Testing whether collapsars synthesize *r*-process elements

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INT 20R-1b on *r*-process nucleosynthesis

and nuclear EoS

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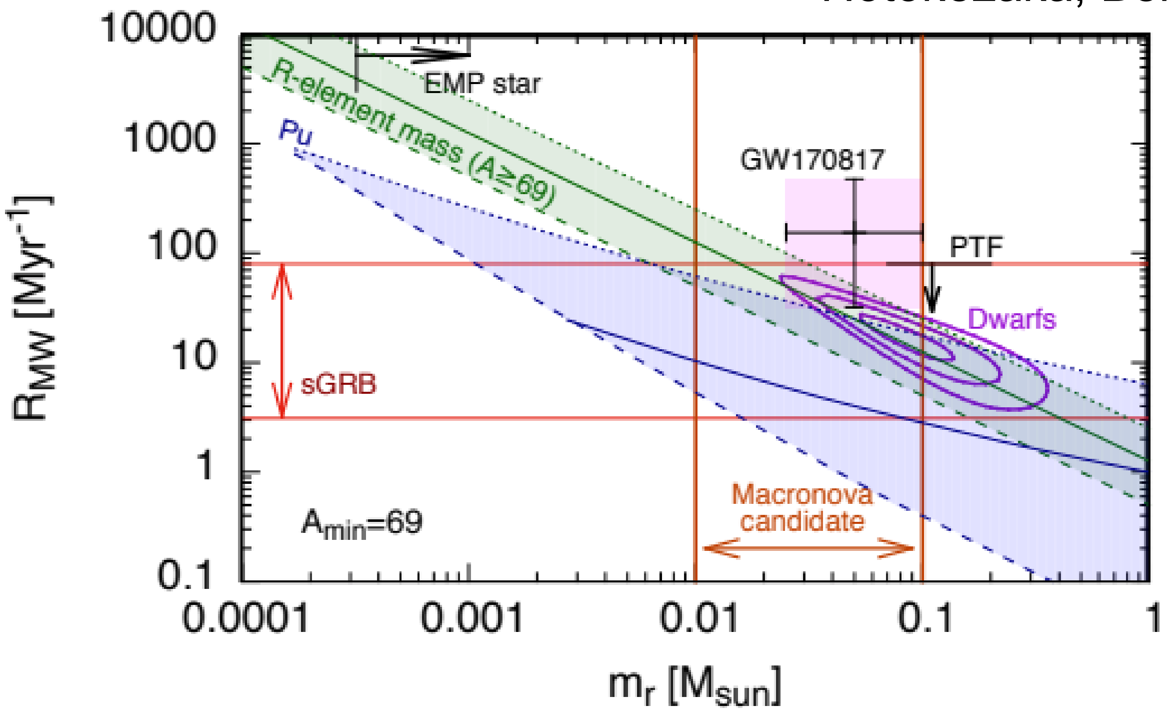
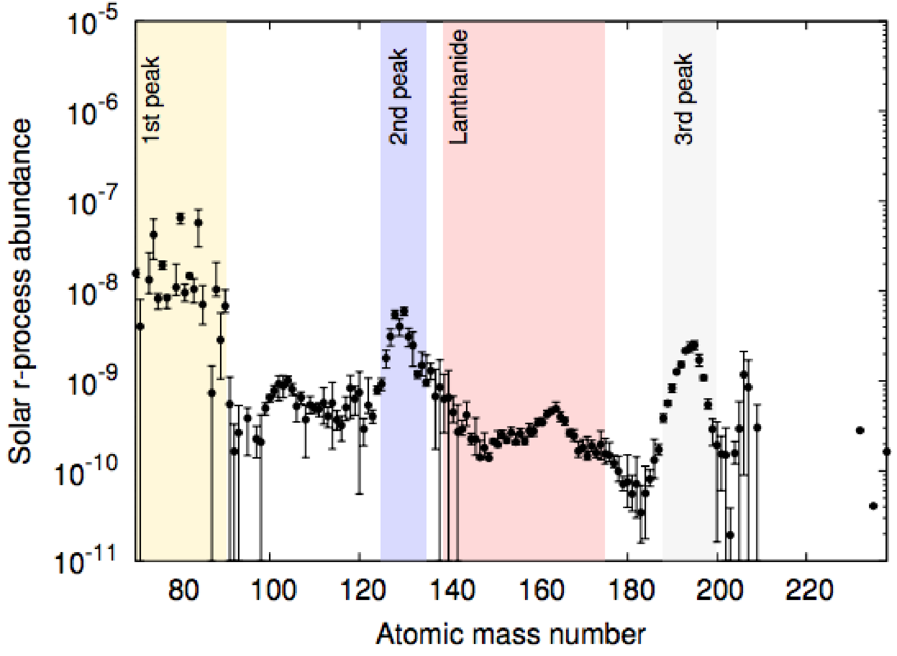
Global Relay of Observatories Watching Transients Happen

Can BNS mergers explain the *r*-process abundance in solar neighborhood?

Hotokezaka, Beniamini, & Piran 2018



Rates and *r*-process yield

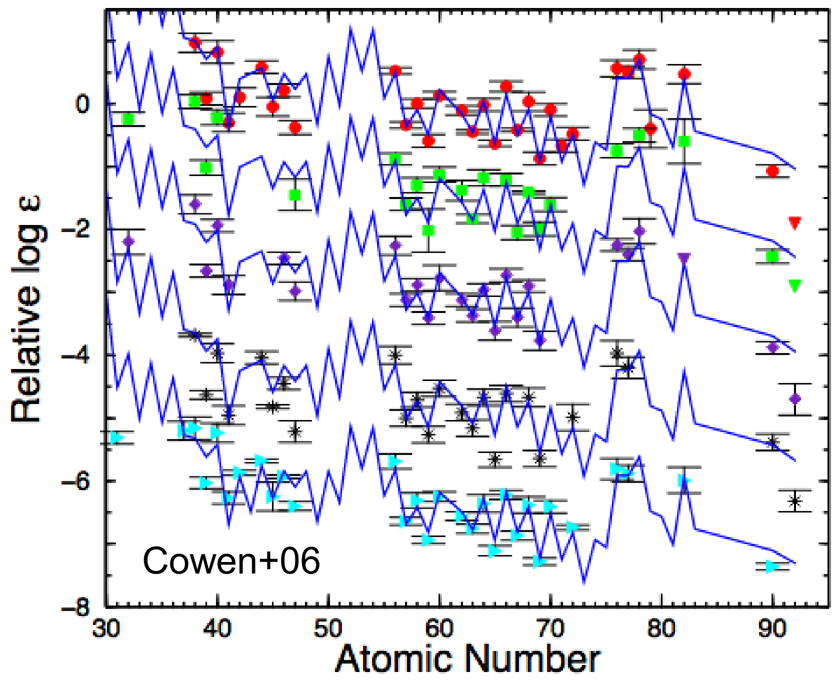


Solar abundance pattern

See also: Talks by Gail Mclaughlin, Daniel Siegel, Kevin Schlaufman, John Ruan, Hsin-Yu Chen, Toshitaka Kajino, Charlie Kilpatrick

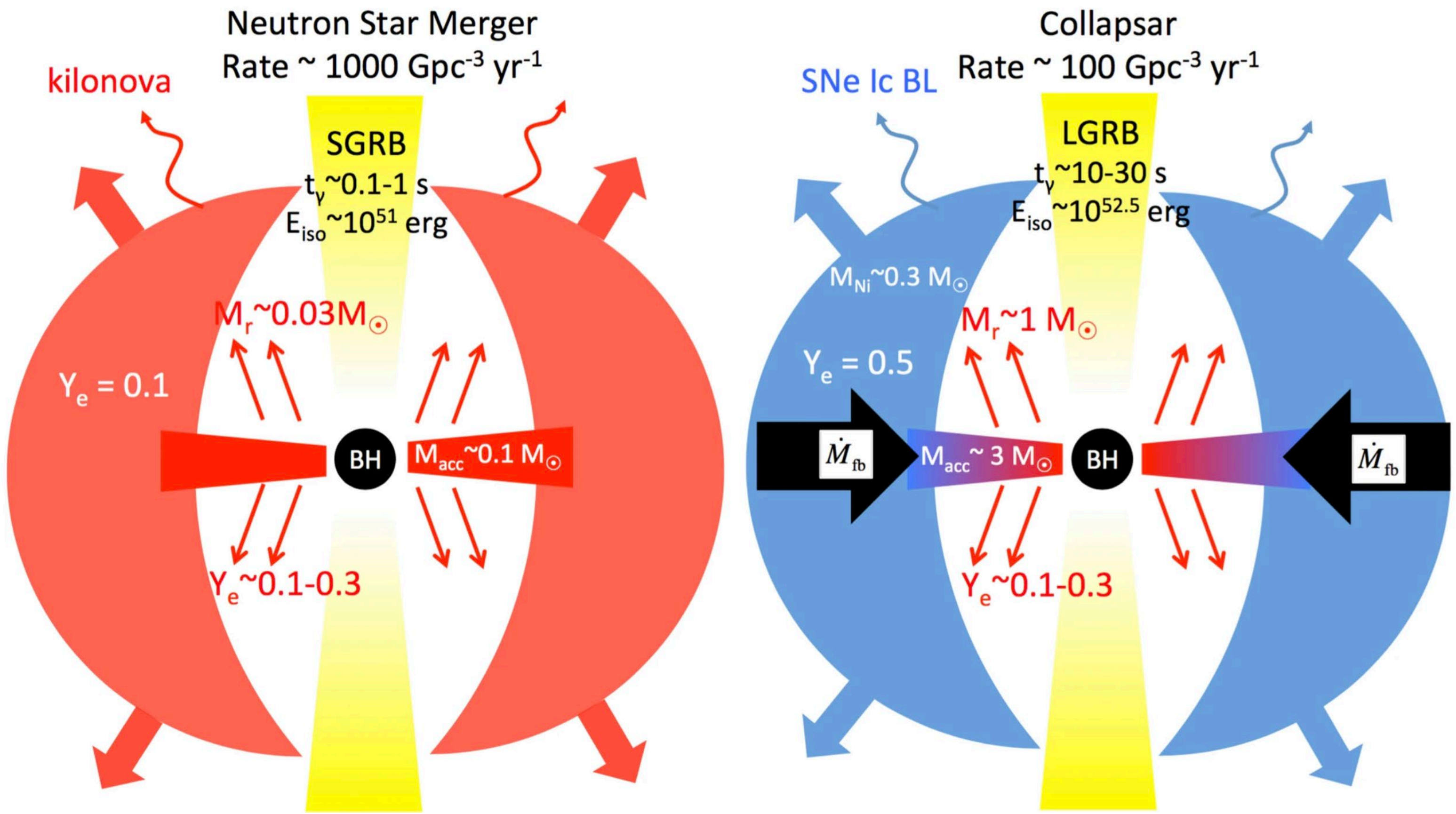
Clues from galactic archaeology

- Eu detections in metal-poor Galactic Halo stars
  - At high Z, matches solar abundance pattern
  - Scatter at low-Z: multiple sites/events?
- [Ba/Fe] and [Eu/Fe] enrichment in dwarf galaxy Reticulum II
  - Rare and prolific enrichment
  - Early enrichment disfavors long merger delay timescales
  - Low mass disfavors NS merger kicks
  - BUT, there may be a population of low-kick, fast-merging binaries (Beniamini+2016)



Cote+2018, Wallner+2015, 2021, Tissot+2016, Ji+2016

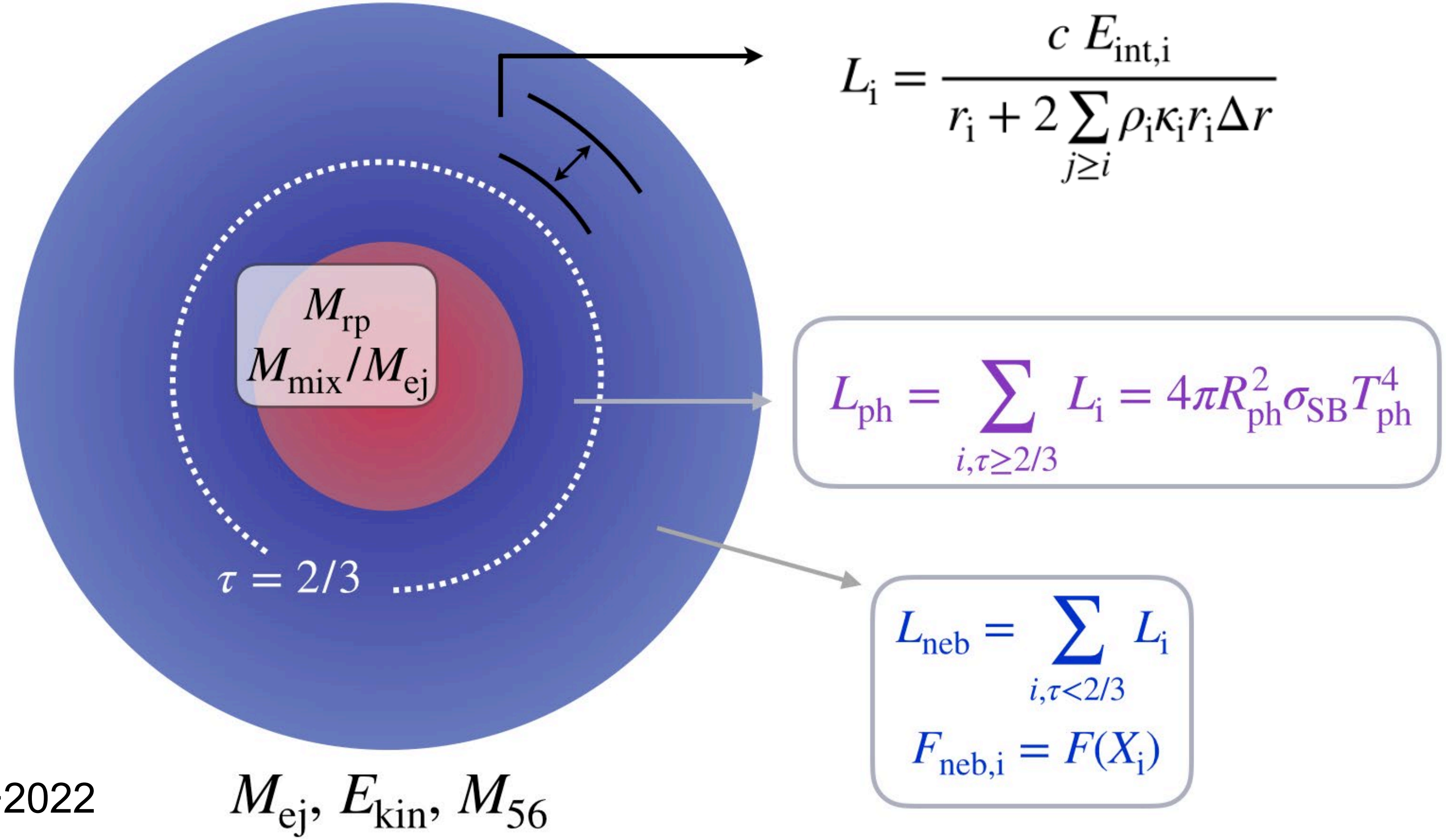
Sites of *r*-process nucleosynthesis



Siegel, Barnes, and Metzger 2019
(See Daniel Siegel's talk from earlier!)

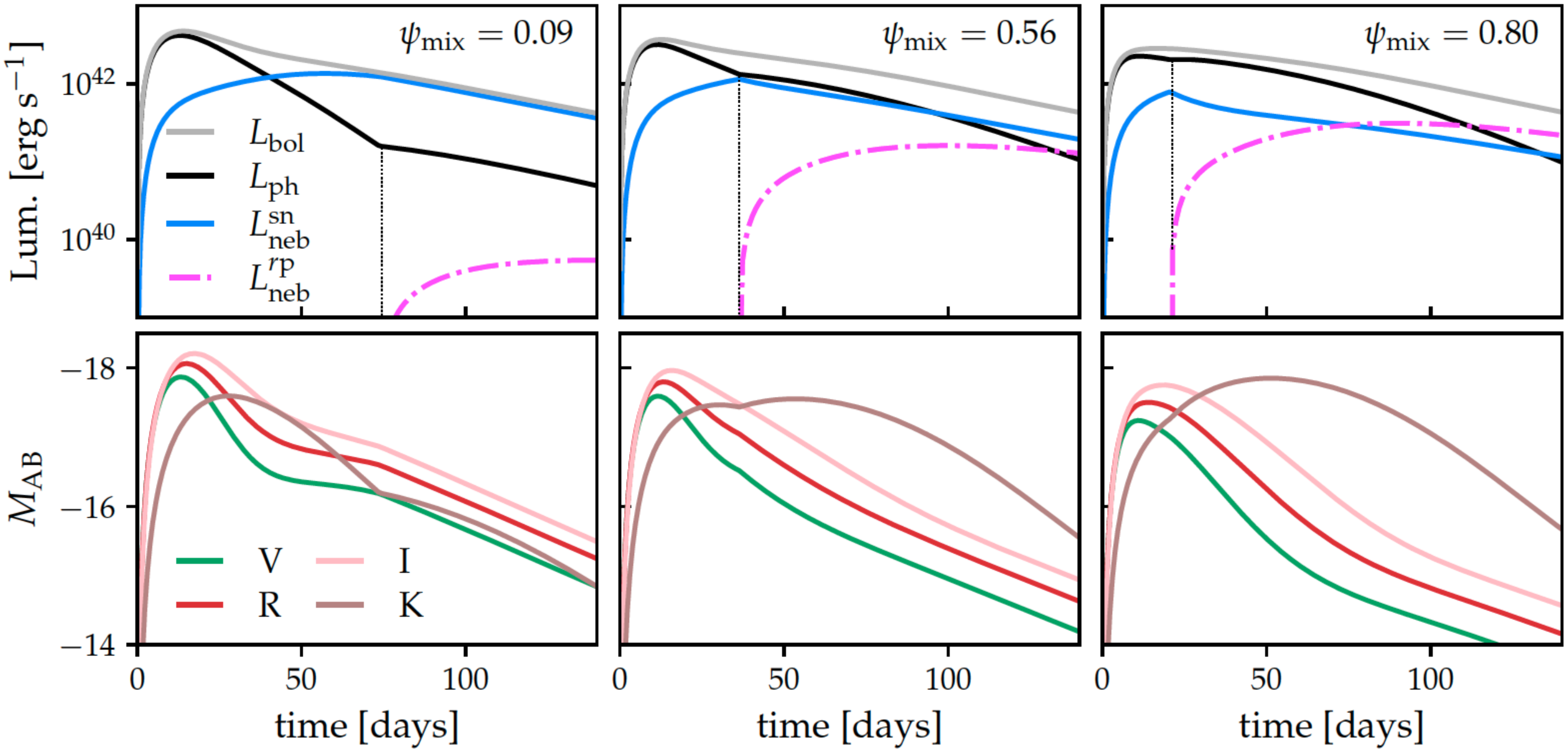
Semi-analytic models for *r*-process production in collapsars

Depending on the level of mixing between *r*-process core and outer SN ejecta, emission could be affected by r-process production even *before* the nebular phase.



Barnes & Metzger+2022

Broadband lightcurve models



Barnes & Metzger+2022

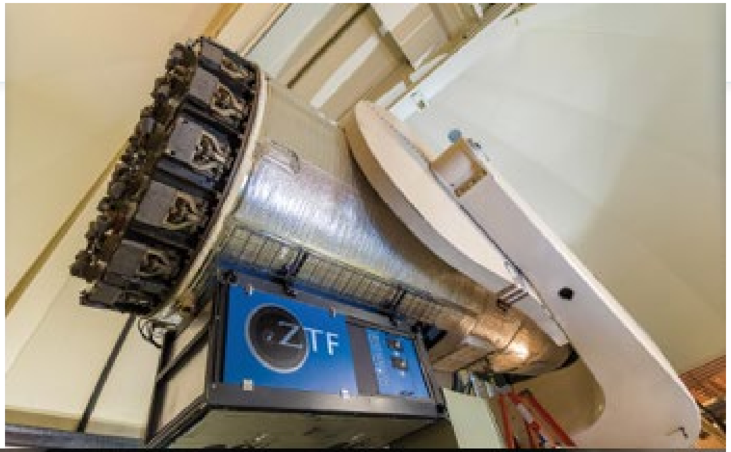
Zwicky Transient Facility

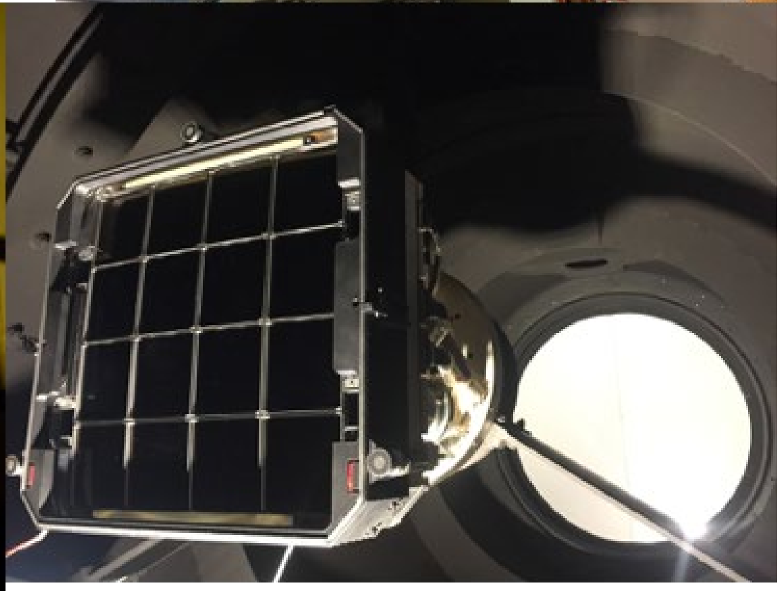
48 square degree FOV imager

mounted on Palomar 48-in telescope

Scans 1000s of sq. deg. in hours

Depth: r~20.5 mag





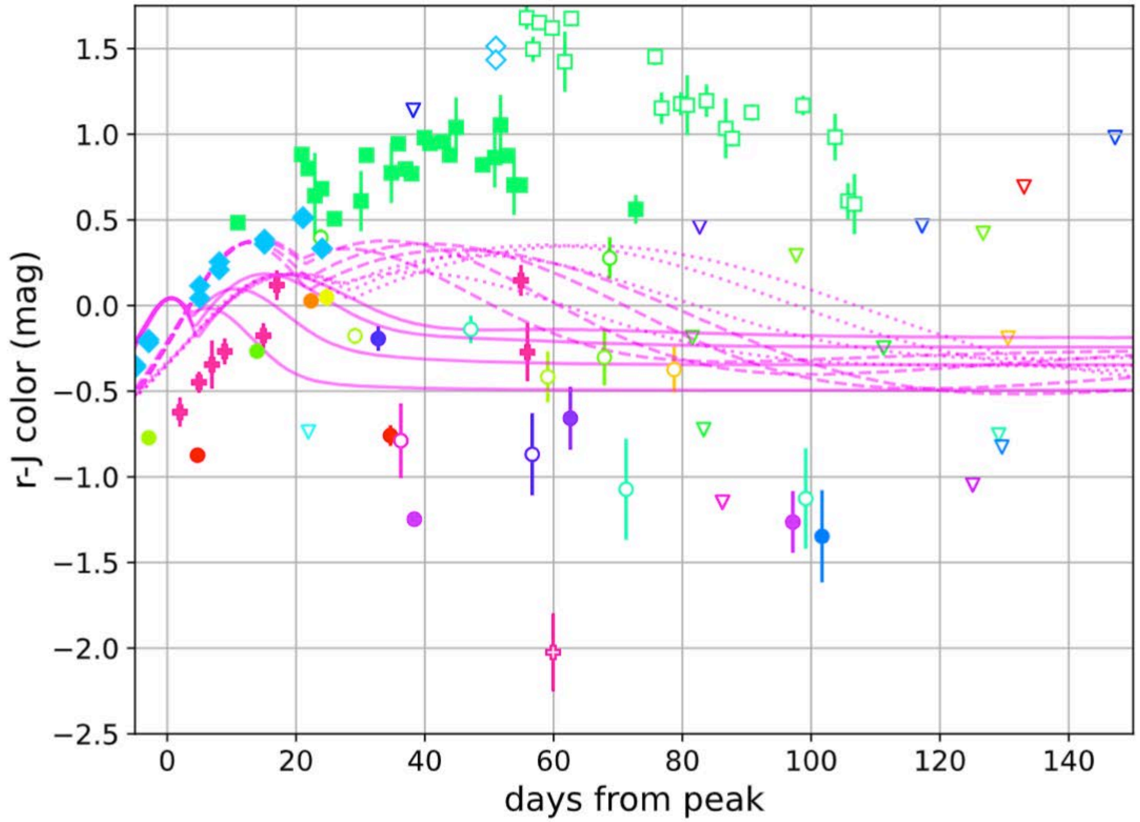
Graham+2019, Bellm+2018, Masci+2019

ZTF Sample selection

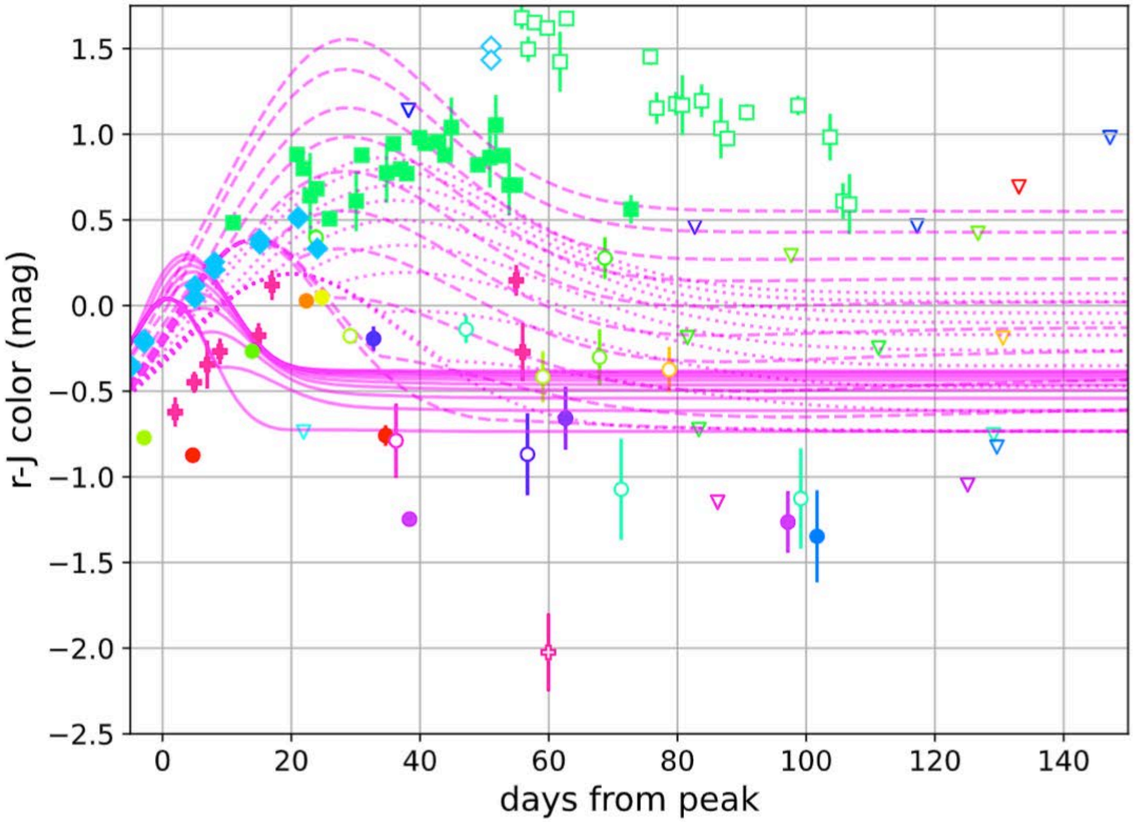
- IcBL SNe: stripped of H, He, high velocity ejecta results in “broad lines”
- 18 SNe discovered via two surveys:
  - Bright Transient Survey: magnitude limited survey that classifies all SNe with m < 19 mag at peak
  - Census of the Local Universe: volume limited survey aimed at classifying all SNe associated with host galaxies within 150 Mpc
- Average discovery rate of ~1/month
- Data collection with the Wide Infrared Camera (WIRC) on Palomar 200 in telescope from 2019-present
- Sample limited to low redshift (within $z < 0.05$)
- Most of them have no coincident GRB

R-J color evolution

Xmix = 0.3, Mrp = [0.01, 0.03, 0.08, 0.15]

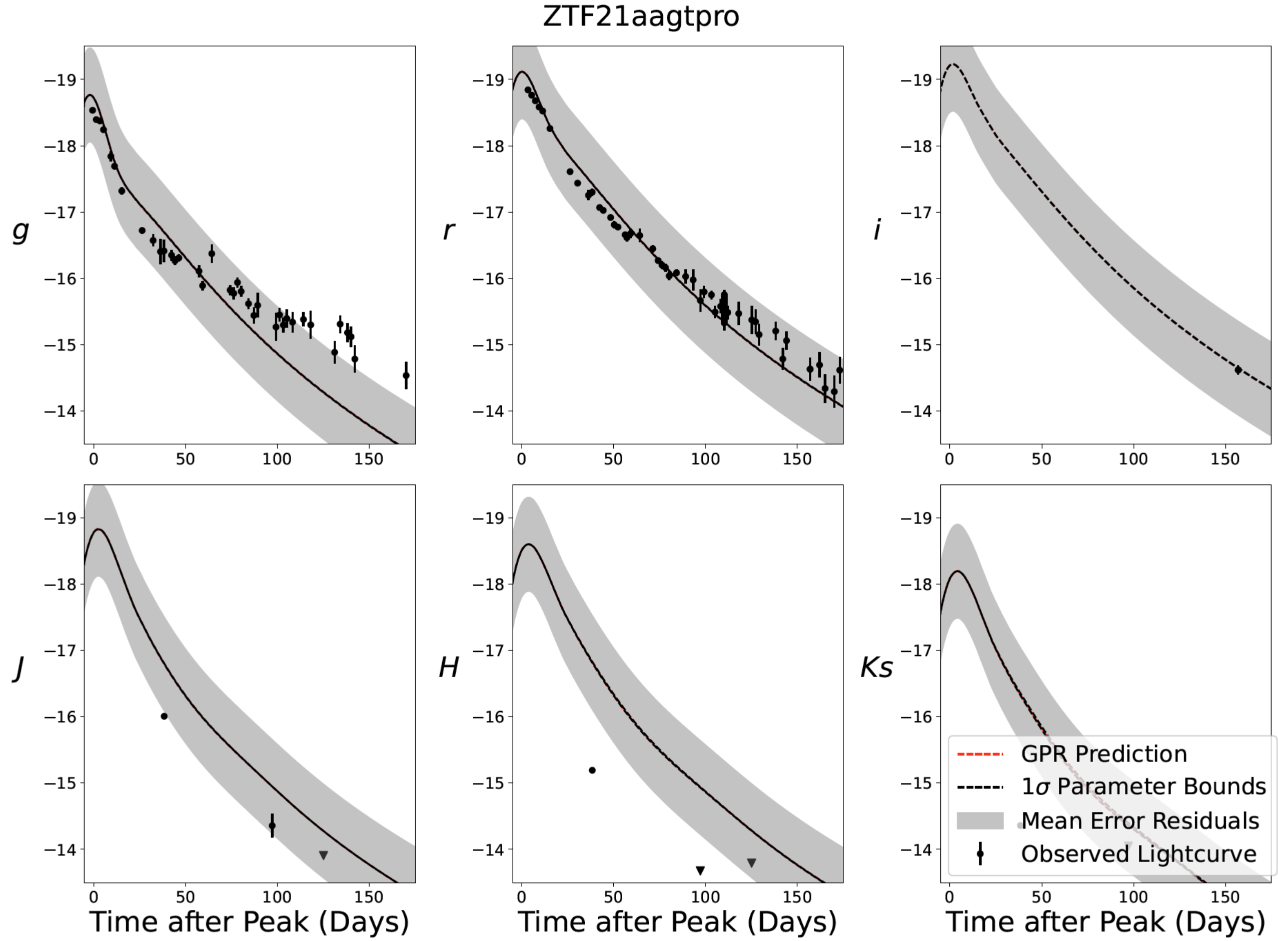


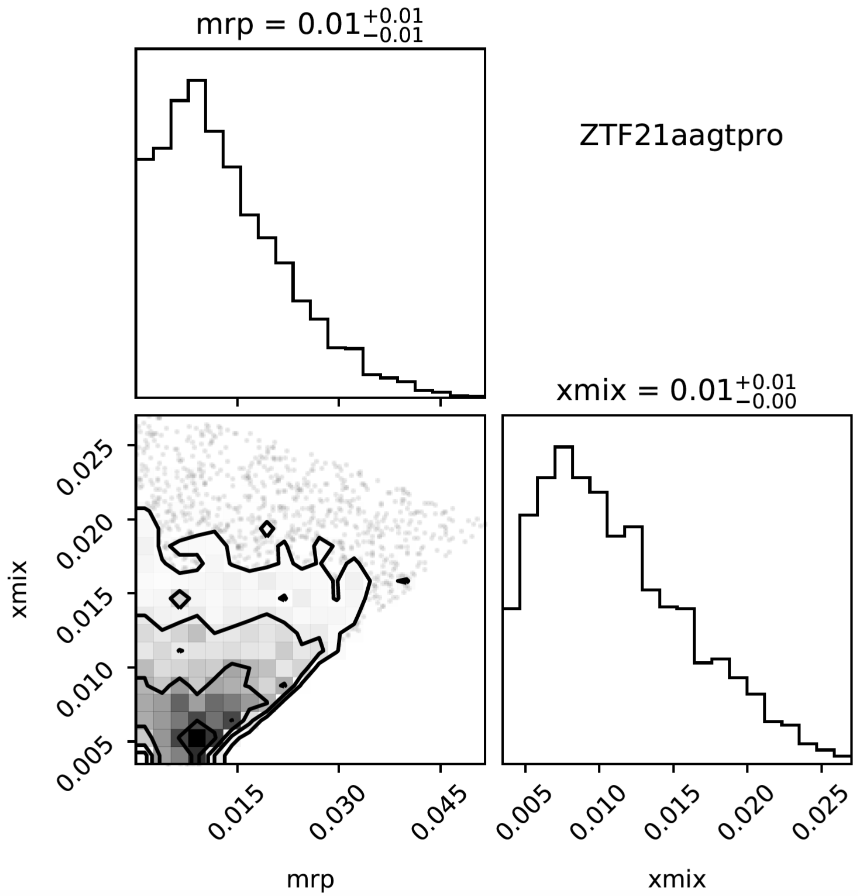
Mrp = 0.01, Xmix = (0.1, 0.9)



Predicted colors are more sensitive to mixing fraction than to *r*-process ejecta mass (Anand+2022, in prep.)

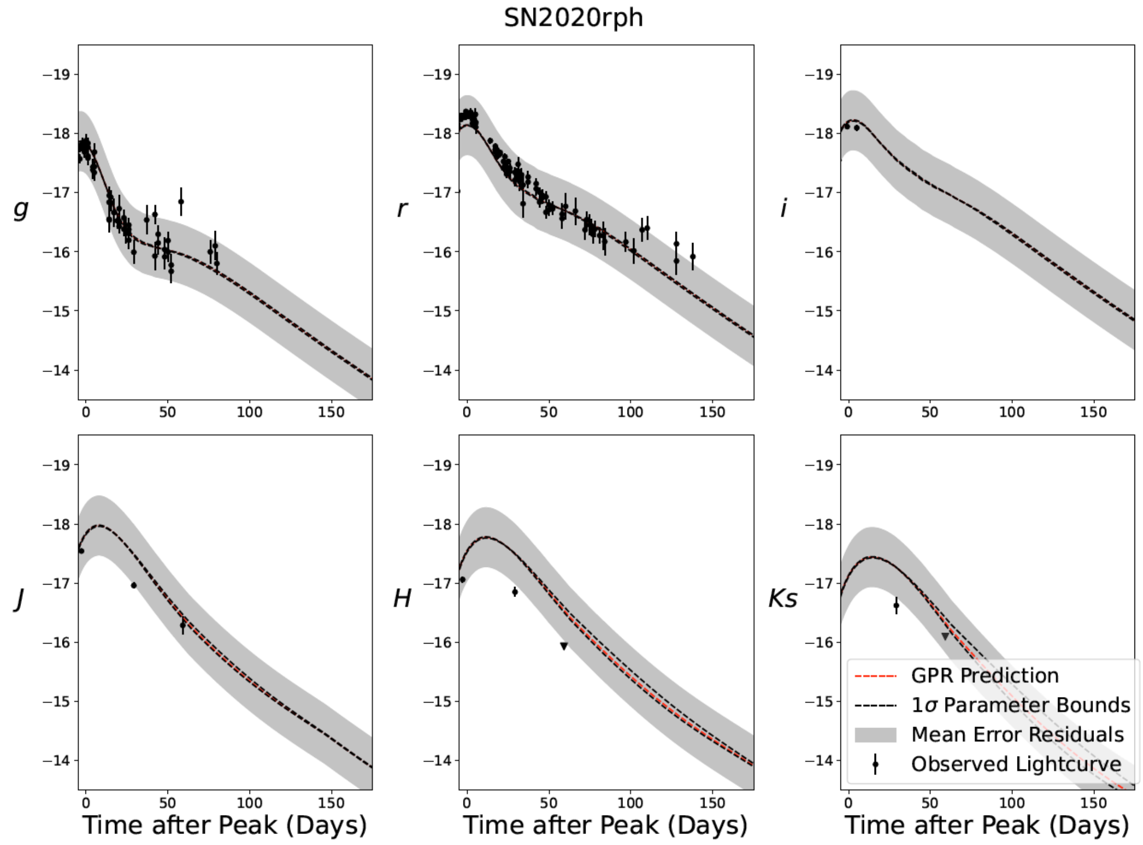
Model fits: little to no *r*-process

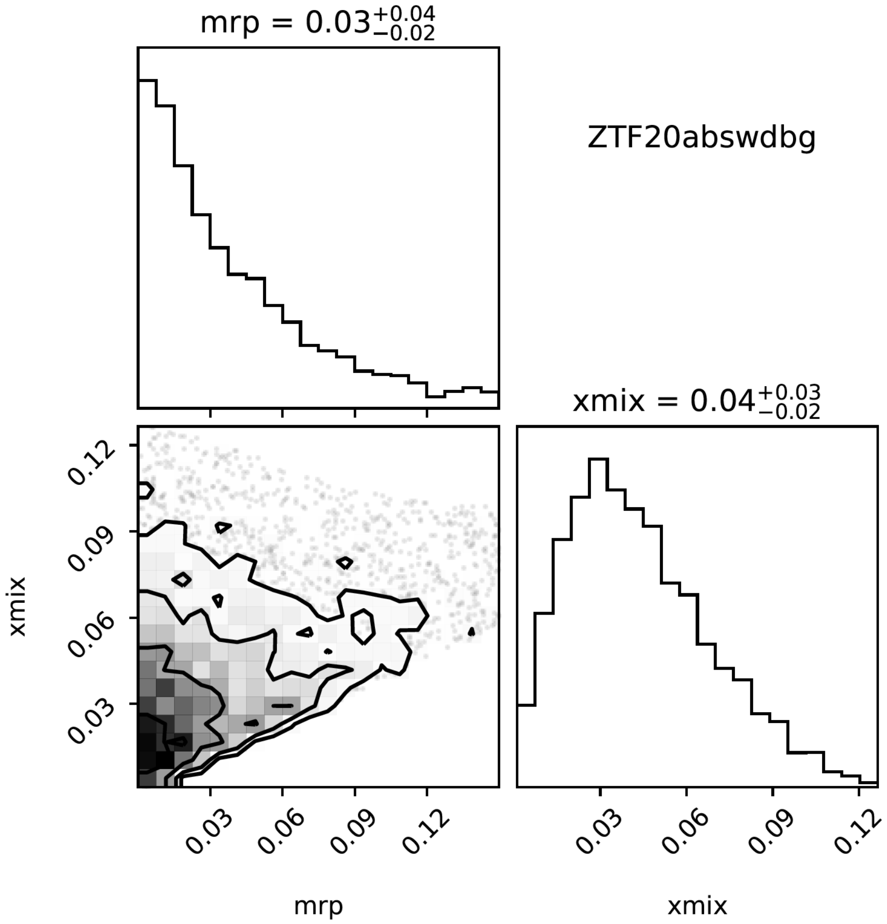




Anand+2022, in prep.

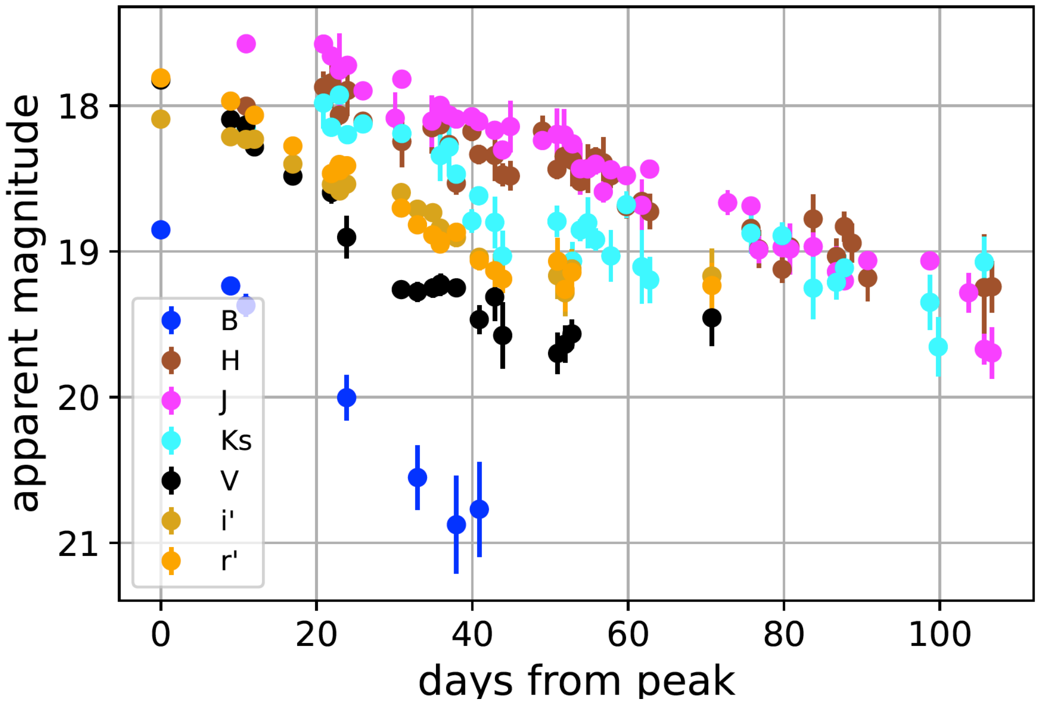
Model fits: mild to moderate *r*-process





Anand+2022, in prep.

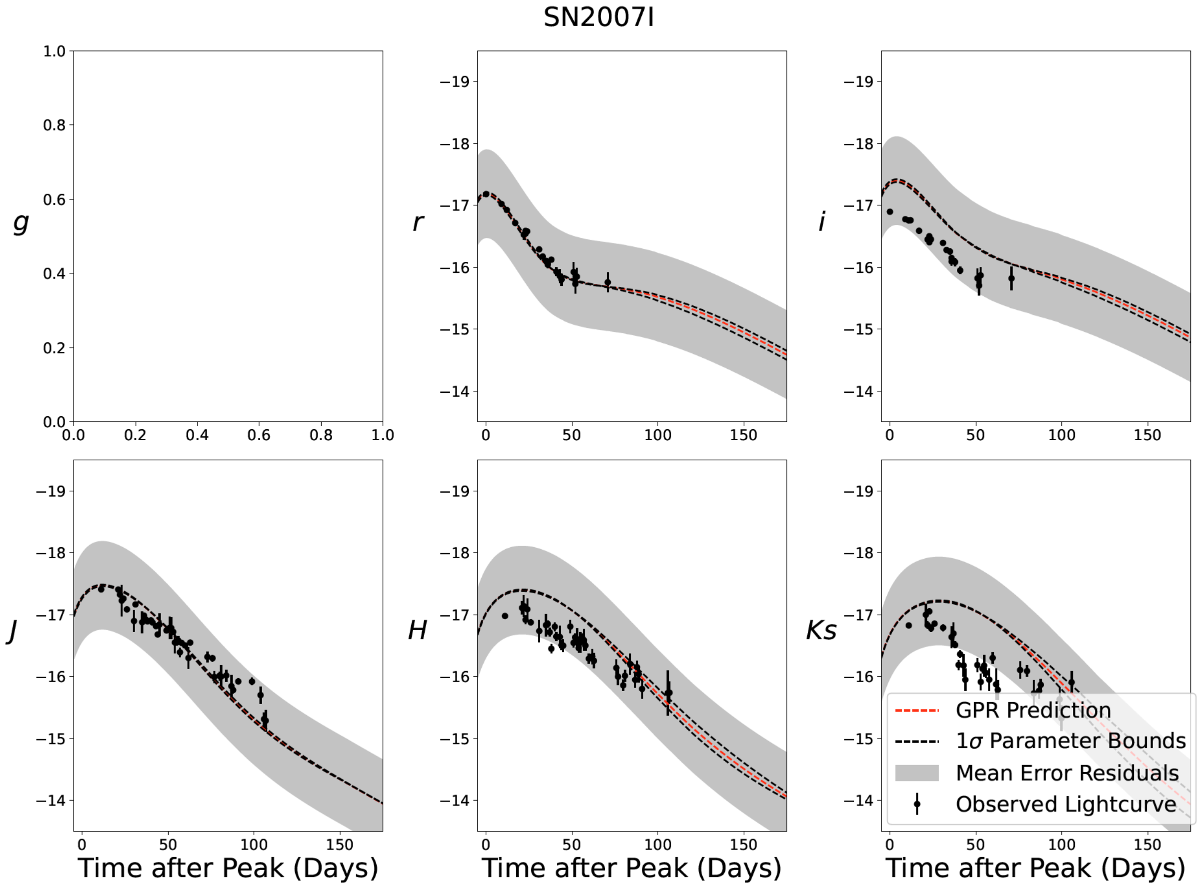
IcBL SNe from the literature with late-time NIR coverage

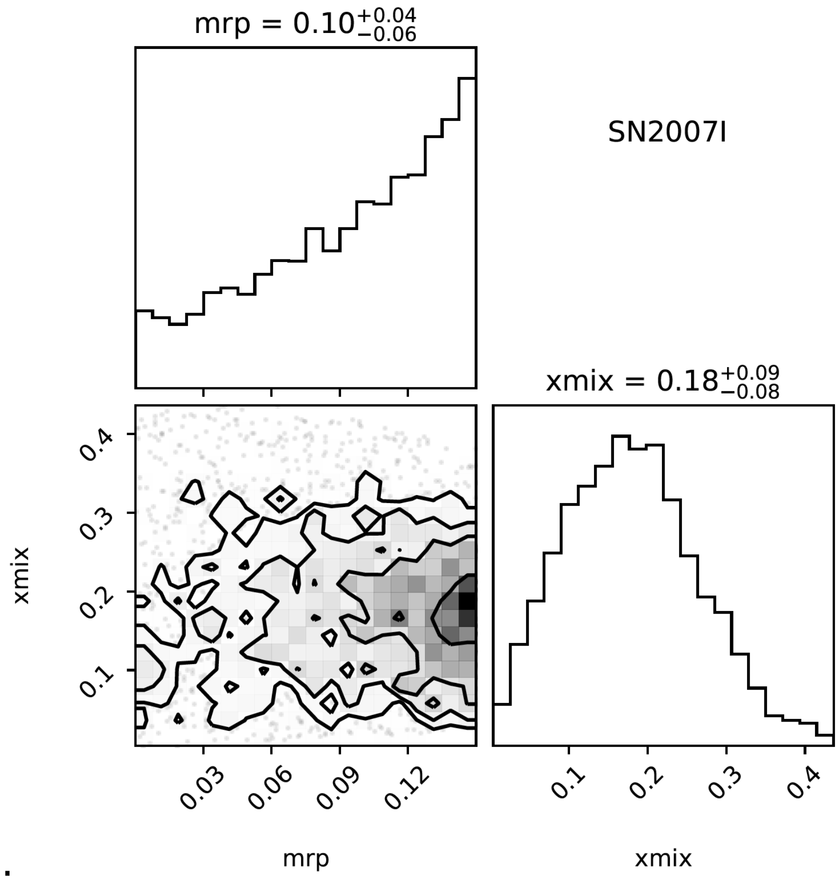


Photometry from Bianco+2014

- SN2007I: Prolific reddening in J,H,Ks
- Located in a small irregular galaxy PGC 1114807
- Lightcurve can't be explained by extinction alone (assuming Rv=3.1)
- In progress: analysis of the OIR lightcurves of SN1998bw, SN2002ap, SN2006aj, SN2010bh, etc

Model fits: strong evidence for *r*-process?

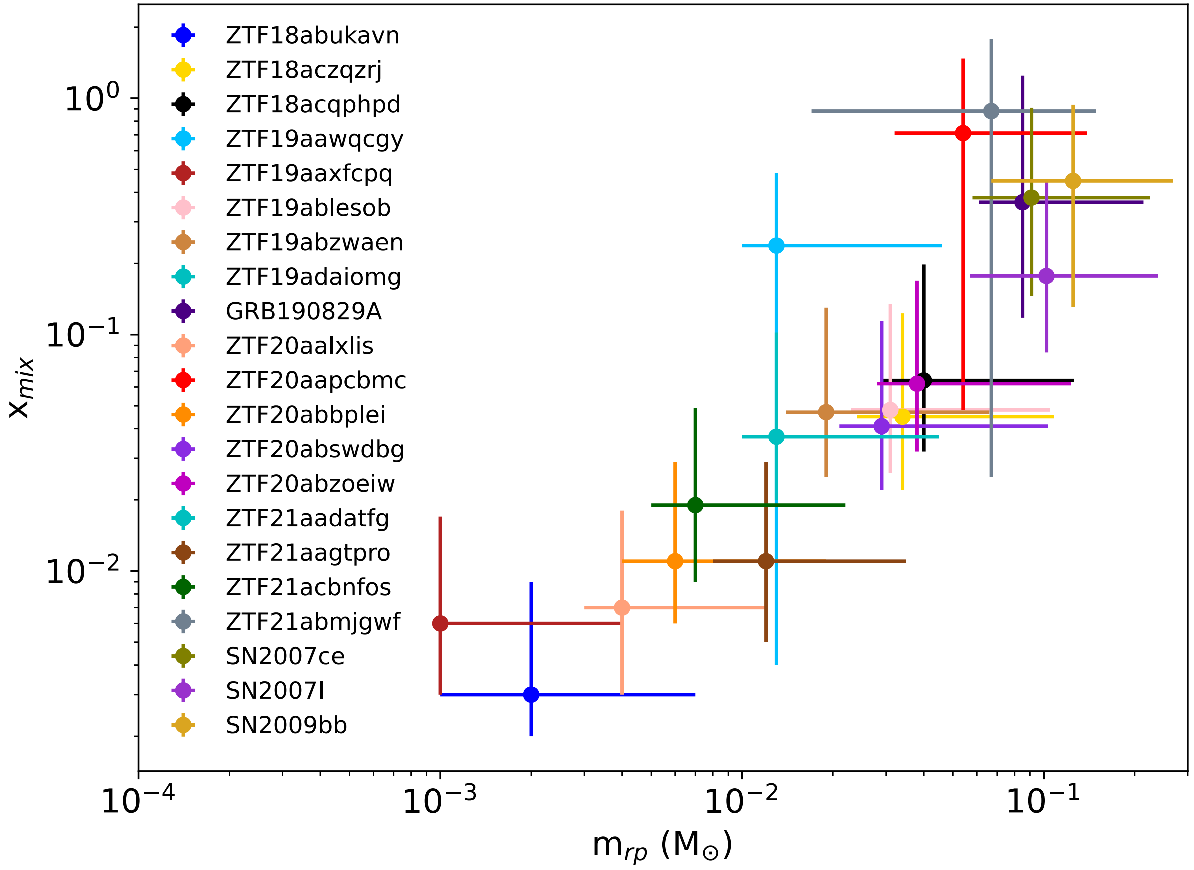




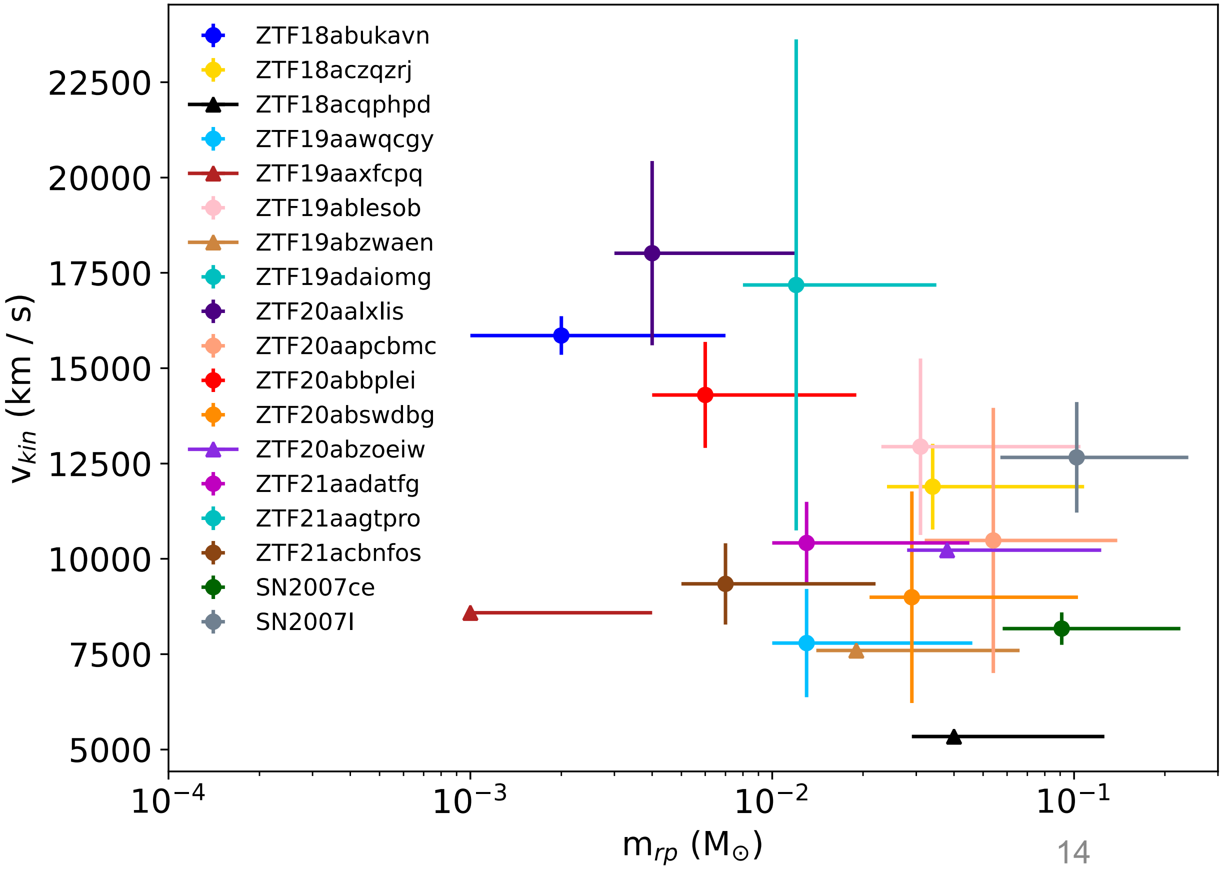
Bianco+2016, Anand+2022, in prep.

Inferred *r*-process ejecta mass and mixing fraction for all SNe

We see correlations between mrp and xmix!



PRELIMINARY: SNe with high velocity show low mrp



Anand+2022, in prep.

No correlations with x-ray/radio observations

IAU name	ZTF name	type	RA	Dec	z	m_{rp}	x_{mix}	Radio[a]	X-ray[b]
SN2018gep	ZTF18abukavn	Ic-BL/FBOT*	16:43:48.21	+41:02:43.29	0.032	0.00	0.00	X$= 34 \pm 4$	< 9.9
SN2019gwc	ZTF19aaxfcpq	Ic-BL	16:03:26.88	+38:11:02.6	0.038	0.00	0.01	-	-
SN2020bvc	ZTF20aalxlis	Ic-BL**	14:33:57.01	+40:14:37.5	0.025	0.00	0.01	X$= 63 \pm 6$	$9.3^{+10.6}_{-6.1}$
SN2020lao	ZTF20abbplei	Ic-BL	17:06:54.61	+30:16:17.3	0.031	0.01	0.01	C$\lesssim 33$	< 2.9
SN2021bmf	ZTF21aagtpro	Ic-BL	16:33:29.41	-06:22:49.53	0.017	0.01	0.01	-	-
SN2021ywf	ZTF21acbnfos	Ic-BL	05:14:11.00	+01:52:52.28	0.028	-	-	B$= 83 \pm 10$	$5.3^{+4.9}_{-3.3}$
SN2021xv	ZTF21aadatfg	Ic-BL	16:07:32.82	+36:46:46.07	0.041	0.01	0.04	A$\lesssim 23$	-
SN2019xcc	ZTF19adaiomg	Ic-BL	11:01:12.39	+16:43:29.30	0.029	0.00	0.84	D$= 62.7 \pm 8.7$	-
SN2019hsx	ZTF19aawqcgy	Ic-BL	18:12:56.22	+68:21:45.2	0.021	0.01	0.24	BnA$\lesssim 19$	$6.2^{+2.3}_{-1.8}$
SN2019qfi	ZTF19abzwaen	Ic-BL	21:51:07.90	+12:25:38.5	0.029	0.02	0.04	-	-
SN2018kva	ZTF18aczqzrj	Ic/Ic-BL	08:35:16.21	+48:19:03.4	0.043	0.03	0.04	-	-
SN2019moc	ZTF19ablesob	Ic-BL	23:55:45.95	+21:57:19.67	0.056	0.03	0.05	-	-
SN2020rph	ZTF20abswdbg	Ic-BL	03:15:17.82	+37:00:50.57	0.042	0.03	0.04	B$= 42.7 \pm 7.4$	< 3.6
SN2018jaw	ZTF18acqphpd	Ic-BL	12:54:04.10	+13:32:47.9	0.047	0.04	0.06	-	-
SN2020tkx	ZTF20abzoeiw	Ic-BL	18:40:09.01	+34:06:59.5	0.027	0.04	0.06	B$= 286 \pm 15$	< 3.3
GRB190829A	-	LLGRB	2:58:10.580	-8:57:29.82	0.077	0.08	0.36	-	-
SN2020dgd	ZTF20aapcbmc	Ic-BL	15:45:35.57	+29:18:38.4	0.03	0.05	0.71	-	-
SN2021too	ZTF21abmjgwf***	Ic-BL	21:40:54.28	+10:19:30.33	0.035	0.07	0.88	-	ND

Table 1. Sample summary table of Ic-BL supernovae. a) Flux density in μJy with the VLA. We list only the first VLA observation at $\lesssim$50 days from the first ZTF detection as reported in Corsi in prep.. b) Swift XRT flux in units of 10^{-14}erg cm^{-2} s^{-1}, taken from Corsi in prep. *This Ic-BL SN is also categorized as a fast blue optical transient, and was published in Ho et al. 2019. **This Ic-BL had a double-peaked lightcurve from shock-cooling; x-ray and radio measurements taken from Ho et al. 2020. ***No VLA coverage, but a non-detection with NOEMA.

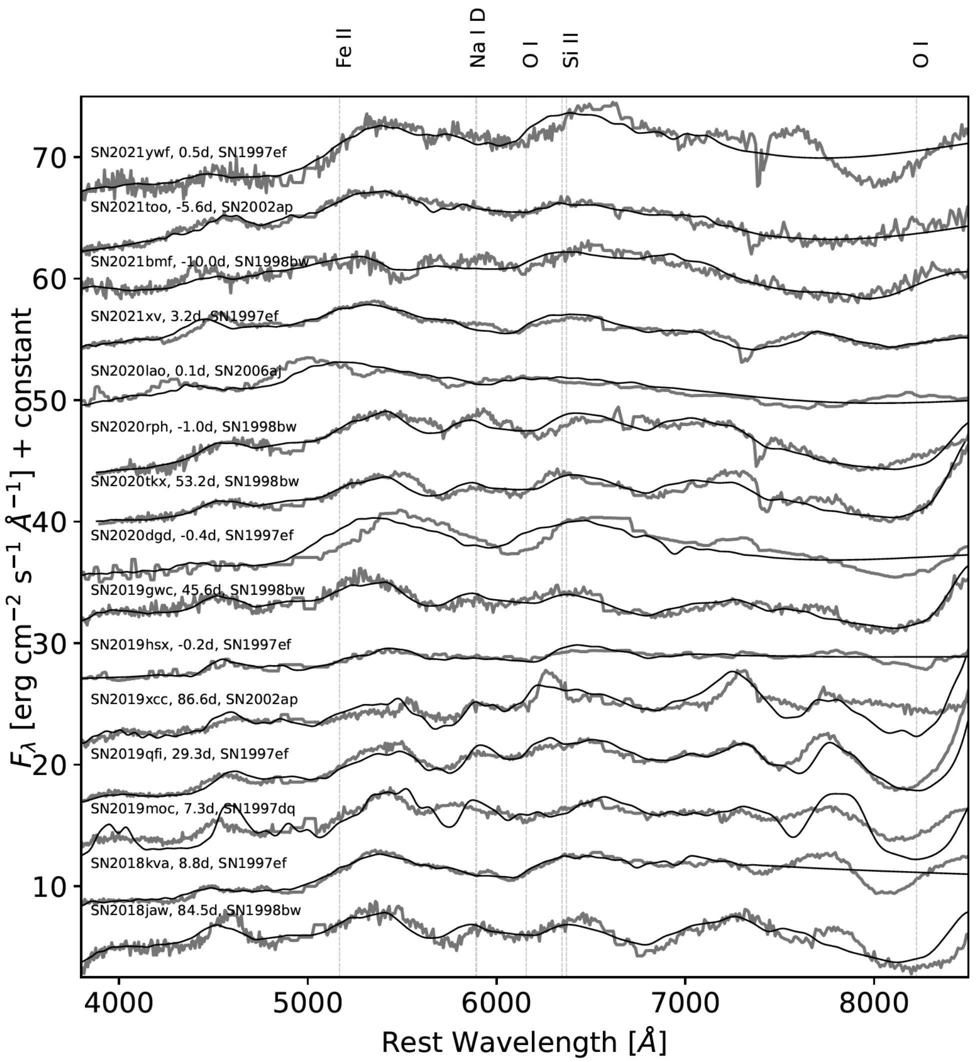
Summary and open questions

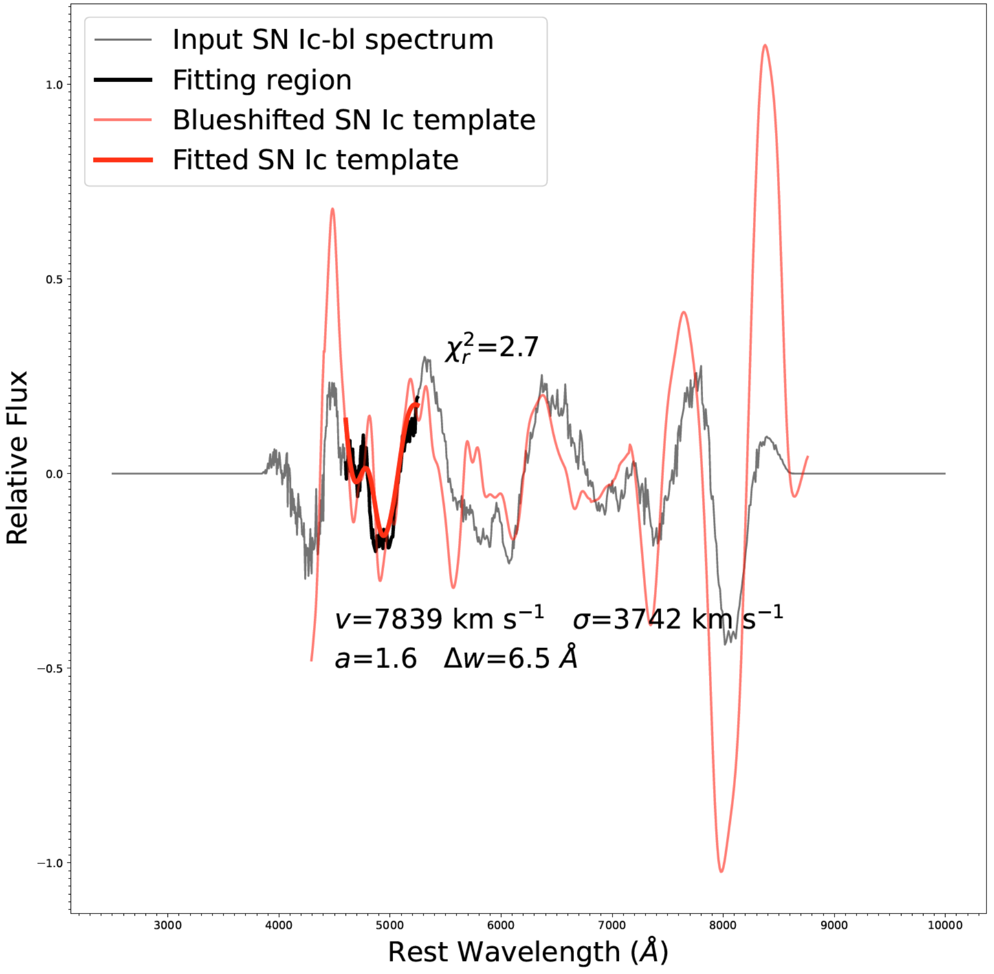
- Summary: 18 ZTF-discovered IcBL with optical/NIR coverage, and 3 more from literature to test for late-time NIR excess + a few more from literature
- Result: Wide diversity in the inferred *r*-process yield from collapsars
  - 1) for 7 SNe, we observe little to no rprocess (xmix < 0.1, mrp < 0.02 Msun)
  - 2) for 8 SNe we observe moderate r-process (xmix < 0.2, mrp < 0.06)
  - 3) for 6 SNe, we see compelling evidence for strong r-process!
- Open questions:
  - What else can cause reddening in LC? (i.e. extinction, dust formation…)
  - What are the characteristics of collapsars that synthesize *r*-process elements? So far, no correlation with jet properties.

Thanks for listening!

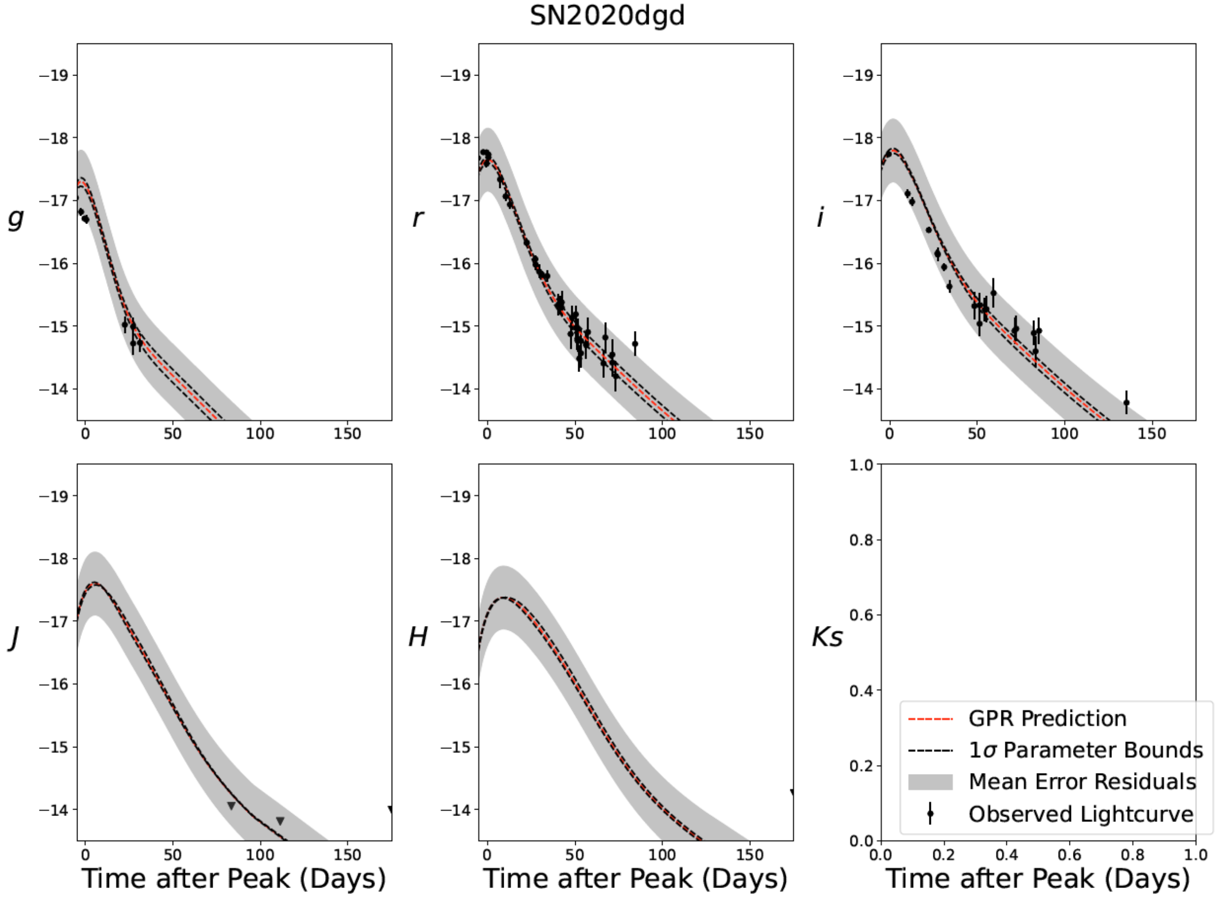
Backup Slides

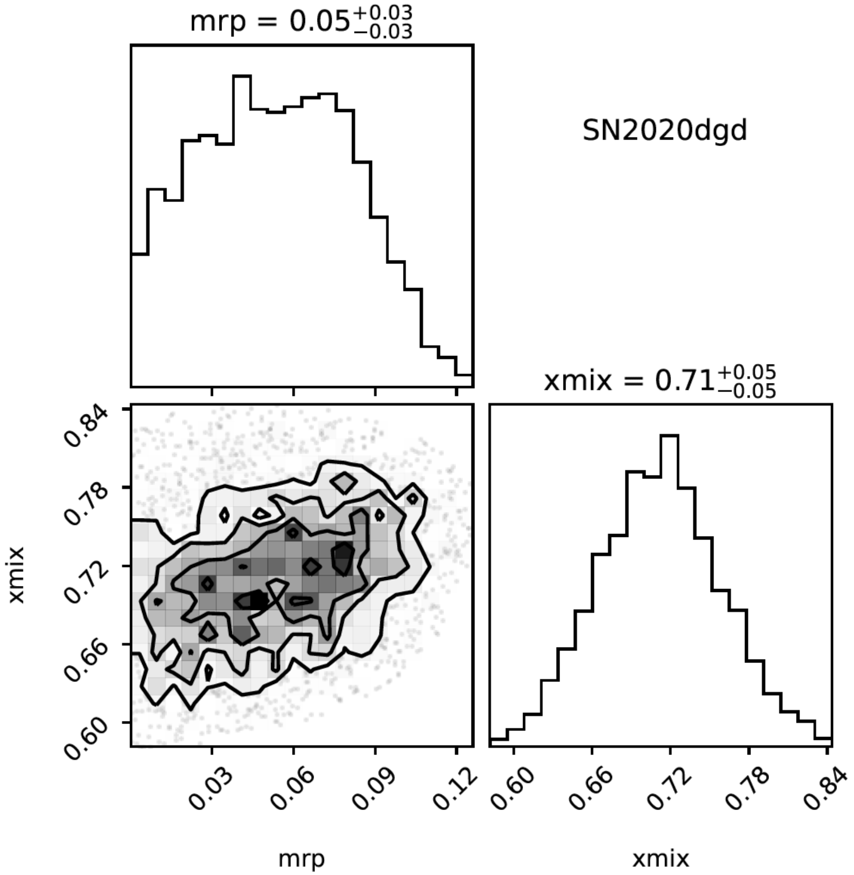
Classification and velocity estimation





ZTF SN showing evidence for strong *r*-process from optical bands





Anand+2022, in prep.

Elemental "fingerprints" of cosmic alchemy

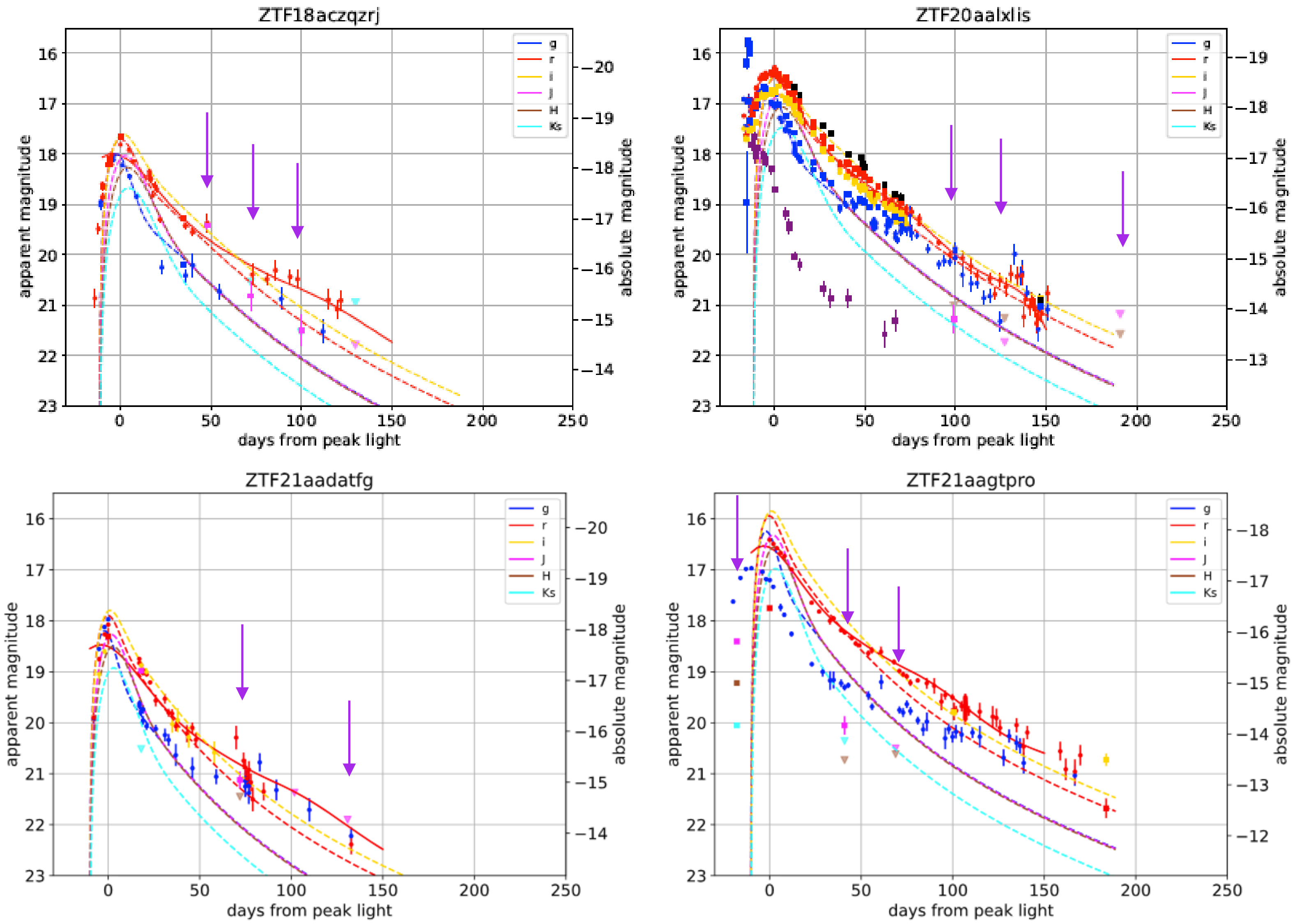
- ^{244}Pu and ^{60}Fe measured in the deep sea
  - Concurrent ^{244}Pu and ^{60}Fe suggest a SN site
  - Low relative ^{244}Pu abundance: CCSN rates incompatible
- ^{247}Cm inferred in a Calcium-Aluminum Inclusion meteorite
  - Different decay timescales suggest multiple *r*-process events

Plutonium

Uranium

Europium

Cote+2018, Wallner+2015, 2021, Tissot+2016, Ji+2016

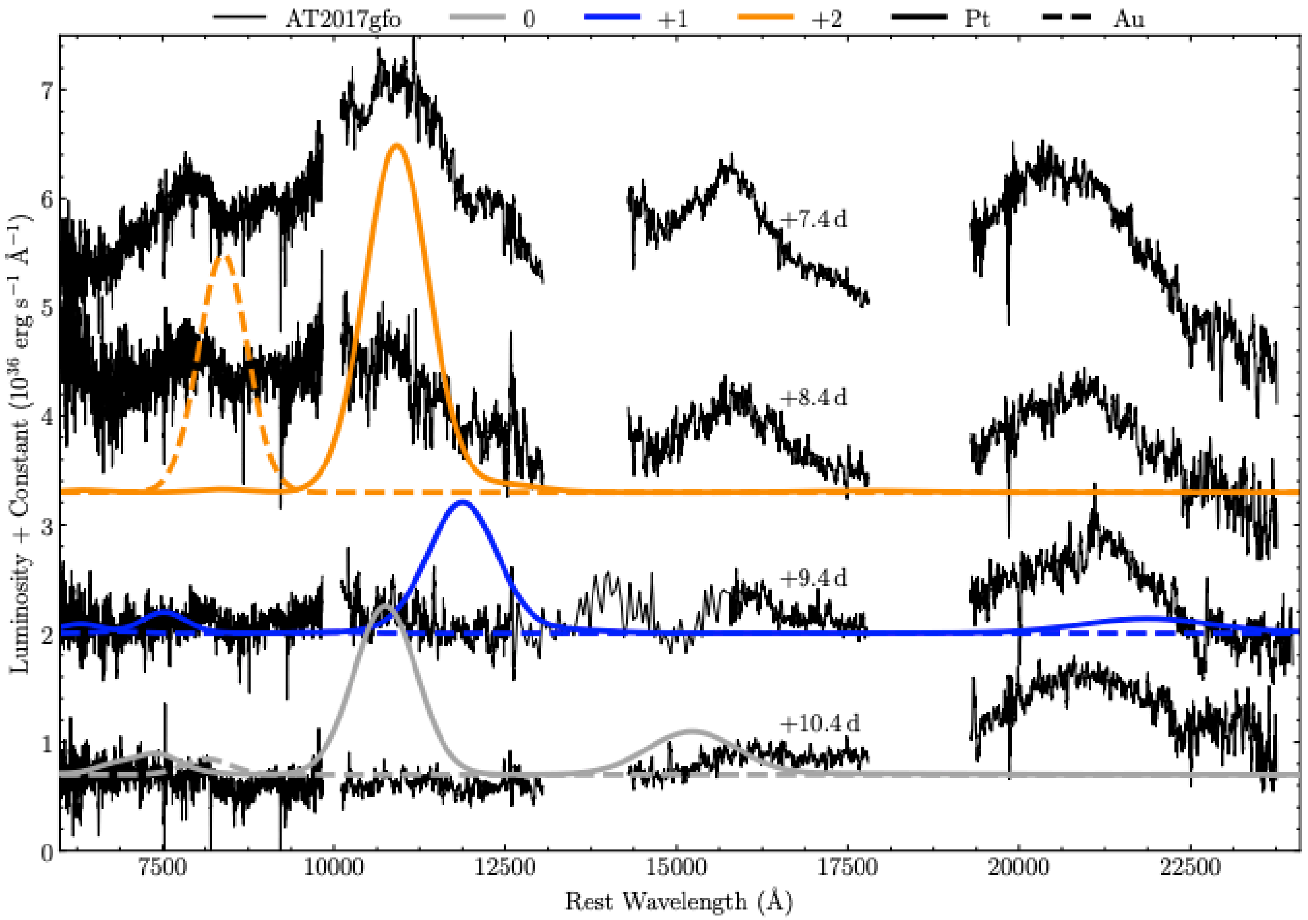


Some supernovae appear redder than the non *r*-process models, while others are bluer.

Alternative scenarios to *r*-process

- Host extinction – Na I D line in optical spectrum
- Dust formation – g+r monitoring at late-times can help rule out dust formation
- Molecular features – check NIR spectrum for any such features

Nebular phase kilonova spectra



Gillilanders+2021

Fitting an extincted blackbody to SN2007I