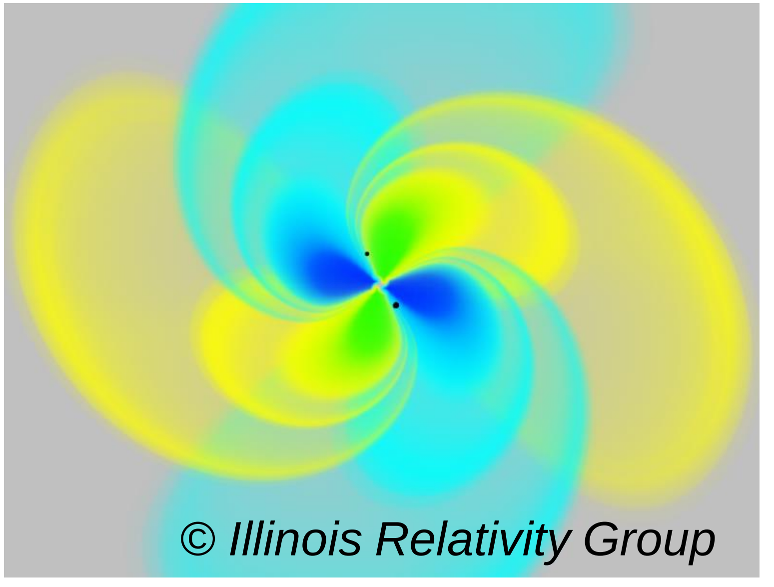
初代星・初代銀河研究会2016@金沢

多重孤立BHの合体による GW150914の説明



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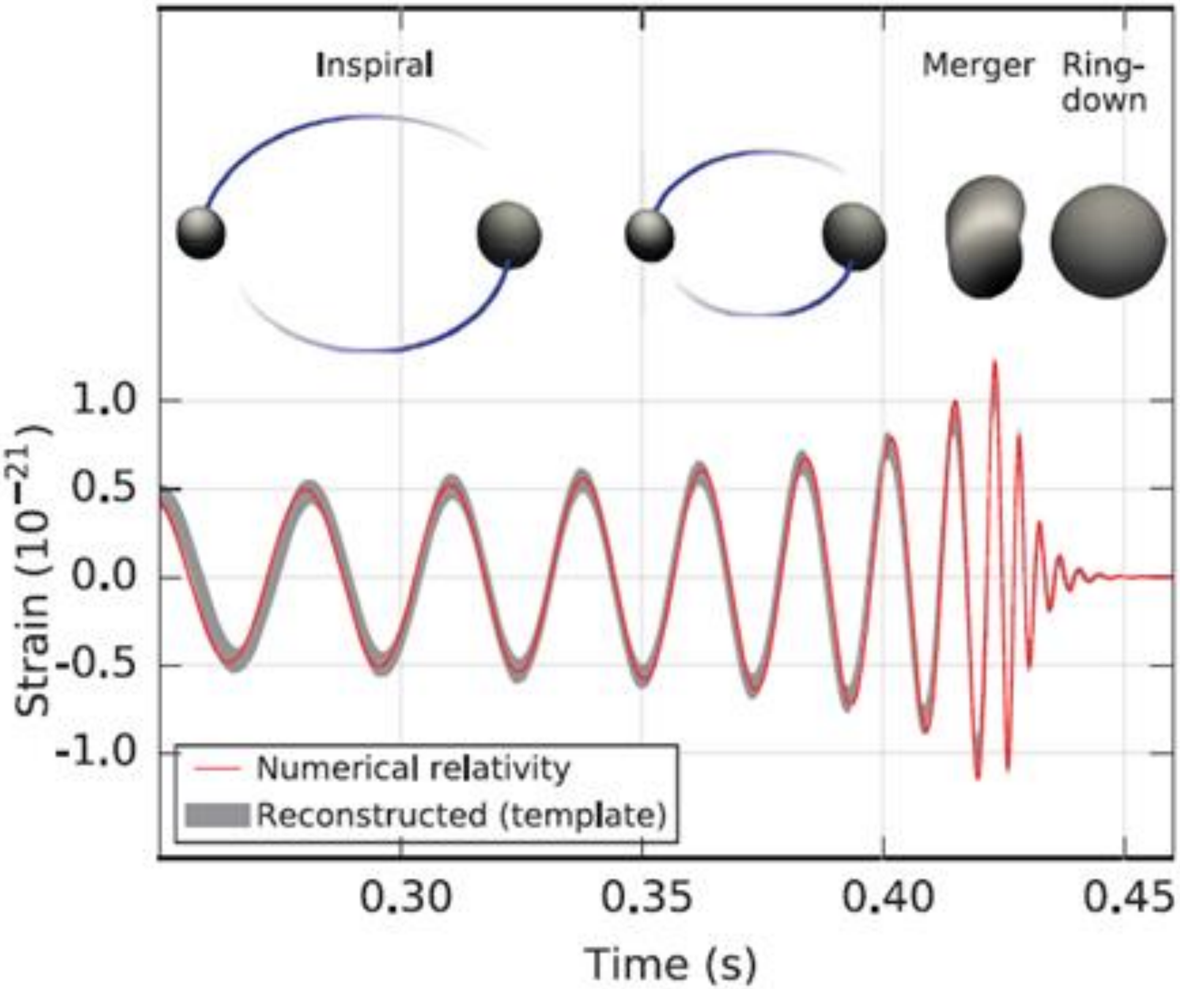
梅村　雅之 (筑波大学)

重力波イベントGW150914

Abbott et al. (2016)

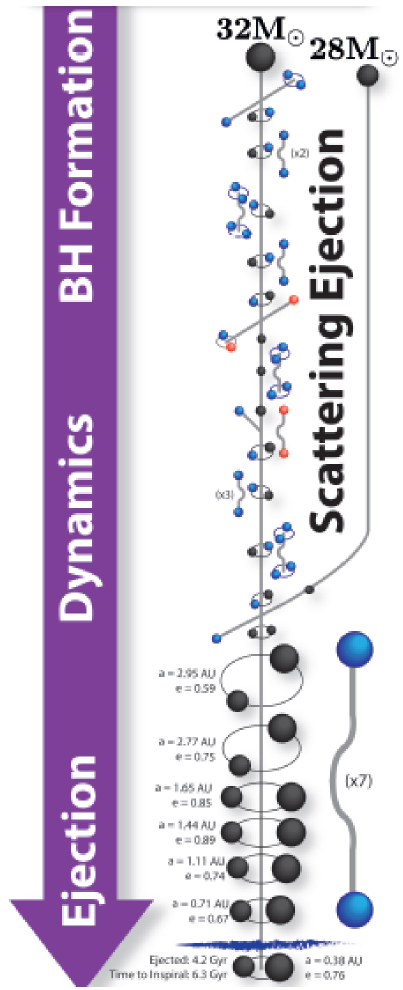


GW150914への進化モデル

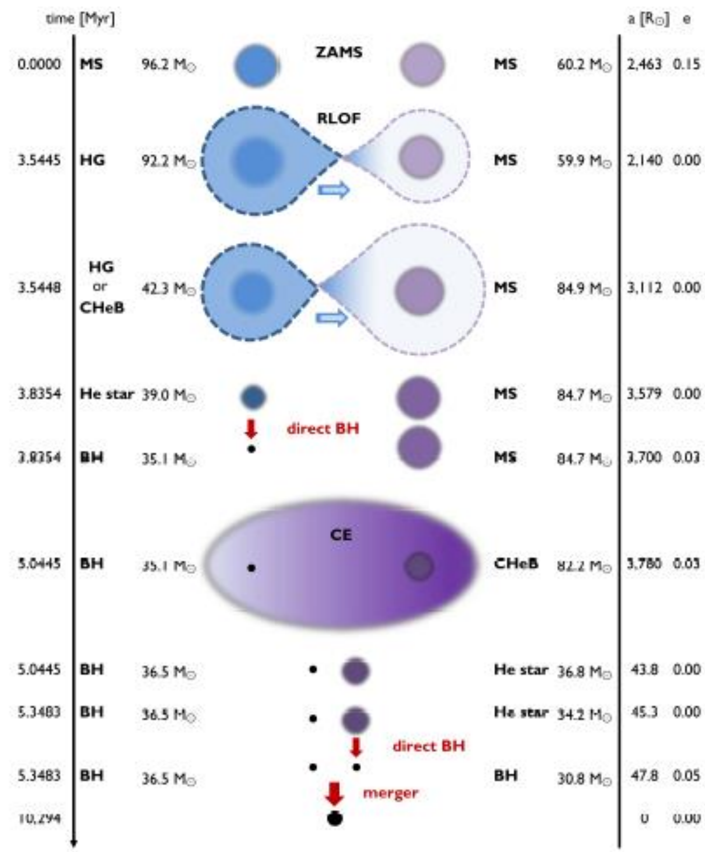
1. 球状星団内での力学的な進化
   (e.g. Rodriguez et al. 2016)

2. 連星進化
   (e.g. Belczynski et al. 2016;
   Marchant et al. 2016;
   de Mink & Mandel 2016)

Rodriguez et al. (2016)



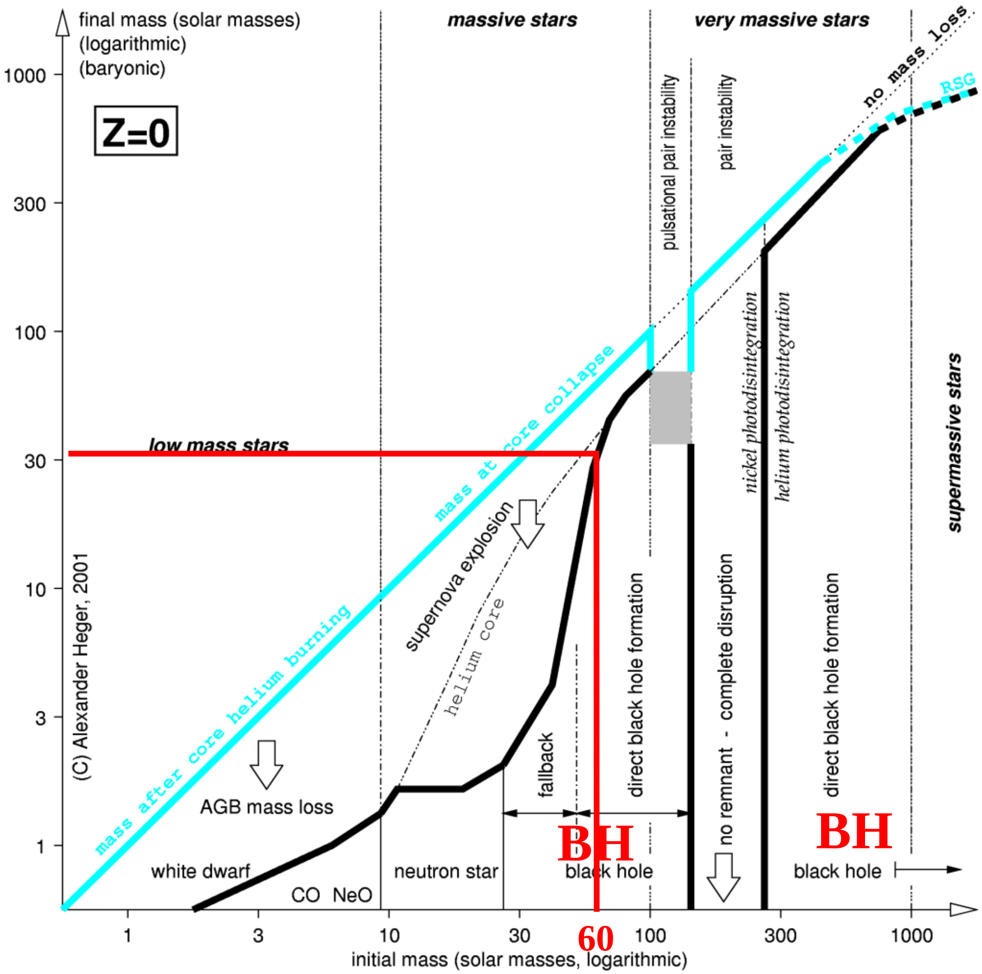
Belczynski et al. (2016)

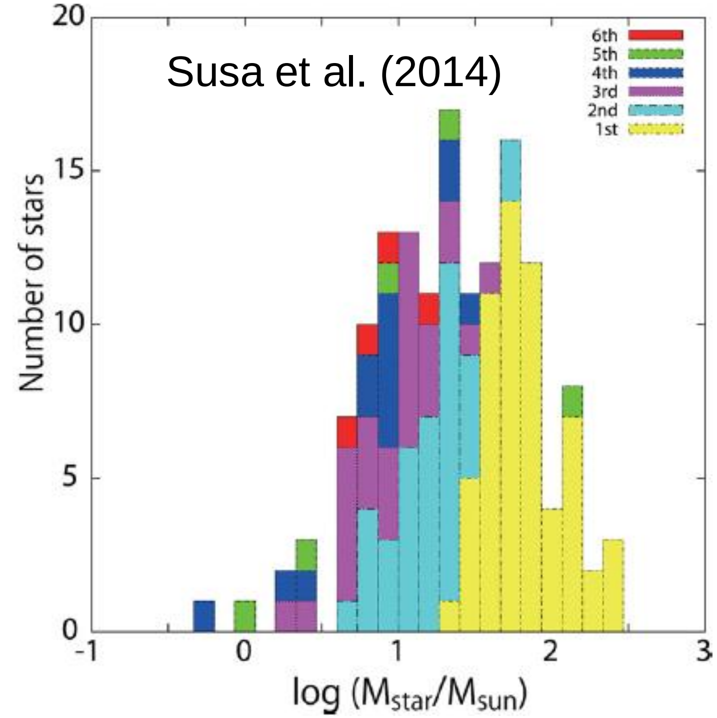


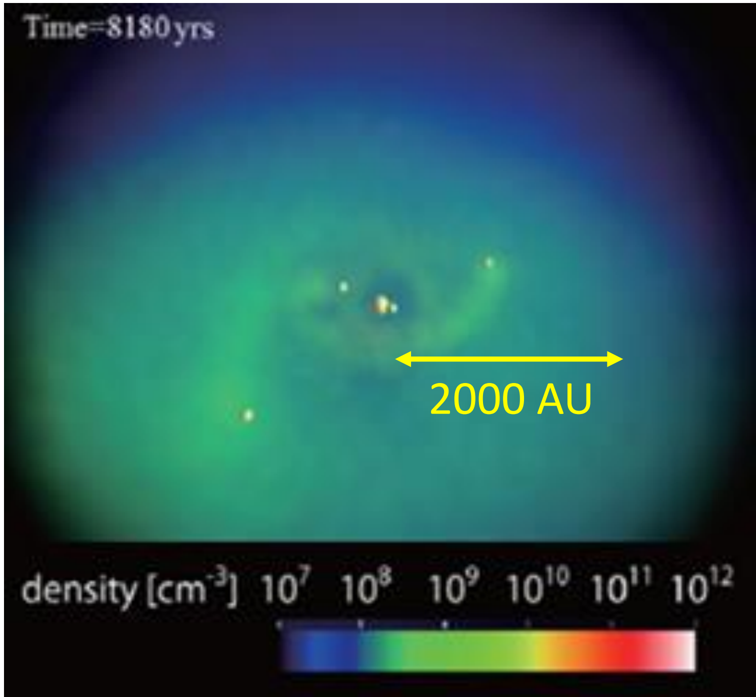
我々は新たに“多重孤立BHからの進化”を提唱

初代星からの多重孤立BH形成

Heger & Woosley (2002)

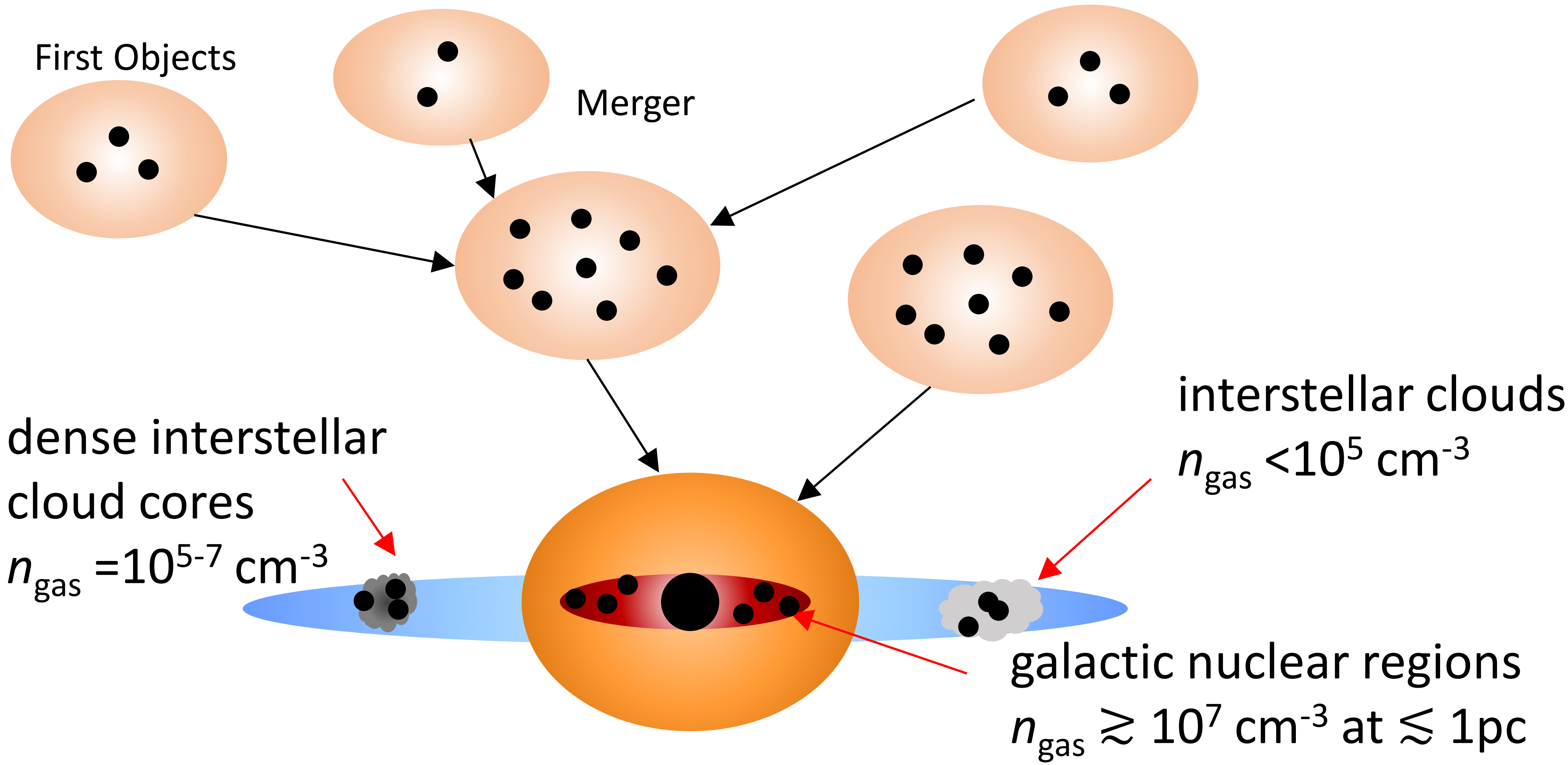






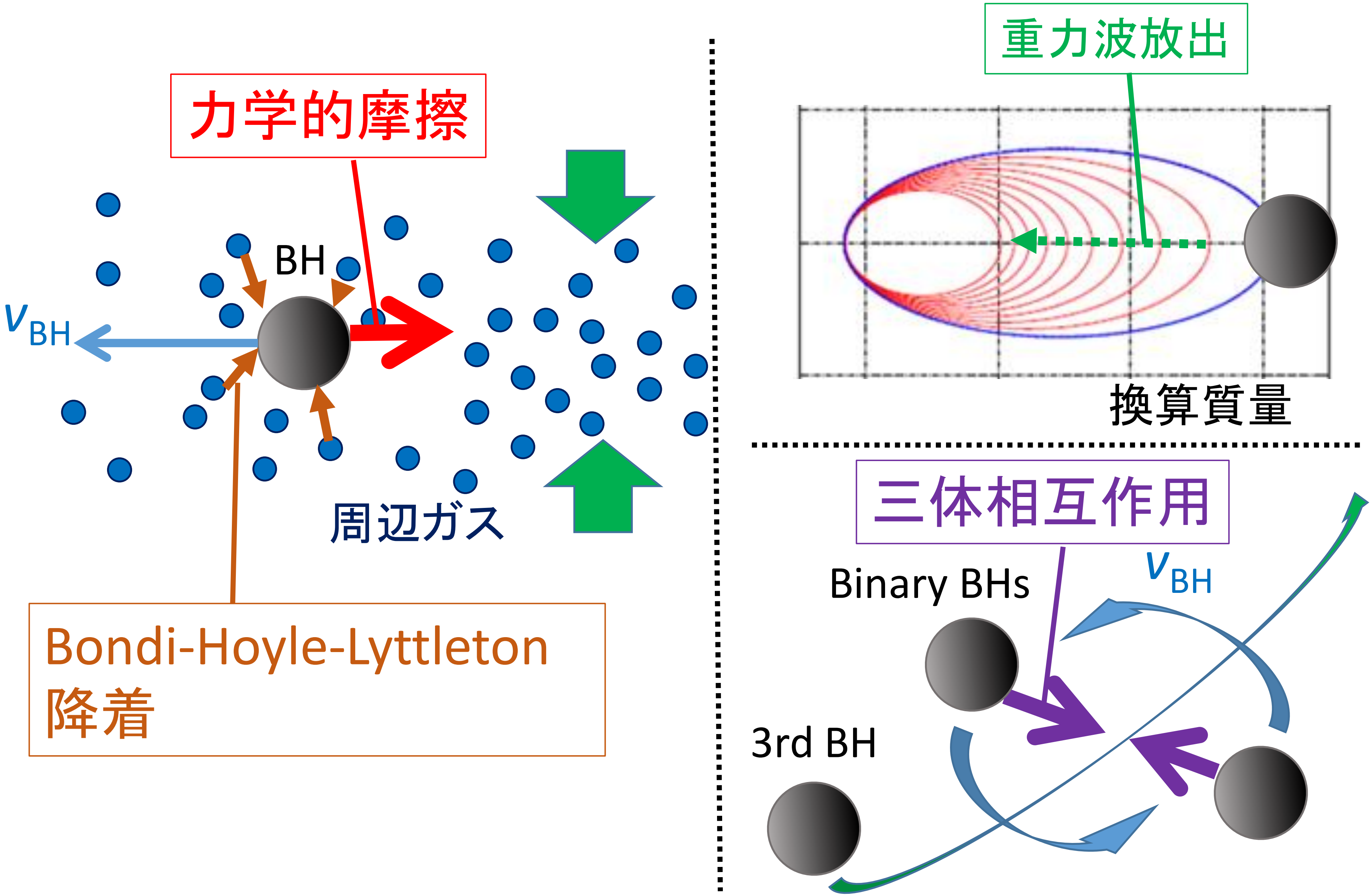
多重孤立BH形成とガスが豊富な環境

Tagawa, Umemura, Gouda, Yano & Yamai, 2015, MNRAS, 451, 2174
Tagawa, Umemura, Gouda, 2016, MNRAS, 462, 3812



目的：　多重孤立BHの進化により、GW150914のようなBH合体が起こる条件を調べる

BH合体の素過程

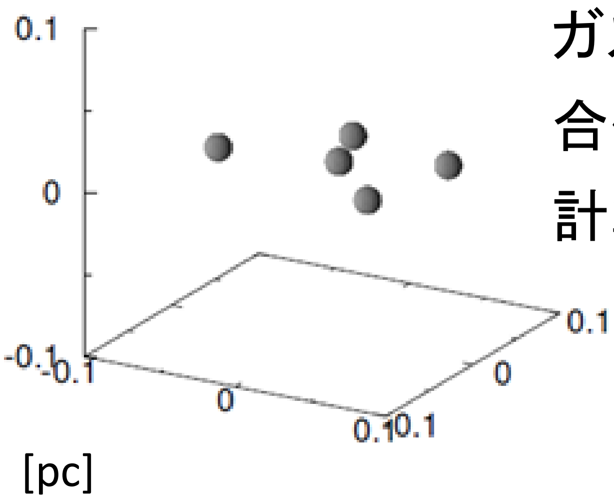

力学的摩擦
BH
v_{BH}
周辺ガス
Bondi-Hoyle-Lyttleton
降着
重力波放出
換算質量
三体相互作用
Binary BHs
v_{BH}
3rd BH

Post-Newtonian N体シミュレーション

BHに関する加速度　　ガスに関する加速度

$$\frac{d^2\mathbf{r}_i}{dt^2} = \sum_{j}^{N_{\rm BH}} \left\{ -Gm_j \frac{\mathbf{r}_i - \mathbf{r}_j}{\left|\mathbf{r}_i - \mathbf{r}_j\right|^3} + a_{{\rm PN},ij} \right\} + \mathbf{a}_{{\rm DF},i} + \mathbf{a}_{{\rm acc},i} + \mathbf{a}_{{\rm pot},i}$$

初期条件



ガス質量 : $10^5\ \mathrm{M_{sun}}$

合体条件 : $100\ r_{\rm sch}$

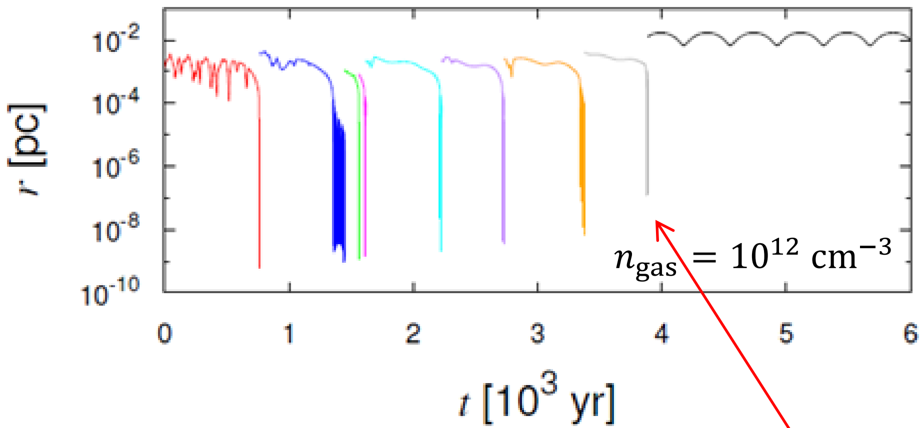
計算時間 : 10 Gyr

パラメータ

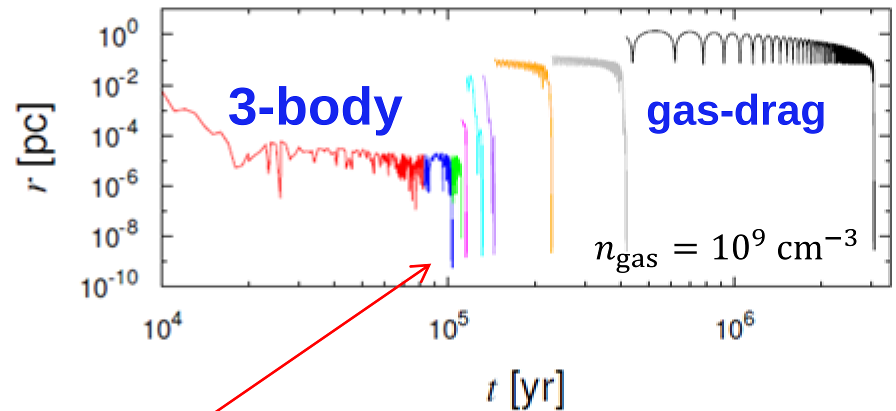
1. 初期BH質量　(m_0)
2. ガス降着率 ($\varepsilon = \frac{\dot{m}}{\dot{m}_{\rm HL}}$)
3. 初期BH間典型的距離 ($r_{\rm typical}$)
4. ガス密度 ($n_{\rm gas}$)

合体機構の分類

Type A
Gas drag-driven merger

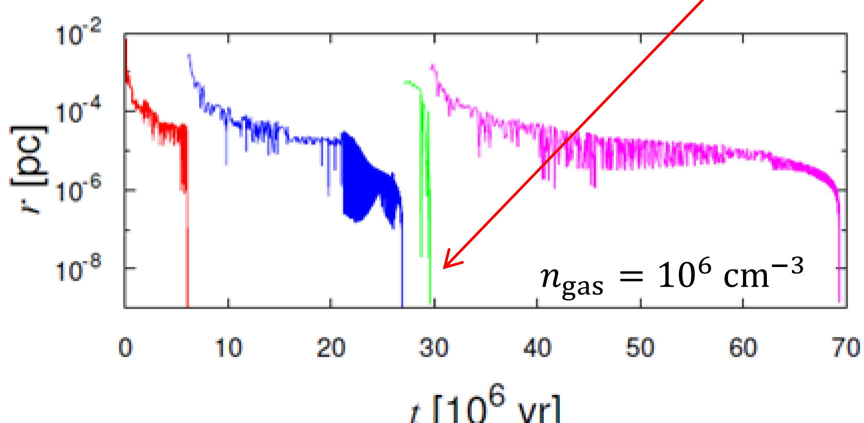


Type B
Interplay-driven merger

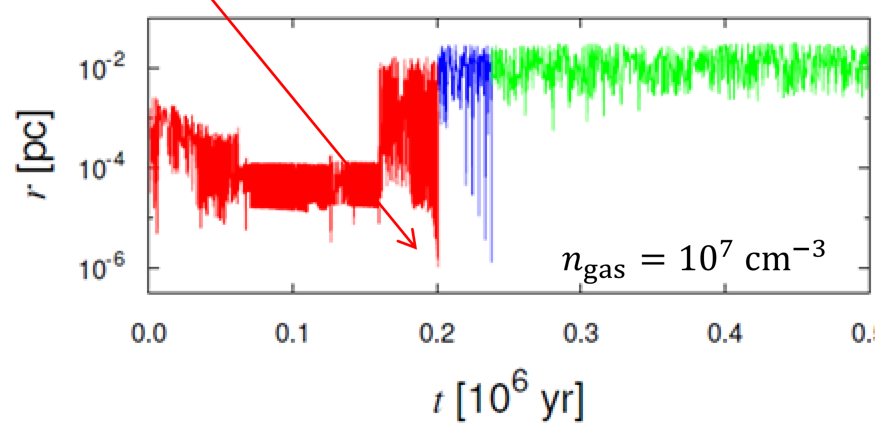


Gravitational Waves

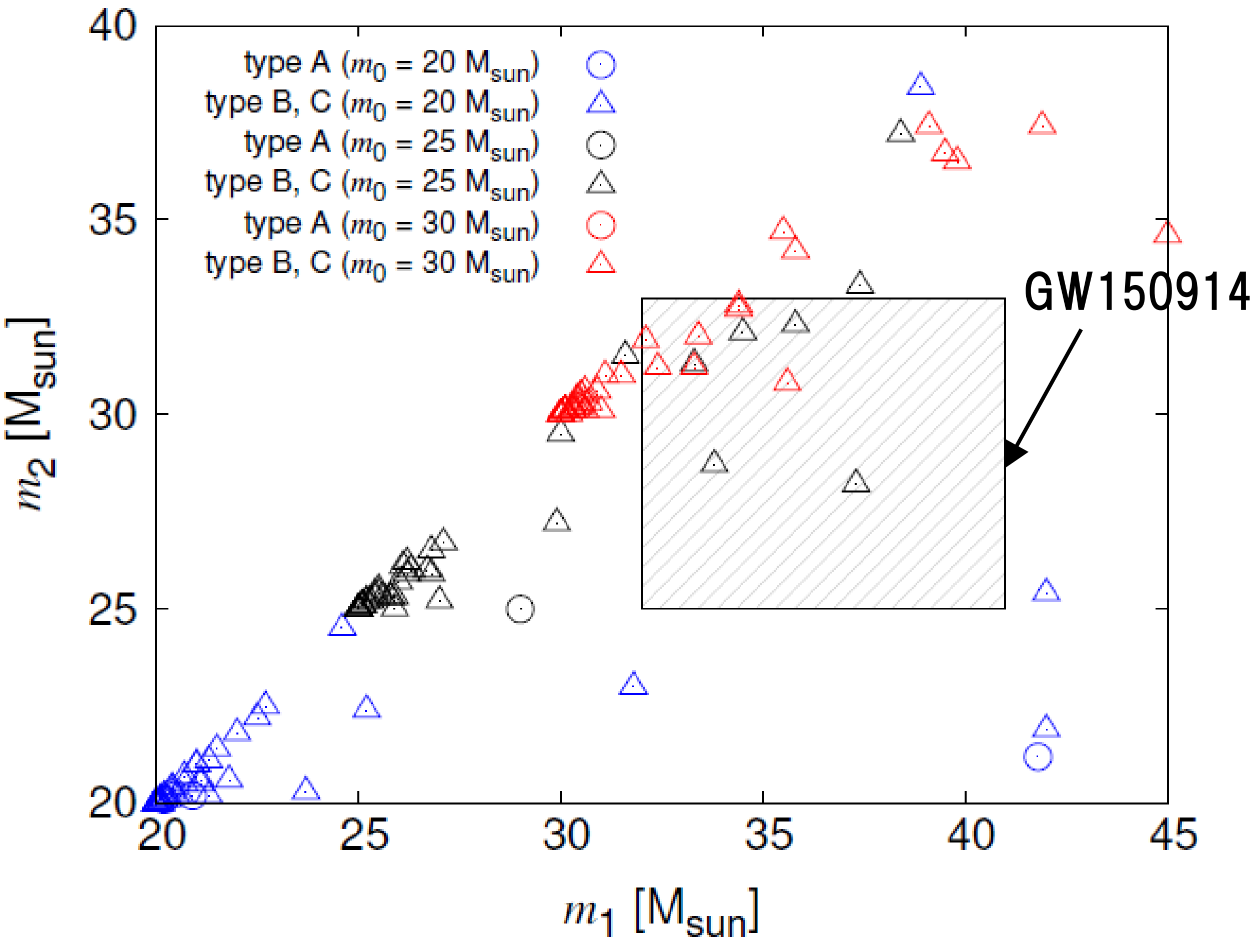
Type C
Three body-driven merger



Type D
Accretion-driven merger



初期と合体時のBH質量



$m_0 \gtrsim 25\ M_{\mathrm{sun}}$, type B or C

$(\dot{m} \sim 0.01\ \dot{m}_{\mathrm{HL}}, r_{\mathrm{typical}} \lesssim 1\ \mathrm{pc})$

孤立BH合体が期待される環境

- 環境は 10^8 yrで変わる

  (AGN duty cycle, galactic rotation timescale)

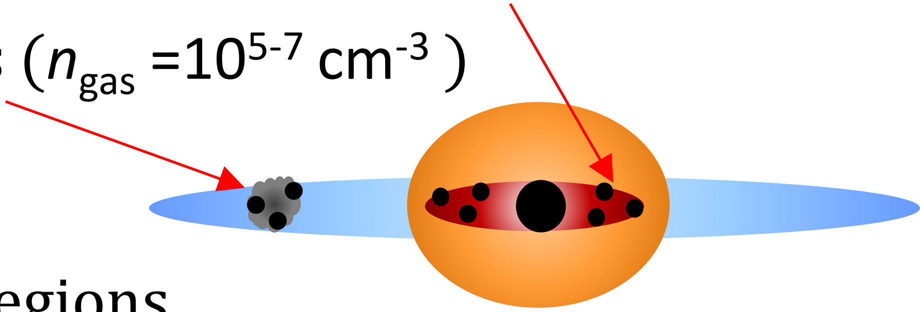
  - $t_{\mathrm{merge}} < 10^8\ \mathrm{yr}$

- $t_{\mathrm{merge}} \propto n_{\mathrm{gas}}^{-1}$ (Tagawa et al. 2015)

  $\rightarrow n_{\mathrm{gas}} > 10^5\ \mathrm{cm}^{-3}$

<u>環境:</u>

- Galactic nuclear regions ($n_{\mathrm{gas}} \gtrsim 10^7\ \mathrm{cm}^{-3}$ at $\lesssim$ 1pc)
- Dense interstellar cloud cores ($n_{\mathrm{gas}} = 10^{5\text{-}7}\ \mathrm{cm}^{-3}$)



<u>Event rate</u> (LIGO O1)

- 0.6-6 yr^{-1} in galactic nuclear regions
- 2-20 yr^{-1} in dense interstellar cloud cores

円盤銀河の方が母銀河として好まれる

結論

1. 多重孤立BHによる合体によって、GW150914を説明できそう

2. 必要な条件は、

   $\dot{m} \sim 0.01\,\dot{m}_{\rm HL}$, $r_{\rm typical} \lesssim 1$ pc,

   $m_0 \gtrsim 25\,M_{\rm sun}$, type B or C

   $n_{\rm gas} > 10^5$ cm^{-3}, $t_{\rm merge} < 10^8$ yr.

3. LIGO O1によるevent ratesは、
   - 0.6-6 yr^{-1} in galactic nuclear regions
   - 2-20 yr^{-1} in dense interstellar cloud cores

Event rate in GMCs

- BH number in Milky Way sized galaxies $\sim 10^8$ (Remillard et al. 2009)
- Volume that BH would exist 10 kpc × 10 kpc × 1 kpc =100 kpc^3
- Volume of GMC 10 pc × 10 pc × 10 pc × 1000 (number) $=10^{-3}$ kpc^3
- Averaged volume per one BH 100 $kpc^3/10^8=10^{-6}$ kpc^3
- Averaged BH number in 1000 GMC 10^{-3} $kpc^3/10^{-6}$ kpc^3=1000
- In this case, about 100 GMC hold multiple BH system
- Merger time is ∼100 Myr (Tagawa et al. 2015)
- Merger rate in one galaxy is 100 event/100 Myr=1 event Myr^{-1}
- Horizon distance by aLIGO $D_h \sim (M_{binary}=75\ M_{sun})$8 Gpc ($z \sim 1.1$)
- Comoving volume V_c=230 Gpc^3
- Number density of MW sized galaxies∼2e6/Gpc^3
- Number of galaxies, which is observed 230×2e6=5e8
- If rate of massive BH to all BH is 10%,

rate of massive BH-massive BH to all BH-BH is 1%

- Event rate is 1 Myr^{-1} ×1% × 5e8=5 yr^{-1}

Event rate for pop III BHs in GMCs

- If each mini halo of 10^5-10^6 M_{sun} hold 100 pop III BHs,

MW sized galaxy hold pop III 10^7 BHs. (Ishiyama et al. 2016)

- Most of pop III BHs possibly formed as multiple BH systems (Susa et al. 2014)
- If all BHs are multiple system of 4 BHs,

25 GMCs hold multiple BH systems.

- Merger time is ～100 Myr
- Merger rate in one galaxy is 25 event/100 Myr=0.25 event Myr^{-1}
- Horizon distance by aLIGO D_h～(M_{binary}=75 M_{sun})8 Gpc (z～1.1)
- Comoving volume V_c=230 Gpc^3
- Number density of MW sized galaxies～2e6/Gpc^3
- Number of galaxies, which is observed 230×2e6=5e8
- If rate of massive BH to all pop III BH is 50%,

rate of massive BH-massive BH to all pop III BH-pop III BH is 25%

- Event rate is 0.25Myr^{-1} ×25% × 5e8=23 yr^{-1}

Event rate in GNRs

- About 3×10^6 stars exist in the 1 pc from SMBH (Alexander 2005), and about 1 BH exist per 1000 stars.
- Therefore, ～3×10^3 BHs may exist in GNRs.
- Merger time and AGN duty cycle are ～100 Myr
- Merger rate in one galaxy is 3×10^3 event/100 Myr=30 event Myr^{-1}
- Horizon distance by aLIGO D_h～(M_{binary}=75 M_{sun})8 Gpc (z～1.1)
- Comoving volume V_c=230 Gpc^3
- Number density of MW sized galaxies～2e6/Gpc^3
- Number of galaxies, which is observed 230×2e6=5e8
- If rate of massive BH to all BH is 10%,

rate of massive BH-massive BH to all BH-BH is 1%

- Rate of merger phase (AGN phase) 100 Myr/10Gyr=1%
- Event rate is 30 Myr^{-1} ×1% × 5e8 ×1%=2 yr^{-1}