Title: TBA

Speakers: Alberto Sesana

Series: Strong Gravity

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Abstract: Abstract and Zoom Link: https://pitp.zoom.us/j/94015816228?pwd=UmV2ald4THk3S0tTcDhTNDd1cjJLZz09

Massive Black Hole Binaries along the cosmic history: evolution, dynamics and gravitational waves

Alberto Sesana
(Universita` di Milano Bicocca)

OUTLINE

massive black hole (MBH) hierarchical assembly

Dynamics of MBH binary (MBHB) mergers

gravitational waves (GWs) from MBHBs

observational prospects:
Laser interferometer space antenna (LISA)
Multimessenger astronomy

1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are $\sim 10^9$ solar masses!

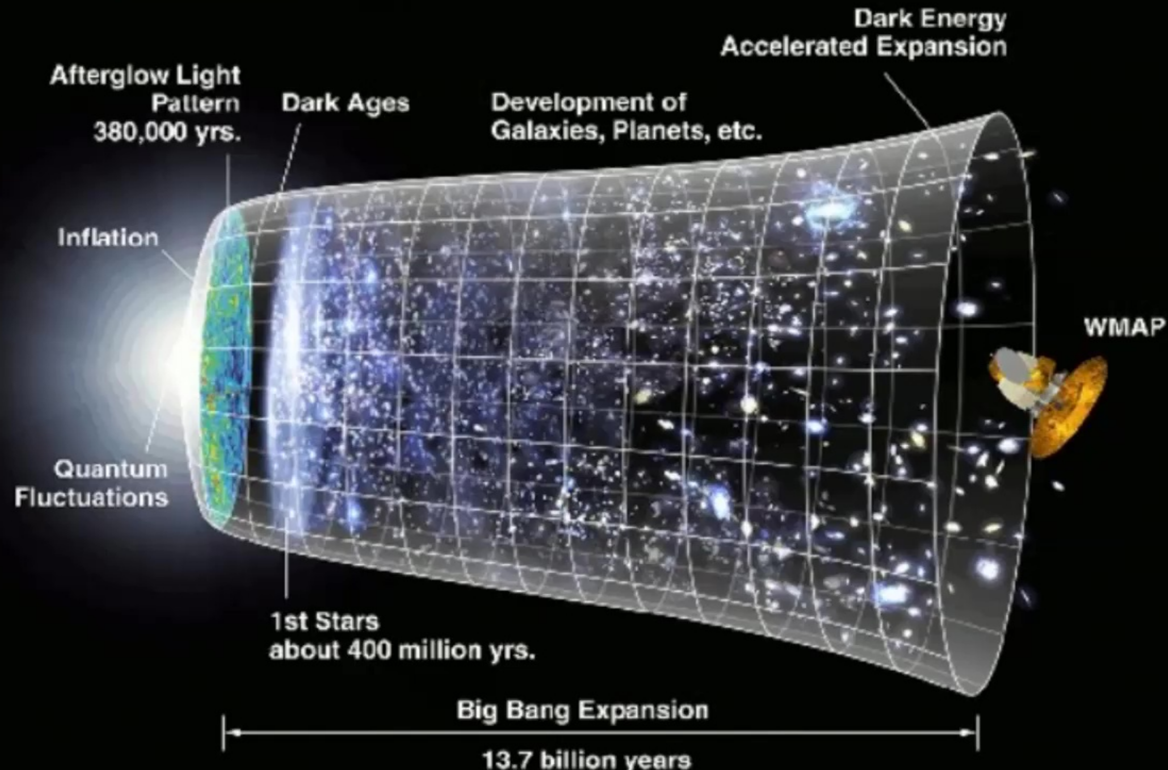
THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy


Quasar 3C175
VLA 6cm image (c) NRAO 1996

Cosmology in two slides

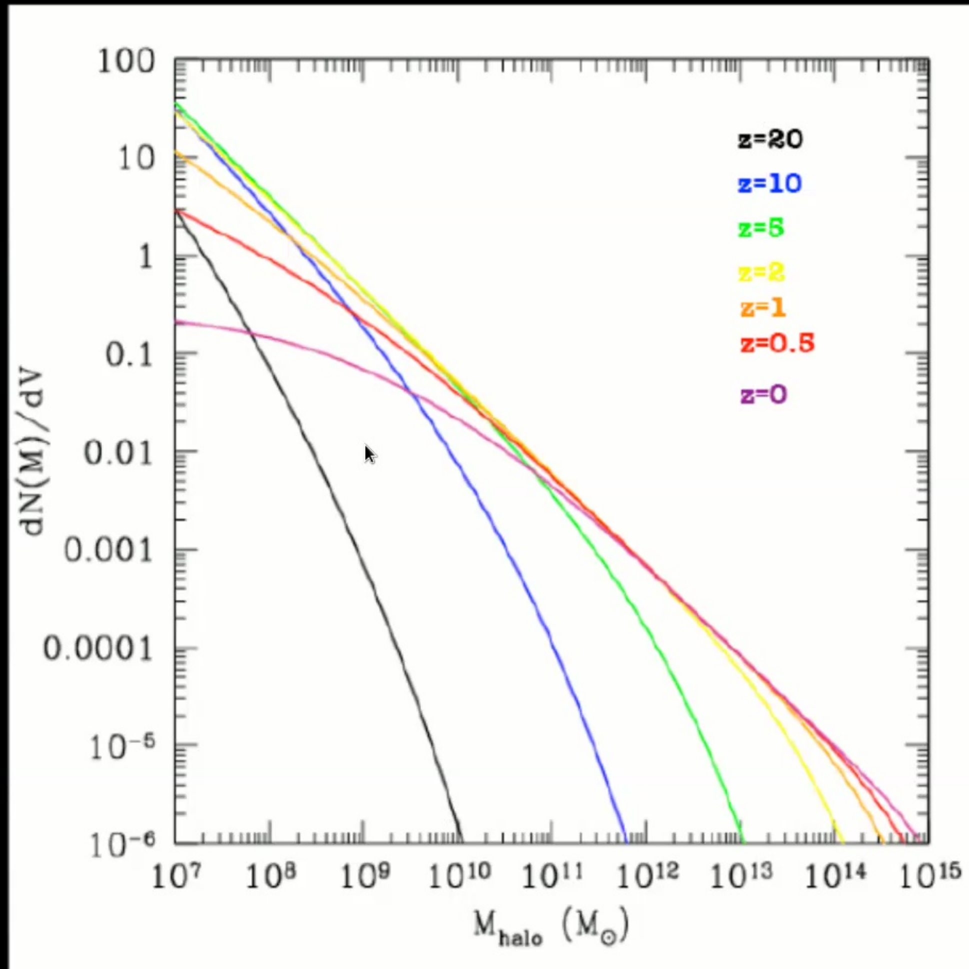
According to our best cosmological models, we live in a *ΛCDM Universe*. The energy content of the Universe is *27%* in the form of *ordinary matter* (~3% baryons, ~24% dark matter) and *73%* in the form of a *cosmological constant* (or Dark energy, or whatever), which would be responsible of the accelerated expansion.

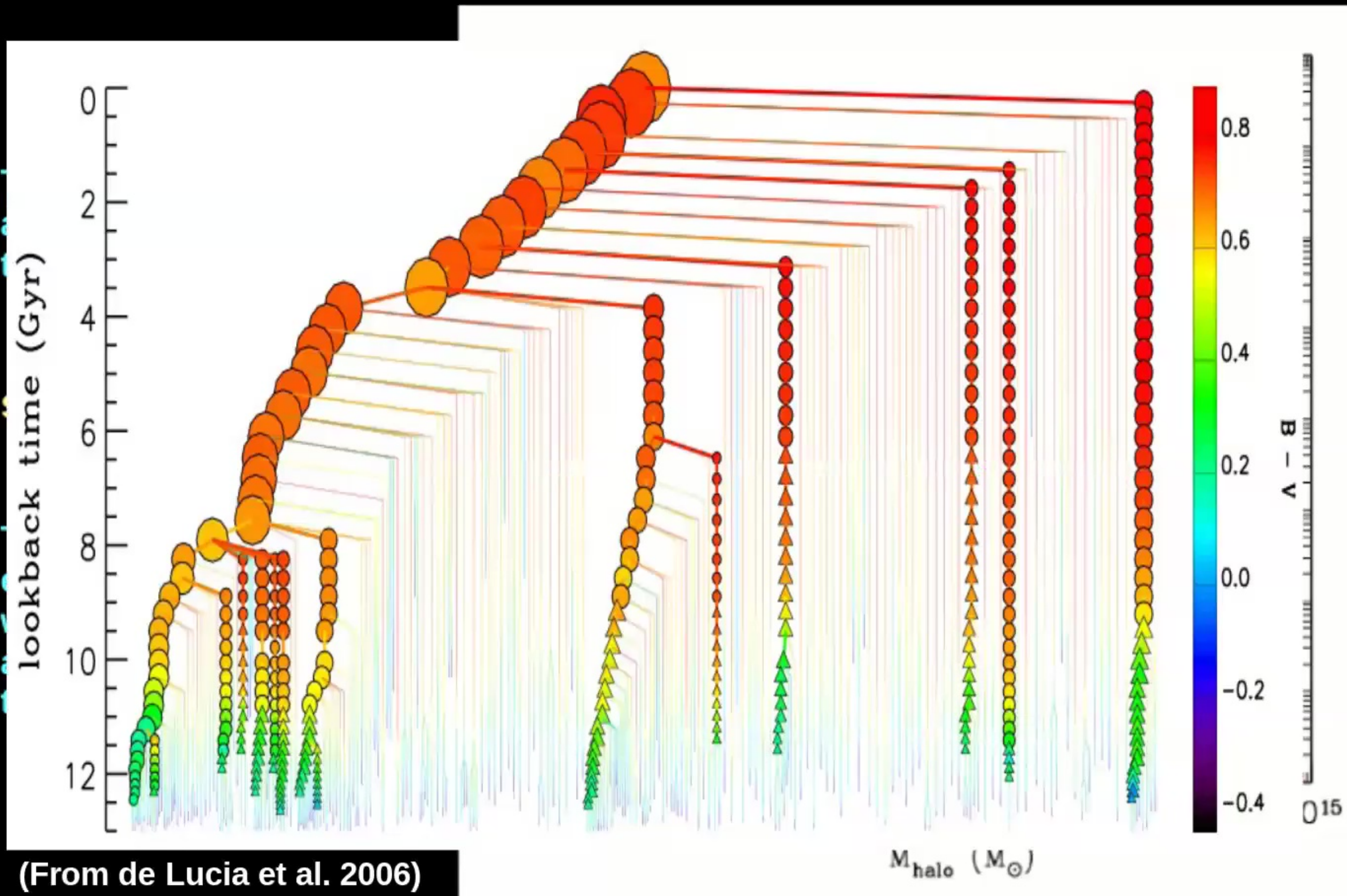


The typical halo mass is an increasing function of time: bottom-up or

HIERARCHICAL structure formation!

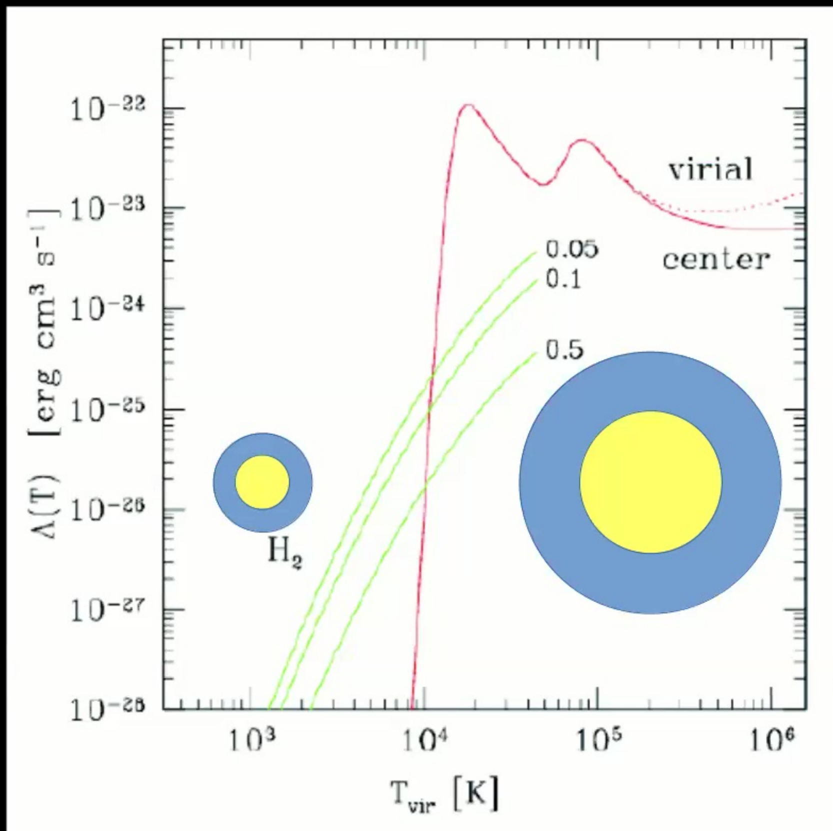
The halo mass function evolves in time (redshift) with larger halos forming at lower redshifts (later times).





(From de Lucia et al. 2006)

What happens to the baryons? In the early Universe most of the baryonic matter is in form of hot *atomic (H) or molecular (H_2) Hydrogen*.



Baryons need to cool down (i.e. loose energy) in order to condense in dense structures and form stars.

The only way to cool down is through transition between different atomic or molecular levels.

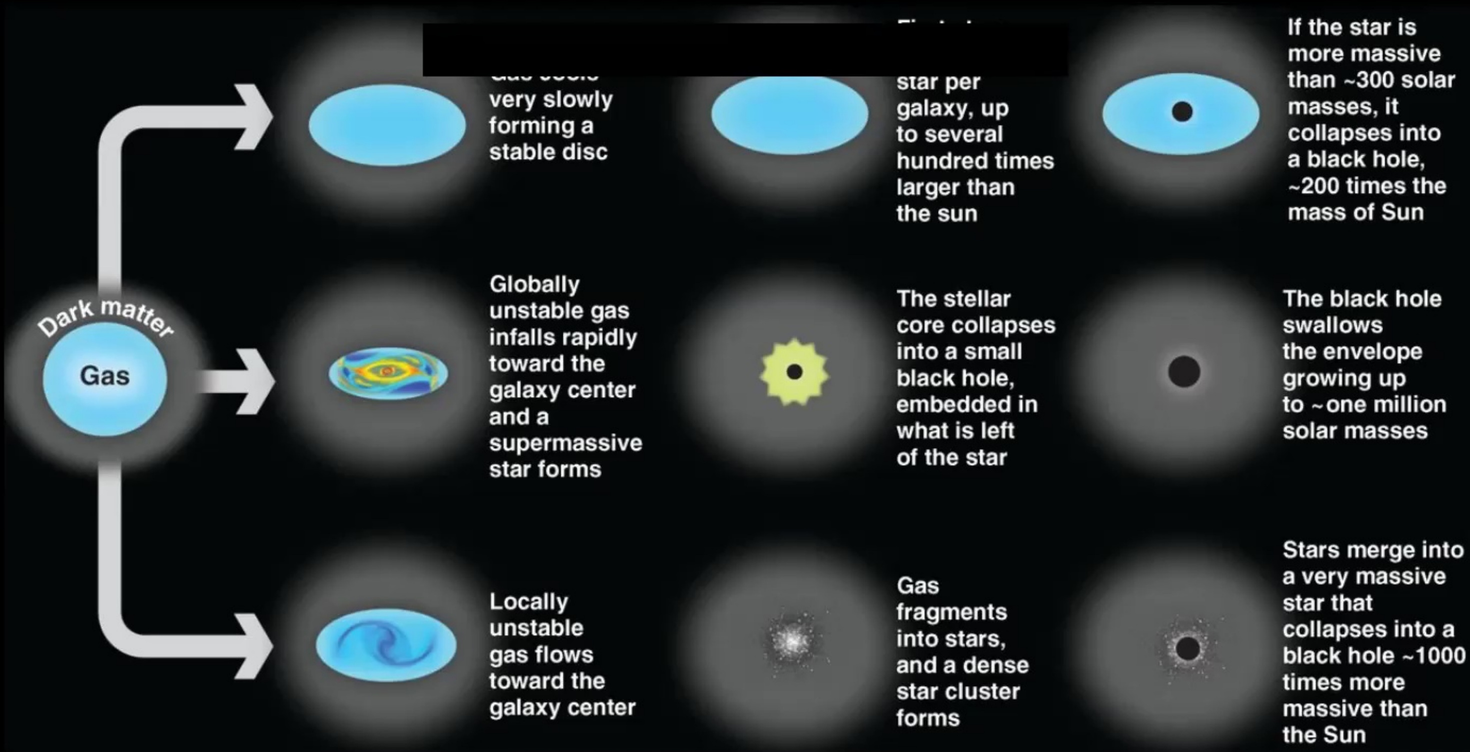
We need to excite high energy levels to radiate this energy away.

The only way is collisional excitation: *we need high temperatures!!!*

Atomic Hydrogen can cool only at temperatures>10^4K, while H_2 can cool already at 10^3K.

NOTE: Temperature increases with halo mass!

Seed BH formation

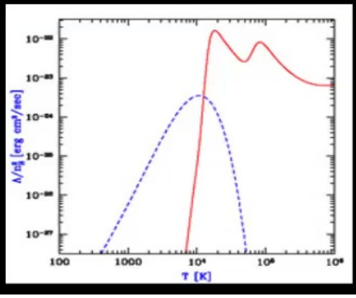


Critically depends on: -content of H_2

-vicinity of an ionizing source

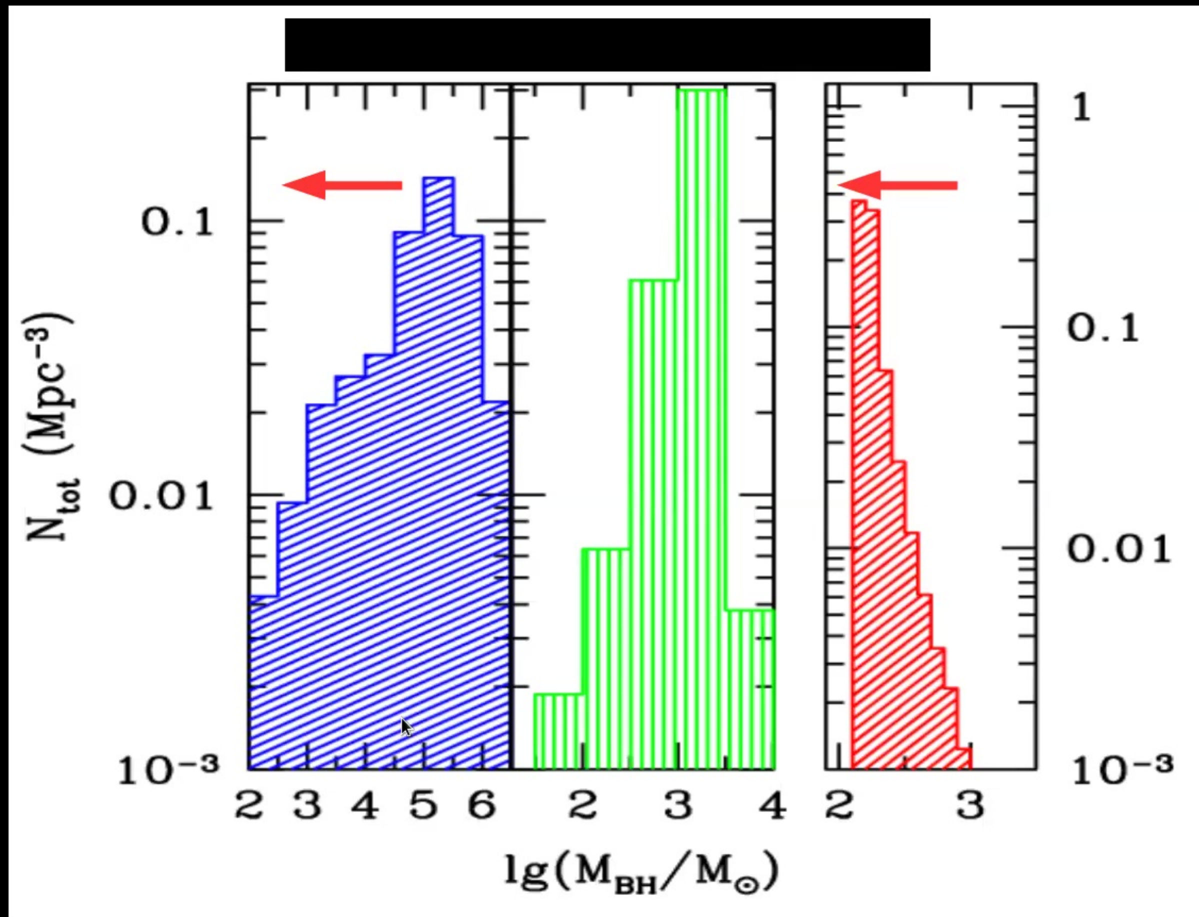
-fragmentation

-metallicity

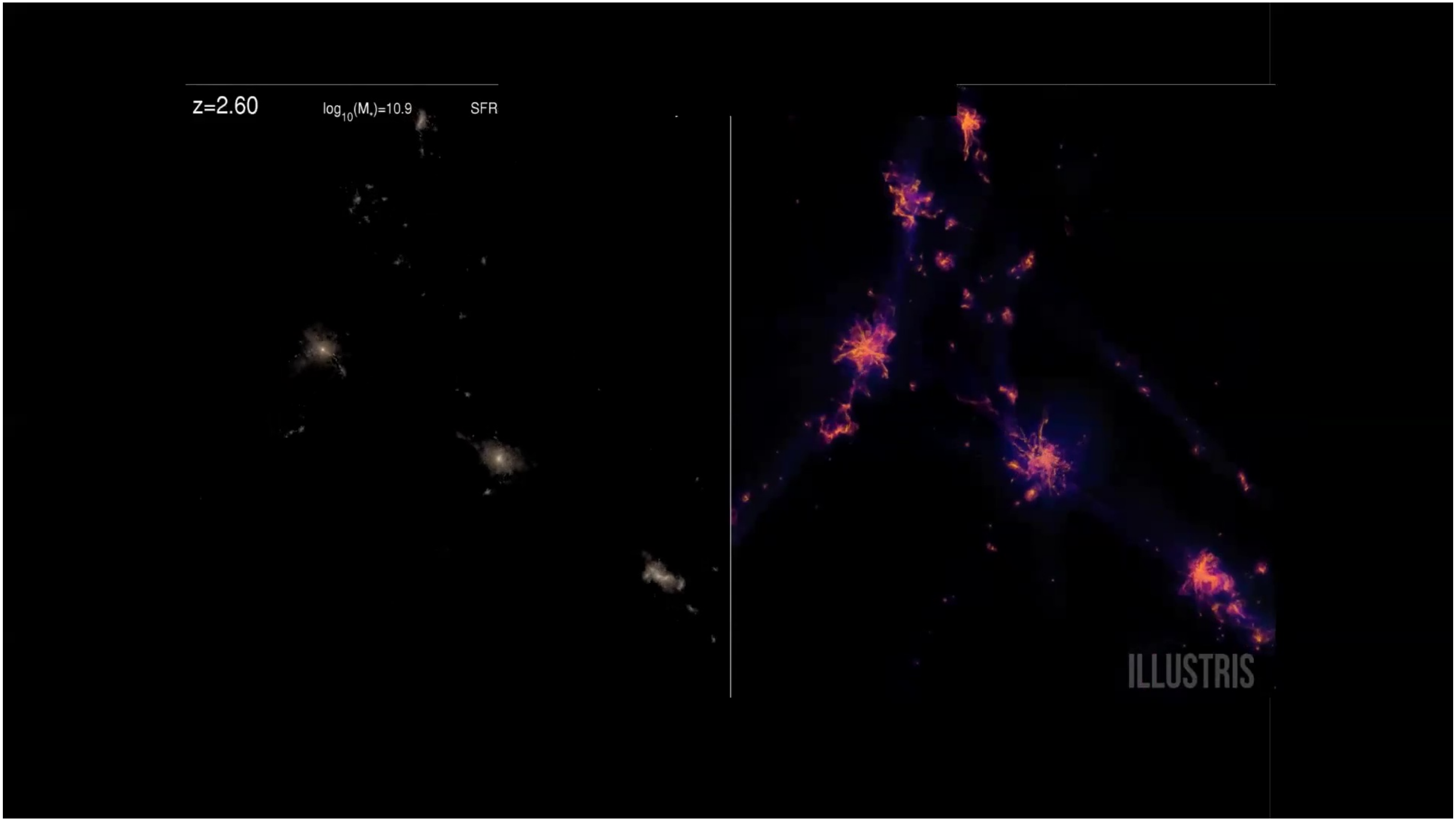


Seed BH mass function

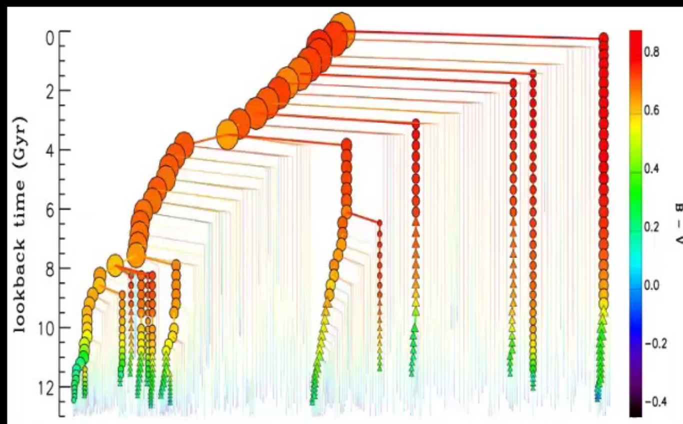
Volonteri 2010



NOTE: The mass function can shift to lower values when wind mass loss and fragmentation are taken into account


z=2.60
log10(M*)=10.9
SFR
ILLUSTRIS

In a nutshell



(From de Lucia et al. 2006)

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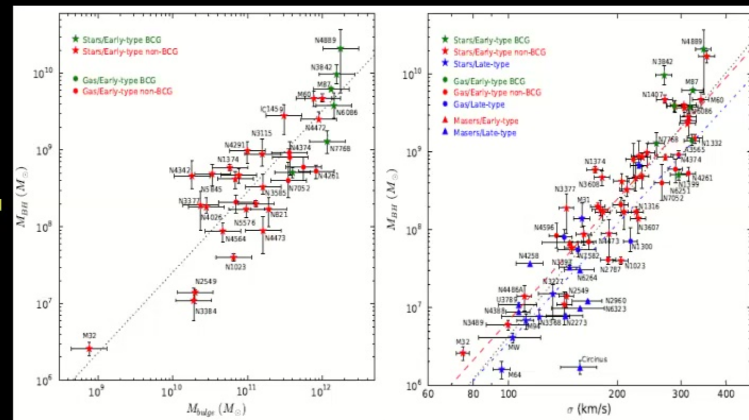

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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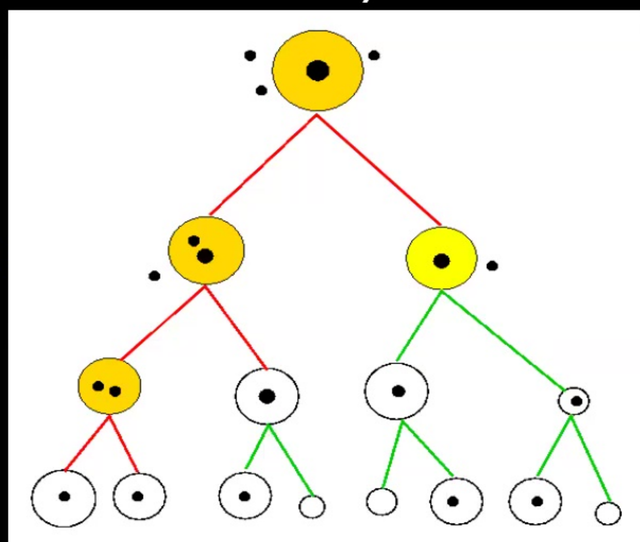
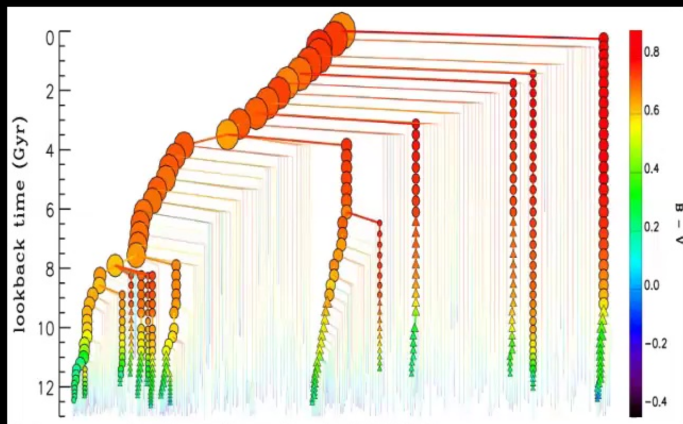


(Menou et al 2001, Volonteri et al. 2003)

In a nutshell



(From de Lucia et al. 2006)

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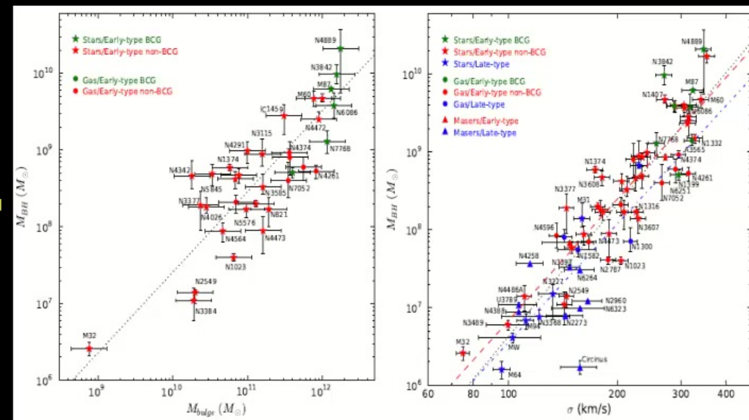

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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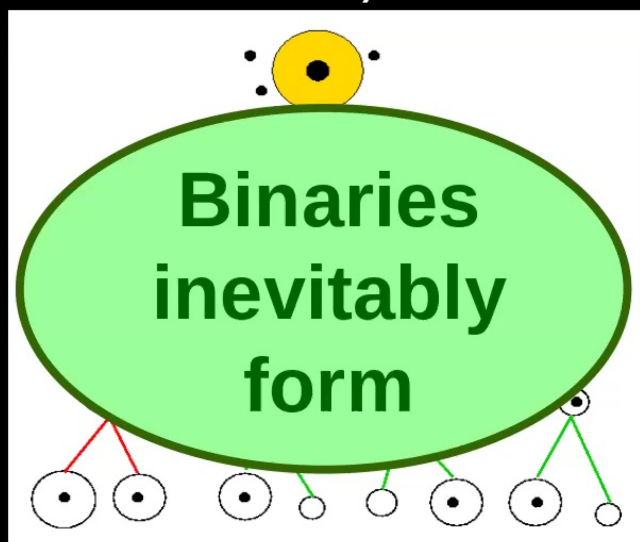


(Menou et al 2001, Volonteri et al. 2003)

*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?

Accretion

During mergers, gravitational instabilities drive cold gas toward the galactic nucleus, this gas can form a thin disk around the MBH, starting the accretion process.

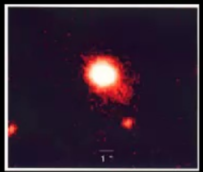
Now consider a flux of proton with density ρ being accreted onto a BH of mass *M*. The accreting material emits radiation with a luminosity *L*. Equating the gravitational force (acting on the accreting material) to the force due to the radiation pressure (exerted by the outward radiation emitted by the accretion disk itself)

$$F_{\rm grav} = \frac{GM(m_e + m_p)}{r^2} \approx \frac{GMm_p}{r^2}$$

$$F_{\rm rad} = p_{\rm rad}\ \sigma_T = \frac{L/c}{4\pi r^2}\sigma_T$$

one found an equilibrium condition (in the spherical limit), which is commonly known as ***Eddington accretion limit***, described by the ***Eddington luminosity***:

$$L_{\rm Edd} = \frac{4\pi GMm_{\rm p}c}{\sigma_{\rm T}}$$



L_{EDD}=1.38x10^{38} erg/s for a solar mass BH and scales as the BH mass. A 10^{9} solar mass MBH shines with a luminosity of about 10^{47} erg/s (10^{14} Suns or 1000 MWs)!!!!!

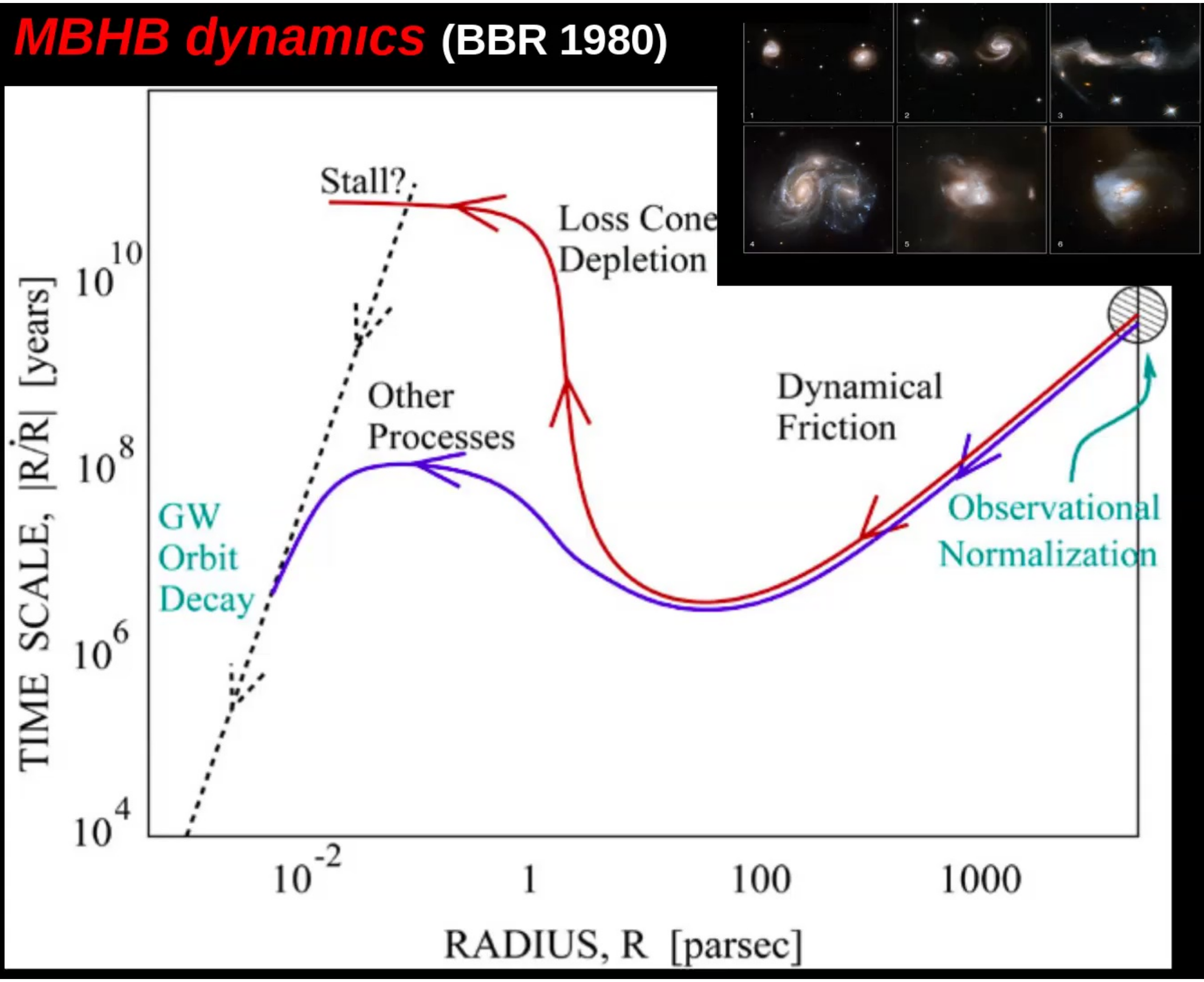
This imply an accretion in mass given by:

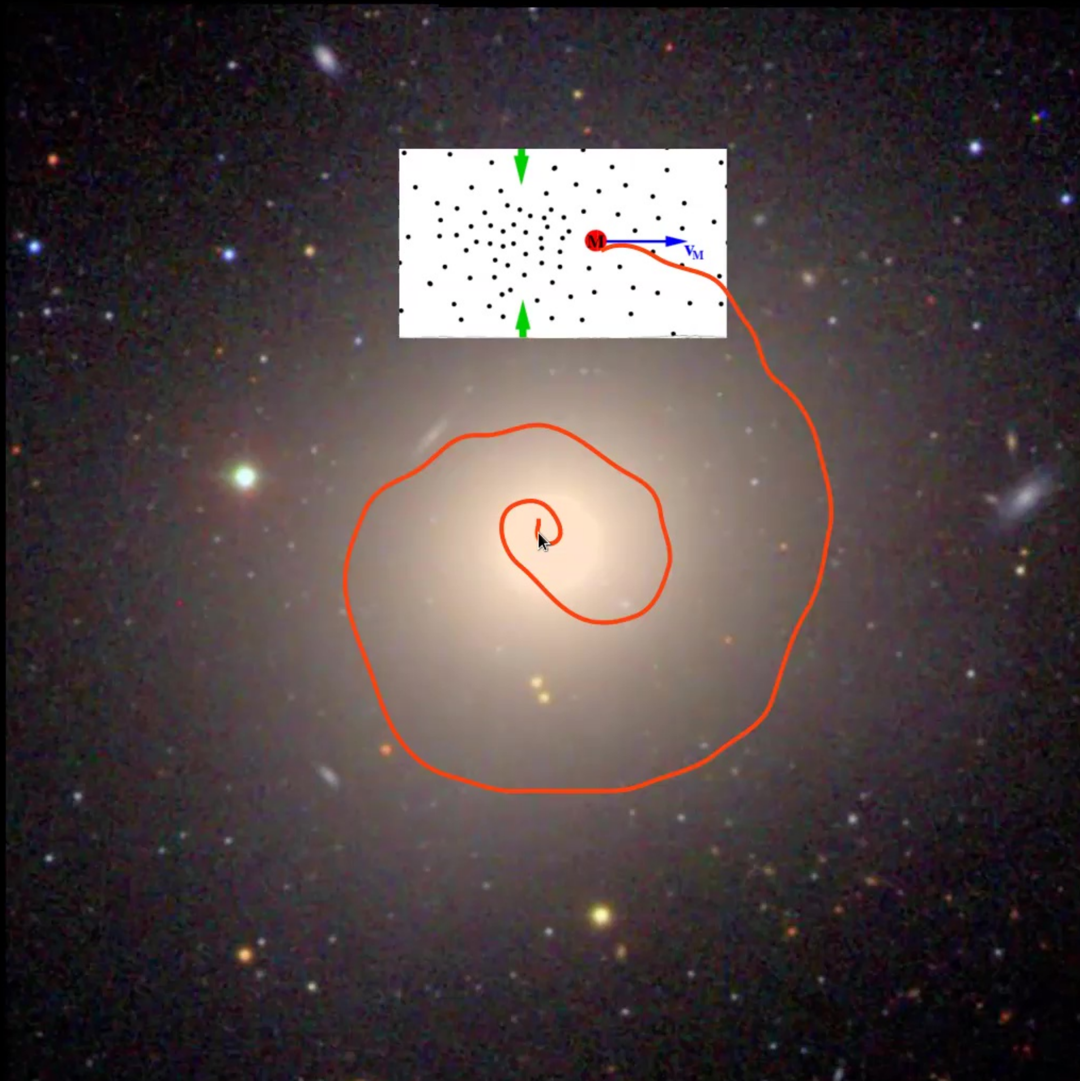
$$\frac{dM}{dt} = 2.5 \times 10^{-8} \left(\frac{M}{\rm M_\odot}\right) {\rm M_\odot yr^{-1}}$$

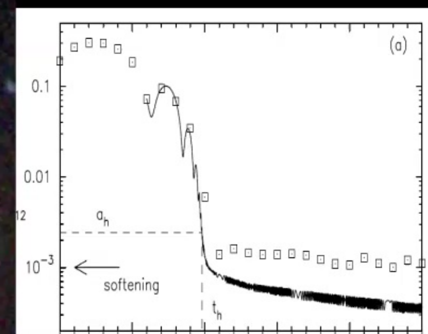
MBHs CAN EFFICIENTLY INCREASE THEIR MASS!!!!!!

Mergers

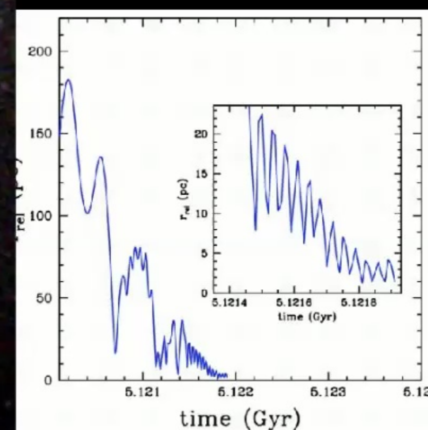
MBHB dynamics (BBR 1980)





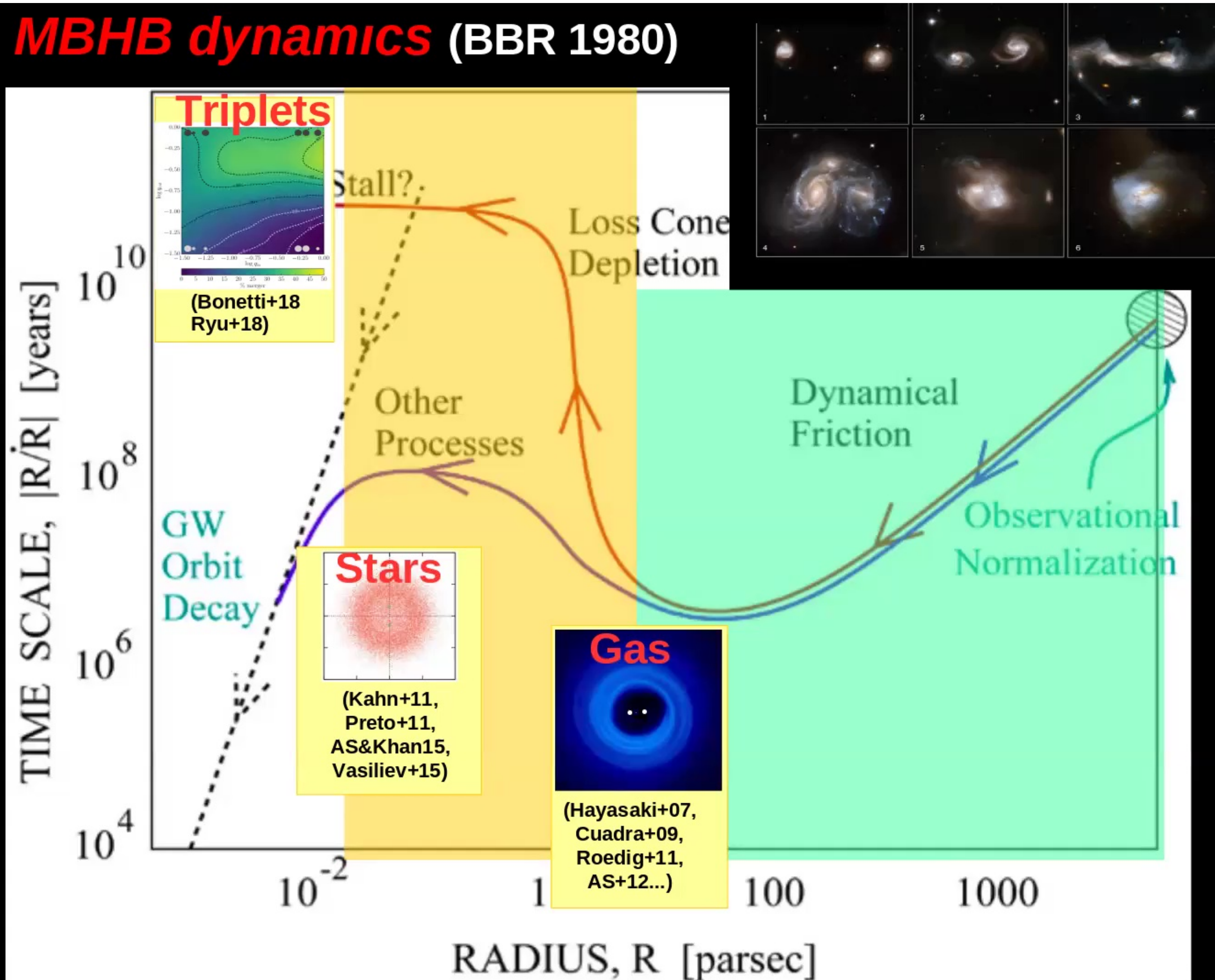


Milosavljevic & Merritt 2001

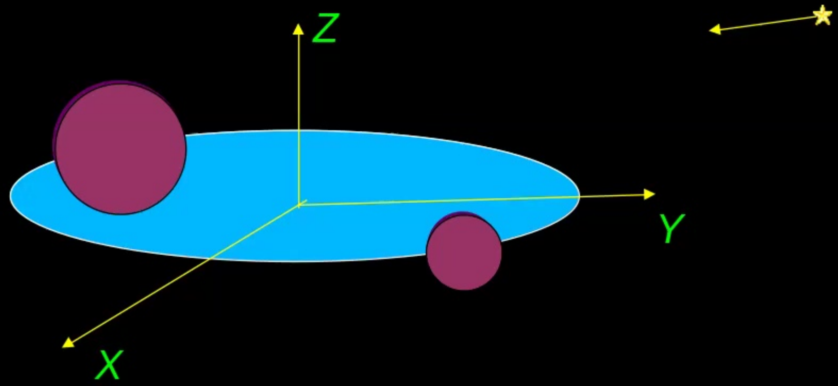


Colpi & Dotti 2009

MBHB dynamics (BBR 1980)



2a-stellar scattering



A star on a intersecting orbit receive a kick taking away from the binary an amount of energy of the order $(3/2)Gm_*\mu_{\rm BH}/a$

This energy, and the relative angular momentum carried away, can be used to define dimensionless rate that describe the evolution of the binary.

$$\frac{dN}{dt} = n\Sigma\sigma = \frac{2\pi G(M_1 + M_2 + m_3)na}{\sigma}$$

$$\frac{da}{dt} = \frac{da}{dt}\Big|_{3b} + \frac{da}{dt}\Big|_{\rm gw} = -Aa^2 - \frac{B}{a^3},$$

$$A = \frac{GH\rho_{\rm inf}}{\sigma_{\rm inf}}, \quad B = \frac{64G^3M_1M_2MF(e)}{5c^5},$$

$$a_{*/\rm gw} = \left[\frac{64G^2\sigma_{\rm inf}M_1M_2MF(e)}{5c^5H\rho_{\rm inf}}\right]^{1/5}$$

Triaxiality of the merger remnant keeps the 'loss cone full' and the hardening rate ~constant

The evolution of the binary can be simply obtained by combining stellar and GW hardening (e.g. AS & Khan 2015)

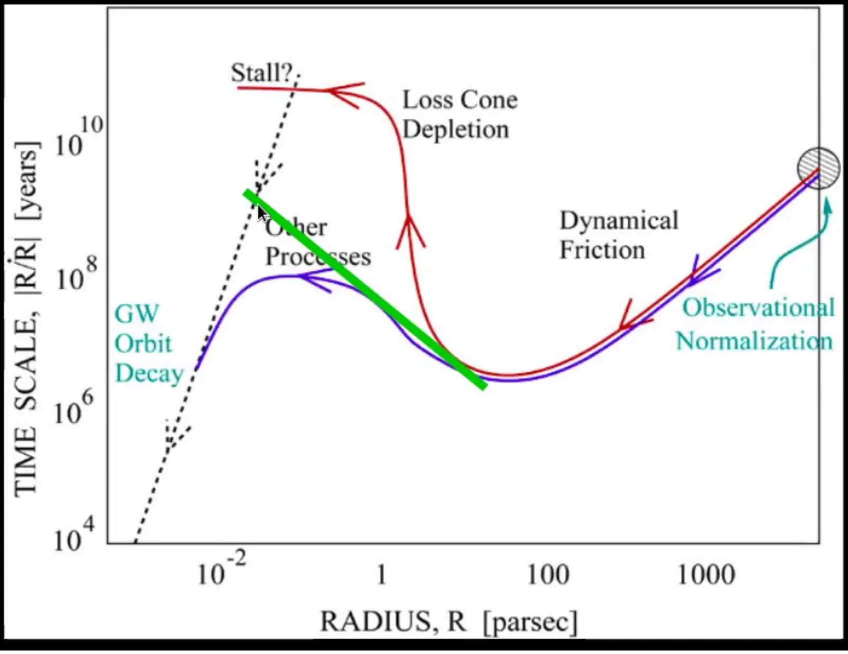
The binary spends most of its time at the transition separation

$$t(a_{*/\rm gw}) = \frac{\sigma_{\rm inf}}{GH\rho_{\rm inf}a_{*/\rm gw}}.$$

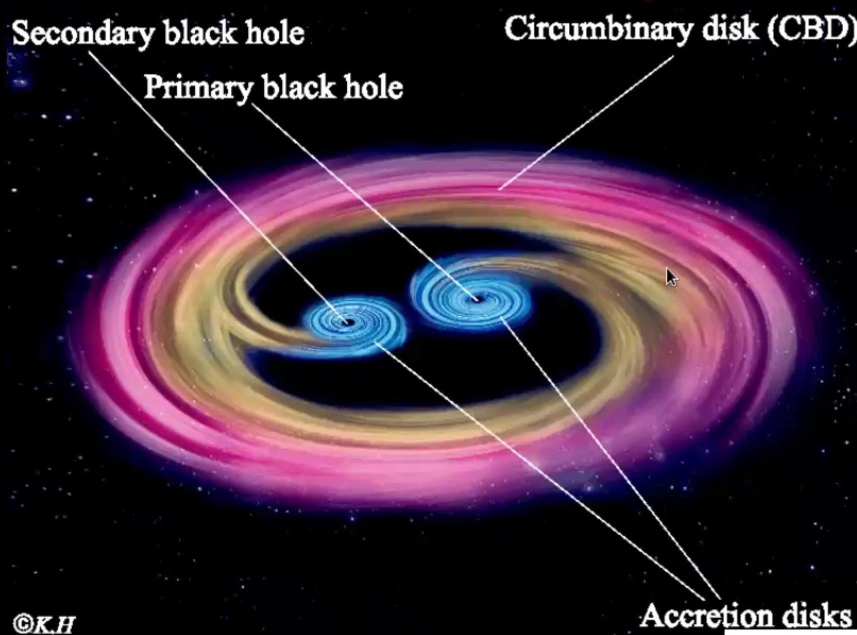
Assuming an isothermal sphere and a simple M-sigma relation

$$a_{*/\rm gw} \approx 0.01\,{\rm pc}\left(\frac{M}{10^8{\rm M}_\odot}\right)^{3/4}$$

$$t(a_{*/\rm gw}) \approx 10^8{\rm yr}.$$



2b-Circumbinary disk-driven binaries



Gas inflows with a constant accretion rate. Its change in angular momentum is

$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

The binary acts as a dam holding the gas at r_{gap} .

Therefore is injecting in the disk an angular momentum equal and opposite to the above

Therefore the angular momentum of the binary also evolve as

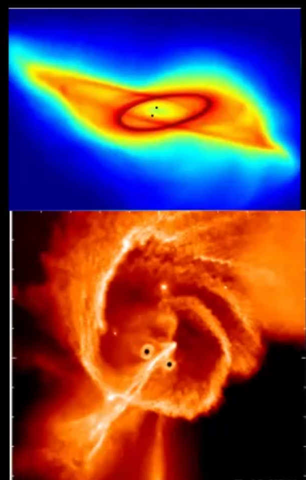
$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

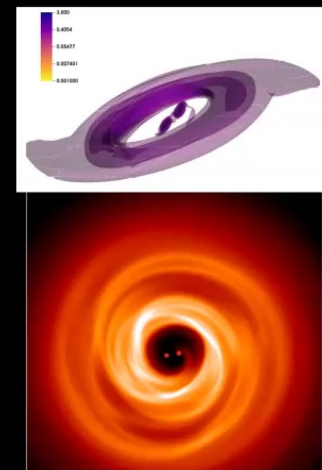
Using $L = \mu\sqrt{GMa}$ and assuming that the mass ratio does not change one get the equation

$$\frac{da}{a} = -2\sqrt{2}\frac{dM}{\mu}$$

The binary makes ~3 e-folds by accreting a mass equal to mu. Assuming Eddington limited accretion this happens in ~4 x 10^7 yrs. (Dotti+15)

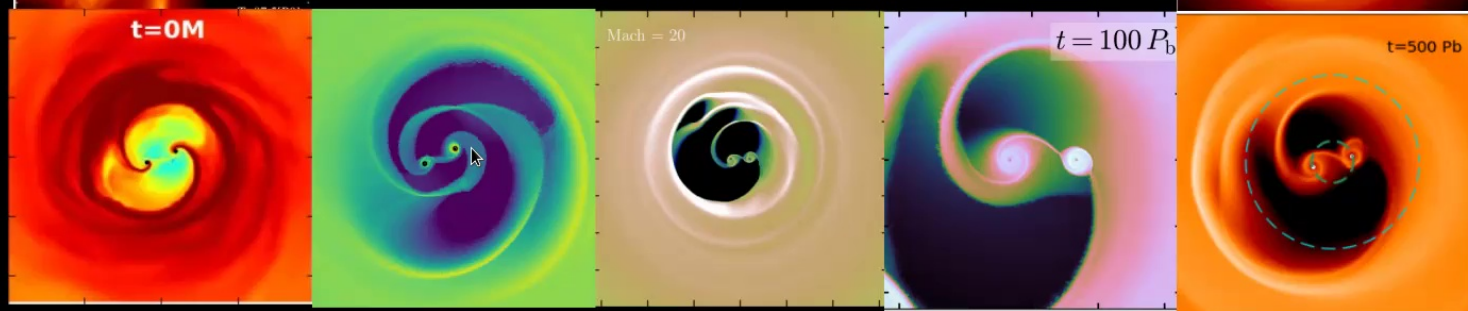
Massive black hole binaries orbital evolution





Magdalena Siwek
(CFA Harvard)

Alberto Sesana
(Universita` di Milano Bicocca)



DISCLAIMER: THIS IS NOT A REVIEW TALK

(If you don’t see your work properly credited, speak up and spark some discussion, it’s the whole point of the session)

Semi-Major axis evolution

-Inspiral vs outspiral?
(Miranda+17, Munoz+19, Tiede+20, Duffell+21, Zrake+21, Franchini+22, and many more)

-Dependence on Mach number / disk aspect ratio
(Tiede+20, Heath&Nixon20, Franchini+22)

-Dependence on eccentricity (Munoz+19)

-Dependence on mass ratio (Duffell+21)

-Dependence on inclination (Moody+19)

Some more things to delve into:

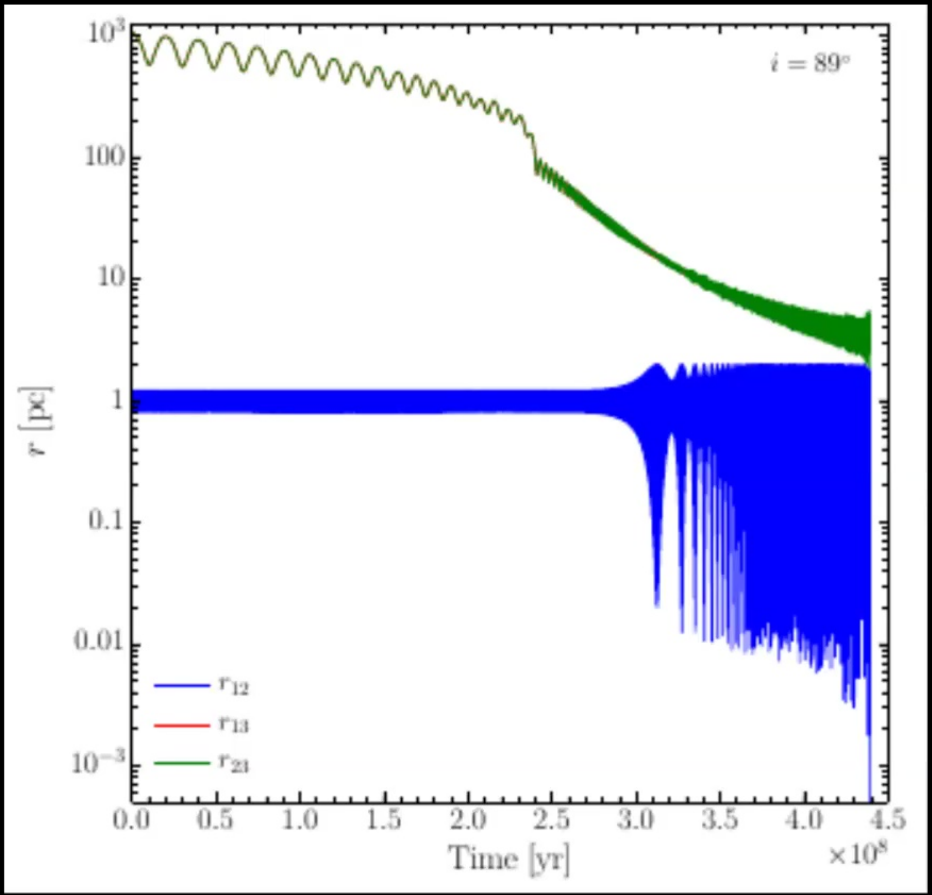
-Retrograde accretion? (Nixon+11, Roedig+14)

-Self gravity? (Cuadra+09, Roedig+11, Franchini+21)

-Clumpy / incoherent feeding (Goicovic+16, Maureira – Fredes+18)

-3D vs 2D simulations?

Integration of the 3-body dynamics



Bonetti et al 2016

We designed a code for evolving MBHB triplets including

-PN dynamics up to 2.5 order, including all terms consistently derived from the 3-body Hamiltonian

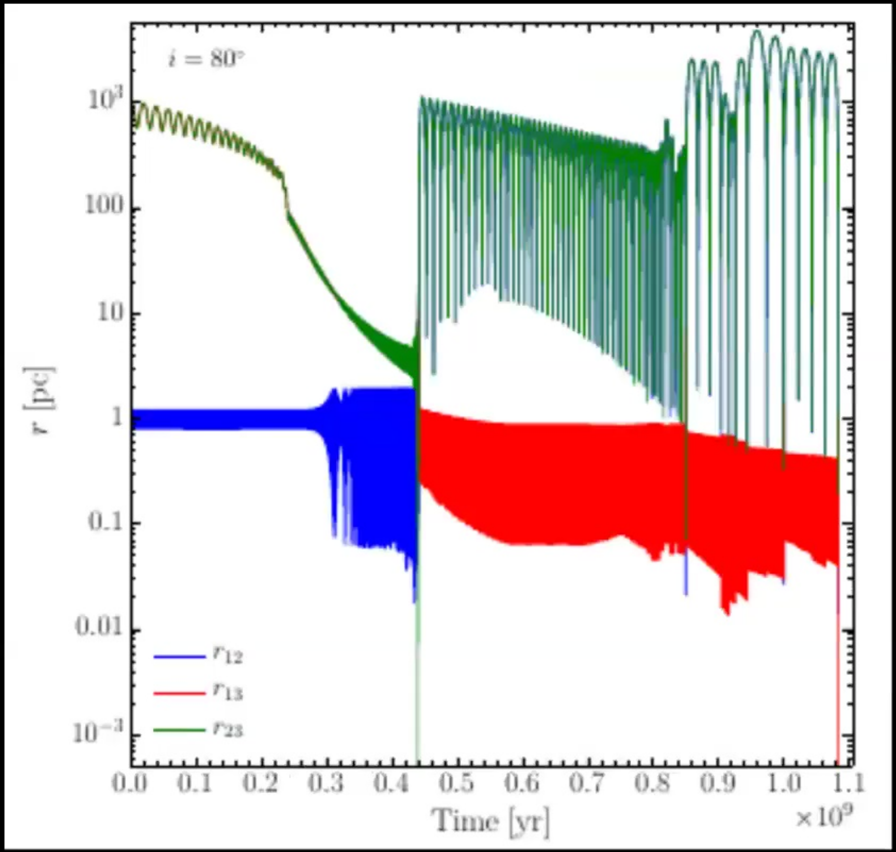
-Dynamical friction (Chandrasekhar 1943)

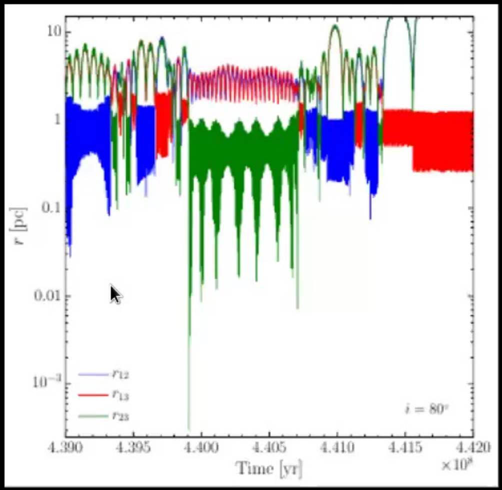
-Stellar hardening (Sesana 2006)

-Spherical external potential

The code has been extensively tested reproducing results from the literature.

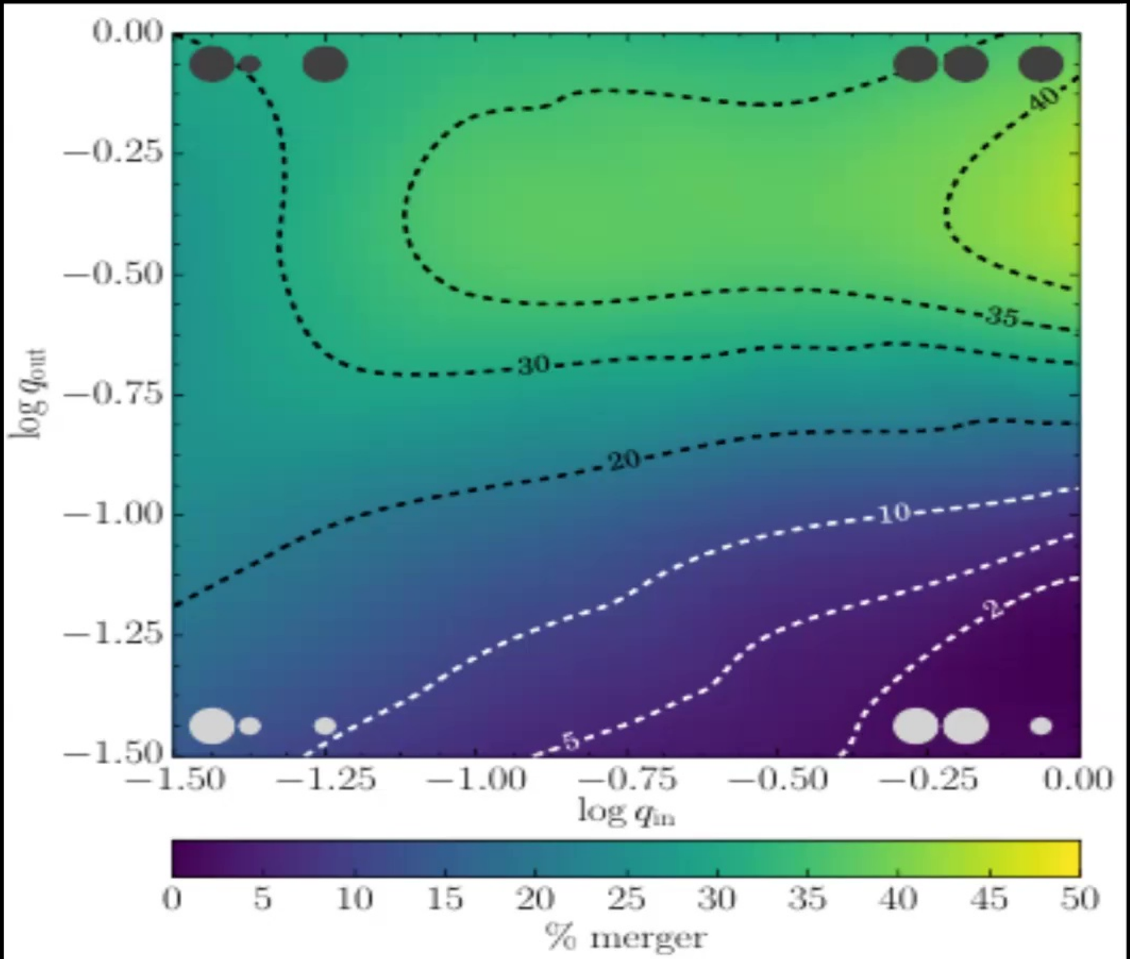
It can handle complex chaotic dynamics



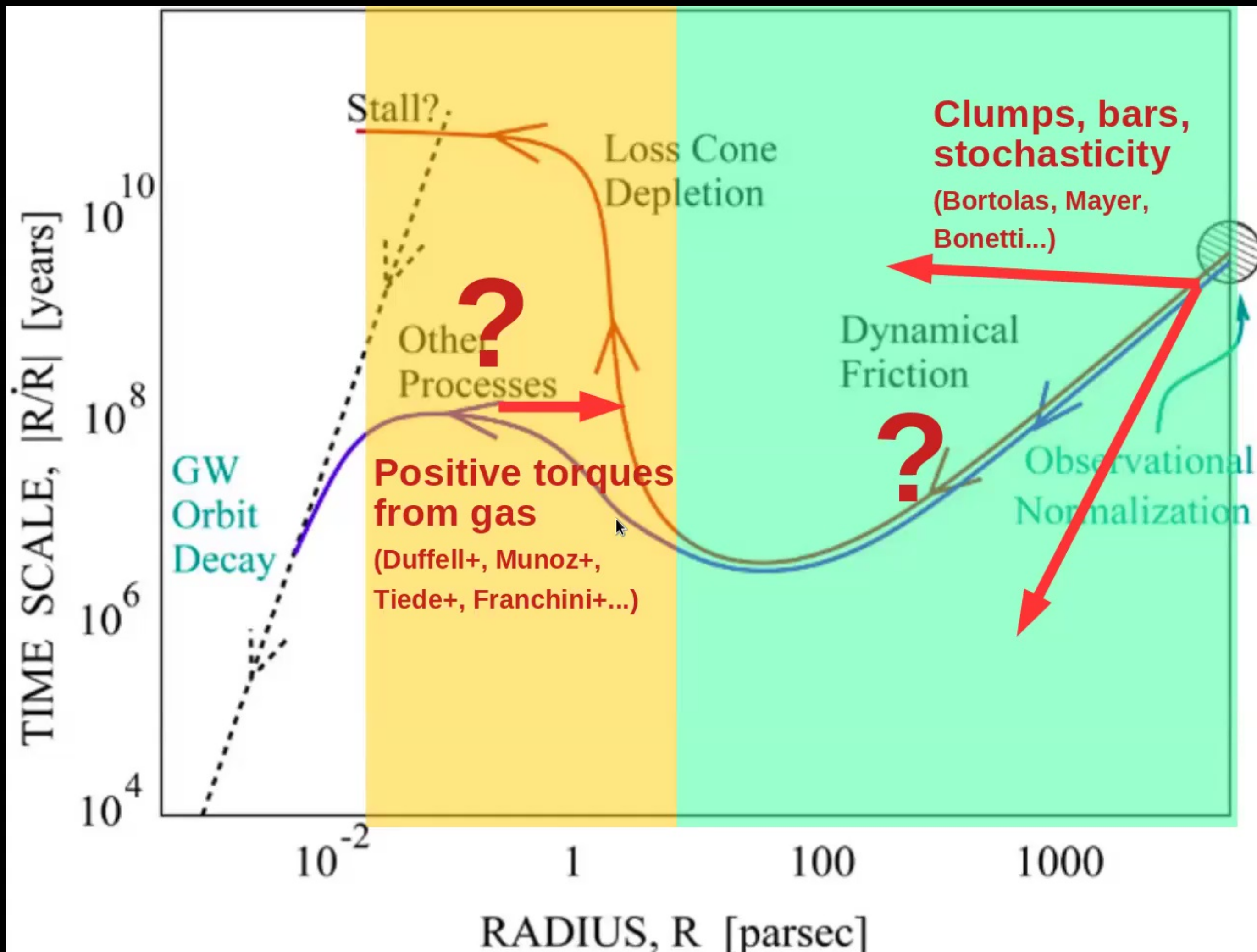


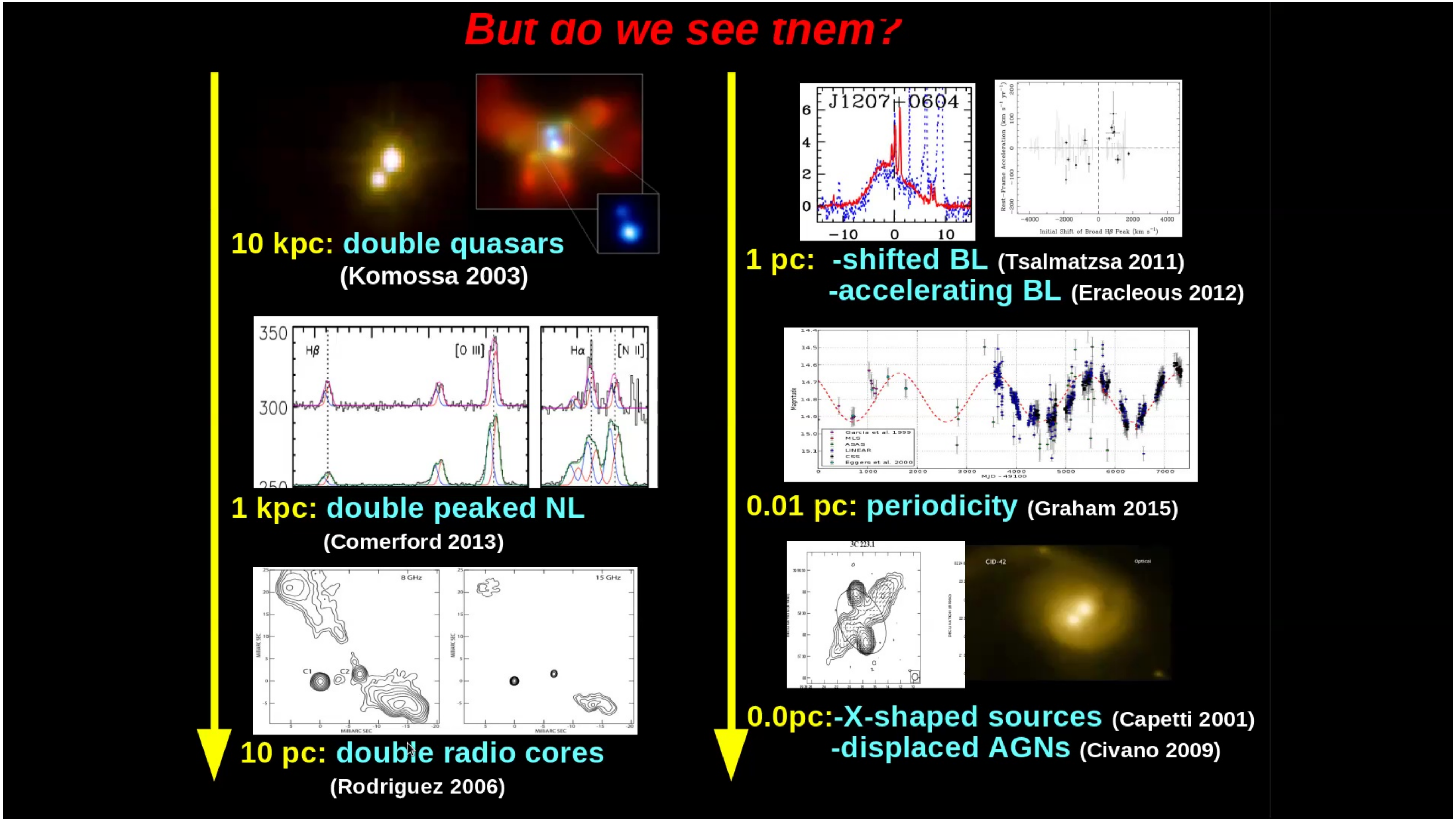
Merger occurs in about 30% of the cases. Equal mass triplets are more likely to produce a merger

Bonetti et al 2018



MBHB dynamics (2020)




But do we see them?
10 kpc: double quasars
(Komossa 2003)
1 kpc: double peaked NL
(Comerford 2013)
10 pc: double radio cores
(Rodriguez 2006)
1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)
0.01 pc: periodicity (Graham 2015)
0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)
J1207+0604
Hβ
[O III]
Hα
[N II]
8 GHz
15 GHz
C1
C2
3C 223.1
CID-42

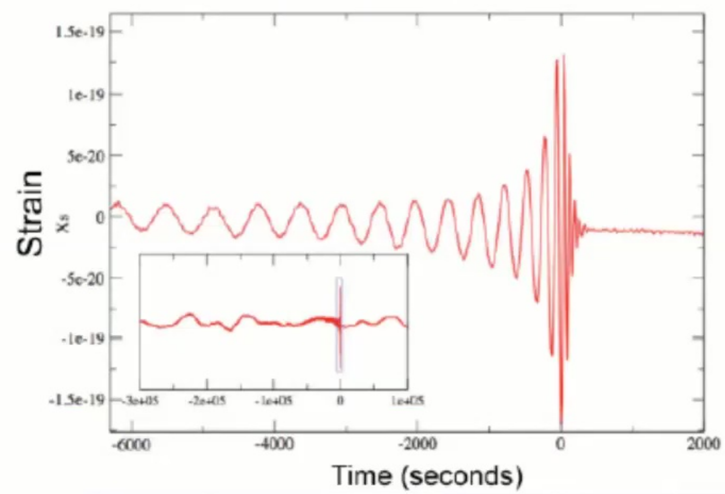
Gravitational waves

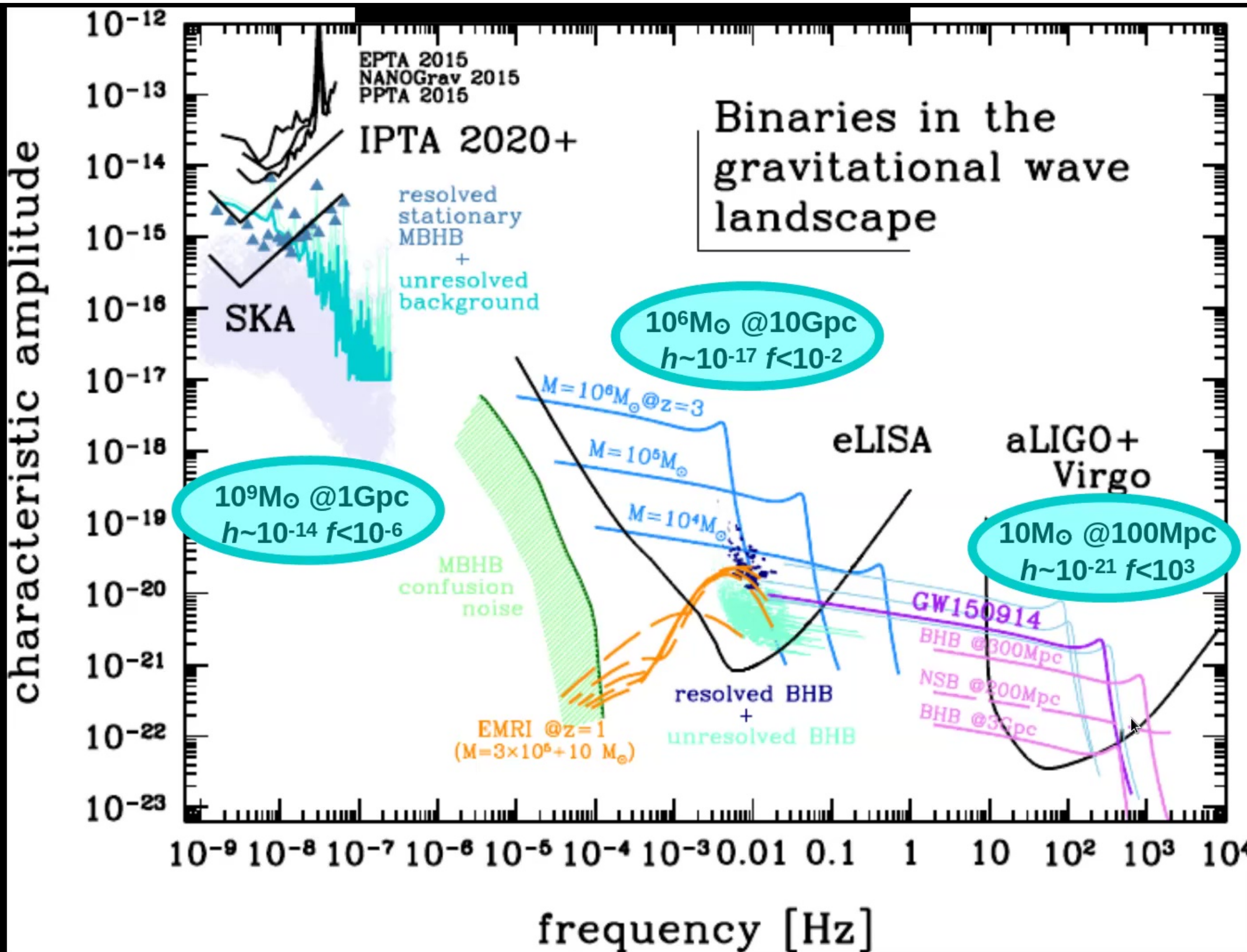
If the binary overcome the final parsec problem then it coalesces on a timescale given by:

$$t_{\rm GW} = \frac{5c^5}{256G^3}\frac{a^4}{M_1 M_2 M F(e)} \approx 0.25{\rm Gyr}\left(\frac{M M_1 M_2}{10^{18.3}\,{\rm M_\odot}^3}\right)^{-1} F(e)^{-1}\left(\frac{a}{0.001{\rm pc}}\right)^4$$

producing the ***loudest gravitational wave signals in the Universe!***

Simulated LISA data stream at merger event,
two $10^5 M_\odot$ BH at z=5 including simulated noise (S/N~500)



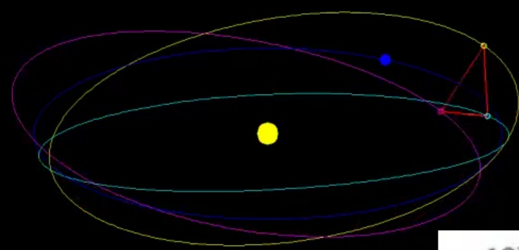


characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
$10^6M_\odot$ @10Gpc
$h\sim10^{-17}$ $f<10^{-2}$
$10^9M_\odot$ @1Gpc
$h\sim10^{-14}$ $f<10^{-6}$
$10M_\odot$ @100Mpc
$h\sim10^{-21}$ $f<10^{3}$
$M=10^6M_\odot$@z=3
$M=10^5M_\odot$
$M=10^4M_\odot$
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
resolved BHB + unresolved BHB
EMRI @z=1 ($M=3\times10^5+10$ $M_\odot$)

The Laser Interferometer Space Antenna

Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

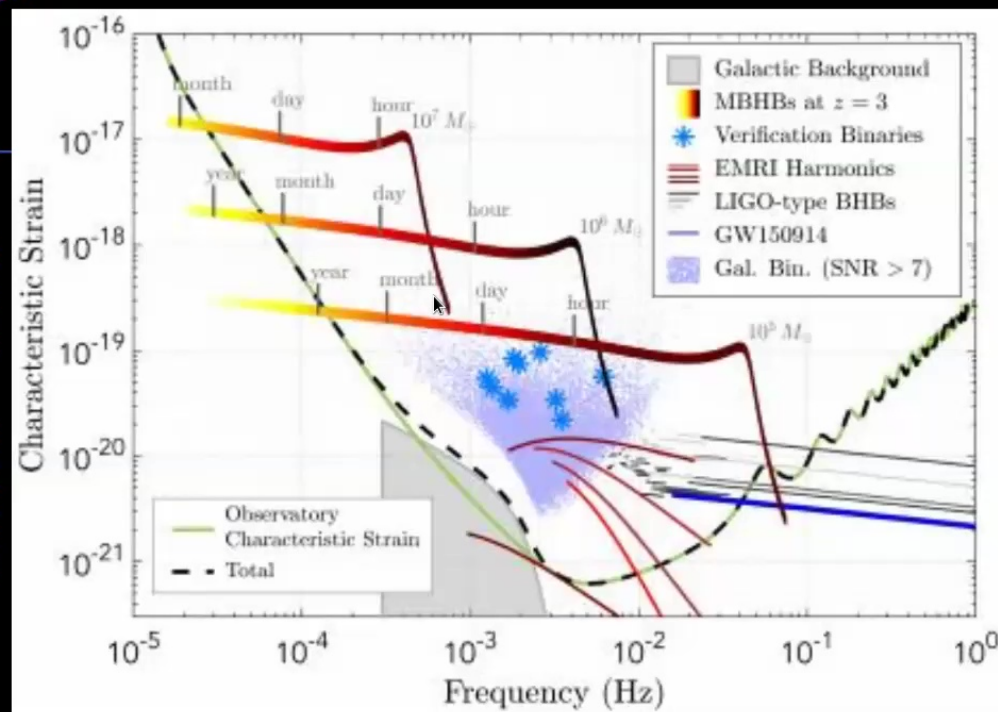
Observes the full inspiral/merger/ringdown

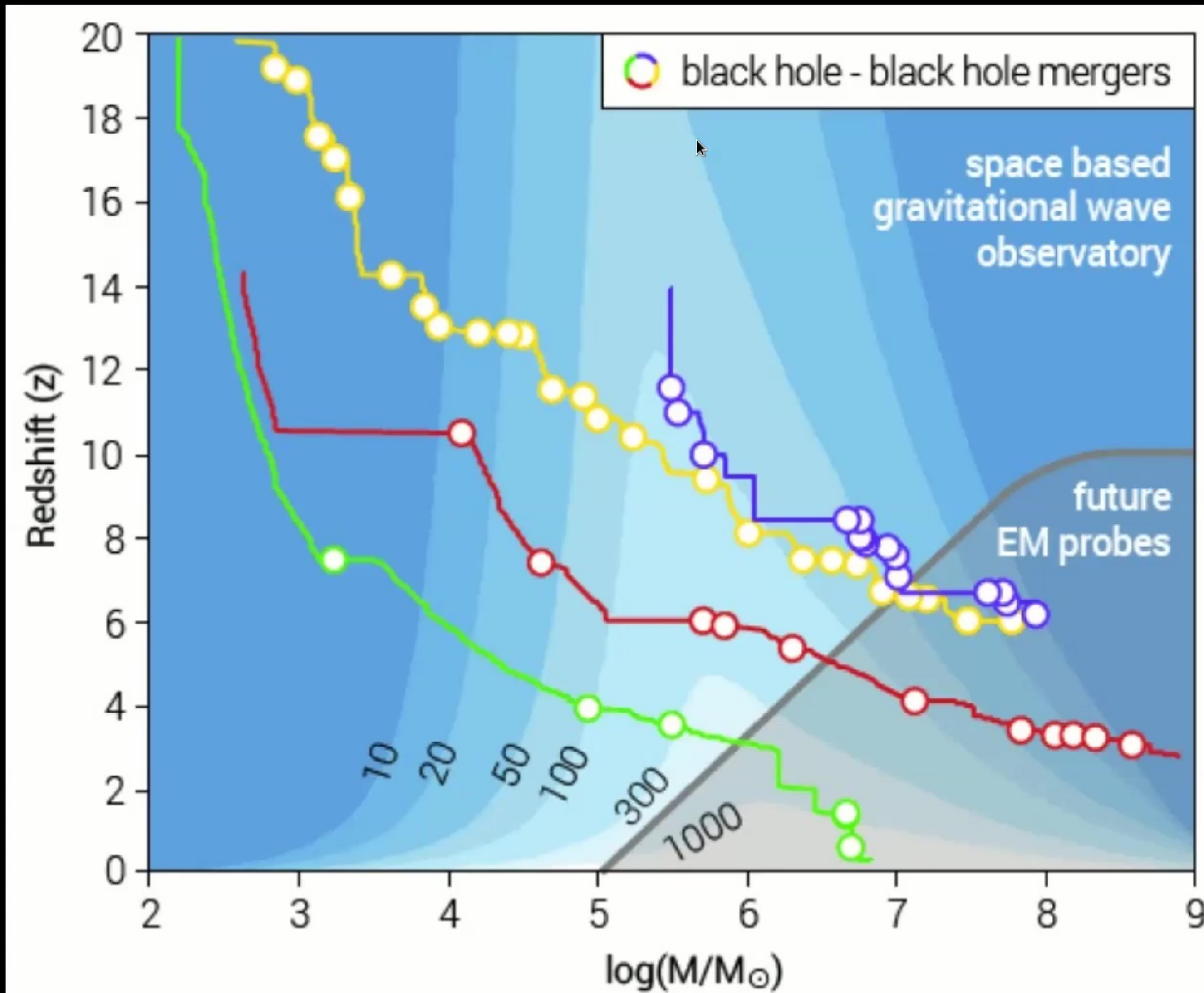


Nicolas Douillet - ARTEMIS

3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)



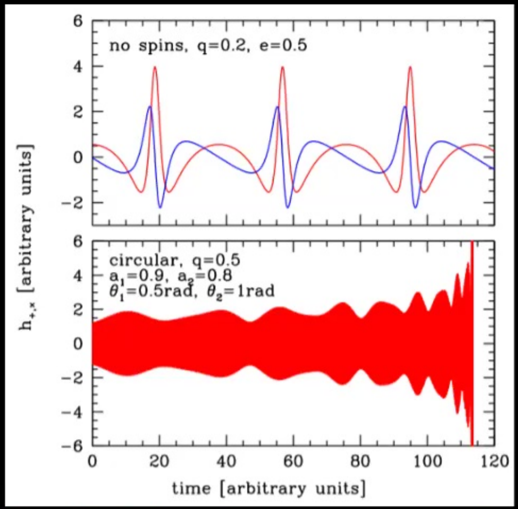

black hole - black hole mergers
space based gravitational wave observatory
future EM probes
Redshift (z)
log(M/M⊙)
10
20
50
100
300
1000
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

What LISA will measure

Assuming 4 years of operation:

~100+ detections

~100+ systems with sky localization to 10 deg2



~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

~50 systems with secondary spin determined to 0.1

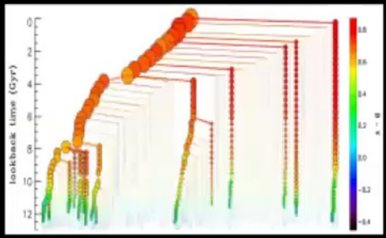
~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

MBH astrophysics with GW observations

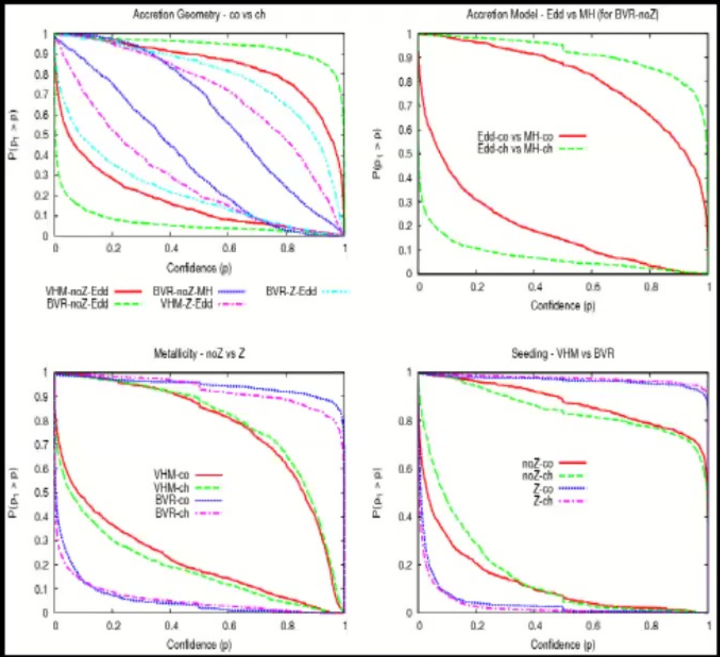
Astrophysical unknowns in MBH formation scenarios

1- **MBH seeding mechanism** (heavy vs light seeds)
2- **Metallicity feedback** (metal free vs all metalliticies)
3- **Accretion efficiency** (Eddington?)
4- **Accretion geometry** (coherent vs. chaotic)



CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

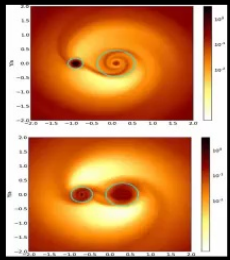
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models



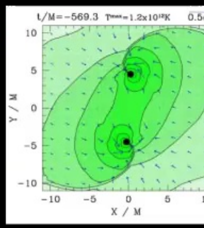
AS et al. 2011, see also Plowman et al 2011

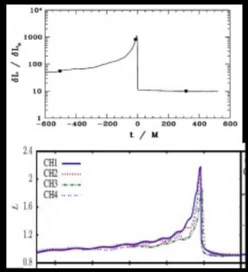
Associated electromagnetic signatures

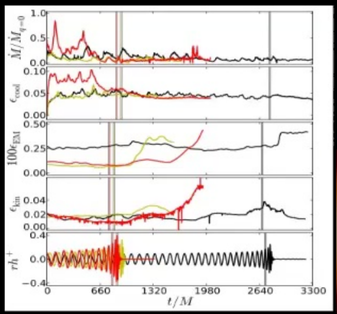
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014, Tang et al. 2018...)

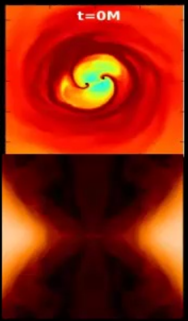


Simulations in hot gaseous clouds. Significant flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)



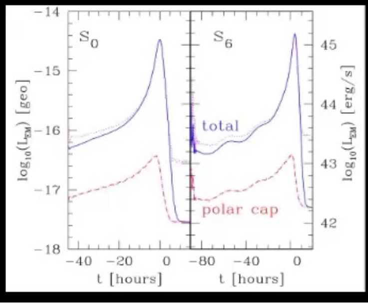


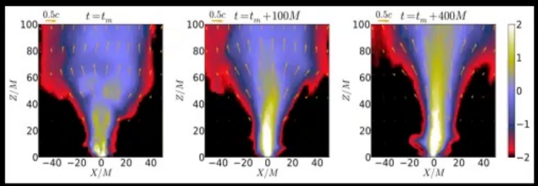


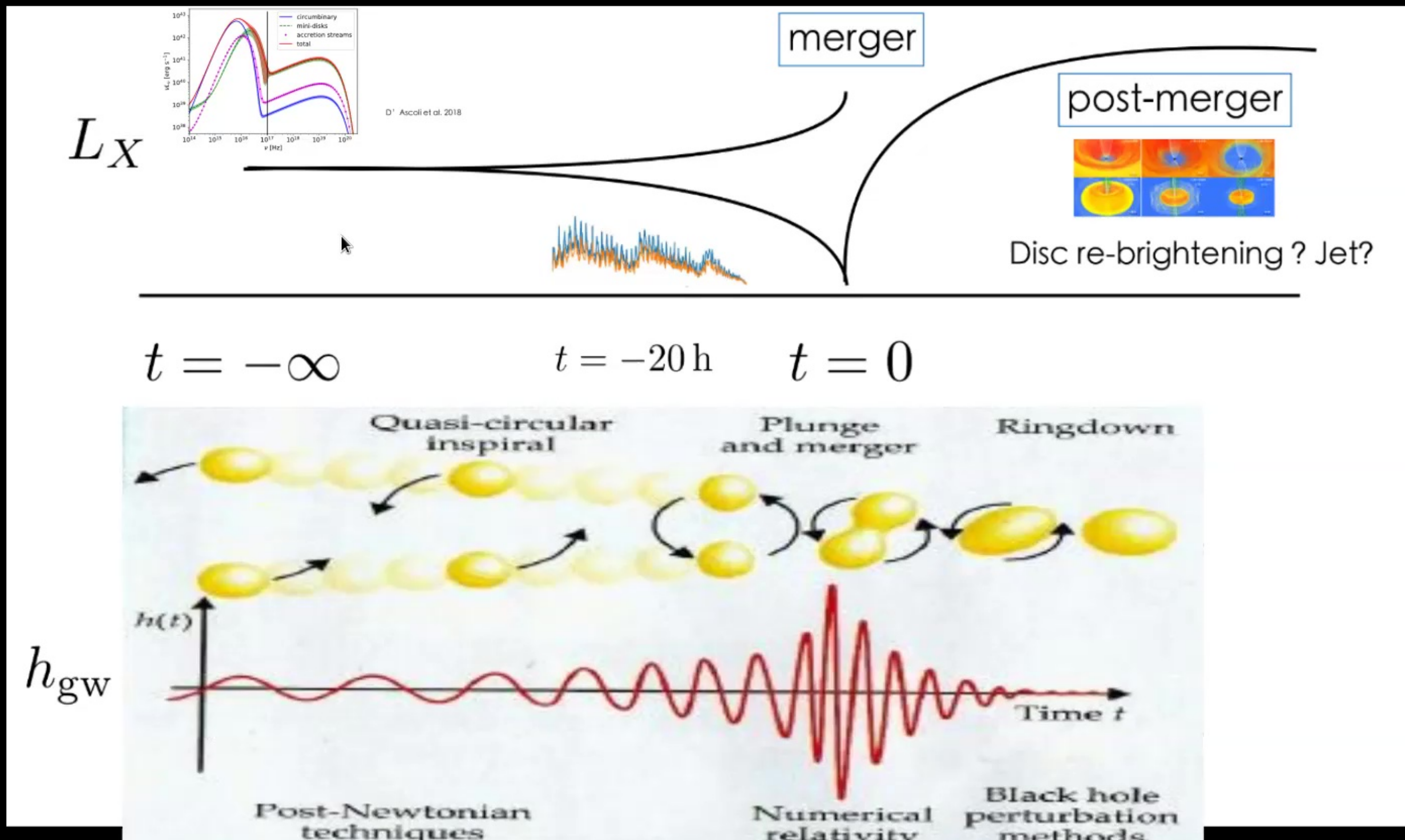


Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

Full GR force free electrodynamics
(Palenzuela et al. 2010, 2012)

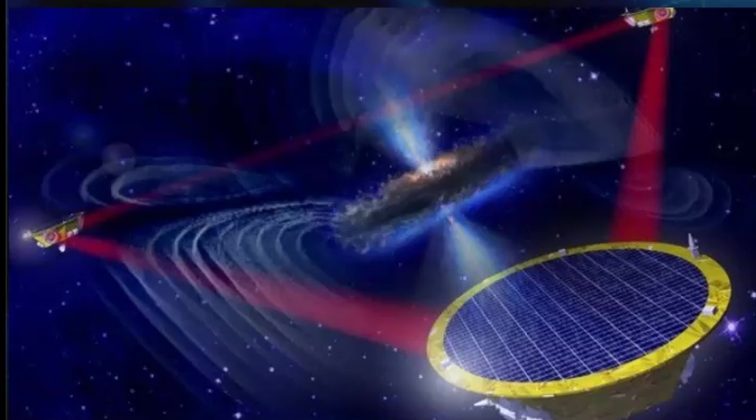






(Palenzuela+ 2010, Gold+ 2014, Farris+ 2014, Tang+ 2017, 2018, D'Ascoli+ 2018, ...)

Opportunities for LISA-Athena (LSST/Rubin) synergies

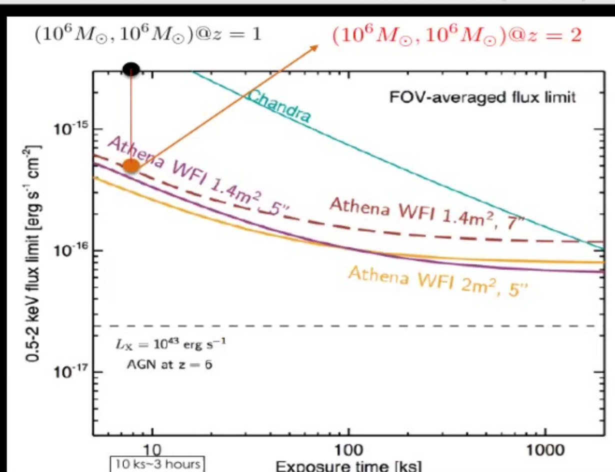


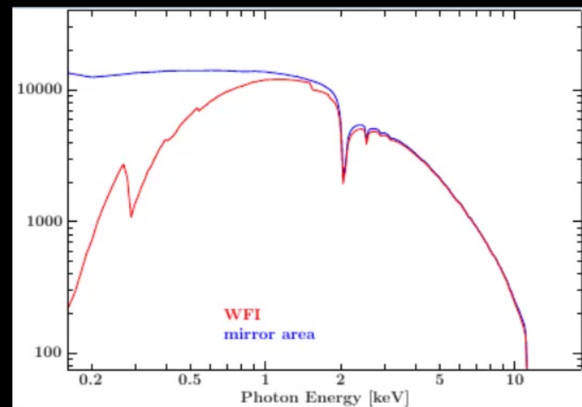
LSST
Large Synoptic Survey Telescope

Athena Wide Field Imager (WFI) (Rau+ 2015)

Parameter	Characteristic
Energy Range	0.1-15 keV
Field of View	ca. 40' x 40' (baseline)

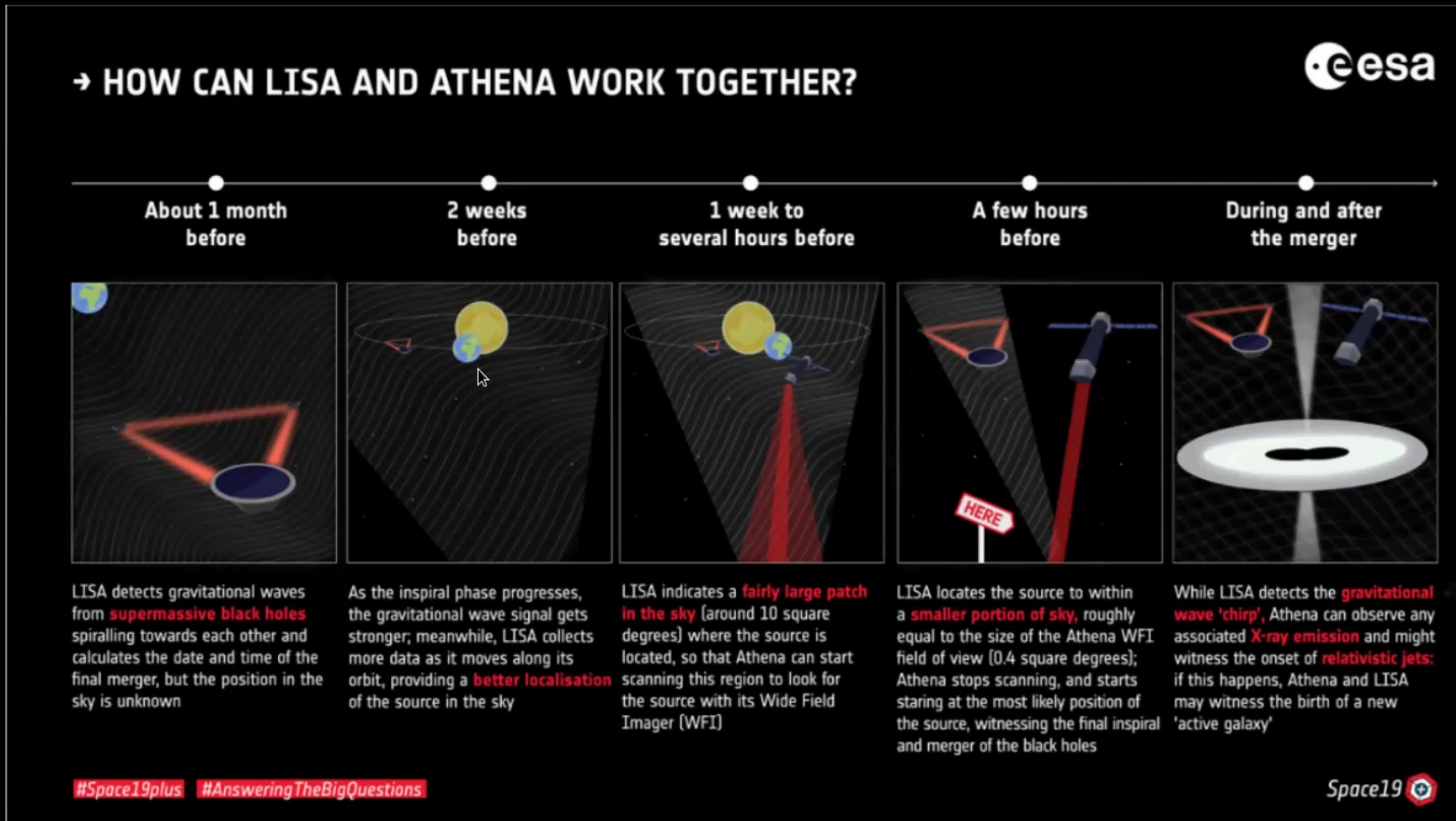
- -X-ray telescope
- -L2 ESA mission (~2030)

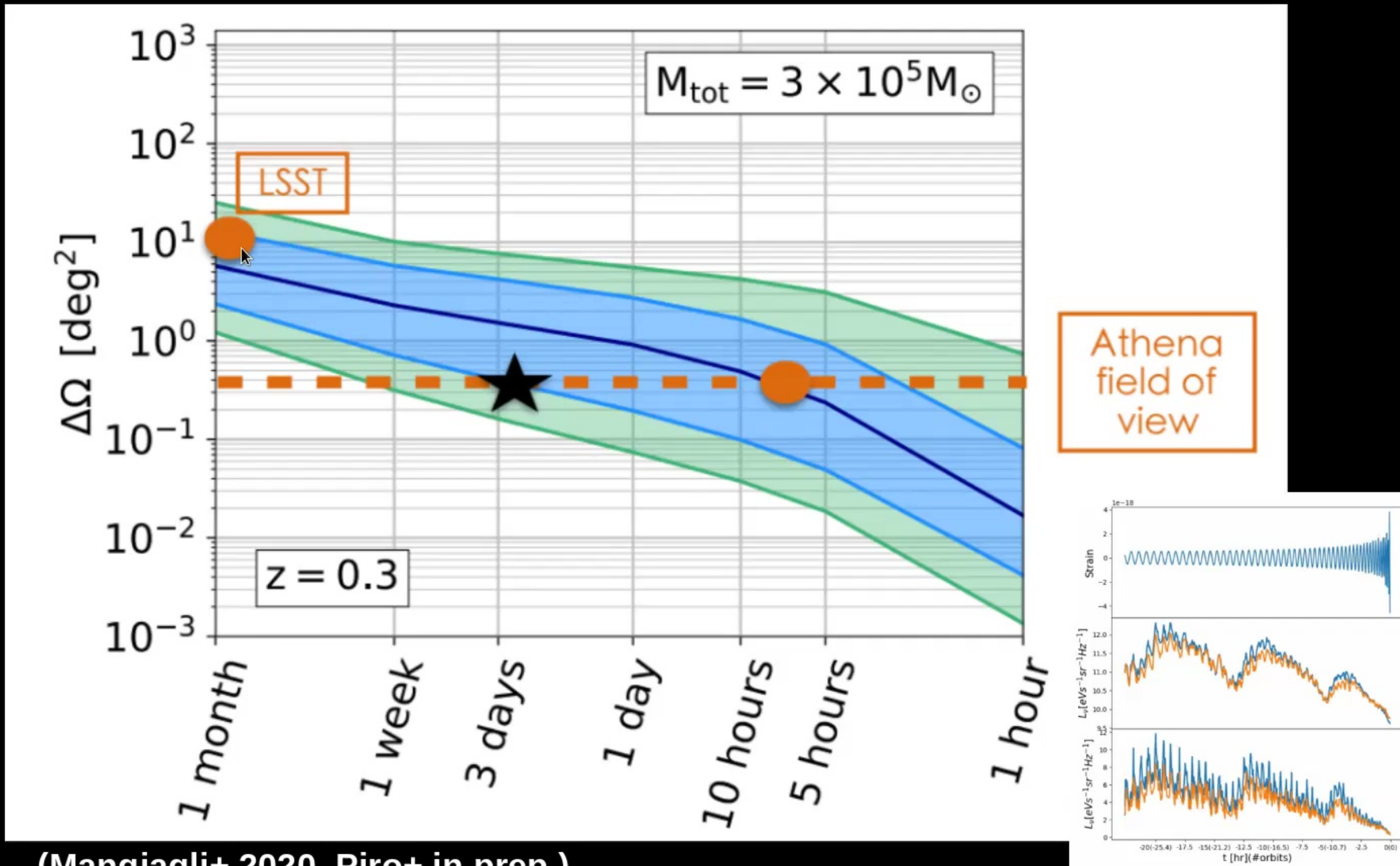




LSST : Vera Rubin observatory (Abell+ 2009)

- -2022+
- -Optical telescope
- -9.6 square degree FoV
- -m~24 within 30s pointings in several different filters


→ HOW CAN LISA AND ATHENA WORK TOGETHER?
esa
About 1 month before
2 weeks before
1 week to several hours before
A few hours before
During and after the merger
HERE
LISA detects gravitational waves from supermassive black holes spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown
As the inspiral phase progresses, the gravitational wave signal gets stronger; meanwhile, LISA collects more data as it moves along its orbit, providing a better localisation of the source in the sky
LISA indicates a fairly large patch in the sky (around 10 square degrees) where the source is located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (WFI)
LISA locates the source to within a smaller portion of sky, roughly equal to the size of the Athena WFI field of view (0.4 square degrees); Athena stops scanning, and starts staring at the most likely position of the source, witnessing the final inspiral and merger of the black holes
While LISA detects the gravitational wave 'chirp', Athena can observe any associated X-ray emission and might witness the onset of relativistic jets: if this happens, Athena and LISA may witness the birth of a new 'active galaxy'
#Space19plus
#AnsweringTheBigQuestions
Space19



(Mangiagli+ 2020, Piro+ in prep.)

- Athena pre-pointing only possible for very low z sources
- LSST/Rubin more suitable for tracking inspiral periodicity (but optical)

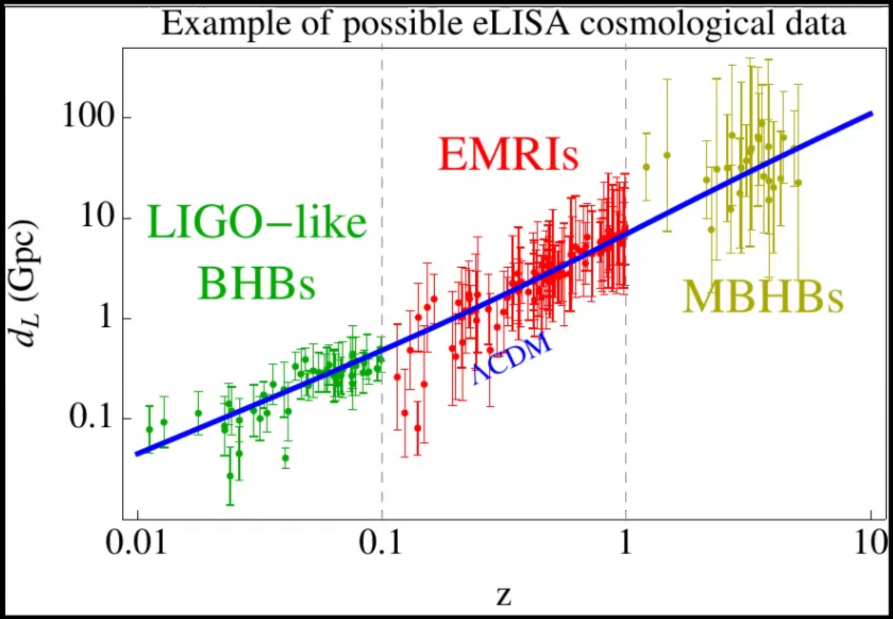
Why multimessenger?

- Cosmology and cosmography at high *z*

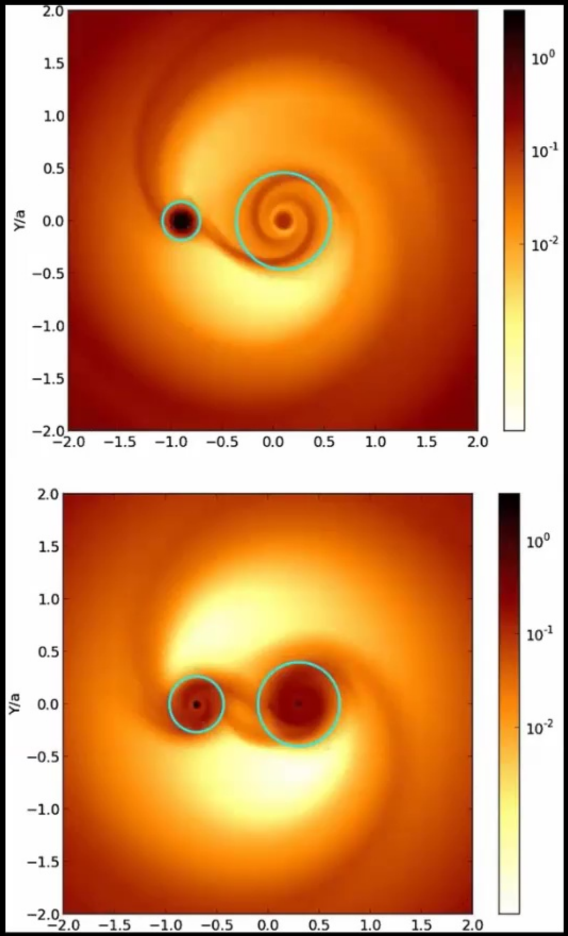
- Study of accretion on MBHs with known mass and spins

- Study of the interplay between MBHs and gas (torques, disk structure, disk models)

- Host galaxy, Jet launches, Quasar birth ...



Courtesy of N. Tamanini



Doggybag

Massive black holes are ubiquitous in the centre of galaxies and exist already at high redshift

The hierarchical model of galaxy evolution imply frequent massive black hole binary mergers

MBHBs are strong sources of gravitational waves for LISA

LISA will probe the whole MBHB cosmic history

Interesting prospects for multimessenger detections of MBHBs
(LISA+Athena? LSST? ….)