  - Ultraviolet (UV) and optical electromagnetic signatures from choked jets
  - Choked jets as potential sources of high-energy neutrinos

FUTURE PROSPECTS FOR MULTI-MESSENGER DETECTIONS

- Description of methodology adopted
- Detection prospects of choked jet progenitors in UV band by the future UV mission ULTRASAT in relation to their visibility in optical (ZTF-like instruments)
- How neutrino observations by Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT) can be used in association to UV and optical signals
- Results and discussion of multi-messenger implications

Core-collapse Supernovae (CCSNe)

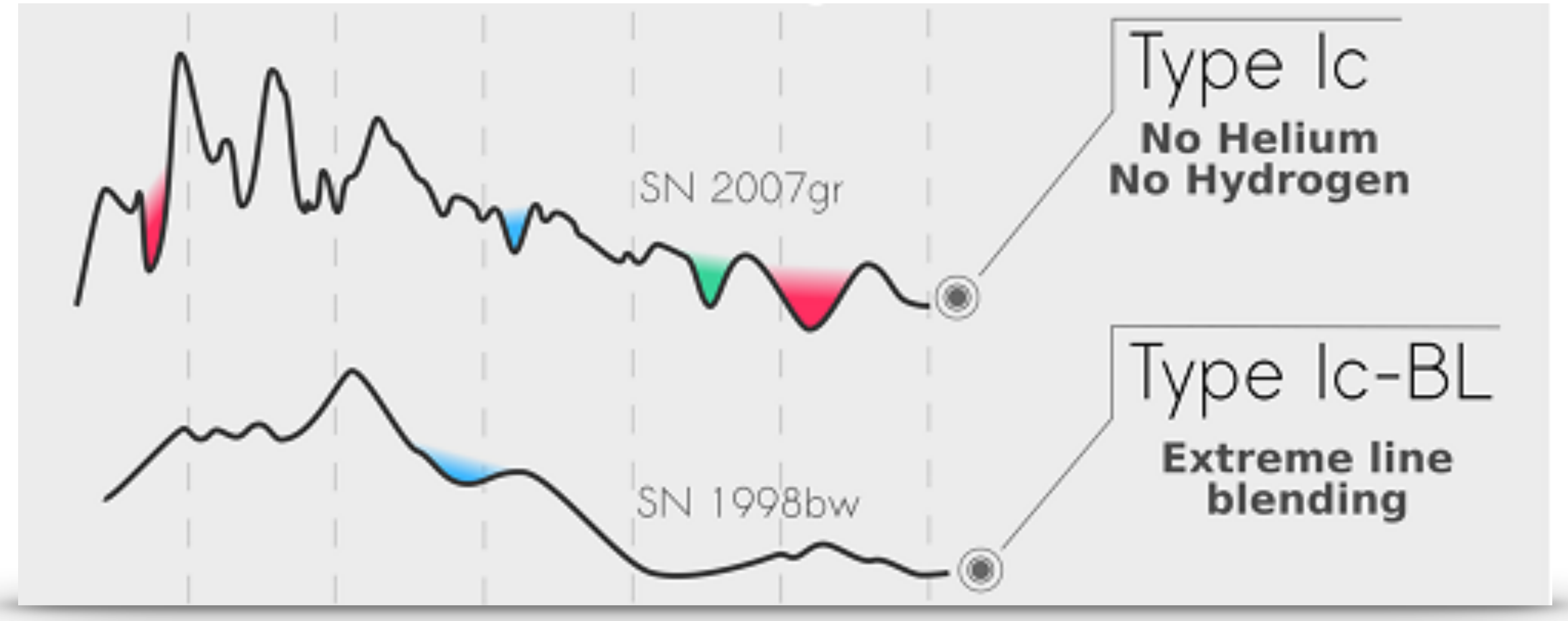


1. Atoms fuse to release energy to power the star, but eventually the star consumes all of its available fuel —> **Gravity dominates**

2. Inward-falling material rebounds off the core, setting up an outward-going pressure wave

3. The shock wave moves outward through the star

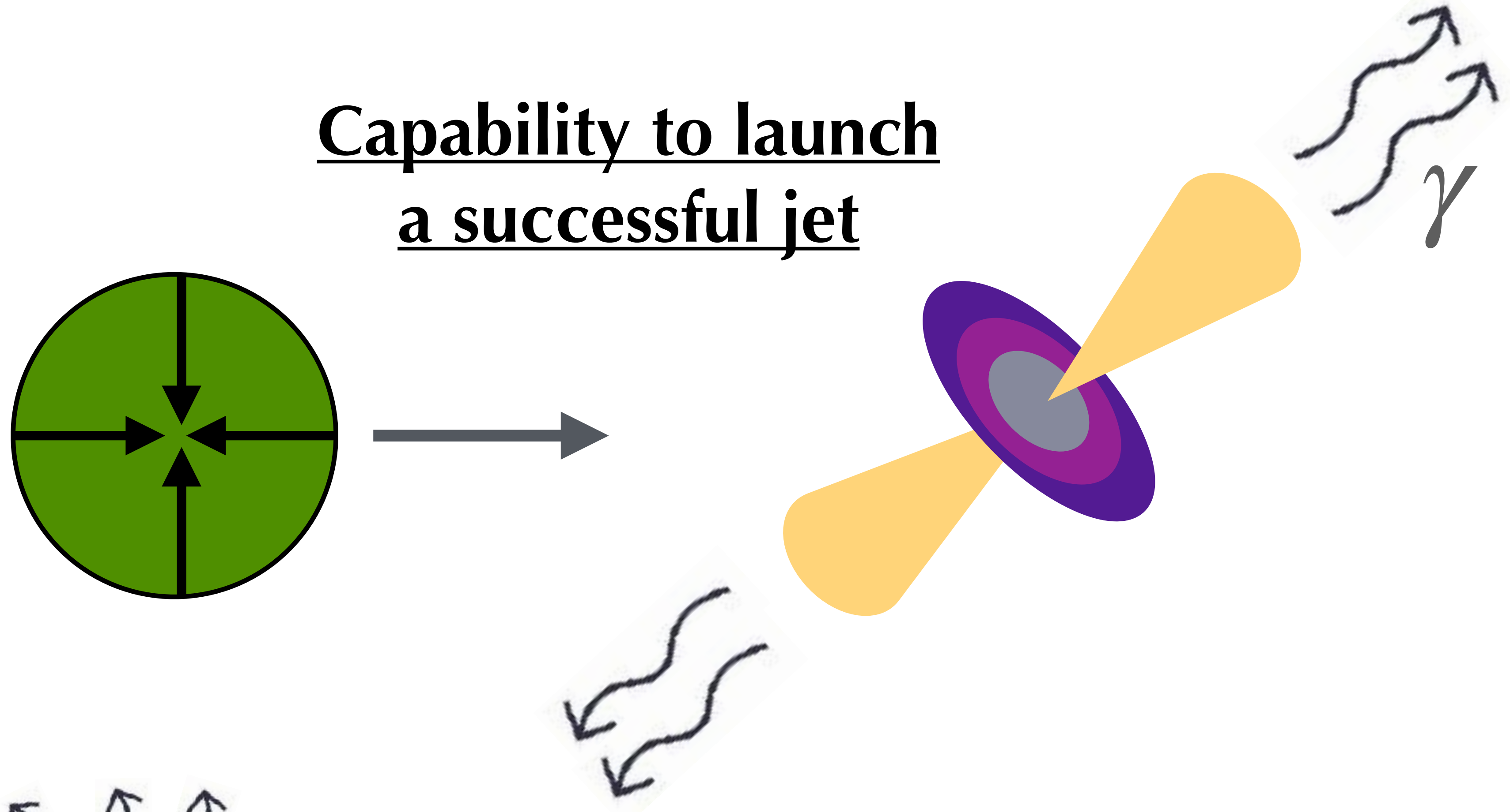
CCSNe and connection with Gamma-Ray Bursts (GRBs)

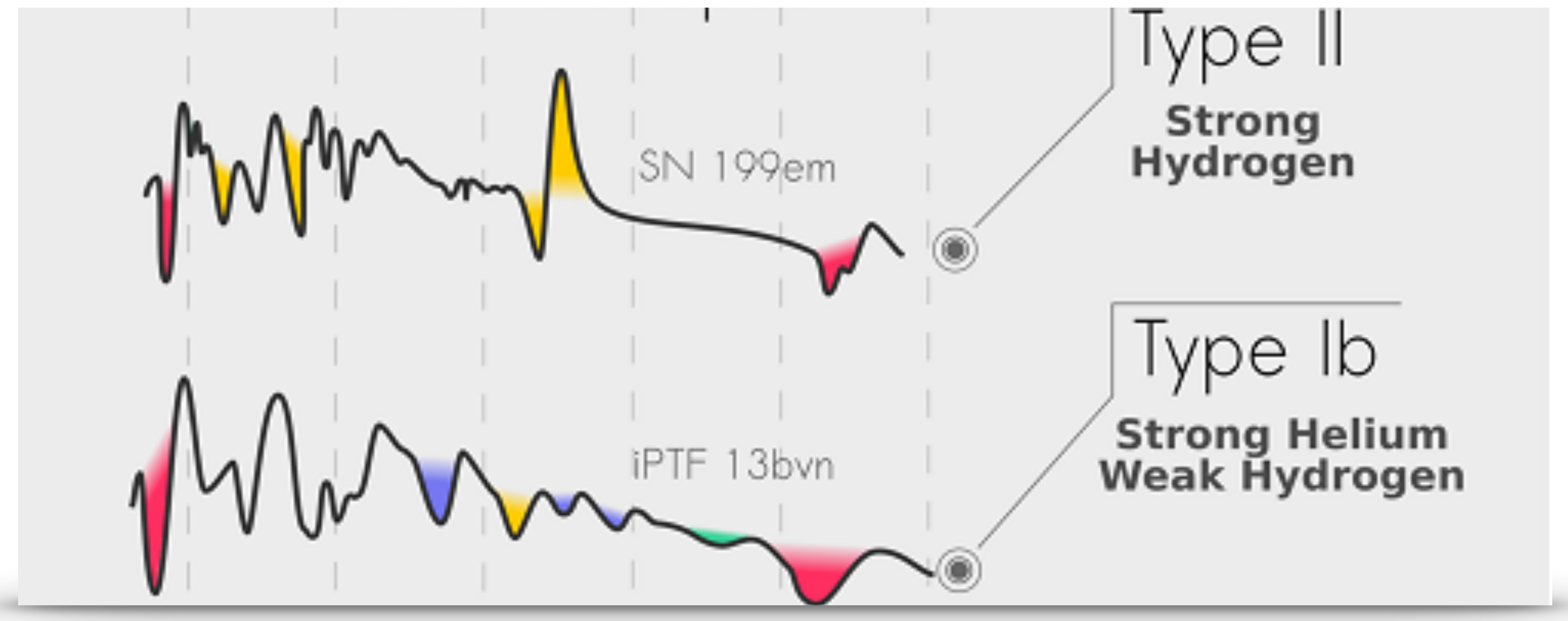


Associated to **standard long GRBs**, whose progenitors are **Wolf-Rayet (WR) stars**: very massive stars with strong winds blowing out most of the material of the stellar envelope

$L_{\gamma,\mathrm{iso}}$ up to $\sim 10^{54}$ erg s^{-1}

Capability to launch a successful jet

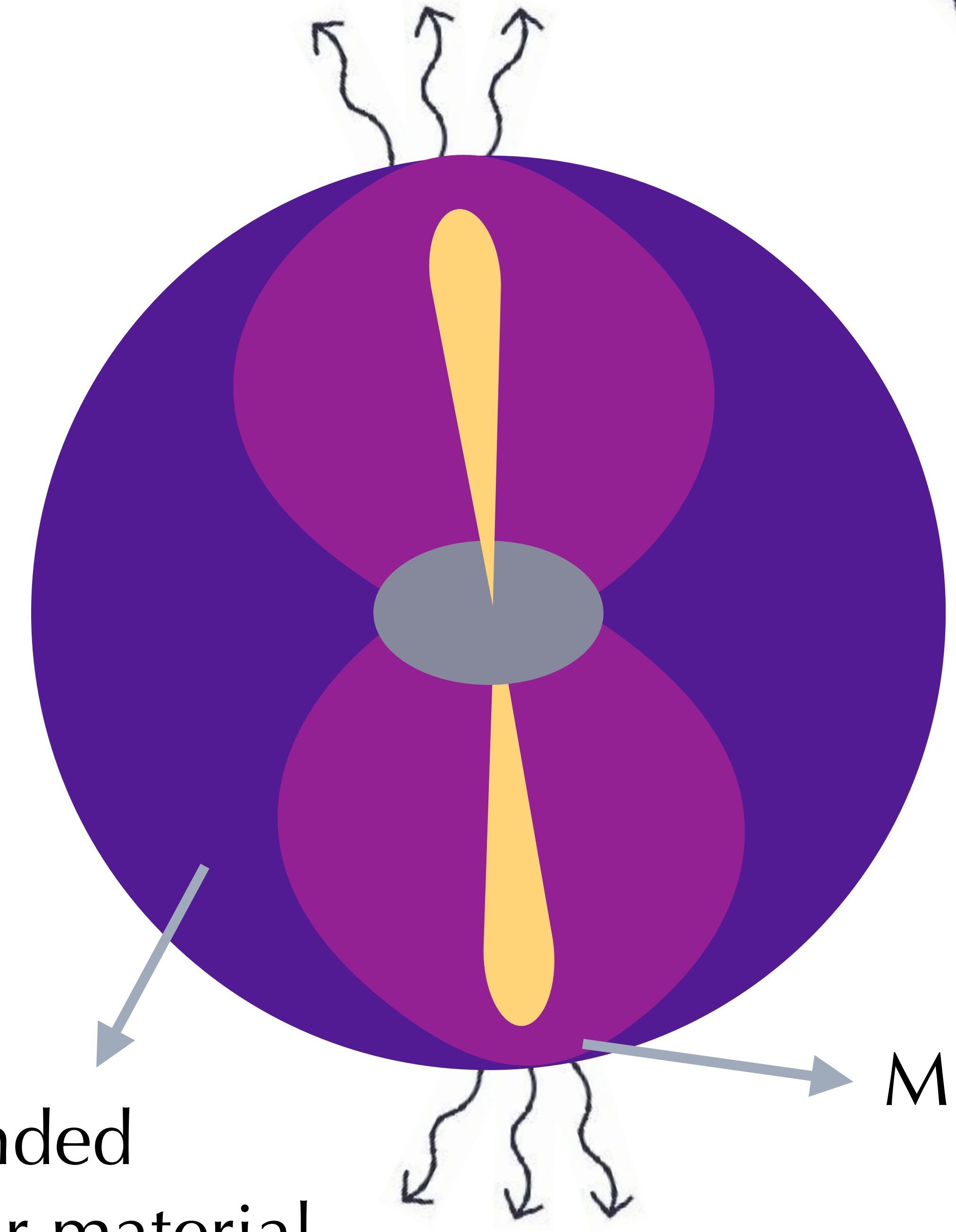




A few associations with **low-luminous GRBs (*ll*GRBs)**

e.g., *ll*GRB 060218 - *SN 2006aj*
Nakar 2015

$L_{\gamma,\mathrm{iso}} < 10^{49}$ erg s^{-1}



Jets do not manage to break out from the star (**choked in the extended material**)

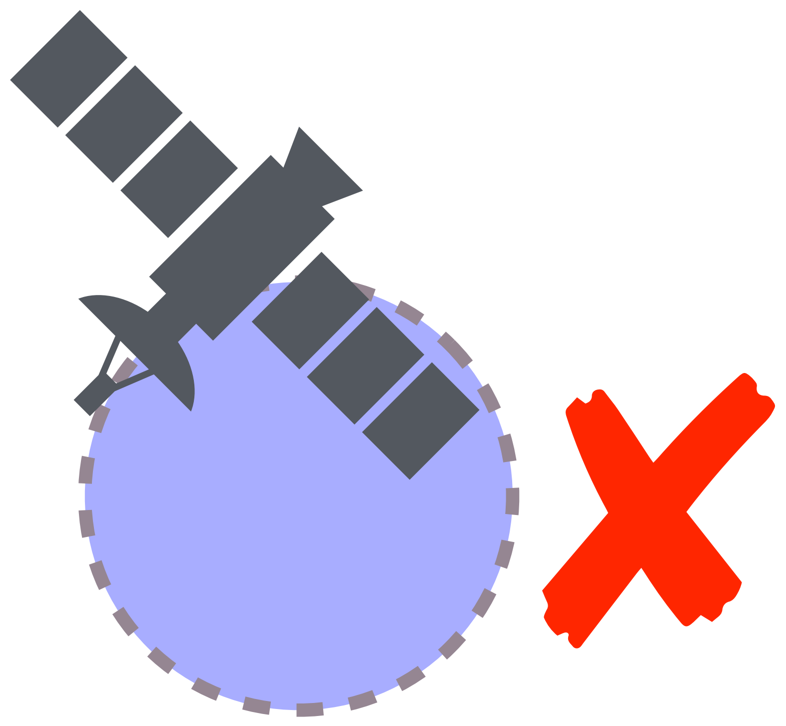
Mildy relativistic shock

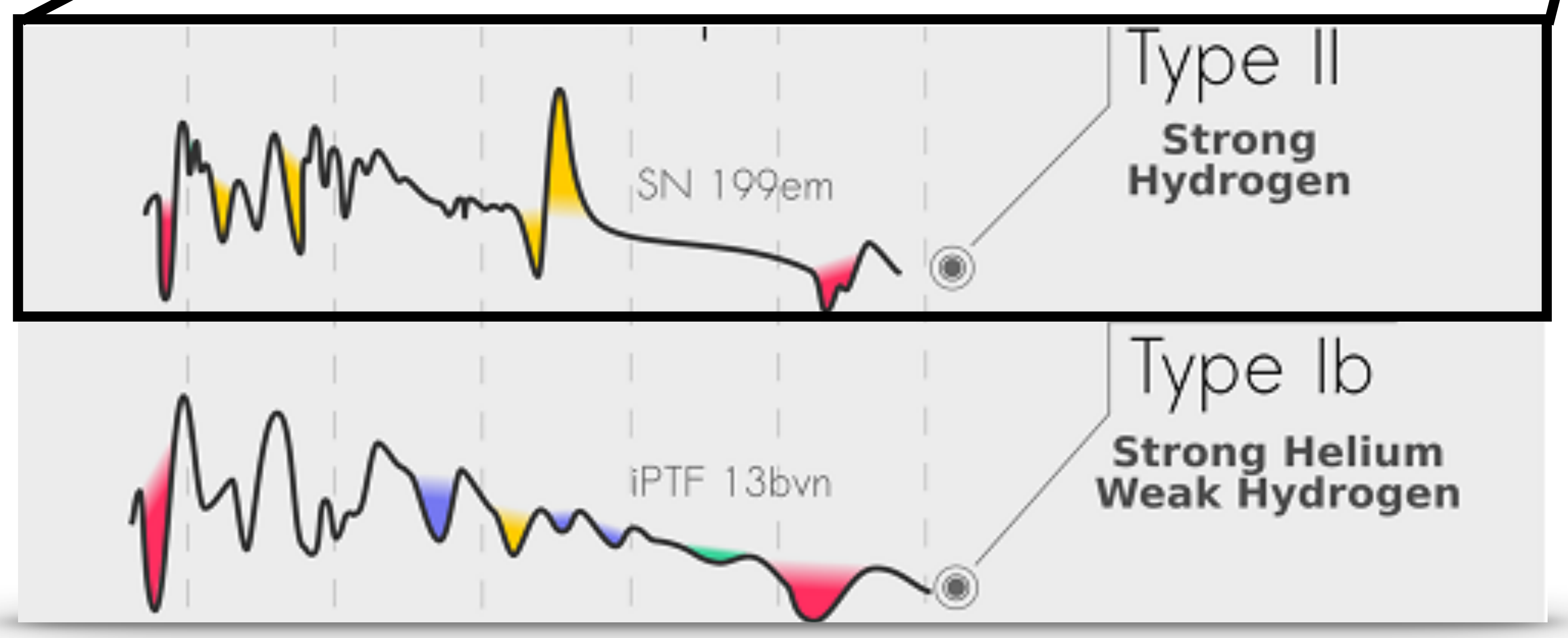
Extended stellar material

Choked jets in CCSNe

For very extended hydrogen-rich envelopes (extended massive stars as progenitors), the jet is expected to be **completely choked**

- Red Super Giants (RSGs)
- Blue Super Giants (BSGs), i.e., underluminous SNe II (e.g., SN 1987A) Arnett et al. 1989





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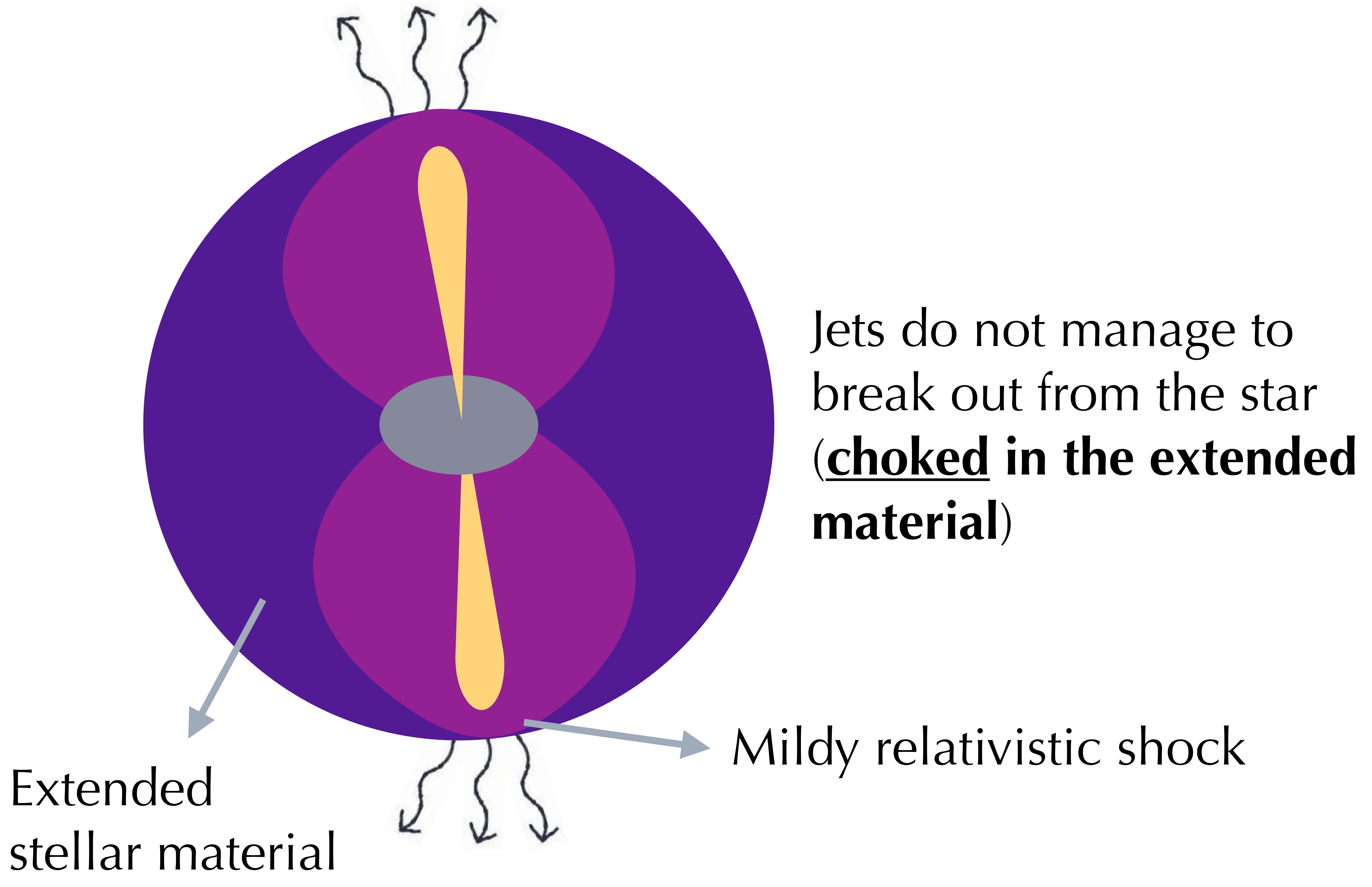

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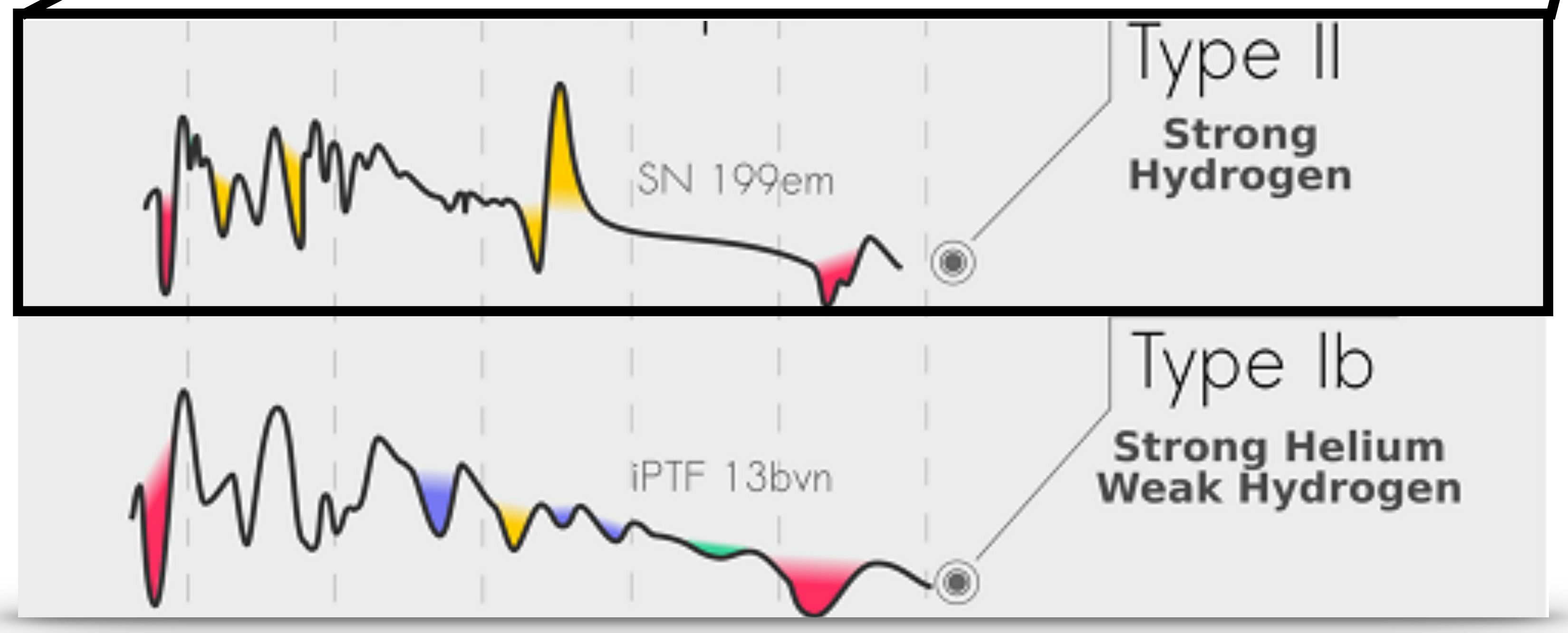

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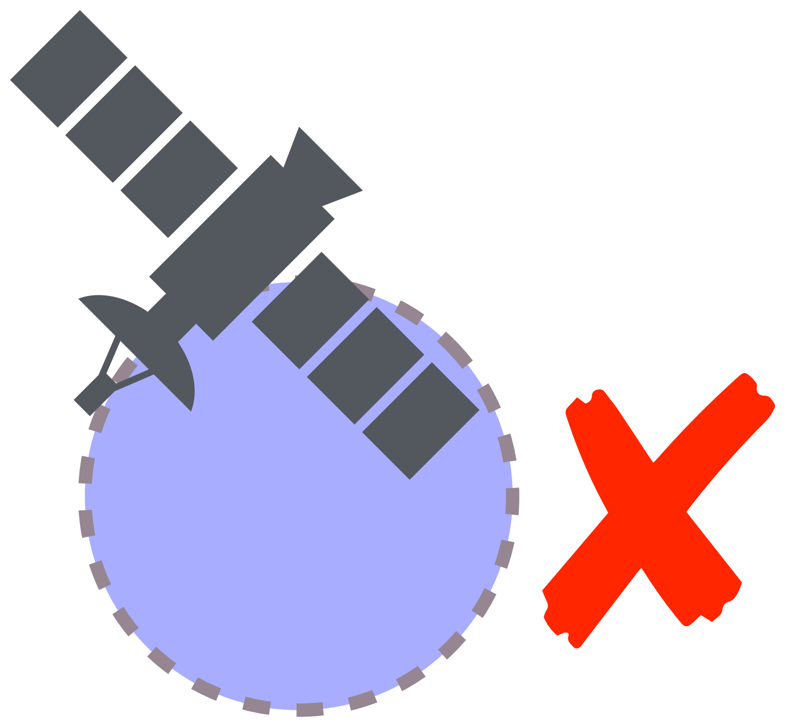
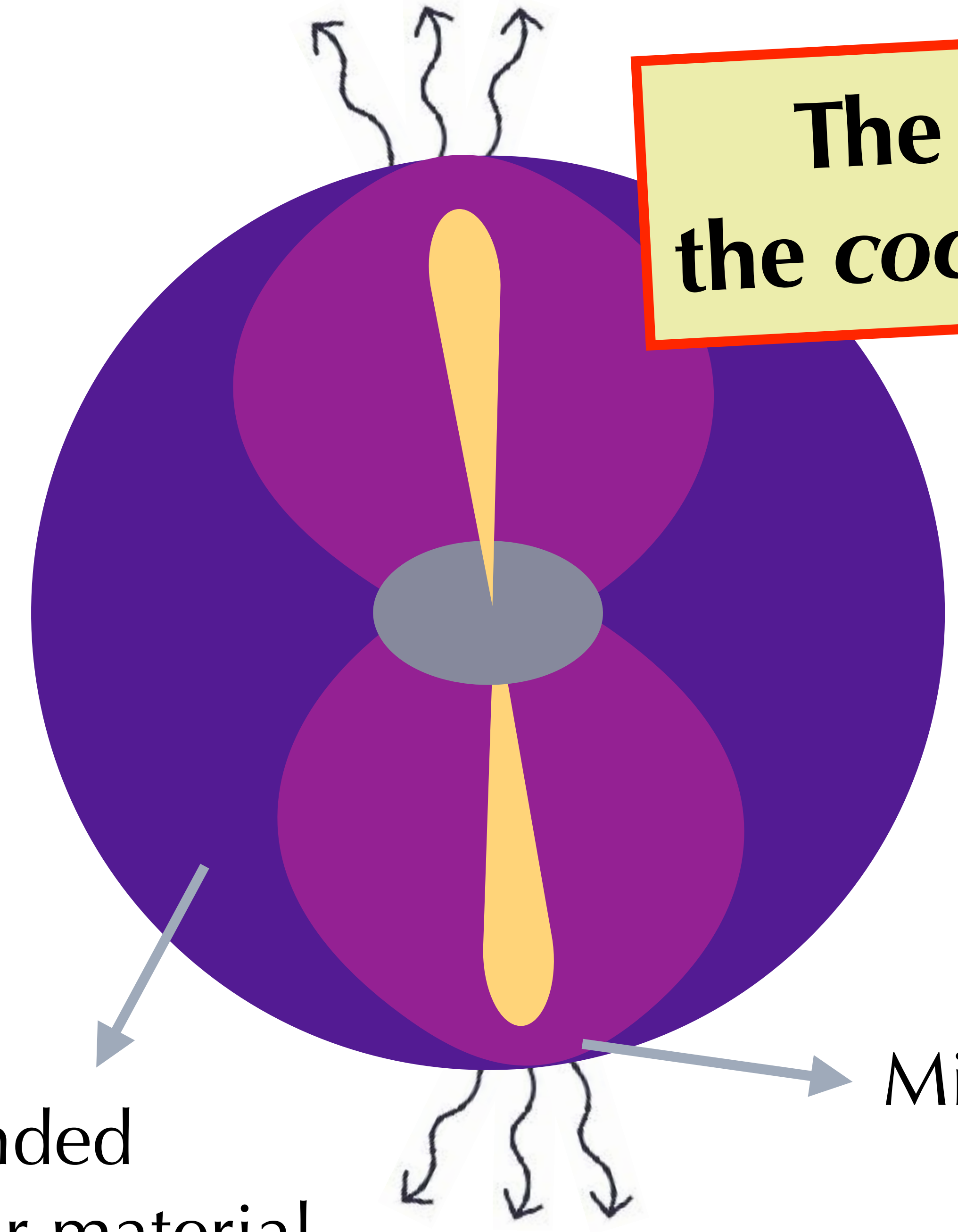


!!!

The jet is choked but …
the *cocoon* can still break out

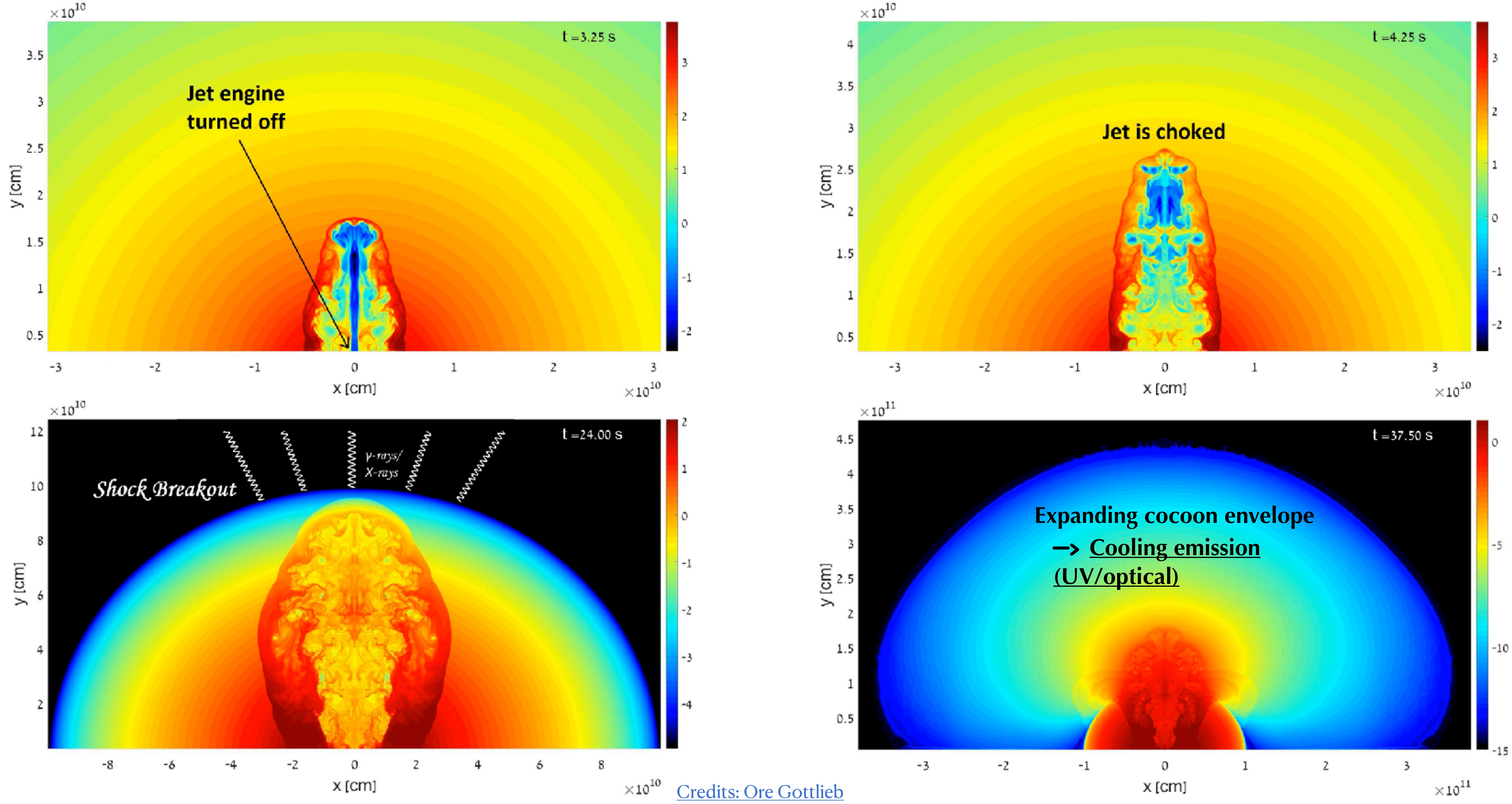


Jets do not manage to break out from the star (**choked in the extended material**)

Mildy relativistic shock

Extended stellar material

A choked jet with a *cocoon* breakout



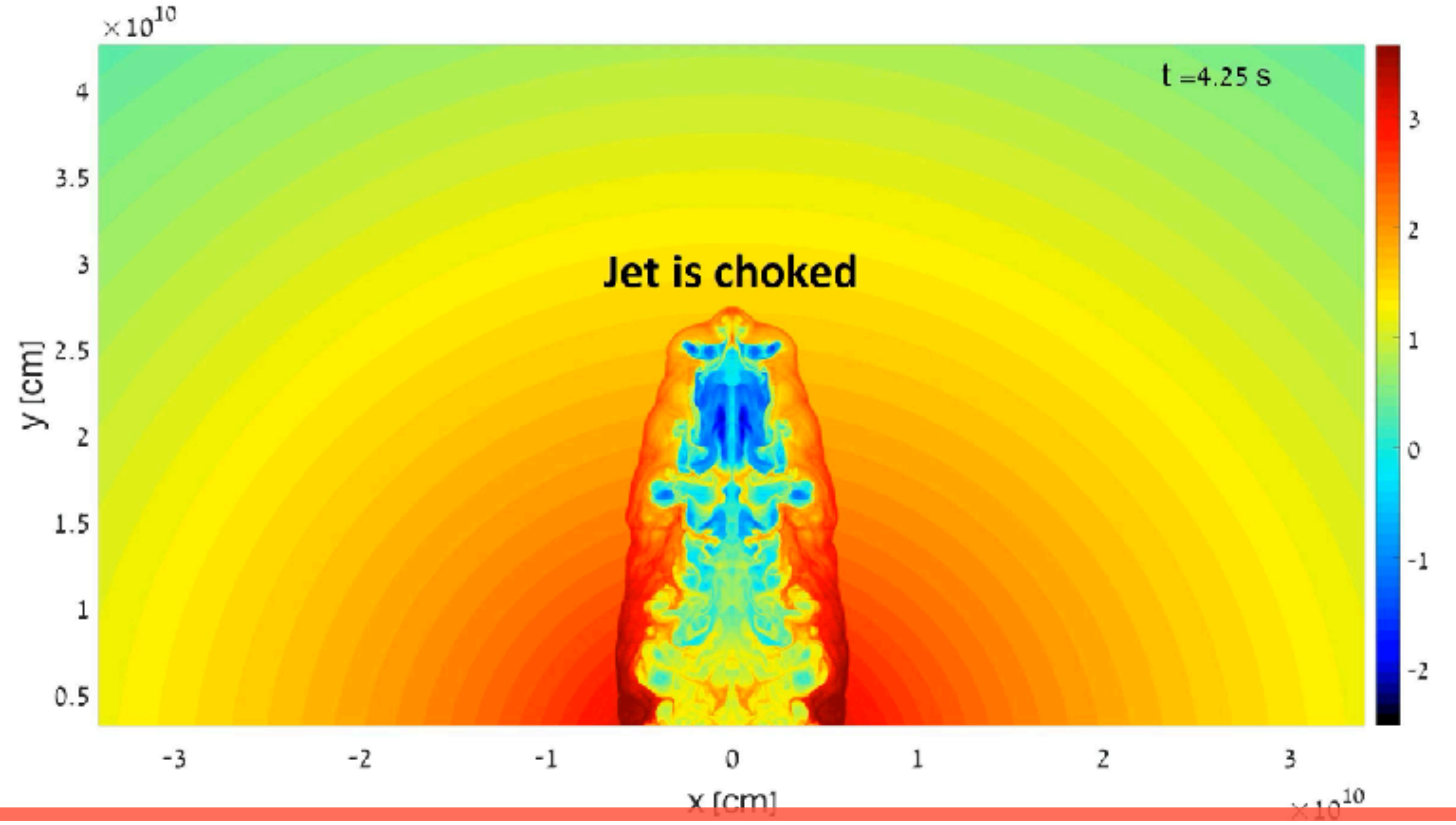
Credits: Ore Gottlieb

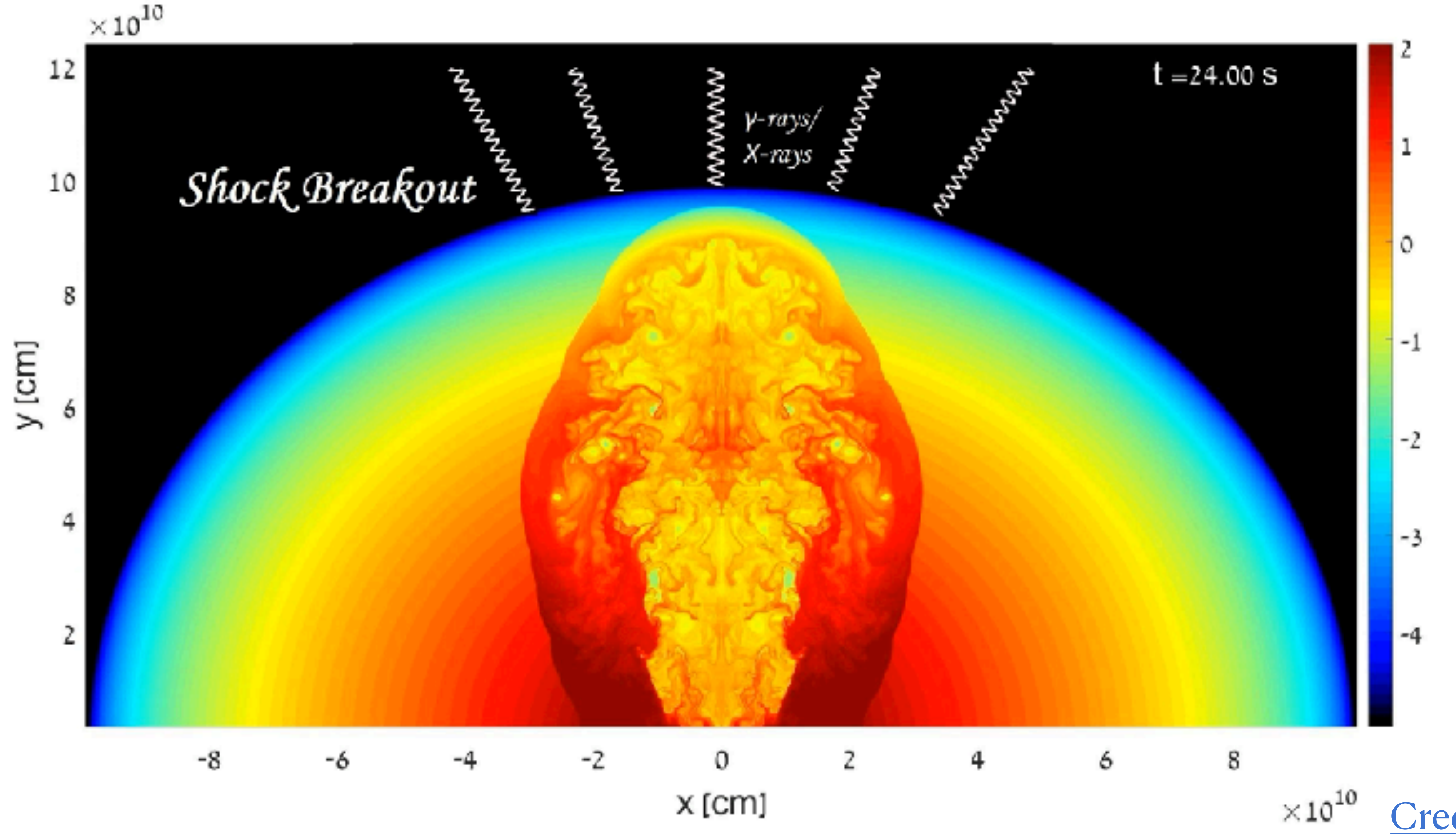
Observable electromagnetic signatures of GRB cocoons

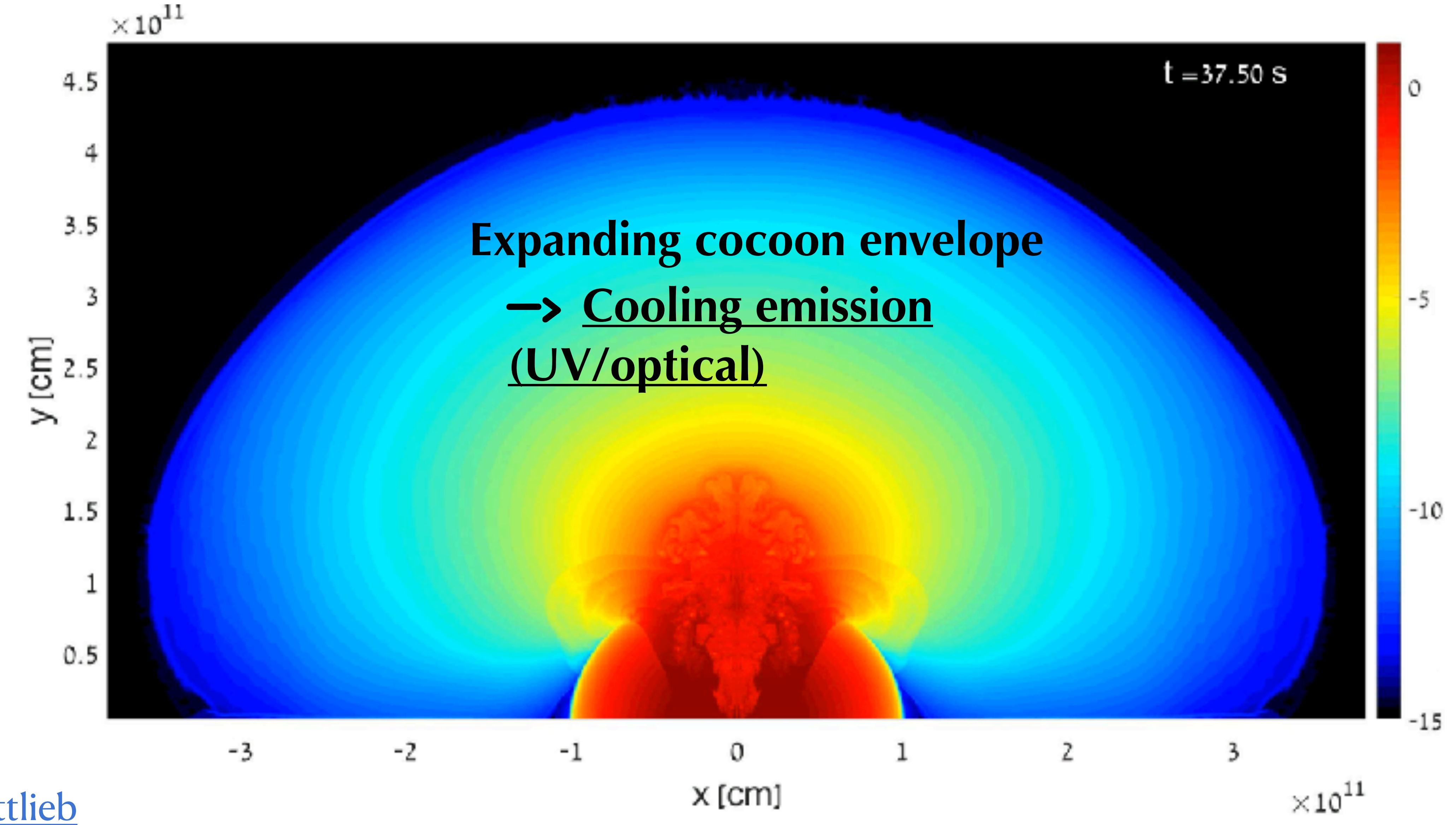
Even if the **jet is choked**, and γ **rays** emitted by the **relativistic jet cannot escape**, other observable electromagnetic (EM) signatures are:

1. **Shock Breakout (SBO)**: bright X-UV-ray or γ-ray flash (it lasts from a few seconds up to fractions of hour)

2. **Cooling phase of the expanding cocoon envelope**: UV and optical signal (timescale of days)







Credits: Ore Gottlieb

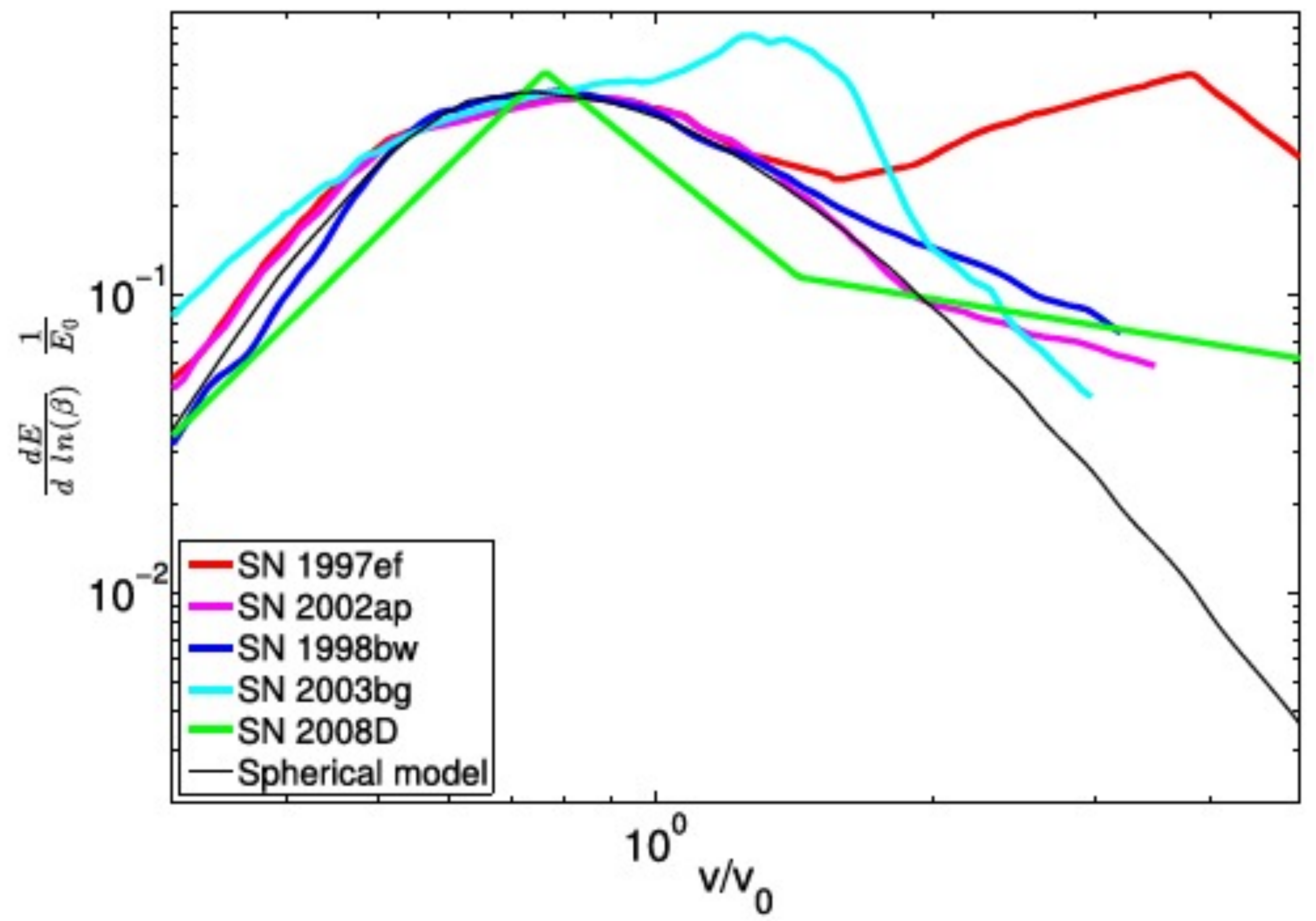
Signatures of a choked jet

The jet launching is terminated while the jet is still inside the star, and the jet is choked, depositing all its energy into the cocoon. The cocoon keeps propagating in the star until it breaks out.

Since the jet is chocked, there is no luminous gamma-ray burst. Similarly to the successful jet, the cocoon radiates a faint flare of soft gamma rays upon breakout, followed by X-ray, UV and optical emission. After breaking out the cocoon spreads sideways in a similar way to the case where the jet is successful.

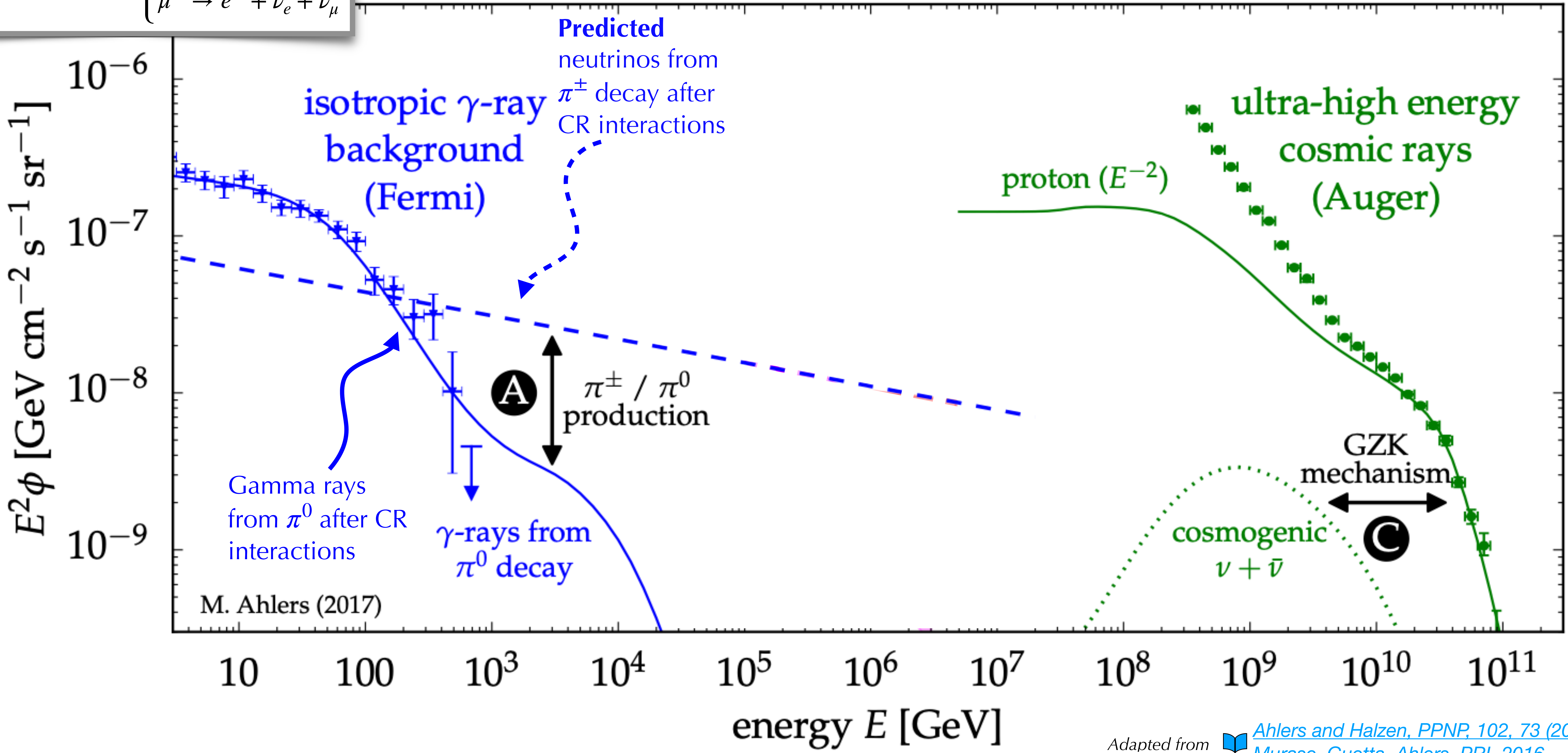
To firmly confirm the hypothesis of hidden jets harboured in stellar envelopes, additional follow-ups would be needed. There are a few observations that could serve as evidence, such as
1) very broad absorption features in SN early spectra because of the fast cocoon material that engulfs the star once the hot cocoon material breaks out and spread, and
2) high-velocity component in the energy-velocity profile of SNe

- **Different spectra taken at different times should allow the SN velocity profile to be compared to the regular spherical explosion case. Piran et al. 2015**



Choked jet in the multi-messenger field

$$p + \gamma \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ n \rightarrow p + e^- + \bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$



Adapted from [Ahlers and Halzen, PPNP, 102, 73 (2018)](#) [Murase, Guetta, Ahlers, PRL 2016](#)

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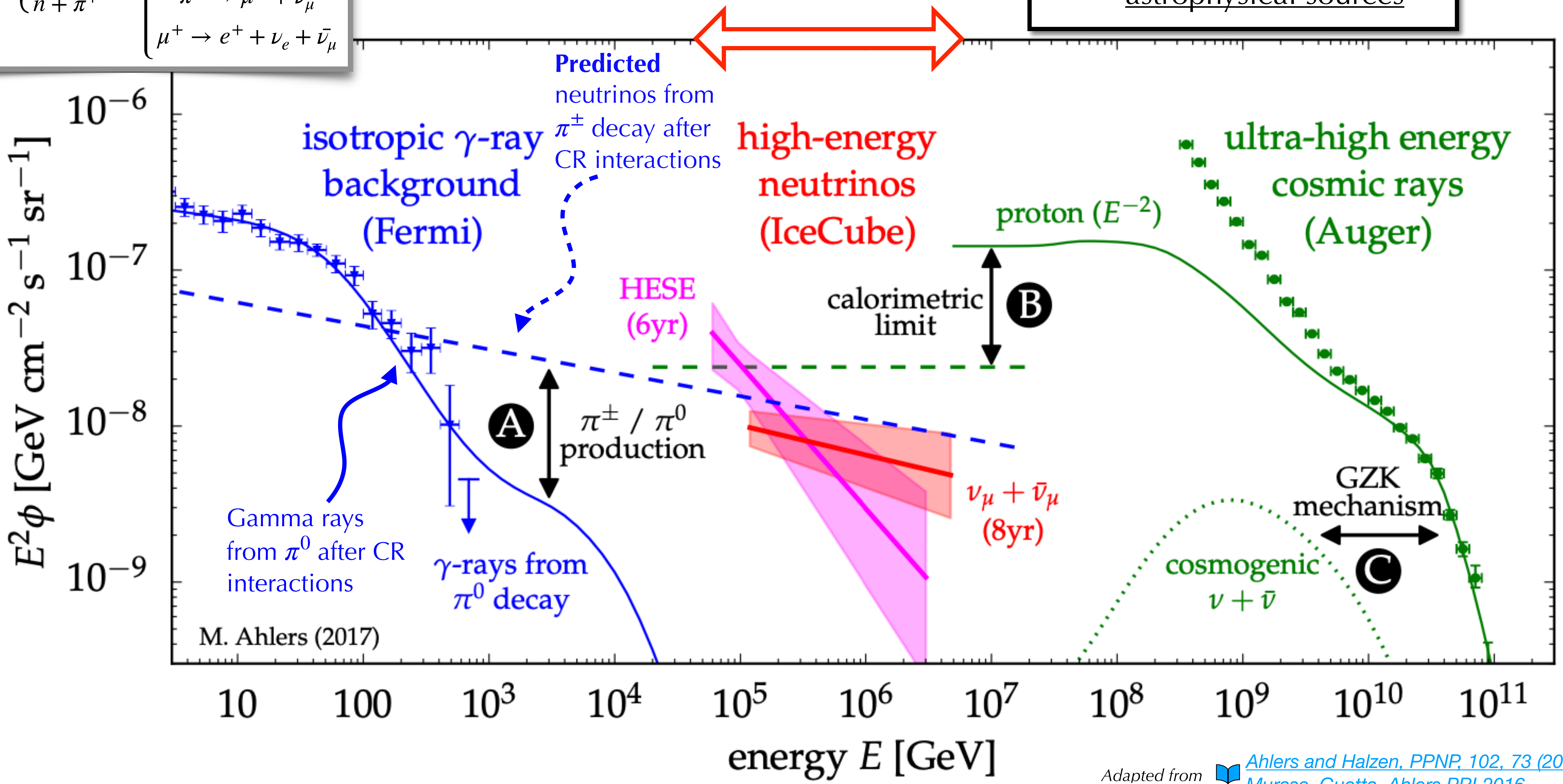
Observed diffuse flux of astrophysical neutrinos

❗❗❗ Most of this flux is still unassociated to known astrophysical sources



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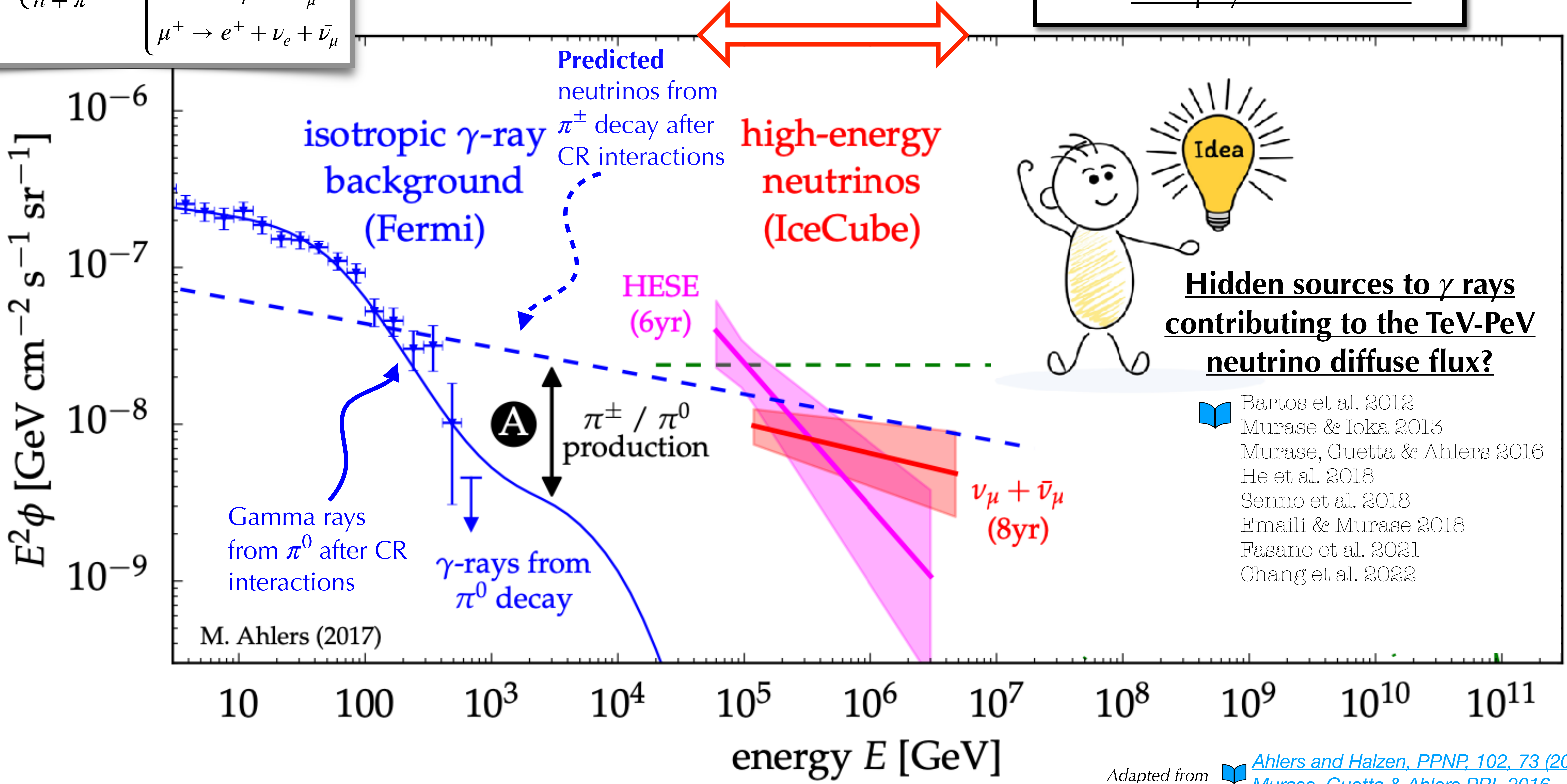


Hidden sources to γ rays contributing to the TeV-PeV neutrino diffuse flux?

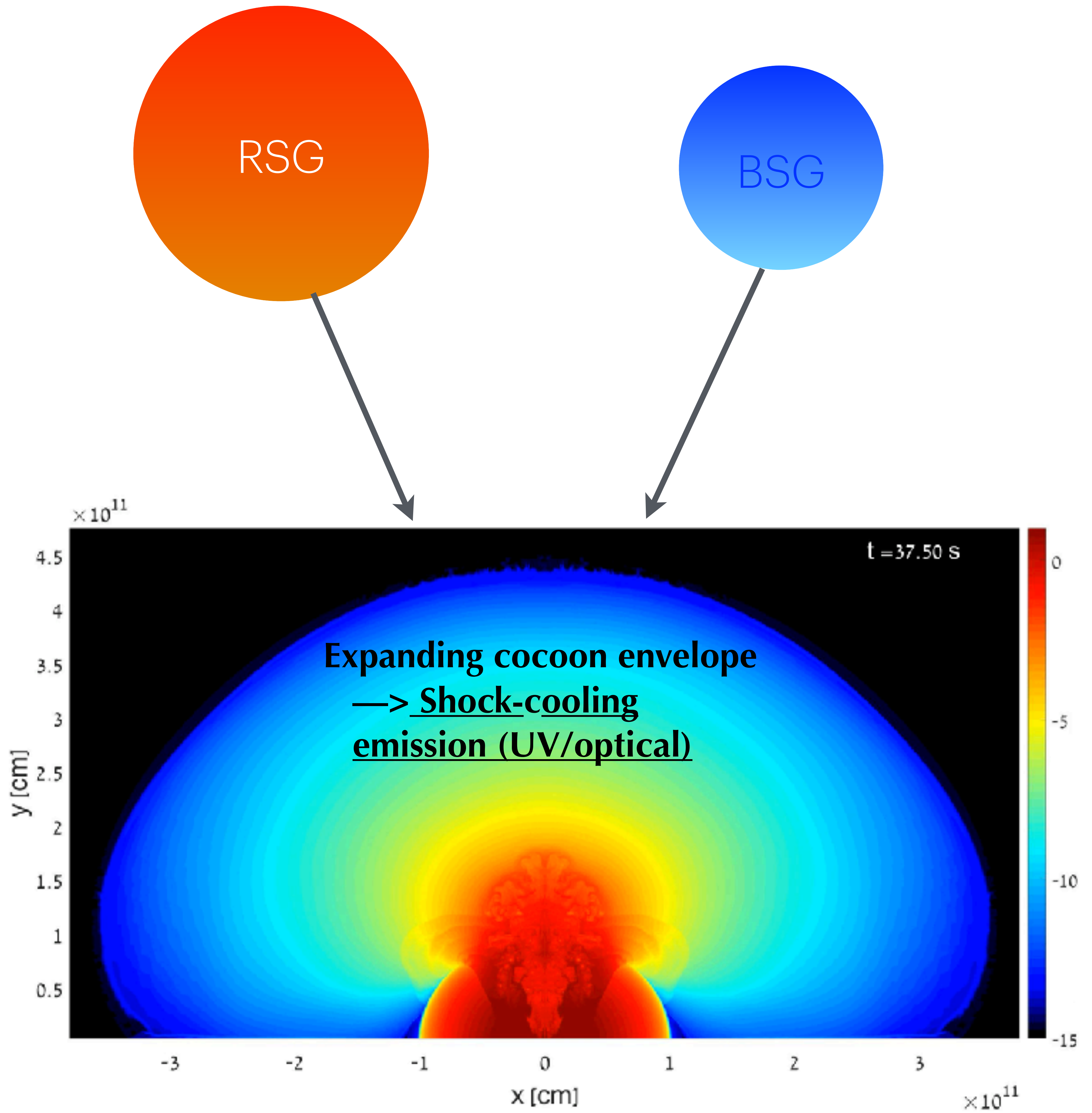
Bartos et al. 2012
Murase & Ioka 2013
Murase, Guetta & Ahlers 2016
He et al. 2018
Senno et al. 2018
Emaili & Murase 2018
Fasano et al. 2021
Chang et al. 2022

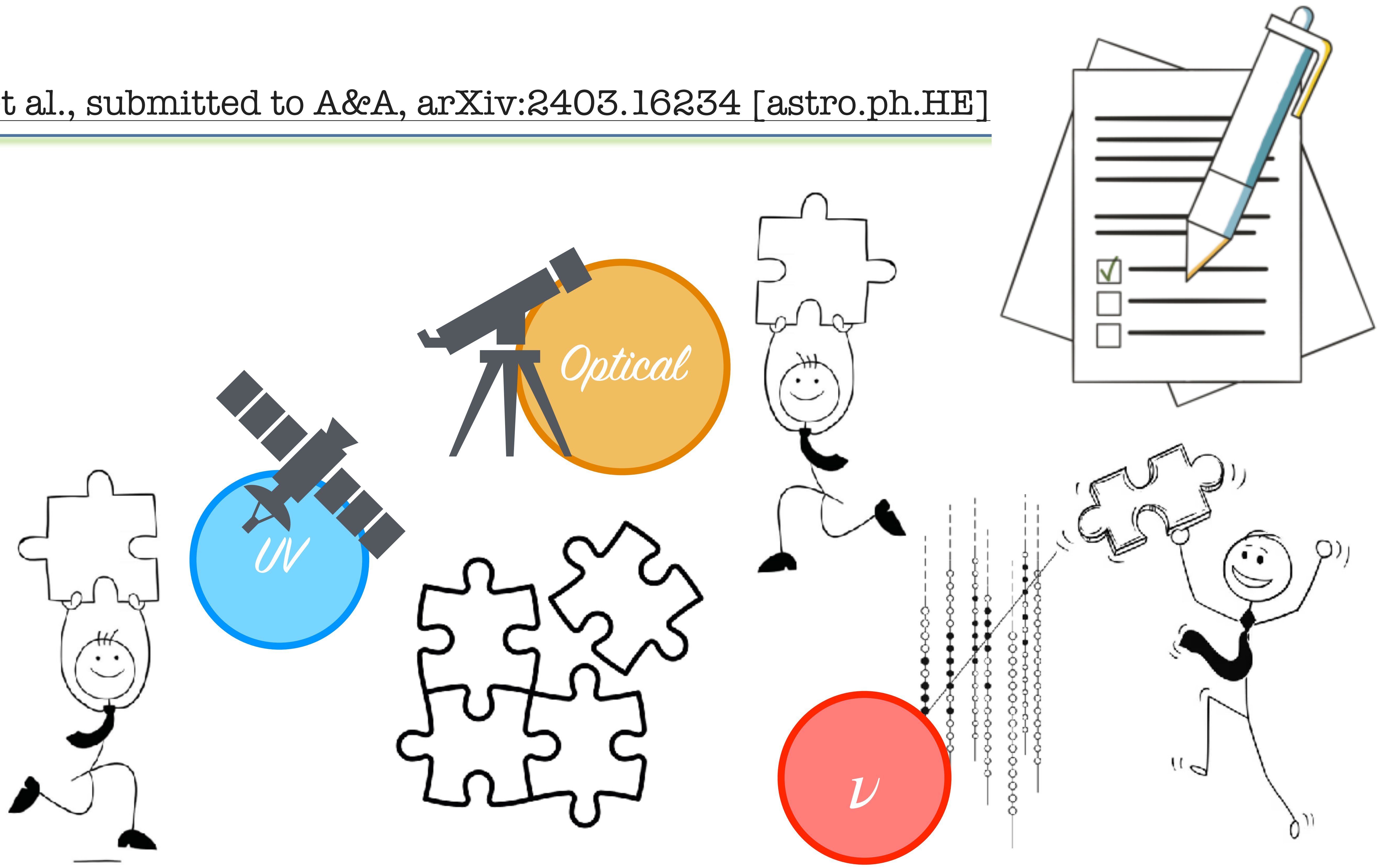
Adapted from [Ahlers and Halzen, PPNP, 102, 73 (2018)](#) [Murase, Guetta & Ahlers PRL 2016](#)

Hidden Sources

Zegarelli et al., submitted to A&A, arXiv:2403.16234 [astro.ph.HE]

RSG and **BSG** stars as progenitors of Type II SNe harbouring **choked relativistic jets** in their stellar envelopes



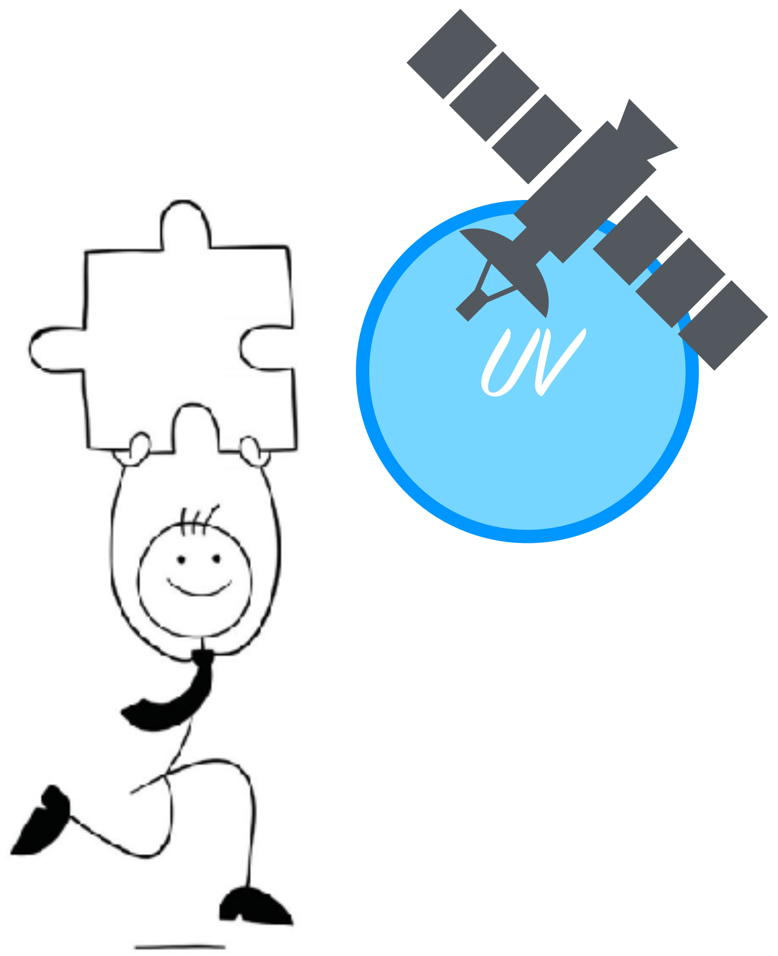


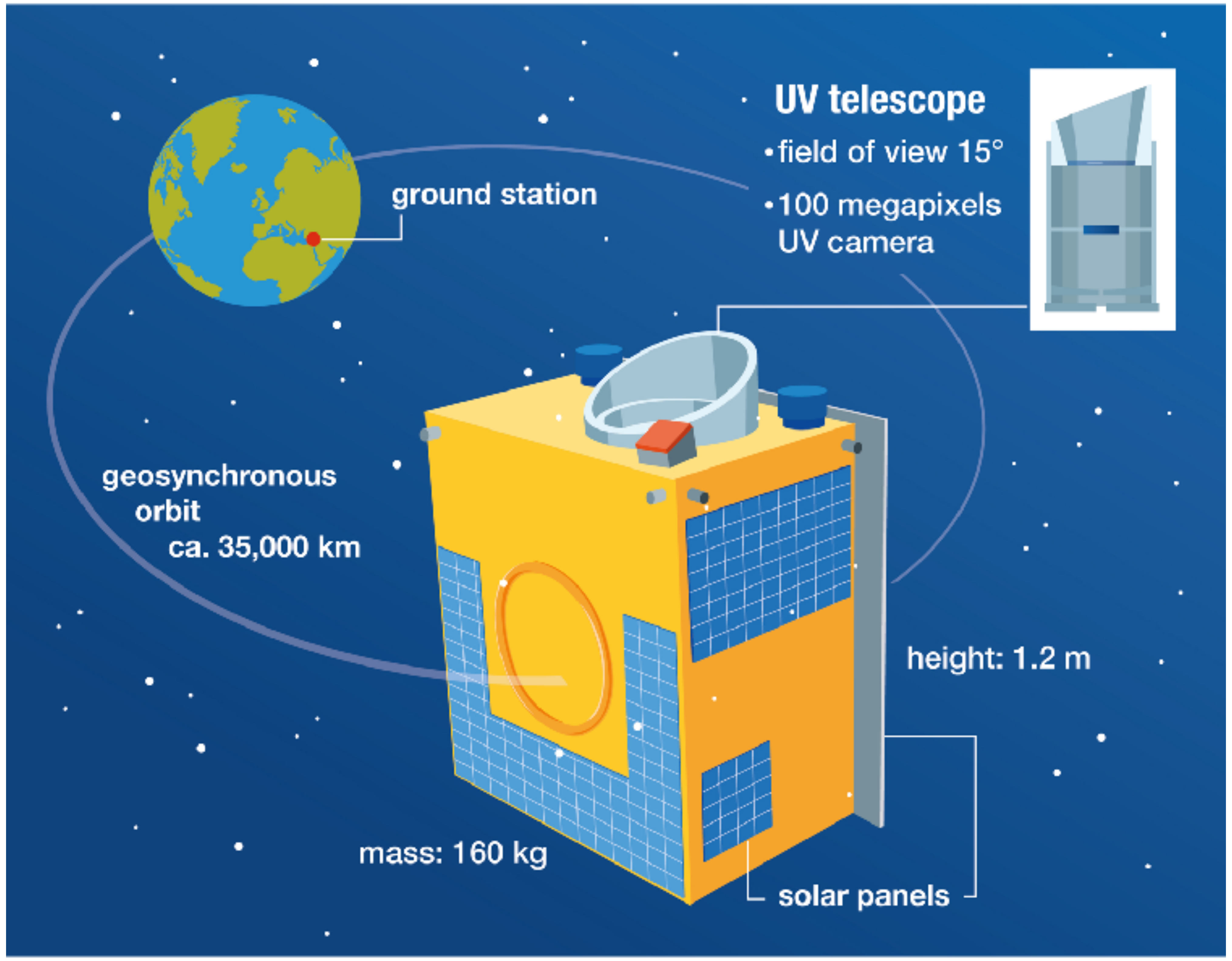
- To understand the **capability** to **follow-up UV** and **optical** emission from the **cooling** of the **expanding cocoon after the shock breakout** occurrence with **current and future facilities**
- To **define** a proper **follow-up strategy** between **UV**, **optical**, and high-energy **neutrino instruments**

Ultraviolet Transient Astronomy Satellite

ULTRASAT
SKYLIGHT TO SPACE

An eye in the UV sky with the **Ul**traviolet **T**ransient **A**stronomy **Sat**ellite (ULTRASAT)
Expected to be launched in 2027





Source: Weizmann Institute of Science / DESY

ULTRASAT Key Properties

Property	Value	Comments
Mission lifetime	3 years	Propellent for 6 years
Orbit	GEO	
Total FoV	204 deg^2	Unprecedented FoV
Operation waveband	230-290 nm	Near-UV band
Cadence	300 s	For the high cadence survey
Mean effective PSF	8.3"	In central 170 deg^2 For T = 20,000 K blackbody source
Mean limiting magnitude (in 900s, 5σ)	22.4 ABmag	In central 170 deg^2 For T = 20,000 K blackbody source

Shvartzvald et al. 2023

The celestial volume monitored by ULTRASAT will be over 300 times that of GALEX.

Zwicky Transient Facility

Palomar Observatory in Southern California, USA

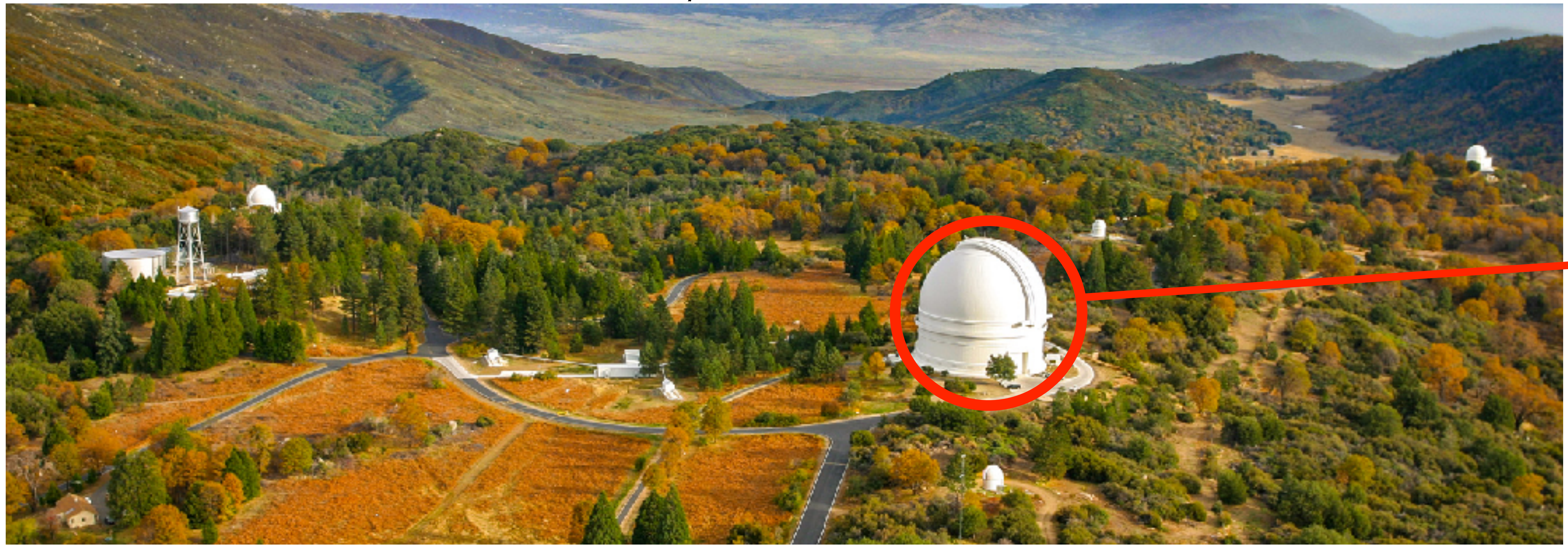
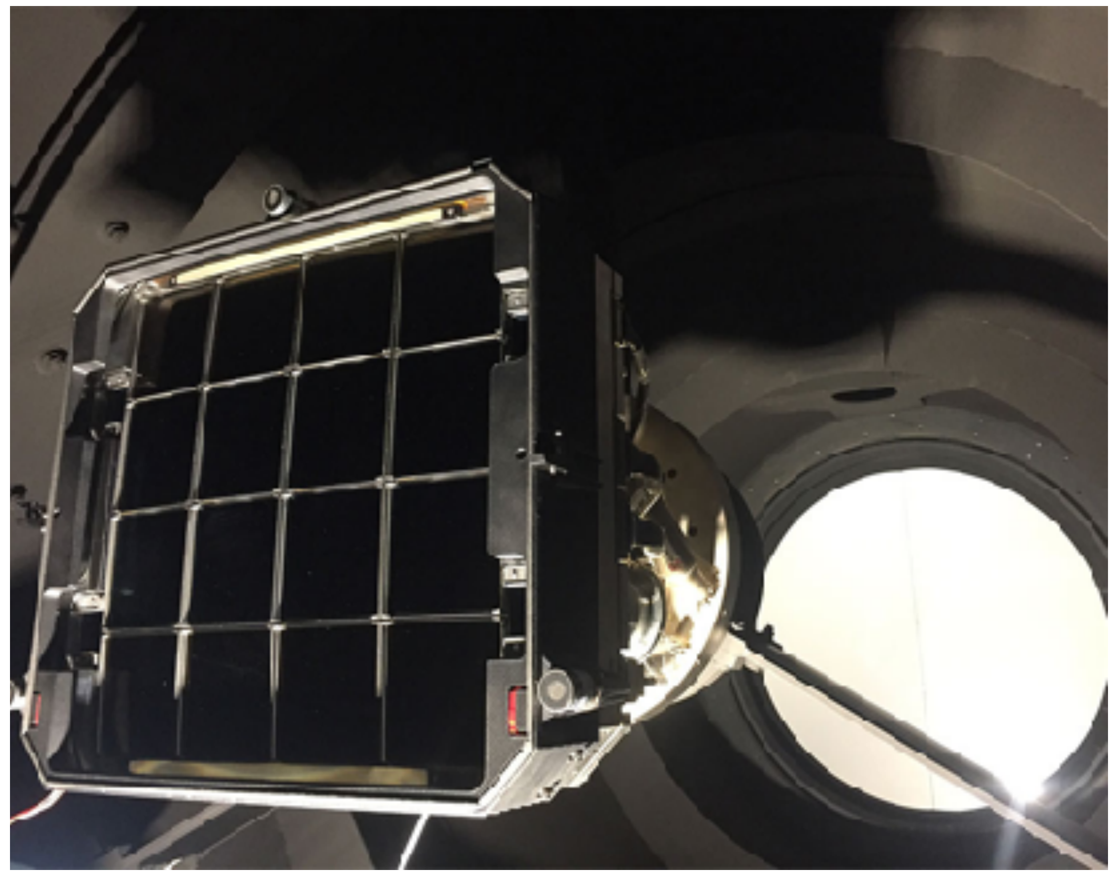
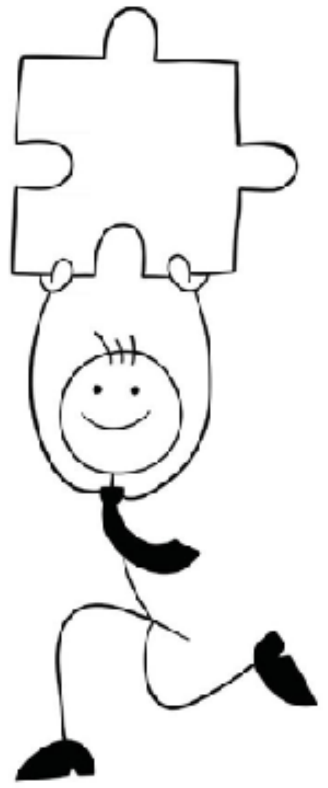


Image credit: Palomar Observatory/Caltech



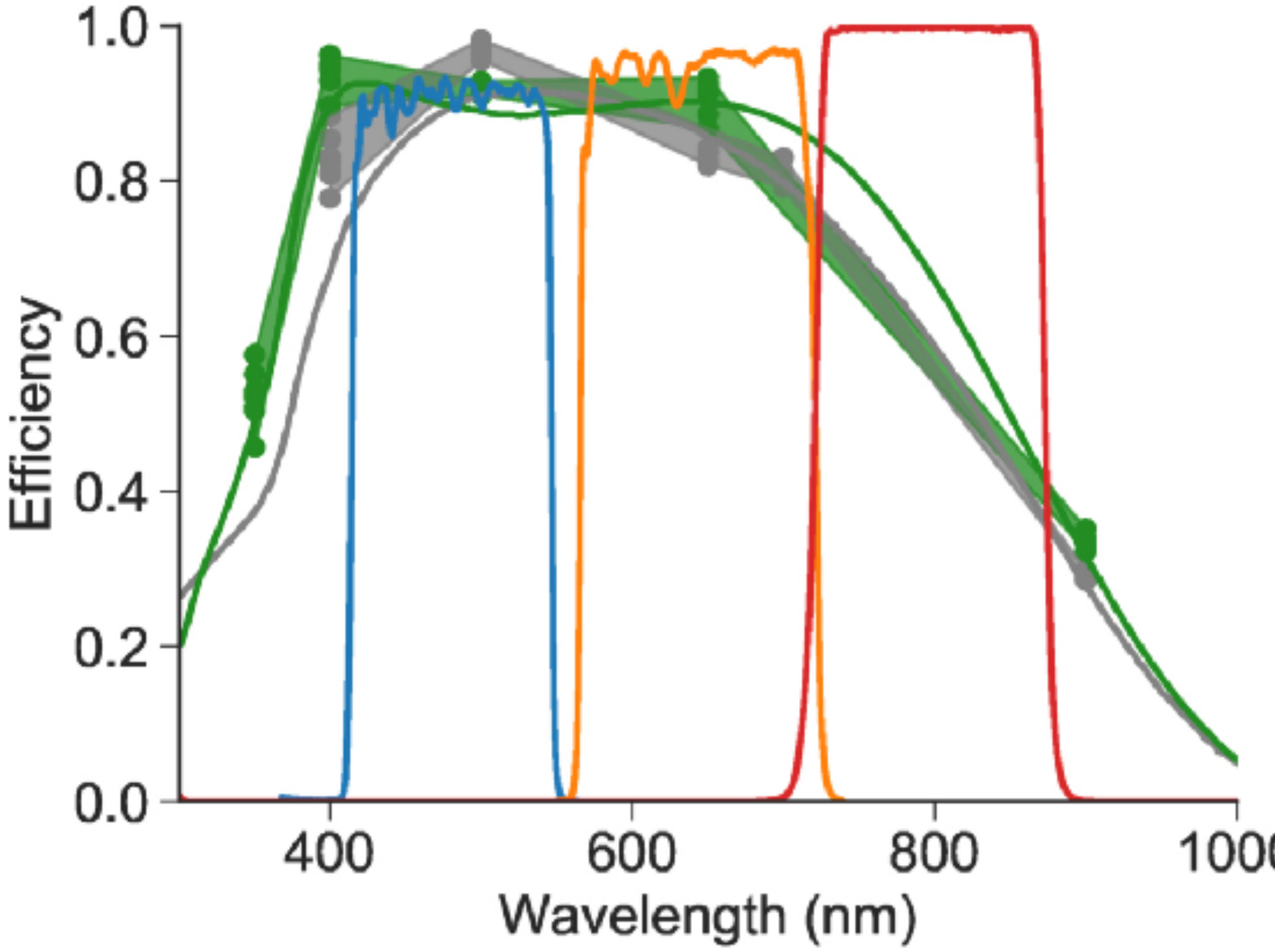


ZTF has been surveying the **Northern sky since June 2018** every 2-3 nights in *g*-band (370-560) nm and *r*-band (550-740) nm filters, while the *i*-band filter at (690-895) nm is used for partnership observations

Bellm et al. 2019

Specifications of the ZTF Observing System

Telescope and Camera	
Telescope	Palomar 48 inch (1.2 m) Samuel Oschin Schmidt
Location	33° 21′ 26.″35 N, 116° 51′ 32.″04 W, 1700 m
Camera field dimensions	7.°50 N-S × 7.°32 E-W
Camera field of view	55.0 deg^2
Light-sensitive area	47.7 deg^2
Fill factor	86.7%
Filters	ZTF-*g*, ZTF-*r*, ZTF-*i*
Filter exchange time	~110 s, including slew to stow
Image quality	$g = 2.''1$, $r = 2.''0$, $i = 2.''1$ FWHM
Median Sensitivity (30 s, 5σ)	$m_g = 20.8$, $m_r = 20.6$, $m_i = 19.9$ $m_g = 21.1$, $m_r = 20.9$, $m_i = 20.2$ (new moon)



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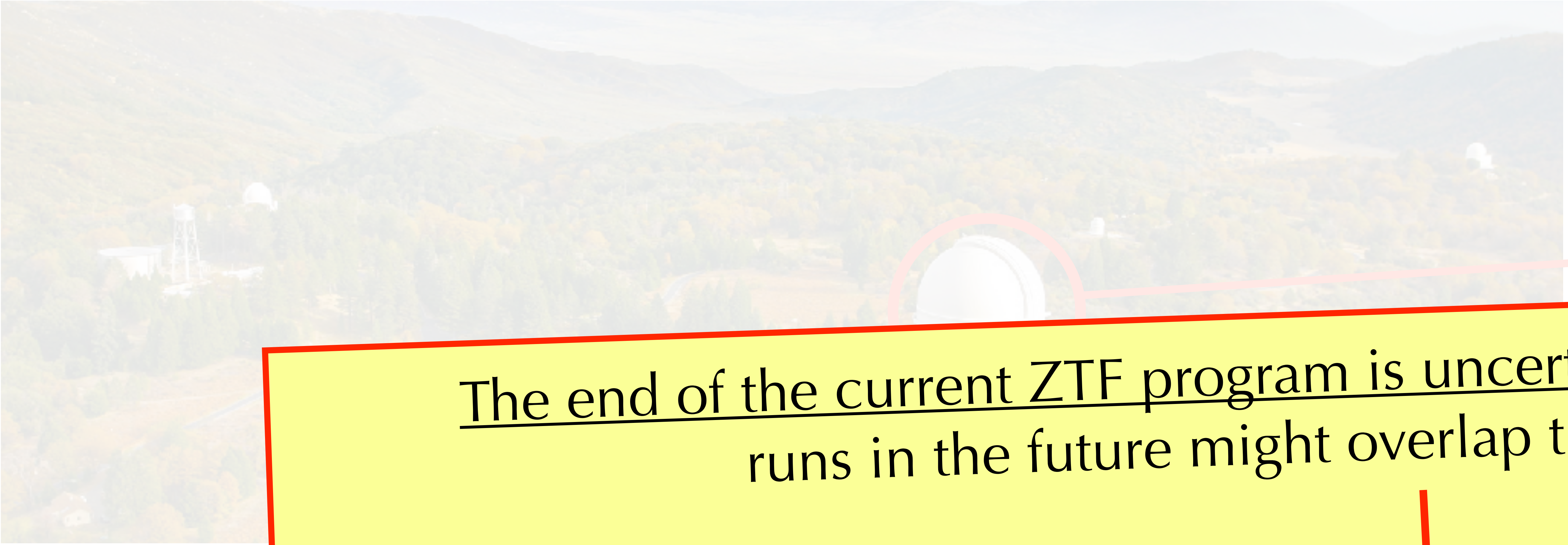
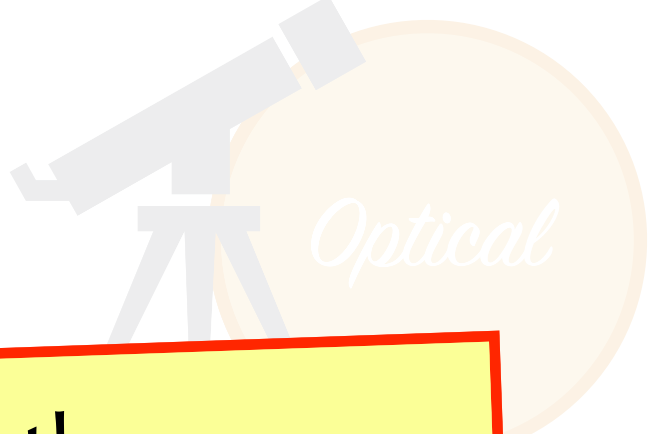


Image credit: Palomar Obser



The end of the current ZTF program is uncertain; still unknown whether other runs in the future might overlap the ULTRASAT activity

↓

All the results will be discussed are to be interpreted in terms of ZTF-like instruments
—> guidance to the scientific community for future multi-messenger studies

The **Z**wicky **T**
been surveyin
June 2018 eve
(370-560) nm and r-band (550-740) nm filters, while the *i*-band filter at (690-895) nm is used for partnership observations

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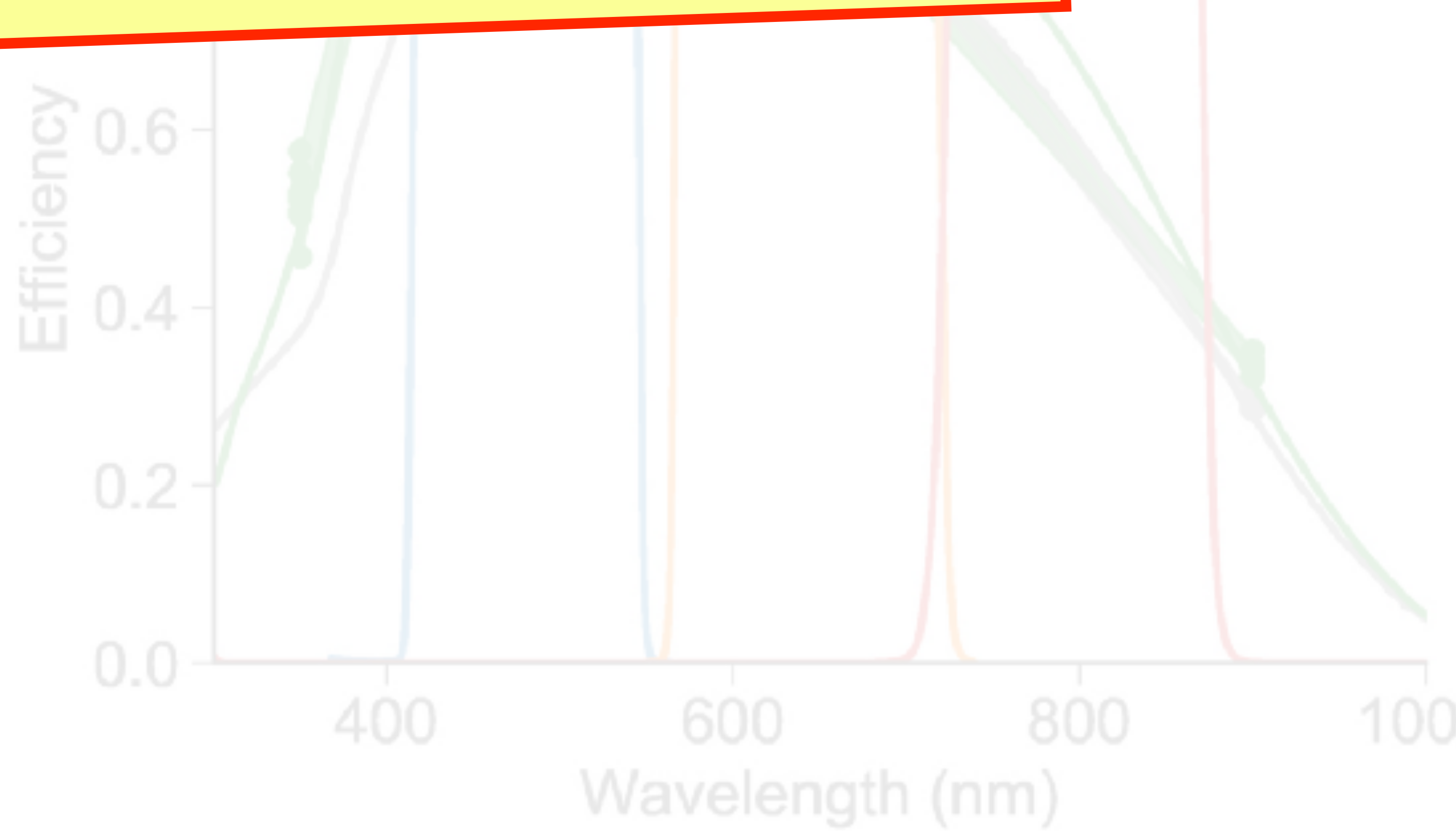
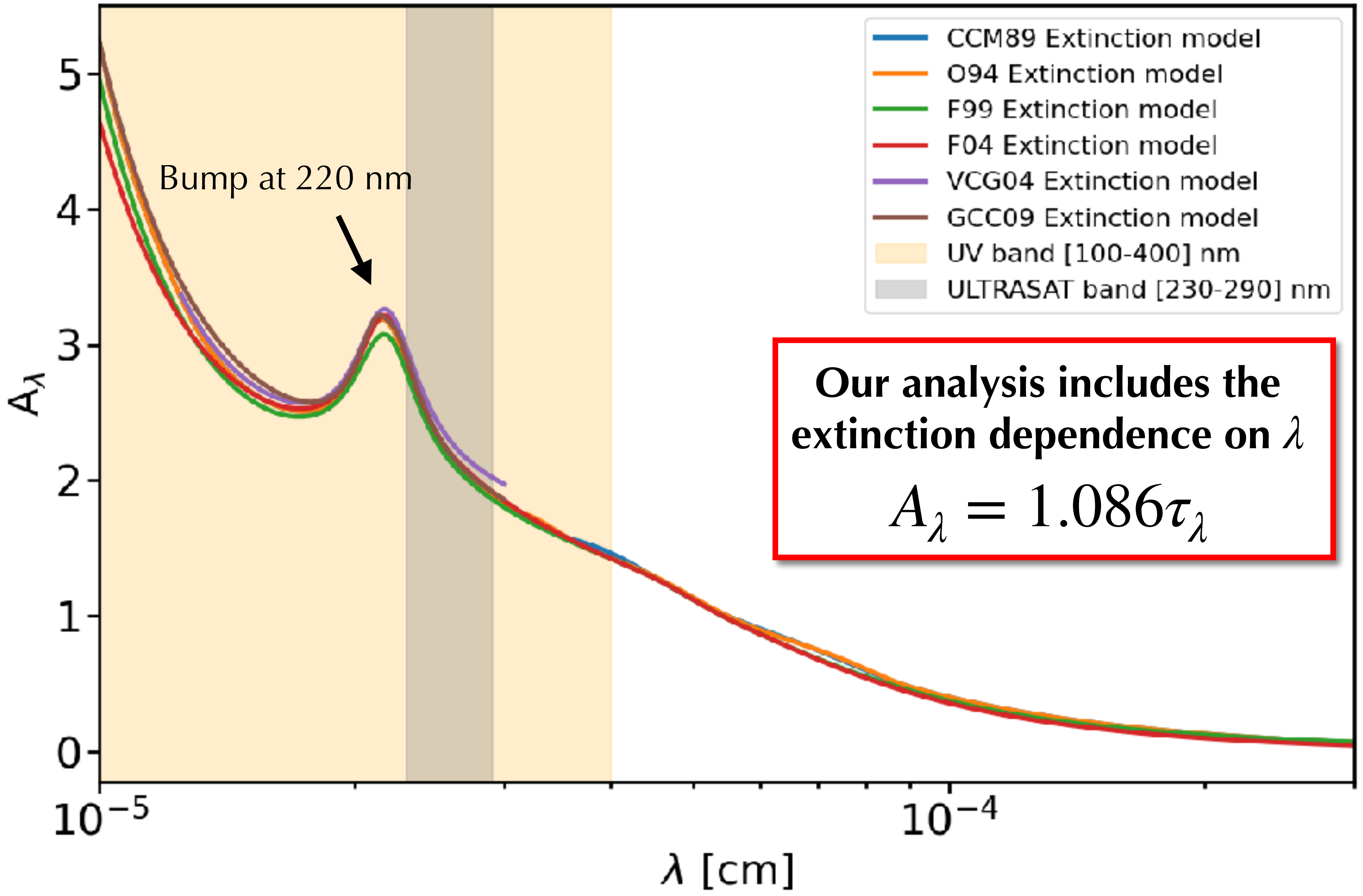


Early UV/optical emission from choked jets embedded in CCSNe

Model from Waxman et al., ApJ 667, 351 (2007), Rabinak & Waxman, ApJ 728, 63 (2011)

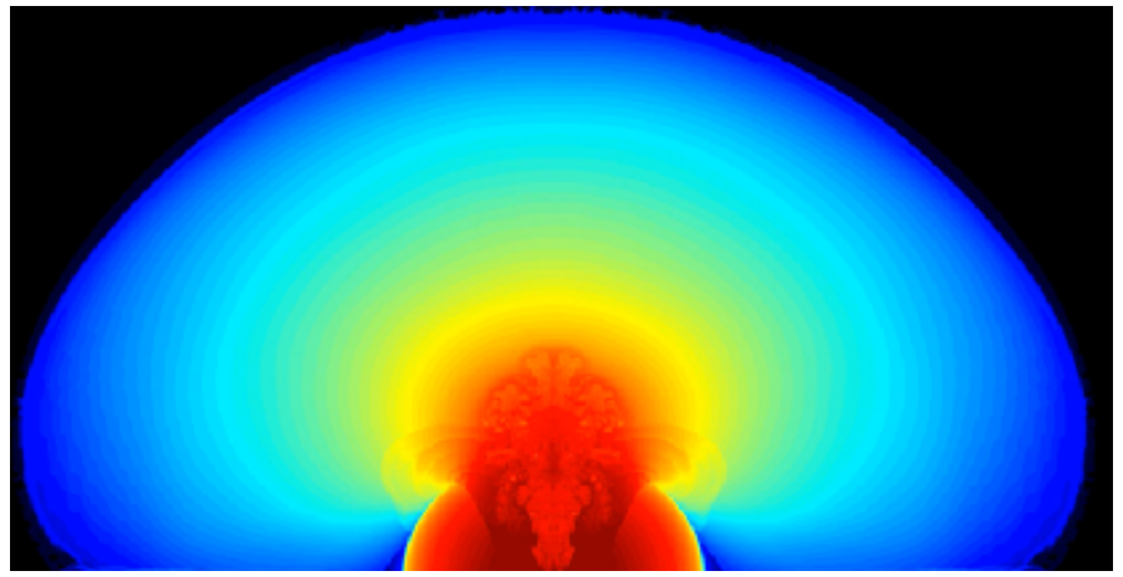
The extinction is very pronounced at UV wavelengths



Our analysis includes the extinction dependence on λ

$$A_\lambda = 1.086\tau_\lambda$$

Model specific intensity observed in UV/optical



Black-Body radiation modified by extinction

$$f_\lambda(\lambda, t) = \left(\frac{r_{\rm ph}}{D_L(z)}\right)^2 \sigma T_{\rm ph}^4 \frac{T_{\rm col}}{hc} g_{BB}(x) e^{-\tau_\lambda}$$

$$g_{BB}(x) = \frac{15}{\pi^4}\frac{x^5}{e^x - 1}$$

$$x = hc/\lambda T_{\rm col}$$

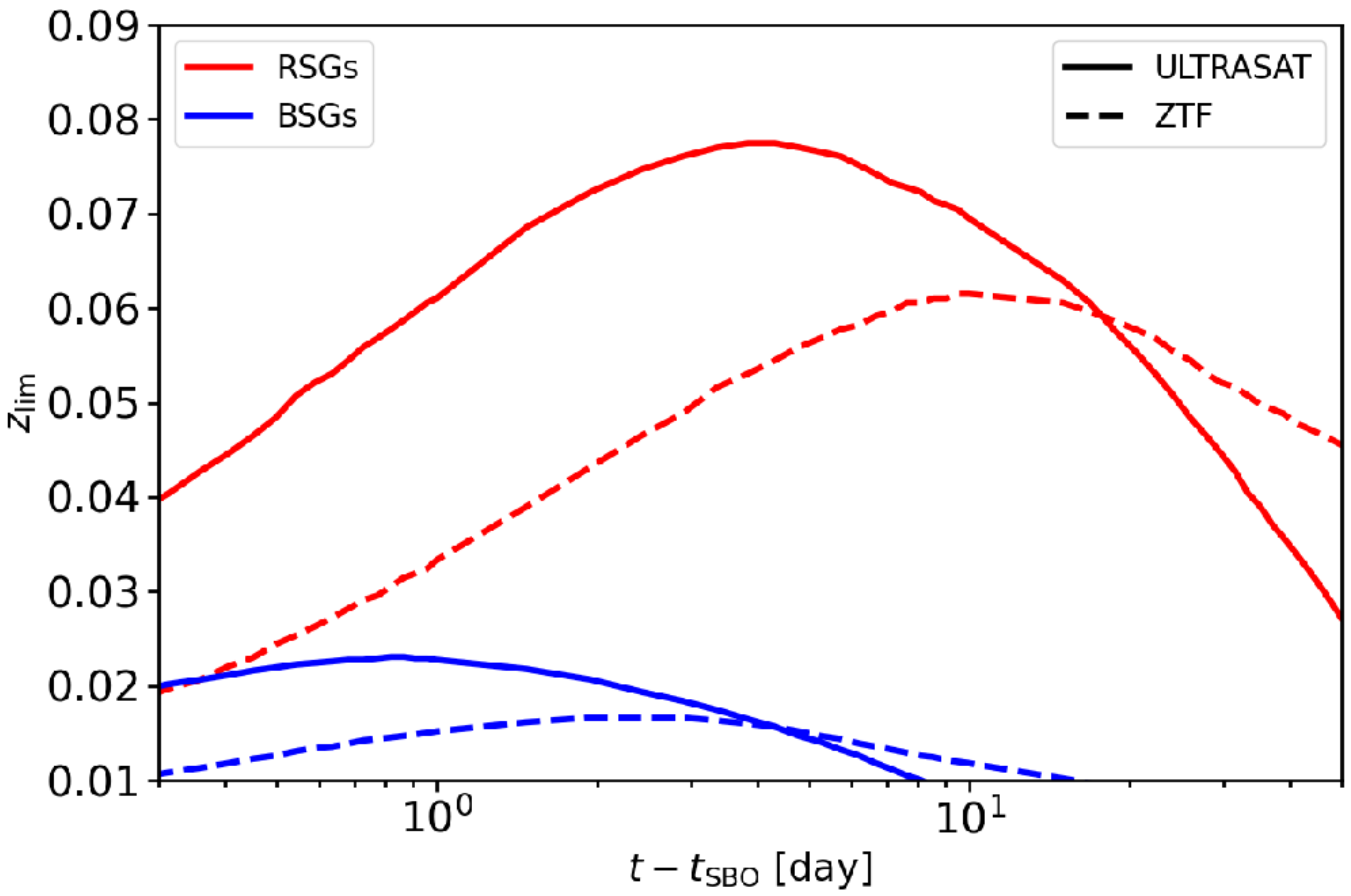
$T_{\rm col} \simeq 1.2\ T_{\rm ph}$ = color temperature, i.e., temperature at which a black body would emit radiation of the same color of a given source

τ_λ = extinction optical depth at a given wavelength λ

Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

Maximum detectable redshift as a function of time after SBO

By investigating the evolution of the cooling UV/optical signal after SBO for different redshift values, the following is obtained



Results for peak of visibility in the emission

	$z_{\rm lim}$	D_L [Mpc]	$t - t_{\rm SBO}$ [days]
ULTRASAT	0.08	360	4
ZTF	0.06	270	10

	$z_{\rm lim}$	D_L [Mpc]	$t - t_{\rm SBO}$ [days]
ULTRASAT	0.023	100	1
ZTF	0.017	75	4

Previous and later emissions can still exceed the sensitivity of the detectors only for closer SNe

Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

Computation of rate of events

$$\forall\ t \rightarrow \dot{N} = \int d\Omega \int_0^{z_{\rm lim}} \frac{dN(z)}{dz} dz = \int d\Omega \int_0^{z_{\rm lim}} \frac{R(z)}{1+z} \frac{dV(z)}{dz} dz$$

Telescope FoV

This factor accounts for the cosmological time dilation of the observed rate

Differential comoving volume

$$R(z) = R_0 \frac{(1+z)^{2.7}}{1 + \left(\frac{1+z}{2.9}\right)^{5.6}}$$

Comoving rate of sources

The redshift dependence follows the star formation rate

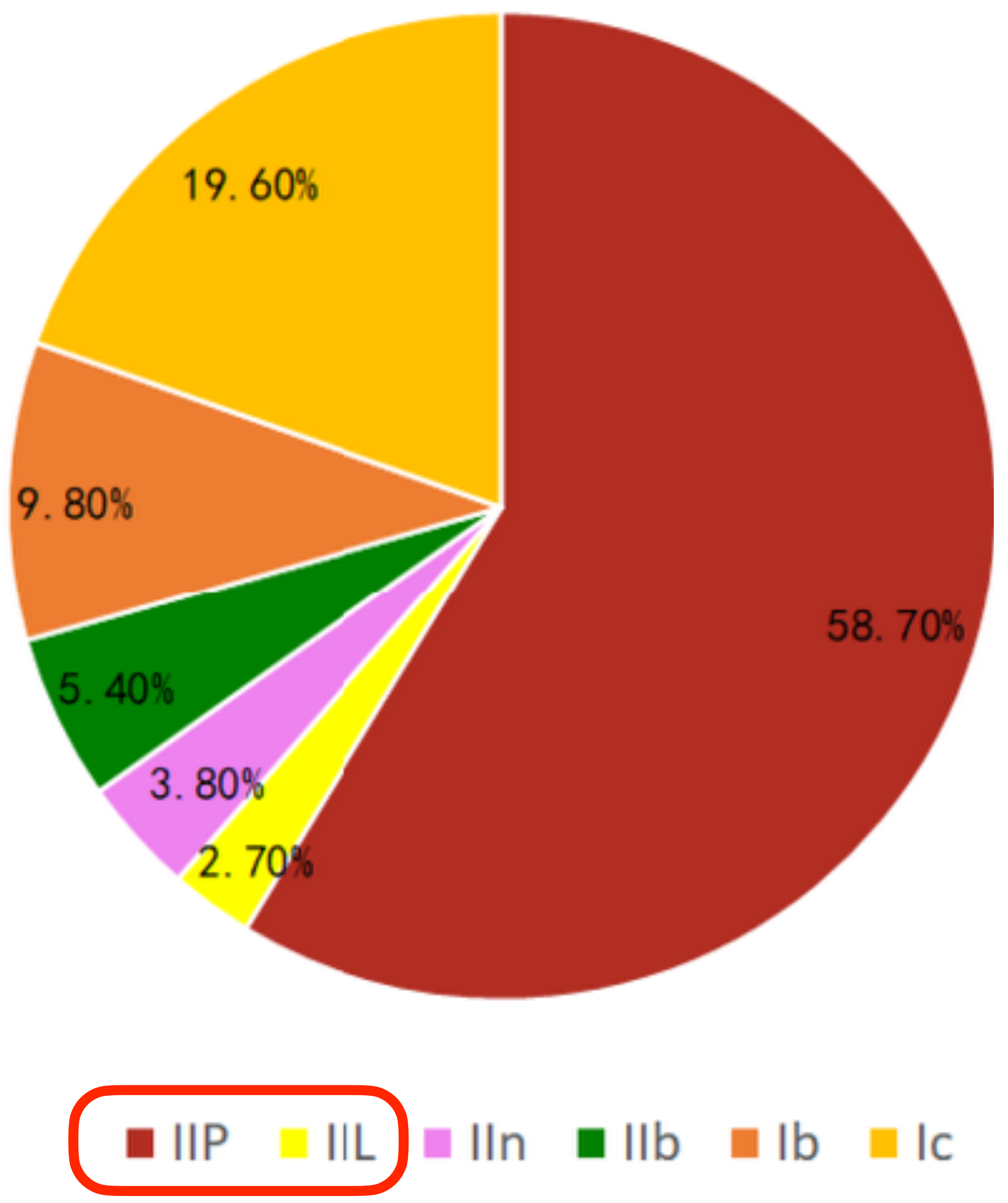
Madau & Dikinson 2014

- Local rate R_0 of Type II SNe with no interaction with CSM taken as 60% of the total rate of Type II SNe $\rightarrow R_0 = 1.1 \times 10^{-5}\ \mathrm{Mpc^{-3}\ yr^{-1}}$ Li et al. 2011, Lin et al. 2023

- On average, ratio between BSG and RSG stars in our Galaxy $\simeq 3$ Eggenberger et al. 2002

RSG $R_0 = 1.1 \times 10^{-5}\ \mathrm{Mpc^{-3}\ yr^{-1}}$

BSG $R_0 = 2.5 \times 10^{-5}\ \mathrm{Mpc^{-3}\ yr^{-1}}$



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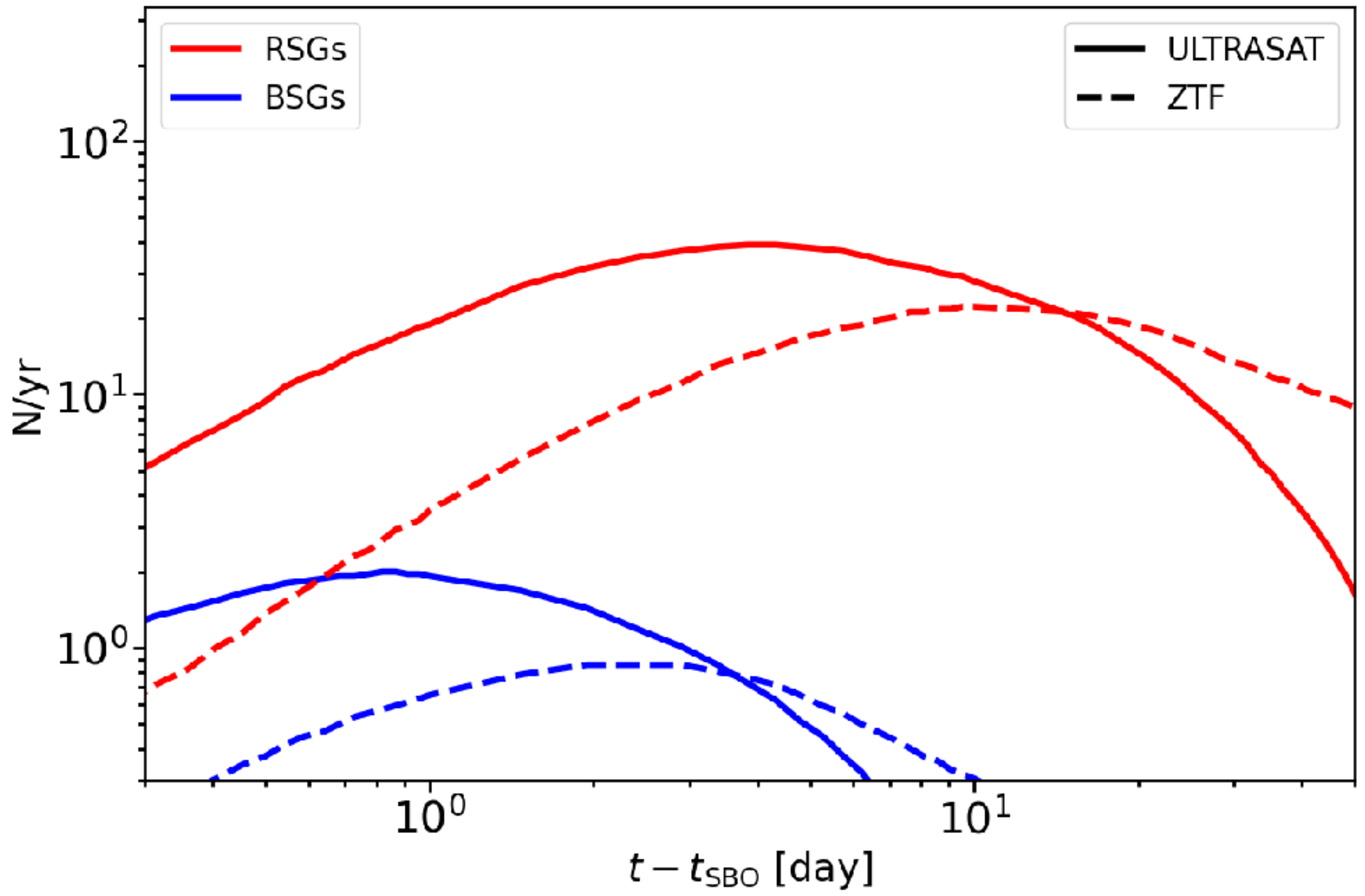
Computation of rate of events

Observation times in 1 hour:

ULTRASAT → 4×900 s, each covering $\mathrm{FoV} = 204$ sqdeg

ZTF → 3750 sqdeg + correction by instrument's duty cycle (e.g., it can operate only nightly and in good weather conditions)



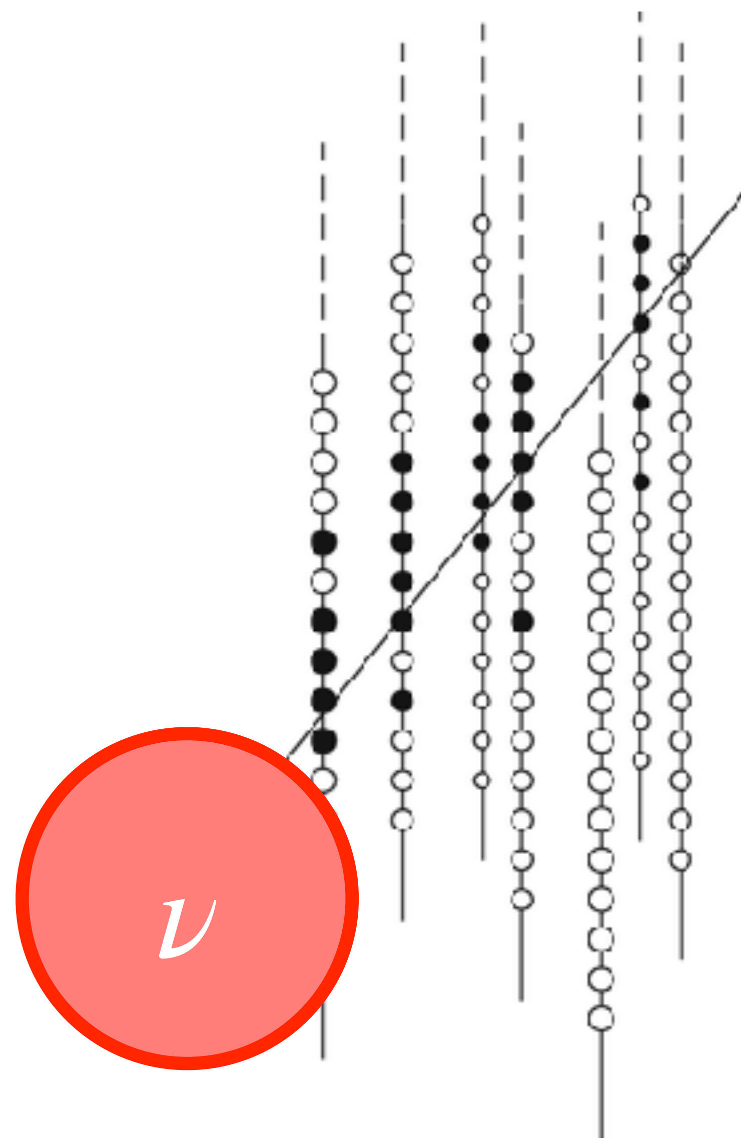
- Around **60% of Type II SNe from RSGs** can be accompanied also by an **optical detection** by ZTF, if it catches optical emission within around 10 days after the SBO (namely, **1 week after the UV detection**)
- **One source out of the three** detectable by **ULTRASAT** in one year for **Type II SNe from BSGs** may be associated with **optical measurements with ZTF**

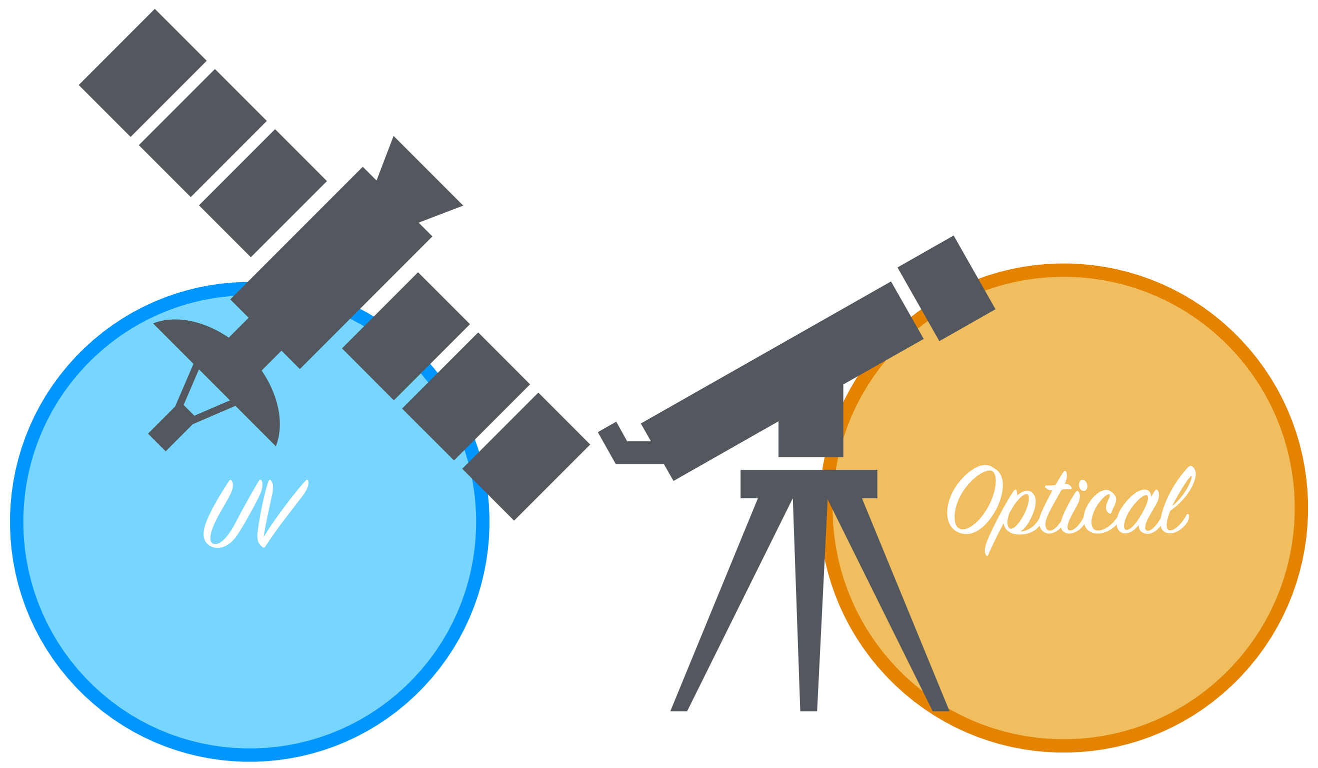
Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

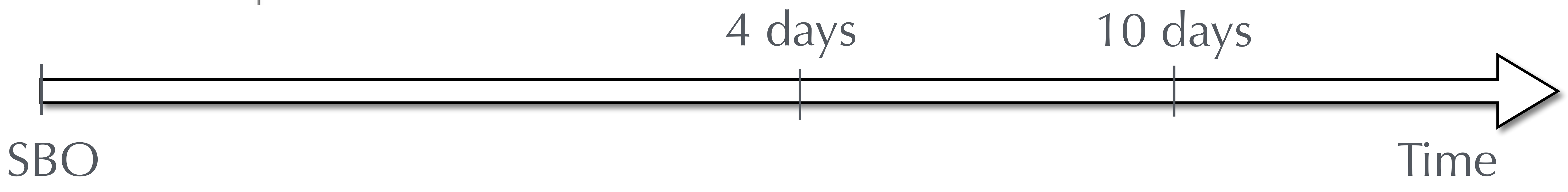
High-energy ν - UV - optical follow-ups

1. **Neutrino alert** from Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT)

2. ULTRASAT(ZTF-like telescopes) could point at the suggested direction in the sky within **~4(10) days** to search for possible EM counterparts **maximising the reachable sky volume and hence the number of detectable sources**



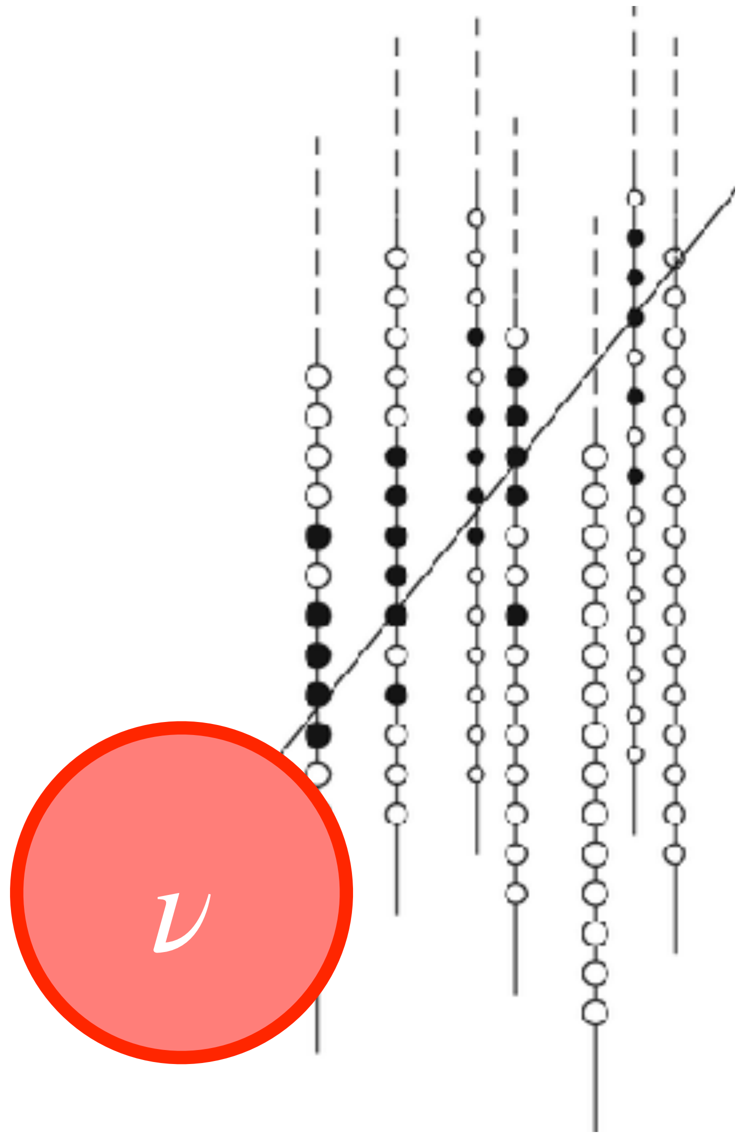




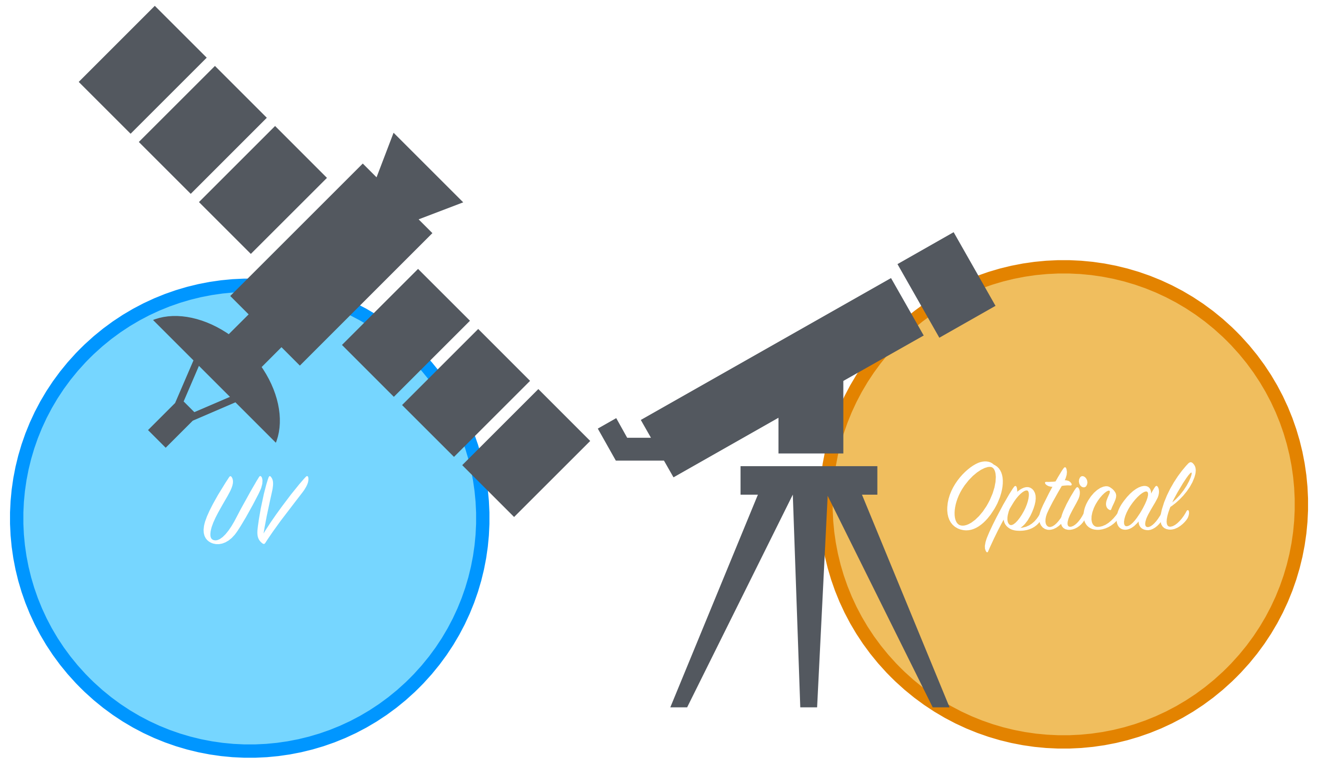
Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

High-energy ν - UV - optical follow-ups

1. **Neutrino alert** from Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT)



2. ULTRASAT(ZTF-like telescopes) could point at the suggested direction in the sky within **~5(11) days** to search for possible EM counterparts **maximising the reachable sky volume and hence the number of detectable sources**



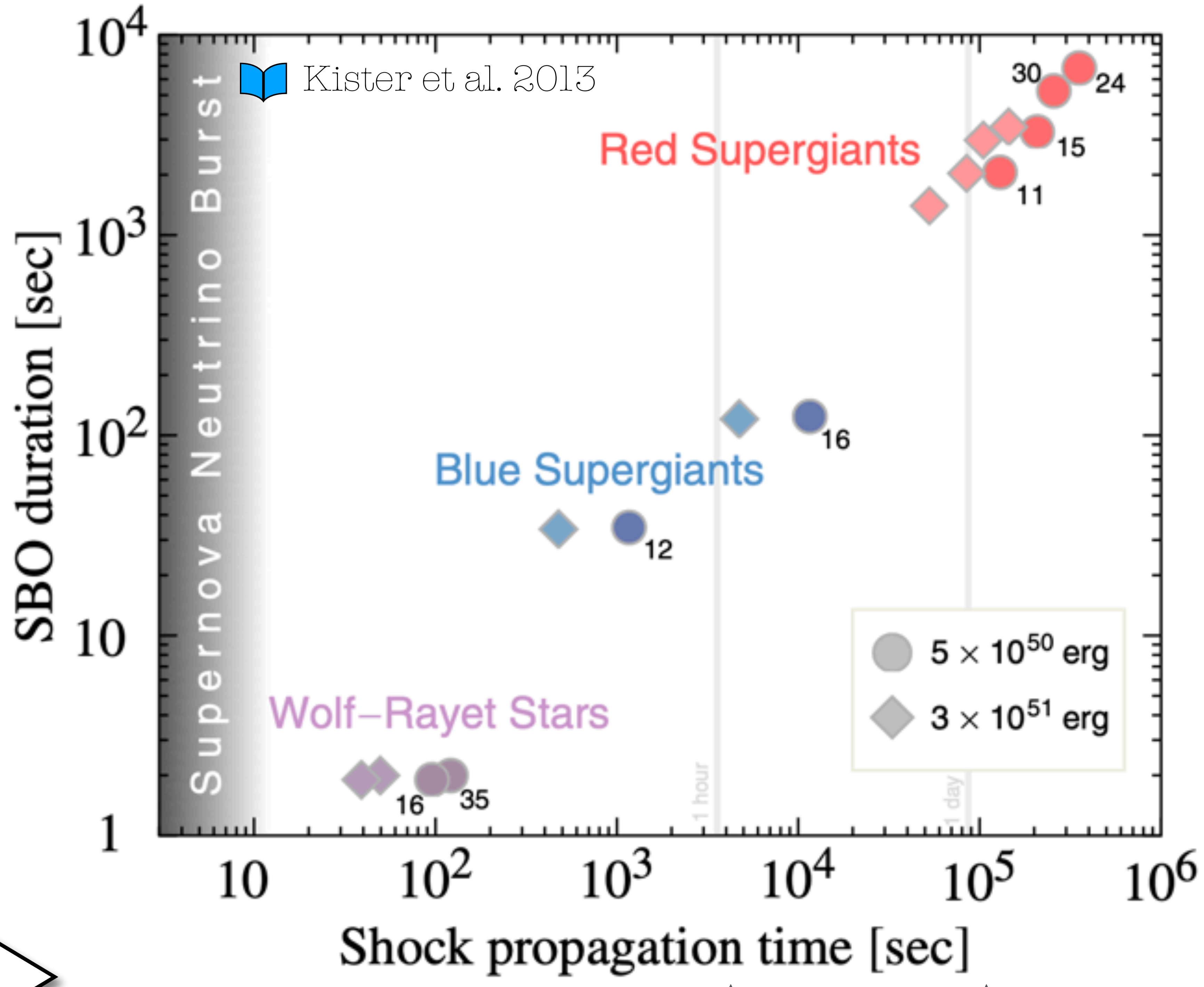
5 days

11 days

Time

Shock propagation inside the stellar envelope

To consider the **production of neutrinos during the shock propagation inside the stellar envelope**, we need to **enlarge these time windows up to ~1 day**



1 hour 1 day

Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

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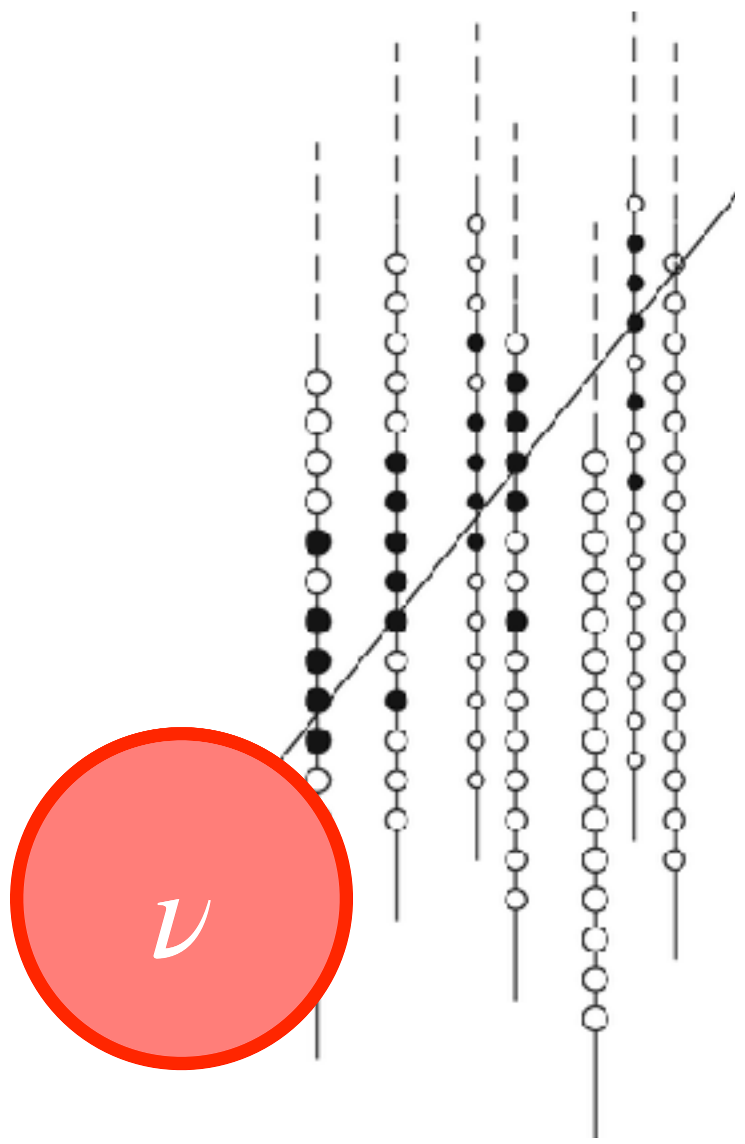

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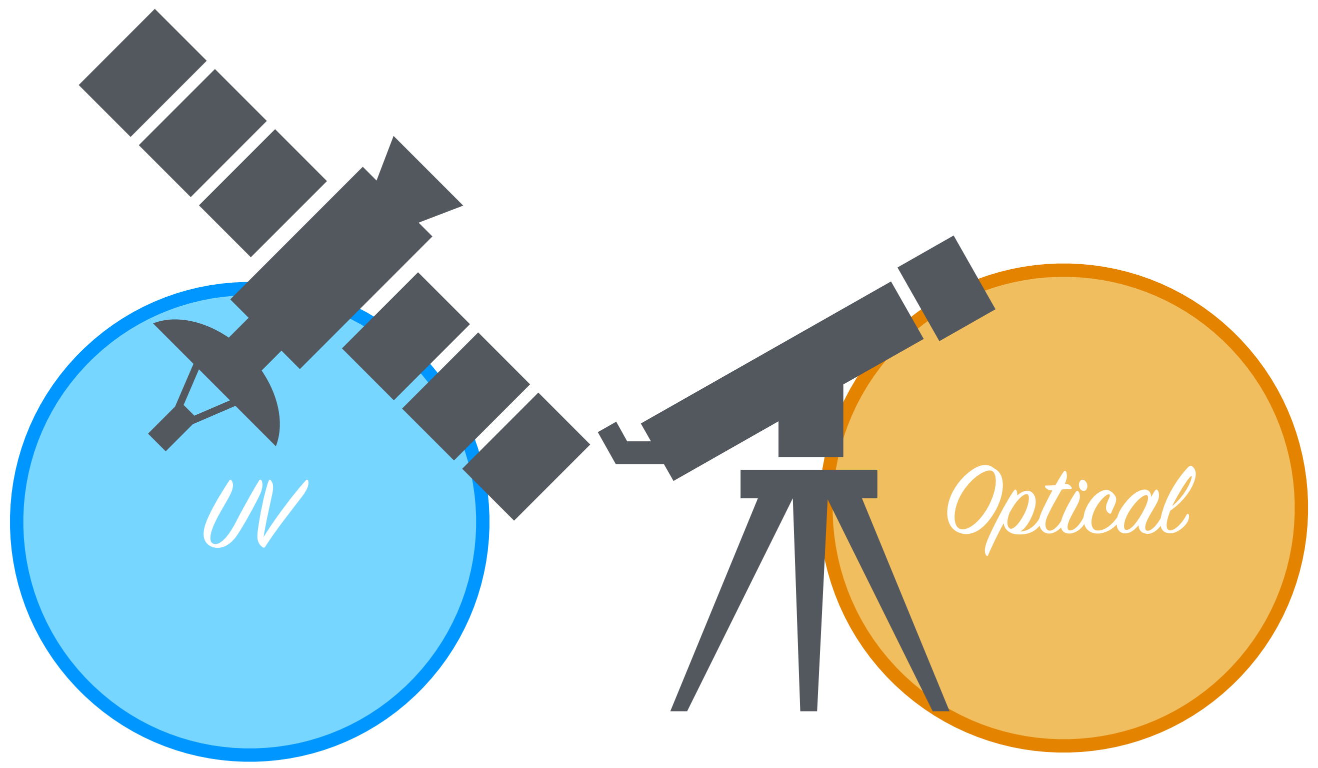
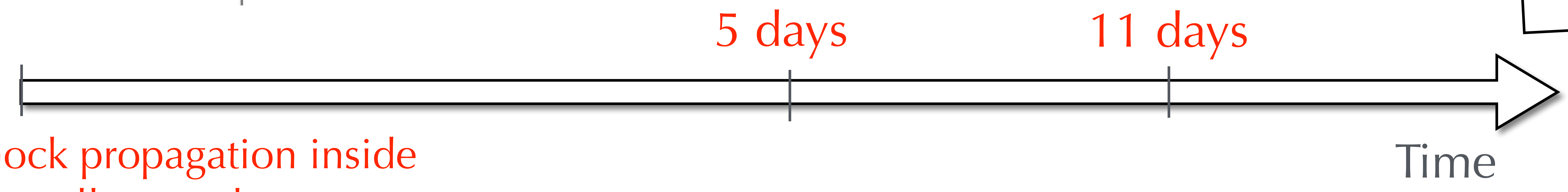




Shock propagation inside the stellar envelope

With our results, we would like to stress the **importance of defining a proper strategy, focused on Type II SNe**

We encourage UV, optical, and neutrino telescopes to optimize both their alert sending and external follow-up programs based on our results

IceCube Collaboration 2023

Type IIP SNe (associated to RSGs) might contribute to the production of high-energy neutrinos **for ~60% of astrophysical diffuse flux between** 10^3 **and** 10^5 GeV

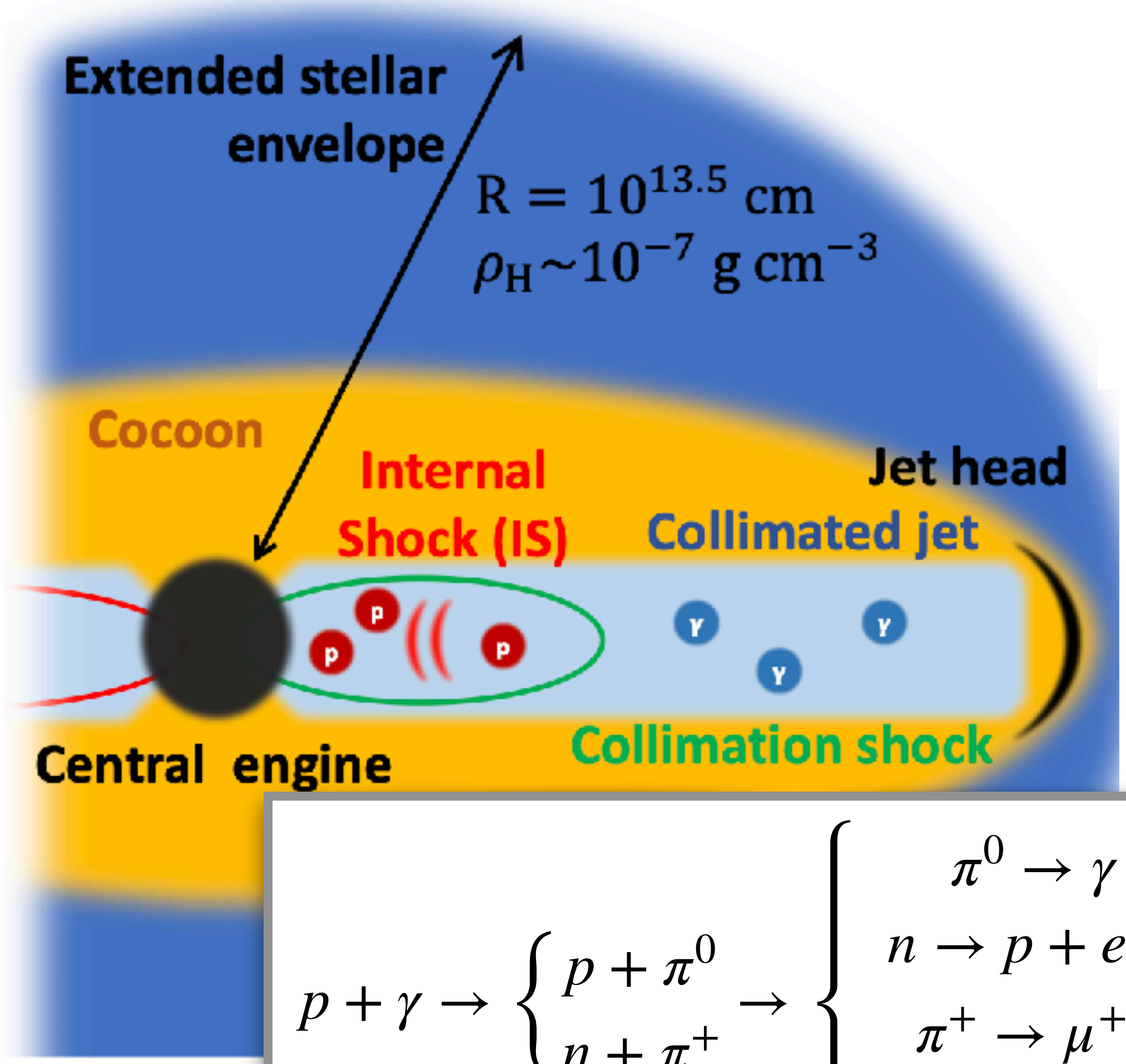
Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

How many choked jets producing neutrinos?

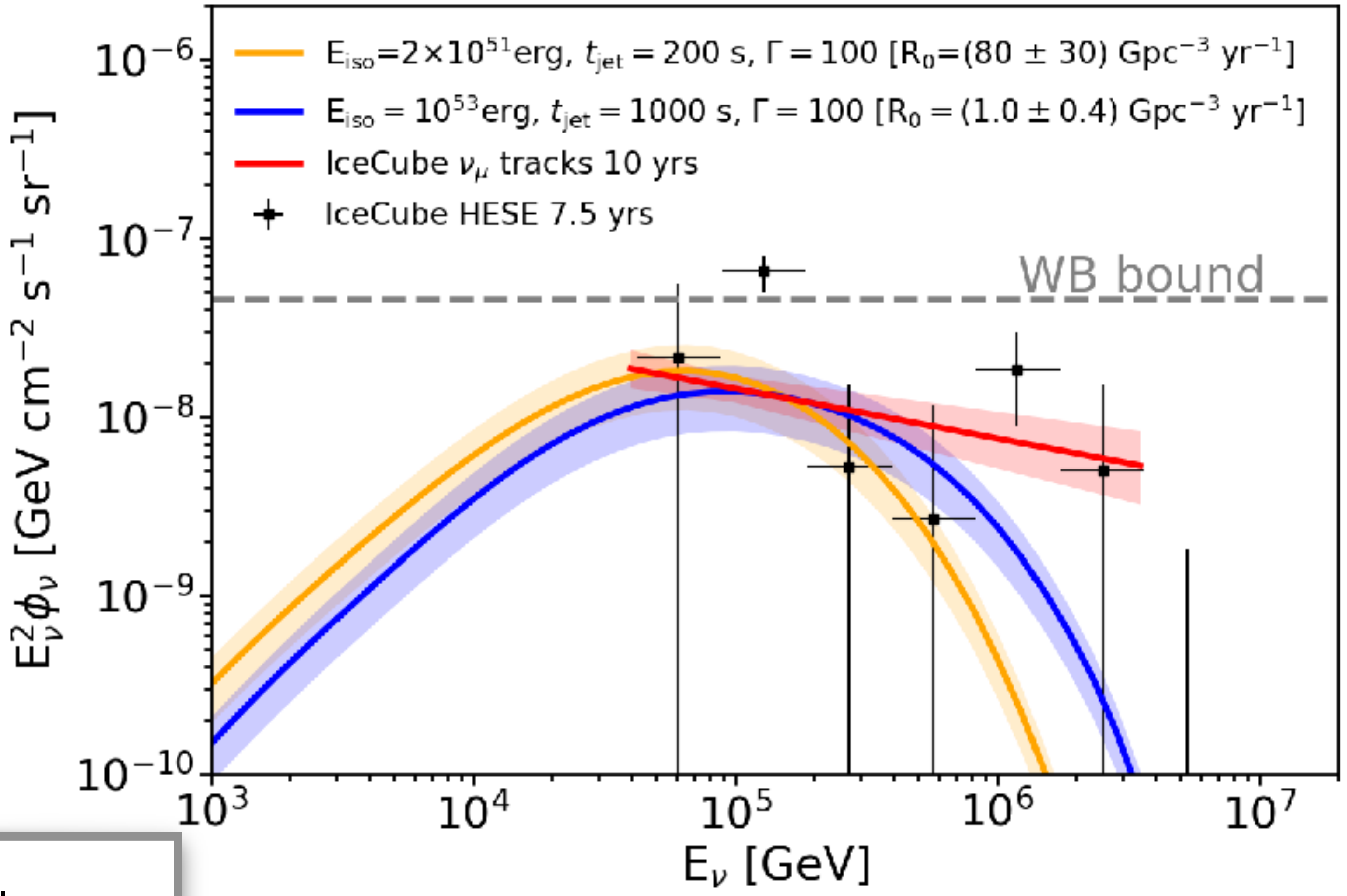
M. Fasano, S. Celli, D. Guetta, A. Capone, A. Zegarelli, I. Di Palma, JCAP09 (2021) 044

$p\gamma$ interactions simulated inside a choked GRB jet through a detailed Monte Carlo code

RSG progenitors



$$p + \gamma \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ n \rightarrow p + e^- + \bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$



Local rate of choked jets from RSGs as to reproduce observations IceCube observations

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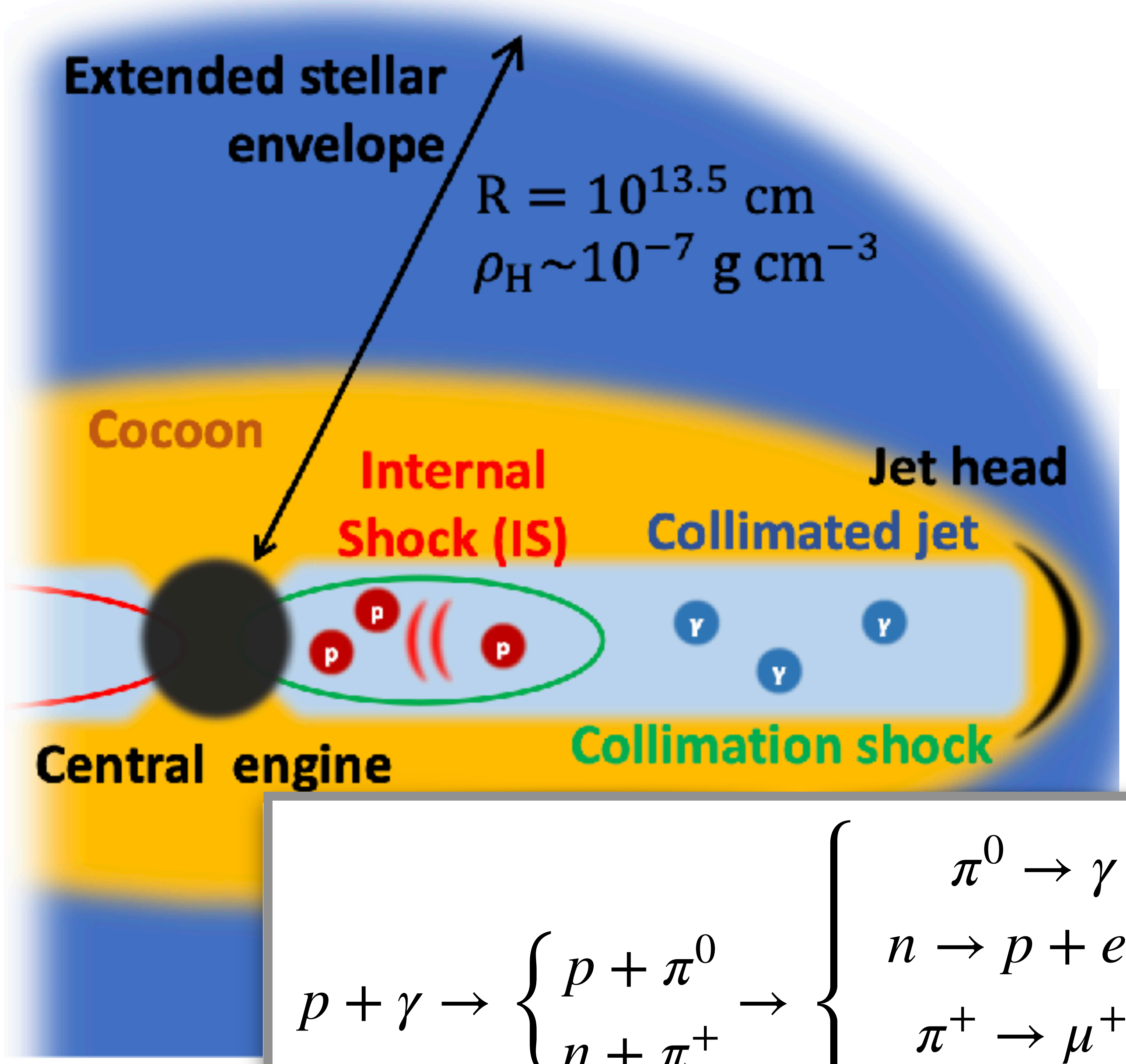

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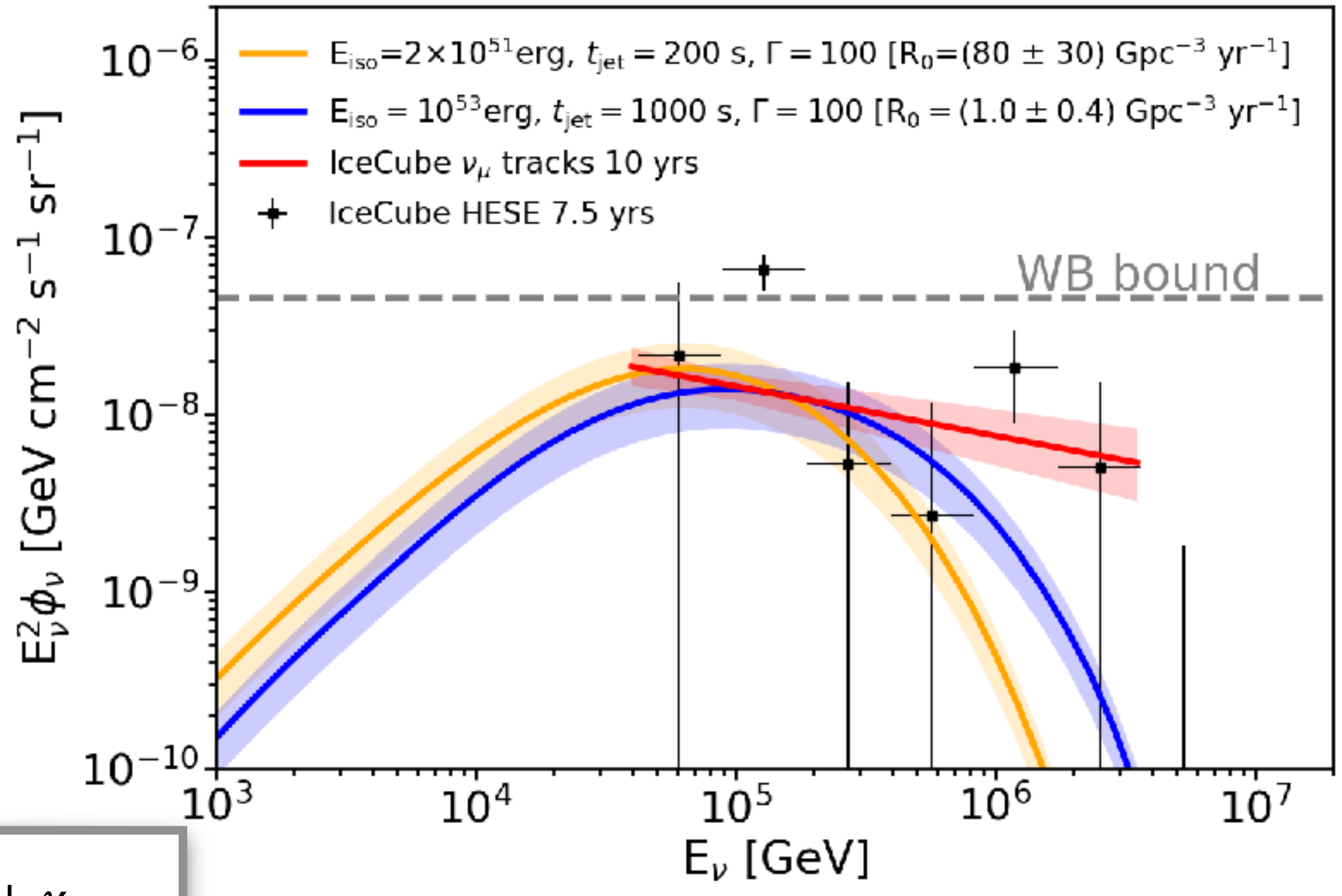


Local rate of choked jets from RSGs as to reproduce observations IceCube observations

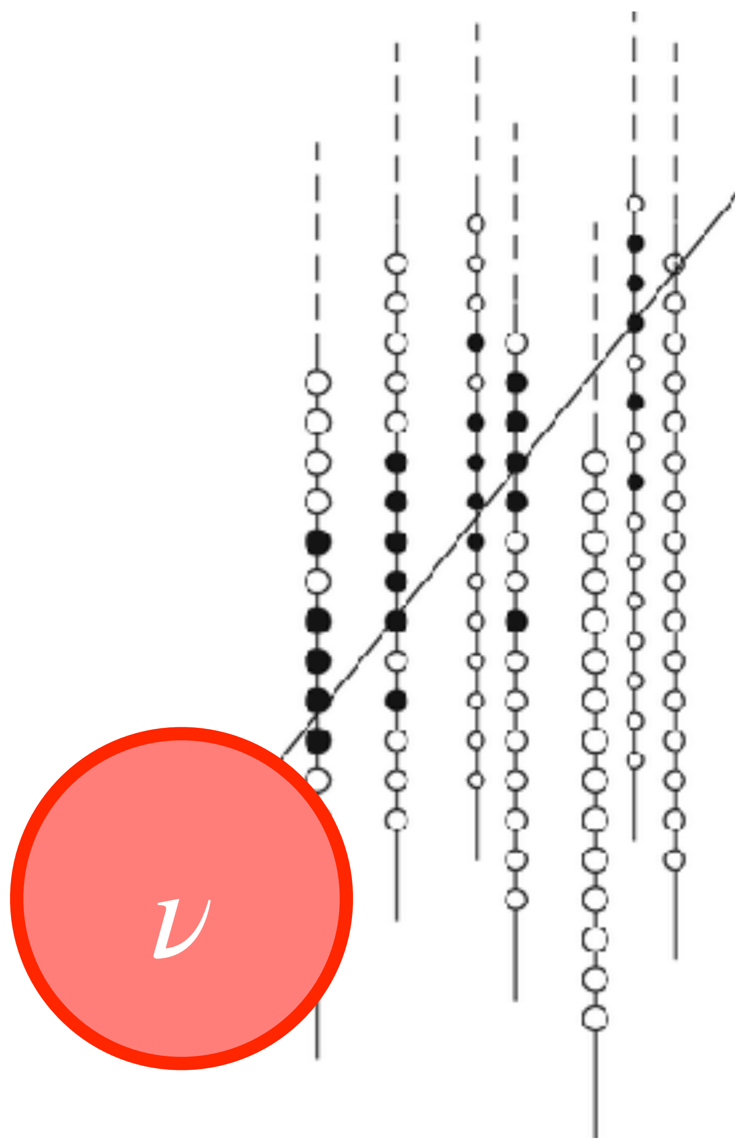
↓

Given the CCSN 60% limit by IceCube, this rate should be restricted to its 60%

Less than 1% of CCSNe from RSGs detectable in UV with ULTRASAT could host a choked jet and release TeV neutrinos

Multi-messenger prospects

1. **Neutrino alert** from Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT)



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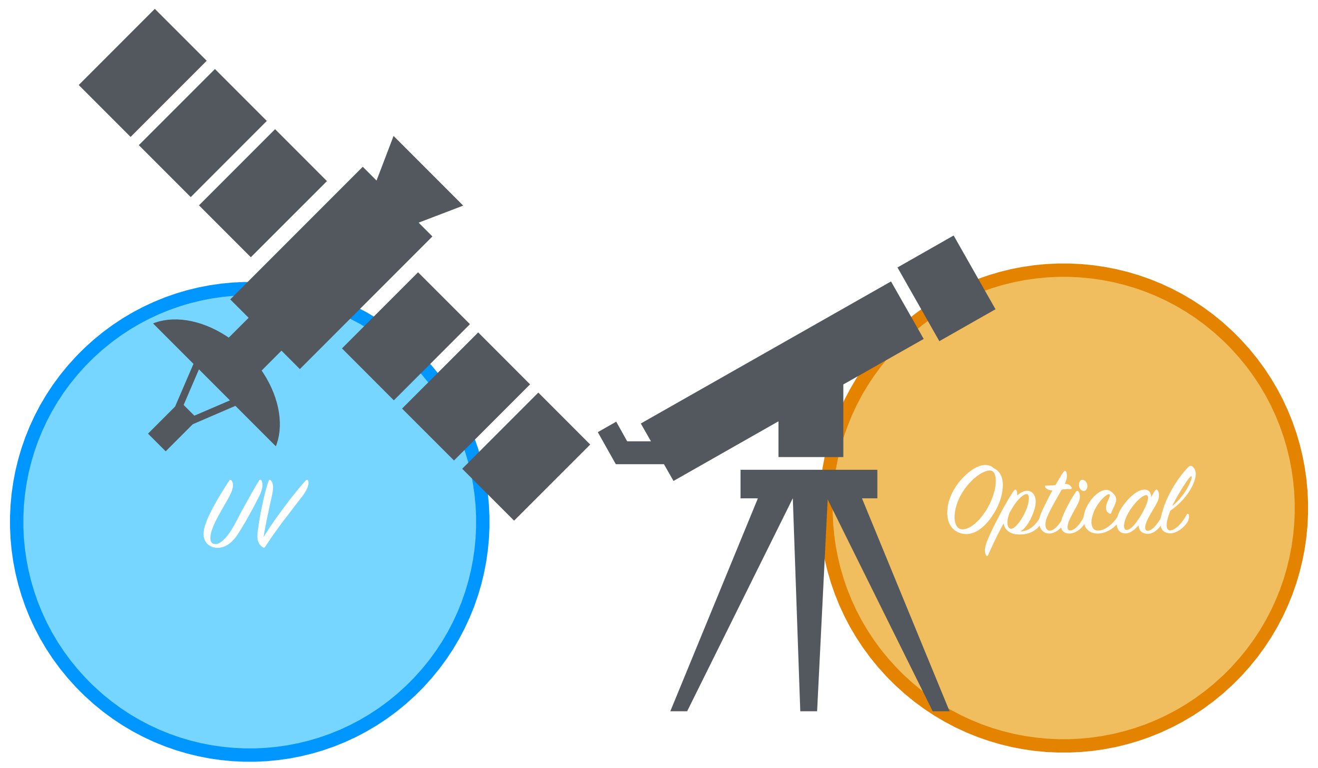

Need to run these multi-messenger analyses for several years

+

additional **photometric and spectroscopic follow-ups** with compelling **evidence for a relativistic jet launched by the central engine**

Piran et al. 2019
Nakar 2015
Pais et al. 2023

5 days

11 days

Shock propagation inside the stellar envelope

Time

Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

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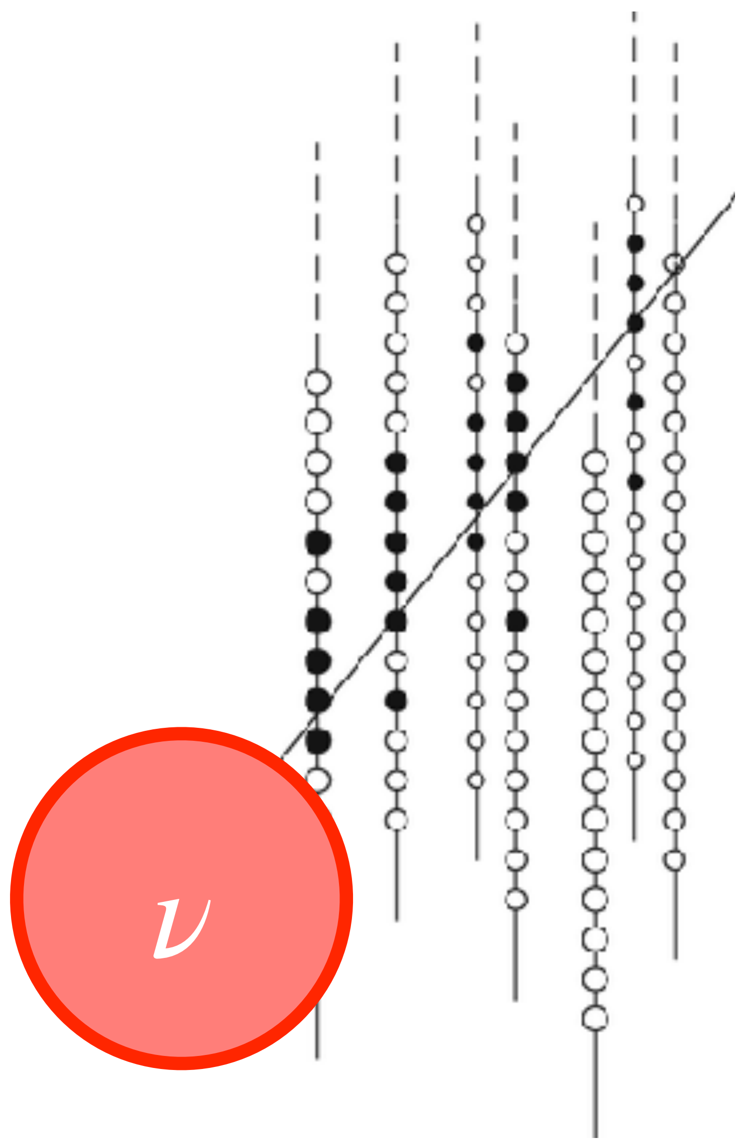

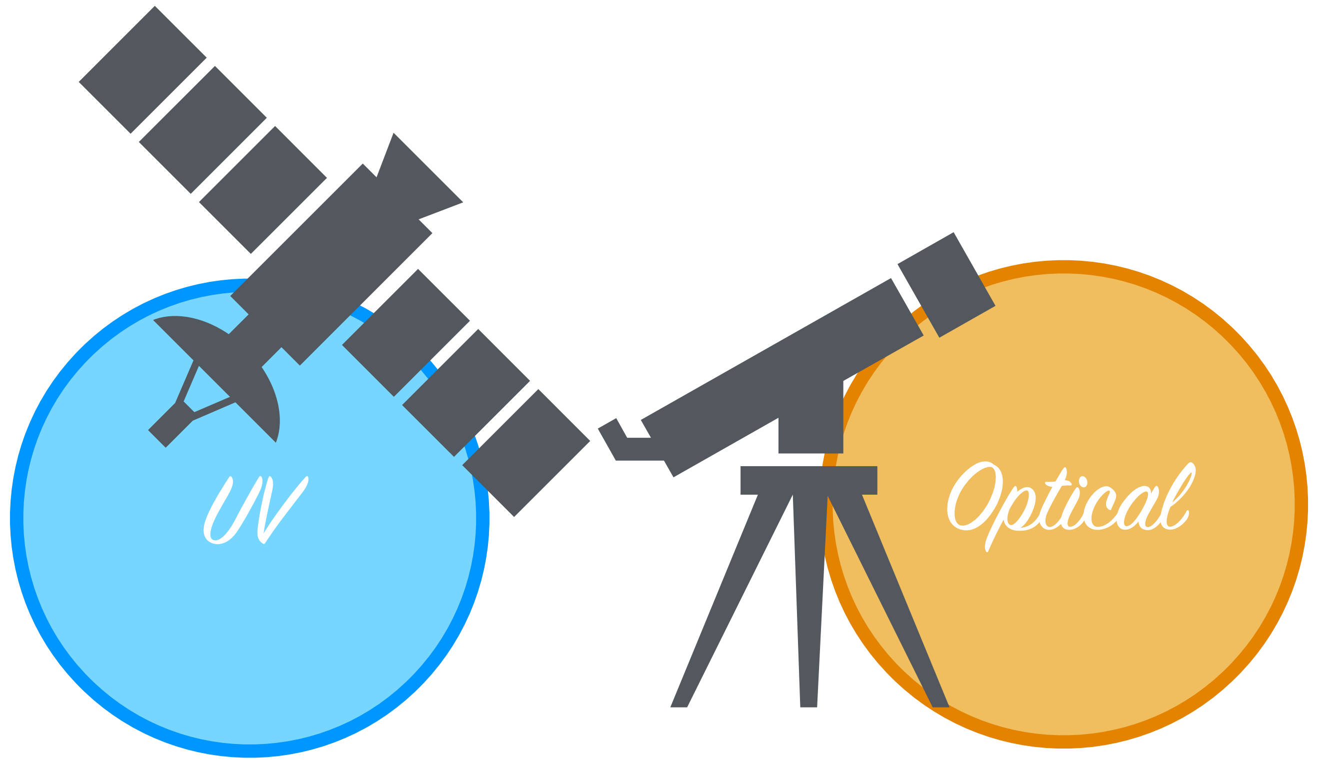

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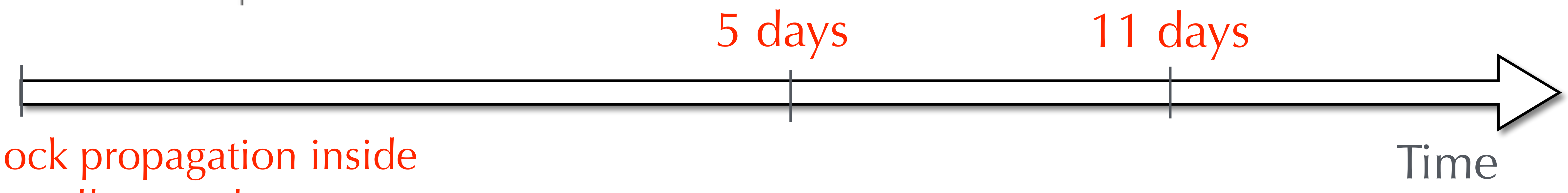


Shock propagation inside the stellar envelope

Zegarelli, Guetta et al., accepted to A&A, arXiv:2403.16234 [astro.ph.HE]

Conclusions (hidden sources)

- **Choked jets** (failed GRBs) as appealing sources in the multi-messenger astronomy field
  —> **possible contributors** to the **astrophysical diffuse neutrino flux**

- We **propose an optimised follow-up strategy** between **UV, ZTF-like,** and **neutrino telescopes**, considering **RSG** and **BSG as progenitors** of **CCSNe possibly harbouring choked jets**, taking into account the evolution of the cocoon emission with time and the extinction dependence with wavelength

- The **delay between neutrino** produced at the **SBO** occurrence **(during the jet propagation inside the stellar envelope)** and **ULTRASAT** (future UV satellite with unprecedented FoV) observations should be of **~4(5) days**, with a **subsequent follow-up** by **instruments like ZTF about one week after**

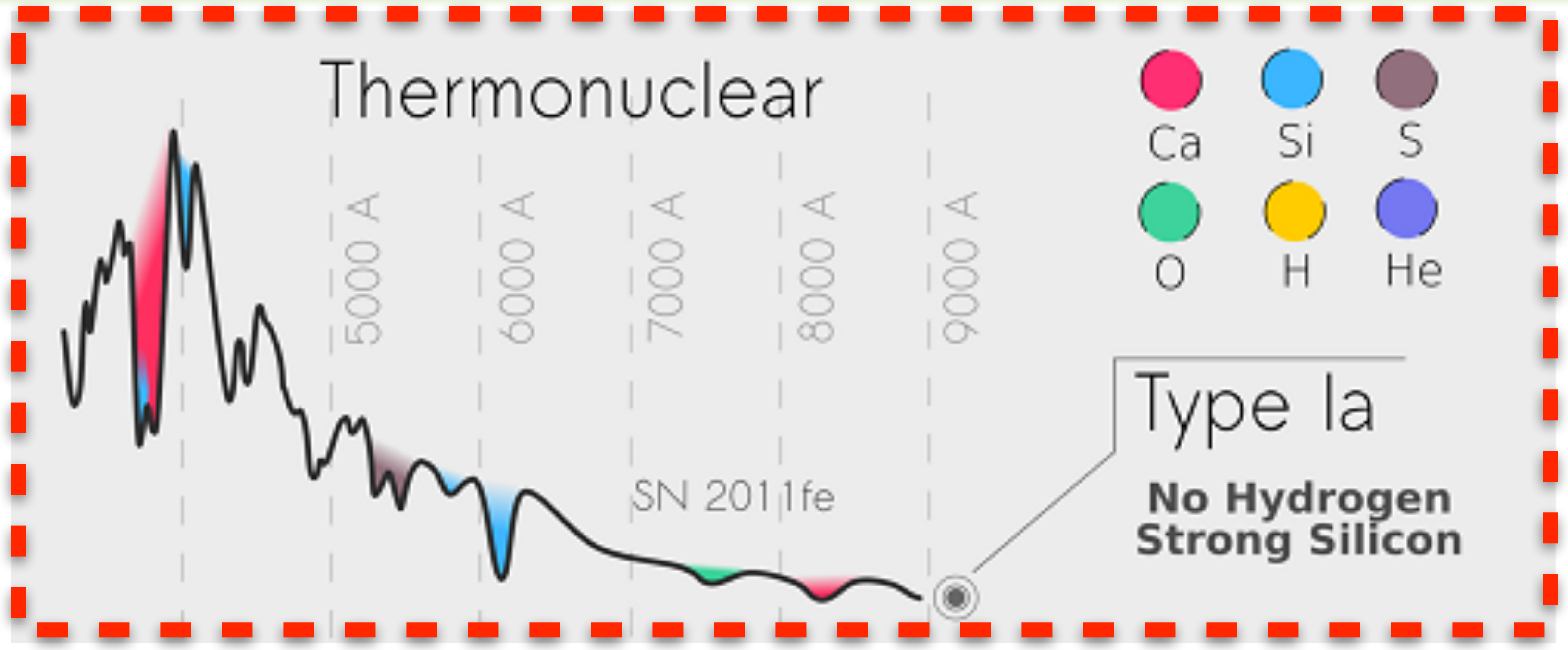
- **Less than 1% of CCSNe** from **RSGs detectable** in UV **with ULTRASAT** could host a **choked jet** and **release TeV neutrinos —>** <u>need to run these multi-messenger analyses for several years</u>

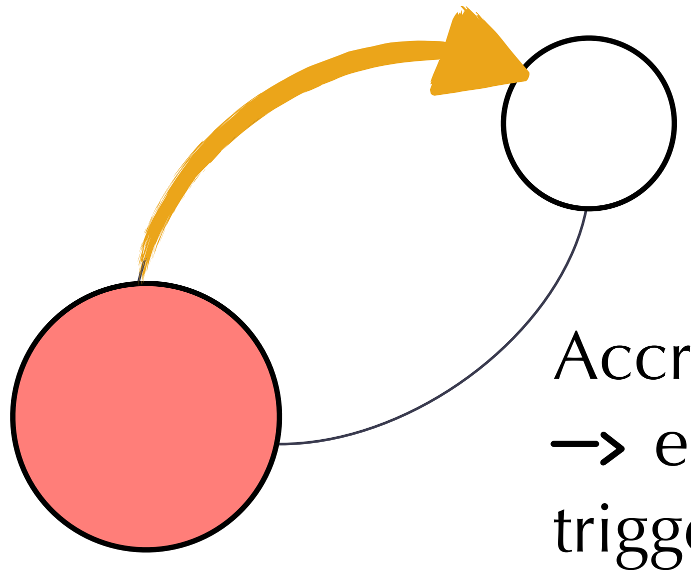
- **EM** and ν **detections**, if **accompanied** by **additional photometric** and **spectroscopic follow-ups** with compelling evidence for a relativistic jet launched by the source central engine, **would suggest CCSNe harbouring choked jets** as **contributors to the diffuse astrophysical high-energy neutrino flux**

Thank you for your attention!

Backup

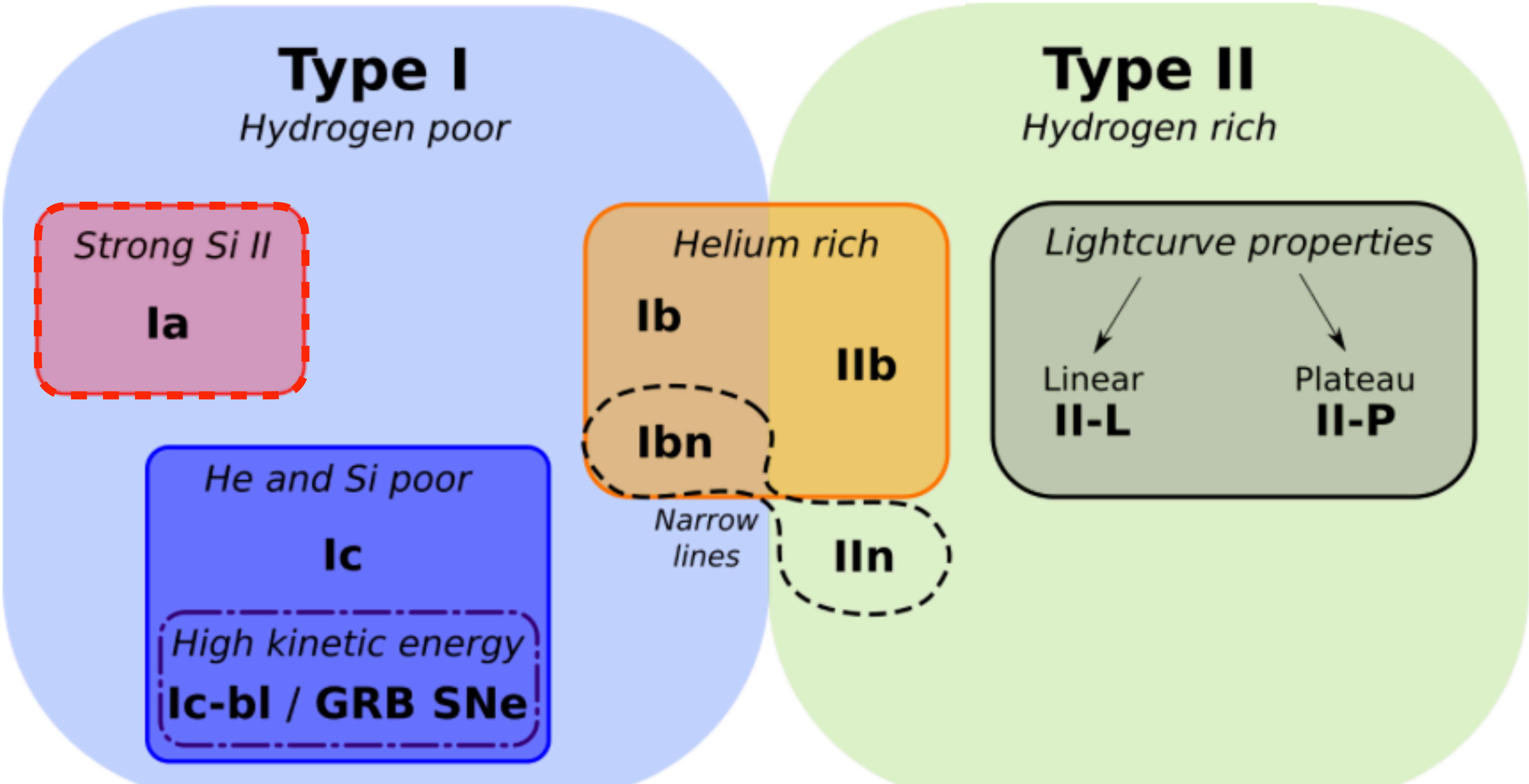
SNe classification



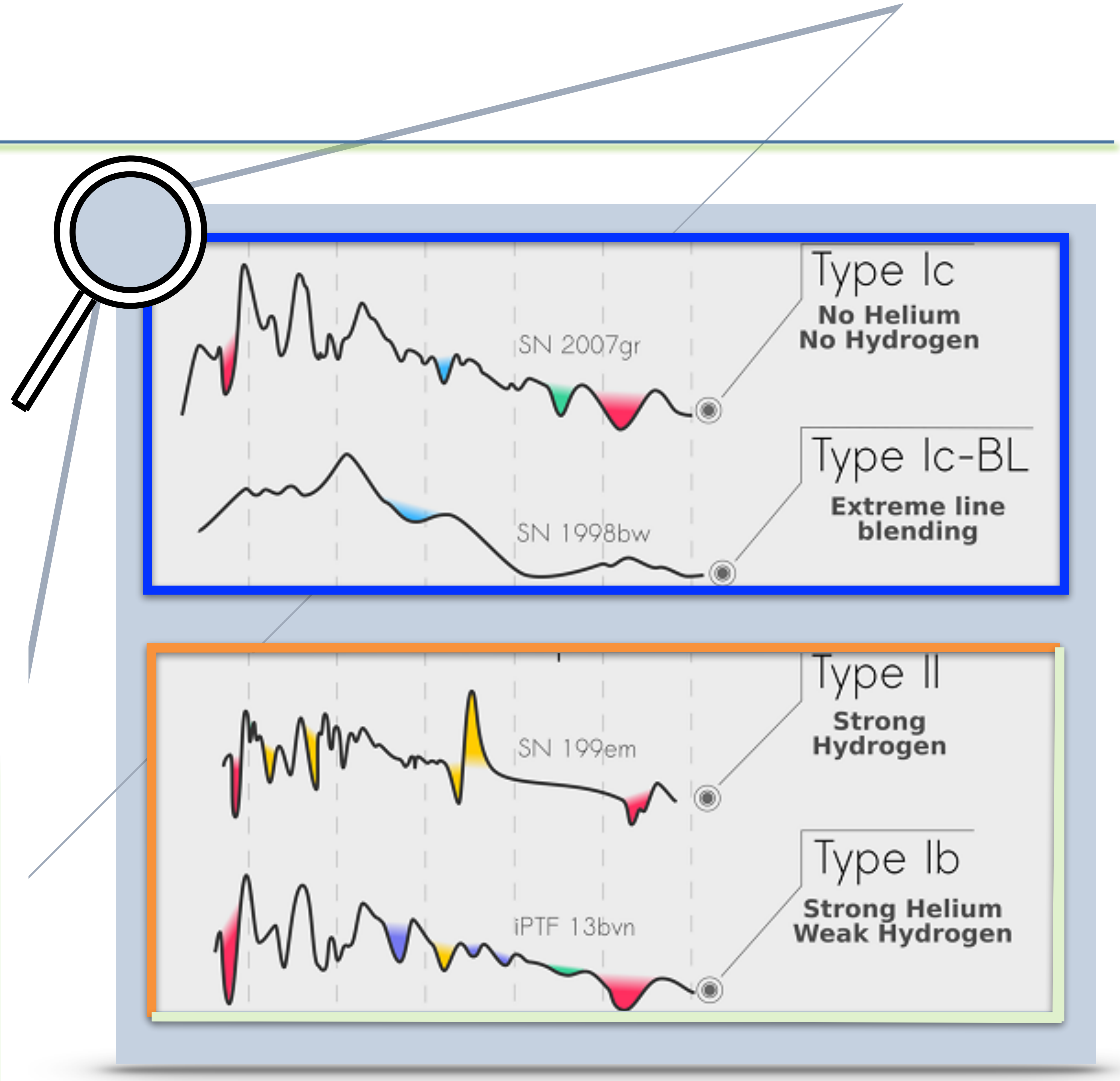


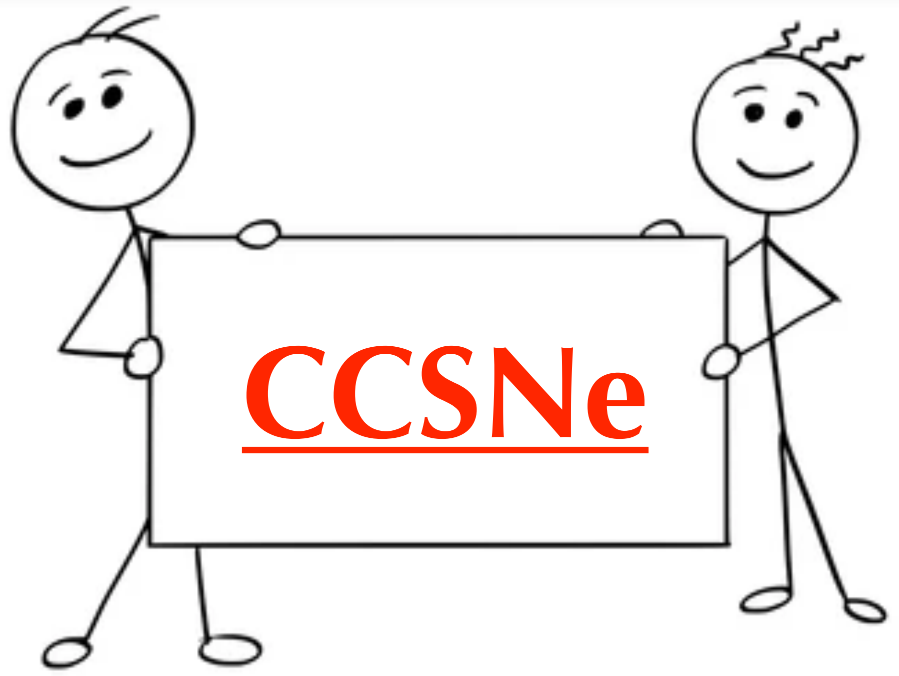
Binary system with a white dwarf

Accretion of material → enough pressure to trigger a core ignition



Adapted from H. Stevance





Effect of dust extinction

$$f_{\rm obs}(\lambda) = f_\lambda(\lambda, t) = \left(\frac{r_{\rm ph}}{D_L(z)}\right)^2 \sigma T_{\rm ph}^4 \frac{T_{\rm col}}{hc} g_{BB}(x) e^{-\tau_\lambda} = f_{\rm int}(\lambda) e^{-\tau_\lambda}$$

$$f_{\rm obs}(\lambda) = f_{\rm int}(\lambda) e^{-\tau_\lambda} = f_{\rm int}(\lambda) 10^{-0.4 A_\lambda}$$

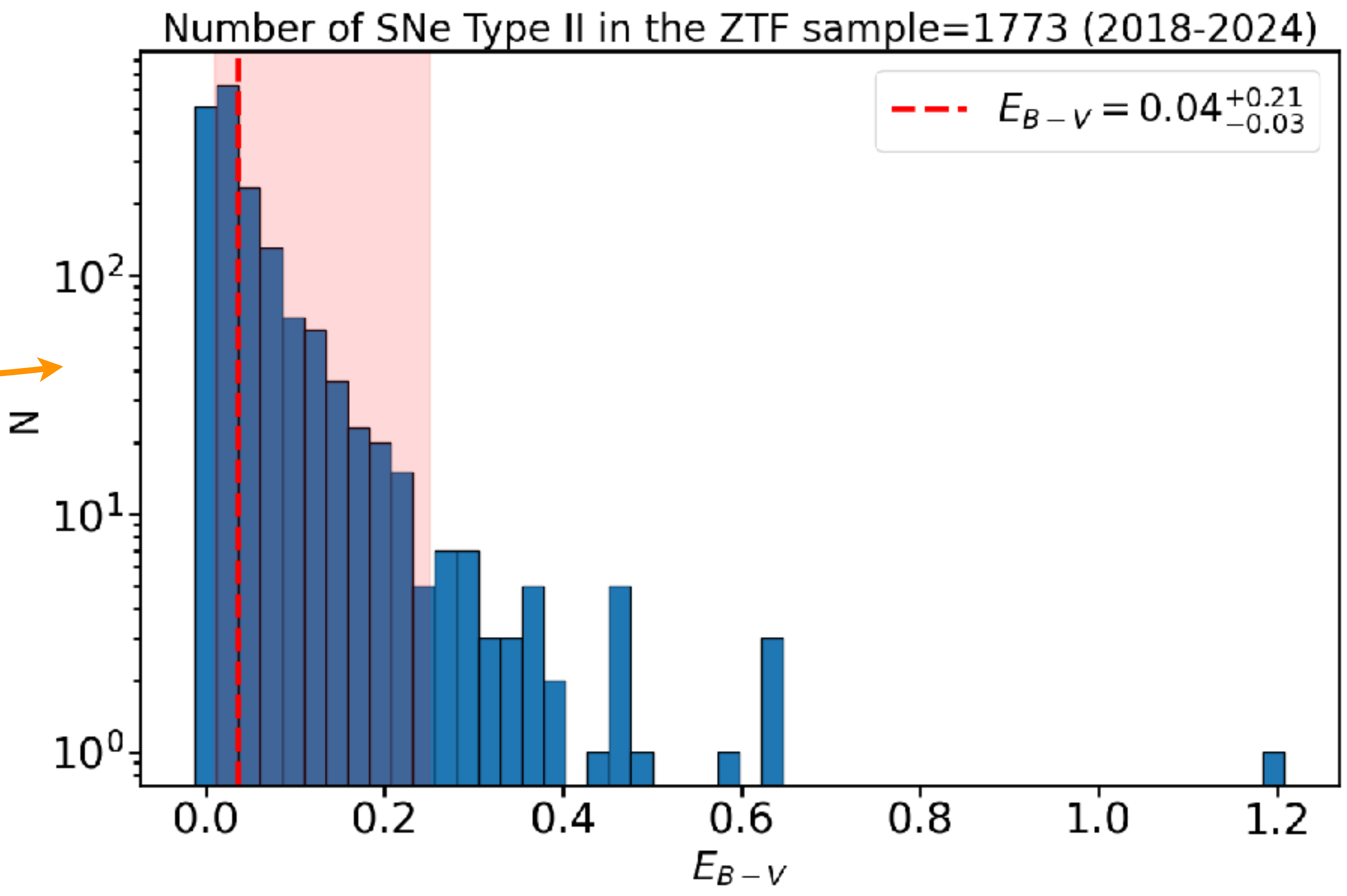
Observed color excess

$$E_{B-V} = E_{B-V}^{\rm observed} - E_{B-V}^{\rm intrinsic}$$

$$A_\lambda = 1.086\tau_\lambda = k(\lambda) E_{B-V} = k(\lambda)\frac{A_V}{R_V}$$

Reddening curve

We adopt the averaged dust extinction model from
Cardelli et al. (1989)
for diffuse interstellar medium in the Milky Way with $R_V = 3.1$



Distribution of Galactic extinction values for galaxies hosting Type II SNe detected by the Zwicky Transient Facility (ZTF)
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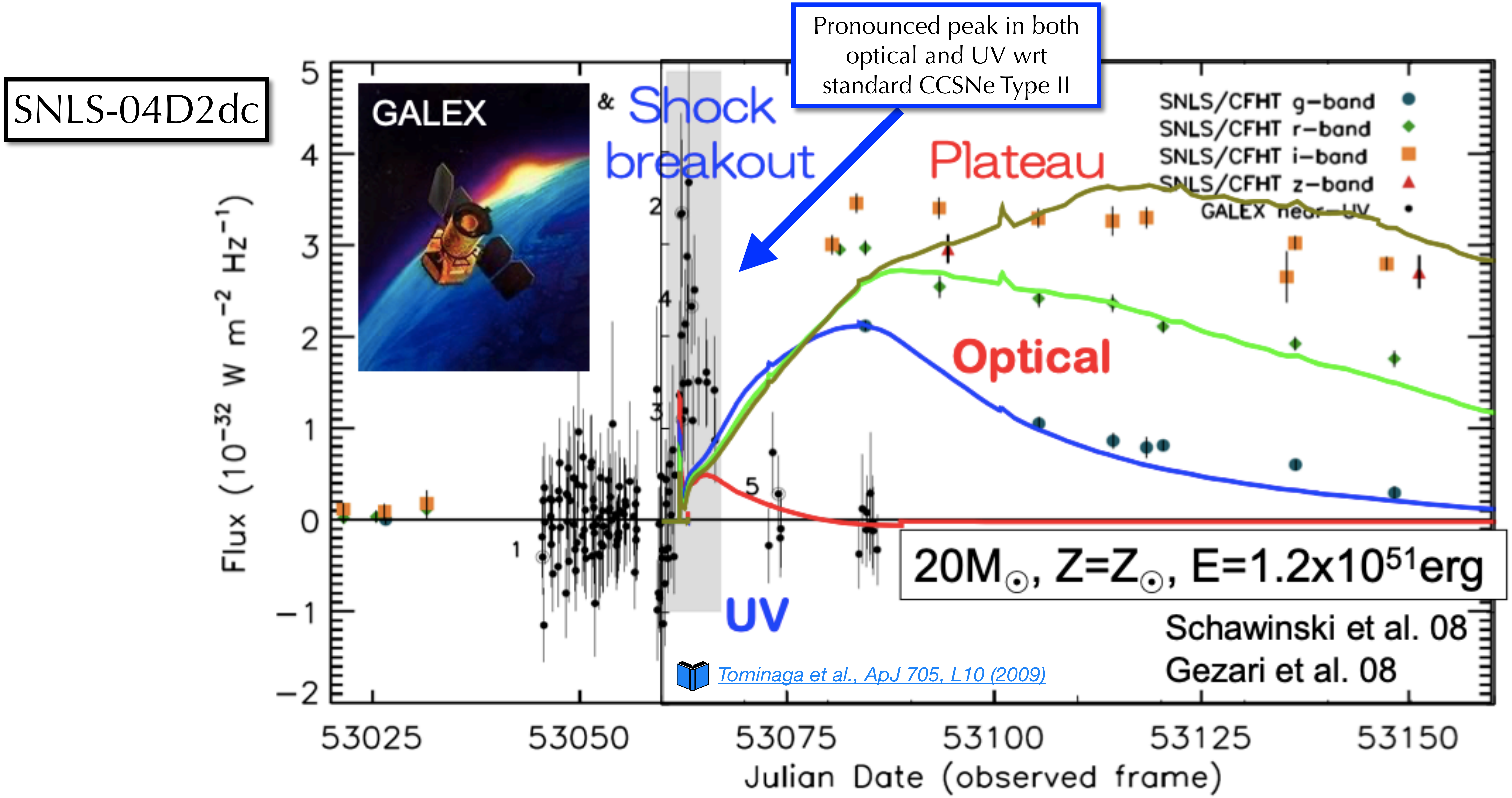
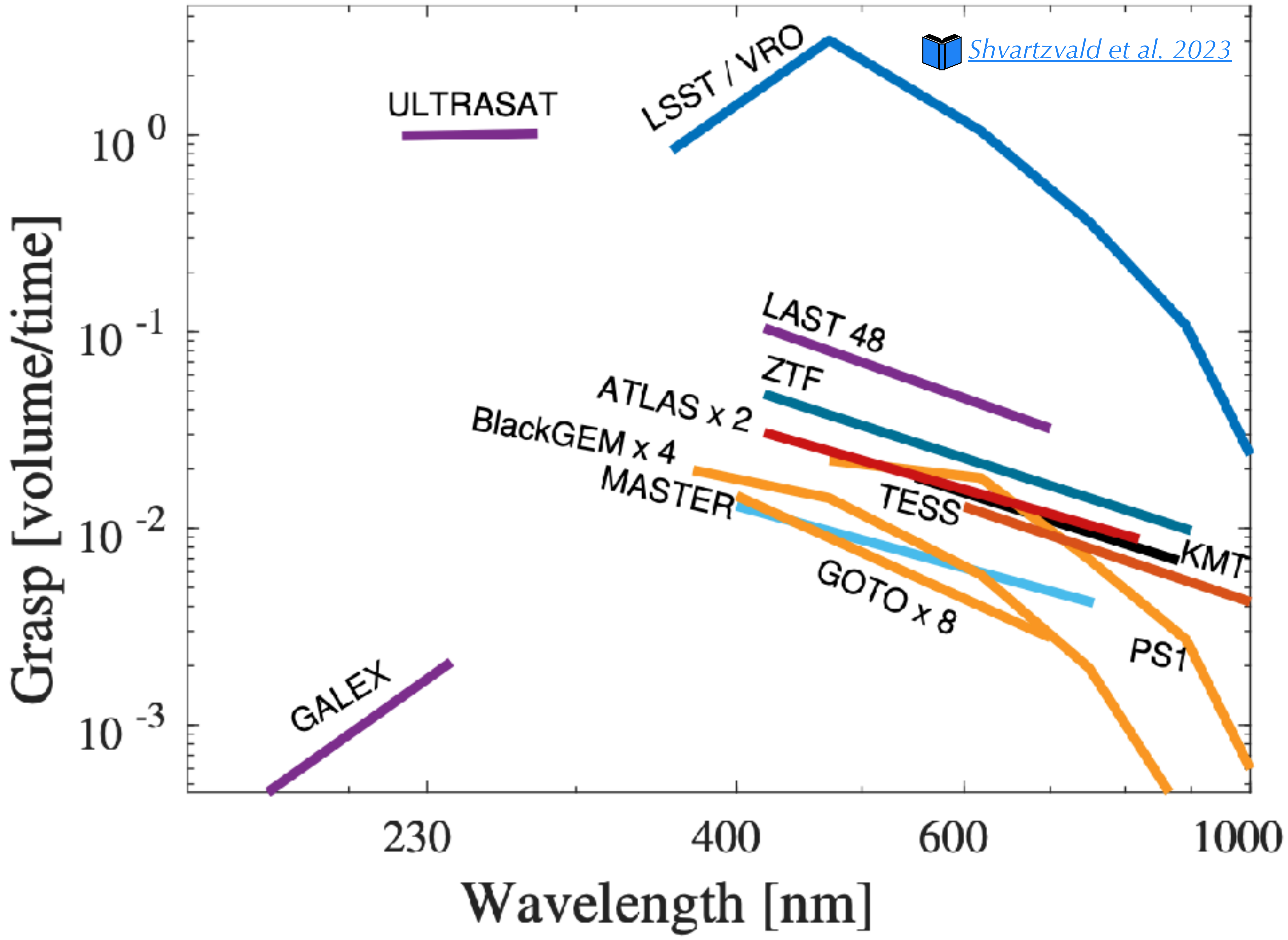
Zegarelli et al., submitted to A&A, arXiv:2403.16234 [astro.ph.HE]

Signatures of SBO in SN light curves

First entire observations of the shock breakouts of Type II Plateau SNe were reported **in 2008 by ultraviolet and optical observations** by the GALEX satellite and supernova legacy survey (SNLS), named *SNLS-04D2dc* and *SNLS-06D1jd*



UV and optical instruments grasp

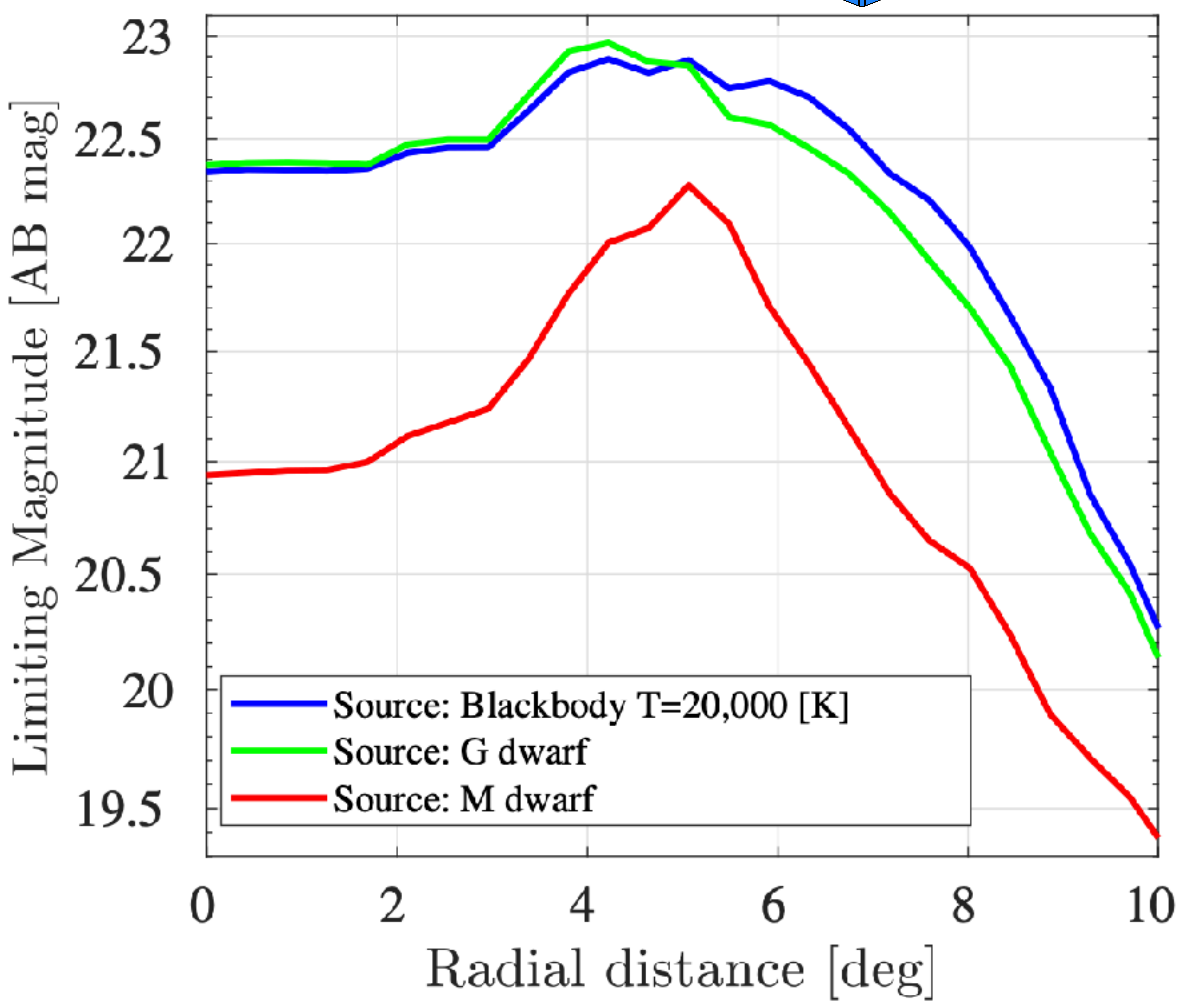


The grasp is given for a 20,000 K black-body source spectrum (e.g., a hot transient).

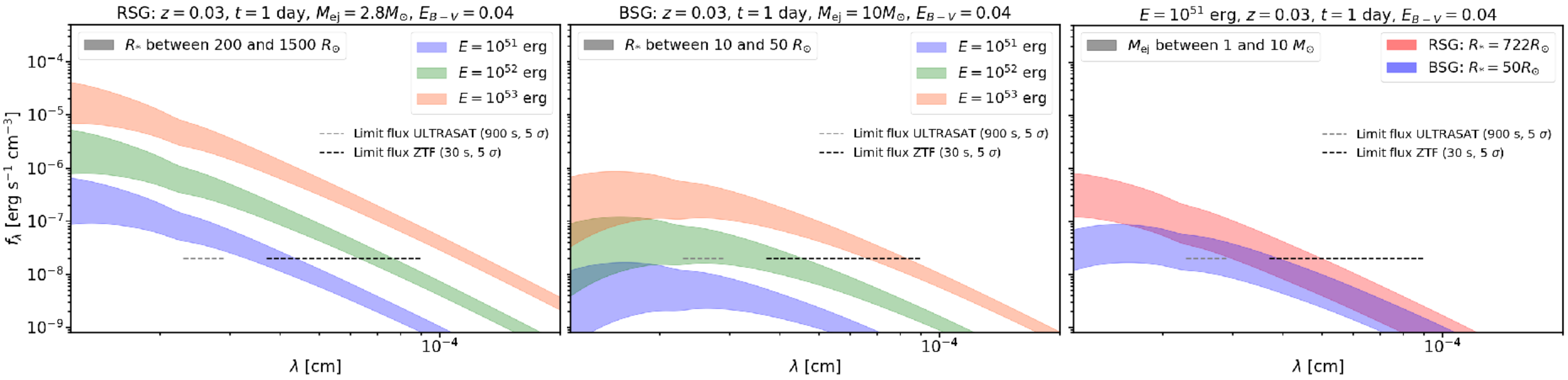
ULTRASAT's grasp is an order of magnitude larger than that of current surveys, two orders of magnitudes larger than that of GALEX, the largest grasp UV mission to date, and com- parable to that of LSST, the largest grasp optical survey under construction.

Limiting magnitude of ULTRASAT

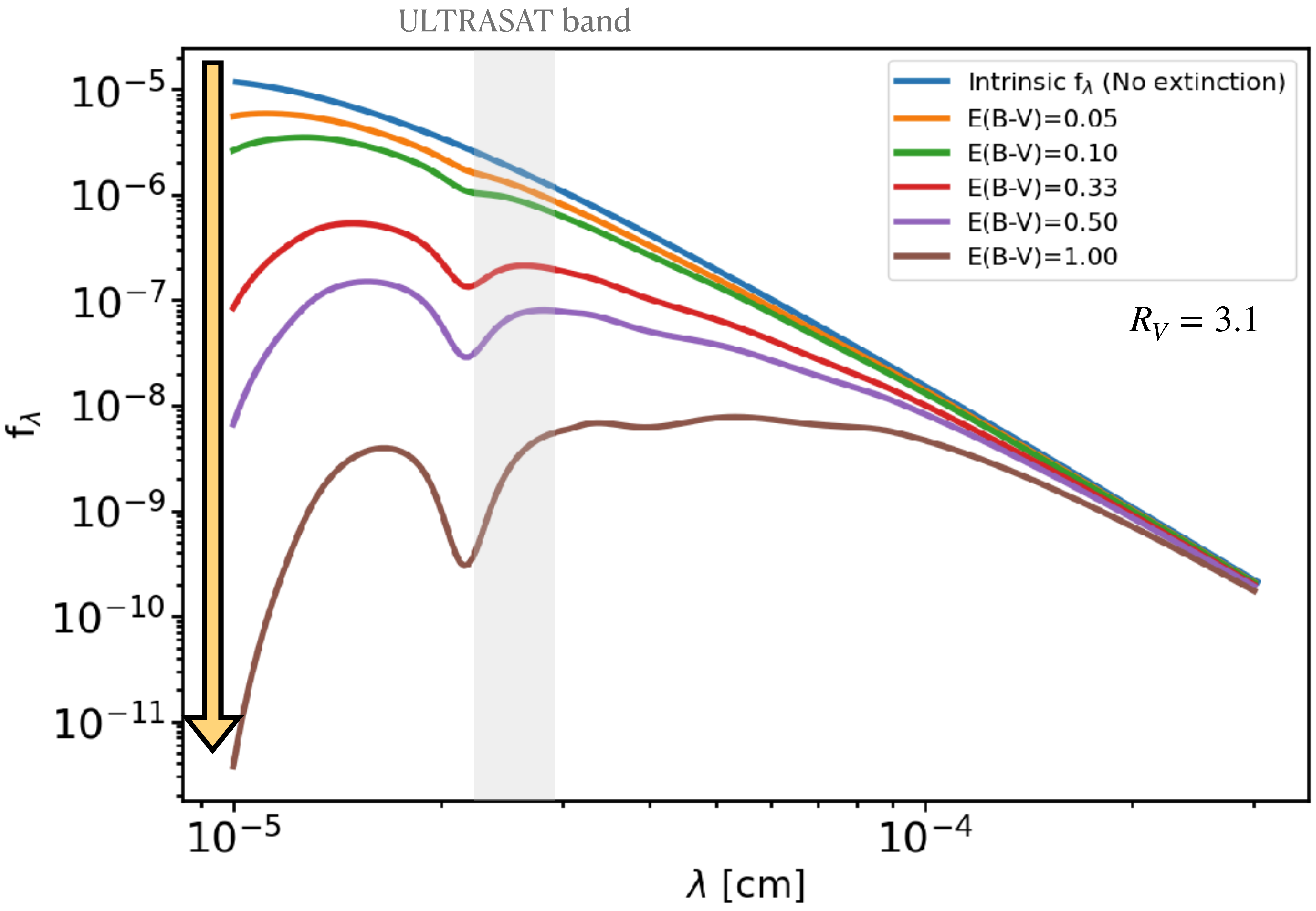
Shvartzvald et al. 2023



Impact of the progenitor parameters on the expected signal

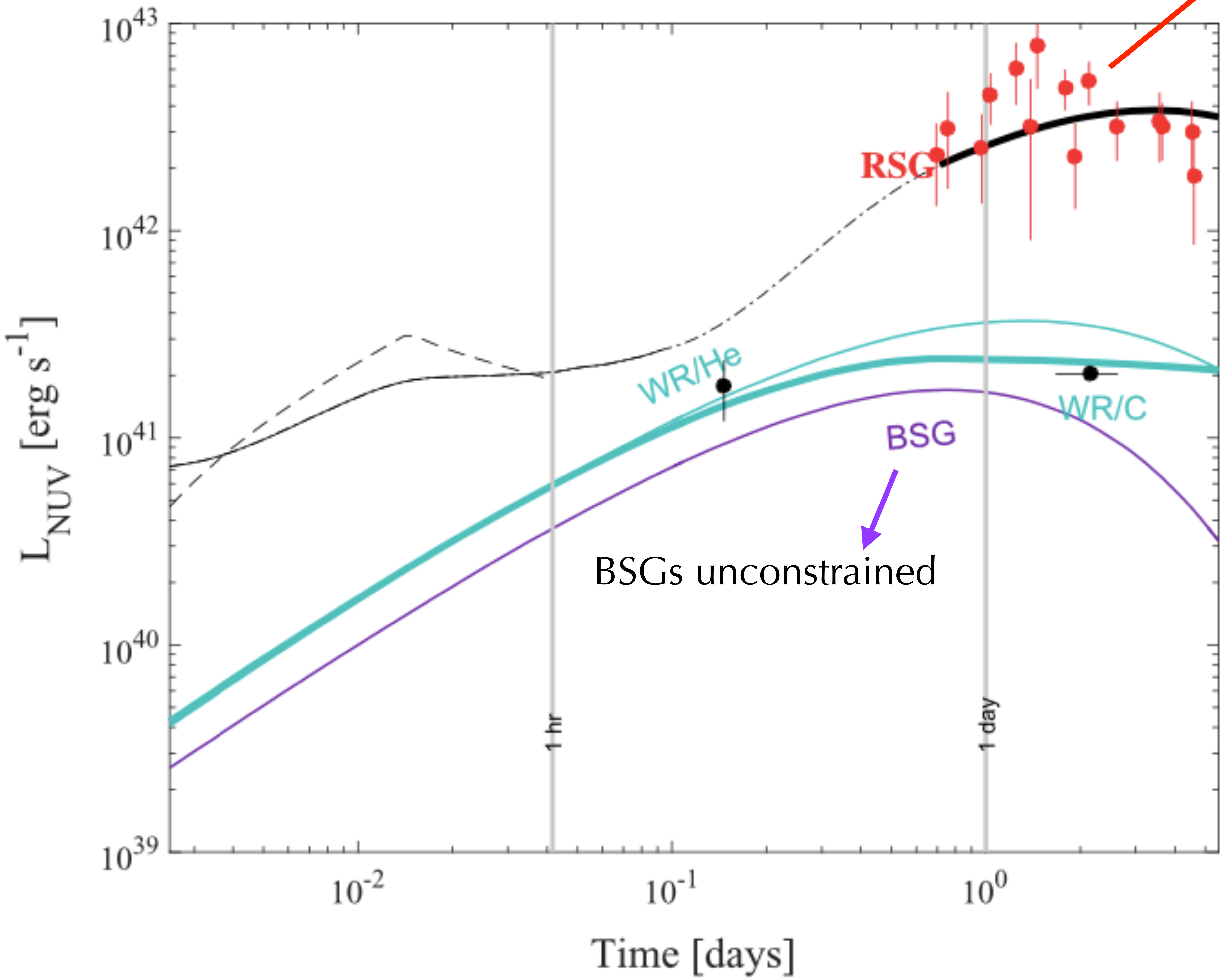


Effect of extinction



Previous predictions for ULTRASAT from literature

Ganot et al., ApJ 820, 57 (2016)



Data points from SNLS-04D2dc Type II detected by GALEX (extinction $A_{NUV} = 1.45$)

$$L_{NUV}(t) = 4\pi D_L^2(z) \int_{\lambda_{min}}^{\lambda_{max}} f_\lambda(\lambda, t) d\lambda$$

assume the reasonable parameters for RSG and BSG stars, i.e.,

$R = 3.5 \times 10^{13}$ cm ($= 500\ R_{Sun}$), $E = 2 \times 10^{51}$ erg, $M = 10 M_{Sun}$

$R = 3.5 \times 10^{12}$ cm ($= 50\ R_{Sun}$), $E = 1 \times 10^{51}$ erg, $M = 10 M_{Sun}$

and for WR, values from SN2008D

$R = 10 \times 10^{11}$ cm, $E = 6 \times 10^{51}$ erg, $M = 7 M_{Sun}$
(extinction $A_{NUV} = 2.2$)

Previous predictions for ULTRASAT from literature

Ganot et al., ApJ 820, 57 (2016)

These estimations were performed considering fiducial parameters for each type of source and without extinction

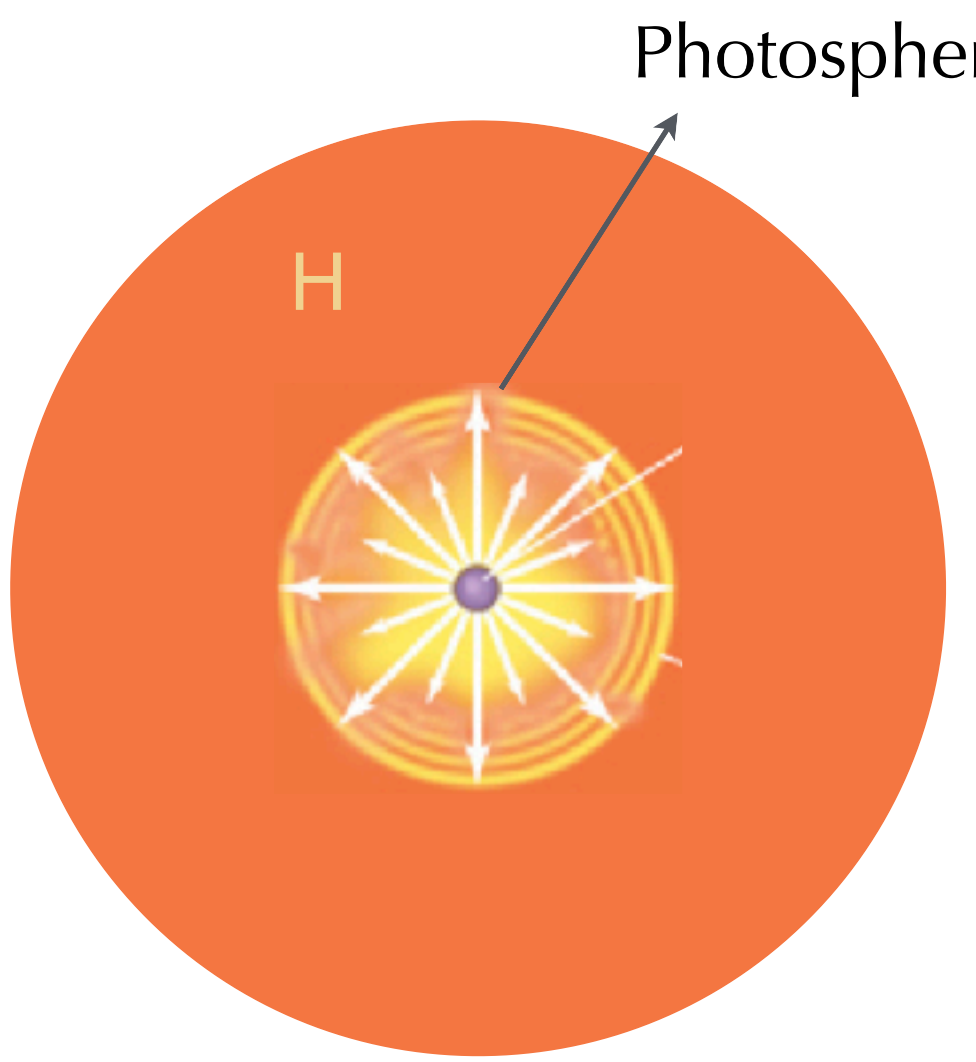
Table 2
Predicted SN Explosion Detection Numbers by Various Surveys

Survey	Band	Cadence	FOV (deg^2)	Expected Number ($SN\ yr^{-1}$)					
				RSG		BSG		W–R	
				<1 hr	<1 day	<1 hr	<1 day	<1 hr	<1 day
GALEX/PTF	NUV	3 day	600	0	30[a]	0	0	0	0
ULTRASAT	NUV	900 s	210	4	85	1	8	0	3
ULTRASAT	NUV	3600 s	210	16	314	2	31	1	14
iPTF[b]	*r*	1 day	1000	0	7	0	2	0	1
ZTF[c]	*g*	0.5 hr	2100	0	10	0	2	0	1
LSST[d]	*g*	0.5 hr	9.6	0	17	0	3	0	1

Notes.
[a] For our *GALEX*/PTF experiment, we report the expected number within three days (not one day) to match its low actual cadence. As the survey ran for 2 m (1/6 yr), the expected number of SNe from RSG explosions for the actual experiment is $30/6 = 5$ events.
[b] Assumed temporal efficiency of 25% (including loss due to daytime and average weather) and lunation-averaged depth of 20.6 mag.
[c] 25% temporal efficiency as above, average depth 20.4 mag, and 50% survey time spent in *g*-band.
[d] Assumed the following for the LSST deep drilling project: 1 LSST field observed at any given time, 25% temporal efficiency as above, and $g = 24.2$ mag lunation-averaged depth.

Early UV/optical emission from choked jets embedded in CCSNe

Model from Waxman et al., ApJ 667, 351 (2007), Rabinak & Waxman, ApJ 728, 63 (2011)

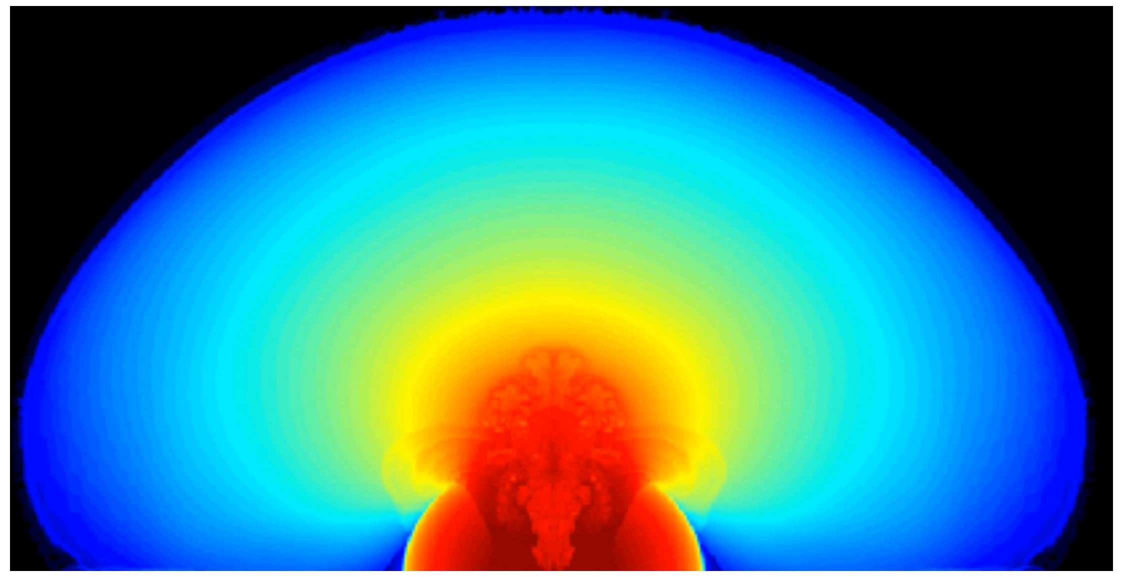


$$r_{\rm ph}(t) = \begin{cases} 3.3\times 10^{14}\, f_\rho^{-0.062} \dfrac{E_{51}^{0.41} k_{0.34}^{0.093}}{(M_{\rm ej}/M_\odot)^{0.31}} t_5^{0.81}\ \text{cm} & (n=3/2) \\ 3.3\times 10^{14}\, f_\rho^{-0.036} \dfrac{E_{51}^{0.39} k_{0.34}^{0.11}}{(M_{\rm ej}/M_\odot)^{0.28}} t_5^{0.78}\ \text{cm} & (n=3) \end{cases}$$

$$T_{\rm ph}(t) = \begin{cases} 1.6\, f_\rho^{-0.037} \dfrac{E_{51}^{0.027} R_{*,13}^{1/4}}{(M_{\rm ej}/M_\odot)^{0.054} k_{0.34}^{0.28}} t_5^{-0.45}\ \text{eV} & (n=3/2) \\ 1.6\, f_\rho^{-0.022} \dfrac{E_{51}^{0.016} R_{*,13}^{1/4}}{(M_{\rm ej}/M_\odot)^{0.033} k_{0.34}^{0.27}} t_5^{-0.47}\ \text{eV} & (n=3) \end{cases}$$

R_* = progenitor radius
f_ρ = factor related to the average ejecta density (it varies linearly with mass of progenitors M)
k = opacity of the stellar envelope in $\text{cm}^2\ \text{g}^{-1}$
$E = 10^{51} E_{51}$ erg = released energy
$t = 10^5 t_5$ s = time from the shock breakout
$n = 3/2$ for convective envelopes (RSGs), and $n = 3$ for radiative envelopes (BSGs)

Model specific intensity observed in UV/optical



Black-Body radiation modified by extinction

$$f_\lambda(\lambda, t) = \left(\frac{r_{\rm ph}}{D_L(z)}\right)^2 \sigma T_{\rm ph}^4 \frac{T_{\rm col}}{hc} g_{BB}(x) e^{-\tau_\lambda}$$

$$g_{BB}(x) = \frac{15}{\pi^4} \frac{x^5}{e^x - 1}$$

$$x = hc/\lambda T_{\rm col}$$

$T_{\rm col} \simeq 1.2\ T_{\rm ph}$ = color temperature, i.e., temperature at which a black body would emit radiation of the same color of a given source
τ_λ = extinction optical depth at a given wavelength λ

Zegarelli et al., submitted to A&A, arXiv:2403.16234 [astro.ph.HE]

Cooling UV/optical signal after SBO in RSGs and BSGs

From SN II observations
Ganot et al. 2022

$R_* = 722\ R_\odot$

$E = 1 \times 10^{51}$ erg

$M_{ej} = 2.8 M_\odot$

$f_\rho = 1.455$

From modelling expectations
e.g., Dessart & Hillier 2019

$R_* = 50\ R_\odot$

$E = 1 \times 10^{51}$ erg

$M_{ej} = 10 M_\odot$

$f_\rho = 0.0465$

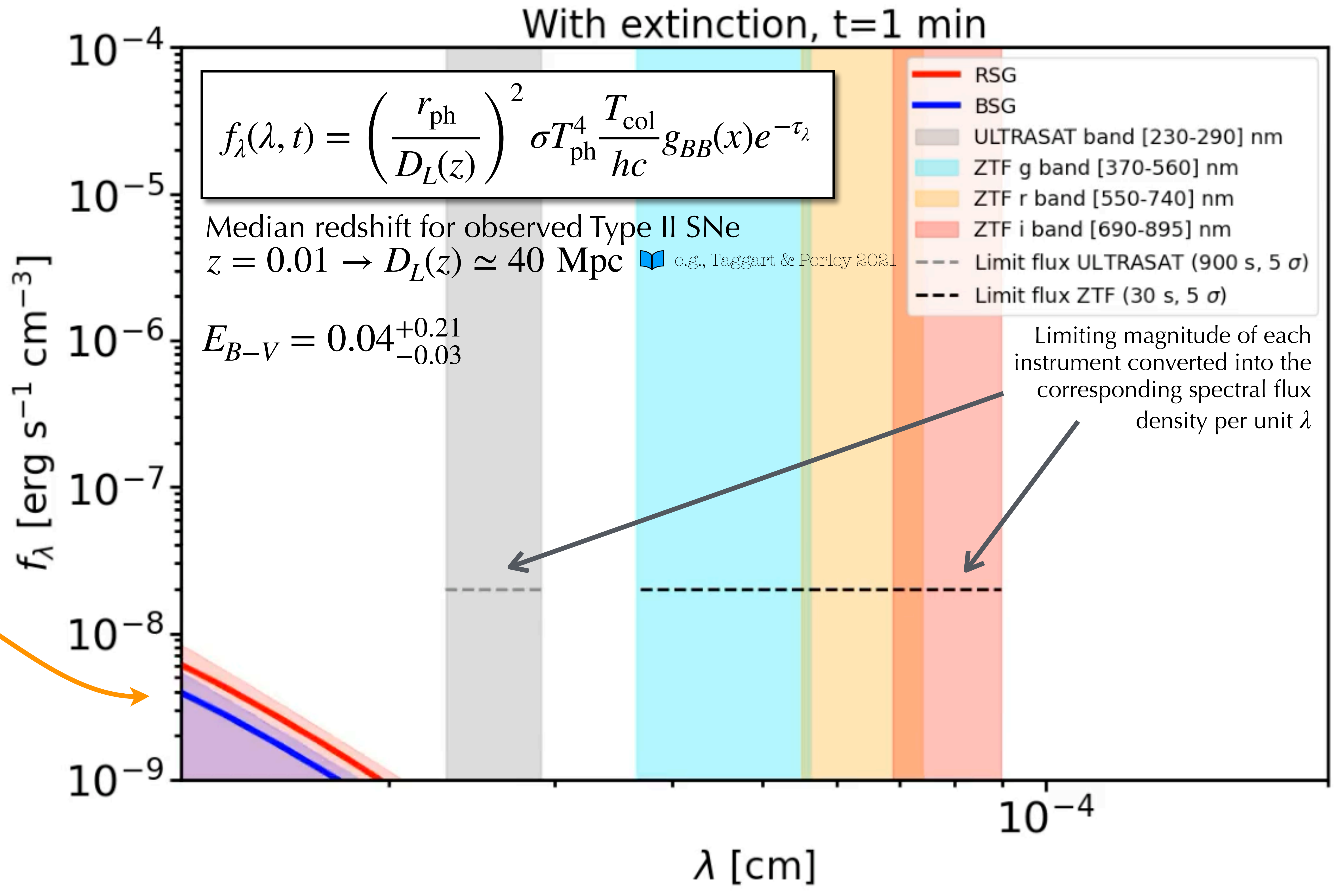
$$A_\lambda = 1.086\tau_\lambda = k(\lambda)E_{B-V}$$

Reddening curve

Averaged dust extinction model from Cardelli et al. (1989)

Distribution of Galactic extinction values for galaxies hosting Type II SNe detected by the Zwicky Transient Facility (ZTF)

ZTF Bright Transient Survey catalogue available online



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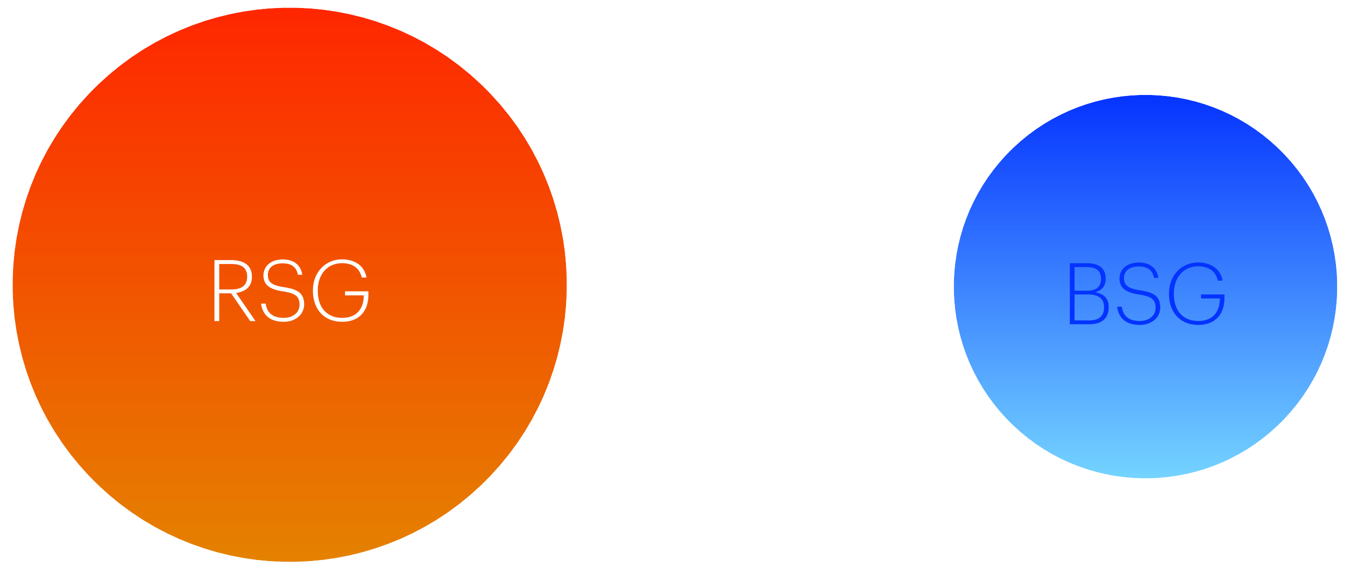

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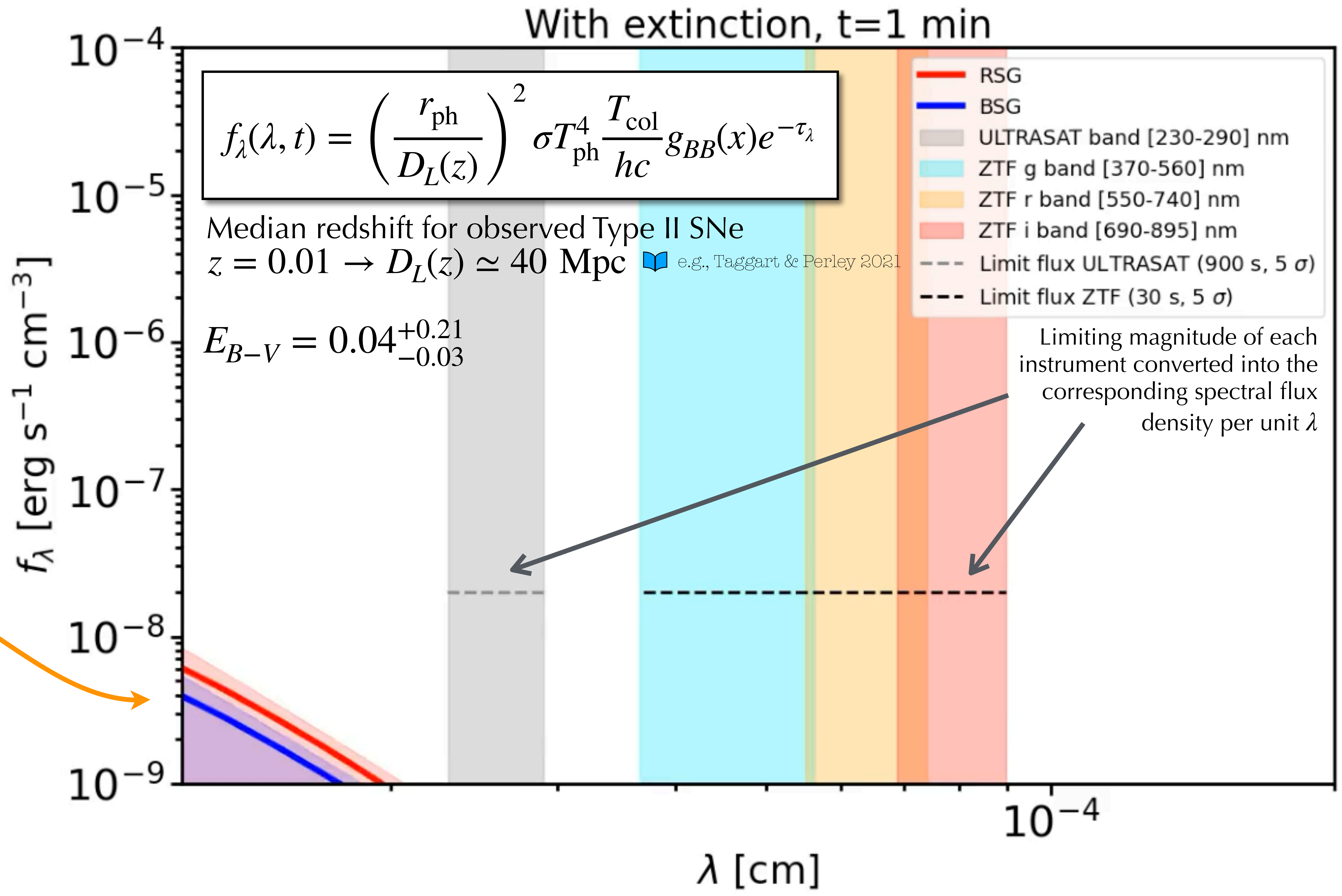

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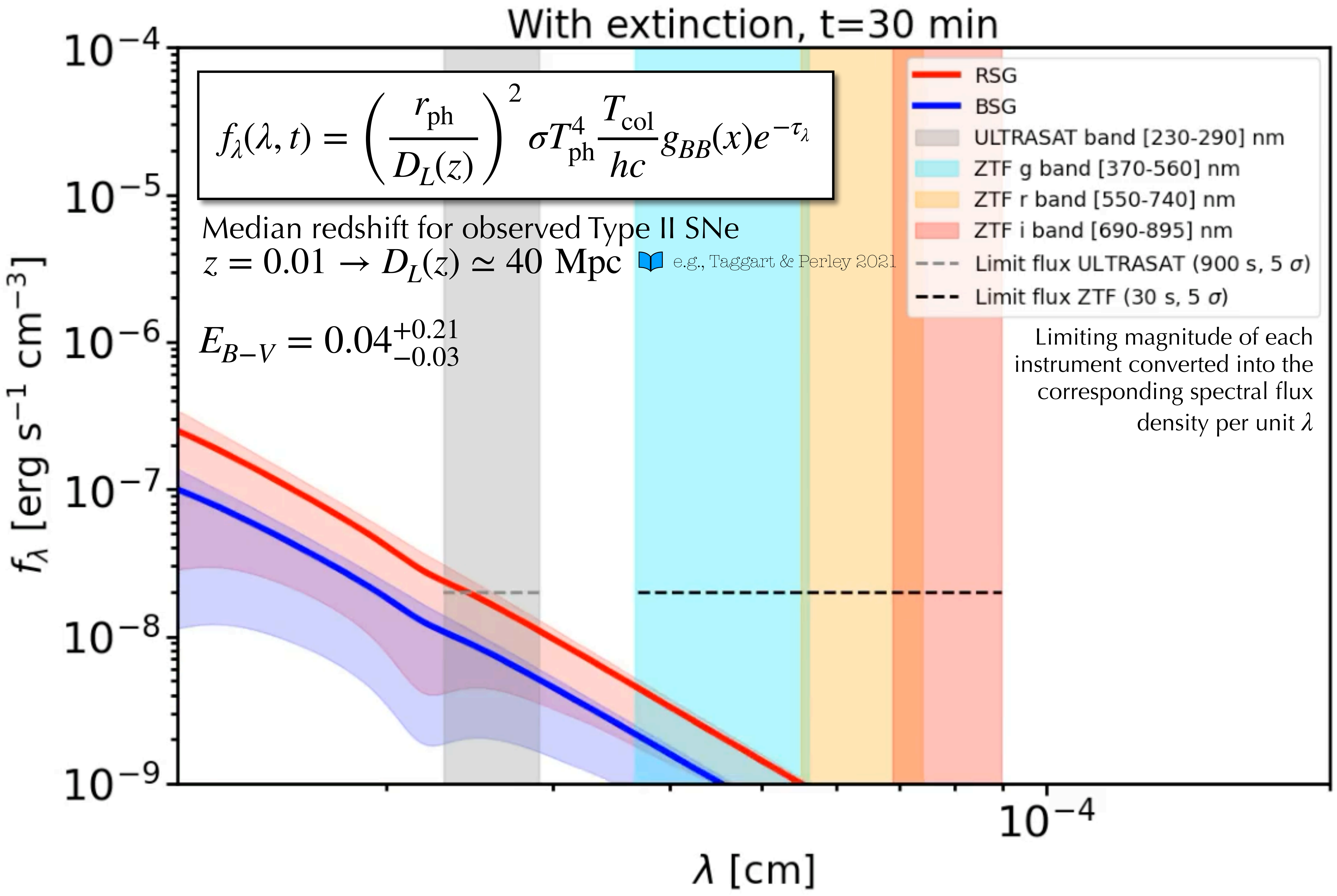
Distribution of Galactic extinction values for galaxies hosting Type II SNe detected by the Zwicky Transient Facility (ZTF)

ZTF Bright Transient Survey catalogue available online



Zegarelli et al., submitted to A&A, arXiv:2403.16234 [astro.ph.HE]

Cooling UV/optical signal after SBO in RSGs and BSGs

From SN II observations
Ganot et al. 2022

$R_* = 722\ R_\odot$

$E = 1 \times 10^{51}$ erg

$M_{ej} = 2.8 M_\odot$

$f_\rho = 1.455$

From modelling expectations
e.g., Dessart & Hillier 2019

$R_* = 50\ R_\odot$

$E = 1 \times 10^{51}$ erg

$M_{ej} = 10 M_\odot$

$f_\rho = 0.0465$

$$A_\lambda = 1.086\tau_\lambda = k(\lambda)E_{B-V}$$

Reddening curve

Averaged dust extinction model from Cardelli et al. (1989)

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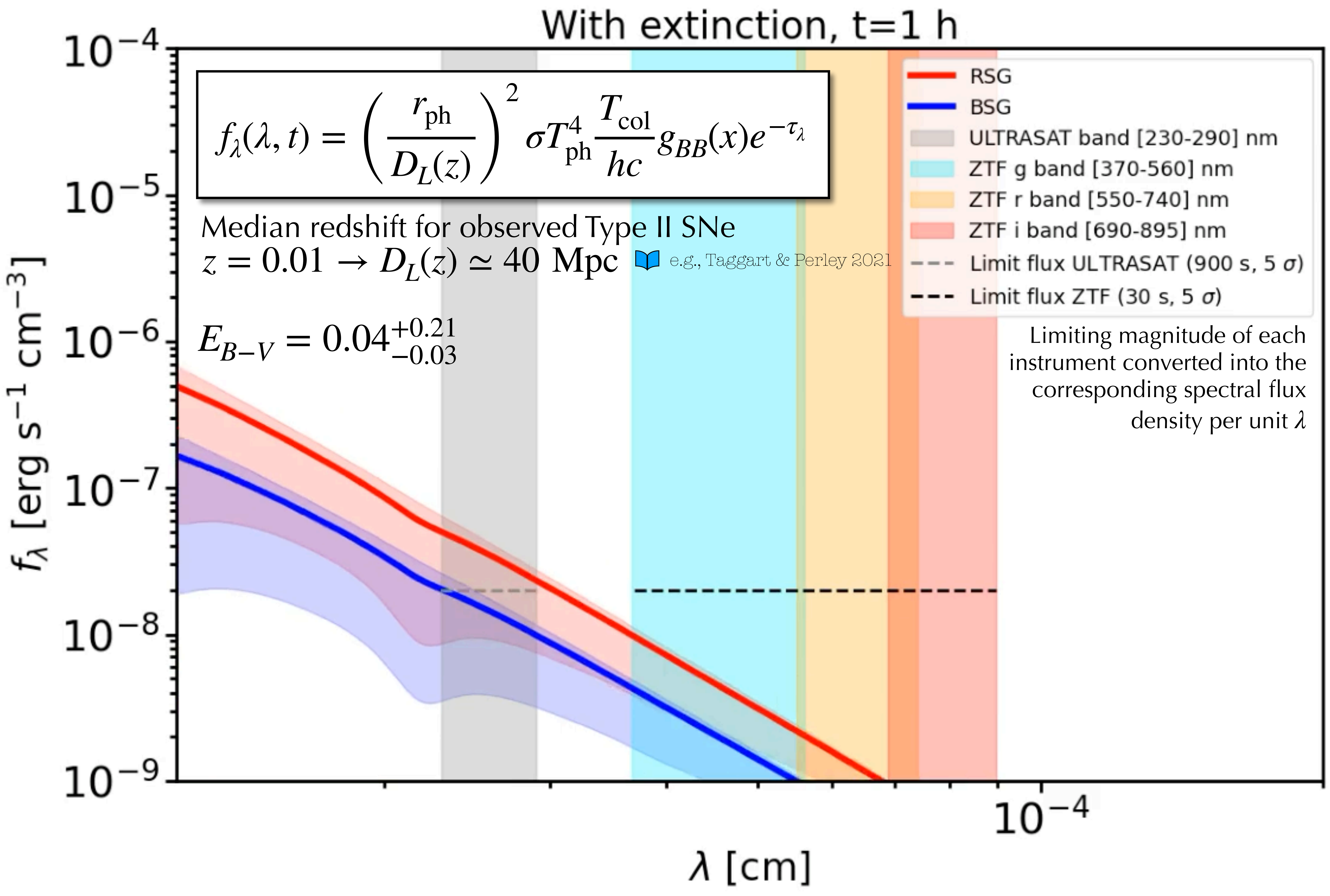

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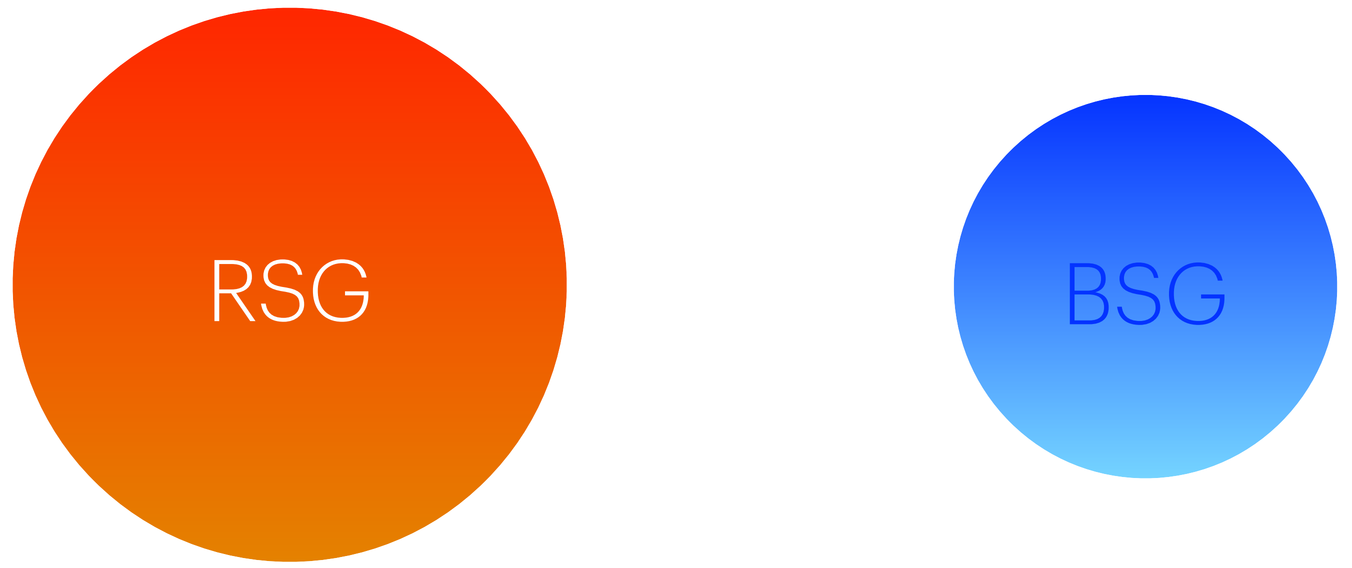

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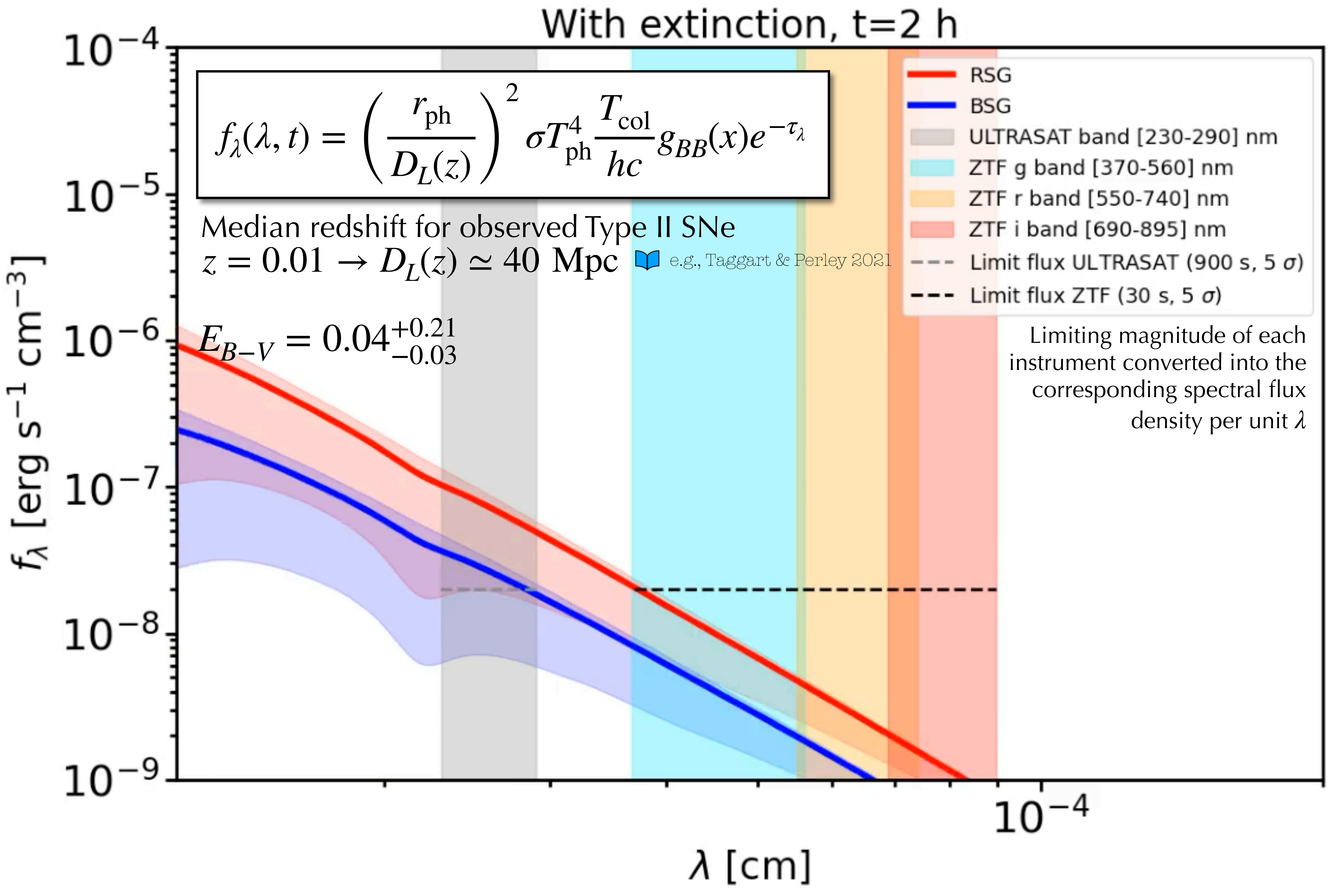

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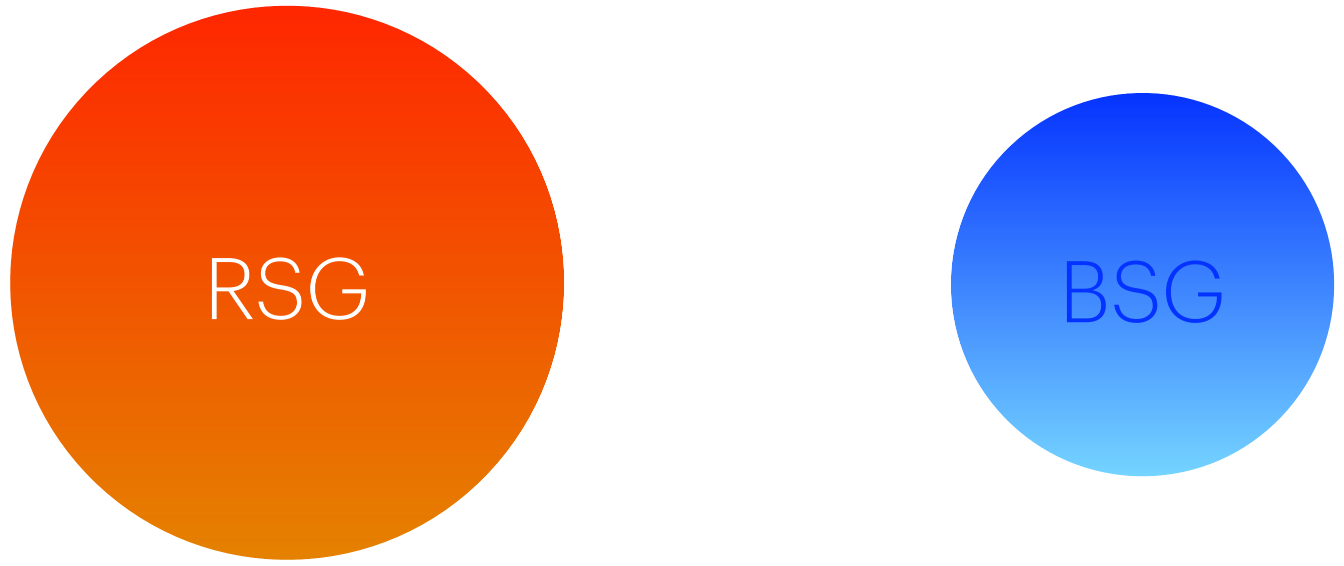

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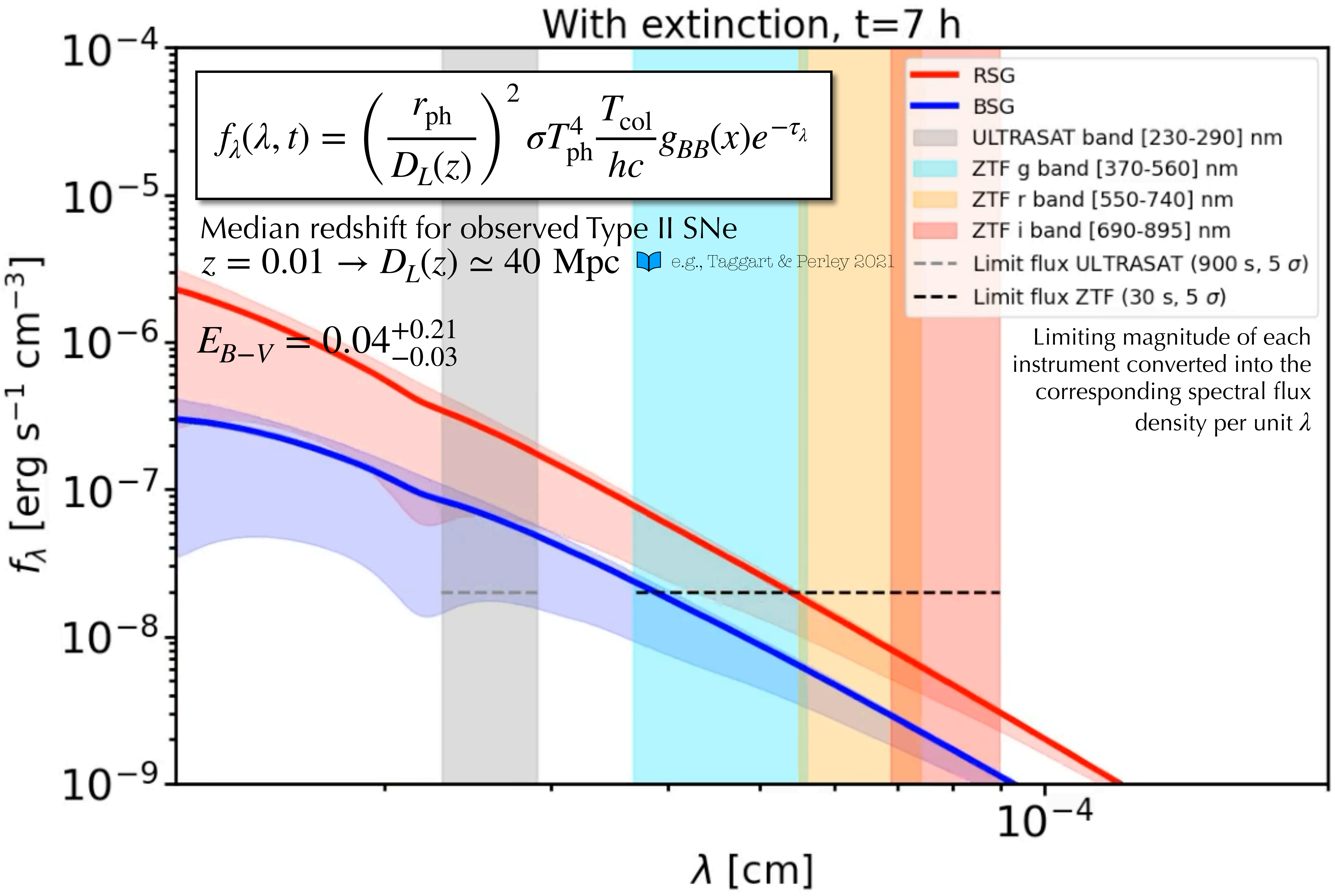

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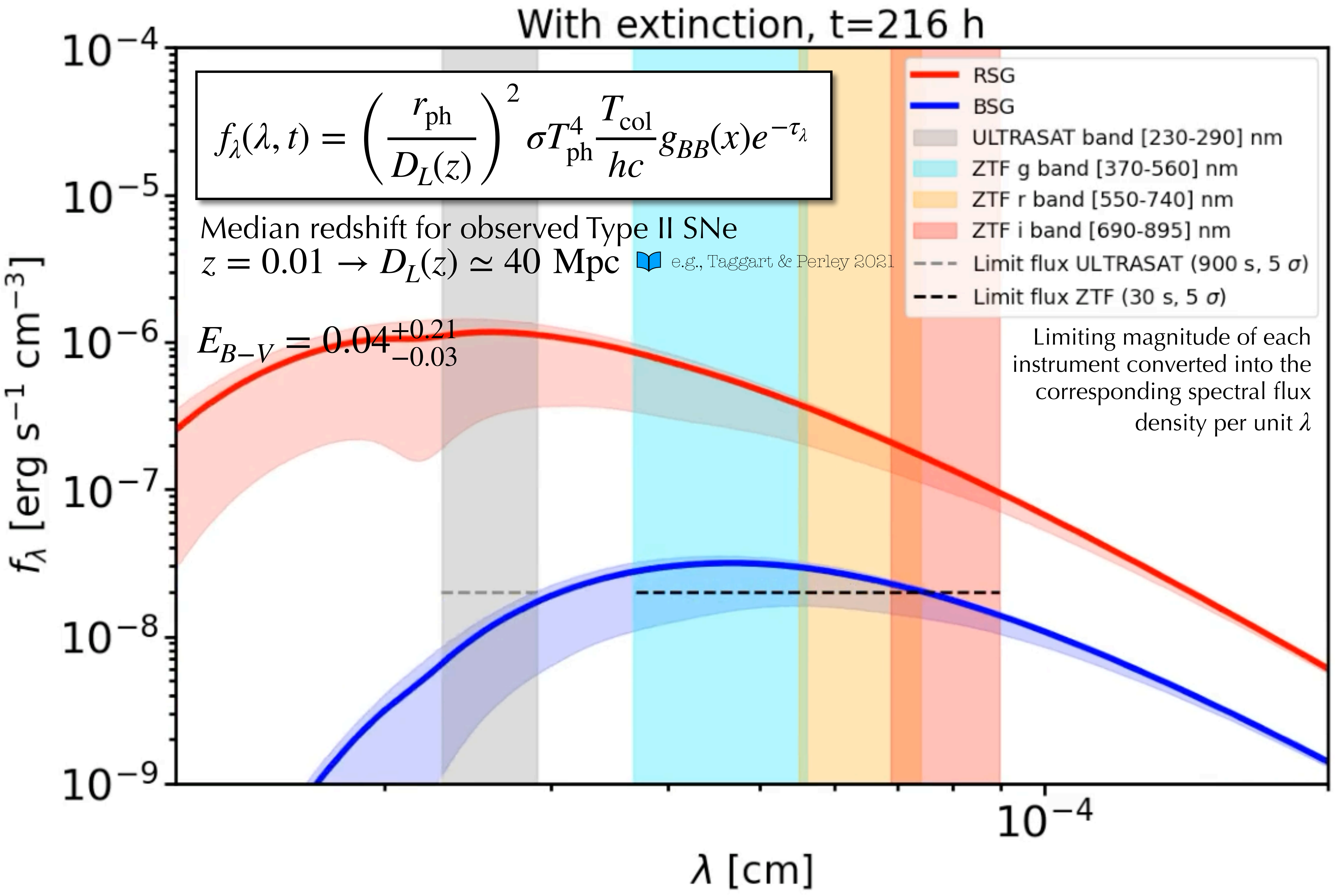

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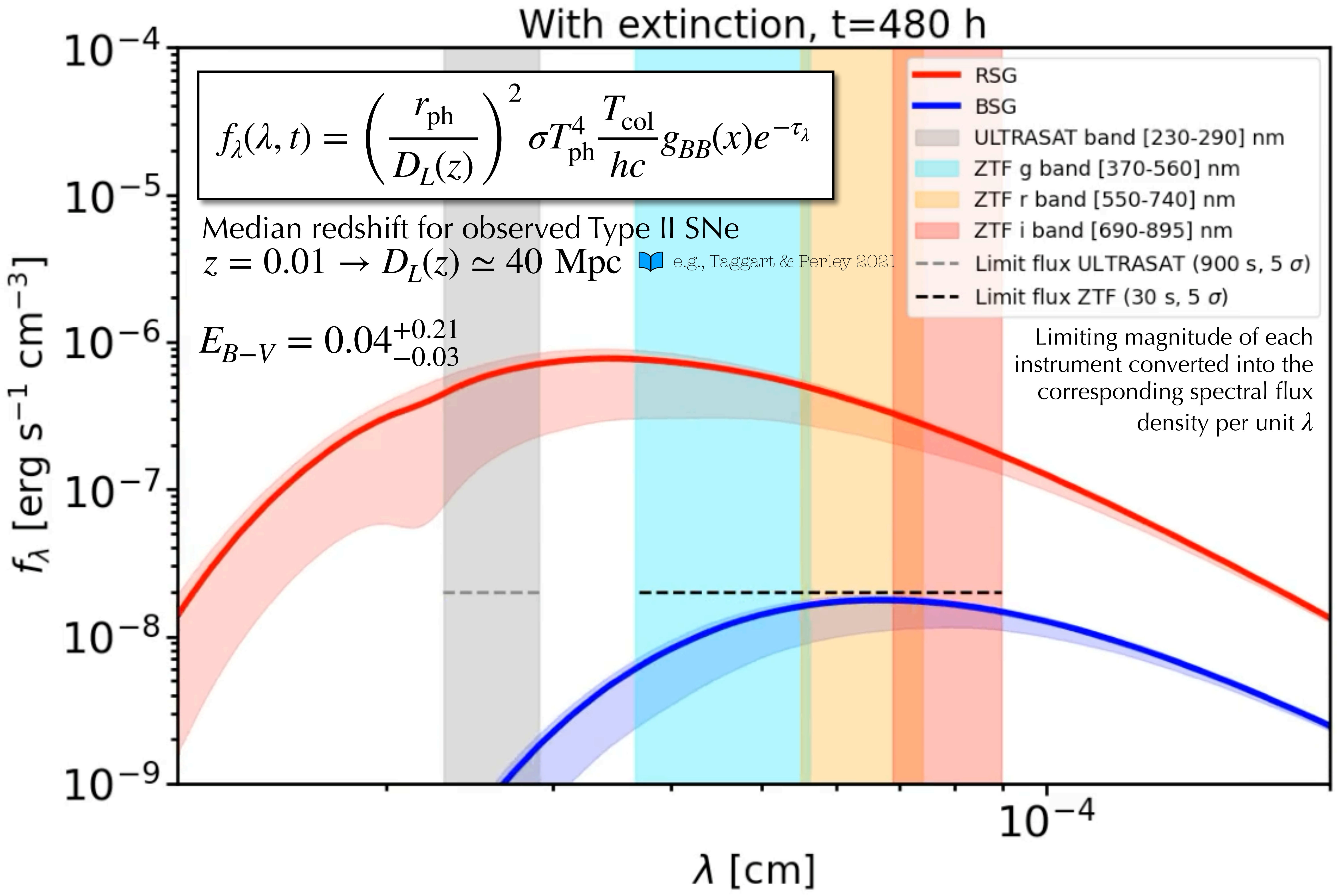

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