

Building up an intermediate mass black hole: the role of stellar collisions

Filippo Simonato

40° cycle, Astroparticle Physics

Supervisors:

Manuel Arca Sedda, Marica Branchesi, Gor Oganesyan



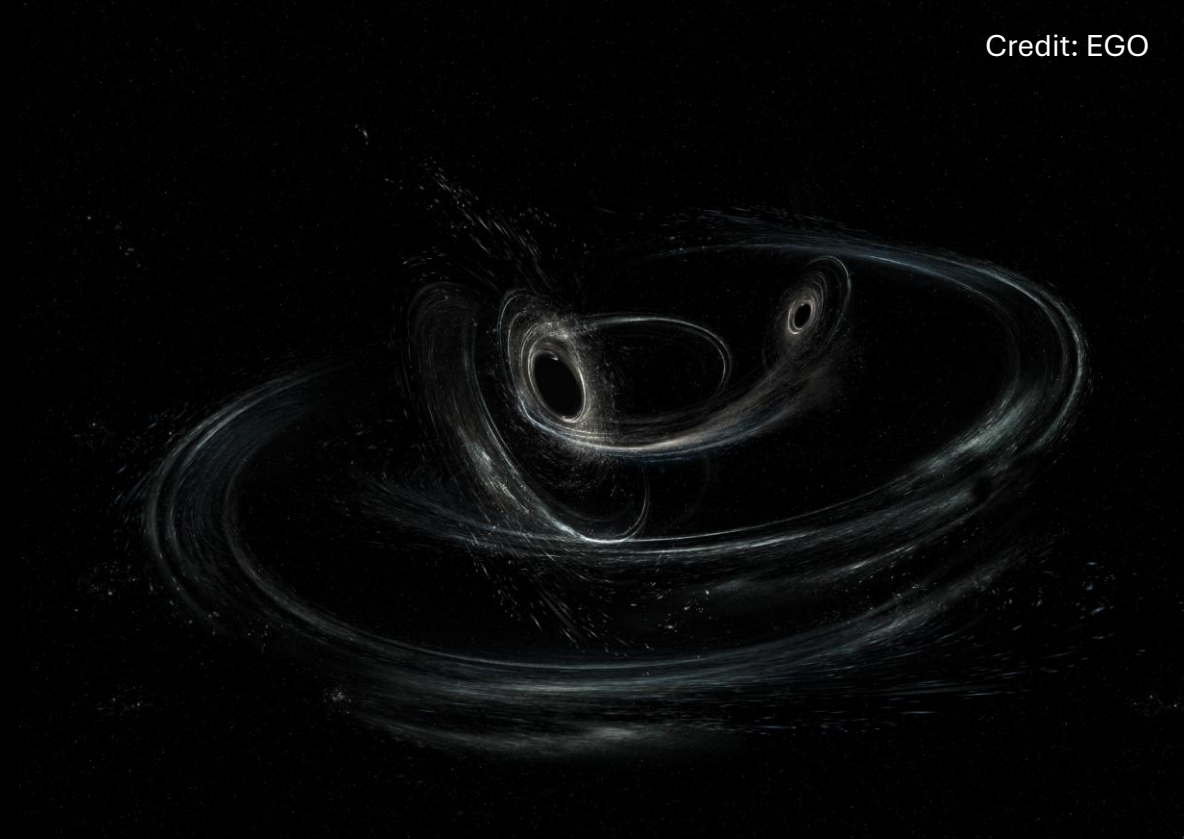
By definition...



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Intermediate-mass black holes:

$$10^2 M_{\odot} \leq M_{\text{BH}} \leq 10^5 M_{\odot}$$

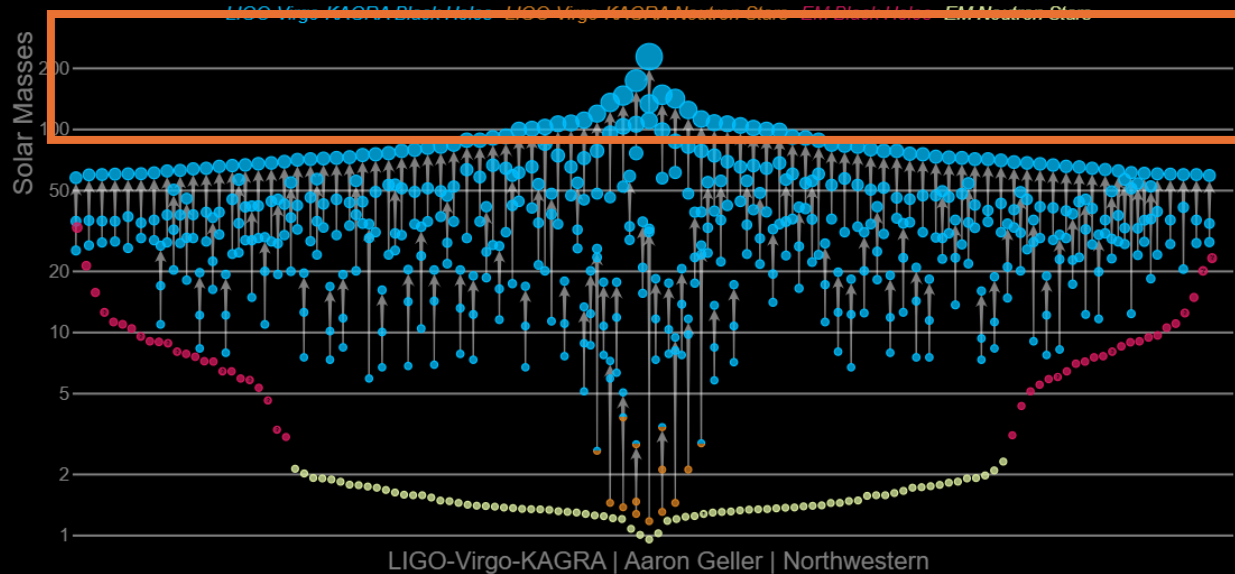


By definition...

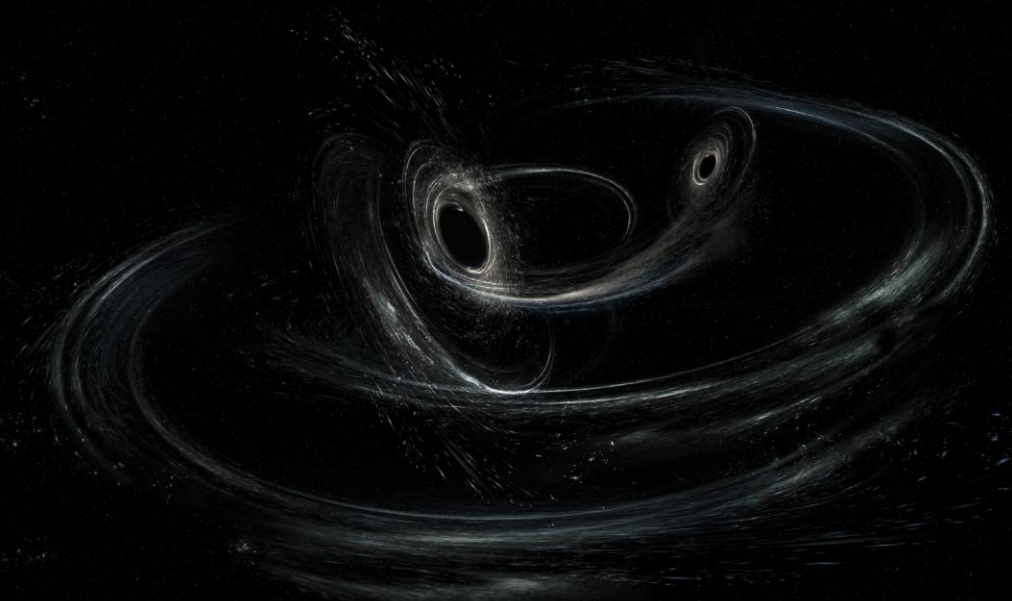
Intermediate-mass black holes:

$$10^2 M_{\odot} \leq M_{\text{BH}} \leq 10^5 M_{\odot}$$

Masses in the Stellar Graveyard



We have seen a few...

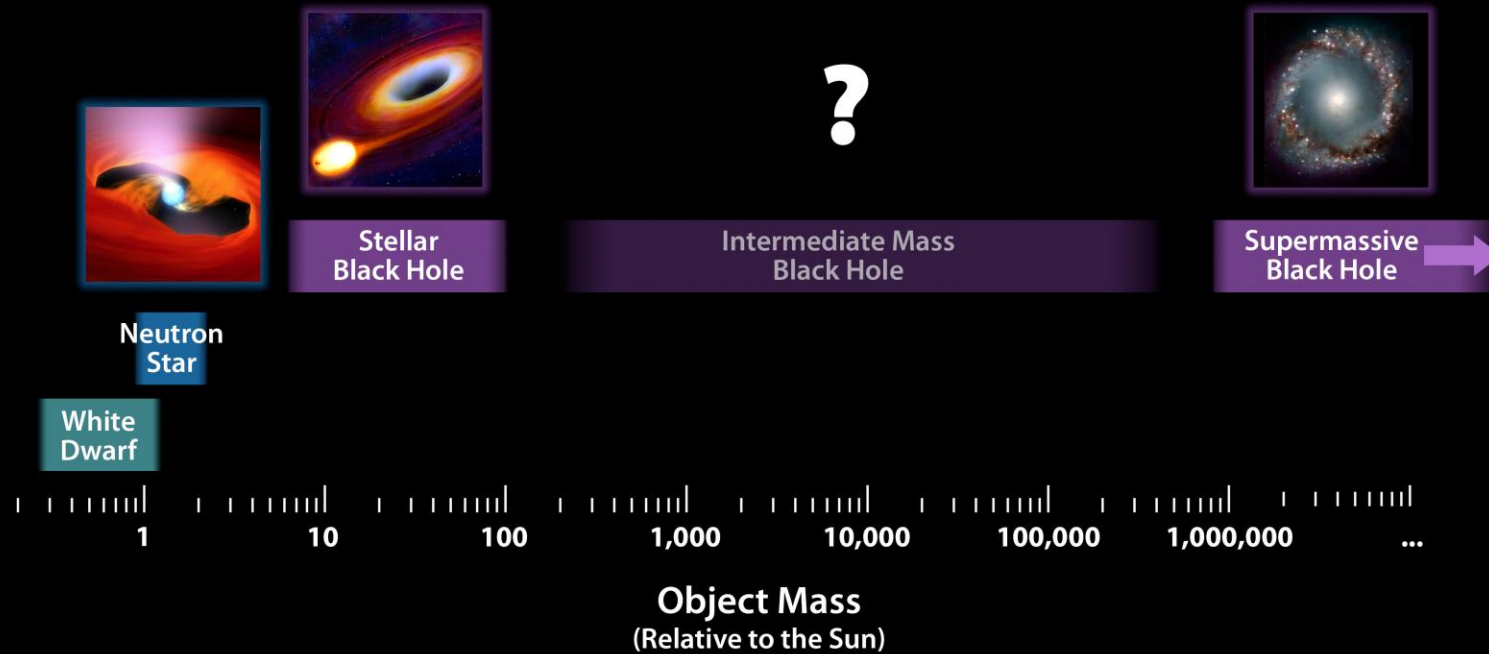


But...

But...

A large mass range remains unexplored

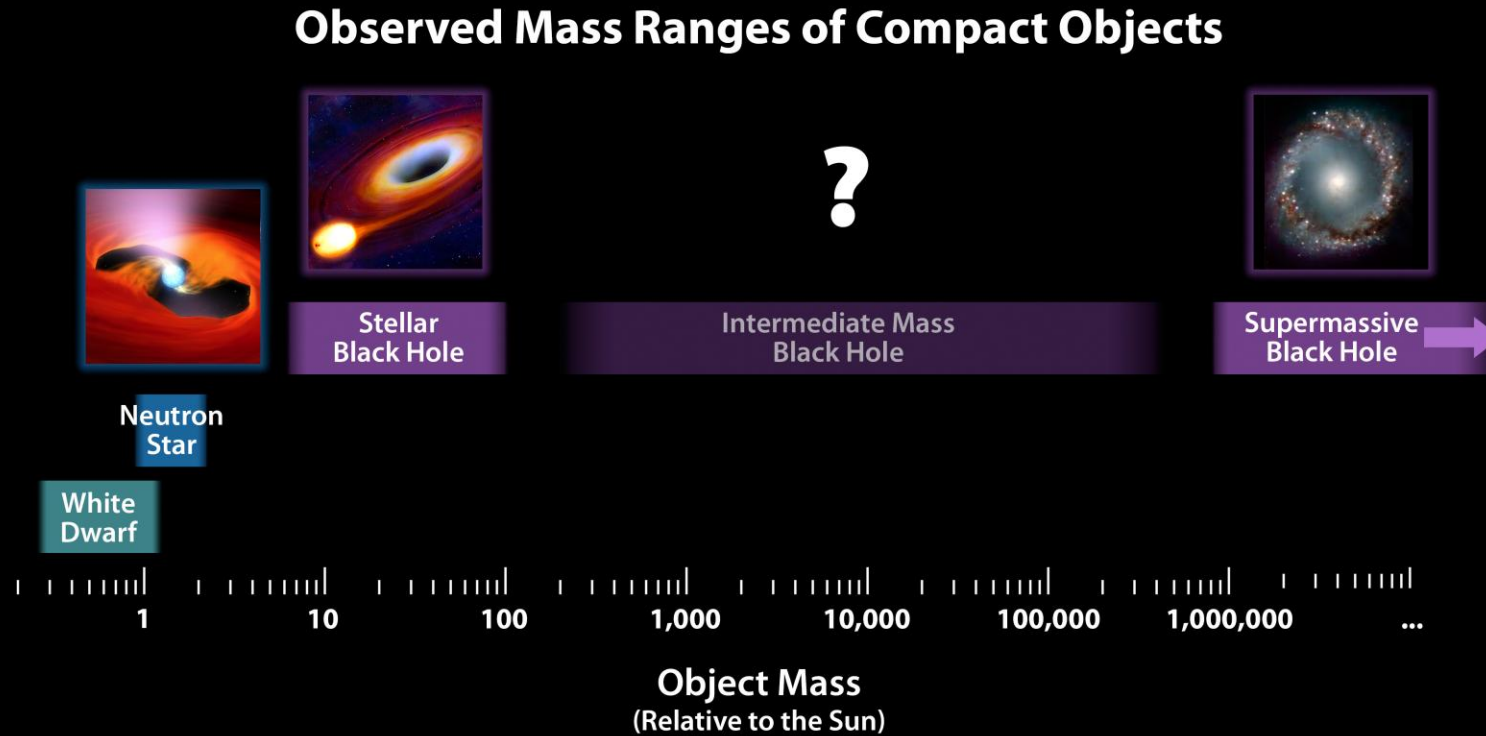
Observed Mass Ranges of Compact Objects



Credit: NASA/JPL-Caltech

But...

A large mass range remains unexplored



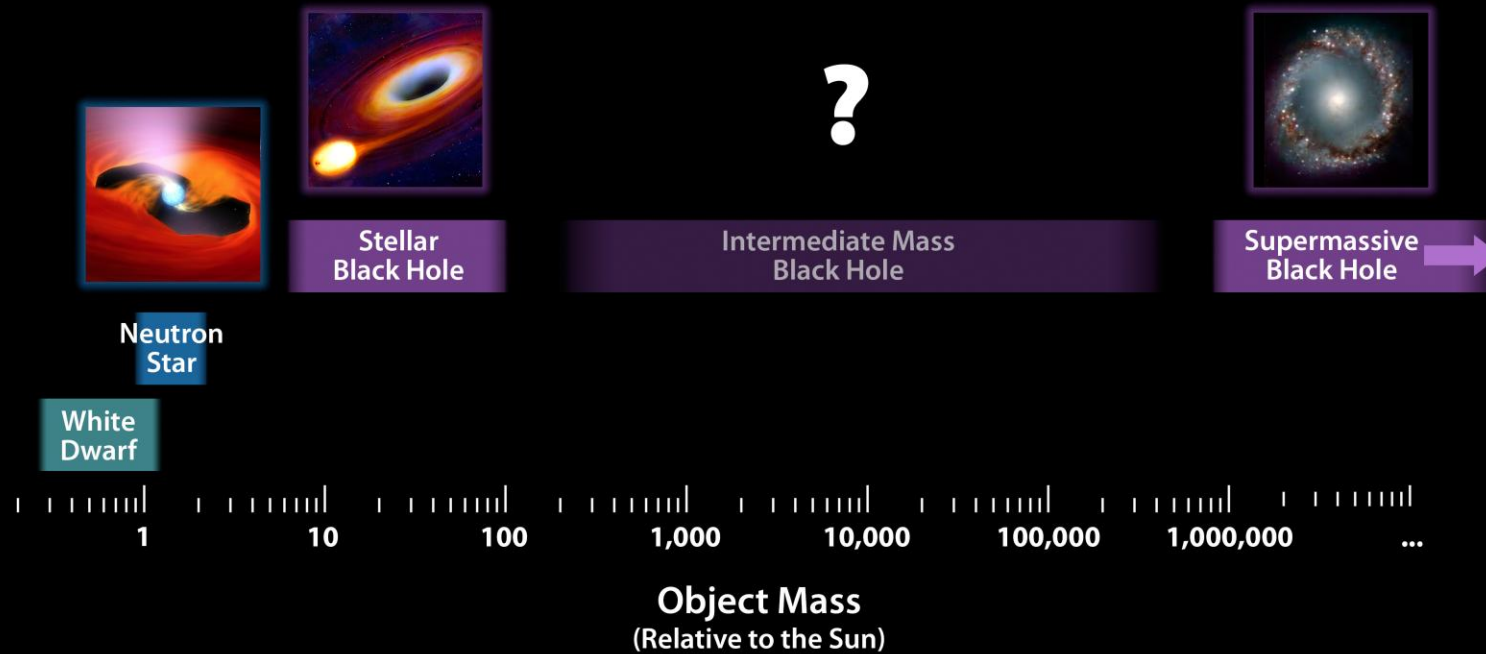
Where is
everybody?

Credit: NASA/JPL-Caltech

But...

A large mass range remains unexplored

Observed Mass Ranges of Compact Objects



Credit: NASA/JPL-Caltech

Where is everybody?

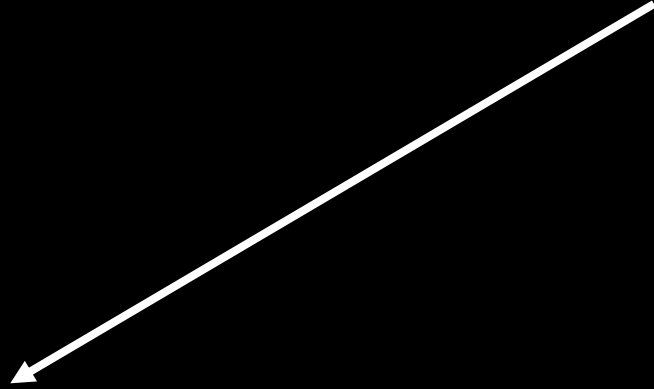
Understanding their formation channels is key

Two main complementary channels

Dense
environments
required!

Two main complementary channels

Dense
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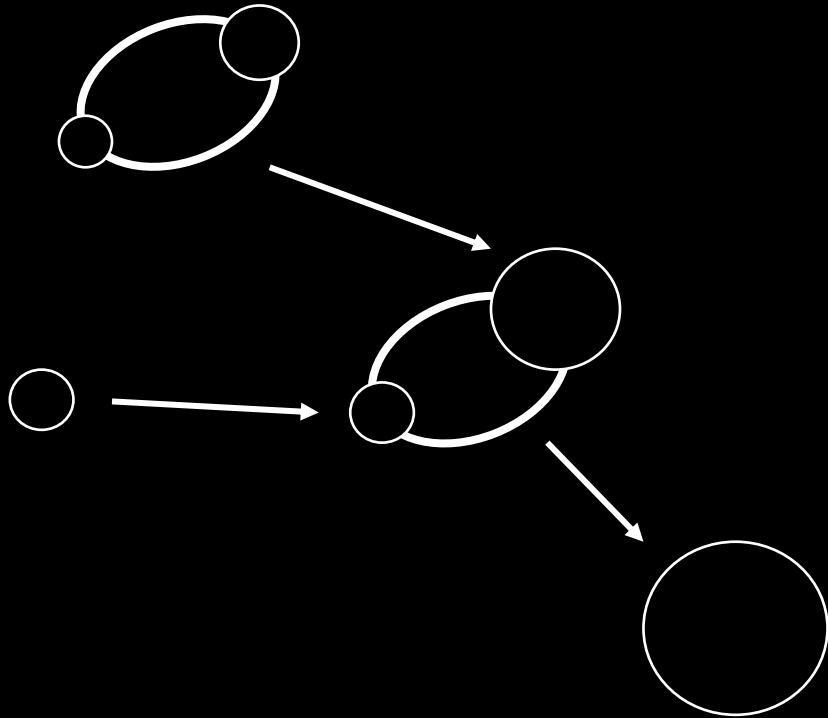


Hierarchical BH-BH mergers

Two main complementary channels

Dense
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Hierarchical BH-BH mergers

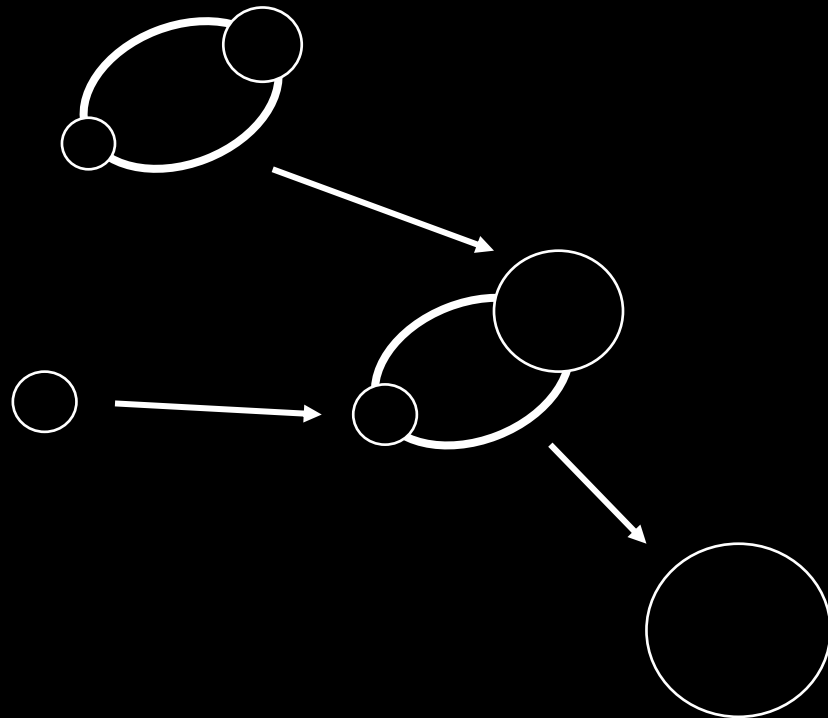


Two main complementary channels

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Hierarchical BH-BH mergers

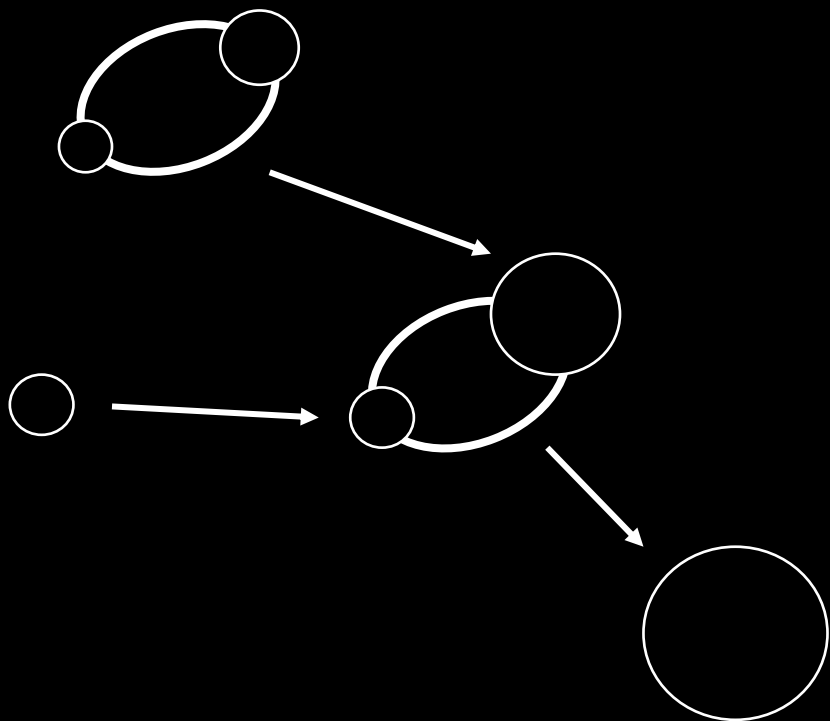
Runaway stellar collisions



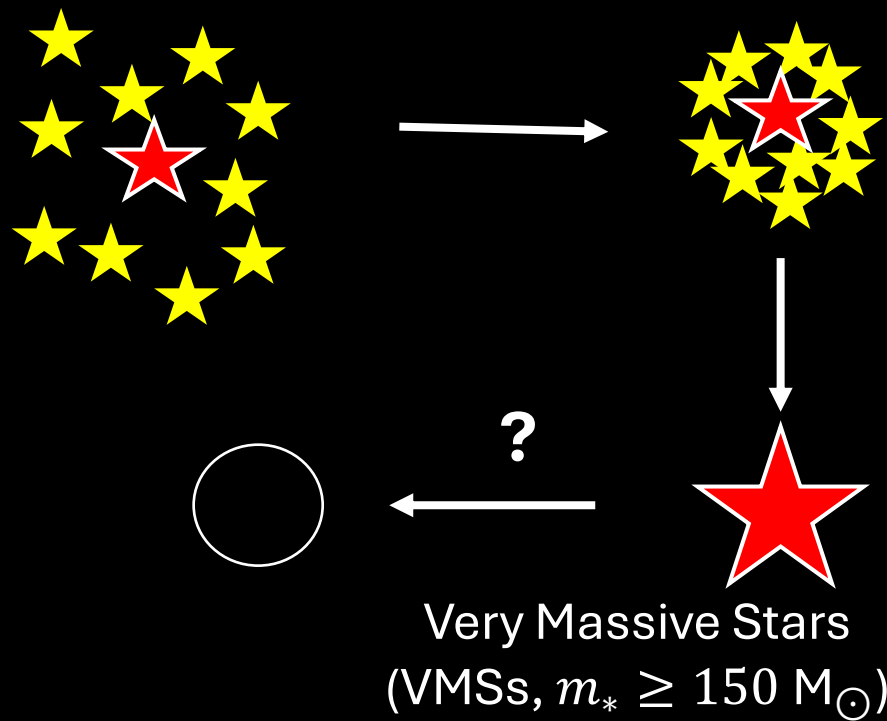
Two main complementary channels

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Hierarchical BH-BH mergers



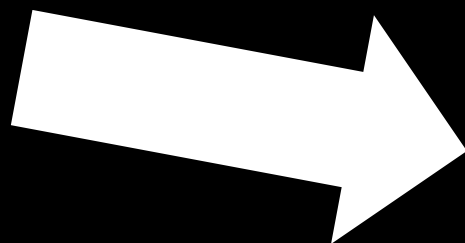
Runaway stellar collisions



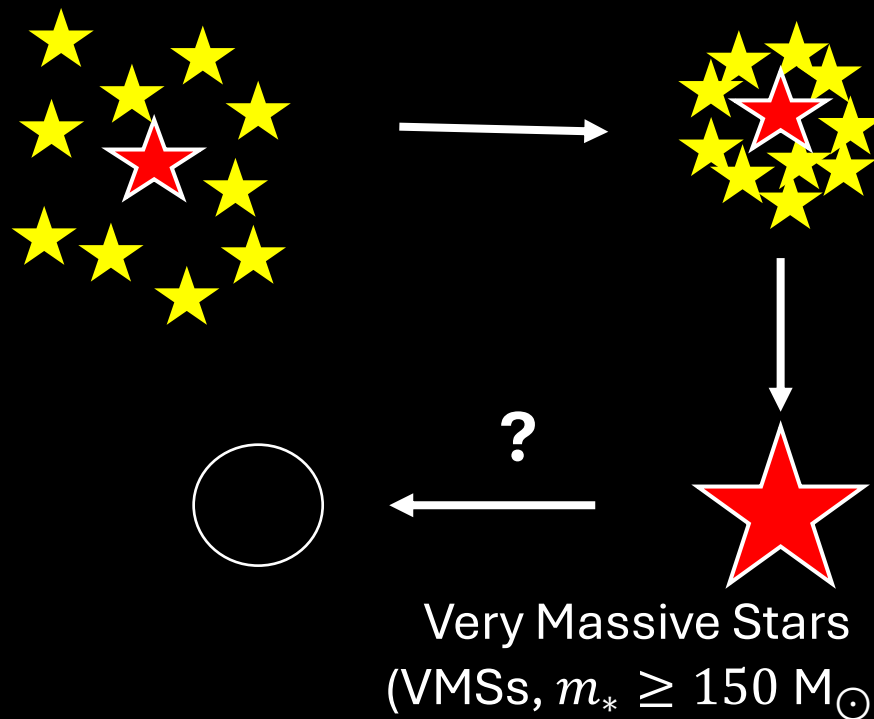
Two main complementary channels

Dense
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required!

I will focus on
this channel!

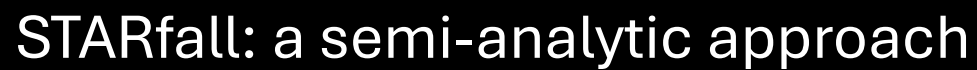


Runaway stellar collisions





STARfall: a semi-analytic approach





STARfall: a semi-analytic approach

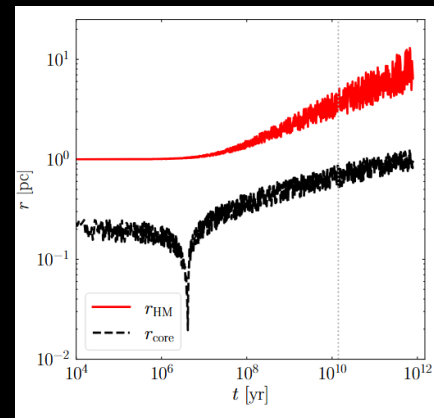
Massive binary
evolution





STARfall: a semi-analytic approach

Massive binary
evolution



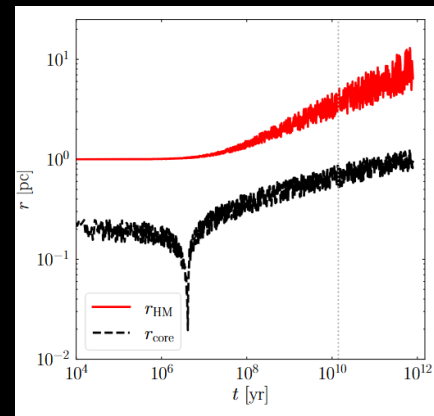
Arca Sedda et al 2026

Host cluster
evolution



STARfall: a semi-analytic approach

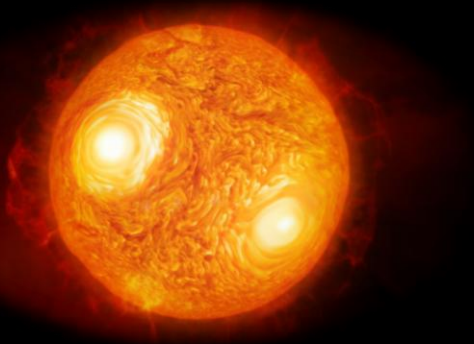
Massive binary
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Arca Sedda et al 2026

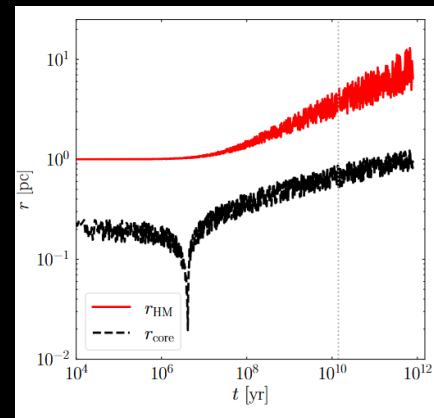
Simplified
stellar evolution





STARfall: a semi-analytic approach

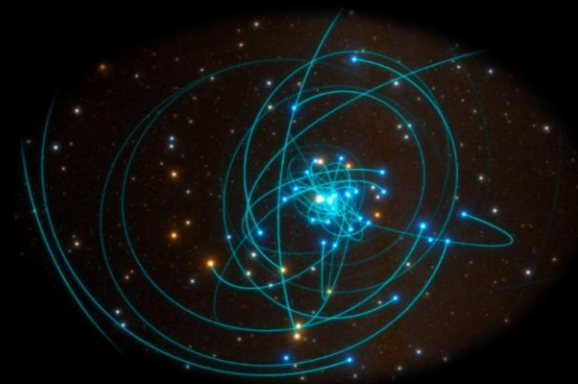
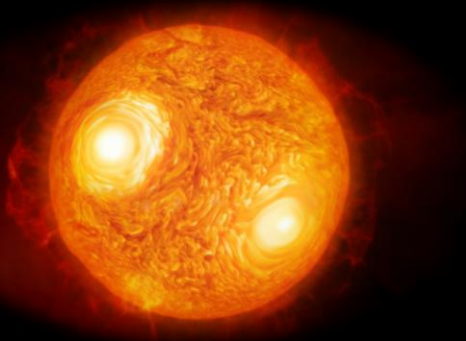
Massive binary
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Arca Sedda et al 2026

Host cluster
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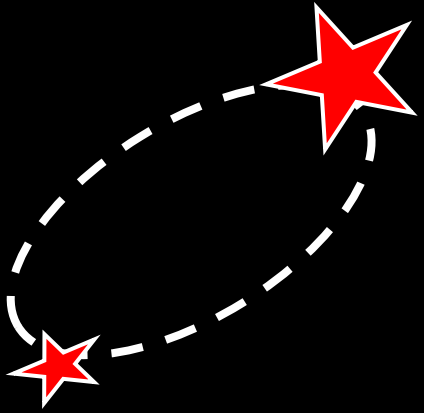
Simplified
stellar evolution



Dynamical
Interactions



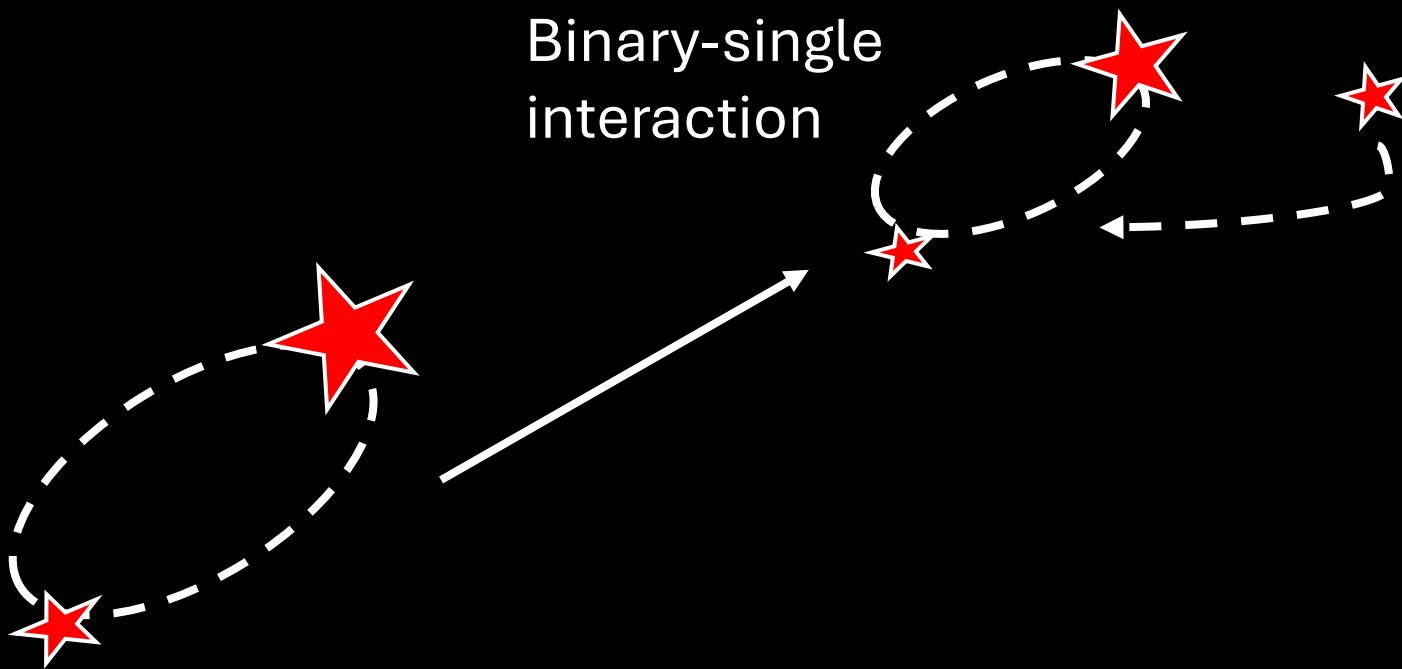
STARfall: a semi-analytic approach





STARfall: a semi-analytic approach

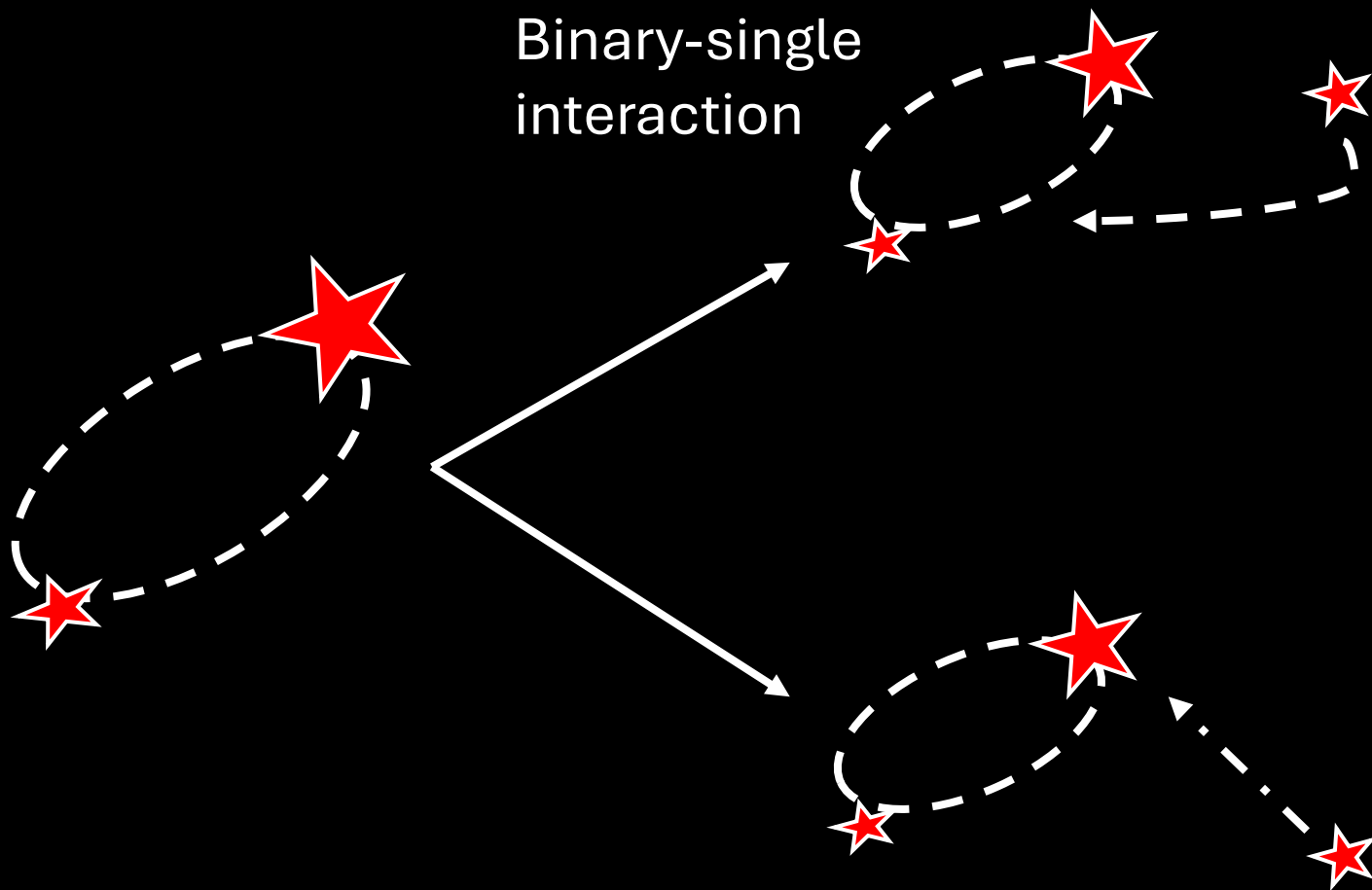
Binary-single
interaction





STARfall: a semi-analytic approach

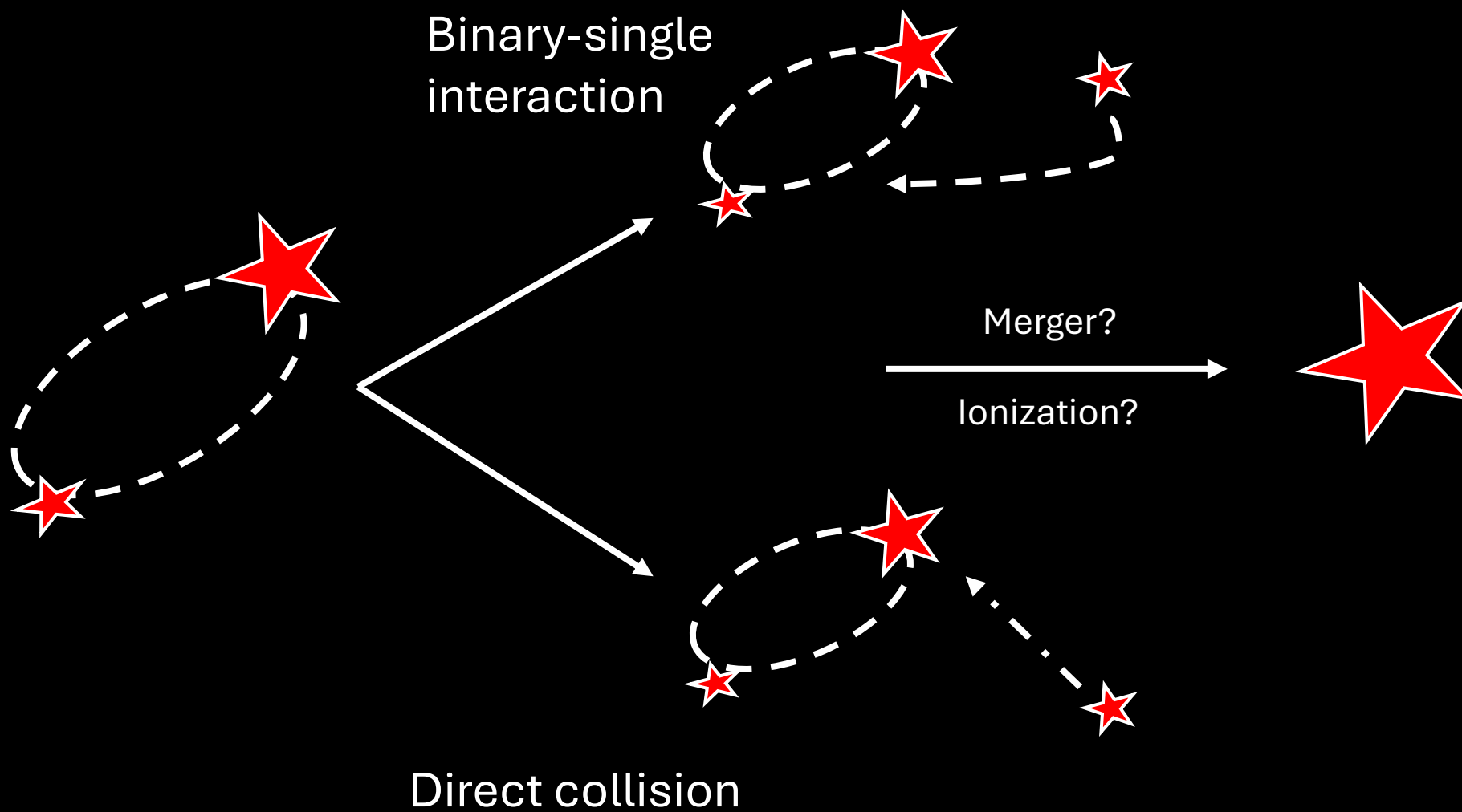
Binary-single
interaction



Direct collision

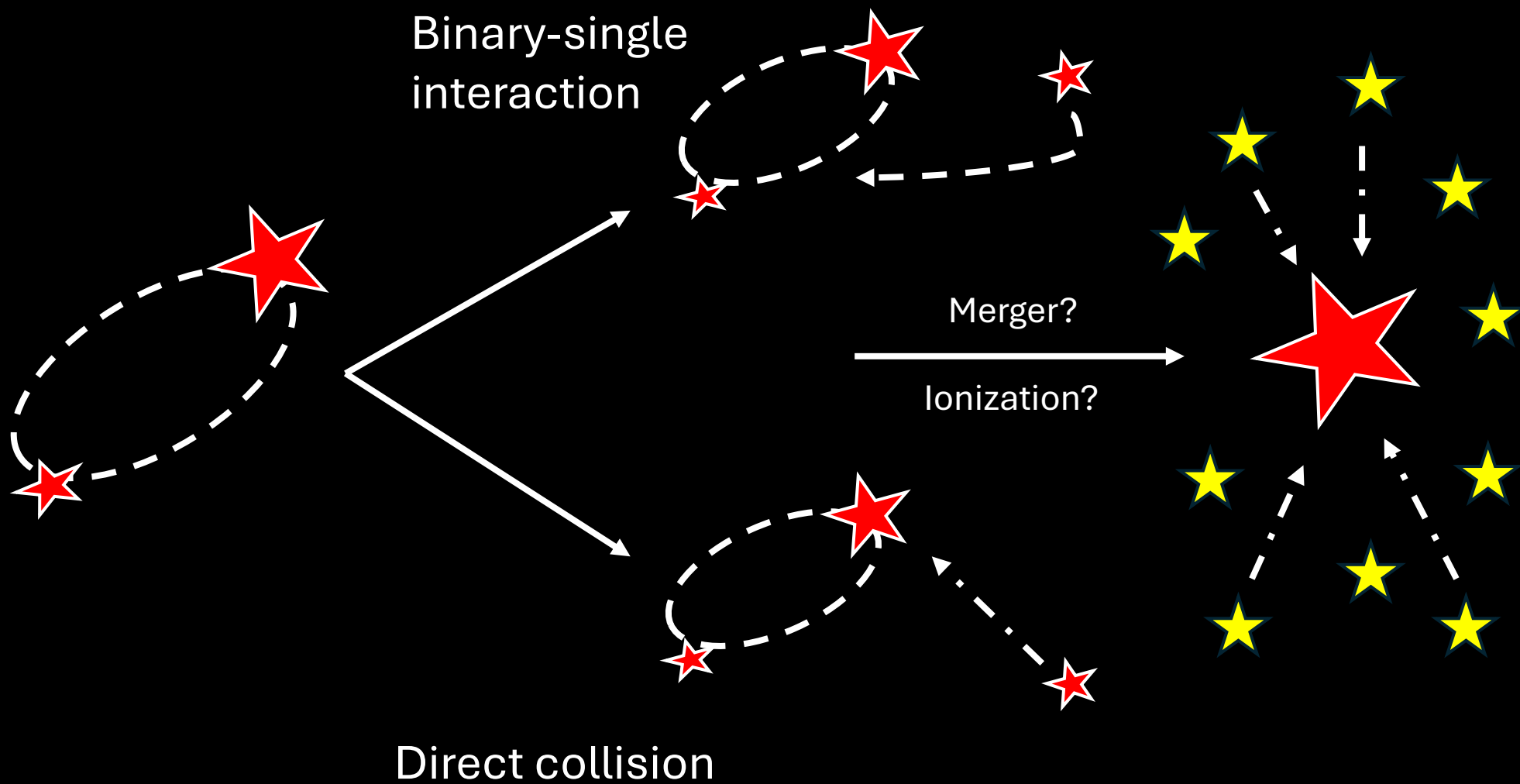


STARfall: a semi-analytic approach





STARfall: a semi-analytic approach





STARfall: a semi-analytic approach

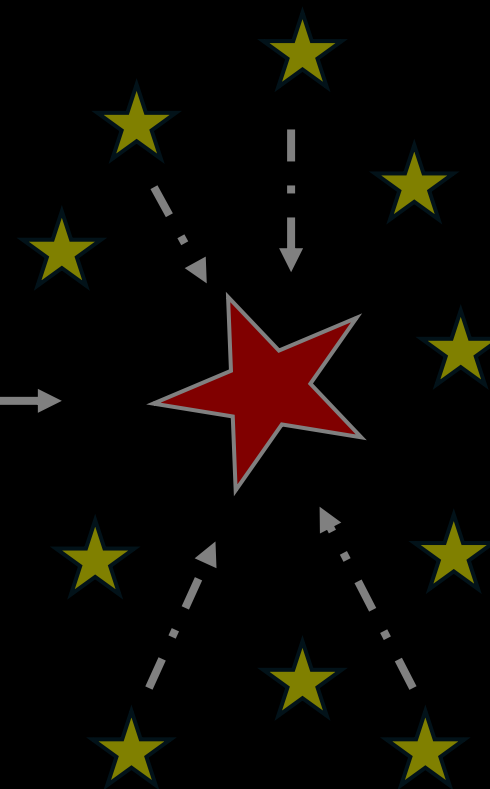
Binary-single
interaction

Mergers or collisions?

Merger?

Ionization?

Direct collision





STARfall: a semi-analytic approach

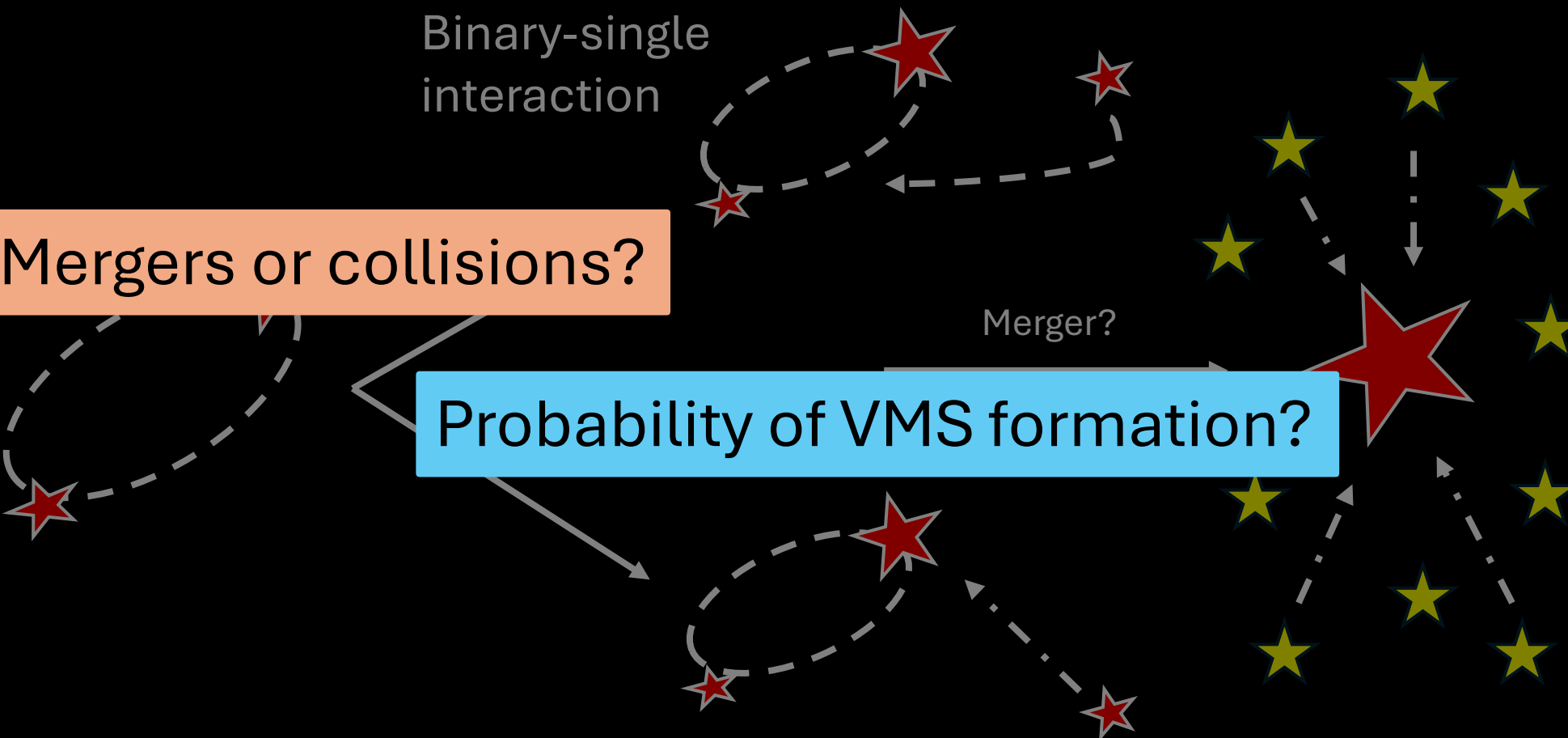
Binary-single
interaction

Mergers or collisions?

Merger?

Probability of VMS formation?

Direct collision





STARfall: a semi-analytic approach

Binary-single
interaction

Mergers or collisions?

Merger?

Probability of VMS formation?

How much massive?

Direct collision

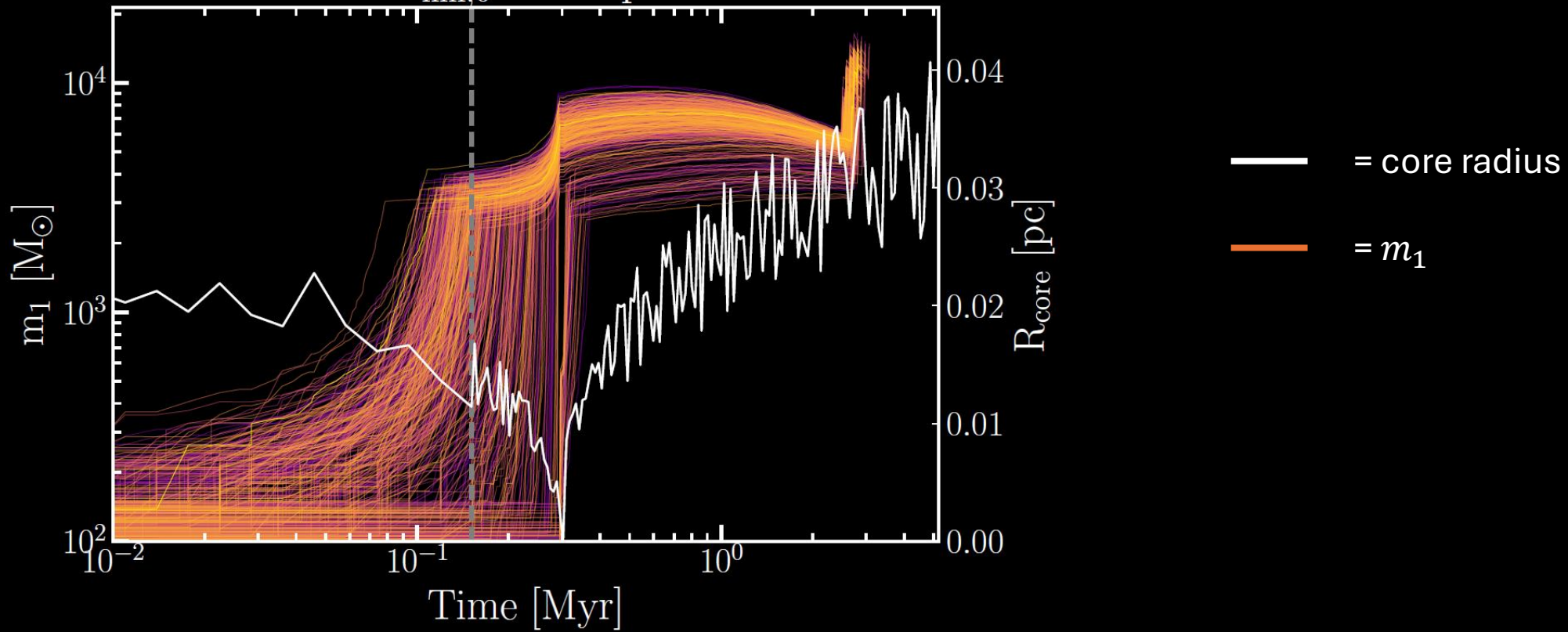
First of all...mass growth

First of all...mass growth

Simonato et al (in prep)

$$M_{\text{cl},0} = 10^6 M_{\odot} - Z = 0.0002$$

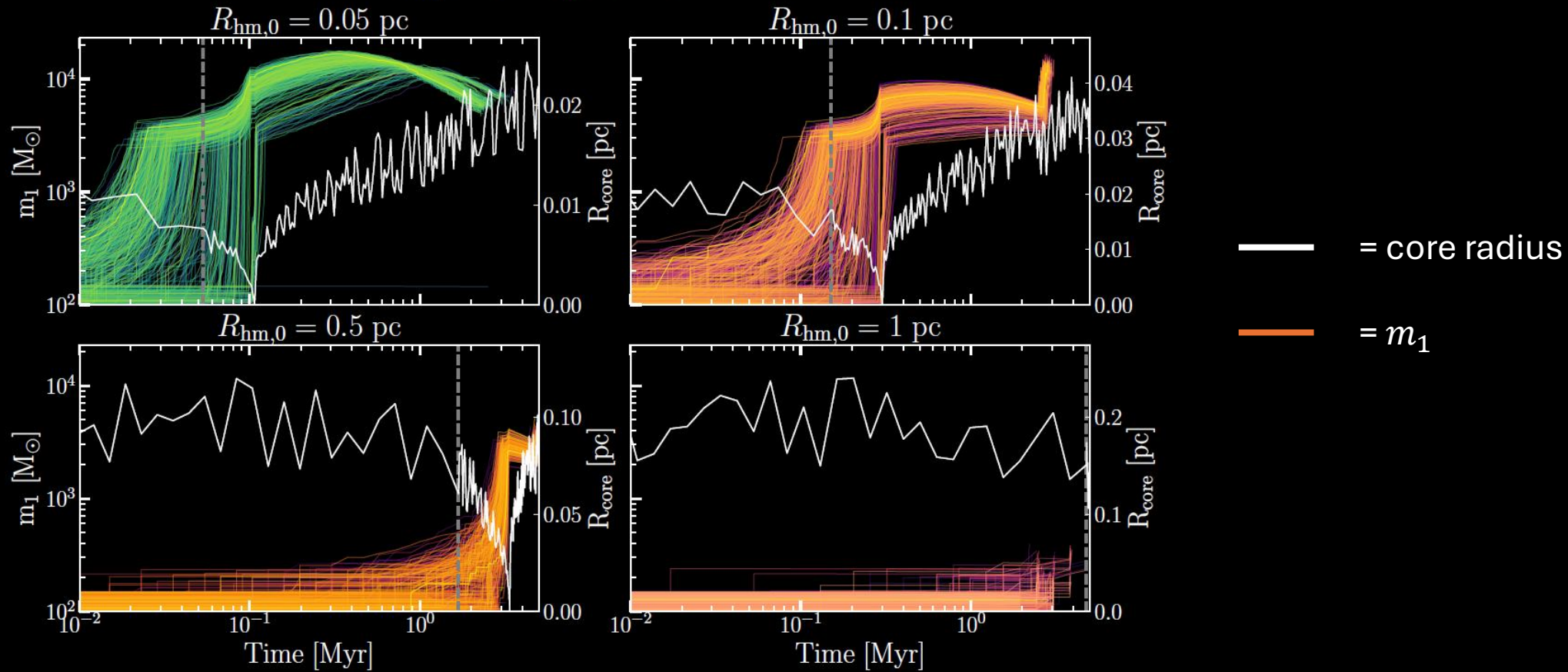
$$R_{\text{hm},0} = 0.1 \text{ pc}$$



First of all...mass growth

Simonato et al (in prep)

$$M_{\text{cl},0} = 10^6 M_{\odot} - Z = 0.0002$$

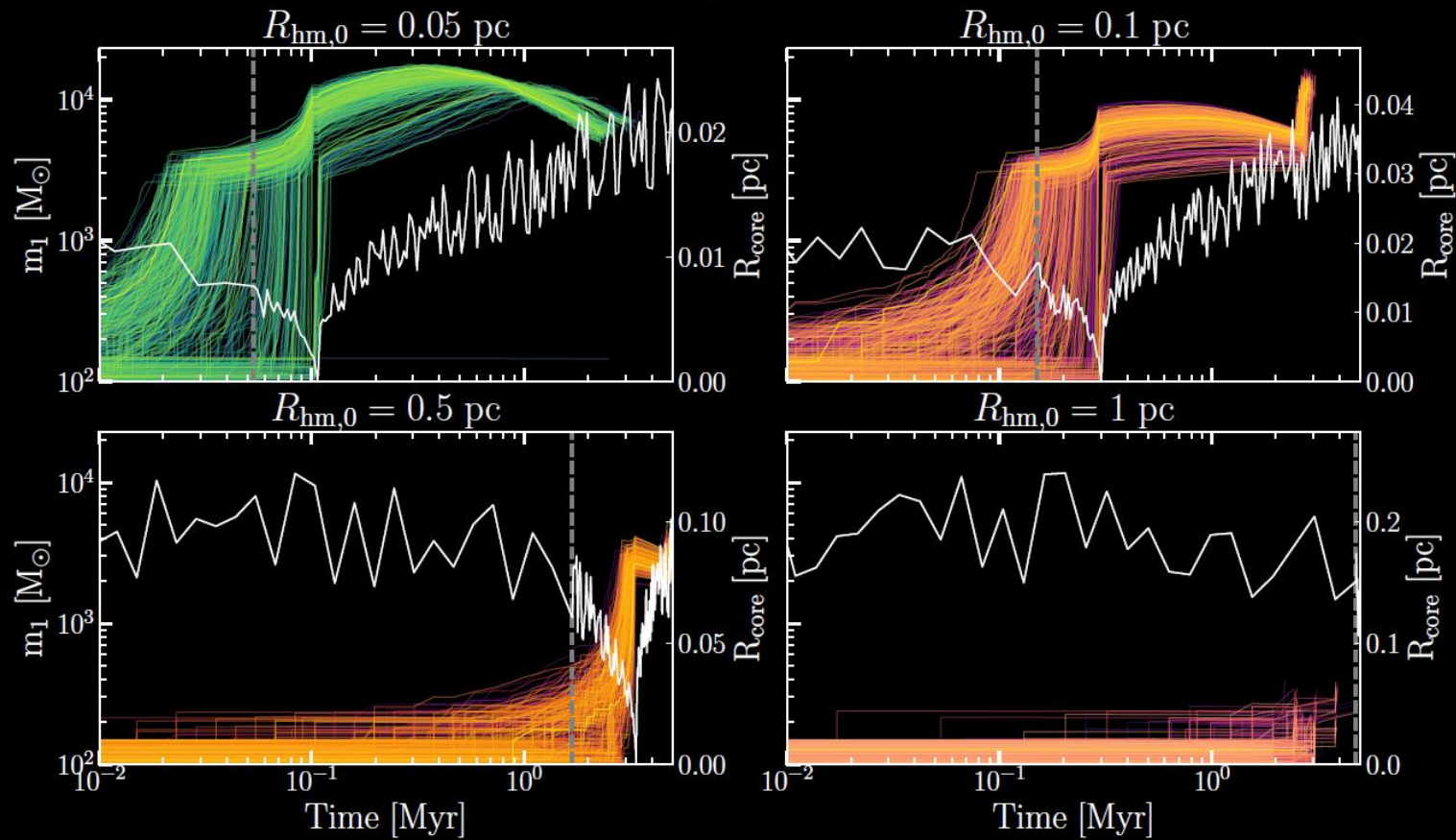


First of all...mass growth

Simonato et al (in prep)

Core-collapse
timescale relevant in
denser environments

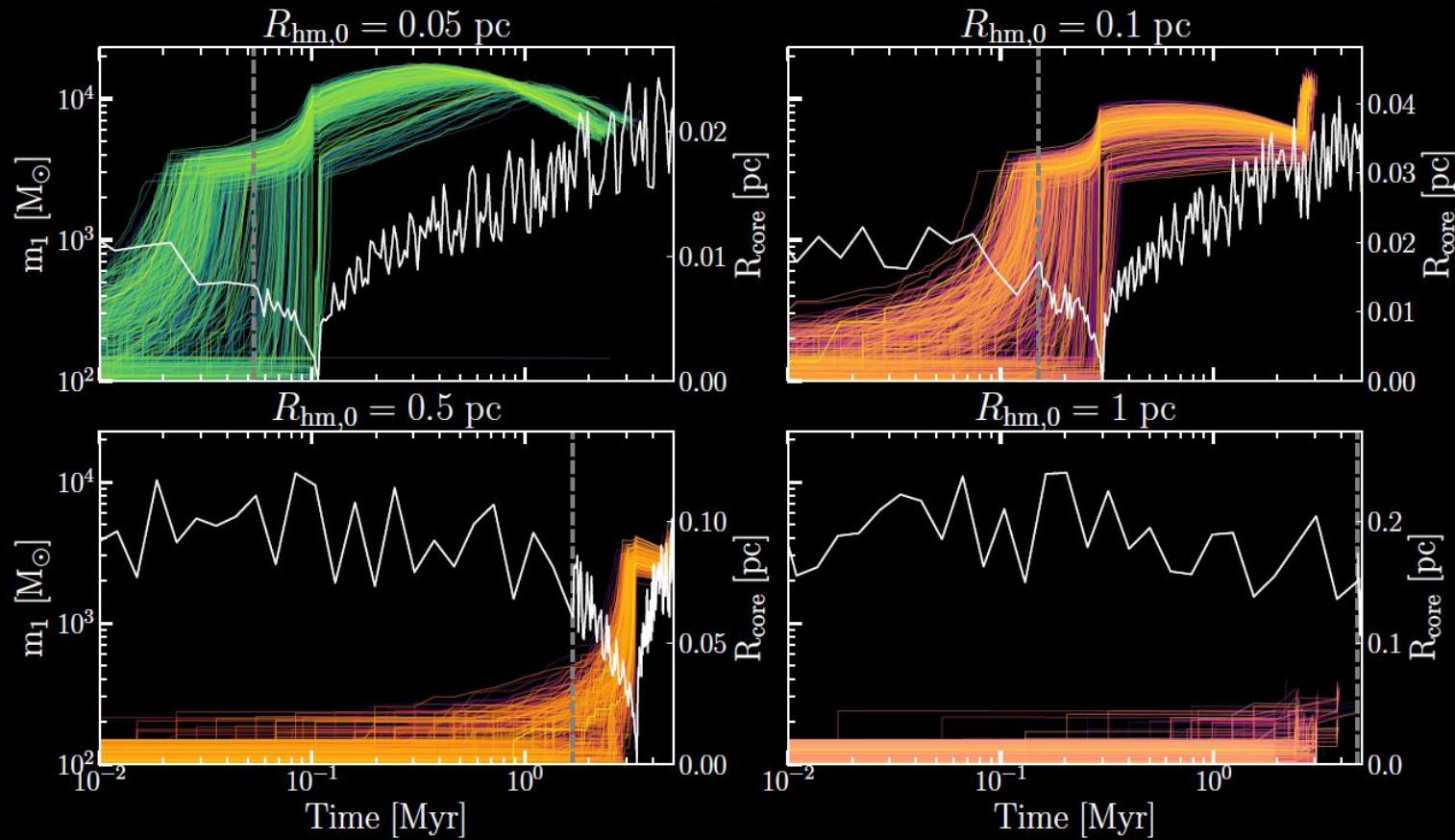
$$M_{\text{cl},0} = 10^6 M_{\odot} - Z = 0.0002$$



First of all...mass growth

Simonato et al (in prep)

$$M_{\text{cl},0} = 10^6 M_{\odot} - Z = 0.0002$$



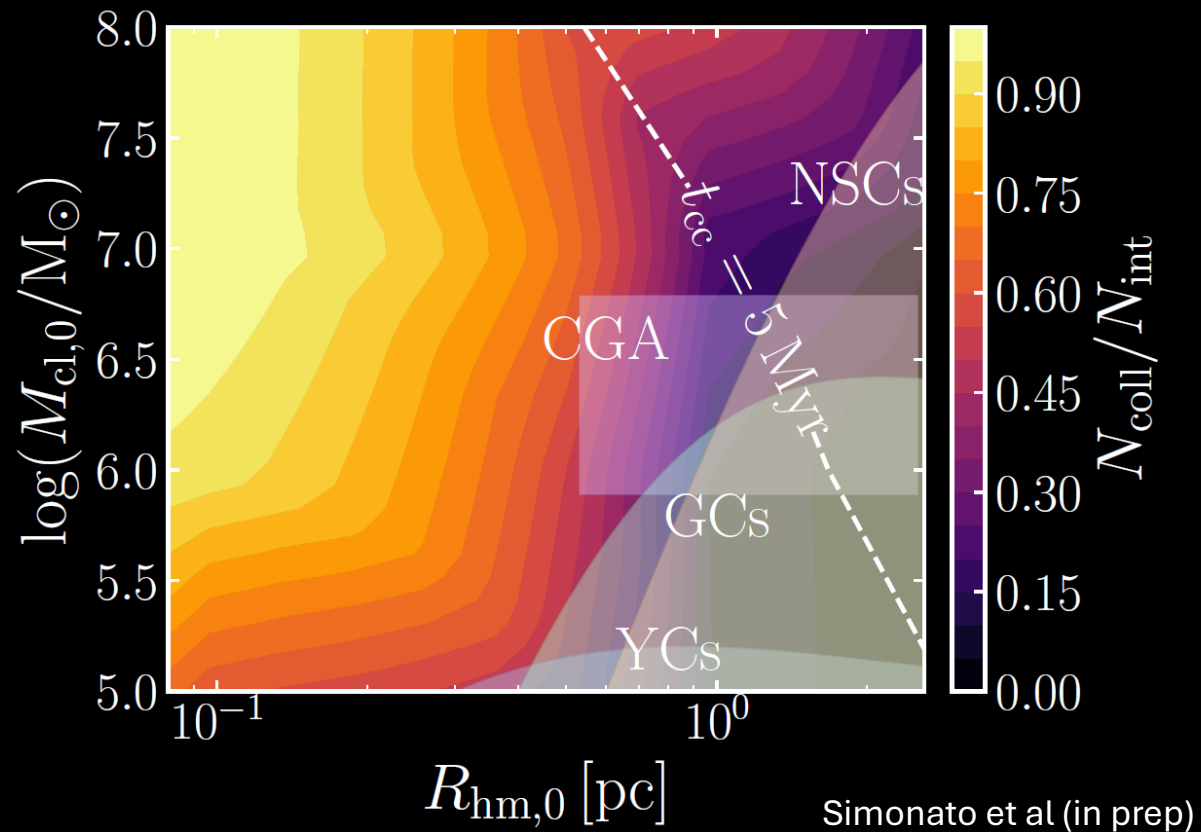
Core-collapse timescale relevant in denser environments

Stellar evolution relevant in less dense environments

$M_{cl,0}$ = initial mass

$R_{hm,0}$ = initial half-mass radius

Mergers or Collisions?



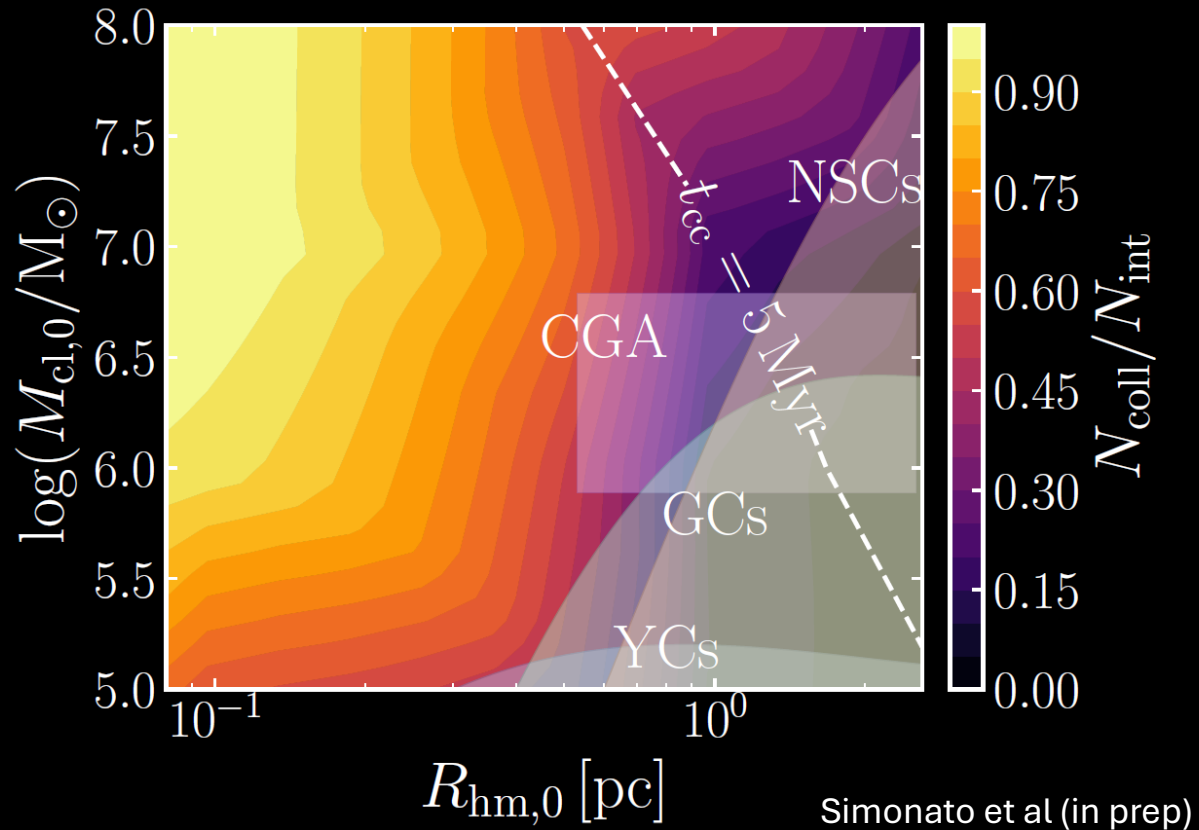
NSCs = Nuclear Star Clusters

GCs = Globular Clusters

YCs = Young star Clusters

CGA = Cosmic Gems Arc

Mergers or Collisions?



$M_{cl,0}$ = initial mass

$R_{hm,0}$ = initial half-mass radius

→ It depends on the initial density

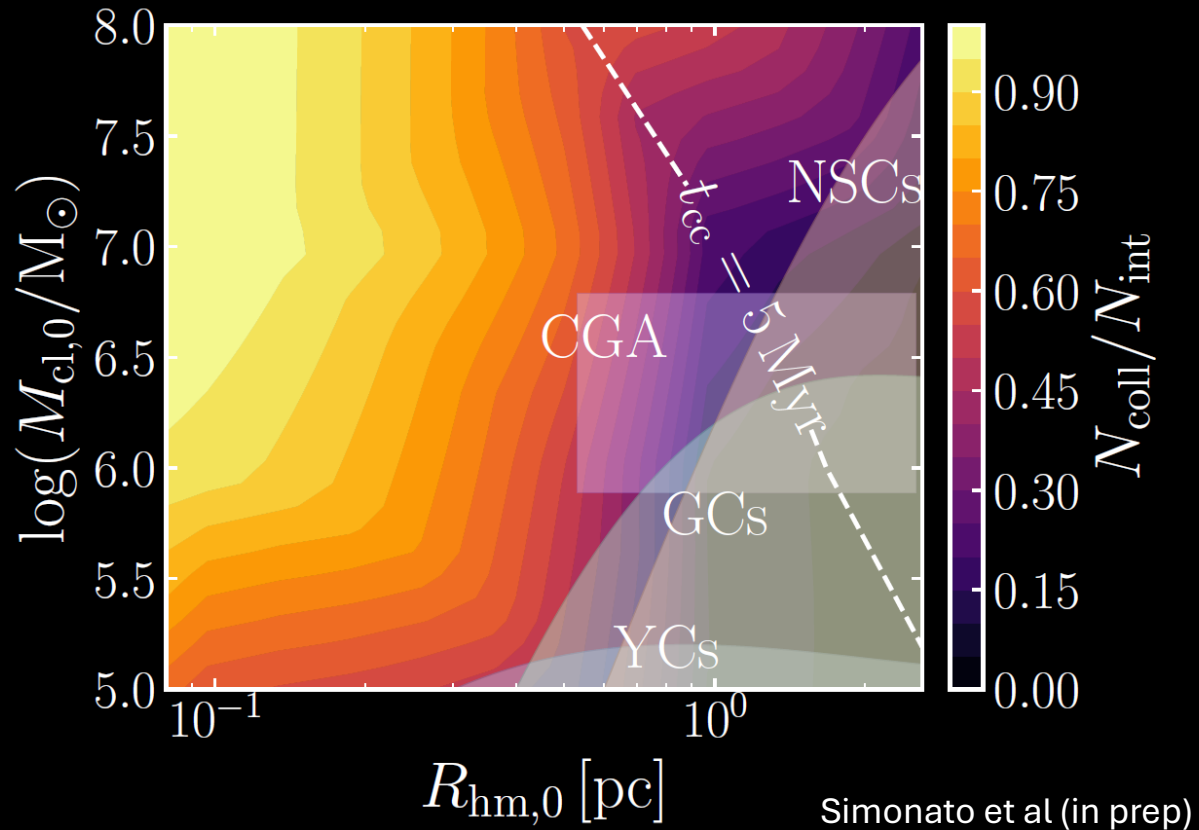
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Mergers or Collisions?



$M_{cl,0}$ = initial mass

$R_{hm,0}$ = initial half-mass radius

→ It depends on the initial density

→ Closely related to the probability of VMS formation

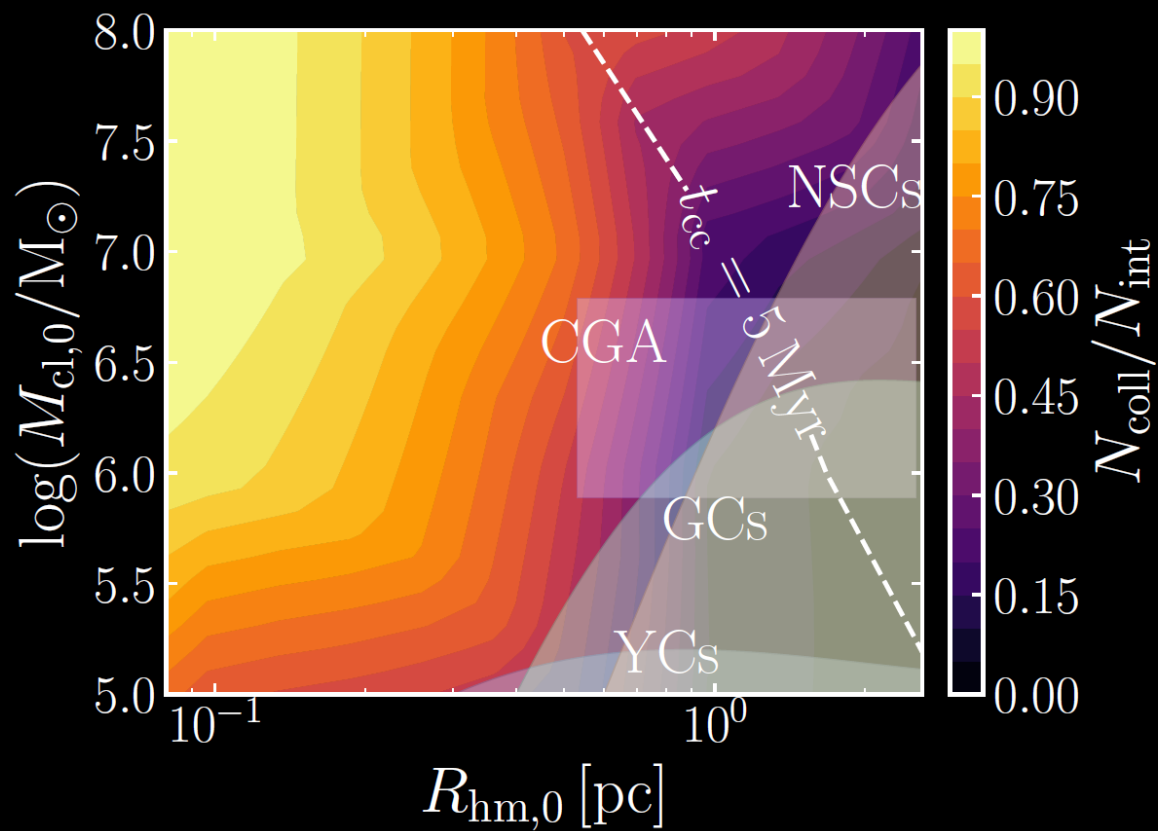
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Mergers or Collisions?



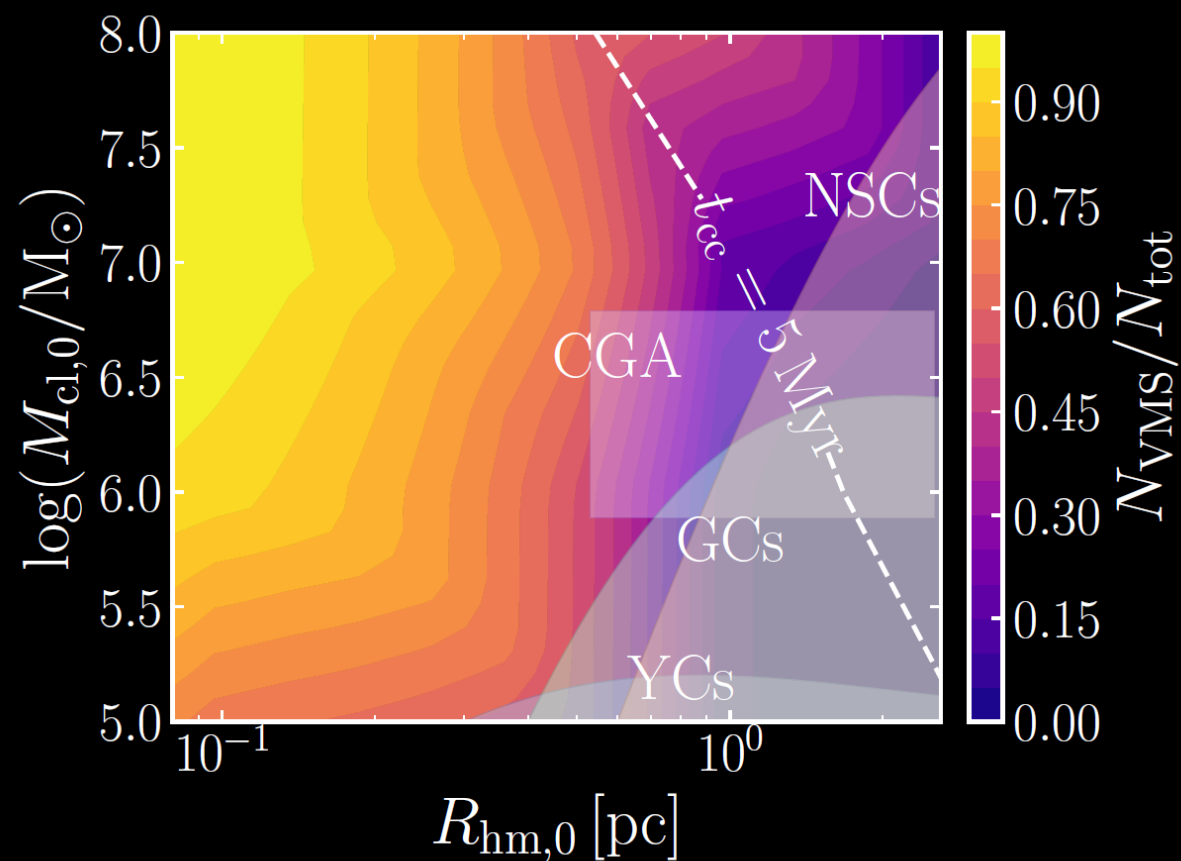
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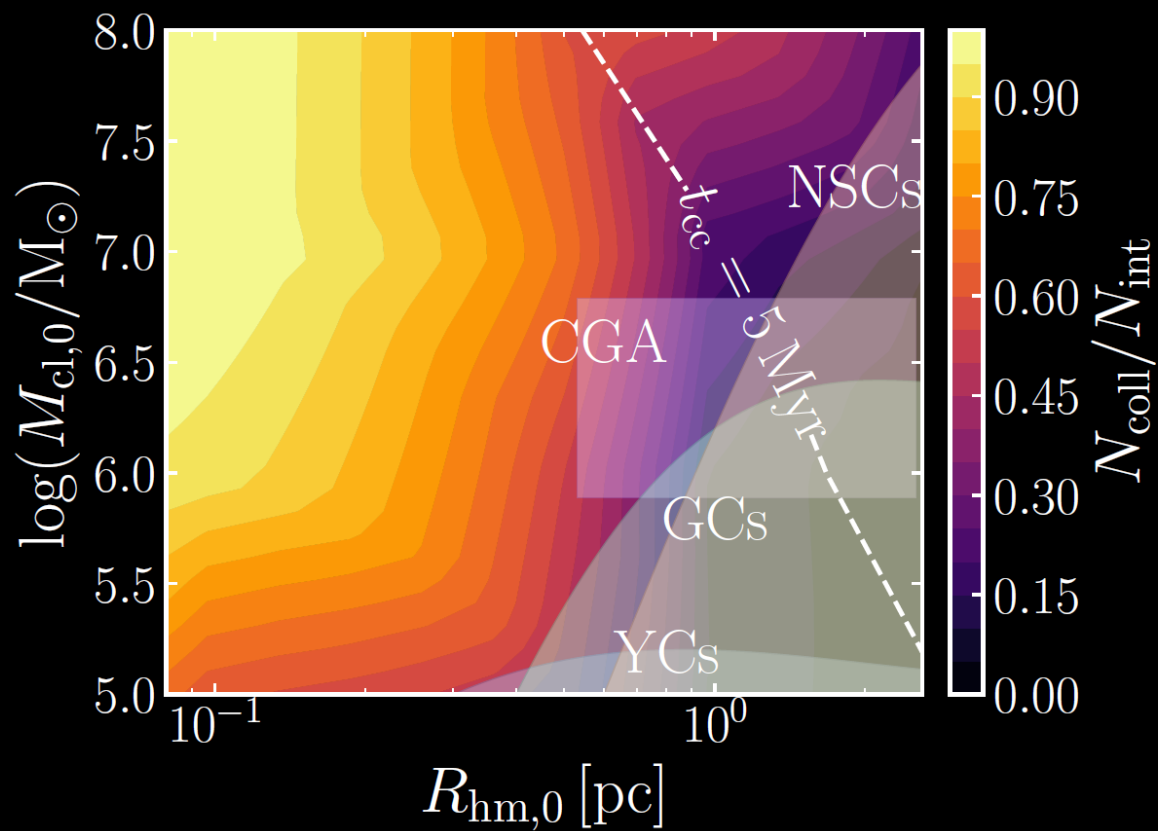
Probability to form a VMS?



VMS = Very Massive Star ($m_* > 300 M_{\odot}$)

Simionato et al (in prep)

Mergers or Collisions?



NSCs = Nuclear Star Clusters

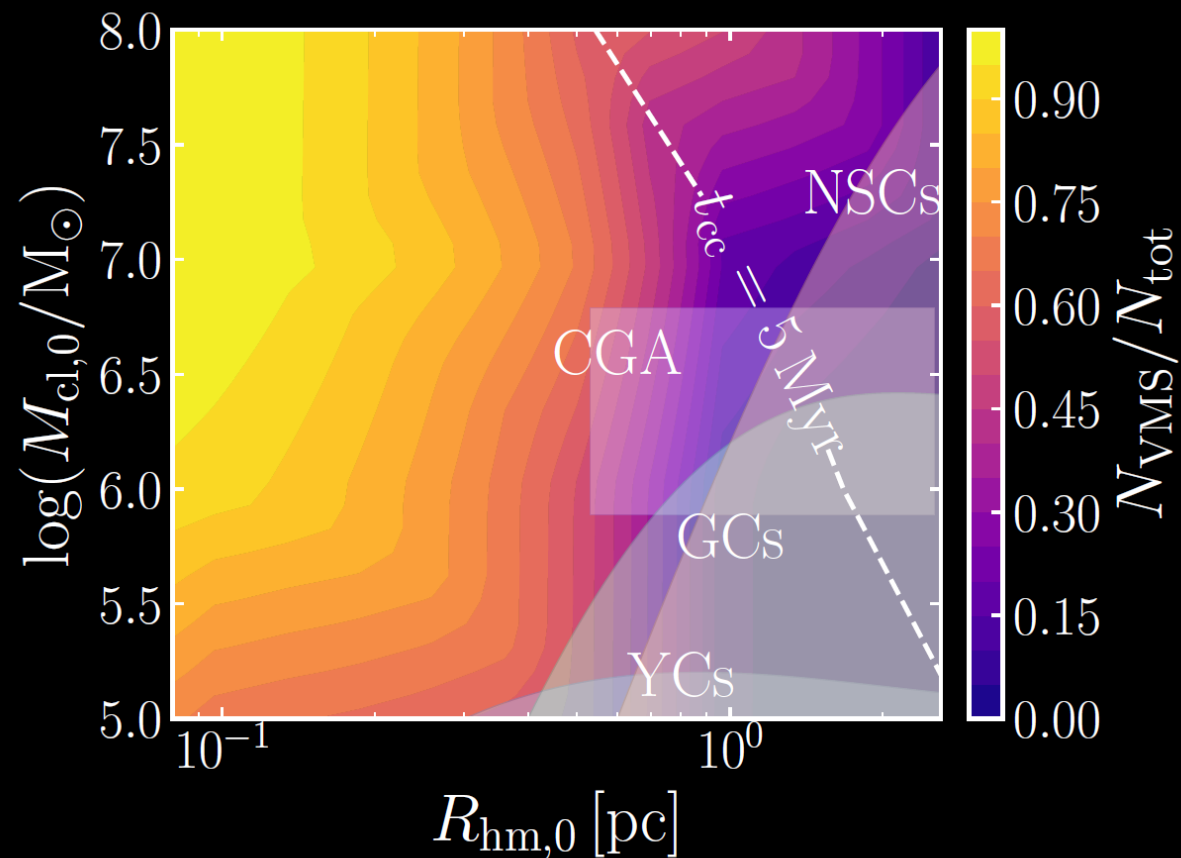
GCs = Globular Clusters

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Same features!!!

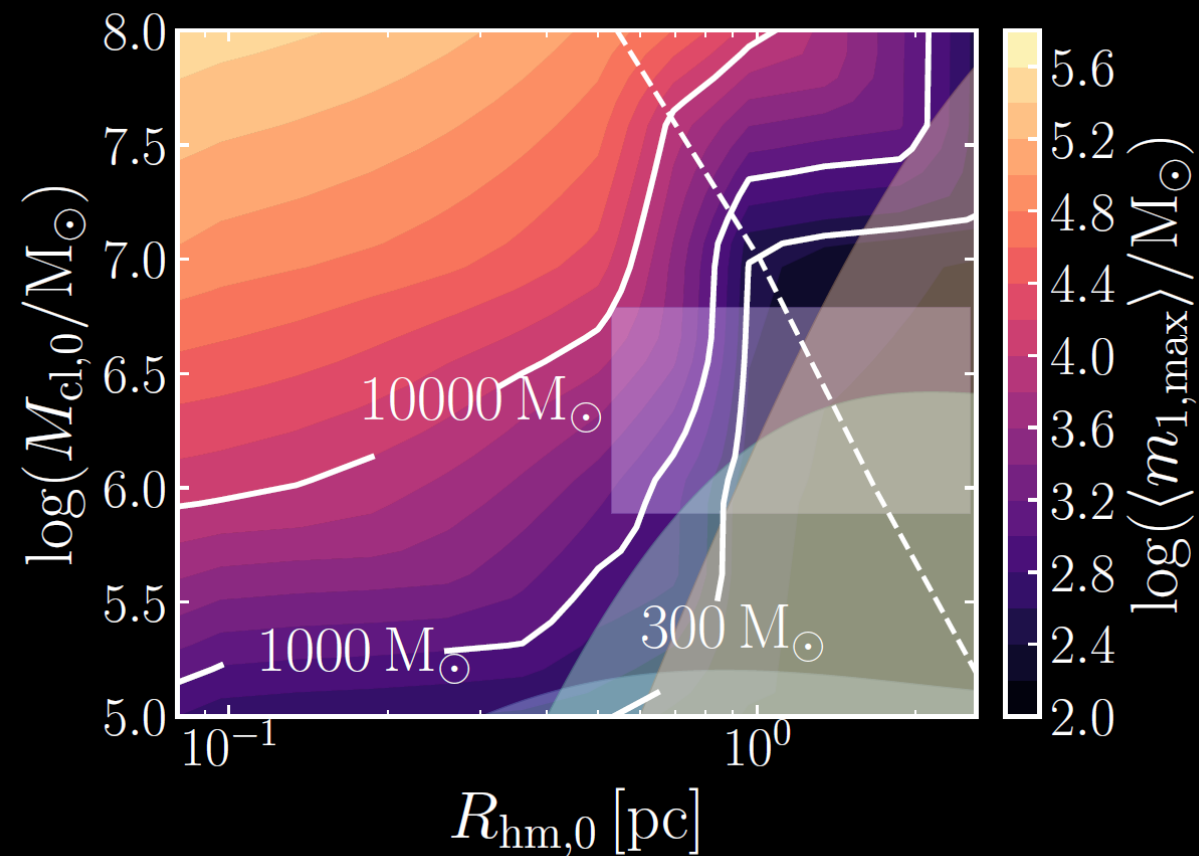
Probability to form a VMS?



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Simionato et al (in prep)

How much massive?



NSCs = Nuclear Star Clusters

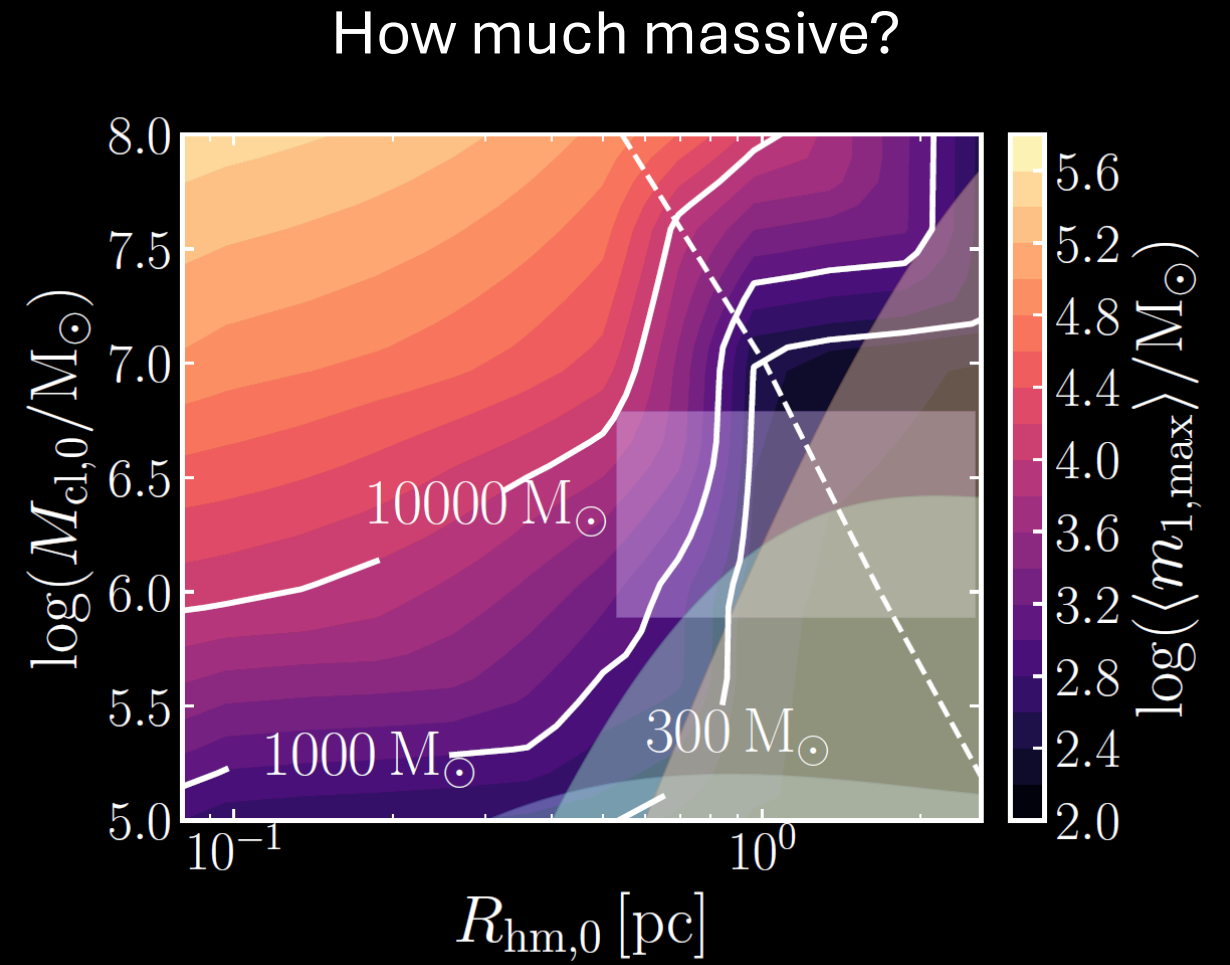
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Simionato et al (in prep)

→ GCs can host VMSs up to $\sim 10^3 M_\odot$



NSCs = Nuclear Star Clusters

GCs = Globular Clusters

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Simionato et al (in prep)

→ GCs can host VMSs up to $\sim 10^3 M_\odot$

→ Up to $\sim 10^4 M_\odot$ in compact systems

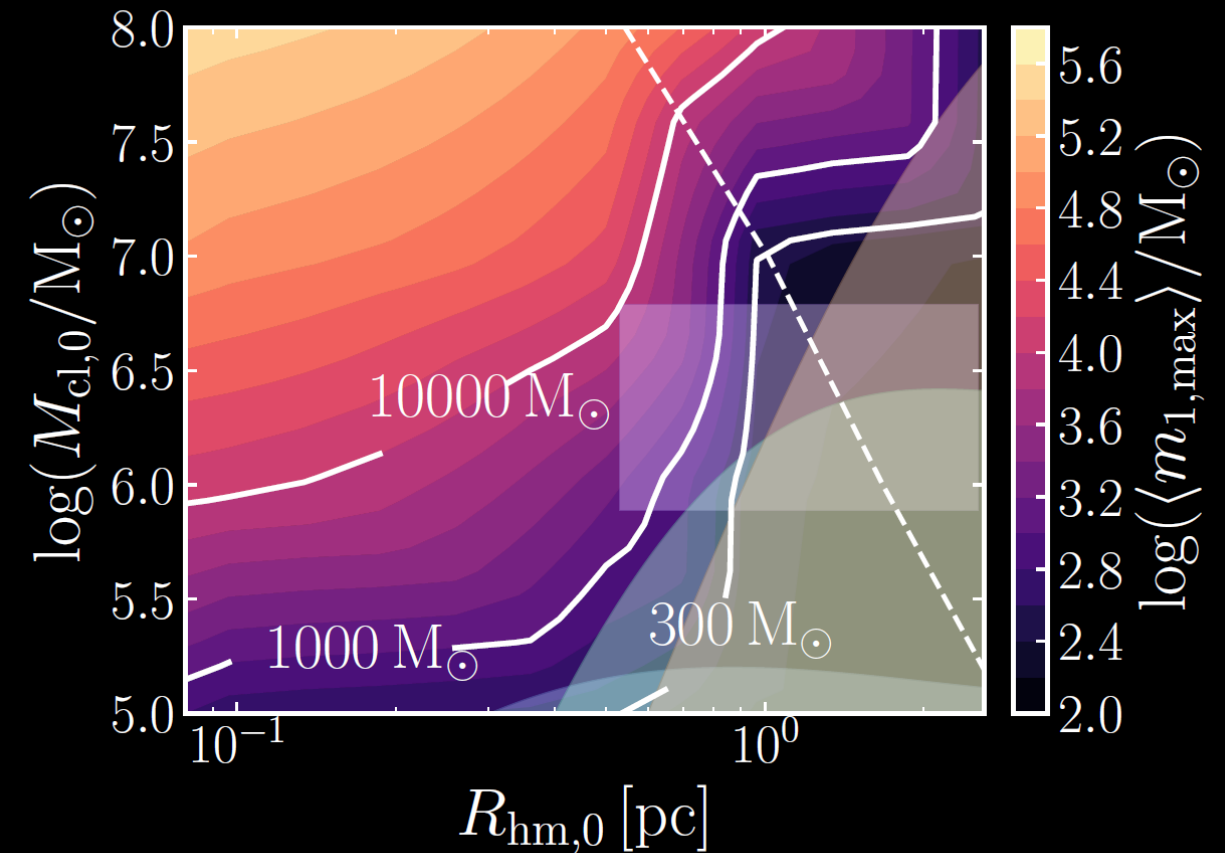
NSCs = Nuclear Star Clusters

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How much massive?



Simionato et al (in prep)

Implications for Cosmic Gems Arc

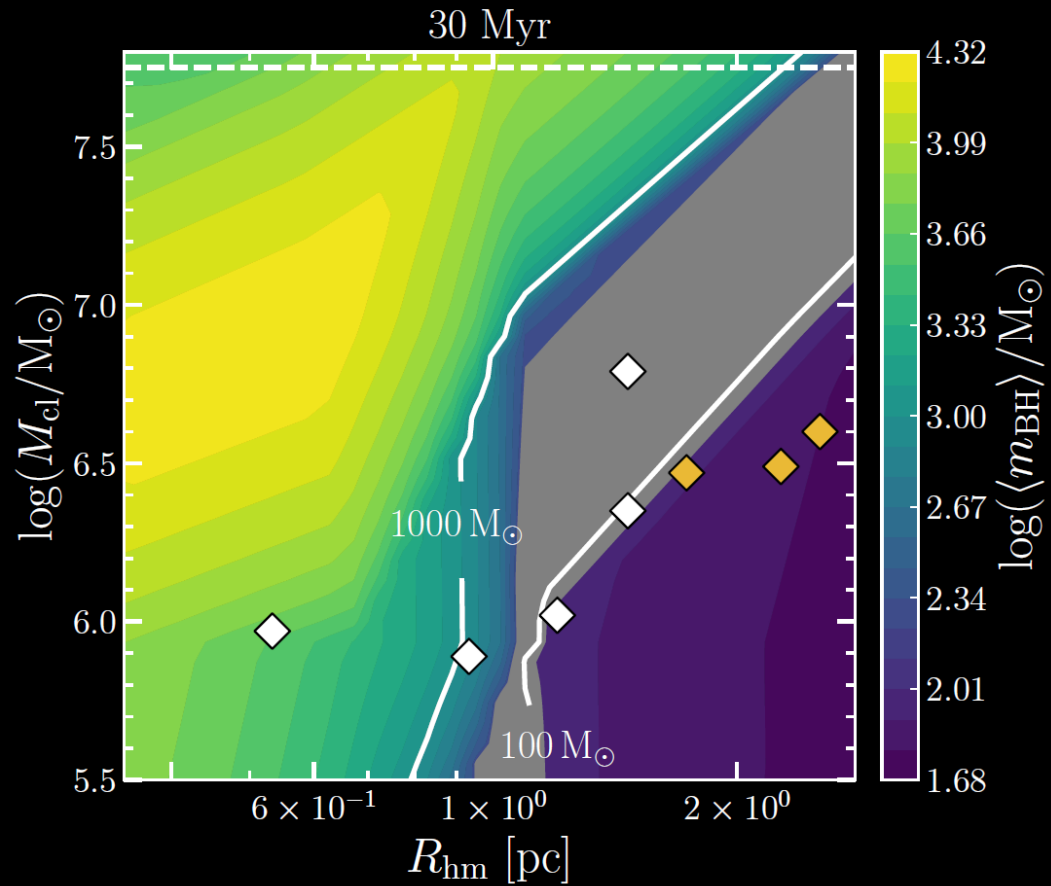
Implications for Cosmic Gems Arc



Credit: ESA/Webb, NASA & CSA, L. Bradley (STScI), A. Adamo (Stockholm University) and the Cosmic Spring collaboration

Implications for Cosmic Gems Arc

Simonato et al (in prep)



◆ = clusters in the Cosmic Gems Arc

◆ = counter-images

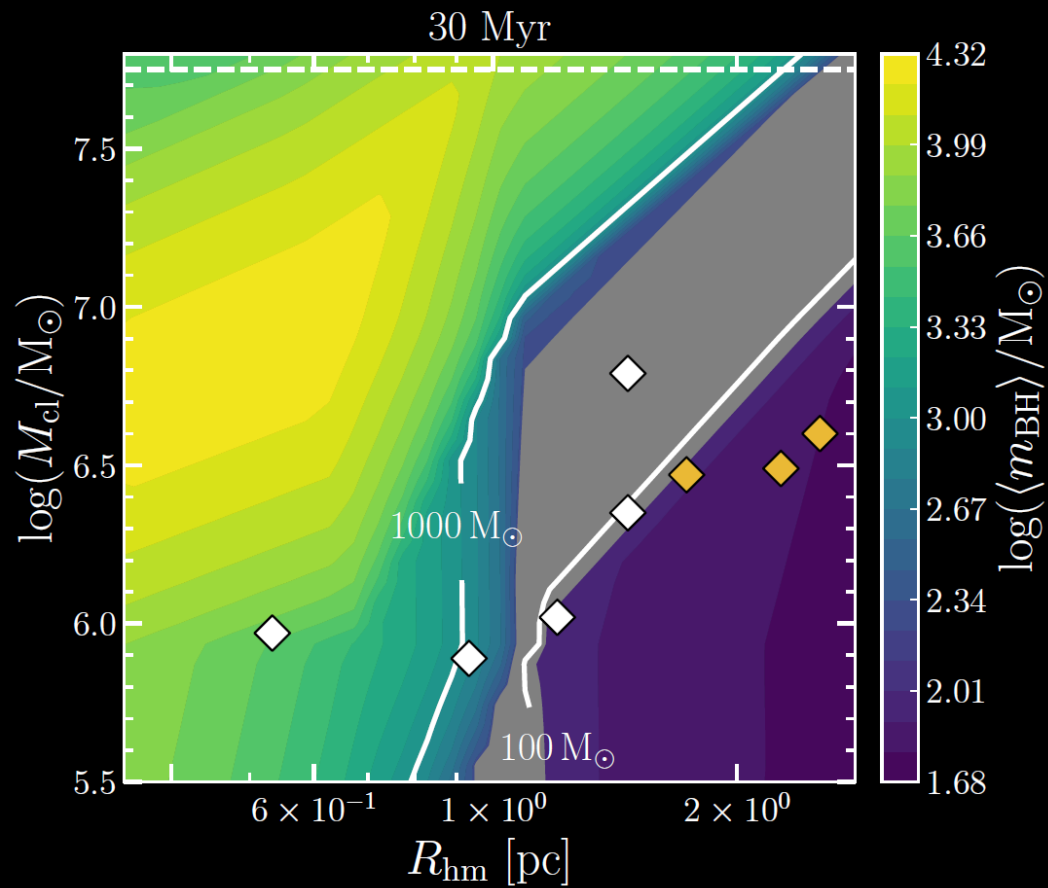
■ = PISN mass gap



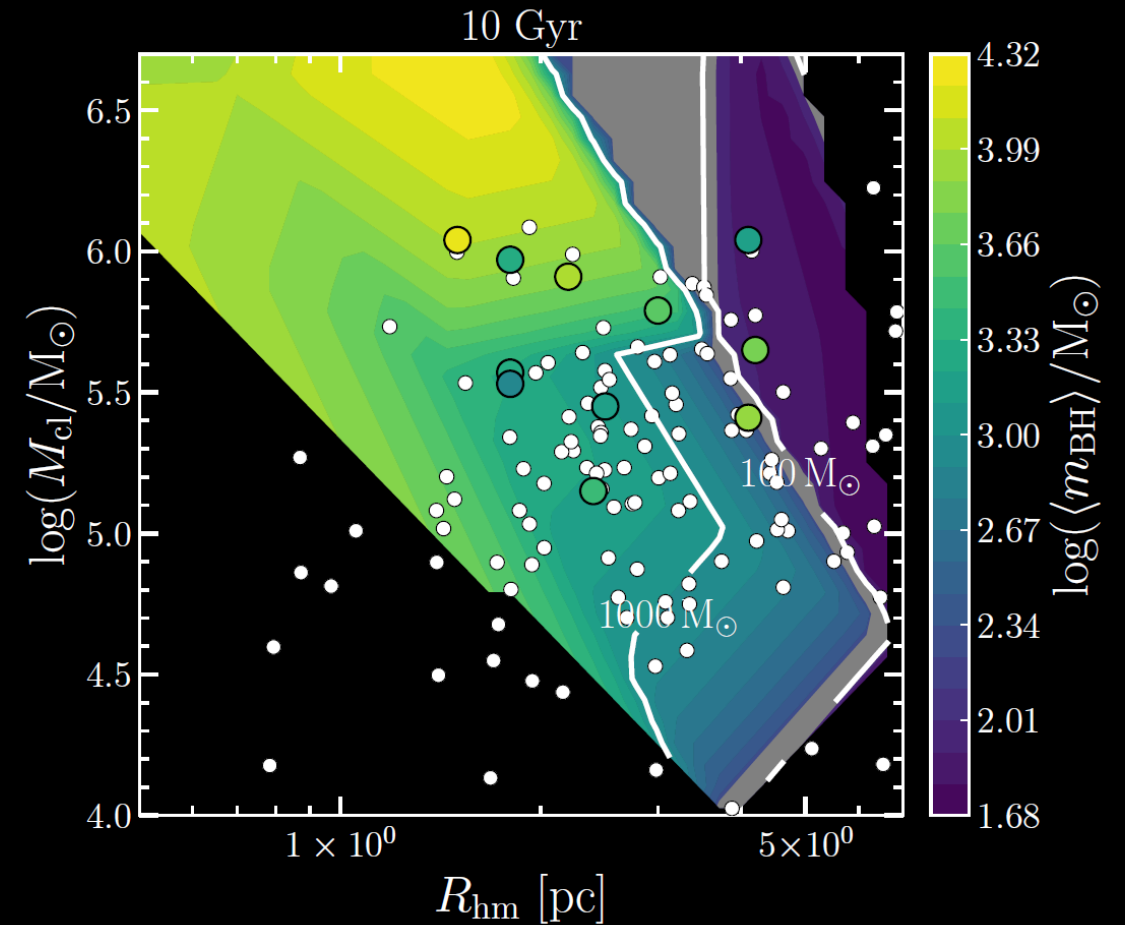
Credit: ESA/Webb, NASA & CSA, L. Bradley (STScI), A. Adamo (Stockholm University) and the Cosmic Spring collaboration

Implications for Cosmic Gems Arc & Globular Clusters

Simonato et al (in prep)



- ◆ = clusters in the Cosmic Gems Arc
- ◆ = counter-images



- = globular clusters
- = PISN mass gap

Next projects

VMS – BH interaction & Little Red Dots

Next projects

VMS – BH interaction & Little Red Dots

Credit: NASA, ESA, CSA, STScI, Dale Kocevski (Colby College)

CEERS 14448 z=4.75	NGDEEP 4321 z=8.92	PRIMER-COS 10539 z=7.48
CEERS 20320 z=5.27	JADES 9186 z=4.99	PRIMER-UDS 17818 z=6.40

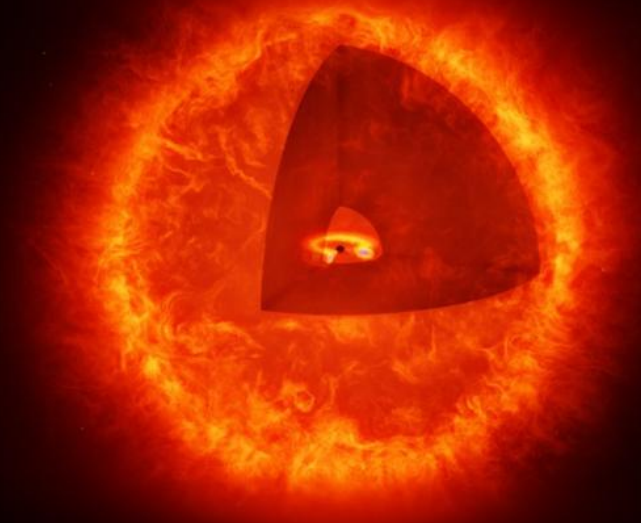
Next projects

VMS – BH interaction & Little Red Dots

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CEERS 14448 $z=4.75$	NGDEEP 4321 $z=8.92$	PRIMER-COS 10539 $z=7.48$
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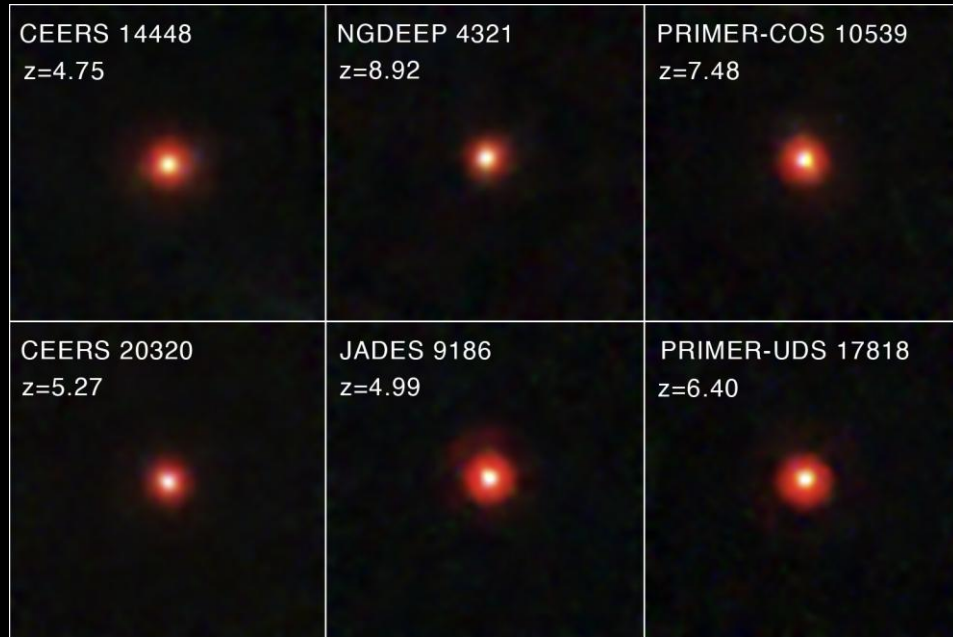
quasi-stars?
Bagelman & Dexter 2026



Next projects

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quasi-stars?
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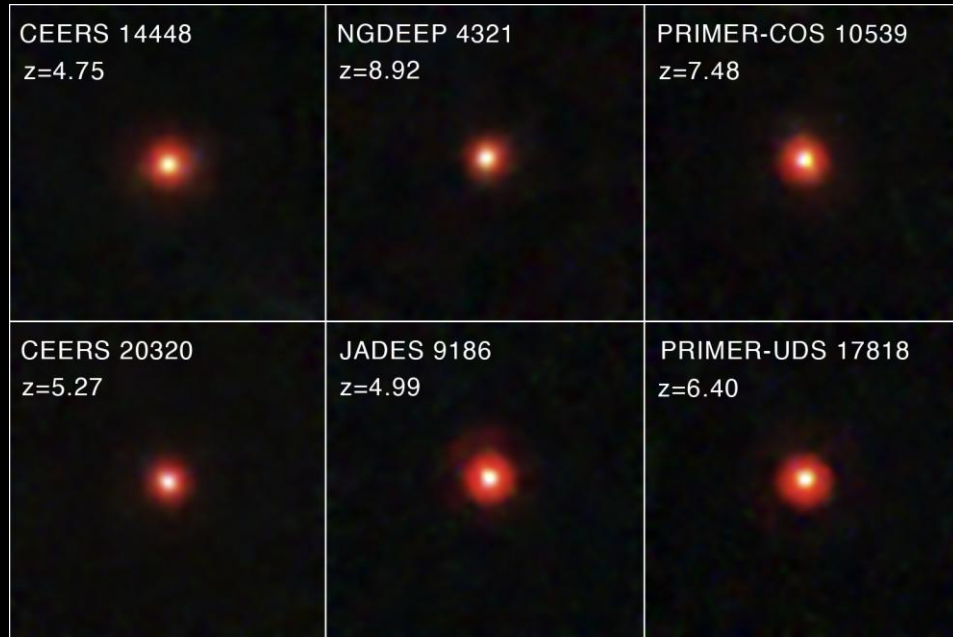


Next projects

VMS – BH interaction & Little Red Dots

Arca Sedda et al
(including Simonato; in prep)

Credit: NASA, ESA, CSA, STScI, Dale Kocevski (Colby College)



Can we form them
dynamically?

quasi-stars?
Bagelman & Dexter 2026





Prof. Taeho Ryu

Next projects

Hydrodynamical simulations of repeated stellar collisions





Prof. Taeho Ryu

Next projects

Hydrodynamical simulations of repeated stellar collisions



Which parameters
determine the outcome?



Prof. Taeho Ryu

Next projects

Hydrodynamical simulations of repeated stellar collisions



Which parameters
determine the outcome?

What does the
remnant look like?



Prof. Taeho Ryu

Next projects

Hydrodynamical simulations of repeated stellar collisions



Which parameters
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What does the
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How much mass is
lost during a collision?



Prof. Taeho Ryu

Next projects

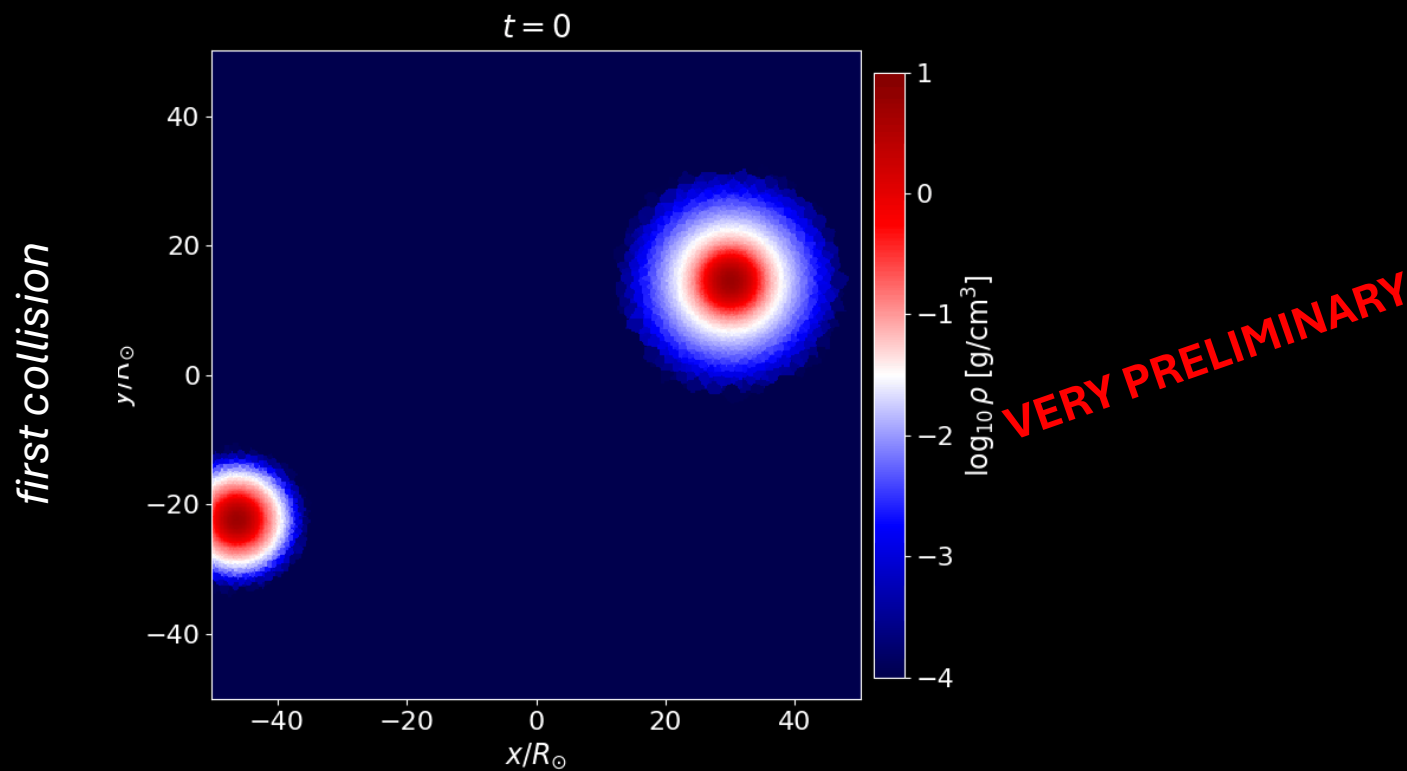
Hydrodynamical simulations of repeated stellar collisions



Which parameters
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Next projects

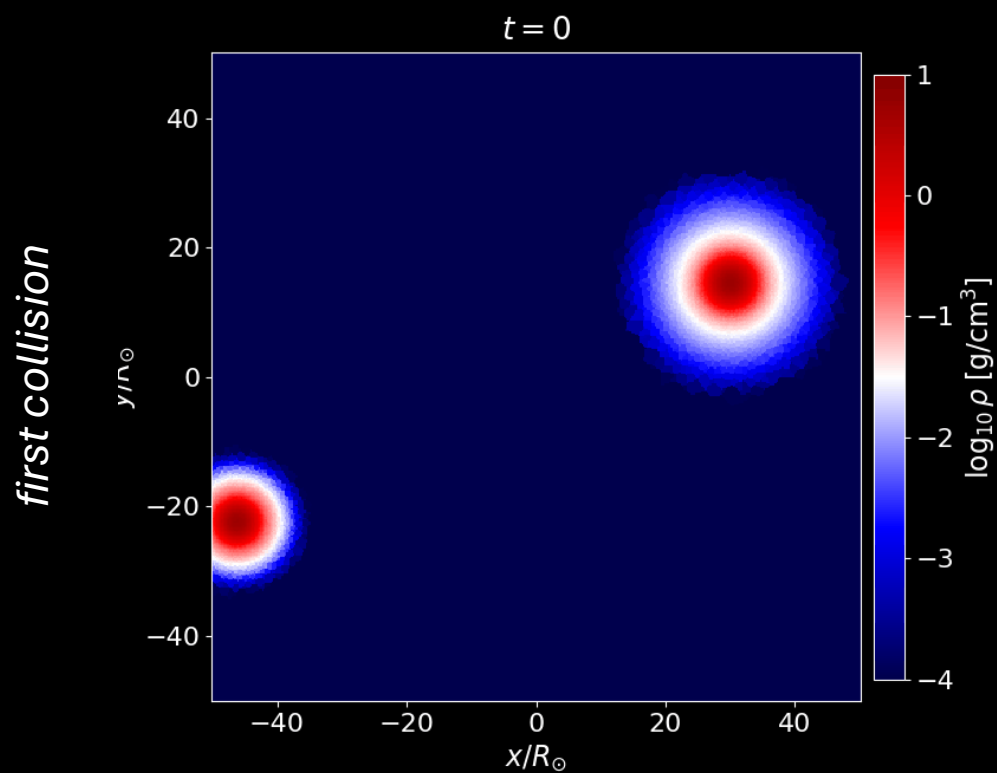
Hydrodynamical simulations of repeated stellar collisions



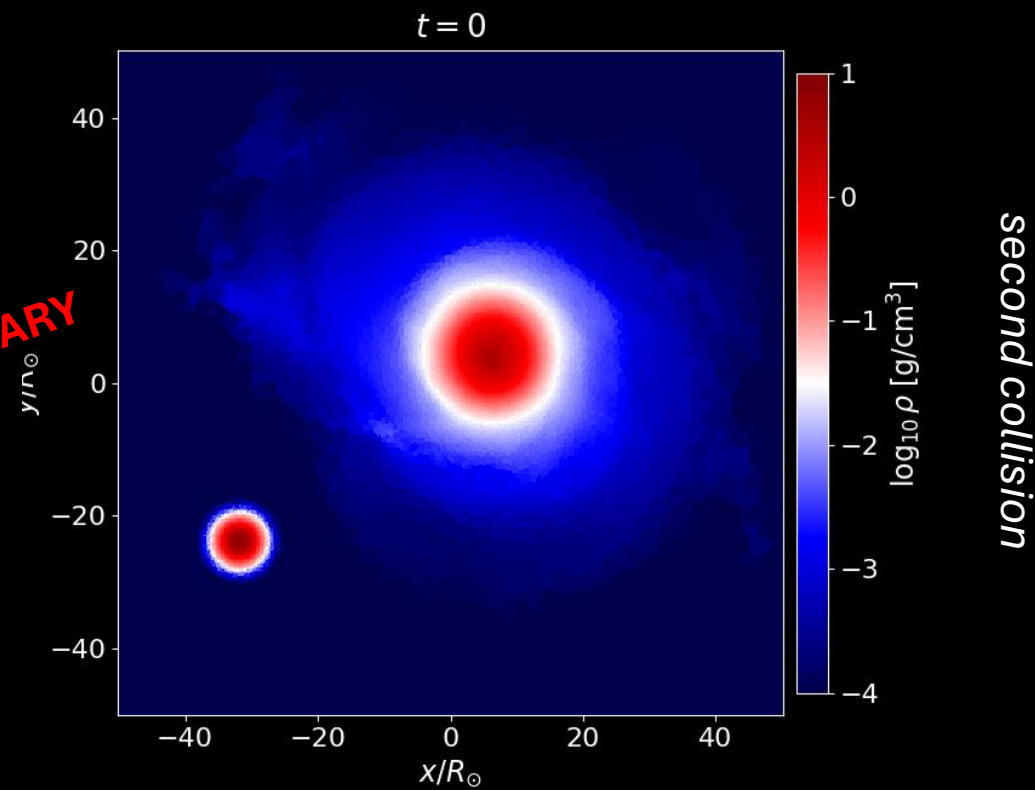
Which parameters determine the outcome?

What does the remnant look like?

How much mass is lost during a collision?



VERY PRELIMINARY



Other projects

Detectability of IMBHs with next-gen interferometers

Works born from
the analysis for
GWSPACE2050

Other projects

Detectability of IMBHs with next-gen interferometers

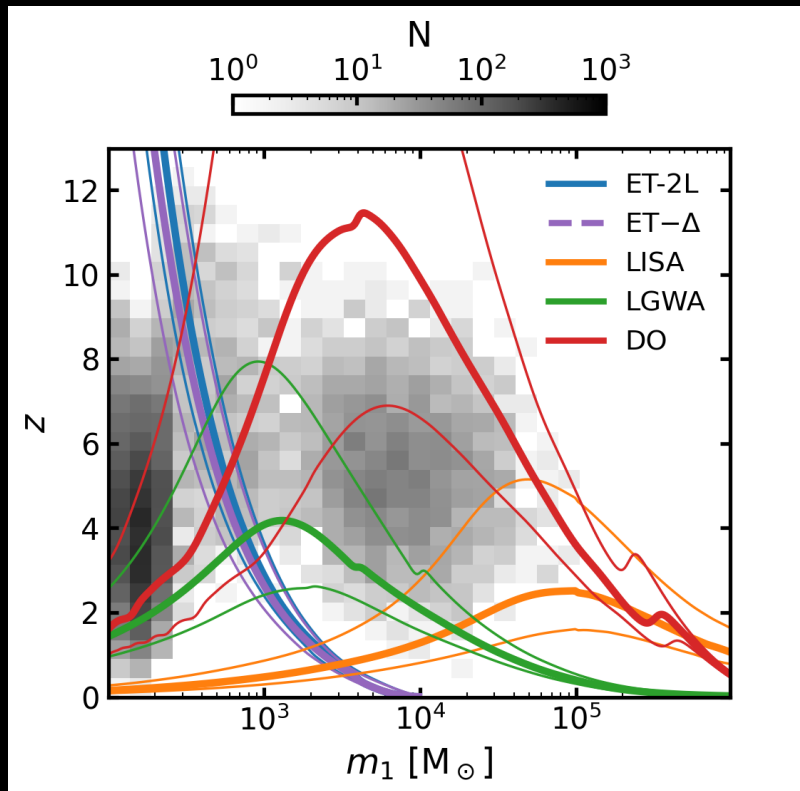
→ assessing advantages of beyond-LISA interferometers in the
deci-Hz, milli-Hz, micro-Hz frequency band

Works born from
the analysis for
GWSPACE2050

Other projects

Detectability of IMBHs with next-gen interferometers

From Pop. II stars



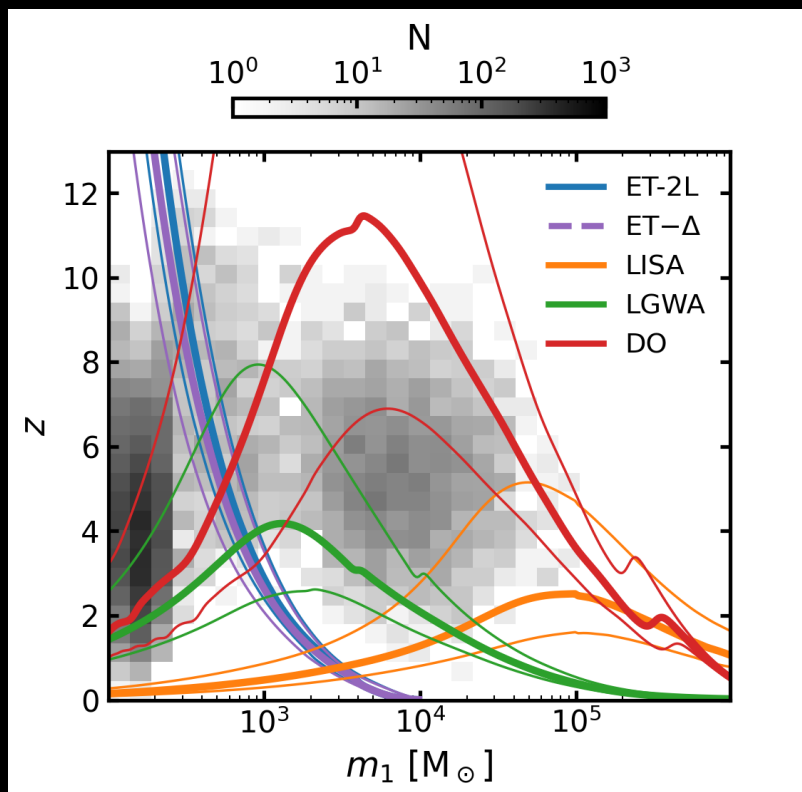
Paiella, Simonato et al (in prep)

Works born from
the analysis for
GWSPACE2050

Other projects

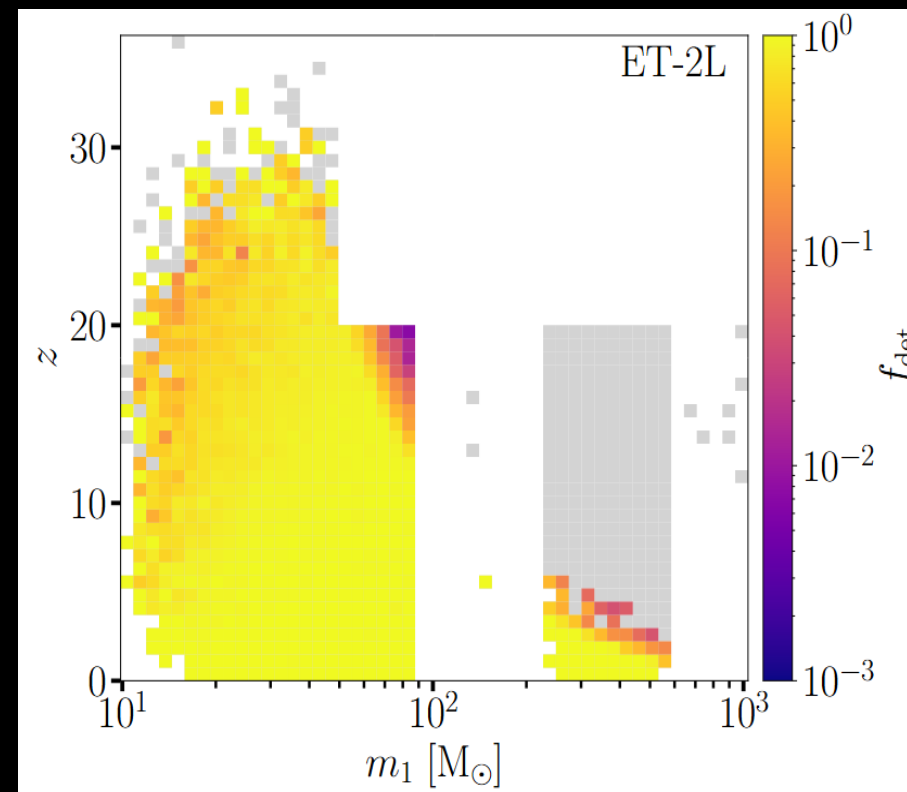
Detectability of IMBHs with next-gen interferometers

From Pop. II stars



Paiella, Simonato et al (in prep)

From Pop. III stars



Mestichelli, Simonato et al (in prep)

Conclusions

Motivation:

- Dense stellar systems are observed at high redshift
- Stellar mass and internal structure of collision products remain uncertain

Main projects:

- **STARfall:** we studied IMBH & VMS formation in star clusters via stellar collisions (*paper submitted*)
- **VMS-BH interactions:** we are studying the dynamical formation of quasi-stars with STARfall and their implications for LRD origin (*ongoing project*)
- **Hydrodynamical simulations:** we are testing the robustness of semi-analytic prescriptions through dedicated hydrodynamical simulations (*ongoing/future project*)

Other projects:

- **GWSPACE2050:** the collaboration is currently finalizing the White Book
- **Detectability:** assessing the detectability of IMBHs by next-gen interferometers (*currently being finalized*)

Publications:

- Arca Sedda et al. (including **Simonato**), 2026, “Isolated or dynamical? Tracing black hole binary formation through the population of gravitational-wave sources”
- Torniamenti et al. (including **Simonato**), 2026, “Optically thick winds of very massive stars suppress intermediate-mass black hole formation”
- **Simonato** et al., 2025, “Impact of stellar winds on the pair-instability supernova rate”

Conferences, seminars & schools (2° year):

- LGWA Meeting, Liege, **contributed talk**
- EAS 2026, remotely, **ePoster with short presentation**
- **Seminar** at University of Colorado, Boulder
- LXVII Congresso Annuale della Società Astronomica Italiana, L'Aquila, **contributed talk**
- ET Workshop for Early Career Researchers, Rome, **poster**
- POSYDON Summer School, Geneva, **as part of the project selected within the ACME TNA Programme**
- International HPC Summer School, Perth

Awards:

- Project “Mass loss driven by stellar collisions and mergers in dense stellar clusters” **selected for funded research visit at the University of Geneva (ACME Programme)**

Research stays:

- University of Padova (7-11 September 2026)
- University of Geneva (22-28 August 2026), **project selected within the ACME TNA Programme**
- University of Colorado, Boulder (19 May - 22 June 2026)

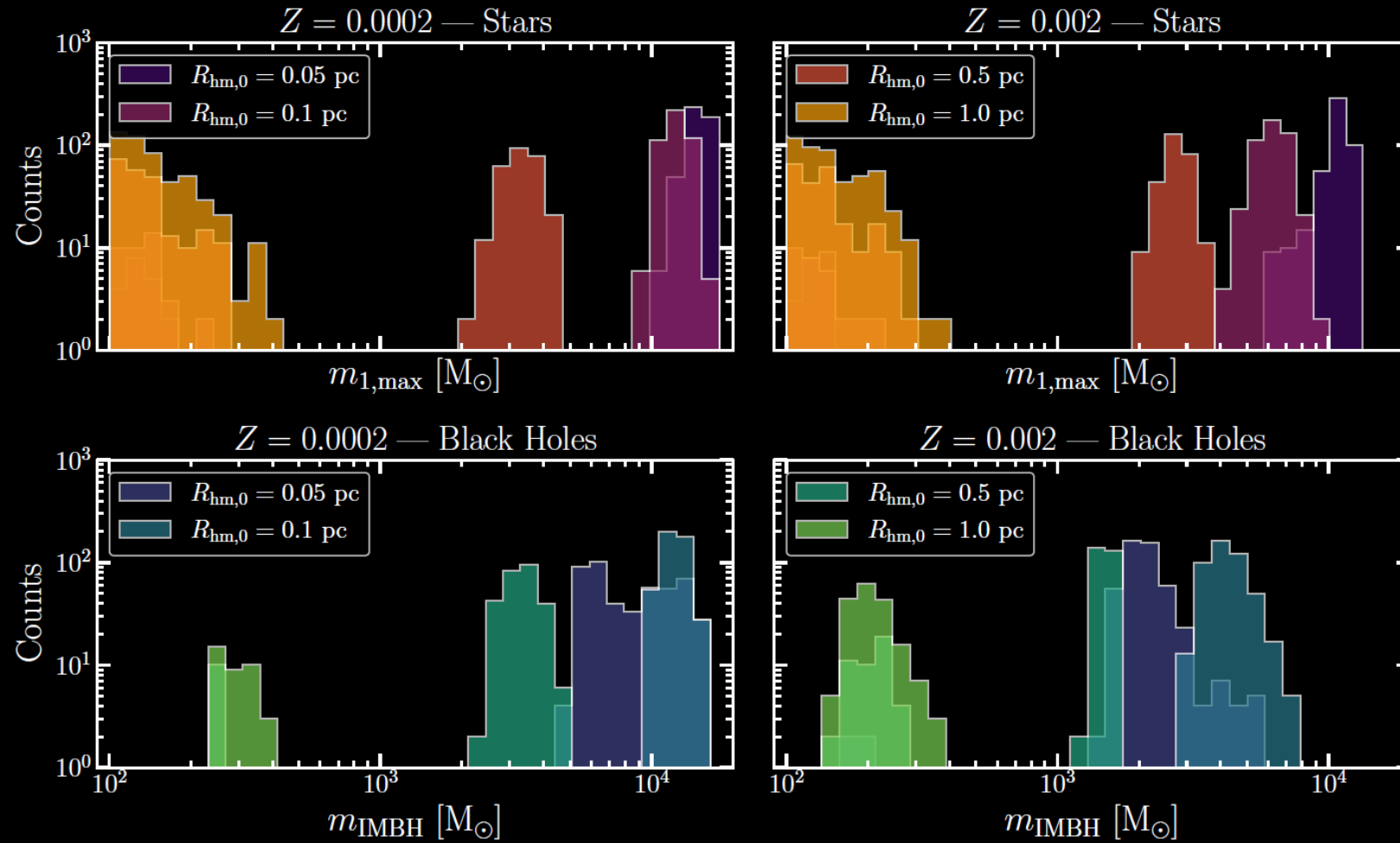
Outreach:

- Sharper 2026, European Research Night
- Space Explorer for primary and secondary school
- Orientation events for high school students

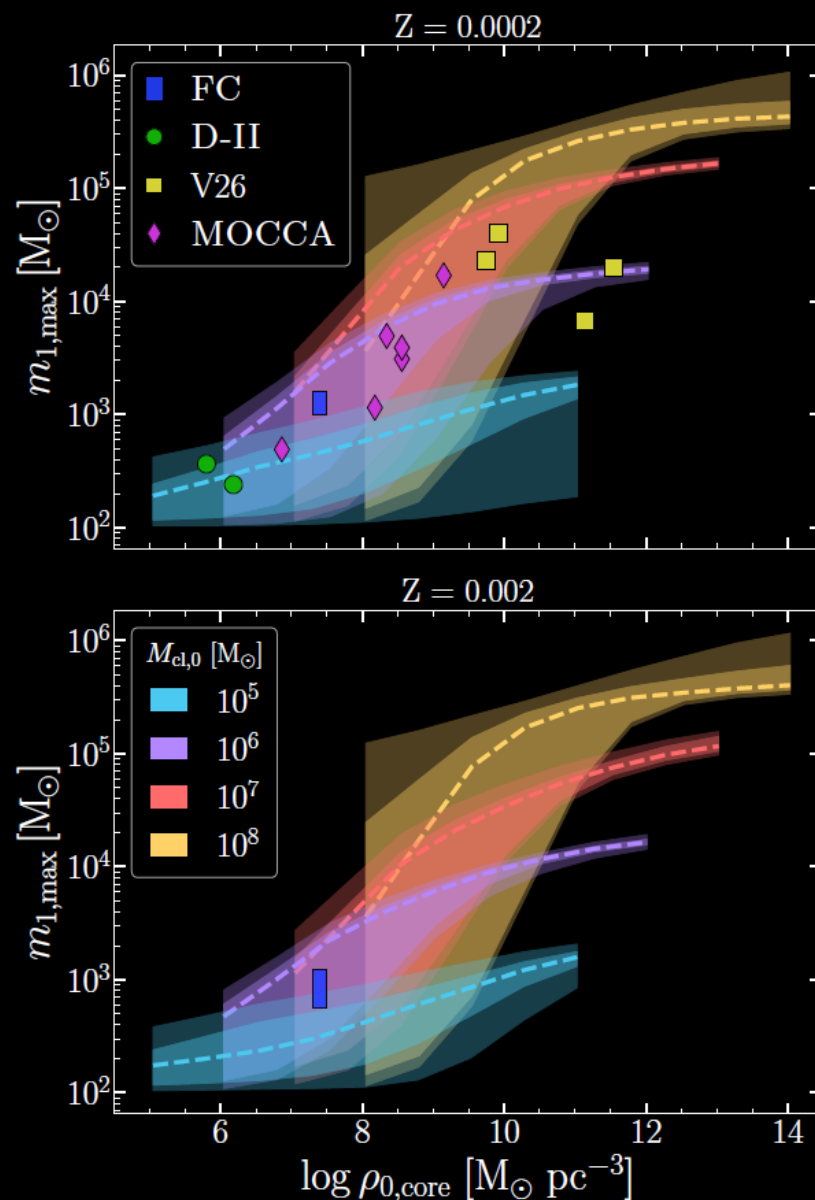
BACK-UP

VMS & IMBH mass distribution

$$M_{\text{cl},0} = 10^6 M_{\odot}$$



VMS mass distribution



$M_{\text{cl},0}$ = initial mass

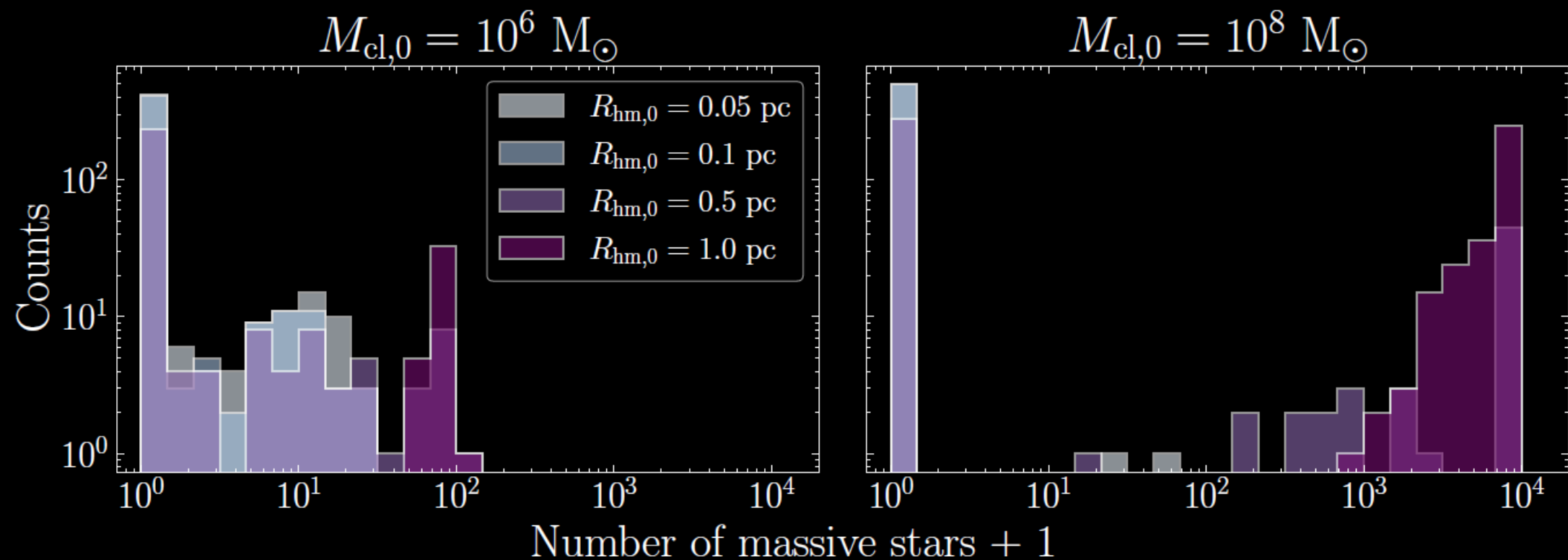
FC = Frost-Clusters (Rantala et al 2026)

D-II = Dragon-II (Arca Sedda et al 2023)

NB6 = Nbody6++GPU (Vergara et al 2025)

MOCCA (Askar et al, in prep; Giersz et al in prep)

Massive star distribution



Collisions outcomes

