Title: The parents of LIGO black holes and their hometown

Speakers: Vishal Baibhav

Series: Strong Gravity

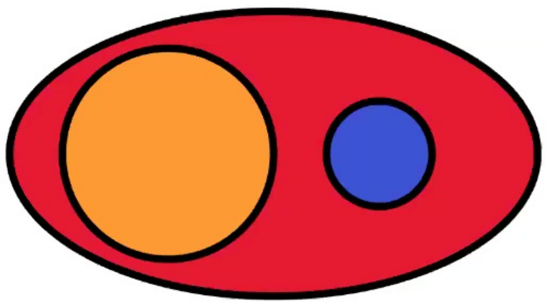
Date: January 14, 2021 - 1:00 PM

URL: http://pirsa.org/21010009

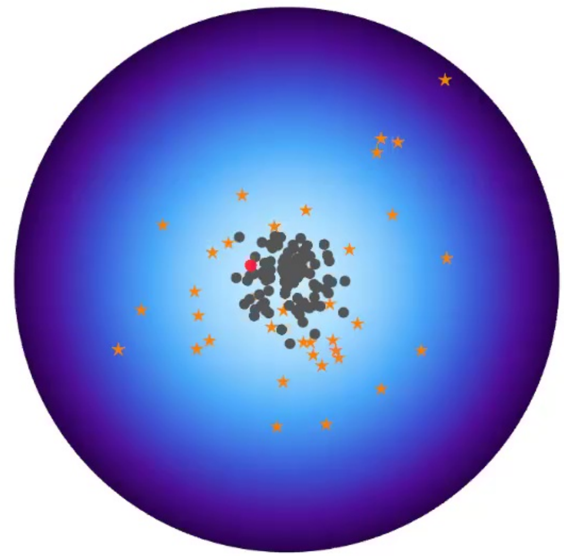
Abstract: Two of the dominant channels to produce black-hole binary mergers are believed to be the isolated evolution of stellar binaries in the field and dynamical formation in star clusters. Pair instabilities prevent stellar collapse from generating black holes more massive than about 45-60 solar mass. This â€œmass gapâ€• only applies to the field formation scenario: repeated mergers in clusters can fill the gap. A similar reasoning applies to the binaryâ€™s spin parameters. If black holes are born slowly rotating, the high-spin portion of the parameter space (the â€œspin gapâ€•) can only be filled by black-hole binaries that are assembled dynamically. I will discuss how such signatures are a smoking gun for the hierarchical origin, and how recent detections (GW190521 and GW190412) fit in this context. I will also talk about how we may be able to reconstruct the properties of progenitors of second-generation black holes.

Perimeter - Google Slides - Google Chrome

The parents of LIGO black holes and their hometown

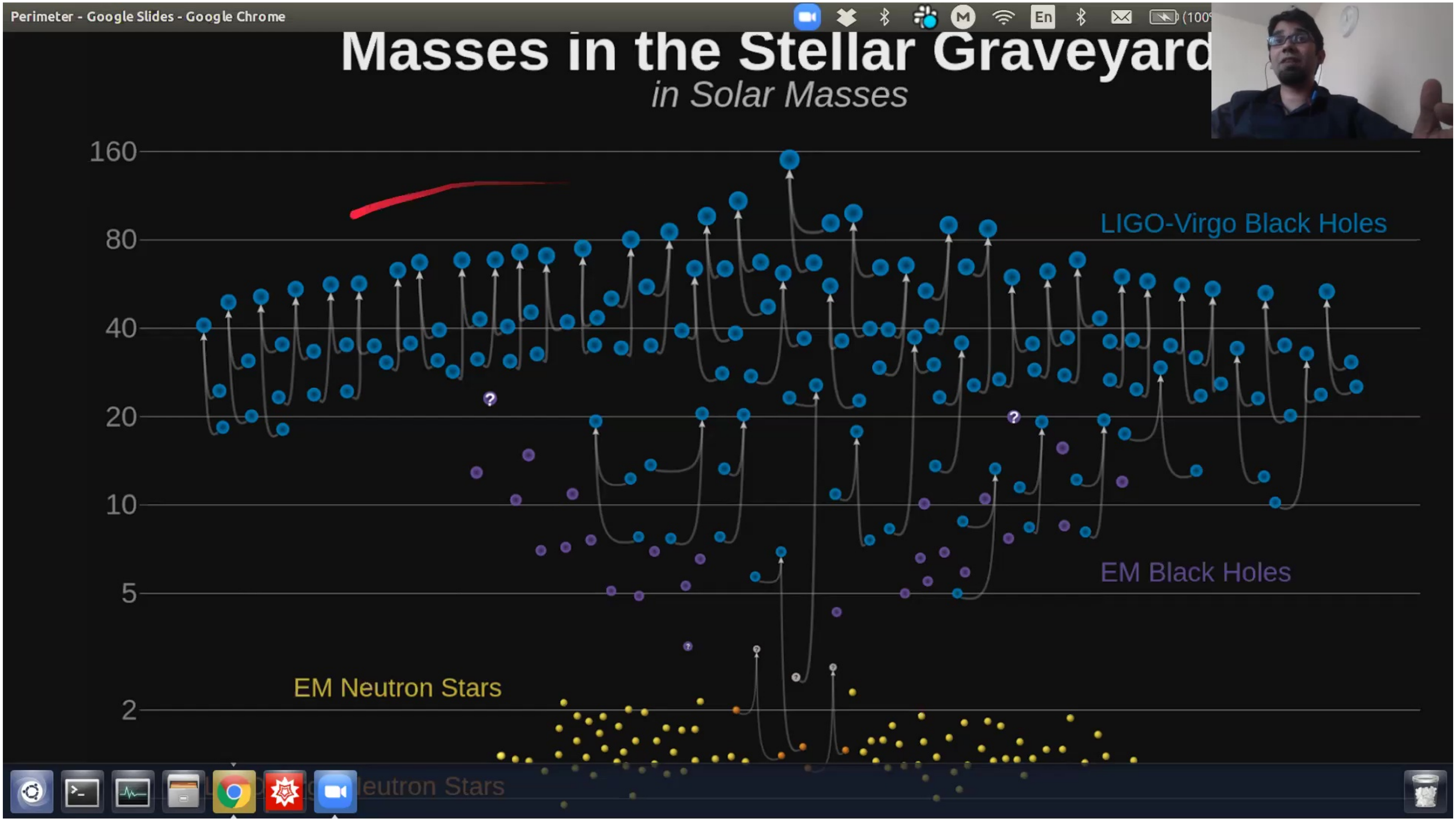


VS

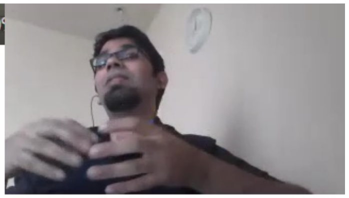


Vishal Baibhav
Johns Hopkins University
with Davide Gerosa, Emanuele Berti, Kaze Wong, Thomas Helfer, Matthew Mould

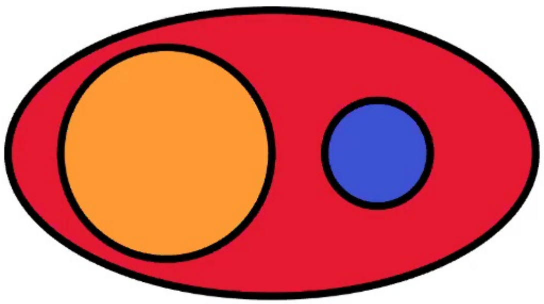
arXiv: 2004.00650
+ongoing work

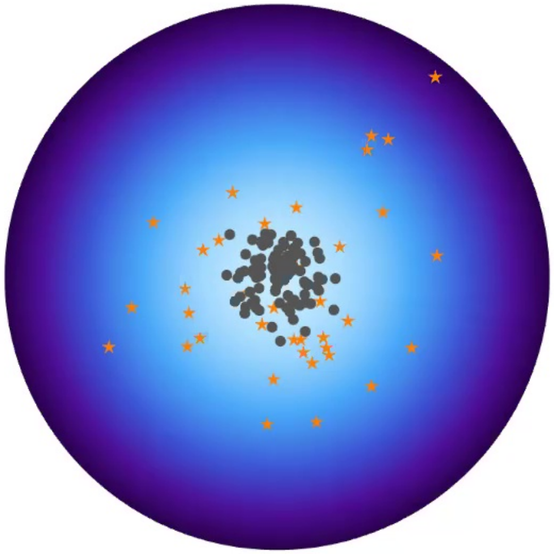

Perimeter - Google Slides - Google Chrome
Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
eutron Stars

Perimeter - Google Slides - Google Chrome

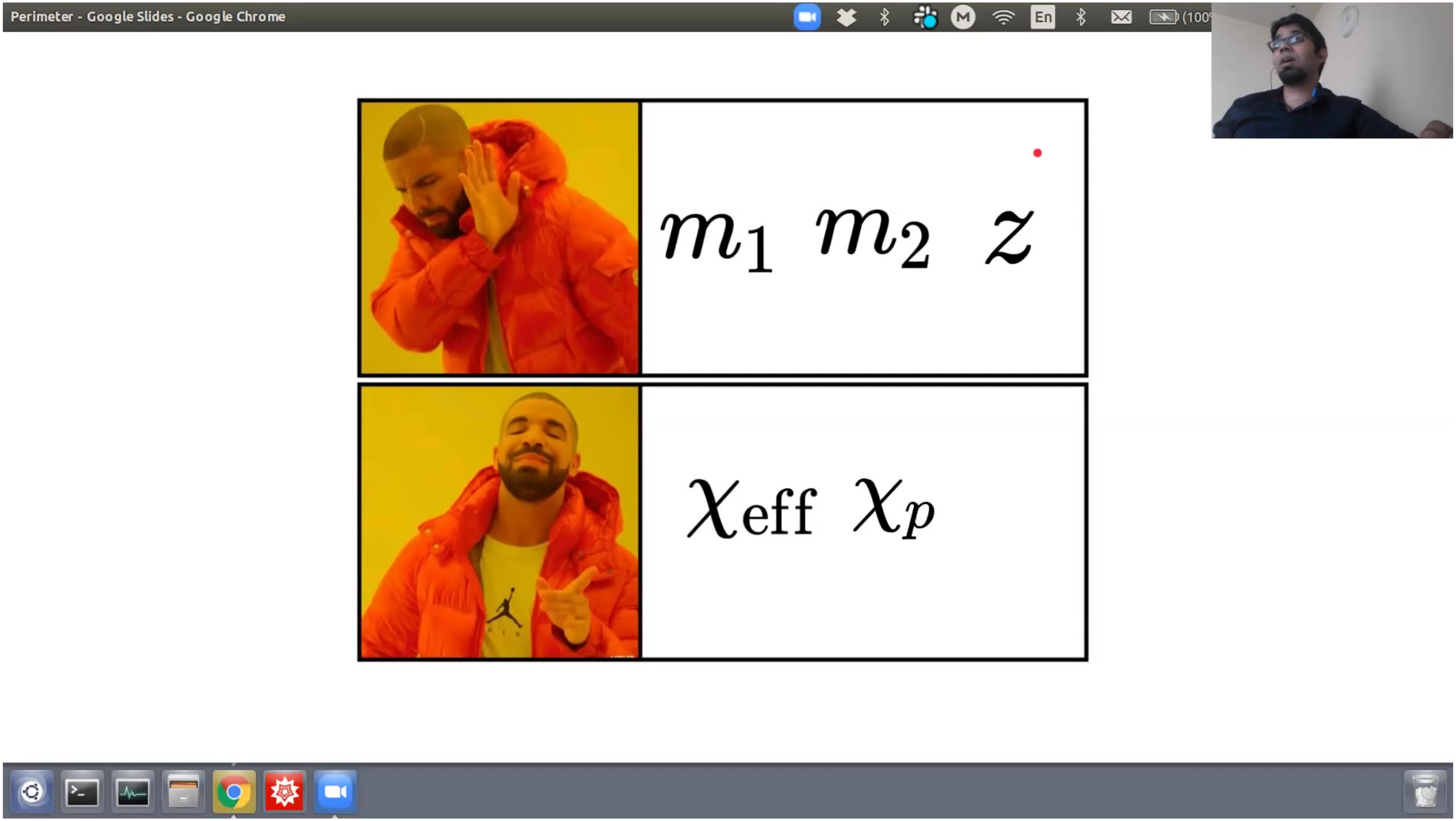


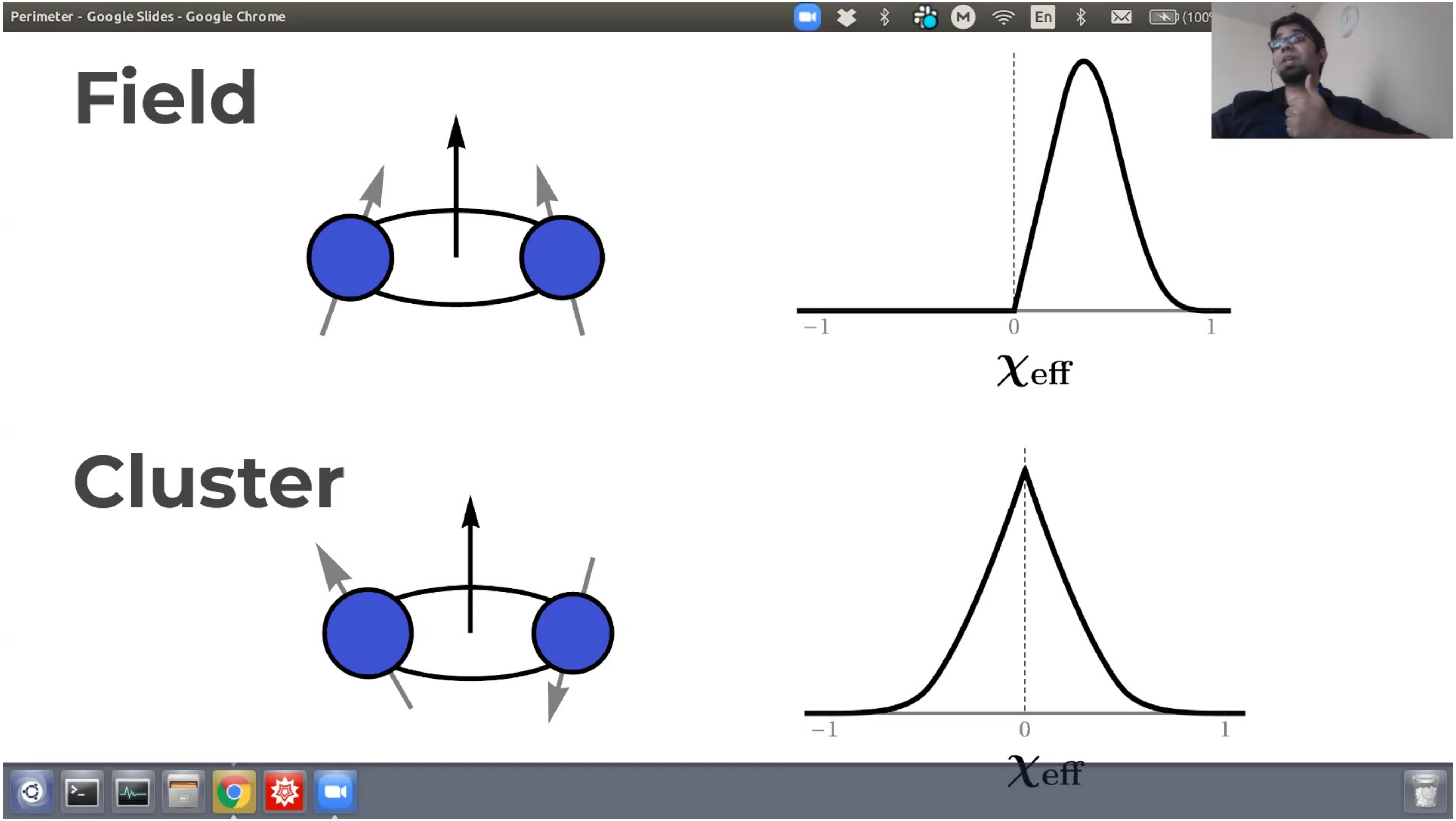
Field vs Cluster





GW Observables m_1 m_2 z χ_{eff} χ_p


Perimeter - Google Slides - Google Chrome
En
m_1 m_2 z
χ_{eff} χ_p


Perimeter - Google Slides - Google Chrome
Field
−1
0
1
χ_{eff}
Cluster
−1
0
1
χ_{eff}

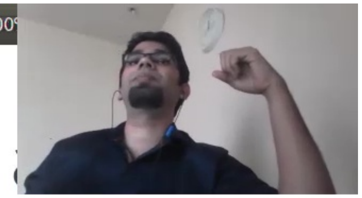
What if black holes have **no spins**?

Most Black Holes Are Born Very Slowly Rotating

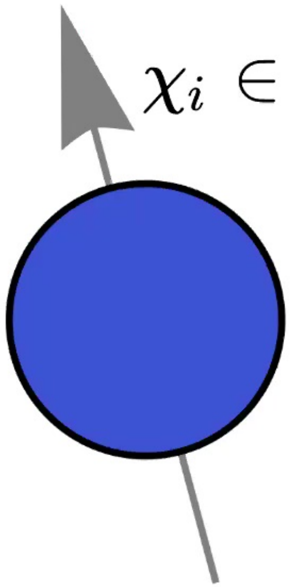
Jim Fuller[1] and Linhao Ma[1,2]

$$a \approx 10^{-2}$$

Perimeter - Google Slides - Google Chrome



Can’t measure spin directions if there no spins?

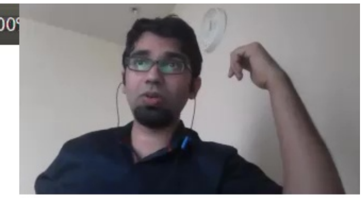


$$\chi_i \in U(0, \chi_{\max})$$

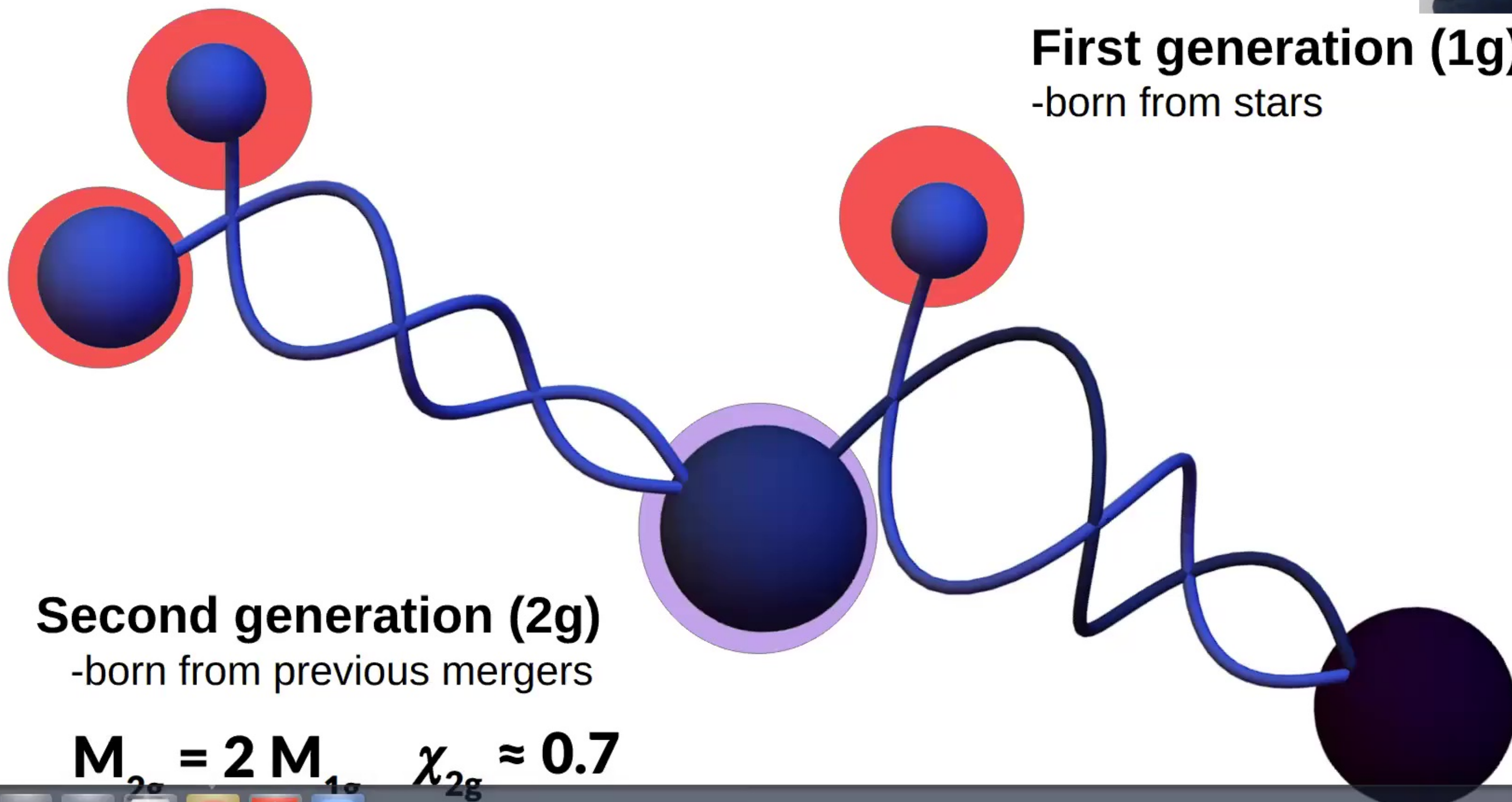
$$\delta f \sim \frac{\mathcal{O}(0.1)}{\chi_{\max}\sqrt{N}}$$

Mixing fraction

$\chi_{\max} = 0.01$ $\quad \delta f = 0.1$ $\quad N > 10^5$



Next generation of mergers

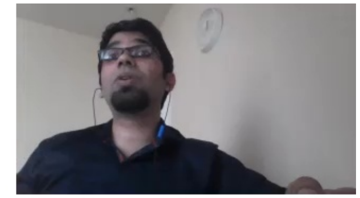


First generation (1g)
-born from stars

Second generation (2g)
-born from previous mergers

$M_{2g} = 2\,M_{1g} \quad \chi_{2g} \approx 0.7$

Next generation of mergers



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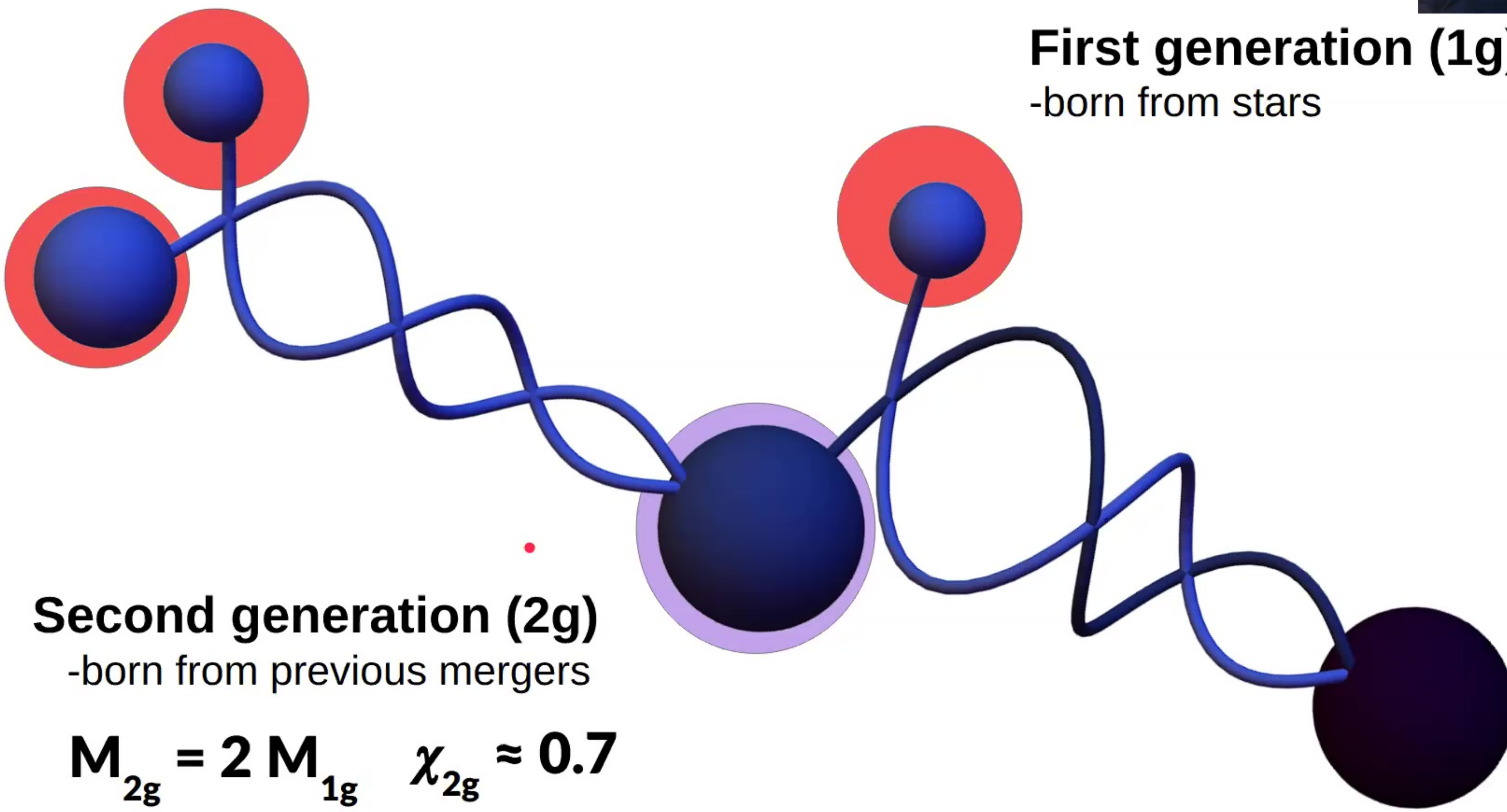

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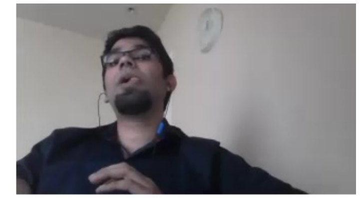
$M_{2g} = 2\,M_{1g} \quad \chi_{2g} \approx 0.7$



OUTLINE

How clusters form binary black holes?

> Forming a binary in a cluster
> Keeping a binary in the cluster

How events in the “gap” determine the mixing fraction?

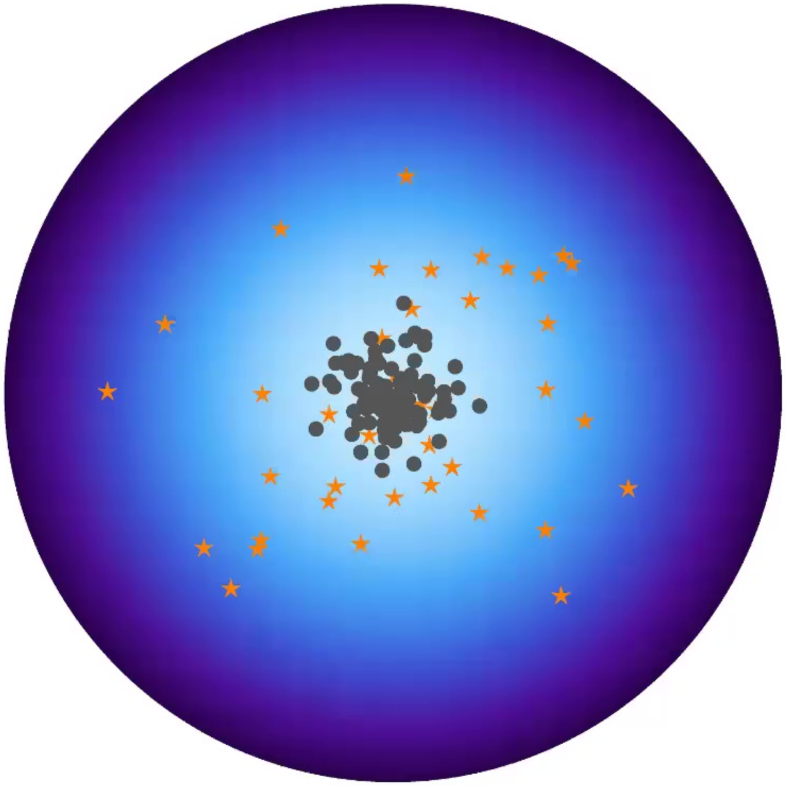
> Mass gap and Spin gap
> Finding the mixing fraction

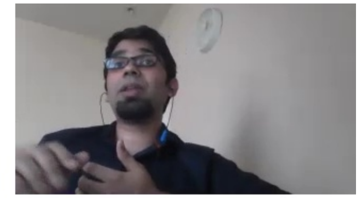
How clusters form binary black holes?

Forming a binary in a cluster

Mass segregation

$$t_{\rm MS} \sim 100\,{\rm Myr}\left(\frac{M_{\rm cl}}{10^7\,M_\odot}\right)^{1/2}$$





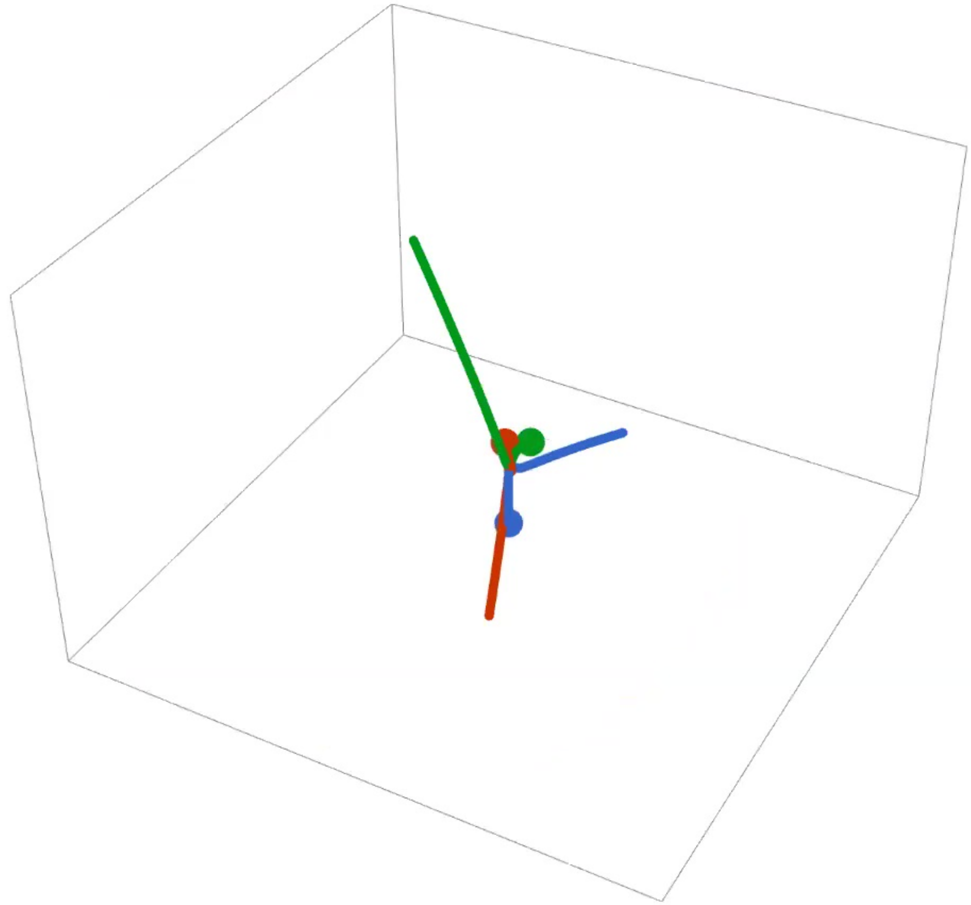
How clusters form binary black holes?

Forming a binary in a cluster

three body binary formation

BH + BH + BH ⟶ (BH-BH) + BH

$$t_{3\mathrm{bb}} \propto n^{-2} v^{9}$$



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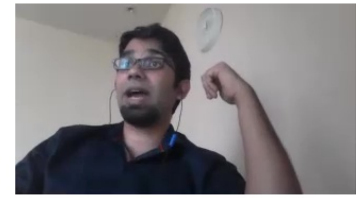

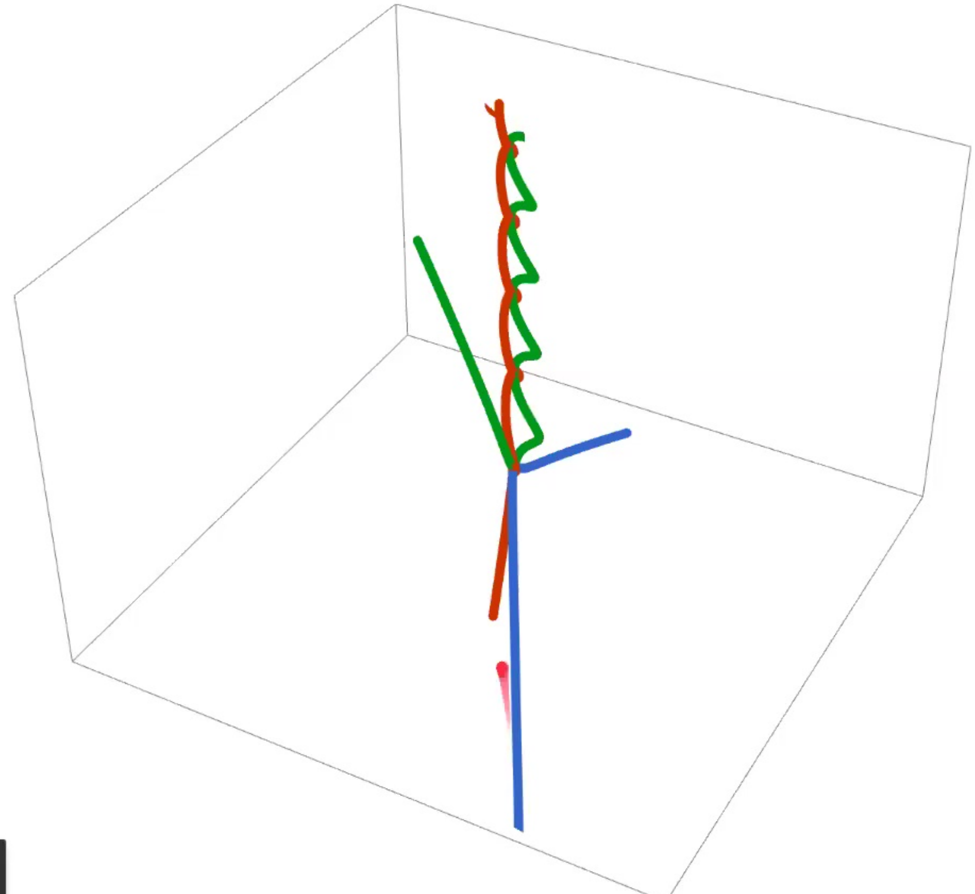

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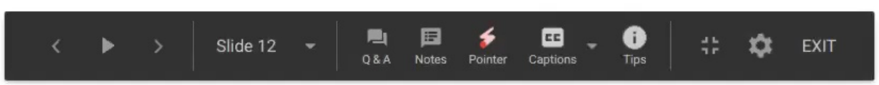

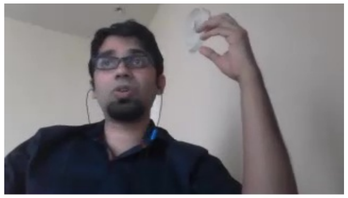

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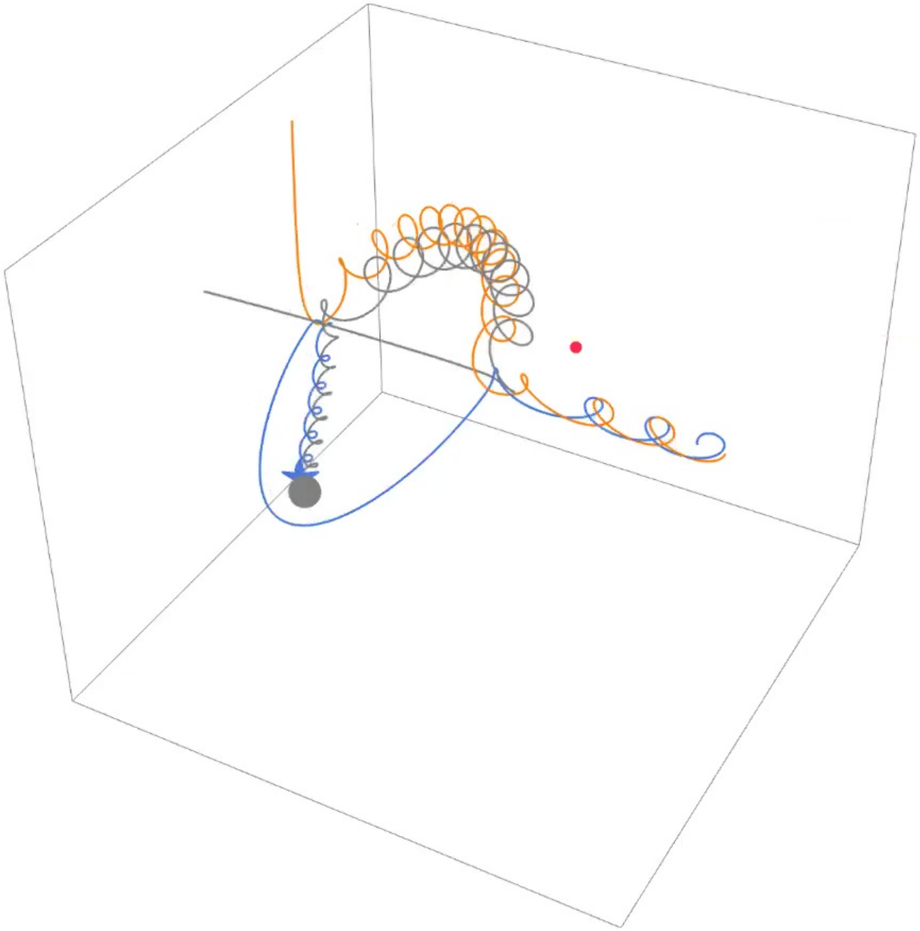
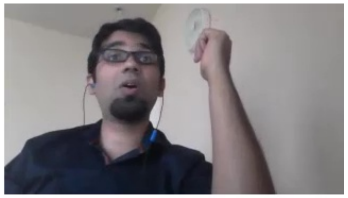


binary-single exchanges

BH + (Star-Star) ⟶ (BH-Star) + Star
BH + (BH - Star) ⟶ (BH-BH) + Star

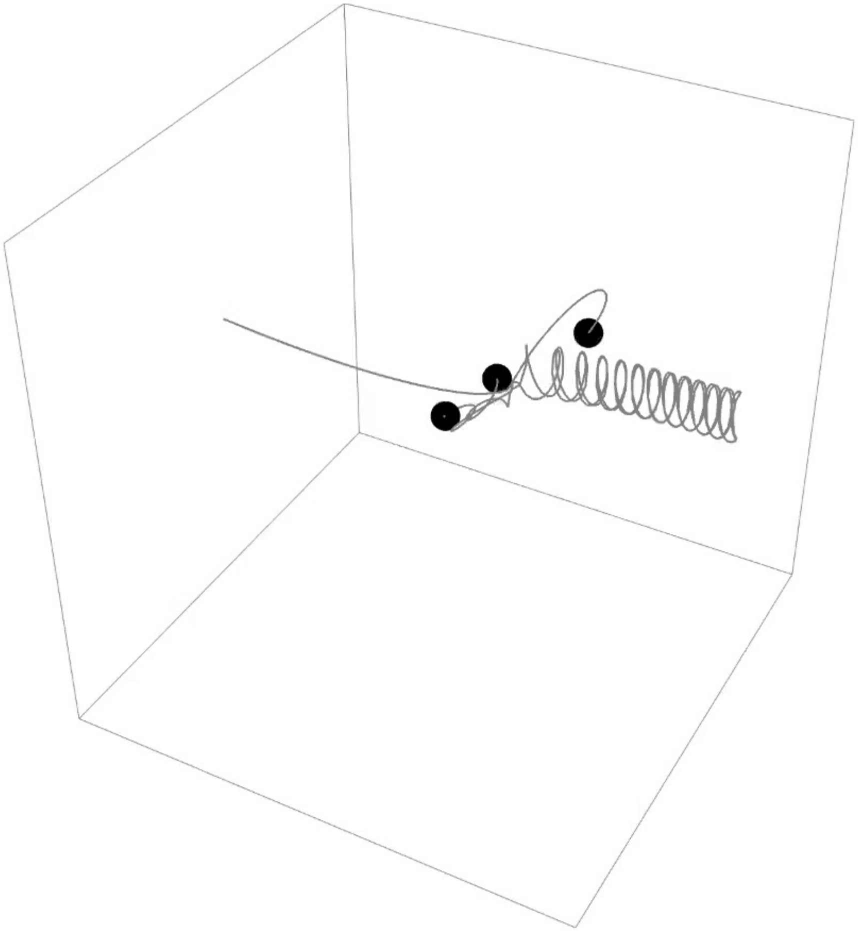
$$t_{1-2} \propto n^{-1} f^{-1} v$$



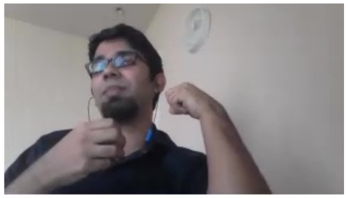
How clusters form binary black holes?

Hardening a binary

BH + (BH---BH) = BH + (BH-BH)



$$t_{\mathrm{GW}} \sim 10^{12}\,\mathrm{yr}\left(\frac{a}{1\,\mathrm{AU}}\right)^4$$



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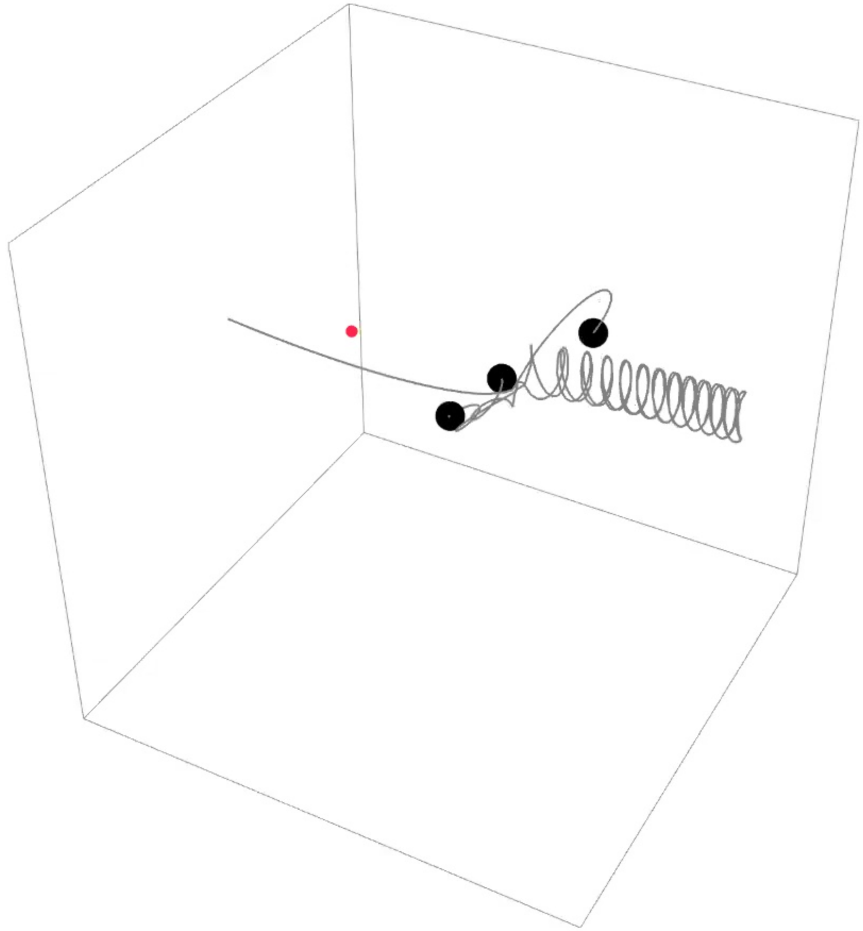
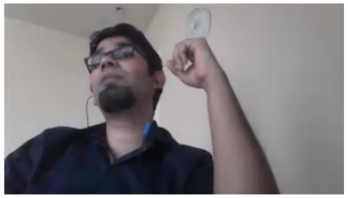




How clusters form binary black holes?

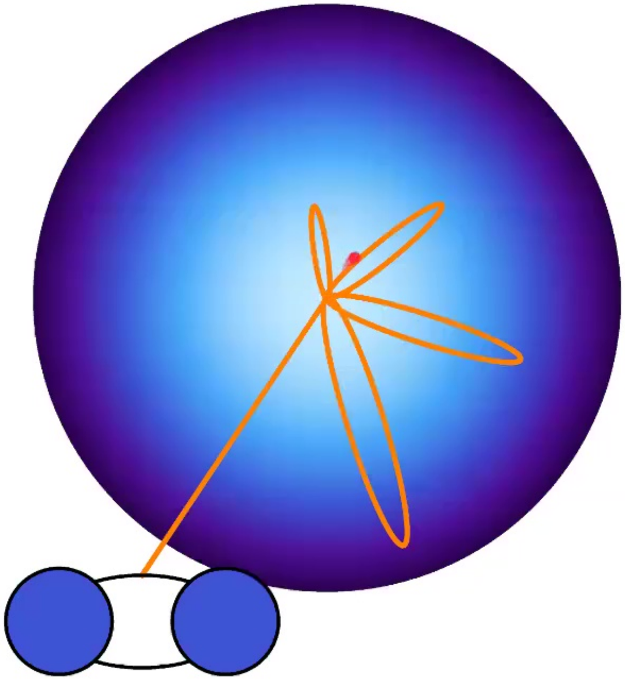
Keeping a binary in the cluster

If binary hardens to semimajor axis: a

$$v_{\mathrm{kick}} \propto \frac{1}{\sqrt{a}}$$

Ejected if

$$v_{\mathrm{kick}} > v_{\mathrm{esc}}$$



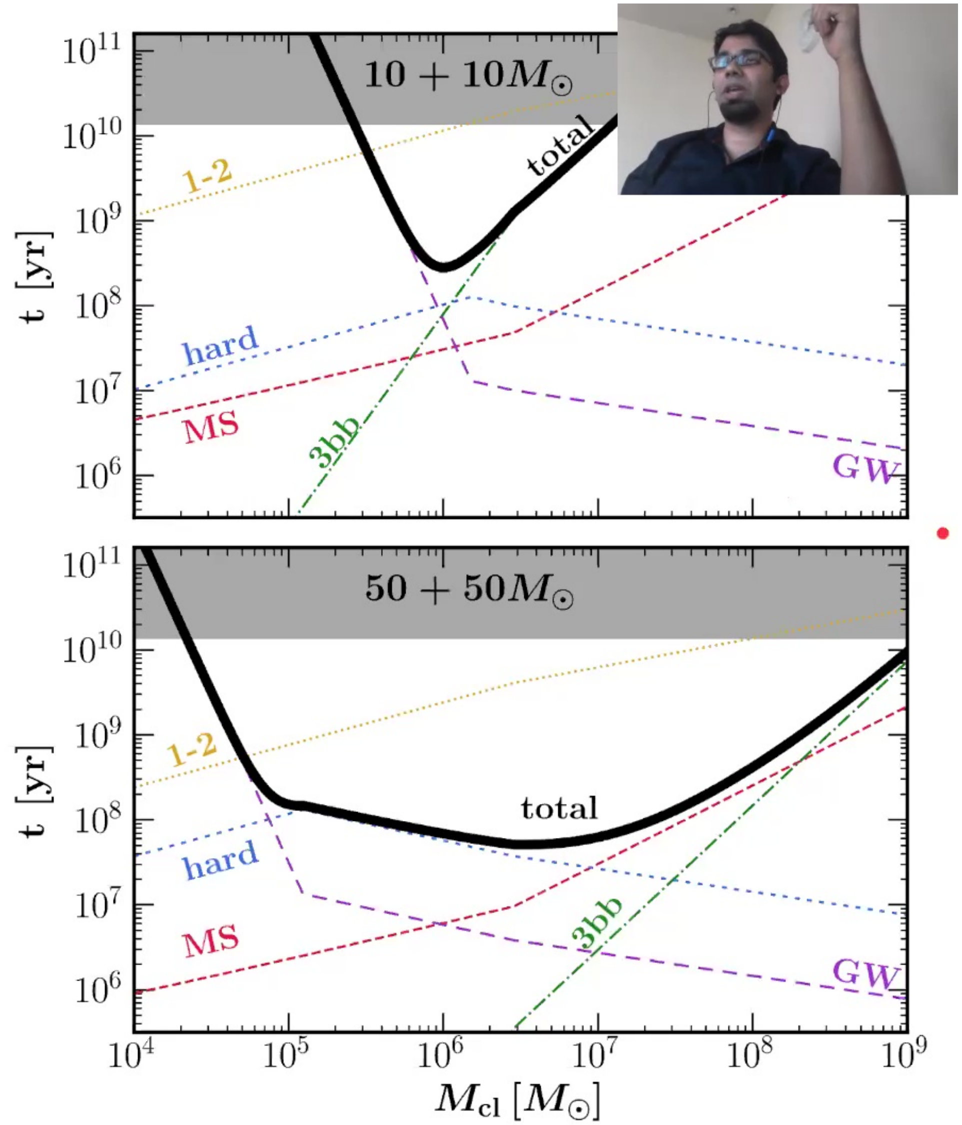
Clusters that form and merge BHs

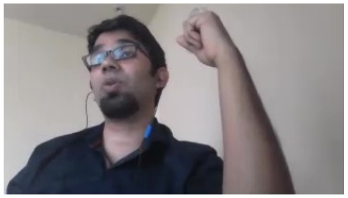
Mass segregation

Binary formation: slow in large clusters
Three body (Dominant)
Binary single

Hardening

Gravitational Waves: slow in small clusters





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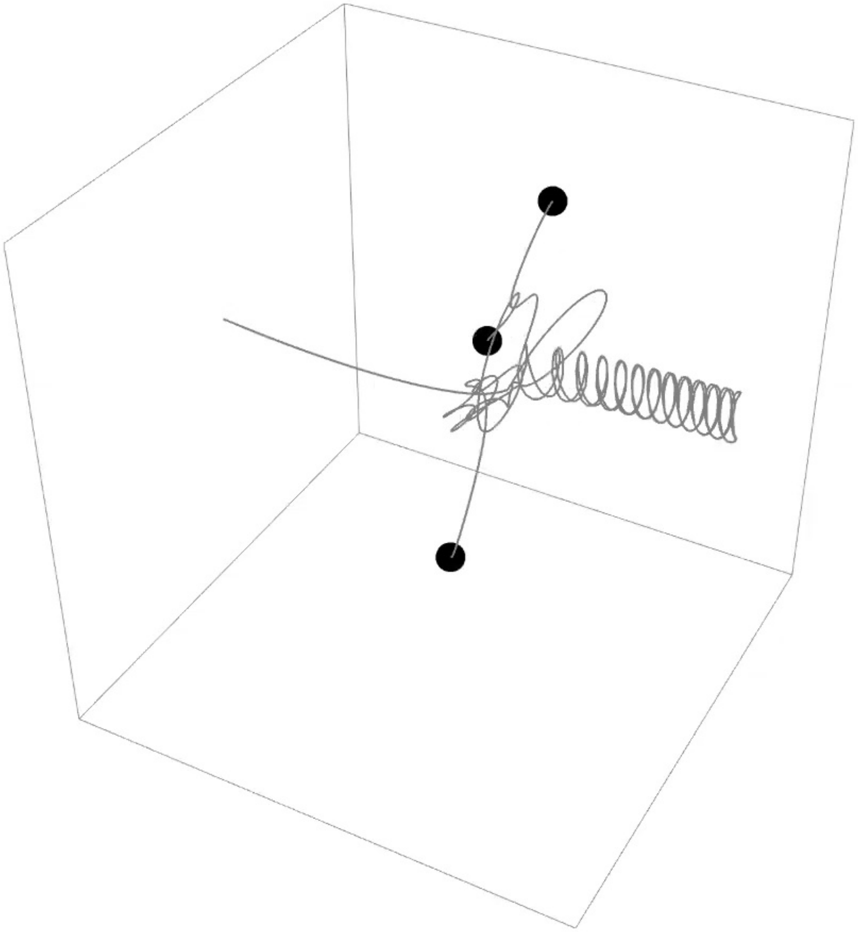

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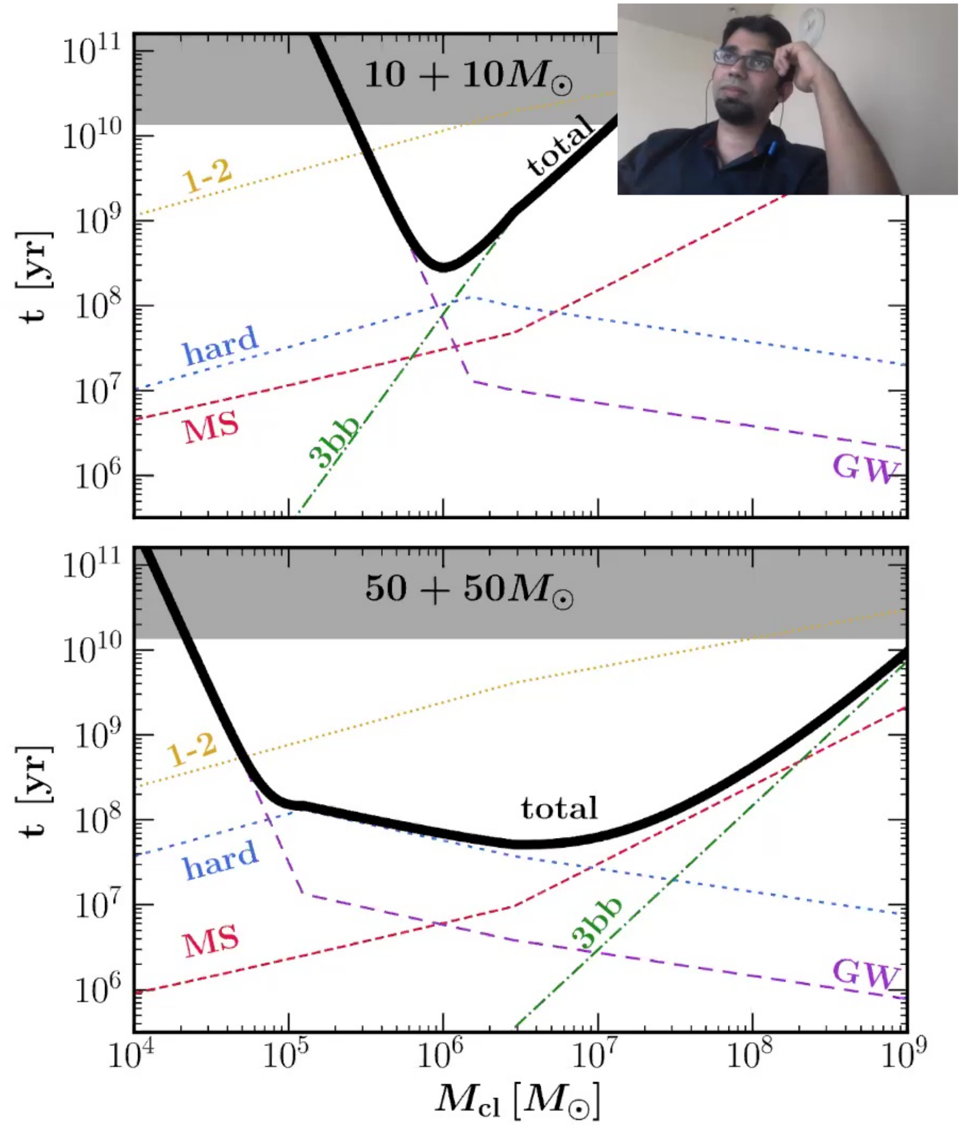

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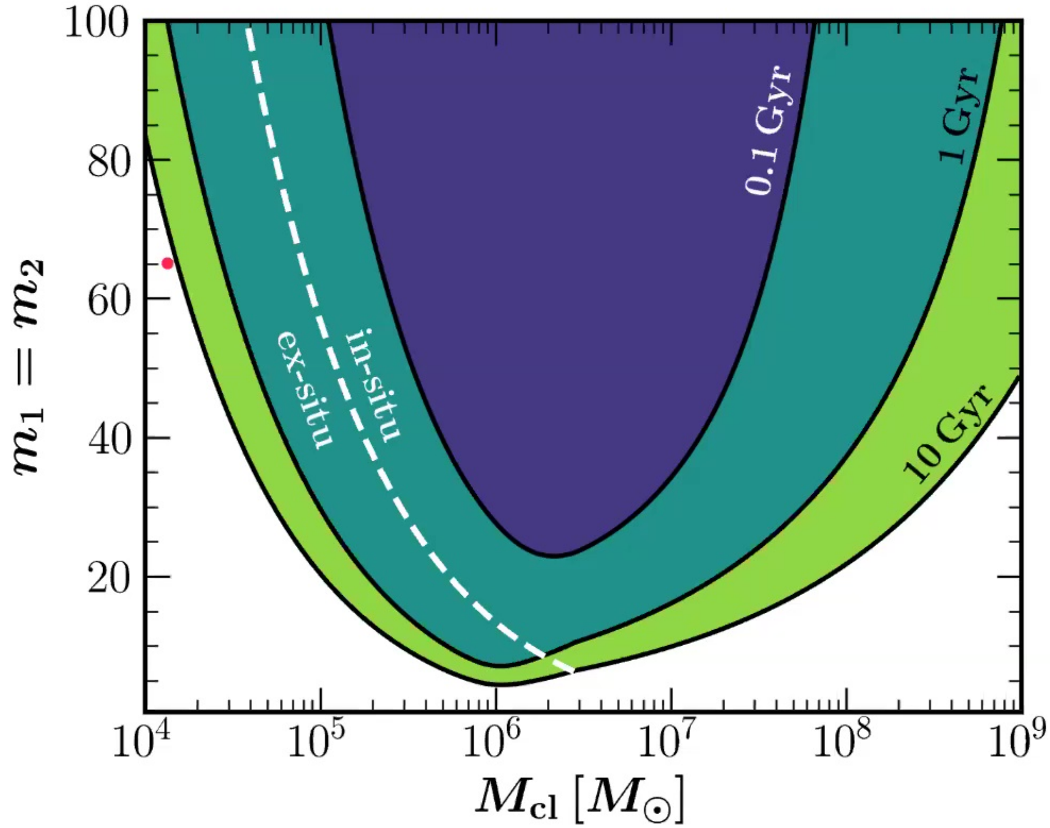
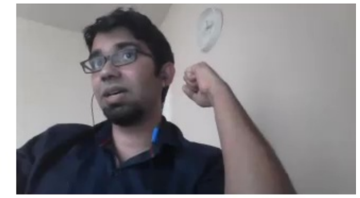
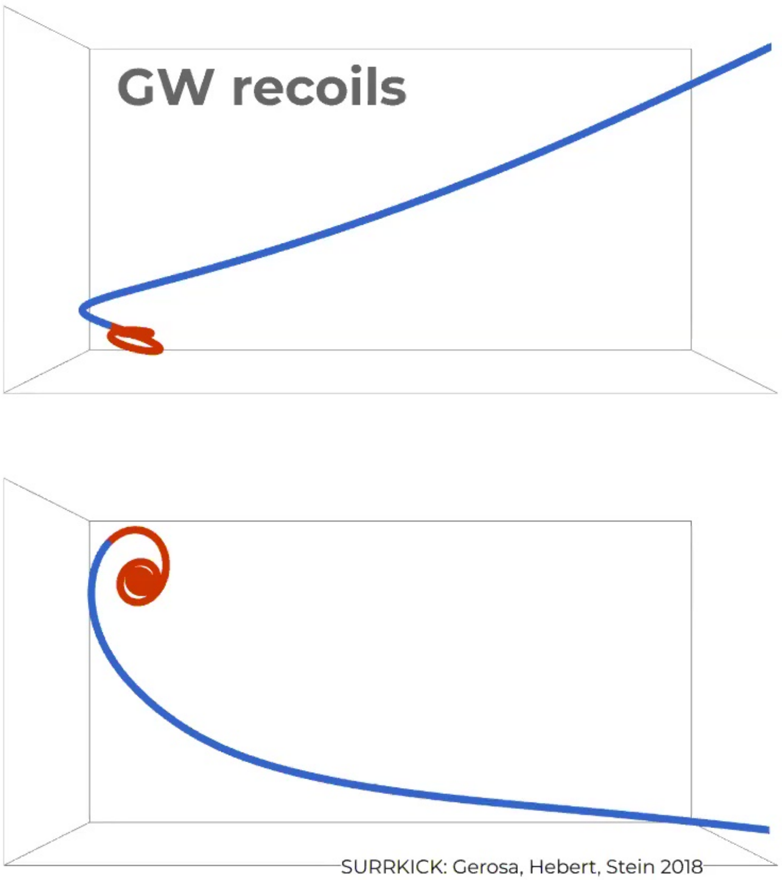
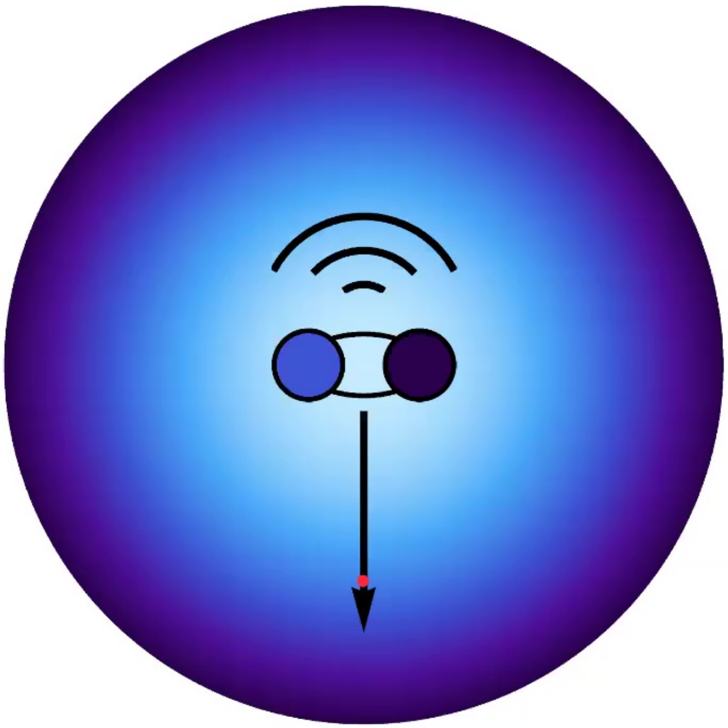




How clusters form binary black holes?

Keeping a binary in the cluster





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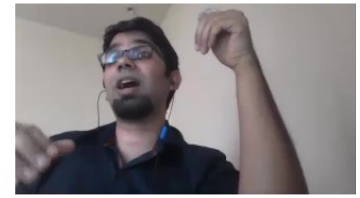
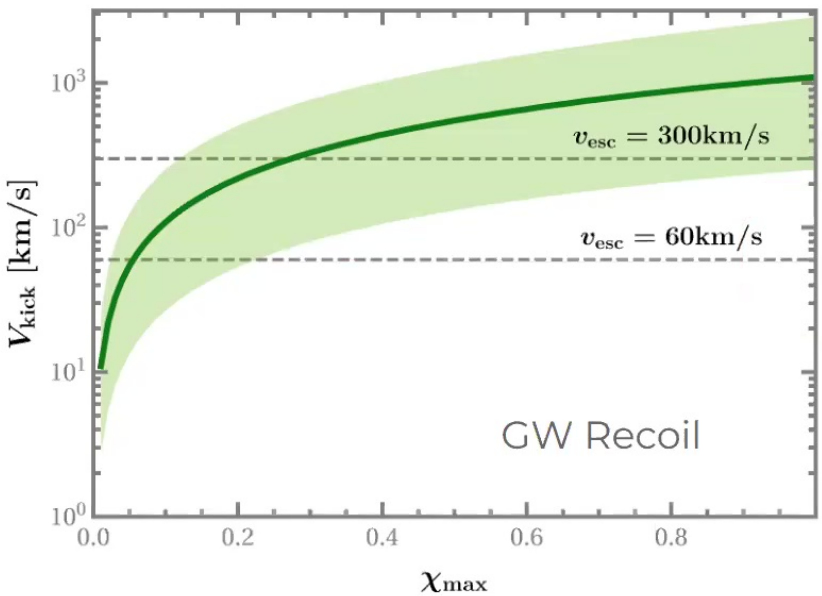
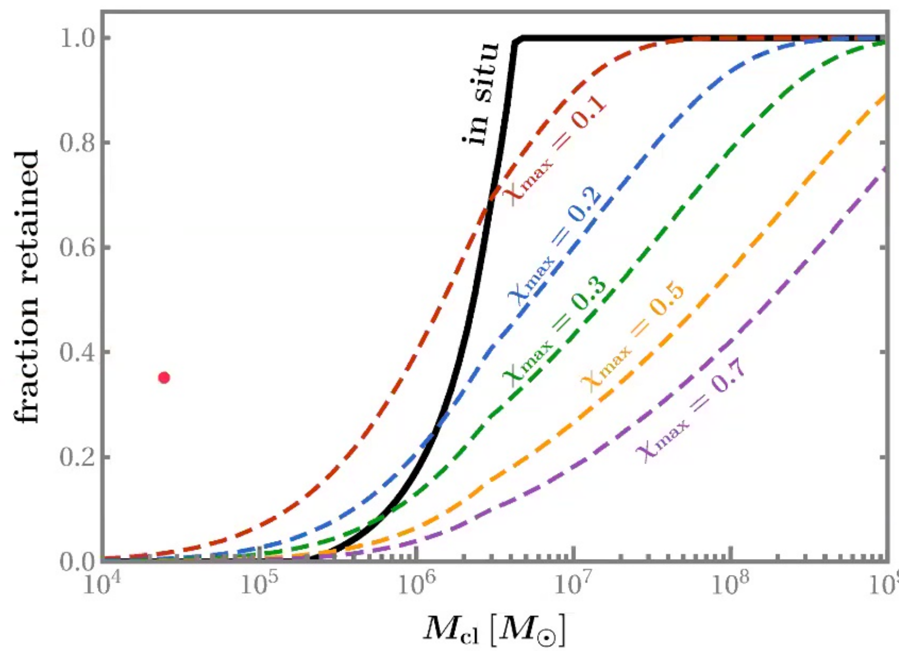
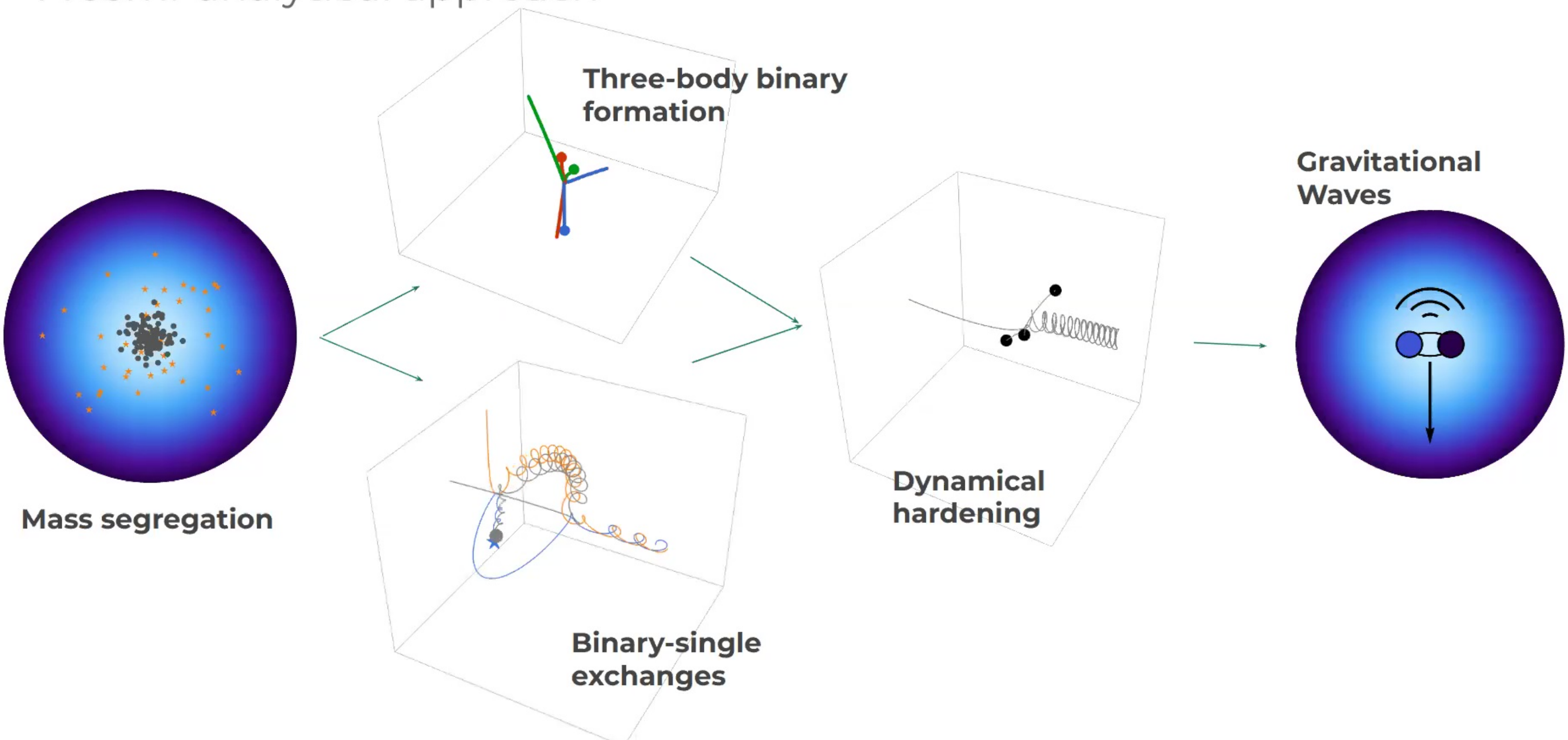






How clusters form and merge binary black holes

A semi-analytical approach



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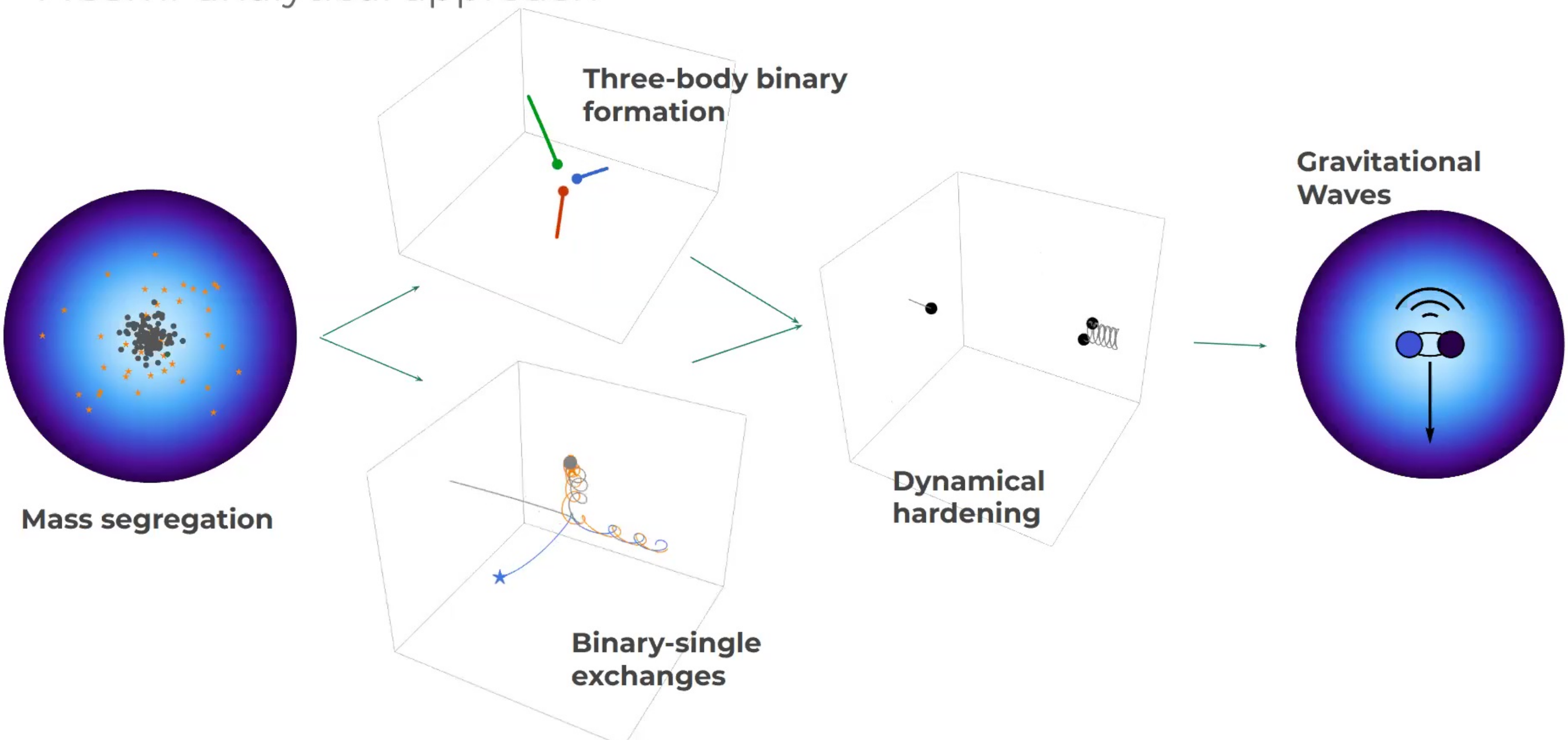

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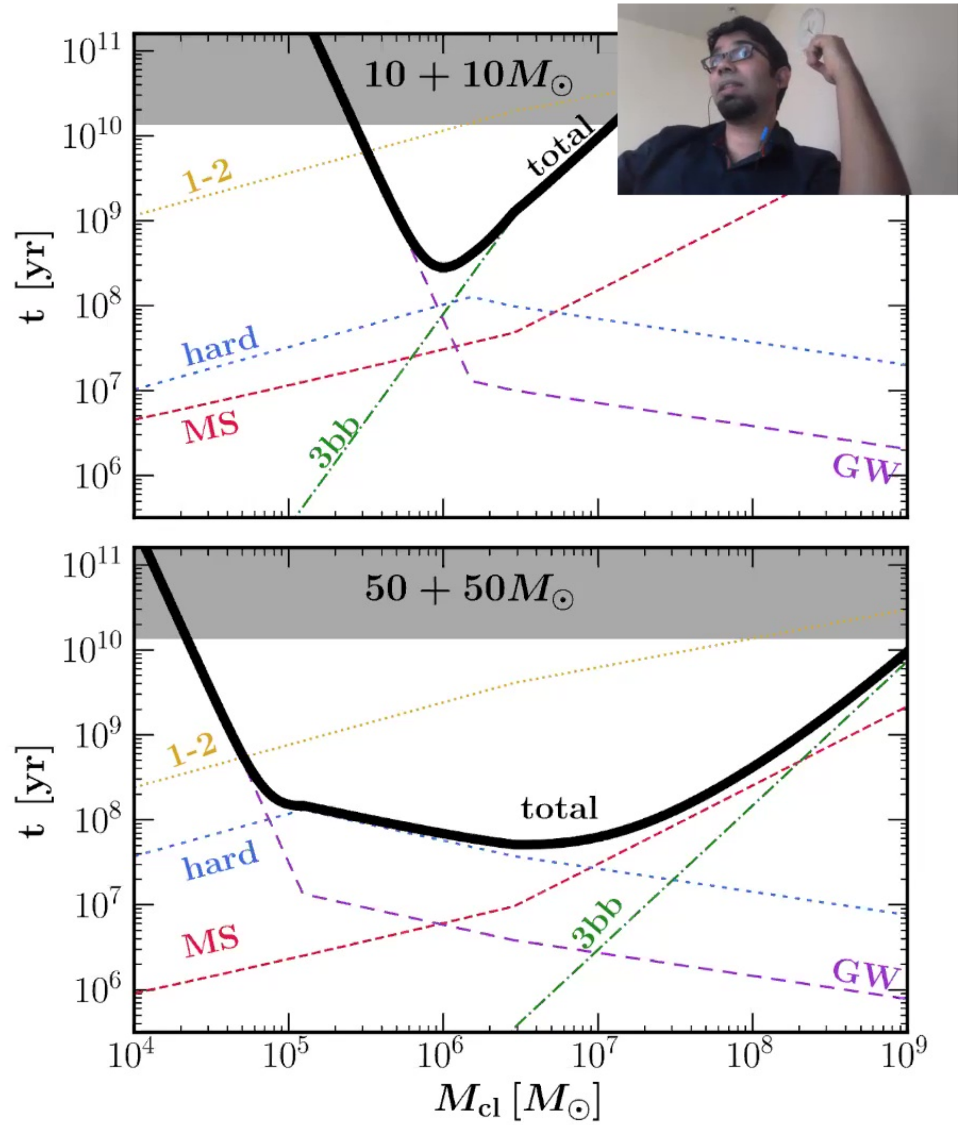

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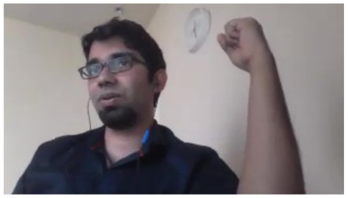

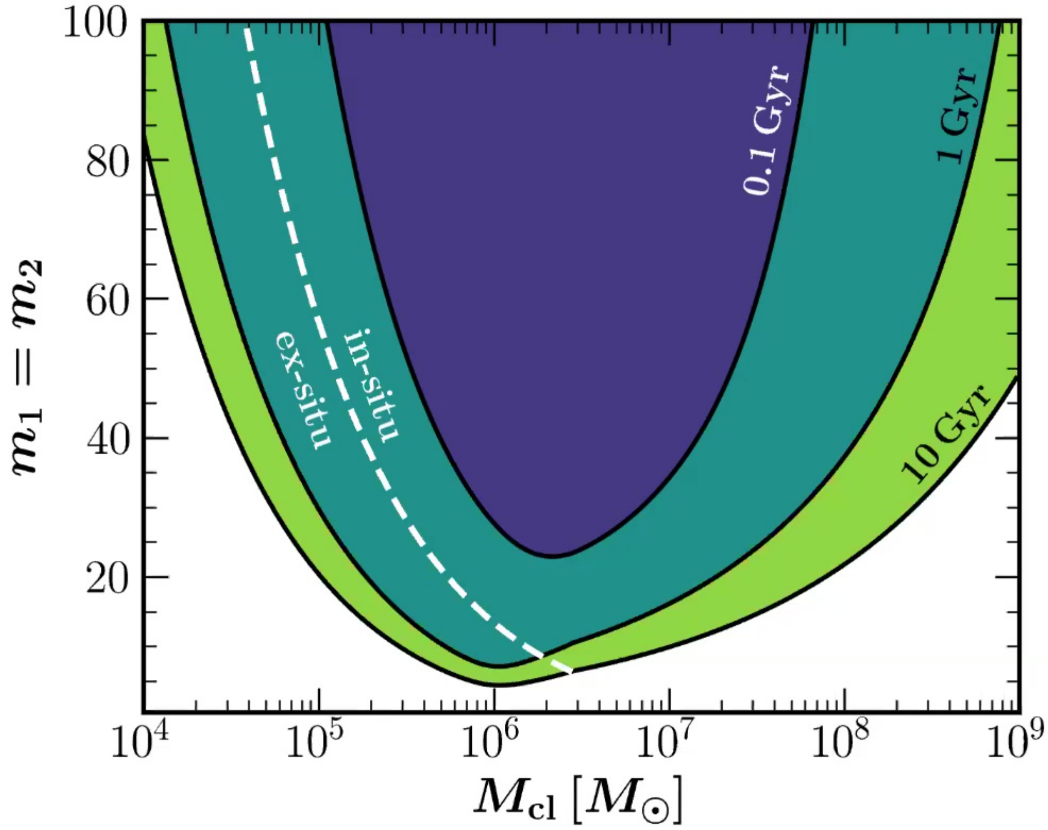

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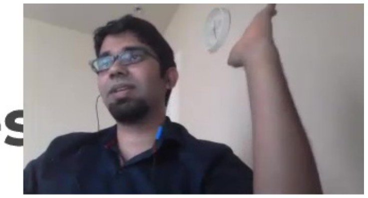
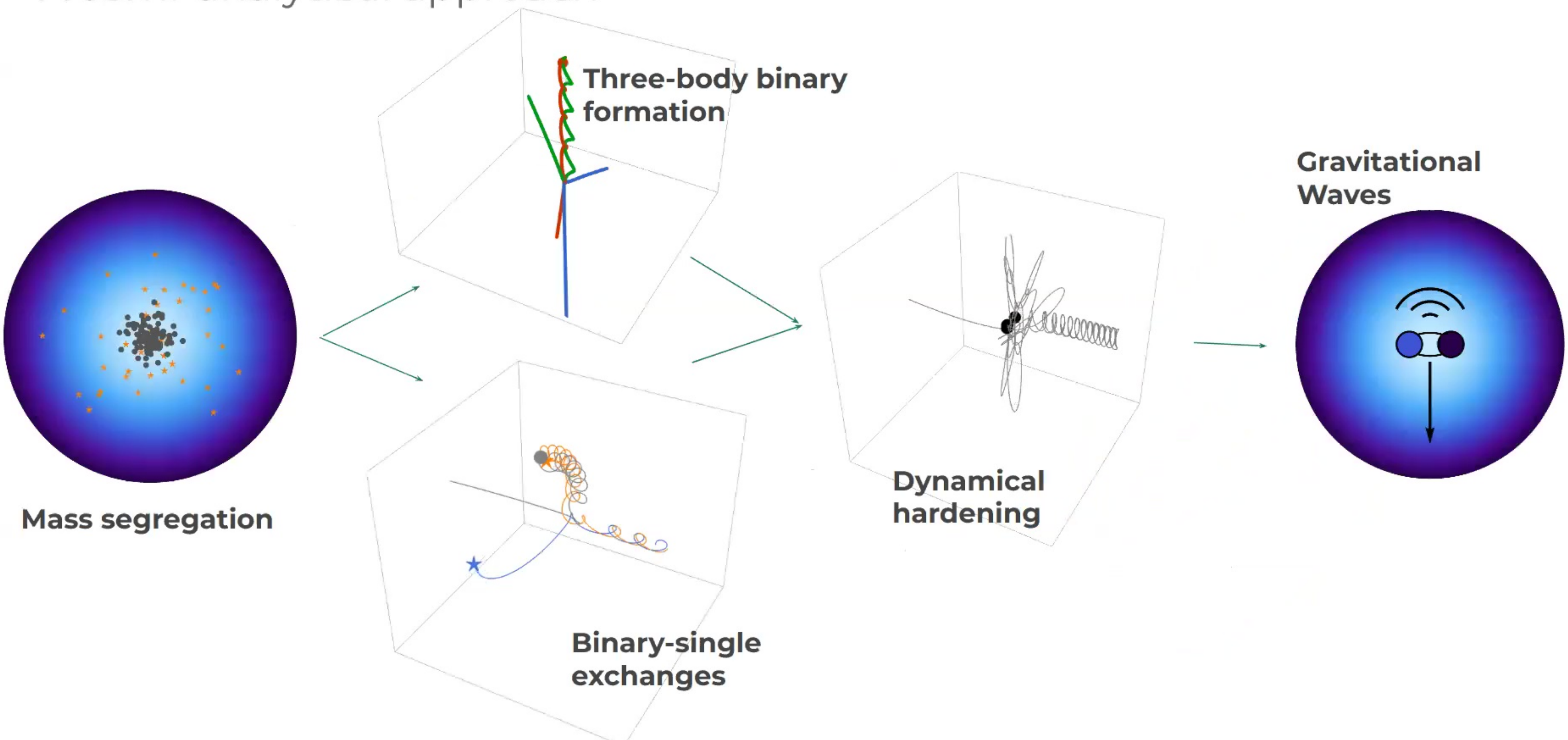
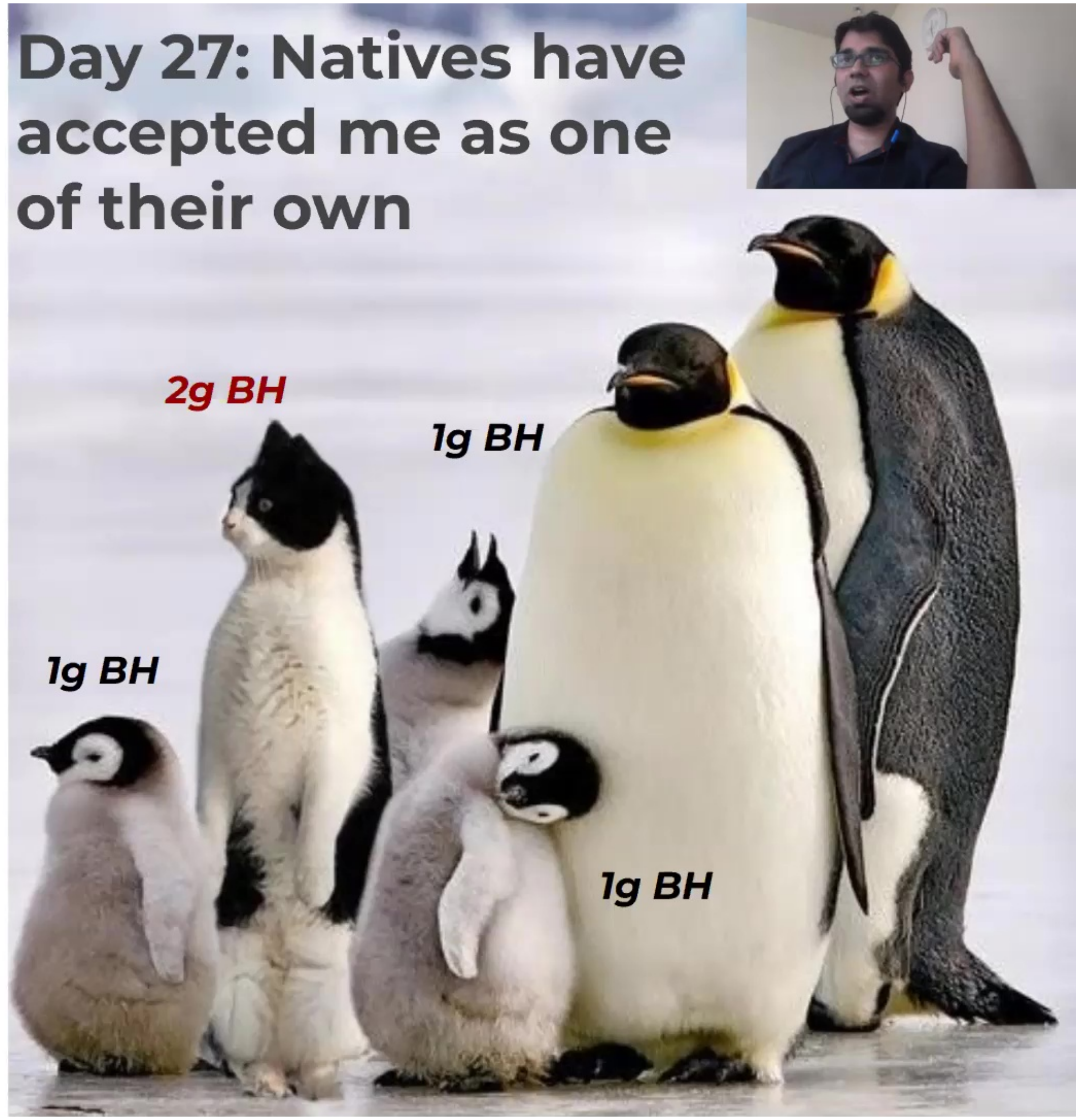




Finding 2g black holes in our midst



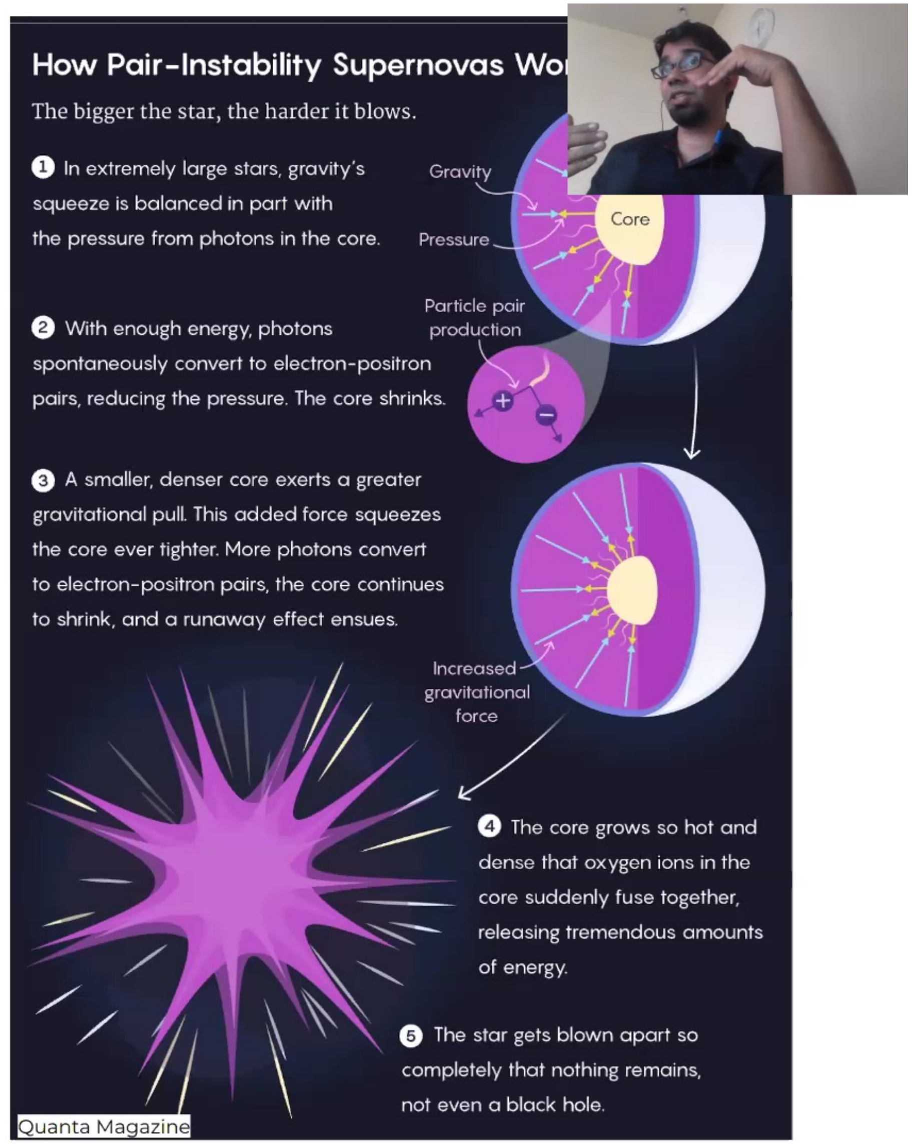
The Mass Gap

$$\gamma + \gamma \rightarrow e^- + e^+$$

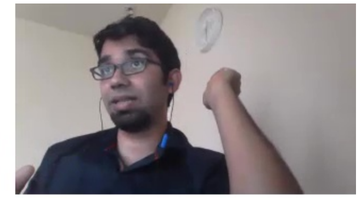
Pulsational pair-instability supernovae
100-130 $M_\odot$

Pair-instability supernovae
130-250 $M_\odot$

Upper limits on BH masses: 45-65+ $M_\odot$

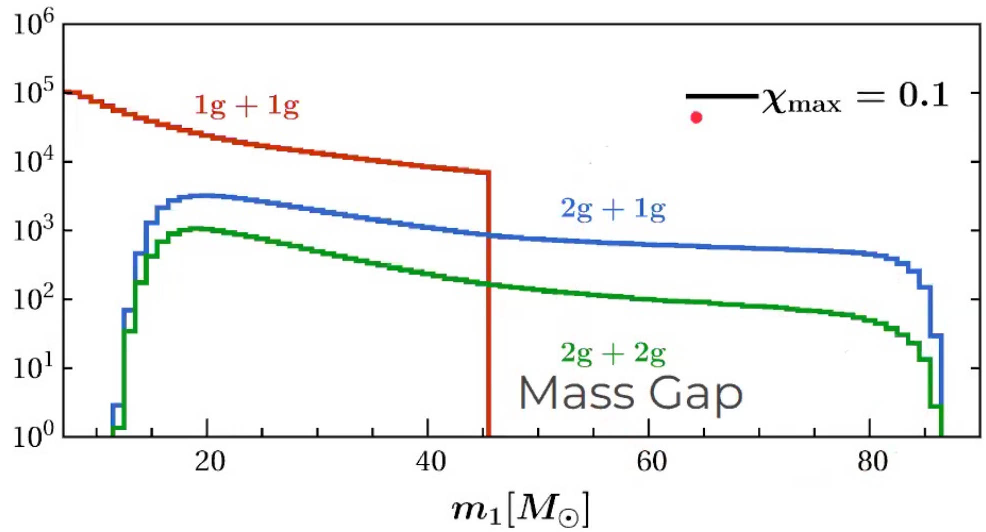


Repeated Mergers fill the Gaps



Mass gap exists due to PISN and PPISN

2g mergers fill the gap



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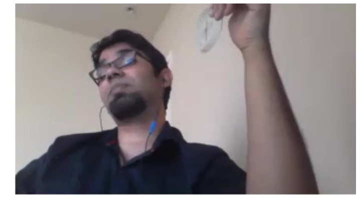
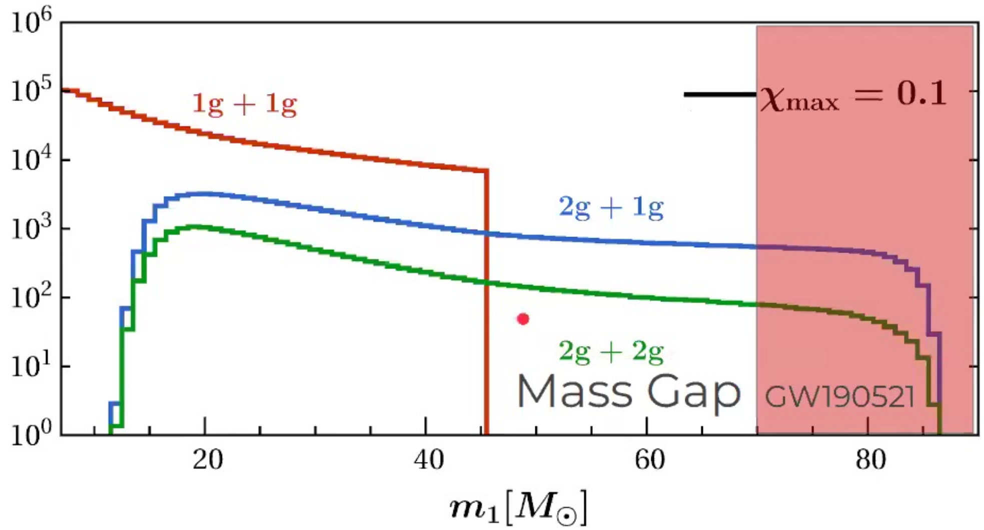


Mass gap exists due to PISN and PPISN

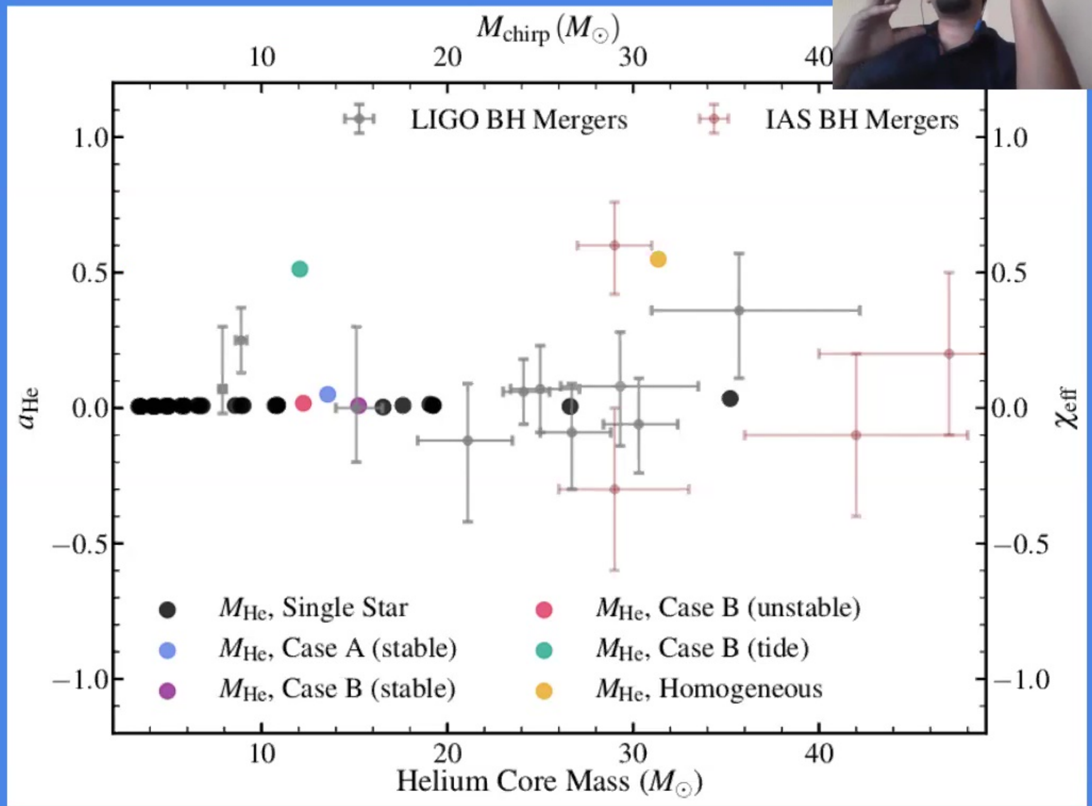
2g mergers fill the gap

GW190521 is in the gap, and hence a 2g merger



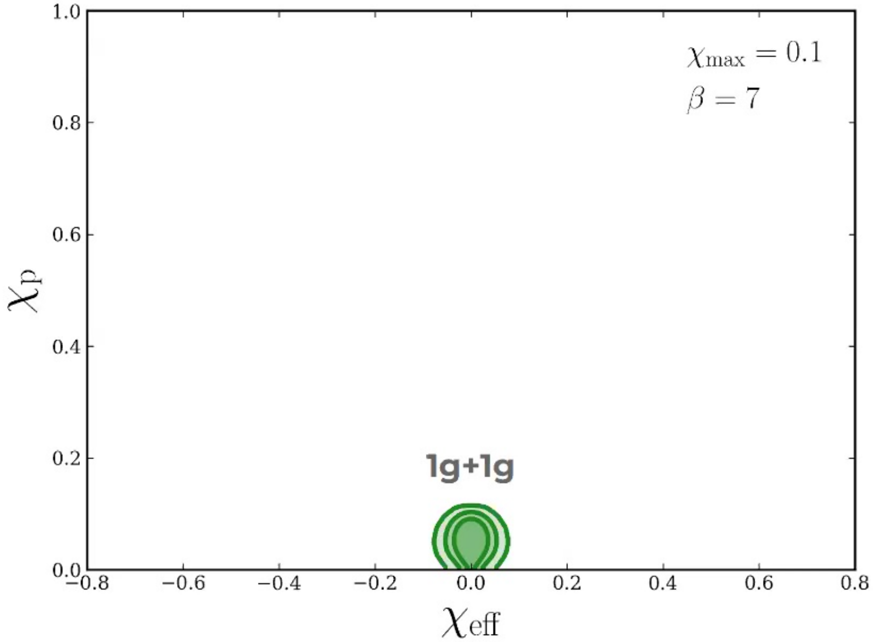
The Spin Gap

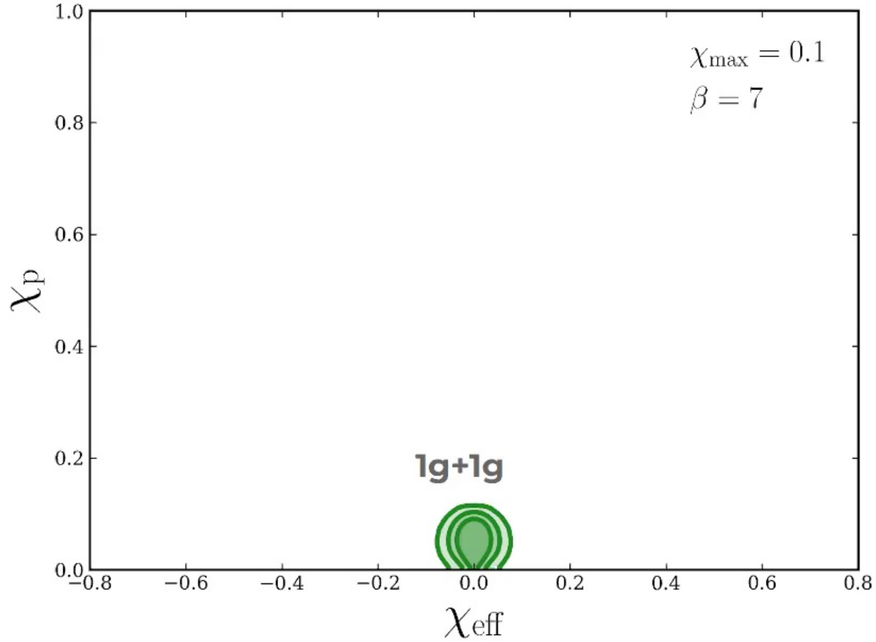
$$a \sim 10^{-2}$$



Fuller, Ma 2019

Repeated Mergers can fill the SPIN GAP





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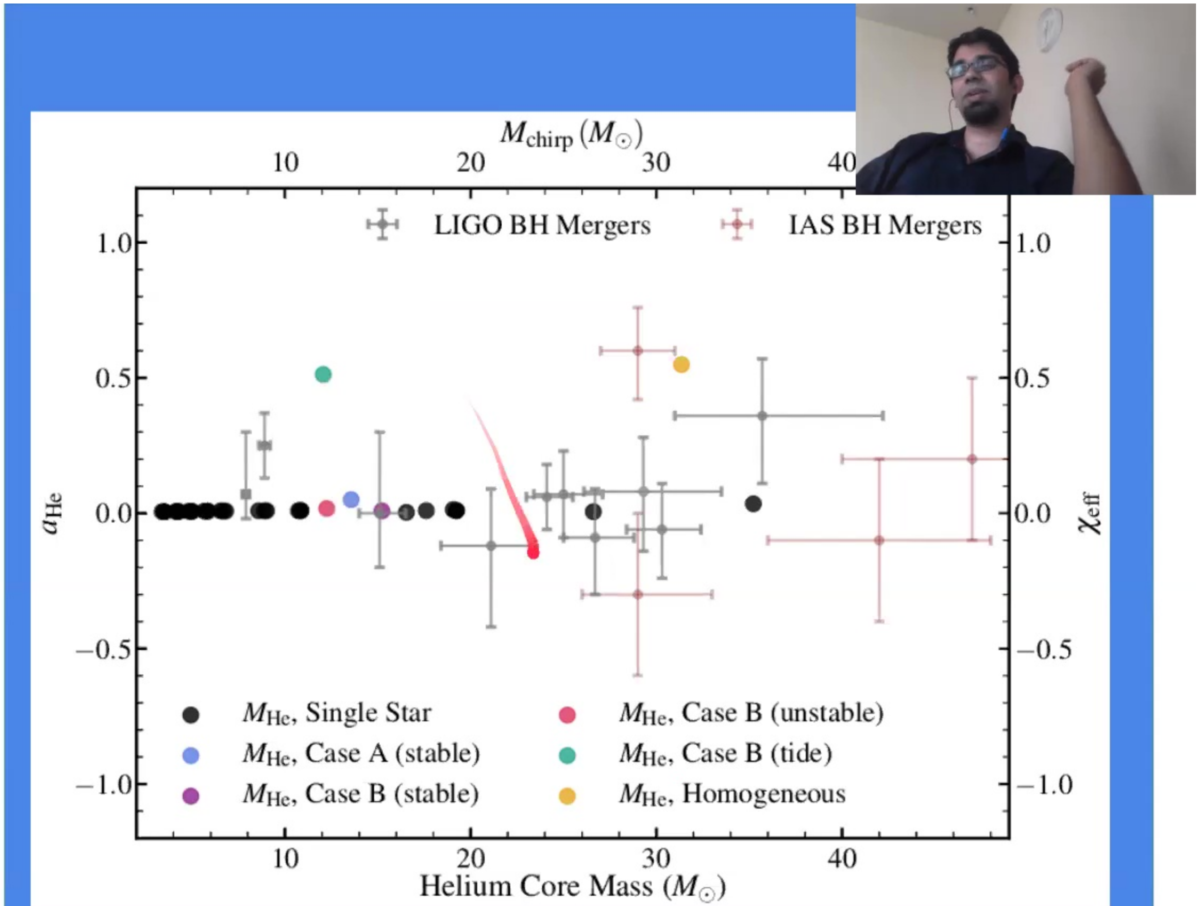
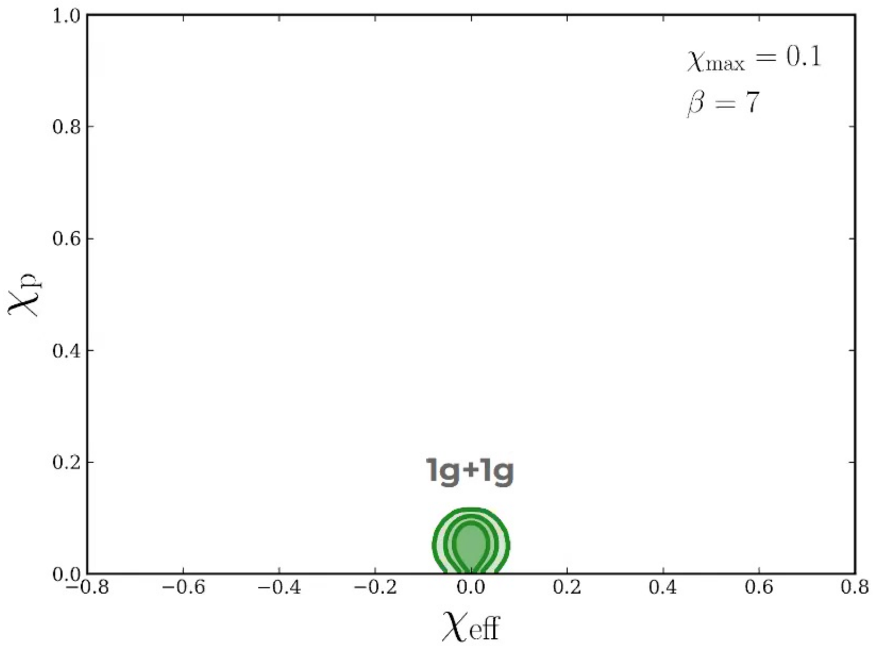
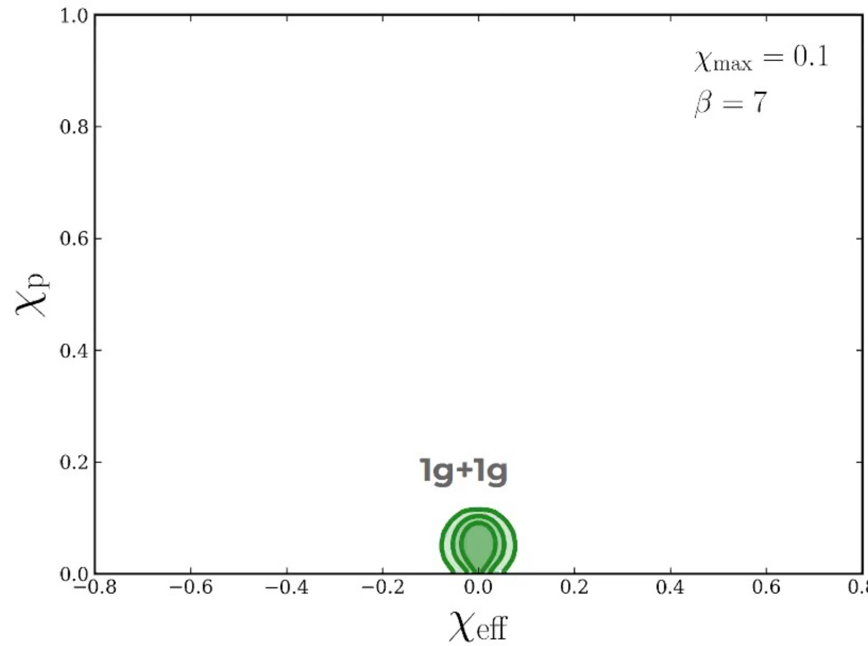


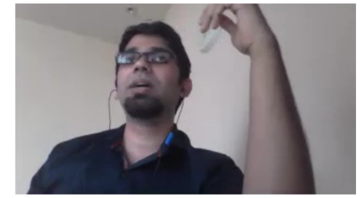
Fuller, Ma 2019

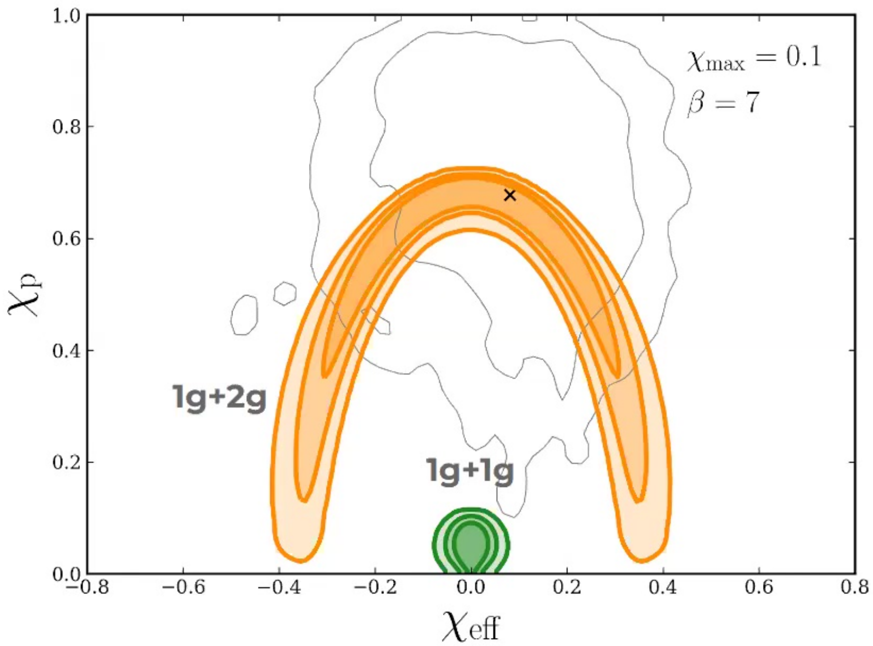
Repeated Mergers can **fill the SPIN GAP**



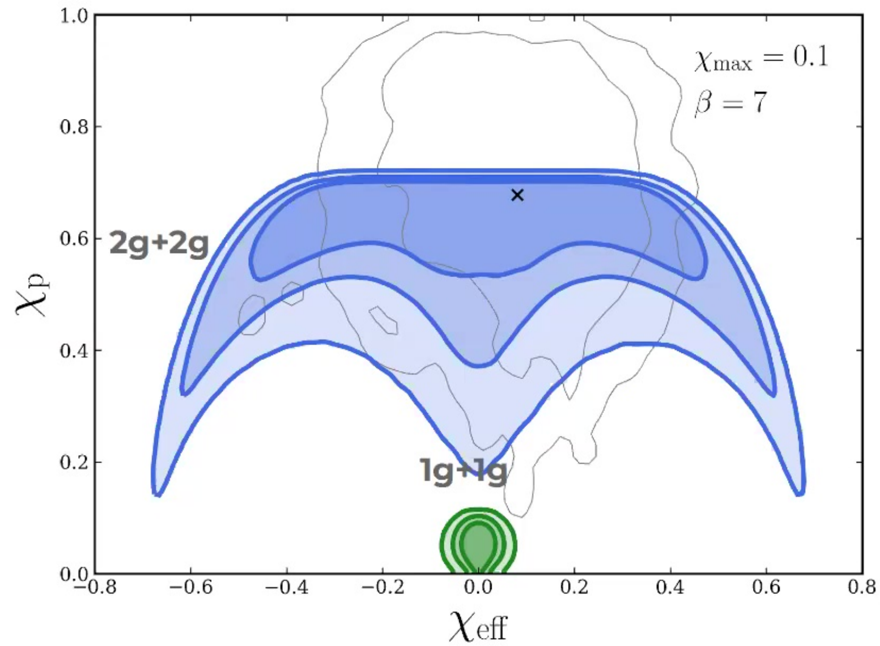


Repeated Mergers can fill the SPIN GAP



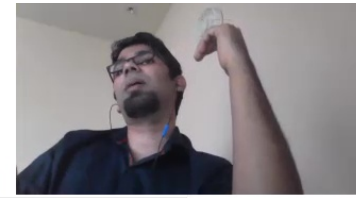


1g+2g



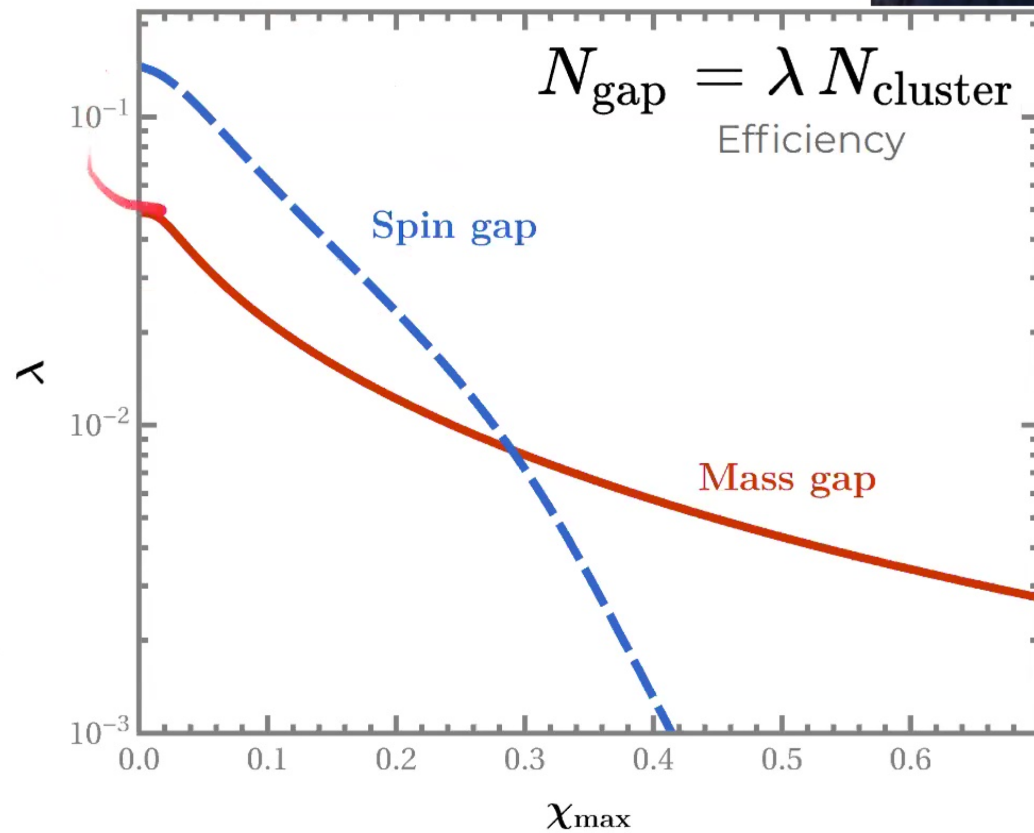
2g+2g

Filling the Gaps

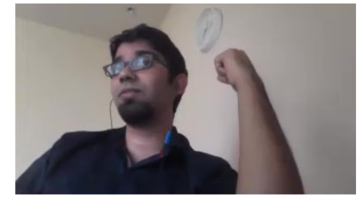


Mass Gap
Pair-instability supernova
Pulsational pair-instability supernova
40-55+ $M_\odot$

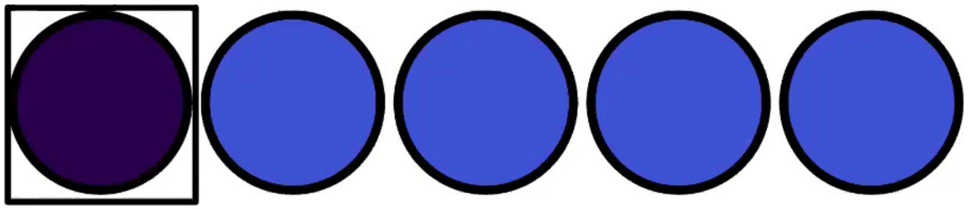
Spin Gap
Efficient angular-momentum transport



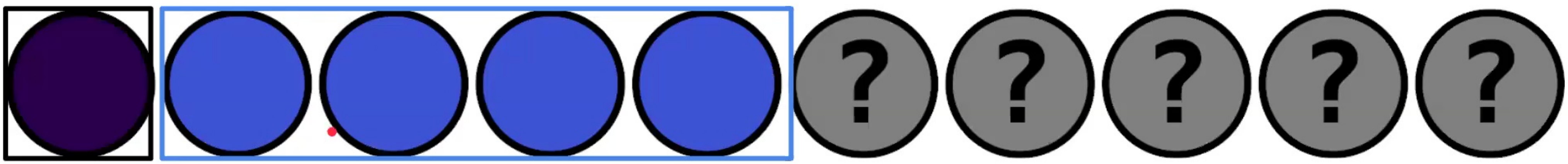
Finding the mixing fraction with “gap” events



Gap Efficiency, λ = 20%

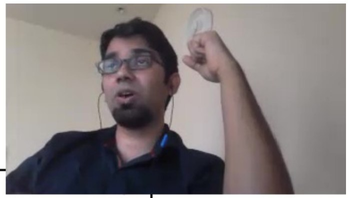


Gap events = 1



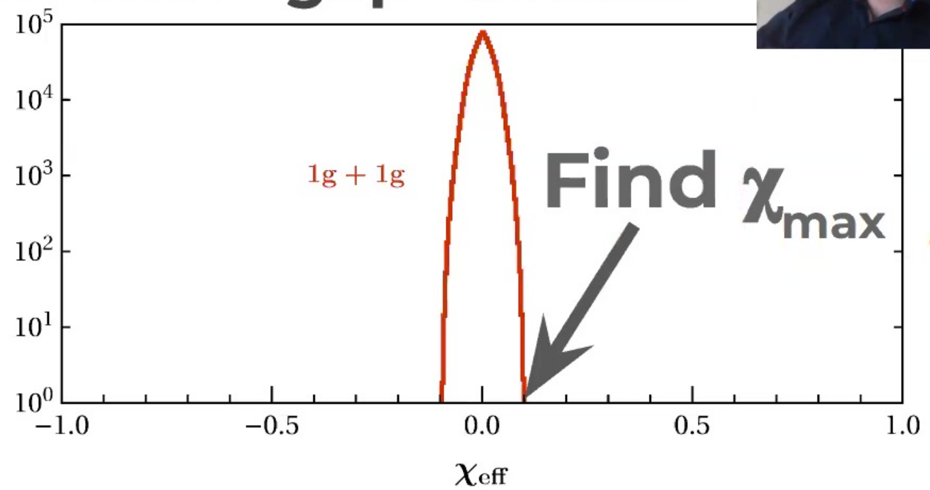
Cluster binaries = 5

Finding the mixing fraction with "gap" events

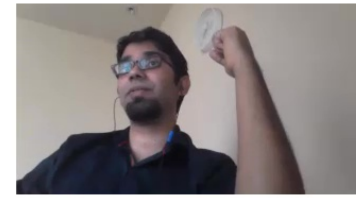


Step 1

Find parameters of 1g population: χ_{max}

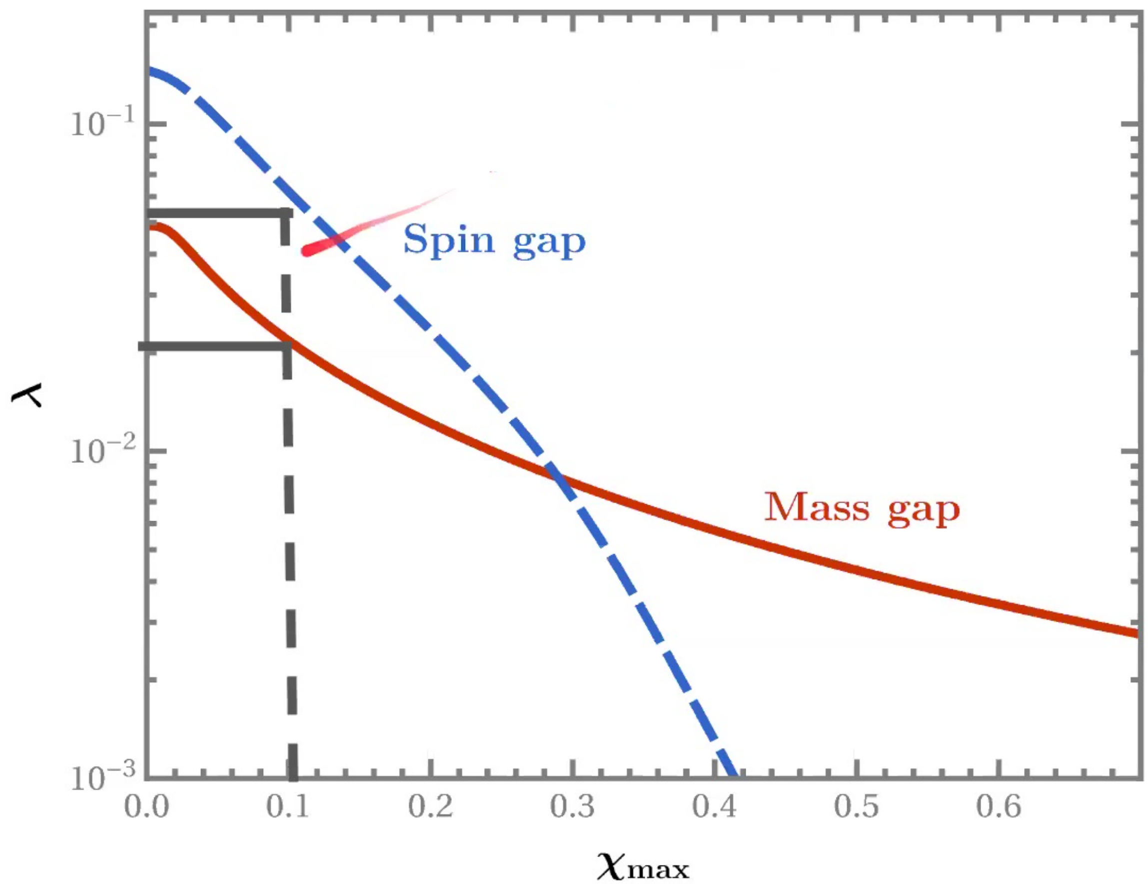


Finding the mixing fraction with "gap" events

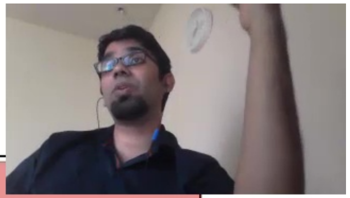


Step 1
Find parameters of 1g population: χ_{max}

Step 2
Find efficiency: λ



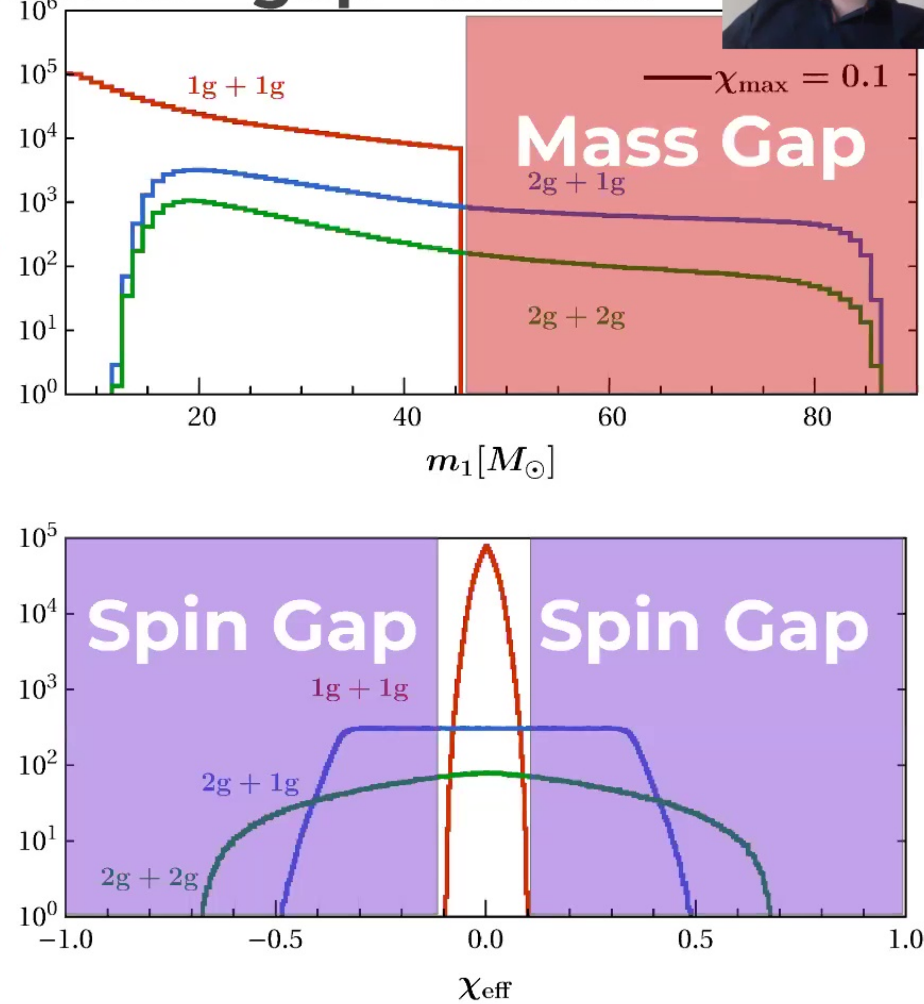
Finding the mixing fraction with "gap" events



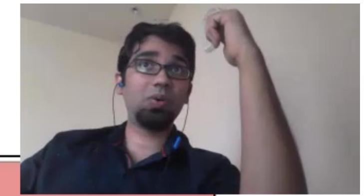
Step 1
Find parameters of 1g population: χ_{max}

Step 2
Find efficiency: λ

Step 3
Find N_{Gap}



Finding the mixing fraction with "gap" events



Step 1

Find parameters of 1g population: χ_{max}

Step 2

Find efficiency: λ

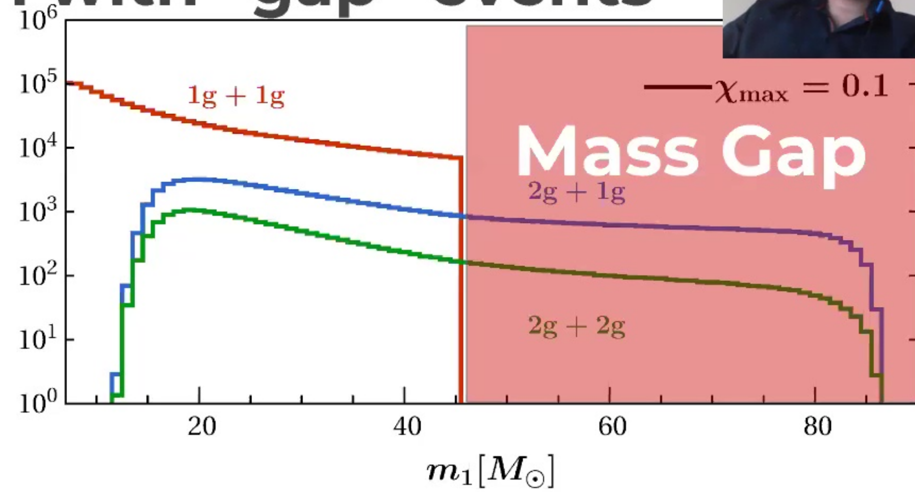
Step 3

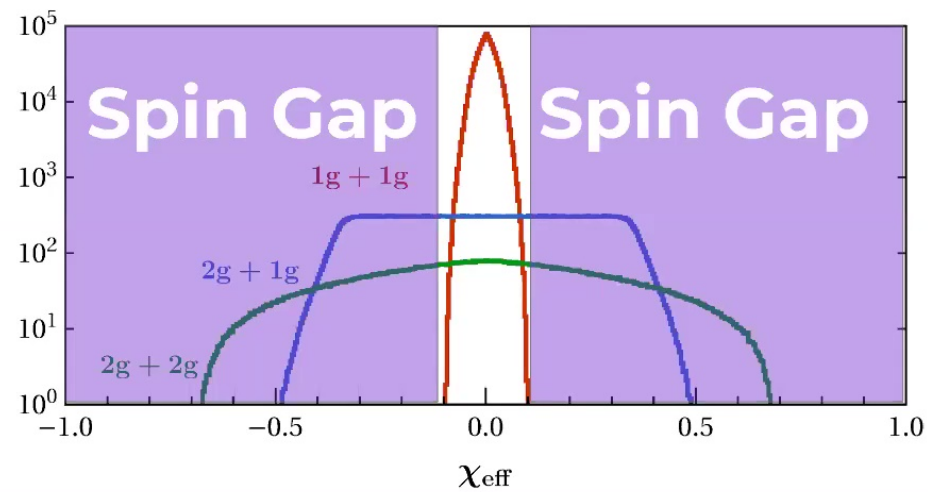
Find N_{Gap}

Step 4

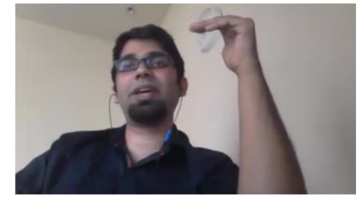
$N_{cluster} = N_{gap} / \lambda$

$f = N_{cluster} / N = N_{gap} / (\lambda N)$





Finding the mixing fraction with "gap" events



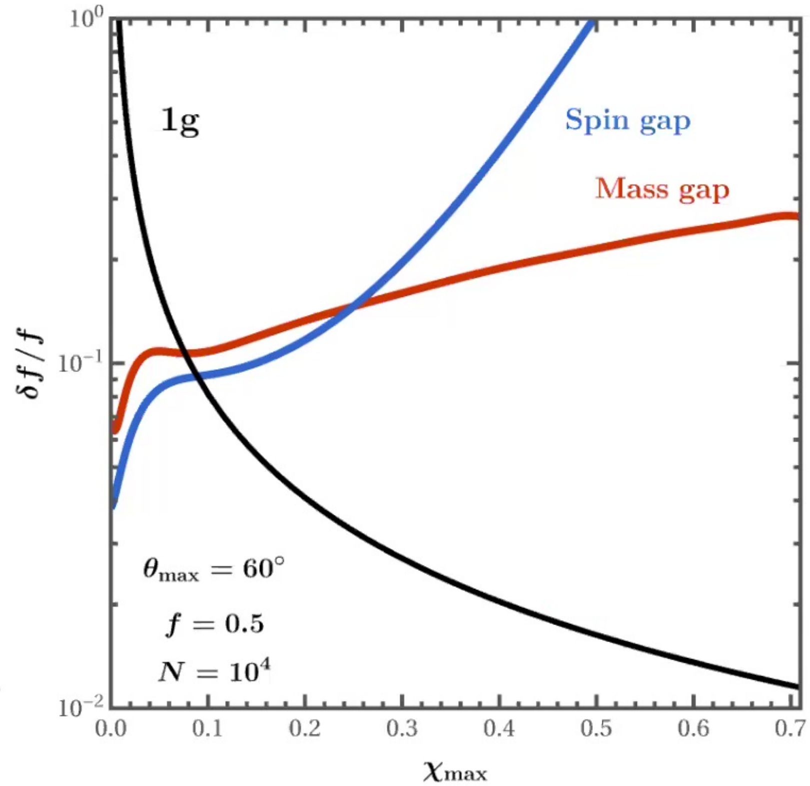
$$f = \frac{N_{\text{cluster}}}{N} = \frac{N_{\text{gap}}}{\lambda\, N}$$

Mixing fraction

Mixing-fraction error

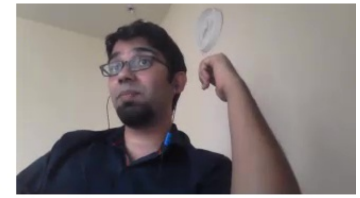
$$\left(\frac{\delta f}{f}\right)^2 = \left(\frac{\lambda'}{\lambda}\delta\chi_{\max}\right)^2 + \frac{1}{\lambda f N}$$

Efficiency error　　Counting error



Slide 37　Q & A　Notes　Pointer　Captions　Tips　EXIT

Finding the mixing fraction with "gap" events



$$f = \frac{N_{\text{cluster}}}{N} = \frac{N_{\text{gap}}}{\lambda\, N}$$

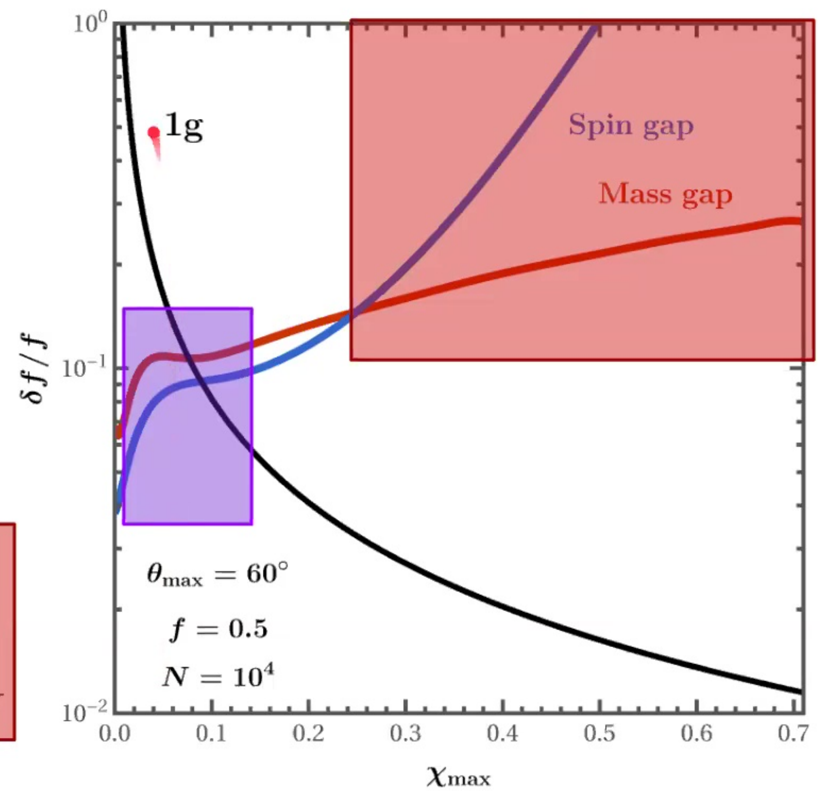
Mixing fraction

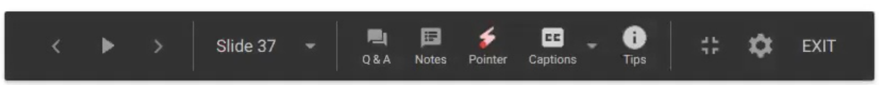
Mixing-fraction error

$$\left(\frac{\delta f}{f}\right)^2 = \left(\frac{\lambda'}{\lambda}\delta\chi_{\text{max}}\right)^2 + \frac{1}{\lambda f N}$$

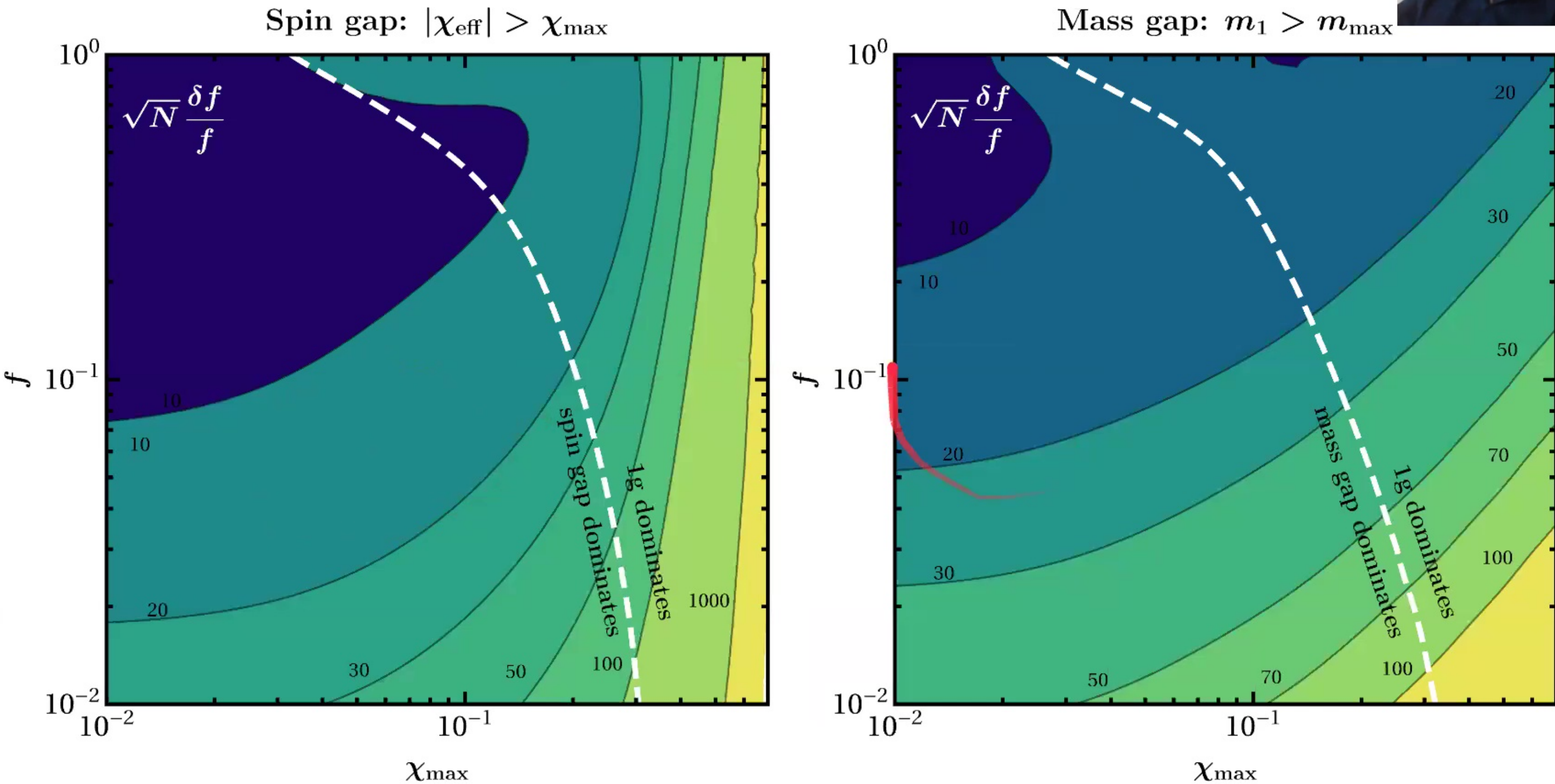
Efficiency error

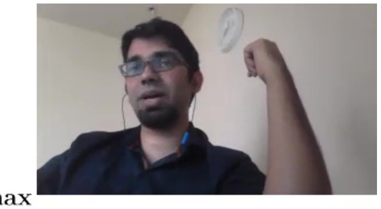
Counting error



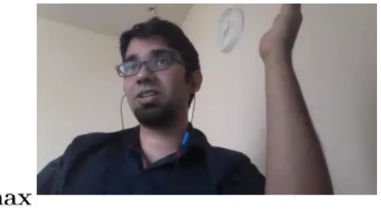


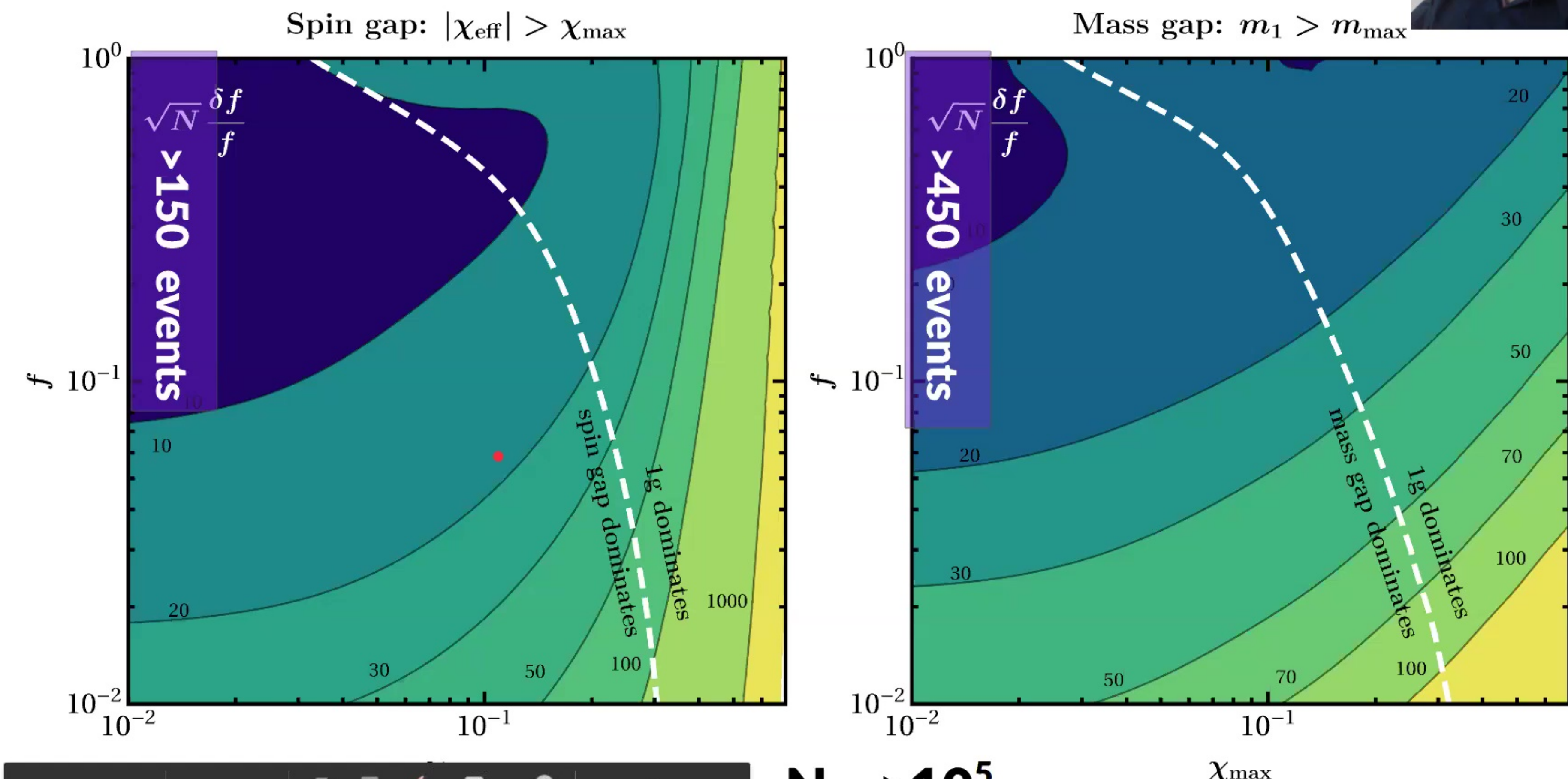
Finding the mixing fraction with “gap” events





Finding the mixing fraction with "gap" events

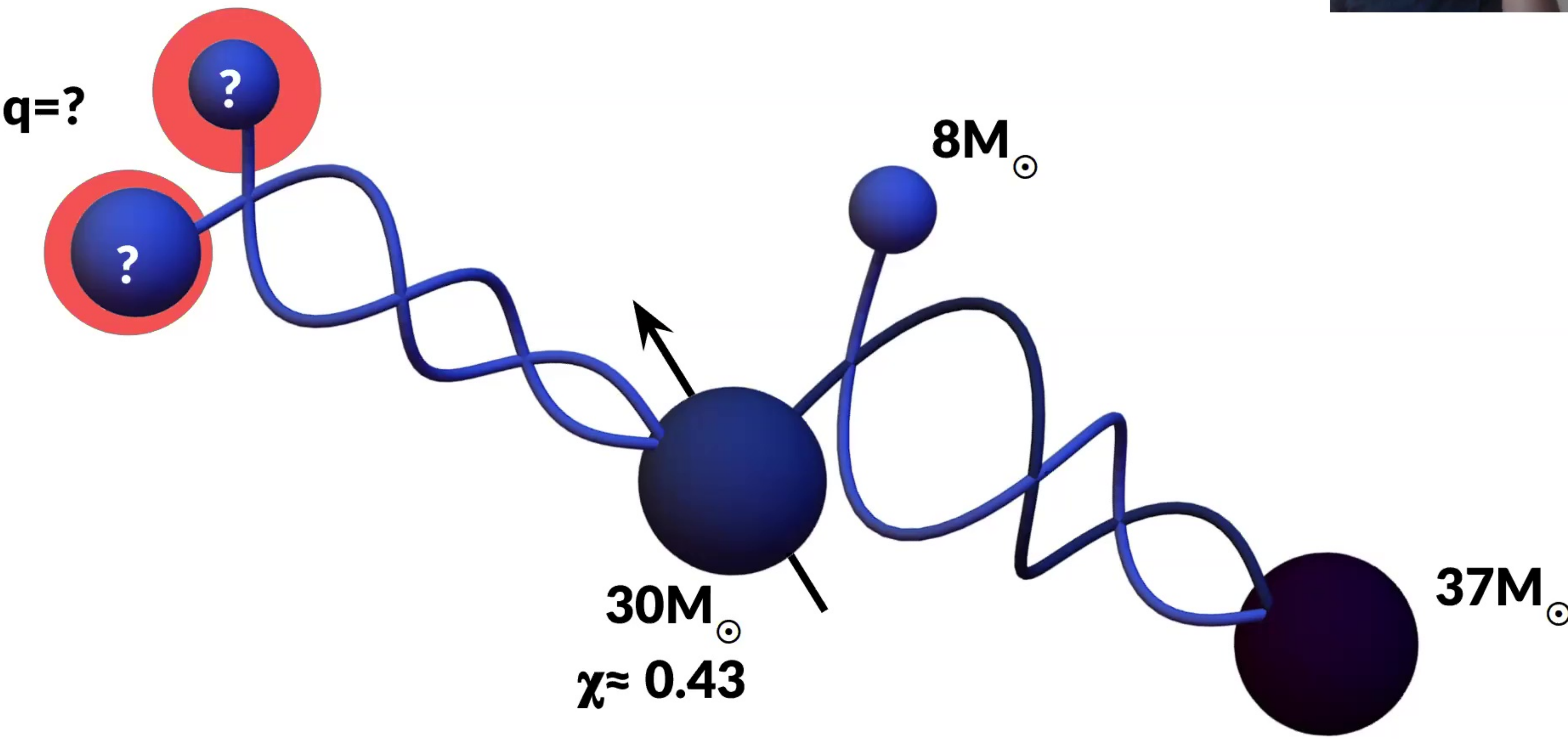


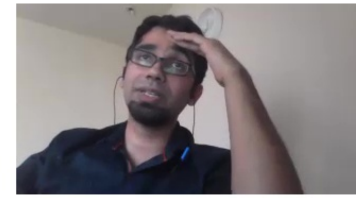


Slide 38

$N_{1g} > 10^5$

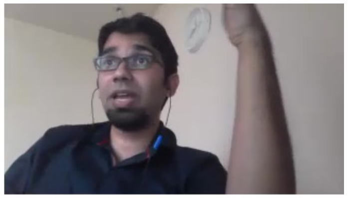
Parents of GW190412



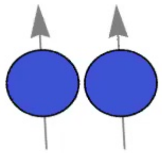


Parents of GW190412

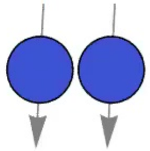
Reconstructing parents from the remnant's spin

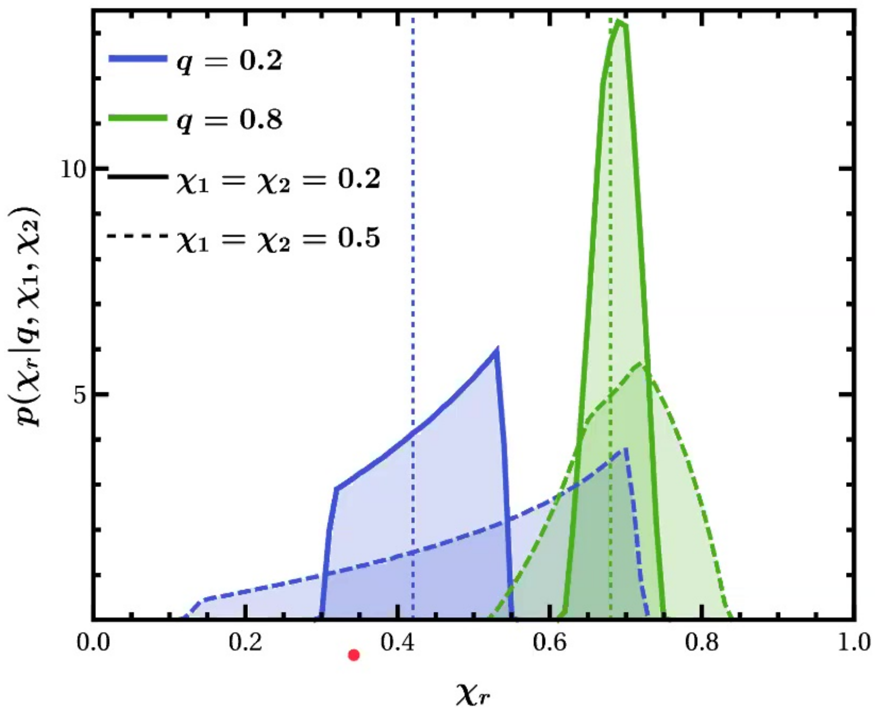


Max remnant's spin



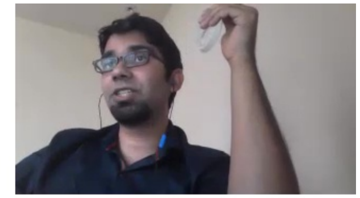
Min remnant's spin



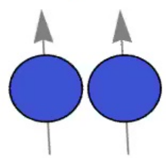


Parents of GW190412

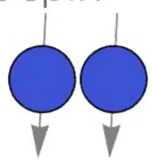
Reconstructing parents from the remnant's spin



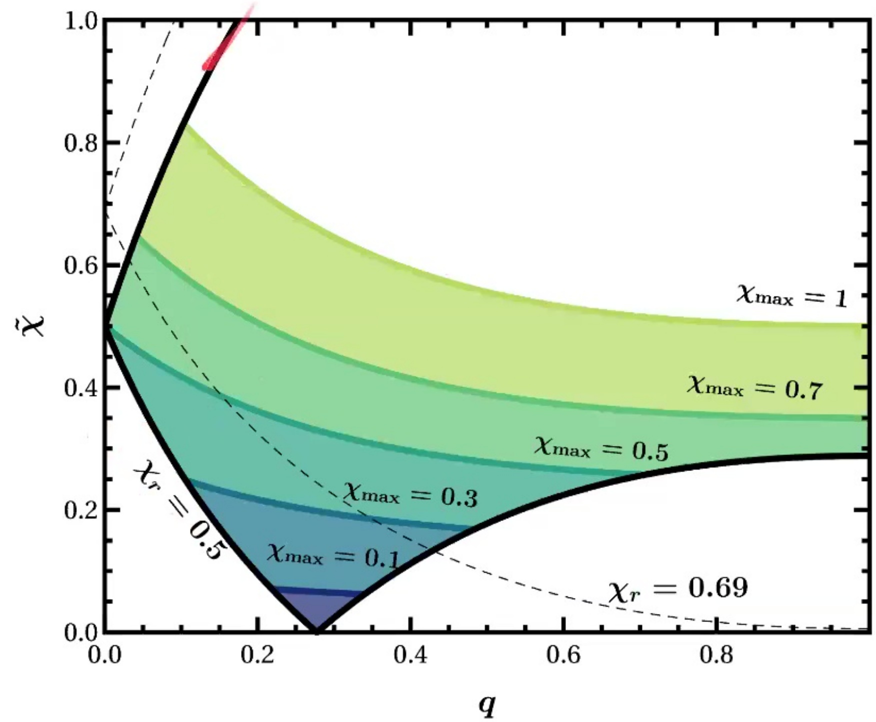
Max remnant's spin



Min remnant's spin

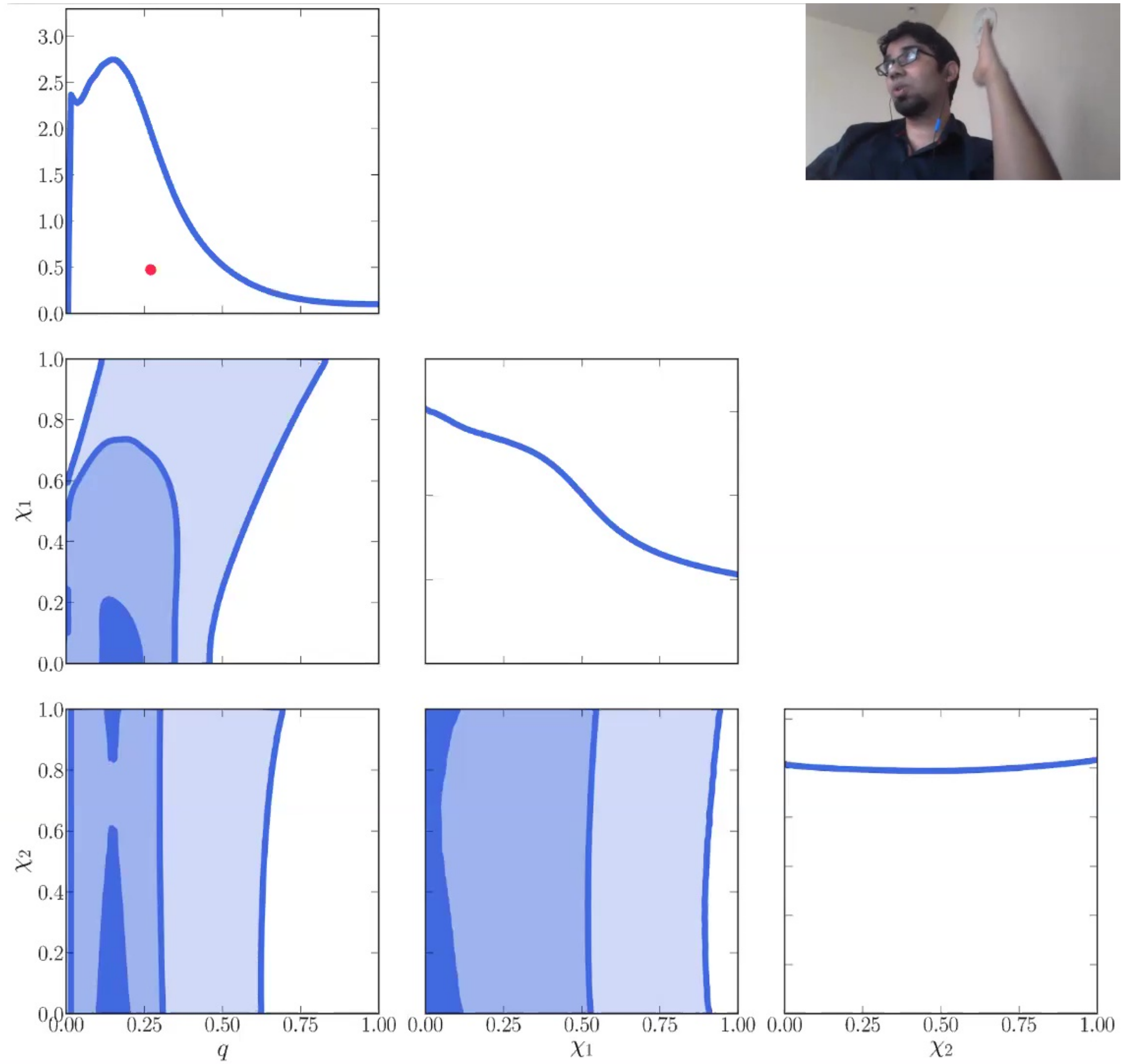


$$\tilde{\chi} = \frac{\chi_1 + q^2 \chi_2}{1 + q^2}$$



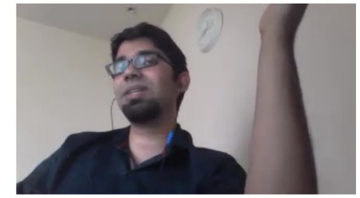
Parents of GW190412

Parents of GW190412 likely had asymmetric masses, q=0.2 and near-zero spins

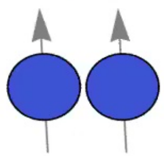


Parents of GW190412

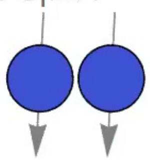
Reconstructing parents from the remnant's spin



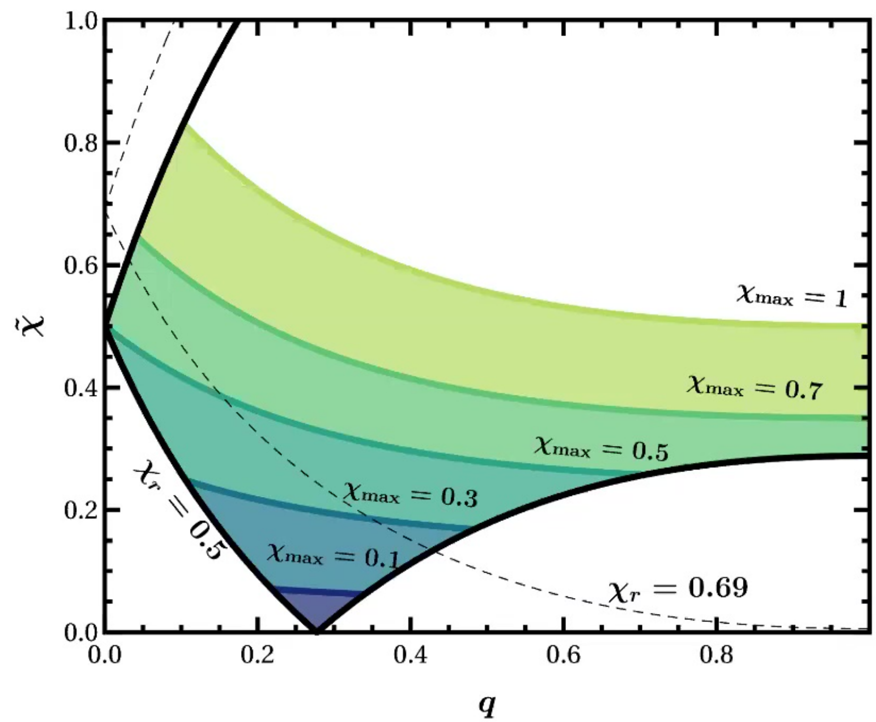
Max remnant's spin

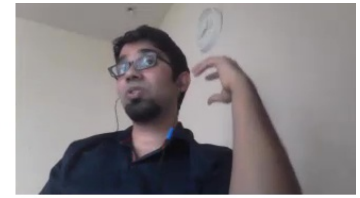


Min remnant's spin



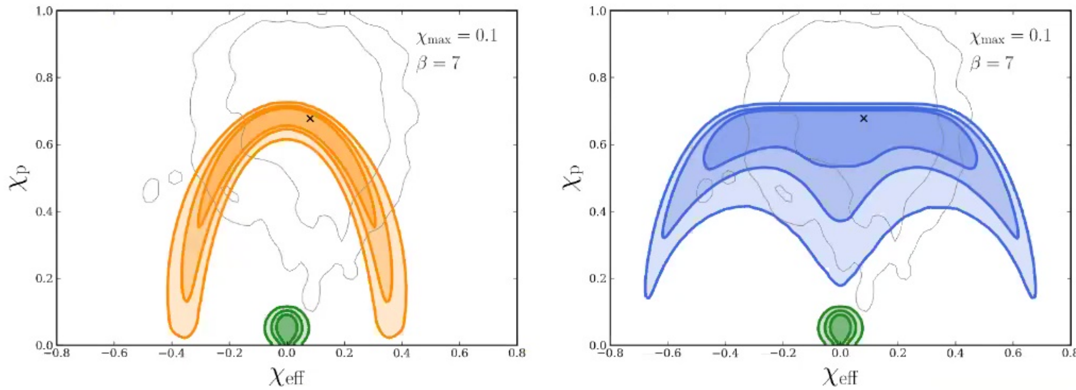
$$\tilde{\chi} = \frac{\chi_1 + q^2 \chi_2}{1+q^2}$$

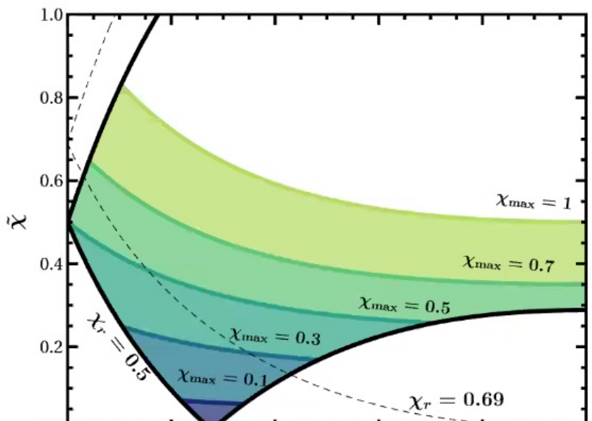




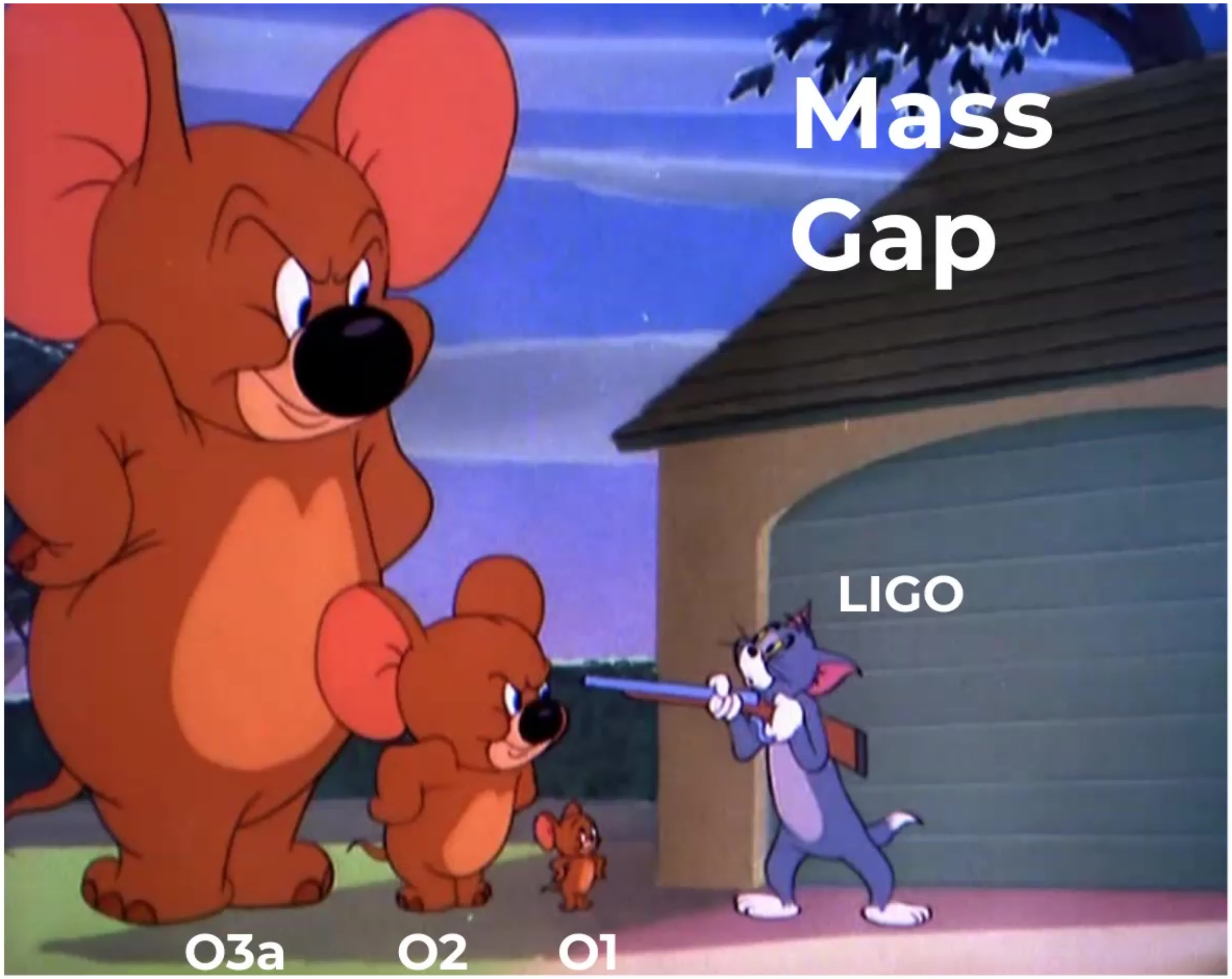
KEY TAKEAWAYS

Repeated mergers can
populate the SPIN GAP





For some *lucky* events, we can
find their PARENTS



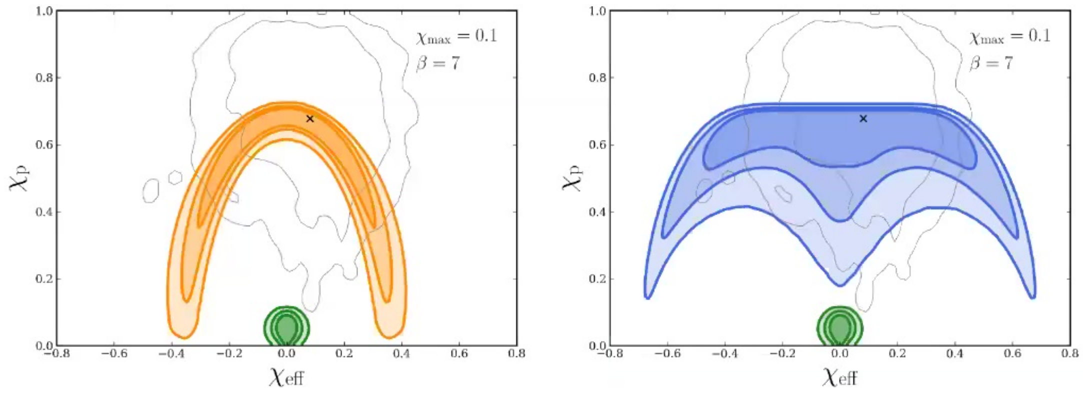
$85M_\odot$ GW190521

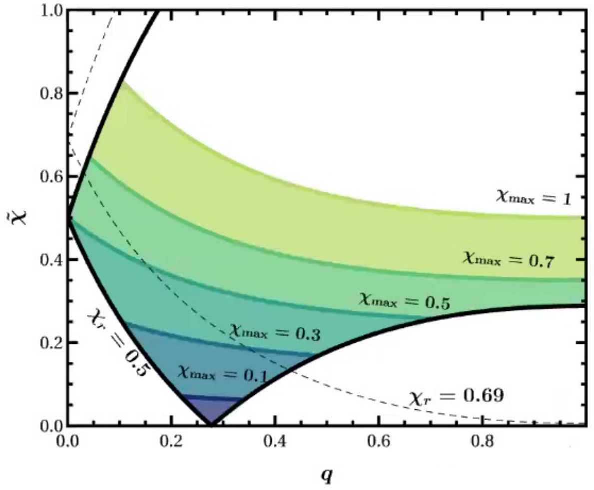
$50M_\odot$ GW170729

$33M_\odot$ GW150914

KEY TAKEAWAYS

Repeated mergers can
populate the SPIN GAP





For some *lucky* events, we can
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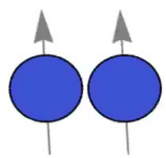
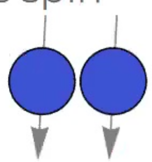
Parents of GW190412

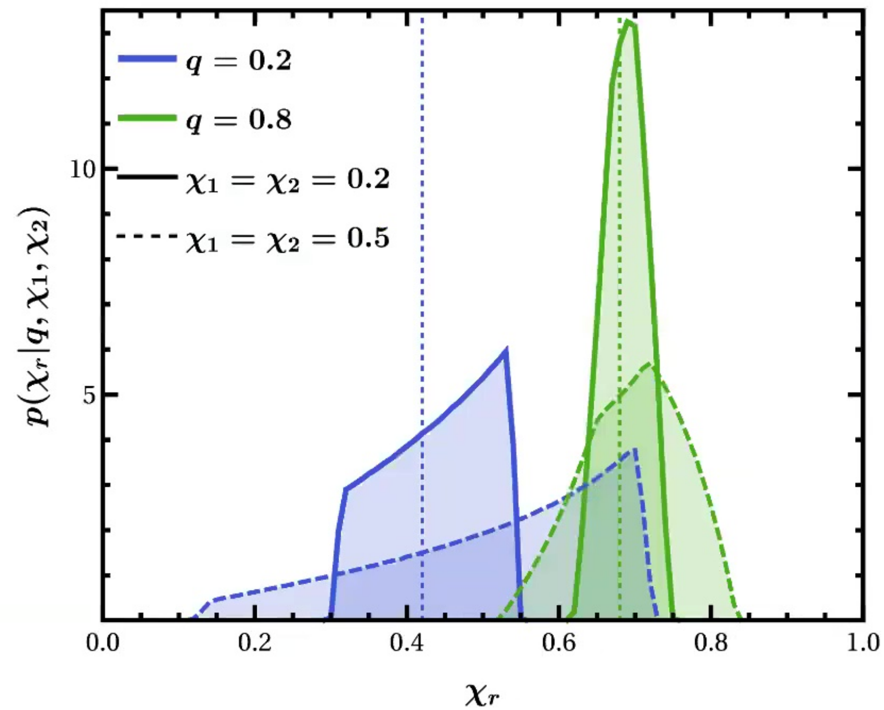
Reconstructing parents from the remnant's spin

Max remnant's spin

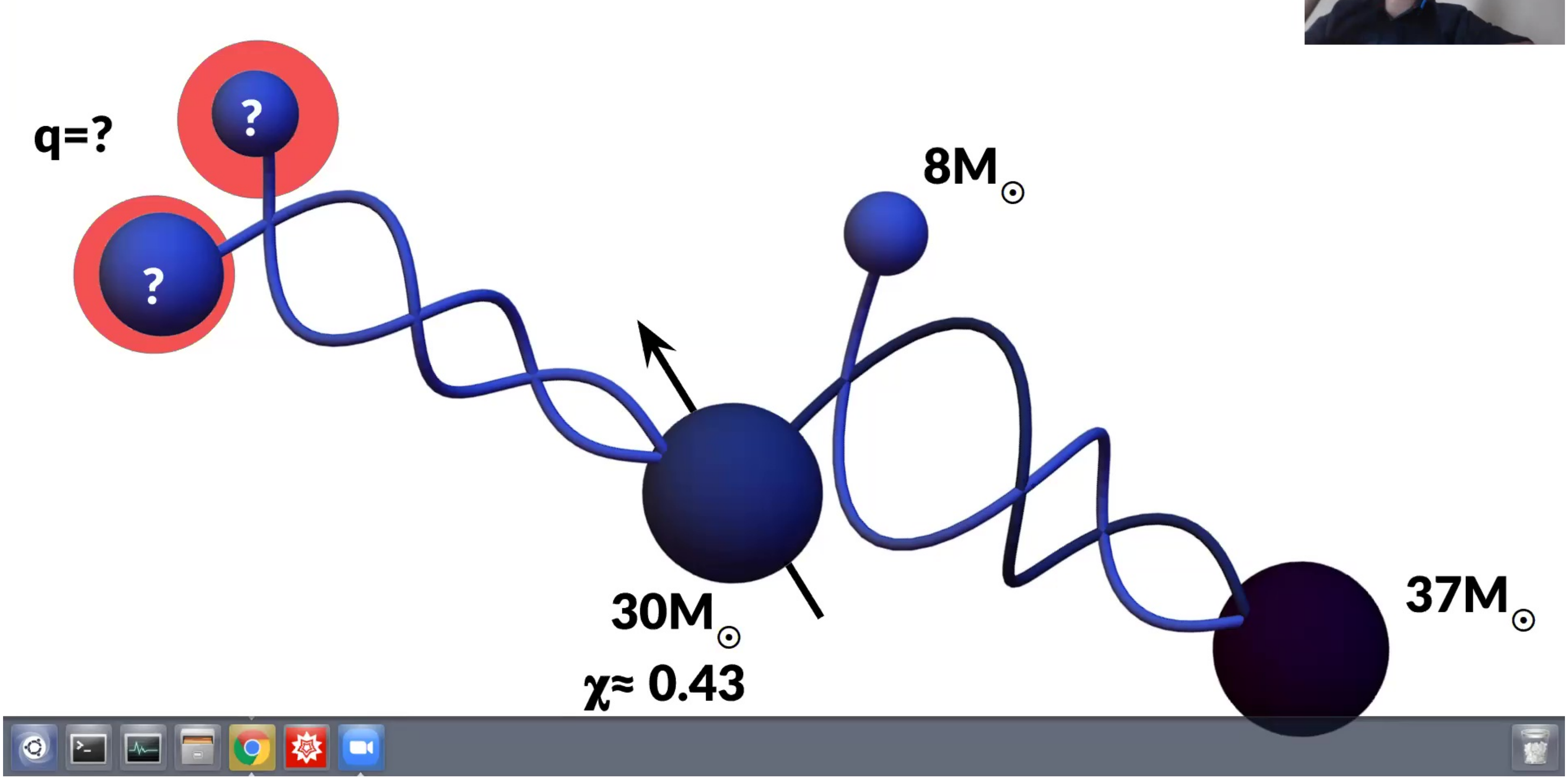


Min remnant's spin





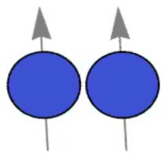
Parents of GW190412



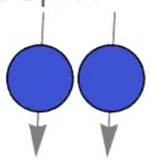
Parents of GW190412

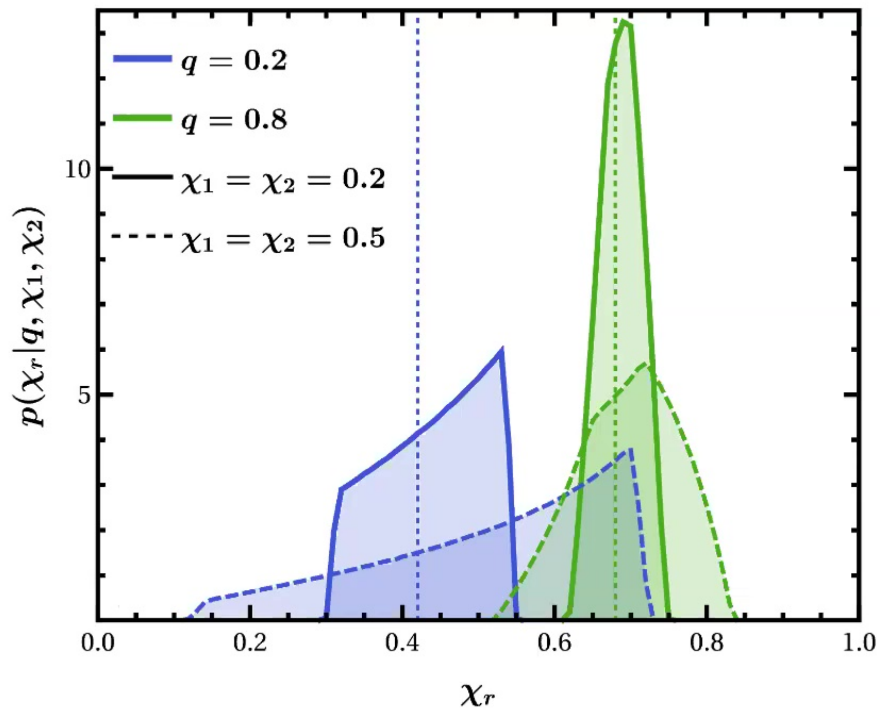
Reconstructing parents from the remnant's spin

Max remnant's spin



Min remnant's spin



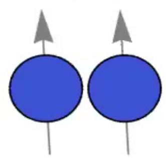


Perimeter - Google Slides - Google Chrome

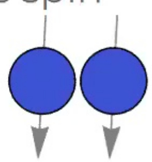
Parents of GW190412

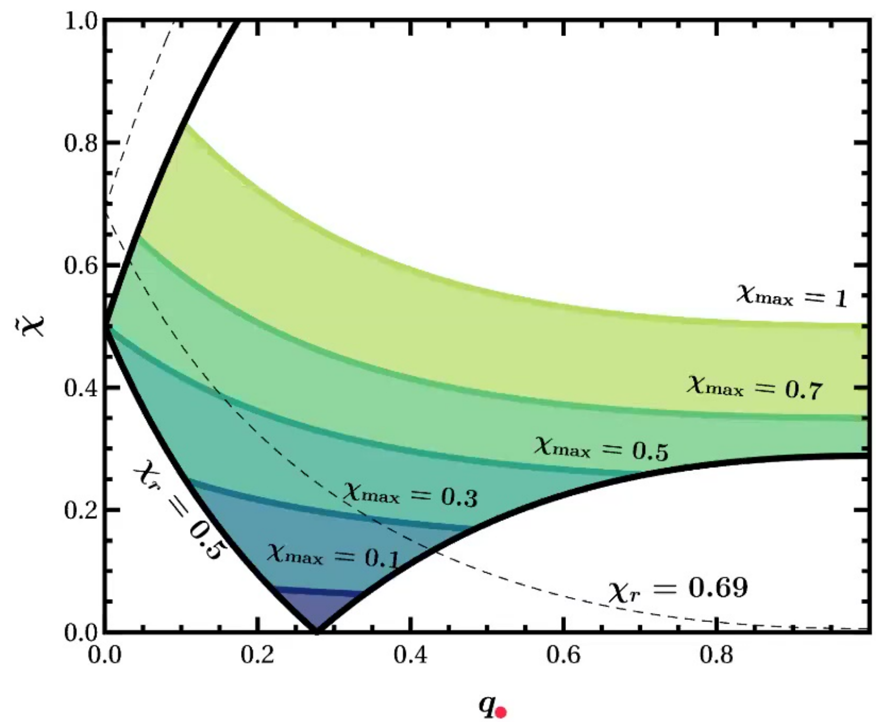
Reconstructing parents from the remnant's spin

Max remnant's spin



Min remnant's spin



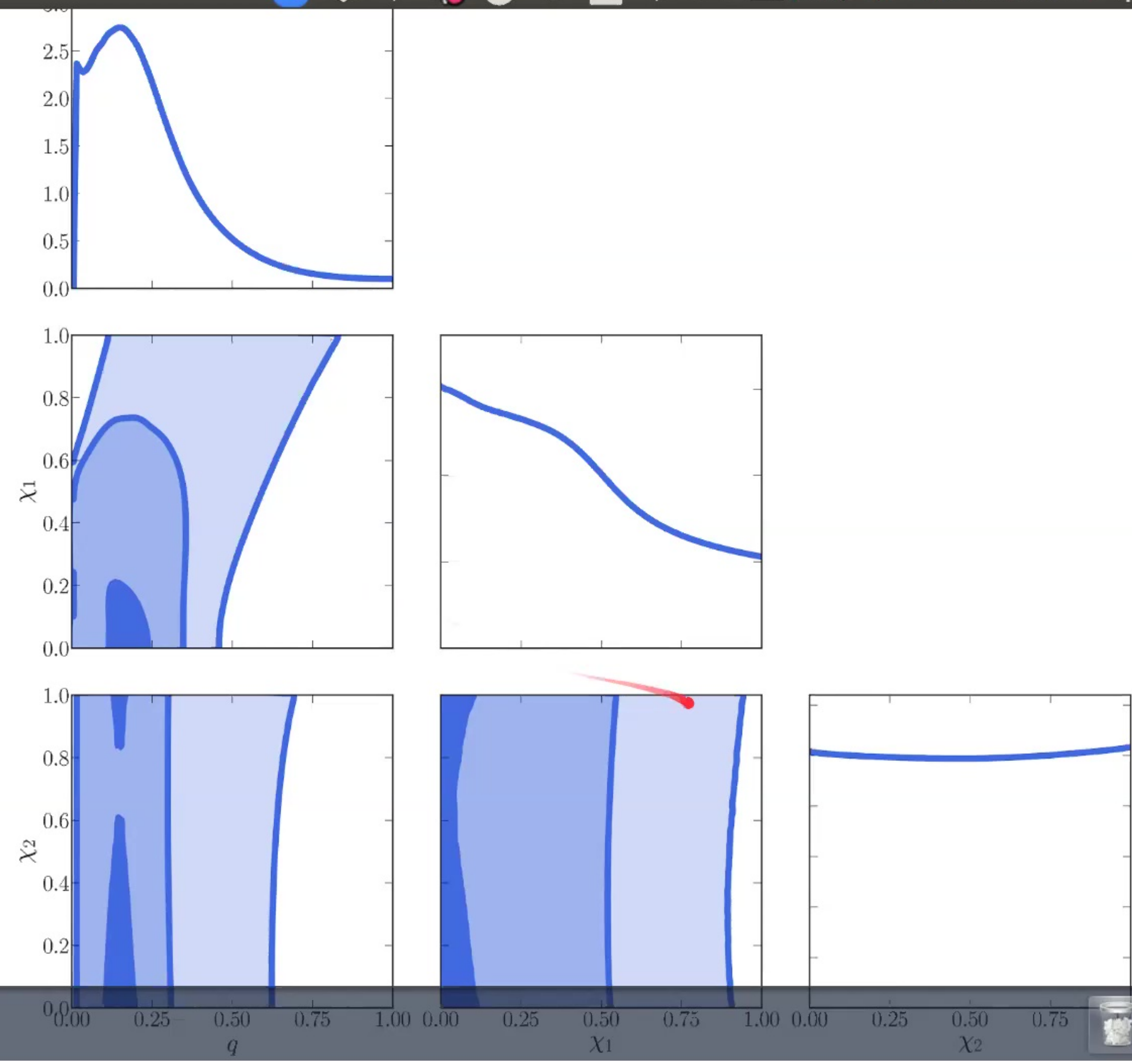


$$\tilde{\chi} = \frac{\chi_1 + q^2 \chi_2}{1+q^2}$$

Perimeter - Google Slides - Google Chrome

Thu Jan 14 12:49 PM

Parents of GW190412



Parents of GW190412 likely had asymmetric masses, q=0.2 and near-zero spins