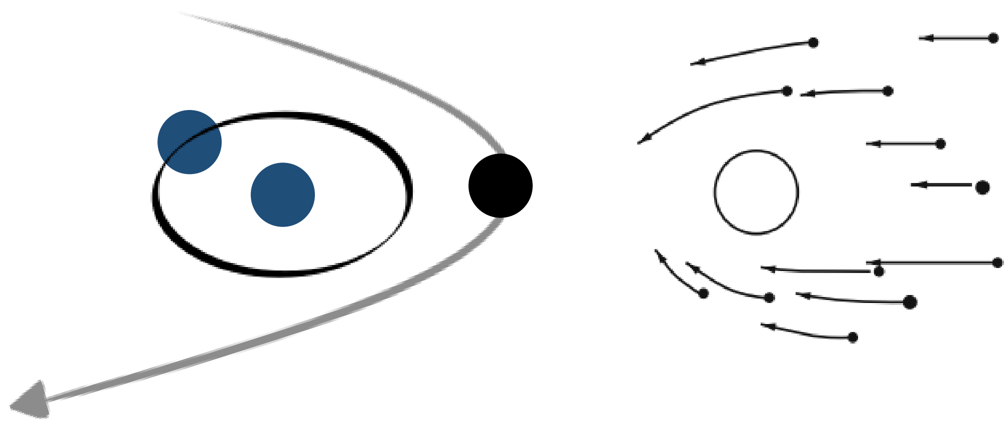
DYNAMICAL PROBES OF DARK COMPACT OBJECTS AND MINIHALOS

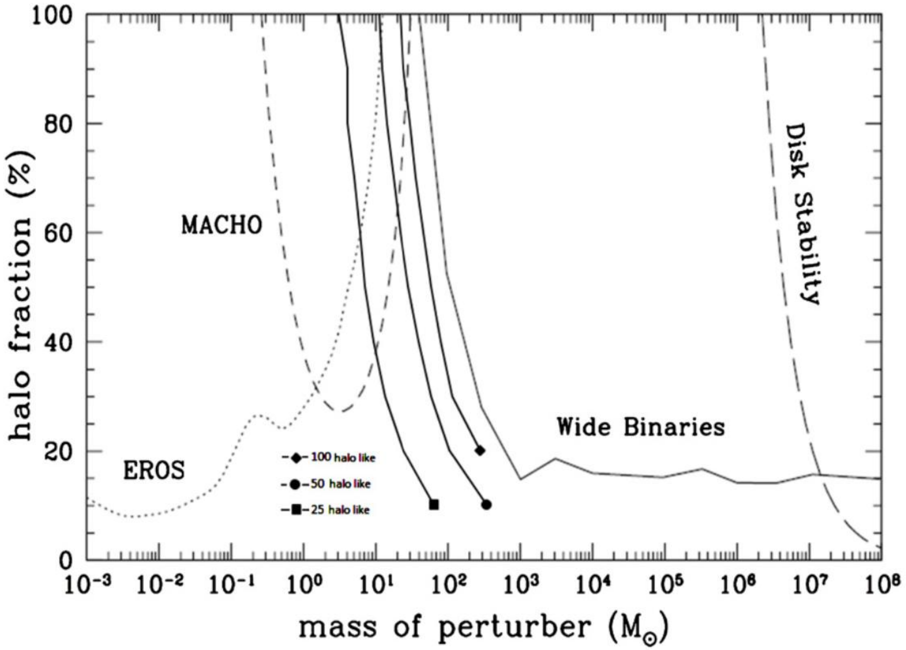


Badal Bhalla

Based on work with Aurora Ireland, Ben Lehmann, Hongwan Liu, Kuver Sinha, Huangyu Xiao, Tao Xu.

MASSIVE ASTROPHYSICAL COMPACT HALO OBJECTS (MACHOS)

When dark matter was first discovered, the most obvious explanation was that the missing mass might consist of compact objects that emit very little light but are otherwise similar to known astrophysical objects such as planets, brown dwarfs, white dwarfs, neutron stars, or black holes.



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

DARK COMPACT OBJECTS

Dark compact objects are predicted by various Beyond the Standard Model (BSM) theories and may constitute all or part of Dark Matter.

1. **Primordial Black Holes (PBHs)** — **Collapse of overdense regions in the early universe.**
   Carr et al. arXiv:1607.06077
2. **Axion Stars** — **Gravitationally bound states of axions.**
   Kolb et al. arXiv: hep-ph/9303313
3. **Q-Balls** — **Stable, long-lived solitons**
   Kusenko et al. arXiv: hep-ph/9712212
4. **Quark Nuggets** — **Dense clumps of quark matter (up, down and strange quarks)**
   Bai et al. arXiv:1810.04360
5. **Mirror Stars** — **Astronomical objects composed of mirror matter**
   Mohapatra et al., arXiv: astro-ph/9902085

PROBES OF DARK COMPACT OBJECTS

1. **Gravitational Lensing**

   A massive object causes light passing nearby to bend, shifting, distorting, magnifying, or even duplicating the image of the background source.

2. **Dynamical Probes**

   Heavy compact objects can significantly alter or even destroy the state of astrophysical entities like binary stars, globular clusters, or dwarf galaxies.

3. **Accretion**

   Dark compact objects, such as primordial black holes (PBHs), can accrete mass, which begins to radiate, giving black holes (BHs) a large luminosity.

4. **Gravitational Waves**

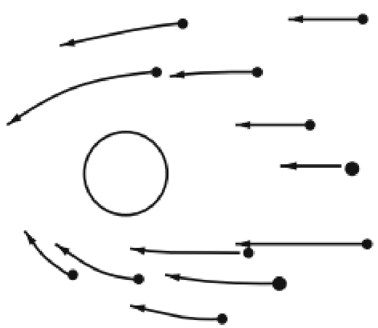
   Mergers of dark compact objects are loud gravitational wave sources.

Carr et al. 2306.03903, 2006.02838

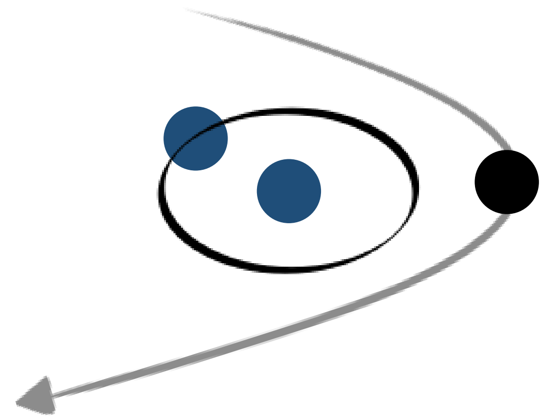
DYNAMICAL PROBES

Dark Compact objects are sufficiently massive to gravitationally reshape the state of an astrophysical system. Through encounters with stars and binaries, dynamical friction, the formation of bound systems, and at times mergers or accretion, they can leave observable traces across astrophysical systems.

Dynamical Friction



Three-body Scattering

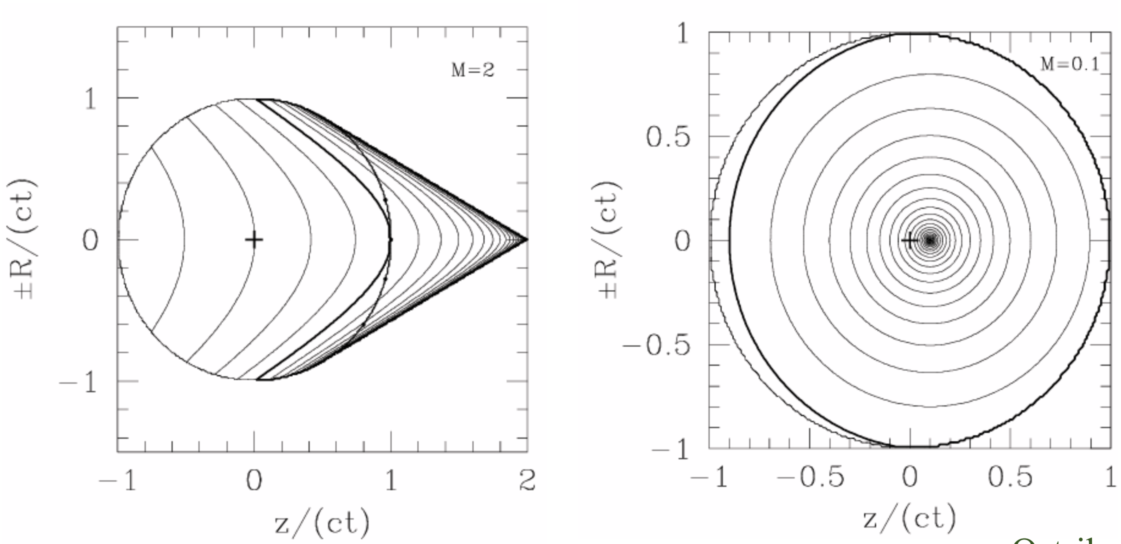


DYNAMICAL FRICTION

Dynamical friction (DF) refers to the deceleration experienced by a massive object moving through a background medium of lighter particles.

$$F_{\rm DF}(M, v_{\rm rel}) = \frac{4\pi G^2 M^2 \rho_{\rm B}}{v_{\rm rel}^2}\,\mathcal{I}(\mathcal{M}, \Lambda)$$

$$\mathcal{I}(\mathcal{M},\Lambda) \approx \begin{cases} \mathcal{M}^3/3\,, & \mathcal{M} \ll 1\,, \\ \ln\Lambda\,, & \mathcal{M} \gg 1\,. \end{cases} \qquad \ln\Lambda \equiv \ln\left(\frac{b_{\rm max}}{b_{\rm min}}\right)$$



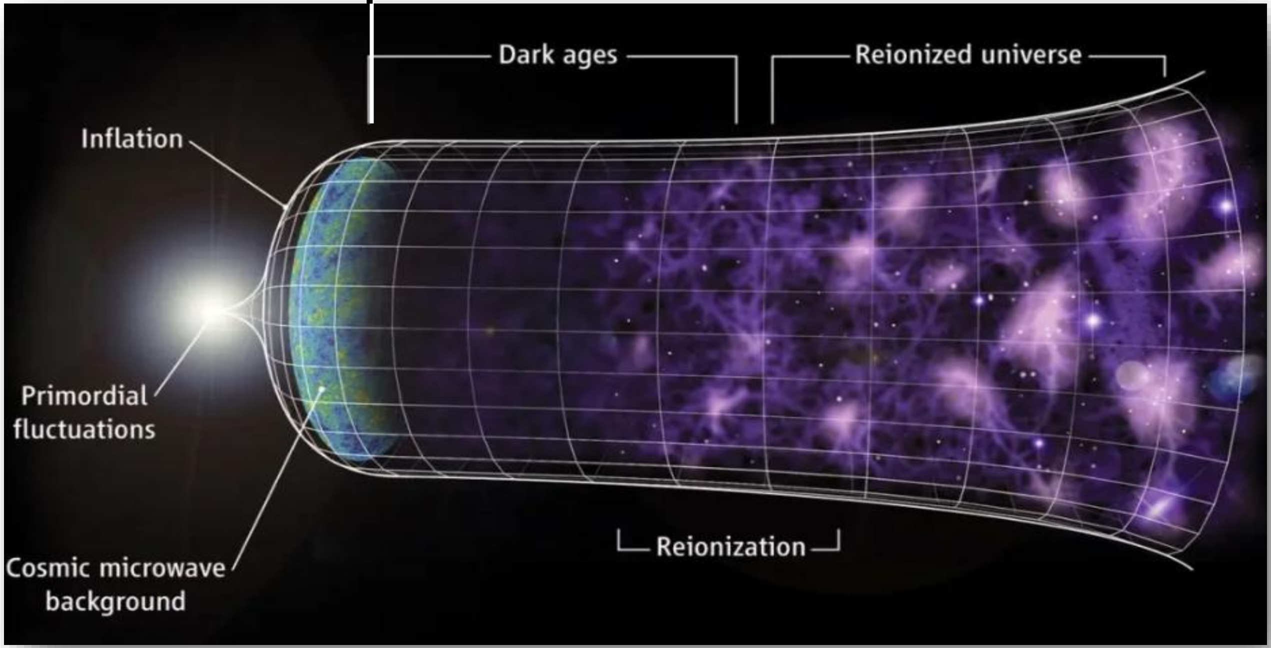
Ostriker: astro-ph/9810324

COSMIC DARK AGES

The hot Big Bang was an energetic, brilliantly luminous event. Today's Universe is alight with stars. But in between, the dark ages ruled.

- Big Think

The bulk relative velocity between baryons and DM at the time of recombination is 30 km/s



DYNAMICAL FRICTION DURING COSMIC DARK AGES

The DF heating rate per baryon is

$$\dot{Q}_{\rm DF}(v_{\rm rel}, z) = \frac{1}{n_{\rm B}} \int {\rm d}M \frac{\rho_{\rm DM}}{M} \frac{{\rm d}f}{{\rm d}M} v_{\rm rel} F_{\rm DF}$$

df/dM is the fraction of DM (by mass) in perturbers of mass M

MACHOs

$${\rm d}f/{\rm d}M' = f_{\rm M}\delta(M' - M)$$

Axion Minihalos

$$M_{\rm h,c} \approx 1.5\times10^{-11}\,{\rm M}_\odot \left(\frac{m_a}{10^{-6}\,{\rm eV}}\right)^{-2}\left(\frac{f_a}{10^{11}\,{\rm GeV}}\right)^{-2} g_{*,{\rm osc}}^{-1/2}$$

$$\frac{{\rm d}f}{{\rm d}M_{\rm h}}(z) = \int_{z_{\rm eq}}^{z} {\rm d}z' \frac{{\rm d}f_{\rm col}^{\rm CDM}}{{\rm d}z'} \frac{{\rm d}f_{\rm h}}{{\rm d}M_{\rm h}}(z') + [1 - f_{\rm col}^{\rm CDM}(z)] \frac{{\rm d}f_{\rm h}}{{\rm d}M_{\rm h}}(z)$$

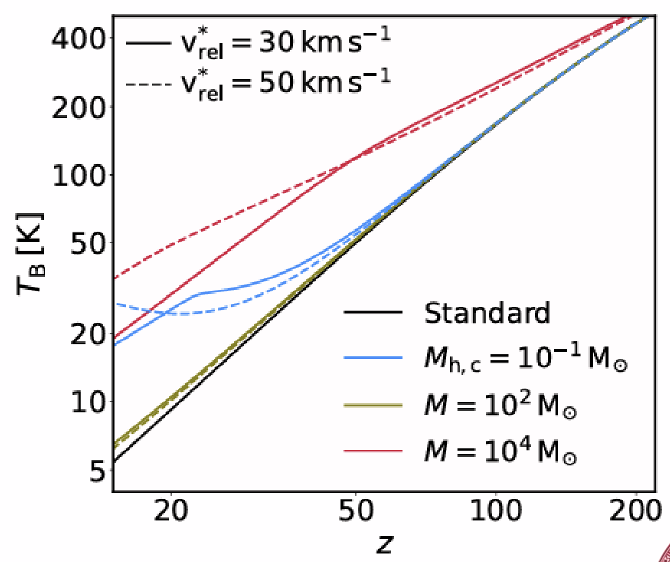
DYNAMICAL FRICTION DURING COSMIC DARK AGES

The DF heating rate per baryon is

$$\dot{Q}_{\rm DF}(v_{\rm rel}, z) = \frac{1}{n_{\rm B}} \int {\rm d}M \frac{\rho_{\rm DM}}{M} \frac{{\rm d}f}{{\rm d}M} v_{\rm rel} F_{\rm DF}$$

The resulting change in baryon temperature can be estimated by

$$\frac{{\rm d}v_{\rm rel}}{{\rm d}\ln a} = -v_{\rm rel} - \frac{F_{\rm DF}}{MH}\,,$$
$$\frac{{\rm d}T_{\rm B}}{{\rm d}\ln a} = -2T_{\rm B} + \frac{\Gamma_C}{H}(T_{\rm CMB} - T_{\rm B}) + \frac{2}{3}\frac{\dot{Q}_{\rm DF}}{H}$$



21-CM SIGNAL FROM COSMIC DAWN

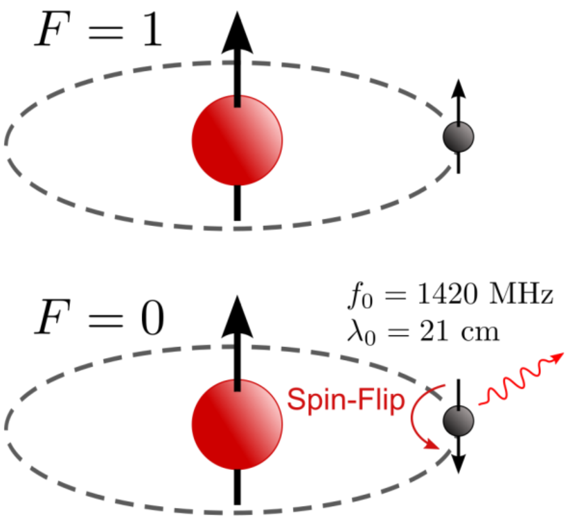
Neutral hydrogen in the ground state can emit 21-cm radiation through the hyperfine spin-flip transition.

The ratio between the number densities of hydrogen atoms in the two hyperfine levels defines the “spin temperature.”

$$\boxed{\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-E_{21}/T_s} \approx 3\left(1 - \frac{E_{21}}{T_s}\right)}$$

The spin temperature is determined by the interactions between the two-level system and CMB photons, other hydrogen atoms, and Lyman-α radiation.

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_G T_{GAS}^{-1}}{1 + x_\alpha + x_G}$$



x_G, x_α are the coupling coefficients due to atomic collisions and scattering of Lyα photons.

OBSERVATION OF THE 21-CM SIGNAL FROM COSMIC DAWN

The absorption or emission of 21-cm blackbody CMB photons via the hyperfine transition of neutral hydrogen atoms at redshift z leads to a spectral distortion of the CMB at wavelength 21cm × (1 + z), typically reported as a differential brightness temperature.

$$\boxed{T_{21}(z) = \frac{1}{1+z}\left[T_S(z) - T_{CMB}(z)\right]\left(1 - e^{-\tau(z)}\right)}$$

$\tau(z)$ is the optical depth of photons

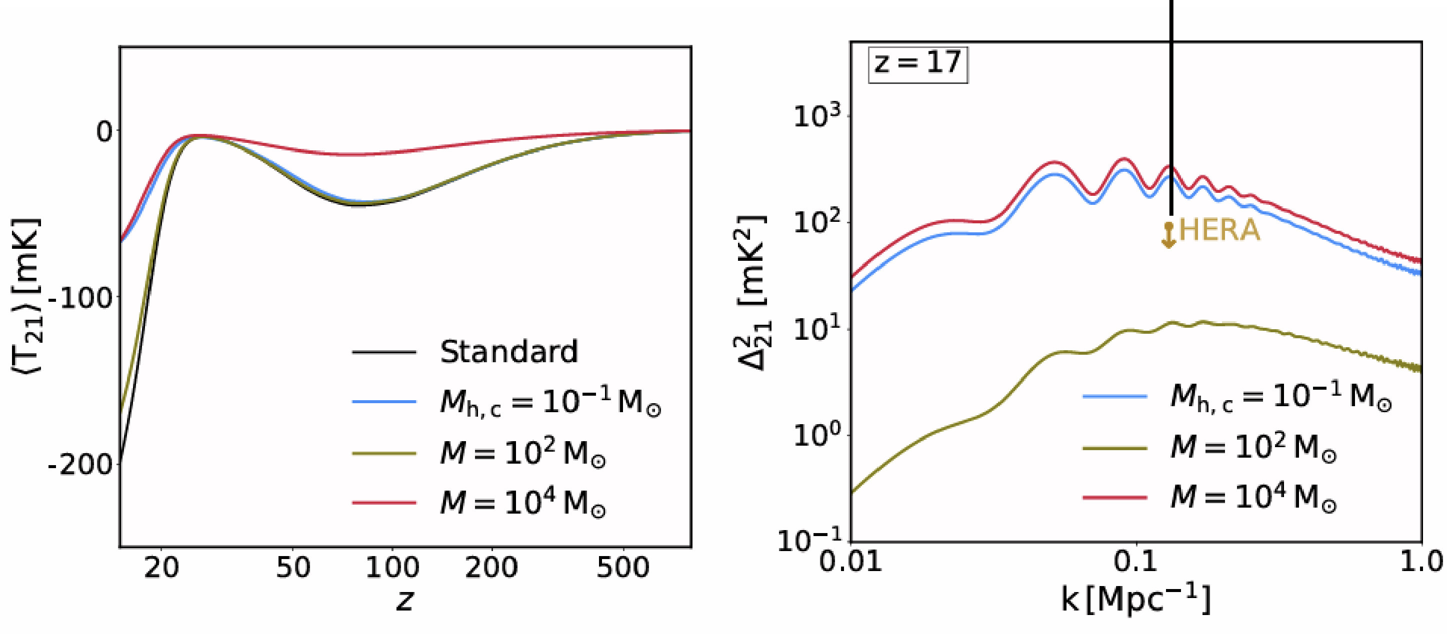
The large-scale fluctuations of the relative velocity imply that two regions with different initial relative velocities will exhibit different brightness temperatures. The sky-averaged brightness temperature is

$$\boxed{\langle T_{21}\rangle(z) = \int \mathrm{d}^3\vec{v}^{\,*}_{\rm rel}\, f(\vec{v}^{\,*}_{\rm rel}) T_{21}(v^*_{\rm rel}, z)}$$

$$\boxed{\Delta^2_{21}(k,z) = \frac{2k^3}{\pi}\langle T_{21}\rangle^2(z)\int_0^\infty \mathrm{d}r\, r^2\xi(r)\frac{\sin(kr)}{kr}}$$

OBSERVATION OF THE 21-CM SIGNAL FROM COSMIC DAWN

Forecasted Sensitivity by
HERA collaboration

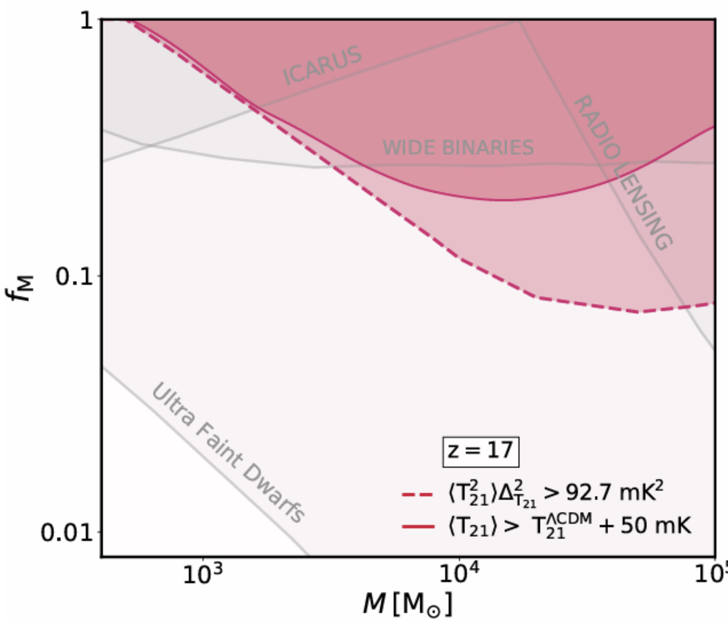


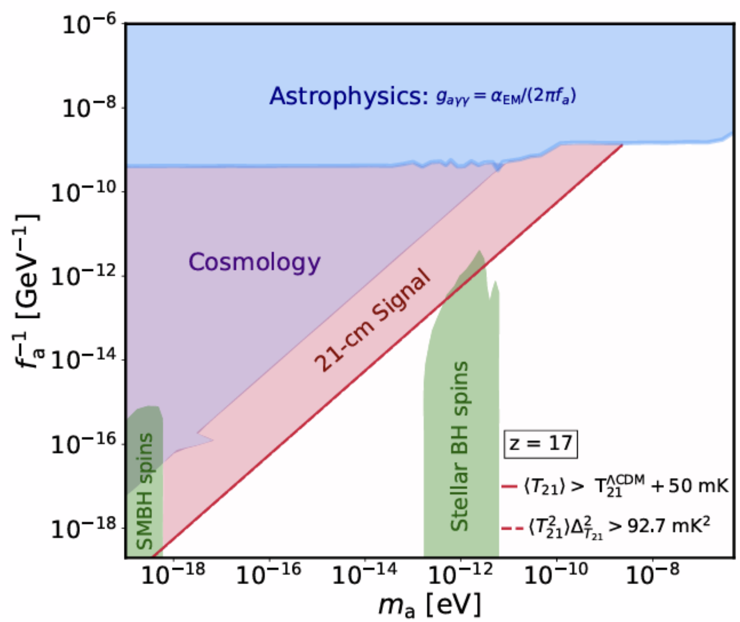
HERA Collaboration arXiv:2210.04912

FORECASTED SENSITIVITY OF THE 21-CM SIGNAL TO DARK OBJECTS

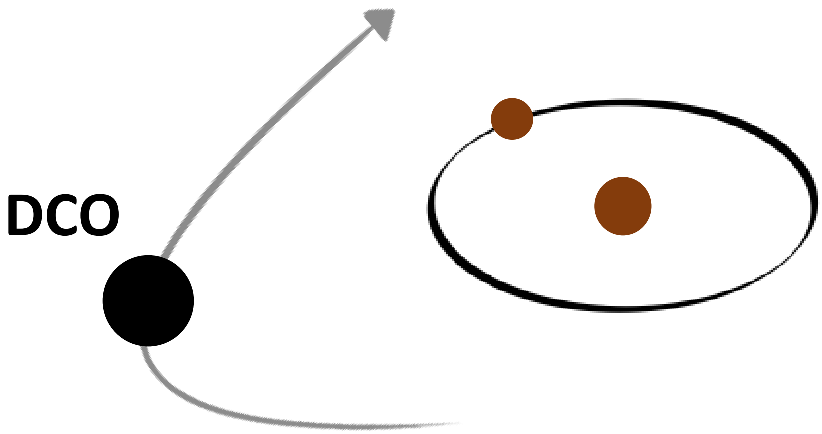
$$\langle T_{21}\rangle > \left\langle T_{21}^{LCDM}\right\rangle + 50\text{ mK}$$

$\Delta_{21}^2 > 92.7\ mK^2$ for k = 0.13 Mpc^{-1} at z =17



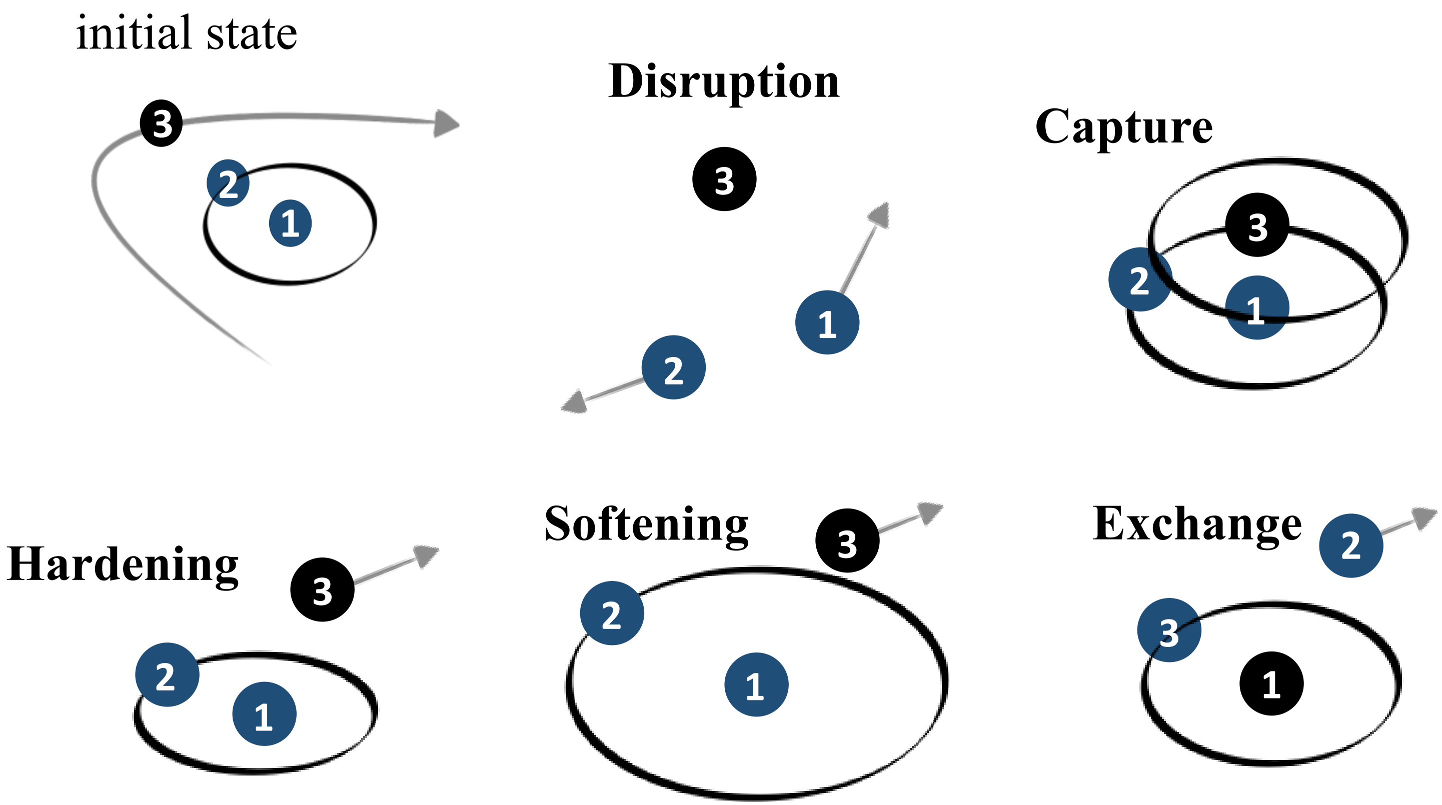


GRAVITATIONAL THREE-BODY PROBLEM

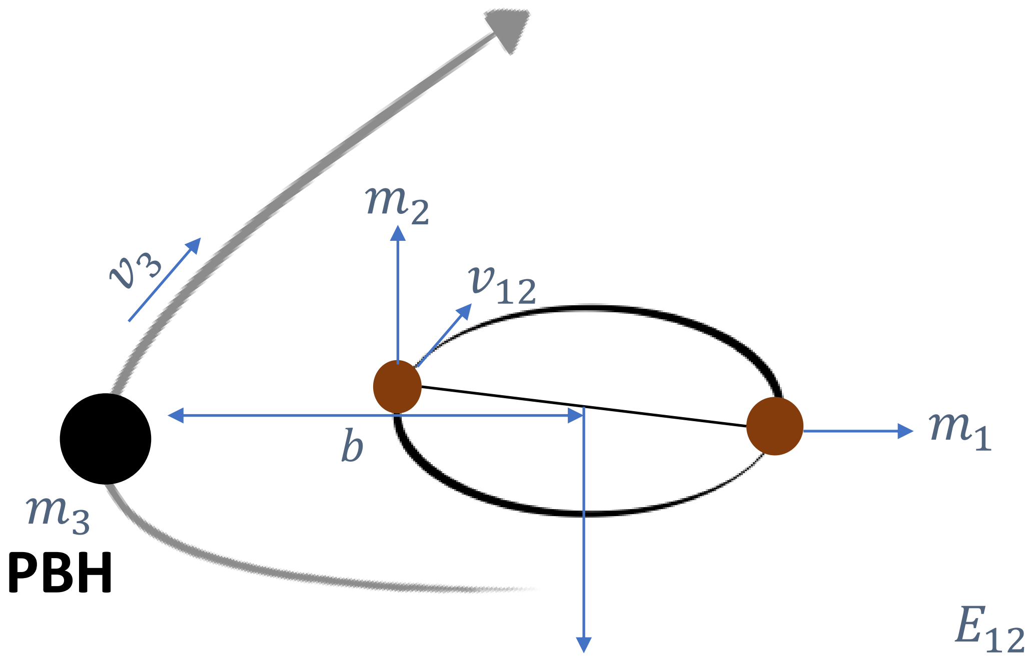


GRAVITATIONAL THREE-BODY PROBLEM

A gravitational three-body problem is extremely complicated and highly sensitive to initial conditions, which can vary a lot. However, it is often possible to analytically describe the statistics of outcomes of three-body encounters. There are five possible outcomes in three-body encounters:



A GENERAL THREE-BODY ENCOUNTER

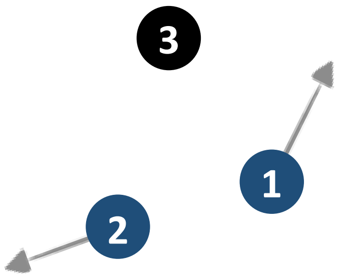


a: separation between the binary components

$$E_{12} = -\frac{G\, m_1 m_2}{2\, a}$$

Binding Energy

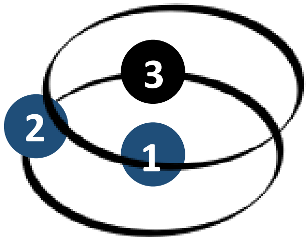
DISRUPTION/IONIZATION



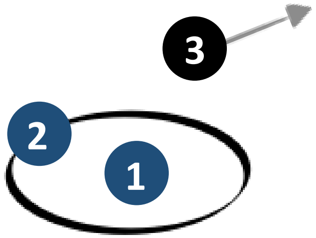
If the typical energy transfer to the binary is large compared to its binding energy, the three-body encounter will lead to a final state in which all three components are free. This is called “Disruption” or “Ionization”.

CAPTURE

Objects 1 and 2 remain bound, and now object 3 becomes bound as well, forming a triple system. In the process, 3 donates energy to the 1-2 system, softening the binary. It is kinematically easier to capture low-mass, slow-moving objects.



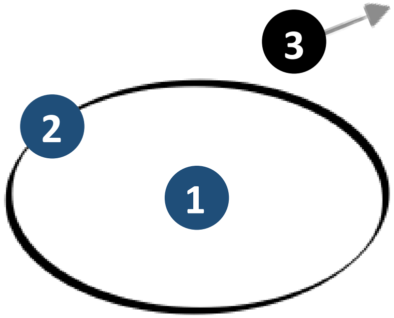
HARDENING



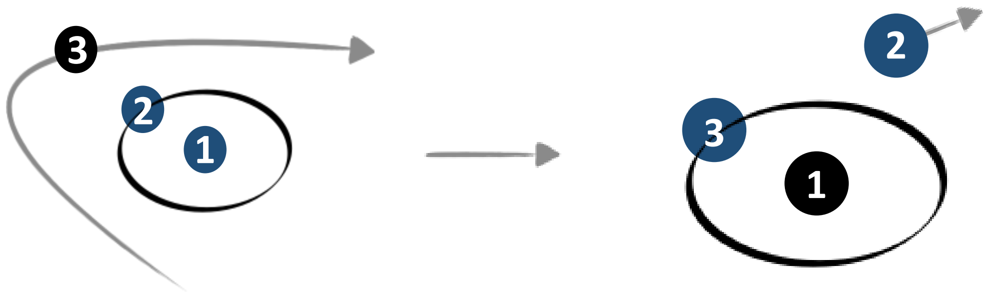
Objects 1 and 2 remain bound, and they give up energy to object 3, causing their separation to decrease. Object 3 remains free.

SOFTENING

Object 3 transfers energy to the 1-2 system, causing their separation to increase, but they remain bound. Object 3 remains free.



EXCHANGE

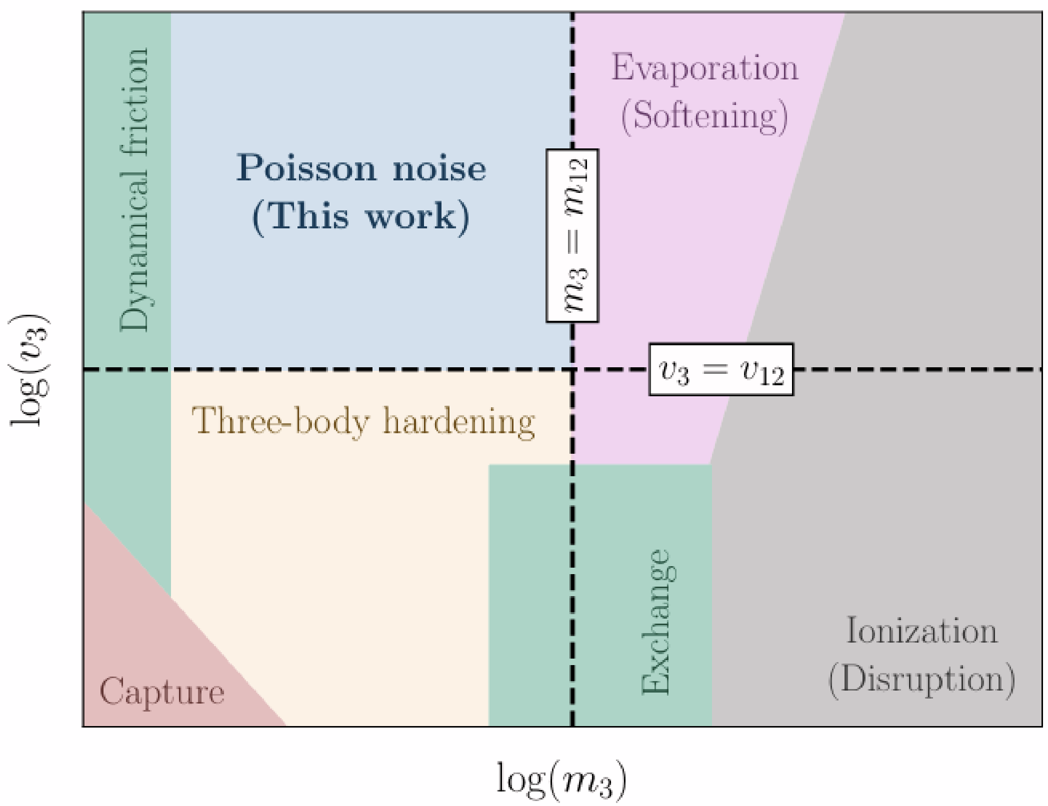


$$(12) + 3 \rightarrow 2 + (13)$$

Object 3 transfers enough energy to object 2 to unbind it from 1, but in the process, 3 loses enough energy that it becomes bound to 1. The result is a bound 1-3 system with object 2 free.

WHAT DETERMINES THE OUTCOME OF A THREE-BODY ENCOUNTER?

The mass and velocity of the third body before the encounter.



v_{12}: the relative velocity of the two components of the binary

m_{12}: Total mass of the binary

v_3: velocity of the dark compact object relative to the center of mass of the binary

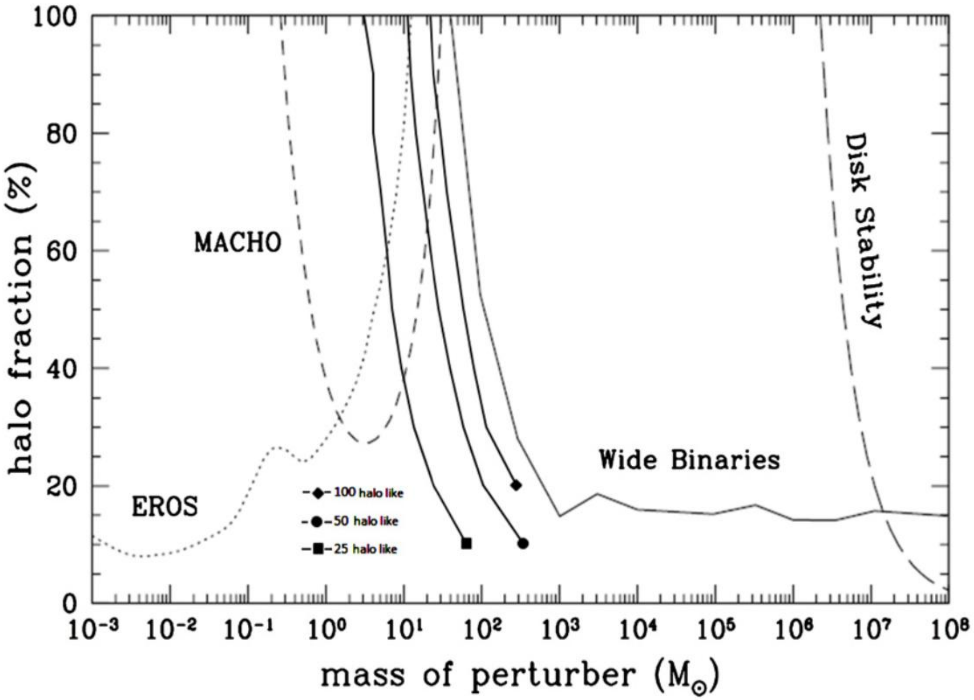
m_3: mass of the dark compact object

PROBE OF DARK COMPACT OBJECTS

All of these processes have been used as probes of dark compact objects.

DISRUPTION/IONIZATION

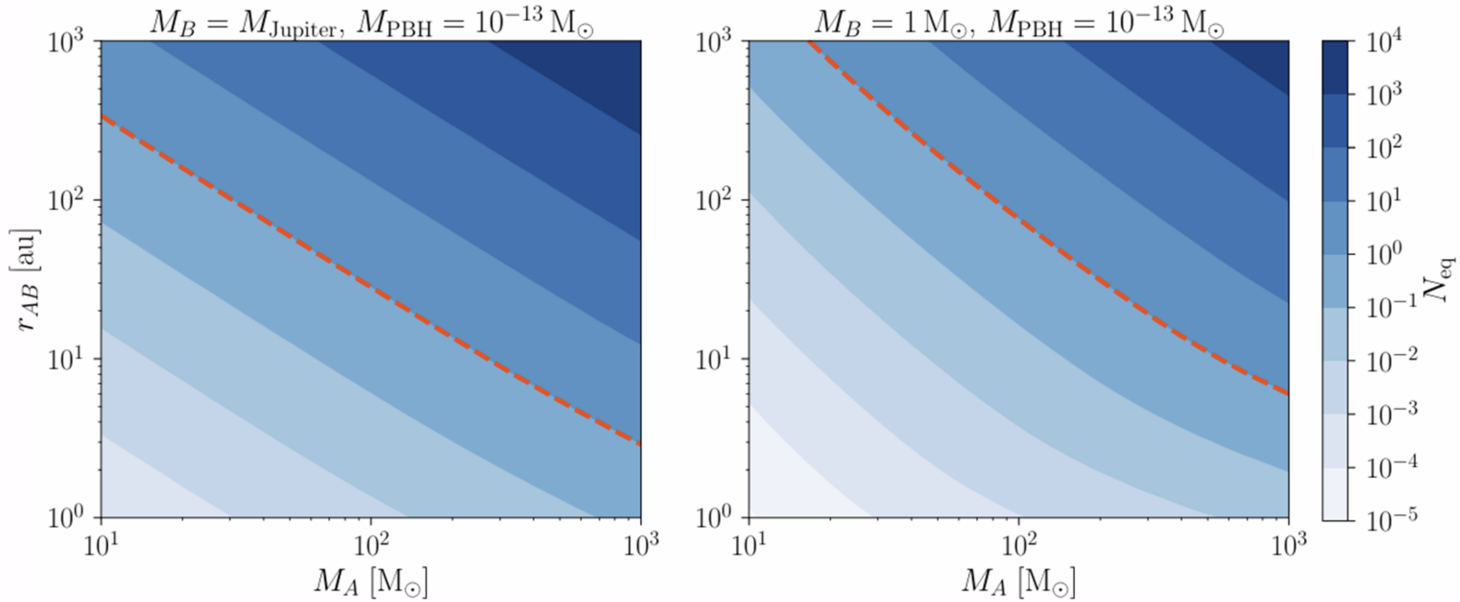
Heavy PBH will destroy the binary. The observed existence of binaries is used to constrain the PBH abundance.



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

CAPTURE

Asteroid mass PBHs can be frequently captured in realistic stellar systems, particularly massive wide binaries.



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

HARDENING/SOFTENING

Designing probes based on softening and hardening requires a more careful analysis.

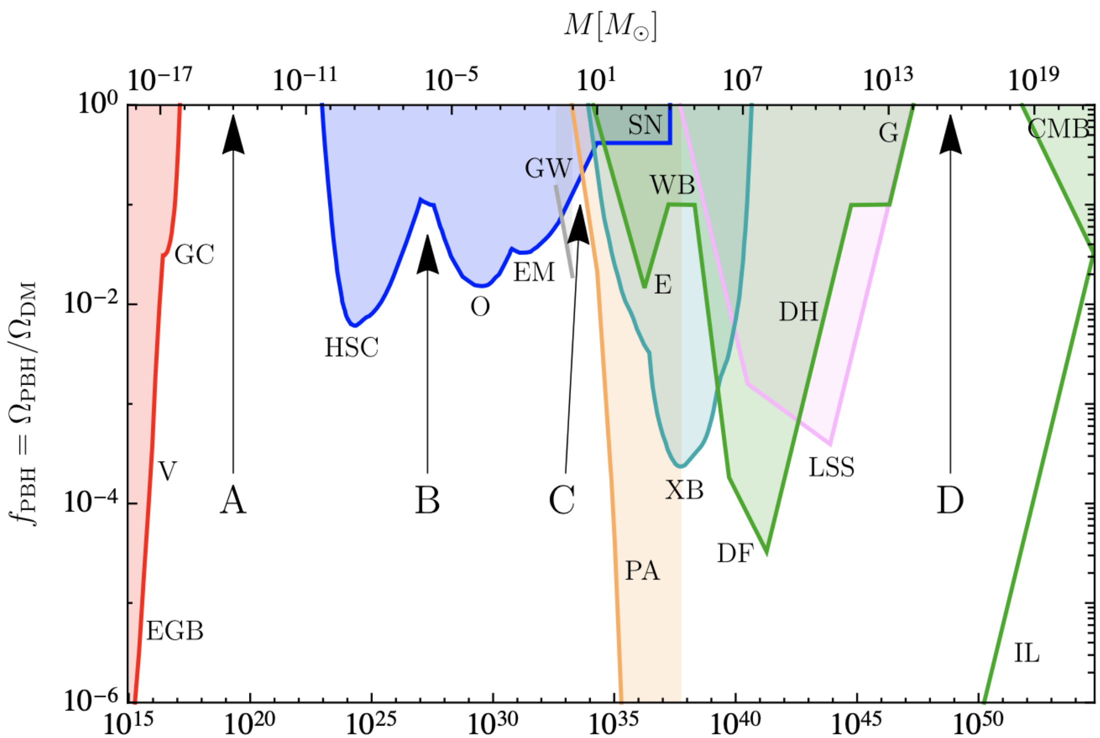
WHAT WE KNOW SO FAR?

D. C. Heggie: A binary system will lose energy and shrink if its binding energy is much greater than the kinetic energy of the perturber, or gain energy if the binding energy is much less than the kinetic energy of the perturber.
[D. C. Heggie, Binary Evolution in Stellar Dynamics, Mon. Not. Roy. Astron. Soc. 173, 729]

J. G. Hills: Perturbers traveling faster than the binary's orbital speed tend to soften the binary, while those traveling slower tend to harden it.
[J.G. Hills AJ 99, 979 (1990)]

The two definitions are in conflict if the third object is fast, but is significantly less massive than the two binary stars.

PRIMORDIAL BLACK HOLES



A/B/C/D: mass windows for large BH abundance

Carr, Kuhnel, 2006.02838

evaporation, lensing, gravitational waves, dynamical effects, accretion, CMB distortion, large-scale structure

HARDENING RATE

The calculations were performed using an N-body simulation code called Rebound.

H. Rein and S.-F. Liu, REBOUND [arXiv:1110.4876]

Hardening Rate at velocity v

Dimensionless energy transfer between the binary and the perturber

$$\frac{d}{dt}\left(\frac{1}{a}\right) = \frac{G\rho}{v} H_1 \longrightarrow H_1 = 8\pi \int_0^\infty dx\, x \langle C \rangle \longrightarrow C = \frac{m_{12}}{2\, m_{\rm PBH}} \frac{\Delta E}{E}$$

Quinlan (1996)[astro-ph/9601092]

Separation between the binary components

Average energy exchange over all angular parameters

x is dimensionless impact parameter defined as $x = b/b_0$ $\quad x = b/b_0, \qquad b_0^2 = 2GM_{12}a/v^2$

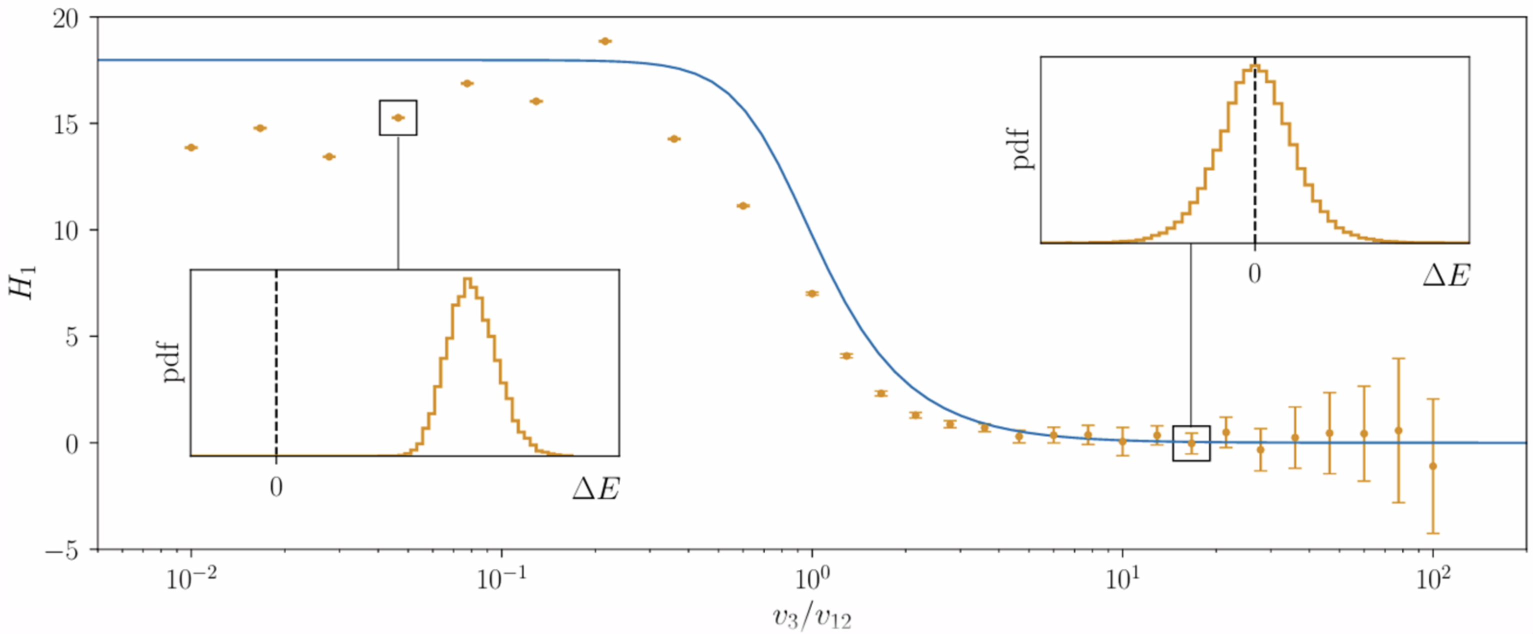
HARDENING RATE

$$H_1 = 8\pi \int_0^\infty dx\, x \langle C \rangle$$

Integrate over 25 randomly sampled impact parameters from $[0, b_{max}^2]$

$$b^2 = r_p^2 \left(1 + \frac{2Gm_{12}}{r_p v_3^2}\right)$$

Averaged over 10^5 random binary orbits for each impact parameter



ENCOUNTER RATE

Slow PBHs

N_E= Large: More Hardening

N_E= Small: Less Hardening

Fast PBHs

N_E= Large: Zero Hardening

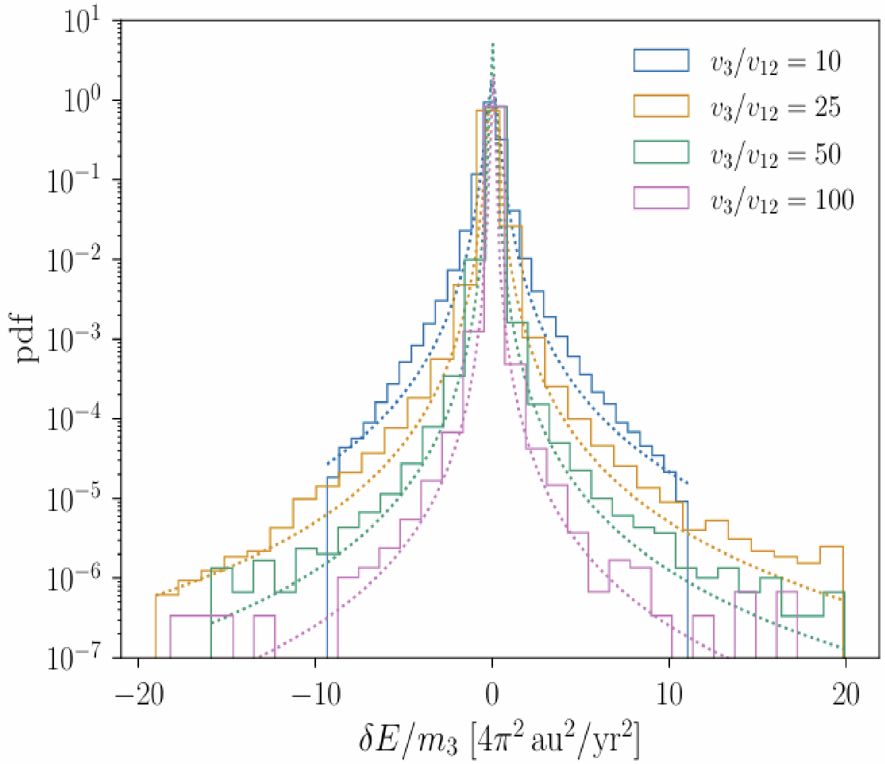
N_E= Small: Shot Noise
Could be Hardening or Softening

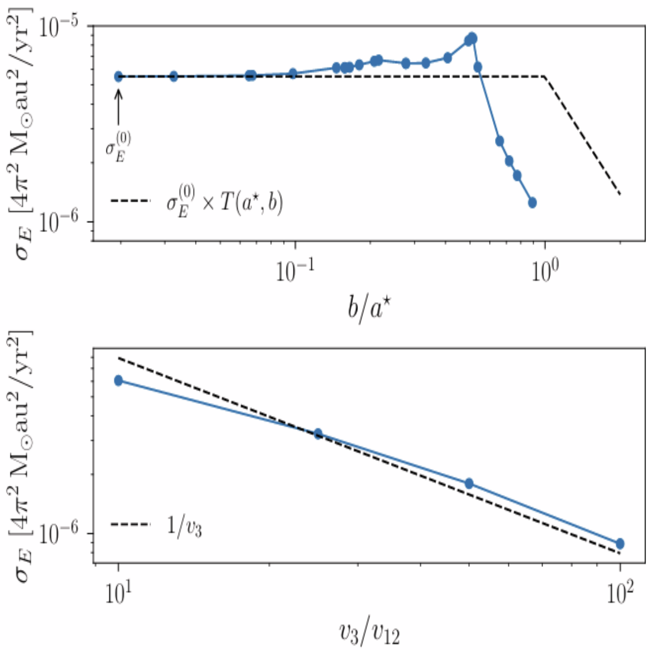
While the average hardening rate does suffer from a substantial suppression when the velocity of the perturber is large, the average is not necessarily the appropriate quantity.

$$N_E = 1.62 \times \left(\frac{m_{BIN}}{M_\odot}\right)\left(\frac{\rho_{DM}}{1\ GeV\ cm^{-3}}\right)\left(\frac{10^{-16} M_\odot}{m_{PBH}}\right)\left(\frac{a}{1\ AU}\right)\left(\frac{220\ km\ s^{-1}}{\sigma_{DM}}\right)\left(\frac{T_{OBS}}{10\ yr}\right)$$

SHOT NOISE: QUANTIFYING THE ENERGY EXCHANGE

Empirically, we find that the distribution of δE is well approximated by Student's t distribution with a scale parameter.





OBSERVATIONAL PROSPECTS

The best observational prospects are found in systems where the period is long (i.e., wide binaries) and can be measured with high precision.

Two systems that meet the above criteria are

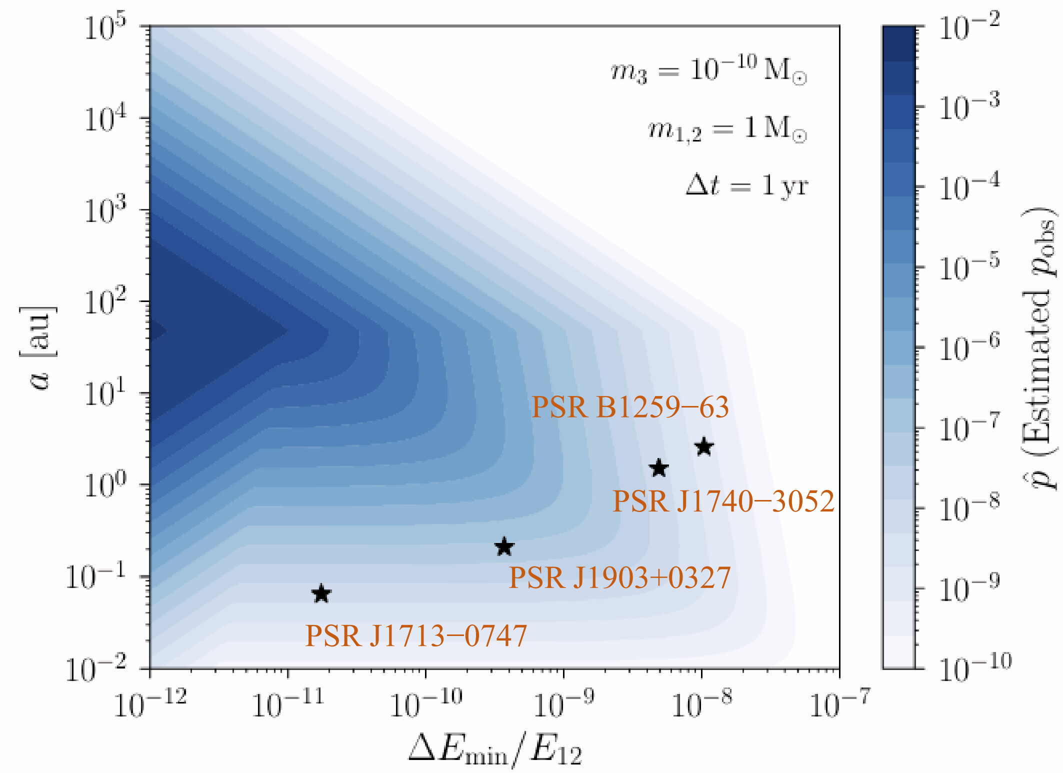
1. Solar System
   Earth-Mars distance serve as an observational probe.
   T.X. Tran et al., arXiv: 2312.17217
   B. Bertrand et al., arXiv: 2312.14520
   V. Thoss et al., arXiv: 2409.04518

2. Binary Pulsars
   Many binary pulsar systems have been detected and characterized at extremely high precision, and their orbital decay rate serve as an observational probe.

OBSERVATIONAL PROSPECTS

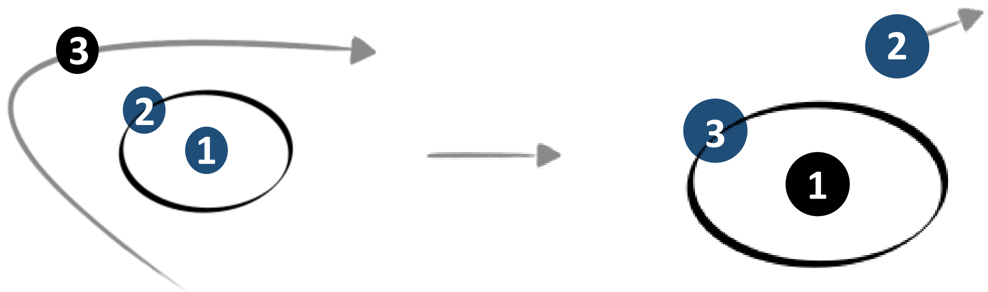
$\widehat{p}$ = probability of an observable perturbation

$$p_{\rm obs} = \sum_{k=1}^{\infty} \Pr(N=k) \times \Pr\Big(\big|\Delta E^{(k)}\big| > E_{\min}\Big)$$



PBH EXCHANGE

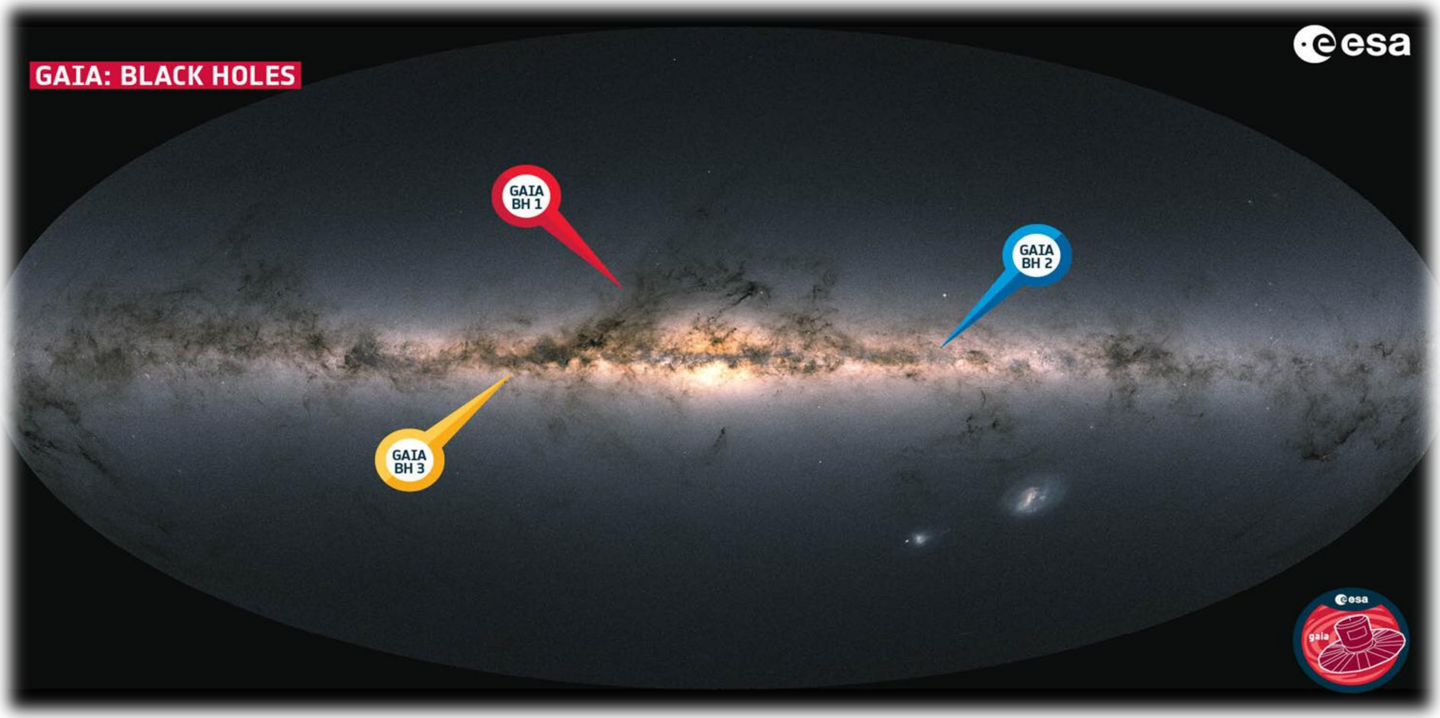
Primordial black holes could also participate in exchange processes, in which one component of a binary system is ejected and replaced by the black hole itself.



OBSERVABLE:

The remaining object in the binary would dynamically appear to have an invisible companion.

GAIA BLACK HOLES



	Stellar type	$M_{\rm BH}[{\rm M}_\odot]$
Gaia BH1	G-type main-sequence	$9.62^{+0.18}_{-0.18}$
Gaia BH2	Red giant	$8.94^{+0.34}_{-0.0.34}$
Gaia BH3	G-type giant	$32.7^{+0.82}_{-0.82}$

At present, the origin of these black holes remains uncertain

El-Badry, 2023, 2024
Fantoccoli et al 2410.17323

GAIA BLACK HOLES

	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

El-Badry, 2023, 2024; Fantoccoli et al 2410.17323

The formation of Gaia black holes binaries is difficult to explain

Orbit is smaller than progenitor star of $30 - 50 M_\odot$ mass with ~10au 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.

EXCHANGE CROSS-SECTION

An exchange requires that the three objects do not all escape to infinity after the encounter, which requires that the initial velocity of the PBH is small.

$$\boxed{v_3 < v_{\max} = (30\,\mathrm{km/s}) \left(\frac{a}{1\,\mathrm{AU}}\right)^{-1/2} \left(\frac{\frac{m_1 m_2}{m_3}\frac{m_{123}}{m_{12}}}{\mathrm{M}_\odot}\right)^{1/2}}$$

The exchange cross-section is

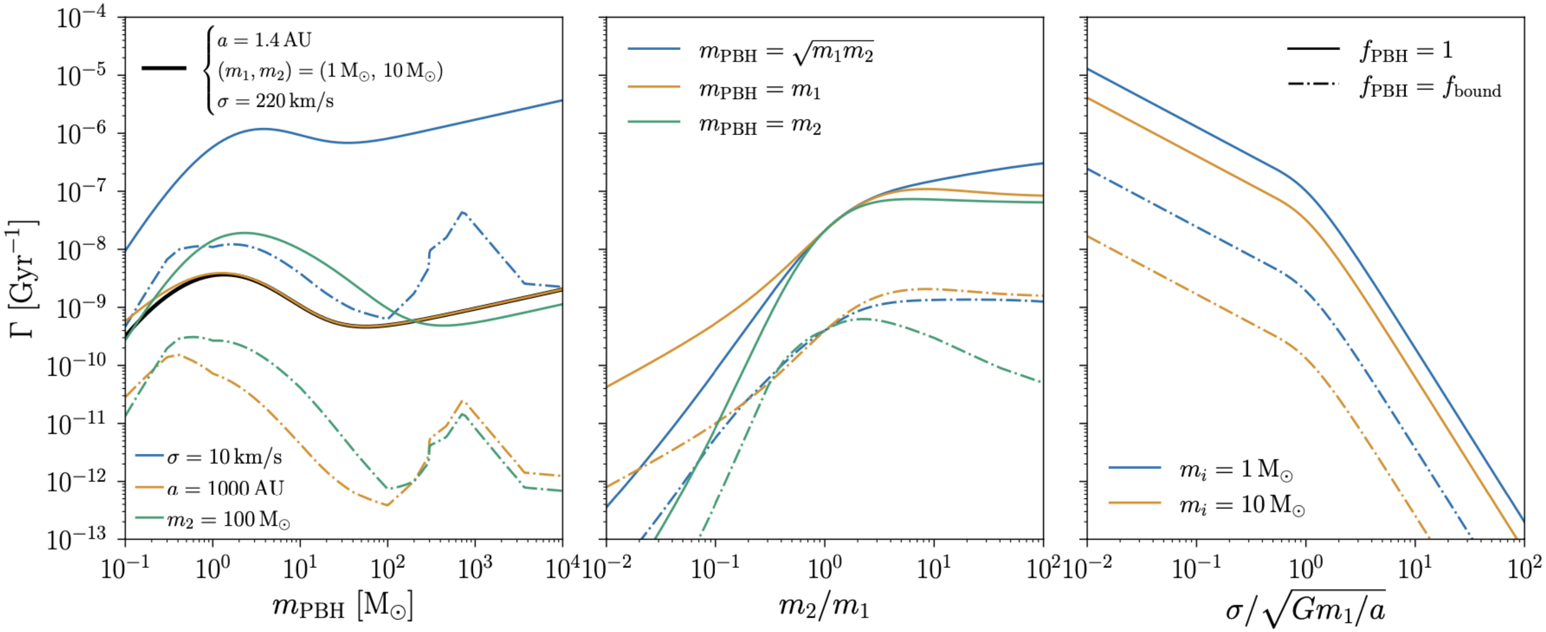
$$\Sigma_{\mathrm{Ex}} = P(\mathrm{Ex})\,\pi b_{\max}^2 \longrightarrow P(Ex) = N_{\mathrm{Ex}}/N_{\mathrm{T}} \longrightarrow b_{\max}^2 = r_p^2\left(1 + \frac{2GM_{123}}{r_p v_3^2}\right)$$

For a fixed PBH velocity v_3, the rate to exchange with object 1 is

$$\Gamma = n_{\mathrm{PBH}}^{v<v_{\max}} \langle \Sigma(v_3) v_3 \rangle$$

$$= n_{\mathrm{PBH}} \int_0^{v_{\max}} \mathrm{d}v_3\, \underbrace{\mathcal{F}_{\mathrm{DM}}(v_3)}_{\text{Maxwell-Boltzmann Distribution}}\underbrace{\Sigma(v_3)}_{\text{Exchange cross-section}} v_3$$

PBH EXCHANGE RATE

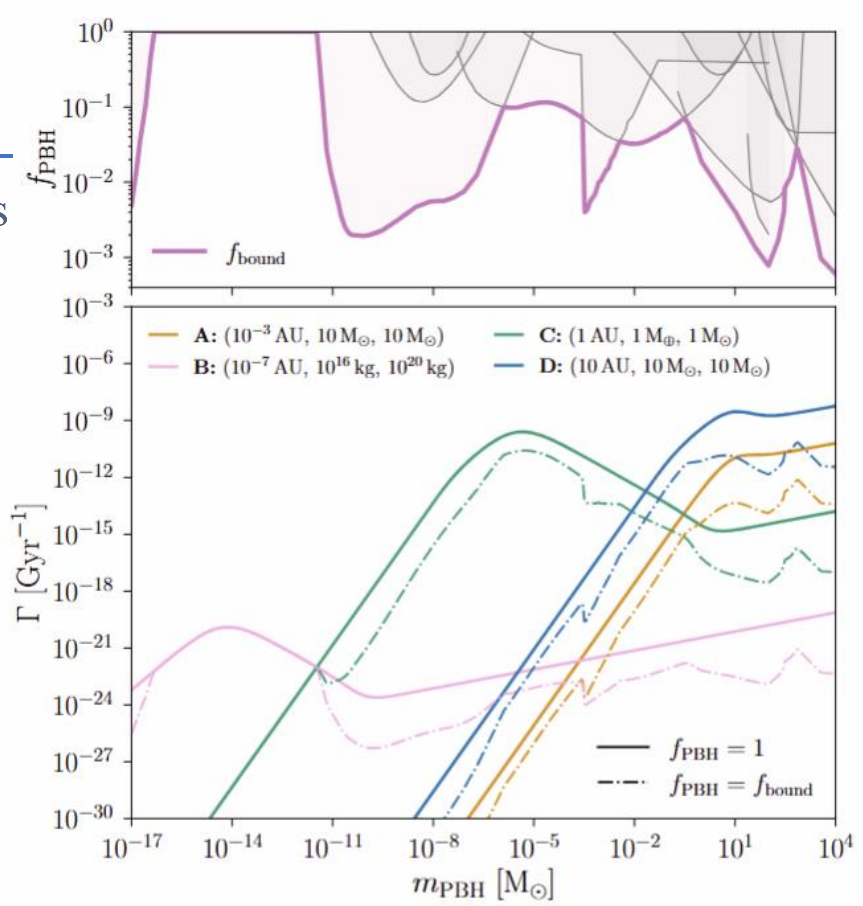


A lower DM velocity dispersion increases the exchange rate due to both the gravitational focusing and the PBH fraction on the velocity tail.

The solid curve shows when PBHs make up all DM, and dashed curves show the reduced rate due to existing constraints.

PBH EXCHANGE IN DIFFERENT BINARY SYSTEMS

Existing Constraints on PBHs



The most promising prospects for detecting PBH exchange are in stellar binaries, at PBH masses comparable to astrophysical BH masses.

ORIGIN OF GAIA BH BINARIES

For all the Gaia BHs, there are three formation mechanisms

1. Isolated evolution from stellar binaries, but disfavored $R_\star^{\rm iso} \sim 10^{-10}$–$10^{-8}\,\mathrm{M}_\odot^{-1}$
2. Dynamical exchange with astro BHs $R_\star^{\rm dyn} \sim 10^{-7}\,\mathrm{M}_\odot^{-1}$

K. El-Badry et al, arXiv:2209.06833; I. Kotko et al, arXiv:2403.13579

3. Dynamical exchange with PBHs

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

Assuming PBH make up all of the DM in the relevant mass range

The PBH exchange rate exceeds the astro BH exchange rate if the velocity of PBHs is much less than the halo velocity dispersion.

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

SUMMARY

Motivated by the physics beyond the Standard Model, dark compact objects or minihaloes can make up all or a fraction of Dark Matter in the relevant mass range.

Future 21-cm observations provide a unique opportunity to explore Dark Compact Objects and Minihalos. Both the global 21-cm signal and its power spectrum can constrain MACHO and axion parameter spaces.

Three-body interaction is also a unique channel to test compact DM objects, as it leads to several effects on binary evolution. Fast-moving perturbers leave stochastic perturbations that may be observed in systems that are measured with great precision, while the Exchange processes should give rise to a sparse but nonvanishing population of PBHs in binaries in the Milky Way.

THANK YOU !

“Dynamical Heating from Dark Compact Objects and Axion Minihalos: Implications for the 21 cm Signal” BB, Aurora Ireland, Hongwan Liu, Huangyu Xiao, and Tao Xu. arXiv: 2512.00169

“Dancing with invisible partners: Three-body exchanges with primordial black holes” BB, Benjamin V. Lehmann, Kuver Sinha, Tao Xu, arXiv: 2408.04697

“Fast and Fewrious: Stochastic binary perturbations from fast compact objects” BB, Benjamin V. Lehmann, Kuver Sinha, Tao Xu, arXiv: 2507.16894