How do Black Holes Grow?
Active Galactic Nuclei as a breeding ground for intermediate-mass Black Holes

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Physics of Data Workshop

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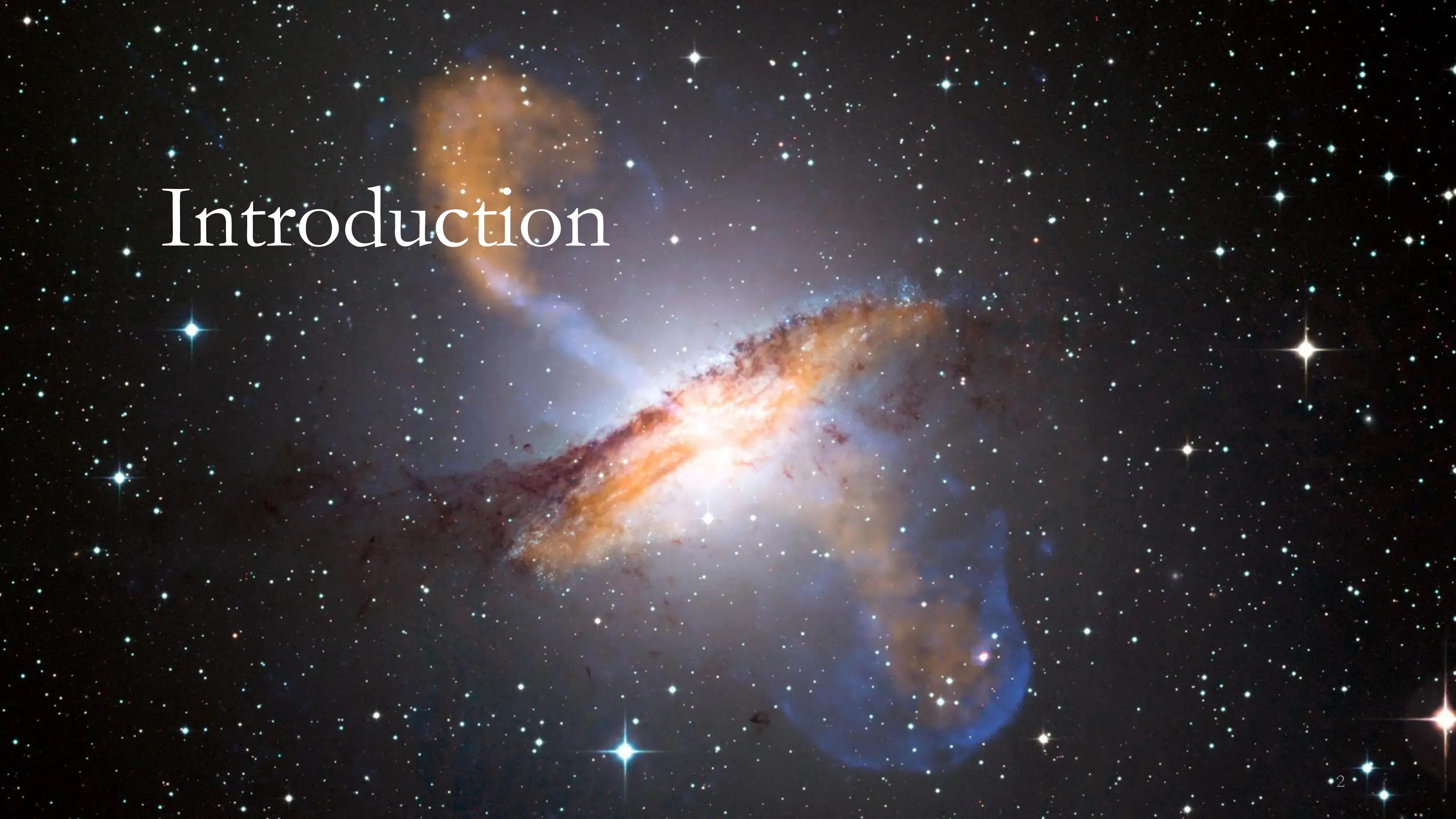
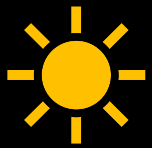
Università degli Studi di Padova

Introduction

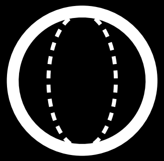


What are Black Holes?

- Compact Objects
  - High mass, low volume



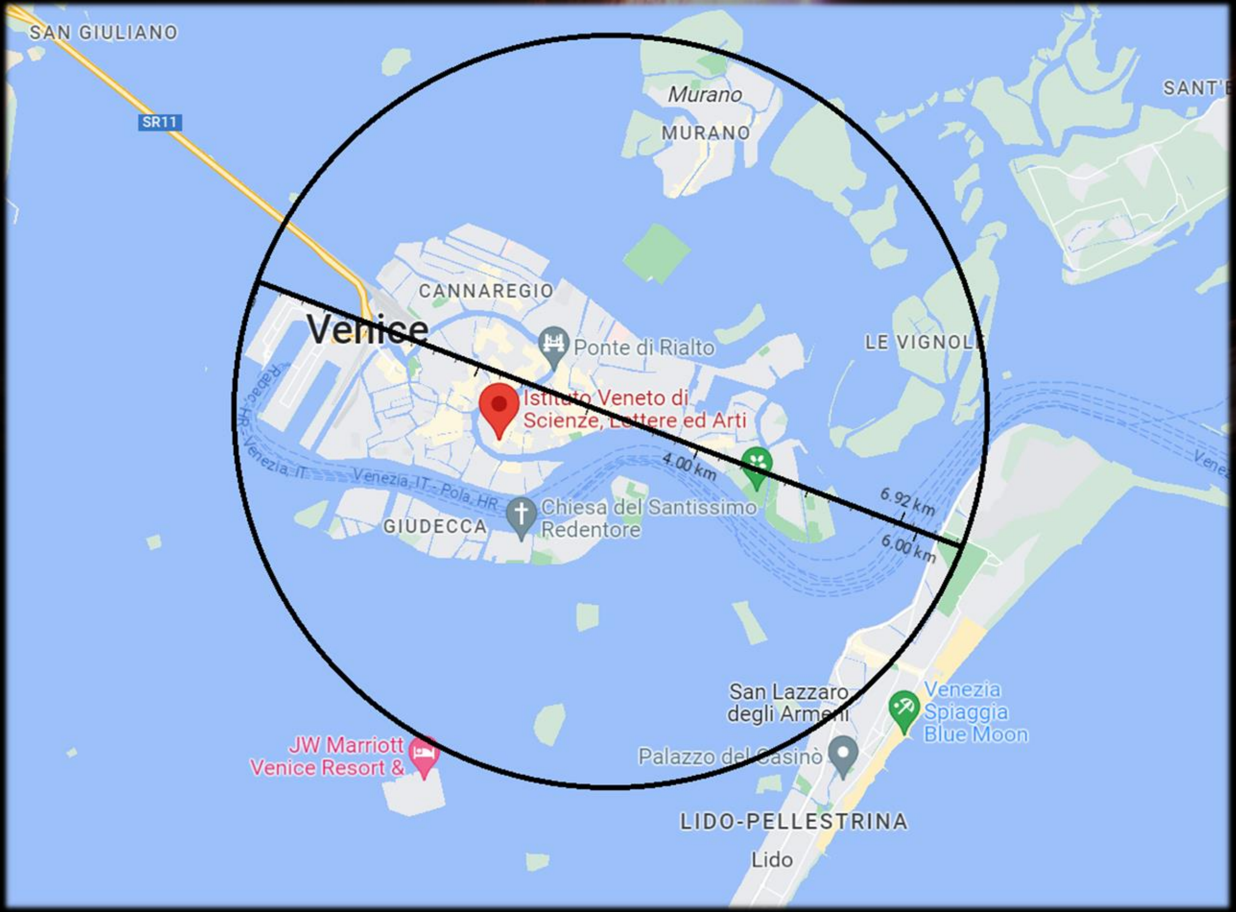
Sun
$1\ M_\odot \sim 10^{30}$kg
$1\ R_\odot \sim 10^{9}$ km



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

↓

Dark!



What are Black Holes?

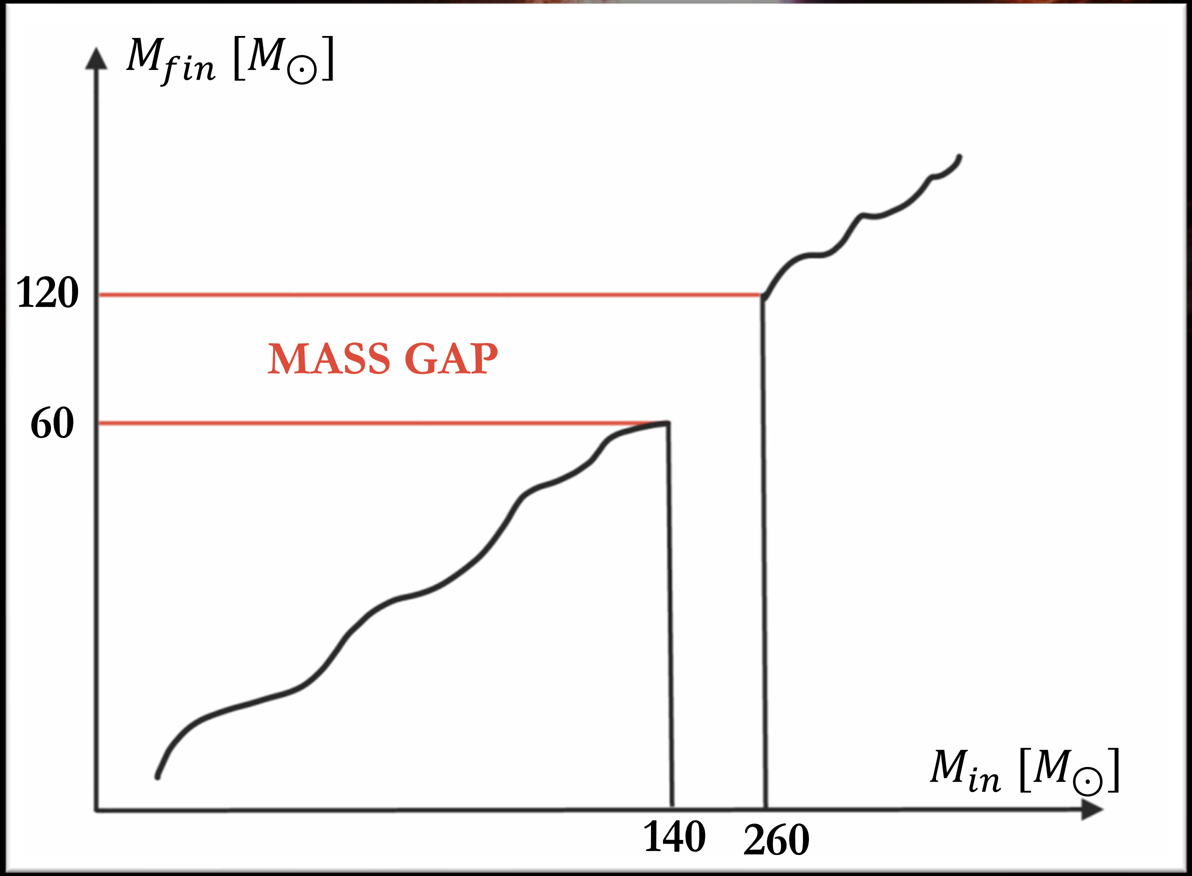
- Compact Objects
  - High mass, low volume

Sun	Black Hole
$1\ M_\odot \sim 10^{30}$kg	$1\ M_\odot \sim 10^{30}$kg
$1\ R_\odot \sim 10^{9}$ km	**3 *km***

↓

Dark!

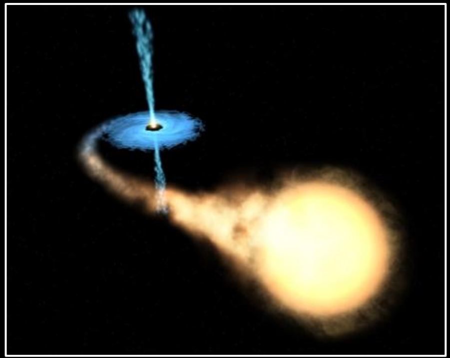
- Stellar evolution remnants

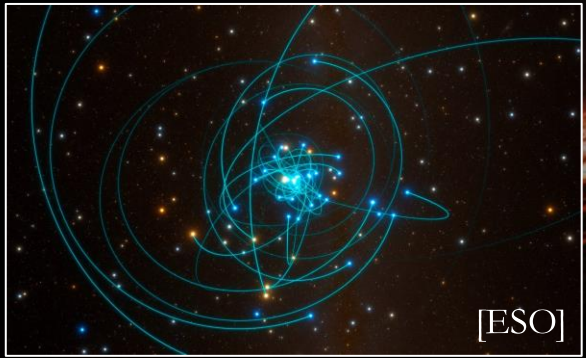


[S.E. Woosley et al., 2002]

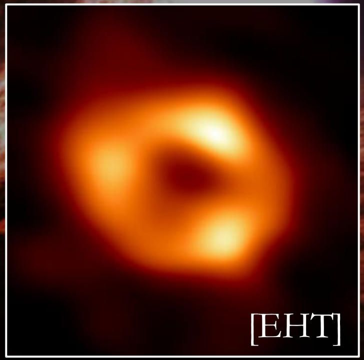
Black Hole observations

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



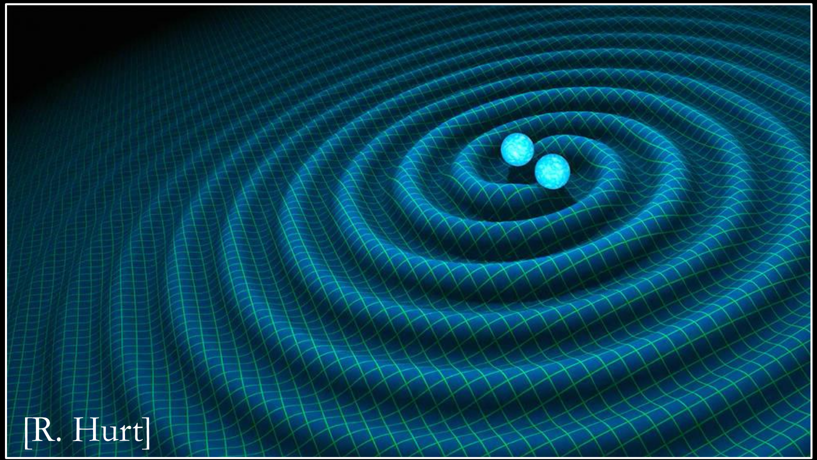


[ESO]



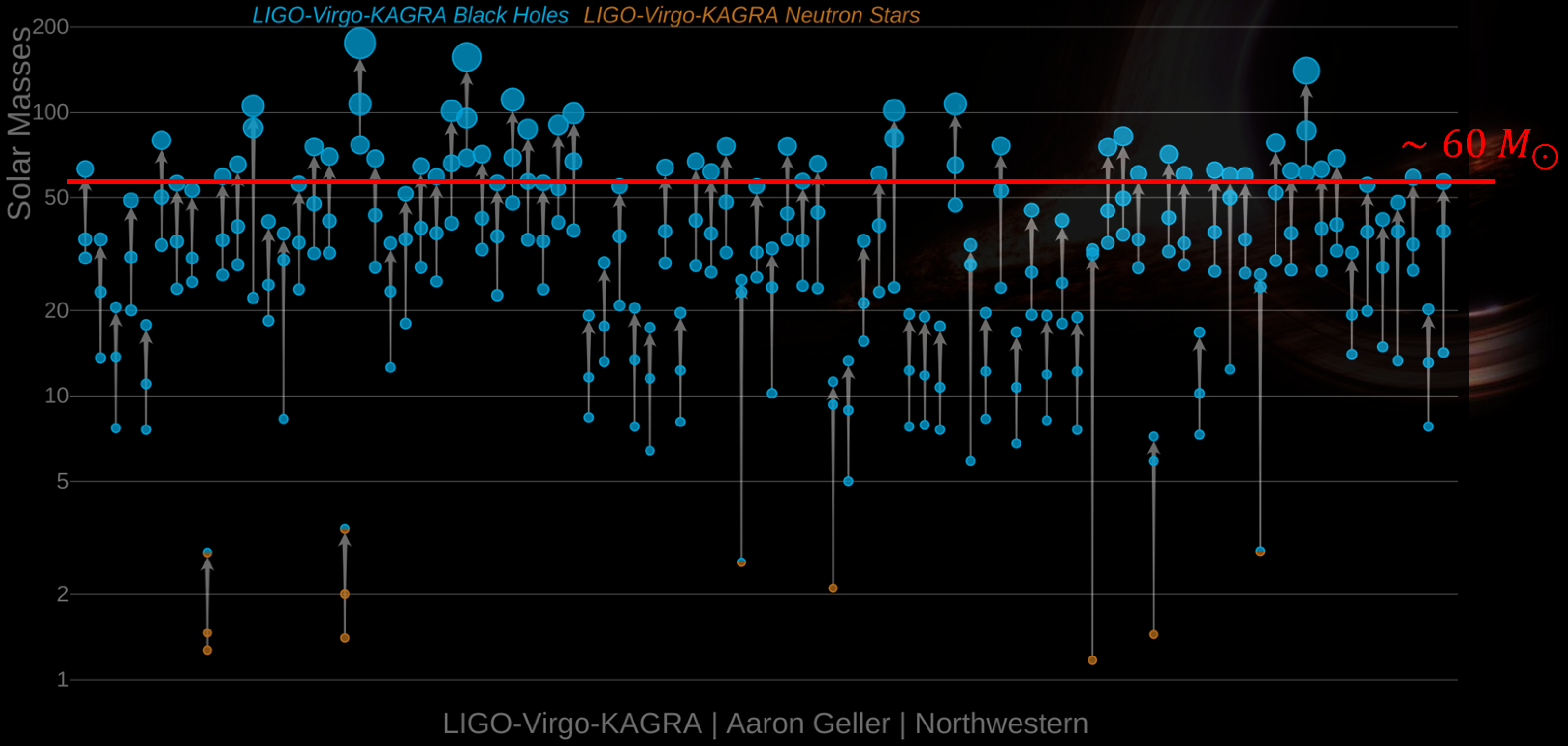
[EHT]

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



[R. Hurt]

Masses in the Stellar Graveyard



Gravitational Waves observations

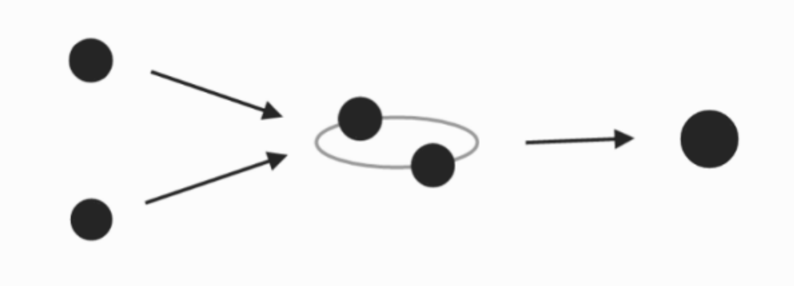
How do these mass gap BHs exist?

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 $^{12}C(\alpha, \gamma)^{16}O$ rate on the pair-instability black hole mass gap

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

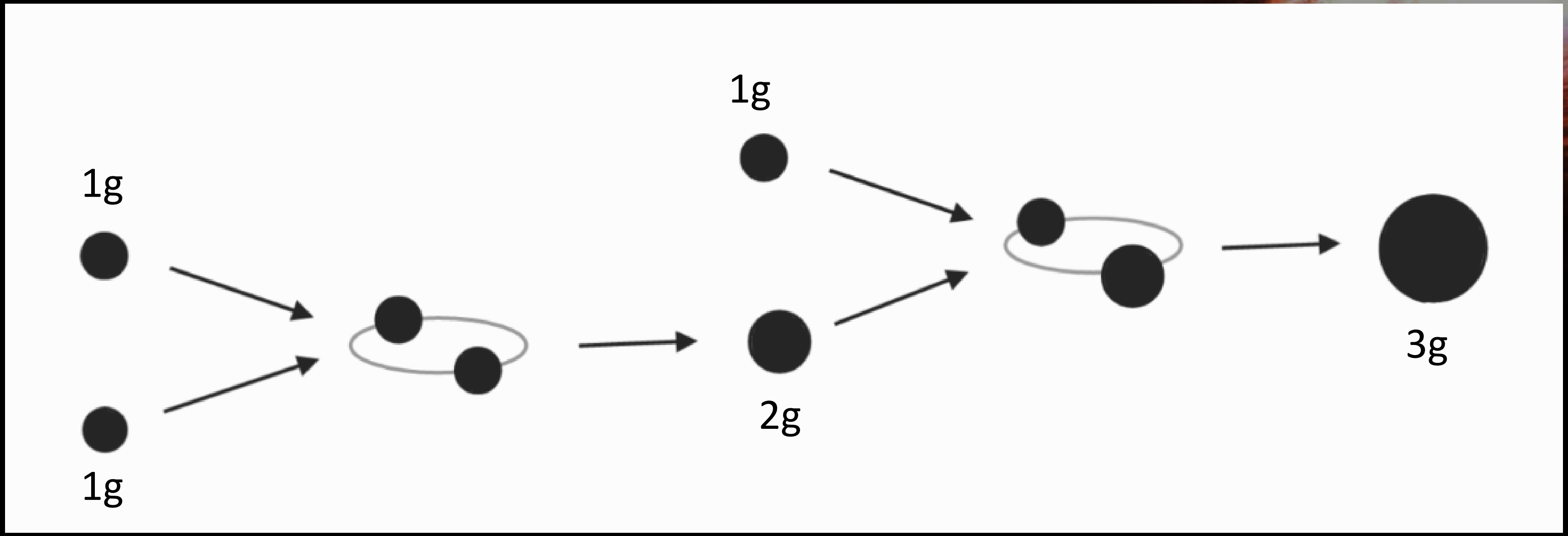
B. These BHs do not come directly from stellar evolution, but from **dynamical formation channels**



Dynamical Formation

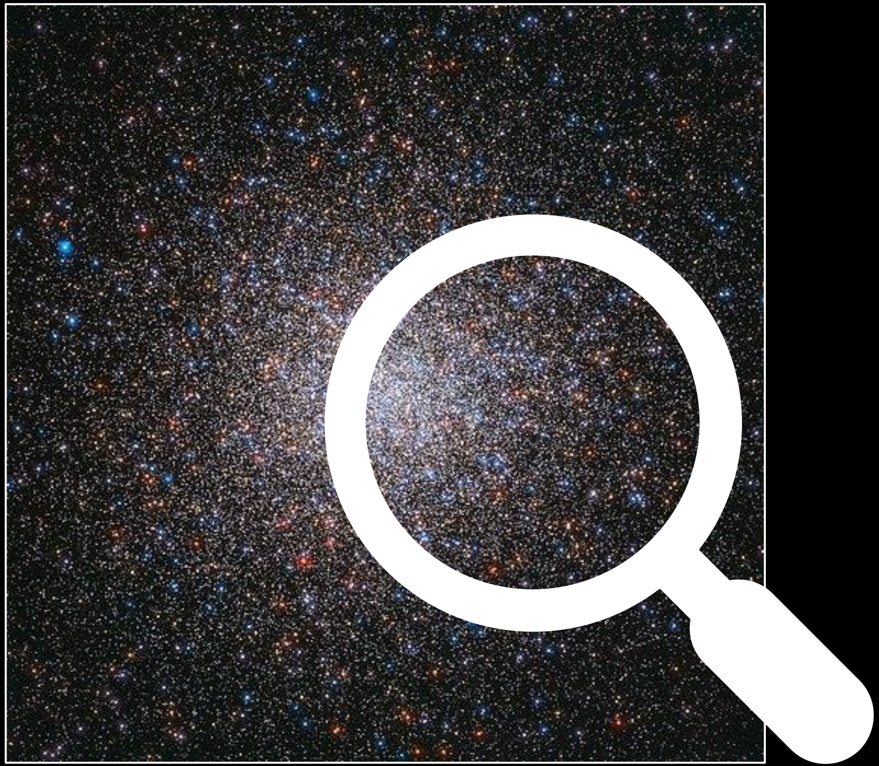
In environments with **high stellar density**:

HIERARCHICAL MERGERS



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

Dense environments

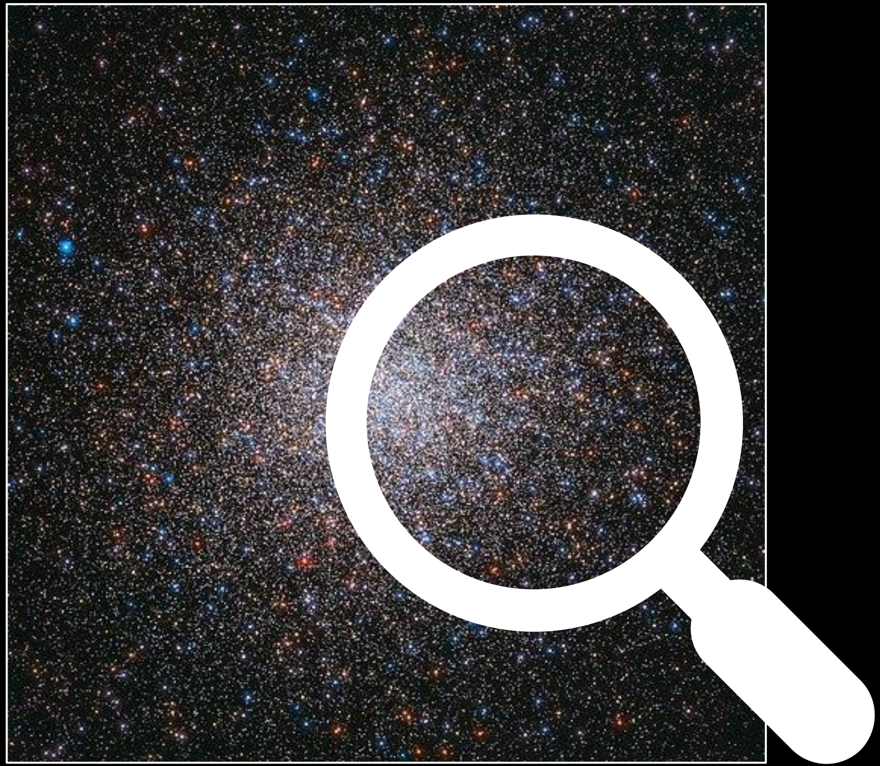


[Globular Cluster M2, HST]

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]

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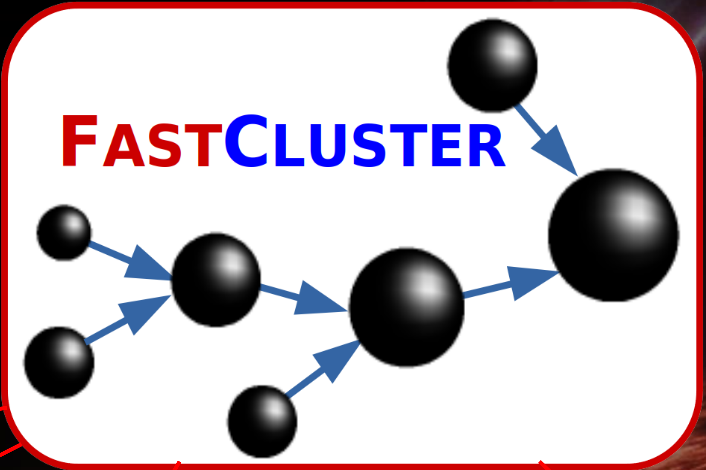
Michela Mapelli, Marco Dall'Amico, Yann Bouffanais, Nicola Giacobbo, Manuel Arca Sedda, M. Celeste Artale, Alessandro Ballone, Ugo N. Di Carlo, Giuliano Iorio, Filippo Santoliquido, Stefano Torniamenti, M. Paola Vaccaro, Dario Barone, Daxal Meta



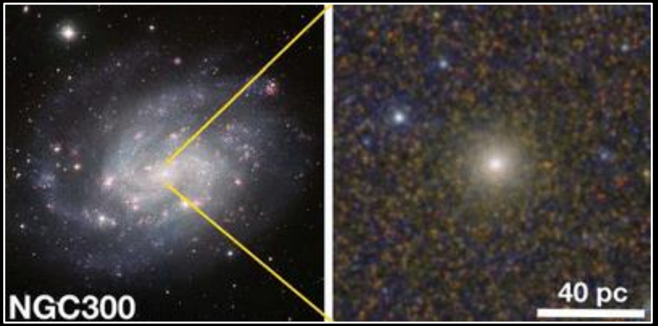
GLOBULAR CLUSTERS

[M2, HST]

OPEN CLUSTERS

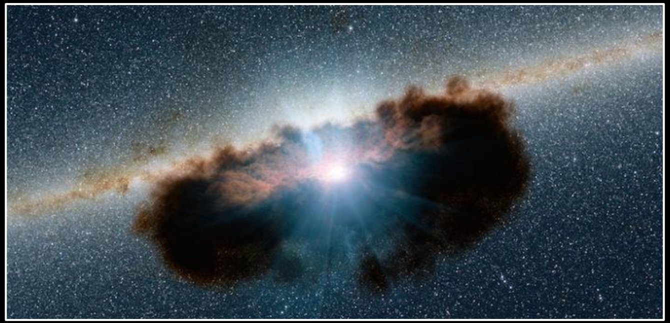
[NGC 2164, HST]

NUCLEAR CLUSTERS



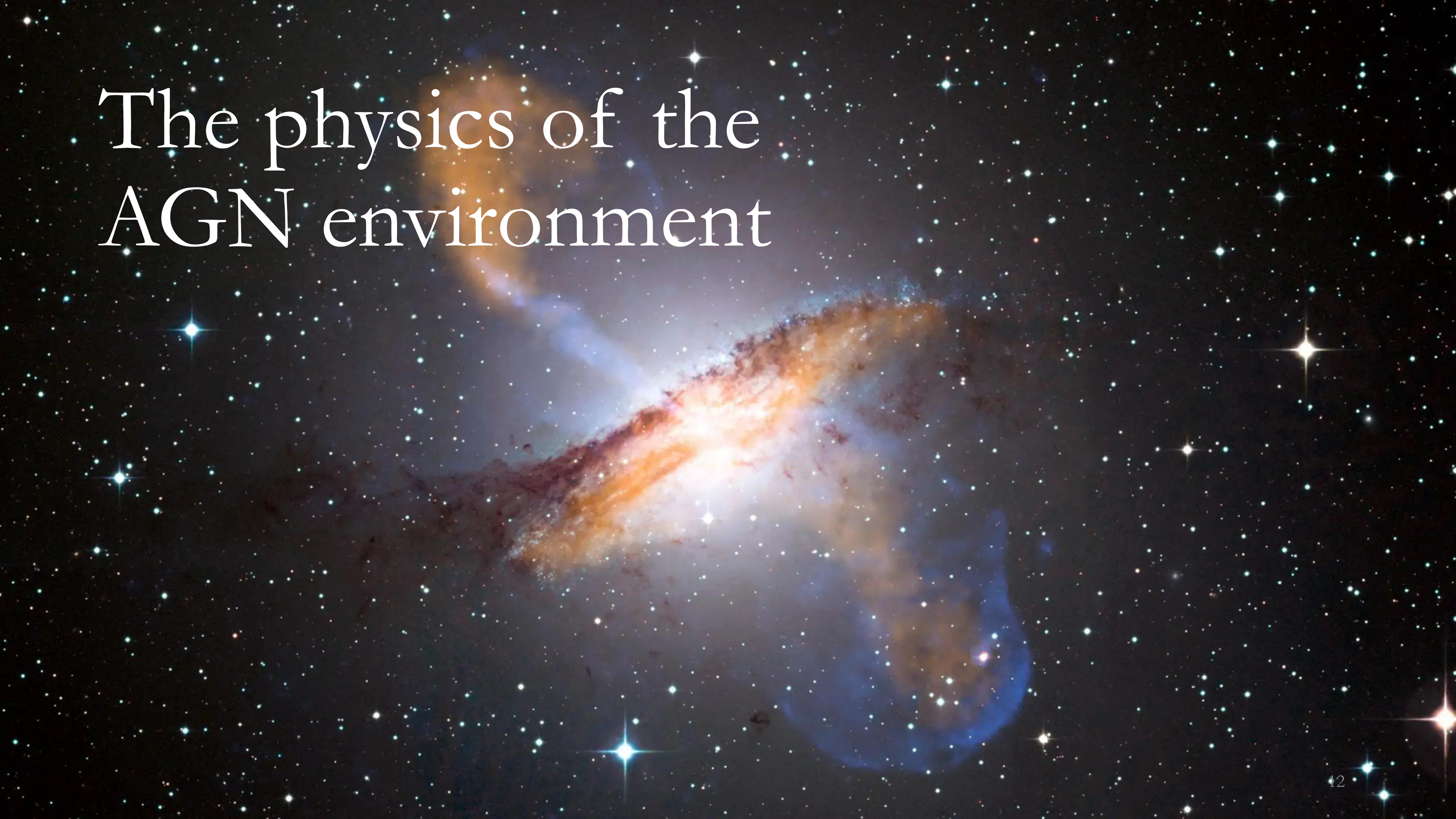
[NGC 300, Nadine Neumayer]

ACTIVE GALACTIC NUCLEI

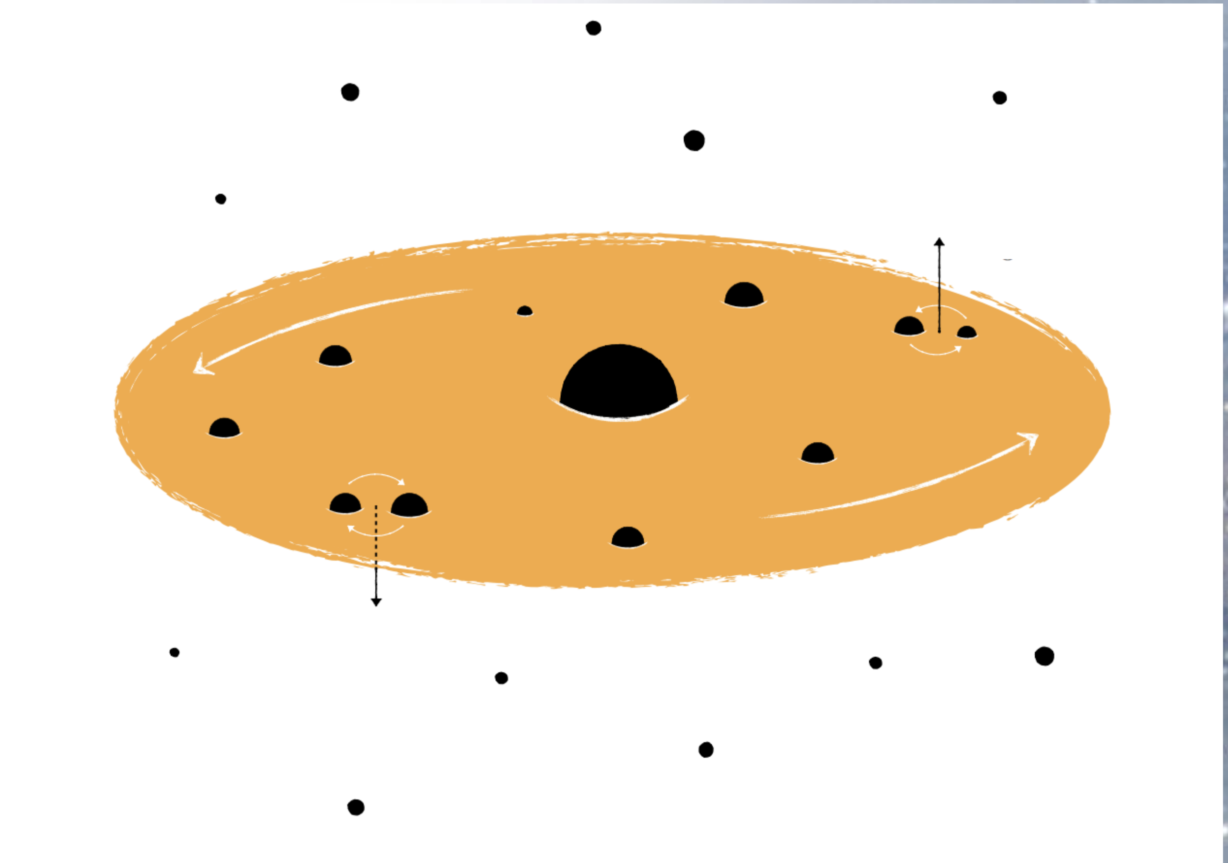


[Artist impression, NASA]

The physics of the AGN environment



Active Galactic Nucleus: the recipe



[Image credits: B. McKernan]

INGREDIENTS

INGREDIENTS FOR A 22 PC MOLD

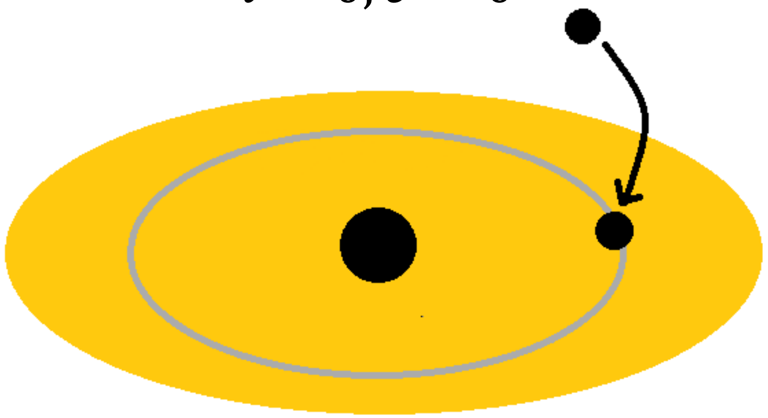
- Super-massive black hole: $M > 10^5 M_\odot$
- Gaseous accretion disk with lifetime τ
- Surrounding black holes (Nuclear Star Cluster)

13

The effects of gas

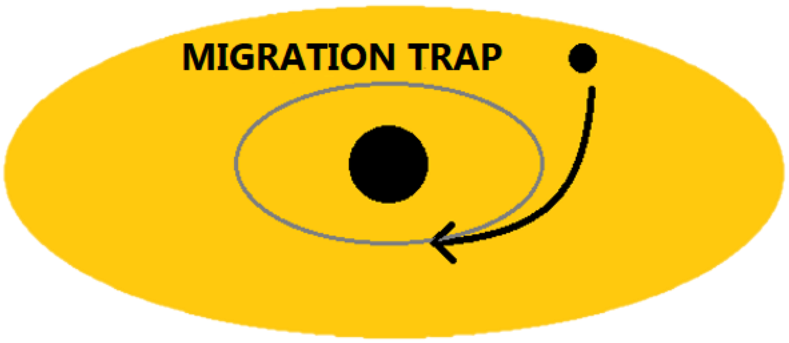
1) **DAMPING**

$i \to 0, e \to 0$



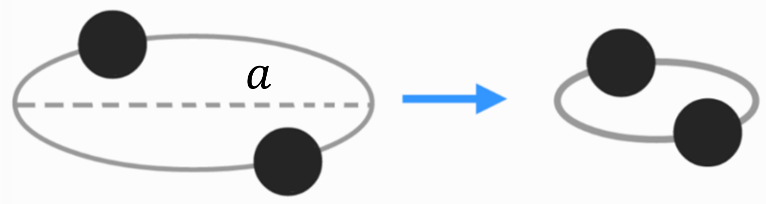
2) **TYPE I MIGRATION**

$R \to R_{\text{trap}}$

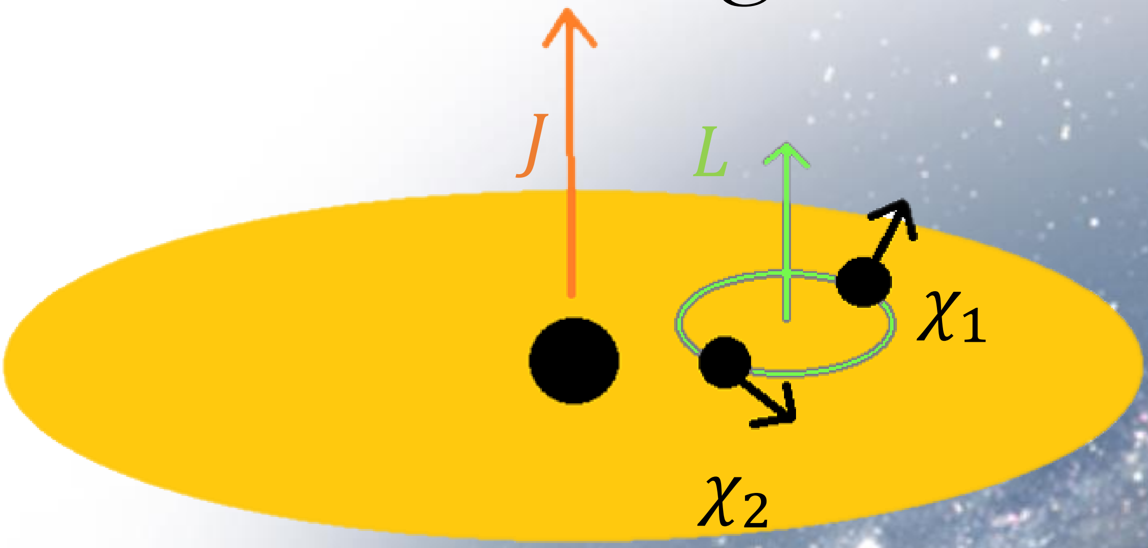


3) **ASSISTED INSPIRAL**

$a \downarrow$



The effects of gas

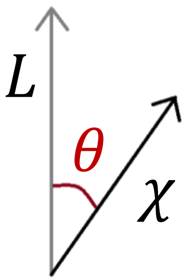


4) **SPIN ALIGNMENT**

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

Gravitational Waves are sensitive to the effective spin

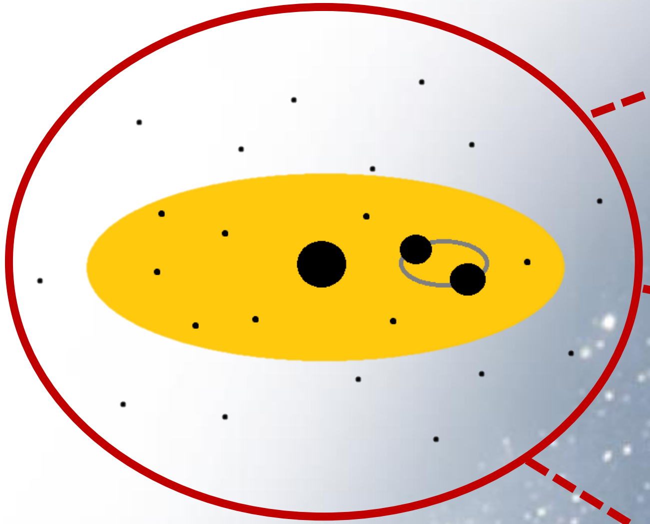
$$\chi_{\mathrm{eff}} = \frac{m_1\,\chi_1\cos\theta_1 + m_2\,\chi_2\cos\theta_2}{m_1 + m_2}$$

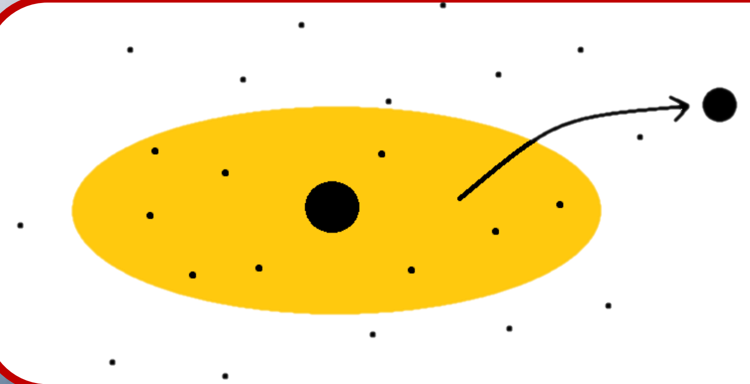


High effective spin is a **signature** of mergers in AGNs

What happens after the merger?

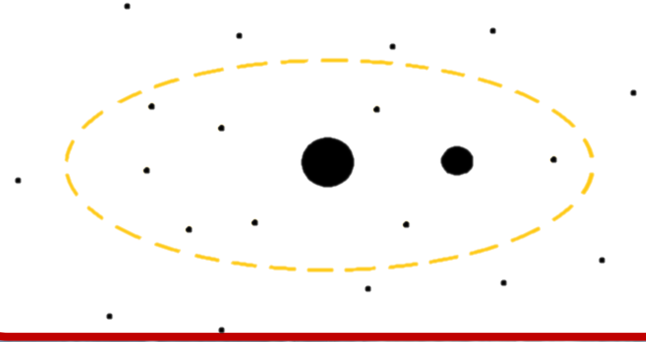
Can the merger remnant go through a new merger event?





Ejection:

$\|\overrightarrow{v_{in}} + \overrightarrow{v_{kick}}\| > v_{esc}$



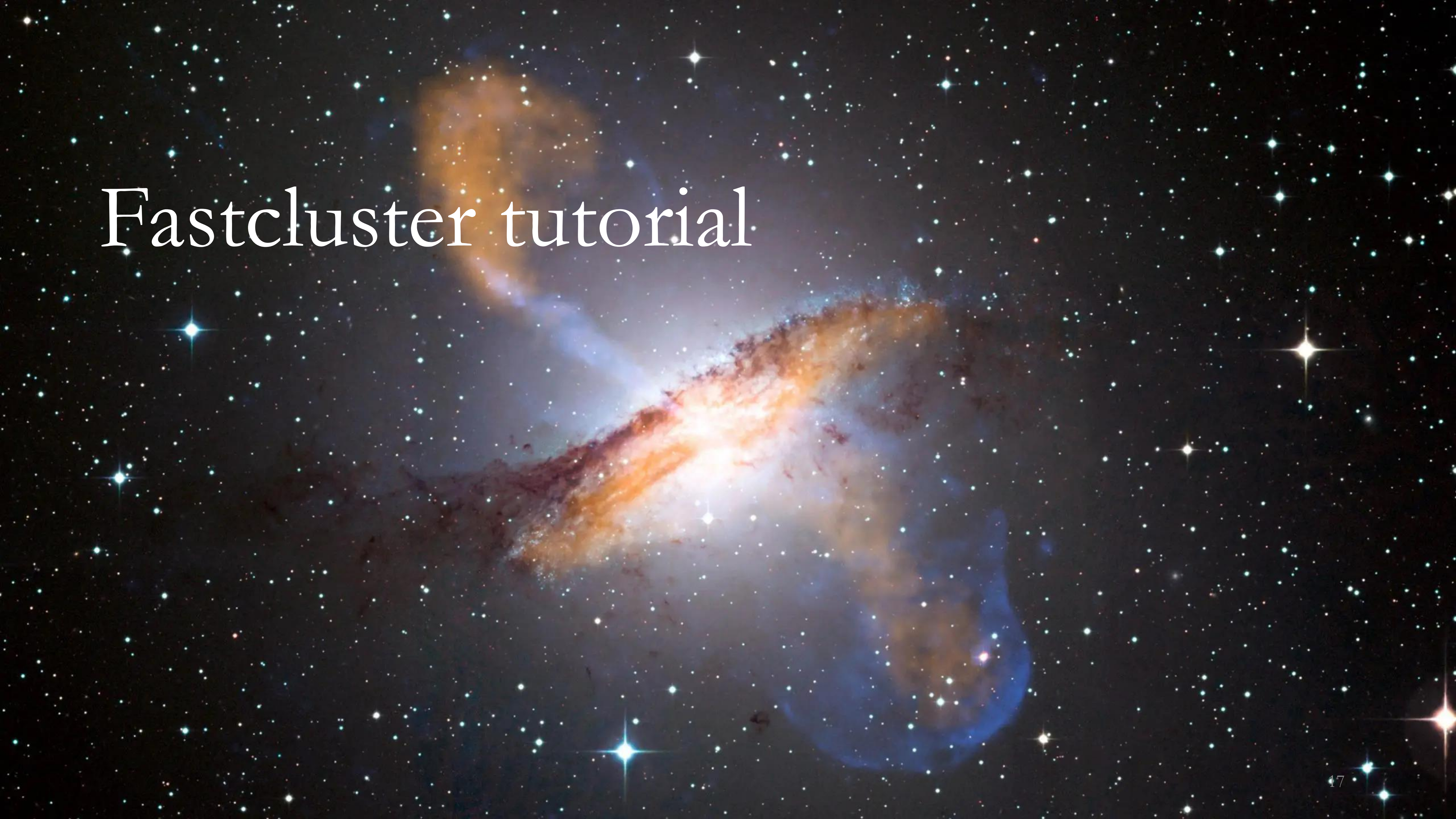
Timescale too long:

$t_{\mathrm{merg}} > \tau$

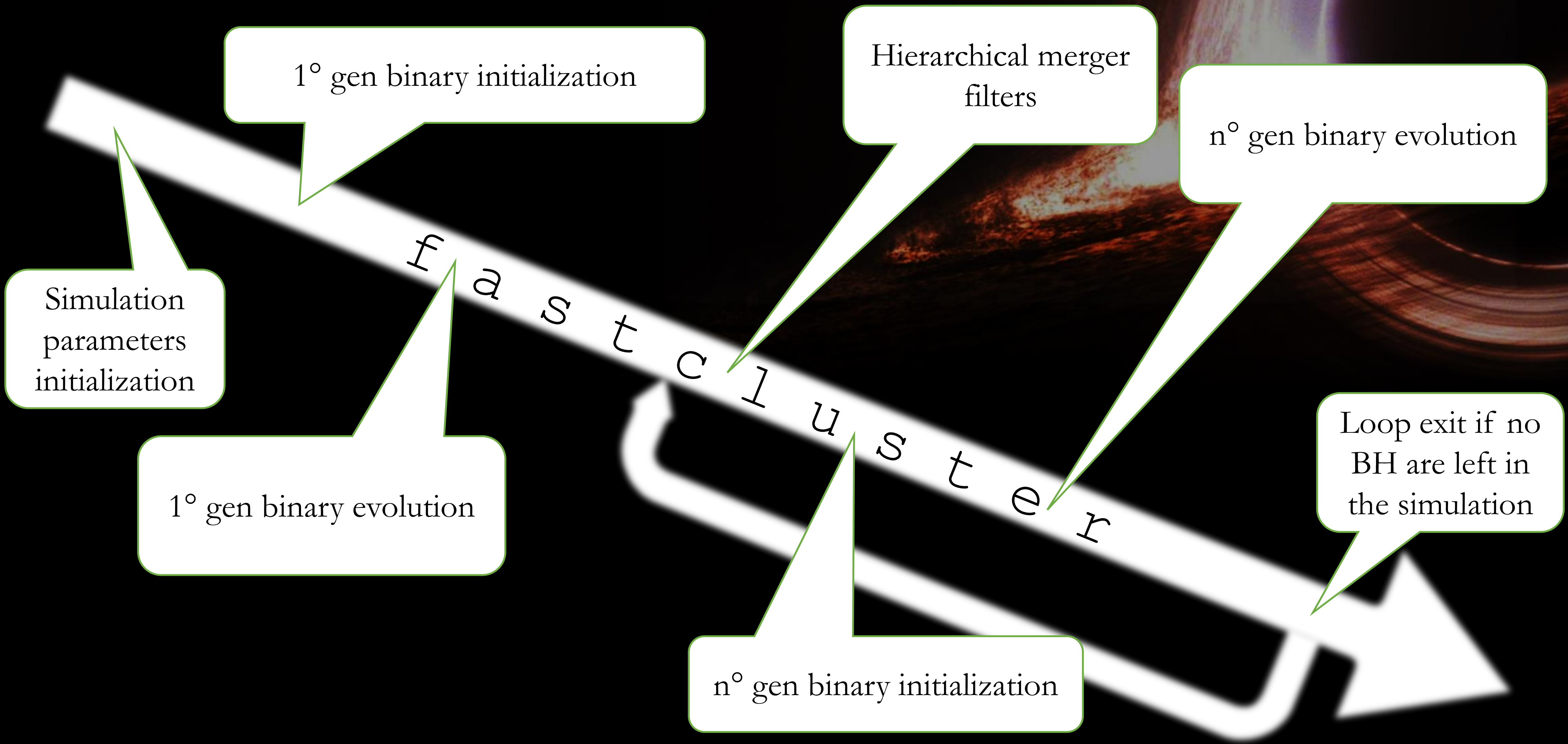
No other BH:

$m_1 + \sum m_2^{(g)} > M_{\mathrm{max}} \propto N_{\mathrm{BH}}$

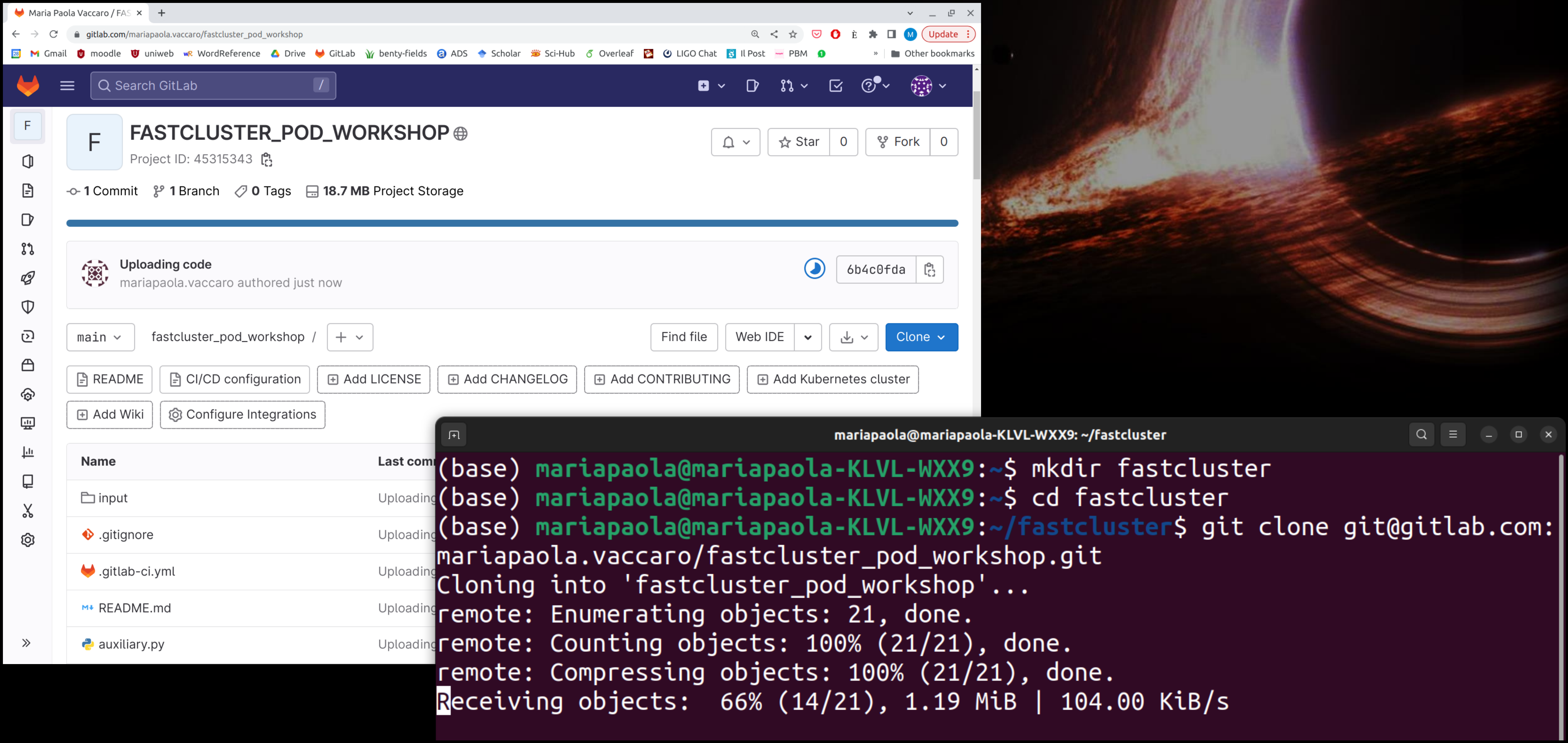
Fastcluster tutorial



Logic sequence of the script



gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop



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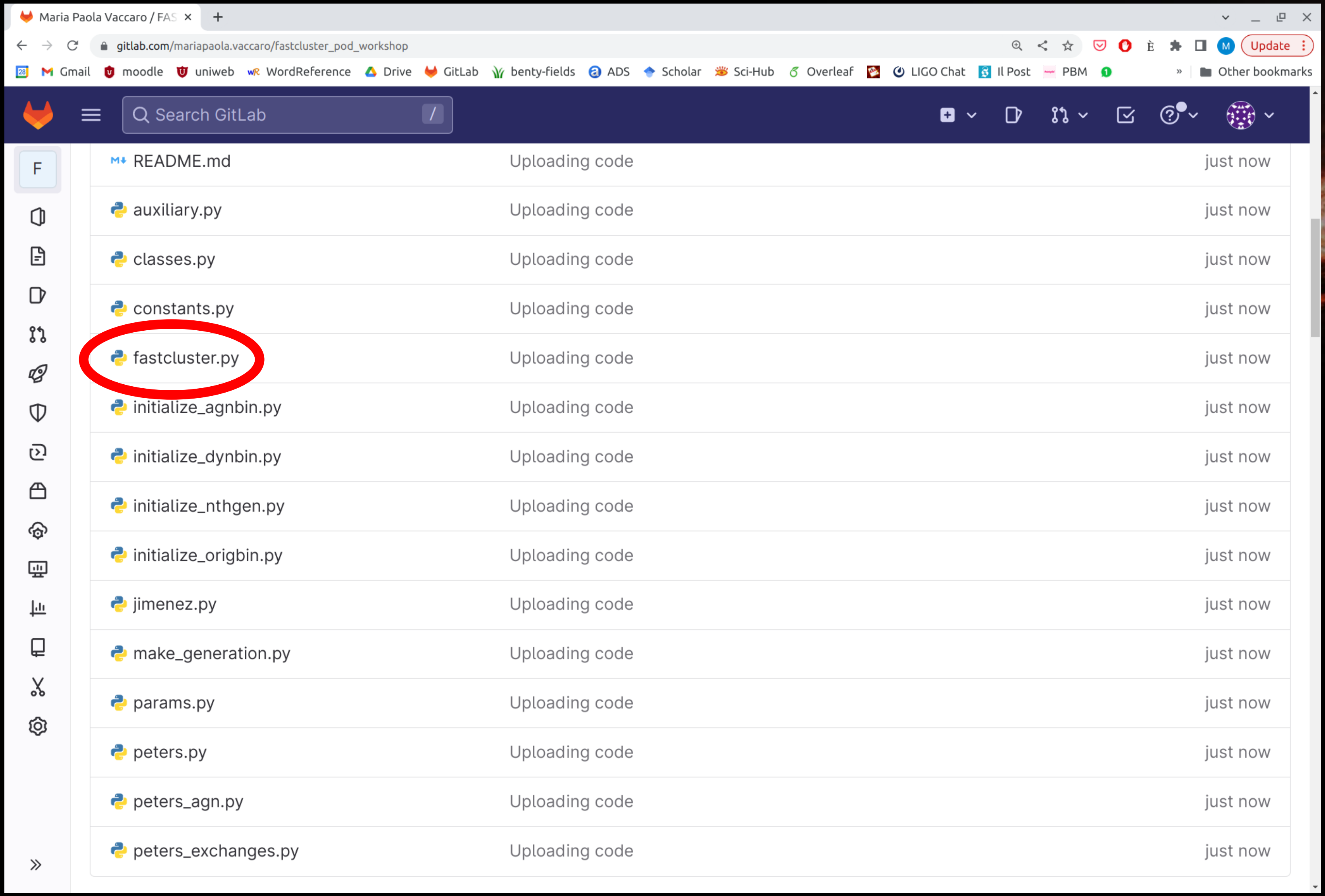


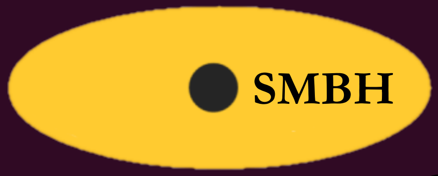
Launch the script from terminal with the command python fastcluster.py

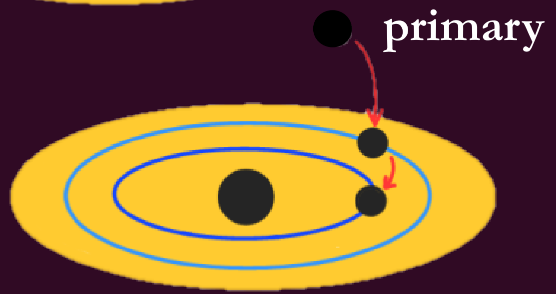
Example

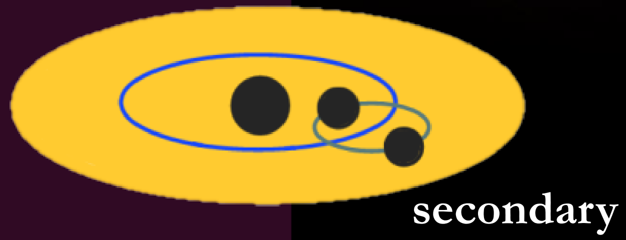
gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop

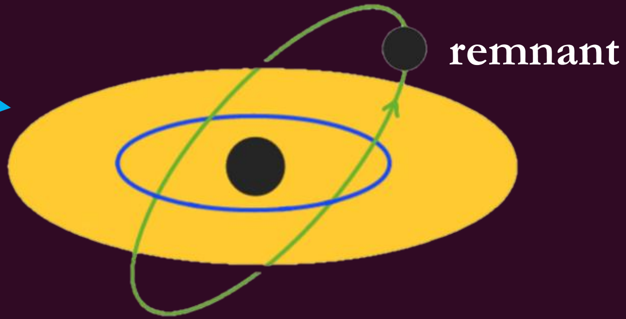
mariapaola@mariapaola-KLVL-WXX9: ~/fastcluster_pod_workshop

```
(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
```



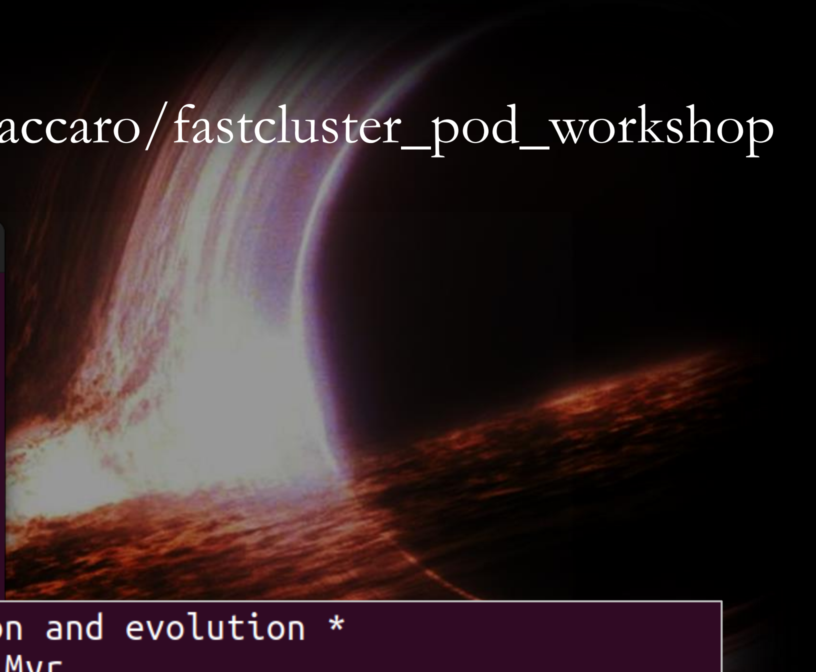






Example

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
```

gitlab.com/mariapaola.vaccaro/fastcluster_pod_workshop

params.py | classes.py | auxiliary.py | make_generation.py

```
import numpy as np
import constants as const

############################################
#############GENERAL PARAMETERS###########
############################################

####################################################
### decide star cluster type (YSC, GC, NSC, AGN) ##
####################################################

star_cluster_type= "AGN"


###################################
### decide channel (Dyn, Orig, AGN)
###################################

channel = "AGN"

```

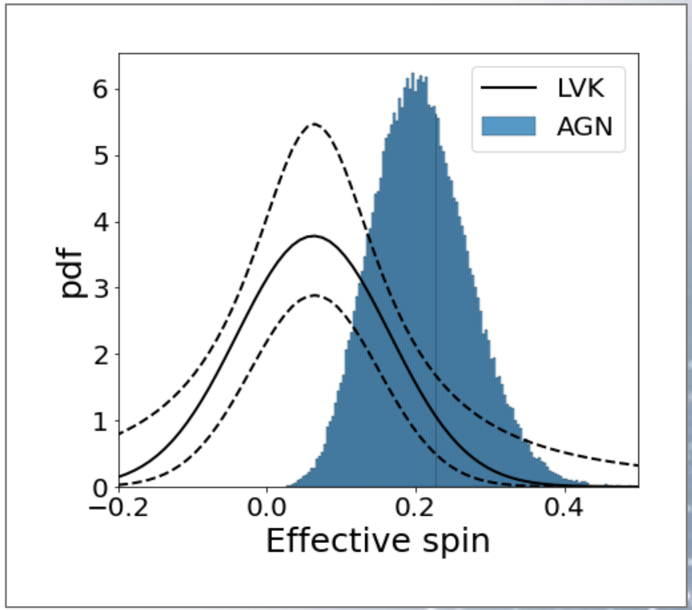
```

###################################
### number of 1g BBHs to simulate
###################################

BBH_number=1e2

```

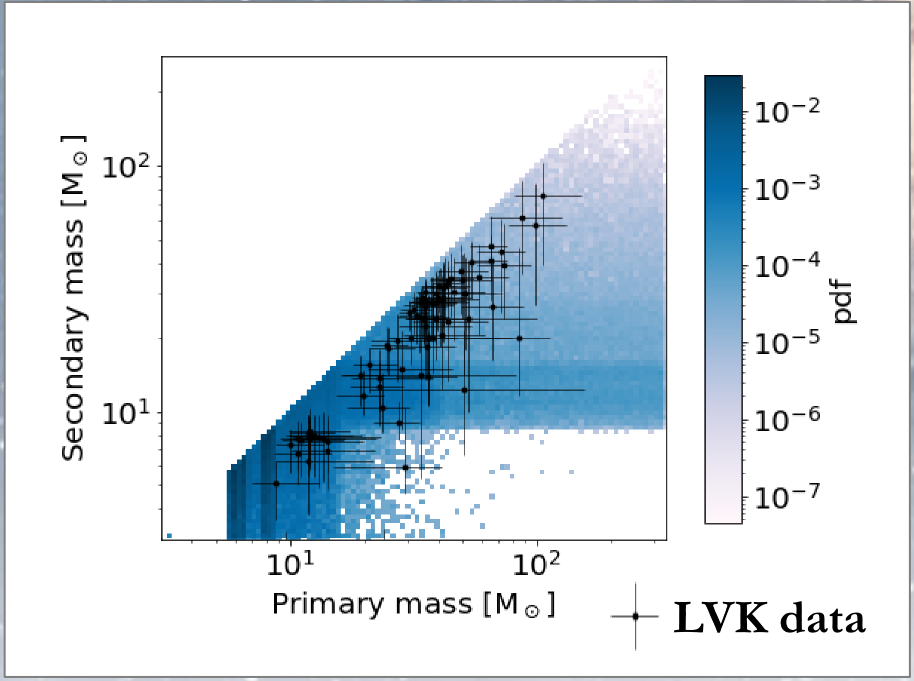
```
* Simulation parameters initialization *
log SMBH mass = 5.89
disk lifetime = 16.87 Myr

* 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

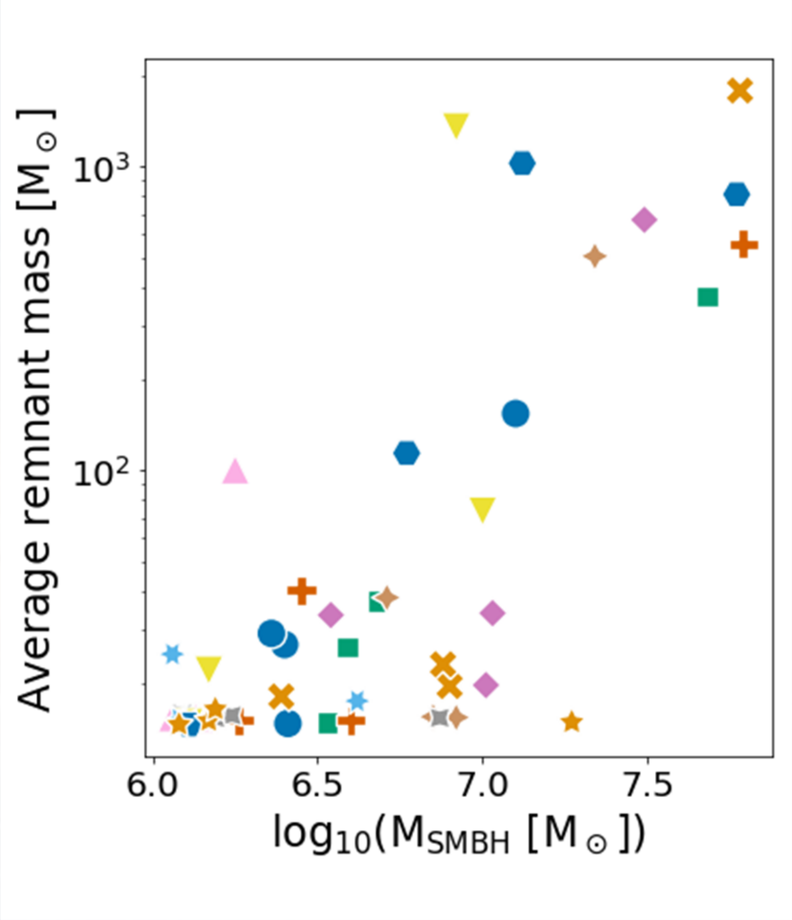
AGNs are a breeding ground for the formation of intermediate-mass black holes

PRELIMINARY!





LVK data



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!