Formation of GW190521 via gas accretion onto population III stellar black hole remnants born in high-redshift minihalos

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FORMATION OF GW190521 VIA GAS ACCRETION ONTO POPULATION III STELLAR BLACK HOLE REMNANTS BORN IN HIGH-REDSHIFT MINIHALOS

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...submitted to ApJ Letters

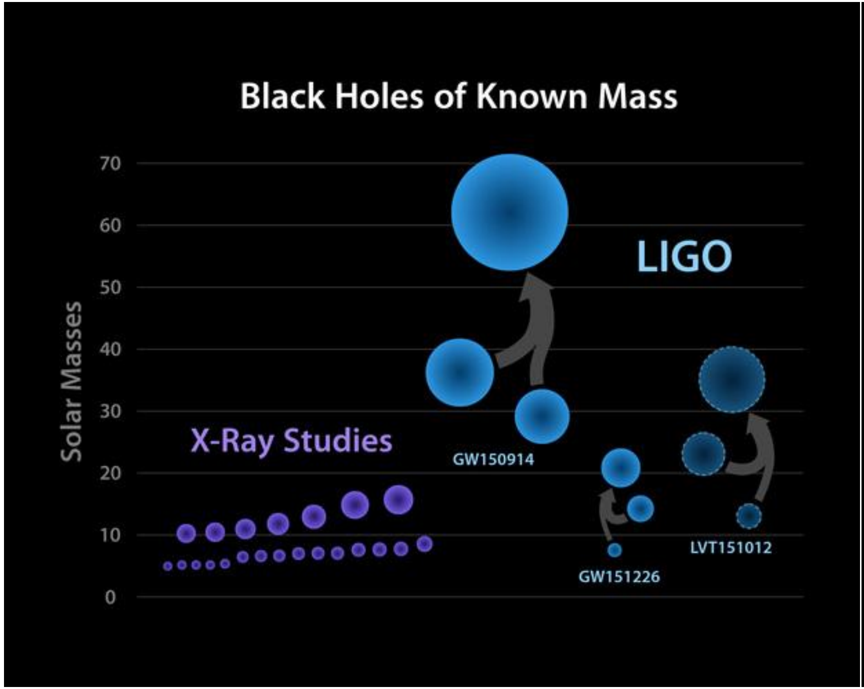
For information on the discovery, properties and implications...

Properties and astrophysical implications of the $150\,\mathrm{M}_\odot$ binary black hole merger GW190521

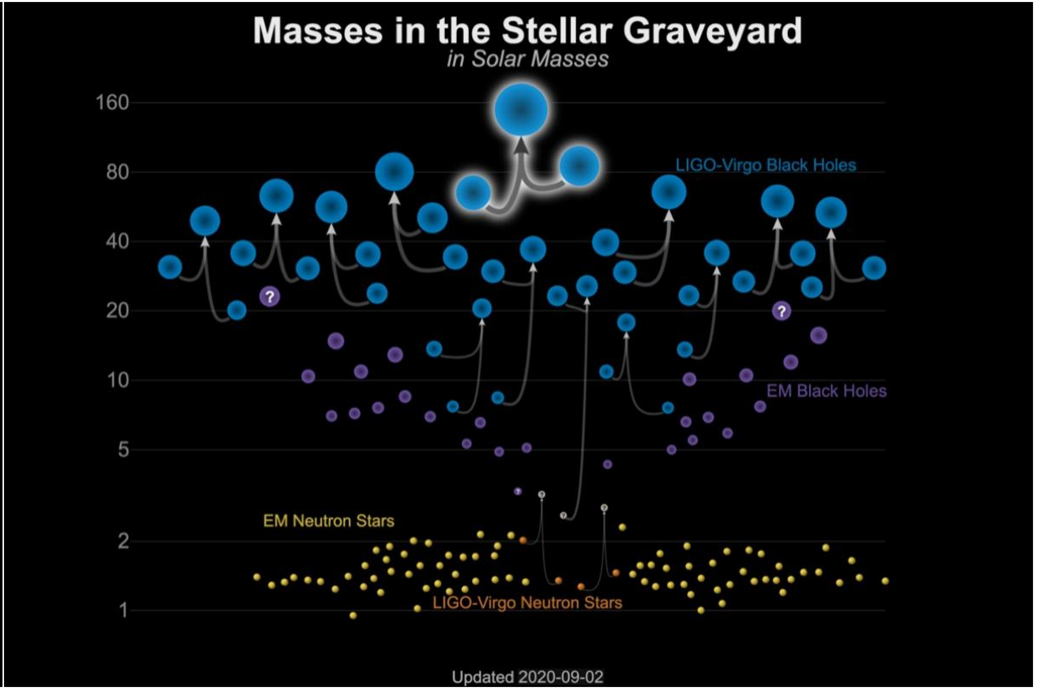
LIGO SCIENTIFIC COLLABORATION AND VIRGO COLLABORATION

What's so important about GW190521?

before



after

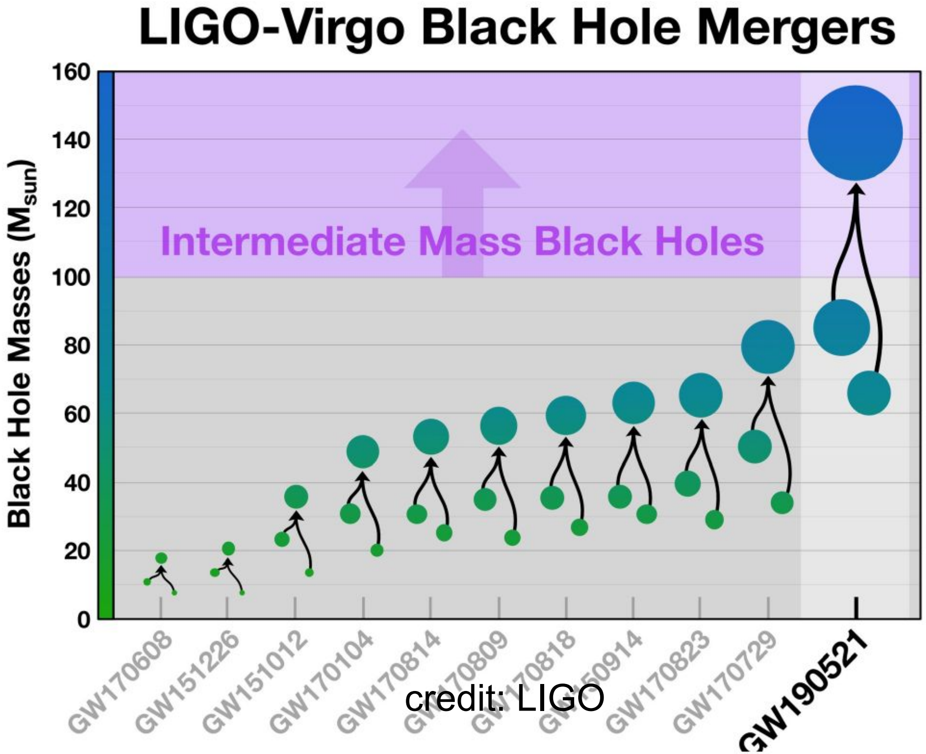


credit: LIGO

What's so important about GW190521?

$$142^{+28}_{-16}\,\mathrm{M}_{\odot}$$

- falls into the class of intermediate-mass black holes
- between the stellar-mass BHs and SMBHs
- "seeds" SMBHs?



credit: LIGO

What’s so important about GW190521?

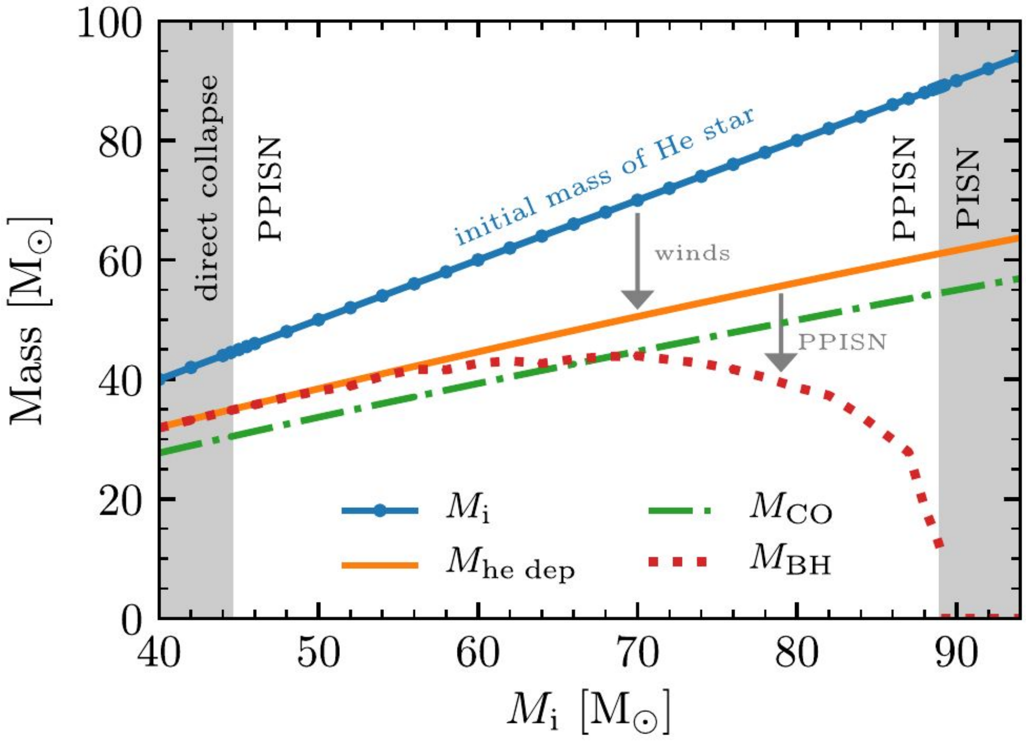
Marchant+19

Masses: ~85 $M_\odot$ and ~66 $M_\odot$

L+V: 99% of simulated BH primaries have masses below 45 $M_\odot$

Cause: pair-instability mass gap

Question: how can we get two companions in the gap?



A possible scenario… Hierarchical mergers

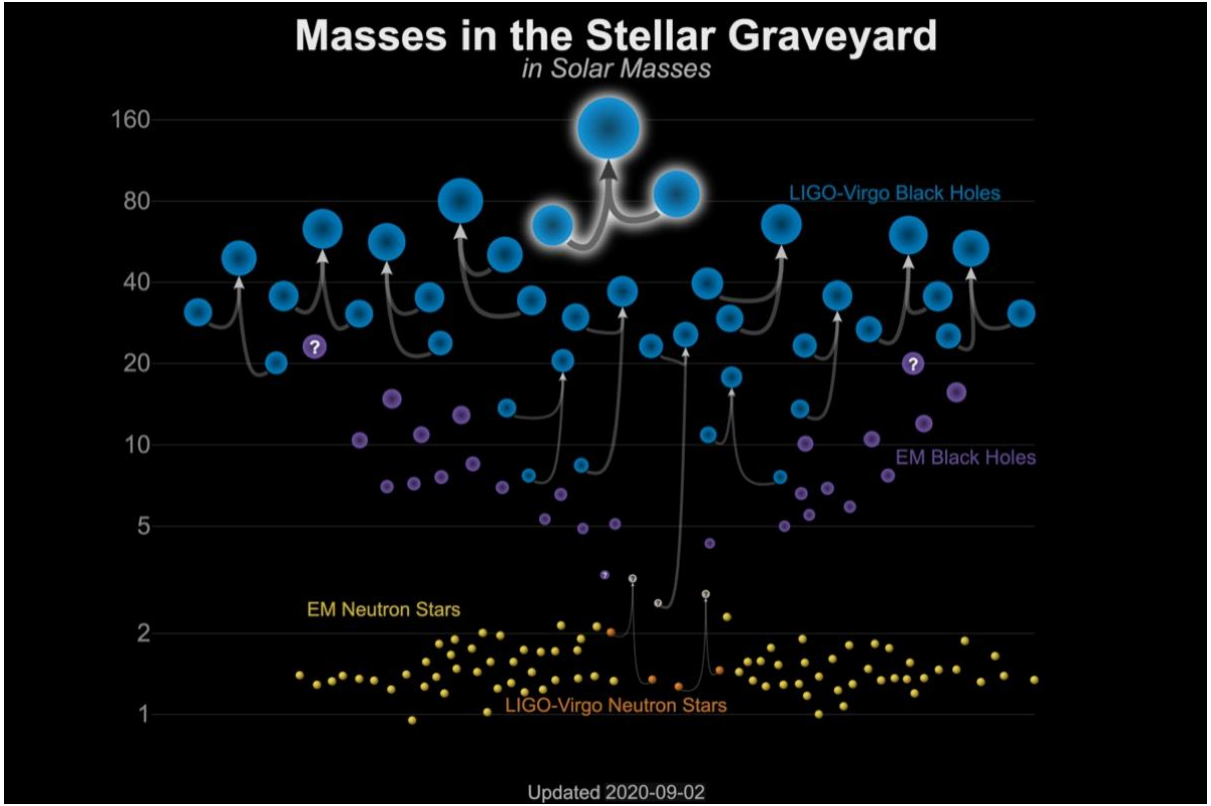
credit: LIGO

Rare and requires really dense environments such as:

young star clusters (e.g., Fragione+20)

AGN accretion disks (e.g., McKernan+12)

globular clusters (e.g., Kimball+20)



Other scenarios

- Wrong assumptions during GW analysis: eccentricity and heads-on collisions (e.g., Calderón Bustillo et al. 2020)

- Gravitational lensing due to a galaxy or a galaxy cluster (e.g., Ng et al. 2018)

- Primordial BHs from dark-matter overdensities (e.g., Carr & Hawking 1974)

- Uncertainties in binary evolution?

A new scenario: Pop III stars formed in a minihalo

Population III stars ($z > 10$) with zero metallicity:

- suppressed fragmentation = **massive stars** are more common (Hirano+15)
- **higher binary fraction** (Sana+12)
- decreased stellar winds and evolution = **massive BH remnants** (Farrell+20)

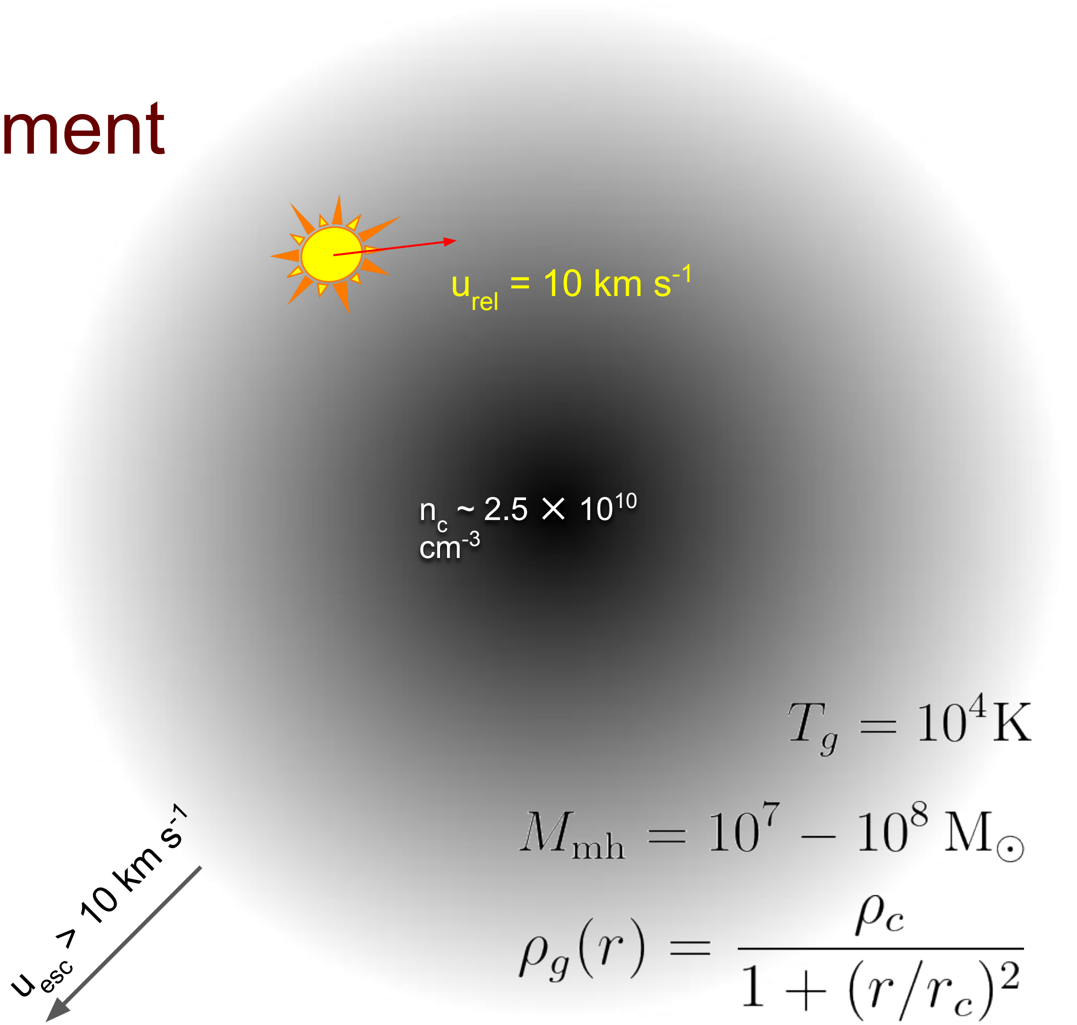
Dark matter minihalos:

- 10^5 - 10^6 $M_\odot$, hosting Pop III stars (e.g., Inayoshi+19)
- proposed for forming SMBHs, but... **radiative feedback**, SN **explosions**, **escaping BHs** (e.g., Whalen+08, Alvarez+09, Smith+18)

The toy model: environment

Once upon a redshift (>15) in a minihalo far far away…
a Pop III binary is born

When (z~10) the minihalo builds up, accretion is efficient



$$T_g = 10^4 \mathrm{K}$$

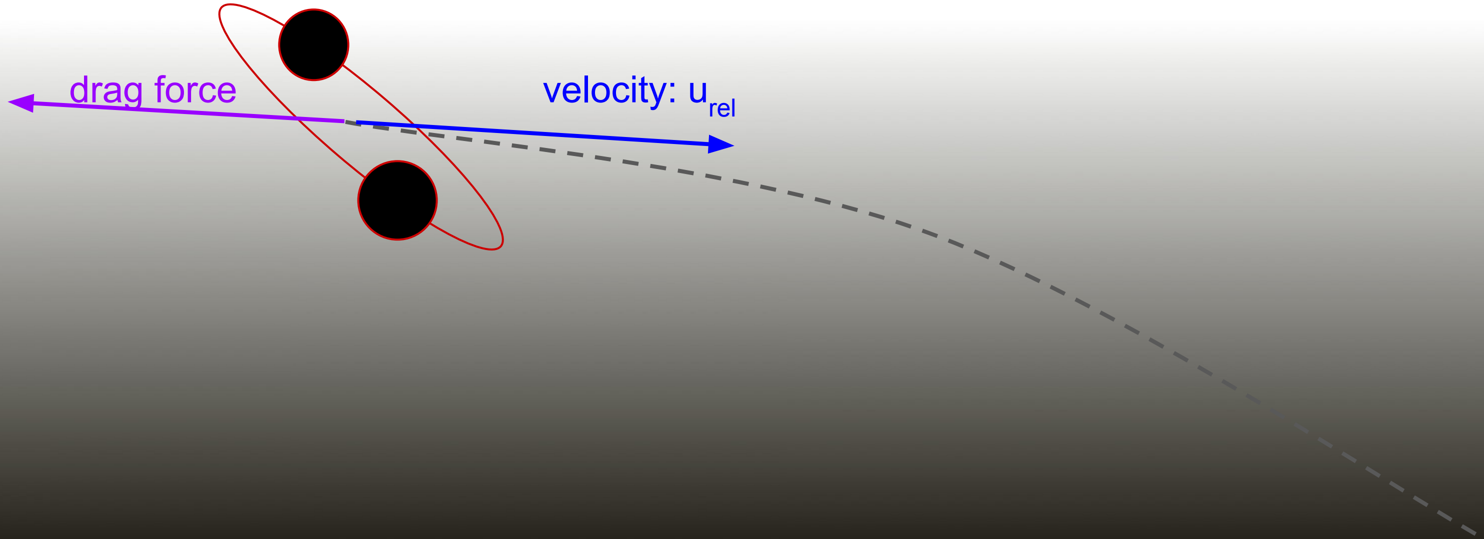
$$M_{\mathrm{mh}} = 10^7 - 10^8\, \mathrm{M}_\odot$$

$$\rho_g(r) = \frac{\rho_c}{1 + (r/r_c)^2}$$

Drag force (gas) → system falls in the central region

two cases: $10M_\odot+10M_\odot$ and $40M_\odot+40M_\odot$

$$\tau_{\rm df}(r) \approx 2\times 10^4 \left(\frac{M_{\rm bh}}{M_\odot}\right)^{-1}\left[1+\left(\frac{r}{r_c}\right)^2\right]\,{\rm yr}$$



The toy model: accretion near the dense core

Bondi-Hoyle-Lyttleton accretion

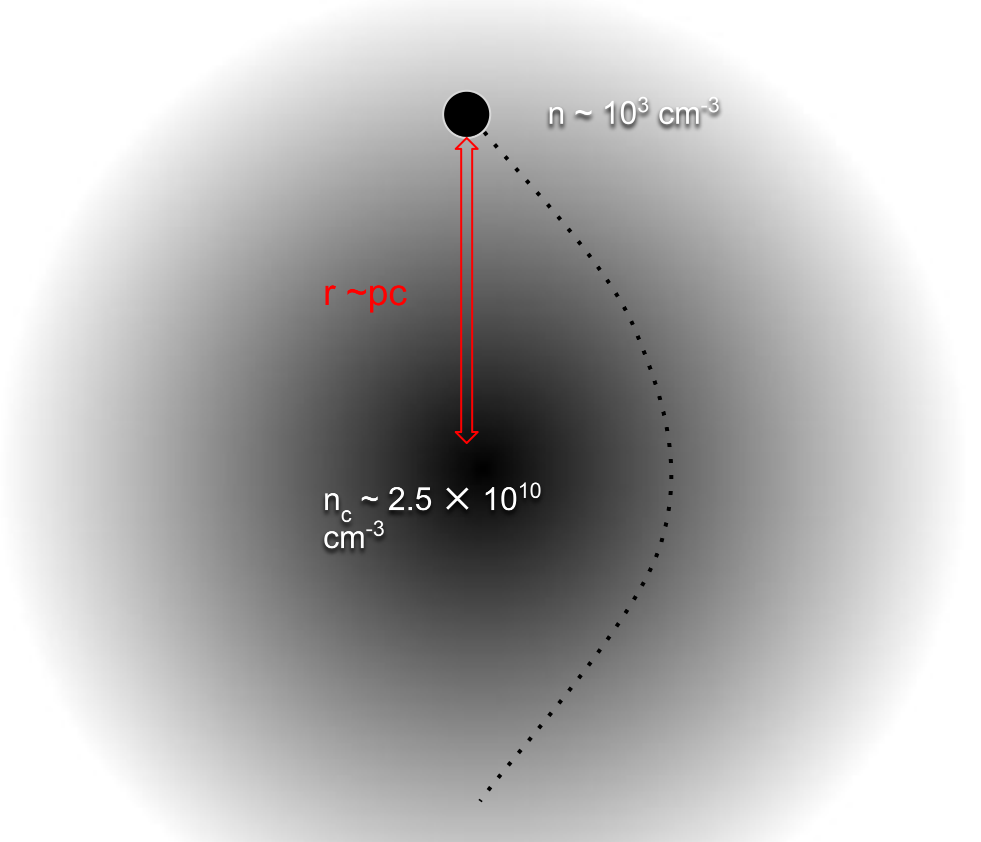
$$\dot{M}_{\rm bh} = \frac{4\pi G^2 M_{\rm bh}^2 \rho_g}{(c_s^2 + v_{\rm rel}^2)^{3/2}}$$

Eddington accretion rate

$$\dot{M}_{\rm Edd} = 2.2 \times 10^{-8} \left(\frac{M}{M_\odot}\right) M_\odot {\rm yr}^{-1}$$

Hyper-Eddington accretion

photon trapping suppresses radiative feedback when BHL accretion rate is >500x the Edd.



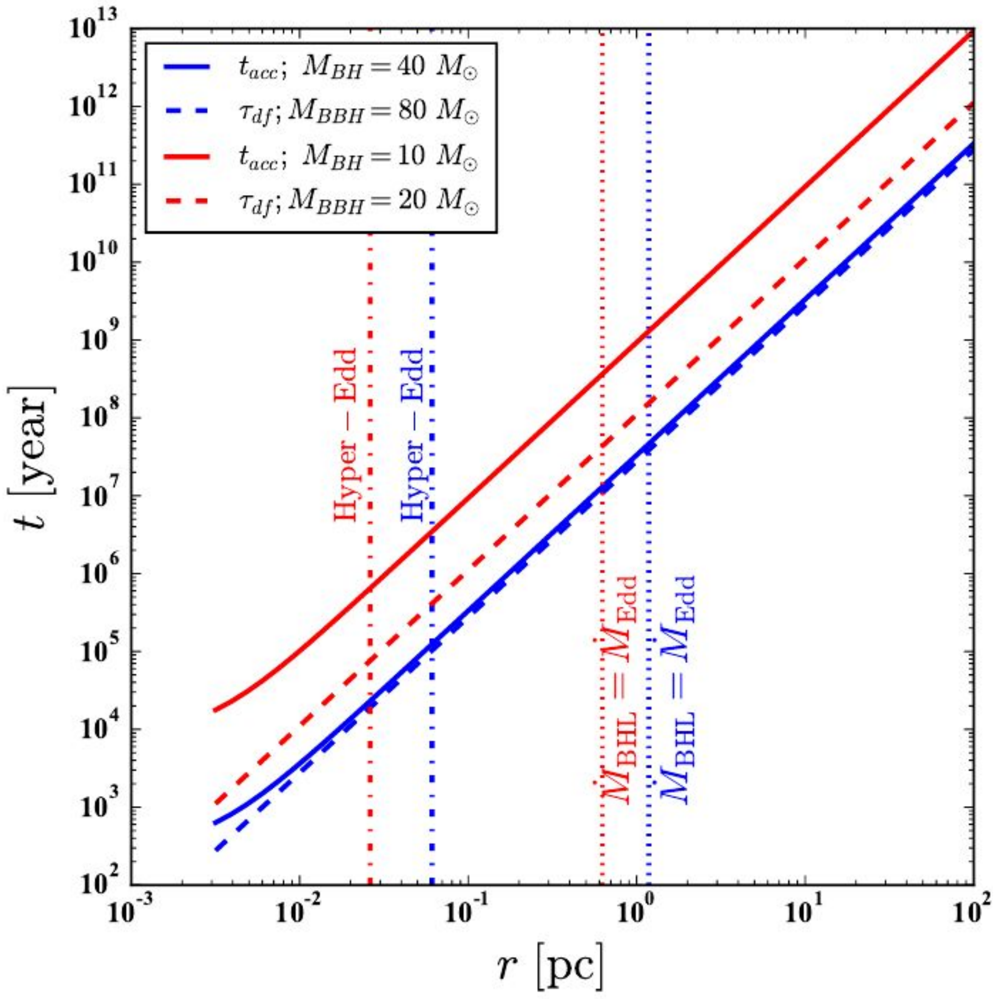
Which binary is favored?

For different galactocentric distances:

- $20M_\odot$ binary:
  dynamical friction << accretion timescale to reach $150M_\odot$ (GW190521)

- Similar timescales for $80M_\odot$ binary

- Only a few thousand years of Hyper-Eddington accretion are need for the more massive case



Predicted merger rates

SFR density

10^4-10^5 $M_\odot$ yr^{-1} Mpc^{-3} at z=10-20

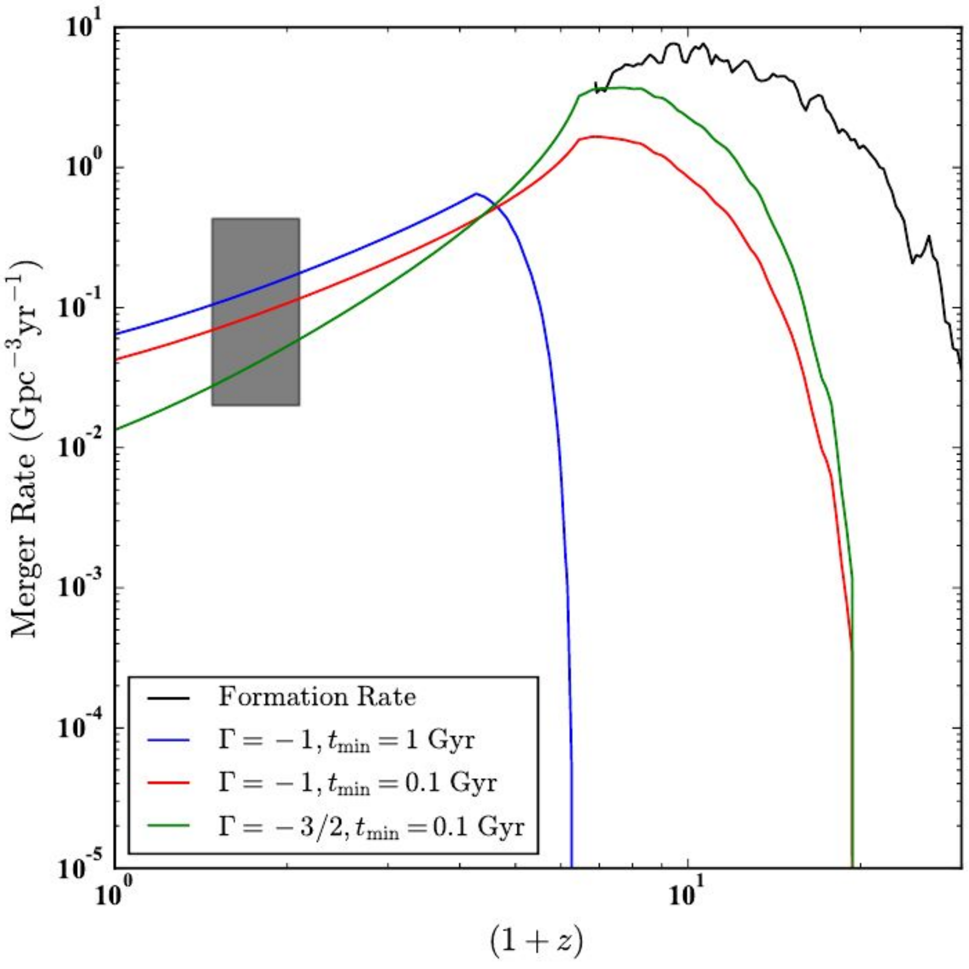
Pop III metallicity

Z_{crit}=3 x 10^{-4} $Z_\odot$

Canonical delay-time distributions

(3 choices of slope/minimum time)

Standard ΛCDM parameters



Discussion / Conclusion

- **Merger rate** and other properties (q / spin) consistent with the L+V result
- Simulations: BBHs spend most of their time in low-density regions, and can orbit away: this model requires **only a few Myrs** to be spent in the dense core
- **3D** simulations with inhomogenous gas distributions to verify this scenario
- Extension: dynamically-captured isolated BHs close to the core
- Even more massive BHs can be formed: lower-f detectors needed (e.g. LISA)