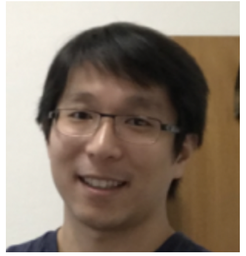
Stars and Dark Objects:
The Gravitational Interaction Landscape

Wisconsin Workshop 2025

Kuver Sinha
University of Oklahoma

based on arXiv: 2408.04697 plus ongoing work with
Badal Bhalla (OU), Benjamin V. Lehmann (MIT), Tao Xu (OU)



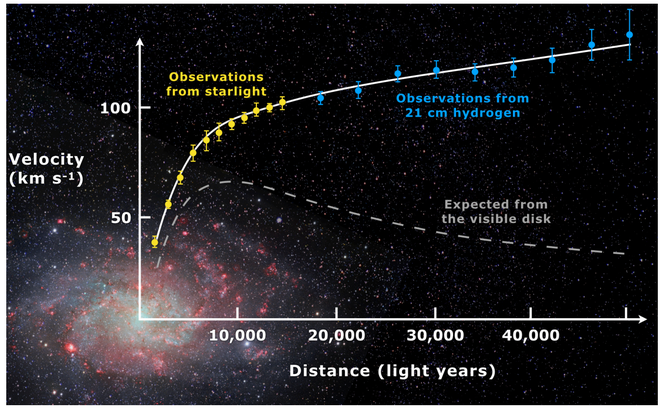


Nice to finally meet Vernon!

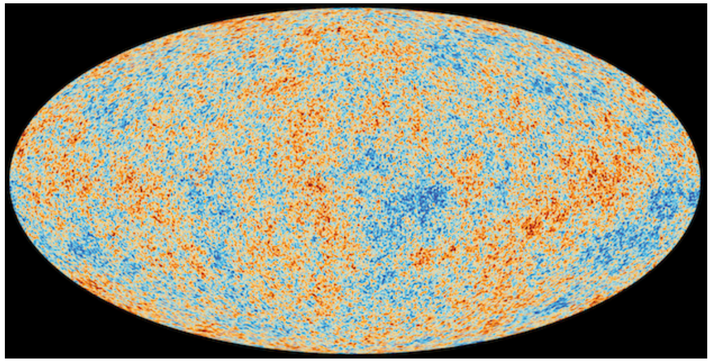
Dark Matter

Presumably, a lot of us here care about dark matter

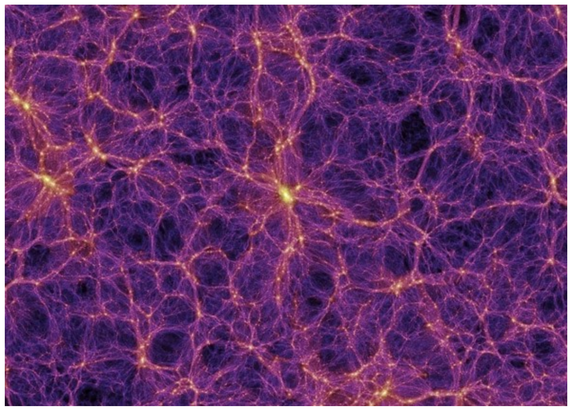
All evidence gravitational



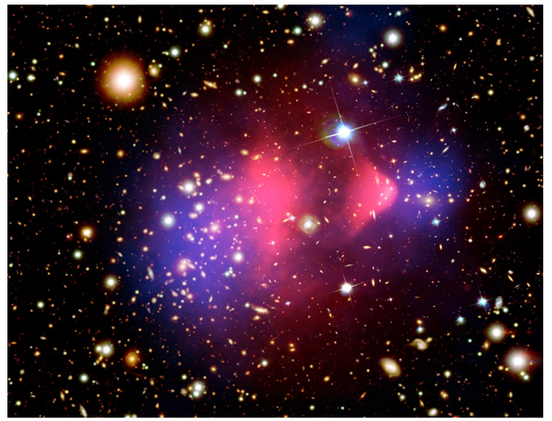
Galaxy rotation curves



CMB



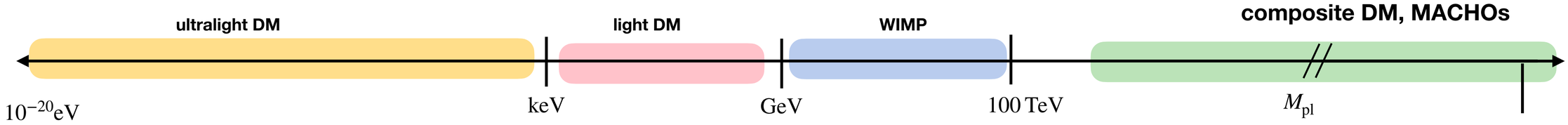
Structure formation

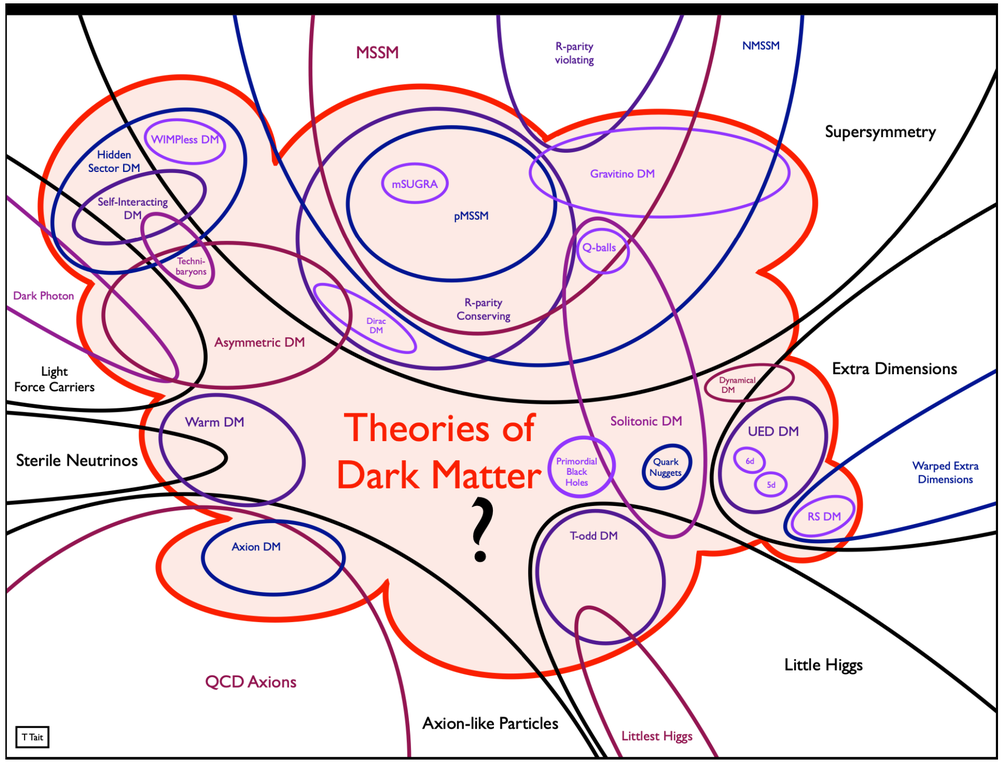


Bullet cluster

Today's talk: what happens if we're confronted with the nightmare scenario?

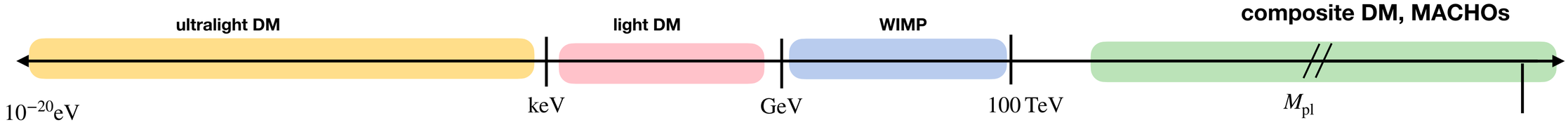
The Landscape of Models: Theory Space

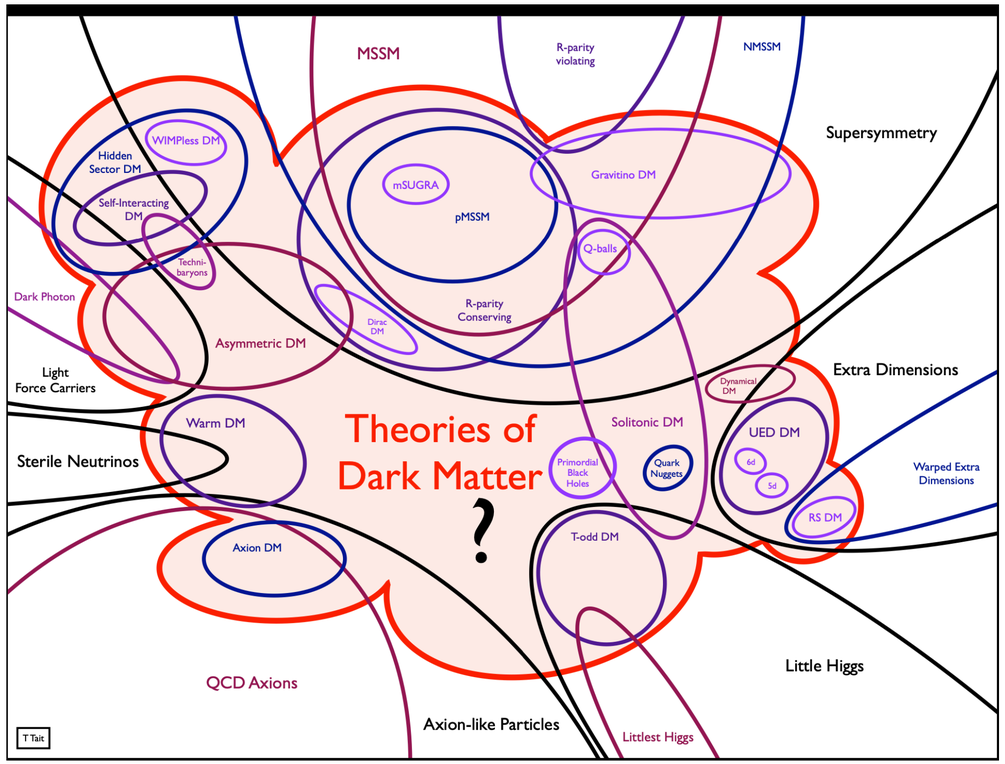




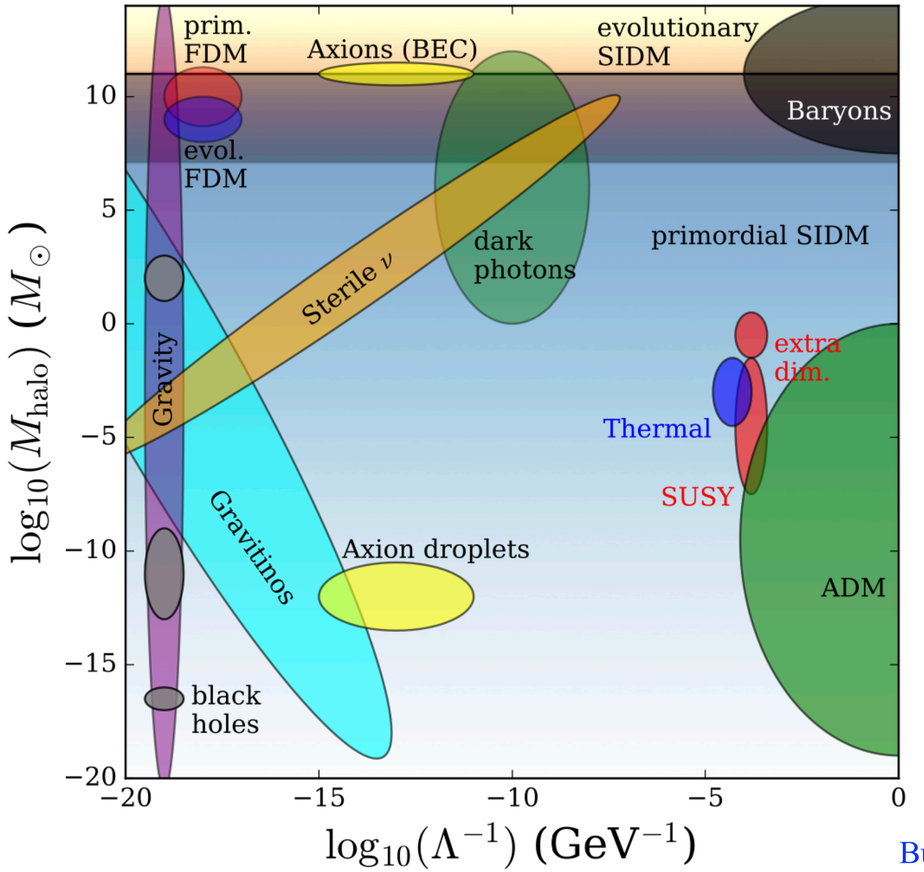
Tim Tait

The Landscape of Models: Talking to Astronomers



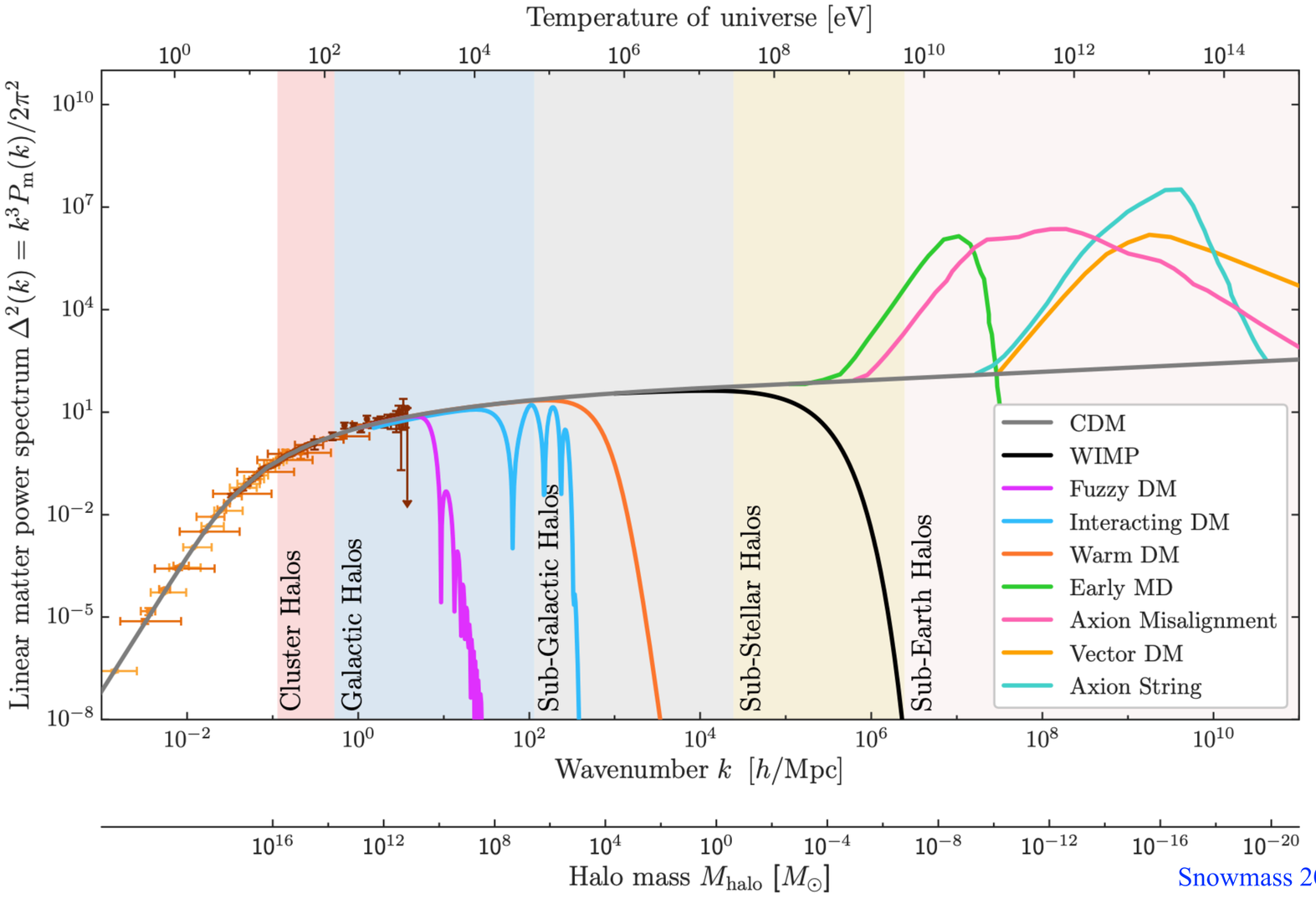


Tim Tait



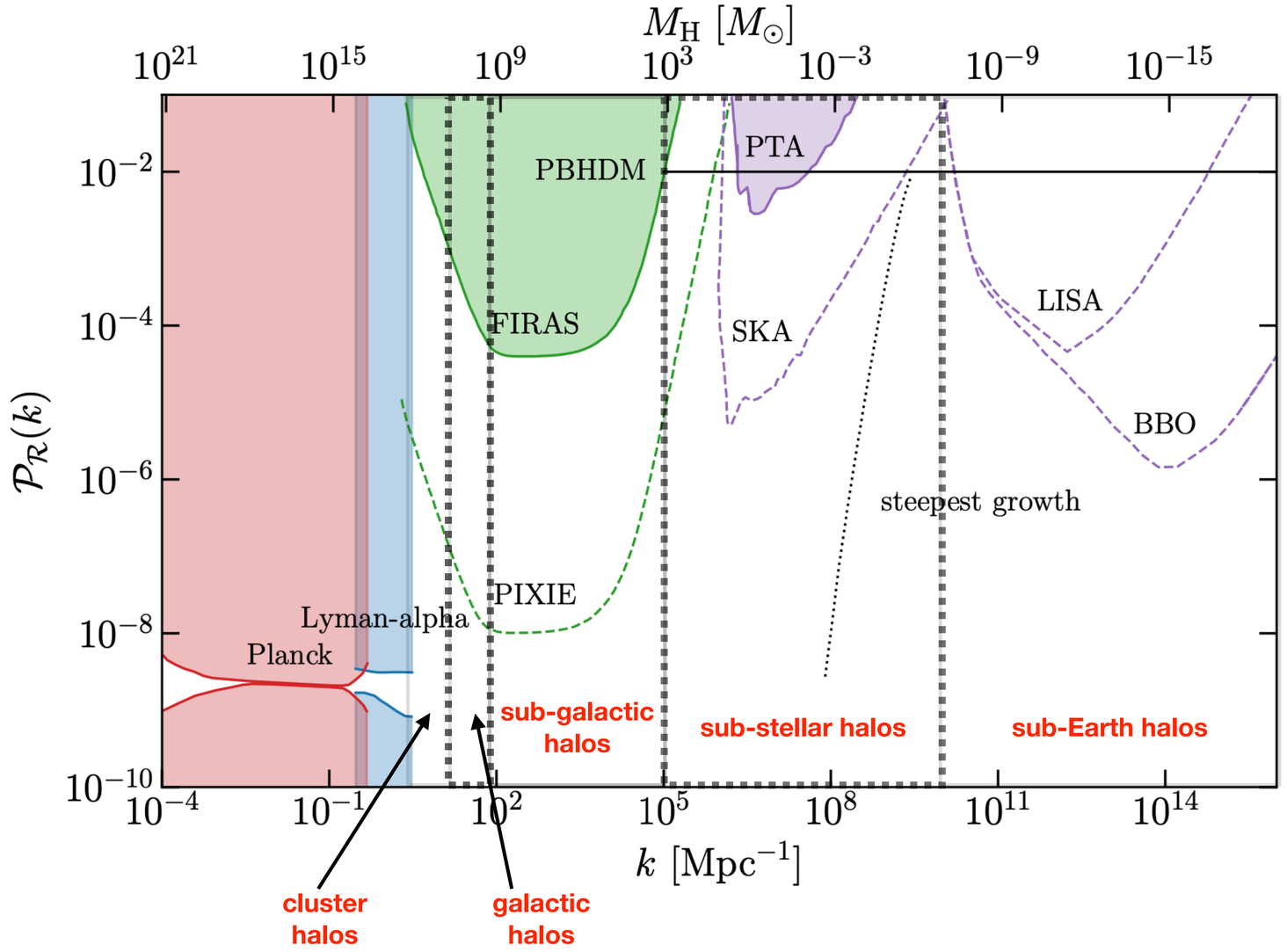
Buckley, Peter (2018)

The Landscape of Models: Matter Power Spectrum Space



Snowmass 2021 White Paper: arXiv:2203.07354
Dark Matter Physics from Halo Measurements

The Landscape of Models: Primordial Power Spectrum Space

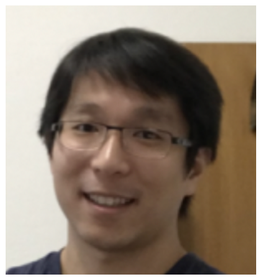


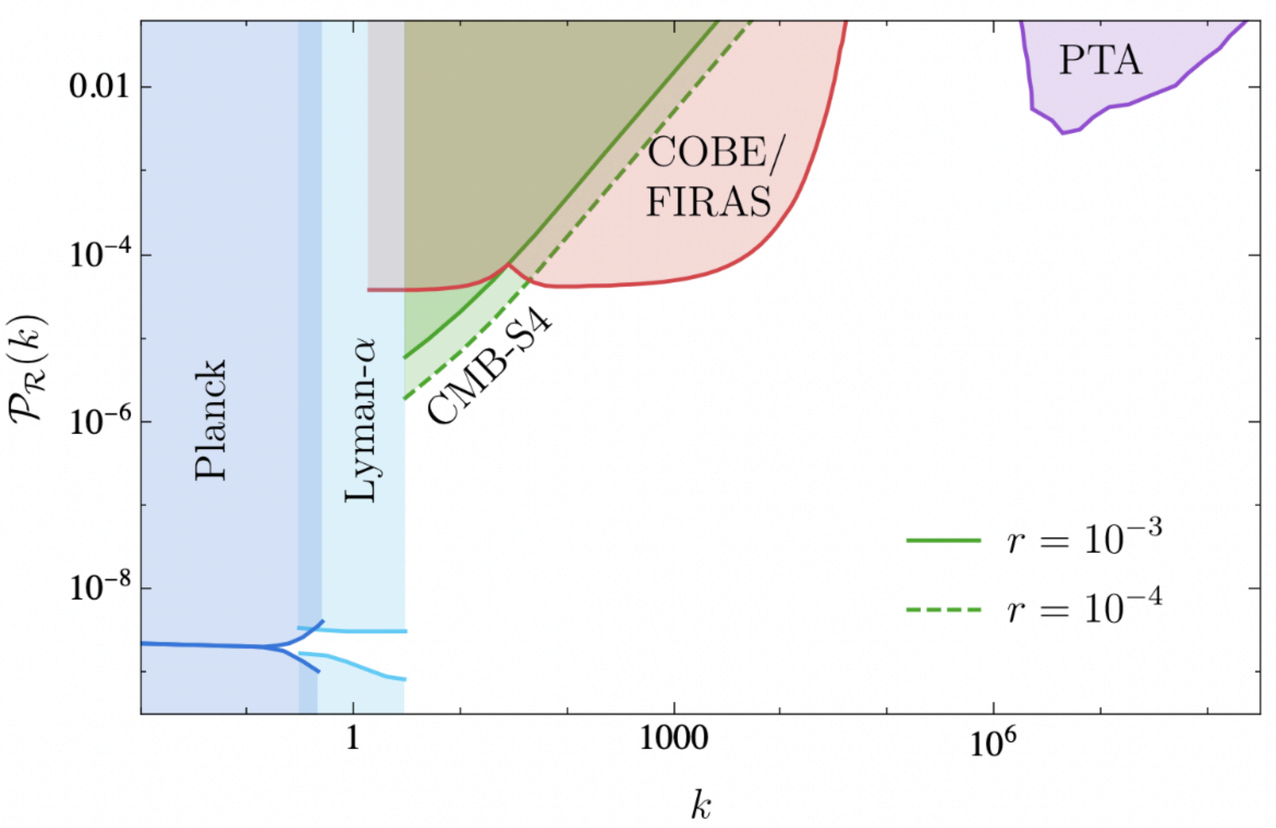
adapted from arXiv: 2007.10722

Advertisement

- GW induced by primordial fluctuations at 2nd order
- GWs then processed into B-modes in the CMB

Greene, Ireland, Krnjaic, Tsai (2024)



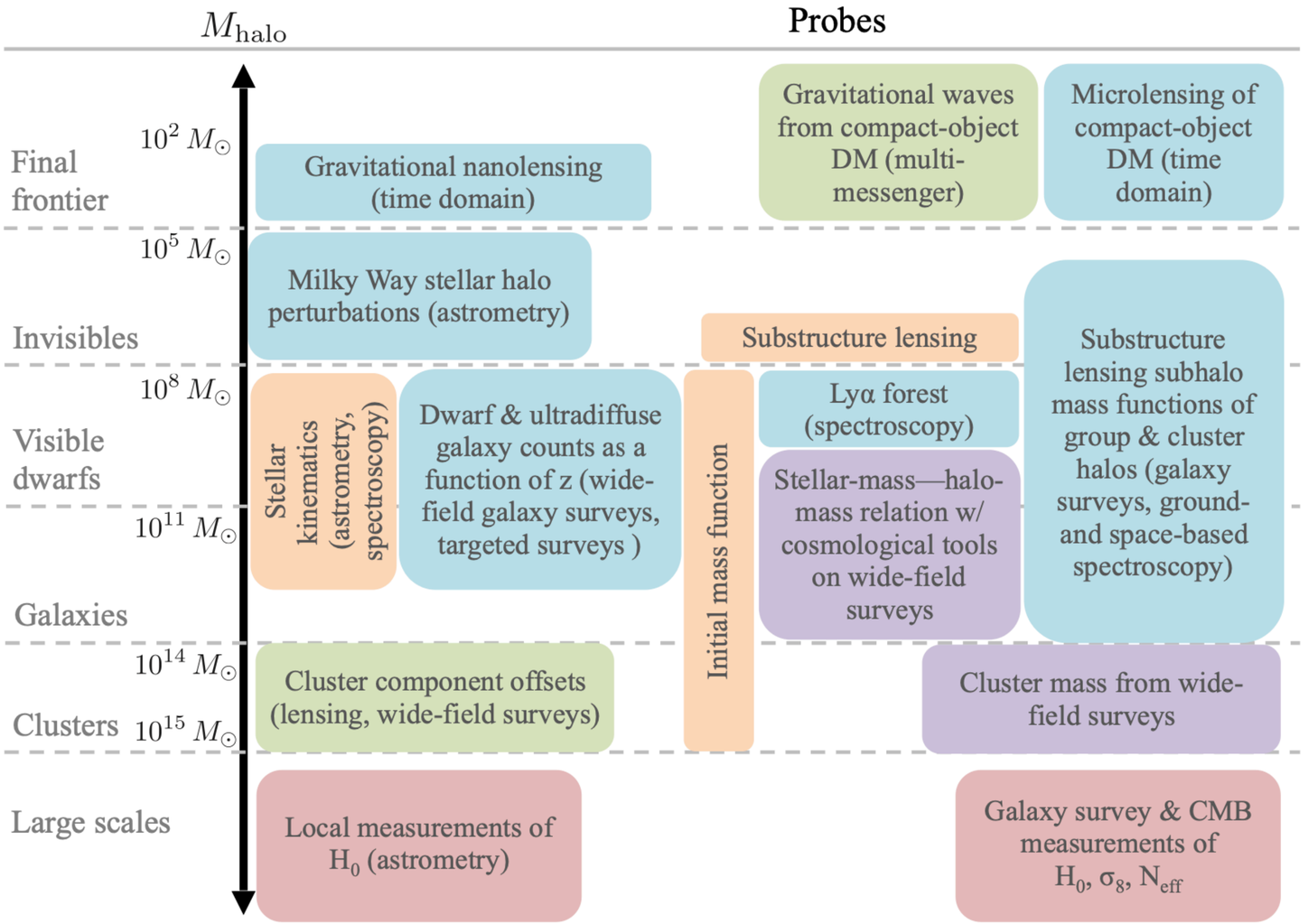


Aurora Ireland, KS, Tao Xu (ongoing)

The Landscape of Cooling Rates (Dark Chemistry)

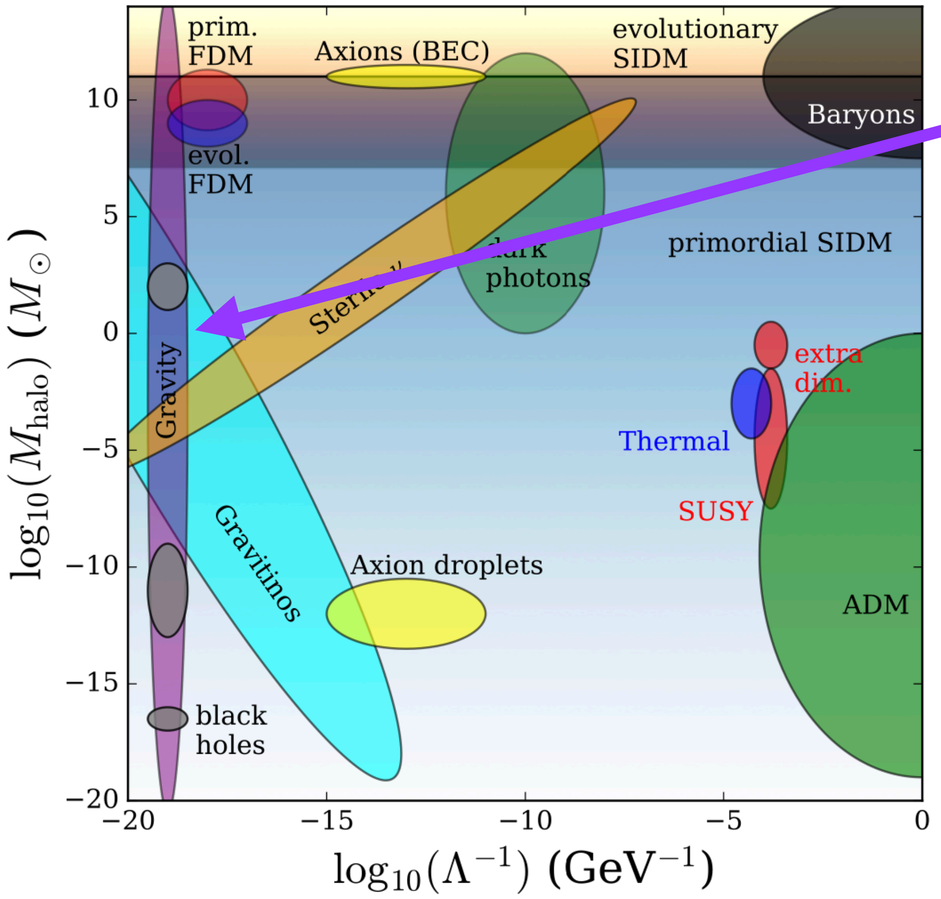
Consensus plot from the community?

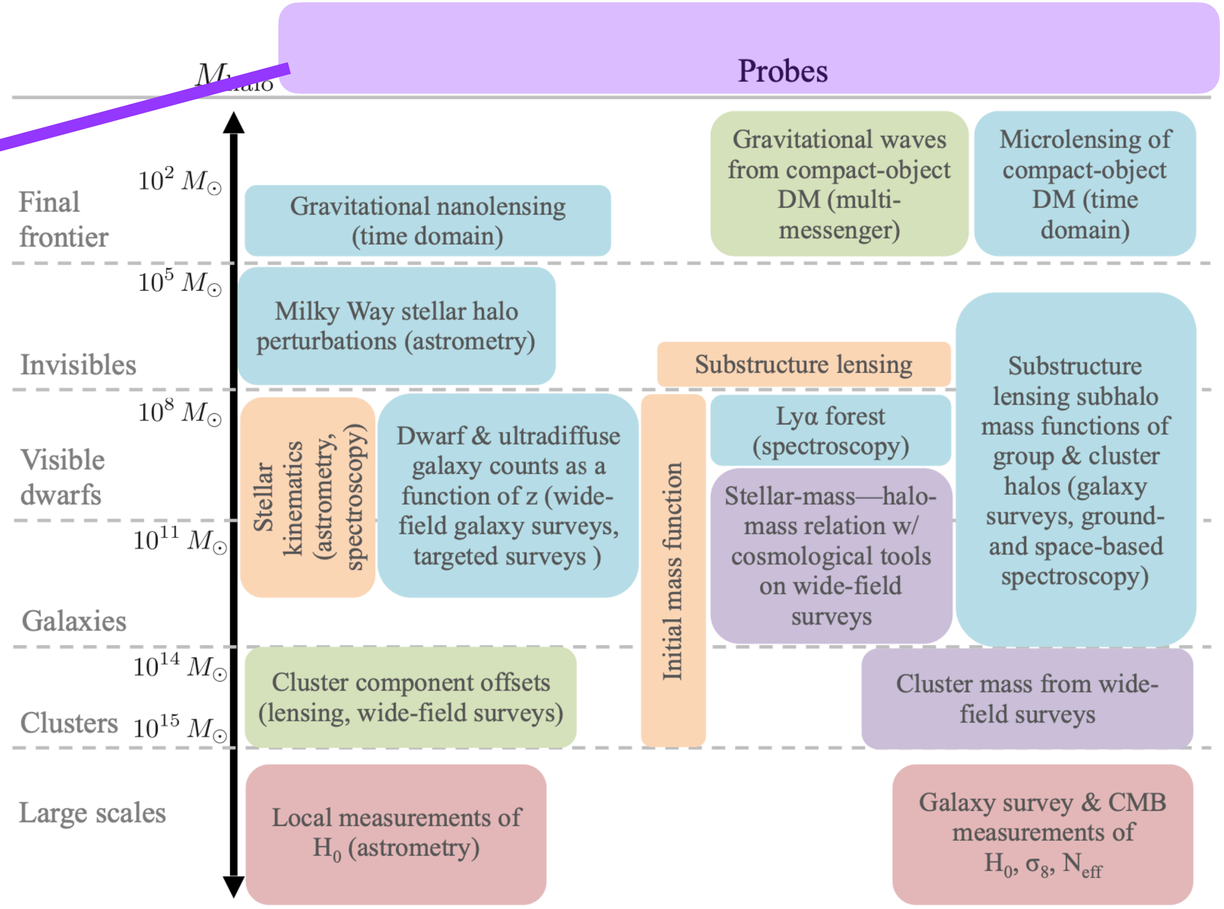
The Landscape of Models: Talking to Astronomers



Buckley, Peter (2018)

Today's Talk: What can stars tell you?



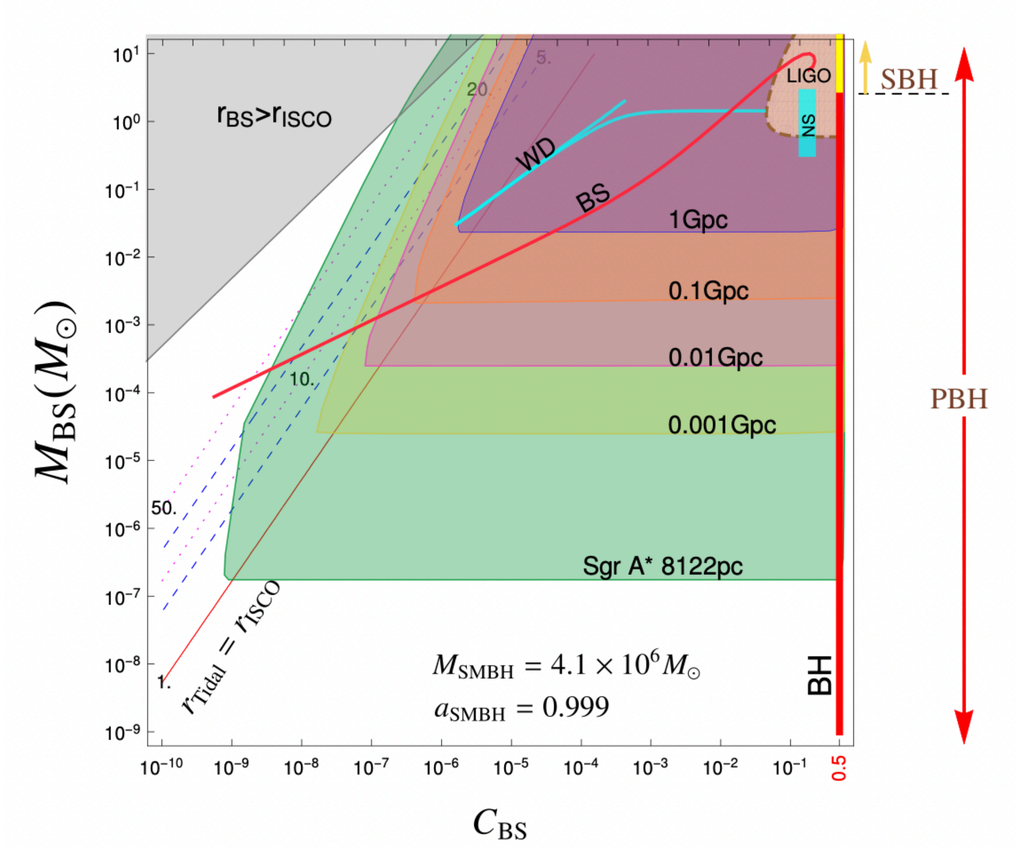


Buckley, Peter (2018)

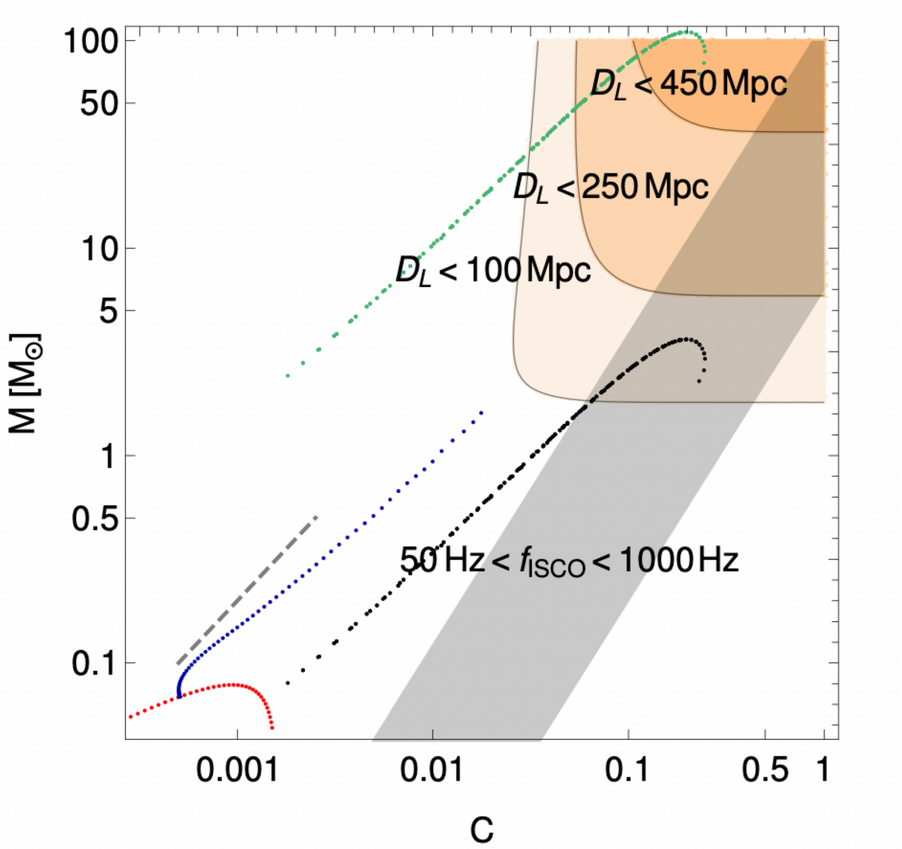
Stellar-sized Dark Objects

Stellar-sized Dark Objects

If they have anomalous mass, you've discovered something exotic



Guo, Sinha, Vagie (2018)

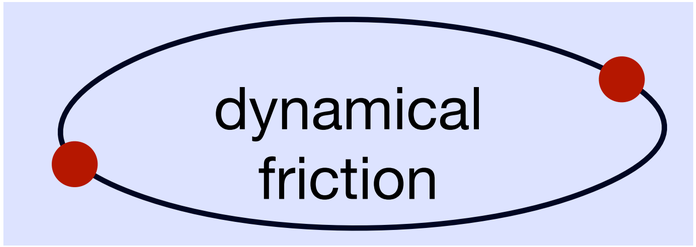


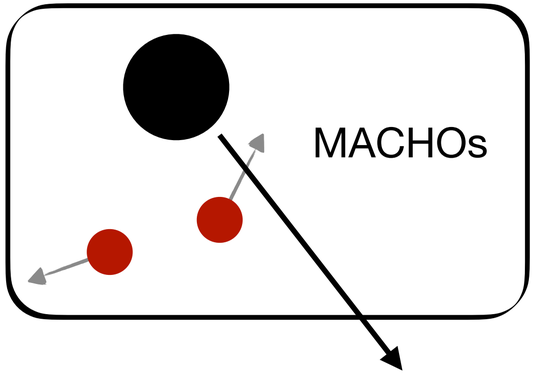
Guo, Sinha, Sun, Swaim, Vagie (2021)

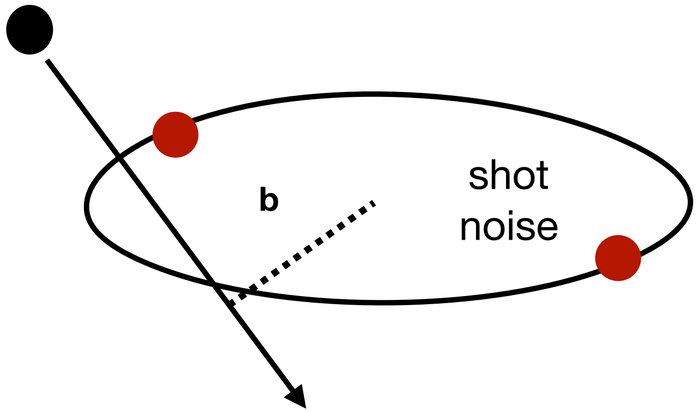
Stellar-sized Dark Objects

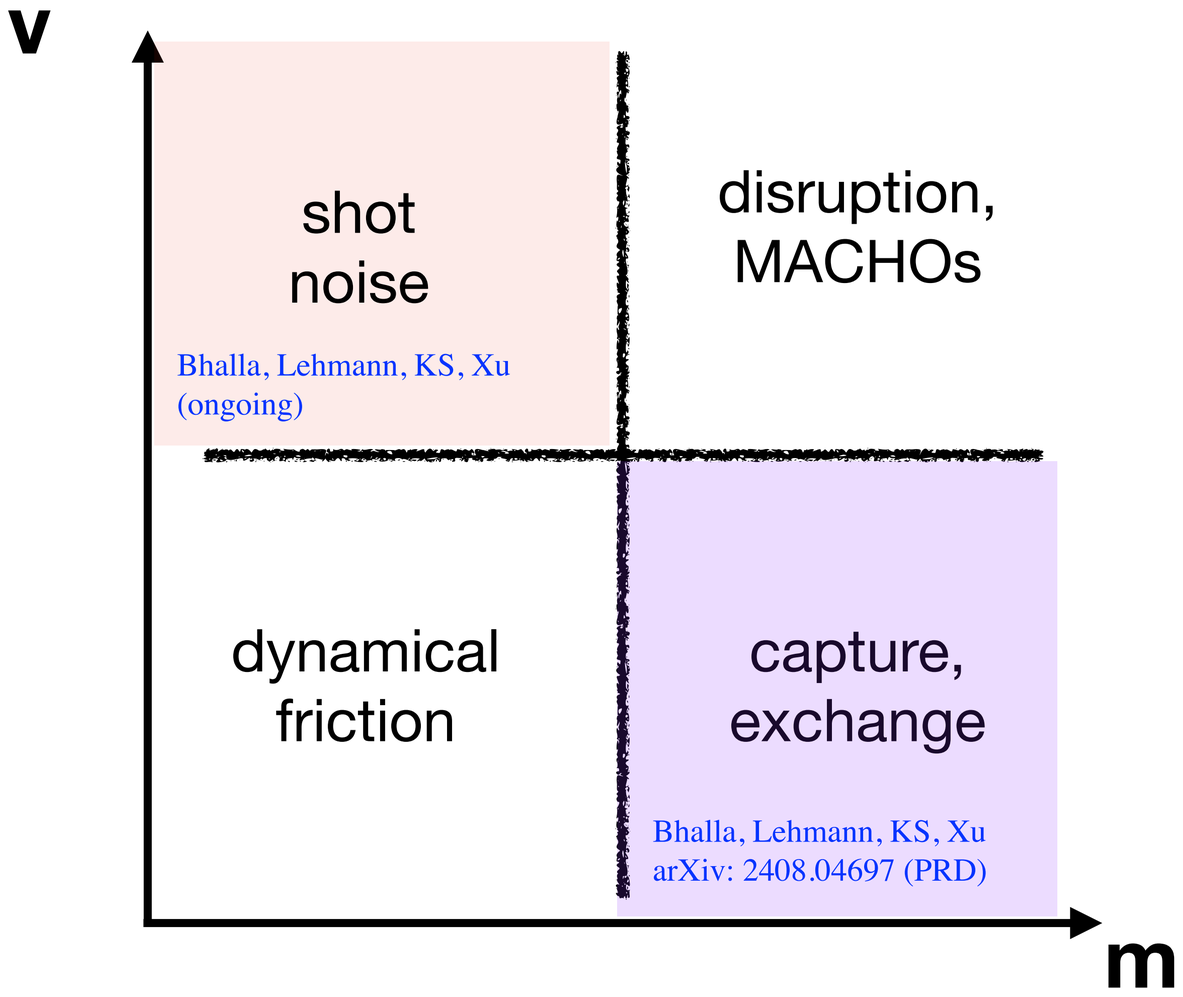
How about interactions with stellar or pulsar binaries?

Landscape of Velocities and Masses

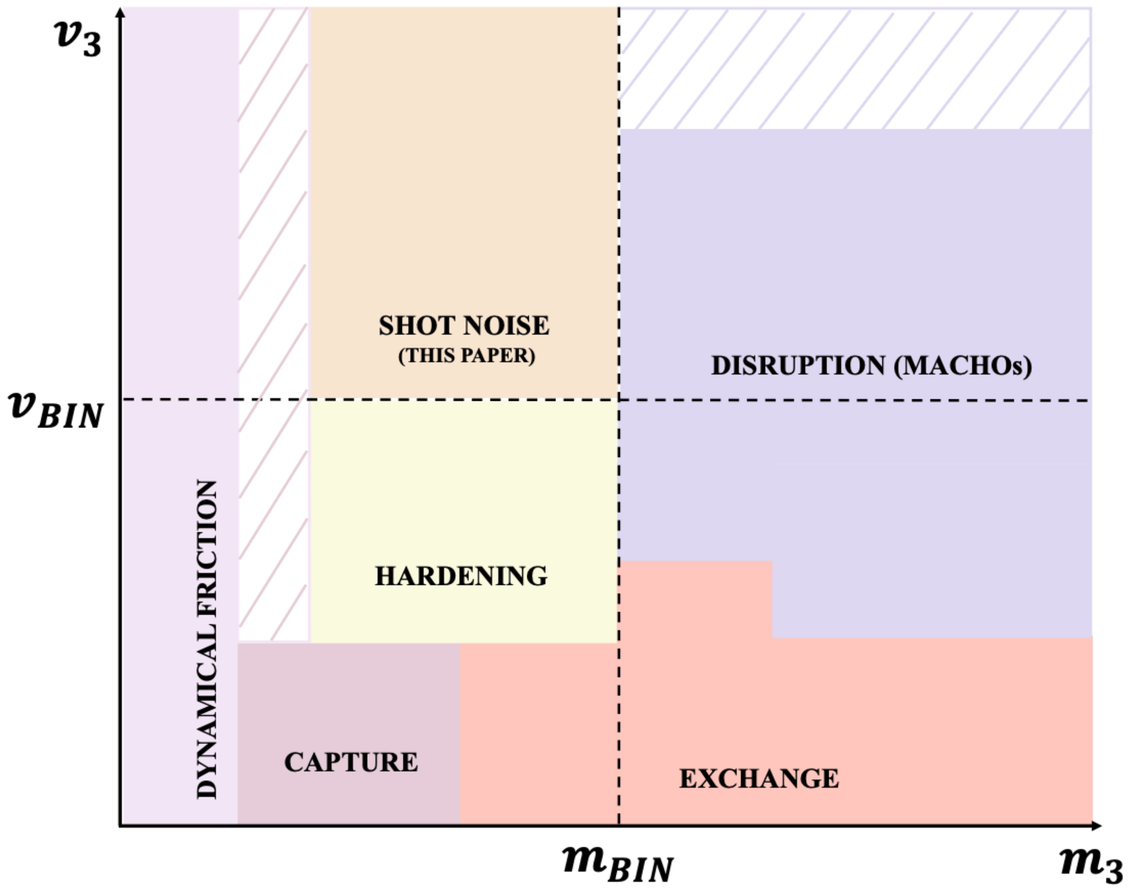




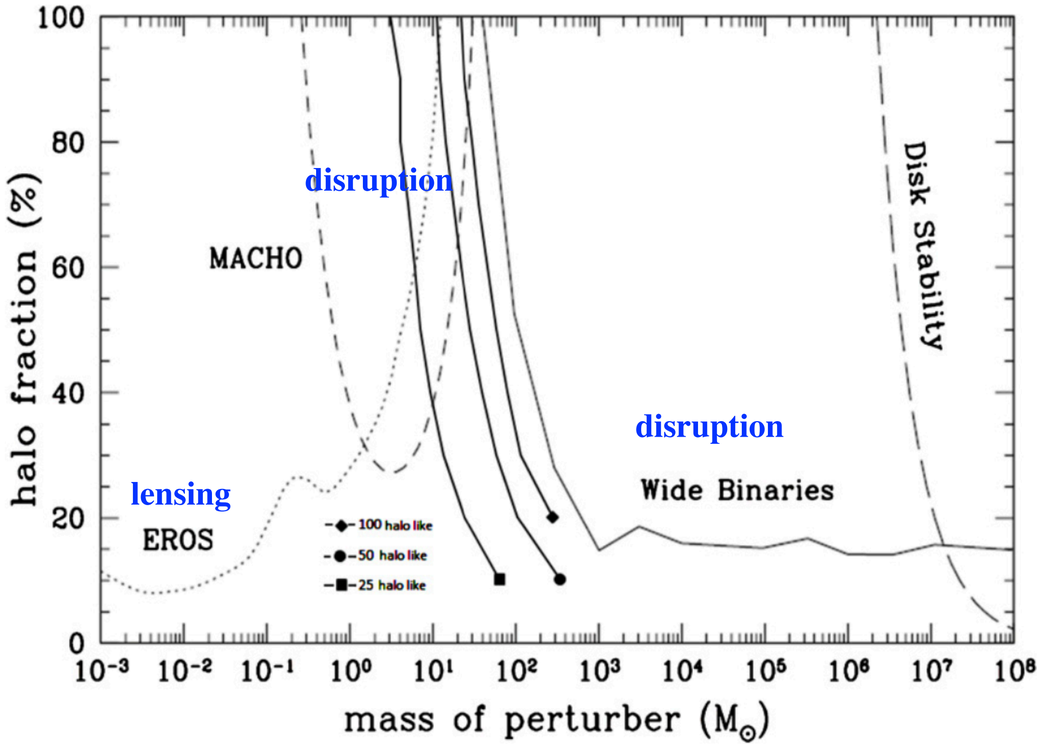




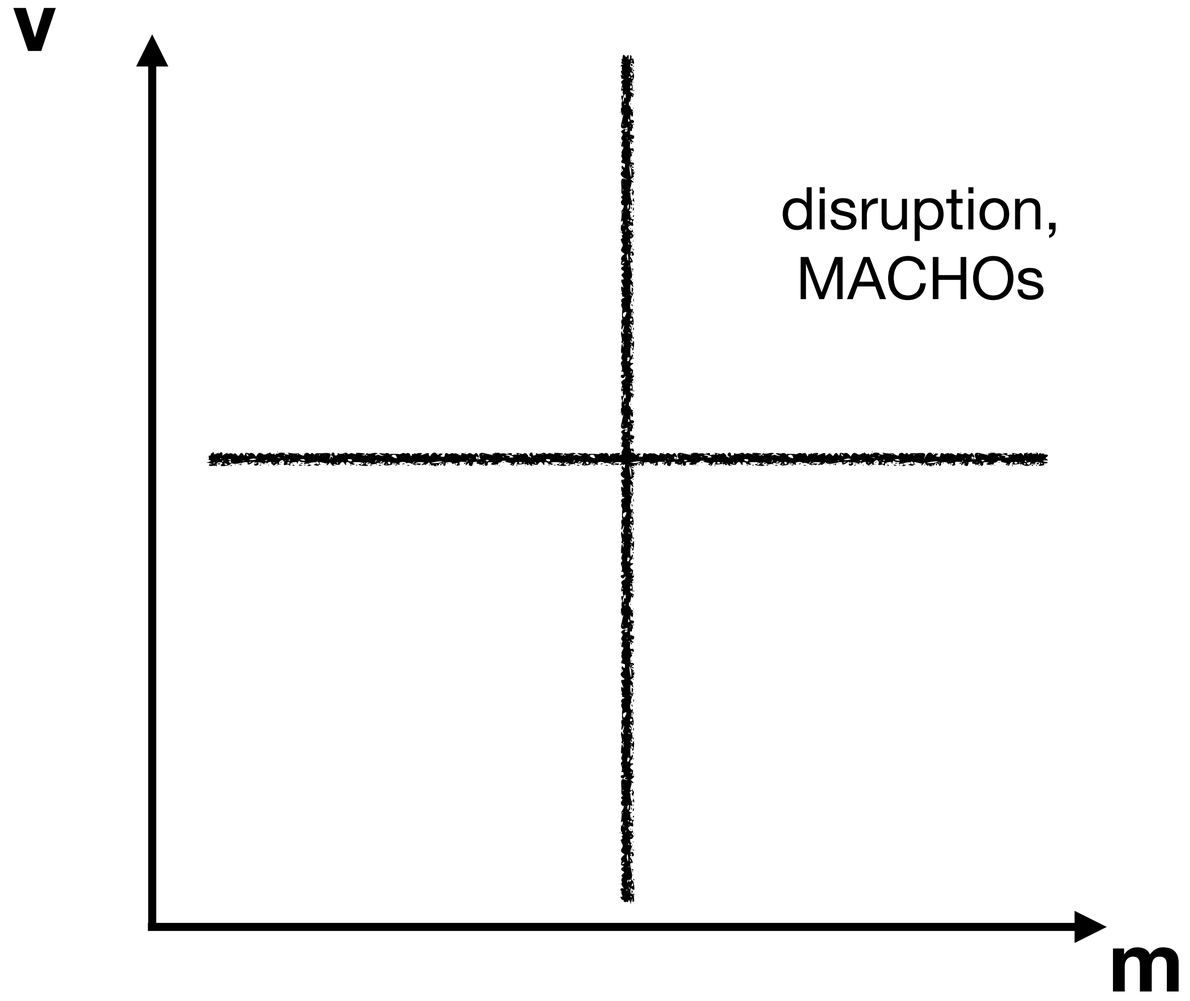
Landscape of Velocities and Masses



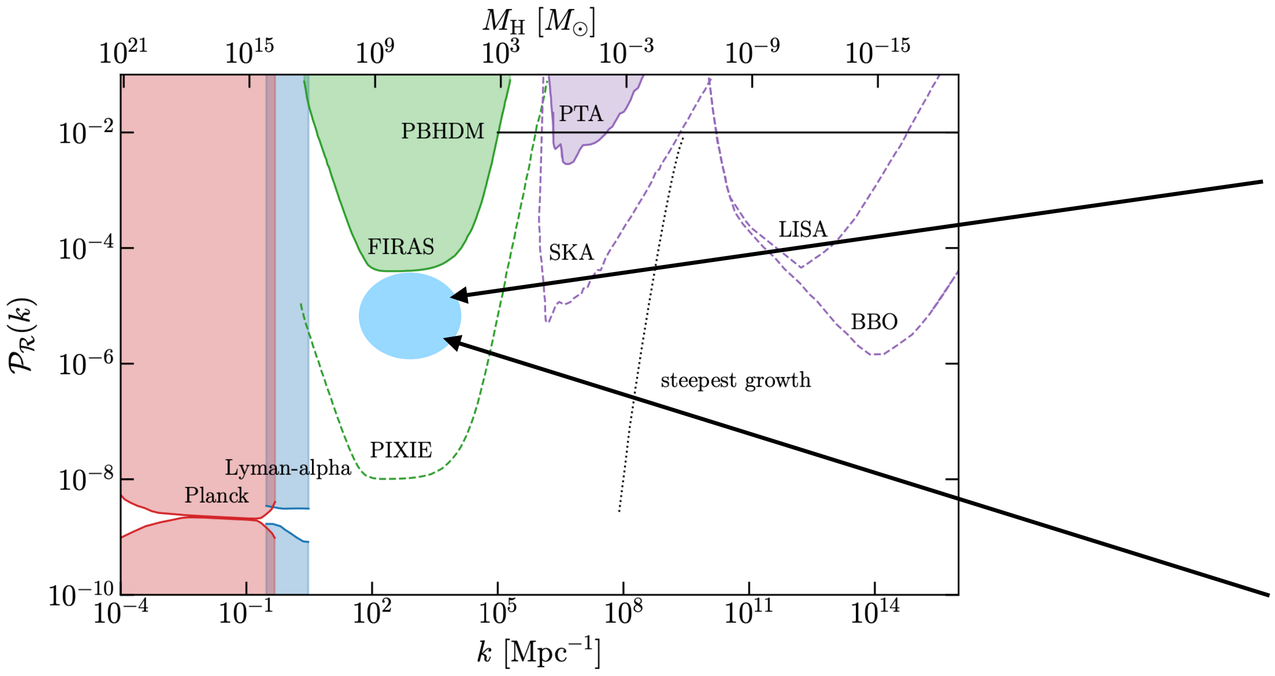
MACHOs, Dark Clumps

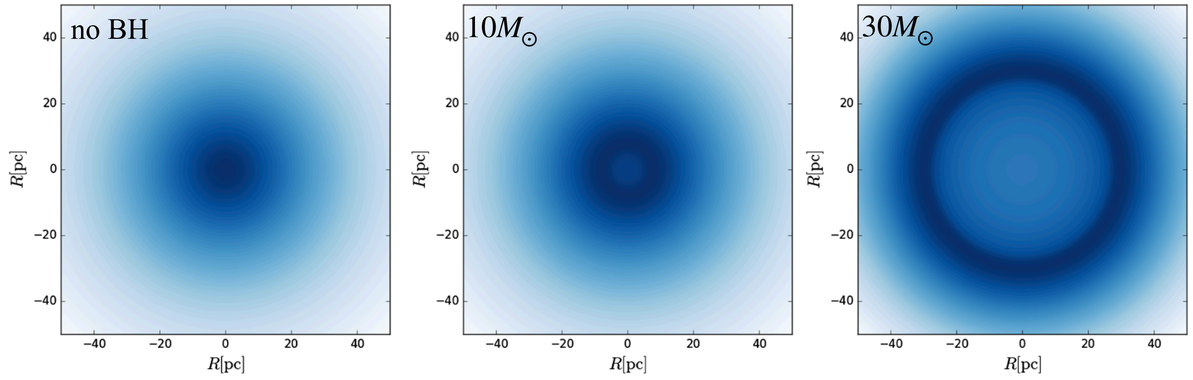


The end of the MACHO era- revisited
Monroy-Rodr´iguez, Allen, APJ 2014



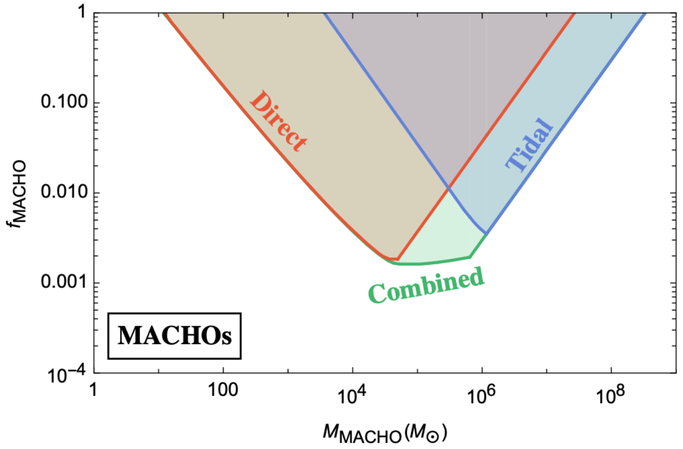
Puff Up Dwarf Galaxies





Koushiappas, Loeb (2017)

Ramirez, Buckley (2022)



Graham, Ramani (2022, 2023)

Dynamical Friction

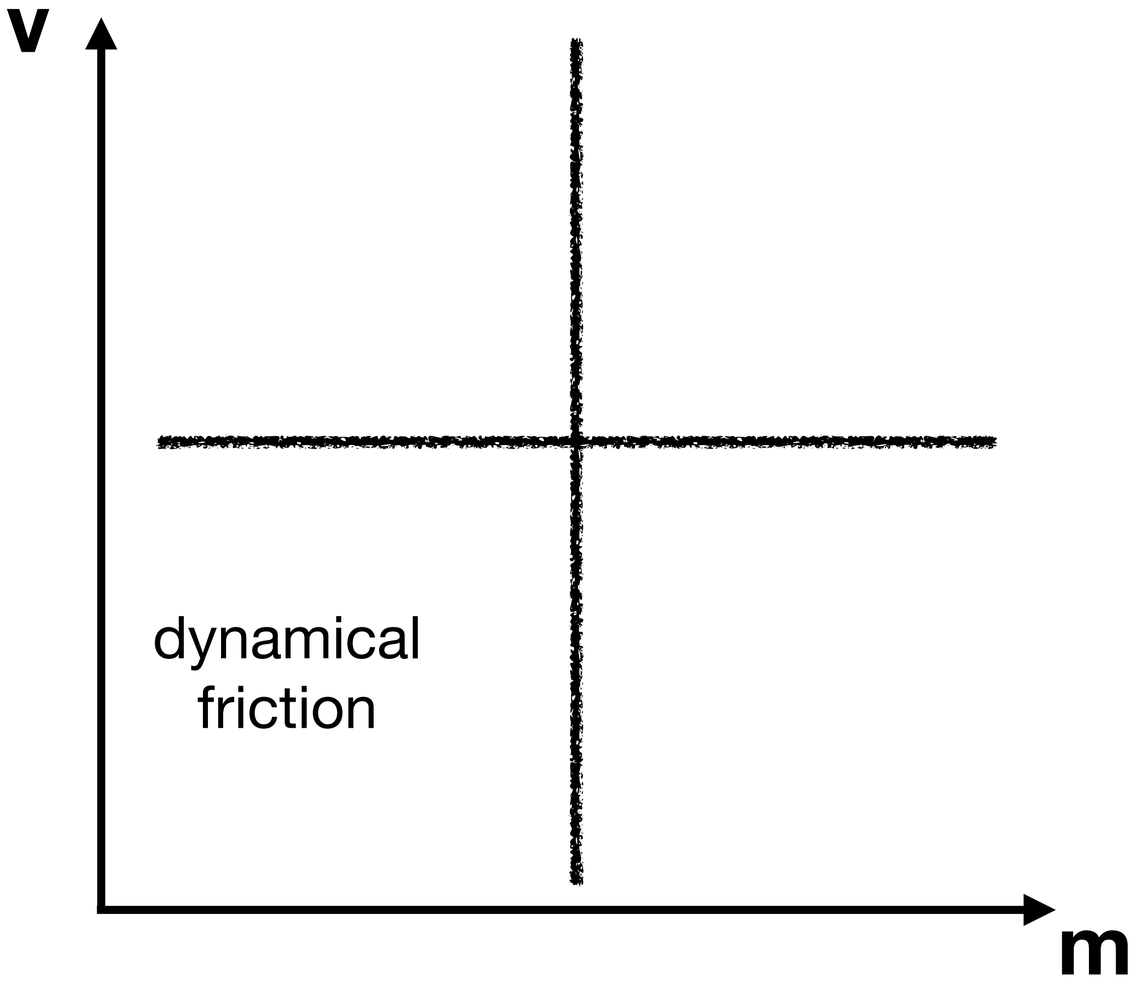
- Classic application to SMBH binaries (stars are perturbers)
- These days: apply to particle dark matter surrounding stars, BHs
- “Dark dressed black holes”, GW dephasing studies

  work of Bertone, Kavanagh et. al.
- Spike effects, SIDM, final parsec problem

  work of Hai-bo Yu et. al. , work of Cline et. al.
- DM constraints from binary pulsars

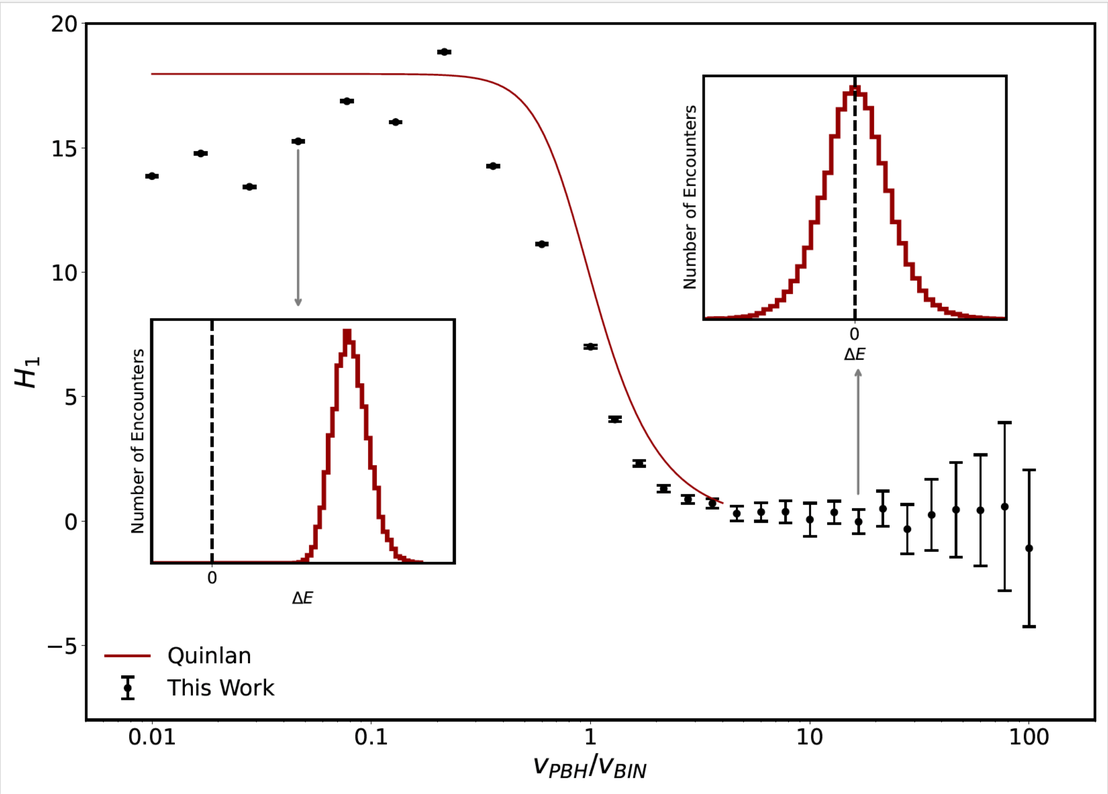
  work of Paolo Pani et. al.
- Simulation packages like KETJU

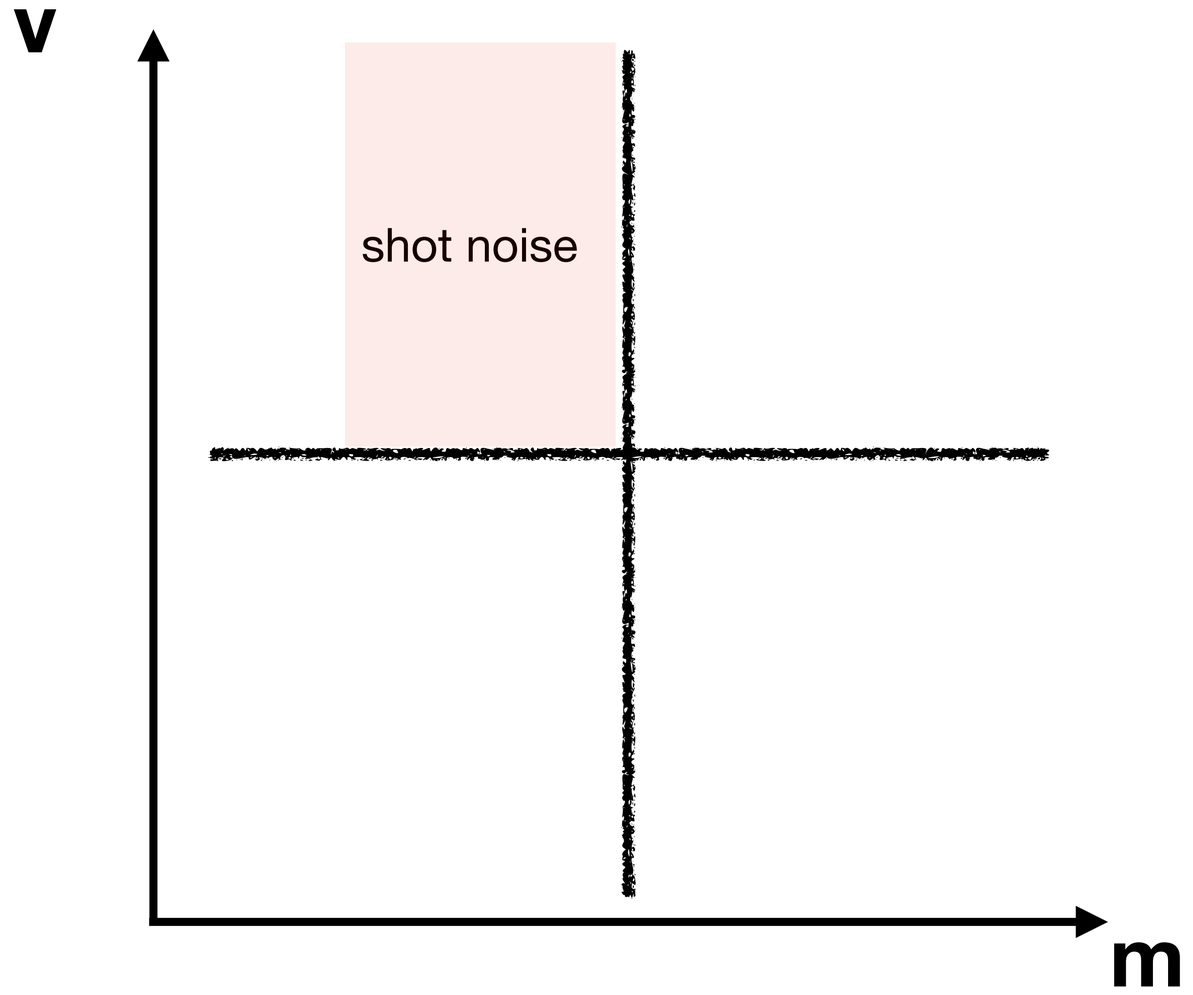
  Mannerkoski et. al. (2019, 2021)



Shot Noise Case 1: Numerous Encounters

- On average, nothing happens for large numbers of encounters at high velocities

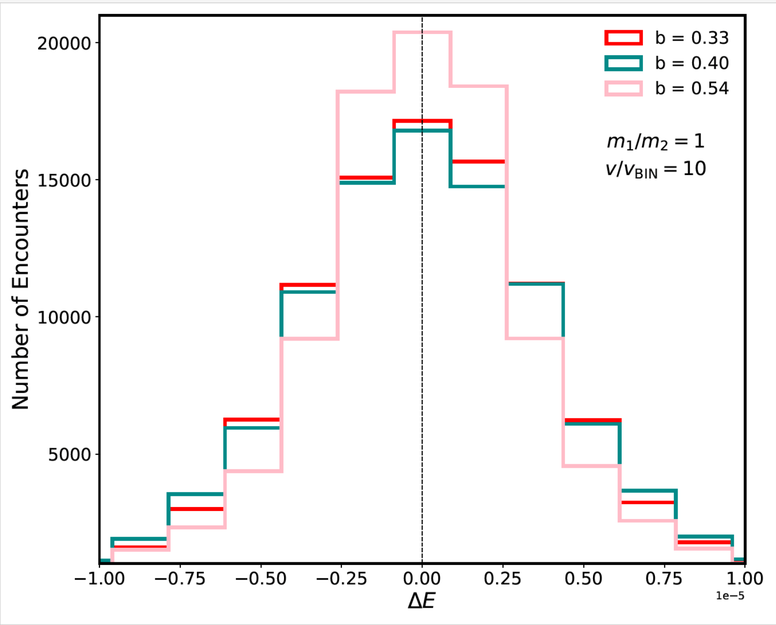


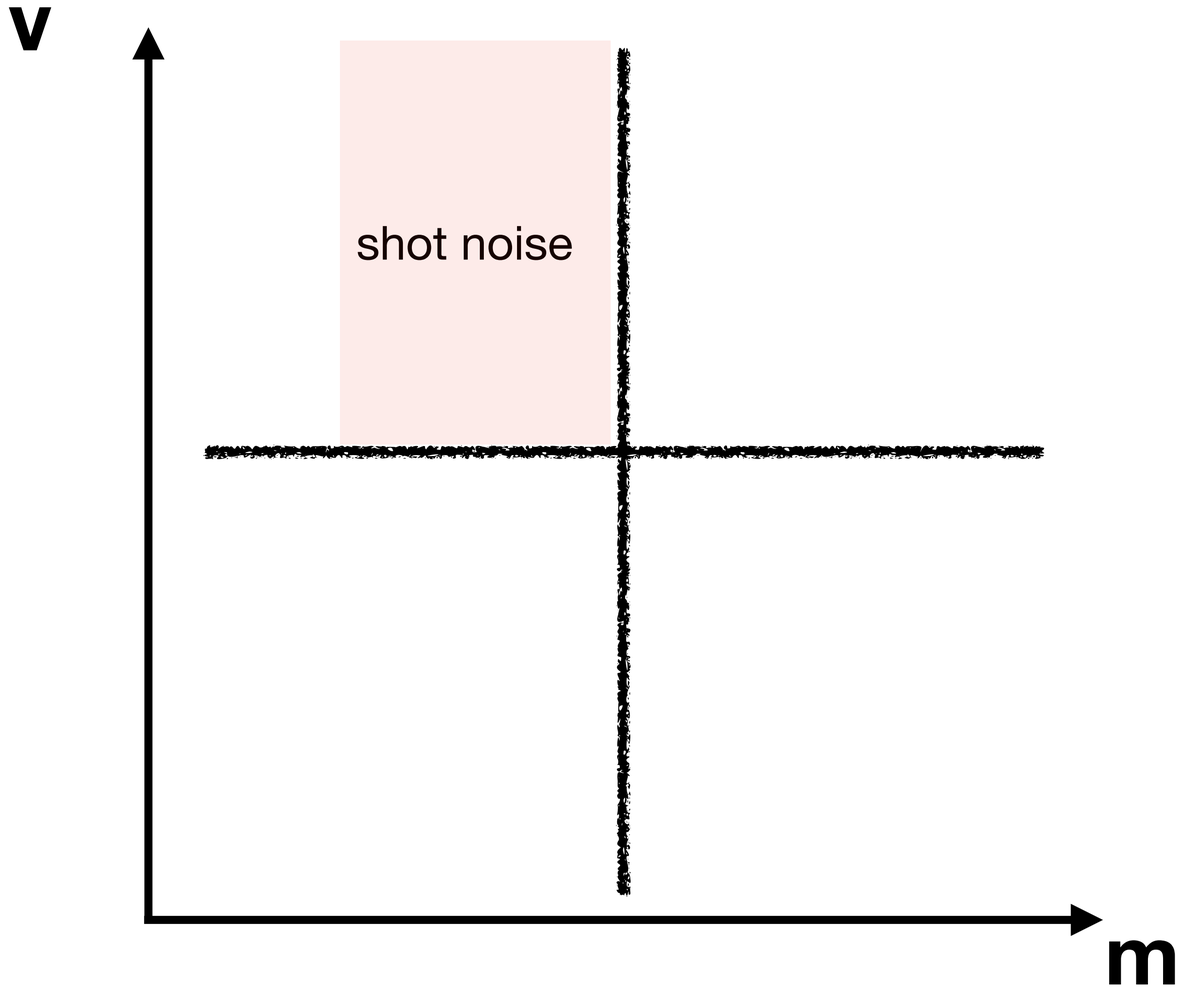


Bhalla, Lehmann, KS, Xu (ongoing)
reproduction of Quinlan (1996): “The dynamical evolution of massive black hole binaries”

Shot Noise Case 2: Fast and Fewrious Regime

- For few encounters, you get a statistical “shot noise” effect



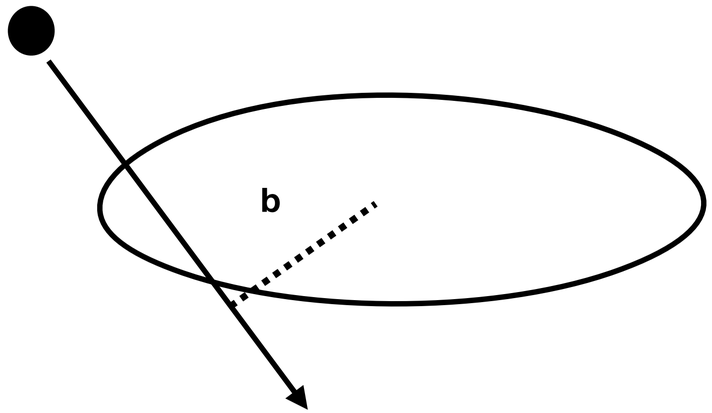


Bhalla, Lehmann, KS, Xu (ongoing)

Fast and Fewrious Regime

- Possible applications: PBH encounters with pulsar binaries, LISA white dwarf binaries, Solar System flybys

Binary Pulsar	Pulsar Mass $[M_\odot]$	Companion Mass $[M_\odot]$	Projected semi-major axis [lt-s]	Eccentricity	Inclination Angle [degrees]	Observed $\dot{P}_B$ $[s\,s^{-1}]$	$\Delta P_{\rm B}/m_{\rm PBH}$ [days/$M_\odot$]
B1259-63 [24, 25]	~ 2	~ 19.8	129627448	0.8698	154 ± 3	1.4×10^{-8}	111.29347
J1713-0747 [26]	1.33	0.29	32.3424	0.00007494	71.69	0.34×10^{-12}	87.65122
J1740-3052 [27]	~ 1.4	~ 19.5	756.90794	0.57887011	53	3×10^{-9}	29.36776
J1903+0327 [28]	1.667	1.029	105.5934628	0.43667841	77.47	-33×10^{-12}	83.79168
J2016+1948 [29]	~ 1	~ 0.29	150.773037	0.00147981	58.58	?	516.71468

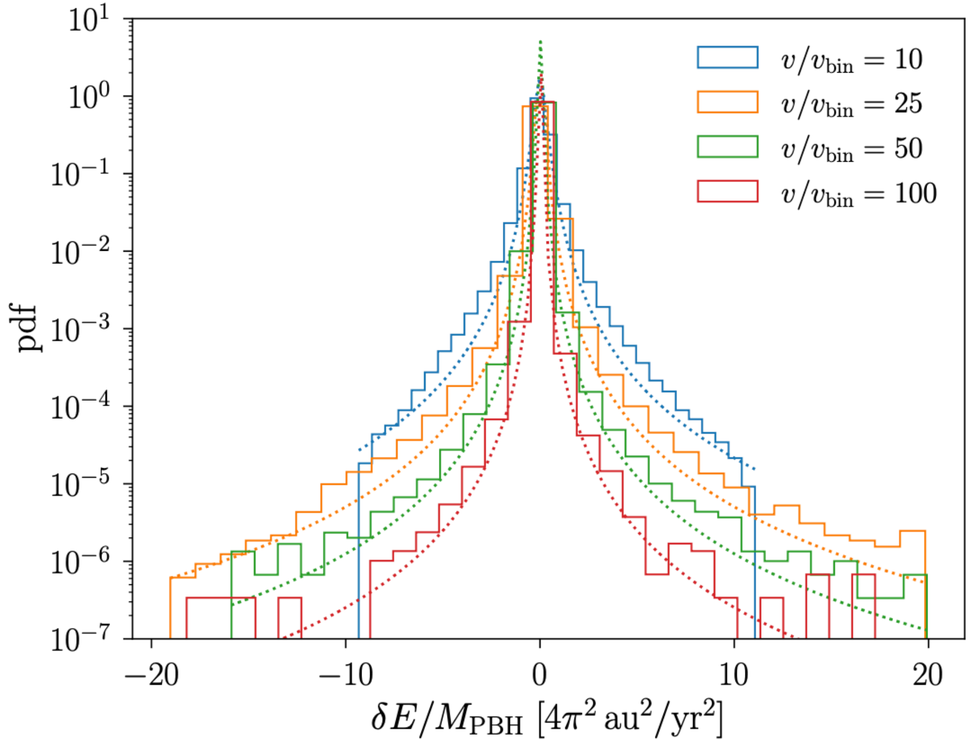


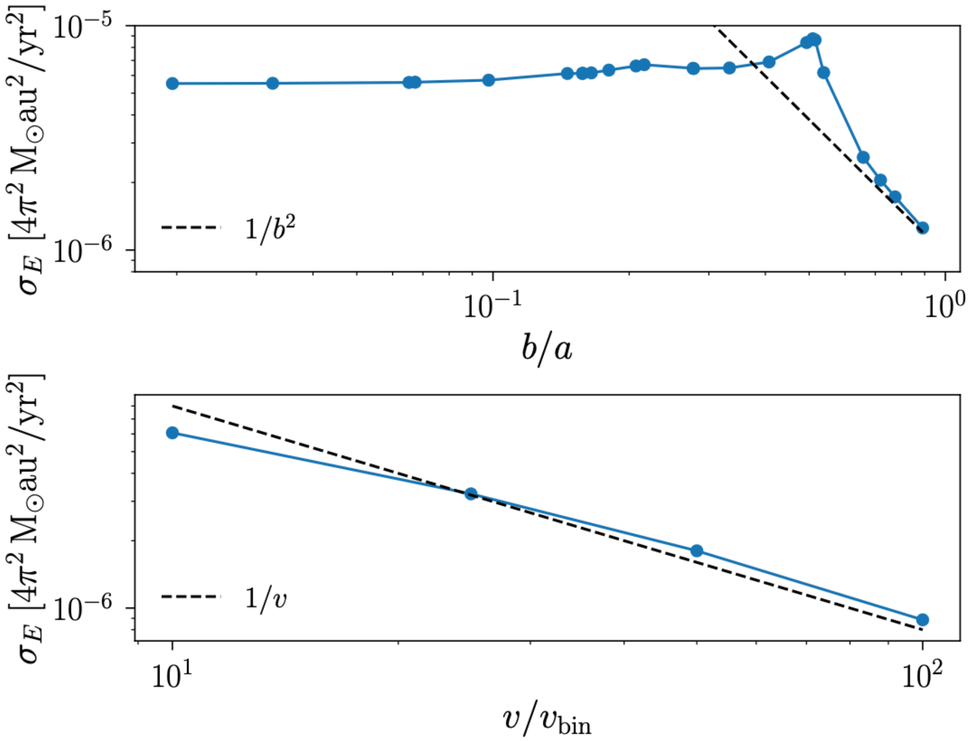
To quantitatively estimate the energy exchange between a binary system and a PBH, we simulate several encounters using the N-body code REBOUND [22]. The setup consists of a binary system with identical components of equal mass. The orbit of the binary is defined by five unique parameters: eccentricity, the cosine of the inclination ($[-1, 1]$), the longitude of the ascending node ($[0, 2\pi]$), the argument of pericenter ($[0, 2\pi]$), and the mean anomaly at some fixed time ($[0, 2\pi]$). The eccentricity is assumed to be zero, while the other four parameters that determine the binary's orientation and phase are selected randomly. Following Ref. [21], we define a

Bhalla, Lehmann, KS, Xu (ongoing)

Fast and Fewrious Regime

- For few encounters, you get a statistical “shot noise” effect

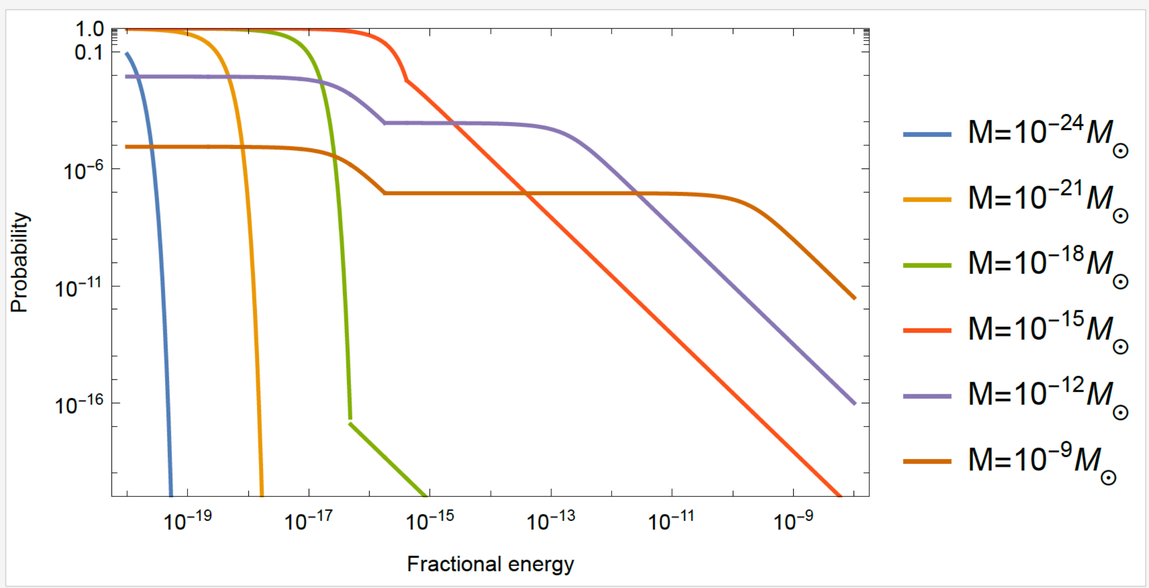


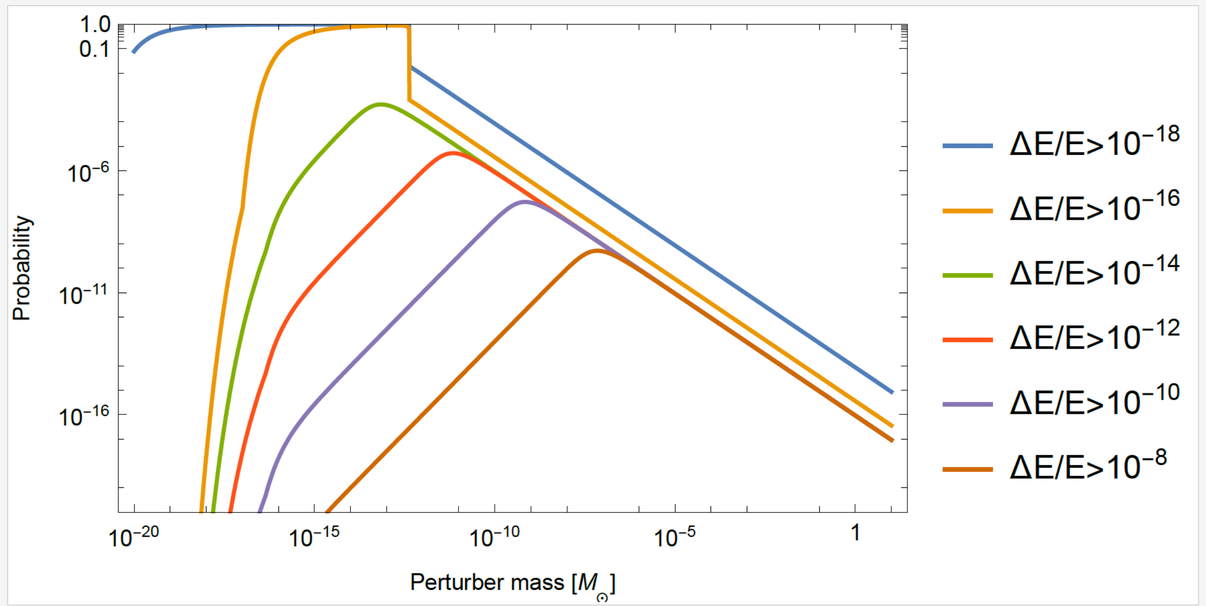


Bhalla, Lehmann, KS, Xu (ongoing)

Fast and Fewrious Regime

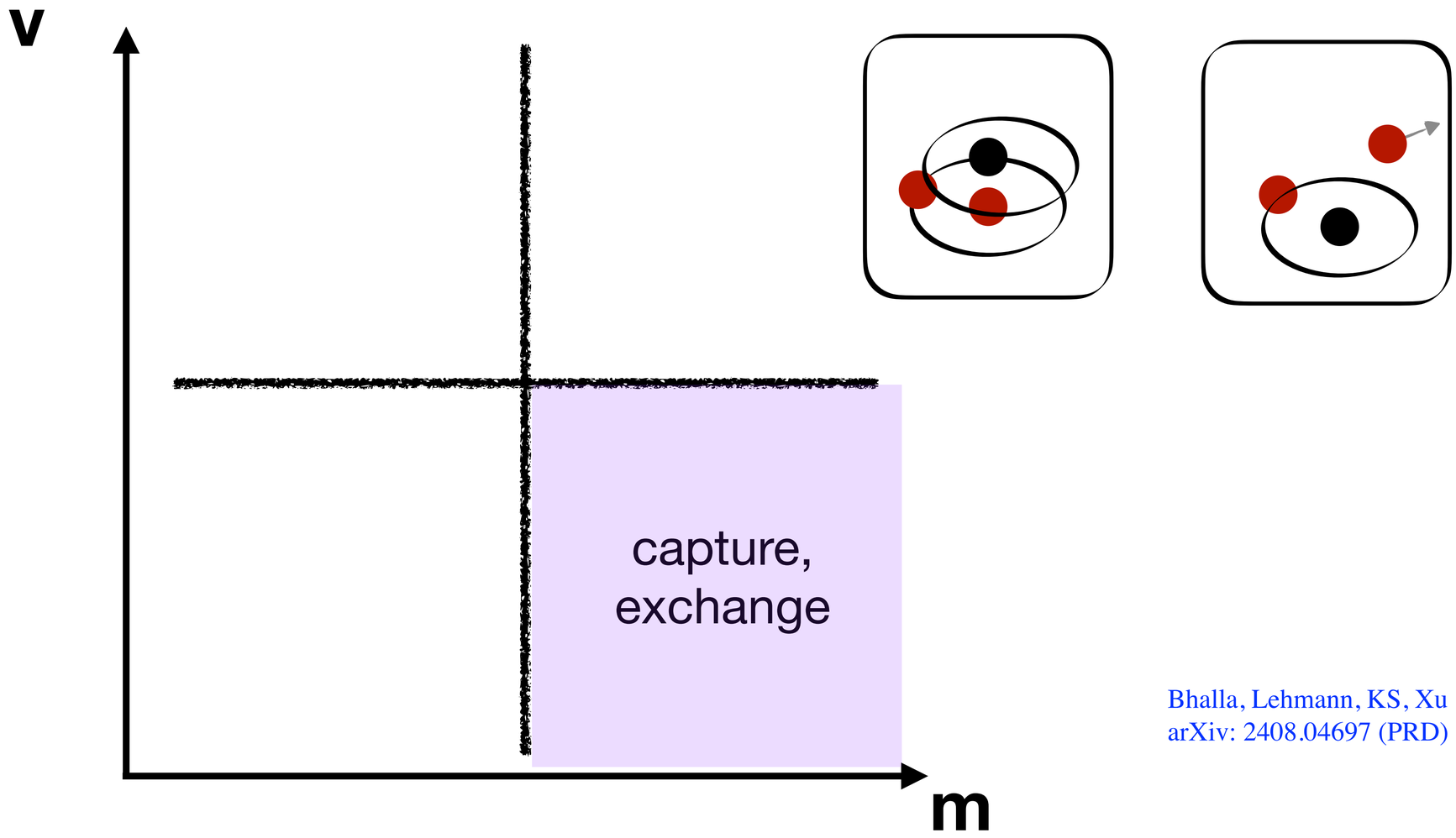
- Possible applications: PBH encounters with pulsar binaries, LISA white dwarf binaries, Solar System flybys





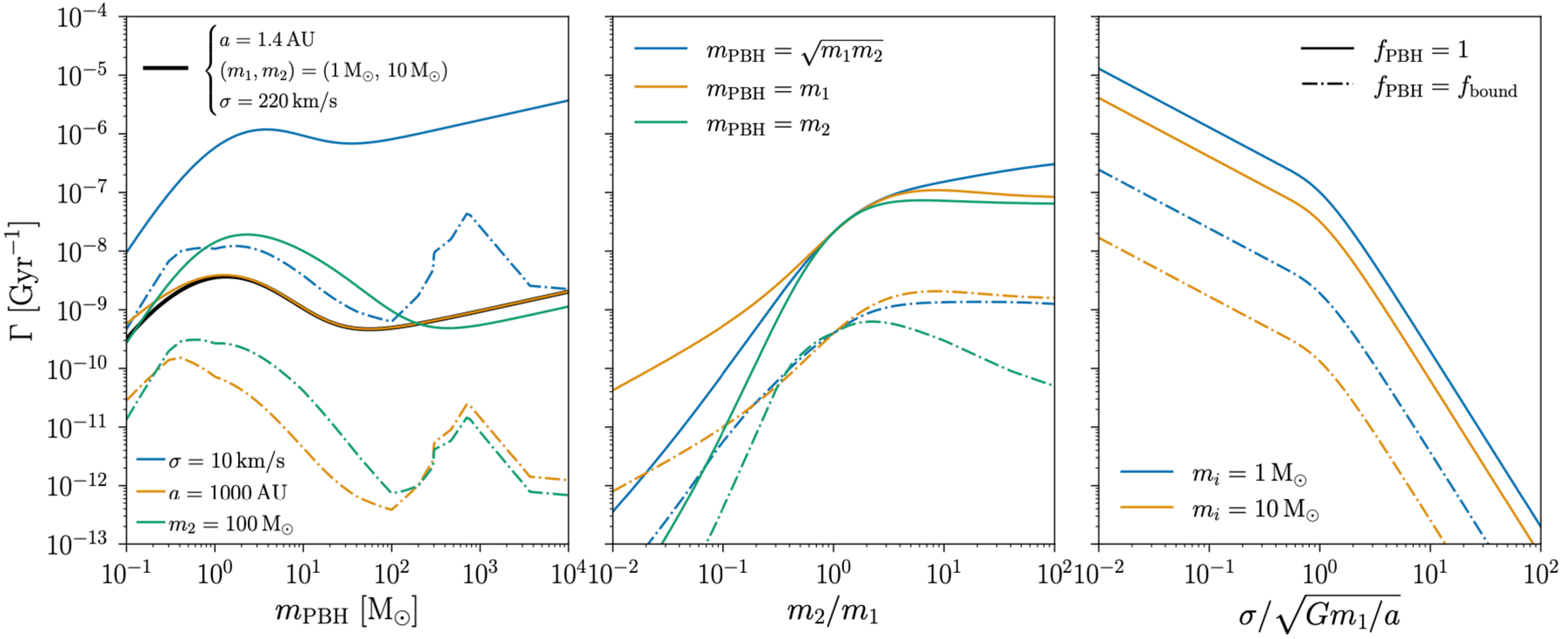
Bhalla, Lehmann, KS, Xu (ongoing)

Exchange/hardening



Bhalla, Lehmann, KS, Xu
arXiv: 2408.04697 (PRD)

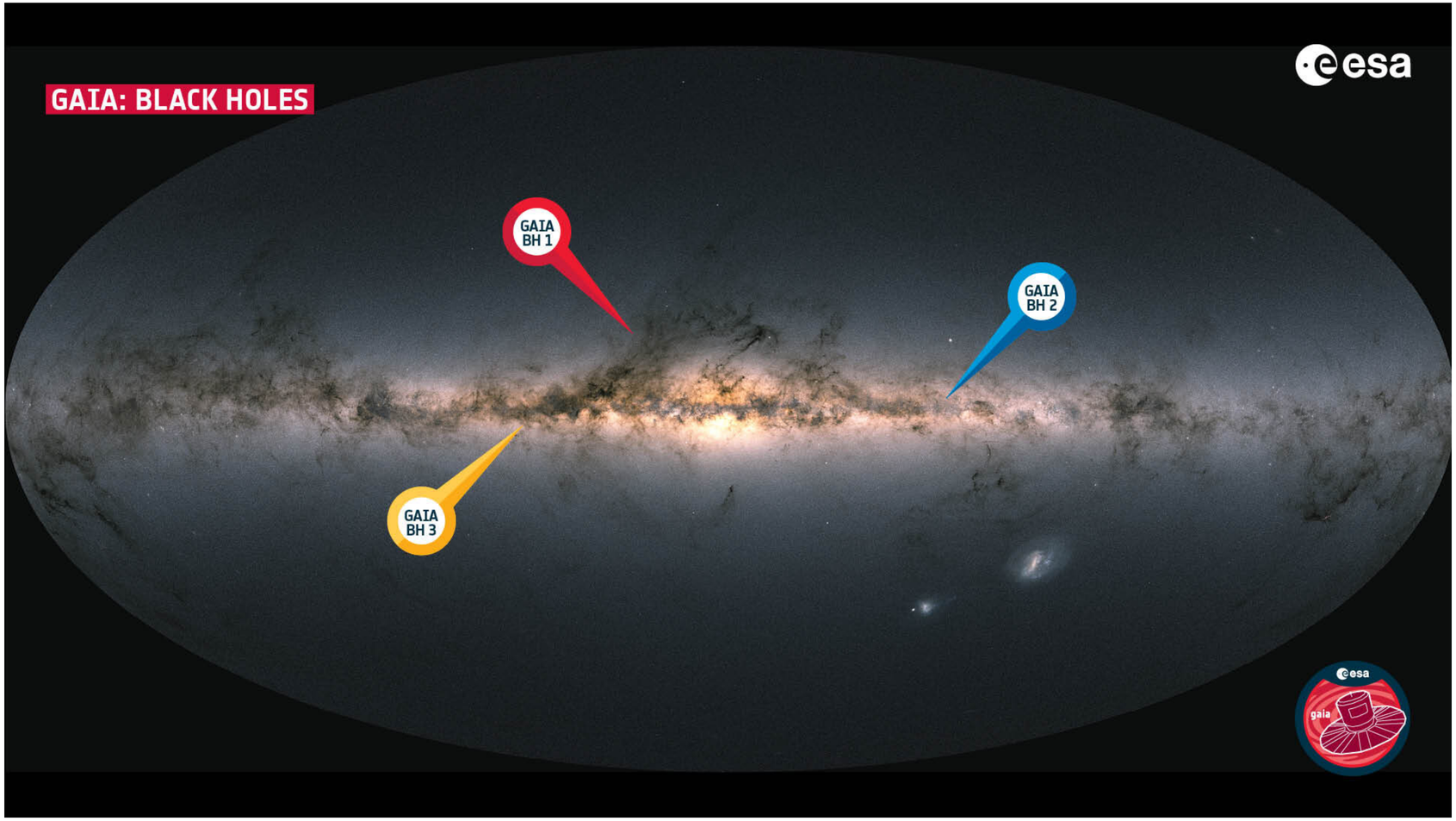
Exchange



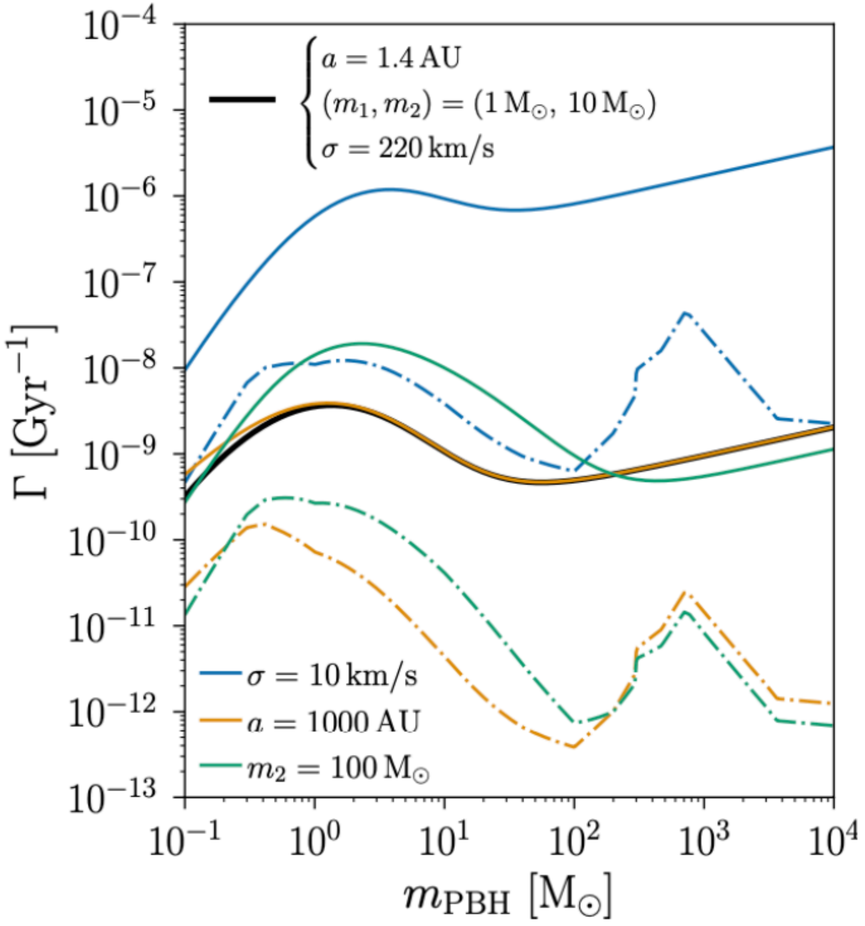
- Dependence on velocity dispersion, binary separation, and the second component.
- Increasing m_2 leads to a larger gravitational focusing cross section effect
- A lower DM velocity dispersion increases the exchange rate due to both the gravitational focusing and the PBH fraction on the velocity tail.

Bhalla, Lehmann, KS, Xu
arXiv: 2408.04697 (PRD)

Gaia Black Holes



Origin of Gaia Binaries



For all the Gaia BHs, there are three formation mechanisms

- Isolated evolution from stellar binaries, but disfavored
- Dynamical exchange with astro BHs
- Dynamical exchange with PBHs

It's difficult to distinguish between the two, but one can look at the exchange rate for a population level estimation.

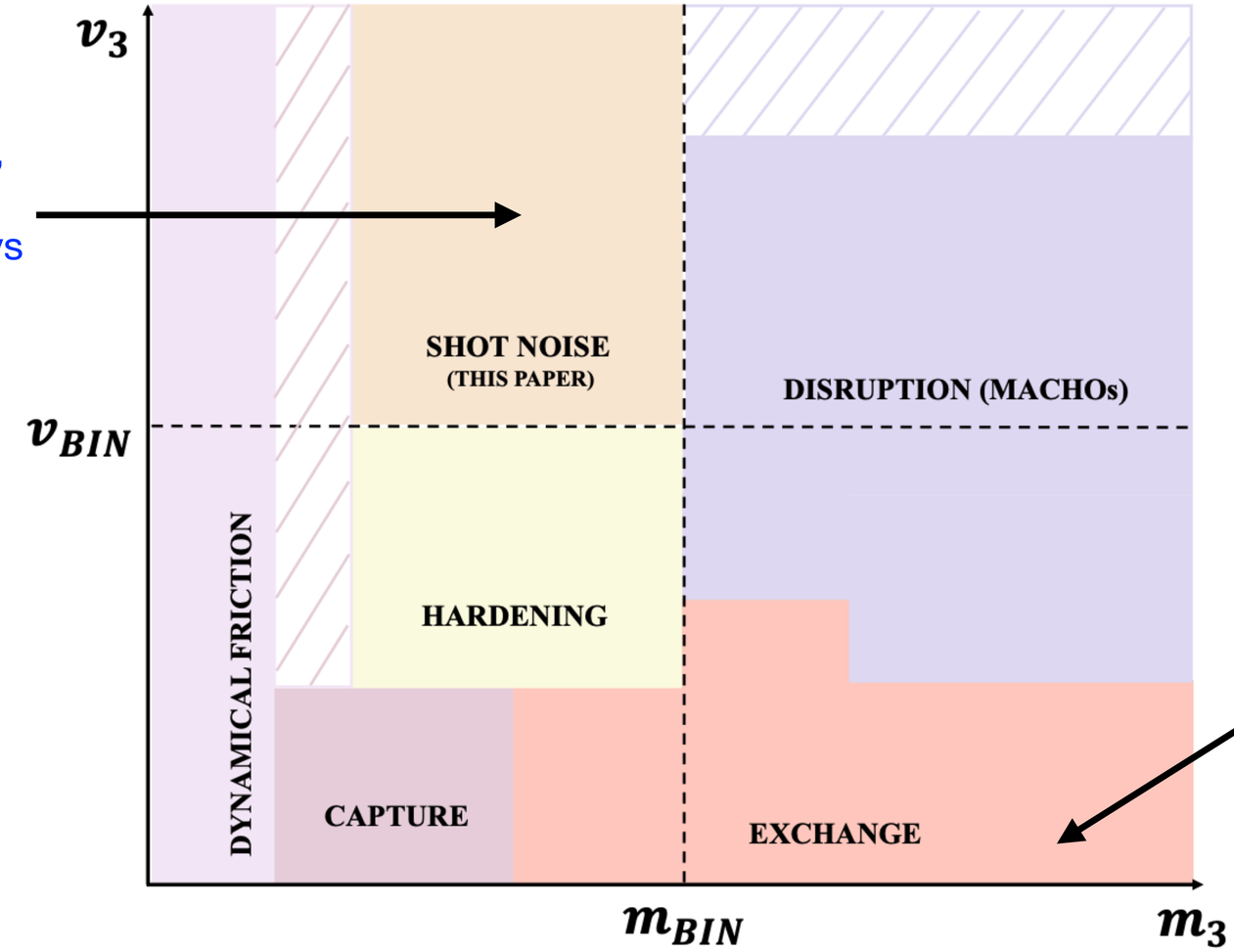
If PBH exchange gives a higher / comparable rate, more likely to explain Gaia BHs.

Bhalla, Lehmann, KS, Xu
arXiv: 2408.04697 (PRD)

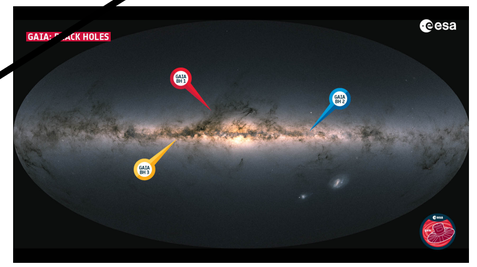
Landscape of Velocities and Masses

Important to cover the whole plane!!

LISA WD Binaries,
Binary Pulsars,
Solar System Flybys



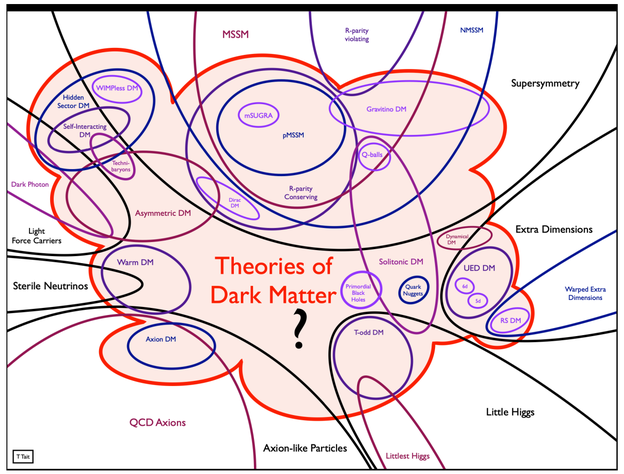
Gaia Stellar-BH Binaries

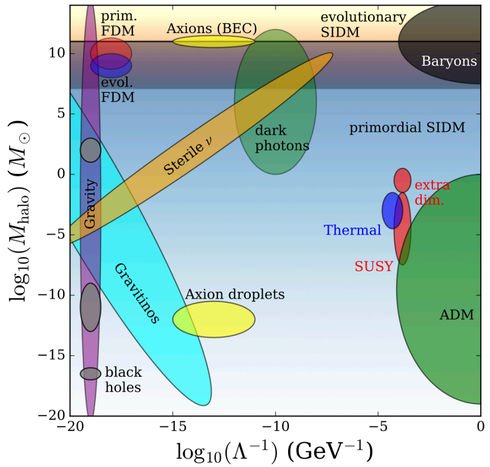


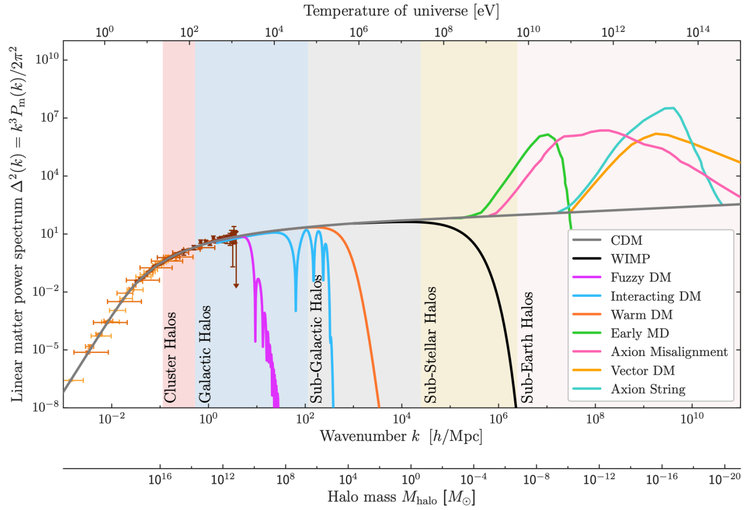
Bhalla, Lehmann, KS, Xu (ongoing)

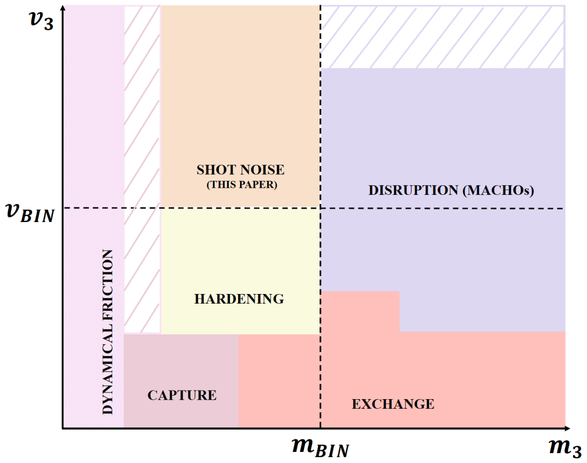
New Landscapes

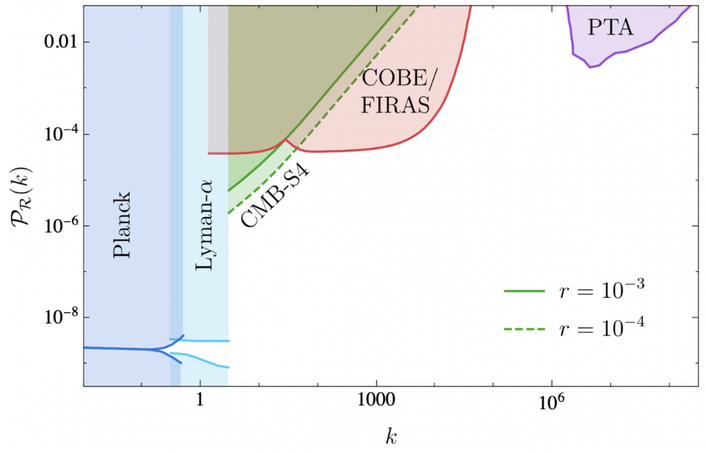
Important to cover as much as possible!





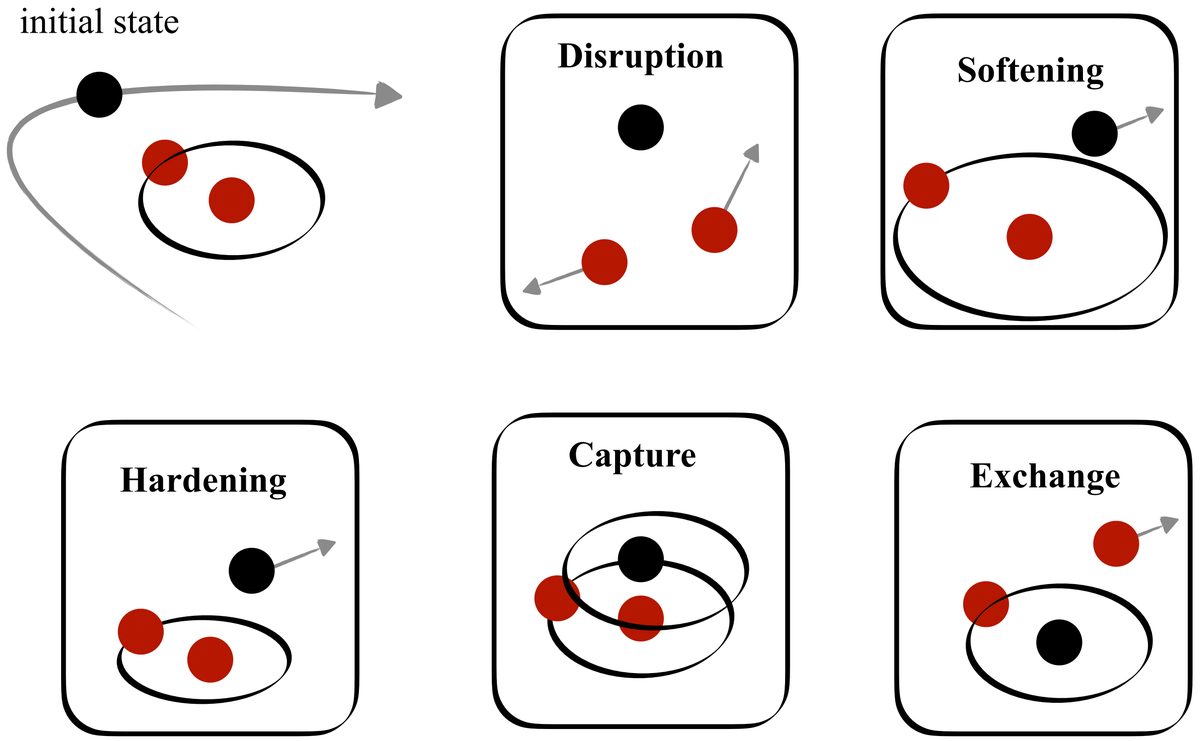






Backup Slides

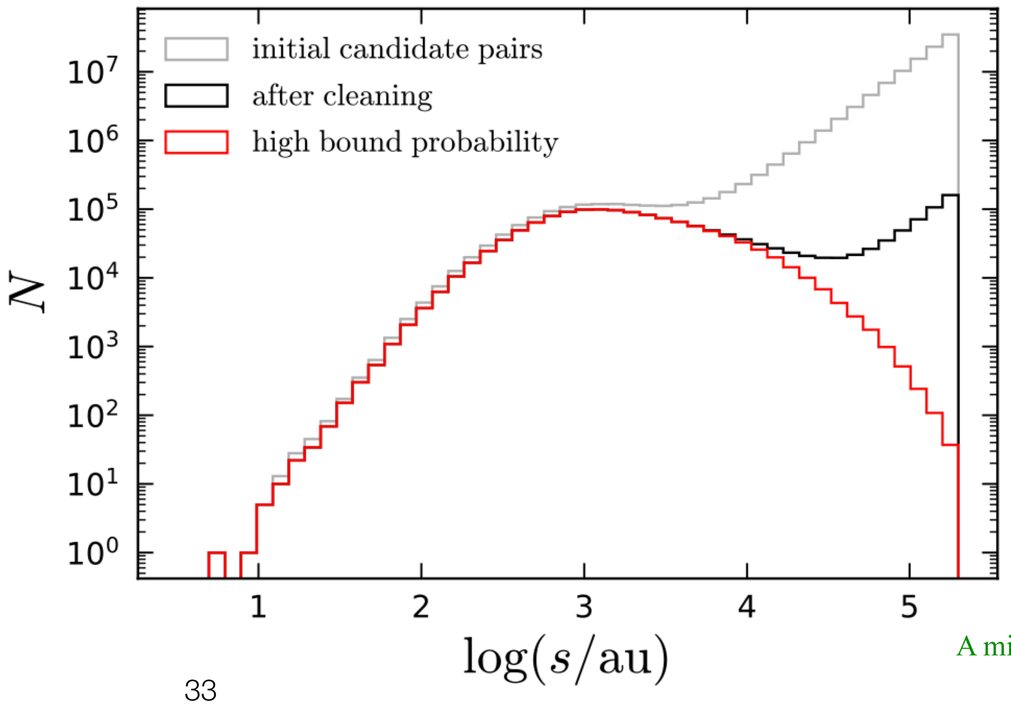
Landscape of Interaction Types with Stellar Binaries



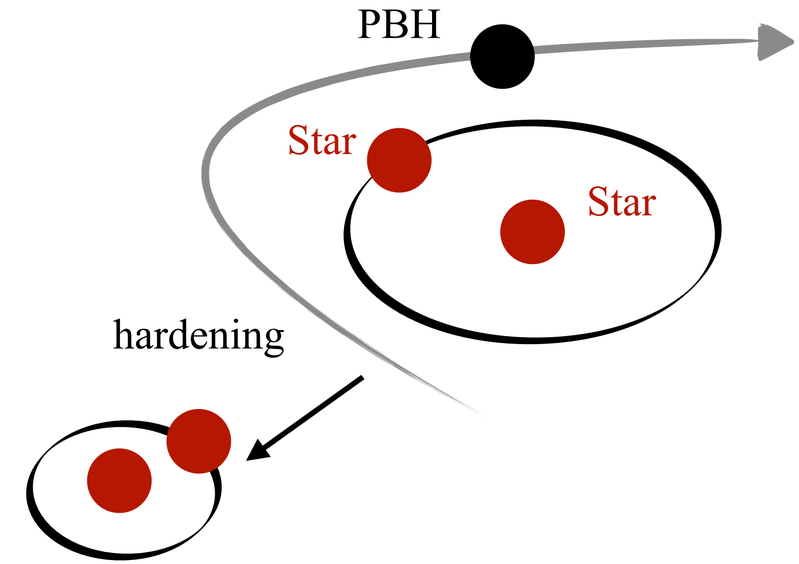
Hardening

We need **wide binaries** such that the encounter cross section is large.

Opportunity with future Gaia binary data.



A million binaries from *Gaia* eDR3
El-Badry, et al, MNRAS 2021

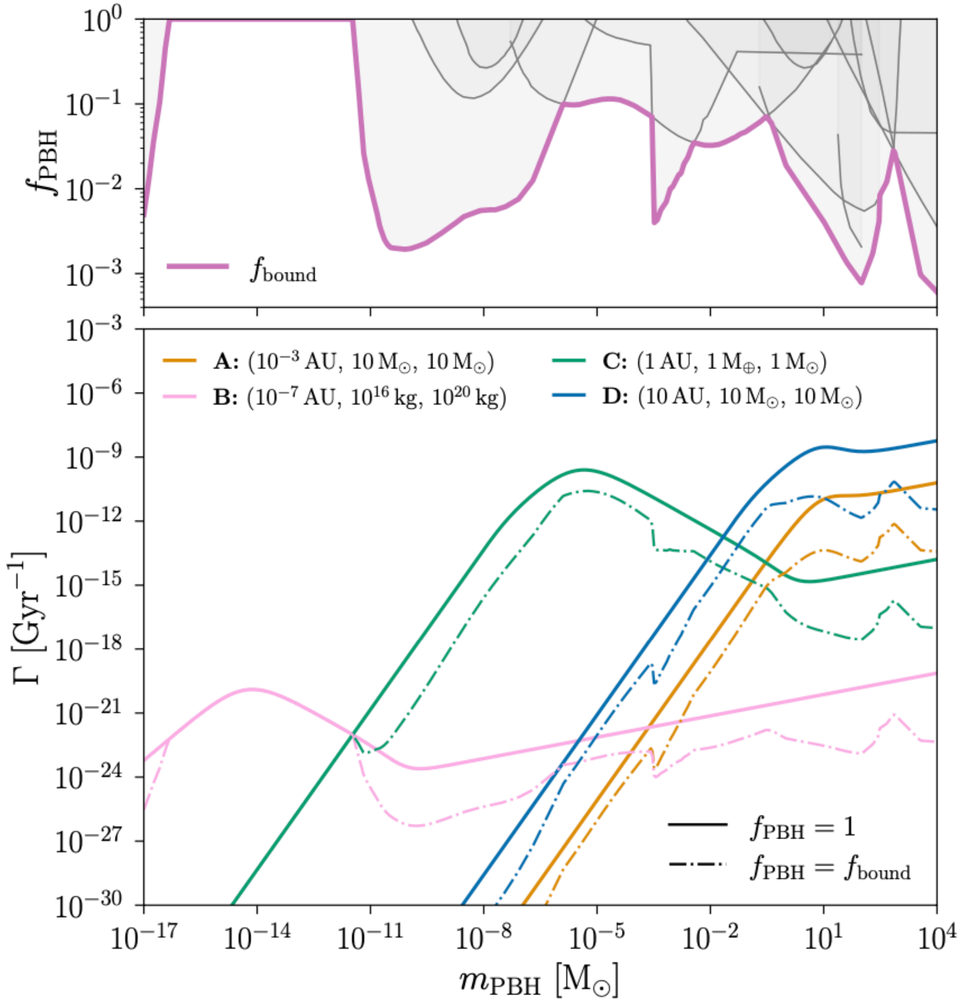


binary orbit shrinking

One problem for hardening is that PBH velocity is much larger than the orbital velocity of wide binaries. Hardening effect suppressed.

Exchange

- Exchange event rate of four typical systems Compact Object, Asteroid, Exoplanet, and Stars.
- PBH exchange rate peaks when PBH mass is comparable to the component mass.
- Solid curve shows when PBHs make up all DM, and dashed curves show the reduced rate due to existing constraints.



How to Observe?

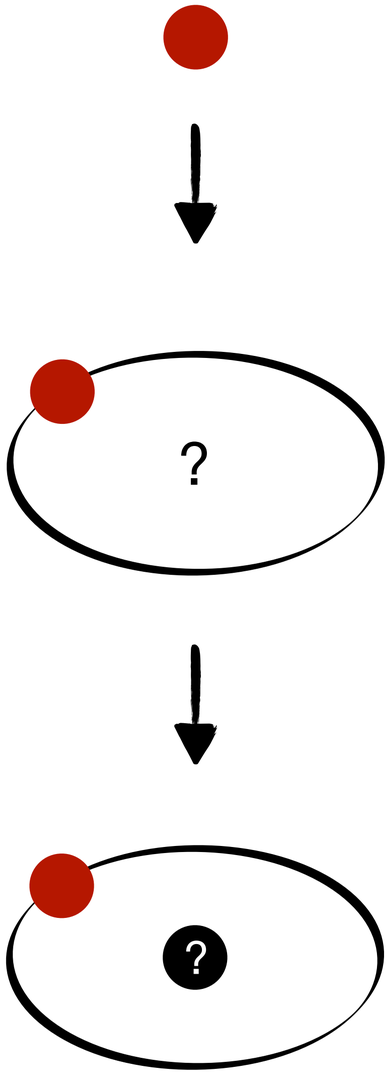
1. See an astrophysical object.

2. Find it's in a binary with an invisible component.

   could be a BH

3. Is the BH primordial?

   distinguish from astro BHs



PBH exchange in astro systems

How is the binary measured?
What is PBH exchange rate?
How to distinguish from astro BH?

Anomalous BH-Star Binaries

	Stellar type	$M_{\rm BH}[{\rm M}_\odot]$	$M_*[{\rm M}_\odot]$	$a[{\rm R}_\odot]$	P[days]	e	[Fe/H]
Gaia BH1	G-type main-sequence	$9.62^{+0.18}_{-0.18}$	$0.93^{+0.05}_{-0.05}$	$301.55^{+2.15}_{-2.15}$	$185.59^{+0.05}_{-0.05}$	$0.45^{+0.005}_{-0.005}$	-0.2
Gaia BH2	Red giant	$8.94^{+0.34}_{-0.0.34}$	$1.07^{+0.19}_{-0.19}$	$1066.55^{+17.20}_{-17.20}$	$1276.7^{+0.6}_{-0.6}$	$0.5176^{+0.0009}_{-0.0009}$	-0.2
Gaia BH3	G-type giant	$32.7^{+0.82}_{-0.82}$	$0.76^{+0.05}_{-0.05}$	$2477.035^{+58.058}_{58.058}$	$4253.1^{+98.5}_{-98.5}$	$0.7291^{+0.0048}_{-0.0048}$	-2.6

$1\ \text{au} \simeq 214\, R_\odot$

El-Badry, 2023, 2024
Fantoccoli et al 2410.17323

- Gaia BH1 and BH2 are challenging in similar ways
  - Orbit is smaller than progenitor star of $30-50 M_\odot$ mass with $\sim$10 au radius; but larger than that expected from common envelope evolution $\sim 10^{-2}$ au.
  - Metallically is close to solar neighborhood stars, i.e. not affected by partner's evolution into BH.
- Isolated stellar evolution faces challenges in fitting Gaia BH1 and BH2.
- Location: thin disk BHs, not very efficient astro BH exchange.

Anomalous BH-Star Binaries

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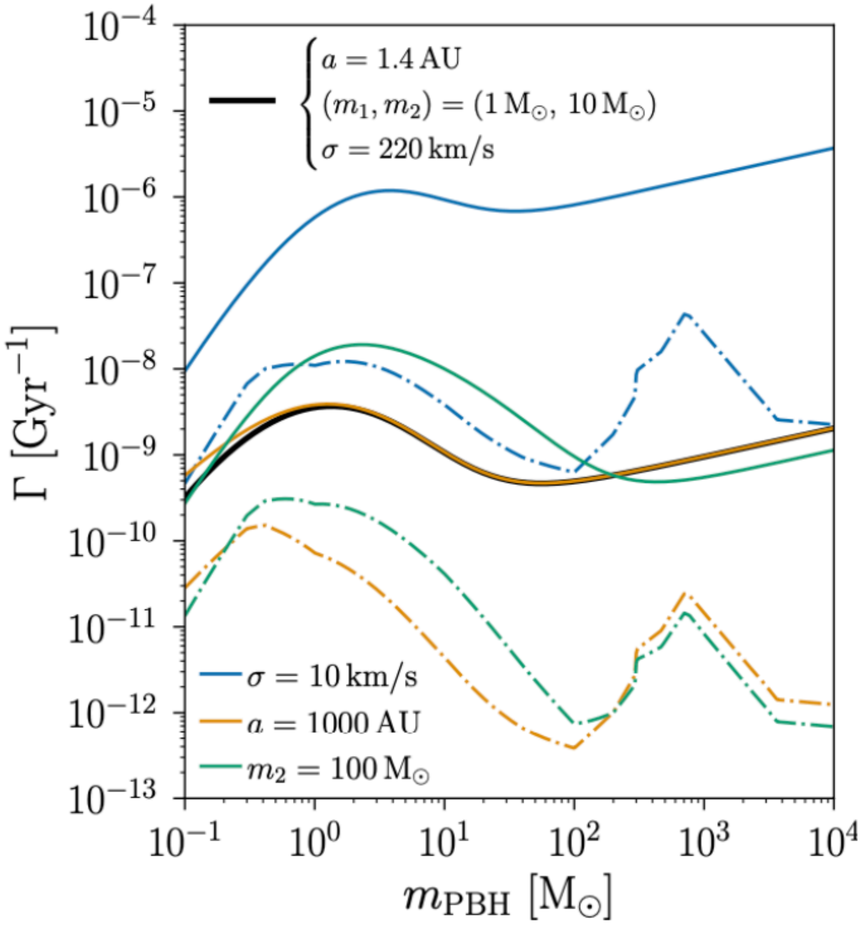
- Gaia BH3 can marginally avoid the common envelope.
- BH3 has low metallicity, hints for origin from ED-2 stellar stream / globular cluster.
- It’s possible BH3 is formed with isolated evolution in globular clusters, but more simulation needed.

Origin of Gaia Binaries



- If from exchange of astro BH and isolated evolution

$$R_\star^{\mathrm{dyn}} \sim 10^{-7}\,\mathrm{M}_\odot^{-1} \quad \text{(dynamical formation)},$$
$$R_\star^{\mathrm{iso}} \sim 10^{-10}\text{–}10^{-8}\,\mathrm{M}_\odot^{-1} \quad \text{(isolated binary evolution)}.$$

- If from PBH exchange with halo velocity dispersion

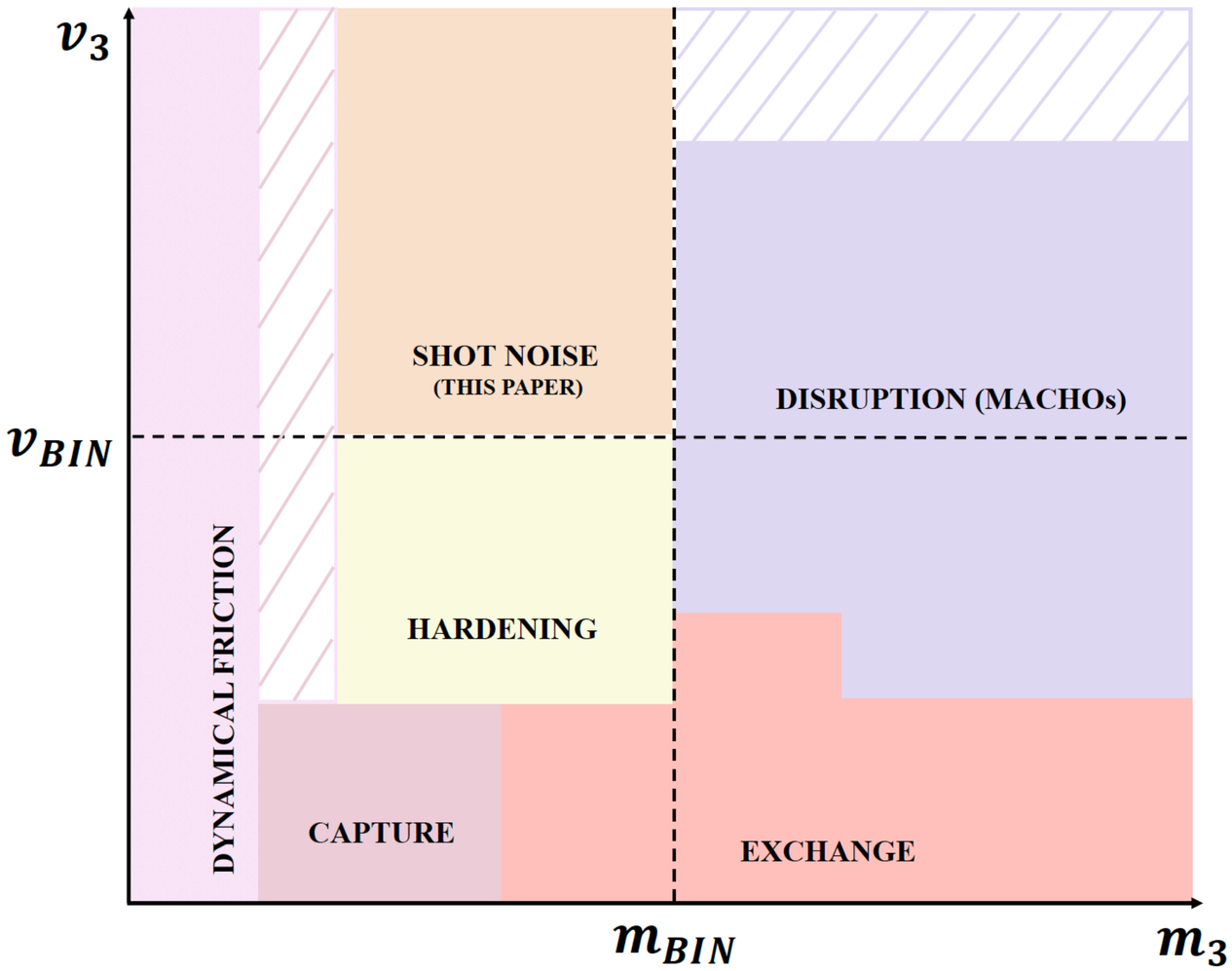
$$R_{\mathrm{PBH}} \sim \mathcal{O}(\mathrm{few}) \times 10^{-8}\,\mathrm{M}_\odot^{-1}$$

- If from PBH exchange, enhanced with cluster dispersion

$$R_{\mathrm{PBH}} \sim \mathcal{O}(\mathrm{few}) \times 10^{-6}\,\mathrm{M}_\odot^{-1}$$

The PBH exchange rate can exceed astro BH exchange with the enhancement from low velocity dispersion, possibly from open clusters.

Landscape of Velocities and Masses



Bhalla, Lehmann, KS, Xu (ongoing)

Anomalous BH-Star Binaries

For all the Gaia BHs, there are three formation mechanism

- Isolated evolution from stellar binaries, but disfavored
- Dynamical exchange with astro BHs
- Dynamical exchange with PBHs

It's difficult to distinguish between the two, but one can look at the exchange rate for a population level estimation.

→ If PBH exchange gives a higher / comparable rate, more likely to explain Gaia BHs.

For all the Gaia BH3, there are three formation mechanism

- Isolated evolution from stellar binaries, but disfavoured
- Dynamical exchange with astro BHs
- Dynamical exchange with PBHs

- If from exchange of astro BH and isolated evolution

$$R_\star^{\rm dyn} \sim 10^{-7}\,{\rm M}_\odot^{-1} \quad \text{(dynamical formation)},$$
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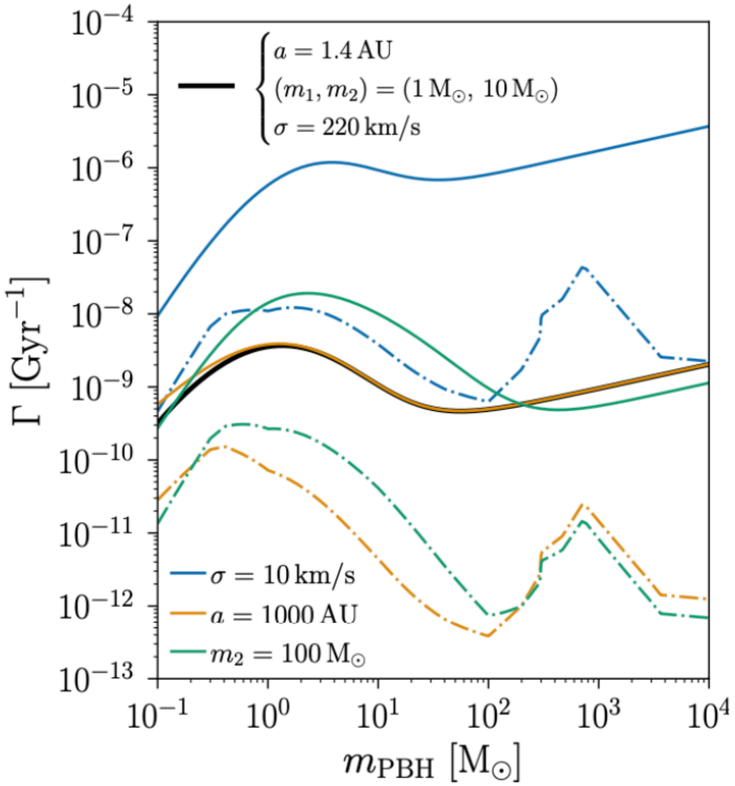
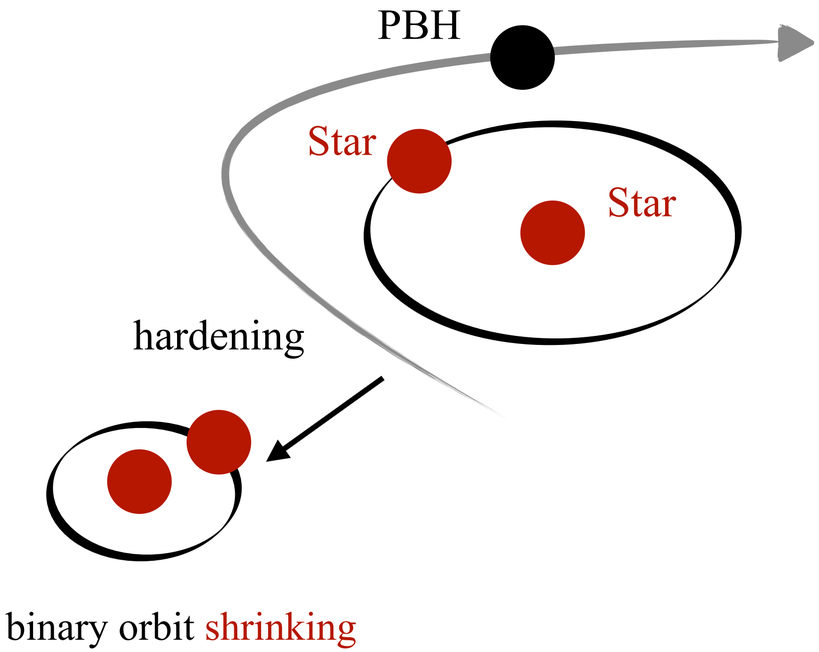


Hardening

- If the perturber is PBH, the velocity is fixed by the DM velocity $\sigma_3 \to \sigma_\chi \sim 10^{-3}$.
- The binary binding energy vs. PBH kinetic energy relation is determined by $M_{\rm PBH}$.

A stellar binary behaves as **hard binary for light PBHs** and as **soft binary for heavy PBHs**



Hardening

- Binary of stars $m_{1,2}$ is described by the **binding energy** E_b and the **semi-major axis** a. $E_b = -\frac{G_N m_1 m_2}{2a}$
- Energy is transferred between the binary and the perturber during the three-body encounter process.
- **Heggie's law** in stellar dynamics: **Hard binaries tend to become harder** and **soft binaries tend to become softer.**

Binary Evolution in Stellar Dynamics, D. Heggie

- Whether a binary is hard or soft depends on the kinetic energy of the perturber,

Hard binary: $\frac{G_N m_1 m_2}{2a} > \frac{1}{2} m_3 \sigma_3^2$

binary **lose energy** to perturber
E_b more negative
axis shrinks $a_f < a_i$

Soft binary: $\frac{G_N m_1 m_2}{2a} < \frac{1}{2} m_3 \sigma_3^2$

binary **gain energy** from perturber
E_b less negative
axis expands $a_f > a_i$

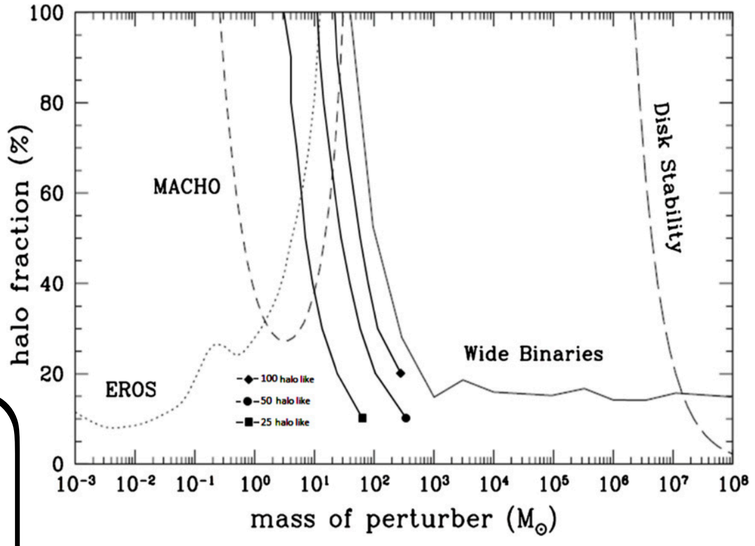
- If the perturber is PBH, the velocity is fixed by the DM velocity $\sigma_3 \to \sigma_\chi \sim 10^{-3}$.
- The binary binding energy vs. PBH kinetic energy relation is determined by $M_{\rm PBH}$.

A stellar binary behaves as **hard binary for light PBHs** and as **soft binary for heavy PBHs**

Disruption/Capture

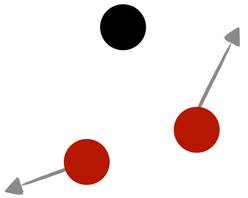
Heavy PBH will destroy the binary.

The observed existence of binaries is used to constrain the PBH abundance.

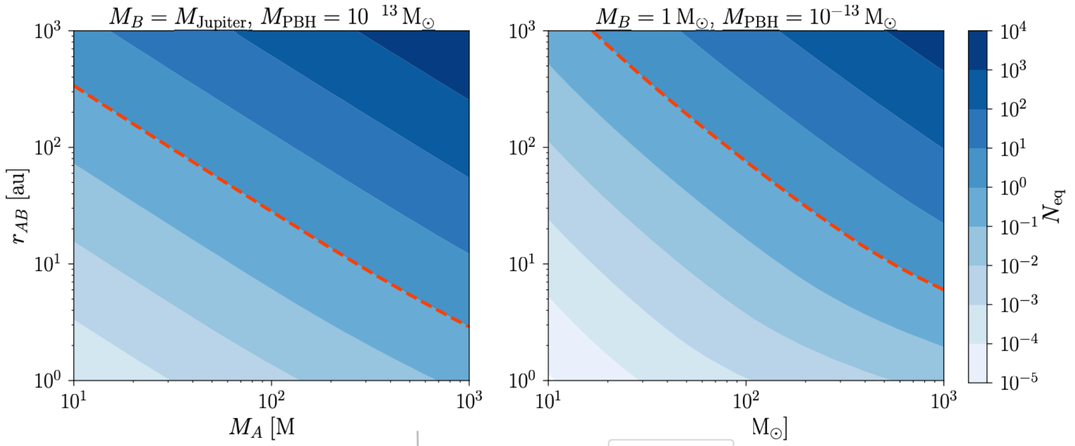


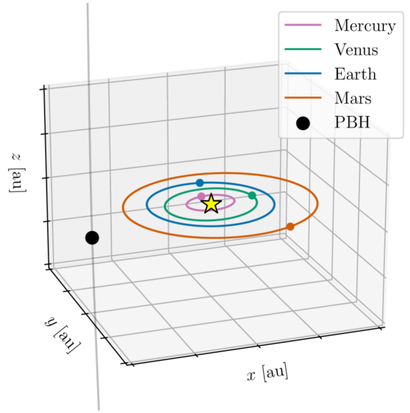
The end of the MACHO era- revisited
Monroy-Rodr´ıguez, Allen, APJ 2014

Disruption



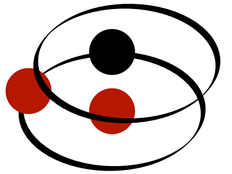
PBHs fly by solar / extrasolar systems may be captured.



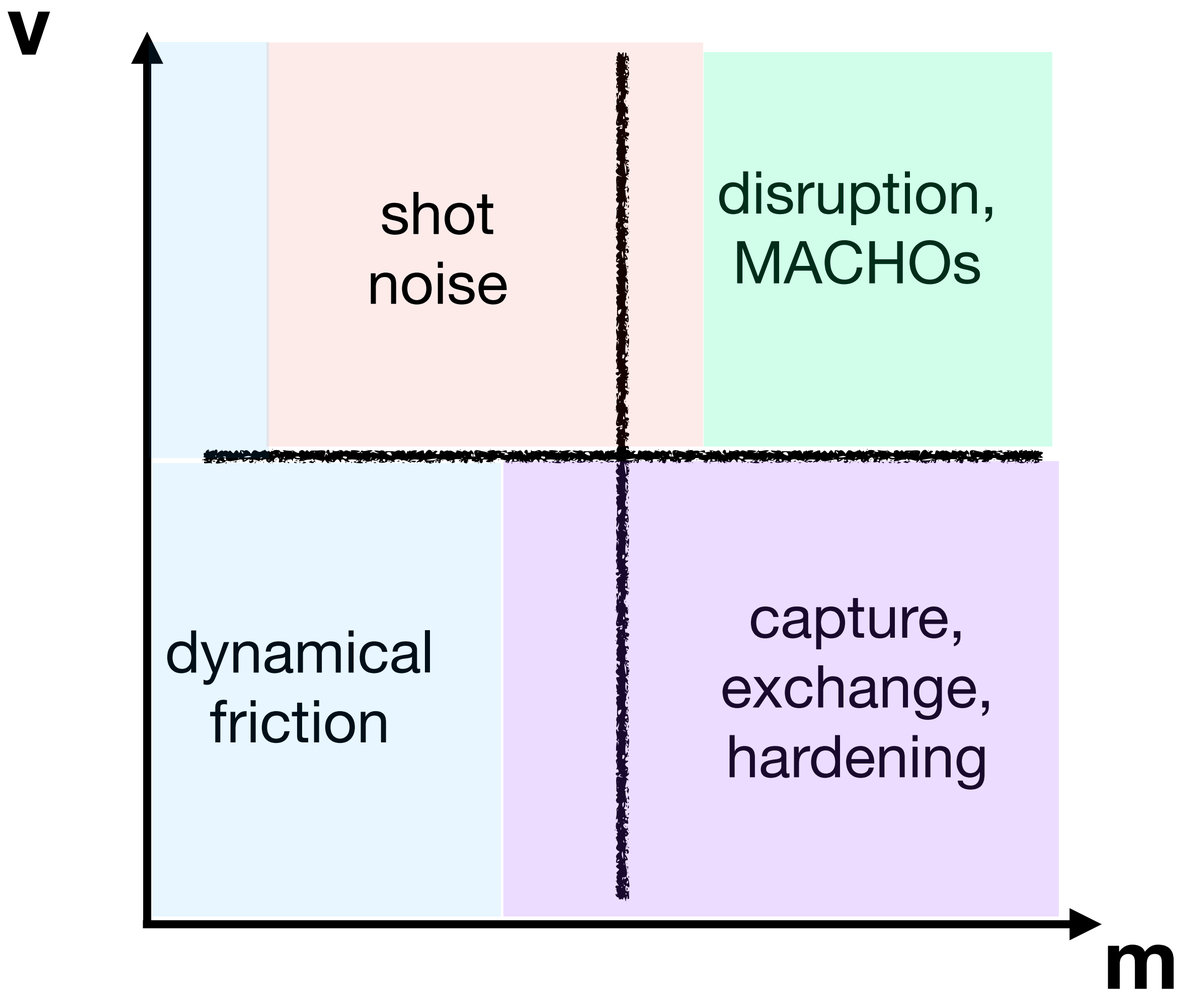


Benjamin V. Lehmann et al,
arXiv: 2205.09756, 2312.17217

Capture



Landscape of Velocities and Masses



Landscape of Velocities and Masses