



How do Black Holes Grow?

Active Galactic Nuclei as a breeding ground for intermediate-mass Black Holes

M. Paola Vaccaro

Supervisor: Prof. Michela Mapelli

Physics of Data Workshop

Venice, 21/04/2023

Introduction

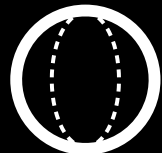
What are Black Holes?

- Compact Objects
 - High mass, low volume



Sun

$1 M_{\odot} \sim 10^{30} \text{ kg}$
 $1 R_{\odot} \sim 10^9 \text{ km}$

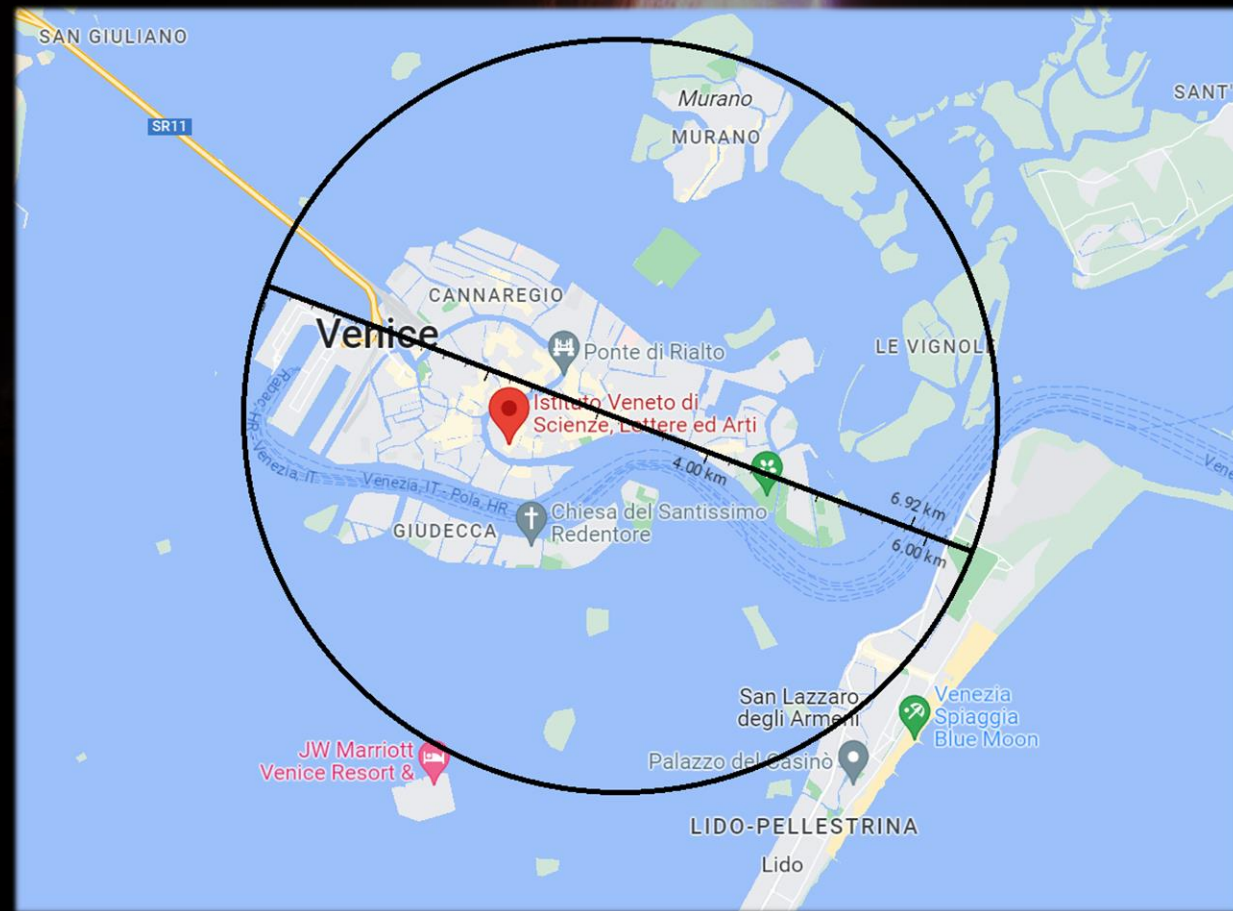


Black Hole

$1 M_{\odot} \sim 10^{30} \text{ kg}$
3 km



Dark!



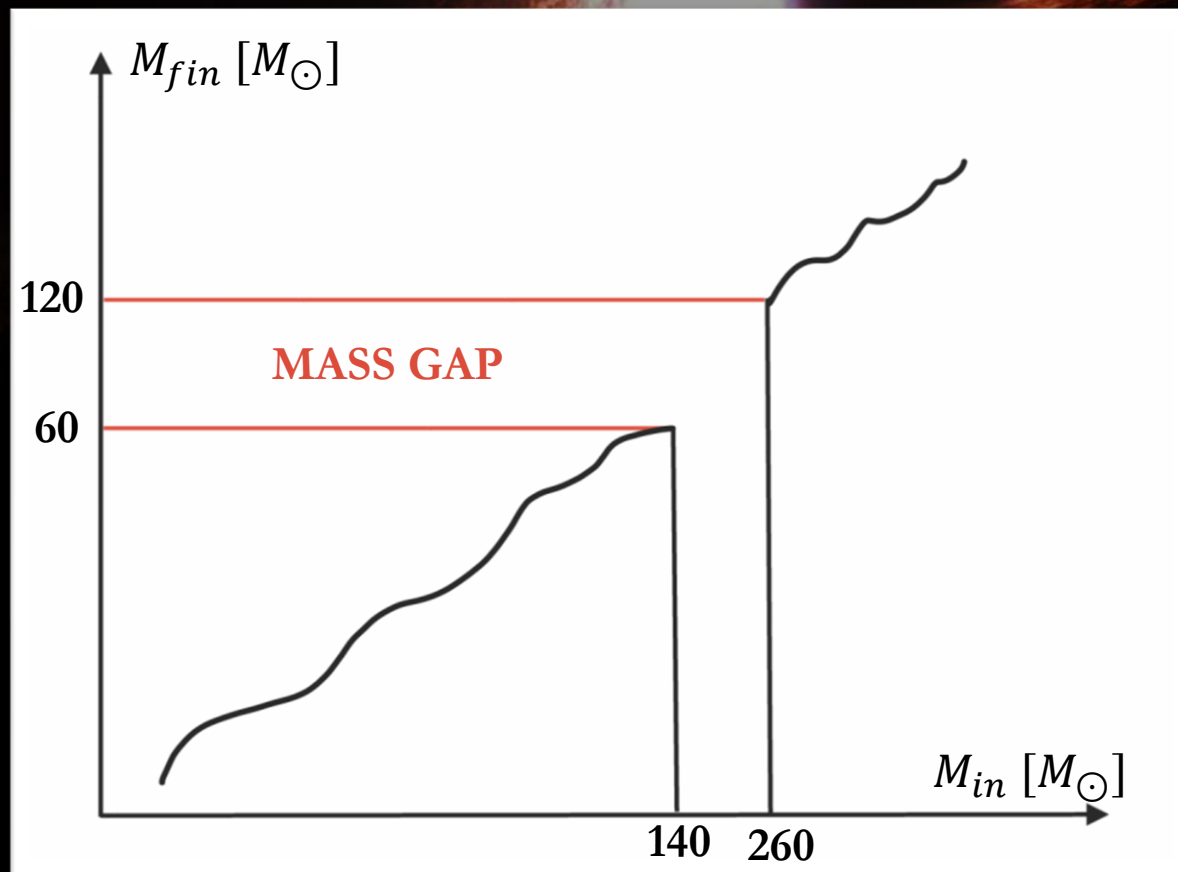
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↓
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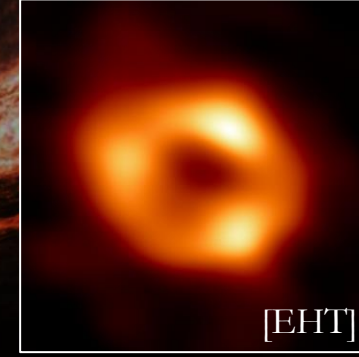
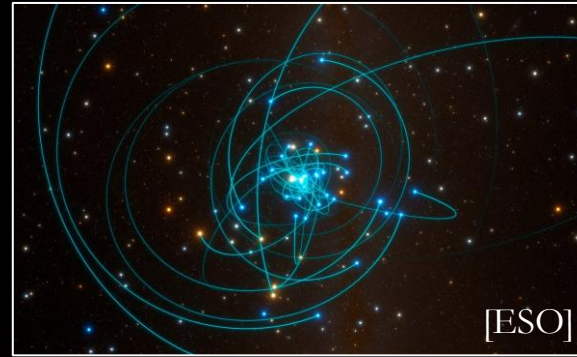
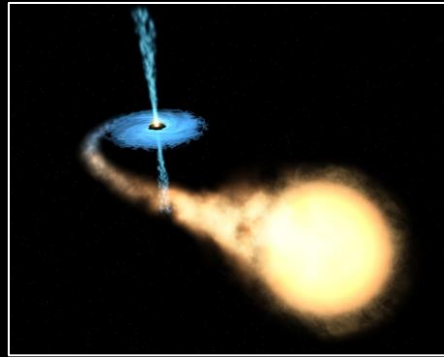
- Stellar evolution remnants



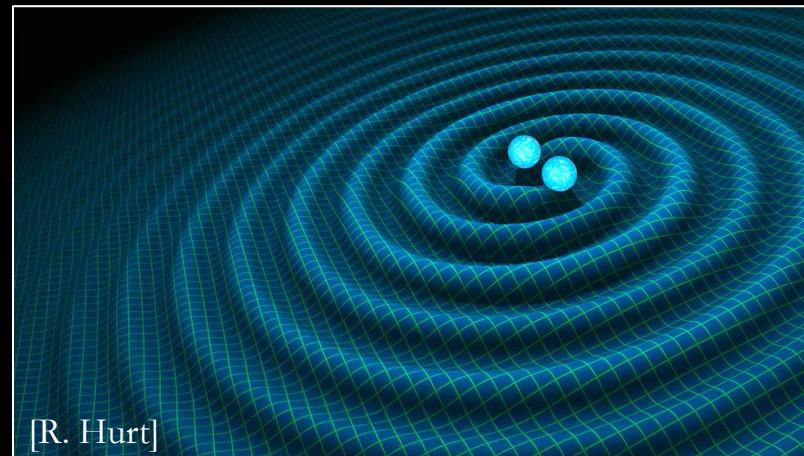
[S.E. Woosley et al., 2002]

Black Hole observations

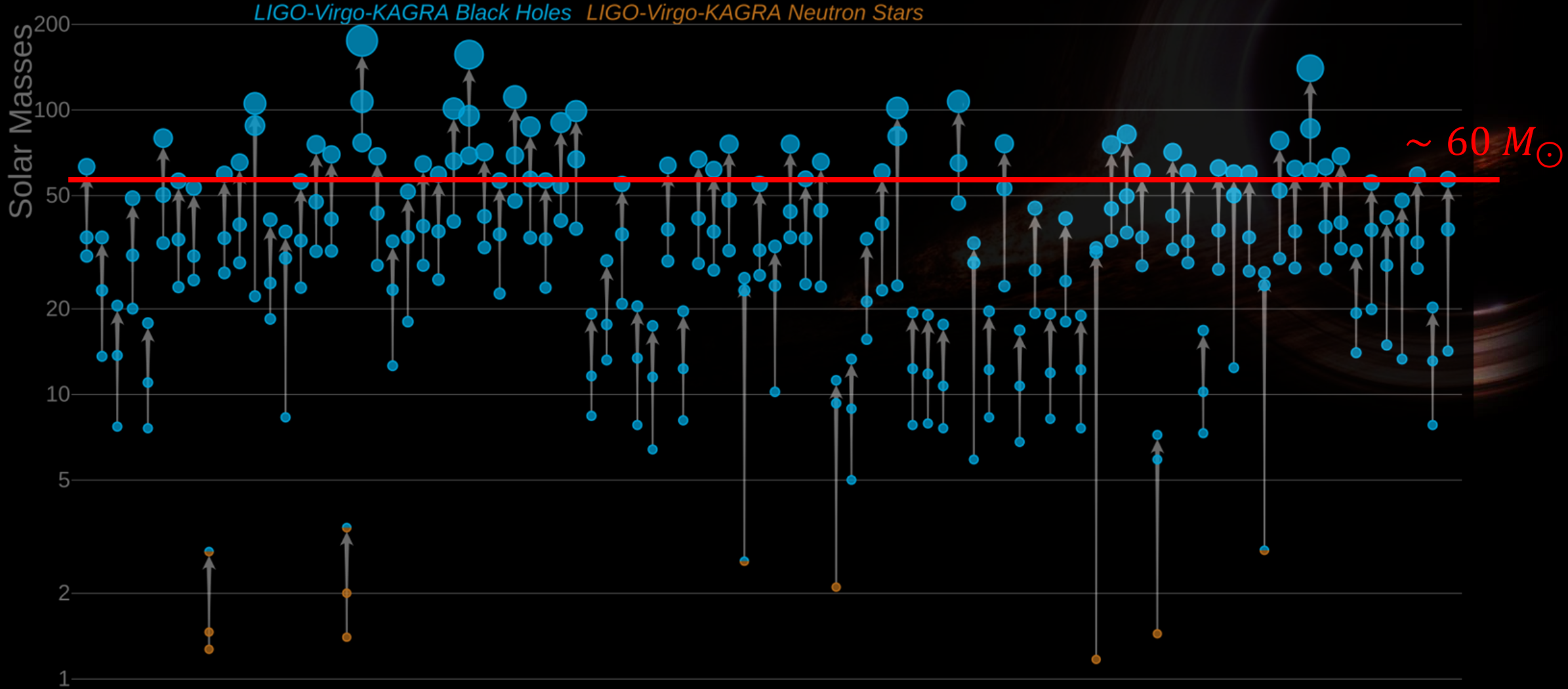
1. **Optical:** we observe the effect of BHs on matter around them



2. **Gravitational Waves**
from black hole binaries



Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Gravitational Waves observations

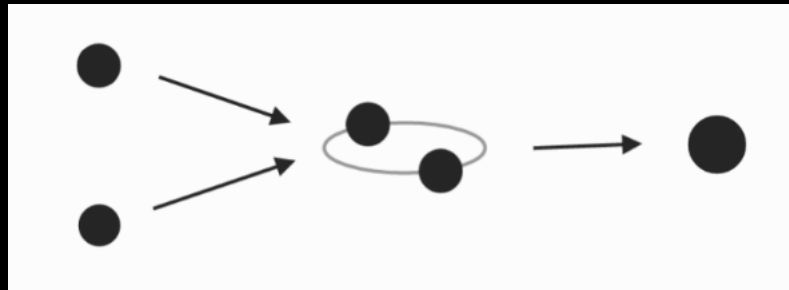
How do these mass gap BHs exist?

A. The theory of stellar evolution is **somewhat wrong**

Formation of GW190521 from stellar evolution: the impact of the hydrogen-rich envelope, dredge-up and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate on the pair-instability black hole mass gap

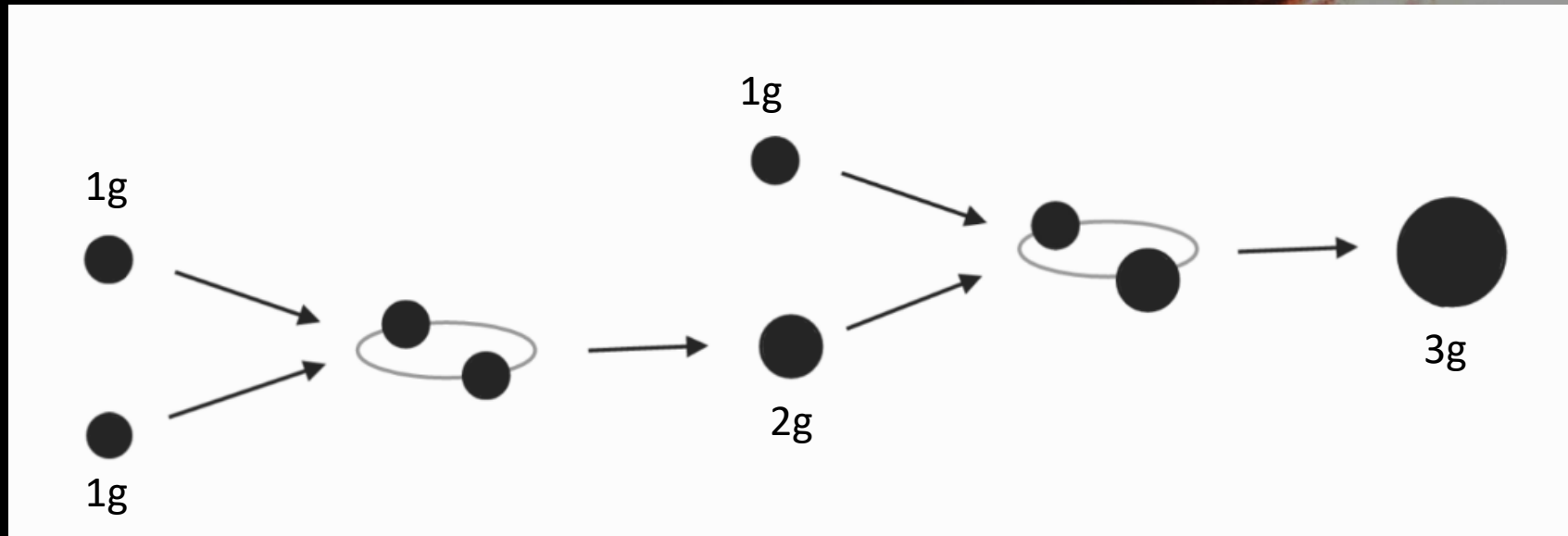
Guglielmo Costa, Alessandro Bressan, Michela Mapelli, Paola Marigo, Giuliano Iorio, Mario Spera

B. These BHs do not come directly from stellar evolution, but from **dynamical formation channels**



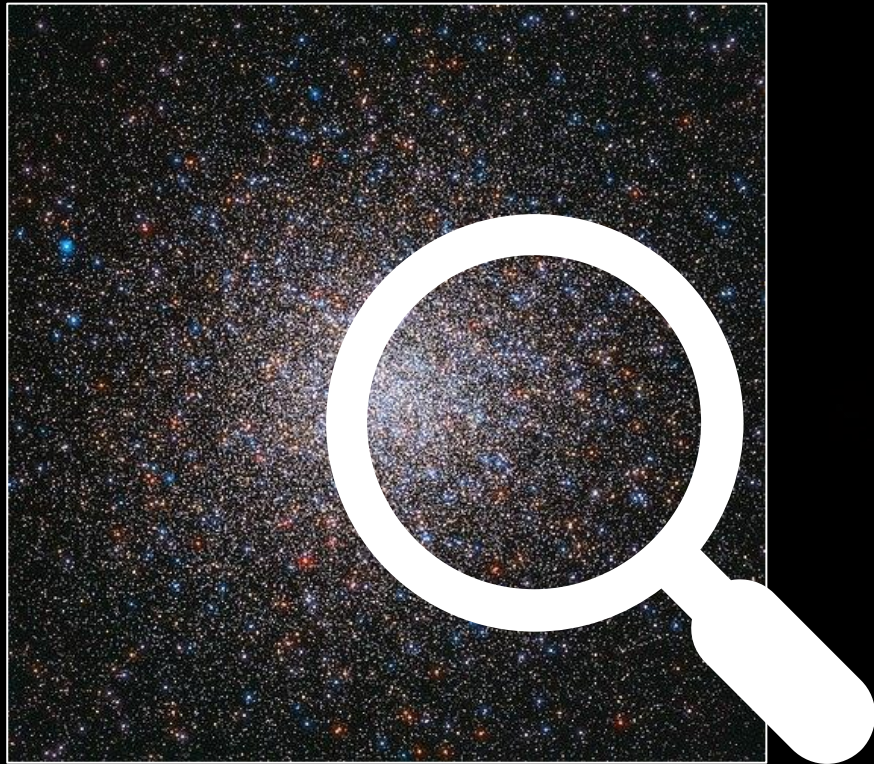
Dynamical Formation

In environments with **high stellar density**:
HIERARCHICAL MERGERS



- Frequent interaction \rightarrow binary formation
- Deep gravitational potential well \rightarrow the remnants of previous mergers are retained and can form new binaries

Dense environments



[Globular Cluster M2, HST]

1. Full N-body simulation

- The most accurate approach
- Computationally slow: it's hard to simulate more than 100 binary BHs

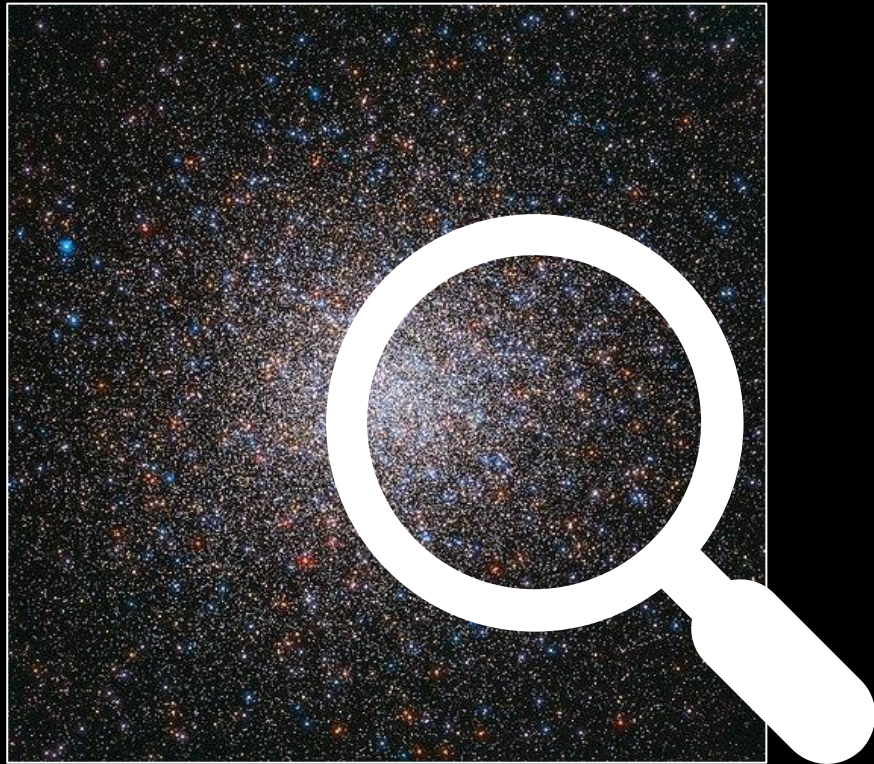


2. Semi-analytical code

- Less accurate: you can only reproduce the average behaviour
- Fast: you can efficiently explore the parameter space



Dense environments



[Globular Cluster M2, HST]

1. Full N-body simulation

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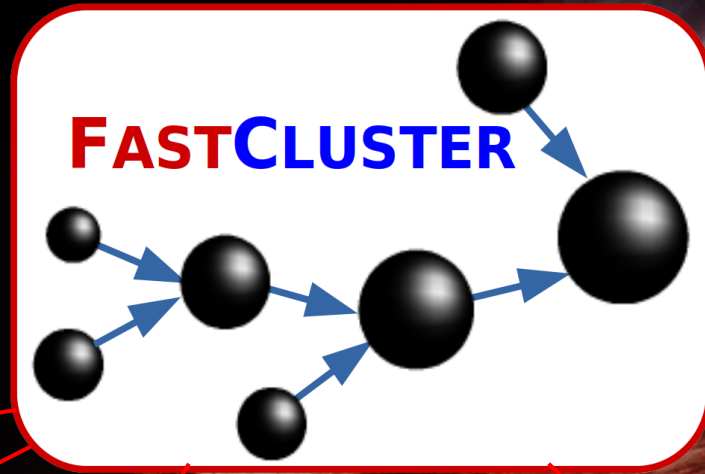


2. Semi-analytical code

- Less accurate: you can only reproduce the average behaviour
- Fast: you can efficiently explore the parameter space



Michela Mapelli, Marco Dall'Amico, Yann Bouffanais,
Nicola Giacobbo, Manuel Arca Sedda, M. Celeste
Artale, Alessandro Ballone, Ugo N. Di Carlo, Giuliano
Iorio, Filippo Santoliquido, Stefano Tornamenti,
M. Paola Vaccaro, Dario Barone, Daxal Meta



GLOBULAR CLUSTERS



[M2, HST]

OPEN CLUSTERS



[NGC 2164, HST]

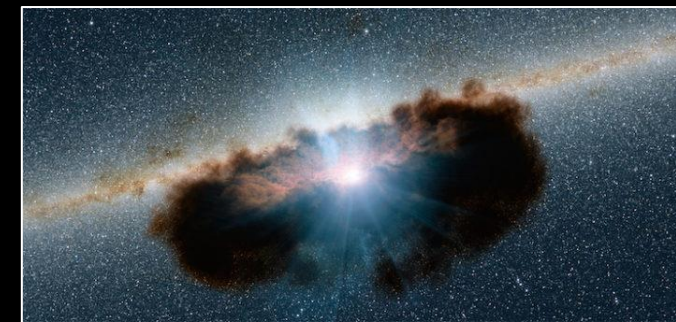
NUCLEAR CLUSTERS



NGC300

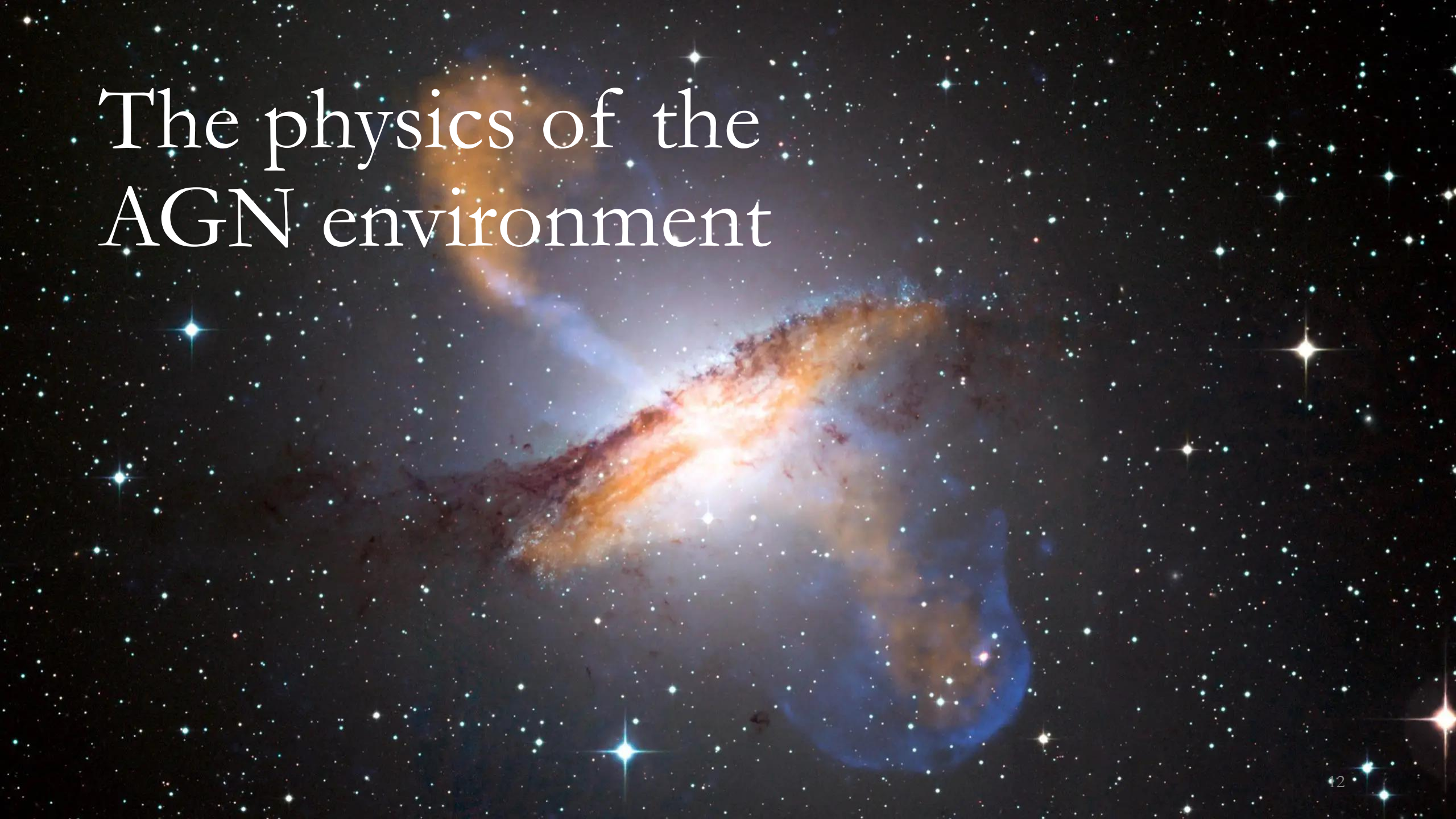
[NGC 300, Nadine Neumayer]

ACTIVE GALACTIC
NUCLEI

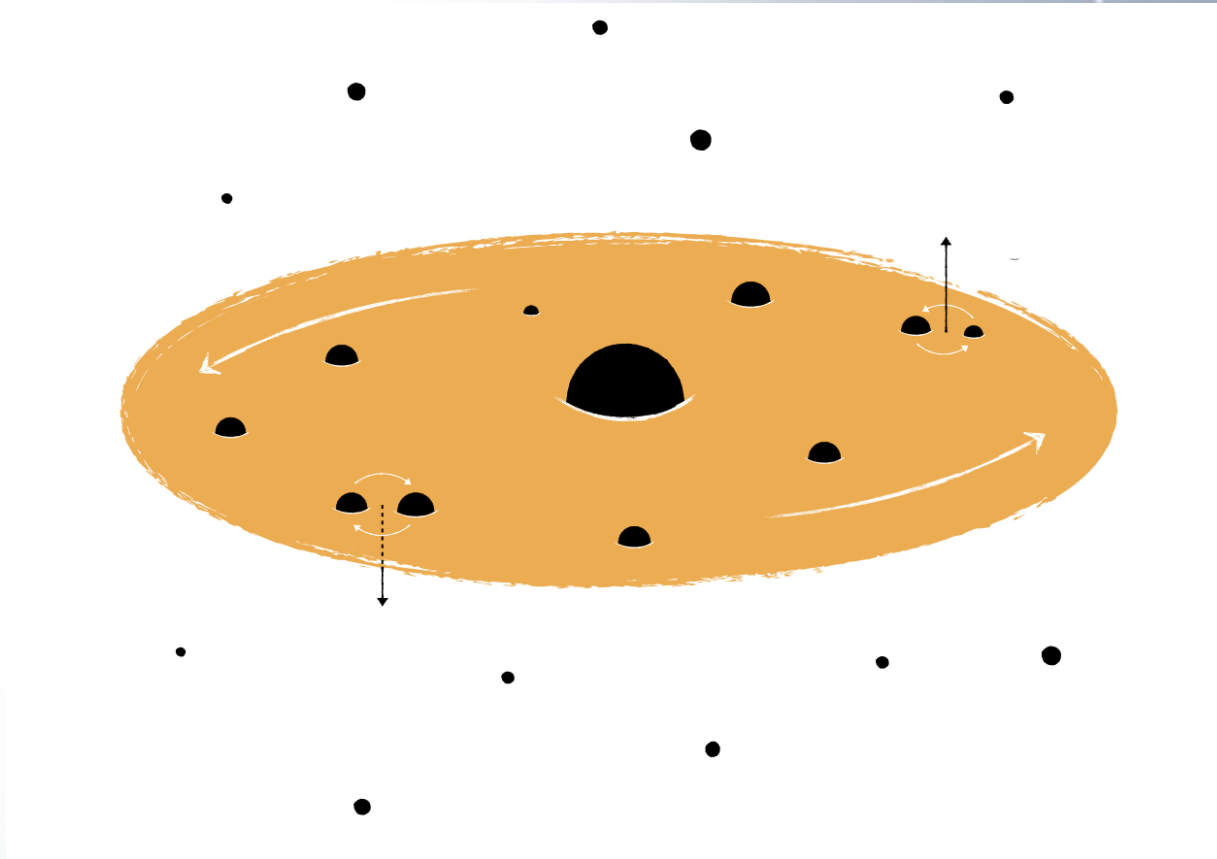


[Artist impression, NASA]

The physics of the AGN environment



Active Galactic Nucleus: the recipe



[Image credits: B. McKernan]

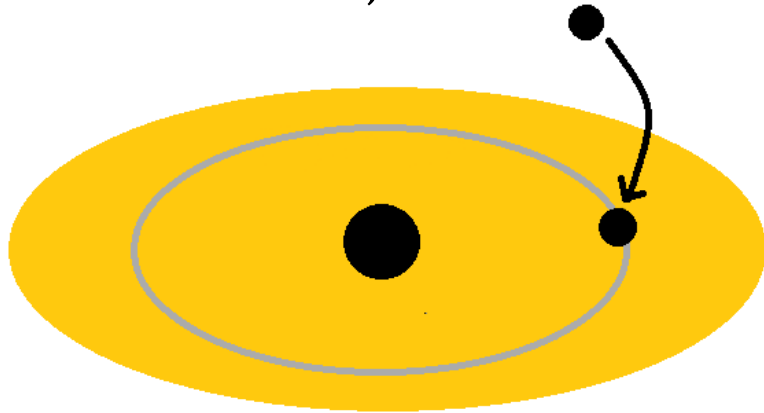
INGREDIENTS

INGREDIENTS FOR A 22 PC MOLD

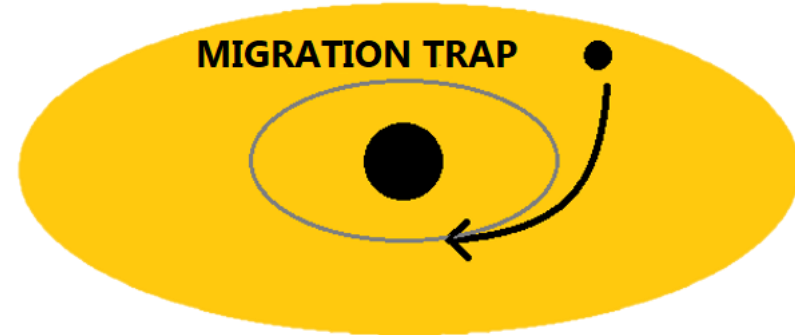
- Super-massive black hole:
 $M > 10^5 M_{\odot}$
- Gaseous accretion disk
with lifetime τ
- Surrounding black holes
(Nuclear Star Cluster)

The effects of gas

1) **DAMPING**
 $i \rightarrow 0, e \rightarrow 0$



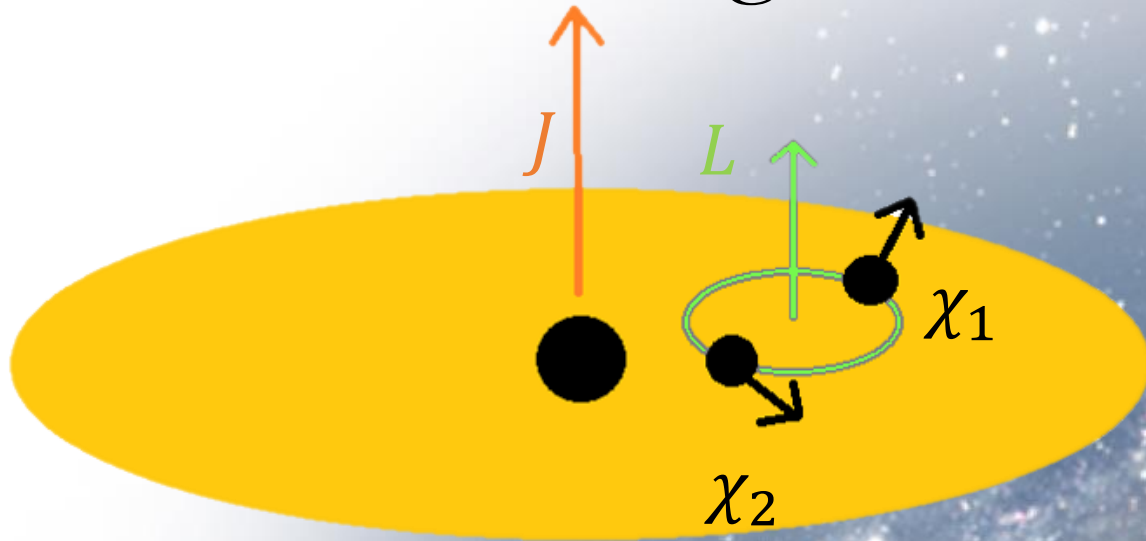
2) **TYPE I MIGRATION**
 $R \rightarrow R_{\text{trap}}$



3) **ASSISTED INSPIRAL**
 $a \downarrow$



The effects of gas

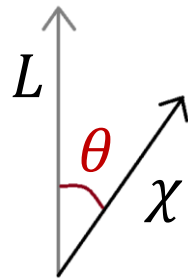


4) SPIN ALIGNMENT

Gas torques align $\overline{\chi_{1,2}}$ and \vec{L} with \vec{J}

Gravitational Waves are sensitive to the effective spin

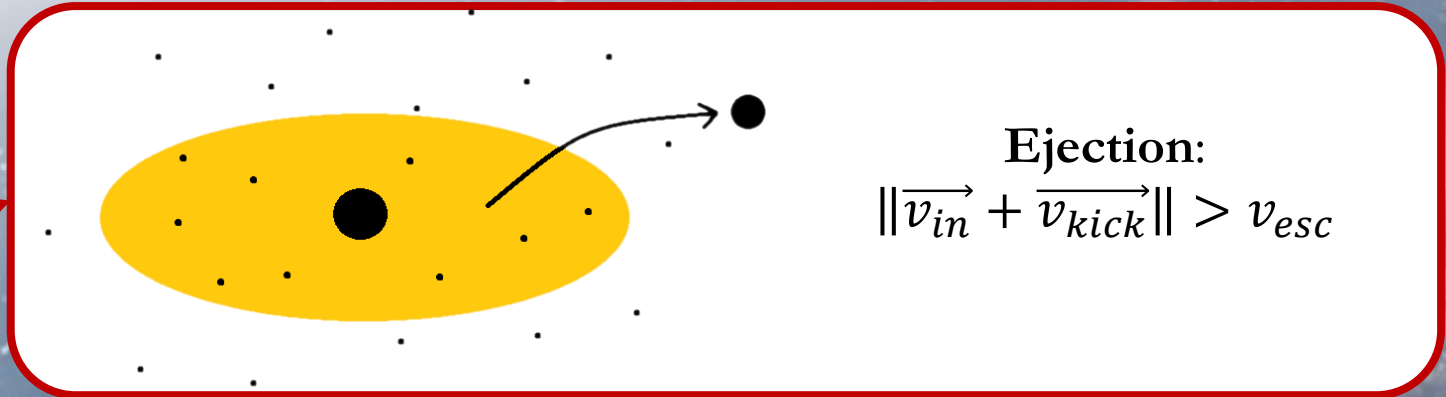
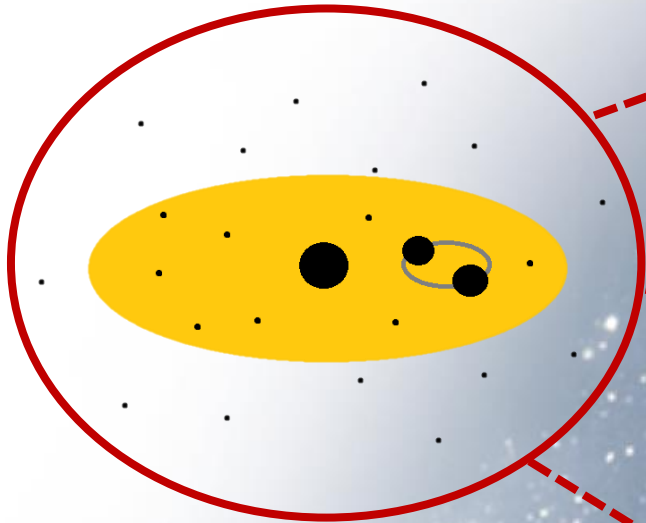
$$\chi_{\text{eff}} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$



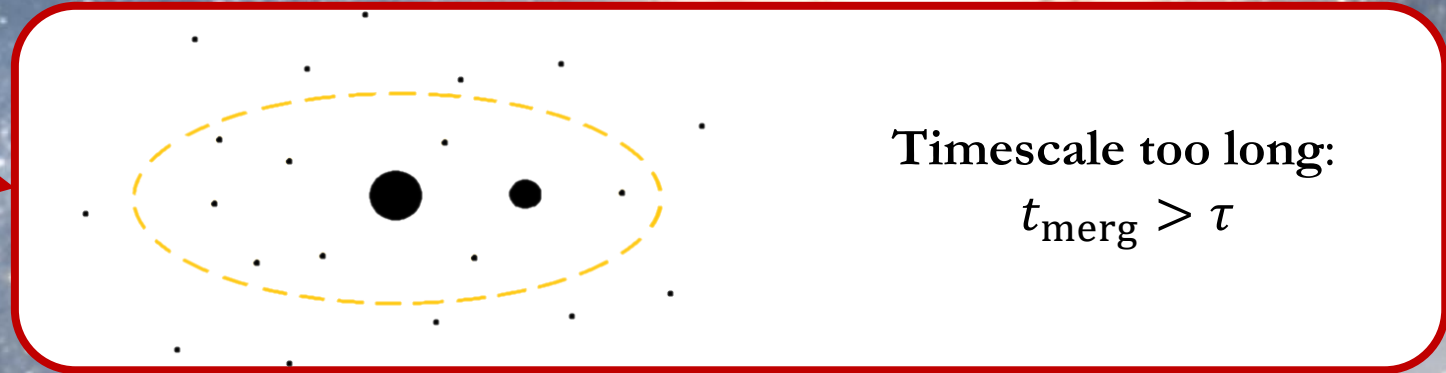
High effective spin is a **signature** of mergers in AGNs

What happens after the merger?

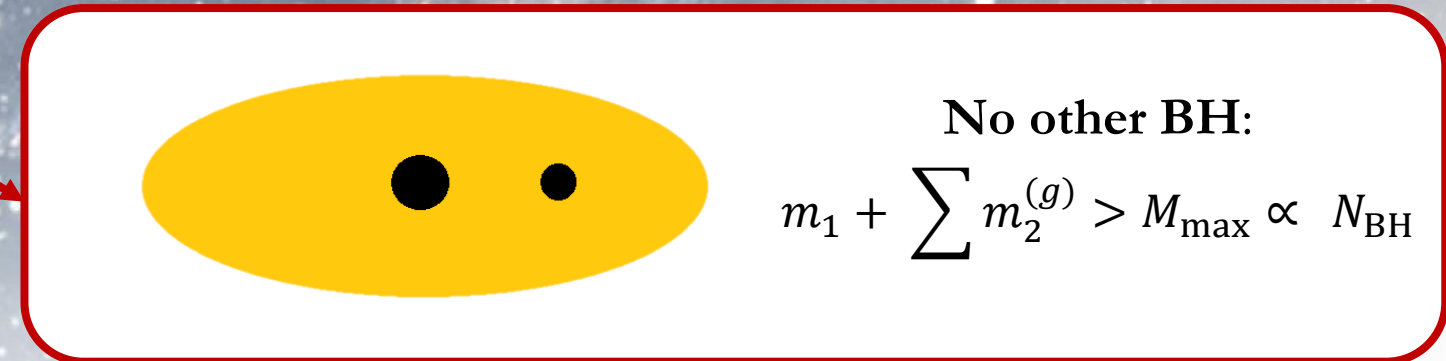
Can the merger remnant go through a new merger event?



Ejection:
 $\|\vec{v}_{in} + \vec{v}_{kick}\| > v_{esc}$

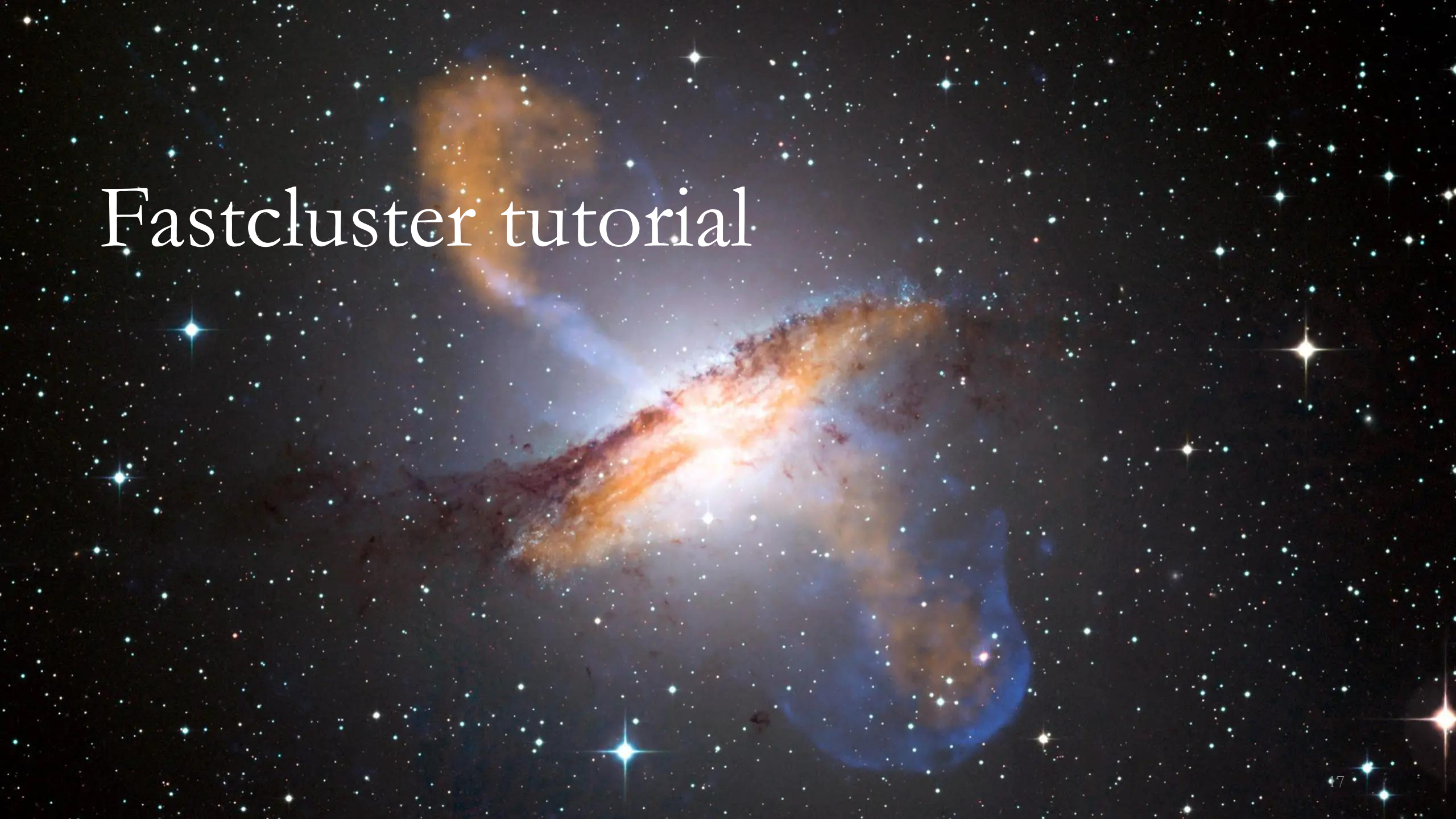


Timescale too long:
 $t_{\text{merg}} > \tau$

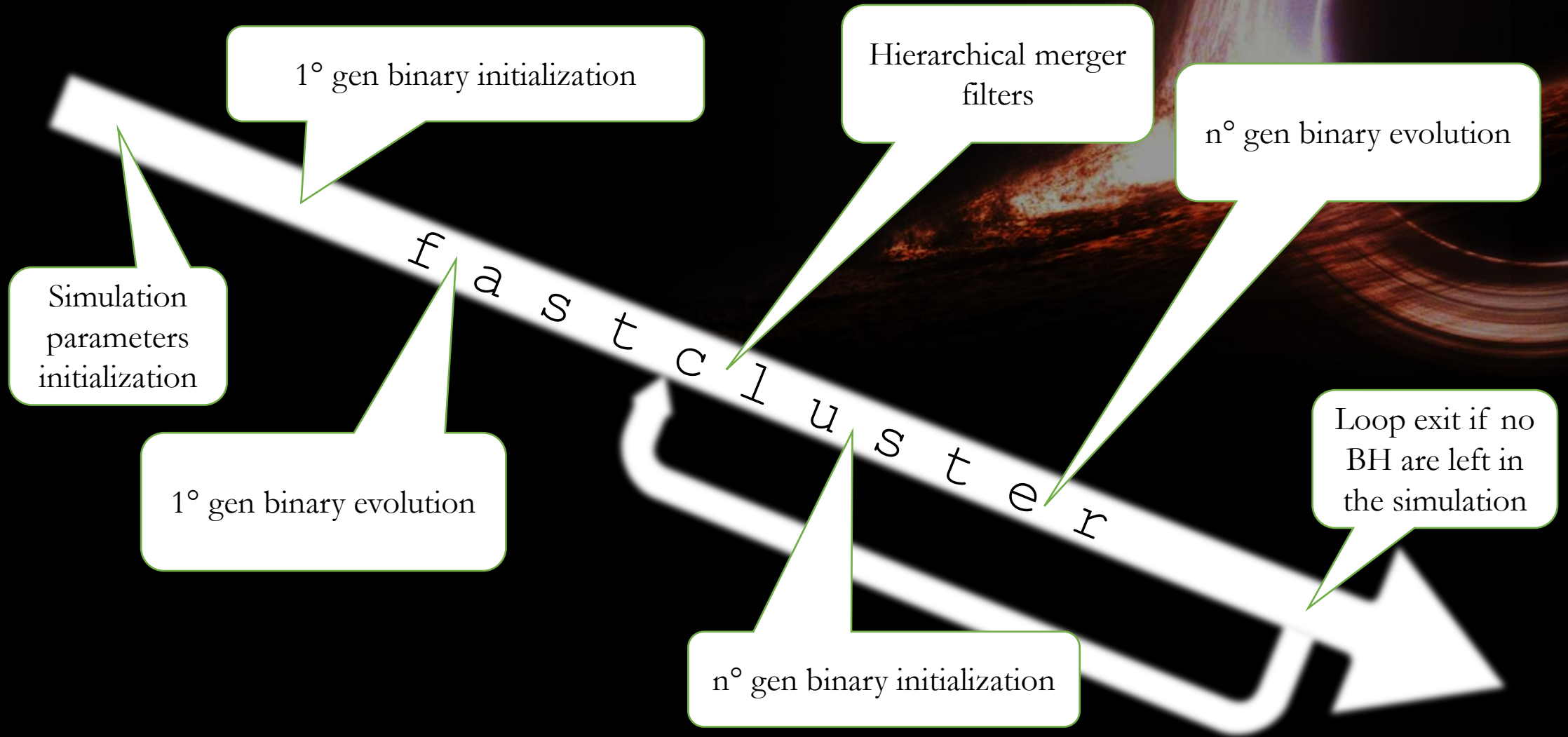


No other BH:
 $m_1 + \sum m_2^{(g)} > M_{\text{max}} \propto N_{\text{BH}}$

Fastcluster tutorial



Logic sequence of the script



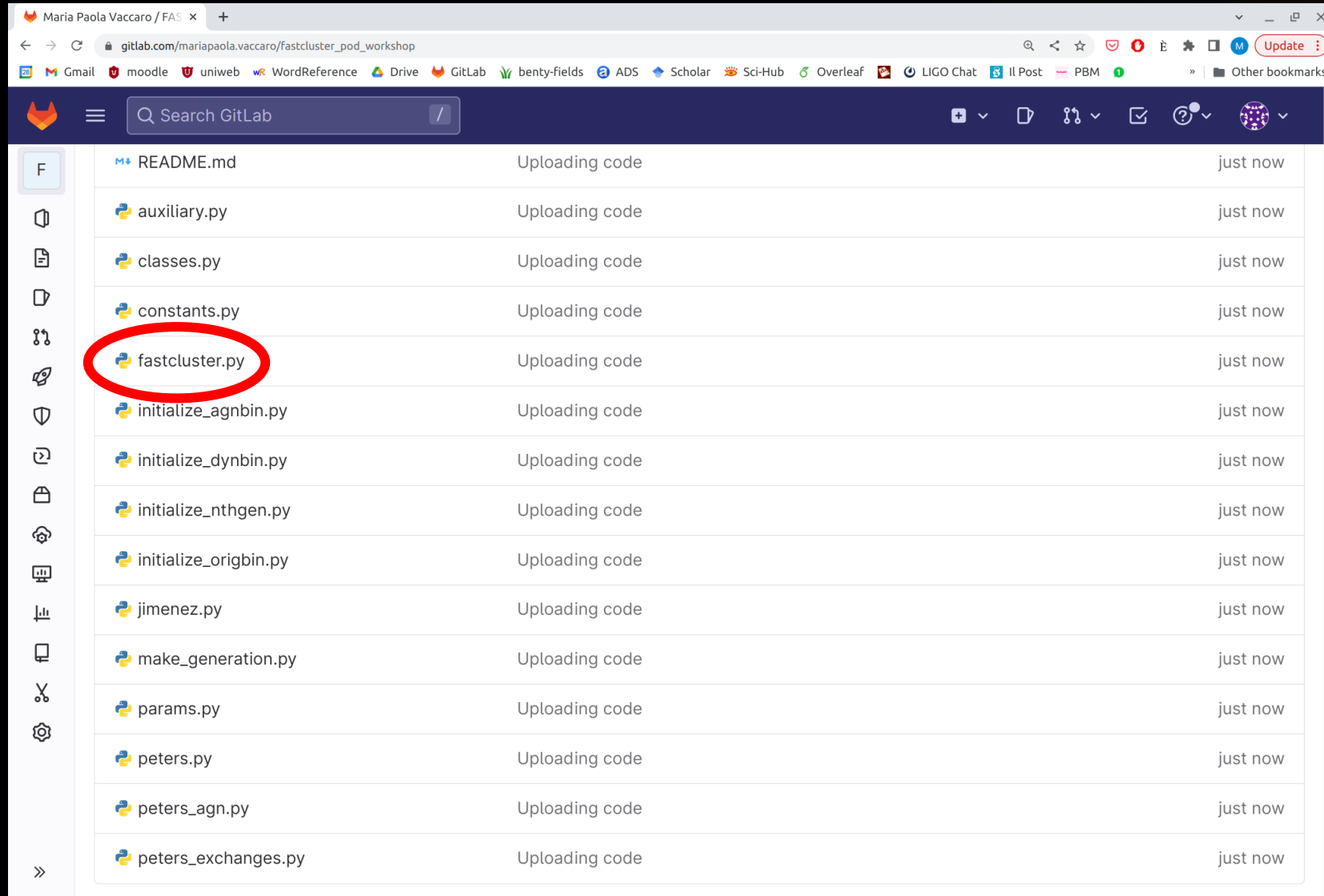
gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop

The screenshot shows the GitLab web interface for the repository 'FASTCLUSTER_POD_WORKSHOP'. The page includes a search bar, navigation icons, and repository statistics: 1 Commit, 1 Branch, 0 Tags, and 18.7 MB Project Storage. A notification indicates 'Uploading code' by mariapaola.vaccaro. Below this, there are buttons for 'main', 'fastcluster_pod_workshop / +', 'Find file', 'Web IDE', and 'Clone'. A list of files is visible, including 'input', '.gitignore', '.gitlab-ci.yml', 'README.md', and 'auxiliary.py', all with 'Uploading' status.

```
mariapaola@mariapaola-KLVL-WXX9: ~/fastcluster
(base) mariapaola@mariapaola-KLVL-WXX9:~$ mkdir fastcluster
(base) mariapaola@mariapaola-KLVL-WXX9:~$ cd fastcluster
(base) mariapaola@mariapaola-KLVL-WXX9:~/fastcluster$ git clone git@gitlab.com:
mariapaola.vaccaro/fastcluster_pod_workshop.git
Cloning into 'fastcluster_pod_workshop'...
remote: Enumerating objects: 21, done.
remote: Counting objects: 100% (21/21), done.
remote: Compressing objects: 100% (21/21), done.
Receiving objects: 66% (14/21), 1.19 MiB | 104.00 KiB/s
```



gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop



The screenshot shows a web browser window displaying the GitLab interface for the repository 'fastcluster_pod_workshop' by Maria Paola Vaccaro. The page lists several files, each with a status of 'Uploading code' and a timestamp of 'just now'. The file 'fastcluster.py' is circled in red. The browser's address bar shows the URL 'gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop'. The browser's bookmark bar includes various sites like Gmail, Moodle, Uniweb, WordReference, Drive, GitLab, Benty-fields, ADS, Scholar, Sci-Hub, Overleaf, LIGO Chat, Il Post, and PBM. The GitLab navigation bar includes a search bar and several utility icons.

File Name	Status	Timestamp
README.md	Uploading code	just now
auxiliary.py	Uploading code	just now
classes.py	Uploading code	just now
constants.py	Uploading code	just now
fastcluster.py	Uploading code	just now
initialize_agsbin.py	Uploading code	just now
initialize_dynbin.py	Uploading code	just now
initialize_nthgen.py	Uploading code	just now
initialize_origbin.py	Uploading code	just now
jimenez.py	Uploading code	just now
make_generation.py	Uploading code	just now
params.py	Uploading code	just now
peters.py	Uploading code	just now
peters_agin.py	Uploading code	just now
peters_exchanges.py	Uploading code	just now

Launch the script
from terminal with
the command
`python fastcluster.py`

Example

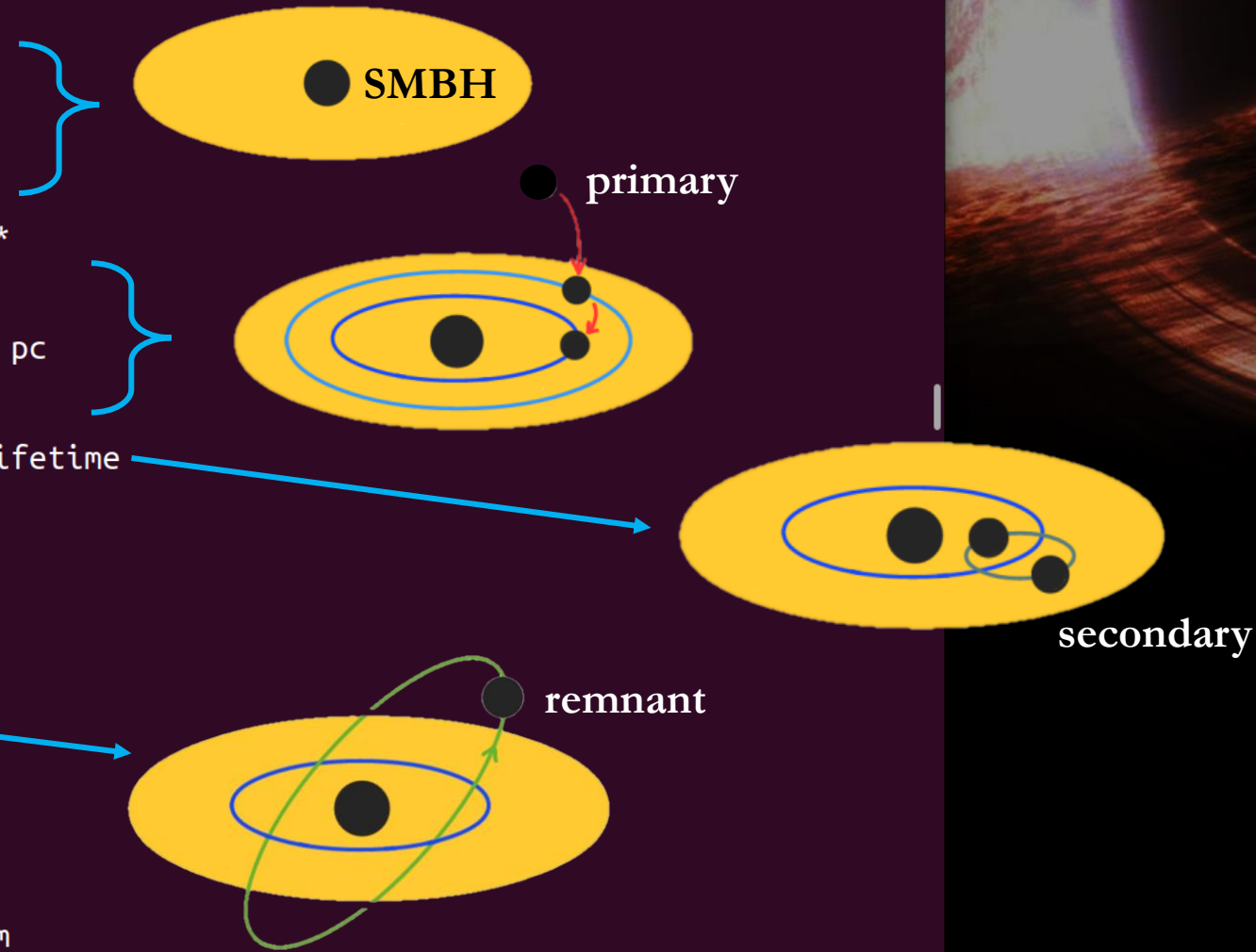
```
mariapaola@mariapaola-KLVL-WXX9: ~/fastcluster_pod_workshop
(base) mariapaola@mariapaola-KLVL-WXX9:~/fastcluster_pod_workshop$ python fastcluster.py
Single stellar BH evolution

* Simulation parameters initialization *
log SMBH mass = 6.76
disk lifetime = 45.62 Myr

* First generation binary initialization *
Primary mass = 11.9 Msun
Initial radial position = 2.73e-05 pc
Migration trap radial position = 1.84e-04 pc
Damping timescale = 1.15e-05 Myr
Migration timescale = 3.03e-01 Myr
The pairing time is lower than the disk lifetime
Secondary mass = 11.1 Msun
Initial semimajor axis = 78.21 Rsun

* First generation binary evolution *
Integration of hardening equations
Delay time = 2.39e-04 Myr
Remnant mass = 21.81 Msun
Effective spin = 0.08

* Hierarchical merger checks *
1) The disk is still present
2) The remnant is retained in the system
3) There are still other BHs in the system
```



Example

gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop

mariapaola@mariapaola-KLVL-WXX9: ~/fastcluster_pod_workshop

```
* Generation 2 initialization and evolution *
```

```
Damping timescale = 5.46e-09 Myr  
Migration timescale = 1.41e-03 Myr  
Secondary mass = 17.8 Msun  
Initial semimajor axis = 78.21 Rsun  
Integration of hardening equations  
Delay time = 2.08e-04 Myr  
Remnant mass = 37.57 Msun  
Effective spin = 0.15
```

```
* Hierarchical merger checks *
```

- 1) The disk is still present
- 2) The remnant is retained in the system
- 3) There are still other BHs in the system

```
* Generation 3 initialization and evolution *
```

```
Damping timescale = 3.19e-09 Myr  
Migration timescale = 8.22e-04 Myr  
Secondary mass = 20.6 Msun  
Initial semimajor axis = 105.82 Rsun  
Integration of hardening equations  
Delay time = 5.47e-03 Myr  
Remnant mass = 55.59 Msun  
Effective spin = 0.13
```

```
* Hierarchical merger checks *
```

- 1) The disk is still present
- 2) The remnant is retained in the system
- 3) There are still other BHs in the system

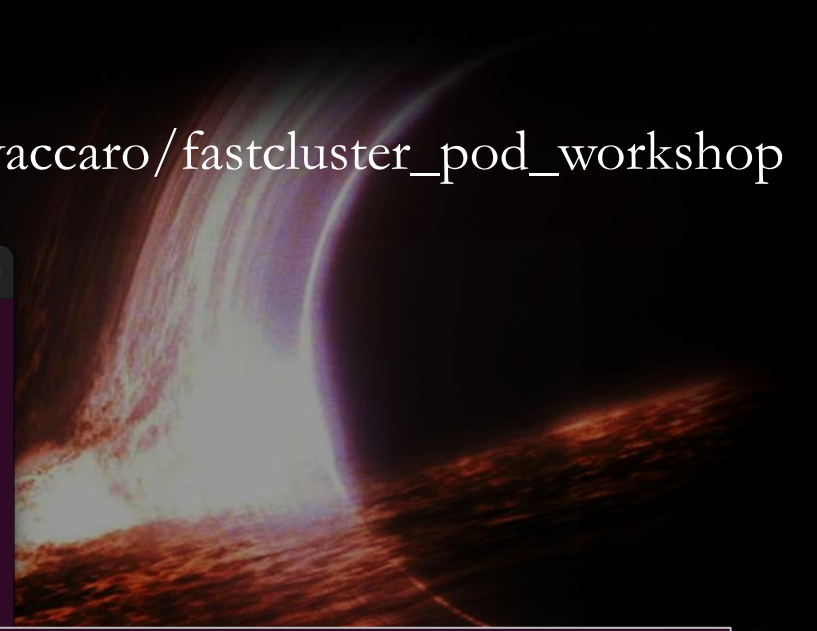
```
* Generation 75 initialization and evolution *
```

```
Damping timescale = 5.49e-11 Myr  
Migration timescale = 1.42e-05 Myr  
Secondary mass = 64.0 Msun  
Initial semimajor axis = 343.82 Rsun  
Integration of hardening equations  
Delay time = 6.17e-03 Myr  
Remnant mass = 2216.05 Msun  
Effective spin = 0.12
```

```
* Hierarchical merger checks *
```

- 1) The disk is still present
- 2) The remnant is retained in the system
- 3) There are no other BHs in the system, stop simulation

```
The last generation is 75
```




```
params.py x classes.py x auxiliary.py x make_generation.py x
1 import numpy as np
2 import constants as const
3
4 #####
5 #####GENERAL PARAMETERS#####
6 #####
7
8 #####
9 ### decide star cluster type (YSC, GC, NSC, AGN) ##
10 #####
11
12 star_cluster_type= "AGN"
13
14
15 #####
16 ### decide channel (Dyn, Orig, AGN)
17 #####
18
19 channel = "AGN"
20
```

```
35
36 #####
37 ### number of 1g BBHs to simulate
38 #####
39
40 BBH_number=1e2
41
```

```
* Simulation parameters initialization *
log SMBH mass = 5.89
disk lifetime = 16.87 Myr

* First generation binary initialization *
Average mass ratio = 0.7

* First generation binary evolution *
Average remnant mass = 16.22 Msun
Average effective spin = 0.21

* Hierarchical merger checks *
Removed 25 for exceeded migration time
Removed 0 for ejection from cluster
Removed 0 for exceeded extracted mass

* Generation 2 initialization and evolution *
Average mass ratio = 0.67
Average remnant mass = 33.78 Msun
Average effective spin = 0.21

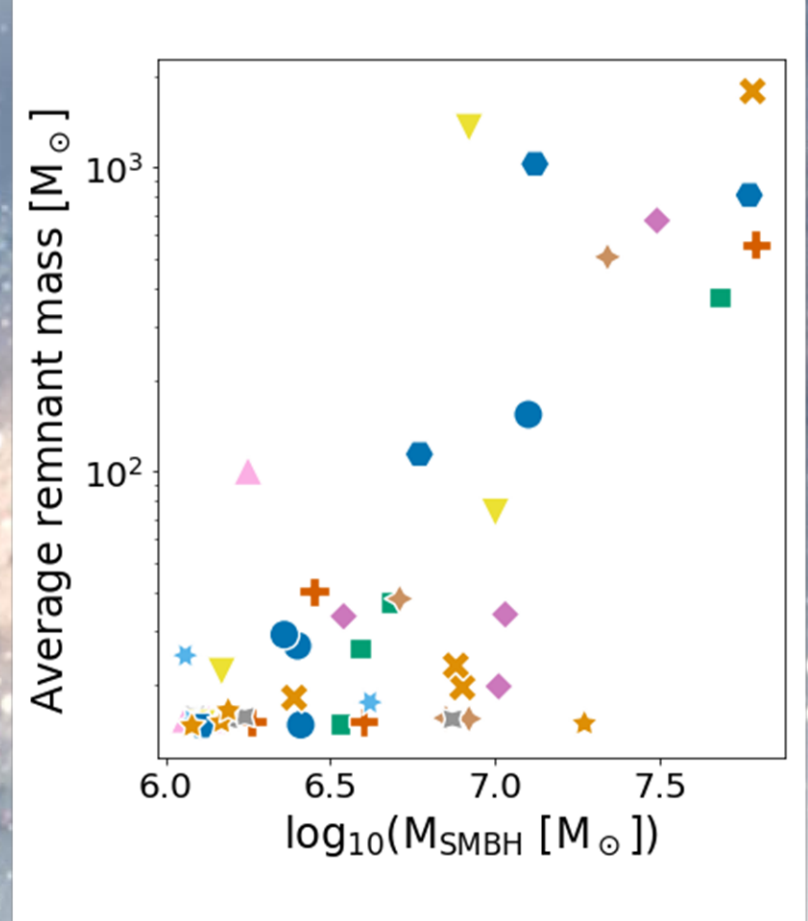
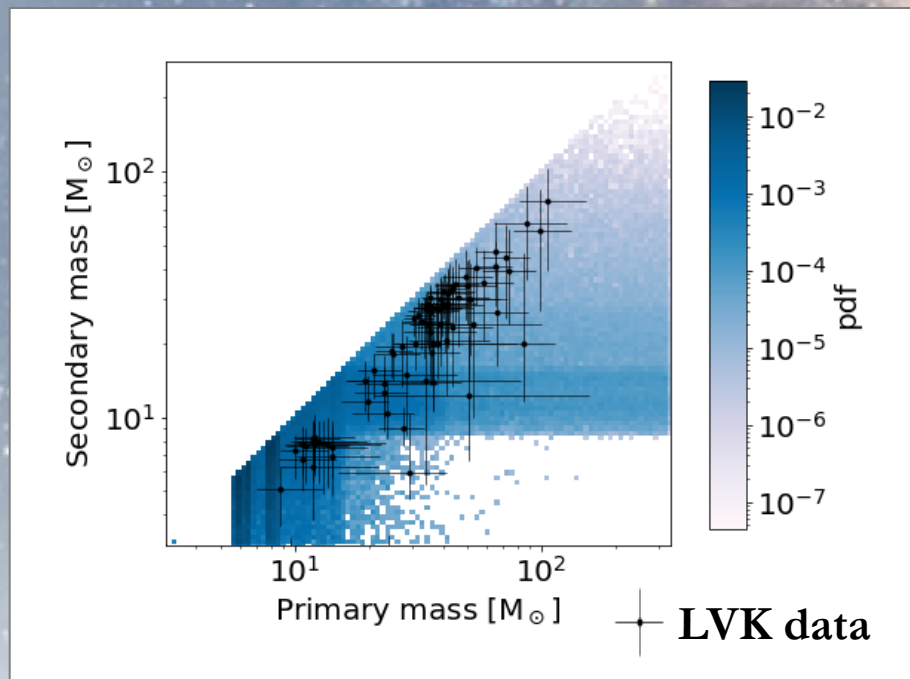
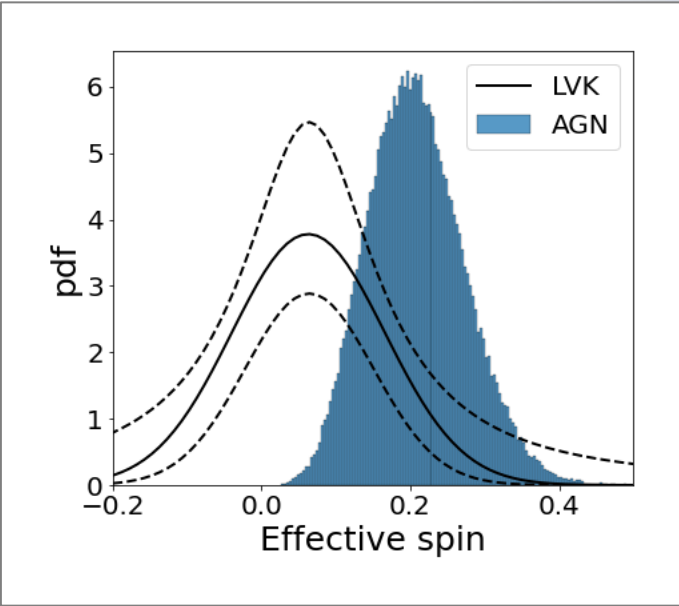
* Hierarchical merger checks *
Removed 0 for exceeded migration time
Removed 0 for ejection from cluster
Removed 0 for exceeded extracted mass
```

Results



AGNs are a breeding ground for the formation of intermediate-mass black holes

PRELIMINARY!



Conclusions

- Is dynamical formation of BBHs possible (and efficient) in AGNs? **Yes!**
 - Merger remnants with masses up to $\sim 10^3 M_{\odot}$
 - The average remnant mass correlates with the SMBH mass
- Has any observed BBH been produced in an AGN? **Maybe.**
 - For a fair comparison we need to account for the **observational biases** of the LIGO-Virgo-KAGRA instruments

Stay tuned, paper in preparation!

