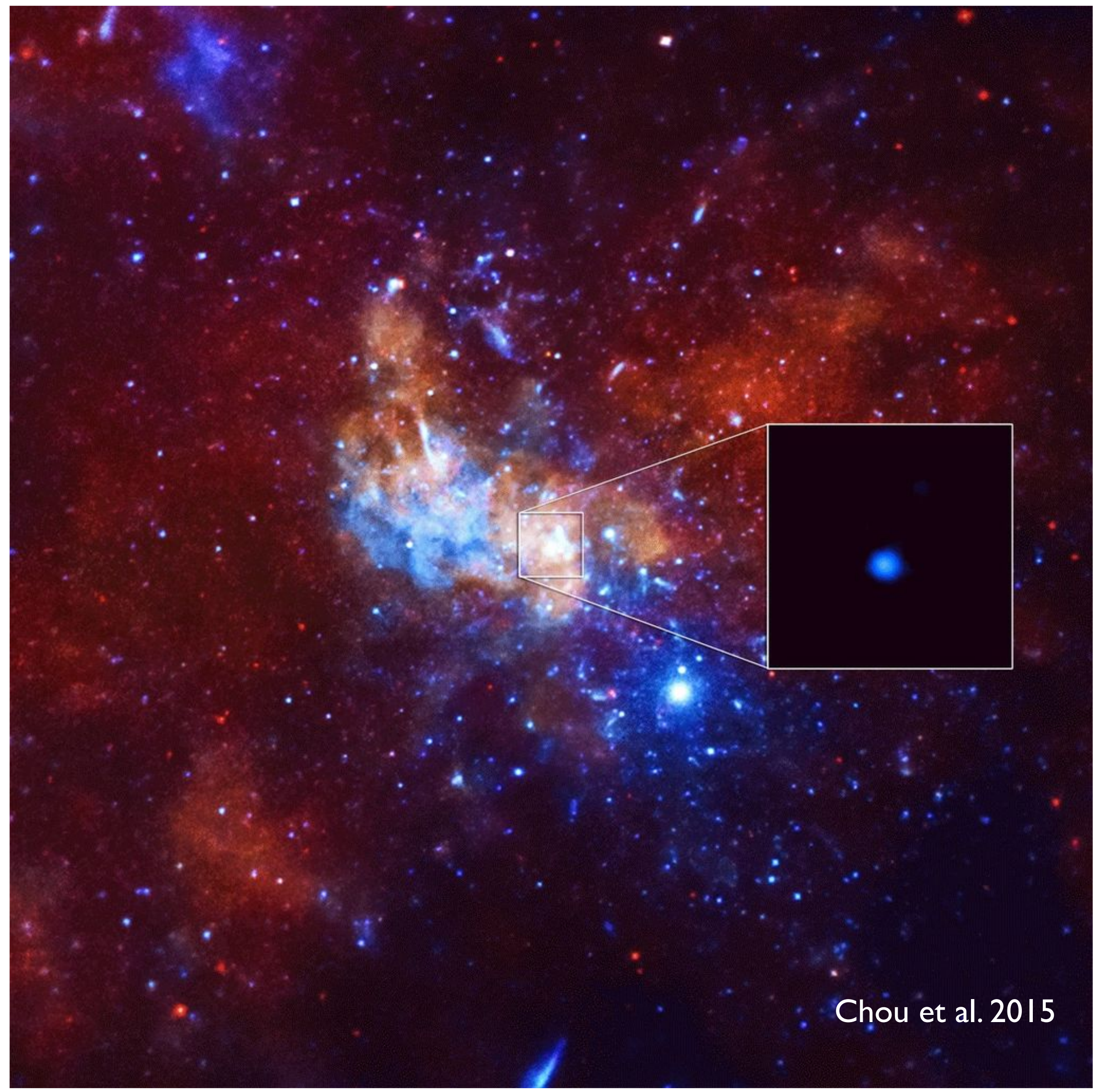
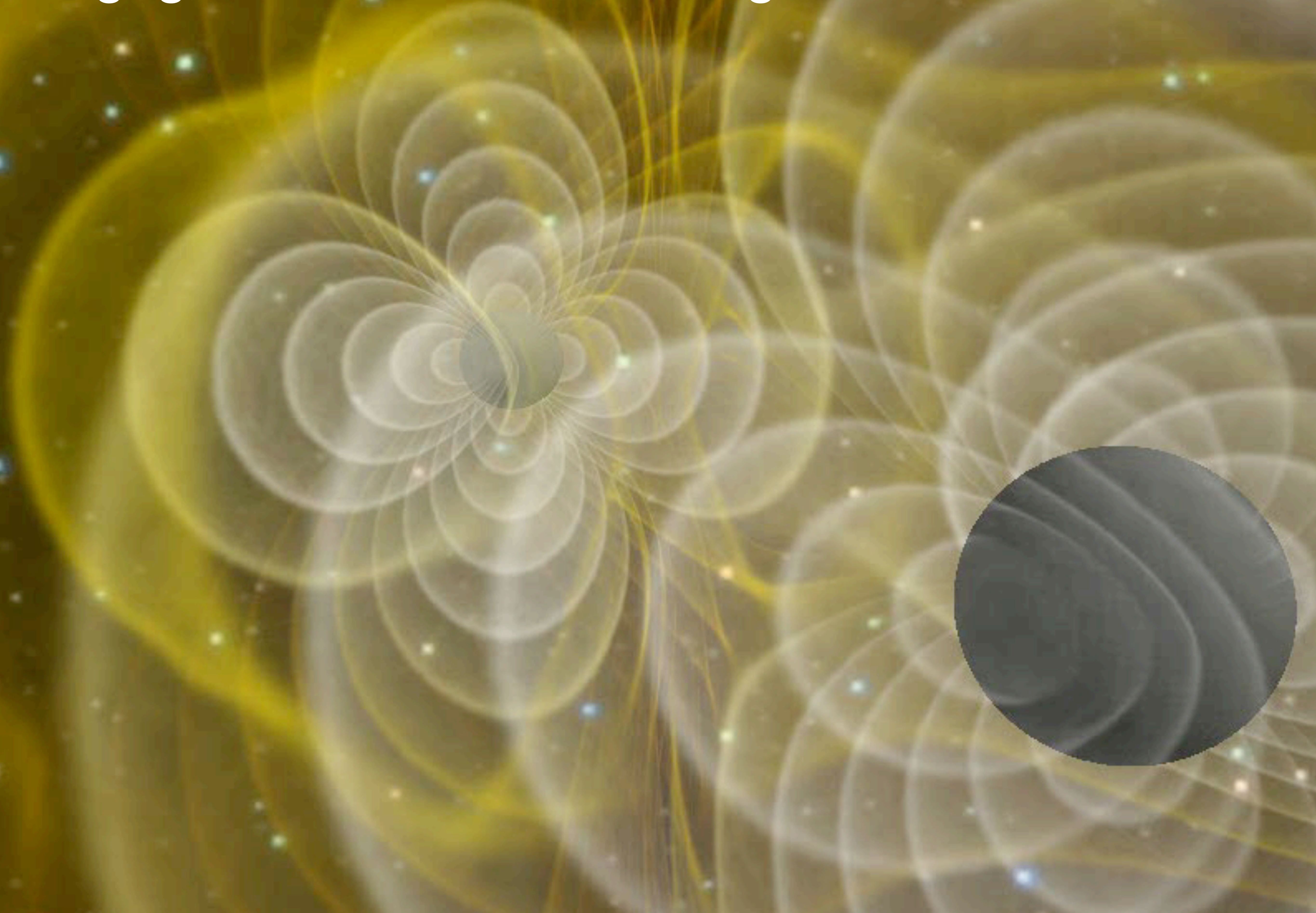
The Universe as Revealed by LISA: How Gravitational Wave Astronomy Will be a Game Changer

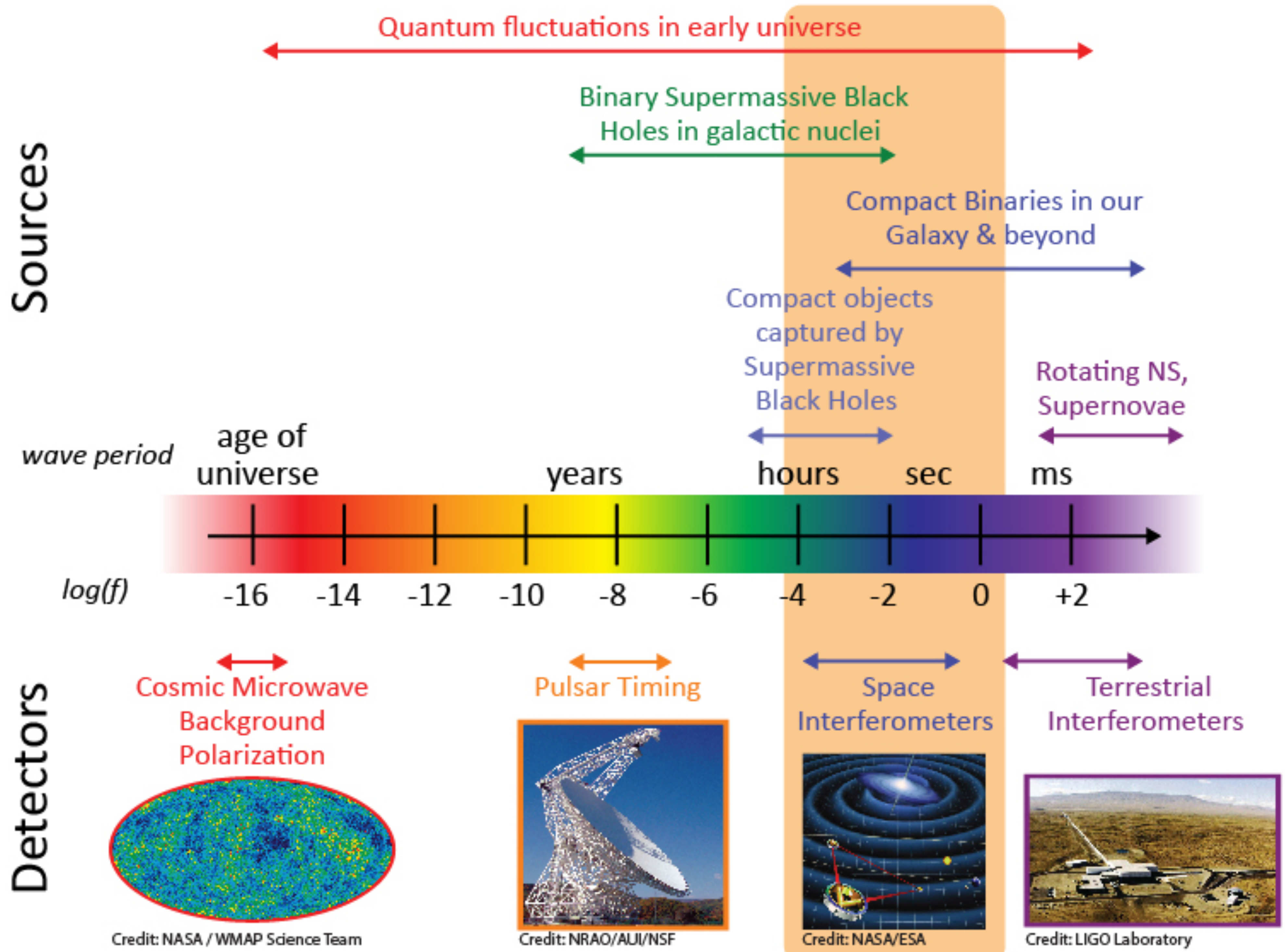


Kelly Holley-Bockelmann
Vanderbilt University and Fisk University
k.holley@vanderbilt.edu

Merging matter makes enormous gravitational waves

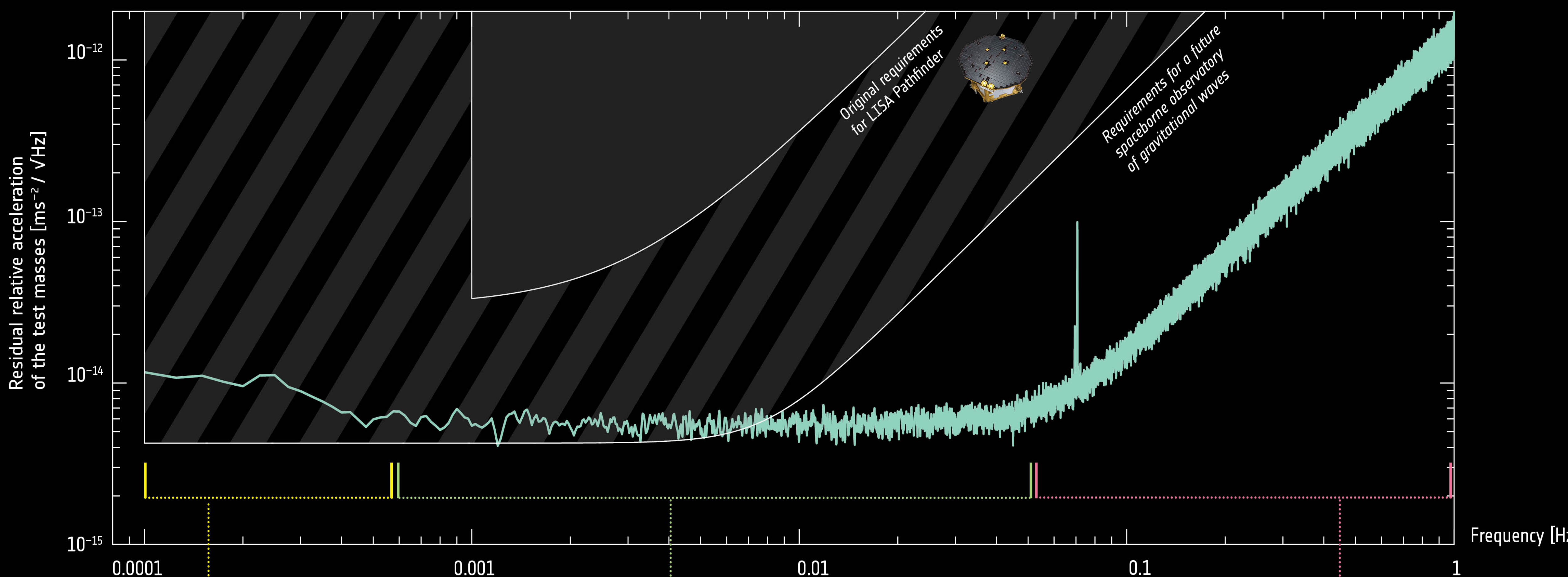


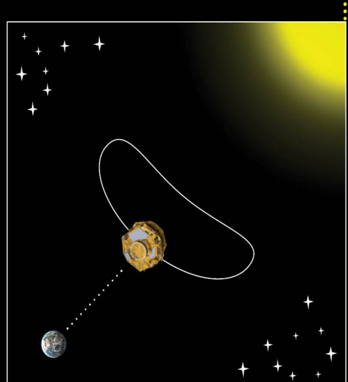
The Gravitational Wave Spectrum



ESA/NASA space-based gravitational wave mission, LISA (proposed launch in 2034)

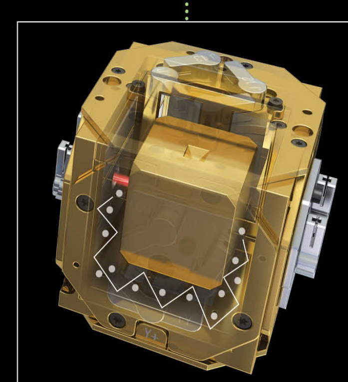
→ LISA PATHFINDER EXCEEDS EXPECTATIONS





Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

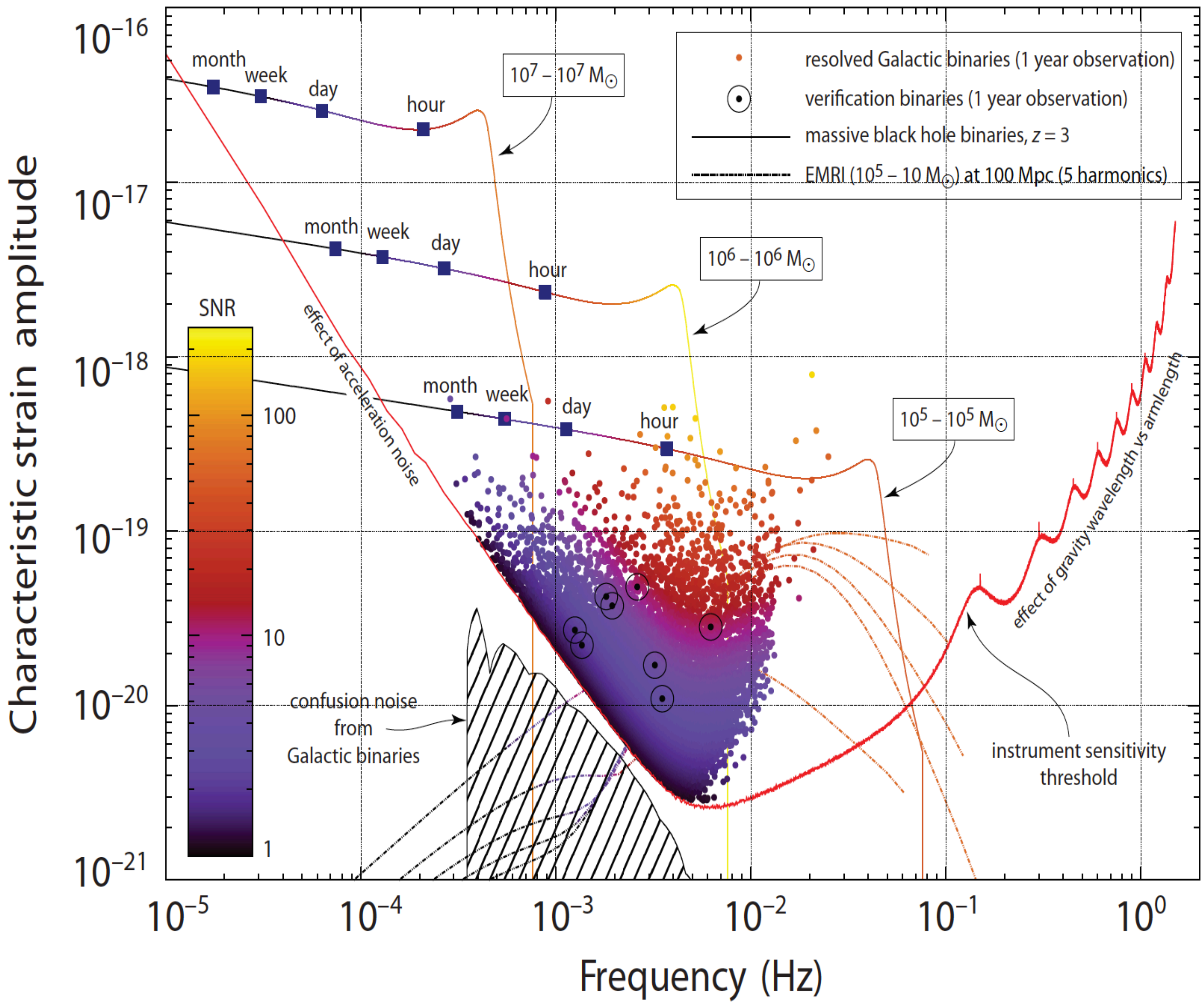
Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.

Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

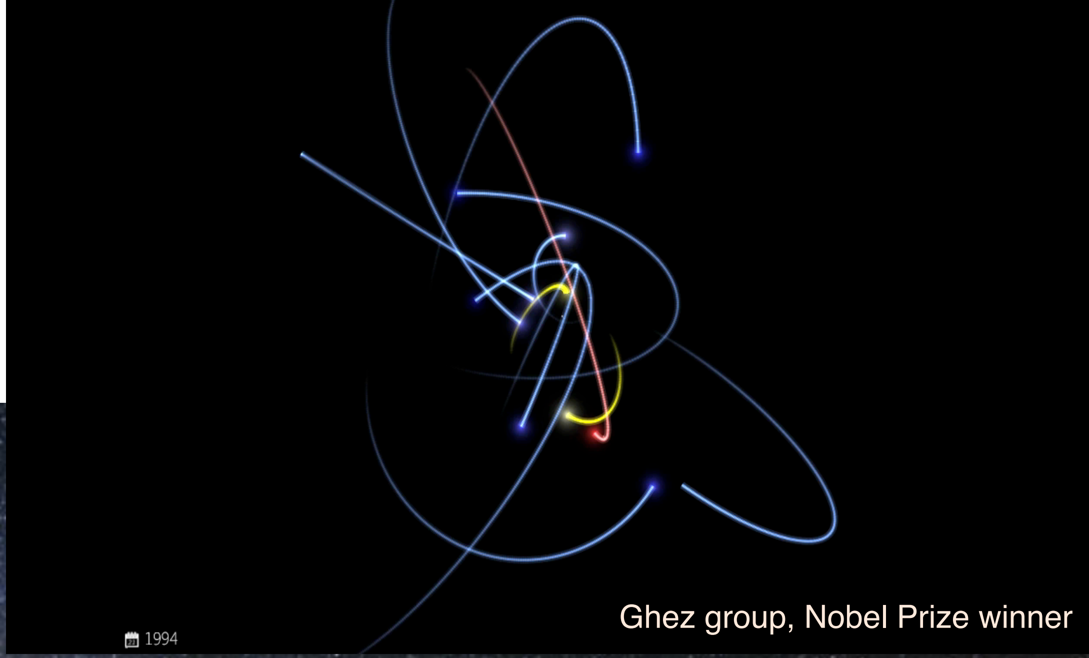
Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

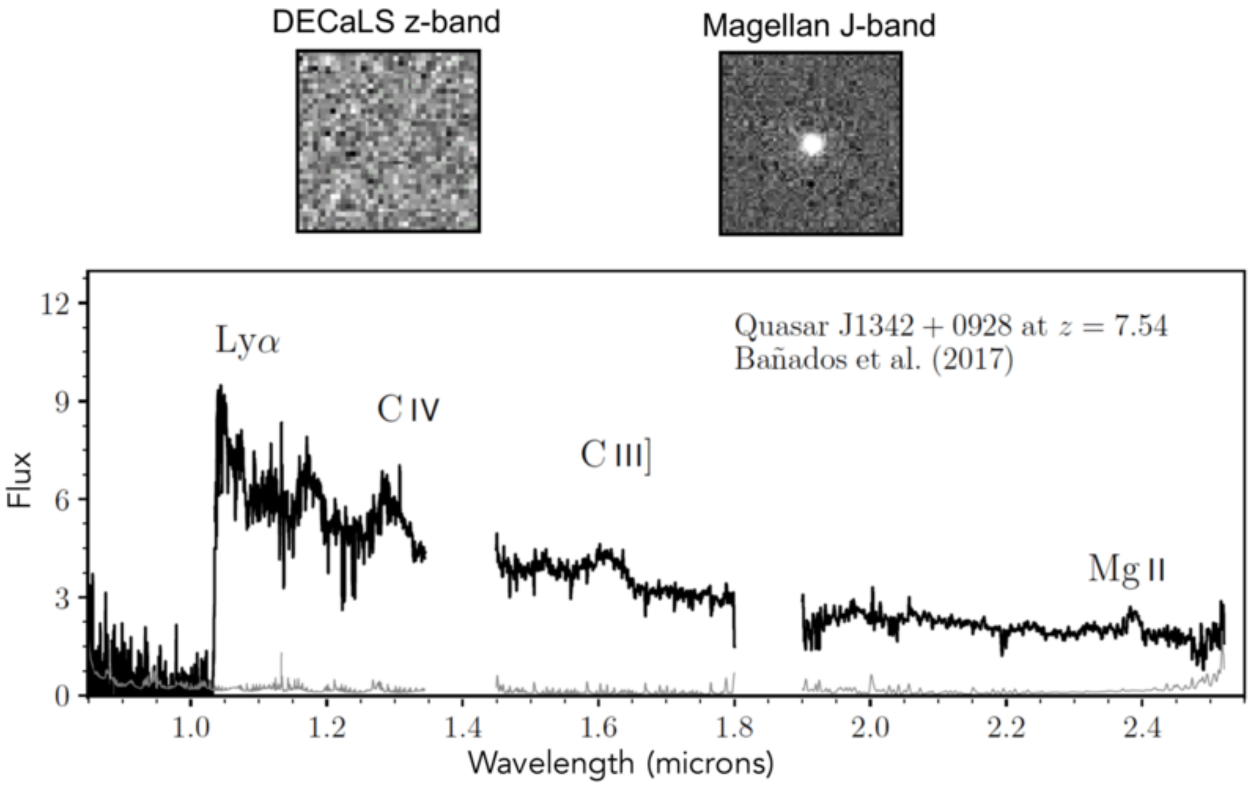
LISA
Discovery Space



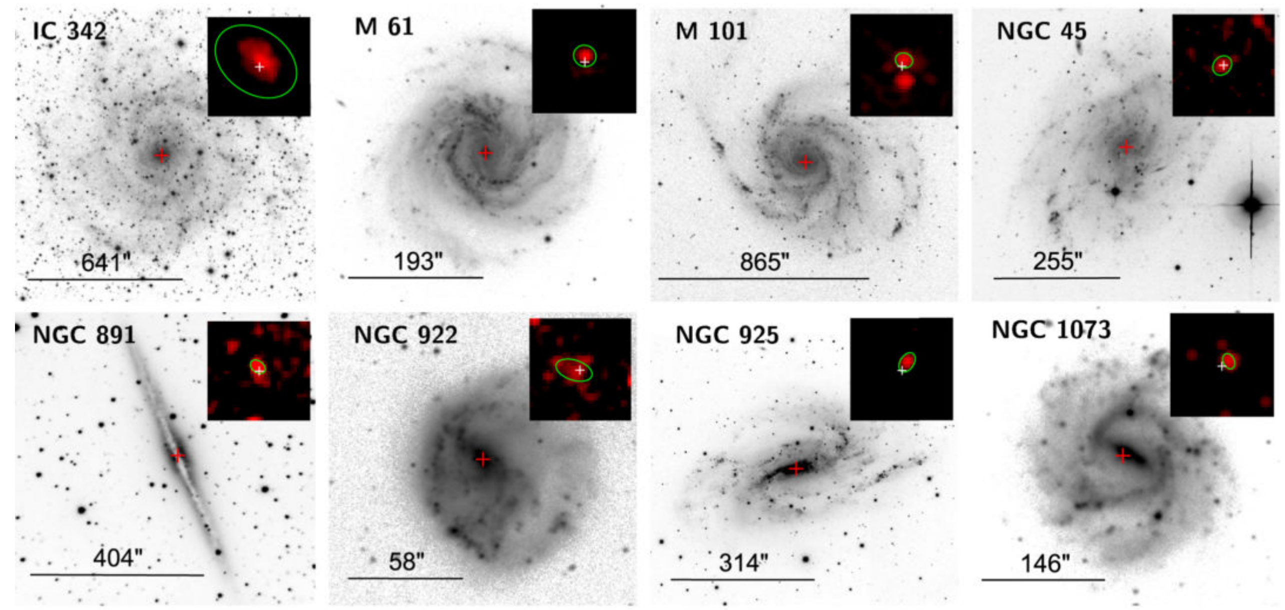
lisa

Backing up: stellar orbits show that the Milky Way hosts a $4x10^6$ solar mass black hole



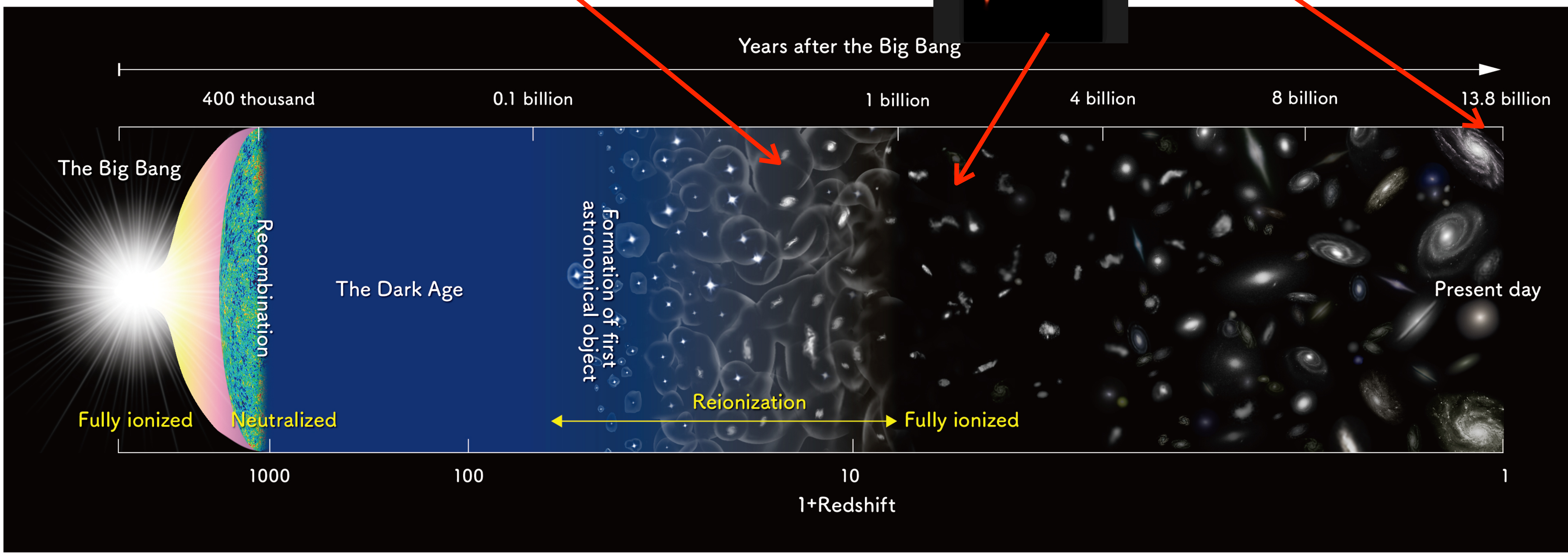


~10^6 — 10^9 $M_\odot$ Black Holes



1.5x10^9 $M_\odot$ Black Hole!

Yang et al. 2020



Heinze 2-10 is dwarf with a million solar mass black hole

and there are SMBHs in bulgeless galaxies, too!

SMBHs are in low surface brightness galaxies, like Malin 1...

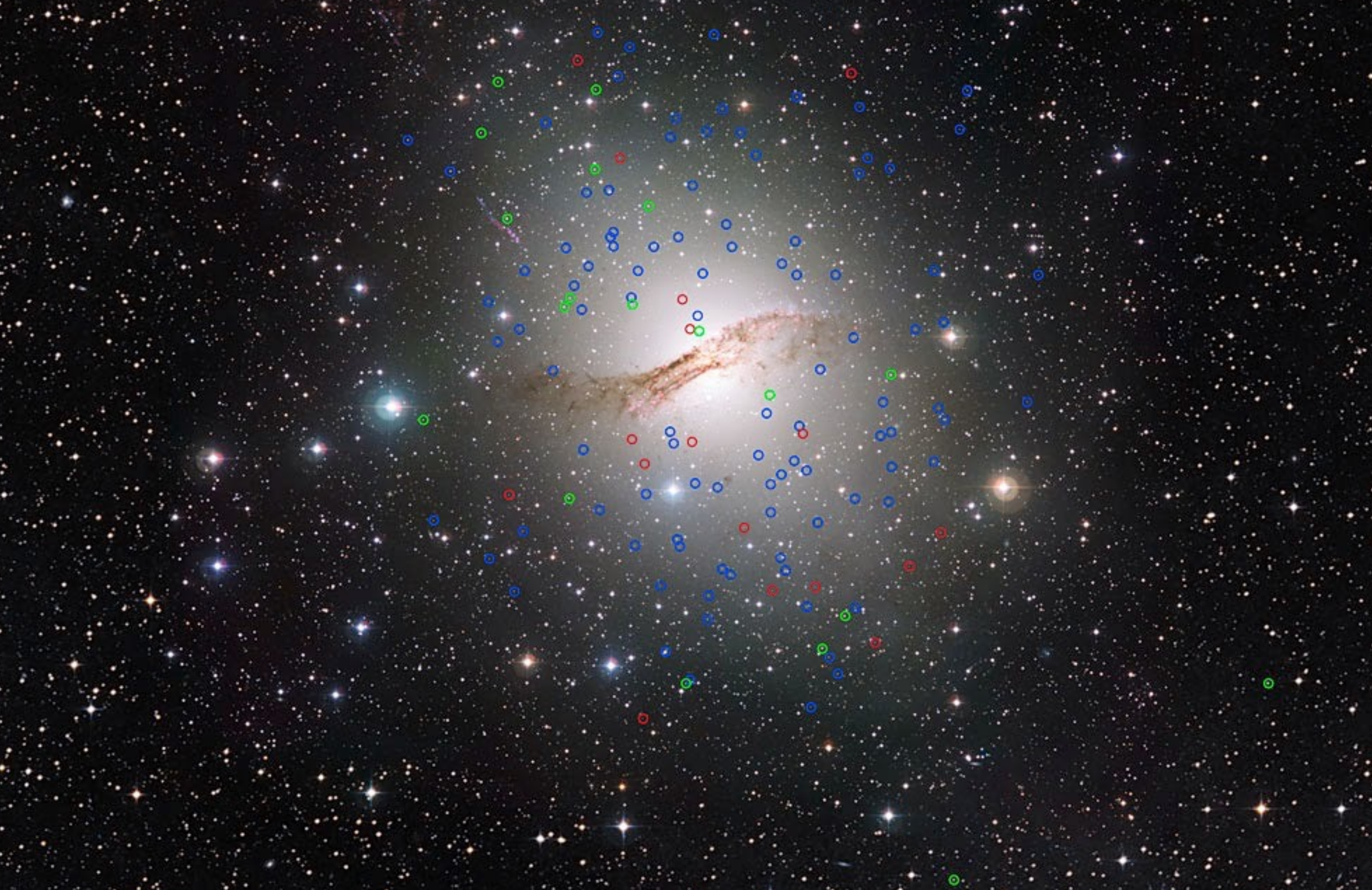
Subramanian et al. 2015

Warning: viral masses — assume line width maps to velocity for Keplerian motion

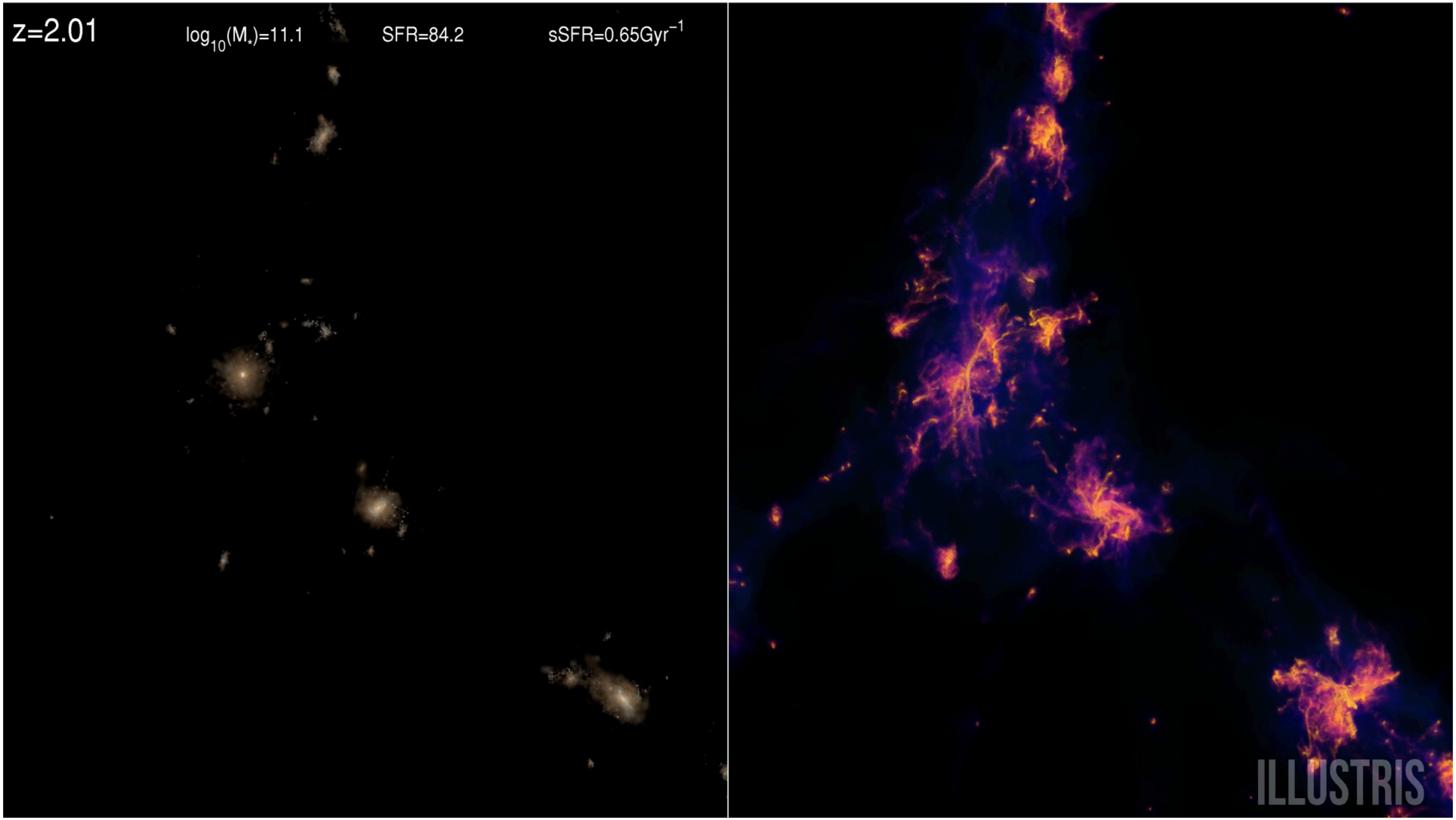
Evidence of an intermediate mass black hole – HLX-1 in the outskirts of a galaxy

Newly discovered dark star clusters may contain IMBHs

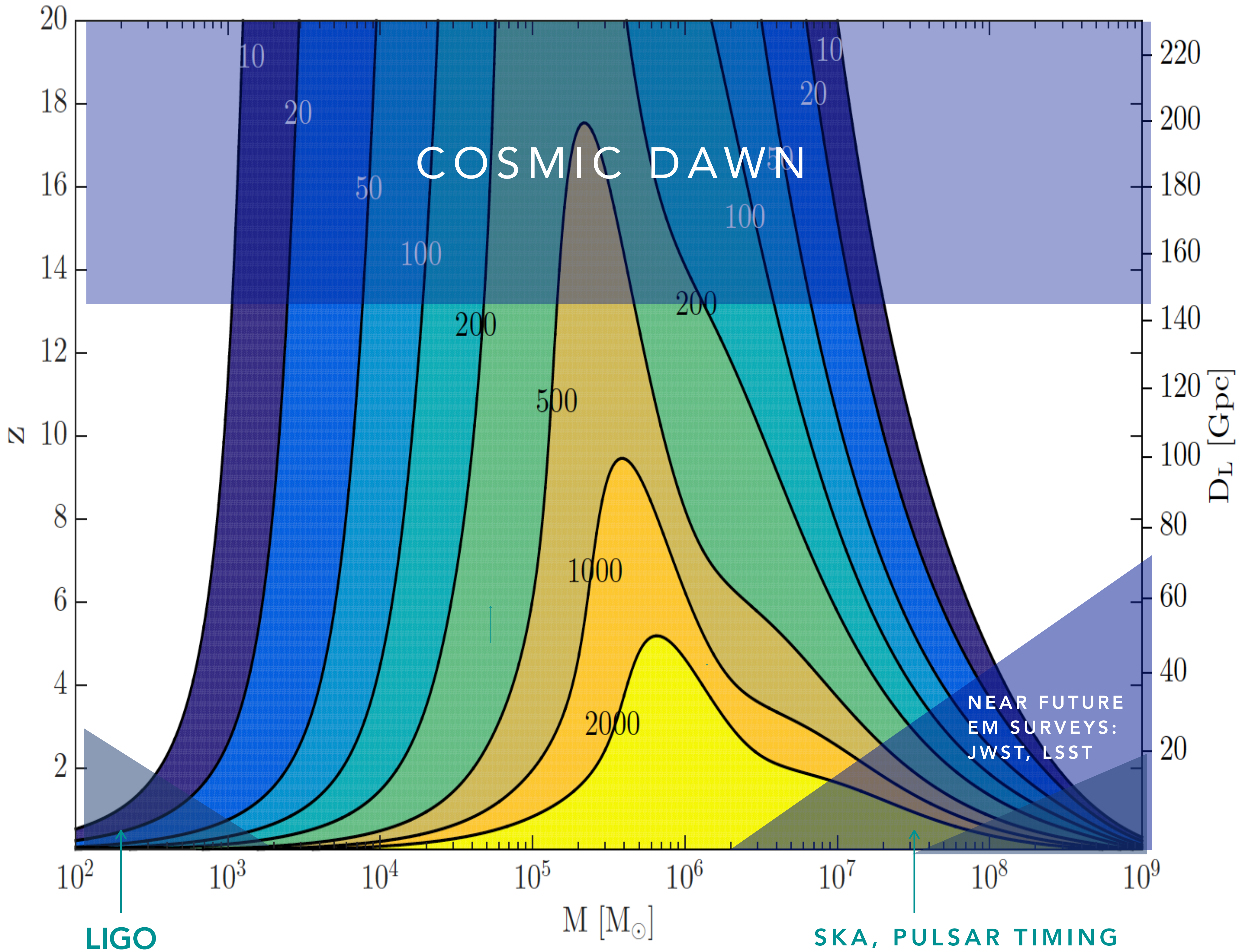
Taylor et al. 2015; Bovill et al 2016



Galaxies grow by merging together, and the black holes merge, too

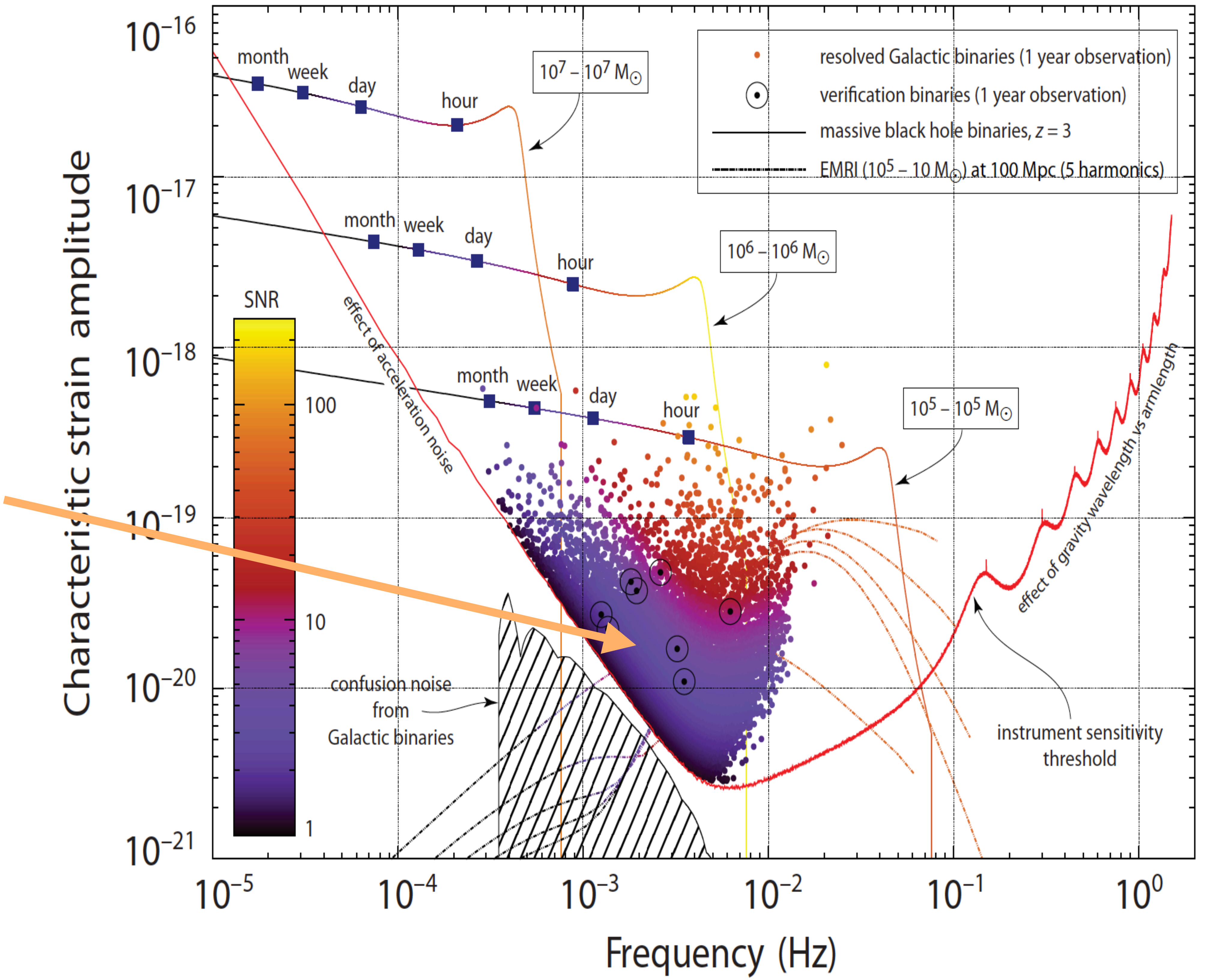


3×10^{18} km

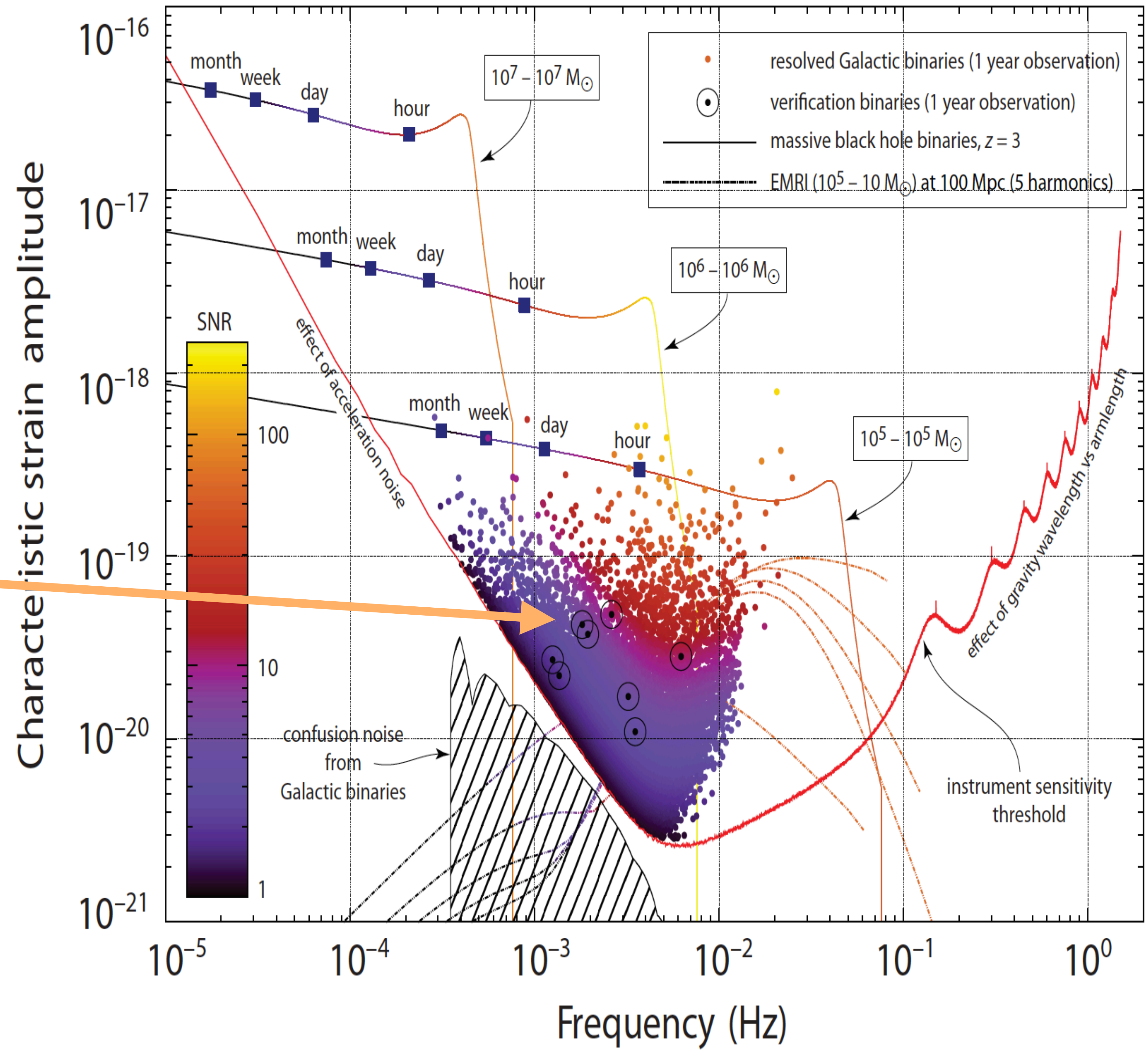


LISA detects the inspiral and merger of intermediate and massive Milky Way-class black holes with huge SNR throughout the observable universe and into the Cosmic Dawn.

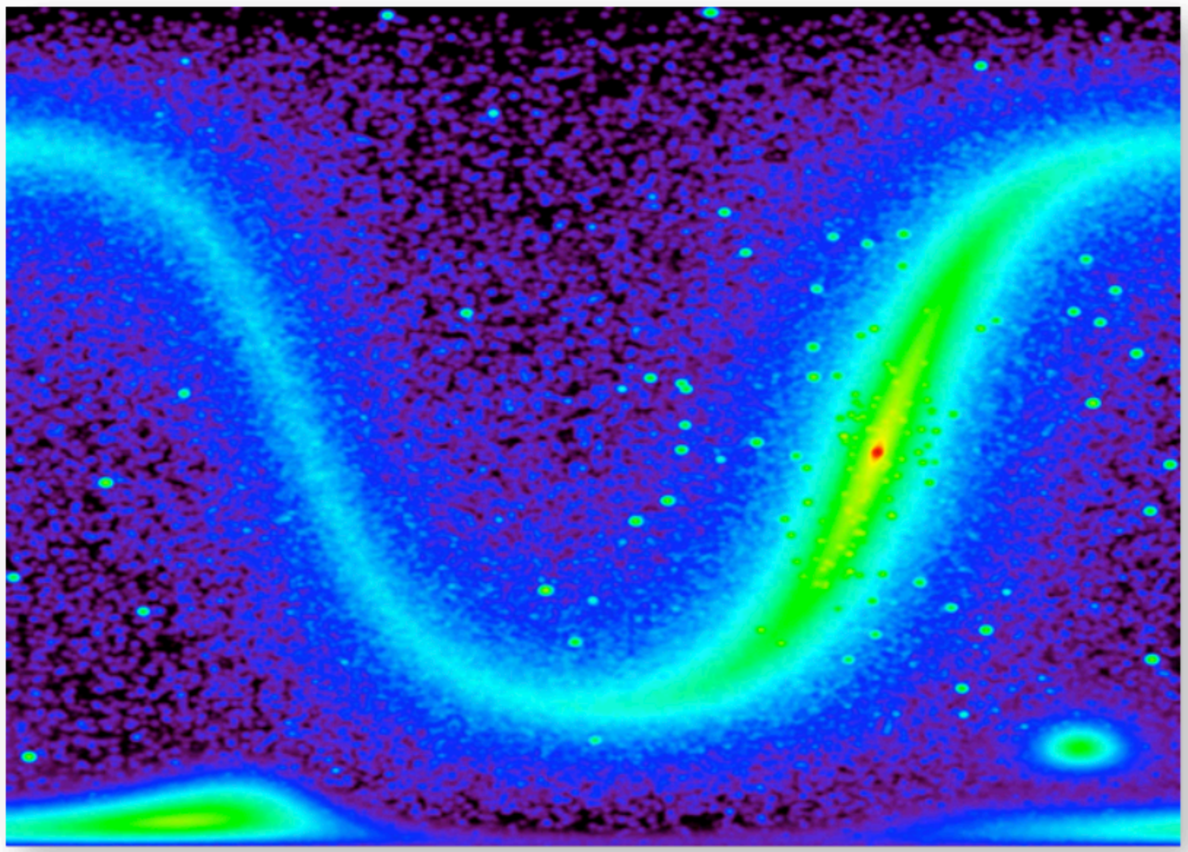
Millions of close compact object binaries



Gravitational waves are unaffected by dust!

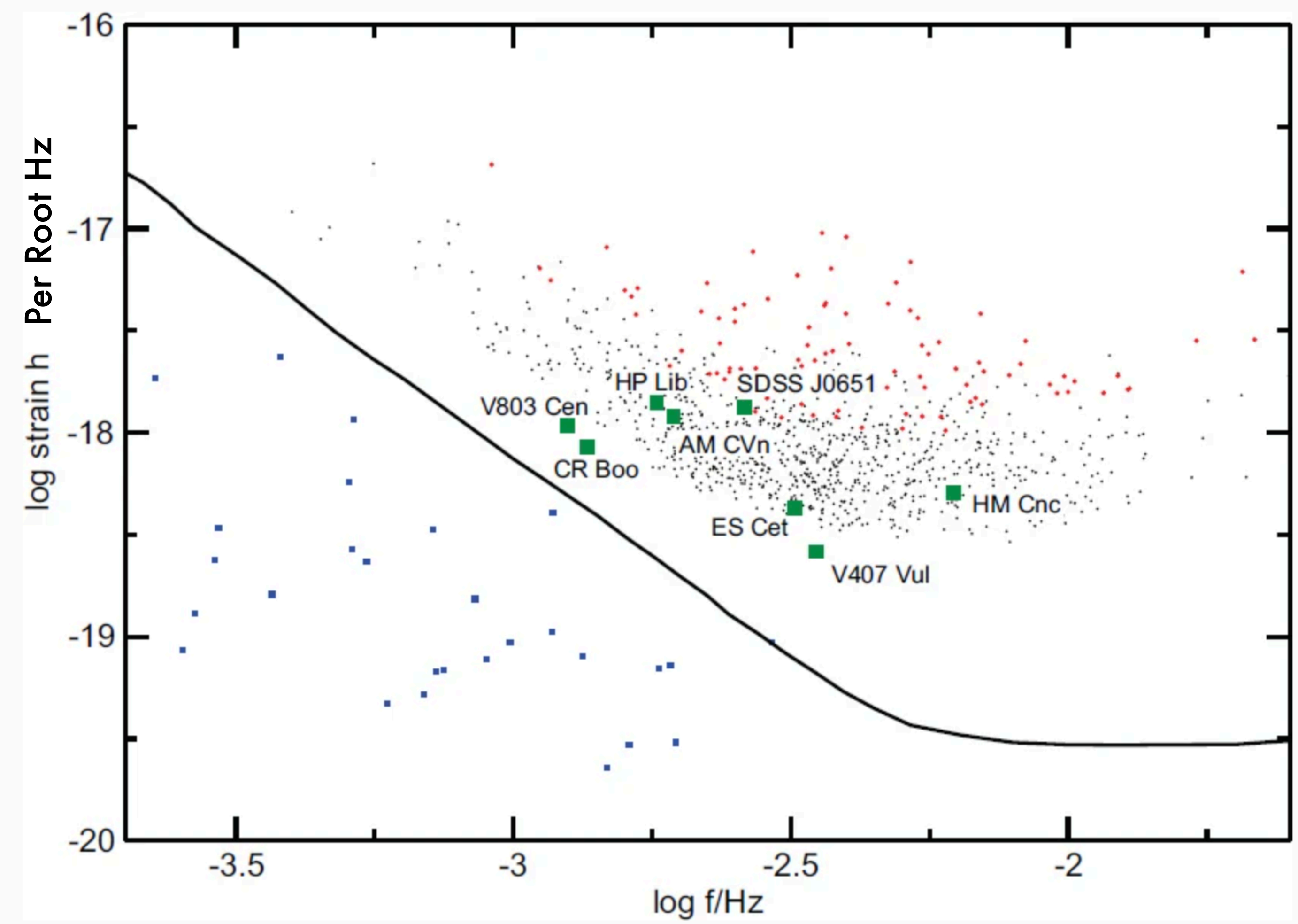


All the close white dwarf binaries in the galactic neighborhood are GW-loud!



KHB+ 2006

A smattering of EM-bright close binary systems

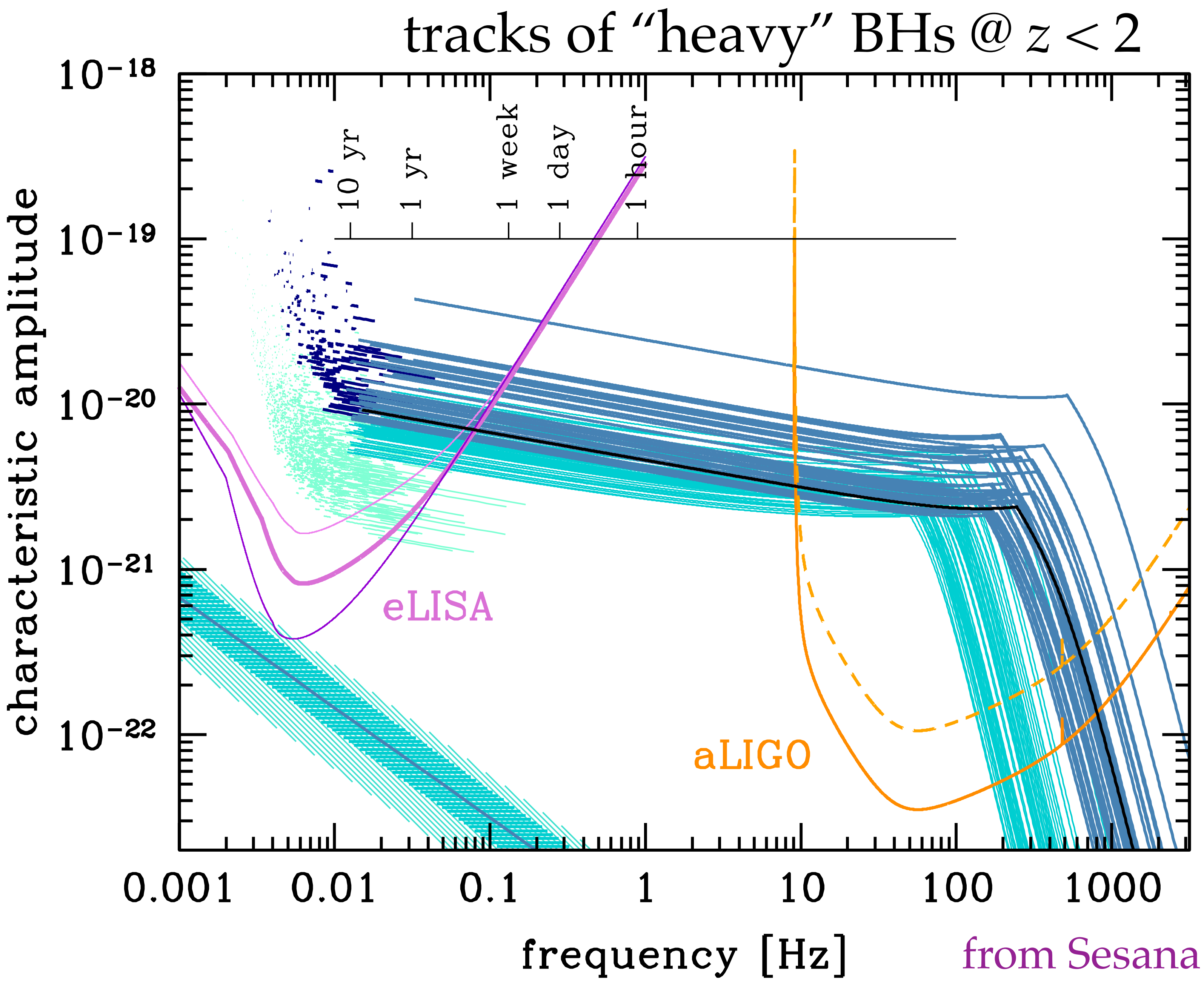


Postnov+Yungelson, 2014

What do we hope to measure with

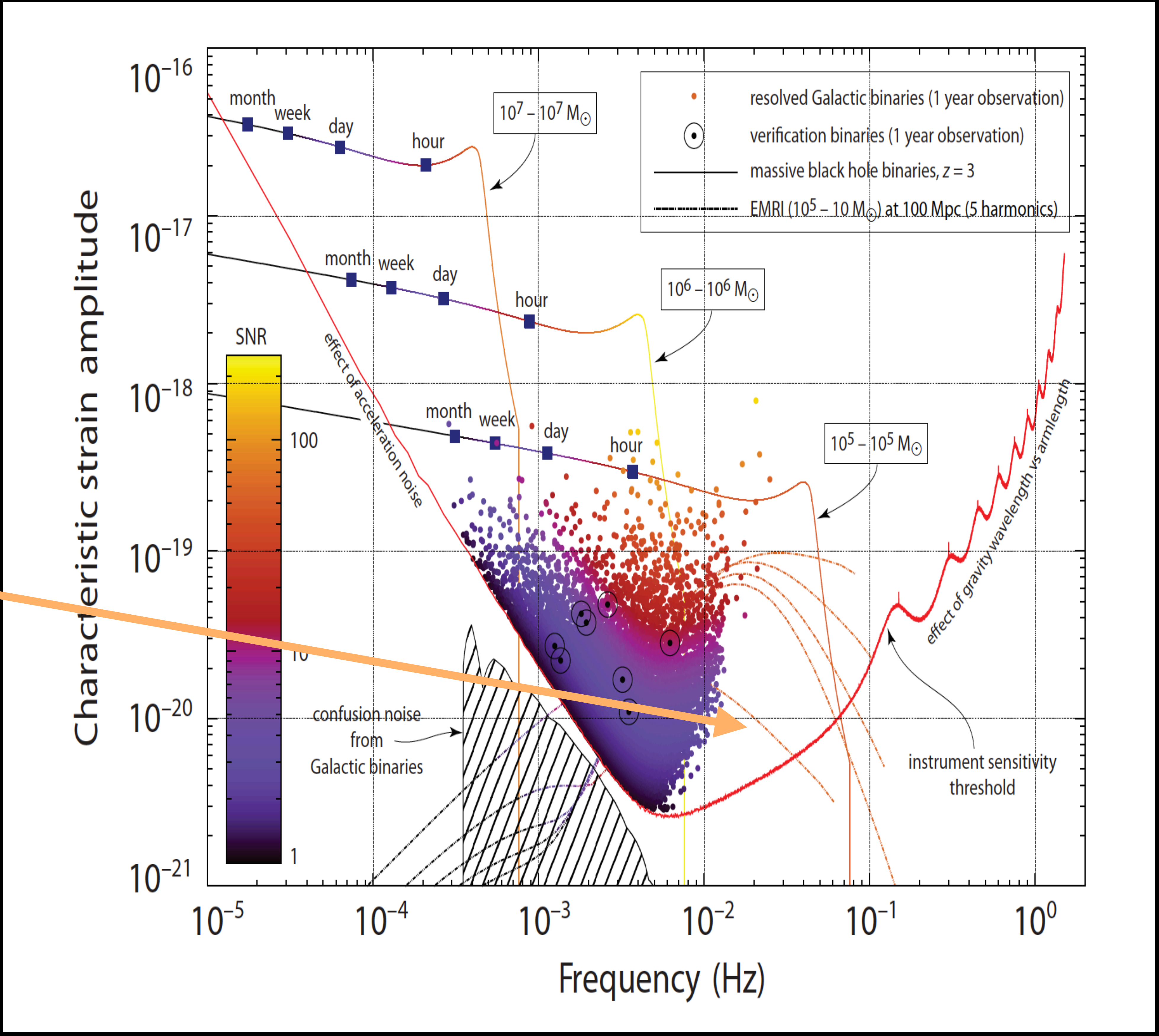
- Binary Star Evolution
  - Census of compact binaries, especially WD+WD
  - Determination of binary parameters
- Mapping of old stellar population in Milky Way
- Accretion Physics
  - Obtain system parameters, especially masses and mass transfer rates

Extending and complementing LIGO



from Sesana 2016, *Phys. Rev. Lett.*, **116**,

STELLAR
REMNANTS
ORBITING
SMBHS

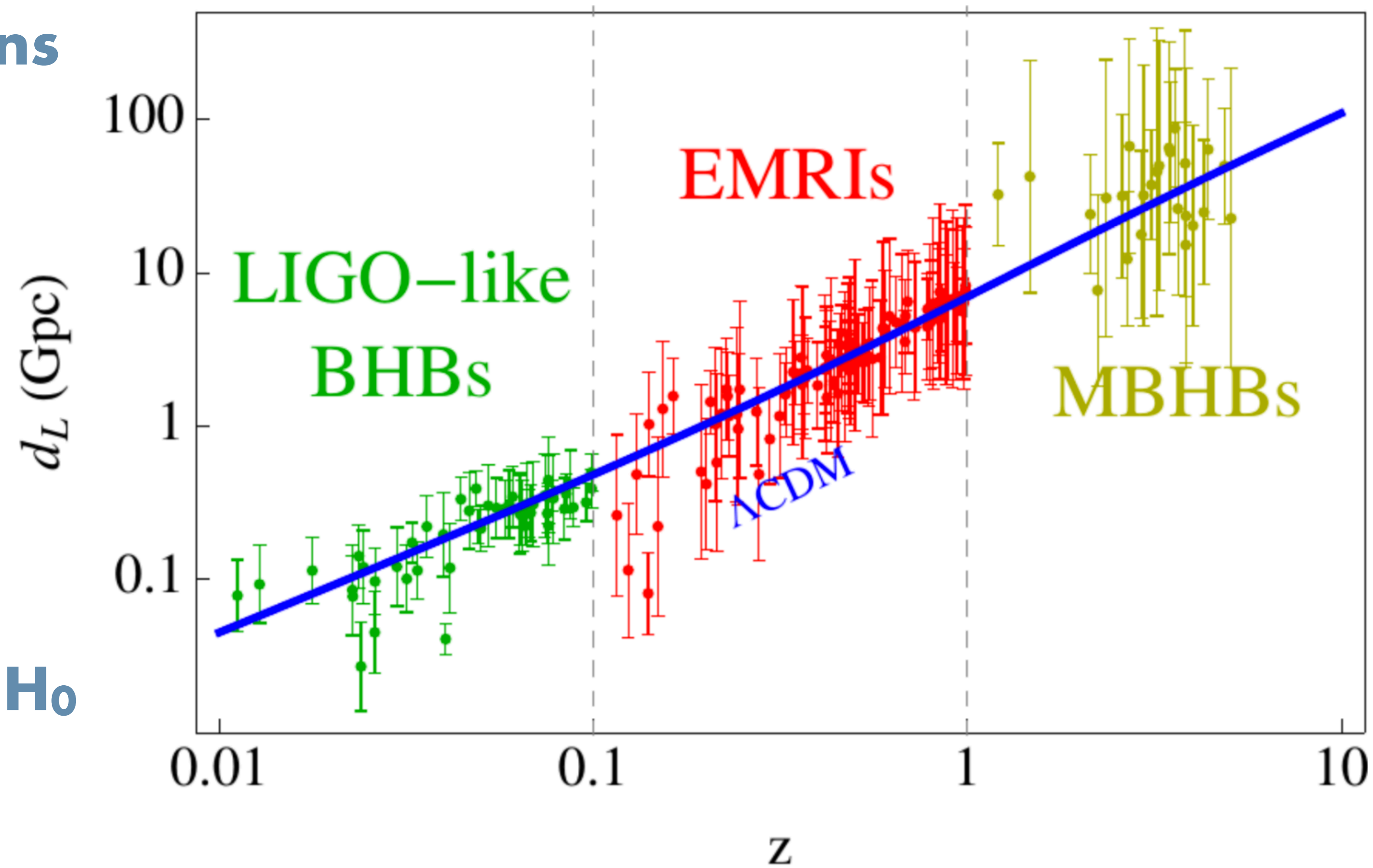


130 days before merger, 34% of light speed

Credit: Steve Drasco, who is awesome

Black hole cosmology with lisa

- **BH mergers as standard sirens**
  - chirp rate gives mass
  - mass gives intrinsic amplitude
  - measured amplitude gives distance
- **combine with redshift to get H_0**
  - Need EM follow-up to identify (or constrain) hosts



Luminosity distances for simulated catalog of LISA BH binaries (N. Tamanini)

Imagine what you could do with:

- Component masses — 1%
- Distances — 3% or better
- Spins — 1-10%
- Spin directions — 10 degrees
- Sky localization — few arcmin — 10 deg^2
- Eccentricity — 1%

It's a wonderful time to be an astronomer!

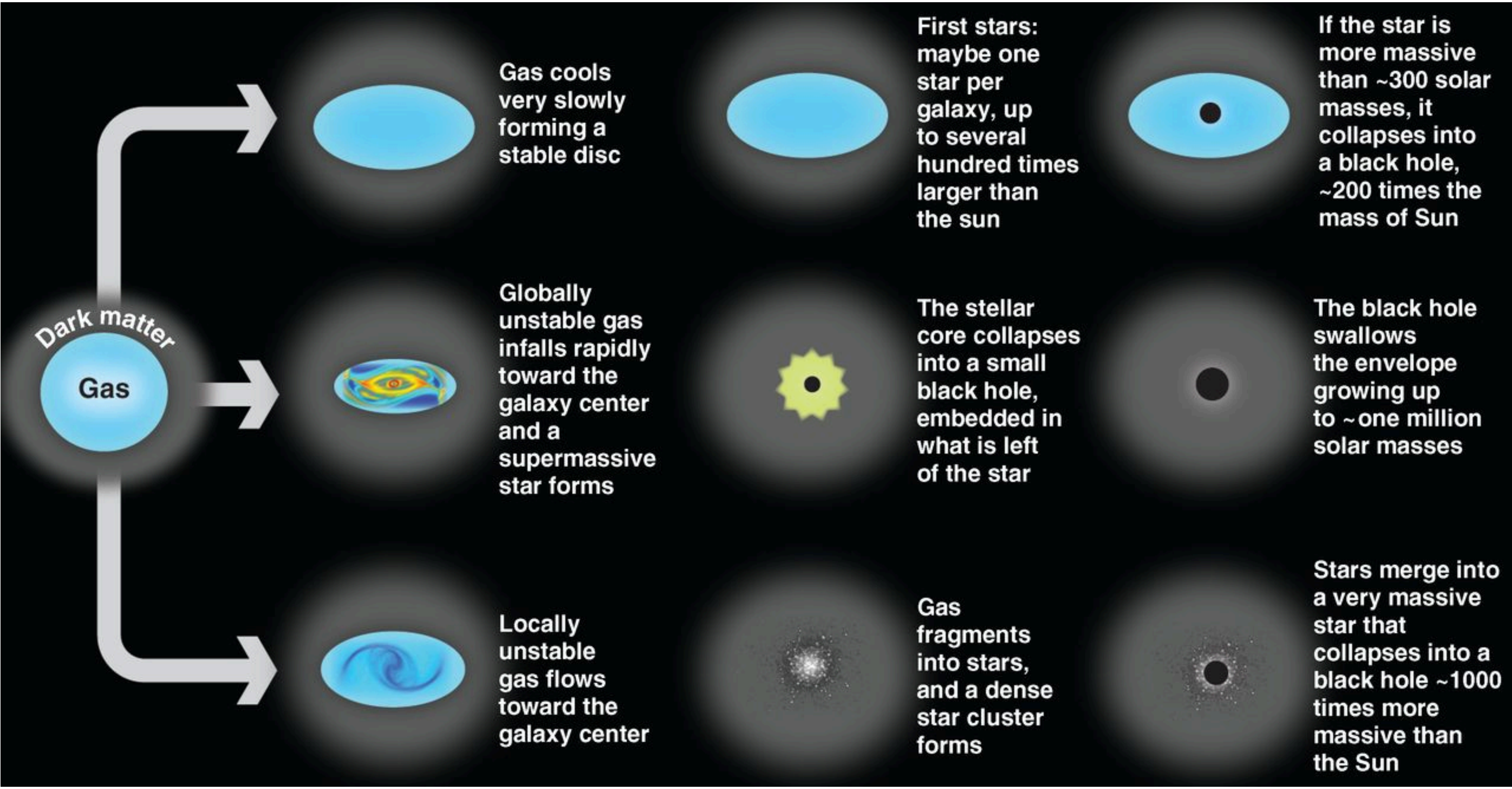
Oh, Canada: **LISA is happening!** It's time to think about how how to get the most science out of LISA data. We need to build capacity in the brand new field of gravitational wave astronomy, and we'd love to work with you.

Thanks!

Backup slides and dregs from other talks, feel free to ignore.

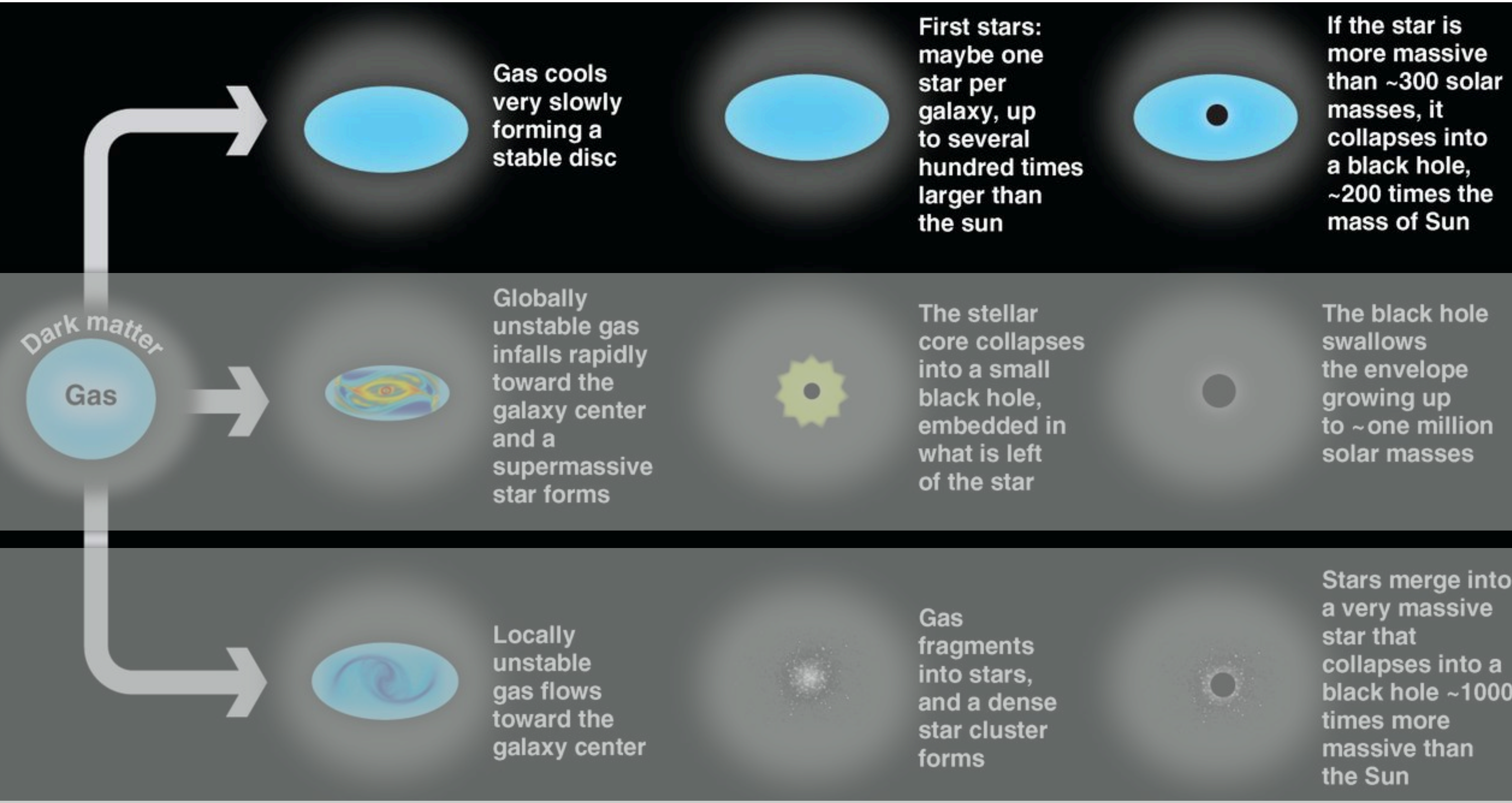
Let's think about what LISA could reveal about SMBH birth and early growth

Forming a black hole: let me count (some of) the ways



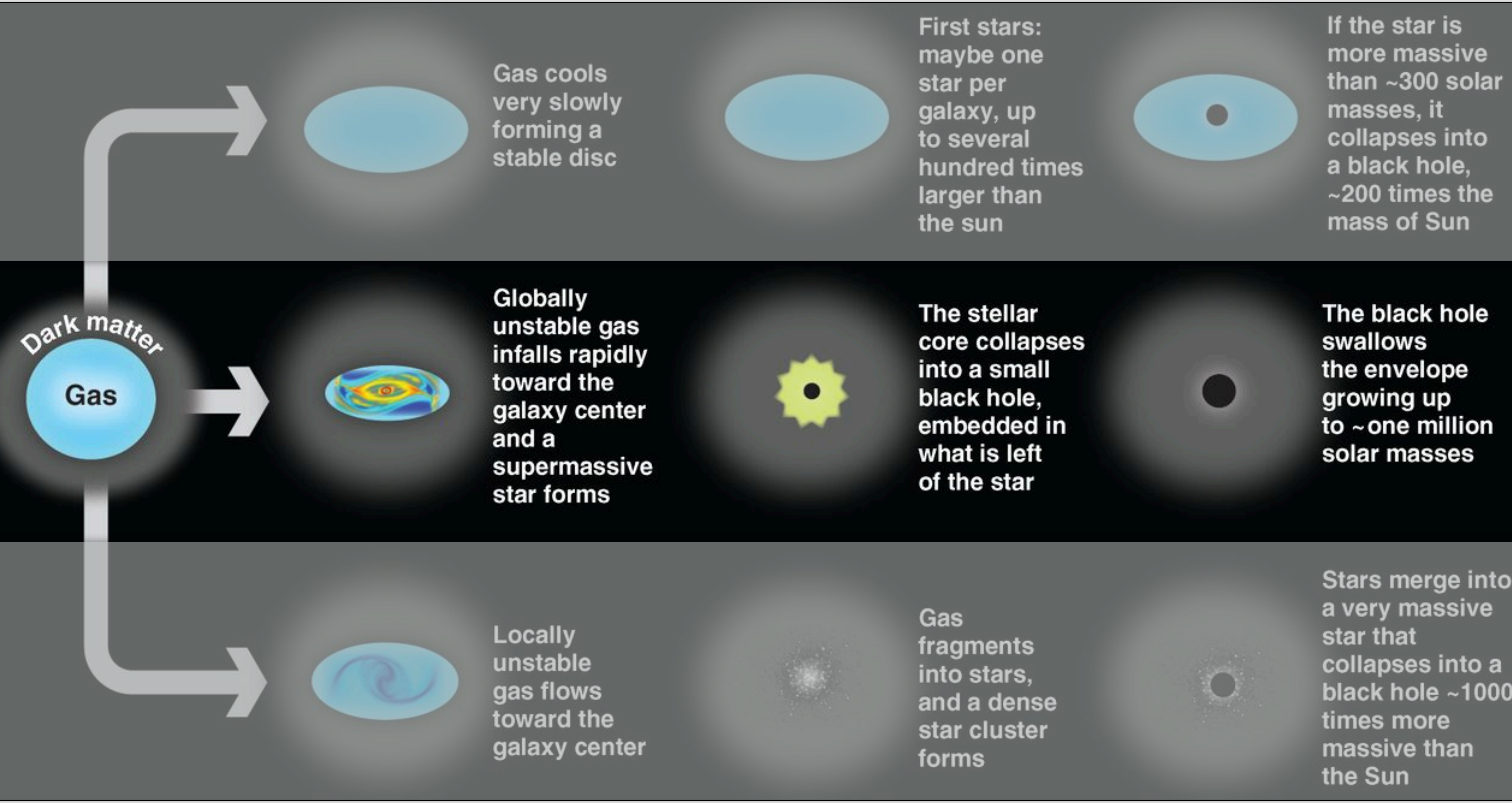
From excellent Volonteri review

One channel: Light seeds from the first generation of stars



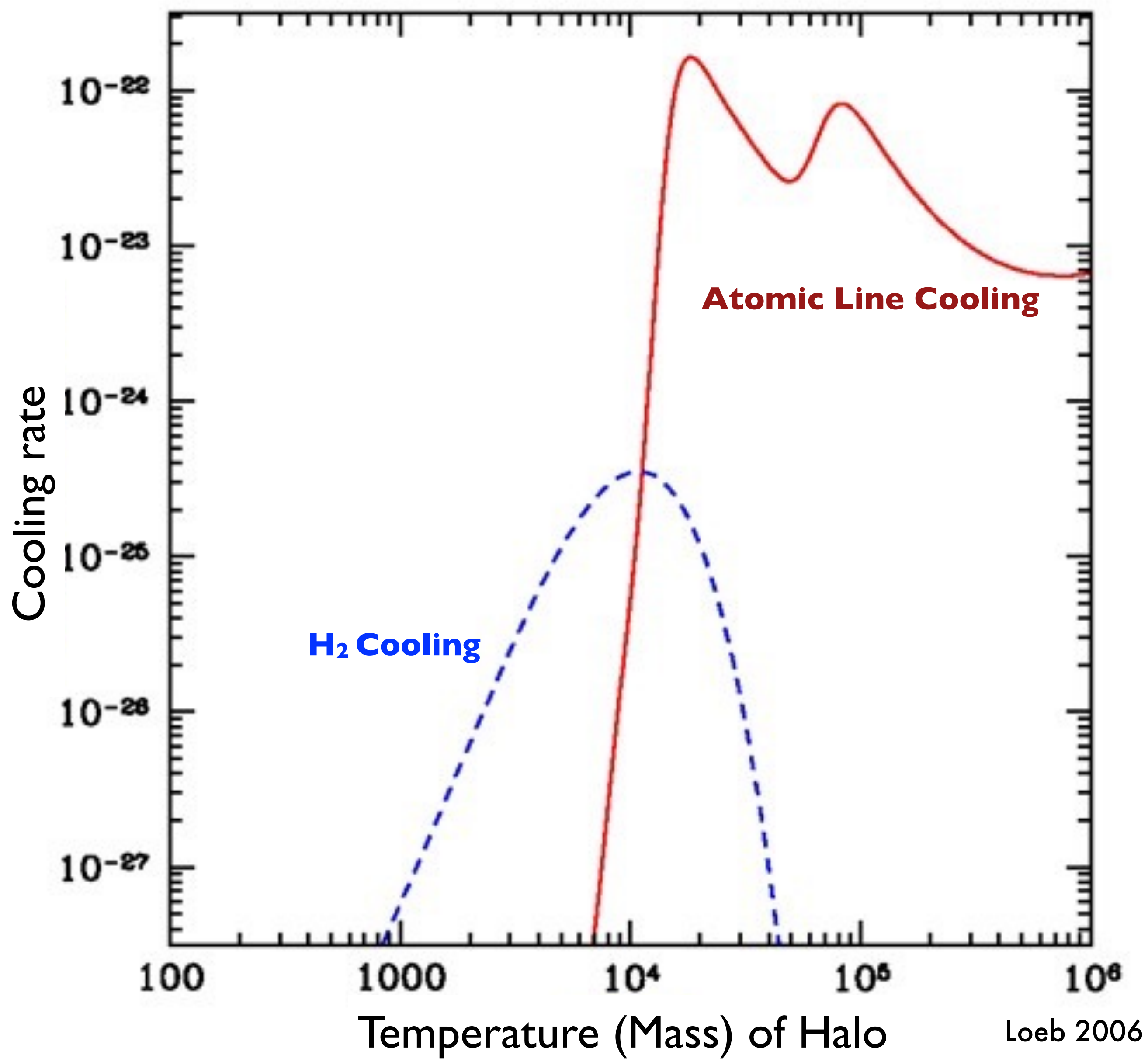
From excellent Volonteri review

One channel: Heavy seeds from directly collapsing black holes

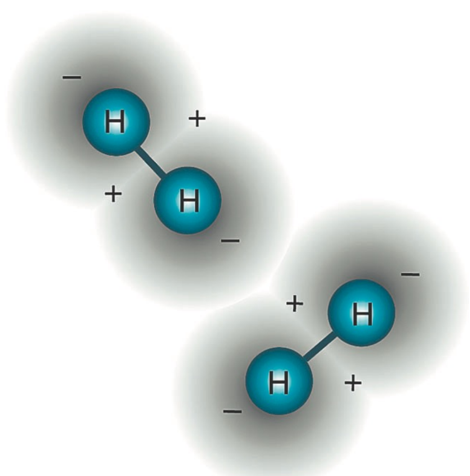


From excellent Volonteri review

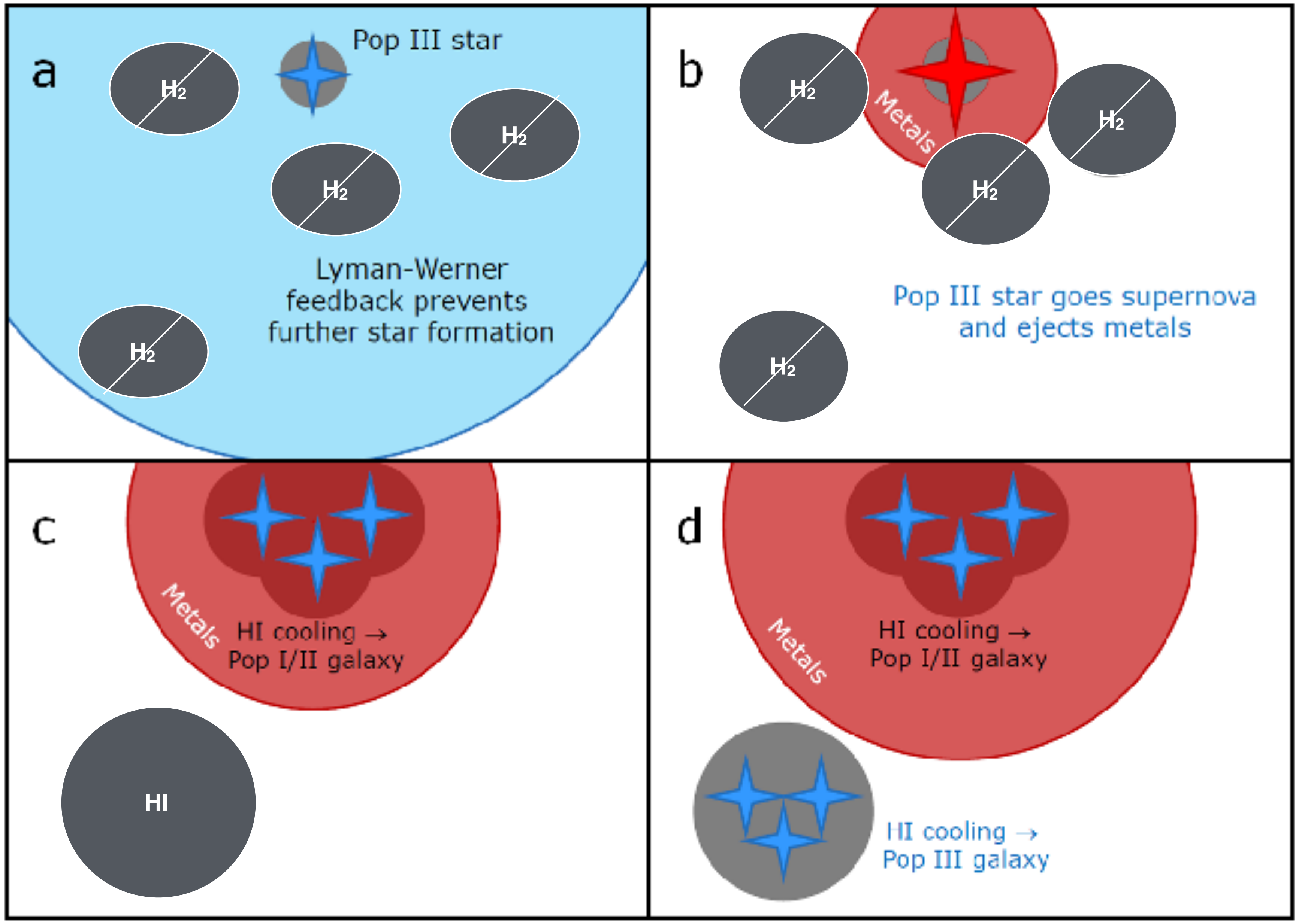
A problem:
To build a heavy seed, gas must battle fragmentation



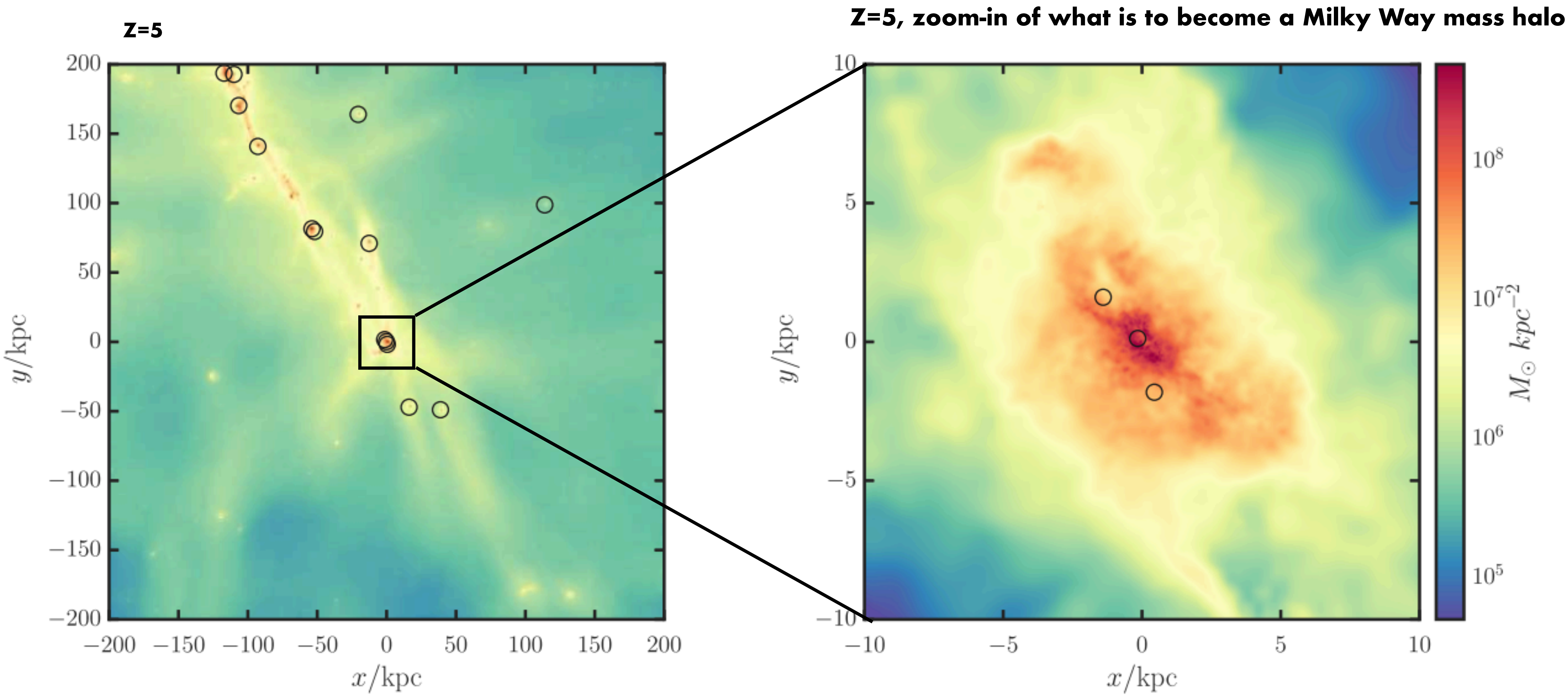
Once halo is polluted with metals, they really dominate cooling!



Low mass halos bathed in Lyman-Werner Flux can form Direct Collapse BHs



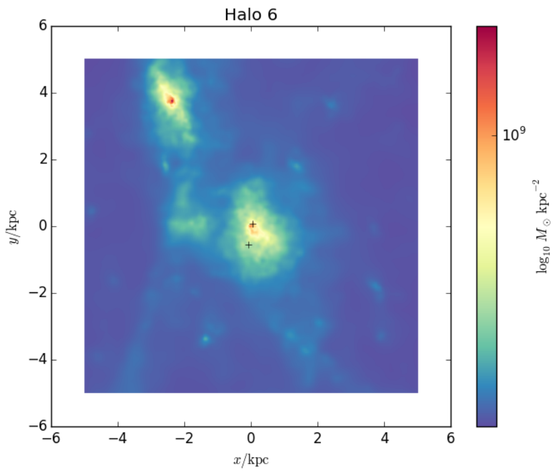
adapted from Zackrisson et al. 2012; see Visbal, Haiman, Bryan 2018

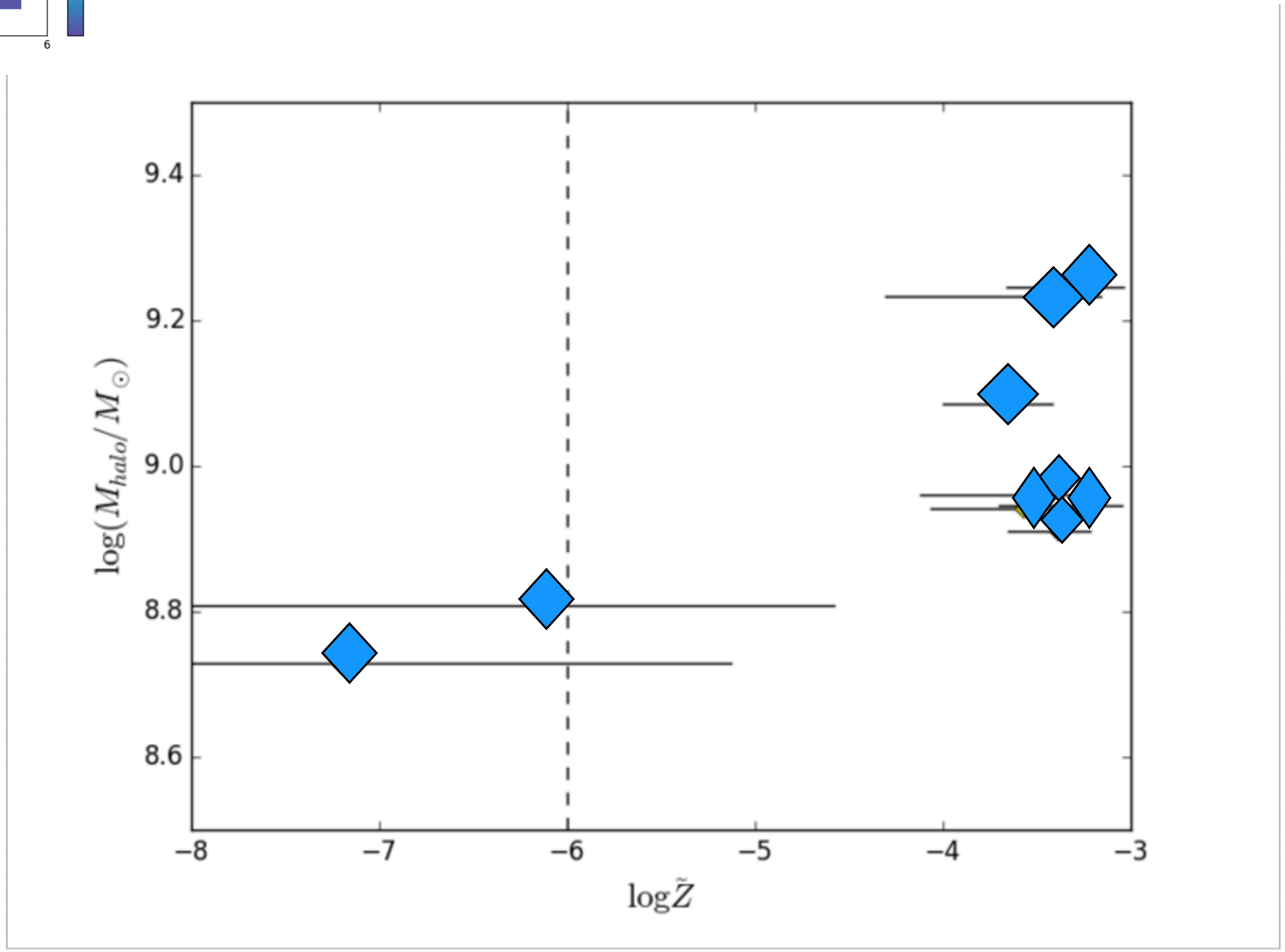


Cosmological Hydrodynamical Simulations of Direct Collapse Black Hole Formation

Dunn, Bellovary, KHB, Christensen, Quinn 2018

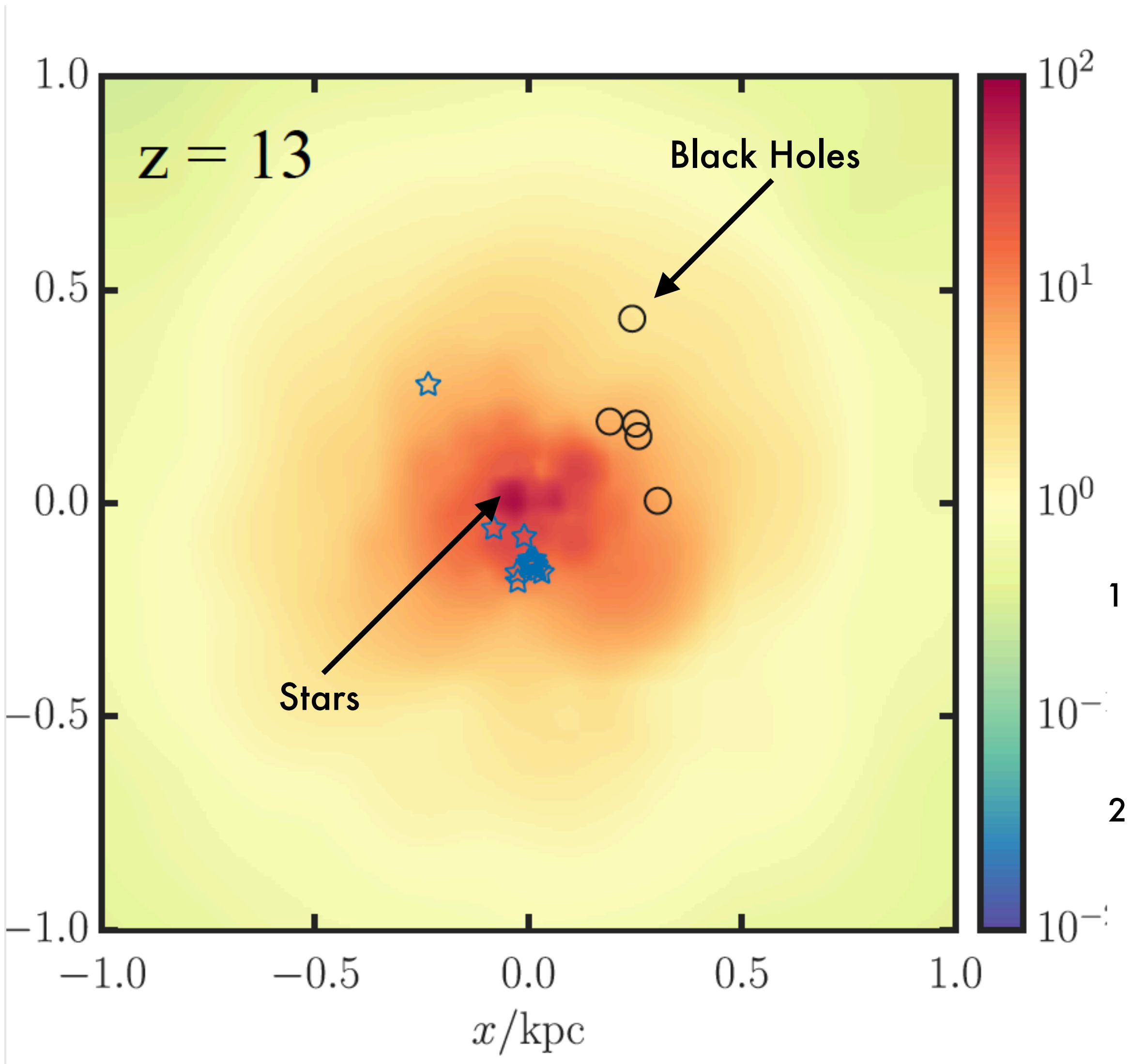
Surprises – several Direct Collapse Black Holes can form in a single halo



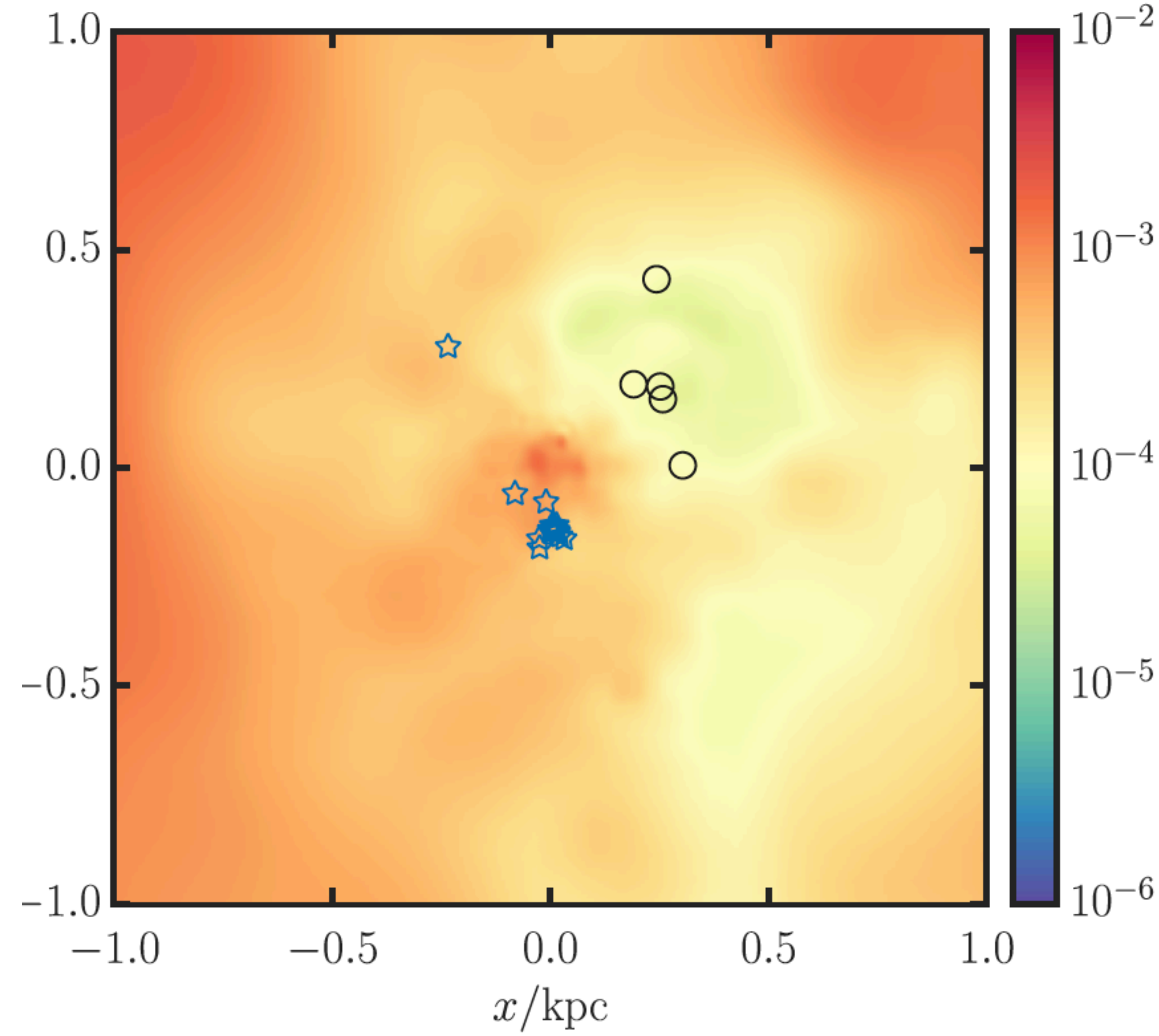


…and seeds can form in 'high' metallicity halos, too!

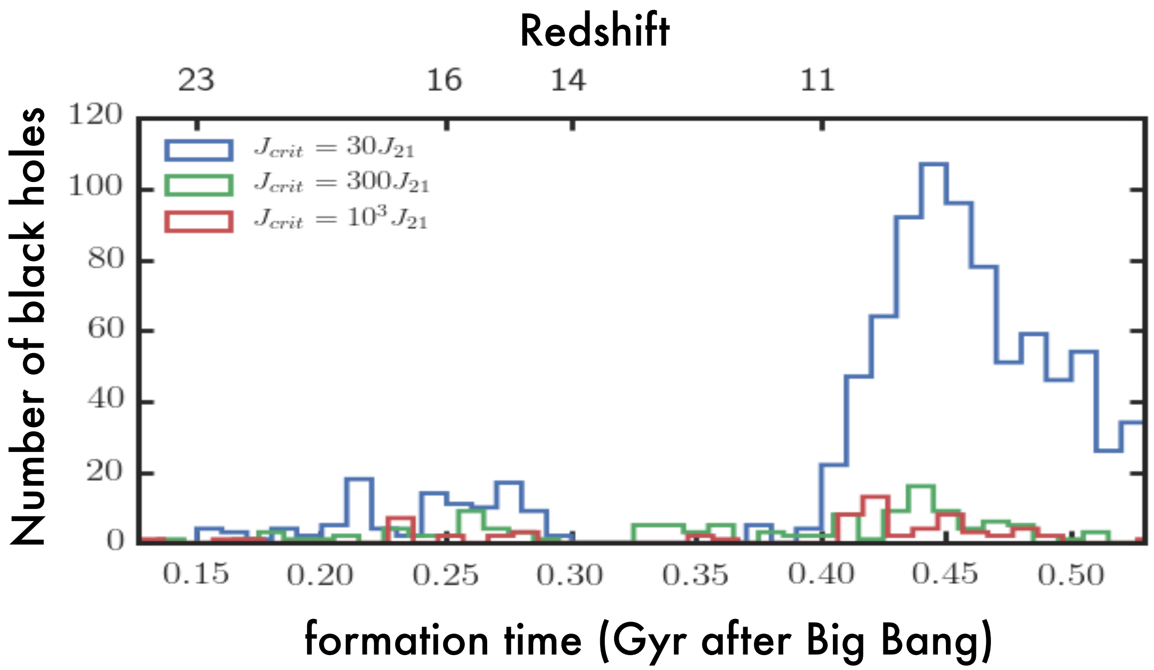
Seed BHs can form in an irradiated, but pristine pocket of gas in a halo polluted with metals.



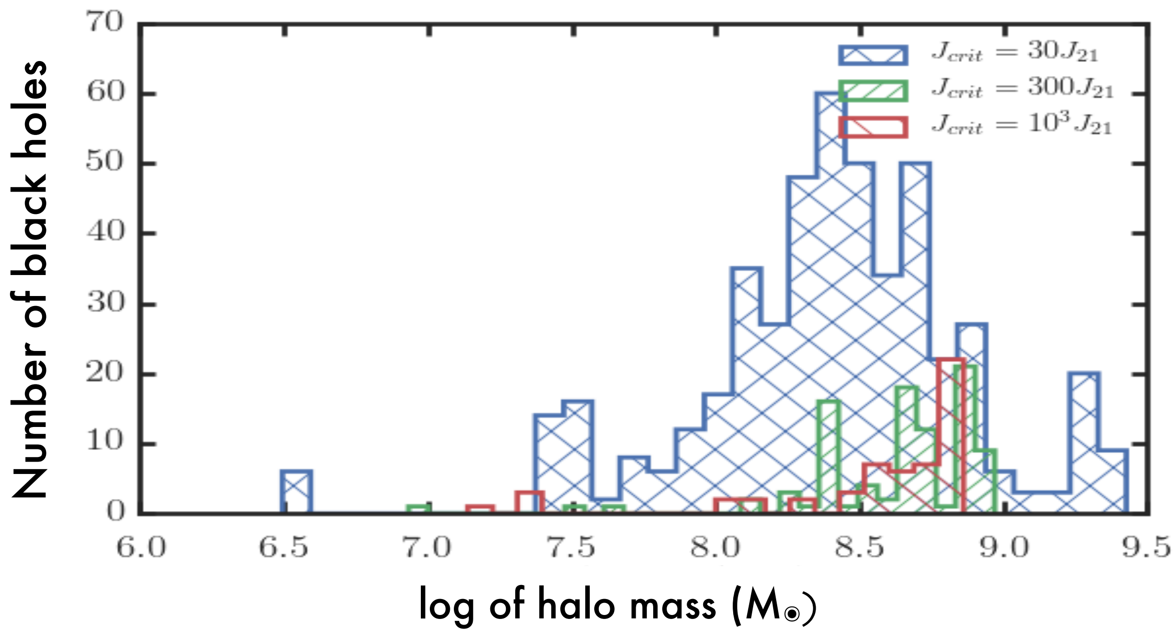
Lyman-Werner Flux



Metallicity

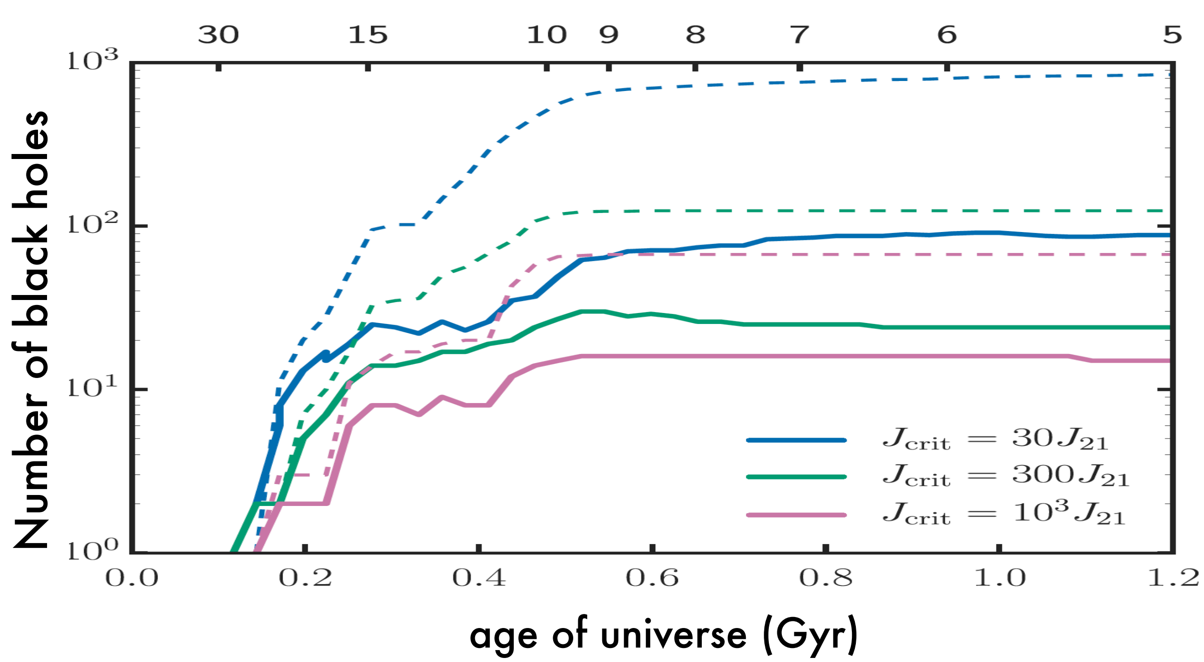


Seeds can form after reionization...



in a wider halo mass spectrum...

>50% of halos with masses ~10^8 $M_{\odot}$ host a seed BH by z=4



by the hundreds and off-center!

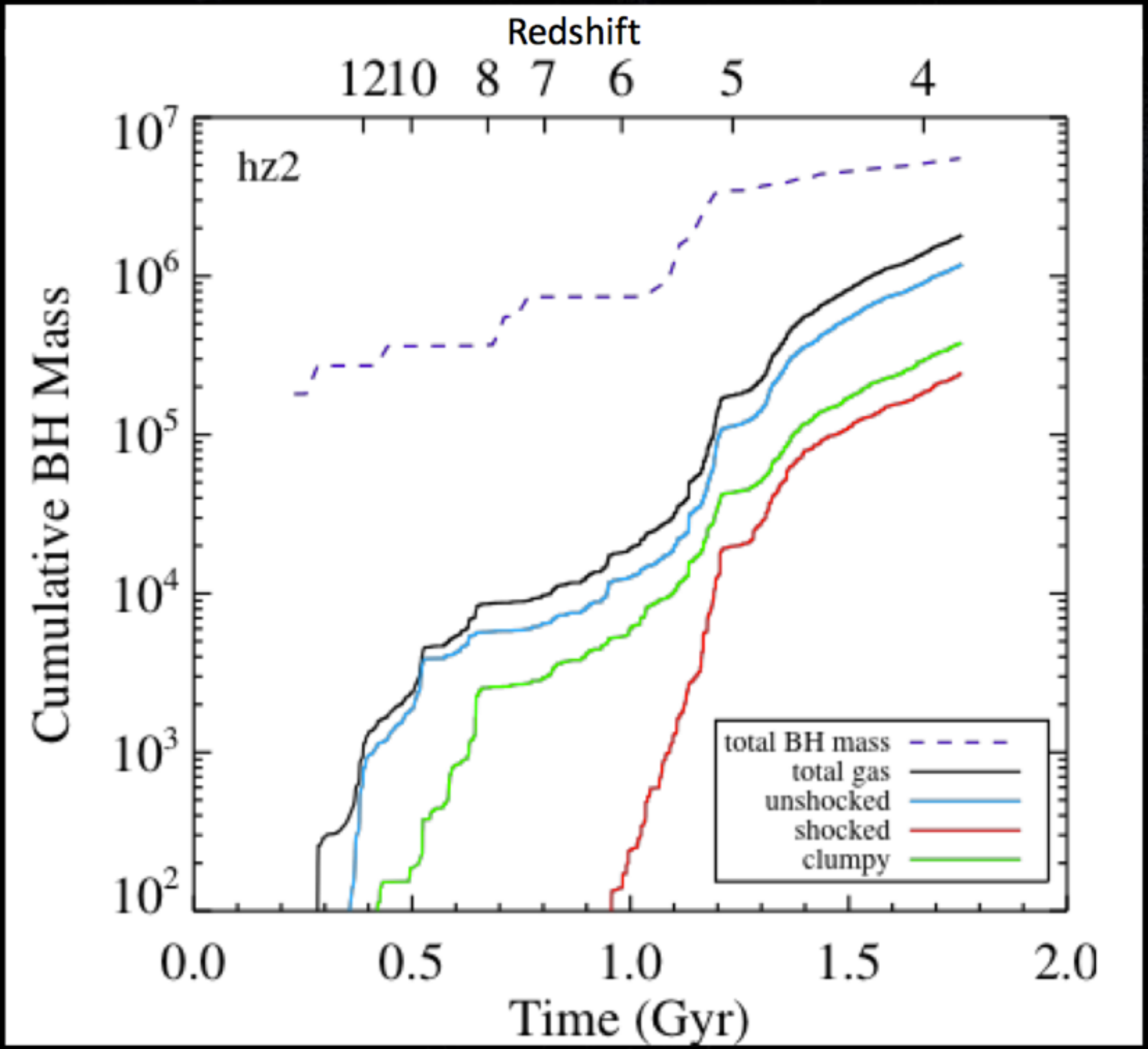
Dunn et al. 2018

How do these heavy seeds grow?

Bellovary et al. 2013

Sanchez et al. 2018

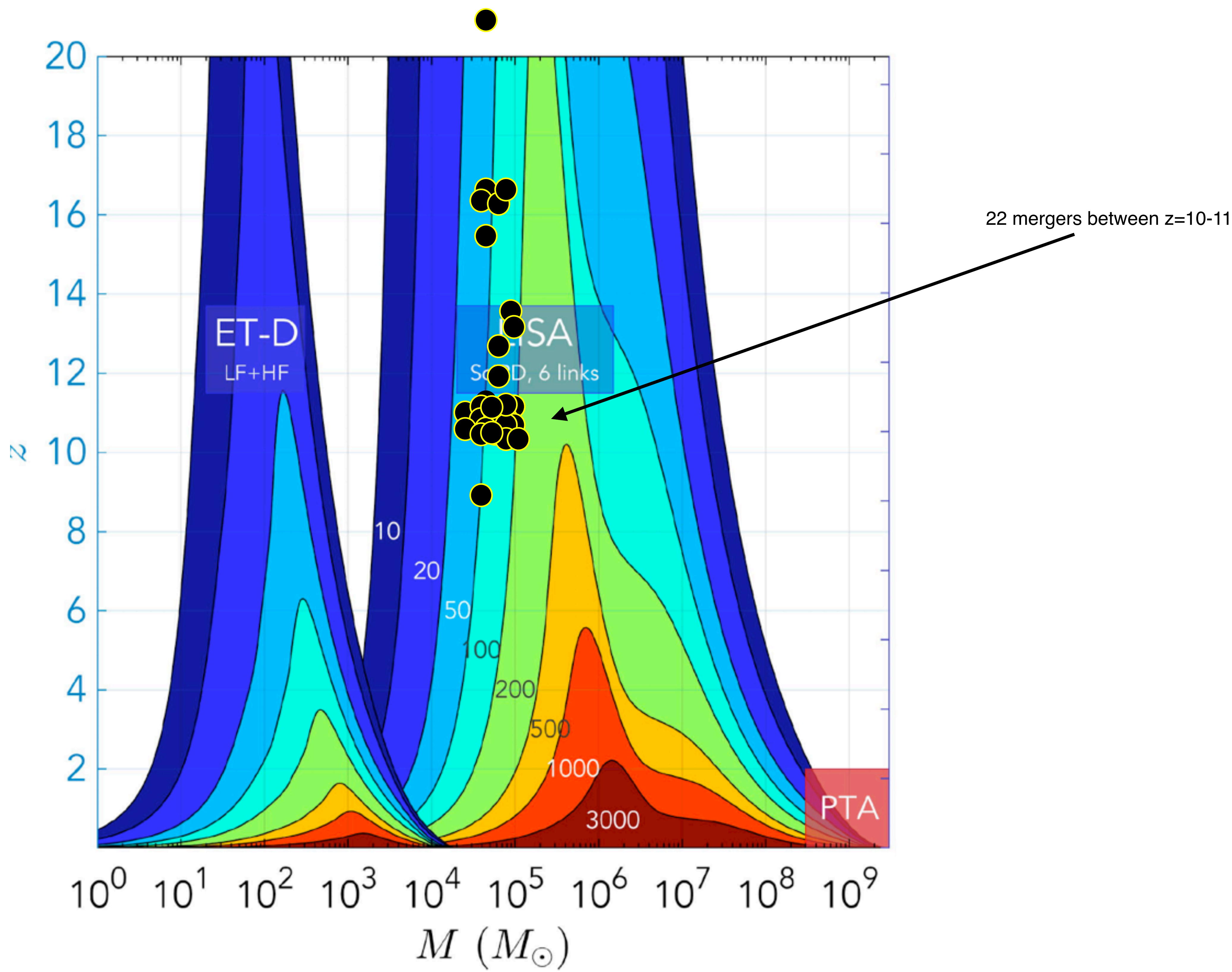
Most of the early SMBH growth is not from gas...



See Sanchez, Bellovary and KHB, 2018 and Dunn, Bellovary, and KHB 2020

What does all this mean for gravitational wave astronomy?

LISA will have an exquisite view of seed BHs. Hopefully, 3G will too – could especially probe the lighter seed channel!



note: actual 3G configuration not selected yet

Glenna Dunn

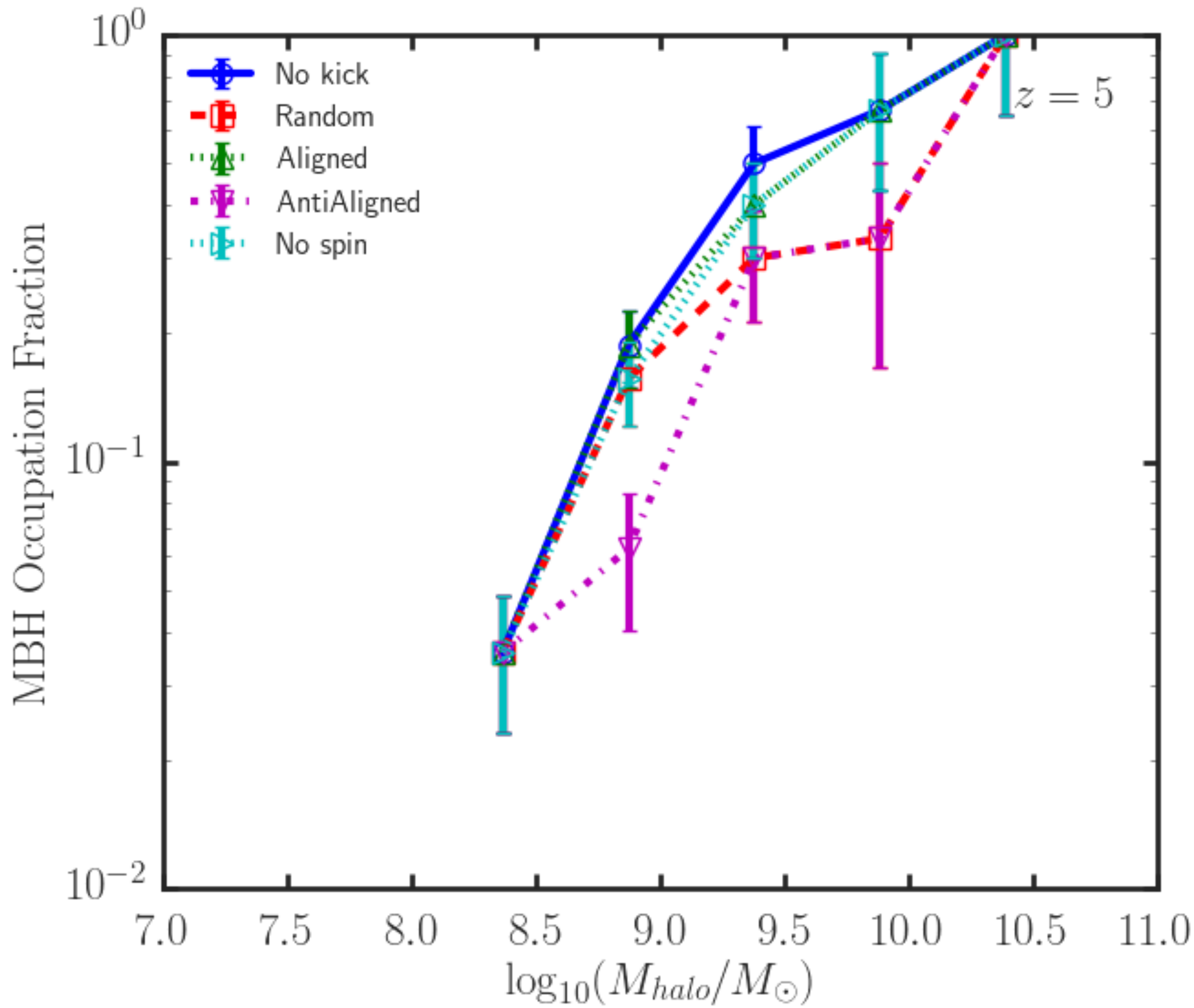
Jillian Bellovary

Thanks!

Nicole Sanchez

How much does gravitational wave recoil change this picture?

Dunn et al. 2020



Not much!

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger rate

Step 4: Sow SMBH seeds

Step 5: Model SMBH growth

Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger

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Rule-breaker: Unassuming galaxy with 17 billion solar mass black hole!

Rule-breaker: Unassuming galaxy with ~~17~~ billion solar mass black hole!

Stay tuned! MASSIVE Sur

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger rate

Step 4: Sow SMBH seeds (see Rossi and Latif talks!)

Step 5: Model SMBH growth

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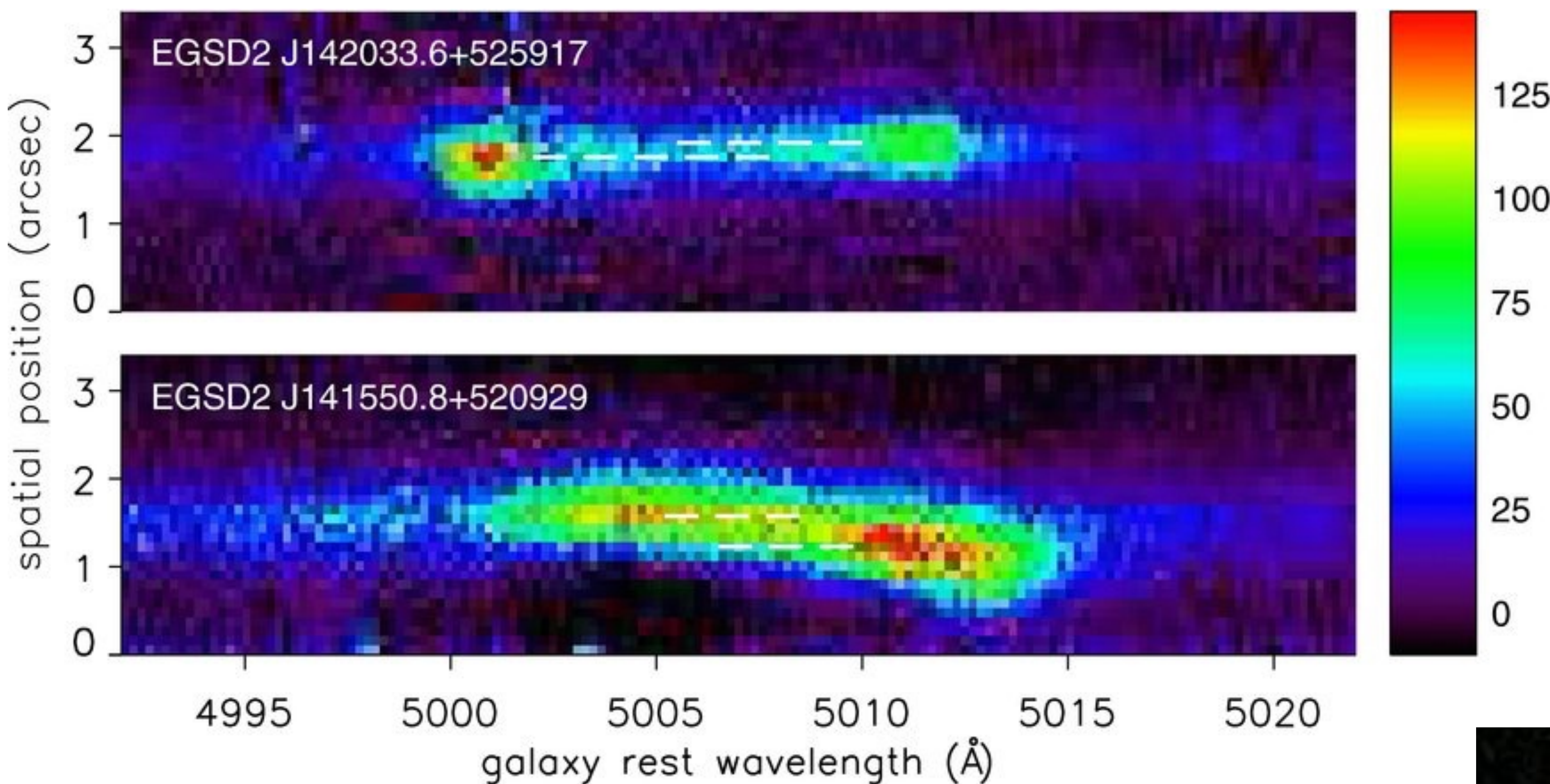
Step 7: Find the strain, SNR for each merger

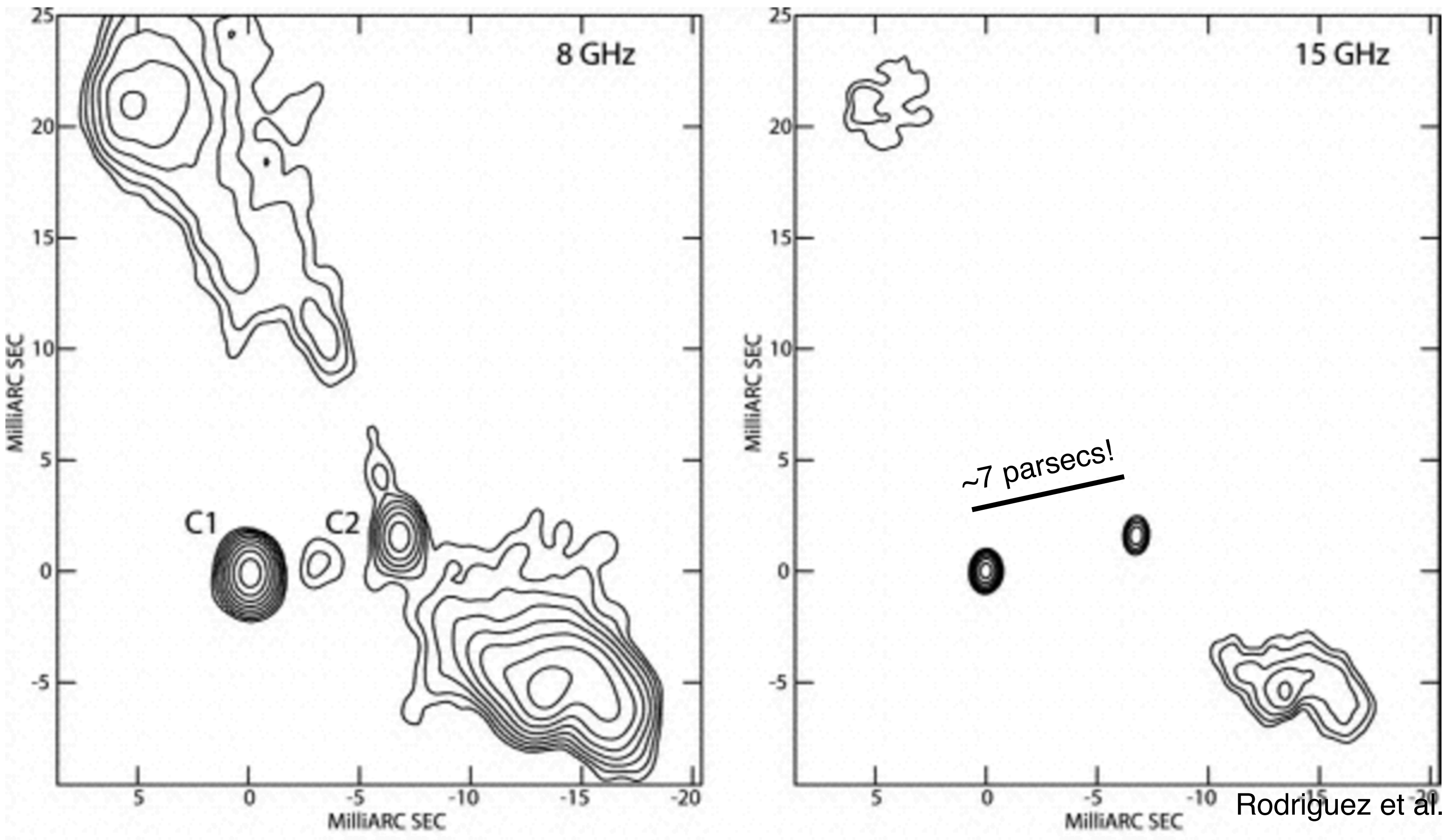
While there are certainly dual AGN,



Comerford et al. 2009 — 1kpc separation [OIII]5007

Liu et al. 2013 — image from galaxy zoo

...there are (arguably) no known binary black holes



Rodriguez et al. 2006

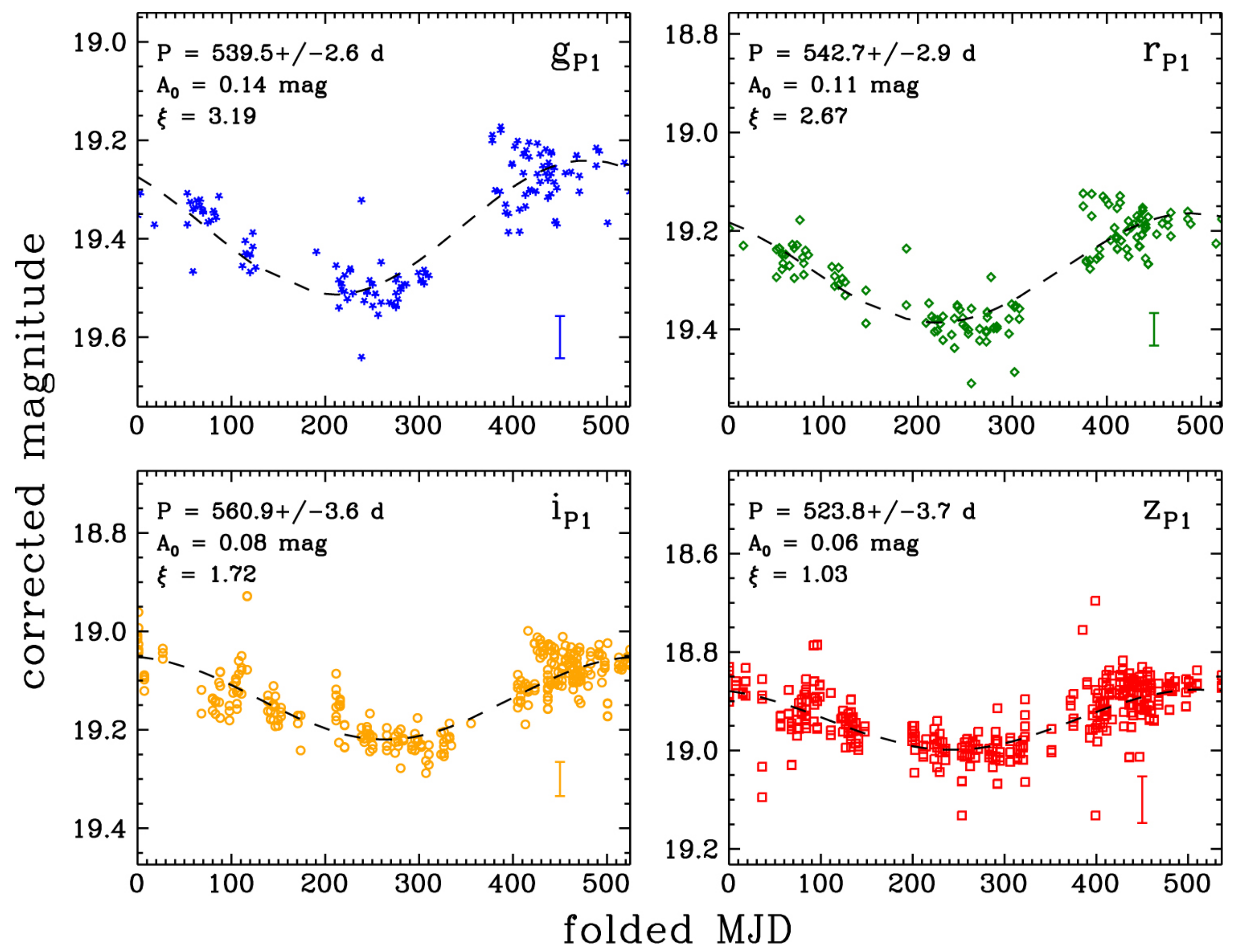
VLBI search OF ~3100 AGN, only 1 found to be consistent with a BBH

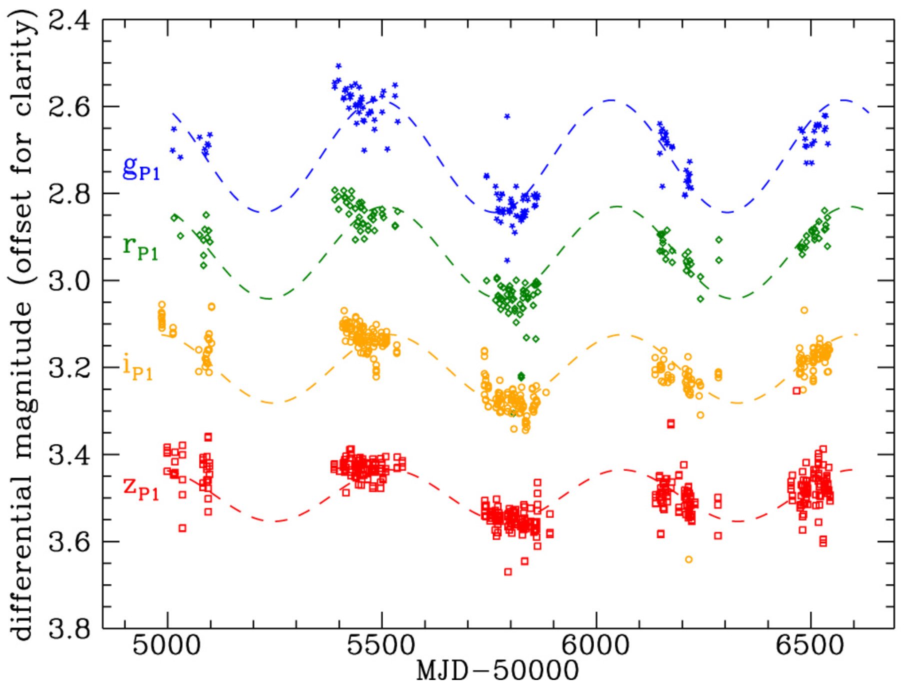
Burke-Spolaor 2011

Stay tuned! Time-domain astronomy will help here...

Pan-Starrs PSO J334.2028+01.4075

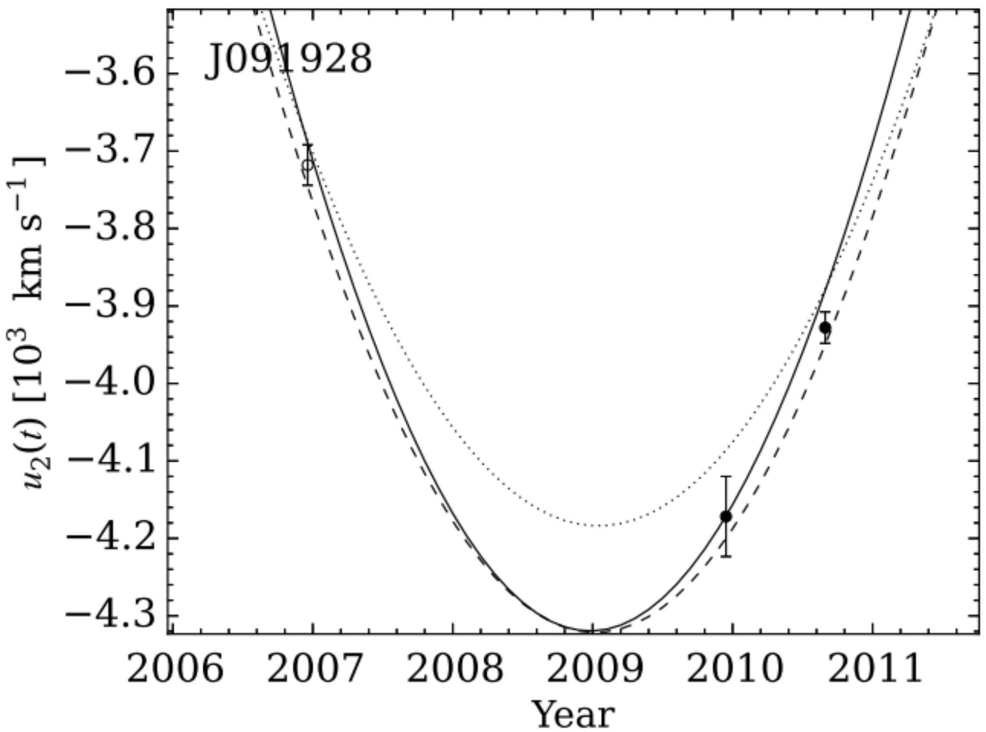
Periodicity caused by 542+/- 15 day orbit of a 10^{10} solar mass binary at 0.05<q<0.25 @ z=2.06 — separation of ~10 R_s!!

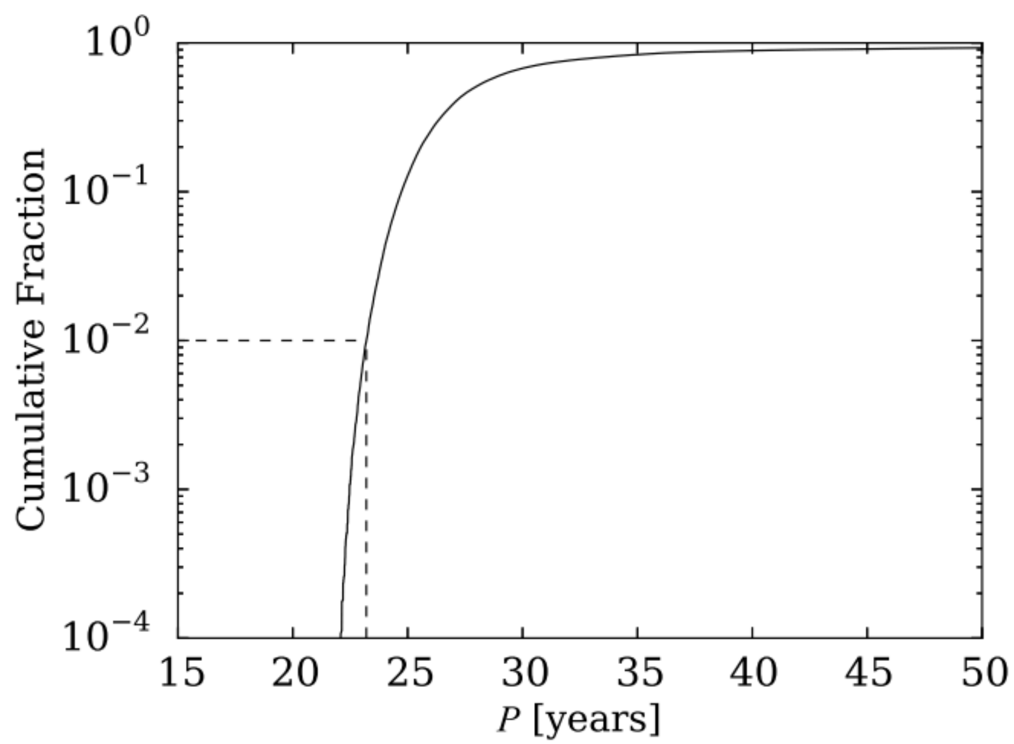




Liu et al. 2015

Looking for the radial motion of the spectral lines in quasars, there are ~3 good BBH candidates





Stay tuned: By 2028, LSST should find ~10^4 BBH candidates

Runnoe et al. 2017

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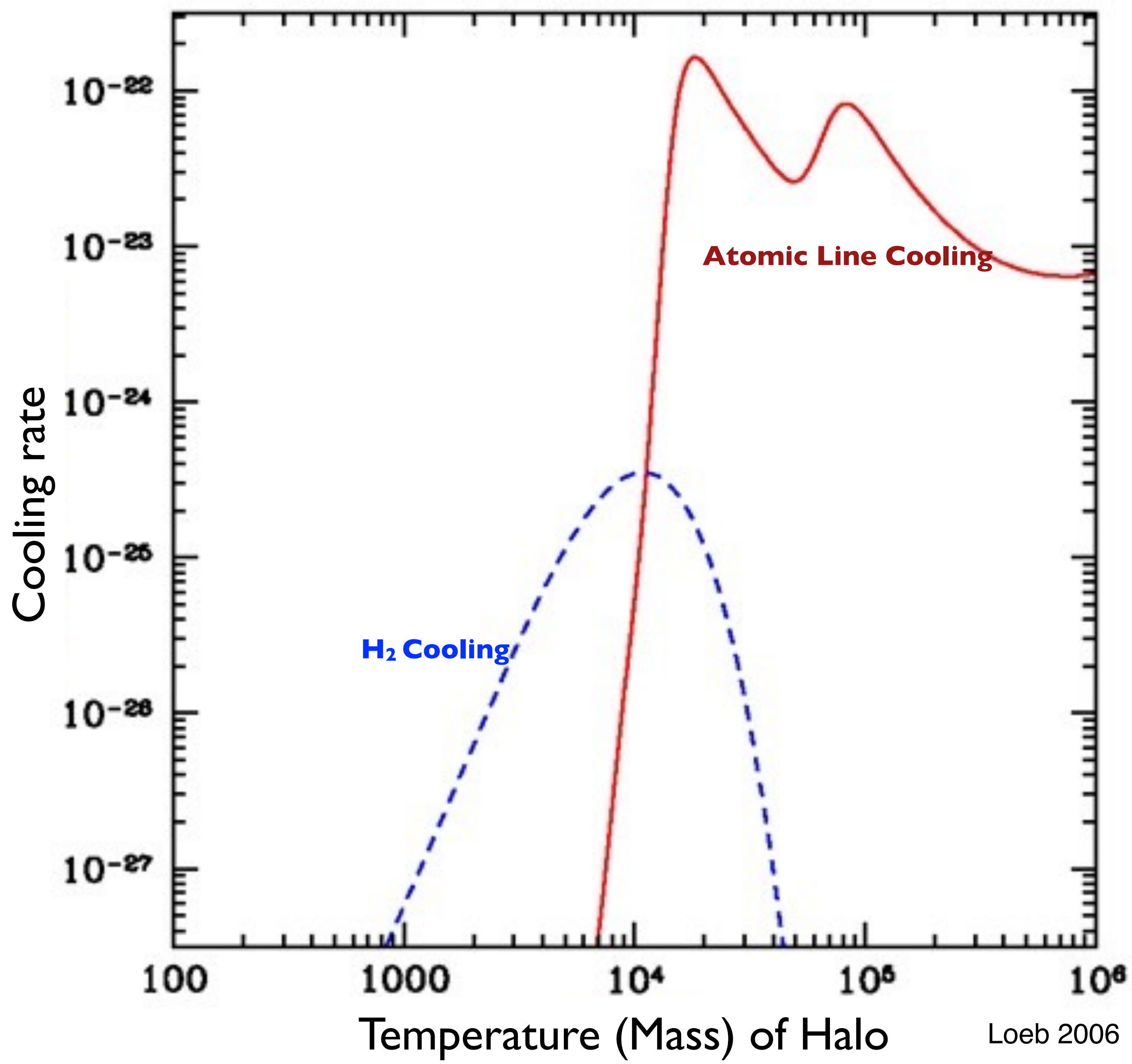
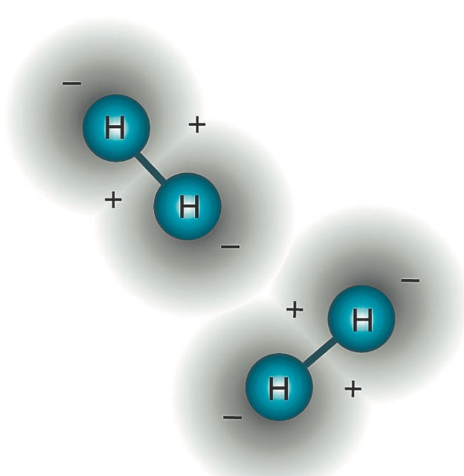
Step 7: Find the strain, SNR for each merger

To build a massive black hole seed, you must battle fragmentation!

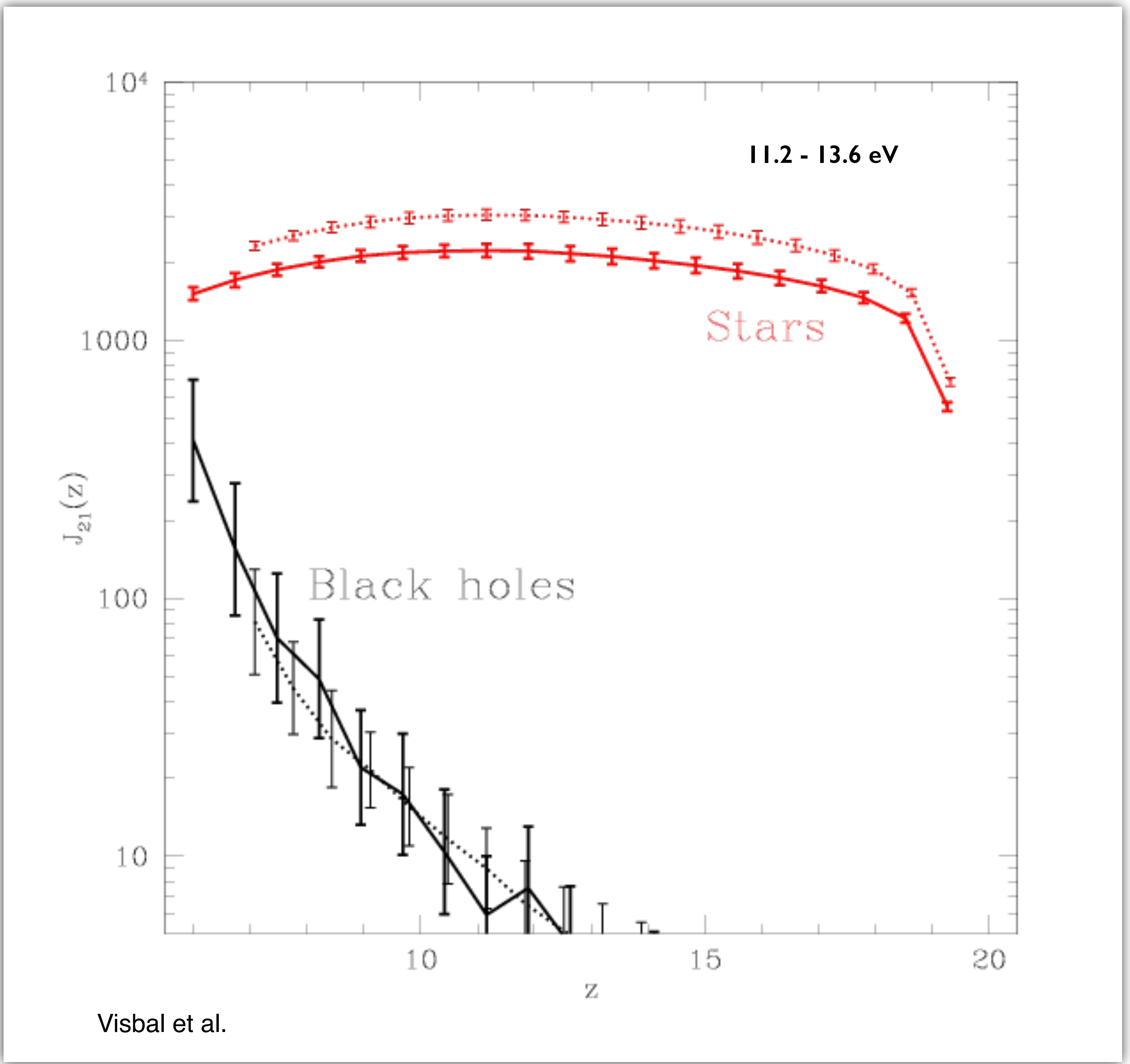


Loeb 2006

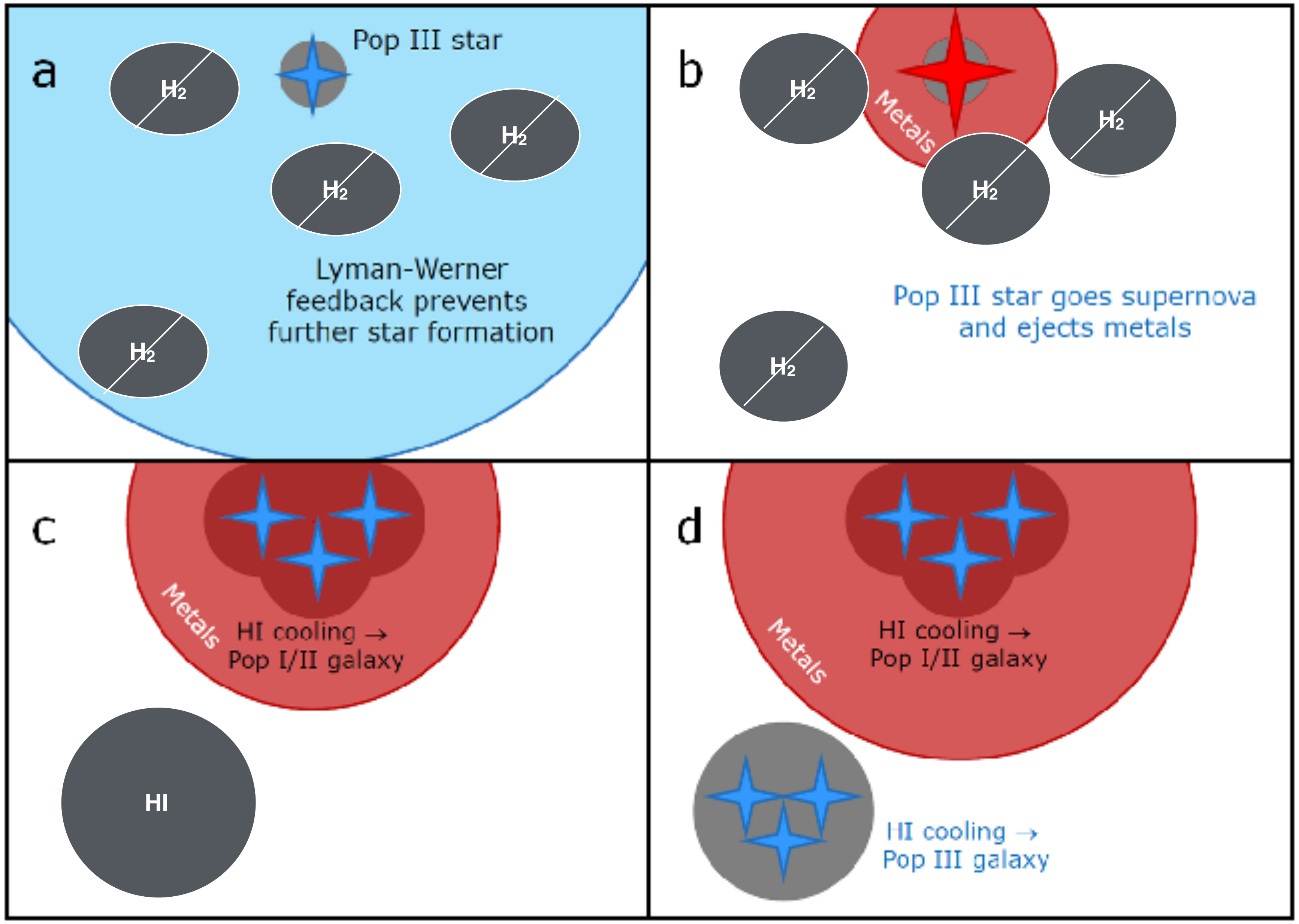
Once halo is polluted with metals, they *really* dominate cooling!



Lyman-Werner radiation from the first stars and black holes can dissociate H_2

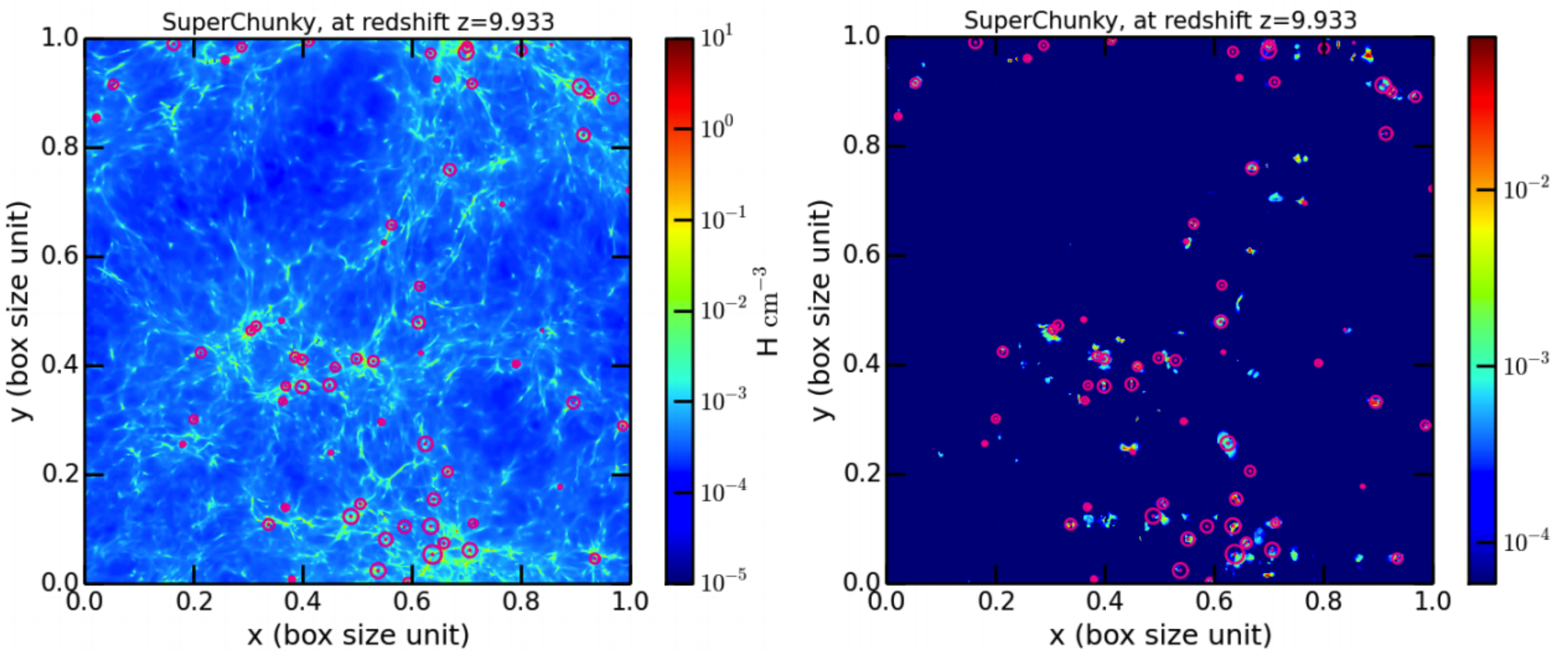


Low mass halos bathed in Lyman-Werner Flux can form Direct Collapse BHs



adapted from Zackrisson et al. 2012

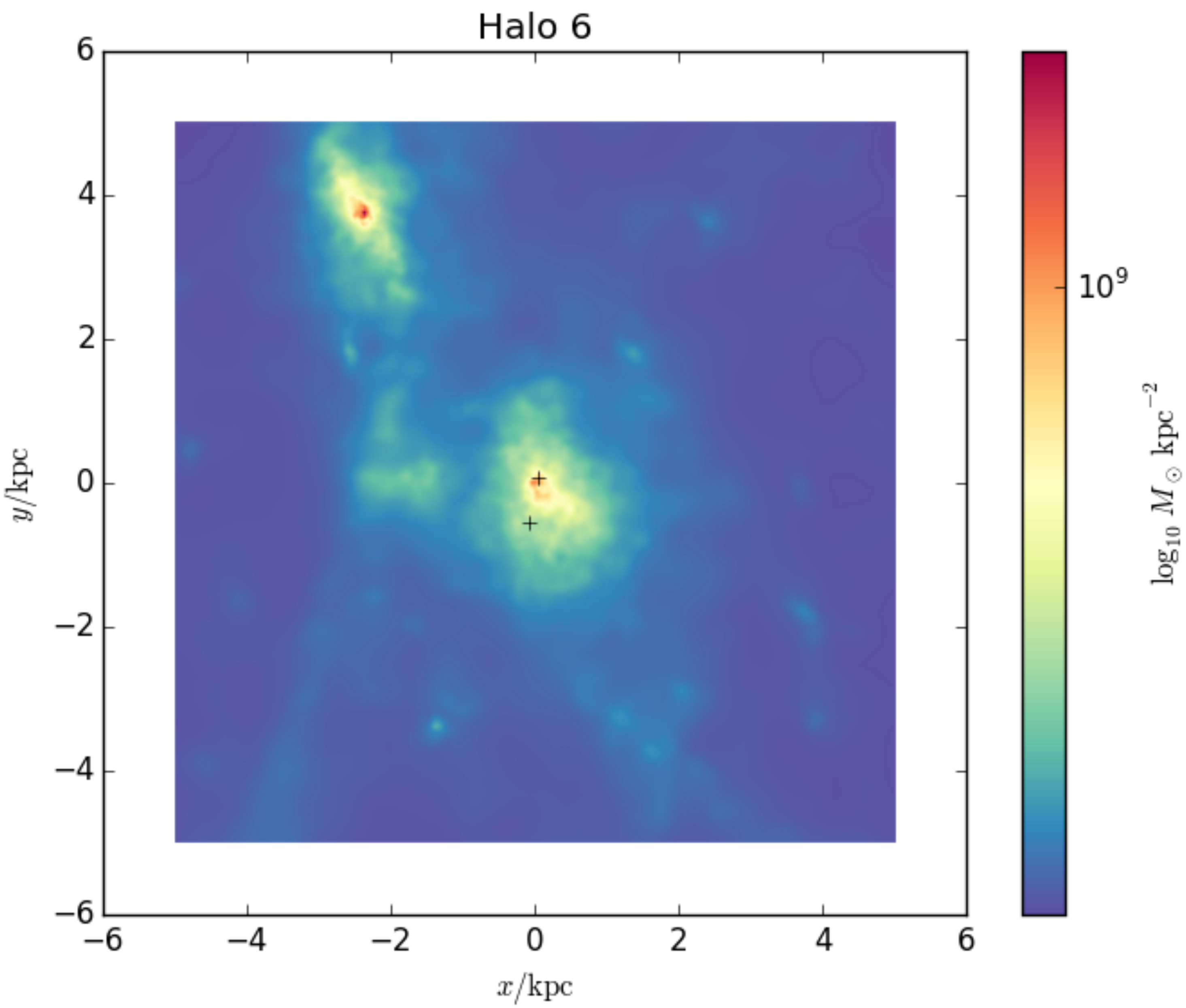
Rare SMBH birthplaces in a uniform UV background



Habouzit et al 2016

See also Agarwal et al. 2013; Akutalp et al. 2014

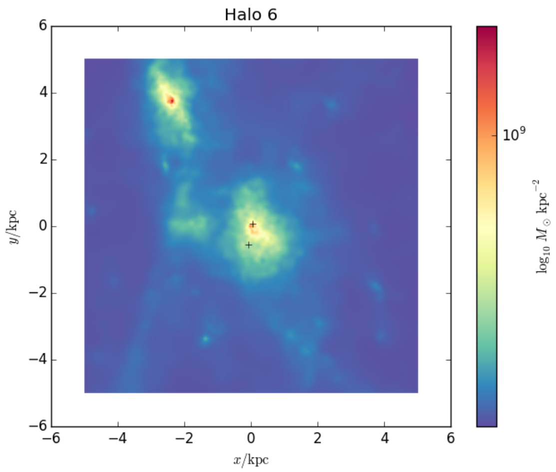
In progress:

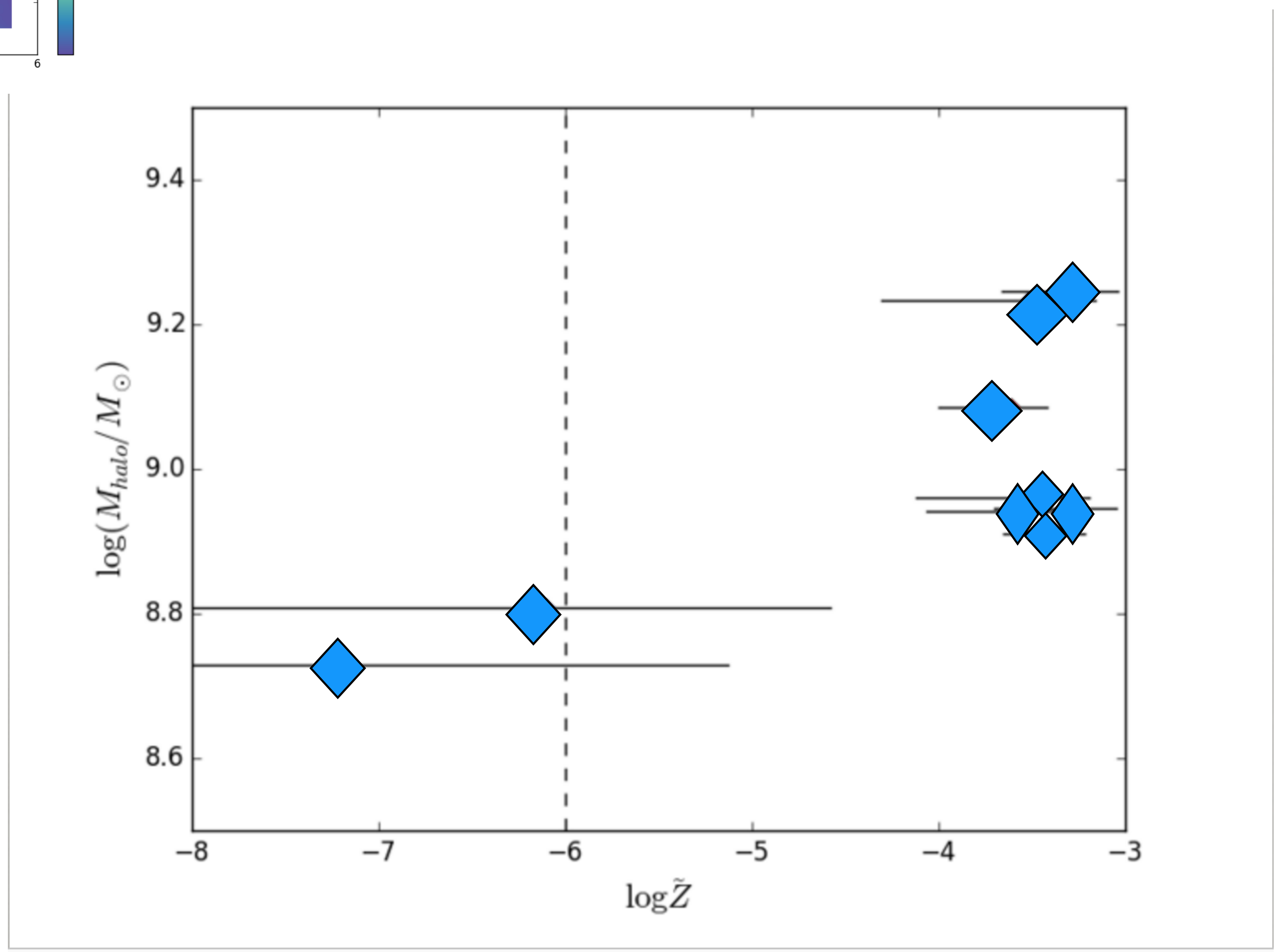


Cosmological Hydrodynamical Simulations of Direct Collapse Black Hole Formation

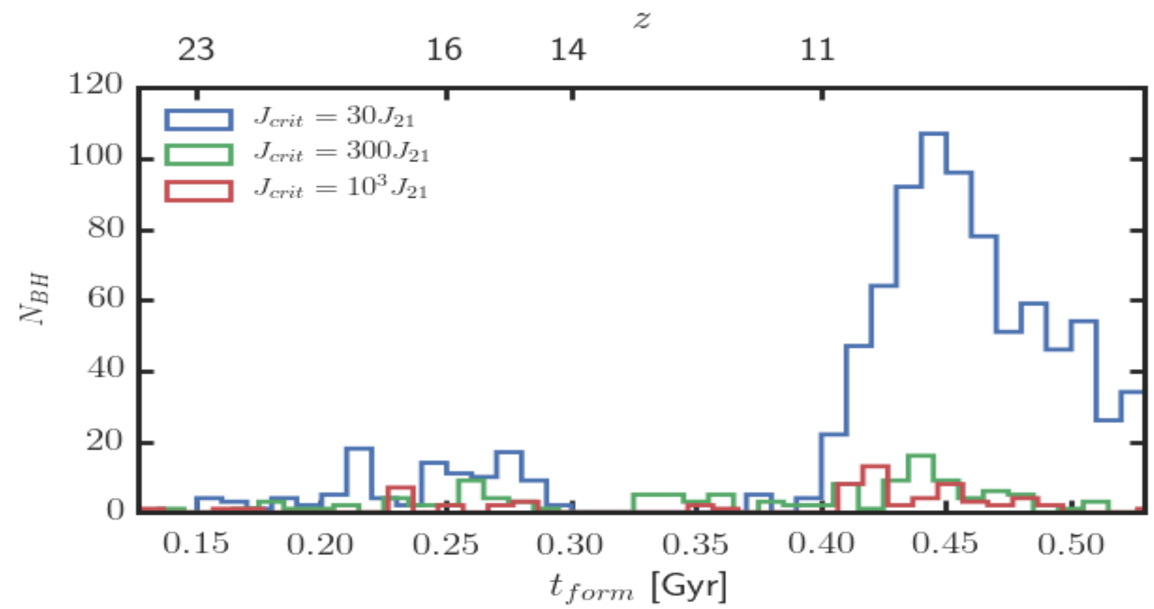
Dunn, KHB, Bellovary, Christensen

Surprises so far — several Direct Collapse Black Holes can form in a single halo

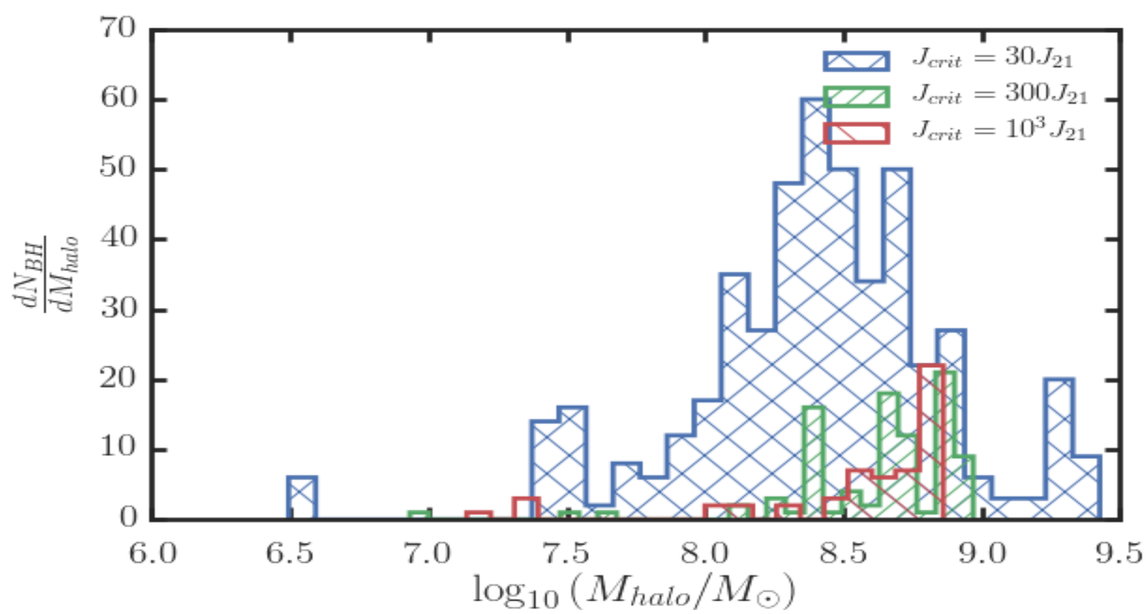




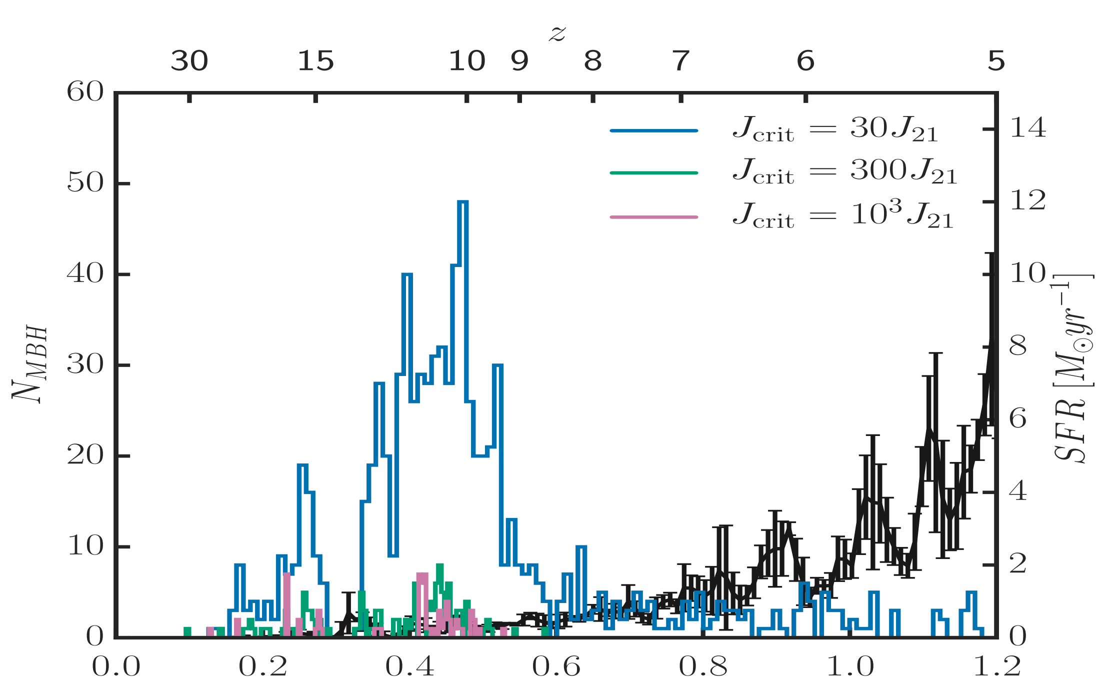
...and seeds can form in 'high' metallicity halos, too!



Seed black holes may form after reionization...



in a wider halo mass spectrum...



and may surpress early star formation...

look for Dunn et al. 2018 on an arXiv near you.

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

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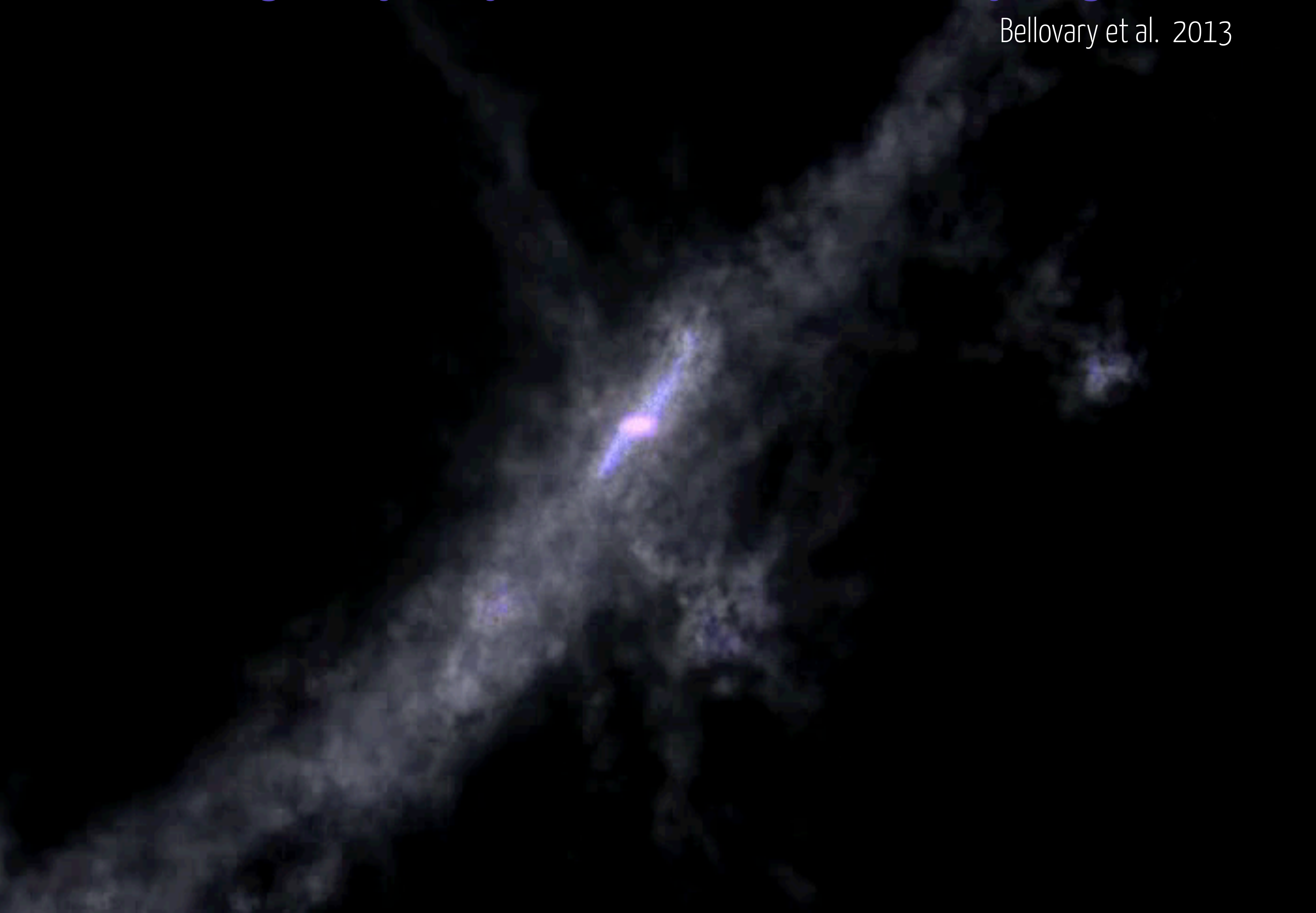
Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger

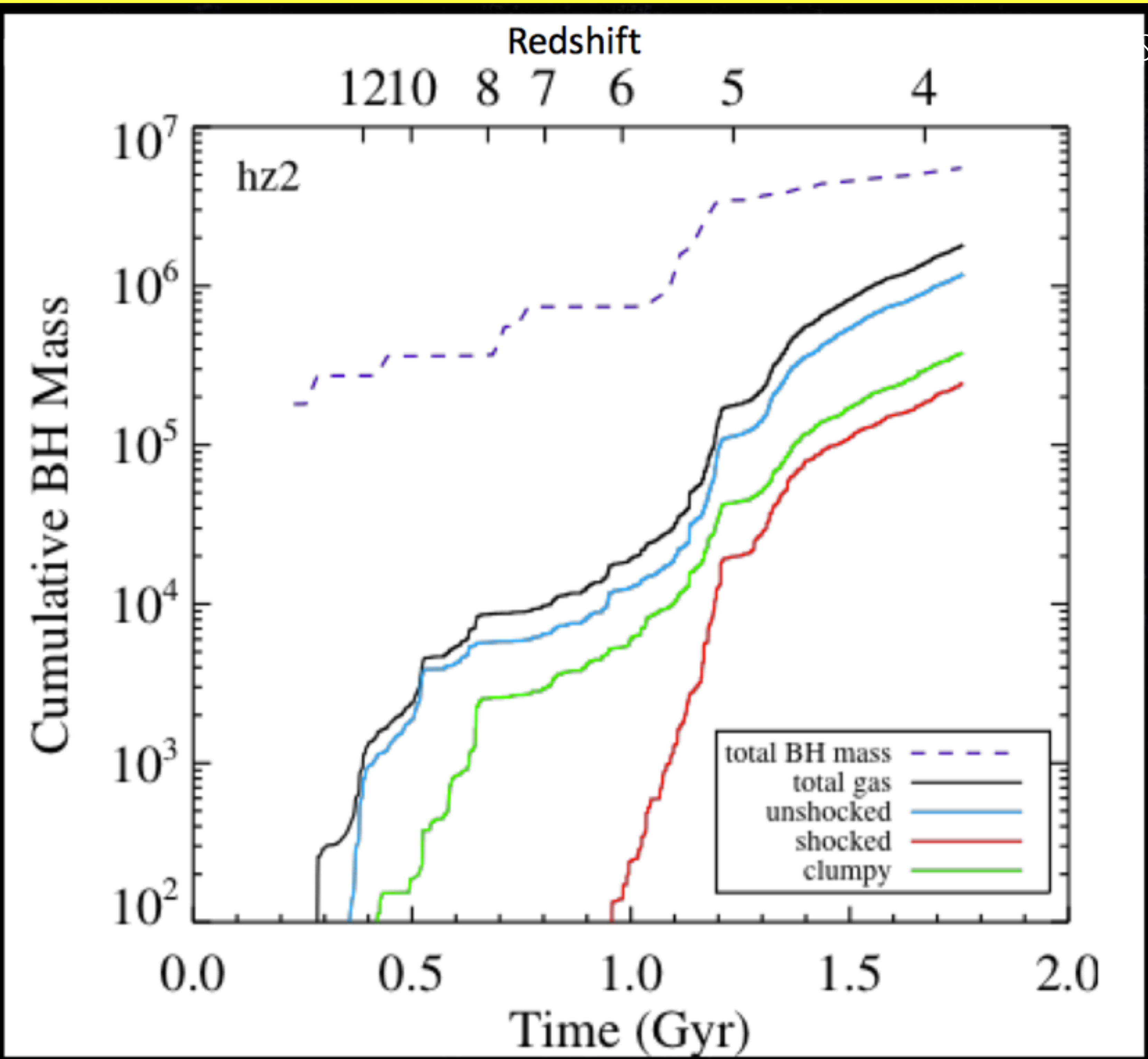
Cosmological Hydrodynamical simulation of early BH growth

Bellovary et al. 2013



Most of the early SMBH growth is not from gas…

…and the gas that **does** fuel the SMBH is not from galaxy mergers



Sanchez, Bellovary and KHB 2016

We simulated the growth of MW-like SMBHs using cosmological N-body simulations

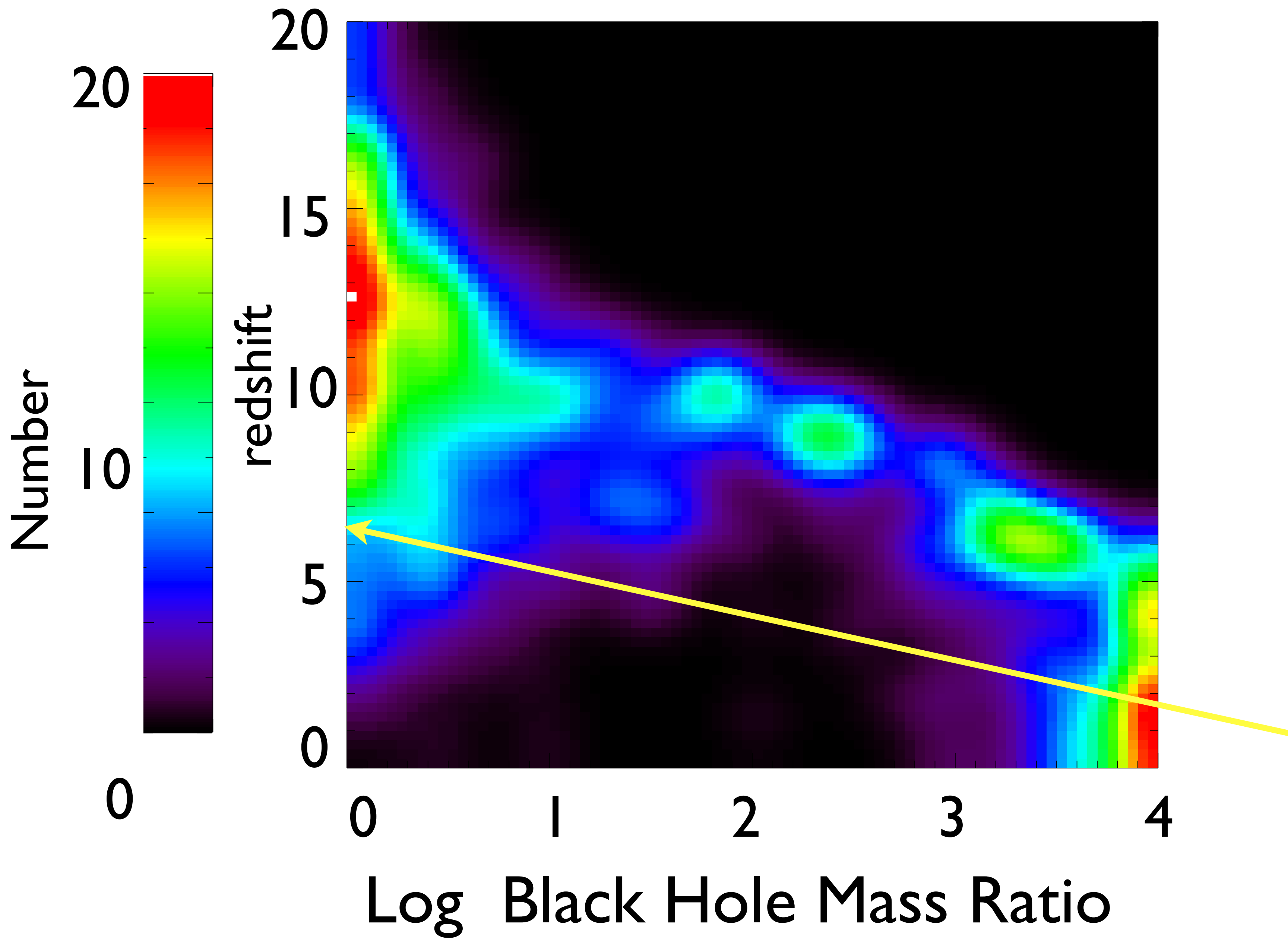
Massive central

Slowly sinking

Ejected

Light SMBHs (like our own) don't assemble from equal mass (or even nearly equal mass) mergers

KHB et al. 2010

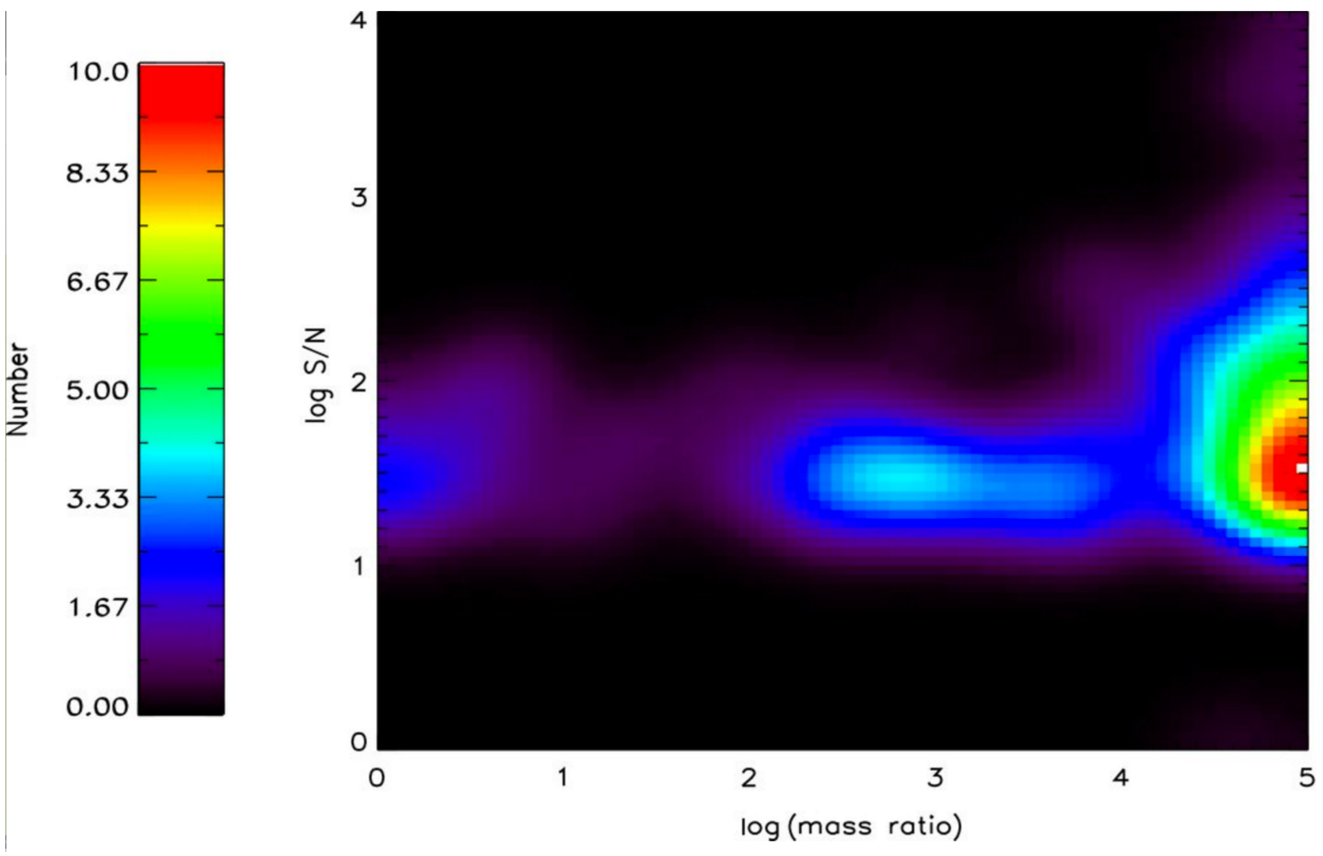


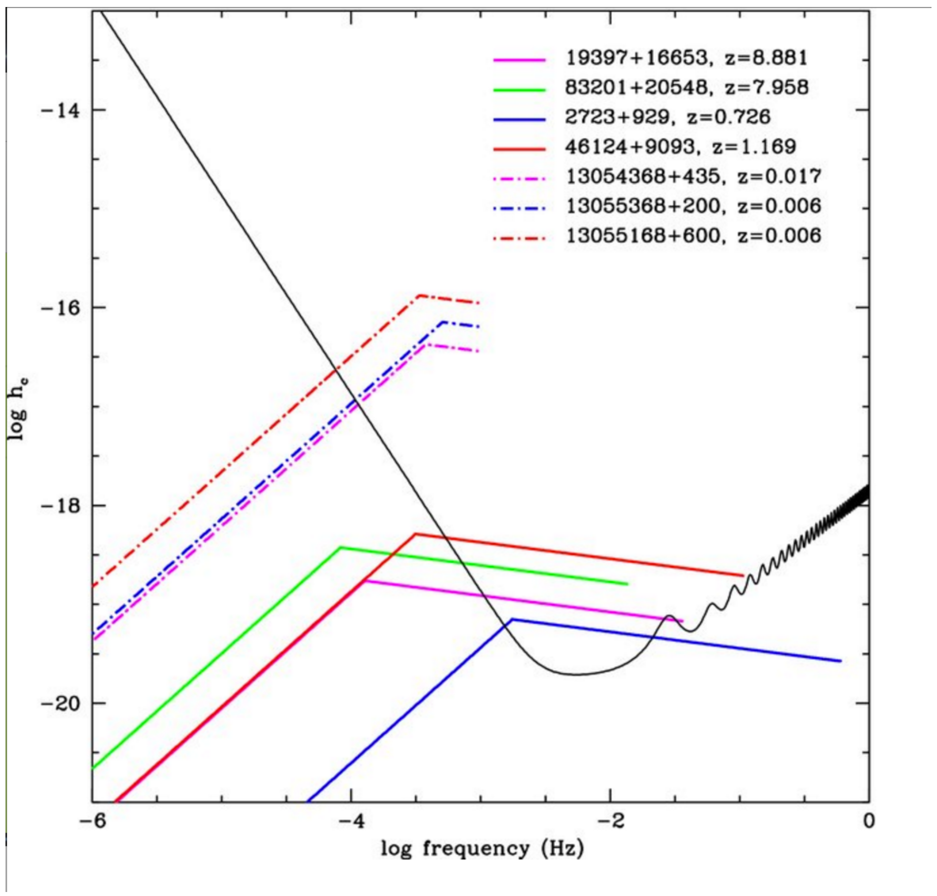
after the dark ages, there are few major mergers

Massive central

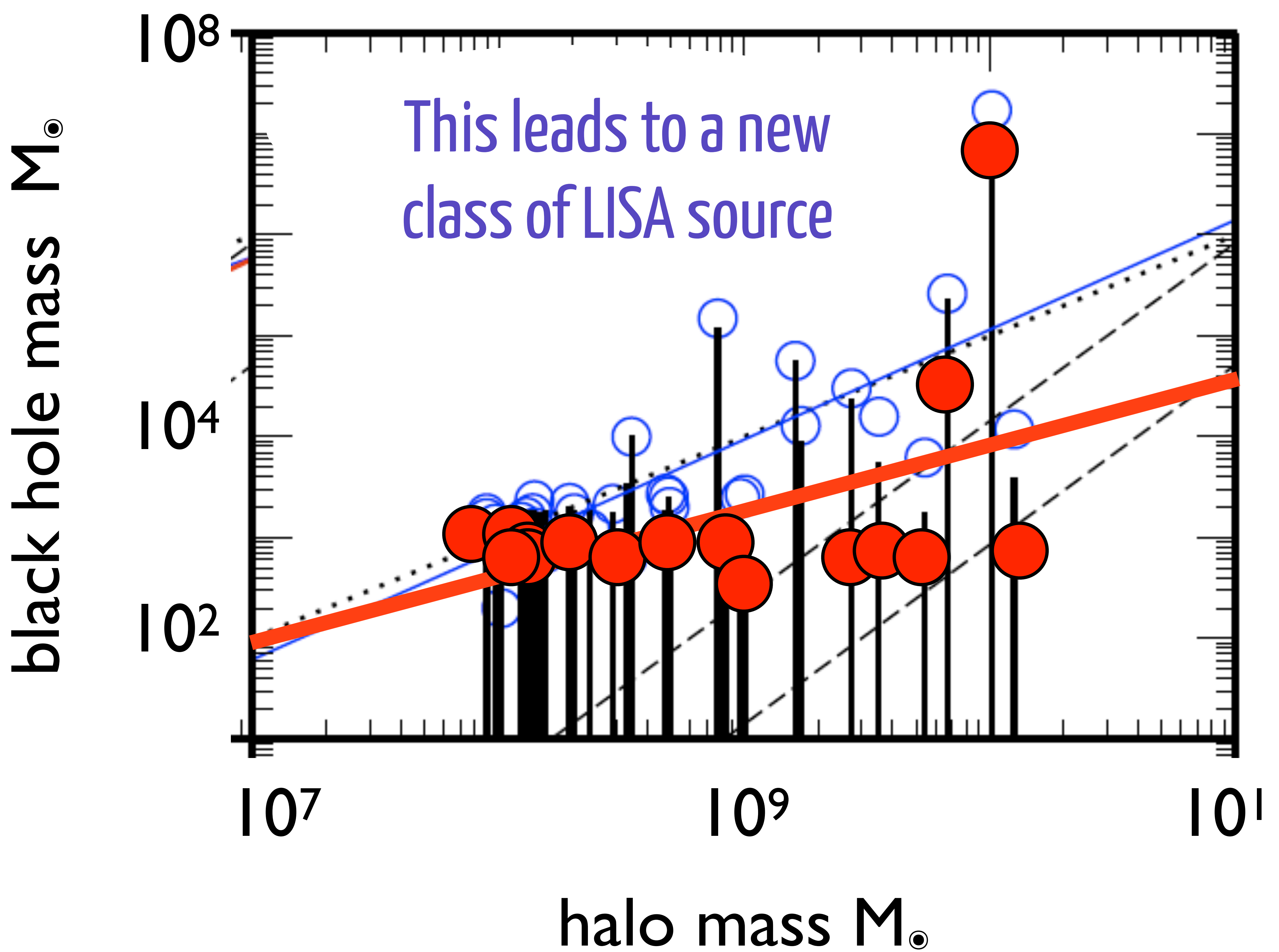
Assembling a MW SMBH results in dozens of loud signals, mostly with really unequal masses

scaling to the universe, ~ 500 sources with SNR>30 for a 5 year mission

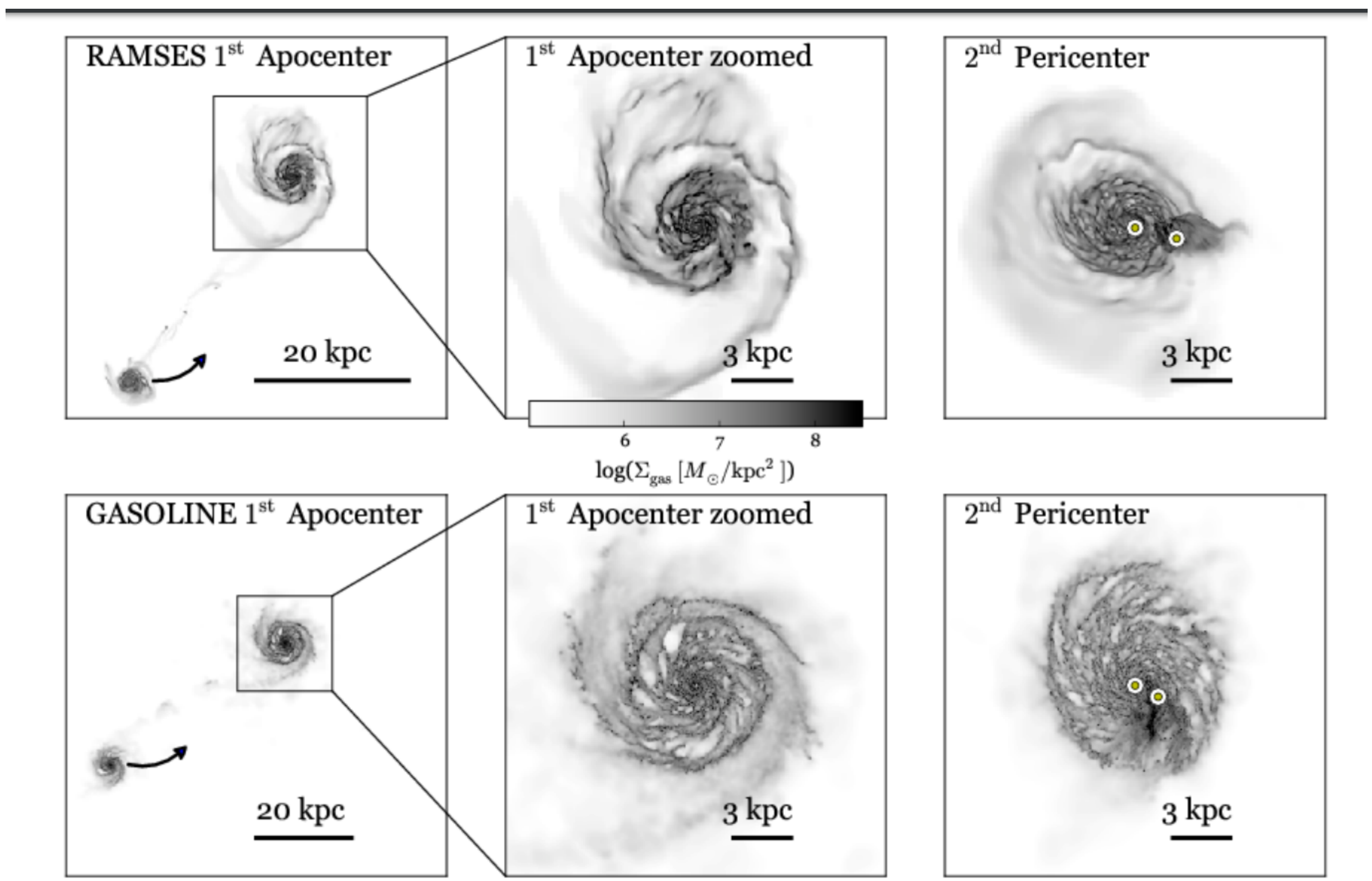




Dwarf galaxies may also have central black holes



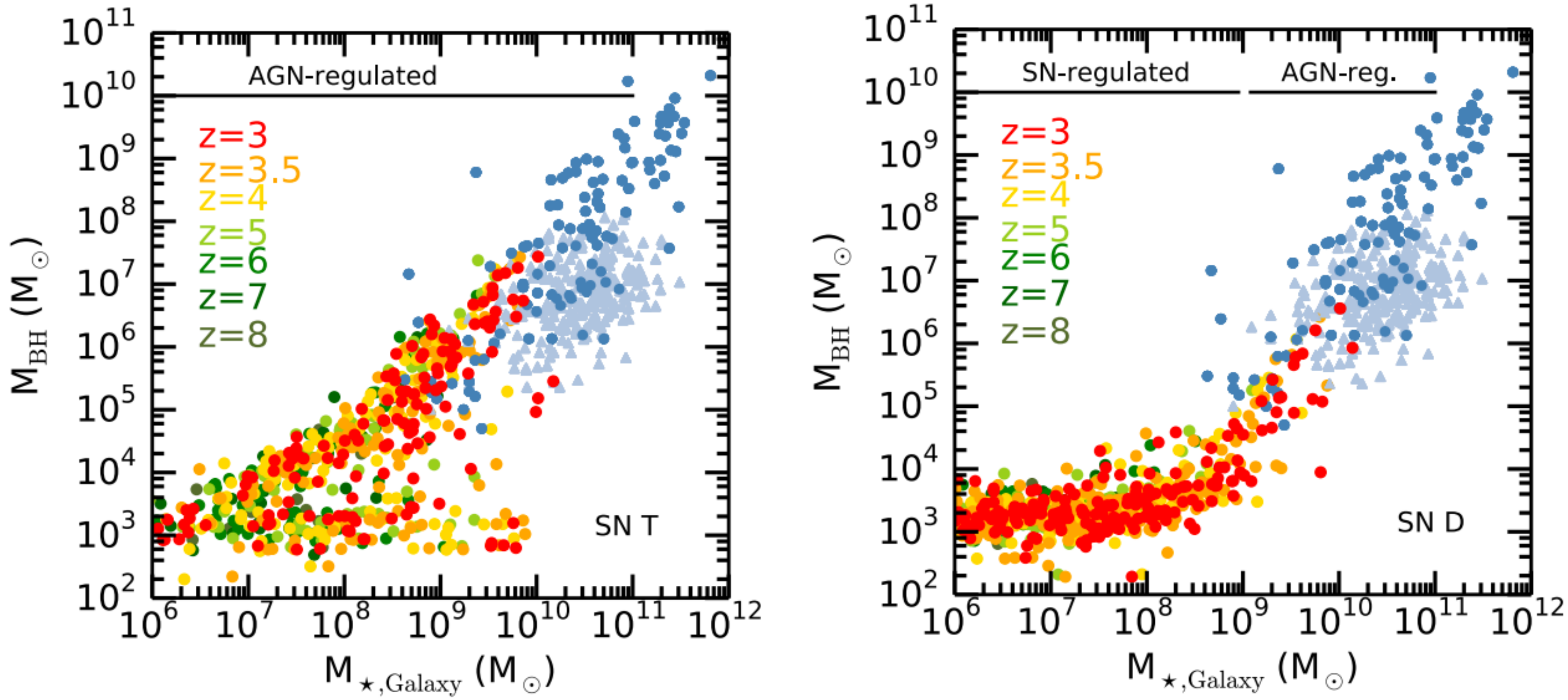
Warning: BH growth depends on the hydrodynamic code



BHs grow less, take longer to merge

Gabor et al. 2015

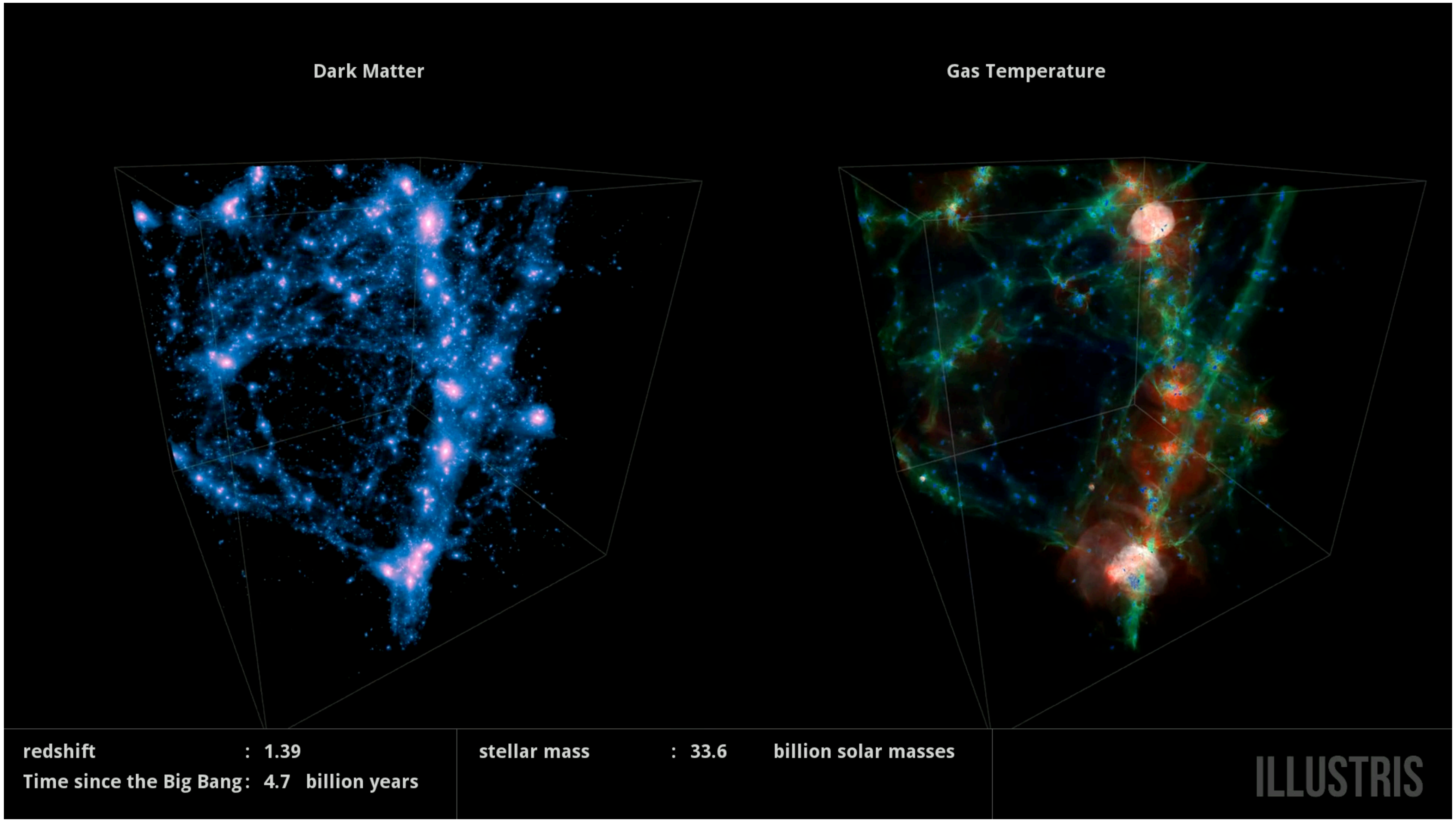
Warning: BH growth depends on a feedback recipe



Ramses 10 Mpc (!) box
Habouzit et al 2016
see also Dubois 2015

Warning: Over-zealous AGN feedback stifles BH growth (and star formation, too)

Volgelsburger et al. 2014



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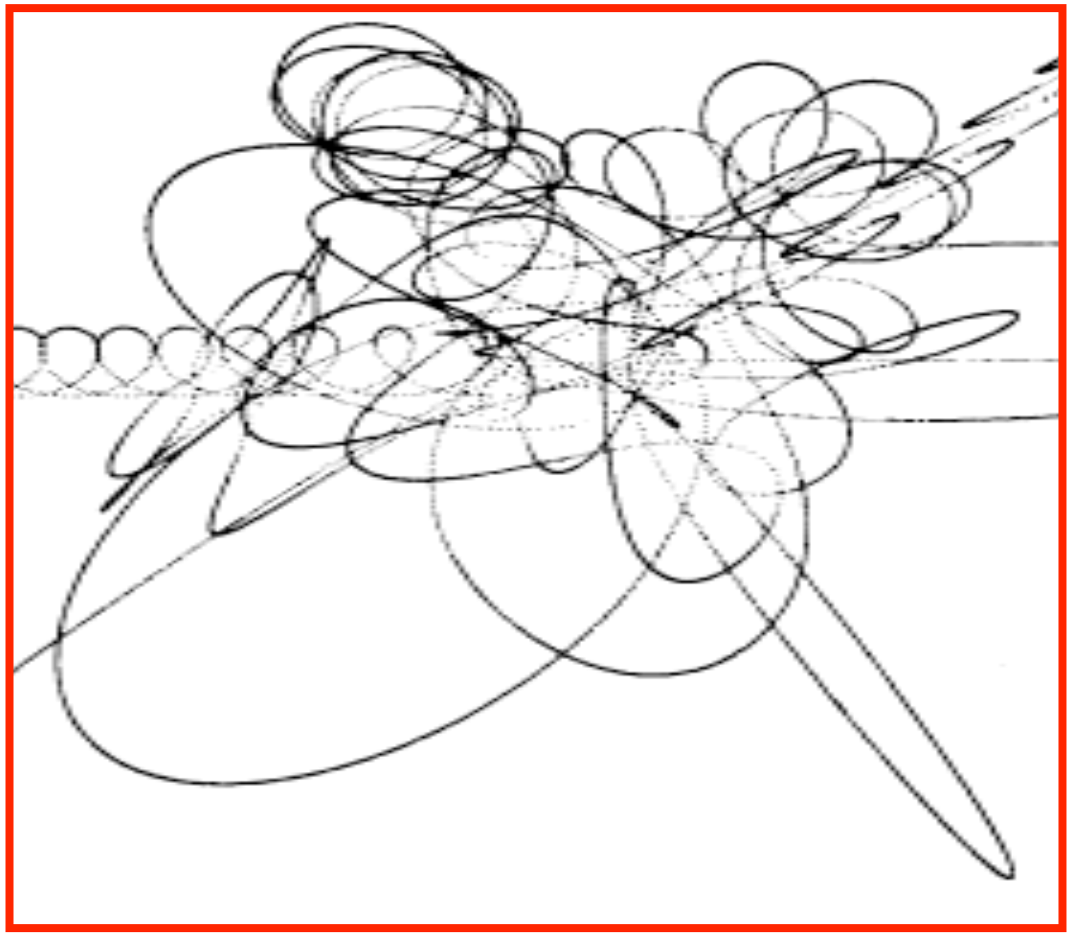
Galaxy mergers sink black holes though dynamical friction

Separation:
$O(10^5)$ pc

Timescale:
$O(10^8)$ yr

Next: black holes sink closer via 3-body scattering.

Quinlan 1997; Sesana et al 2006,2007,2008

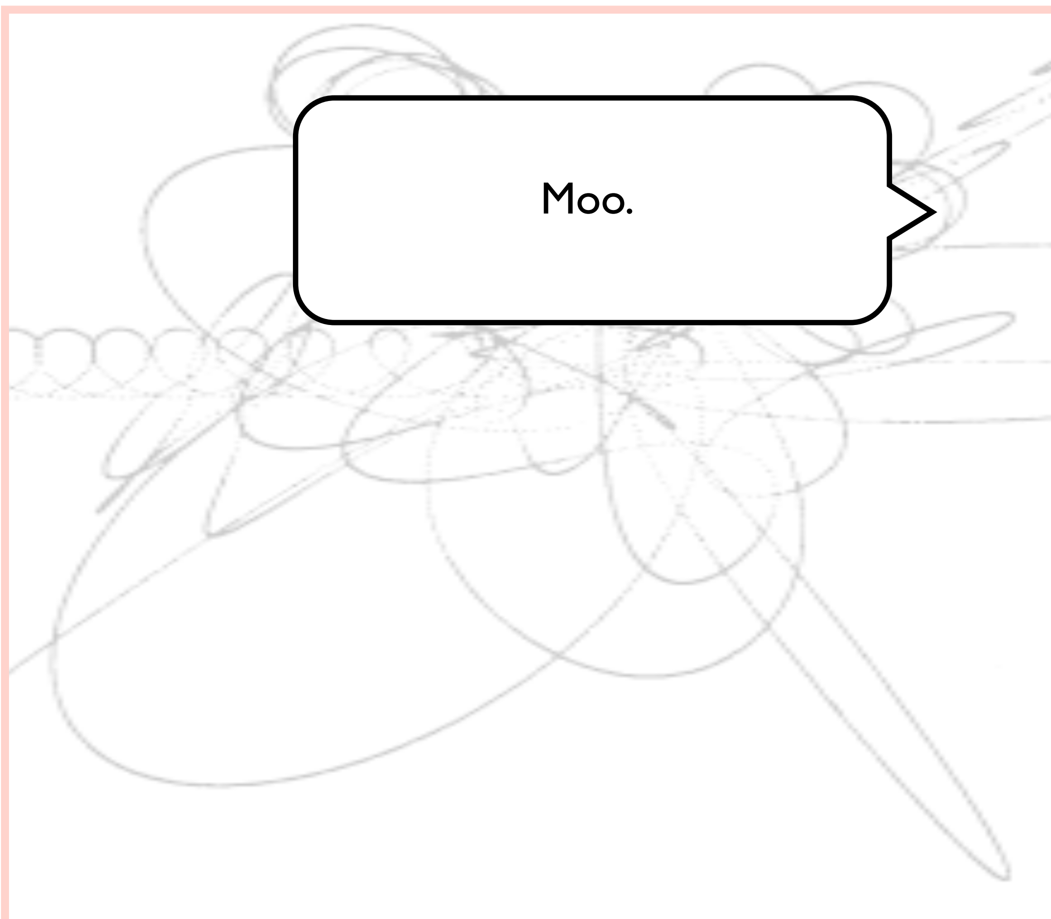


$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2}r_h,$$

> $O(10^{10})$ yr!**

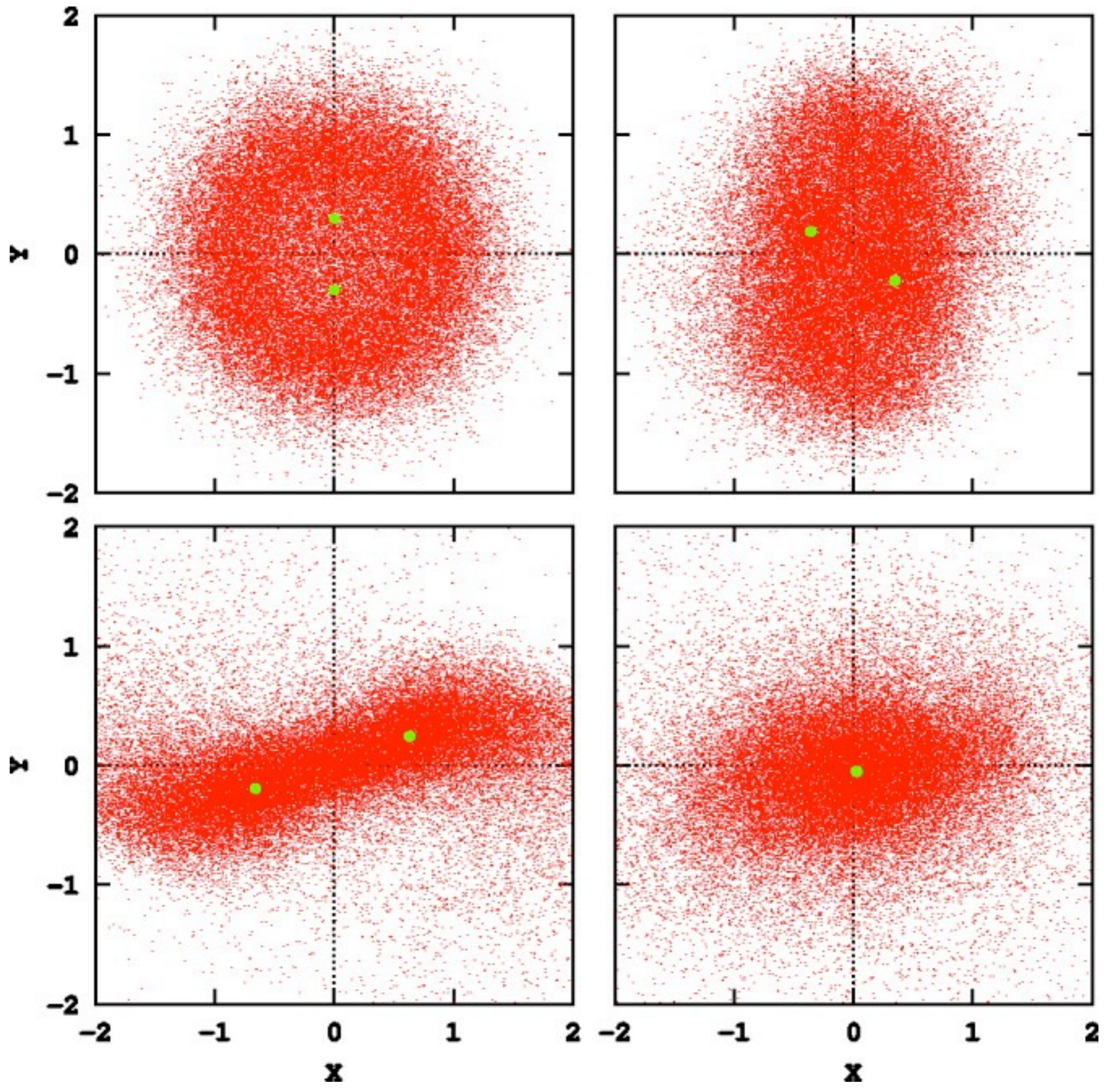
**in a static spherical galaxy with permanent ejections and no resonances

The final parsec problem -- refilling a spherical loss cone takes > t_{Hub}

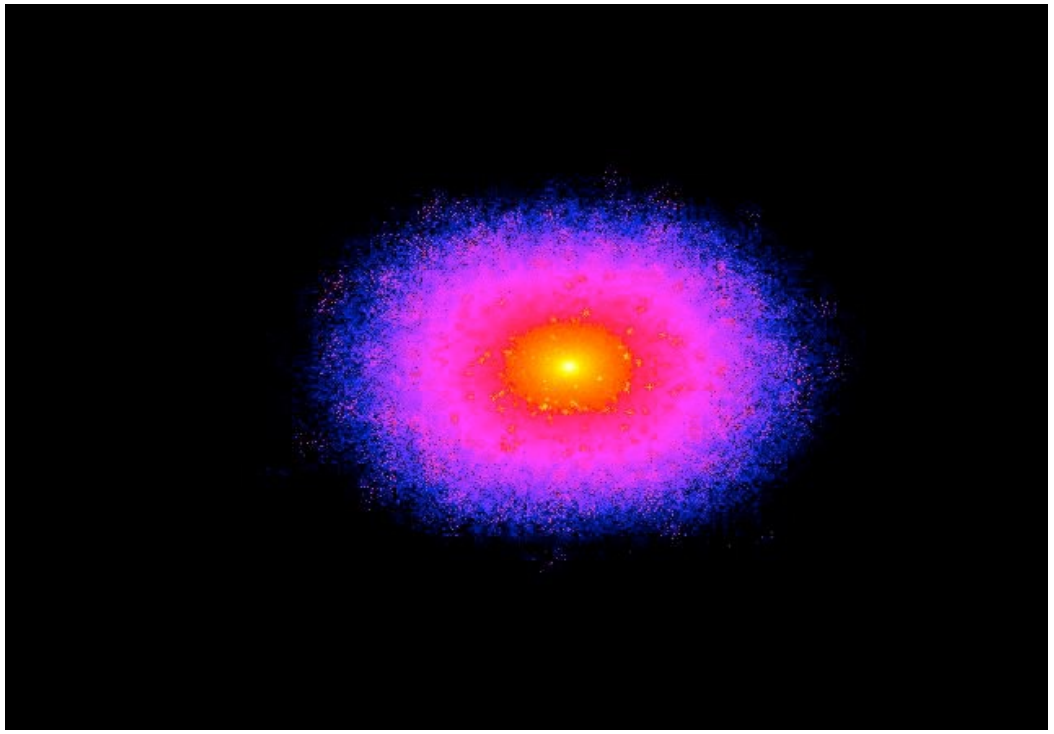


$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2} r_h,$$

Final Parsec Problem? Not a problem for a non-spherical galaxy!



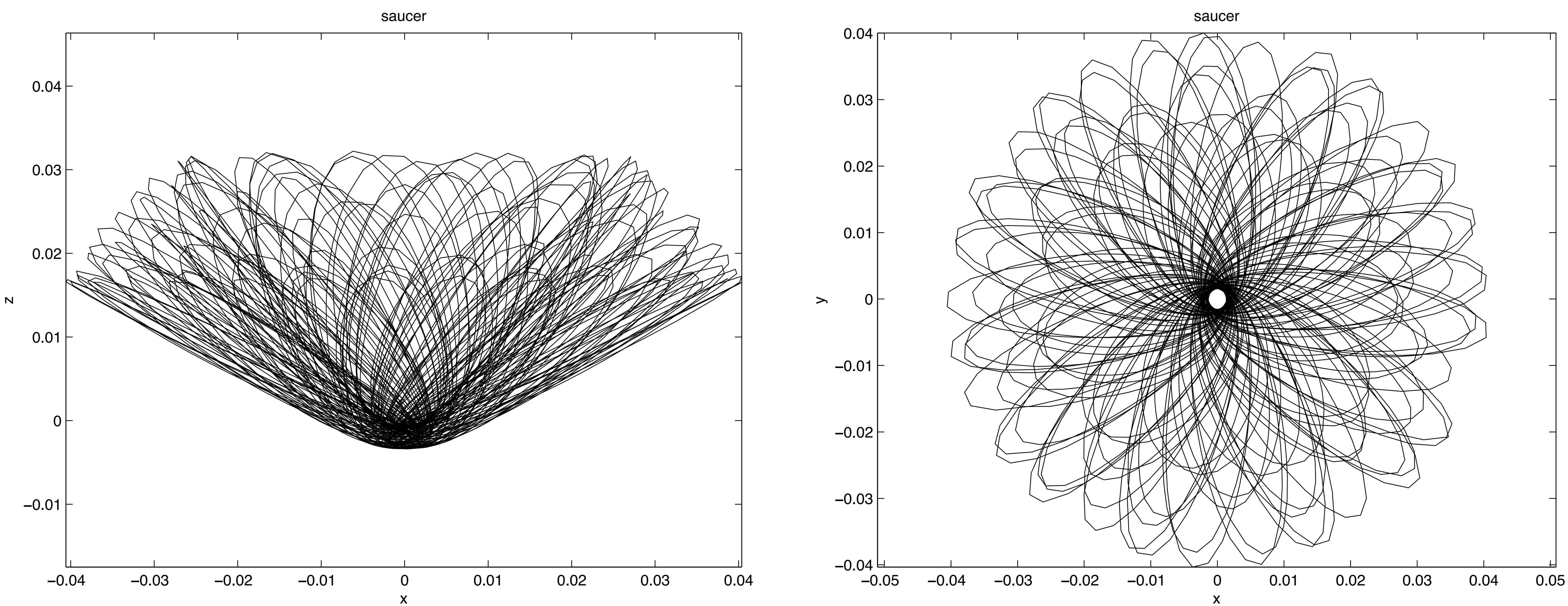
Berczik et al. 2006



KHB+Sigurdsson 2006
Khan+KHB 2013

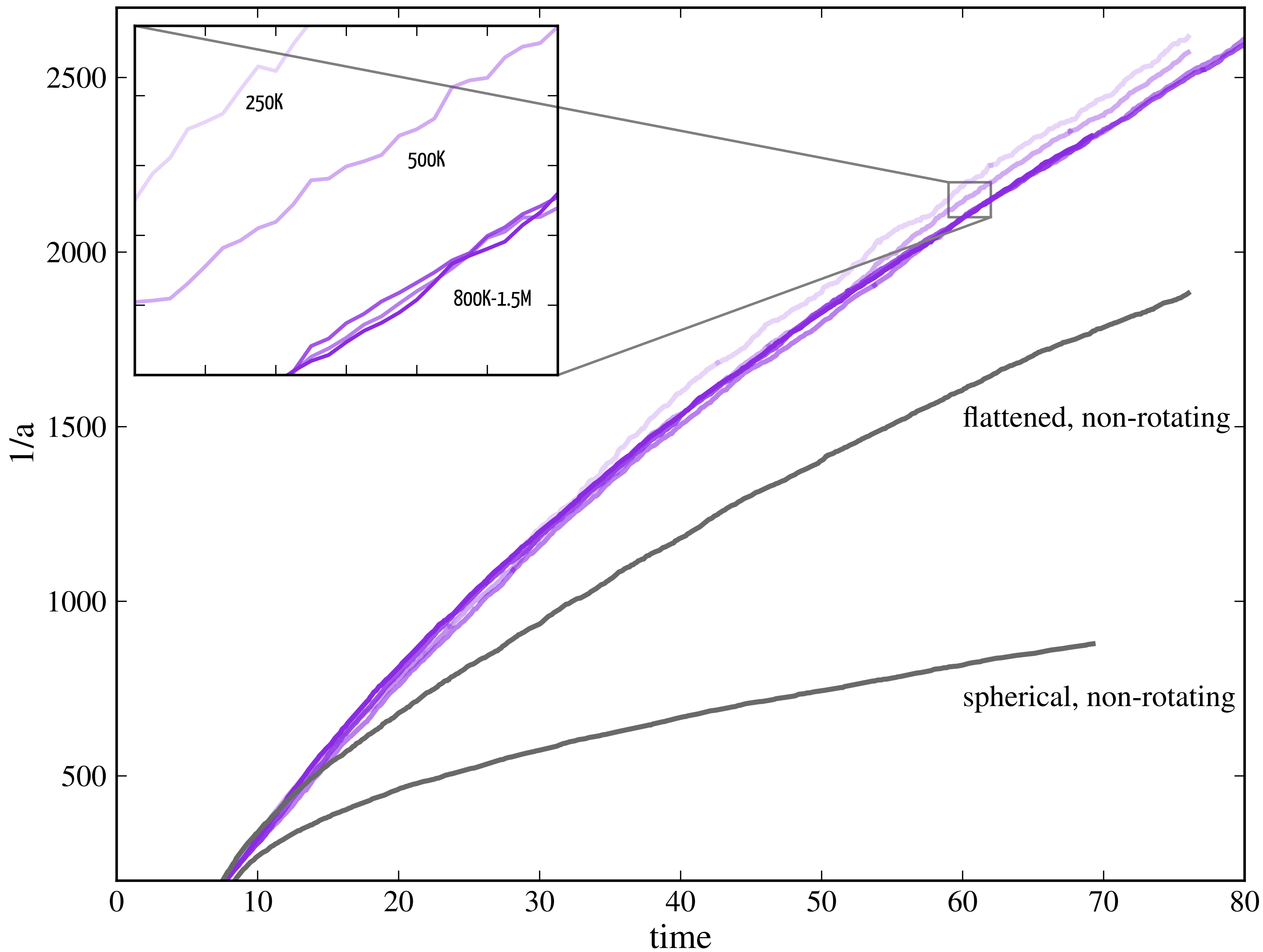
Expect $10^8\ M_\odot$ Binary BHs to take less than 3 Gyr to coalesce in an equilibrium axisymmetric galaxy

Axisymmetric galaxies have low angular momentum orbits that overfill the loss cone



~60% of the stars within the inner 100 pc are saucers

Now, let's add rotation — and the black hole orbit shrinks faster



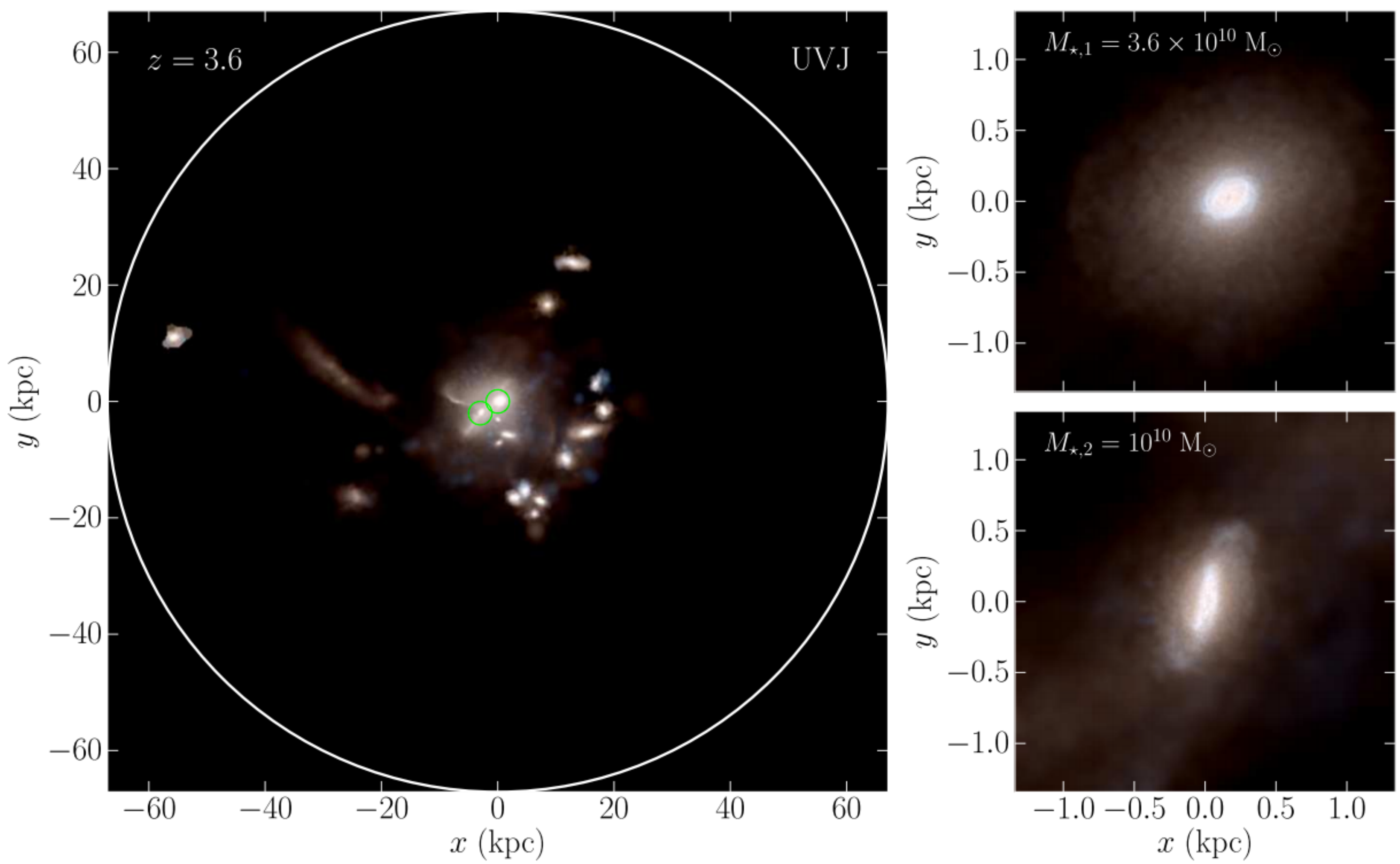
Direct N-body code with GPU acceleration and 2.5 PN terms included.

Black holes *can* merge quickly...or not.

galaxy type	black hole merger timescale	eccentricity in the gw regime
spherical	> 15 Gyr	N/A
axisymmetric (c/a=0.75)	3 Gyr (t_{Hub}@z~0.4)	0.1
axisymmetric, rotating	1 Gyr	0.1
axisymmetric, counterrotating	100 Myr	~1
triaxial	O(10) Myr	large
Gas-Rich	10 Myr — 1Gyr	~0.0

Latest advance: BBH merger in a cosmological volume — 10 Myr!

merger caused not by gas — by new star formation



Khan et al. 2016

More astrophysically realistic things to think about:

~few Gyr SMBH merger times interestingly long -- subparsec dual BHs abound? Triple black holes less rare?

Need to add realistic merger times to semi-analytic models and simulations to help predictions for PTA, BH growth, circumbinary disk observational signals, and so **much** more

We need to calculate merger timescales for a realistic suite of galaxy models/interactions.

It’s a wonderful era to be an astronomer!

We need to get robust SMBH masses and pin down SMBH binaries

We need to know the real SMBH-galaxy correlation

We don’t know how black holes are born

We don’t understand SMBH accretion and feedback (including secular mass growth from, e.g., stellar plunges)

We need to include accurate SMBH dynamics in predictive models

Spin! We aren’t thinking enough about spin!

P.S. Please cite generously!

Dunn et al. 2017 (coming soon)

Sanchez et al. 2017

Mirza et al. 2017

KHB, Khan 2015

Li, KHB, Khan 2015

Khan, KHB, et al 2013

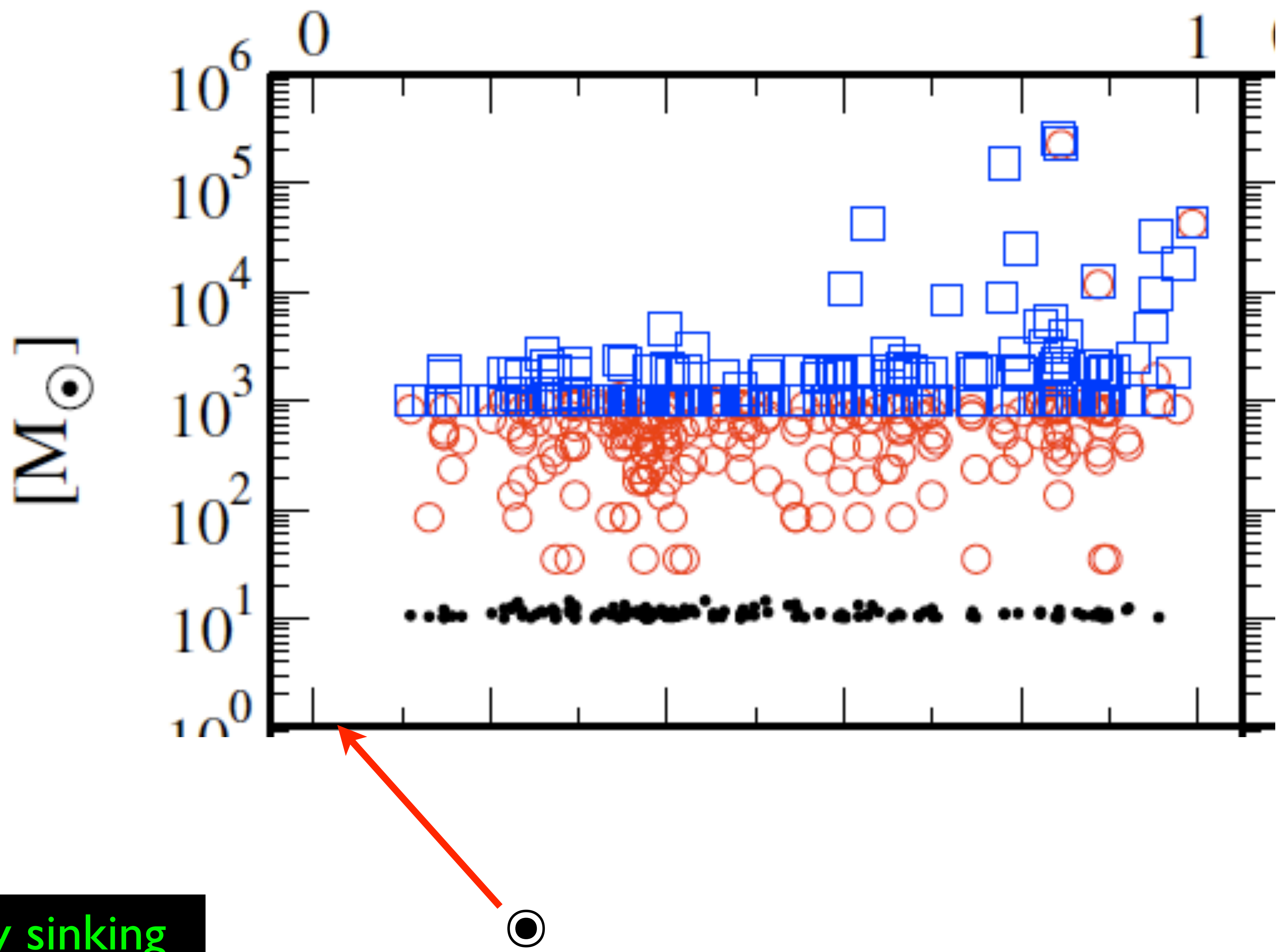
Bellovary et al. 2013

Micic, HB + Sigurdsson 2011

HB, Micic, Sigurdsson + Rubbo 2010

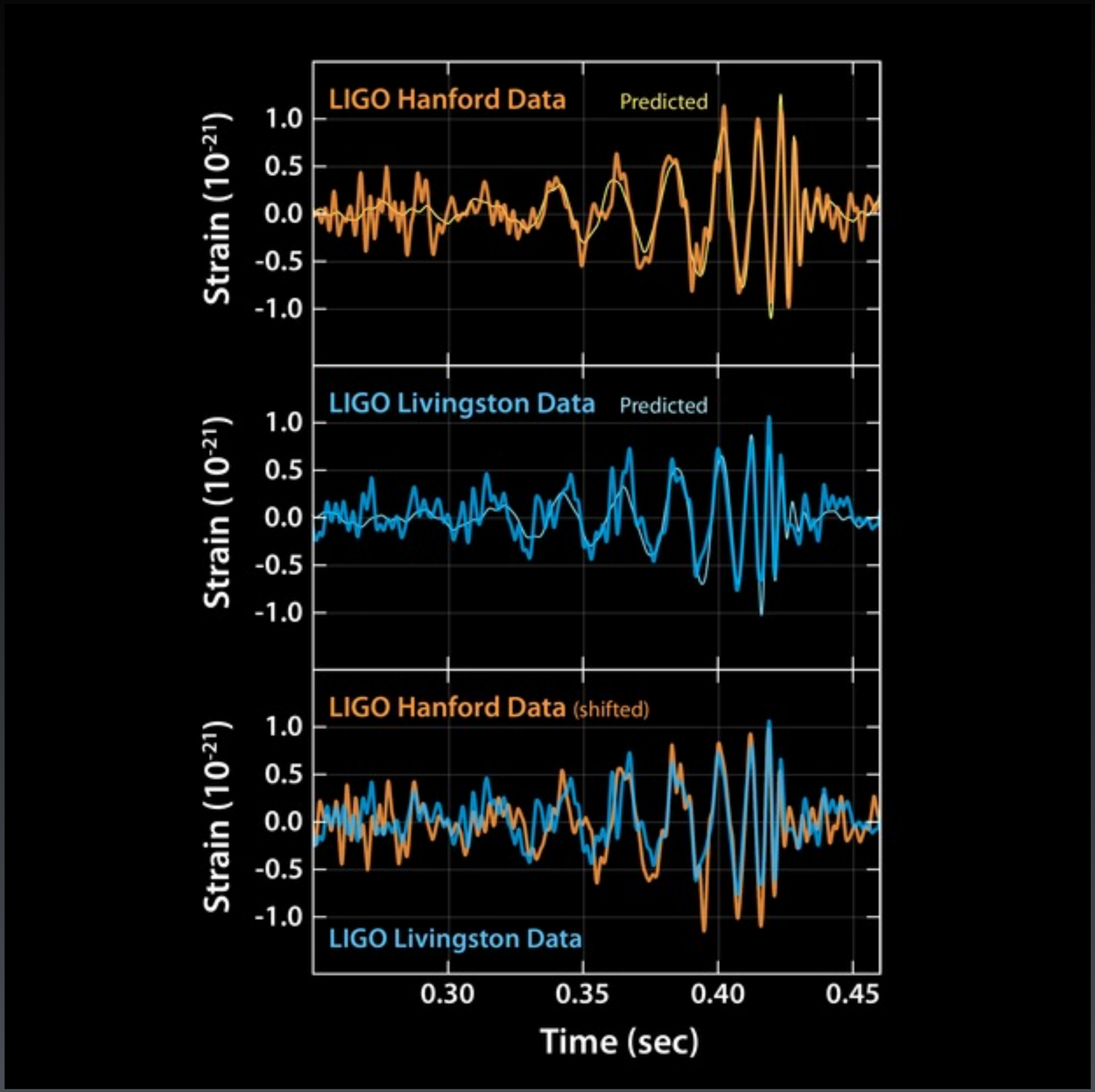
Micic, HB + Sigurdsson 2008

Rogue Black Holes sit in the outer halo



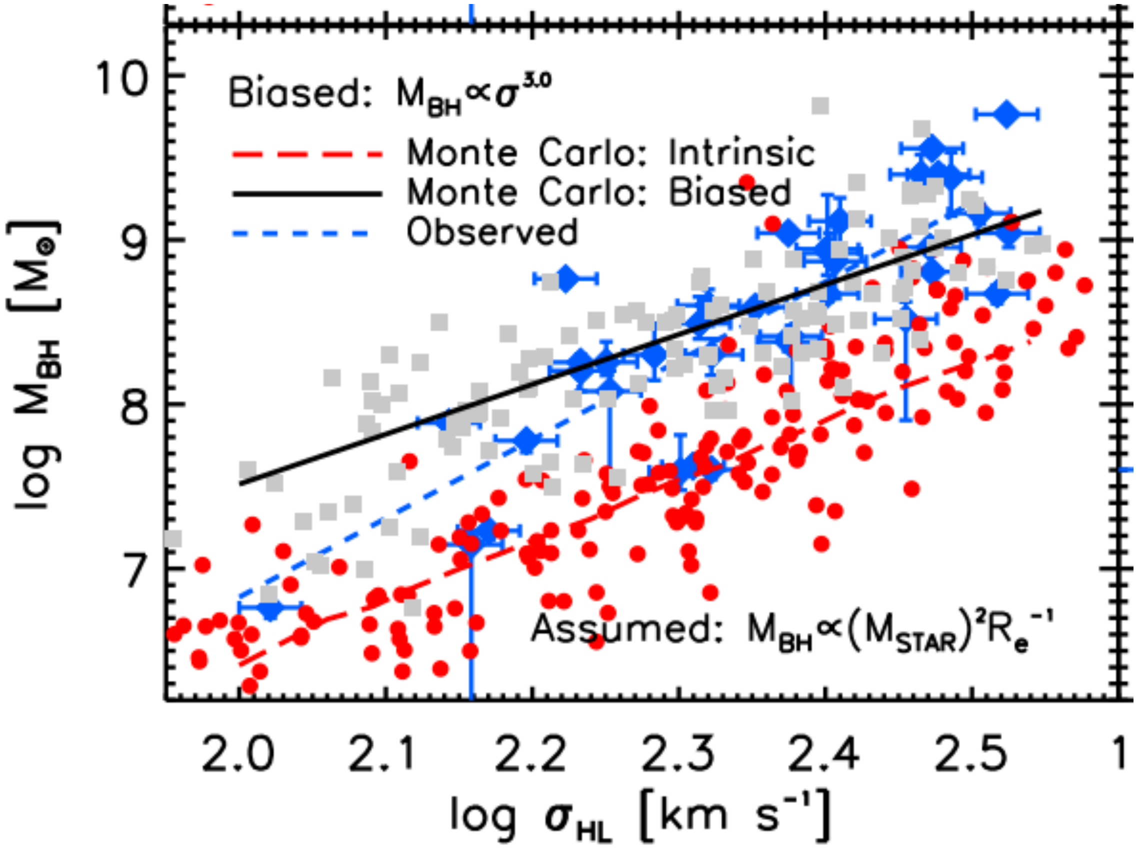
Slowly sinking

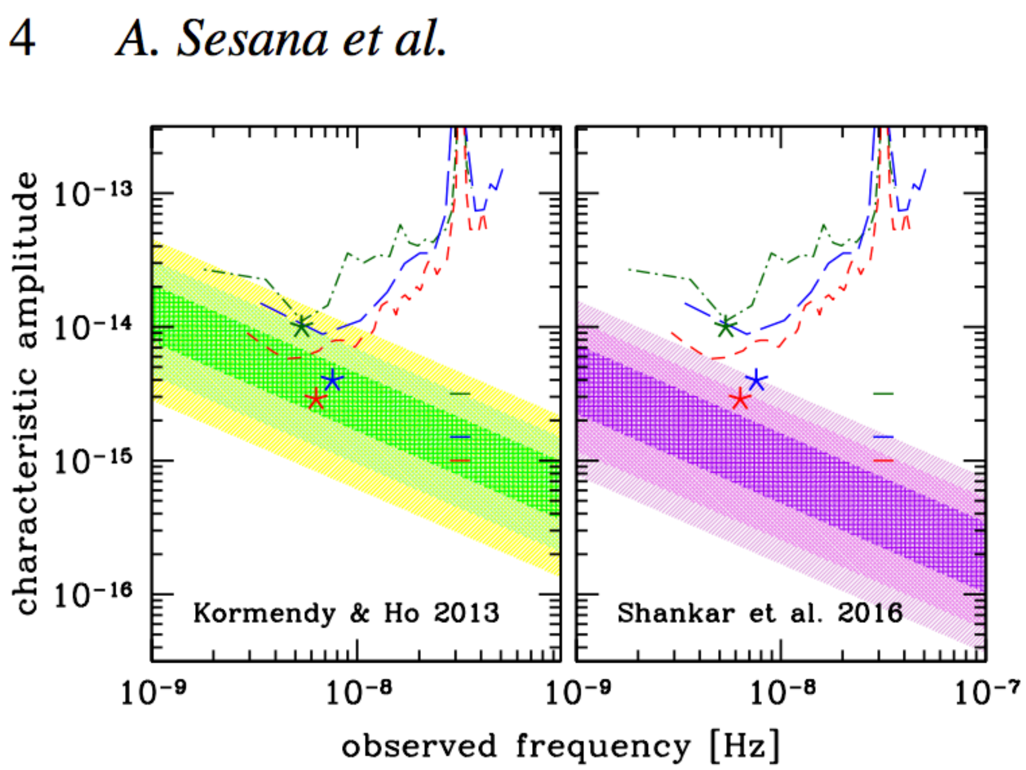
..but 4 days earlier, as luck would have it...



Sample bias can offset the normalization of SMBH relations

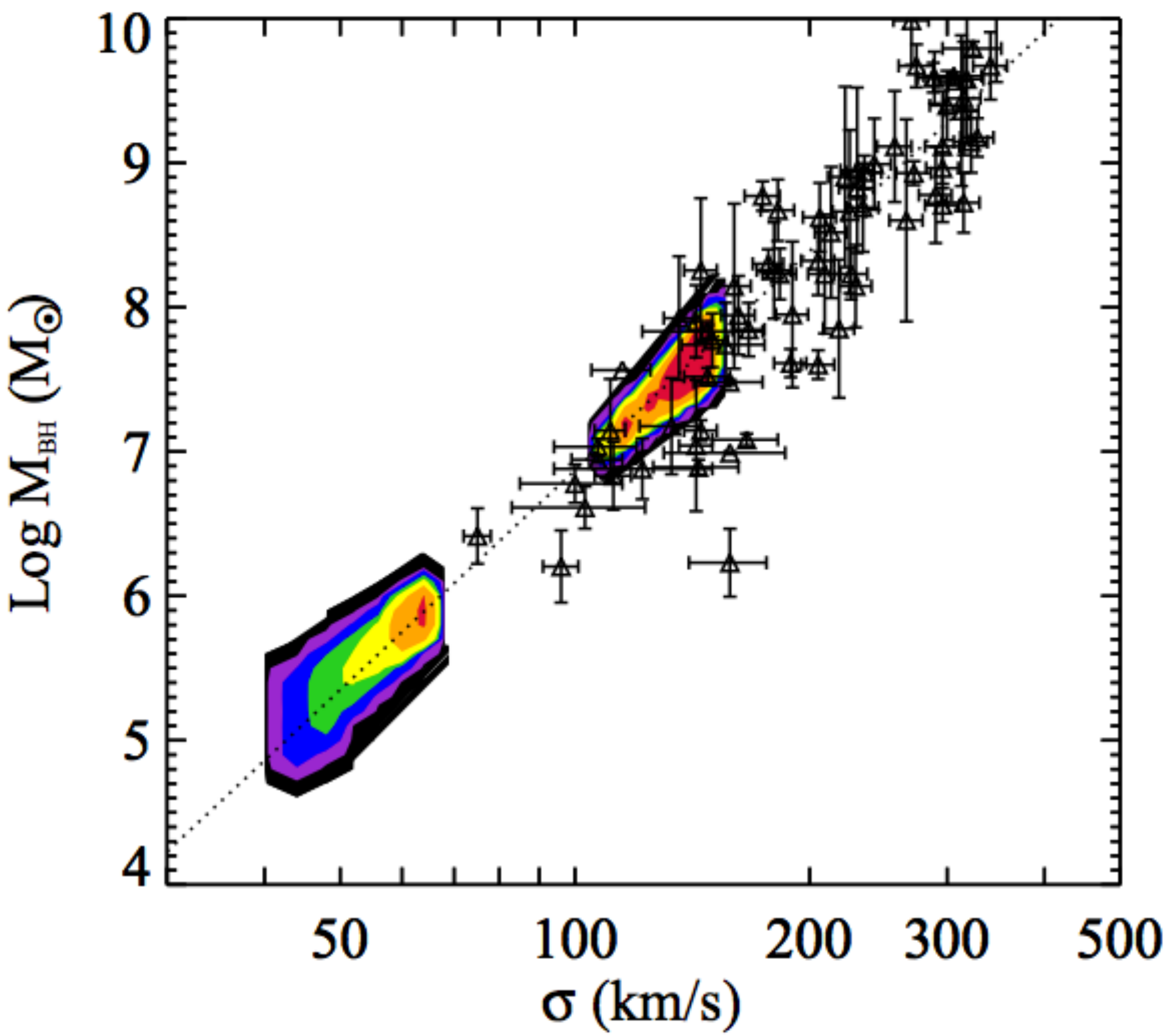
Shankar et al. 2016





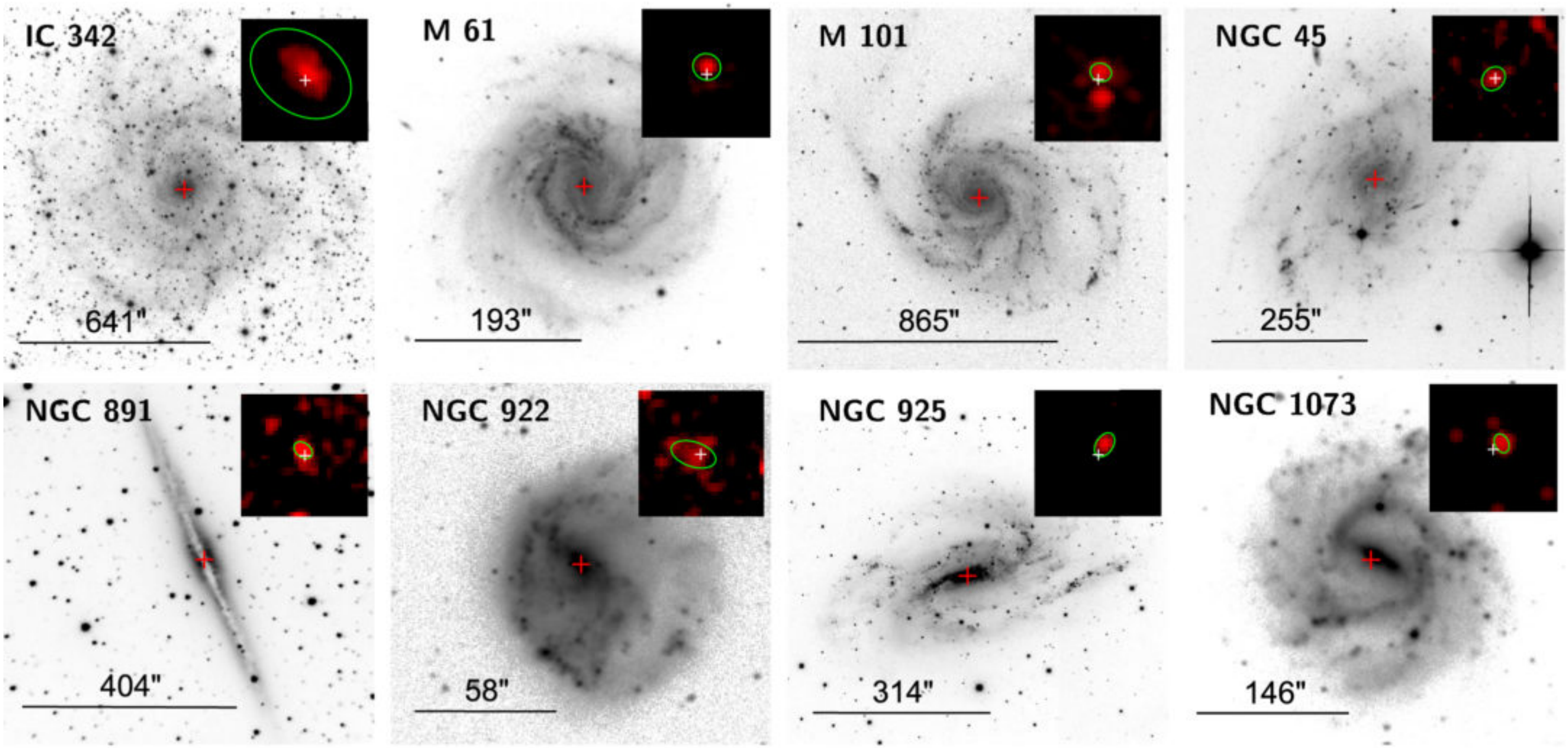
Dynamical mass estimates themselves are uncertain by factors of 3-10 by including dark matter and galaxy shape

Orientation changes the measurement of velocity dispersion, too



Bellovary, KHB, et al. 2014

Chandra reveals new SMBHs with <10^6 solar masses in disky galaxies

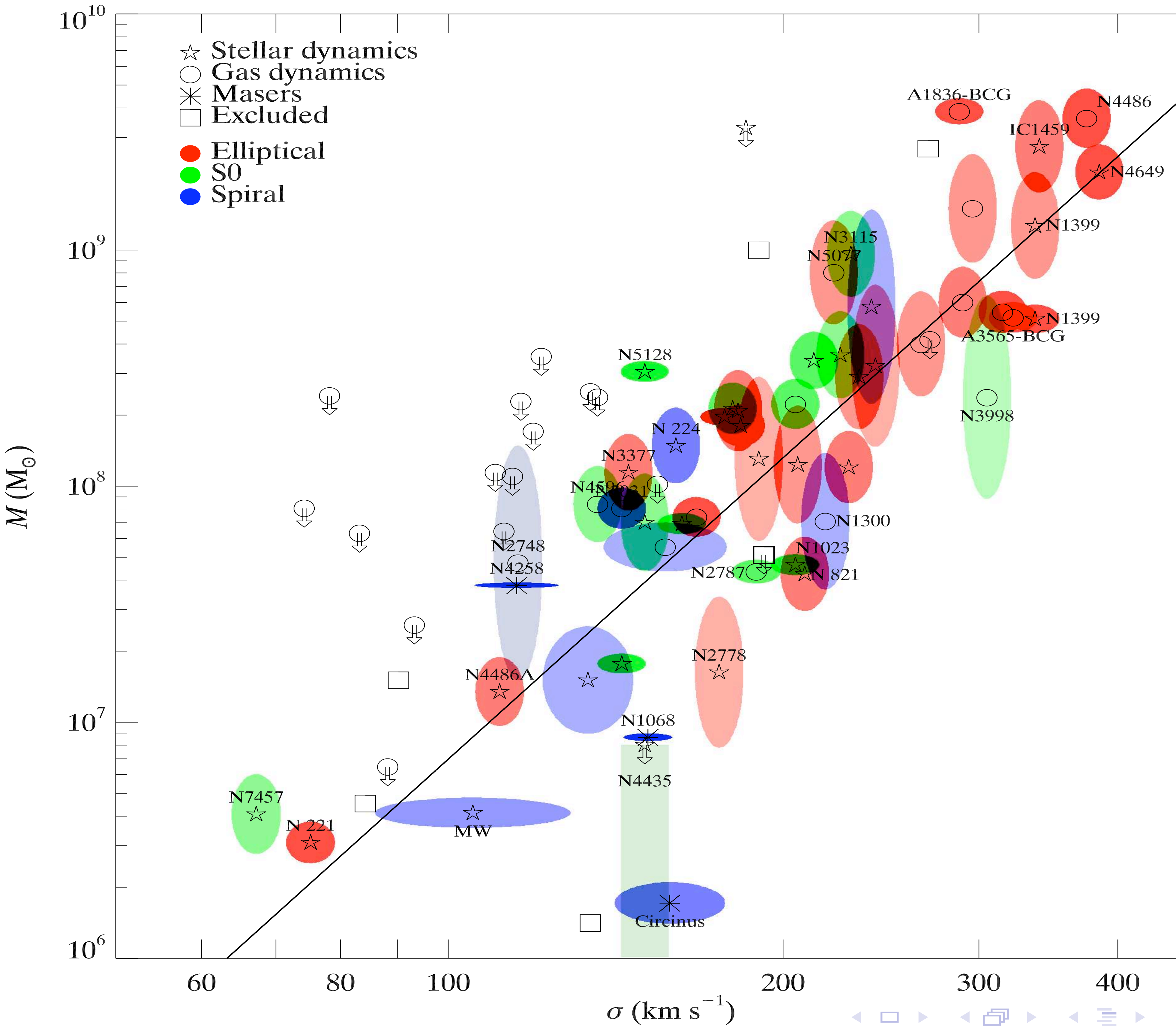


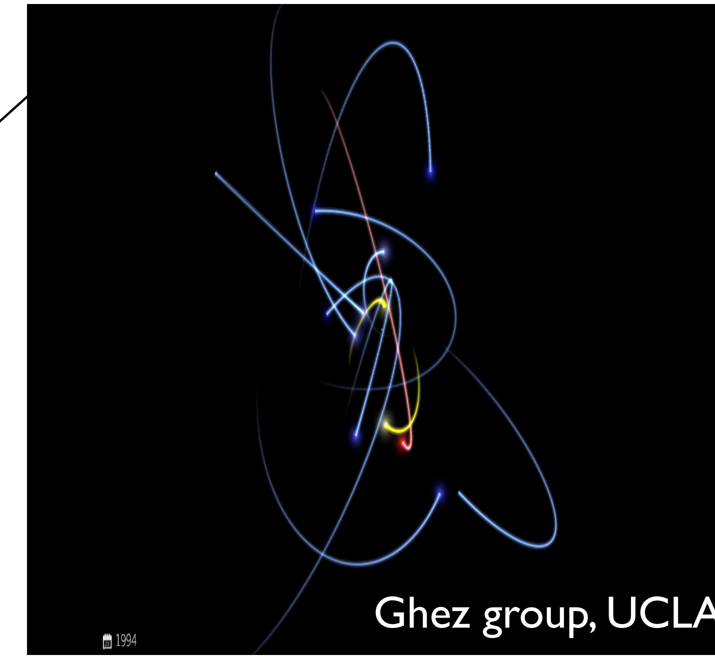
She et al 2017 — 21% of disky galaxies host SMBHs like these.

Do **YOU** want to shape the future of LISA?
Apply to be on the LISA Study Team!

See me for details…

A Supermassive Black Hole for ‘Every’ Galaxy





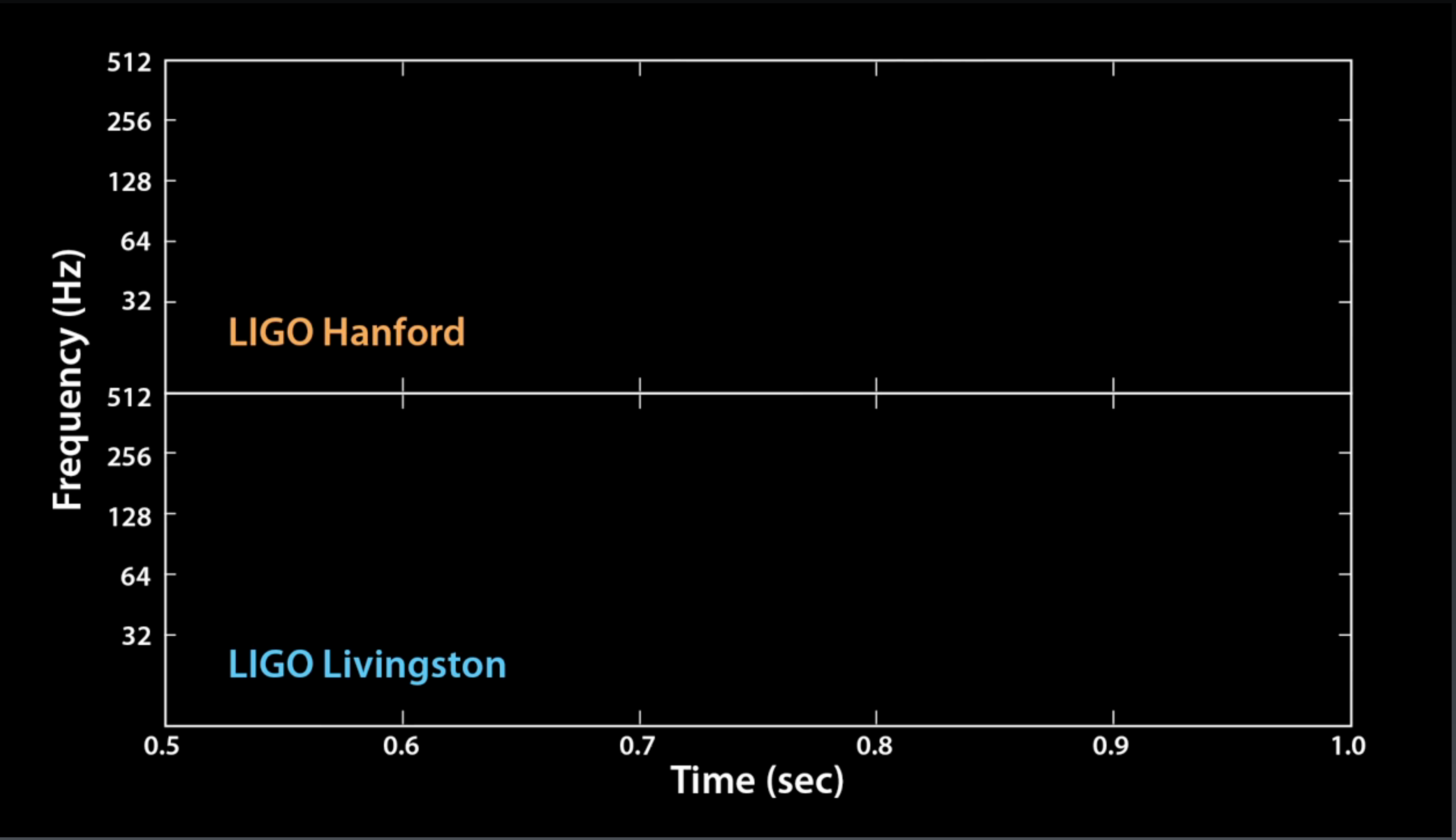
$R_{sch}=2\,G\,M/c^2=O(10^{-6})$ pc

$R_{infl}=G\,M/\sigma_0{}^2=O(10^0)$ pc

$R_e=O(10^3)$ pc

Gultekin et al 2009 -- see also Gebhardt et al 2000; Ferrarese & Merritt 2000; McConnell+Ma 2013, and work is on-going…

GW150914:The chirp heard around the world



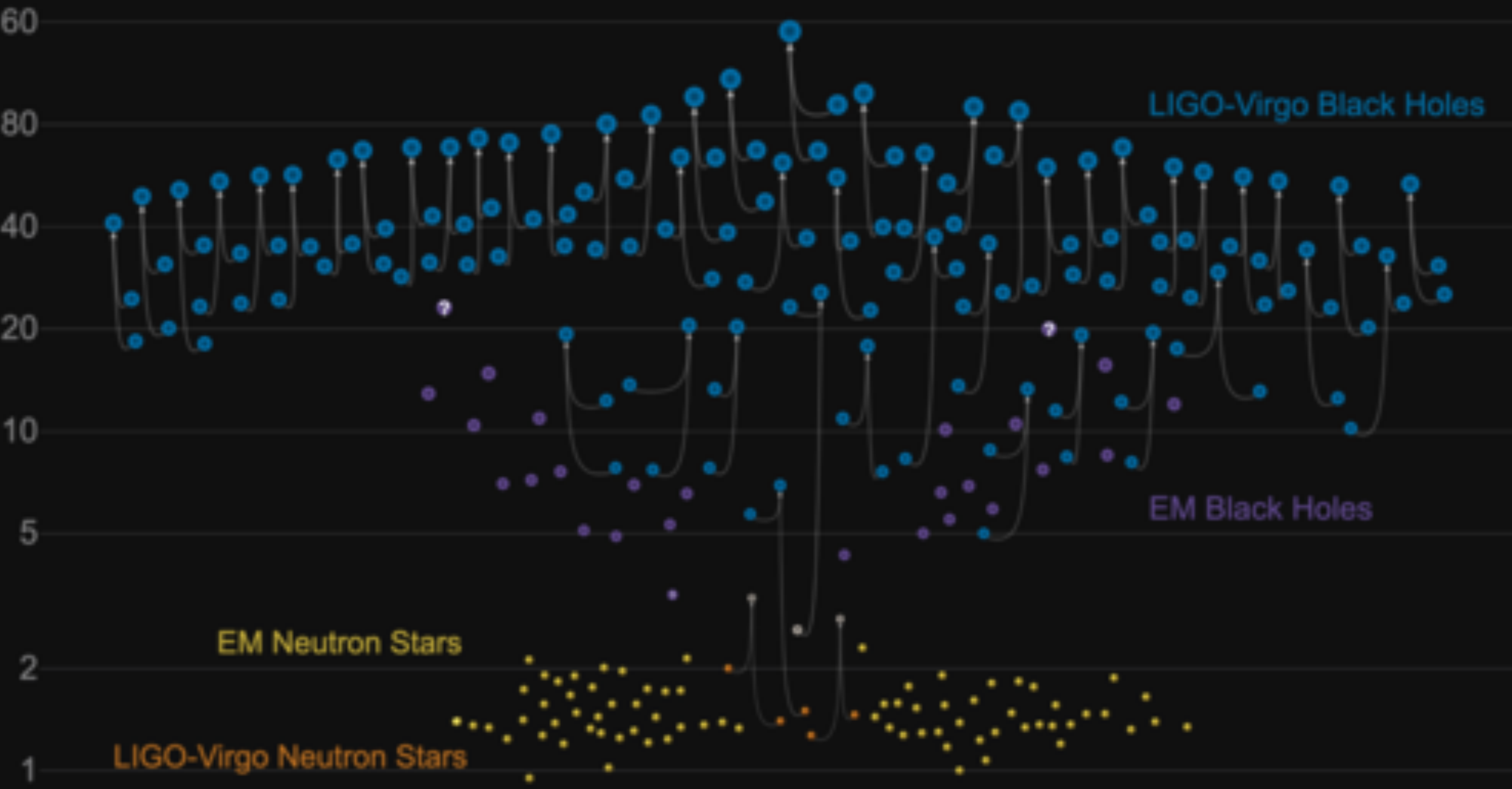
36 + 29=62 + 3

Pssst…See my TEDx Talk on YouTube?

Huzzah! The age of gravitational wave astronomy has begun!

Masses in the Stellar Graveyard

in Solar Masses



GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern