Title: Illuminating the pair-instability supernova mass gap with super-kilonovae

Speakers: Aman Agarwal

Collection: Young Researchers Conference

Date: June 21, 2022 - 9:00 AM

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Abstract: The core collapse of rapidly rotating massive 10Msun stars ("collapsars"), and resulting formation of hyper-accreting black holes, are a leading model for the central engines of long-duration gamma-ray bursts (GRB) and promising sources of r-process nucleosynthesis. In this talk, I will explore the signatures of collapsars from progenitors with extremely massive helium cores >= 130Msun above the pair-instability mass gap. While rapid collapse to a black hole likely precludes a prompt explosion in these systems, we demonstrate that disk outflows can generate a large quantity (up to >= 50Msun) of ejecta, comprised of >= 5 10Msun in r-process elements and 0.1 1M of 56Ni, expanding at velocities 0.1 c. Radioactive heating of the disk-wind ejecta powers an optical/infrared transient, with a characteristic luminosity 1042 erg s1and spectral peak in the near-infrared (due to the high optical/UV opacities of lanthanide elements) similar to kilonovae from neutron star mergers, but with longer durations >= 1 month. These "super-kilonovae" (superKNe) herald the birth of massive black holes >= 60M, which-- as a result of disk wind mass-loss--can populate the pair-instability mass gap "from above" and could potentially create the binary components of GW190521. SuperKNe could be discovered via wide-field surveys such as those planned with the Roman Space Telescope or via late-time infrared follow-up observations of extremely energetic GRBs. Gravitational waves of frequency 0.1 50 Hz from non-axisymmetric instabilities in self-gravitating massive collapsar disks are potentially detectable by proposed third-generation intermediate and high-frequency observatories at distances up to hundreds of Mpc; in contrast to the "chirp" from binary mergers, the collapsar gravitational-wave signal decreases in frequency as the disk radius grows ("sad trombone").

Illuminating the pair-instability supernova mass-gap with super-kilonovae

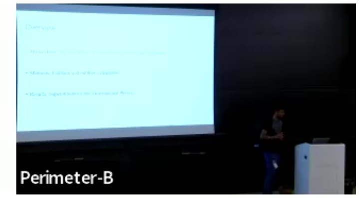
D. Siegel, A. Agarwal, J. Barnes, B. Metzger, M. Renzo and V.A. Villar 2021,
arXiv:2111.03094

Aman Agarwal, Ph.D. Student

Supervisor: Dr. Daniel Siegel

Young Researcher's Conference 2022, Perimeter Institute

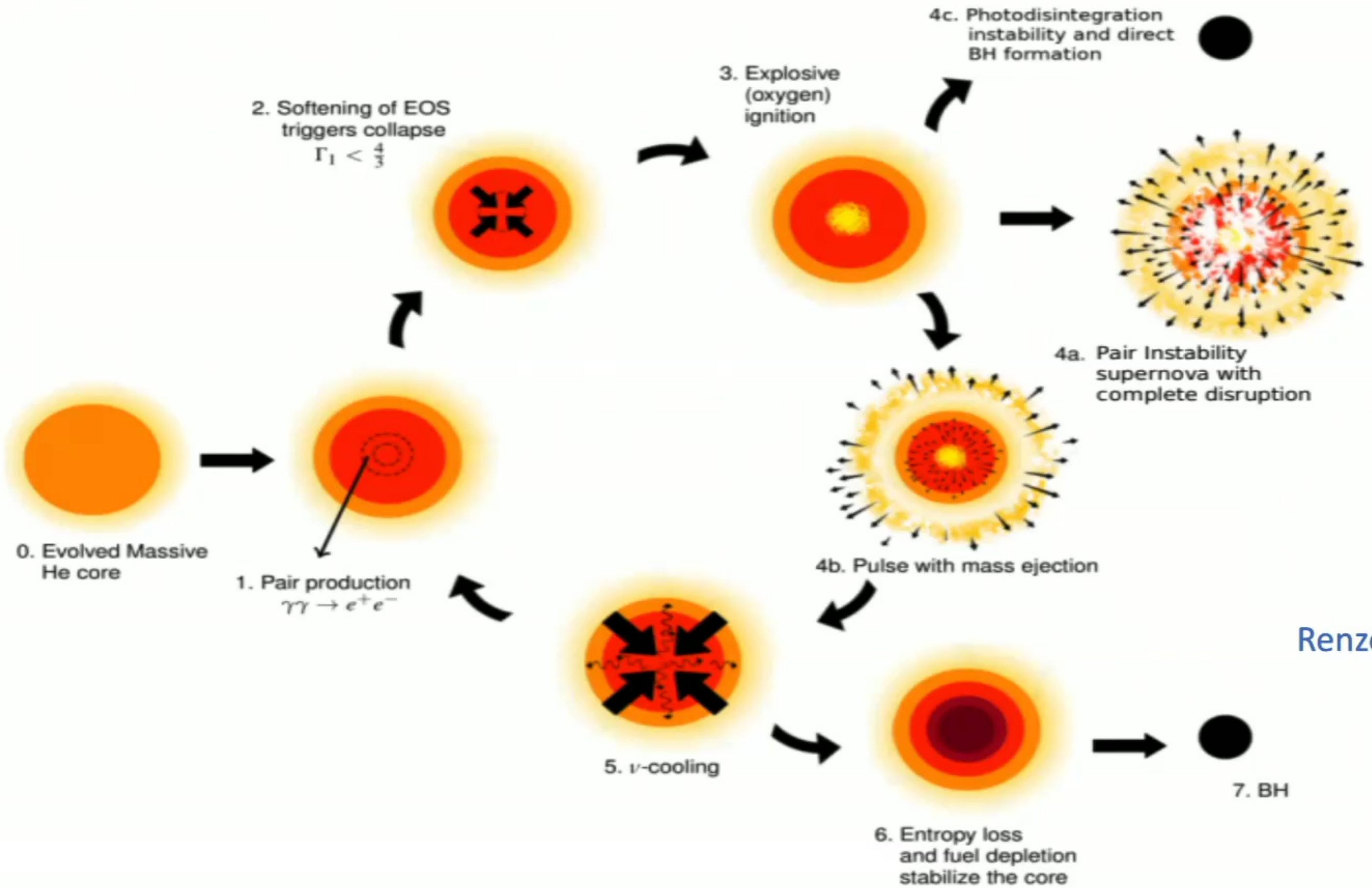
Overview



- **Motivation**: The pair instability supernova mass gap and collapsars
- Methods: Fallback and outflow calculation
- Results: Super-Kilonova and Gravitational Waves

The pair-instability mass gap....in theory

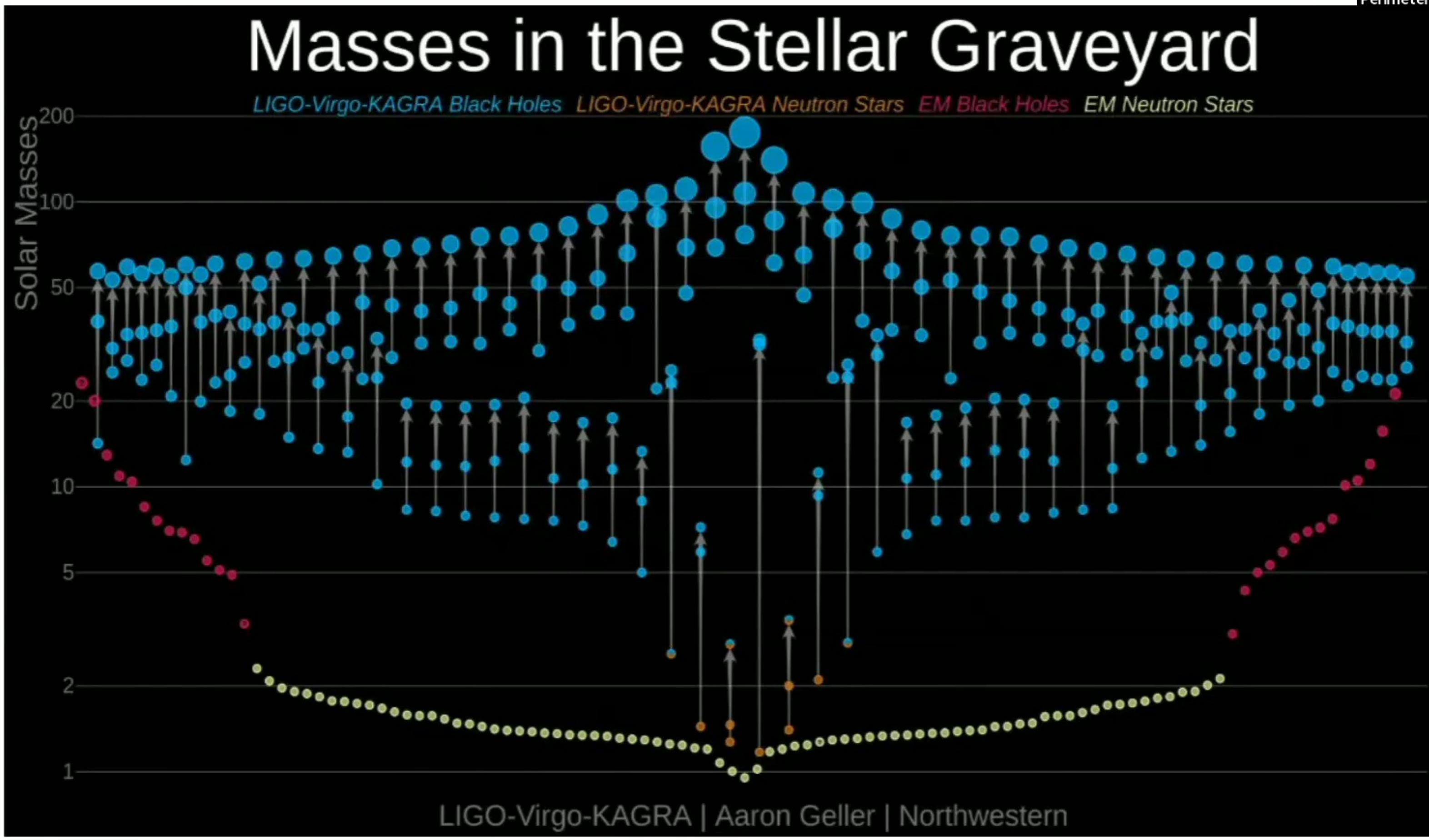
Stellar evolution models predict an **absence of black holes** in the mass range of ~ **55-130 M**



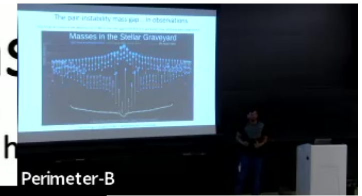
Renzo et. al. 2020

The pair-instability mass gap….in observations

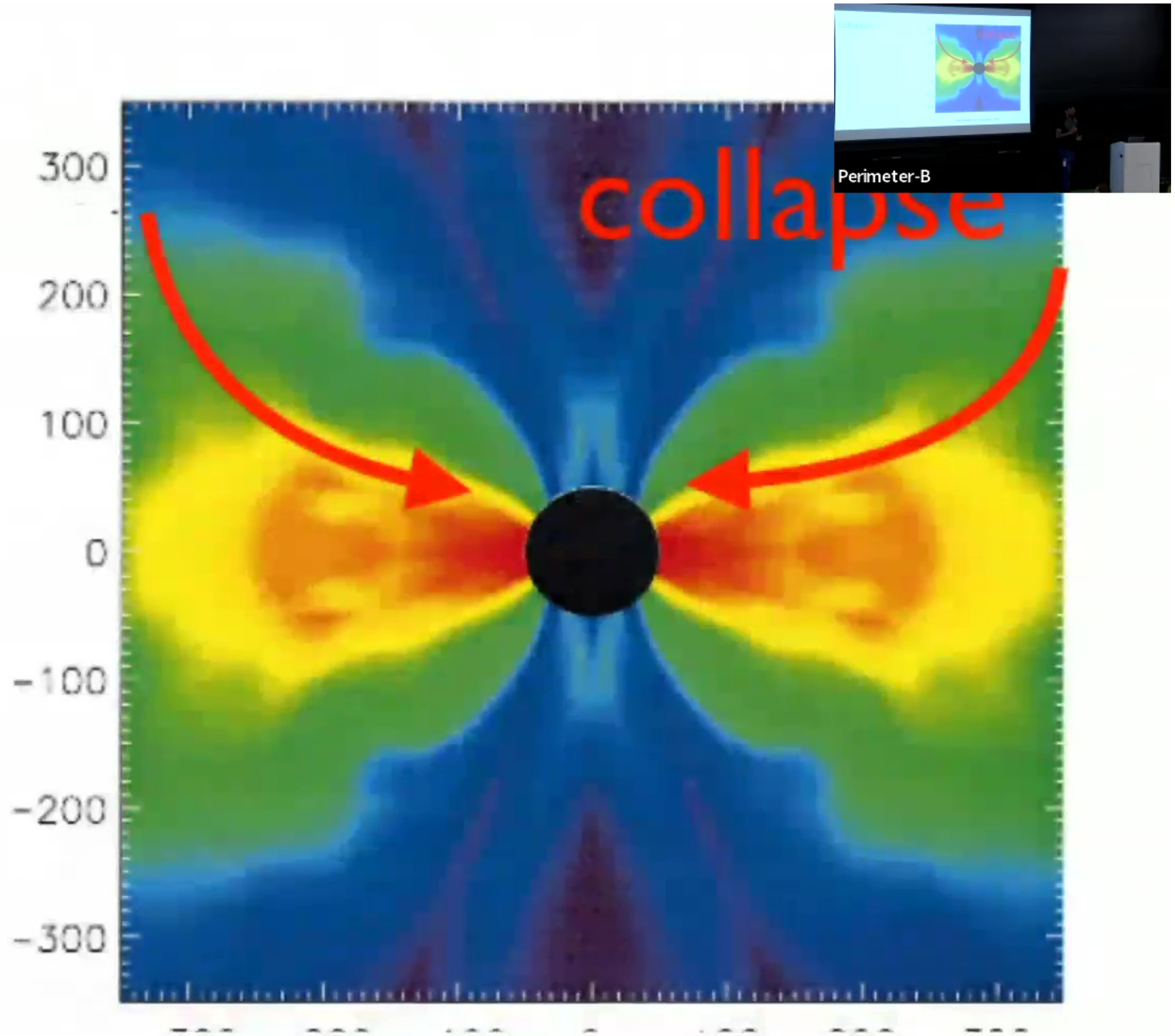
LIGO/Virgo announced the detection of >7 BHs in the mass gap (**GW190521** in particular) How did these black h



LIGO-Virgo / Aaron Geller / Northwestern University



Collapsars



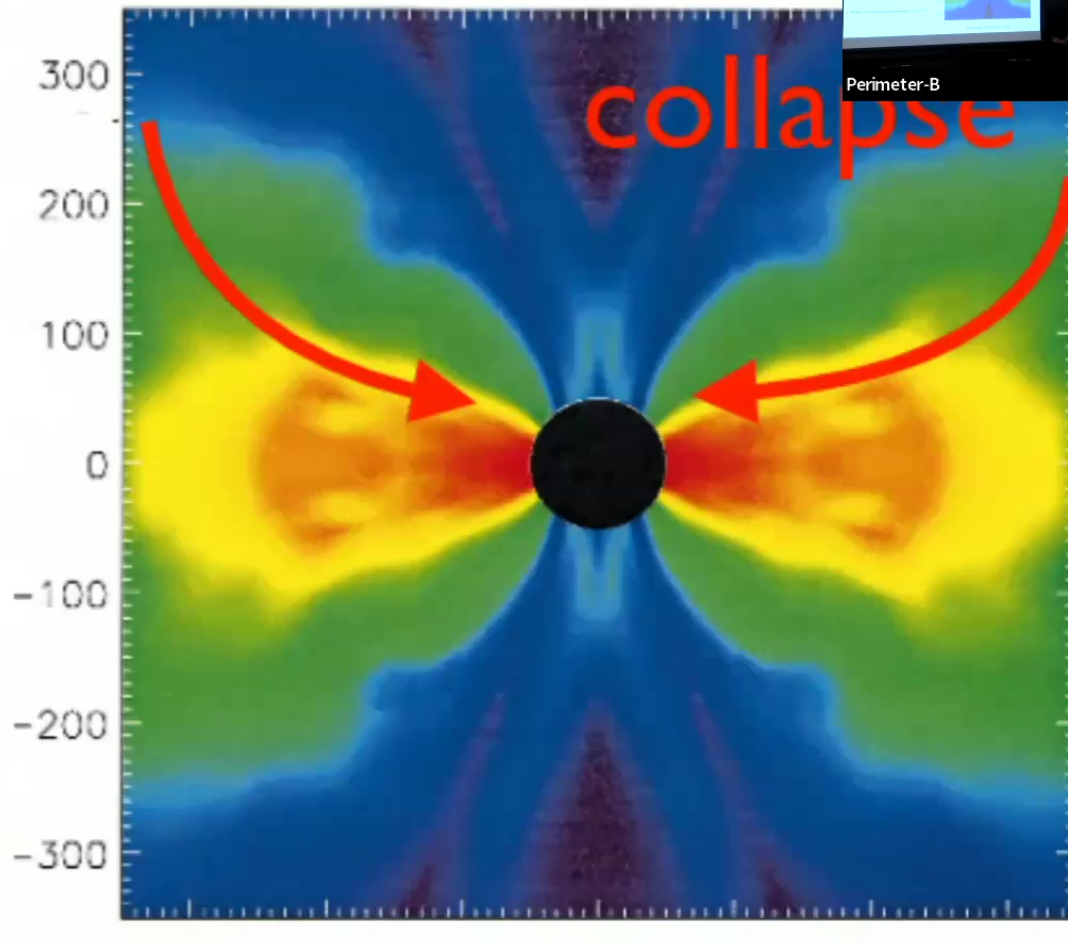
MacFayden and Woosley, 1999

Collapsars

- BH-accretion disk from collapse of rapidly rotating massive stars ($M > 20\ M_{sun}$)

- Angular momentum of infalling material -> circularization and accretion disk formation.

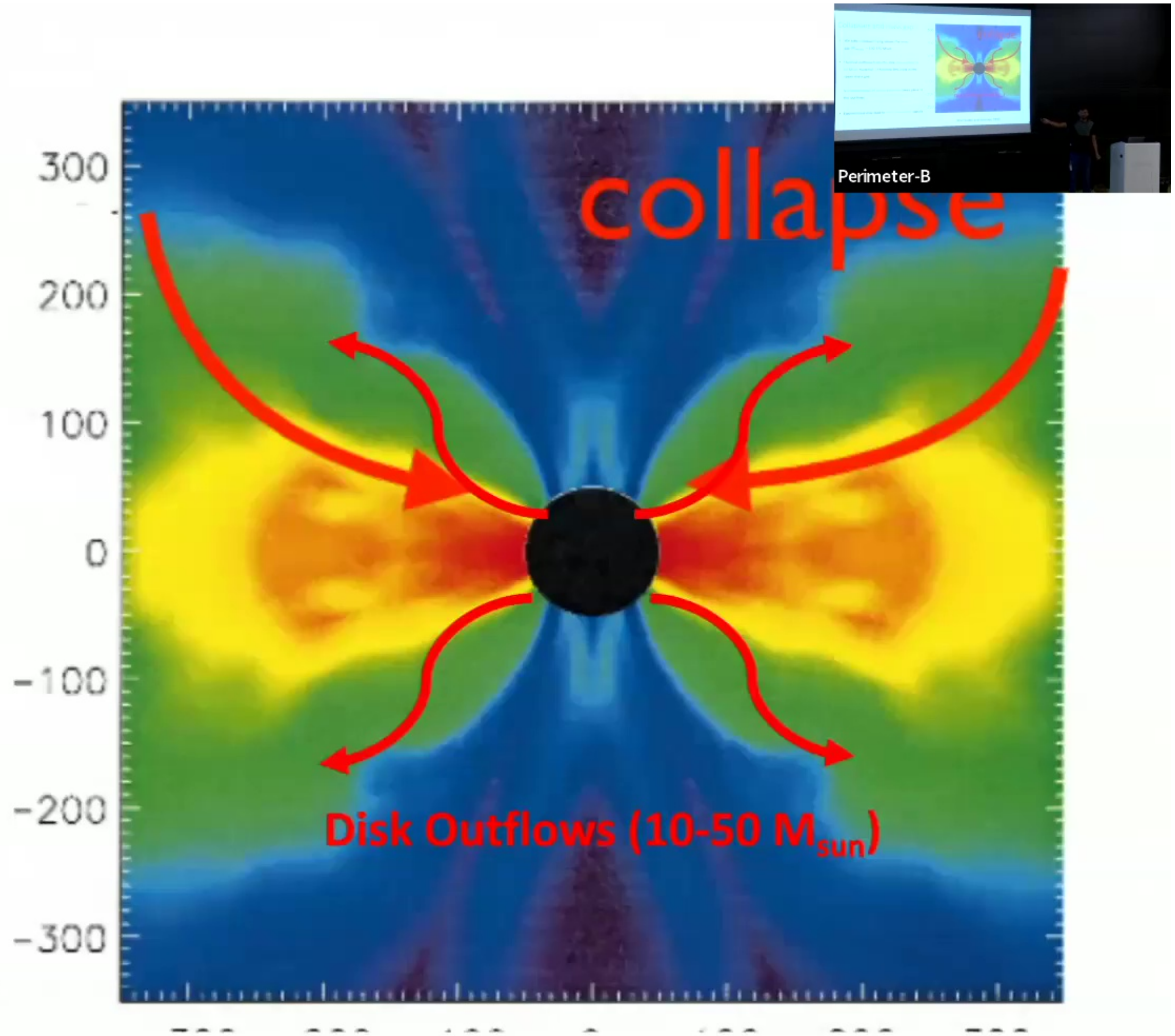
- Widely accepted model to generate long GRBs



MacFayden and Woosley, 1999

Collapsars and mass gap

- We take collapsars lying above the mass gap $M_{collapse} \approx$ 130-150 Msun
- Thermal outflows from this disk **may unbind 10-50 Msun** material -> forming BHs lying in the upper mass gap.
- **Nucleosynthesis of heavy elements** takes place in the outflows.
- Ejected mass may lead to multi-messenger signals



MacFayden and Woosley, 1999

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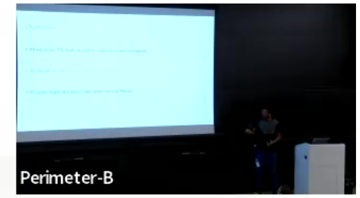

- Motivation: The pair-instability supernova and collapsars

- **Methods**: Fallback and outflow calculation

- Results: Super-Kilonova and Gravitational Waves

Stellar Models

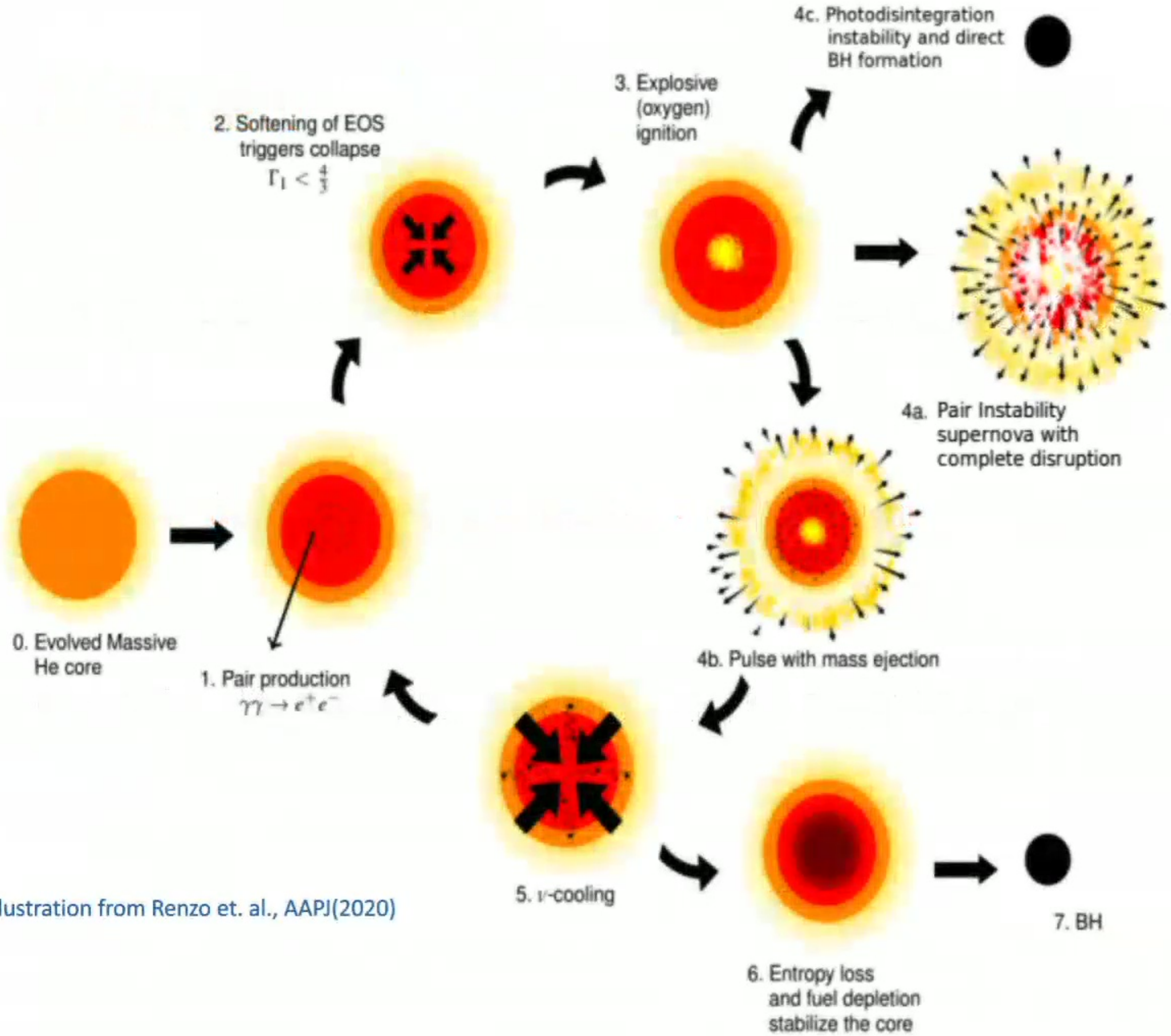

Illustration from Renzo et. al., AAPJ(2020)

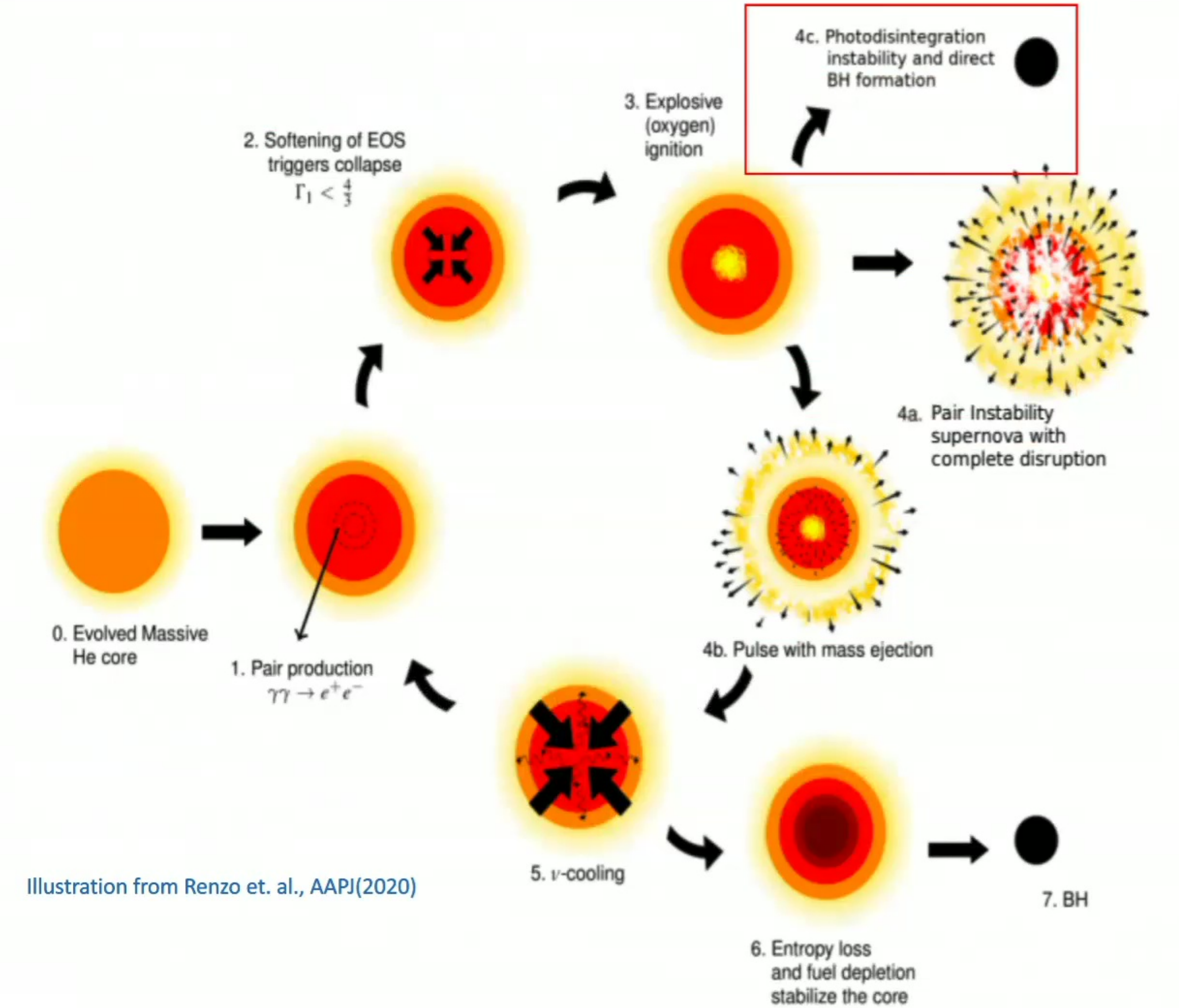

Illustration from Renzo et. al., AAPJ(2020)

Stellar Models

- Mass at collapse~130-150 M_{sun}
- Massive and Compact models

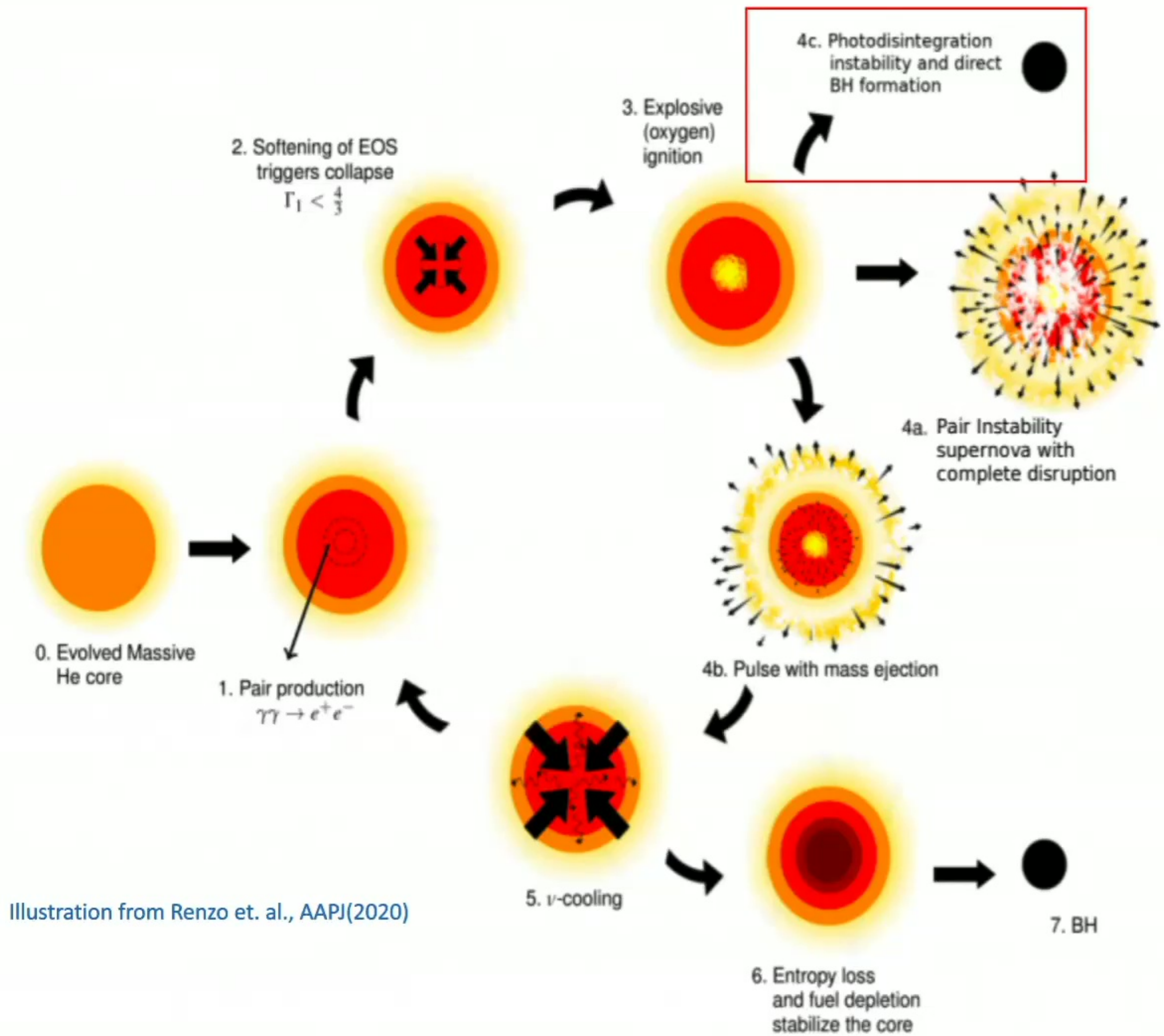

Illustration from Renzo et. al., AAPJ(2020)

Stellar Models

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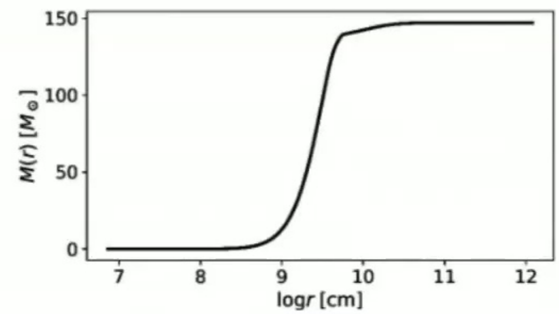
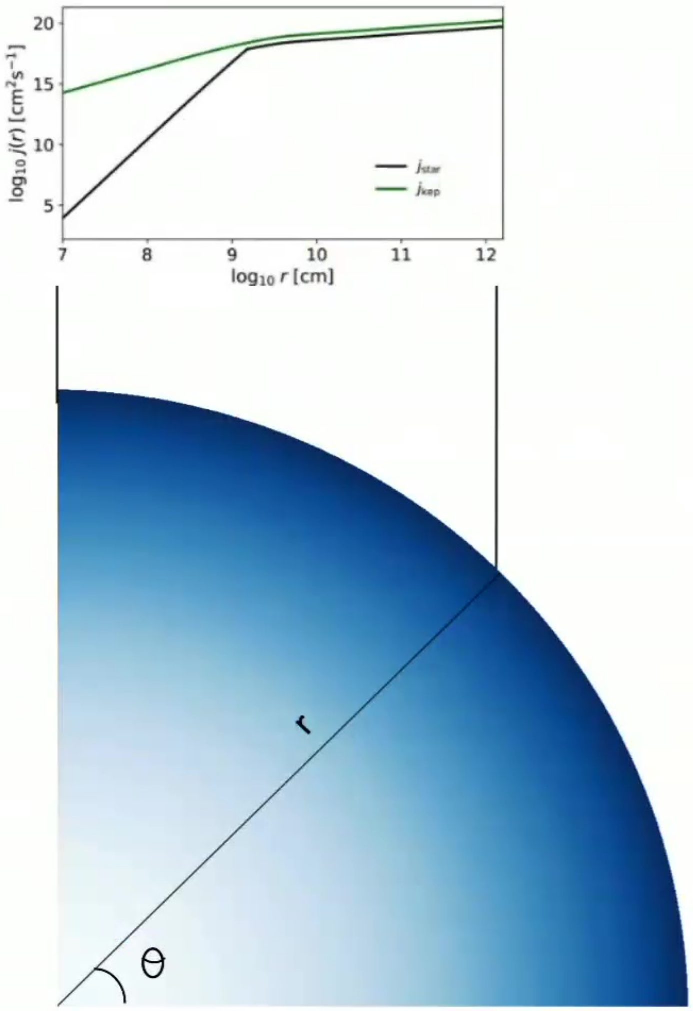
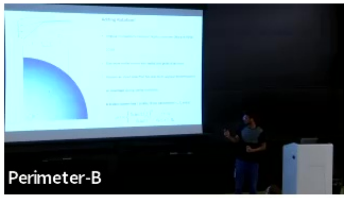


- Angular momentum transport and mass loss history uncertain

Adding Rotation!

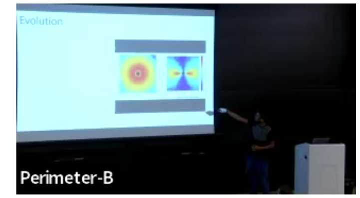


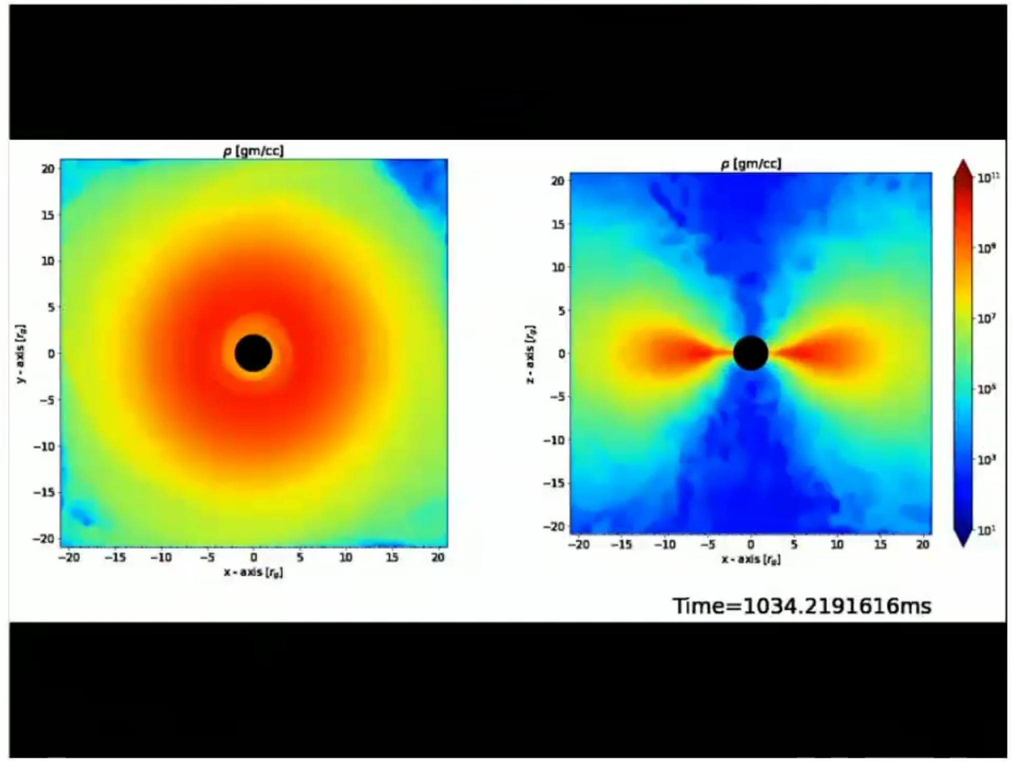


- Angular momentum transport highly uncertain [Ma and Fuller 2019]
- Discretize stellar model into **radial** and **polar** directions.
- Assume an inner **core** that has lost all its angular momentum to an **envelope** during stellar evolution.
- **A broken power-law** J profile, three parameters: r_b, f_k and p

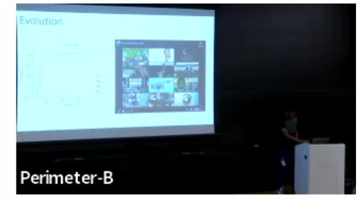
$$j(r) = \begin{cases} f_{\rm K} j_{\rm K}(r) \left(\frac{r}{r_{\rm b}}\right)^p, & r < r_{\rm b} \\ f_{\rm K} j_{\rm K}(r), & r_{\rm b} \leq r \leq R_\star \end{cases}$$

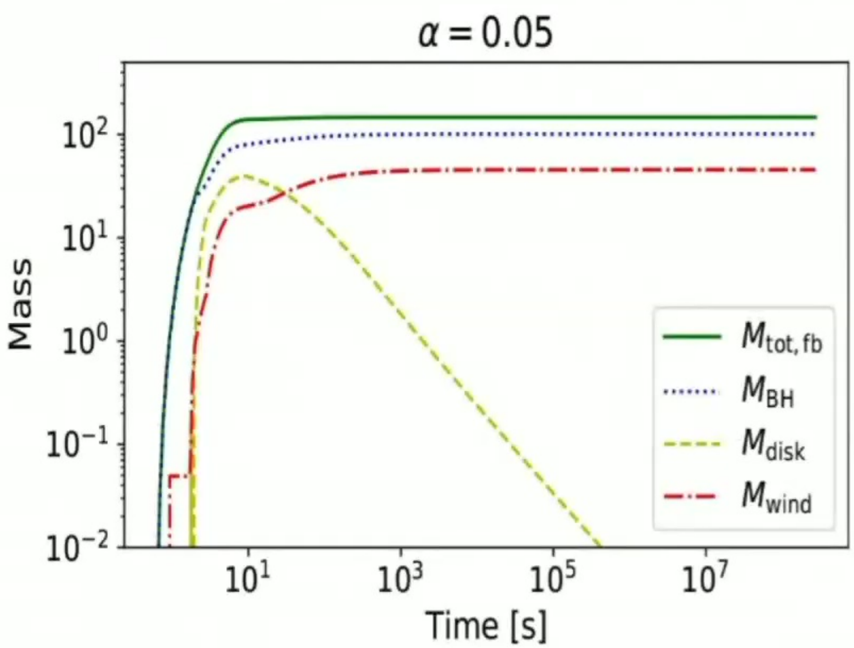
Evolution

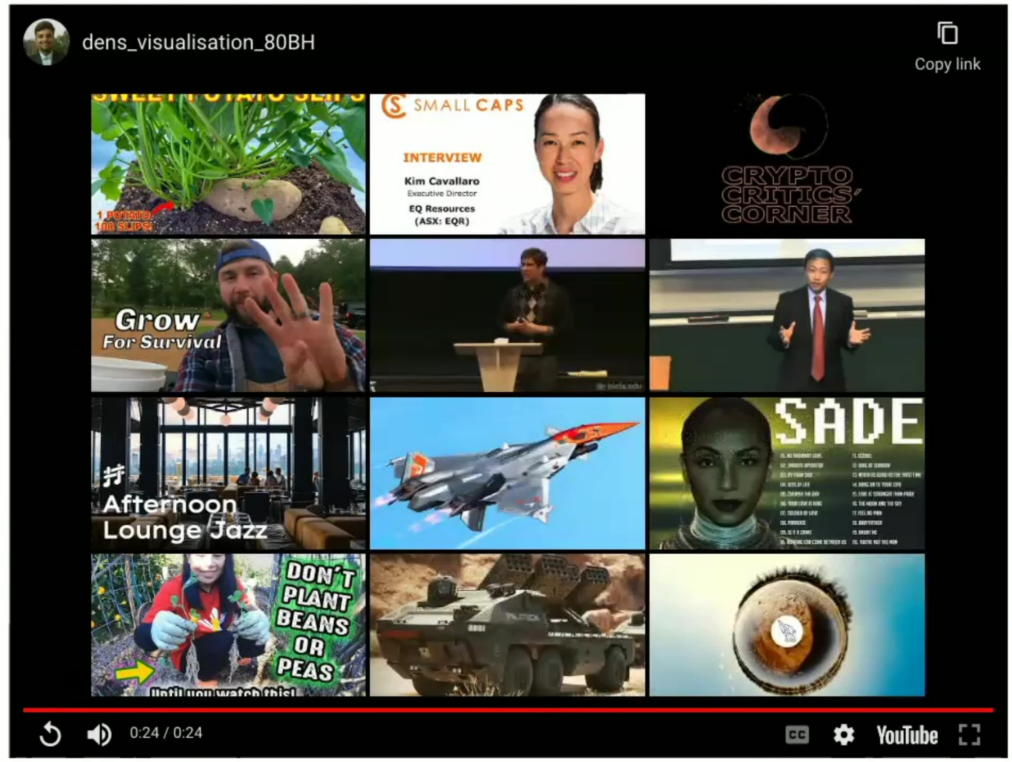

Perimeter-B


ρ [gm/cc]
ρ [gm/cc]
y - axis [r_g]
z - axis [r_g]
x - axis [r_g]
x - axis [r_g]
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
Time=1034.2191616ms

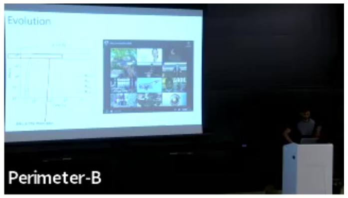
Evolution

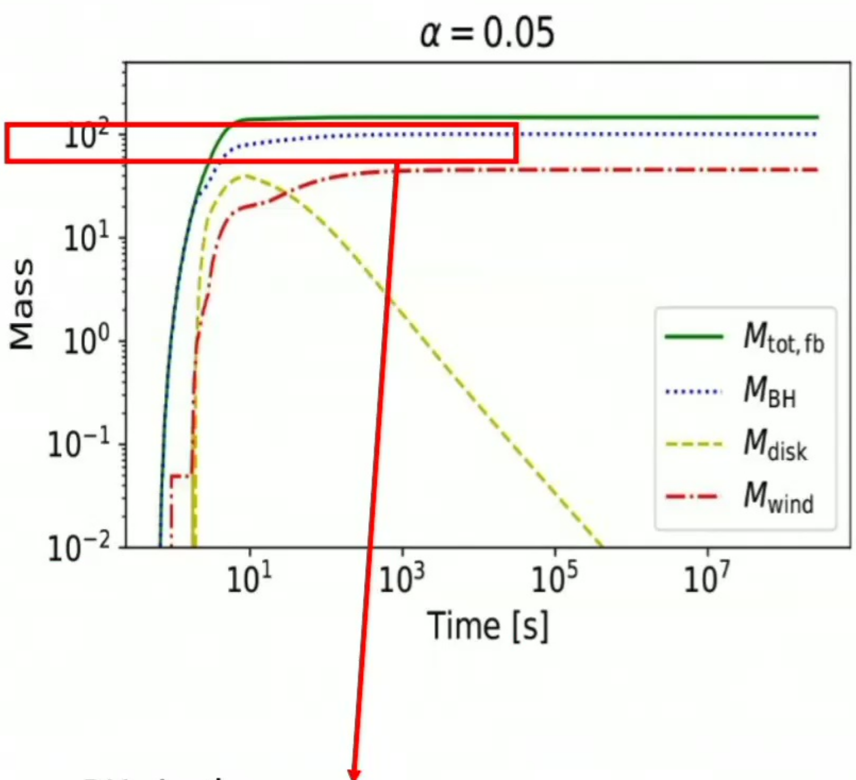

Perimeter-B


$\alpha = 0.05$
Mass
Time [s]
$M_{tot,fb}$
M_{BH}
M_{disk}
M_{wind}

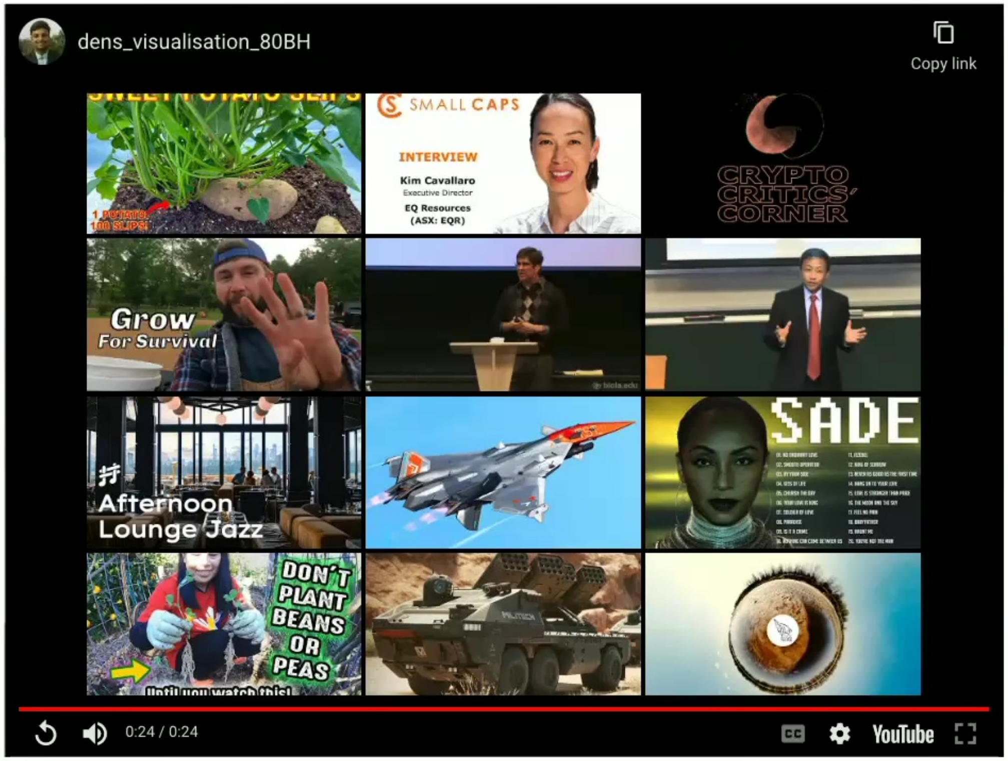

dens_visualisation_80BH
Copy link
SMALL CAPS
INTERVIEW
Kim Cavallaro
Executive Director
EQ Resources
(ASX: EQR)
CRYPTO CRITICS' CORNER
Grow
For Survival
Afternoon
Lounge Jazz
SADE
DON'T PLANT BEANS OR PEAS
0:24 / 0:24
YouTube

Evolution

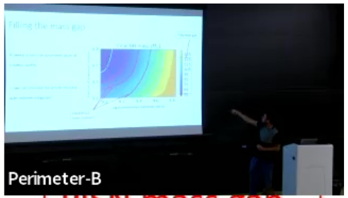




BHs in the mass gap

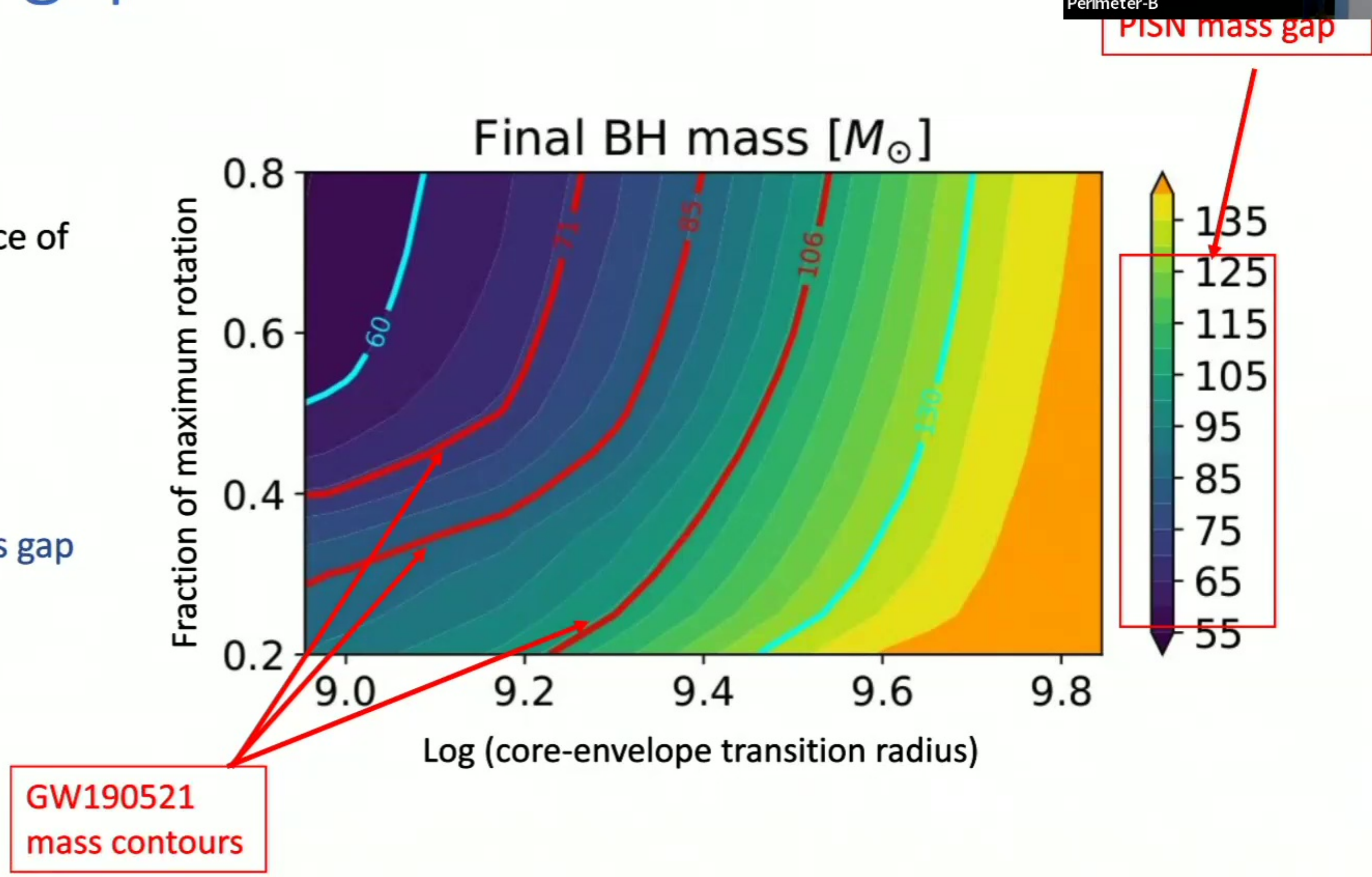


Filling the mass gap

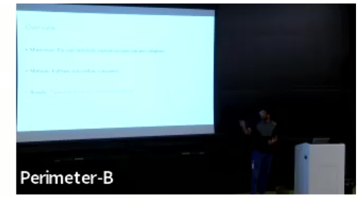


A sweep across the parameter space of rotation profile

-> we can populate the whole mass gap with massive collapsars!



Overview



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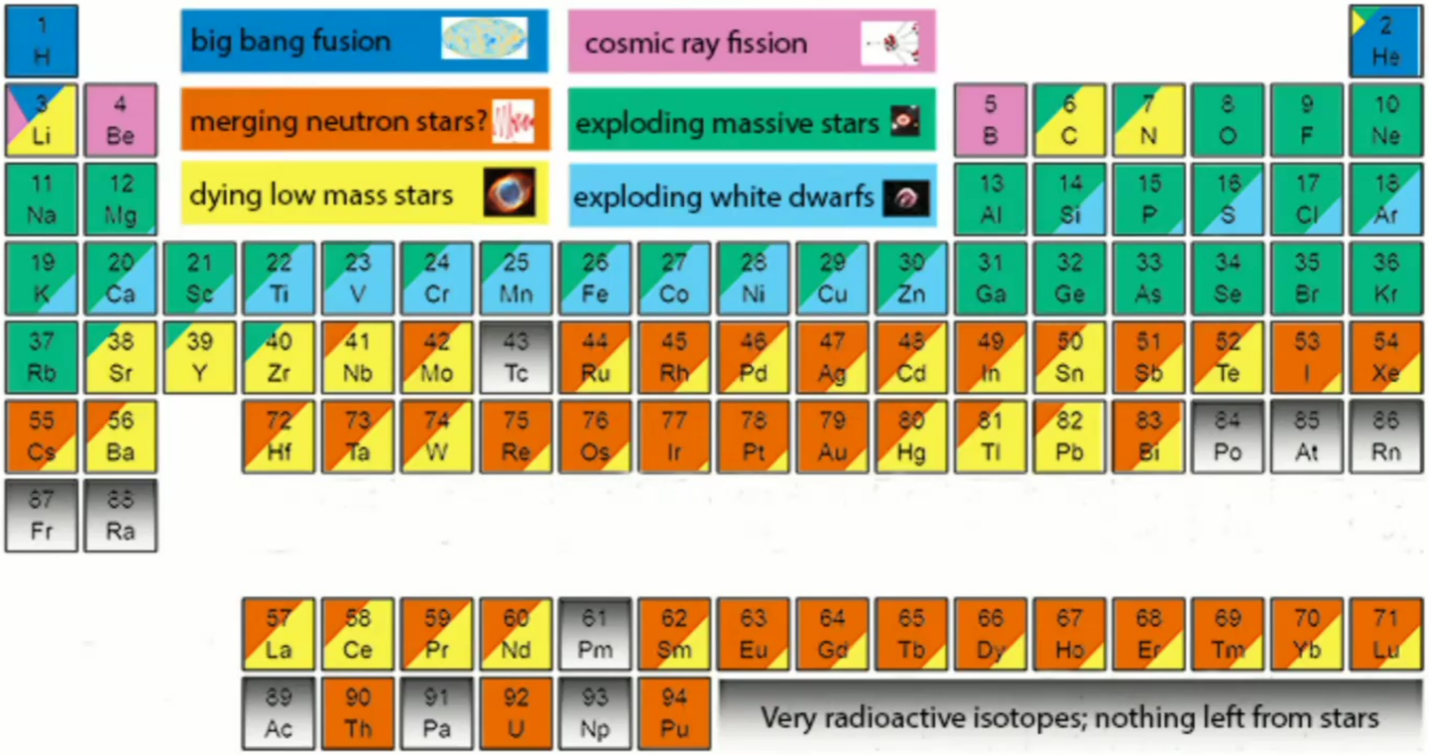
- **Results**: Super-Kilonova and Gravitational Waves

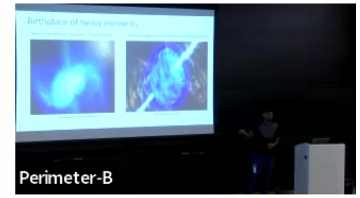
Origins of heavy elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

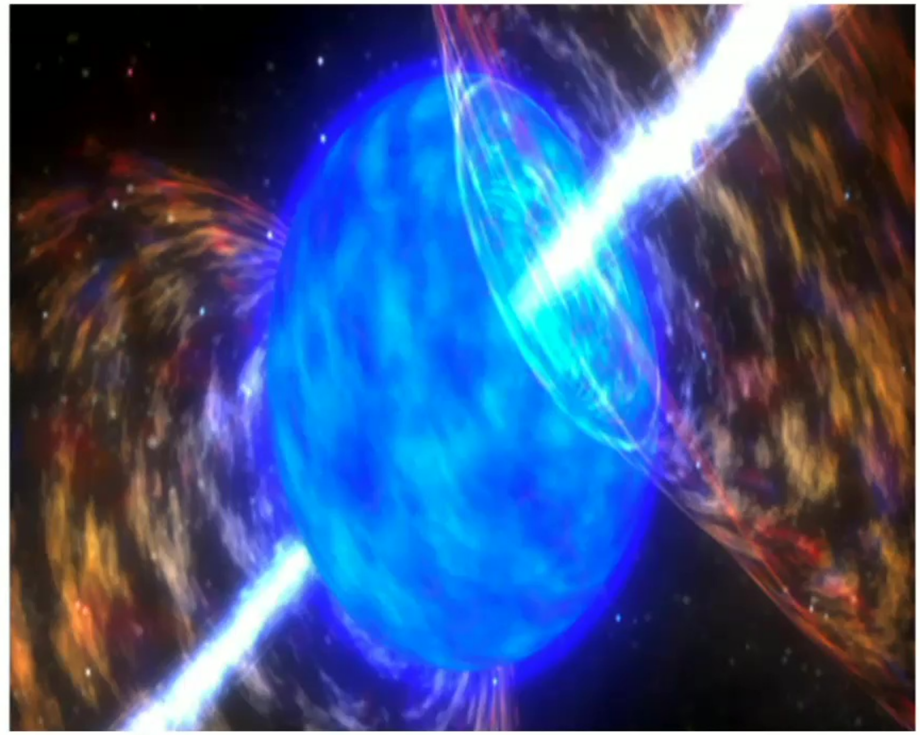
Birthplace of heavy elements



Neutron Star Mergers [observed but has shortfalls]

Collapsars [Proposed by Siegel, Barnes and Metzger, 2019]

Credit: University of Warwick/Mark Garlick



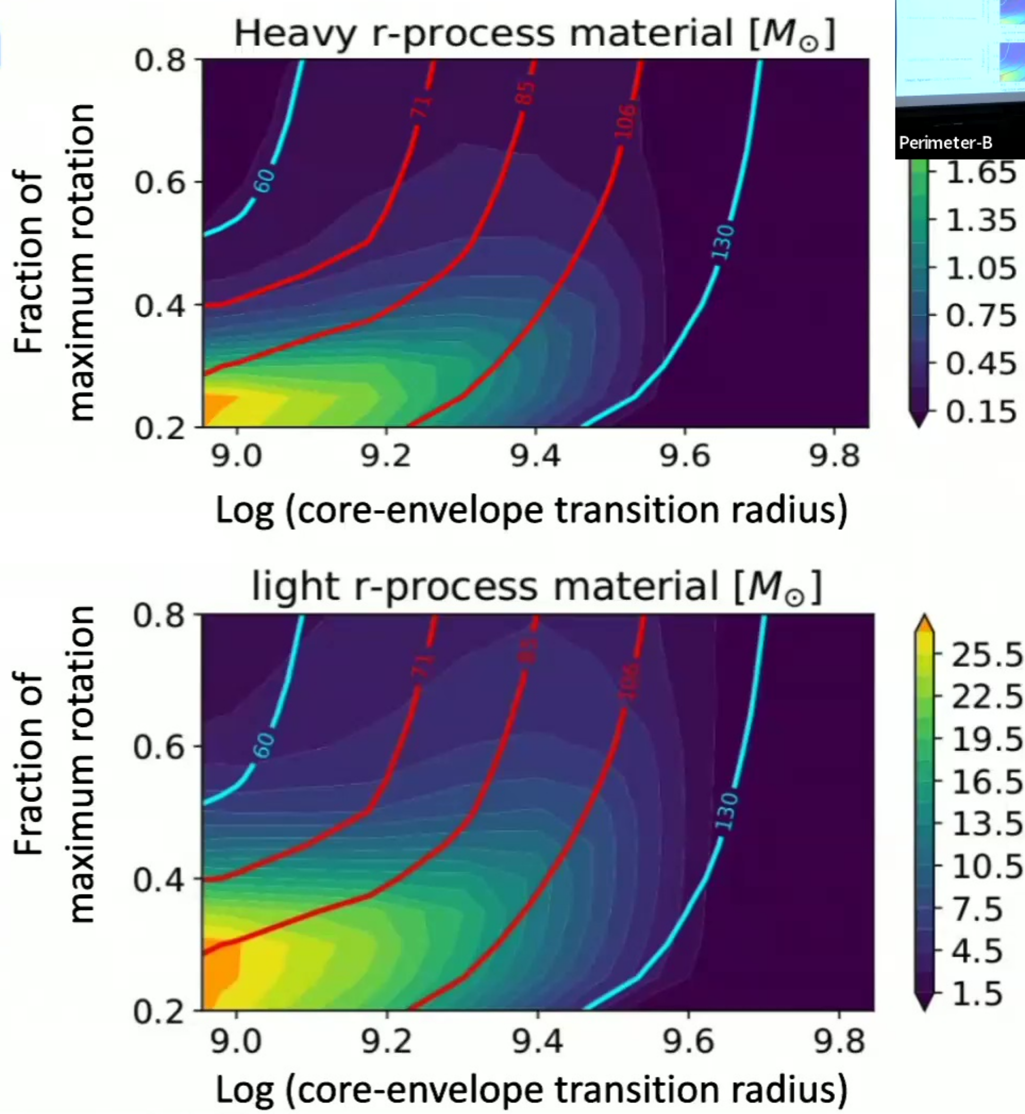
Credit: NASA/SkyWorks Digital

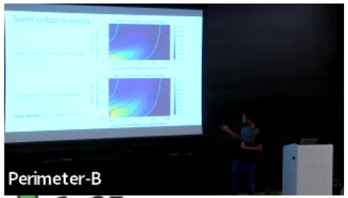
Super collapsar ejecta

- Heavy r-process ~ 0.5-2.5 solar masses

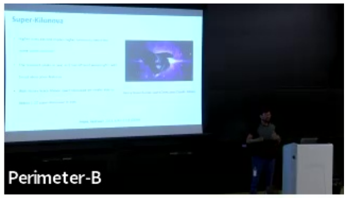
- Light r-process ~ 10-20 solar masses

Siegel, Agarwal+ 2021, arXiv:2111.03094

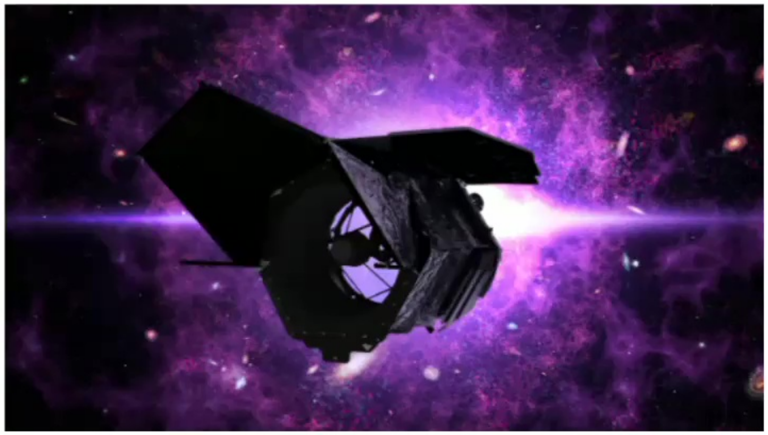




Super-Kilonova



- Higher mass ejected implies higher luminosity hence the name super-kilonova!
- The transient peaks in near and mid-infrared wavelengths with broad absorption features.
- With Nancy Grace Roman space telescope we maybe able to detect 1-20 super-Kilonovae in 5yrs



Nancy Grace Roman Space Telescope [Credit: NASA]

Siegel, Agarwal+ 2021, arXiv:2111.03094

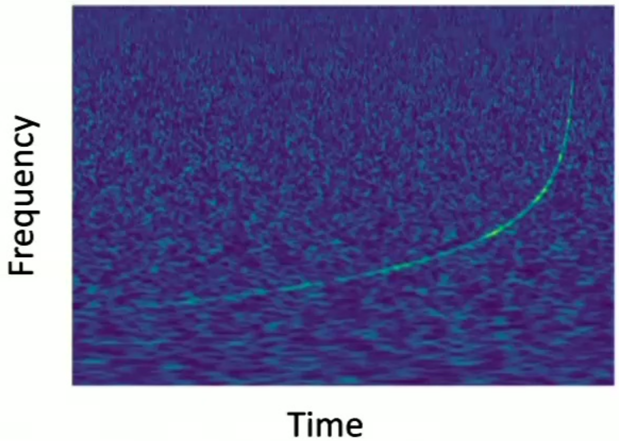
Gravitational Waves

- Massive disks -> Toomre like gravitational instabilitites -> Gravtational Waves

- GWs have "sad-trombone" nature in constrast to "chirp" nature

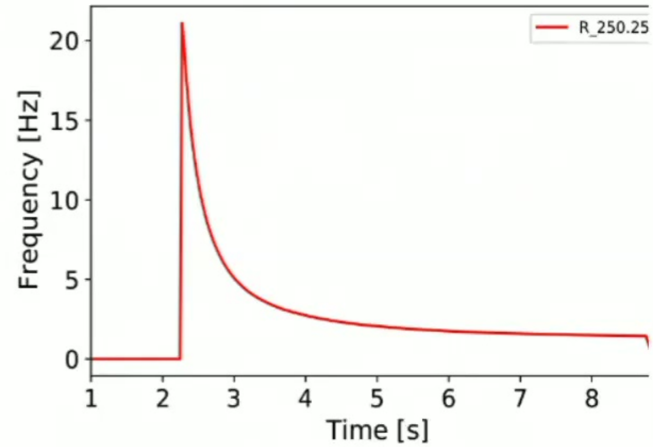
- Multiband signals detectable by planned 3G and decihertz detectors

chirp



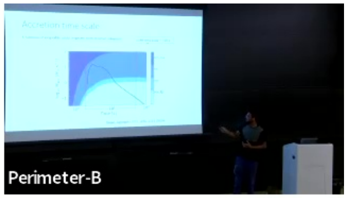
Credit: LIGO/Virgo

Sad trombone

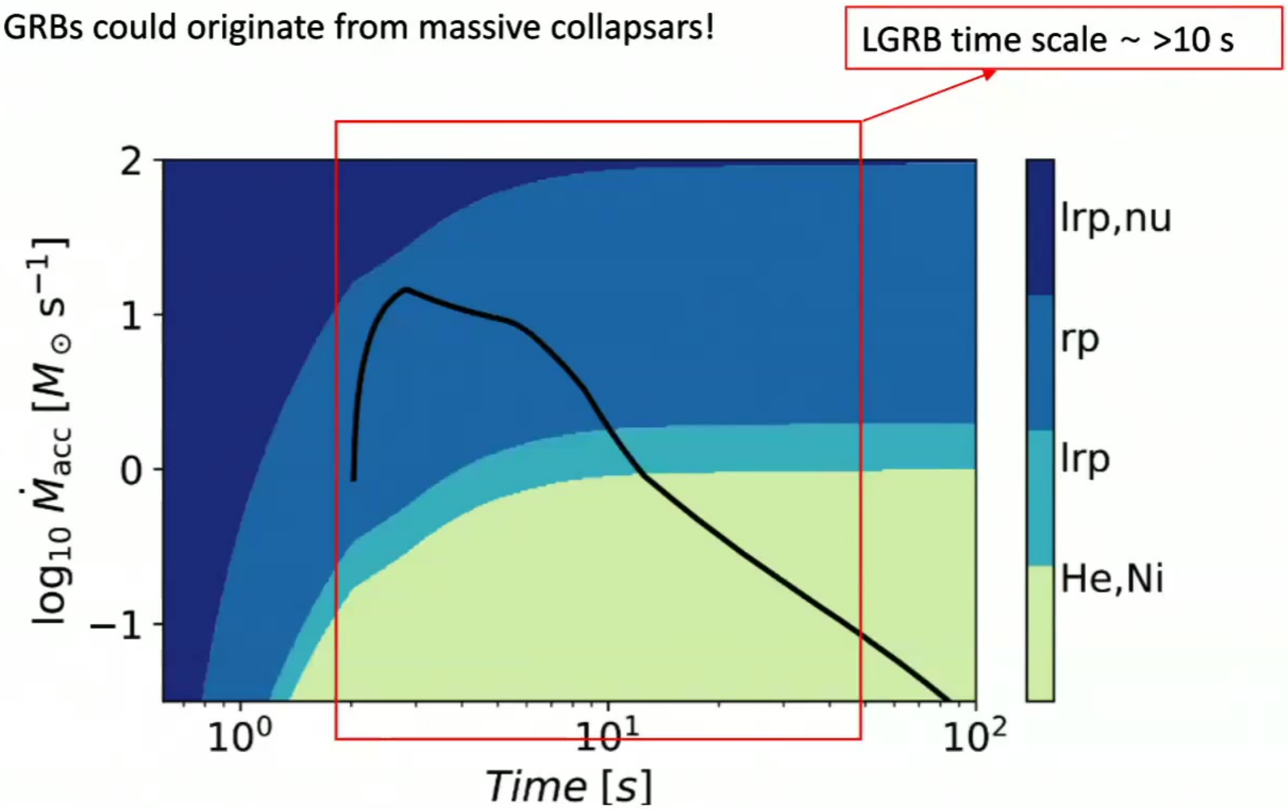


Siegel, Agarwal+ 2021, arXiv:2111.03094

Accretion time scale



A subclass of long GRBs could originate from massive collapsars!



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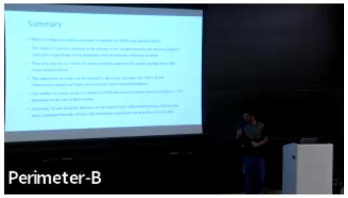
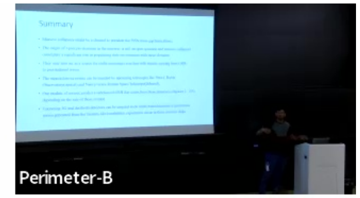
Summary



- Massive collapsars might be a channel to populate the PISN mass gap from above.
- The origin of r-process elements in the universe is still an open question and massive collapsars could play a significant role in populating their environment with these elements.
- They may also act as a source for multi-messenger searches with signals varying from GRBs to gravitational waves.
- The superkilonova events can be targeted by upcoming telescopes like Vera C Rubin Observatory(optical) and Nancy Grace Roman Space Telescope(infrared).
- Our models, if correct, predict a subclass of GRB that come from these massive collapsars (~ 10% depending on the rate of these events)
- Upcoming 3G and decihertz detectors can be targeted to do multi-band detection of gravitation waves generated from the Toomre-like instabilities expected to occur in these massive disks.

Summary



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