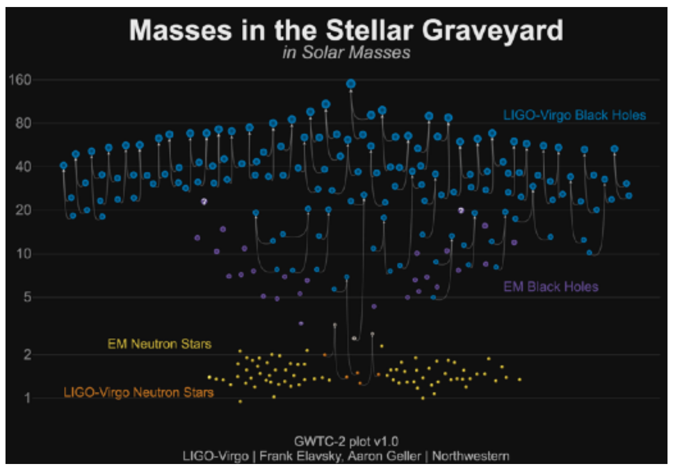
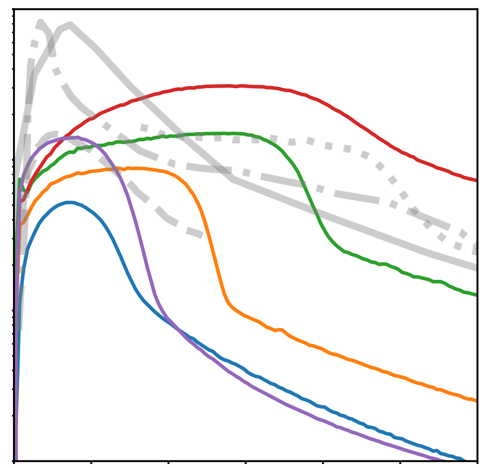
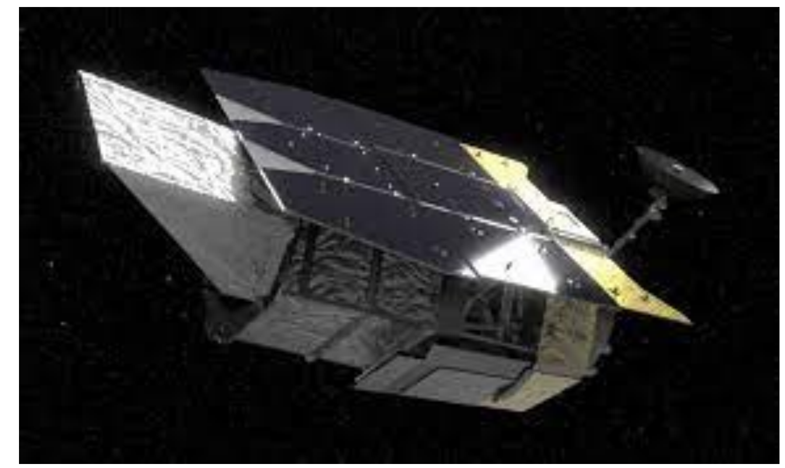
“Super-Kilonovae” as Signatures of Black-Hole Birth in the Pair-instability Mass Gap







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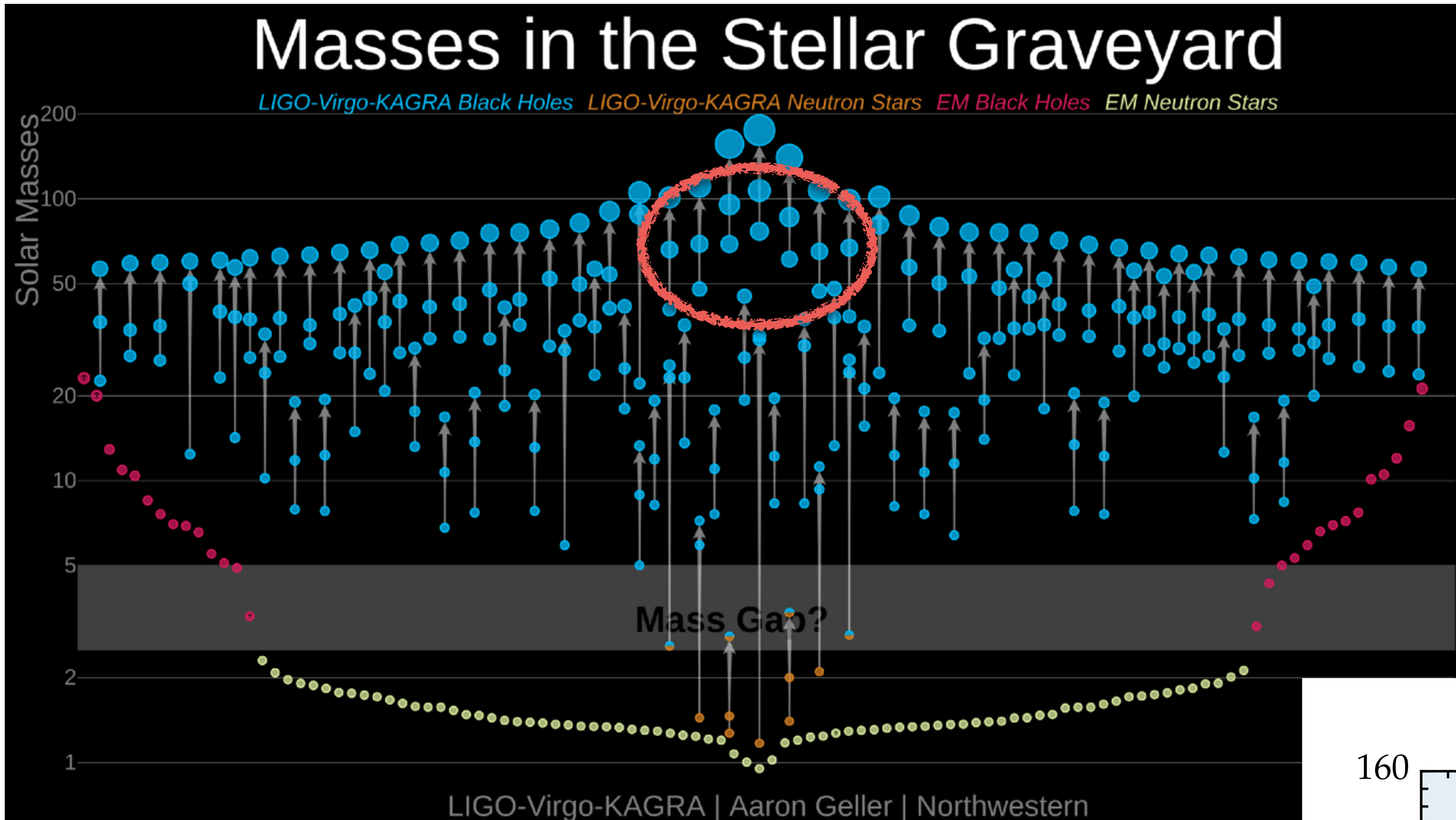
Roman Time Domain Science Conference, Feb 9, 2022

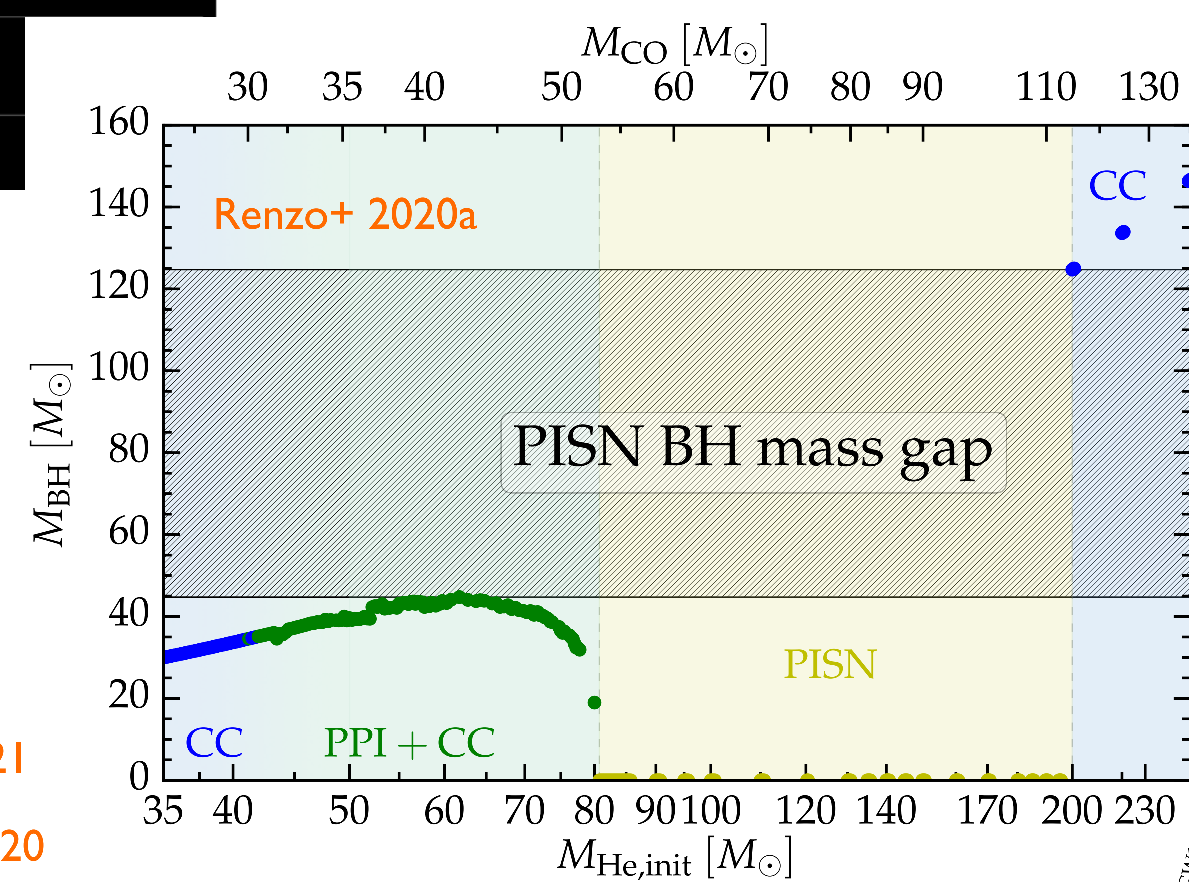
Together with: Aman Agarwal, Jennifer Barnes, Brian Metzger, Mathieu Renzo, Ashley Villar

Siegel+ 2022, arXiv:2111.03094

Black holes in the pair-instability mass gap



PISN BH mass gap

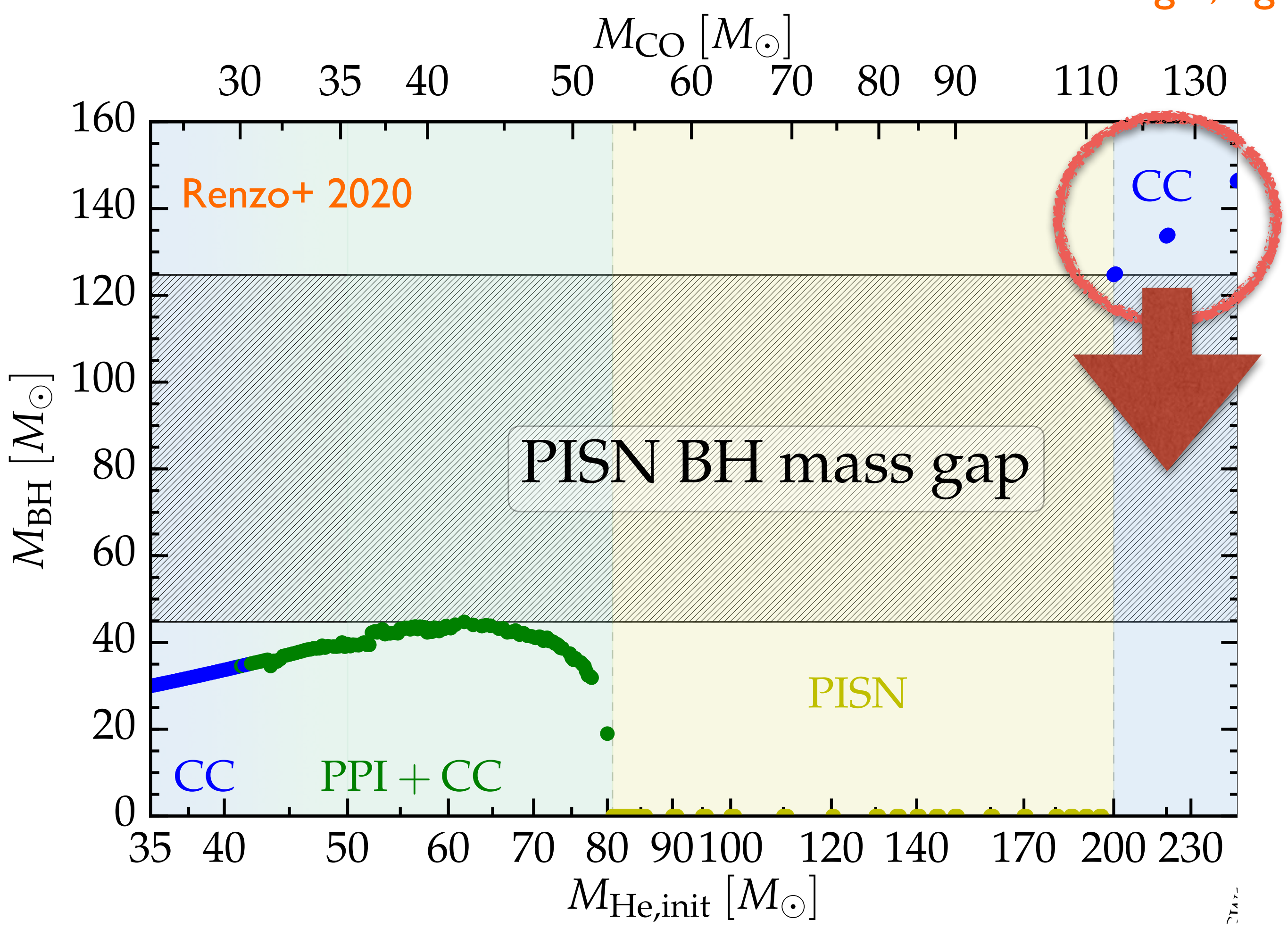


How to populate the PISN BH mass gap?

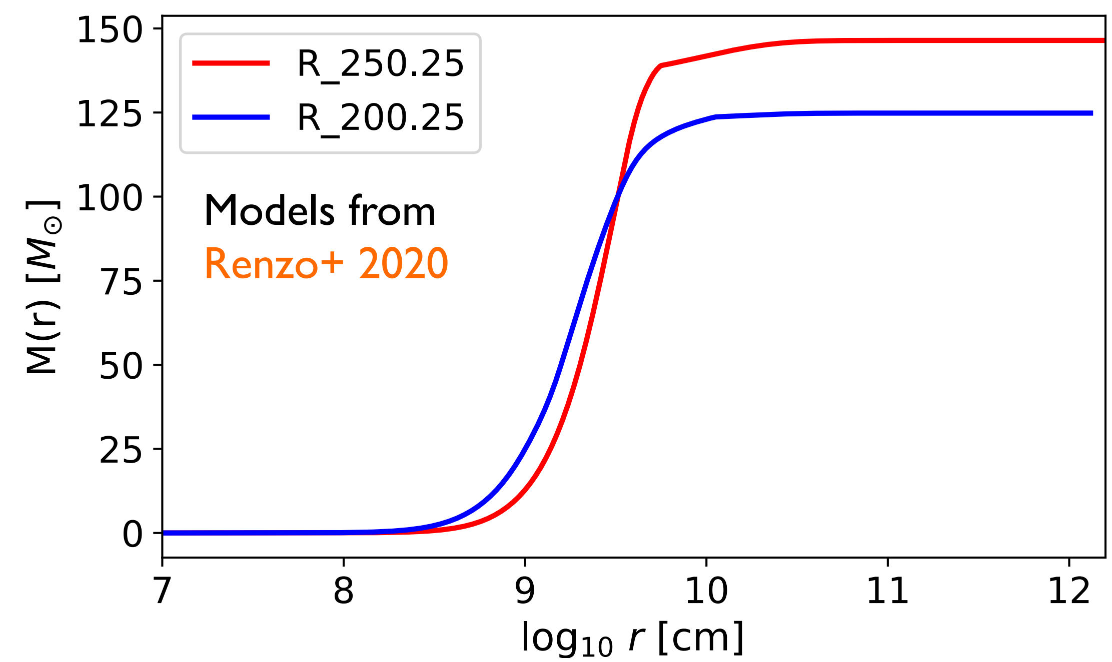
- Stellar mergers DiCarlo+ 2019, Renzo+ 2020b
- Hierarchical BBH mergers Antonini & Rasio 2016, …
- Modifying stellar physics at low metallicity Farell+ 21, Vink+ 21
- Gas accretion onto PopIII remnant BHs Safarzadeh & Haiman 20
- To some extent: nuclear reaction rates & rotation Woosley & Heger 21, …

Massive collapsars form BHs in the pair-instability mass gap

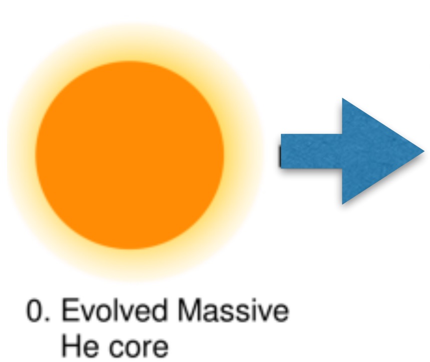
Siegel, Agarwal, Barnes, Metzger, Renzo, Villar 2022, arXiv:2111.03094

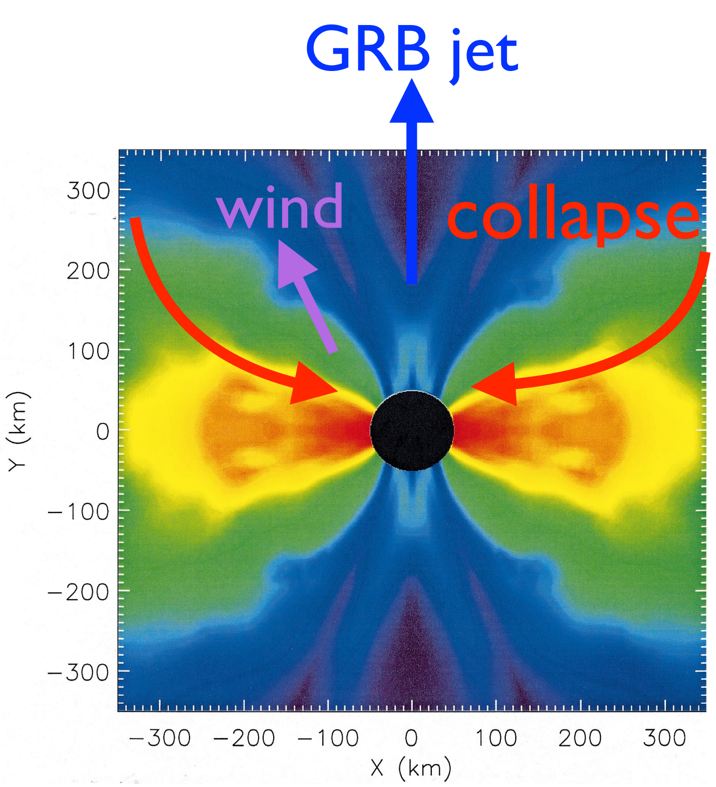


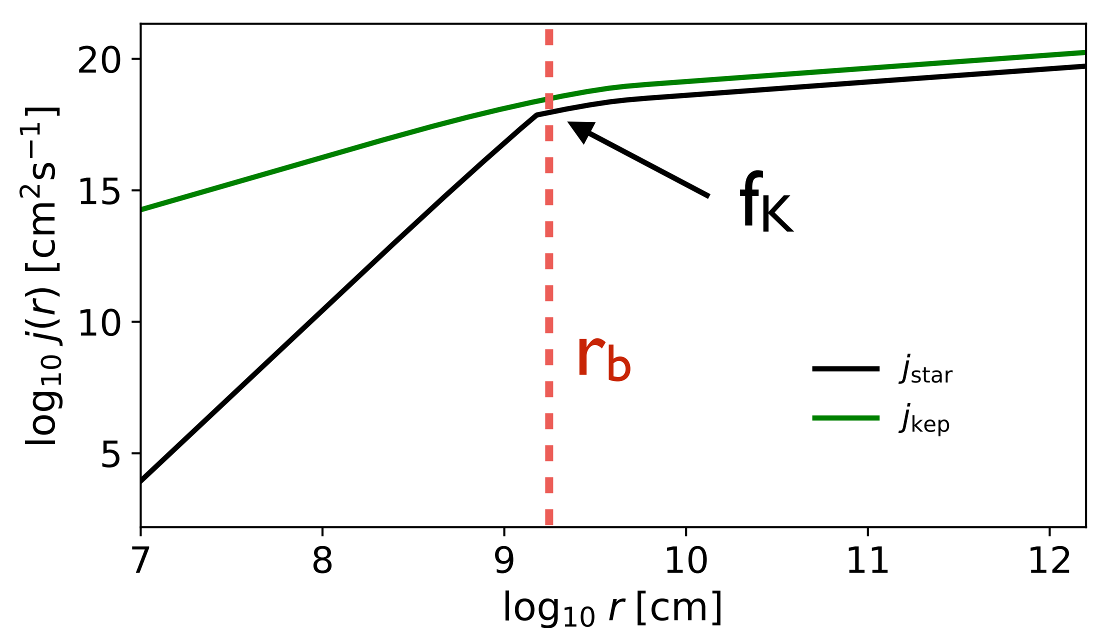
- fill the PISN mass gap "from above"
- compact massive progenitors >130 M_{sun}
- endowed with parametrized rotation profile



Collapse of massive, rapidly rotating progenitors > 130 M_{sun}







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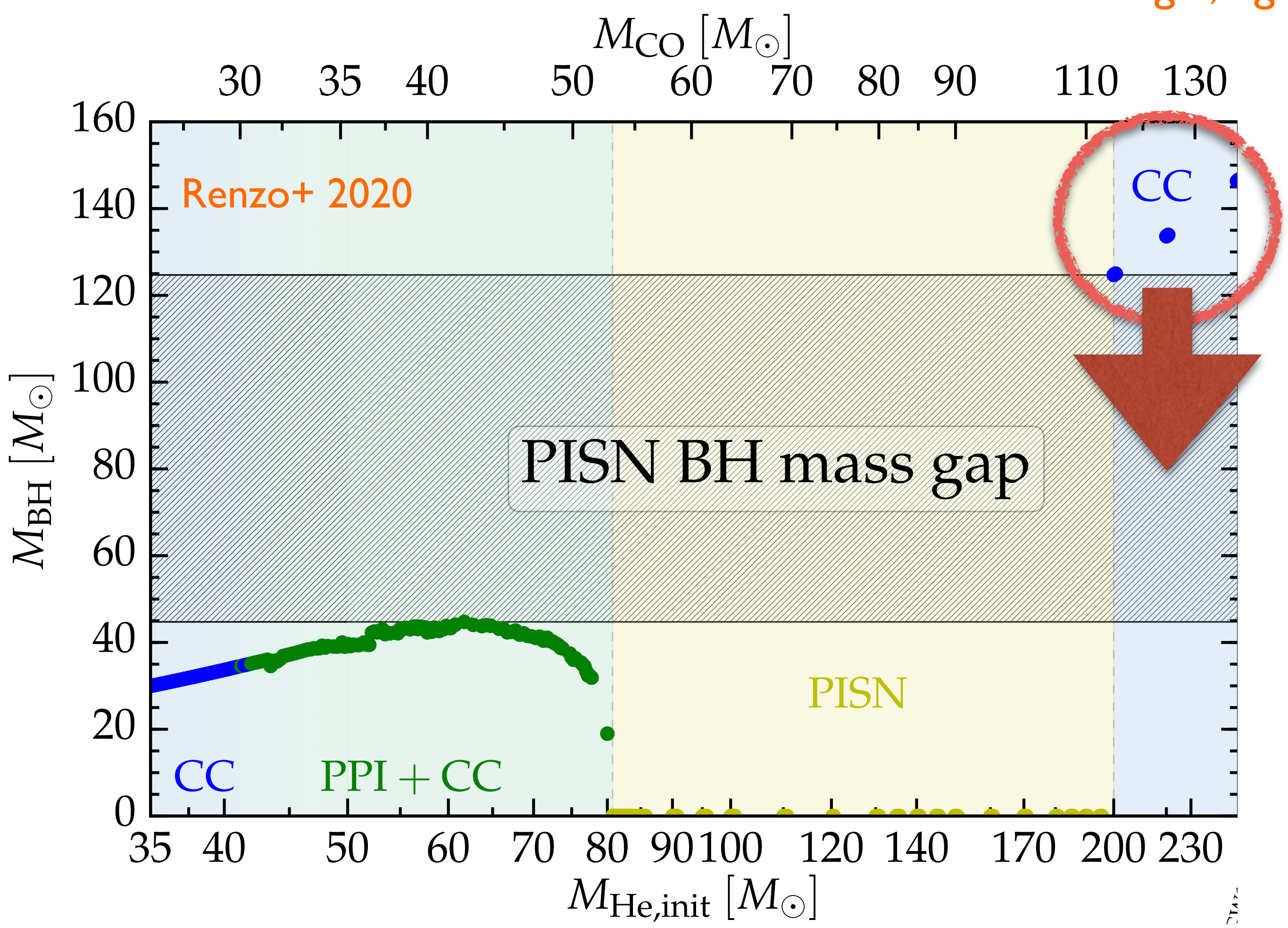

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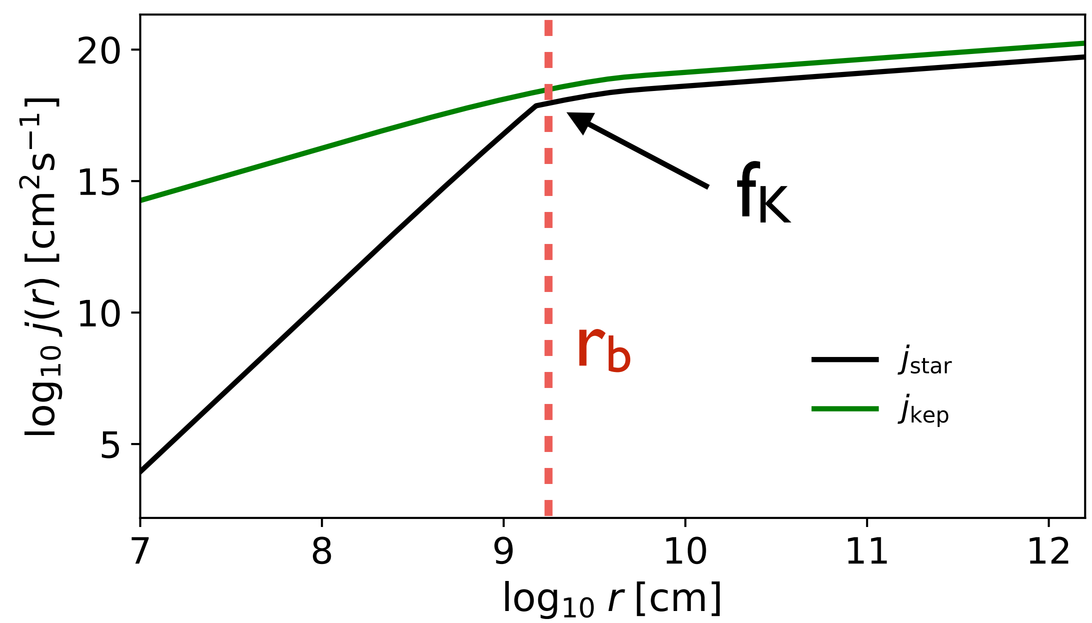

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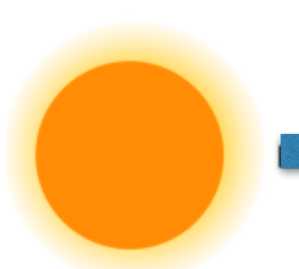
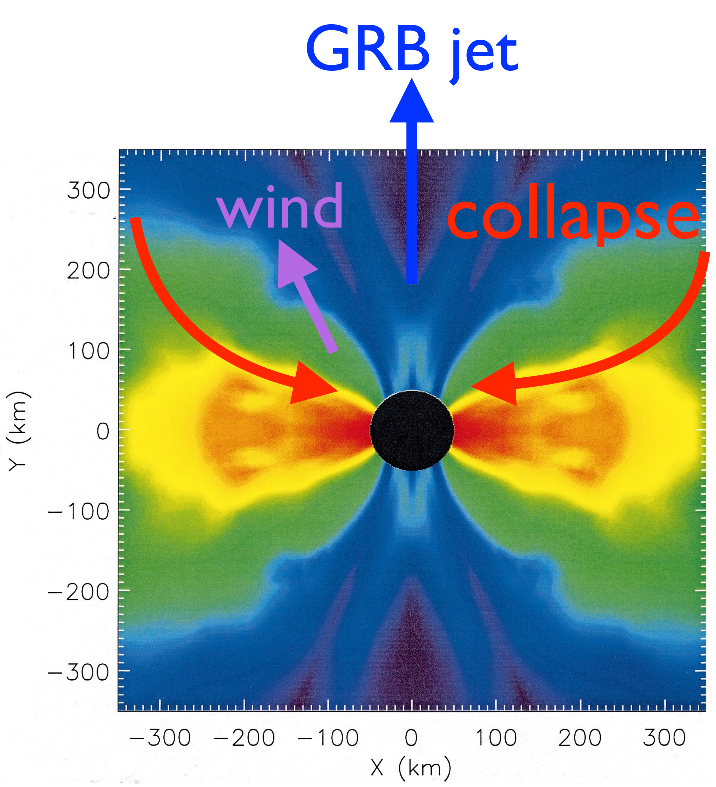
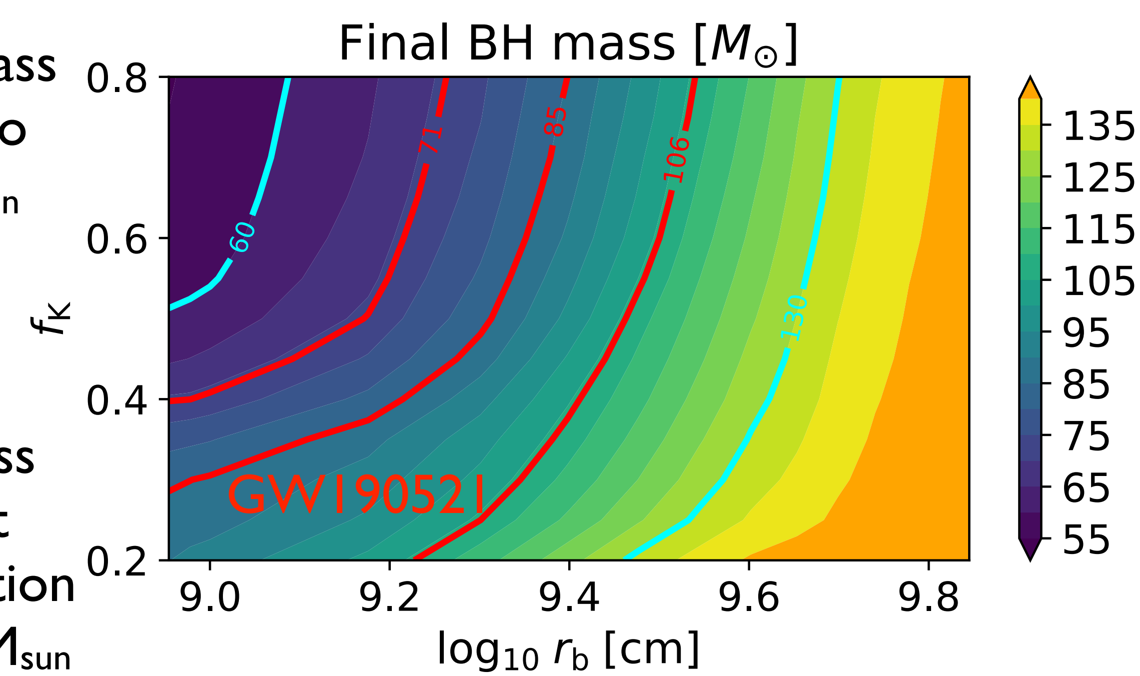


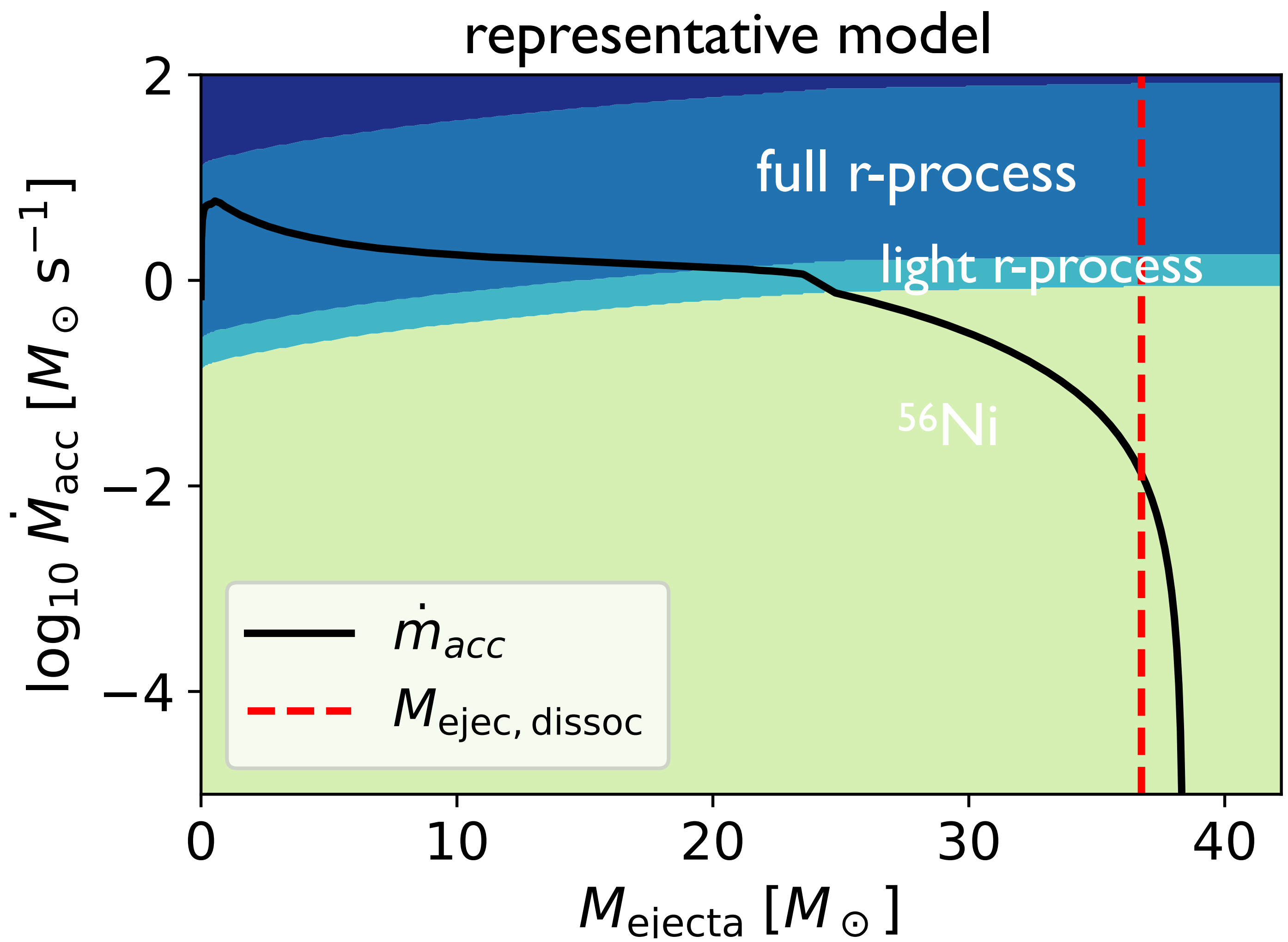


Wind mass loss up to > 50 M_{sun}

r-process element production ~1-10 M_{sun}



Ejecta composition reflects accretion process in massive collapsars



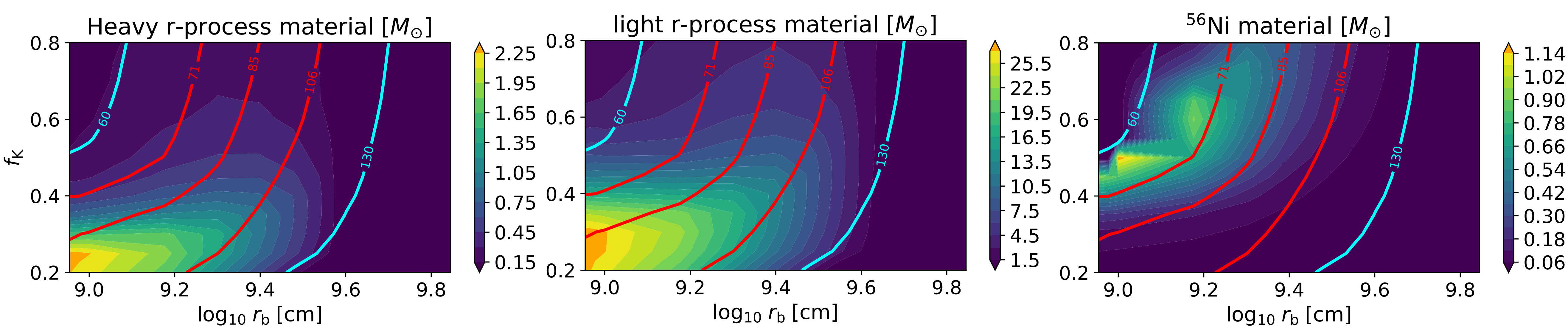
- At high accretion rates, flow neutronizes
  Beloborodov 2003, Siegel & Metzger 2017, Siegel+ 2019
- Various nucleosynthesis regimes, see also
  Siegel, Barnes, Metzger 2019, Nature
- Ejecta contains high-opacity, lanthanide-rich material, $X_{La} \sim 10^{-4}$–10^{-2}

  $M_{ej} \sim 10$–$60\ M_{sun}$

  $M_{ej,\,r\text{-}p} \sim 1$–$20\ M_{sun}$

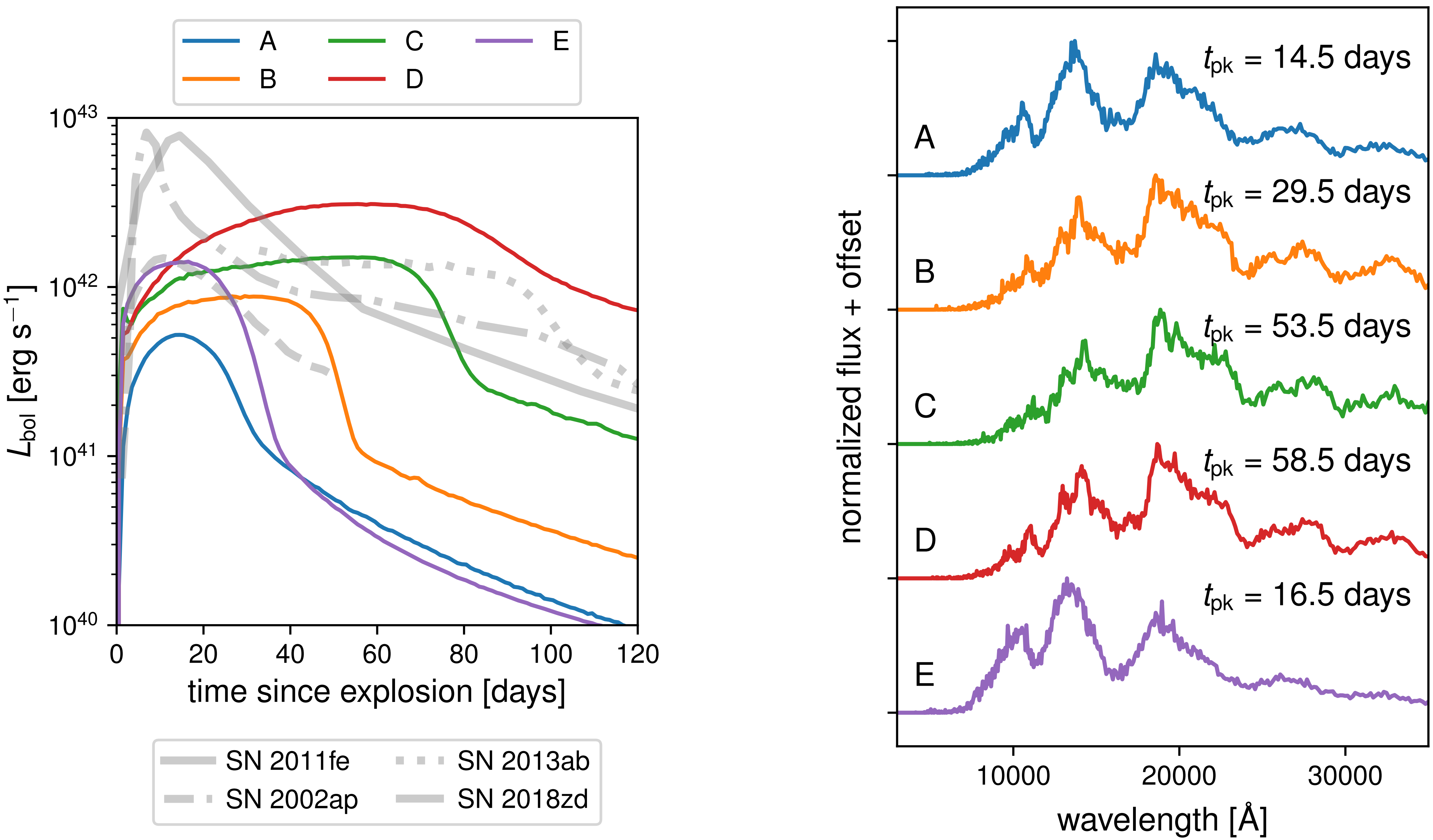
  $M_{ej,\,Ni56} \sim 0.05$–$1\ M_{sun}$

  $M_{BH} \sim 60$–$130\ M_{sun}$



parameter space scan

Super-Kilonovae



- representative models span a range of light curve morphologies
- r-process + ^{56}Ni powered transients on timescales ~tens of days ('scaled-up NS merger')
- red colors and distinctive spectra with and broad lines (v ~ 0.1c)

Super-Kilonovae detection prospects

- Targeted follow-up of very bright long GRBs in the IR with Roman, JWST
- Blind searches with *Optical/IR surveys* (Rubin/Roman)

SuperKN Light Curve Models and Survey Detection Rates

Model	$M_{\rm ej}$ $(M_\odot)$	$v_{\rm ej}$ (c)	$M_{\rm Ni}$ $(M_\odot)$	$M_{\rm lrp}$ $(M_\odot)$	$X_{\rm La}$ (10^{-3})	$R^{(a)}_{\rm Rubin}$ $({\rm yr}^{-1})$	$R^{(b)}_{\rm Roman}$ $({\rm yr}^{-1})$
a	8.6	0.1	0.019	0.83	1.4	0.01	0.02
b	31.0	0.1	0.012	8.28	17.0	0.03	0.4
c	35.6	0.1	0.087	23.2	4.0	0.1	2
d	50.0	0.1	0.53	9.59	0.53	0.1	4
e	60.0	0.1	0.0	5.6	0.17	0.2	0.01

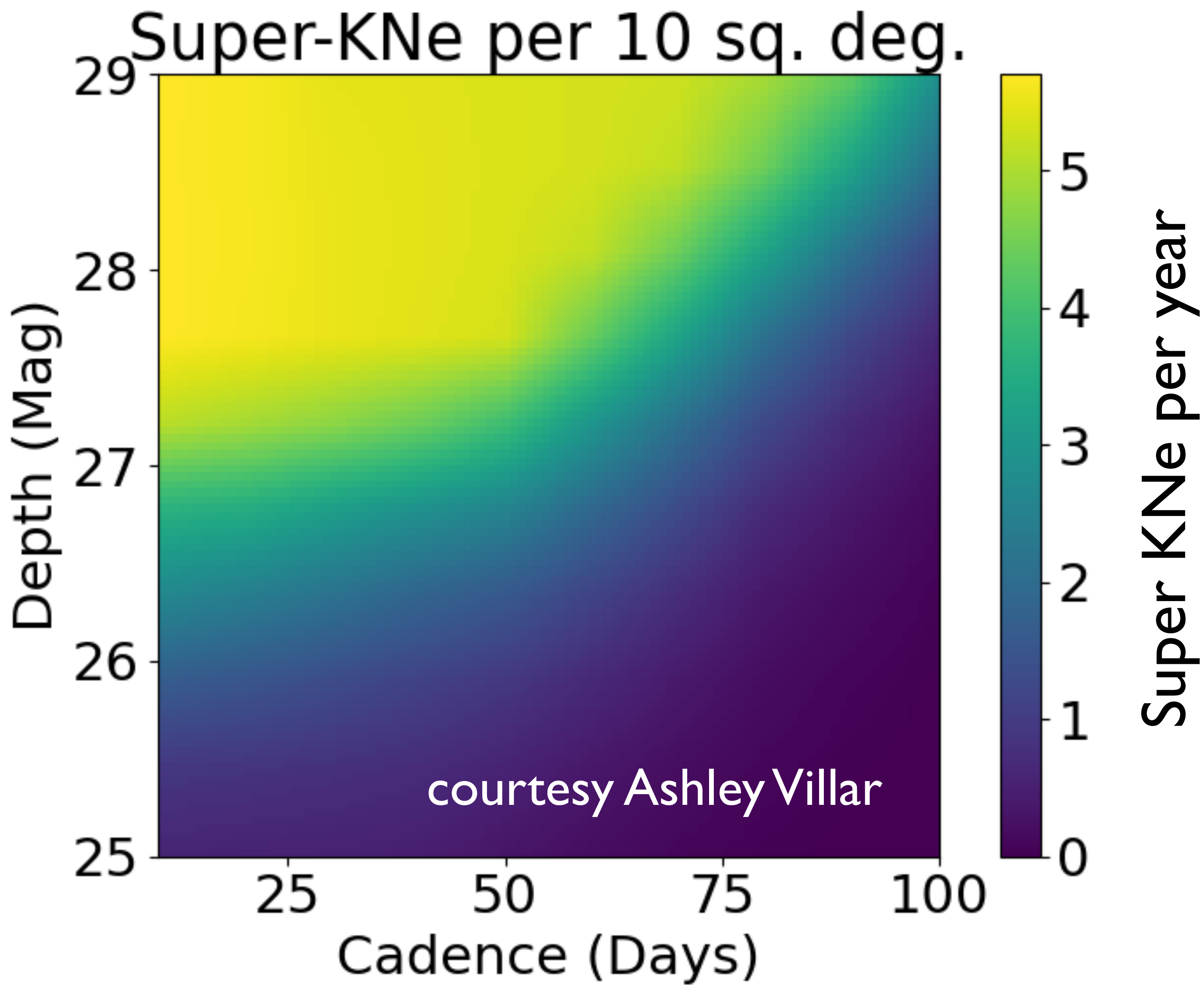
Rubin: sensitive to ^{56}Ni-rich, light r-process models

Roman: sensitive to lanthanide-rich models

- scaled-up, beaming corrected GRB rate using Salpeter IMF, out to z = 0.1
- 10 deg^2 Roman WFI survey with filters F062, F158 and F184 to ~27th mag
- detection = at least 3 SNR>3 points

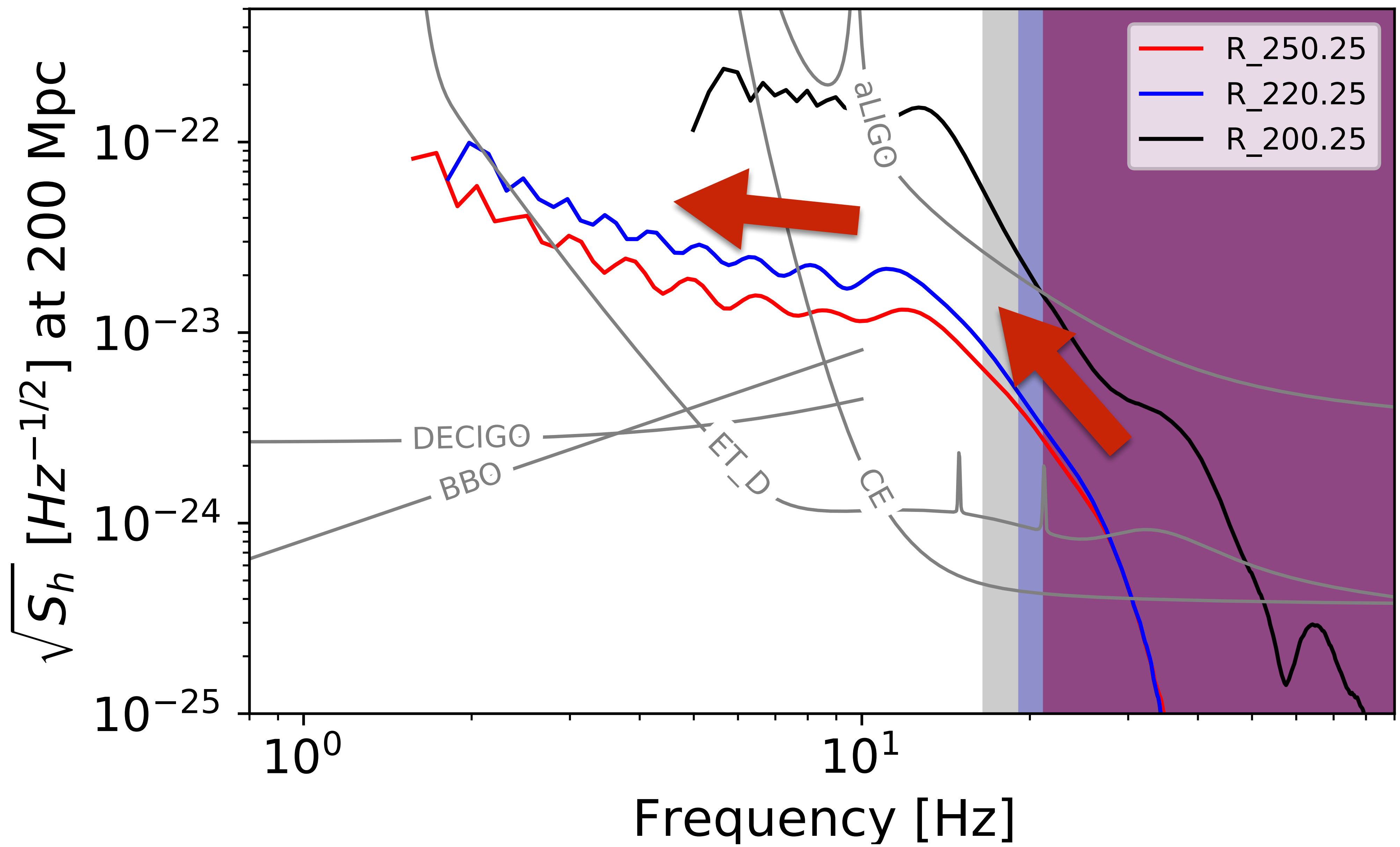
Uncertainties: intrinsic event rates, stellar structure, accretion dynamics & wind composition/mixing, …

Super-Kilonovae detection prospects depend on survey strategy



need survey with a cadence of ~1–2 months for planned (realistic) depths of ~26–27 mag to detect several Super-Kilonovae per year

Super-Kilonovae are multimessenger events



- Gravitational instabilities in the accretion disk give rise to gravitational-wave emission observable with 3rd generation GW observatories (Cosmic Explorer, Einstein Telescope)
- GW frequency decreases as disk expands: distinctive "sad-trombone" GW signal

Conclusions

- Roman may be able to detect "Super-Kilonovae" and thus witness the birth of BHs in the PISN mass gap

- Roman to observe/constrain the fate of massive stars and extreme r-process nucleosynthesis events

- Roman WFI Ia survey to detect 1-20 Super-KNe over 5 yr

- If mission lifetime long enough (~10 yrs), likely to overlap with ET & CE to detect multimessenger GW—SuperKNe events