General Relativity and Dynamics in Galactic Centers

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Black Holes in General Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Black Holes in General Relativity

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

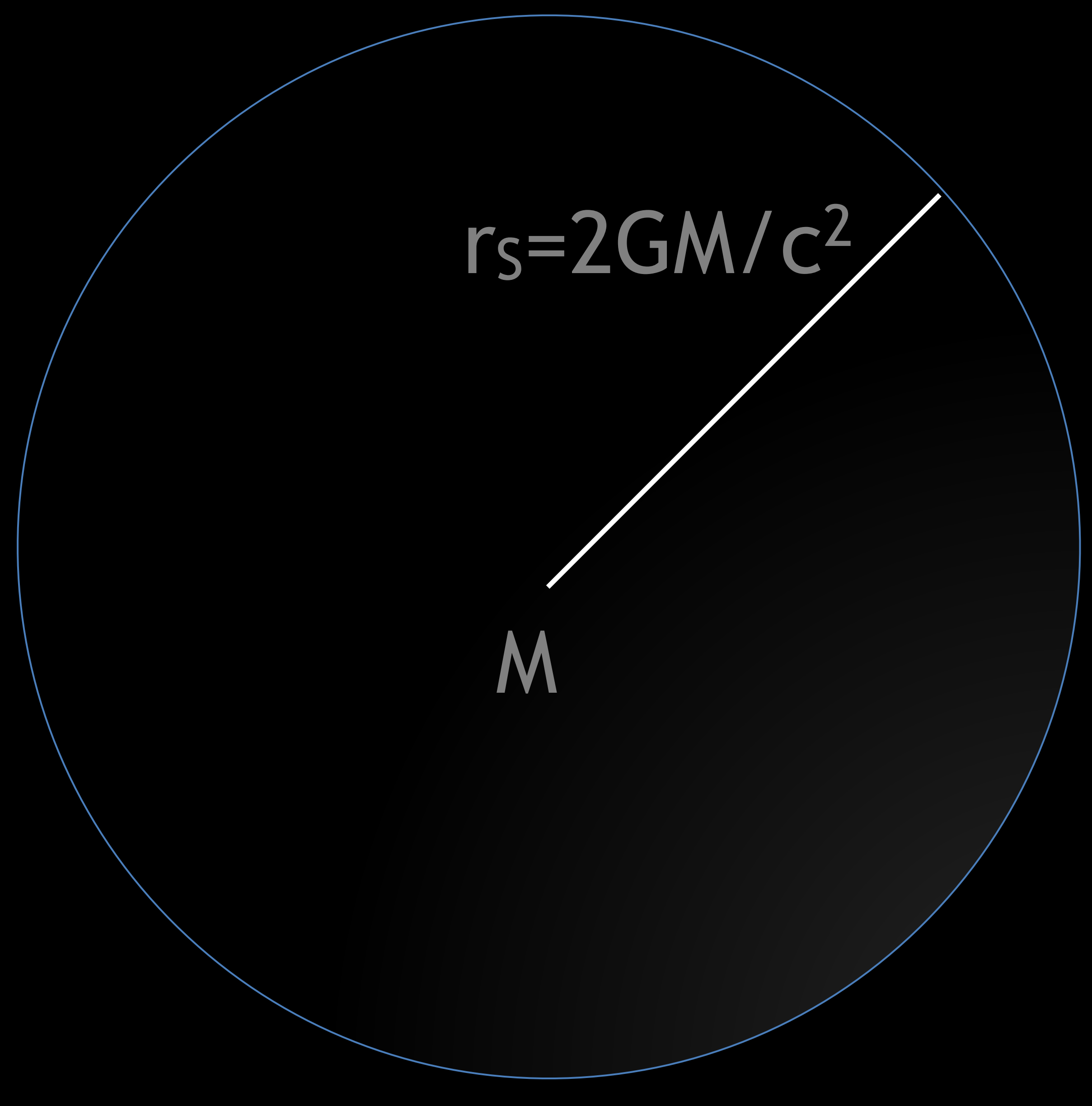
Black Holes in General Relativity

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2(\mathrm{d}\theta^2 - \sin^2\theta\mathrm{d}\phi^2)$$

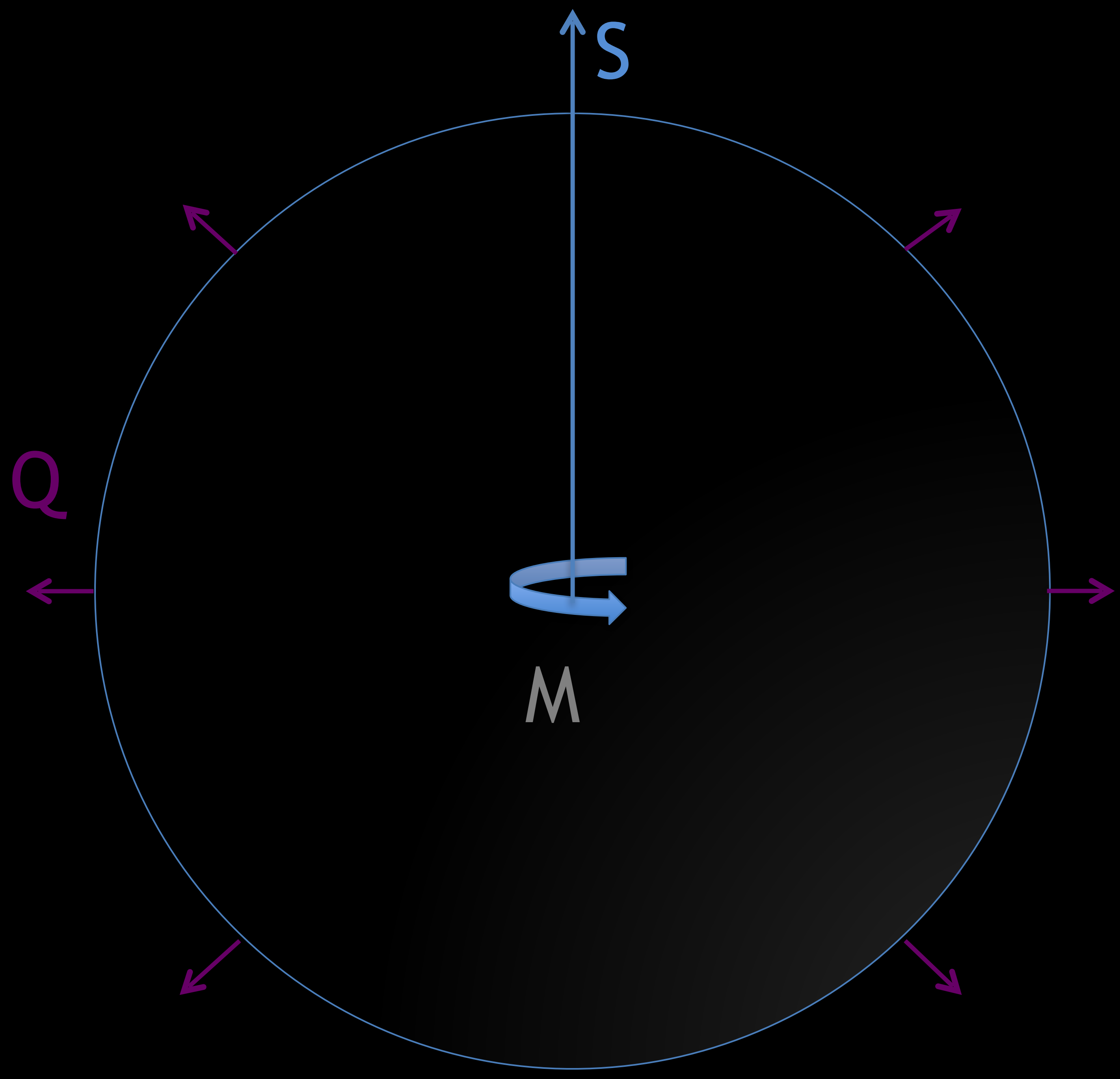
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Black Holes in General Relativity

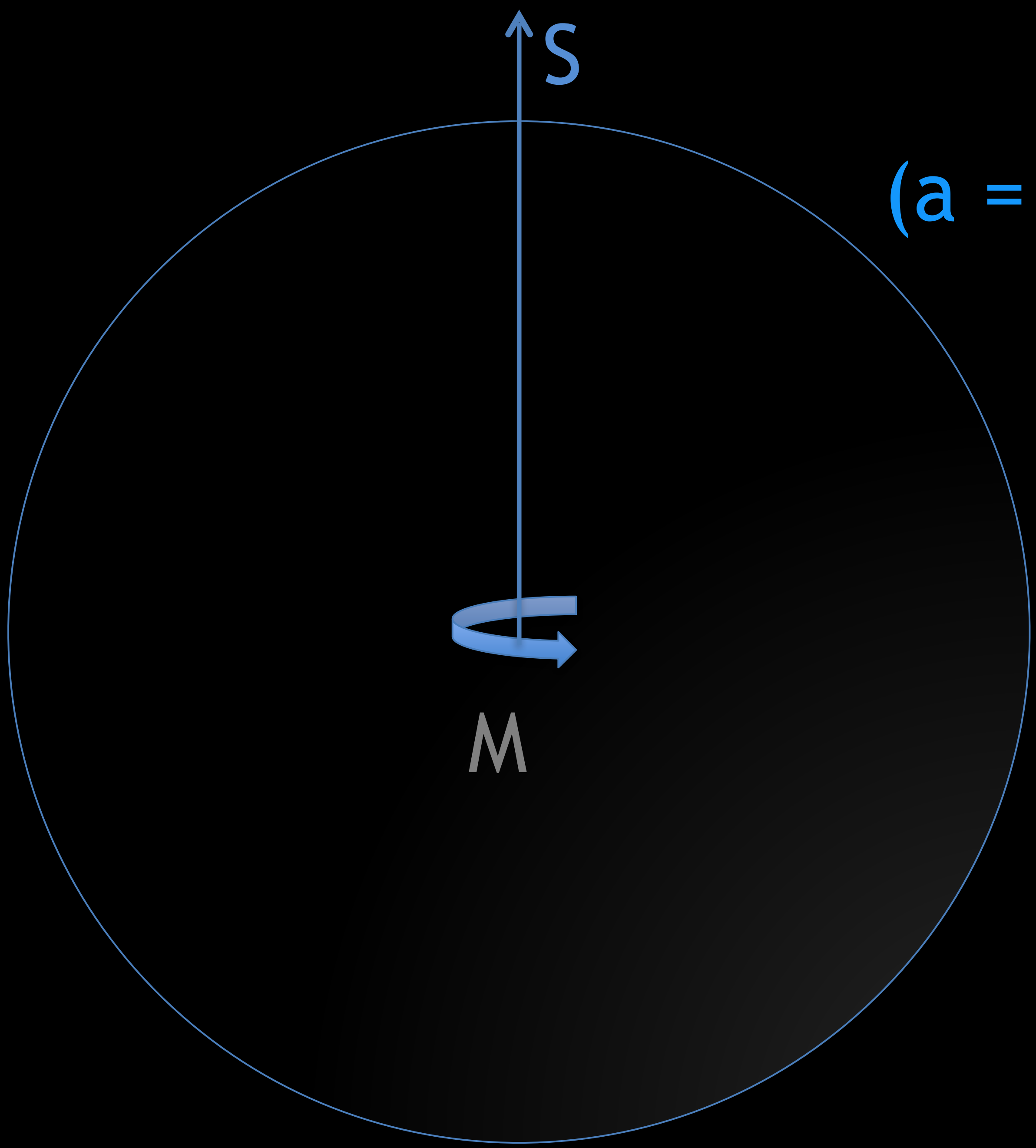
$$ds^2 = c^2\left(1 - \frac{2GM}{rc^2}\right)dt^2 - \left(1 - \frac{2GM}{rc^2}\right)^{-1}dr^2 - r^2(d\theta^2 - \sin^2\theta d\phi^2)$$



Black Holes in General Relativity



Black Holes in General Relativity



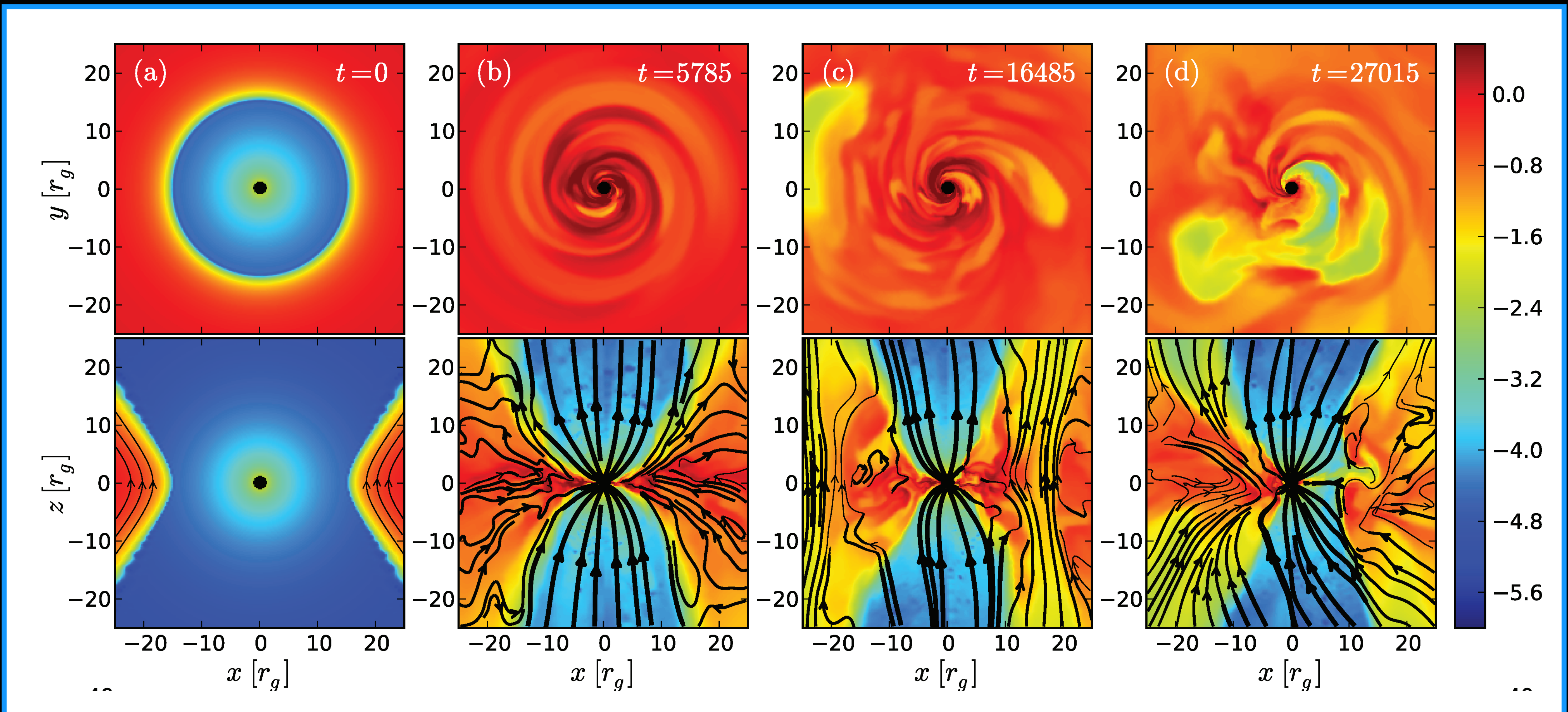
(a = S / M² < 1)

Black Holes in the Universe

- Two flavors of black hole (BH):
  - Stellar mass: ($36M_{\odot} > M_{BH} > 5M_{\odot}$)
  - Supermassive (SMBH): ($10^{10}M_{\odot} > M_{BH} > 10^{6}M_{\odot}$)
  - Intermediate (IMBH): ($10^{6}M_{\odot} > M_{BH} > 36M_{\odot}$) ???
- Origin of SMBHs entirely unknown
  - Rare; each galaxy has one and only one
  - Usually located in galactic nuclei
- Stellar mass BHs originate in supernovae
  - Common; each galaxy has millions

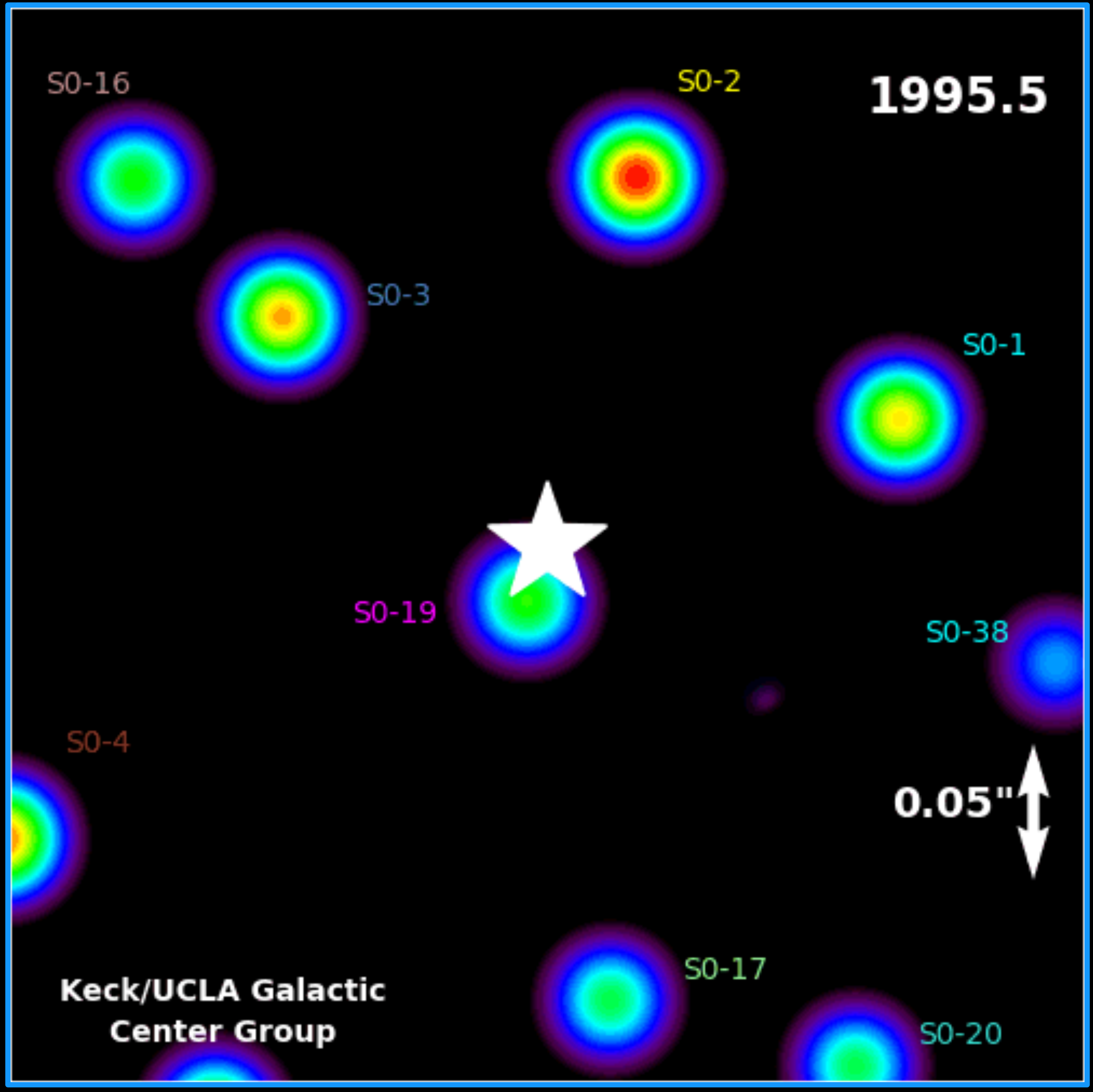
(Wikimedia)

Observing Black Holes: Accretion

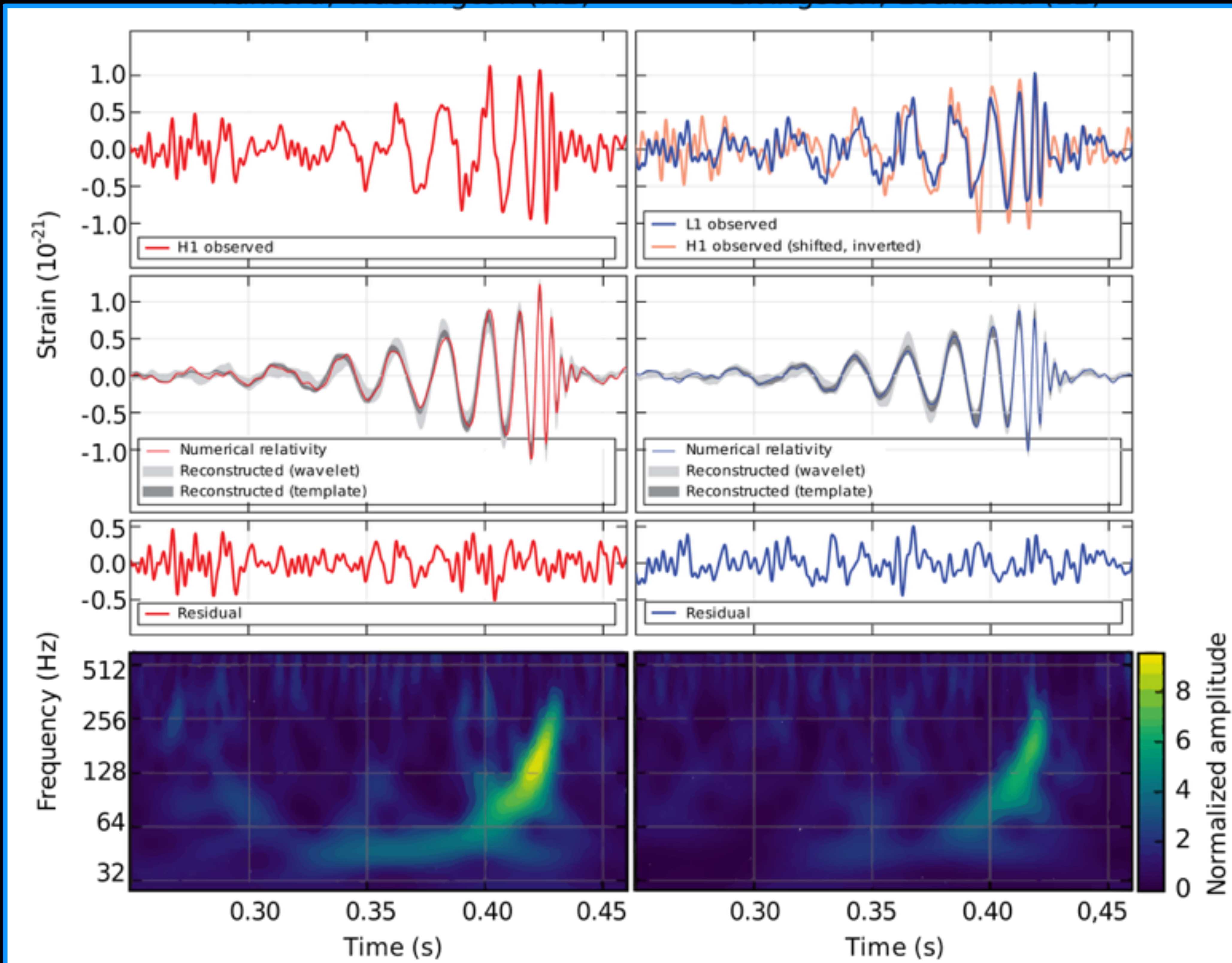


(Tchekhovskoy+10)

Observing Black Holes: Dynamics



Observing Black Holes: Gravitational Waves

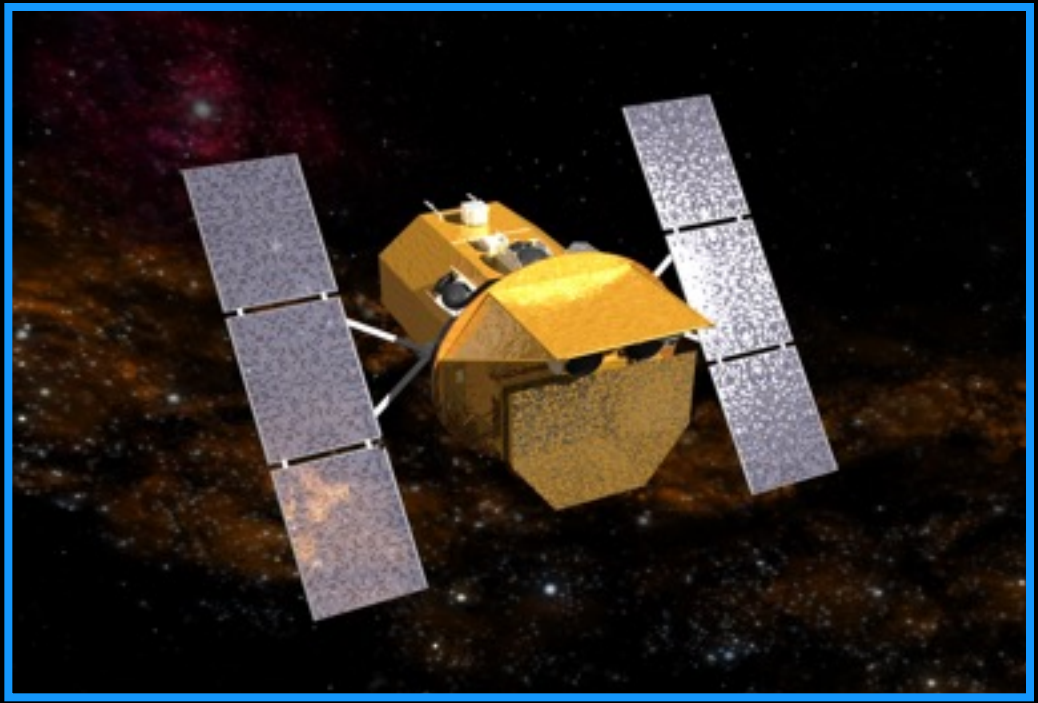


(LIGO Scientific Collaboration)

Why Study Black Holes?

- Test general relativity (GR), look for signatures of modified gravity
  - Specific targets (e.g. **no hair theorem**, dipole radiation, quasi-normal mode spectrum…)
  - Generically great GR laboratories: **strongly curved spacetime**
  - With gravitational waves (GWs), can also probe **dynamical spacetime**
- Search for internal problems within GR
  - **Cosmic censorship**: failure of causality if naked singularities ($a_{BH}>1$) exist
- Astrophysical significance
  - Supermassive BHs seem to **control host galaxy evolution**
  - **Brightest electromagnetic sources** in the Universe
  - BH mergers can be **standards sirens** probing cosmology

Time Domain Astronomy (2010s)

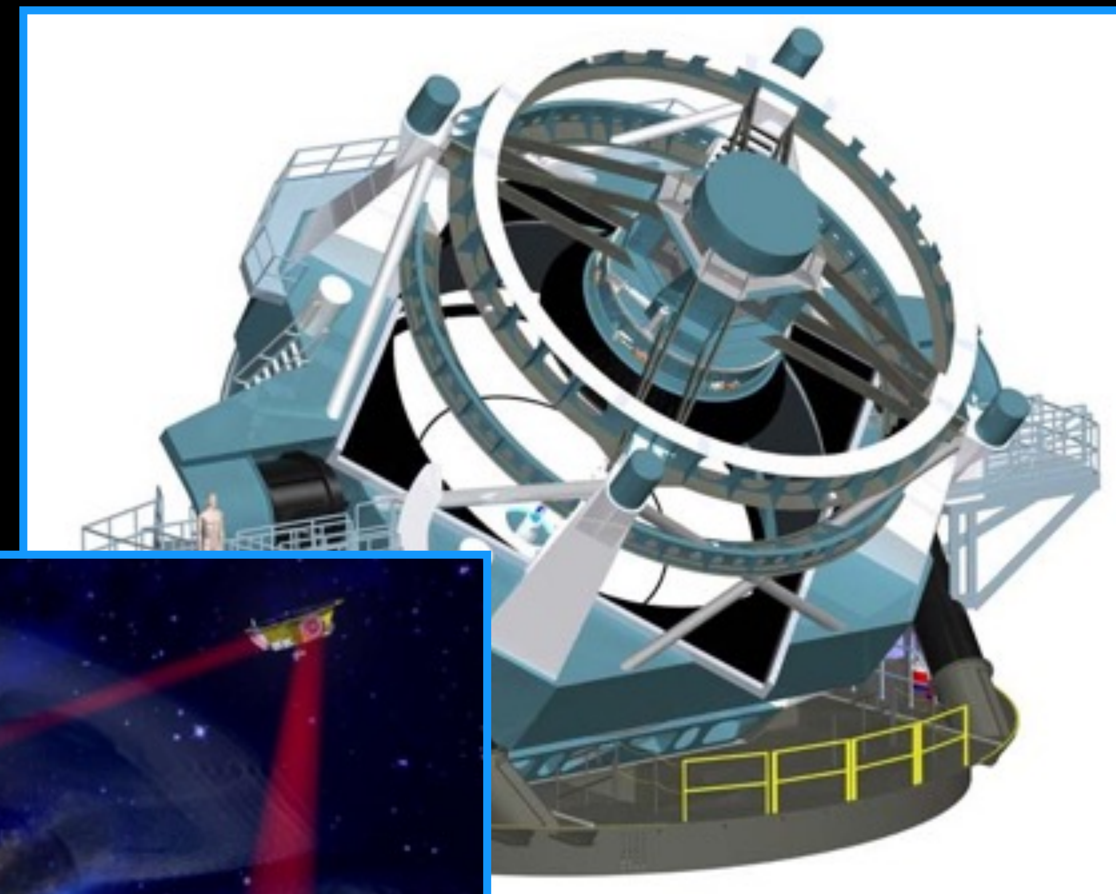

(Swift; NASA)


(Virgo; Caltech)

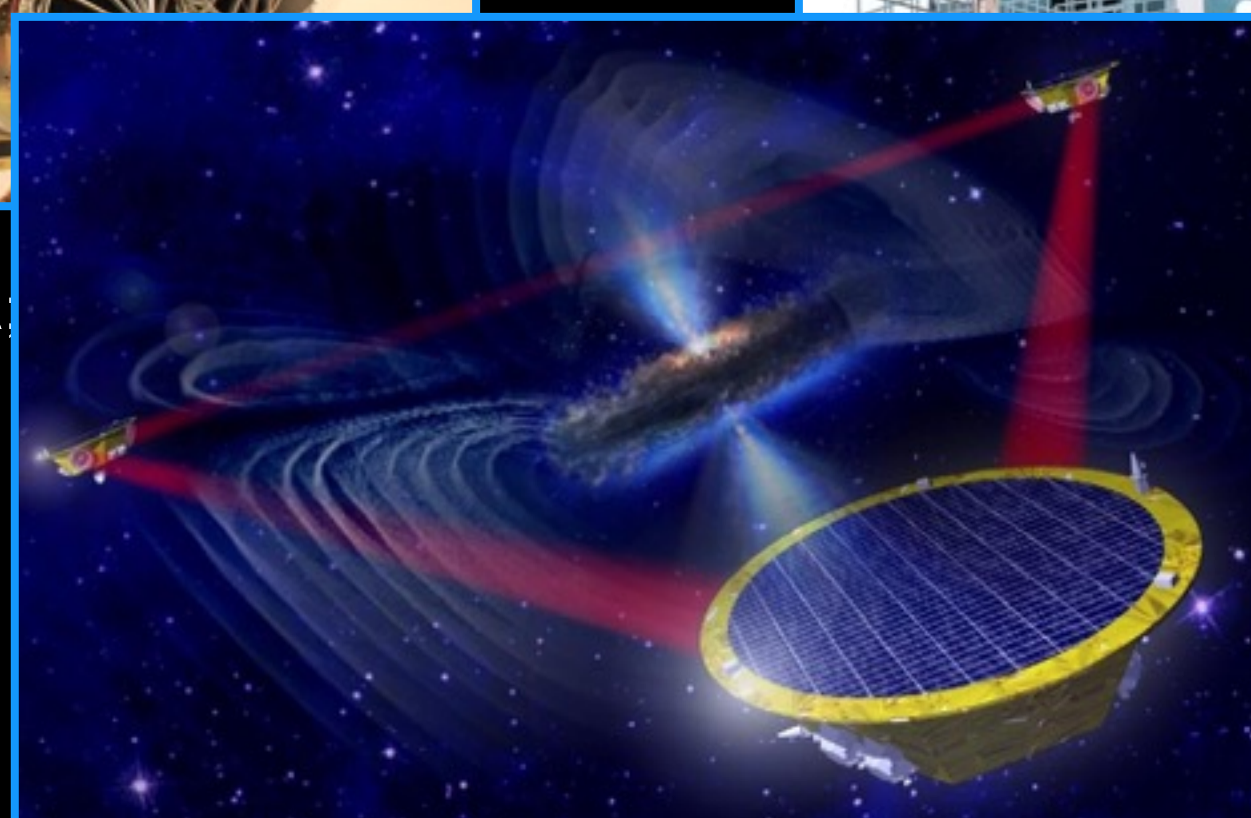

(PTF/ZTF; Caltech)

Time Domain Astronomy (20s-30s)

(eROSITA;



SST; NOAO)



(LISA; EADS)

Galactic Nuclei

- In most regions of space, stellar dynamics are collisionless
- In dense environments, dynamics are collisional
  - Open clusters
  - Globular clusters
  - **Nuclear clusters**
- Frequent dynamical interactions
  - Bulk cluster evolution
  - **Tidal disruptions**
  - **X-ray binary formation**
  - **Production of GW sources**

(47 Tucanae; NASA)

Tidal Disruptions

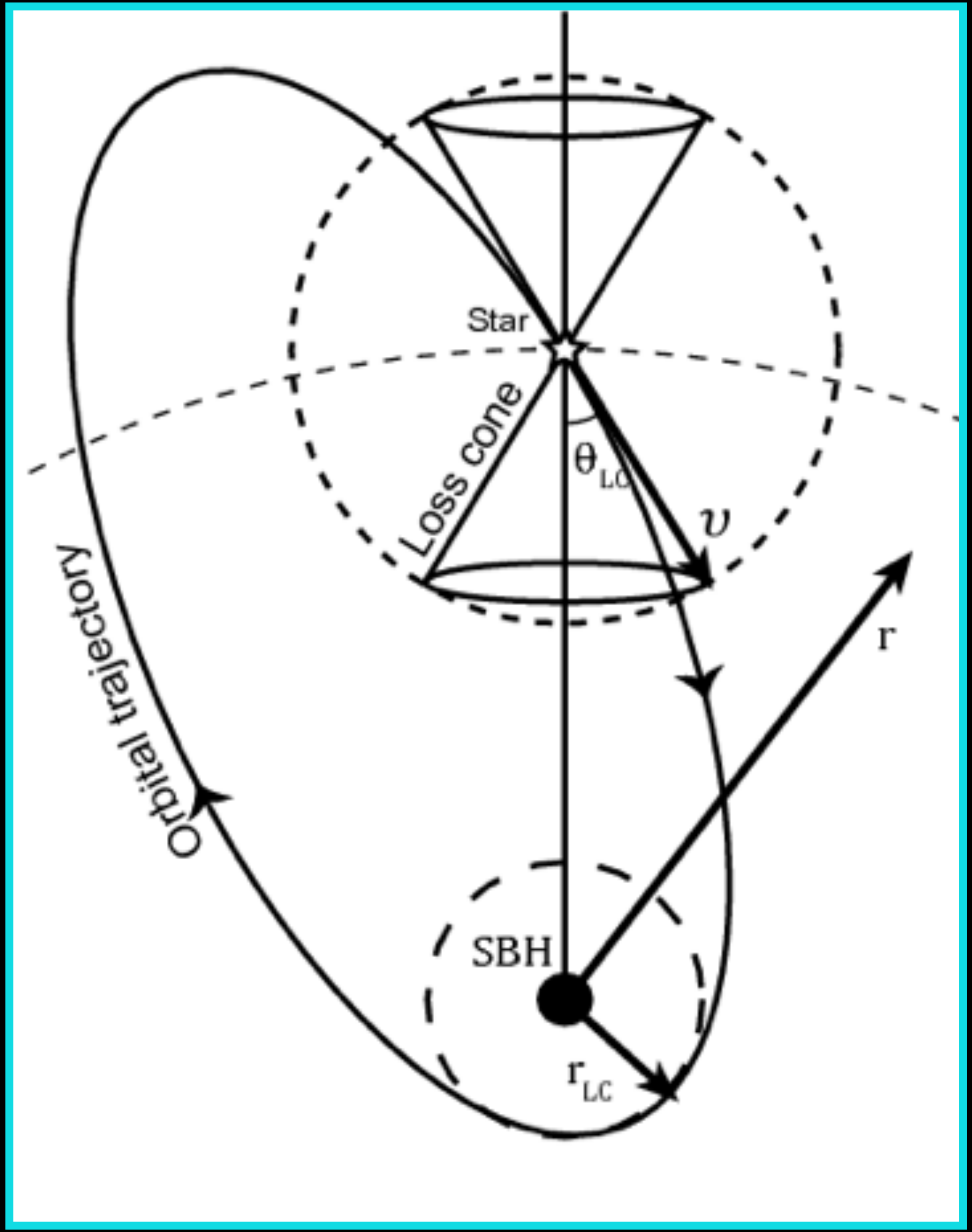
(ESO; Leloudas, Fraser, **NCS**+16)

Tidal Disruption Overview

- Tidal Disruption Events (TDEs):
  - Rare multiwavelength (radio -> soft γ-ray) transients
  - Few strong candidate flares per year, soon to be tens (ZTF) hundreds (eROSITA), and thousands (LSST)
- Many applications:
  - Tools to measure **SMBH demography** (mass, spin)
  - Controlled **accretion physics laboratories**
  - Rates encode **stellar dynamical processes**
  - Probes of **cosmic censorship/no hair theorem?**
  - SMBH binaries can tidally disrupt stars: **standard sirens?**

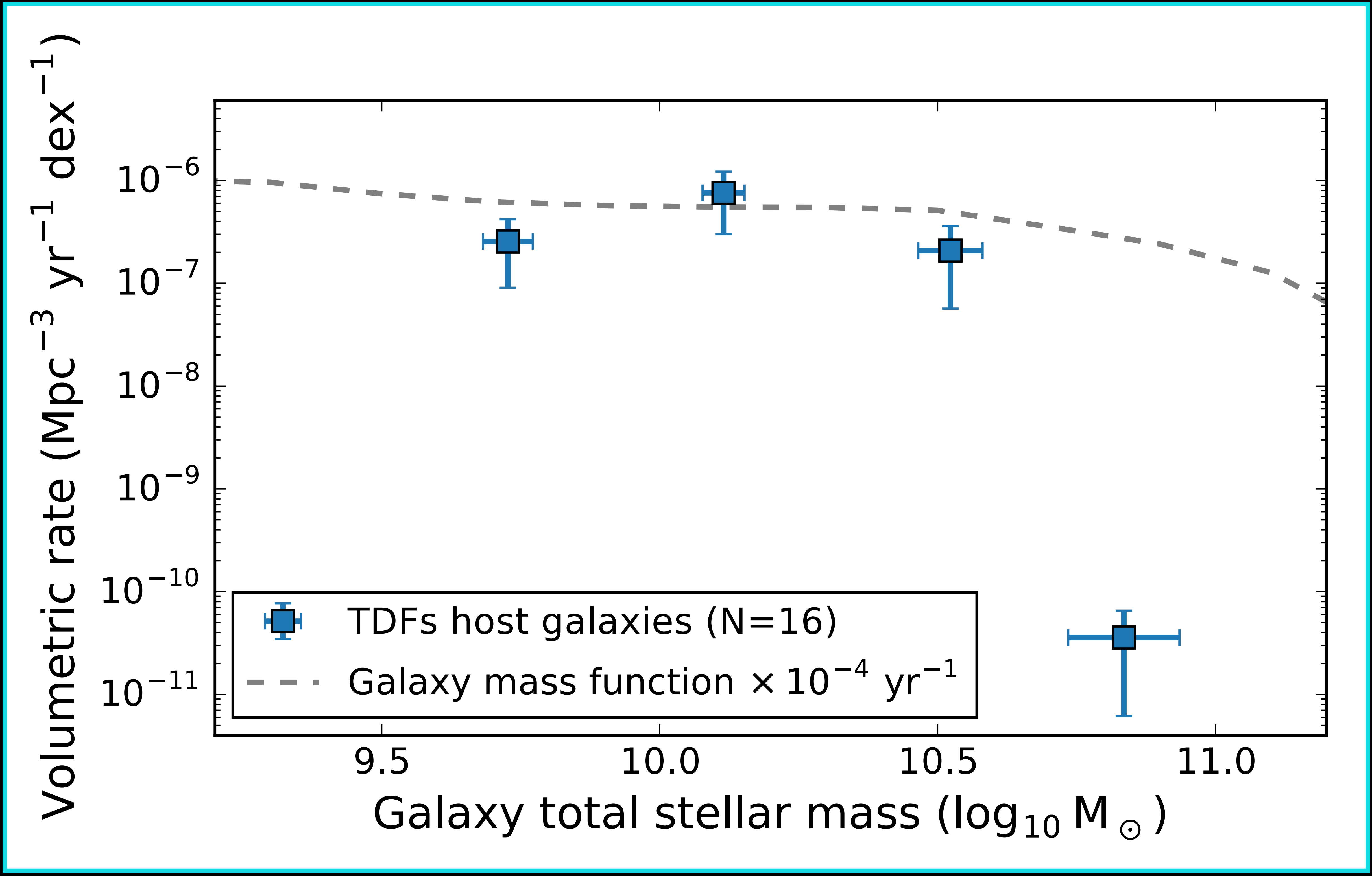
TDE Rates

- Optical/X-ray/UV rate estimates find $\Gamma_{obs} \sim 1 \times 10^{-5}$/galaxy/yr
- Theoretical rate estimates set by diffusion of stars into **loss cone**
  - ✦ Two-body relaxation ubiquitous
- Theoretical rates calculated semi-empirically (**NCS** & Metzger 16):
  - ✦ Use sample of 140 nearby galaxies
  - ✦ Solve Fokker-Planck equation describing diffusion in angular momentum space
- $\Gamma_{obs} \sim 1 \times 10^{-5}$/gal/yr << $\Gamma_{theory} \sim$ 2-50 $\times 10^{-4}$/gal/yr



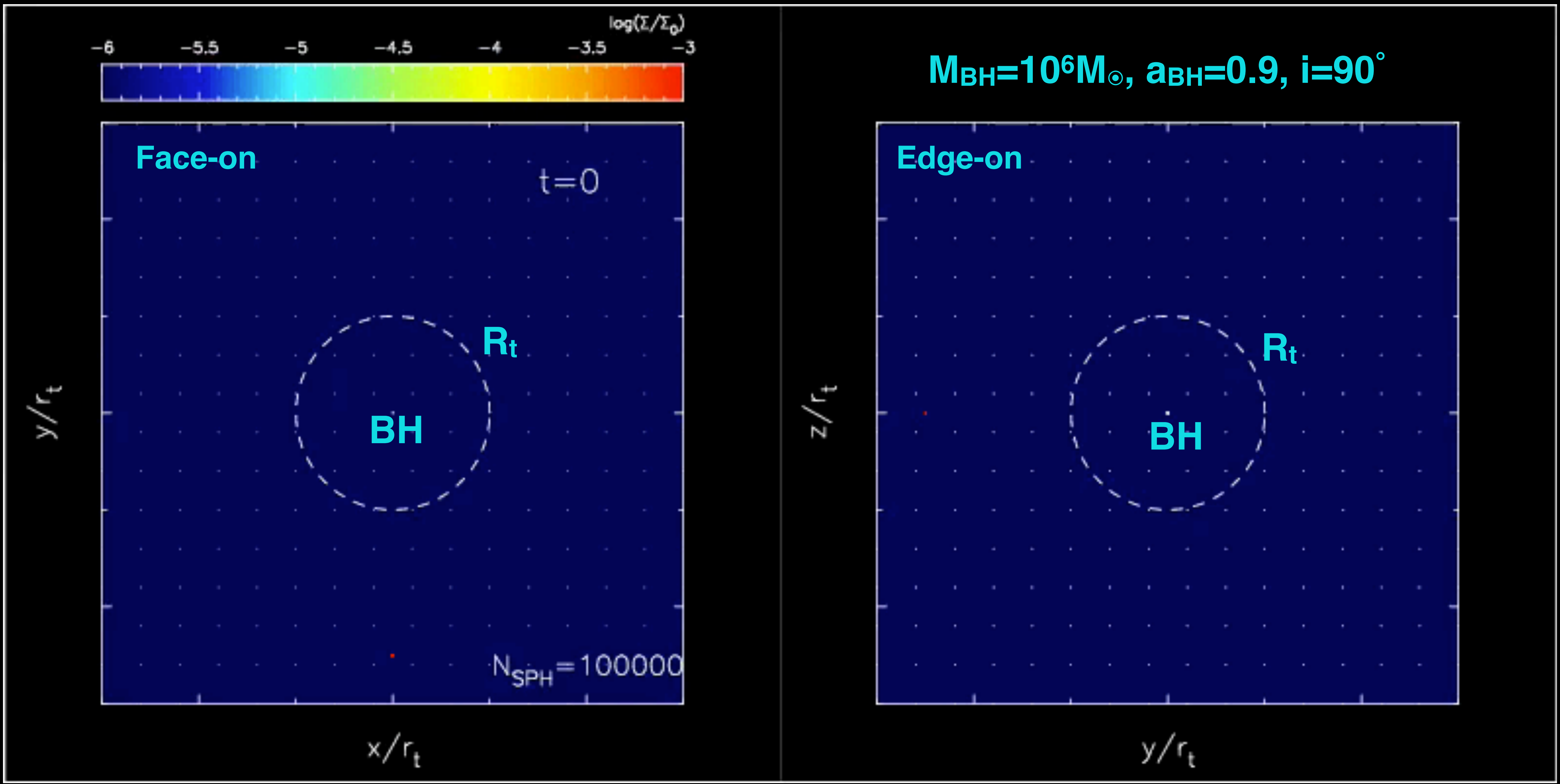
(Merritt 13)

Theory Meets Observation?



(van Velzen 17)

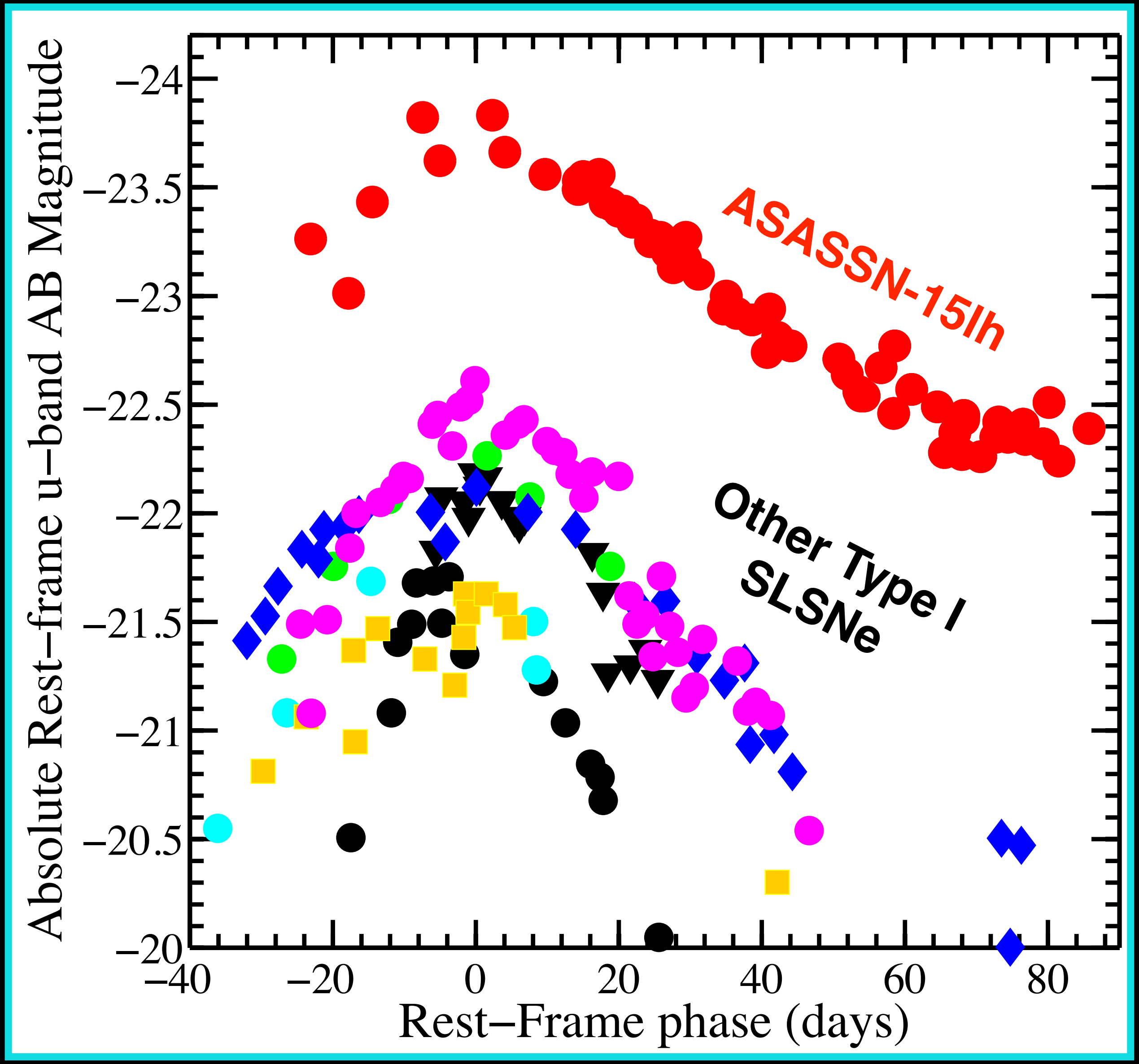
General Relativity in His Labyrinth



(Hayasaki, **NCS** & Loeb 16)

ASASSN-15lh: Observations

- Detected by ASASSN survey as "brightest supernova" ever discovered
- Peak luminosity $L_{bol}=2.2\times10^{45}$ erg/s
  - Energy release 1.1×10^{52} erg
- TDE explanation initially discounted because of large SMBH mass
  - $\log_{10}M_{BH}=8.8\pm0.6M_{\odot}$
- Coincident with center of galaxy to within 131±192 pc (Leloudas, Fraser, **NCS**+16)
  - Host galaxy **very** unlike other SLSNe hosts

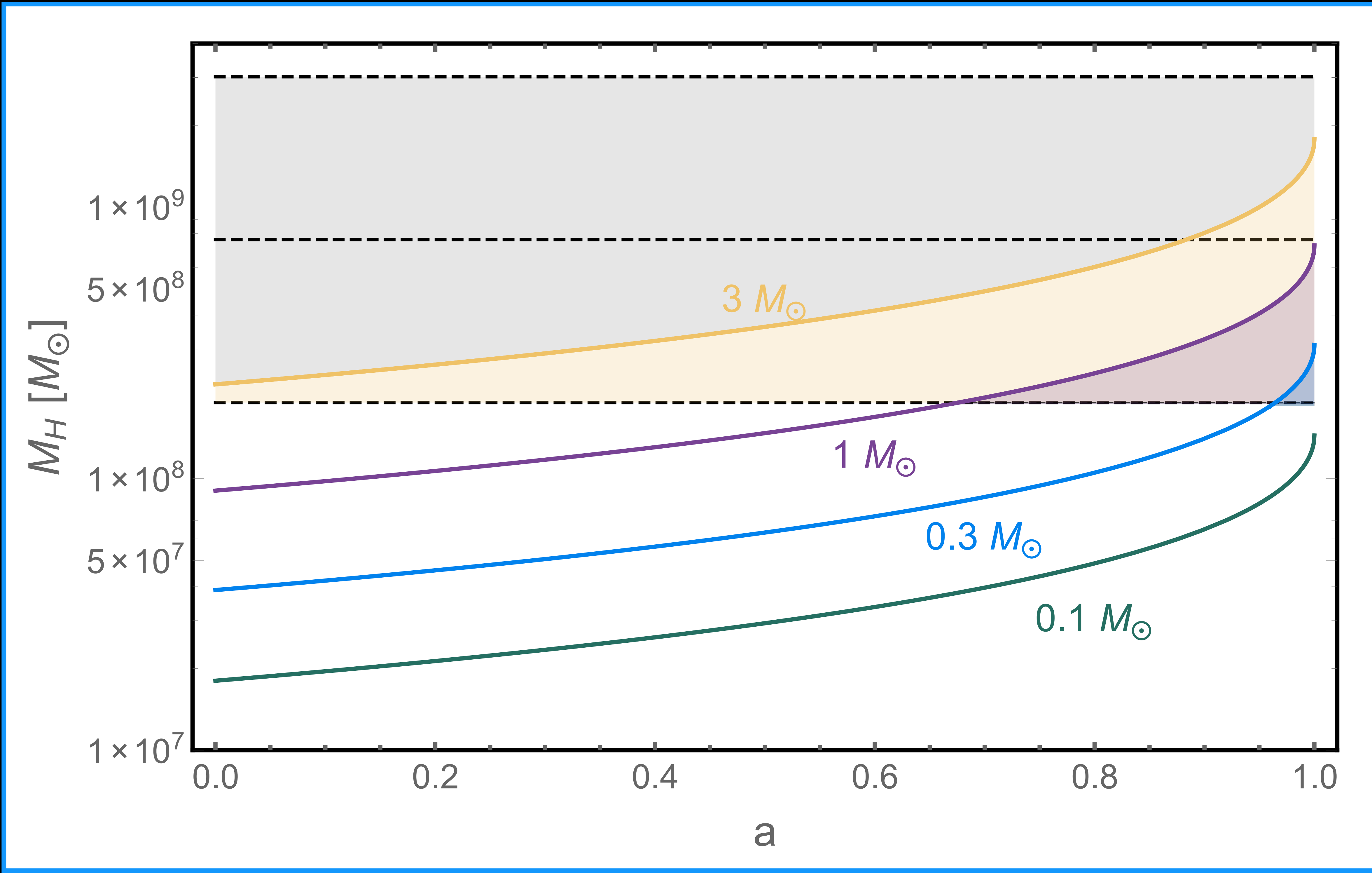


(Dong+16)

To Disrupt or Not to Disrupt?

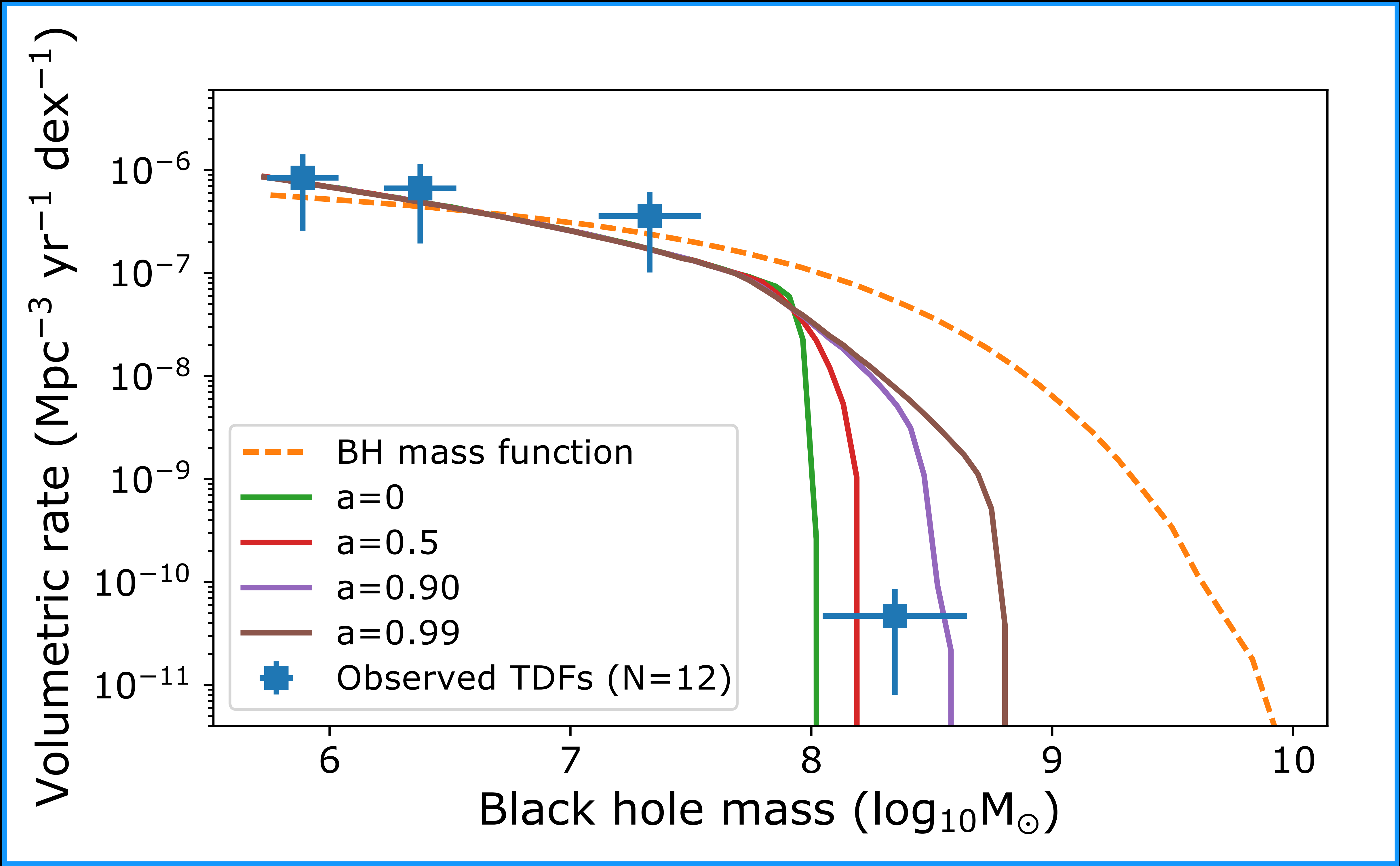
- Hills Mass: maximum SMBH mass that can produce a TDE
  - ✦ $R_t \approx R_\star (M_{BH}/M_\star)^{1/3}$, while $R_g = GM_{BH}/c^2$
  - ✦ Above $M_{Hill} \sim 9\times10^7 M_\odot$, TDEs impossible…
  - ✦ …in Schwarzschild metric
- M_{Hill} **increases a factor of ~8 with SMBH spin**
  - ✦ Smaller IBCO (parabolic ISCO)
  - ✦ Stronger tidal tensor

ASASSN-15lh: a Kerr SMBH



(Leloudas, Fraser, **NCS**+ 2016)

The Wages of Spin



(**NCS** & van Velzen in prep)

Our Galactic Center

thermal X-ray sources

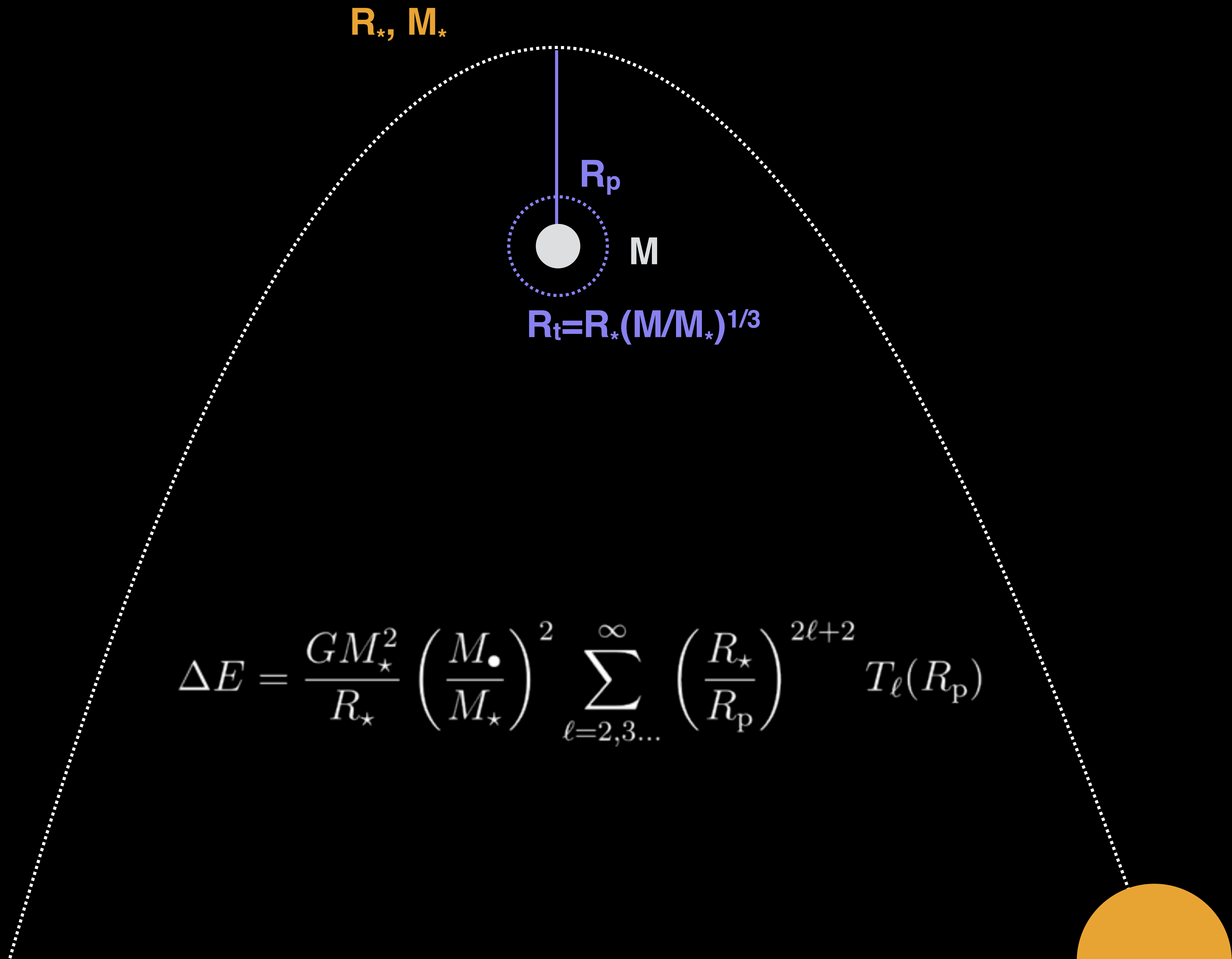
R=1 pc

nonthermal X-ray sources

(Hailey+17, in press)

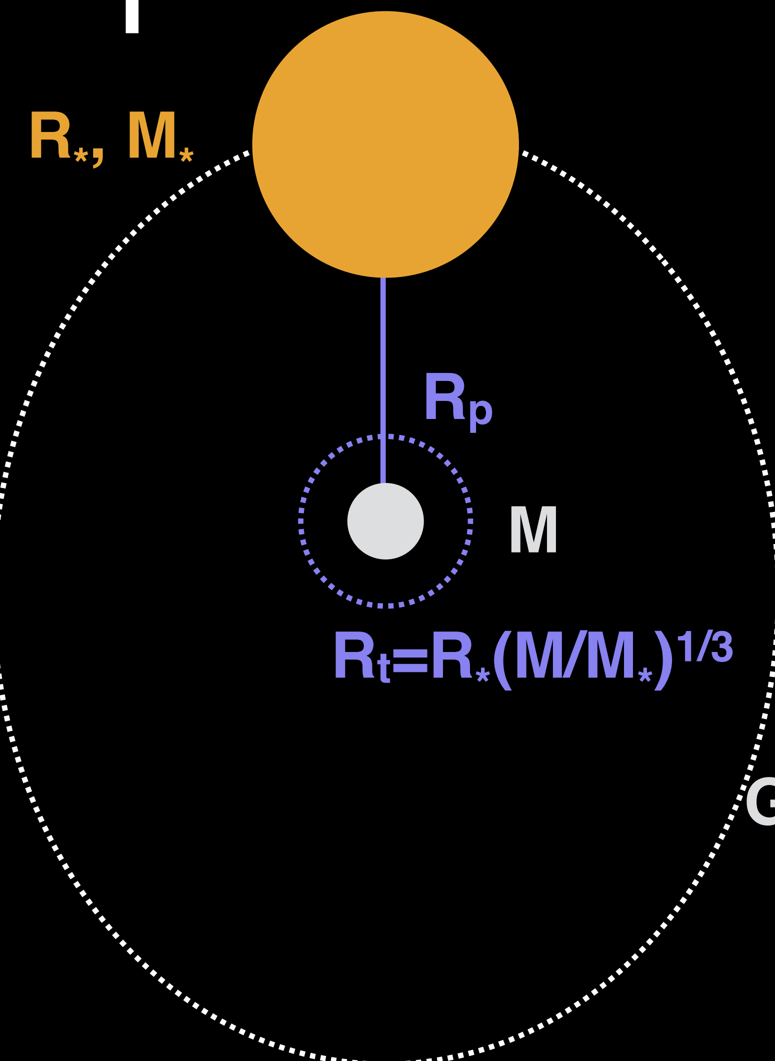
(apologies for the redaction!)

Tidal Capture: Physics



$$\Delta E = \frac{GM_\star^2}{R_\star}\left(\frac{M_\bullet}{M_\star}\right)^2 \sum_{\ell=2,3\ldots}^{\infty}\left(\frac{R_\star}{R_\mathrm{p}}\right)^{2\ell+2} T_\ell(R_\mathrm{p})$$

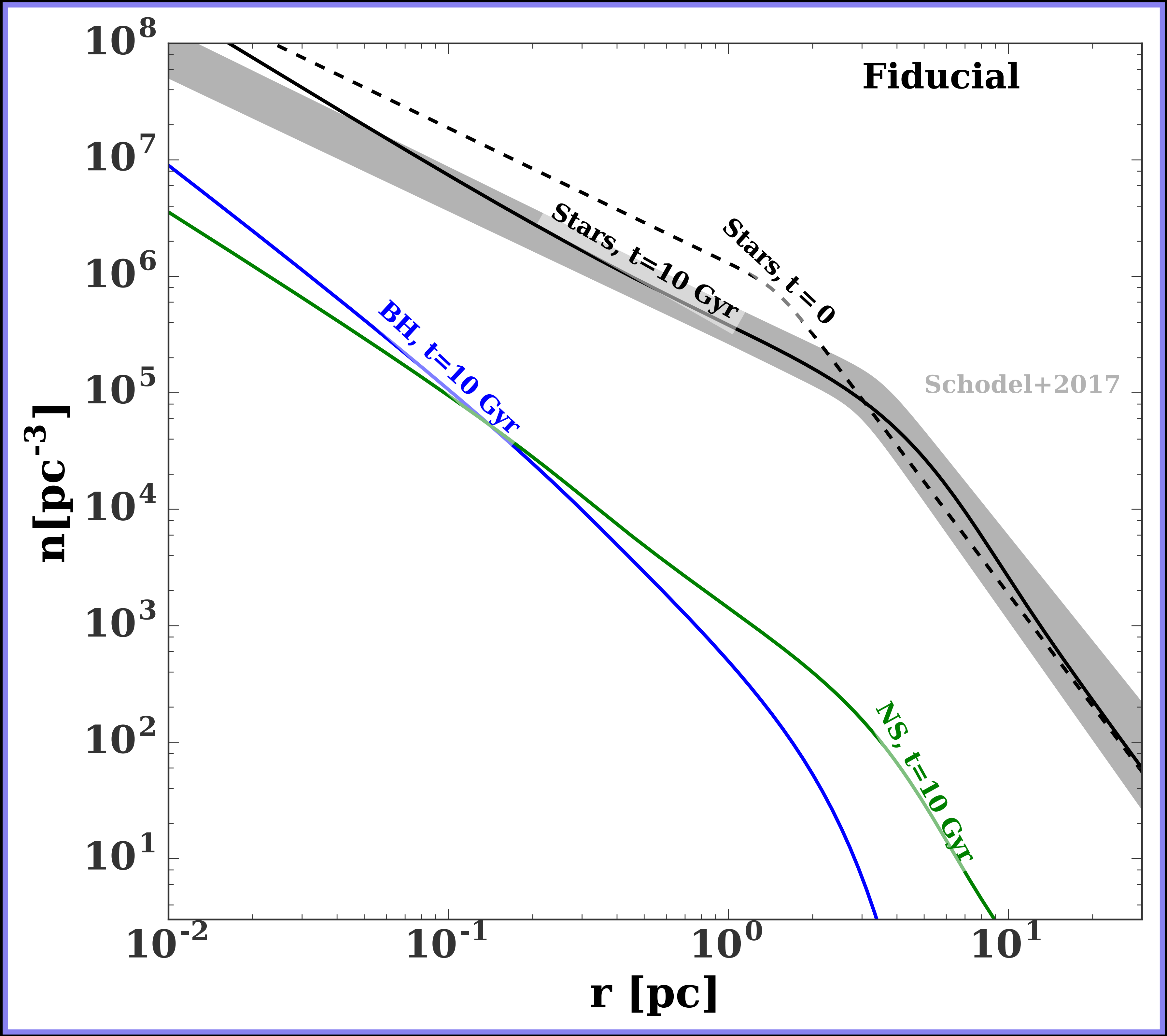
Tidal Capture: Physics



$$G\,M\,M_* / a = M_*\,v_\infty^2 - 2\Delta E$$

$$\Delta E = \frac{GM_\star^2}{R_\star}\left(\frac{M_\bullet}{M_\star}\right)^2 \sum_{\ell=2,3...}^{\infty}\left(\frac{R_\star}{R_{\rm p}}\right)^{2\ell+2} T_\ell(R_{\rm p})$$

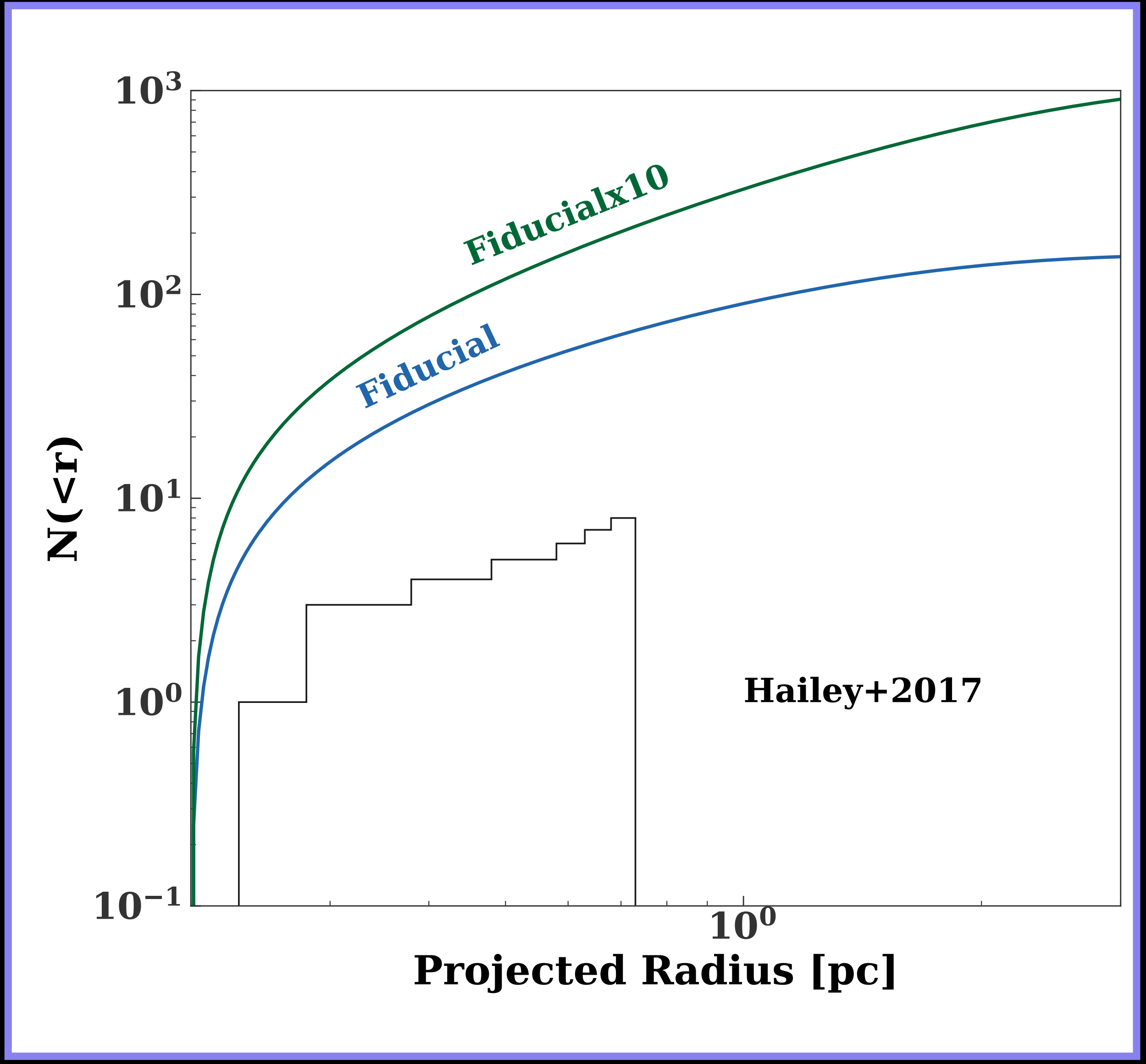
Fokker-Planck Model: Energy Space



(Generozov, **NCS**+ submitted)

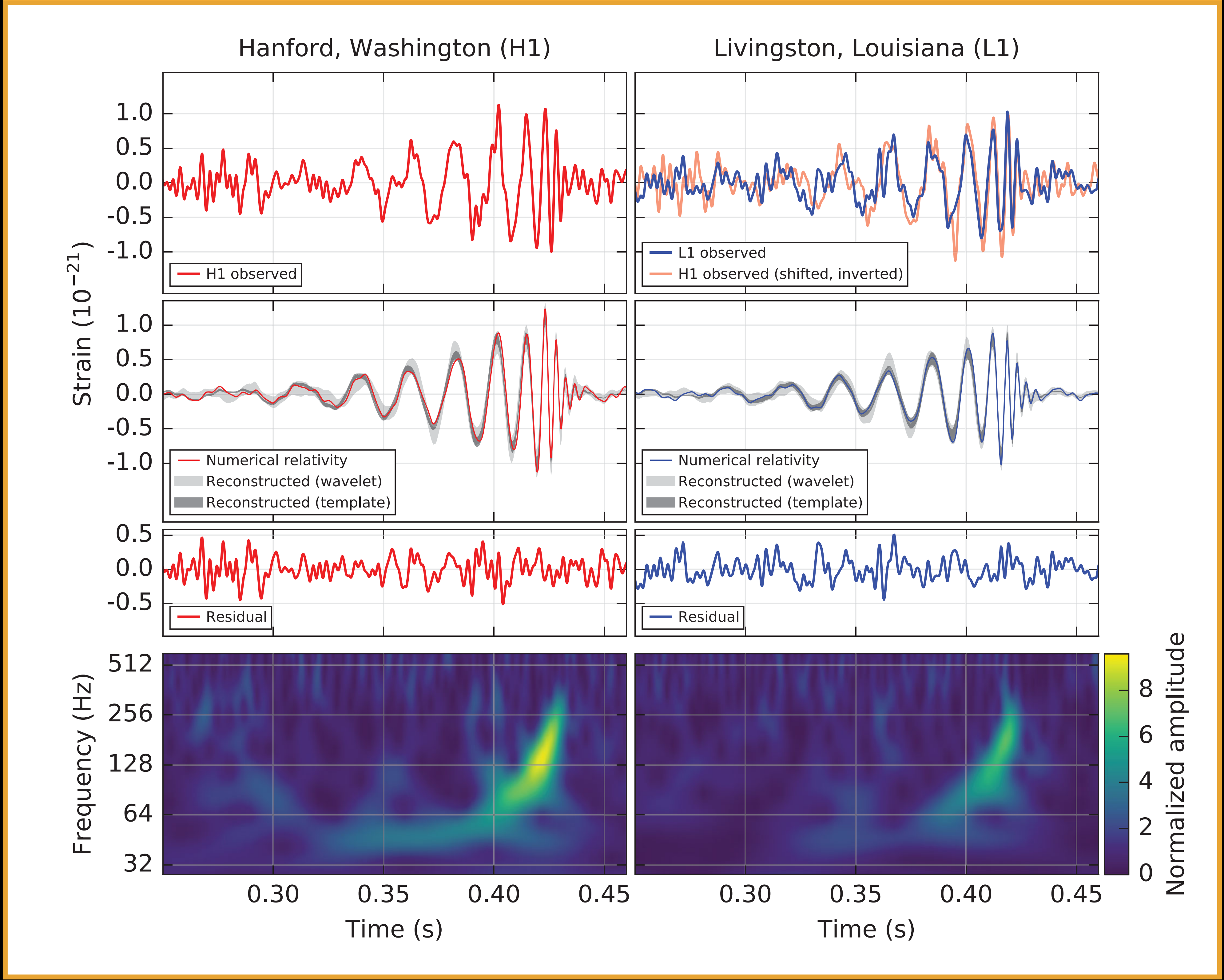
Tidal Captures in the Galactic Center

- Tidal capture can reproduce observed population of BH-XRBs
- Important caveats
  - Extrapolating down the luminosity function gives ~100s of BH-XRBs
  - Possible overproduction of NS-XRBs
- Once BH-XRB origin is understood, the GC will calibrate our knowledge of dark cusps in galactic nuclei:
  - Extreme mass ratio inspirals (LISA-band GWs)
  - Exotic LIGO-band GW implications
  - IMBH formation (**NCS**, Kuepper & Ostriker 17)



(Generozov, **NCS**+ submitted)

Gravitational Waves from Black Hole Mergers



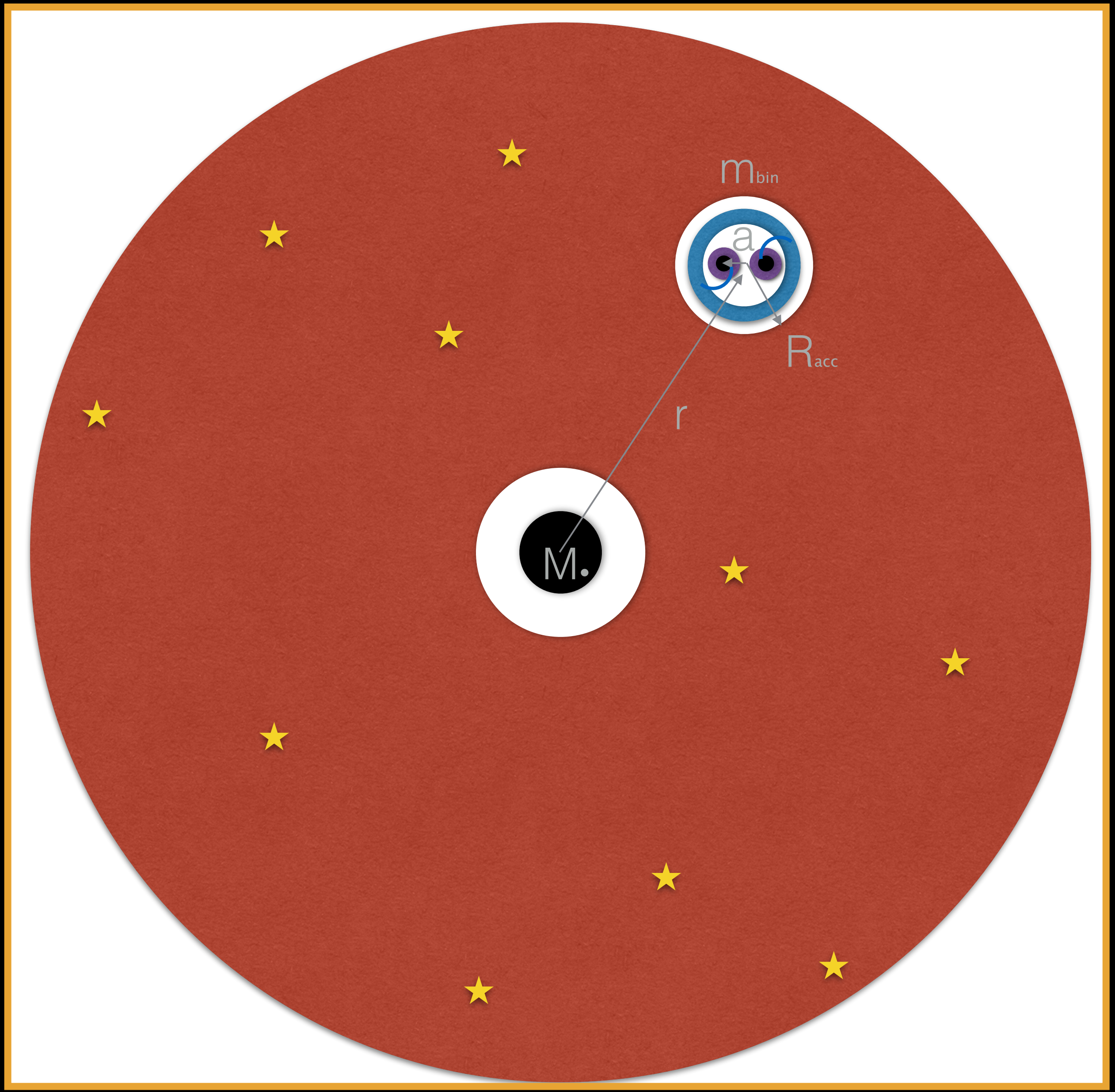
(Abbott+16)

Mergers & Acquisitions

- LIGO has seen four BH-BH mergers! (and one double neutron star merger…)
    - $\mathscr{R}$ ~ 12-200 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
    - Unusually large mass (M_{BH}~$30M_{\odot}$)
- Classical channels:
    - Isolated binary evolution
    - Dynamical assembly in globular clusters
- More exotic dynamical channels:
    - Kozai-Lidov effect: galactic nuclei and globular/open clusters (e.g. Leigh, **NCS**+16)
    - **Externally induced mergers** in *active* galactic nuclei gas disks (**NCS+17**, Bartos+17)

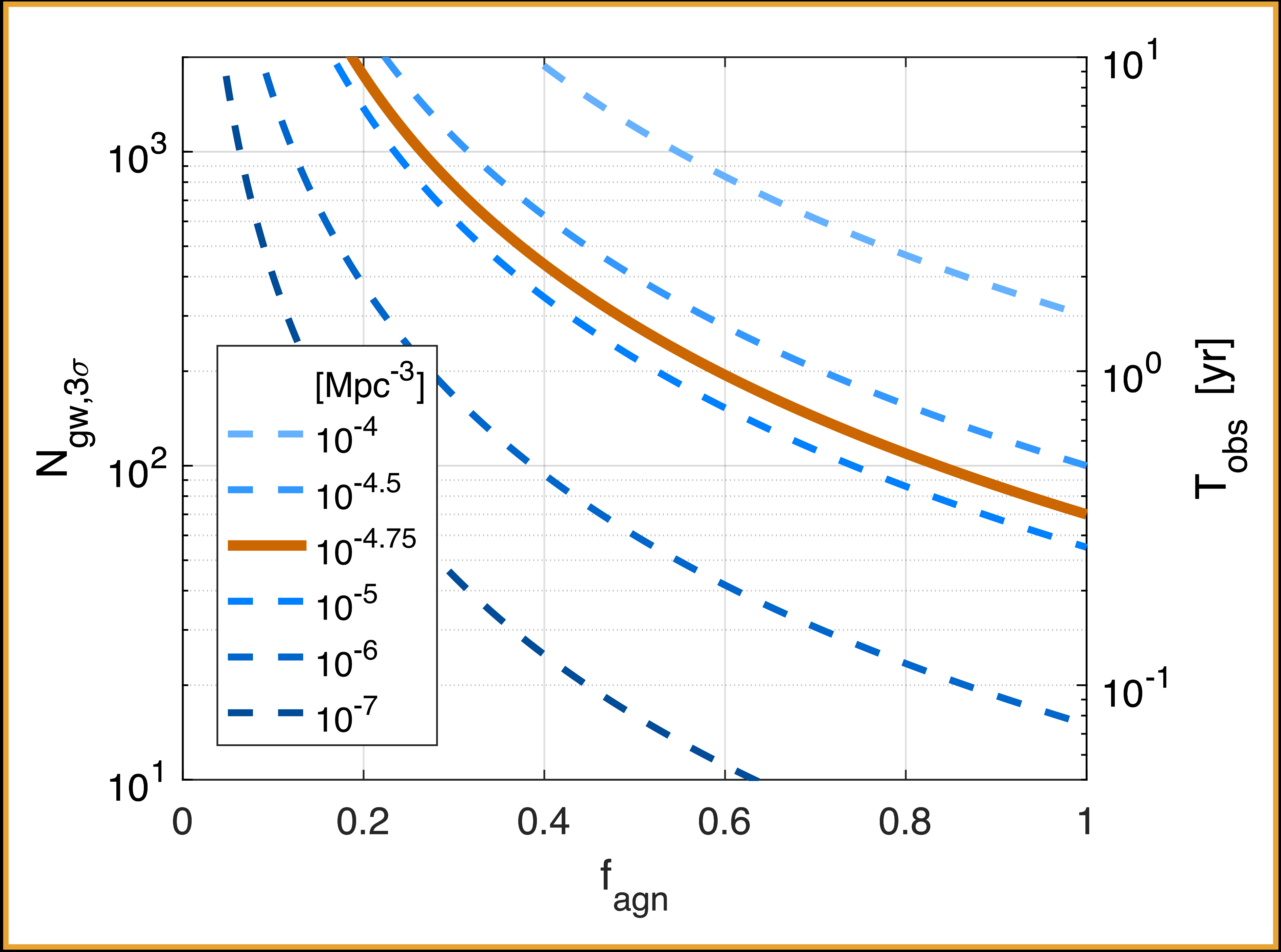
BH Binaries in AGN Disks

- Outskirts (~pc scale) of AGN disks Toomre unstable
    - Toomre $Q=c_s\Omega/(\pi G\Sigma)<1$ implies instability
    - Dense, collisional stellar disk forms
- Rapid merging of wide BH binaries
    - Binary-single scatterings harden very wide BH binaries
    - Circumbinary gas torques harden tighter ones
- Disk-induced merger rate $\mathscr{R}$ ~3-30 $Gpc^{-3}yr^{-1}$
    - Are there electromagnetic counterparts?
    - Repeated mergers/hierarchical growth?



(**NCS**+17)

Localization of Exotic Source Populations



(Bartos+ 17)

Future Steps

- In the near future, time domain surveys will find ~1000s of TDEs
  - ZTF (10/yr starting 2018), eROSITA (~500/yr starting 2018), LSST (~4000/yr starting 2022)
- Vast astrophysical potential for SMBH demography and accretion physics, but theoretical challenges remain:
  - Model for disk formation needed to understand X-ray light curve
  - Predictive optical emission models for parameter extraction (M_{BH}, a_{BH}, i, R_p, M_*)
  - Physics applications: cosmic censorship? Quadrupole moment? Standard sirens?
- Observations of the Milky Way Center indicate the presence of a "dark cusp"
  - Extragalactic cusps will create interesting gravitational waves in *LISA* or *LIGO* bands
- Advanced LIGO/Virgo era enables novel tests of GR, opens new window of GW astrophysics
  - Zeroth order question: where are most observed BHBH mergers coming from?
  - First order question: which formation channels hold greatest scientific potential (GR tests, neutron star equation of state, etc)?