Stellar-mass black holes in star clusters I

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Astrophysical Black Holes

Black holes

- Relativist's definition: a *closed 'null hypersurface'* or an *'event horizon'* --- a surface through which mass can only move radially inwards.

- Necessarily spherically symmetric or axisymmetric --- 'no-hair theorem'.

- Mathematically well-studied.

- But has anyone detected an event horizon & proven any of its properties? (is it possible?) [Mission "Event Horizon" underway]

- All black holes we talk about in astrophysics are only candidates! --- a combination of predicted theoretical properties and observed data.

Celestial black holes: wide mass-range

- Stellar mass black holes (BH) $M_{BH} < 100 M_\odot$
  --- end products of massive stars.

- Intermediate mass black holes (IMBH) (?)
  $\sim 10^2 M_\odot - \sim 10^4 M_\odot$ --- *existence still unclear!*
  formed via runaway merger of stars in clusters, gas accretion by seed stellar BHs, direct collapse of massive 'first stars'.

- Supermassive black holes (SMBH) $M_{BH} > 10^5 M_\odot$
  galaxies' central engines, e.g., active galactic nuclei, radio galaxies: possible formation by matter infall at galaxy center, galaxy-galaxy mergers

Stellar mass BHs are remnants of *Type-II supernova explosions of massive stars* after their nuclear fuel gets exhausted.

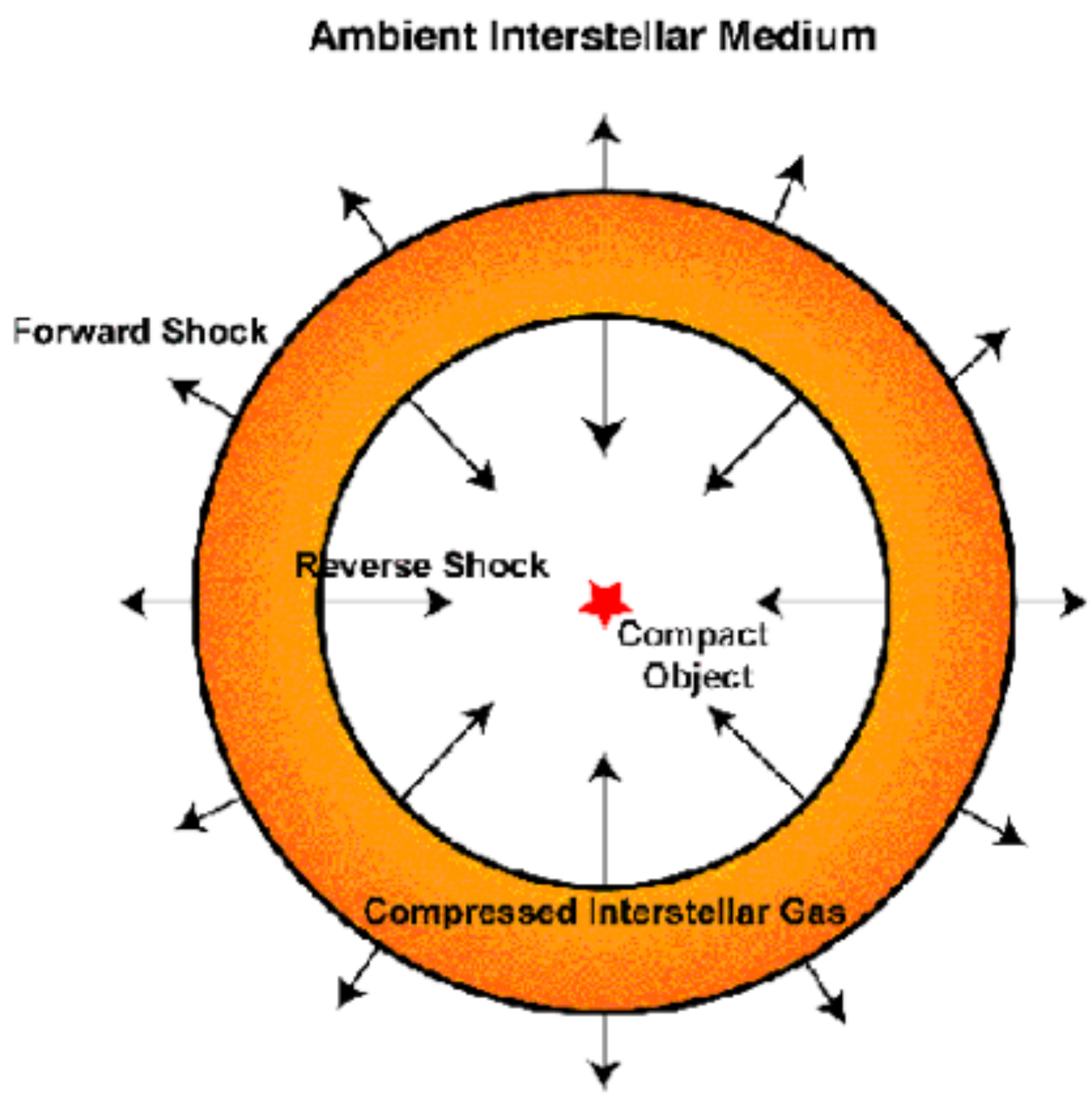


Image credit: nasa.gov

Central compact object massive than $\sim 3M_\odot$ collapses to BH, otherwise neutron star (NS) is formed.

Stars $\gtrsim 100M_\odot$ collapse directly to a BH

Zero-age main sequence (ZAMS) mass $\gtrsim 8 M_\odot$

NS

Mass $\approx 1.4 M_\odot$ (Chandrasekhar limit) $-\approx 3 M_\odot$

Radius ~ 10 Km

Maximum mass & radius depends on equation of state (EOS) of matter at nuclear density

Zero-age main sequence (ZAMS) mass $\gtrsim 18 M_\odot$

BH

mass depends on (a) stellar metallicity Z (b) nature of stellar wind [(c) supernova characteristics]

average mass $\approx 10 M_\odot$ (low Z), maximum measured mass so far $\approx 30 M_\odot$ (IC10 SFR)

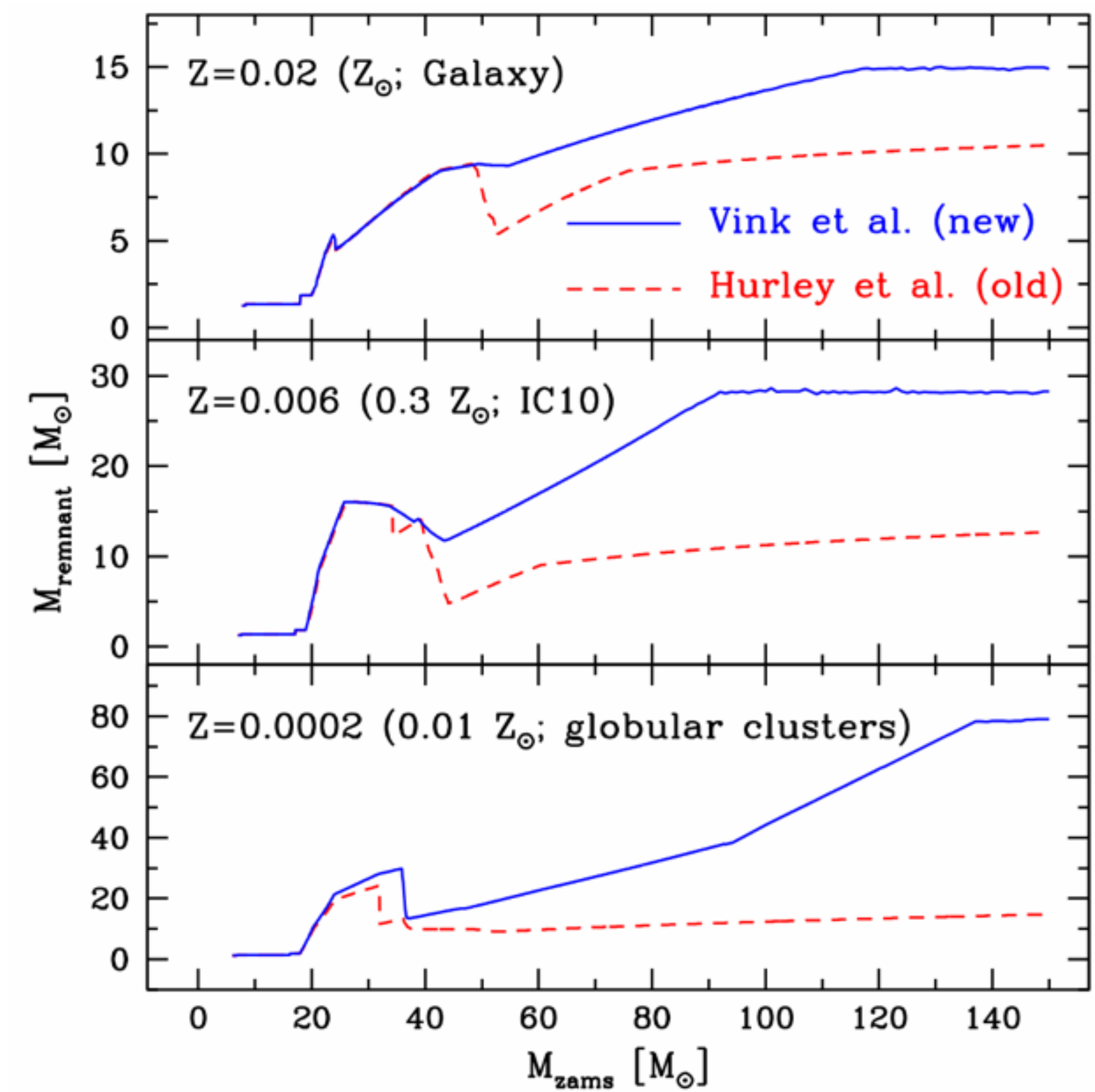
Radius = event-horizon =

$$\frac{r_s + \sqrt{r_s^2 - 4\alpha^2}}{2},$$

$$r_s = 2GM/c^2, \quad \alpha = J/Mc$$

Stellar BH mass-function (from theory)

From Belczynski et al. 2010



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- Accretion of matter onto BHs from binary stellar companion : inner region of accretion disk becomes hot enough to emit in X-rays --- *X-ray binaries.*

- Accreting BH candidates in X-rays have been detected in galactic fields and globular clusters through "Chandra" / "XMM-Newton" observatories.

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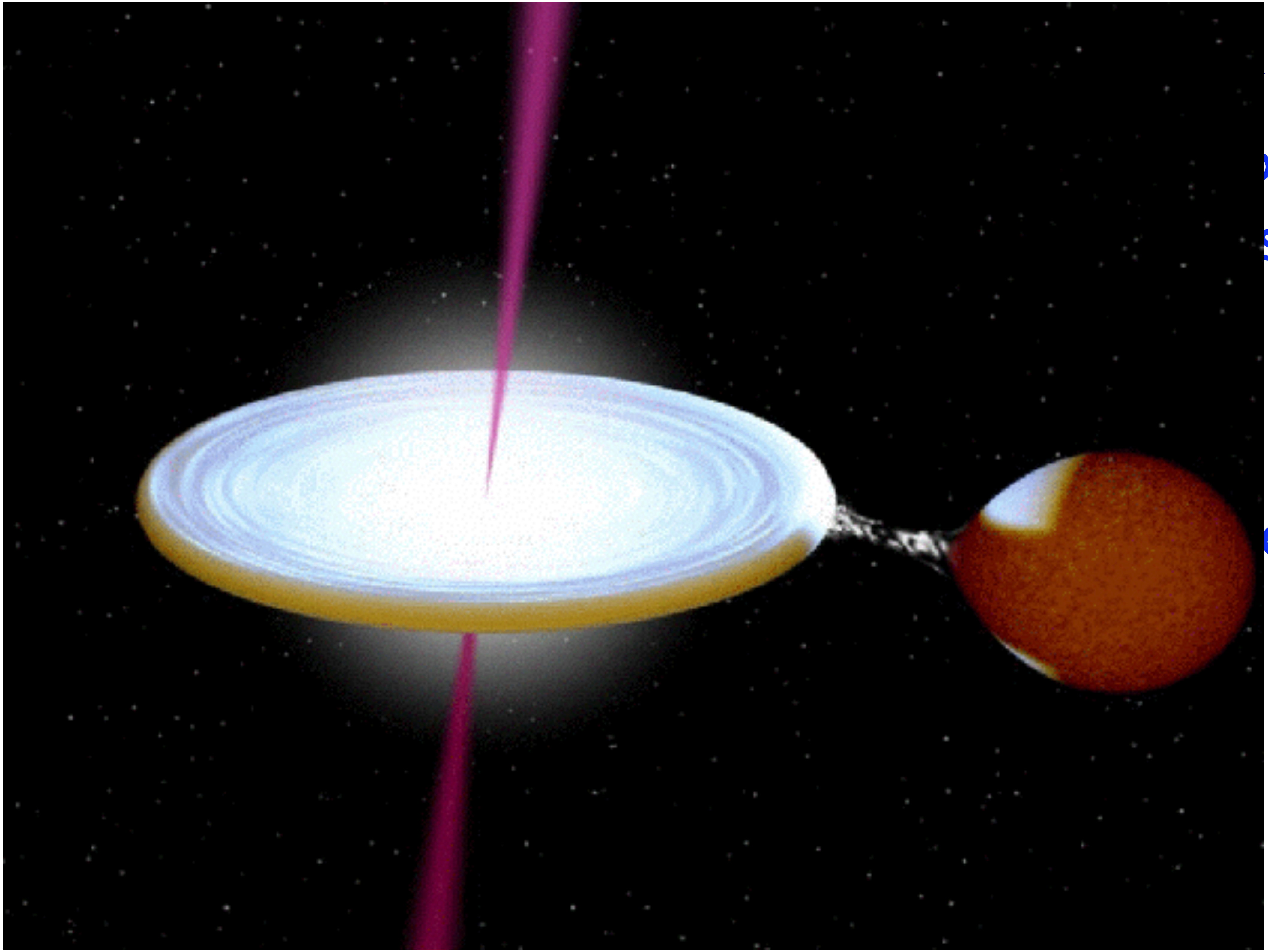

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Accreting BHs are also bright radio sources: radio waves produced by synchrotron emission in jets.

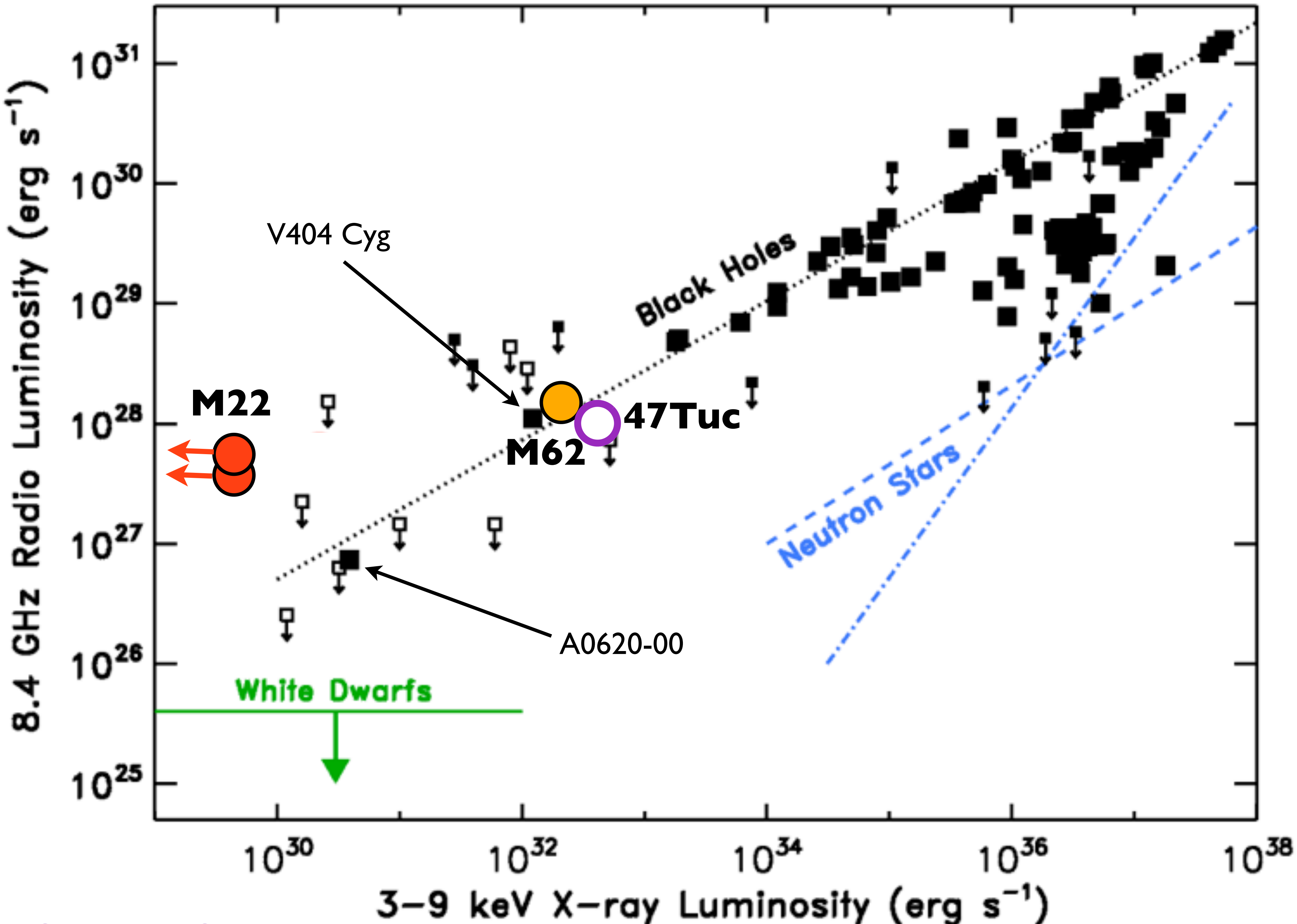

Fig. credit: Jay Strader, MSU

How stellar BHs can be seen?

- Tight (semi-major-axis of few solar radii) BH-BH binaries radiate gravitational waves (GW) to spiral in and finally merge into single BH.

- GWs are "ripples" in space-time --- a fundamental prediction of Einstein's general theory of relativity. [any varying mass quadruple moment emits GW]

- Peters' (1964) orbit-averaged formula for orbital evolution of semi-major-axis a and eccentricity e :

$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64G^3}{5c^5} m_1 m_2 (m_1 + m_2) a^{-3} (1-e^2)^{-\frac{7}{2}}$$

Tested with high accuracy for binary pulsars (e.g. the Hans-Taylor pulsar)

Equal mass (M_{BH}) BH-BH merger time:

$$T_{mrg} = 150\mathrm{Myr} \left(\frac{M_\odot}{M_{BH}}\right)^3 \left(\frac{a}{R_\odot}\right)^4 (1-e^2)^{\frac{7}{2}}$$

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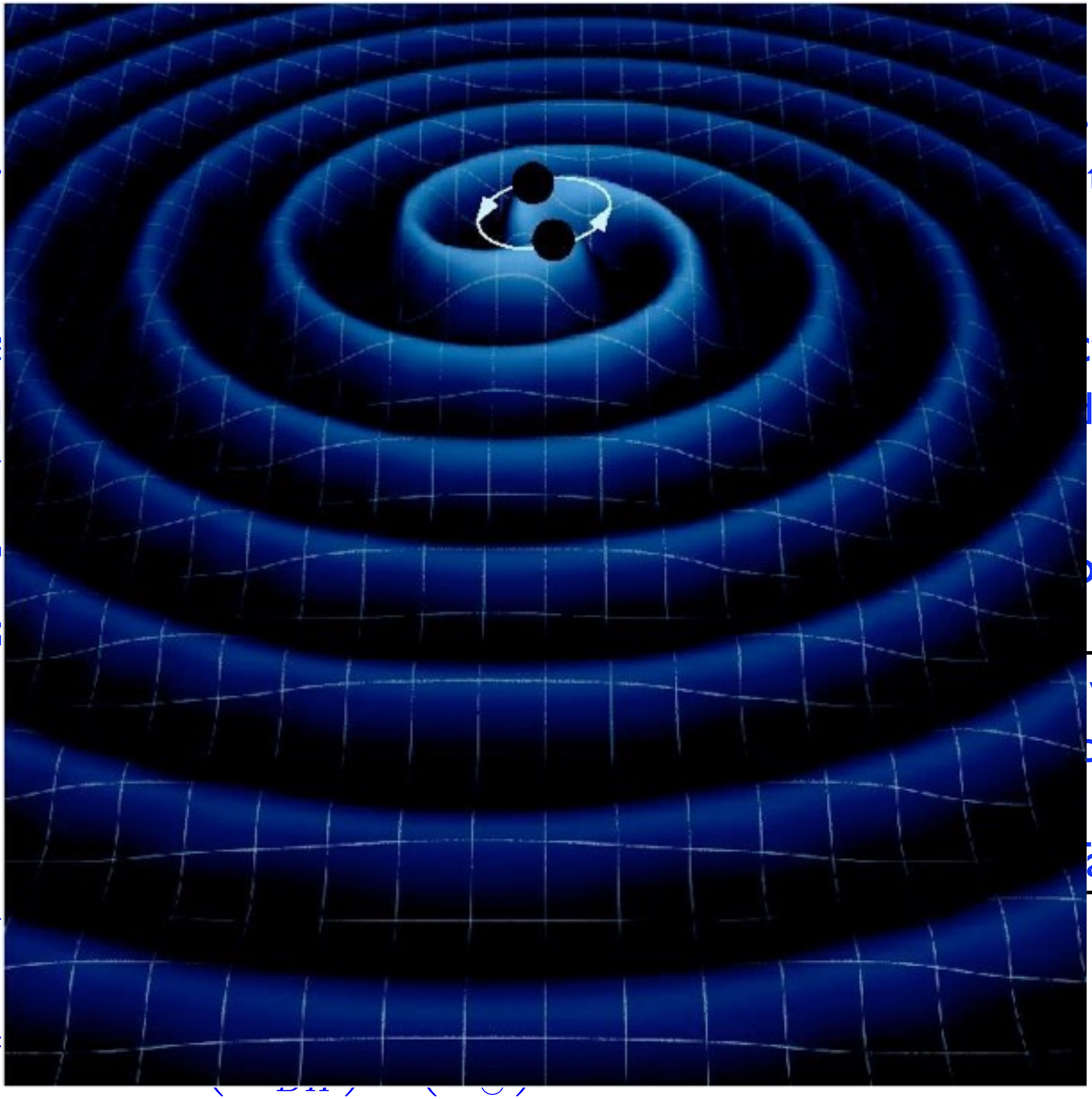

- Tight (… radiate gravita… to single BH.
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- Peters' … on of semi- major-a…

$\left\langle \frac{da}{dt} \right\rangle$

with high … y for binary (e.g. the … aylor pulsar)

Equal

$T_{mrg} =$

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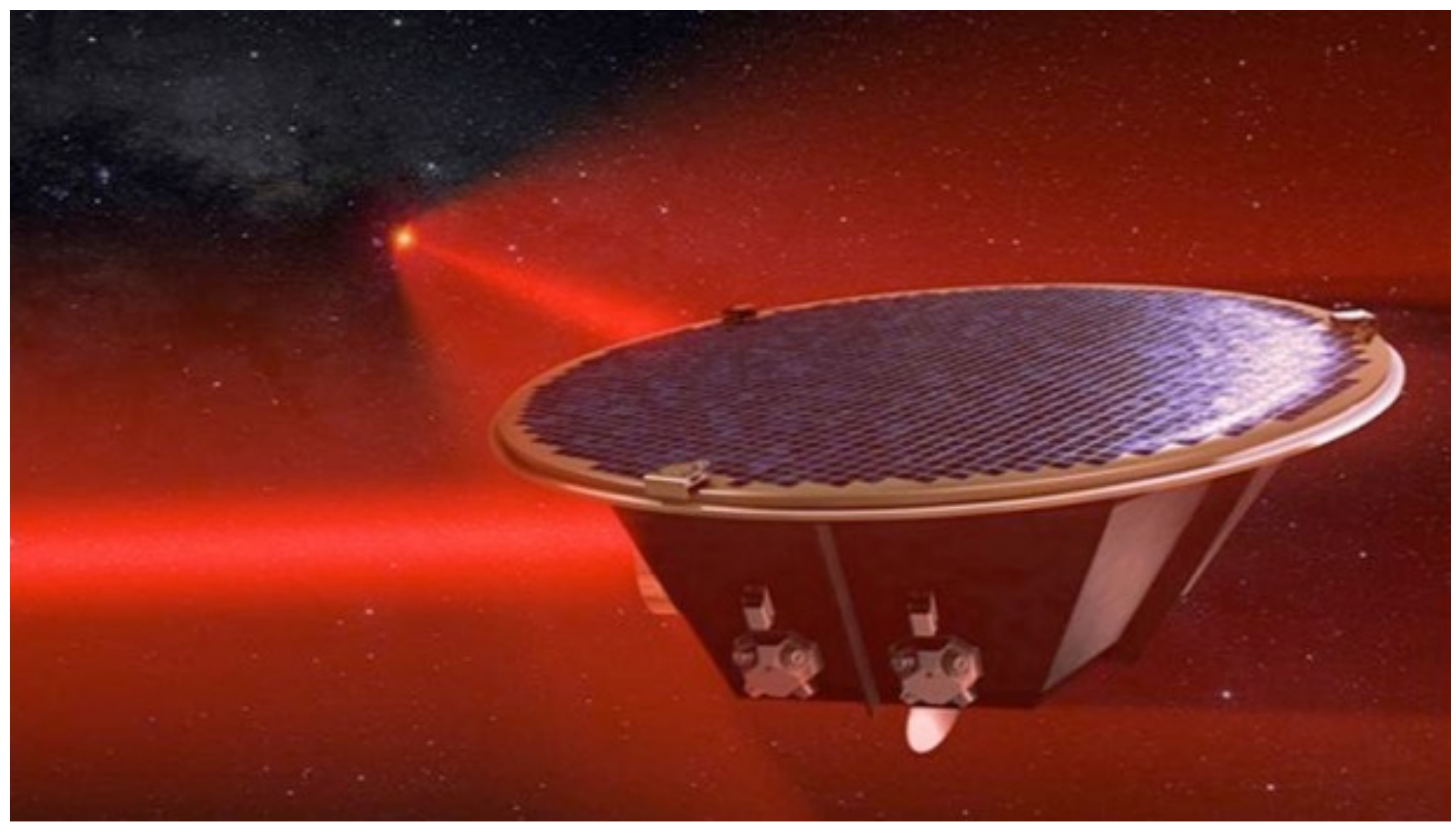
How stellar BHs can be seen?

- Detection of GW essential for verification of Einstein's general theory of relativity.
- Detection of GW can determine masses & spins of merging BHs (see Hughes' review) --- strong constraints on supernova, stellar & binary evolution models.
- Other astrophysics (from stellar BHs): massive stellar evolution, stellar binary population, star cluster population in galaxies.
- GW yet to be detected --- possible in near future by upcoming GW missions, e.g., "Advanced LIGO" & "eLISA" (also "Virgo", "Indigo", "GEO 600").
- GW detection among most important technological challenges.

Laser Interferometer Gravitational Observatory (LIGO) at Hanford

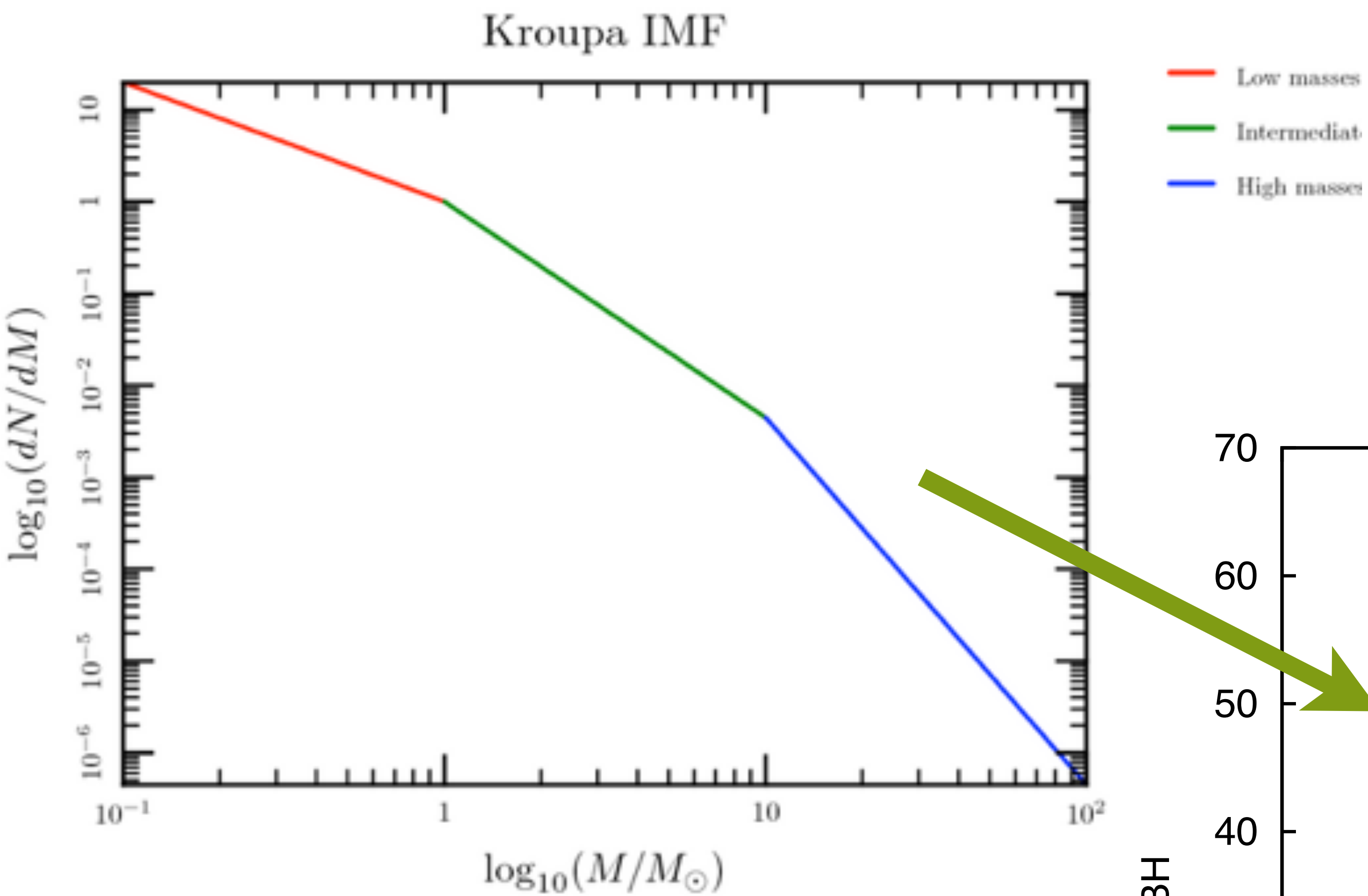
[Arm length: 4 Km, currently under upgrade to "Advanced LIGO"]

(evolving) Laser Interferometer Space Antenna (eLISA)

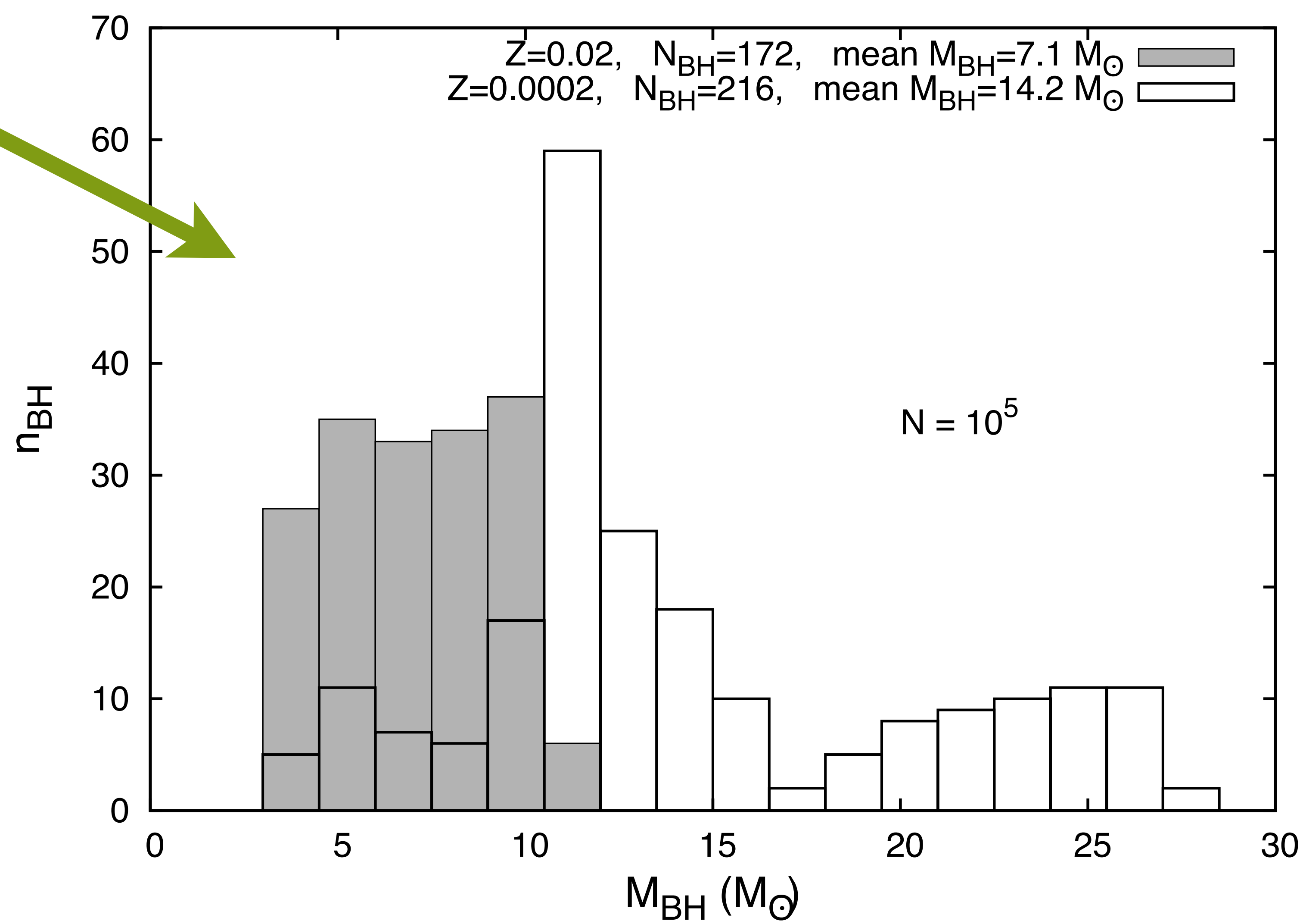


Stellar mass black holes in star clusters

Massive stars (ZAMS mass $\gtrsim 18 M_\odot$) evolve in clusters to produce stellar BHs. BH mass function depends on cluster initial mass function (IMF) and metallicity.



Cluster IMF; Kroupa (2001)



BH mass function

What happens to these BHs ?

- Compact remnants (NS/BH) can receive birth / *"natal" velocity kick* due to asymmetry in supernova ejecta which carries net momentum.

- Amount of kick for BH uncertain (in theory & observation).

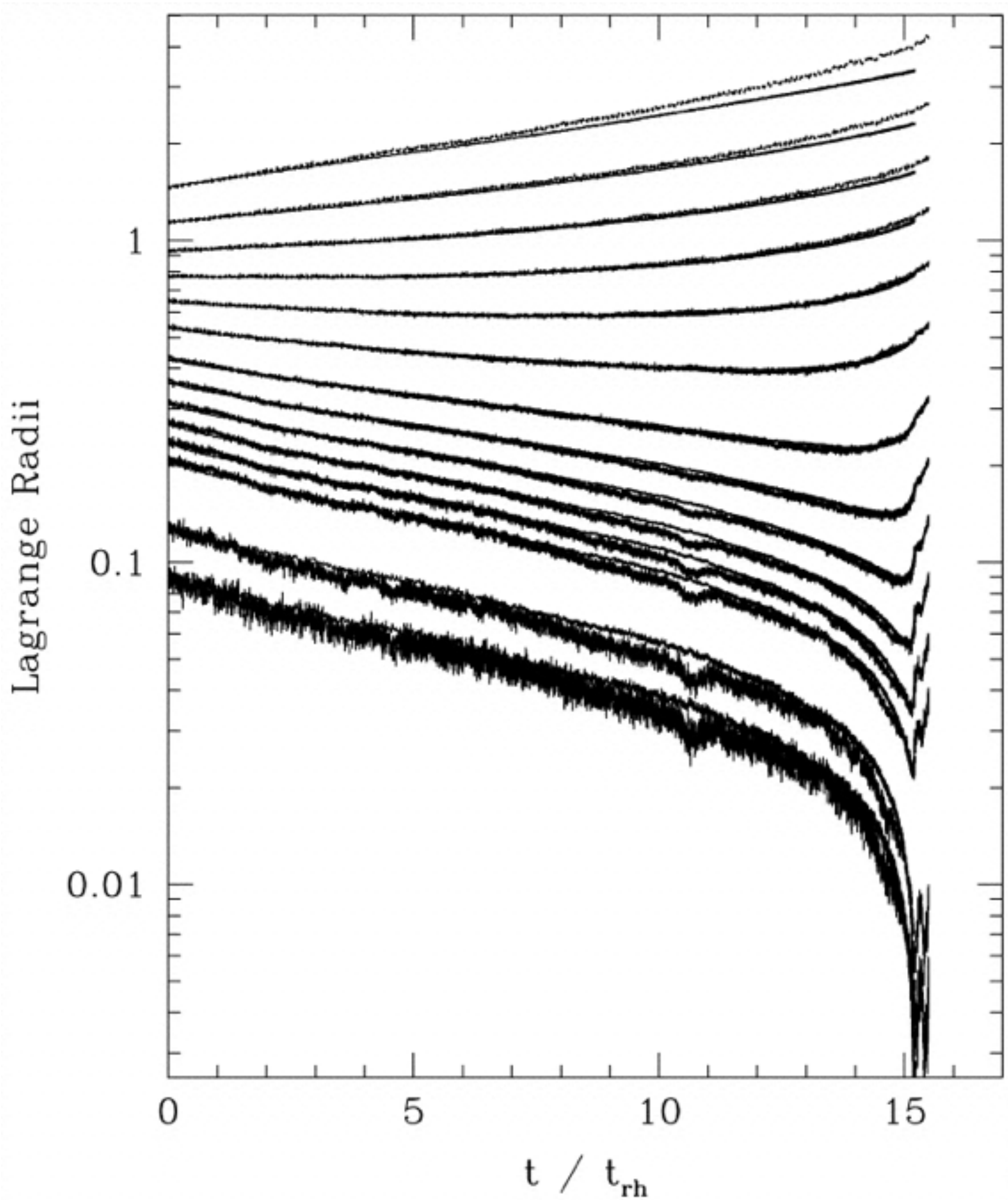
- Can be observationally inferred from "back-tracing" orbital motion of Galactic BH X-ray binaries [e.g. ,Willems et al., 2005, ApJ, 625, 324, Repetto et al.] --- indicate *very low to high natal kicks*.

- Computations of core-collapse supernova also support a wide range of natal kicks (Janka et al.).

- "Electron Capture" mechanism necessarily produces remnants with small kick velocities.

Dynamical evolution of stellar BH population in star clusters

Core collapse



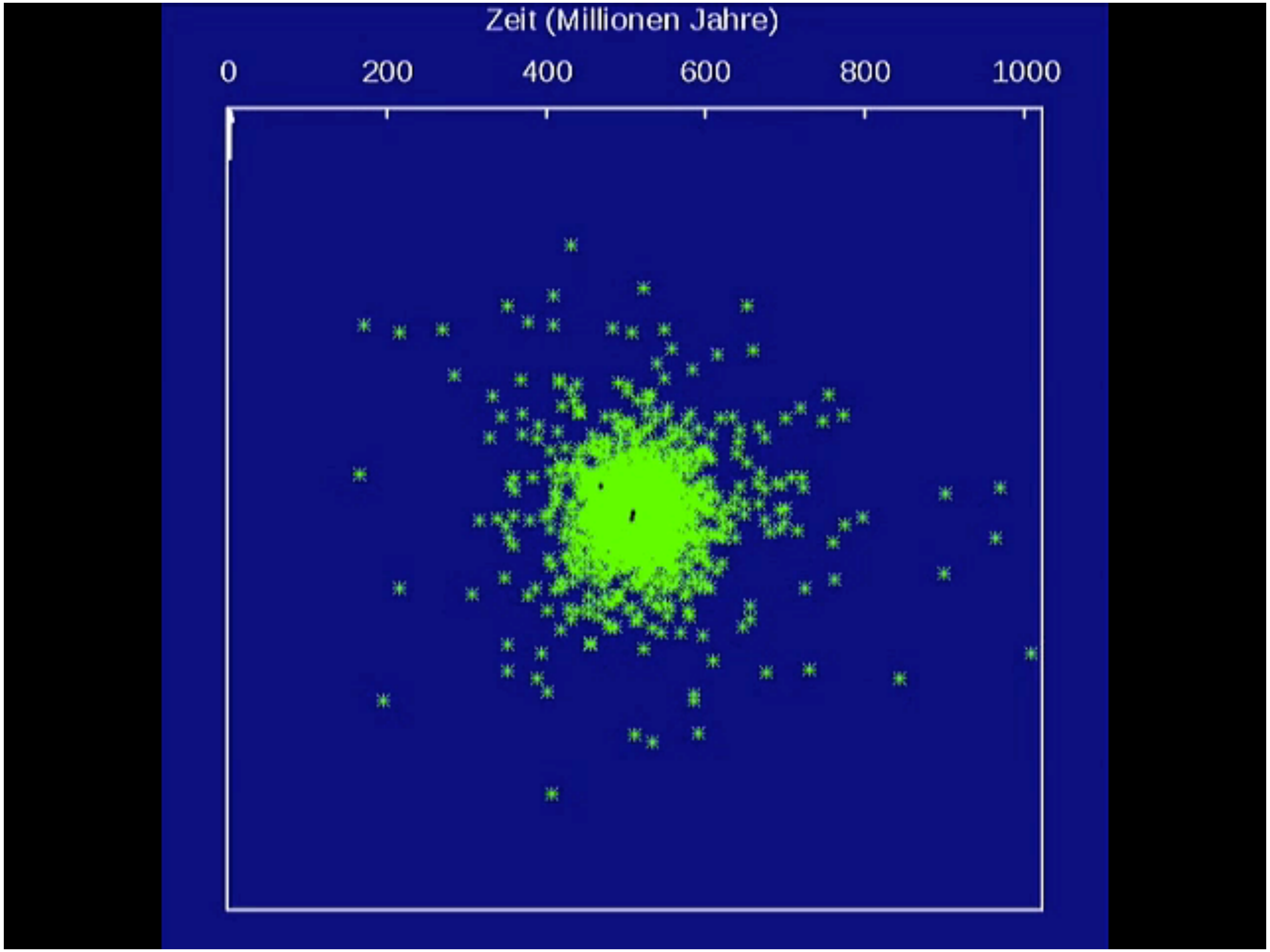
Runaway contraction of the core of a star cluster due to *gravothermal instability* in the final phase of dynamical relaxation.

Core-collapse of model cluster (tidally truncated $W_0 = 3$ King model) without primordial binaries & no stellar evolution.

Monte-Carlo computation superposed with corresponding N-body computation.

From Joshi et al. (2000).

Mass segregation of BHs



N-body computation with "NBODY6" : $N \approx 5 \times 10^4$,
$r_h(0) = 1\ \mathrm{pc}$, complete BH retention

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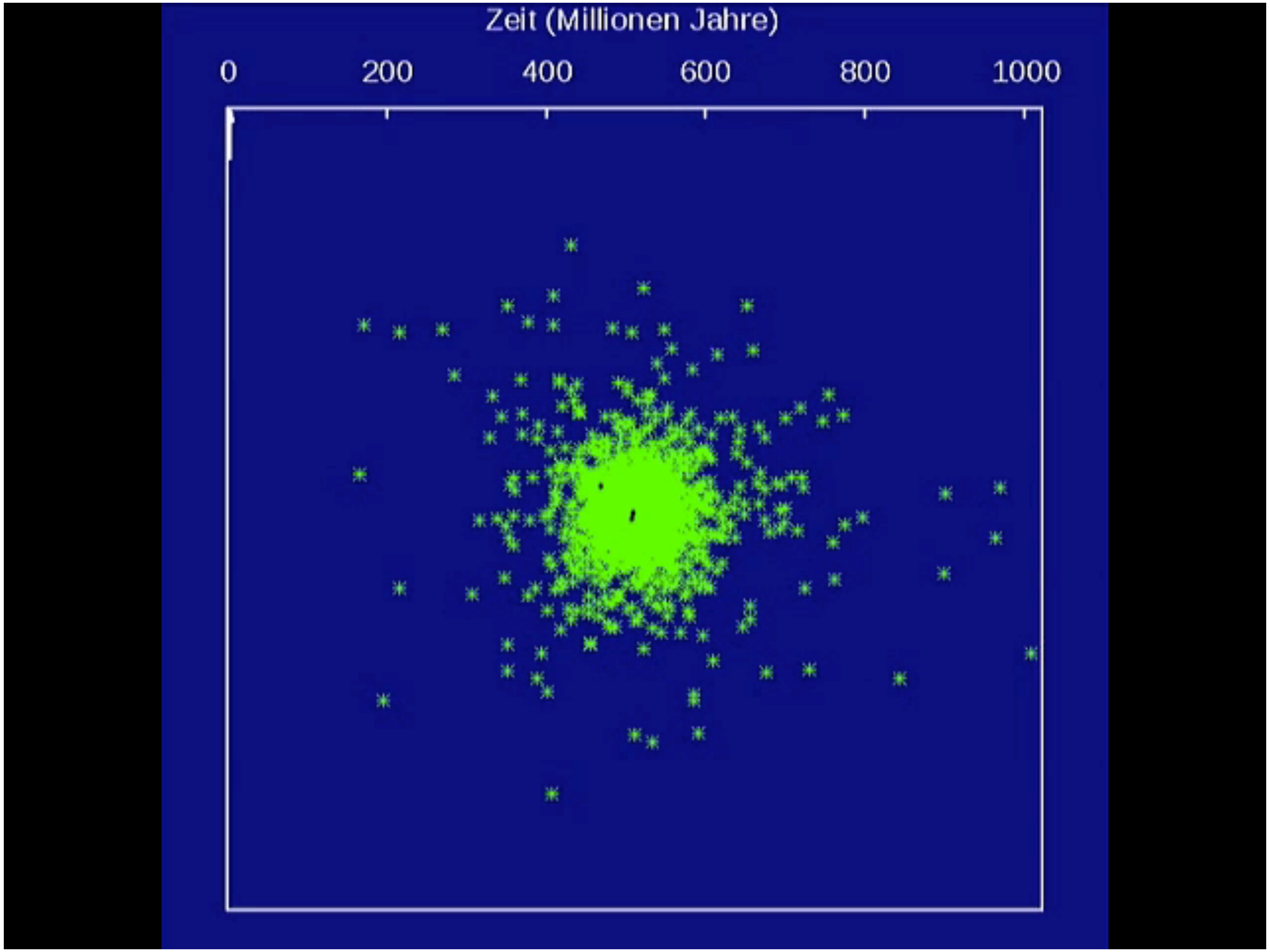

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Dynamical friction caused by "wake" formation behind fast-moving massive particle due to its "gravitational focussing" effect. The wake applies retarding force to the particle.
[see Chandrashekhar's stellar dynamics book for details]

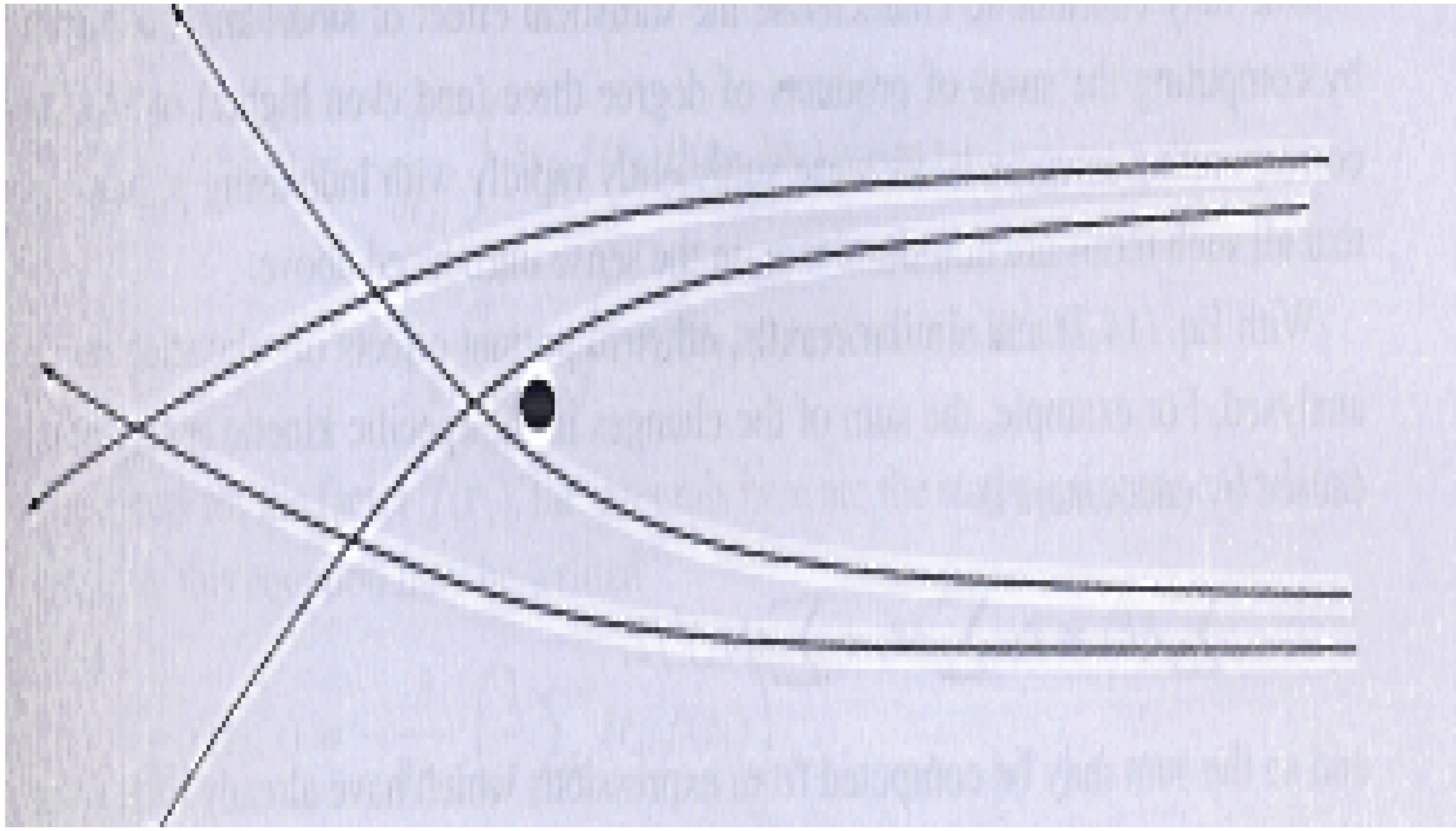

Image from Heggie & Hut's book