# Hearing, seeing, and understanding the universe

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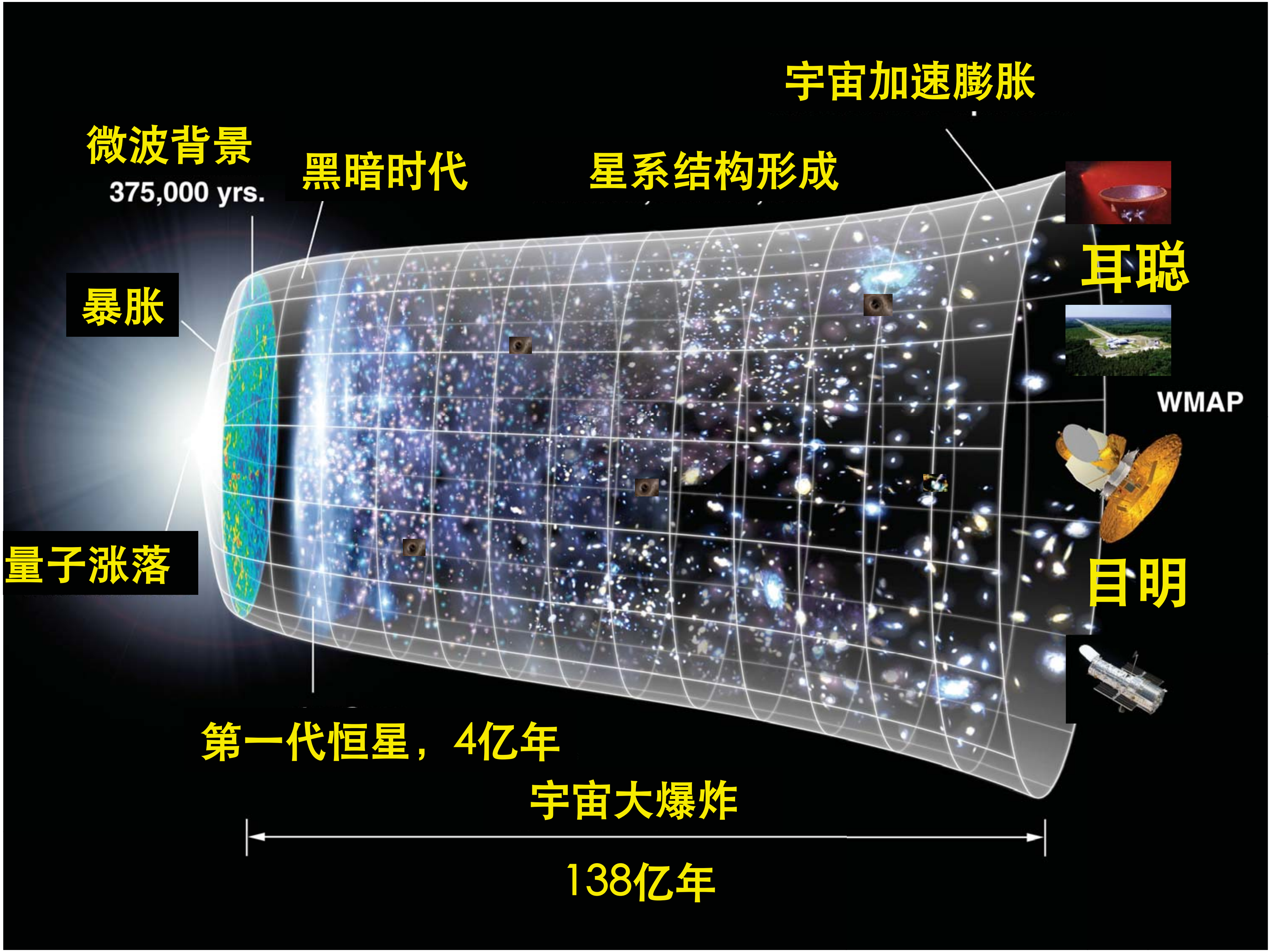
December 19, 2019



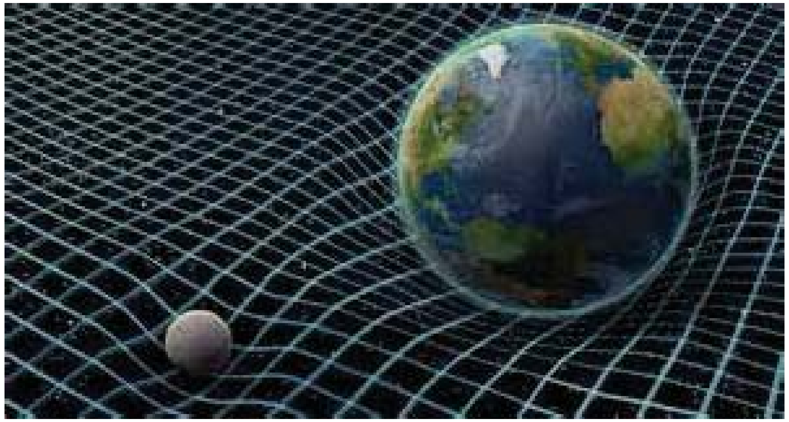
宇宙加速膨胀
微波背景
375,000 yrs.
黑暗时代
星系结构形成
暴胀
耳聪
WMAP
量子涨落
目明
第一代恒星，4亿年
宇宙大爆炸
138亿年

# Outline

- Gravitational waves (GWs)
  - Basics
  - detection
  - significance
- Supermassive binary black holes (BBHs)
  - BHs
    - Stellar-mass BHs
    - Supermassive at galactic centers
      - Evidence: AGNs & Nearby galaxies
      - Galactic center
  - Supermassive BBHs
    - Observational characteristics, BH companion to Sgr A*?
    - Orbital evolution
    - Detection prospects
- Formation and evolution of galaxies and supermassive (BHs)
  - BH growth
  - Galaxy evolution
  - Semi-analytical models
- Opportunities, Challenge & Summary

# Gravitational Waves

- Waves: sonic waves, electromagnetic waves, seismic waves, gravity waves (fluid mechanics) … …
- Gravitational Waves
  - Gravity: Spacetime
    - Static space+time: Newton's gravity
    - Curved spacetime: General relativity
      - Matter/energy distribution→ geometry of spacetime
      - Geometry of spacetime→ motion
      - Change of matter/energy distribution → change of geometry of spacetime
  - Wave properties
- Quantization? Gravitons?
- New probes: Astrophysics



# Spacetime solutions from Einstein's General Relativity

- Einstein field equation
  - Equivalence principle
  - Principle of general covariance

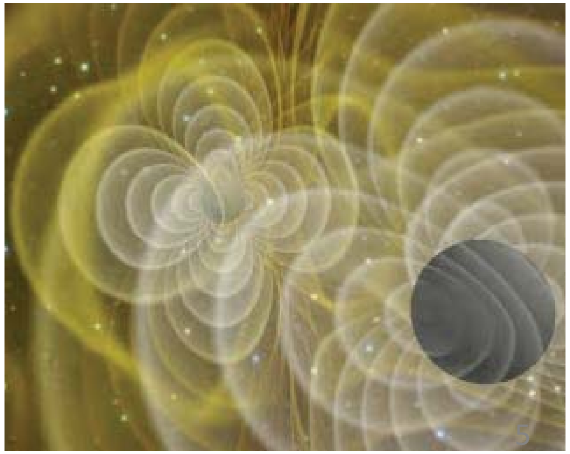
$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

- Weak field: linearization
  - Metric perturbation: Wave equation

$$-\Box \bar{h}_{\alpha\beta} = \frac{16\pi G}{c^4} T_{\alpha\beta} \quad \text{(Lorenz gauge)} \qquad \partial \bar{h}^{\mu\alpha}/\partial x^{\mu} = 0.$$

- Strong field: numerical relativity
  - Breakthrough
  - Challenge

- Observations: no contradictions so far.



# Strength

- Mass, size, velocity,
  (non-spherical symmetric) quadrupole

- Strong source: $v \rightarrow c$, $r \rightarrow GM/c^2$

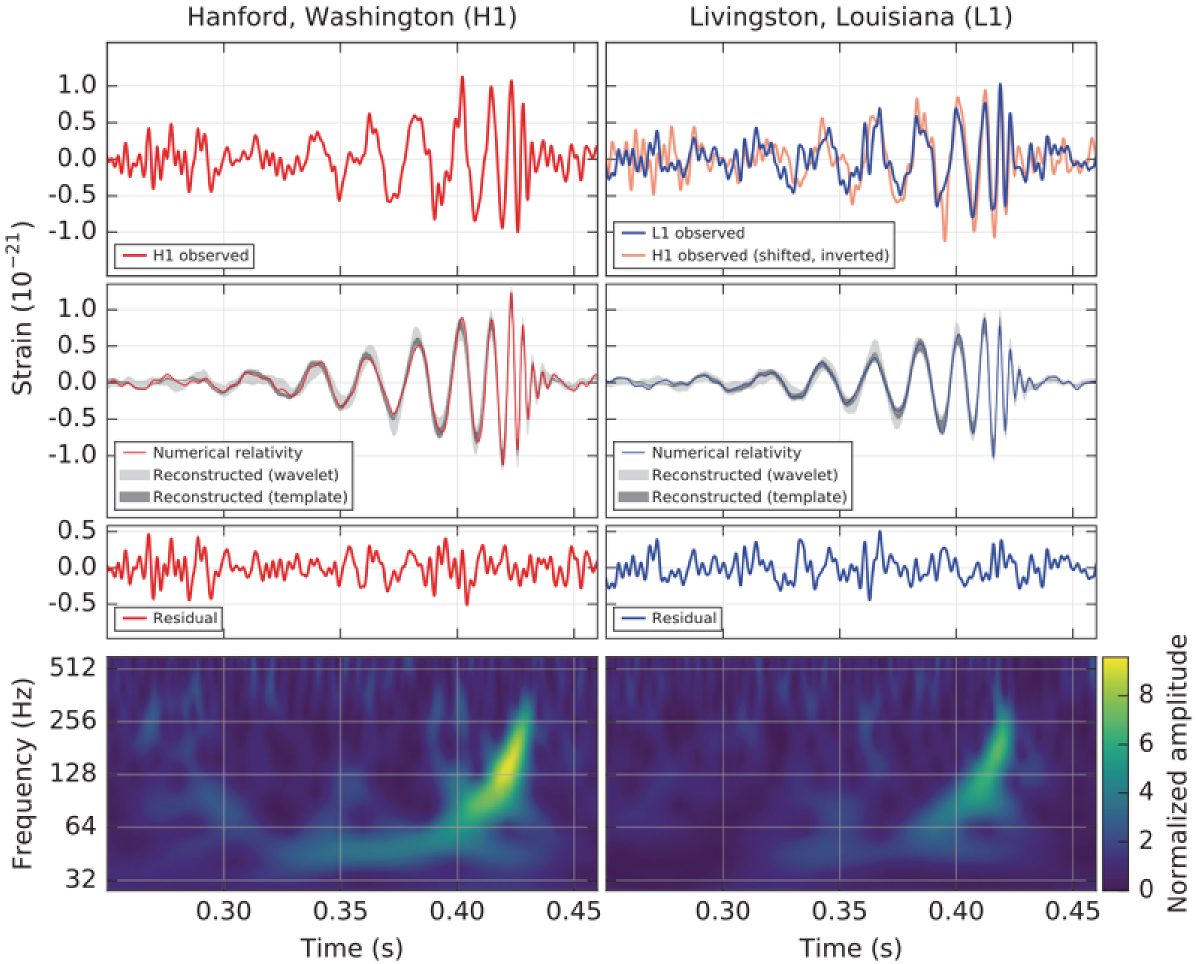
- Strong sources of astronomical objects:
  - Formation/collapse of compact objects (BHs, neutron stars)
  - Inspiral/merger of compact object binaries

- Extremely weak attenuation (why?)

# Gravitational wave direct detection

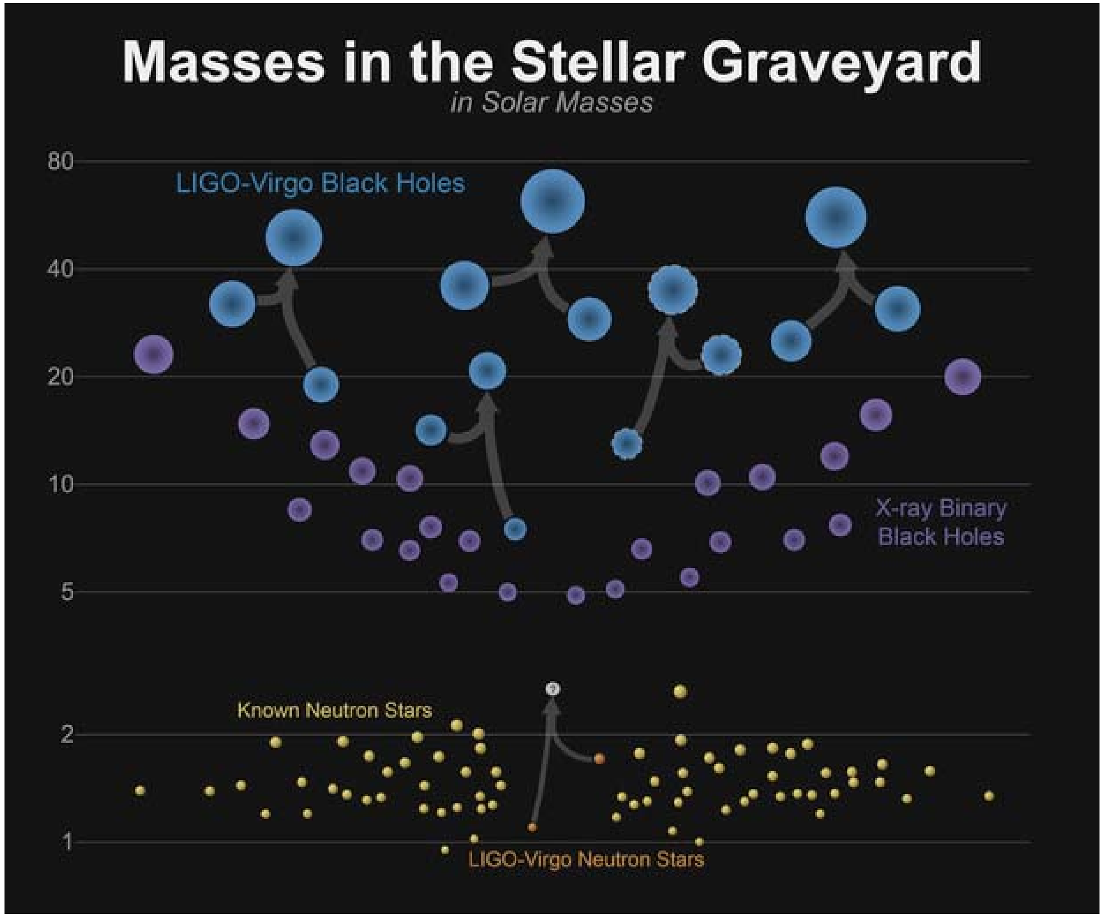

BBH mergers

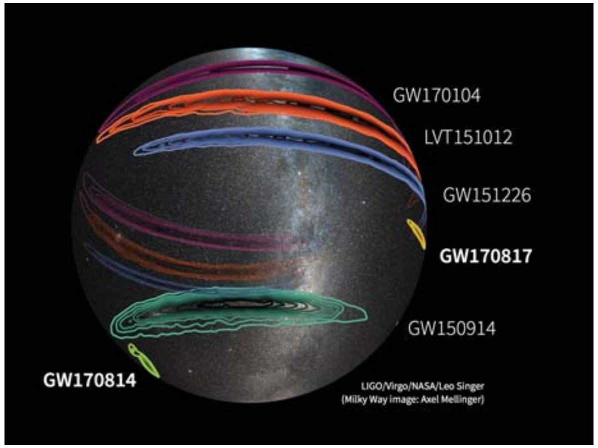
**GW150914**

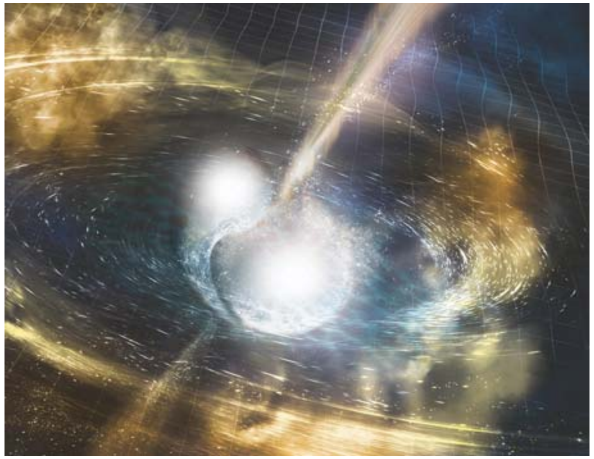



LIGO

(Abbott et al. 2016)

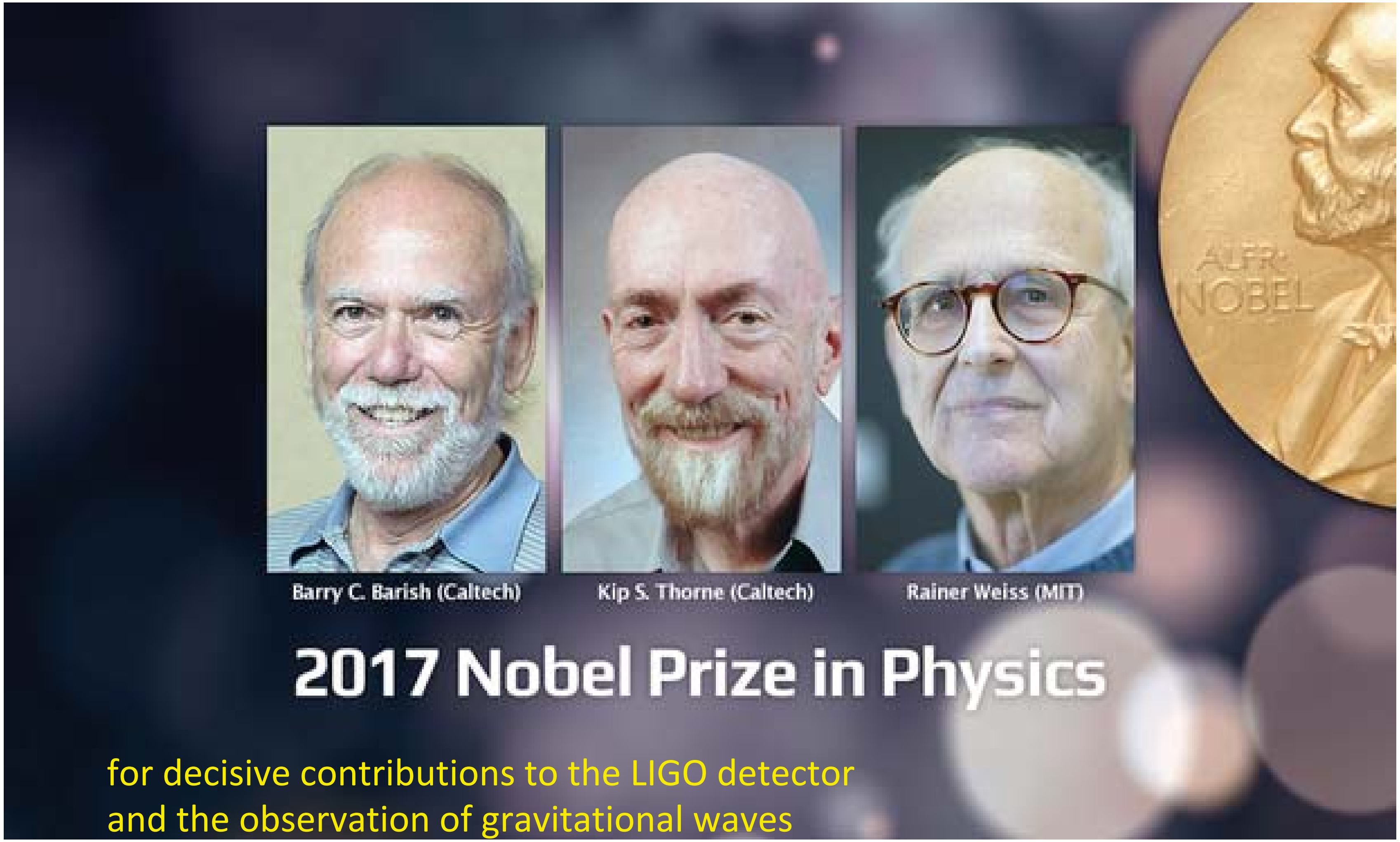


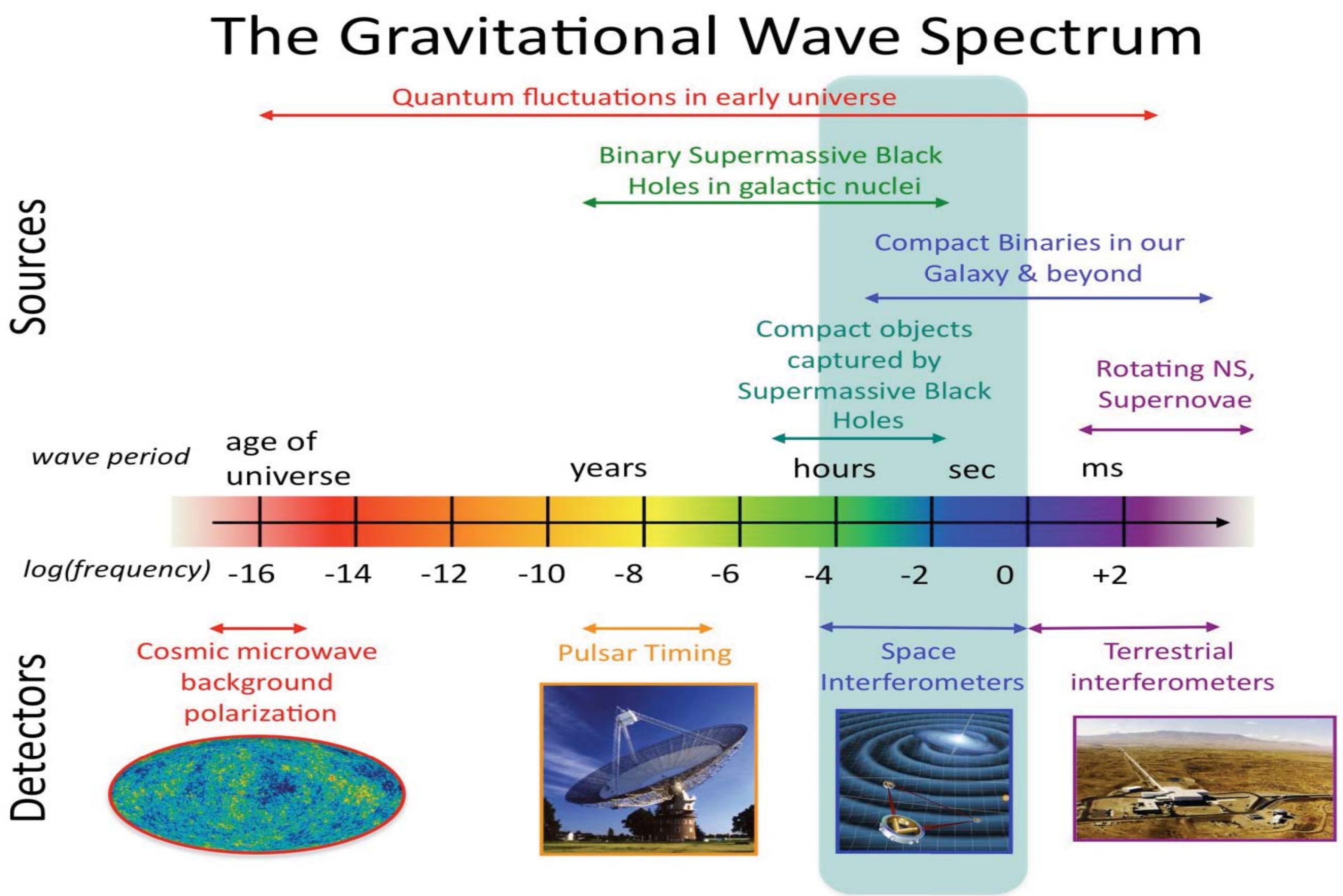



Kilonova/macronova/Li-Paczynski nova

Neutron star mergers
Electromagnetic counterpart




for decisive contributions to the LIGO detector
and the observation of gravitational waves




**高频： 1-1000Hz；中子双星、双黑洞并合、超新星、脉冲星X射线双星背景；**
**低频：0.001-1Hz，超大质量双黑洞并合，极端质量比旋近，白矮星并合及背景；**
**甚低频：$10^{-9}$-$10^{-3}$Hz，超大质量双黑洞旋近，宇宙弦，QCD尺度相变；**
**极低频：$10^{-18}$-$10^{-15}$Hz，原初引力波背景及其在微波背景光子上的印迹。**

# New/Great Era

Scientific significance of GW studies in astrophysics/ fundamental physics/cosmology

- Gravity?
- GR? (speed of light, equivalence principle…)
- Formation and evolution of compact objects (BHs, neutron stars)? Mass and spin distributions?
- Equation of states (superdense)
- Hubble constant (cosmological parameter)
- Generation of the universe
- … …

# Gravitational wave radiation, supermassive binary black holes, formation and evolution of galaxies and supermassive black holes

Supermassive BBHs, formation and evolution of BHs

- GW radiation at the PTA bands?
- GW radiation at the LISA bands, EMRIs?
- Origin of seed black holes, clues from the LIGO bands?

Galaxy formation and evolution

- Hosts: GW astrophysical sources
- Correlation between supermassive BHs and galaxies
- First galaxies/BHs in the early universe

Both

- Probing the cosmological structure formation and evolution

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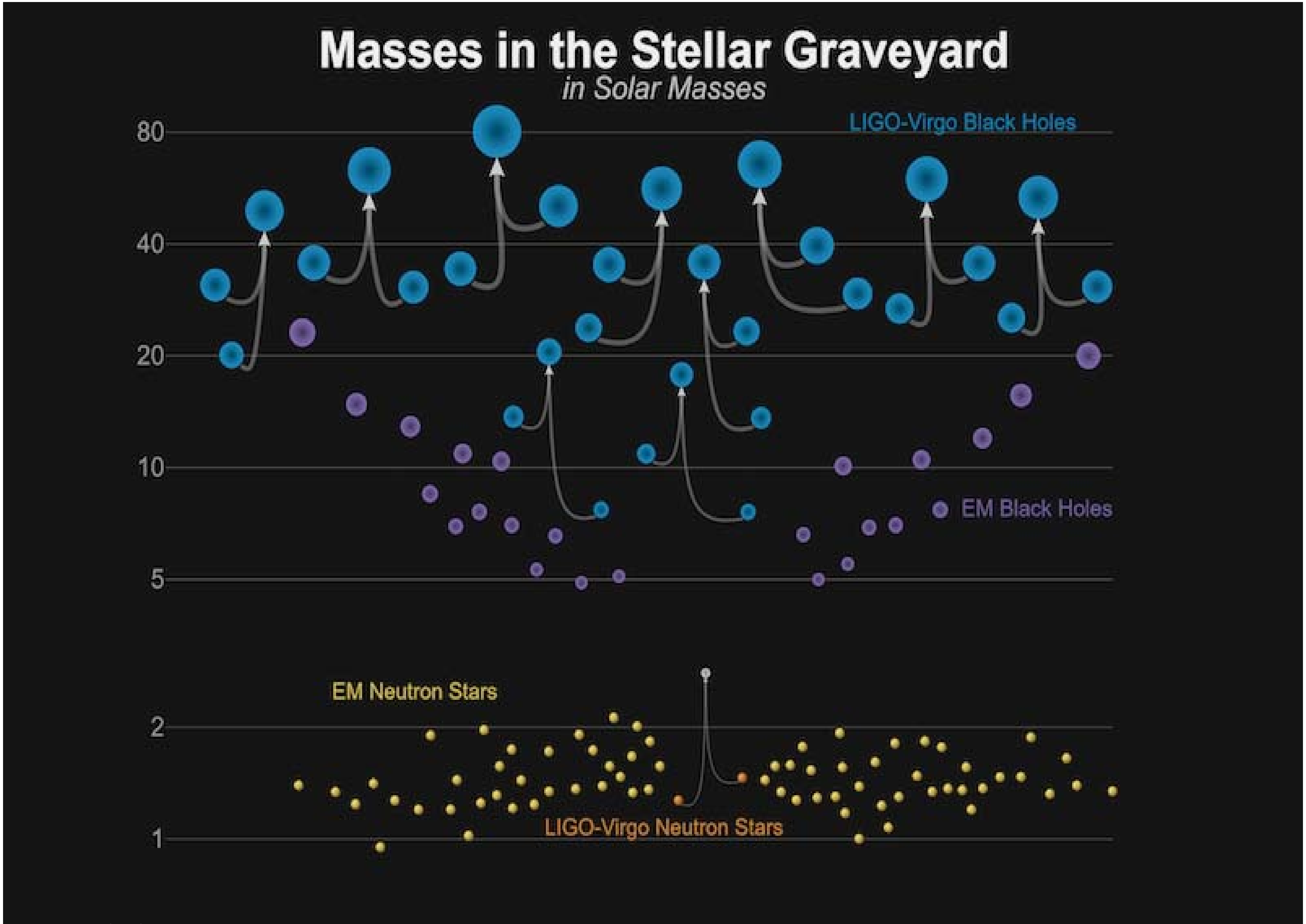
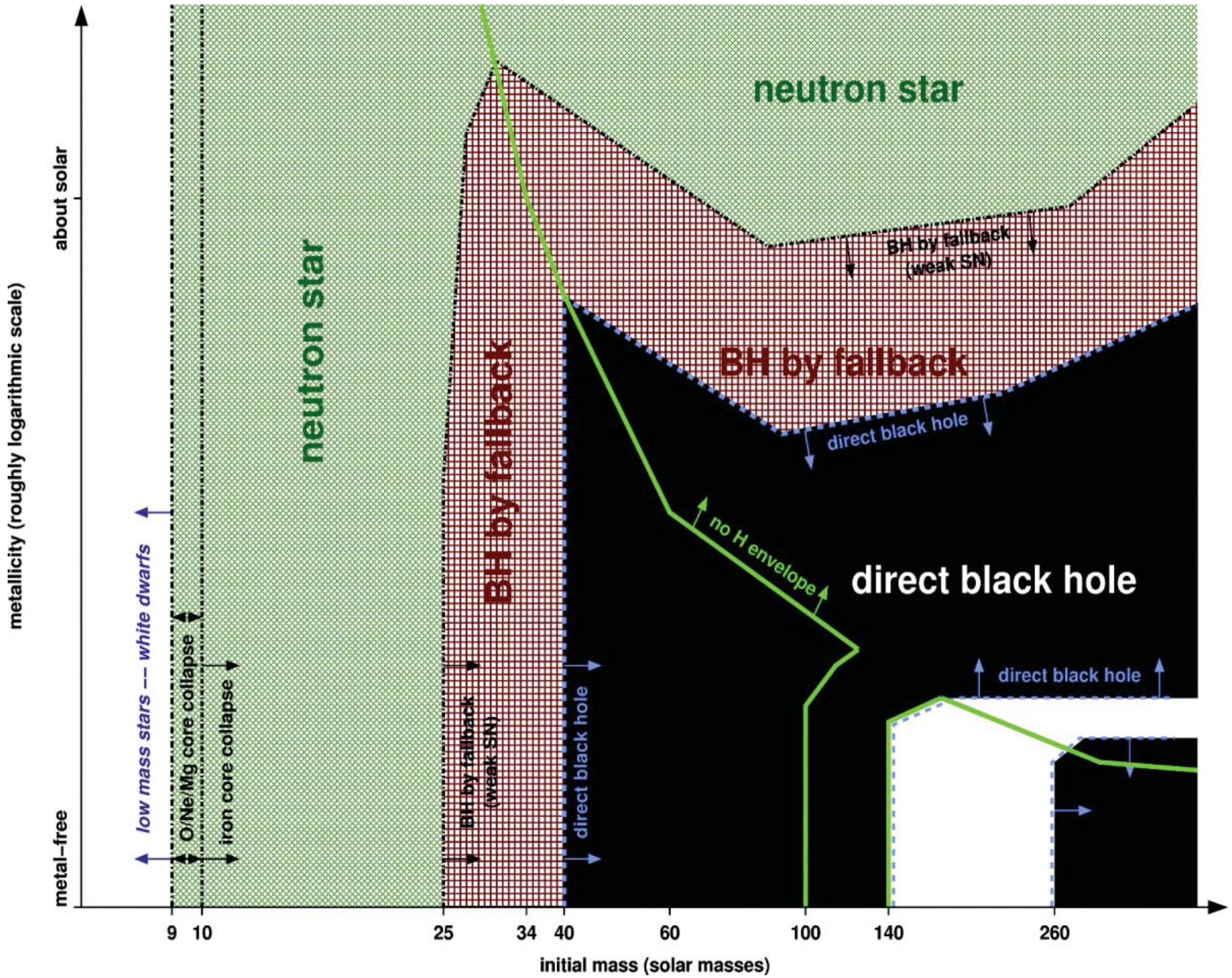
# Black Holes as astronomical objects

Classification by mass

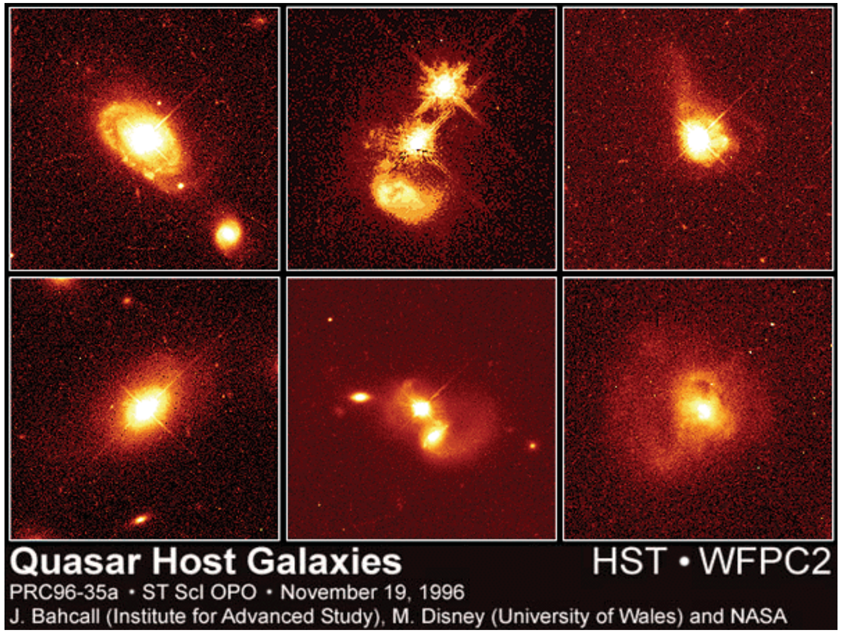
- Stellar-mass BHs:
  - Observations: several ten solar masses
  - Remnants of stellar evolution, mass limits? (Liu et al. 2019), Mergers?
- Intermediate-mass BHs (~$10^3$ solar mass)?
- Supermassive BHs in galactic centers (~$10^5$-$10^{10}$ solar mass)
- Micro-BHs, primordial BHs

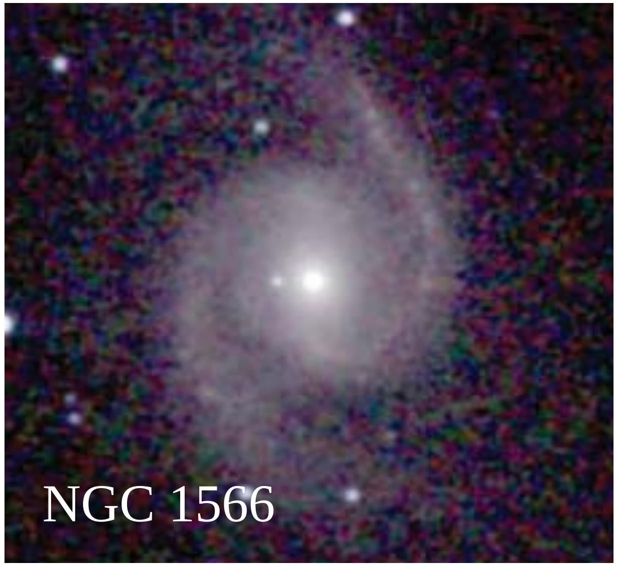

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

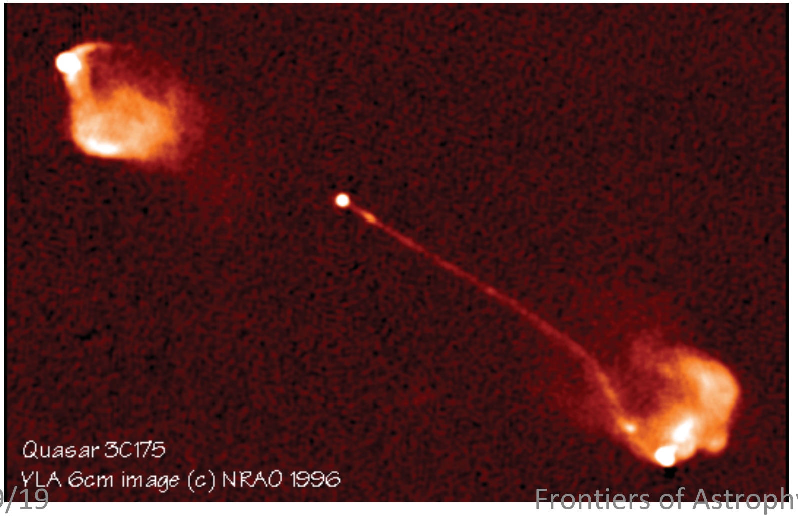



(Heger et al. 2003)

# QSOs and Active Galactic Nuclei



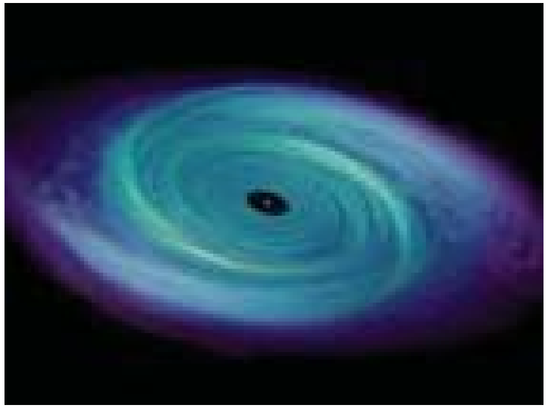

# Energy generation mechanism

Fundamental question:
How is the energy generated?

- ~$10^{42}$-$10^{48}$erg/s (10$^{9}$-10$^{15}$ Lsun)
  characteristic luminosity of field galaxies: ~ $10^{44}$erg/s
- Small size (short-term variability): ~cδt (solar system)

Accretion onto massive BHs

- Mass:



$$F_{\rm grav} \geq F_{\rm rad}$$

$$\frac{GMm_p}{r^2} \geq \frac{\sigma_e L}{4\pi c r^2}$$

$$M \geq \frac{\sigma_e L}{4\pi G c m_p} = 8\times10^{7} M_{\rm sun}\left( L \big/ 10^{46}\,{\rm erg/s} \right)$$

# Supermassive BHs in AGNs

- Efficiency:

$$L = \varepsilon \dot{M} c^2,\ \dot{M} \approx \frac{0.2}{\varepsilon} \cdot \frac{L}{10^{46}\,\mathrm{erg/s}}\,\mathrm{M_{sun}/yr}$$

$$\varepsilon = 0.007,\ \text{nuclear reaction}$$

$$U = \frac{GMm}{r}$$

$$L \approx \frac{dU}{dt} = \frac{GM}{r}\frac{dm}{dt} = \frac{GM\dot{M}}{r},$$

$$\varepsilon = \frac{GM}{c^2 r} \sim 0.1 \quad (r \sim 5R_S = 10\frac{GM}{c^2})$$

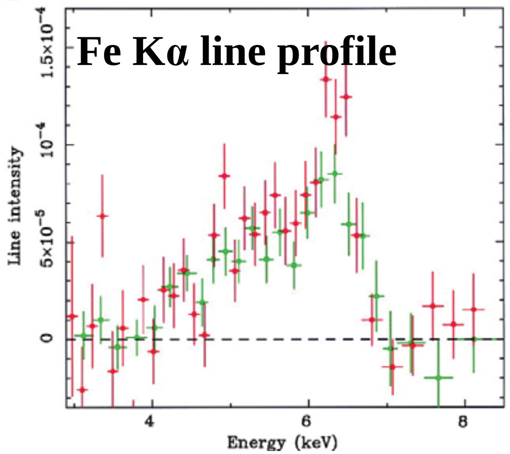
  - Schwarzschild BH and Kerr BH: 0.057, 0.31 (a=0.998)

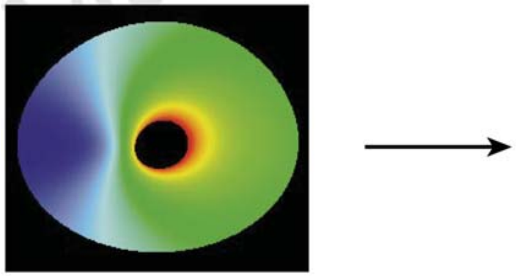
(Angular momentum: how to lose?)

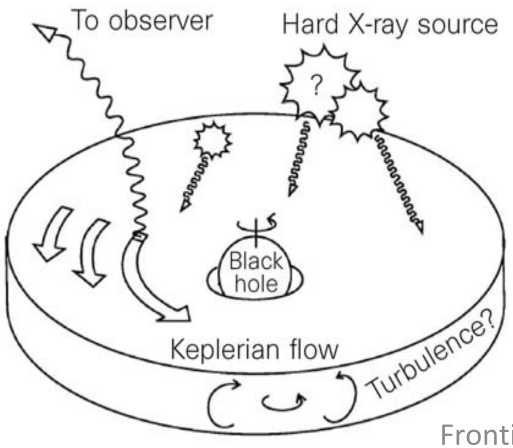
- Jets: ~c, sign of deep potential

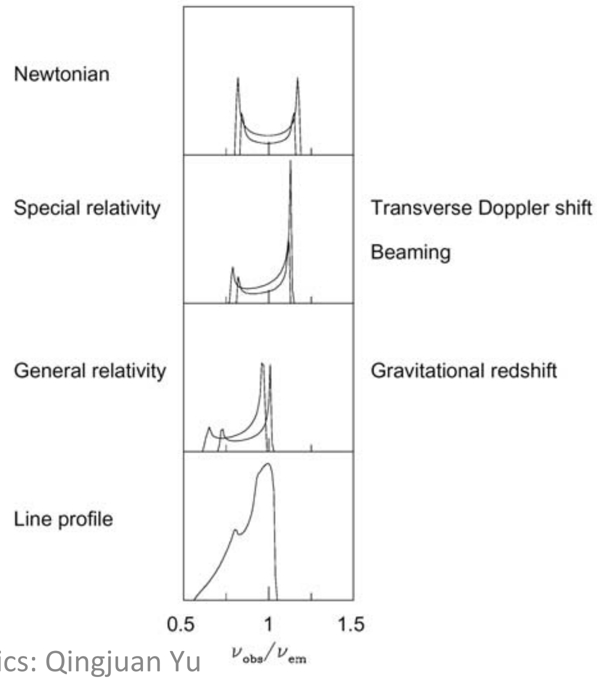
# Fe Ka emission lines:
# Strongest lines of evidence for the existence of massive BHs

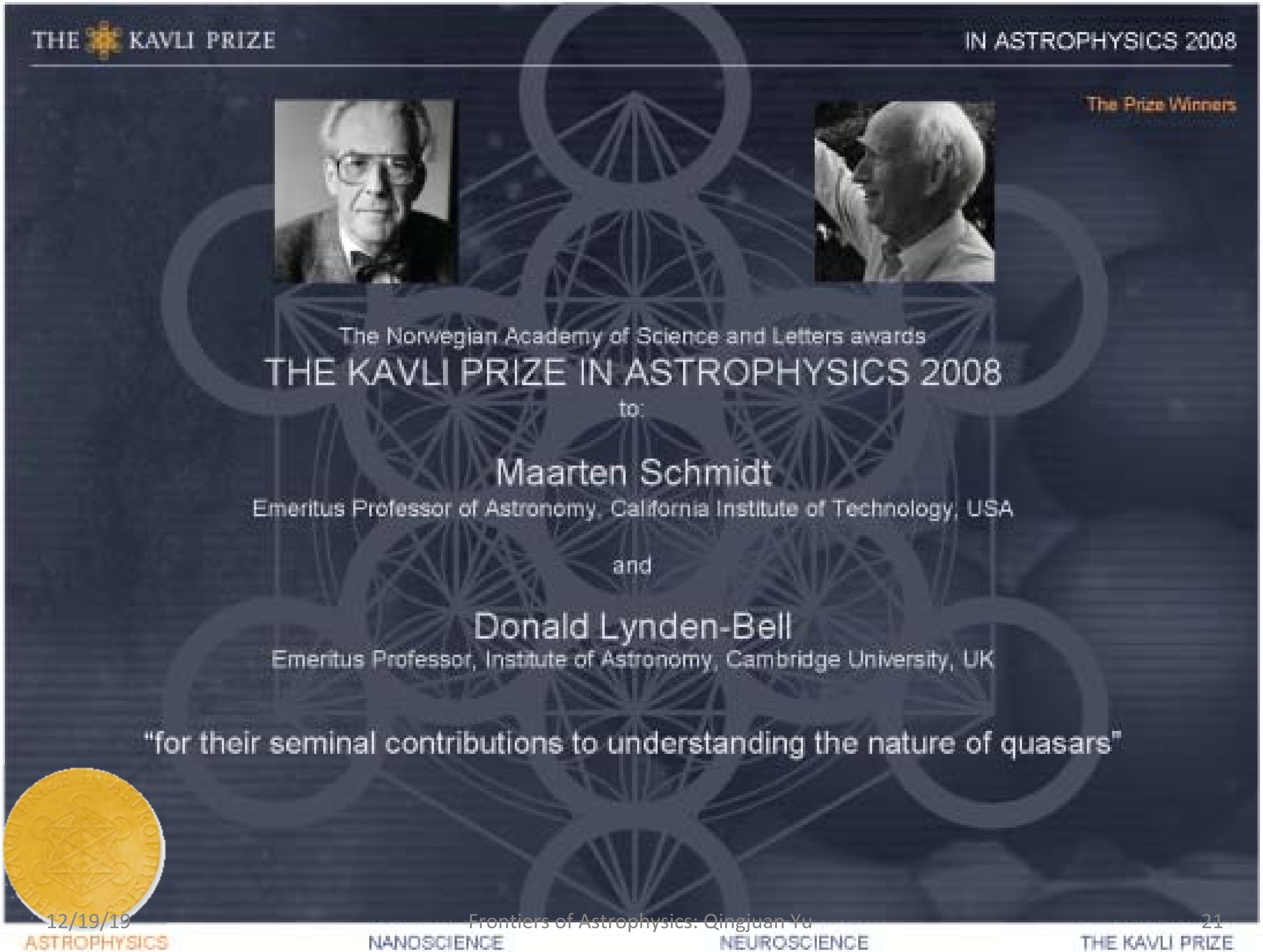
- Broad and asymmetric (Doppler and gravitational broadening)
- Short-term variability (~$10^4$s)
- Emitted from inner disc region






THE KAVLI PRIZE
IN ASTROPHYSICS 2008
The Prize Winners
The Norwegian Academy of Science and Letters awards
THE KAVLI PRIZE IN ASTROPHYSICS 2008
to:
Maarten Schmidt
Emeritus Professor of Astronomy, California Institute of Technology, USA
and
Donald Lynden-Bell
Emeritus Professor, Institute of Astronomy, Cambridge University, UK
"for their seminal contributions to understanding the nature of quasars"
ASTROPHYSICS
NANOSCIENCE
NEUROSCIENCE
THE KAVLI PRIZE

# Existence of massive black holes in galactic centers

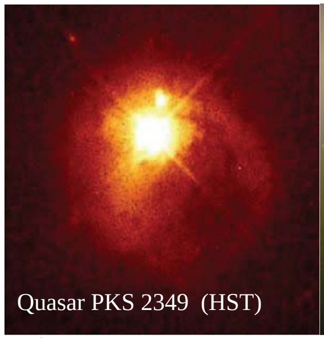
- QSOs: powered by accretion onto massive BHs in faraway galaxies (Schmidt 1963; Salpeter 1964; Zel'dolvich & Novikov 1964; Lynden-Bell 1969; Rees 1984).

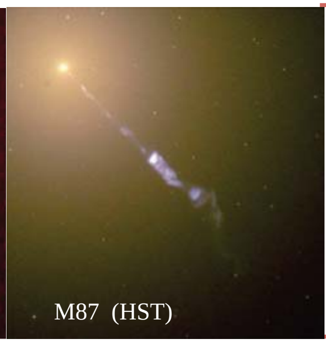
- Faraway galaxies represent history of nearby galaxies (cosmological principle).

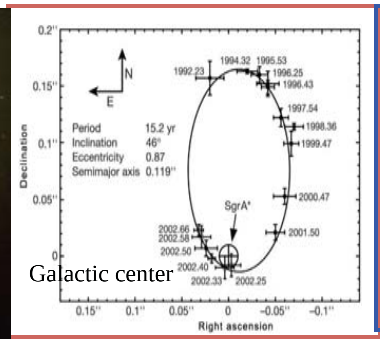
  --> QSO remnants in local galaxies?

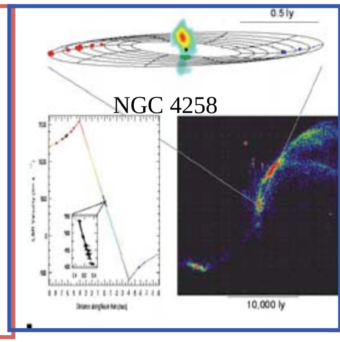
  (Lynden-Bell 1969; Soltan 1982; Small & Blandford 1992; Yu & Tremaine 2002)

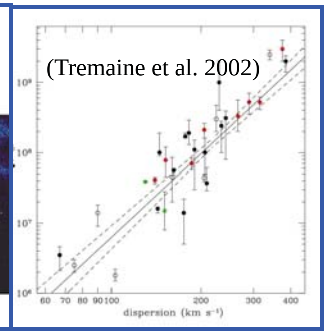
- Nearby galactic centers indeed contain massive dark objects (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2002; Pinkney et al. 2003; Ferrarese & Ford 2005).



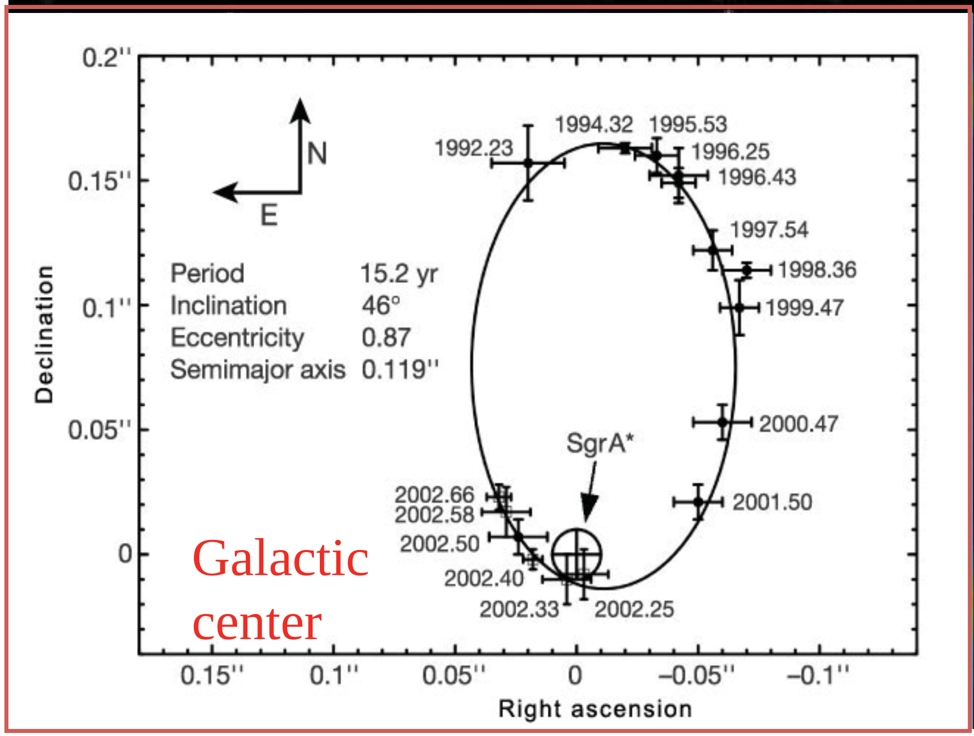



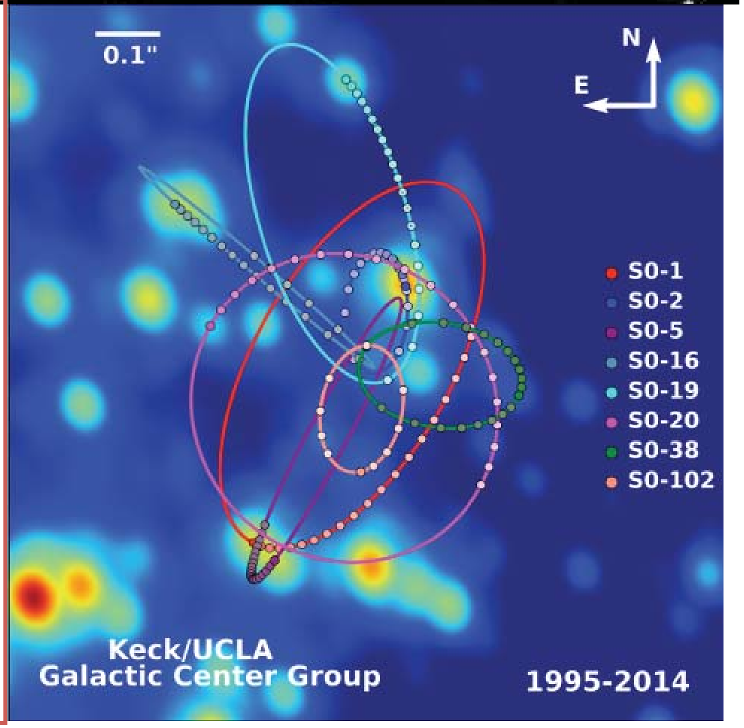



# Toward the Galactic center

From Gillenssen

# Evidence of Massive BHs in Nearby Galaxies


(Reinhard Genzel
Andrea Ghez)

$M=rv^2/G$

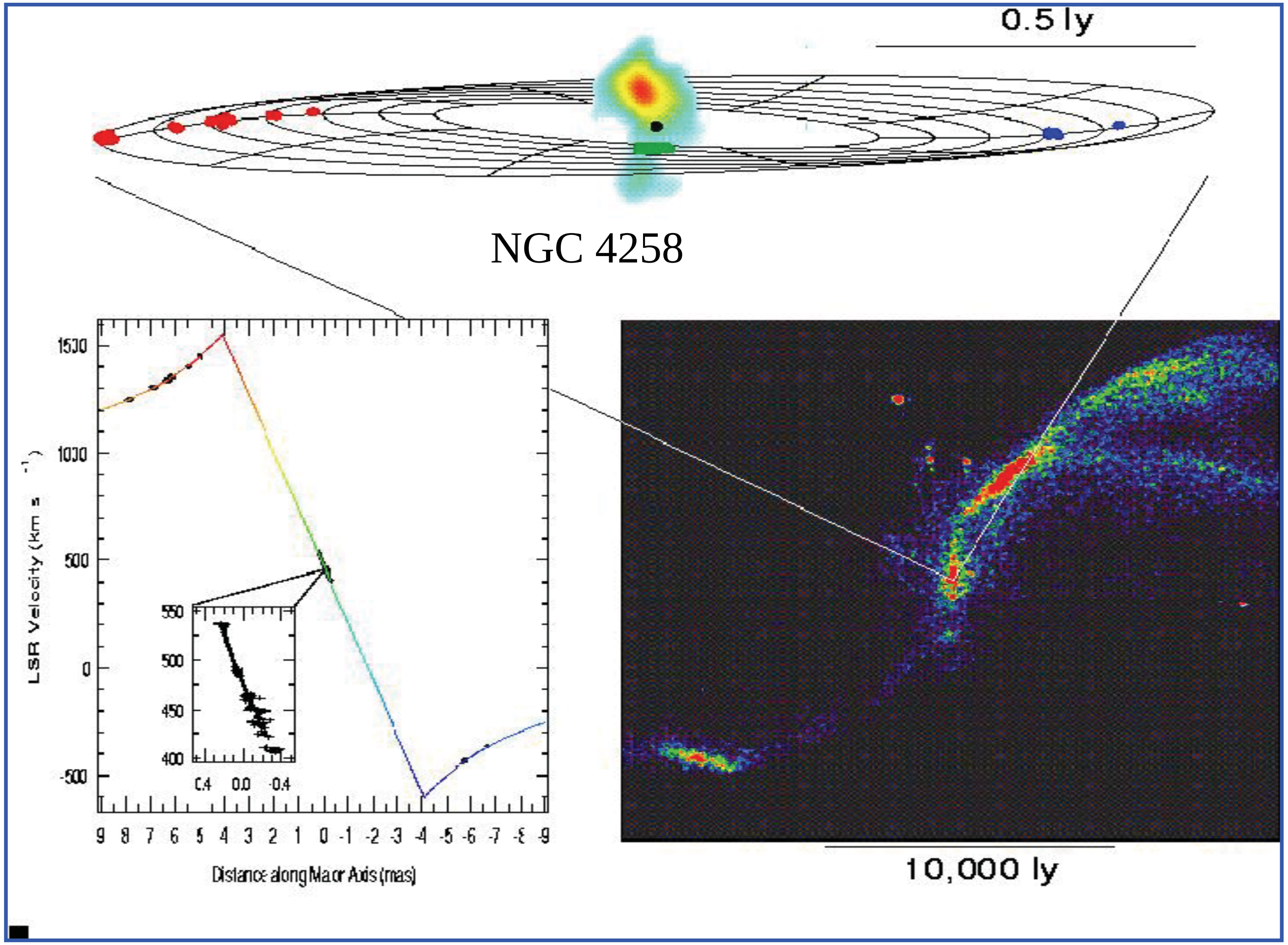
$M_{BH}=4\times10^6 M_{sun}$

# Supermassive BH in the GC: Shaw prize


Reinhard Genzel

In recognition of his outstanding contributions in demonstrating that the Milky Way contains a supermassive black hole at its centre.

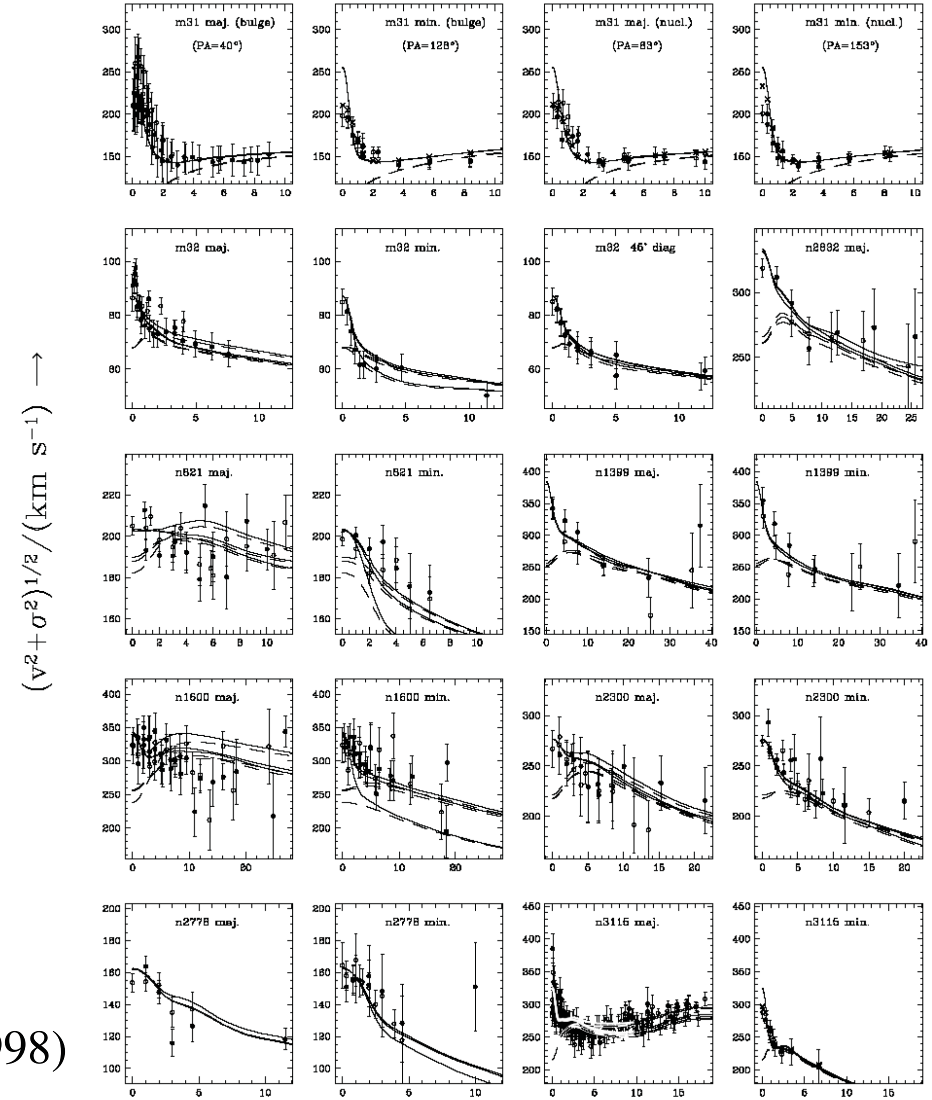
# Evidence of Massive BHs in Nearby Galaxies




$M_{BH}=(3.9\pm0.1)\times10^{7}\,M_{sun}$

# Evidence of Massive BHs in Nearby Galaxies

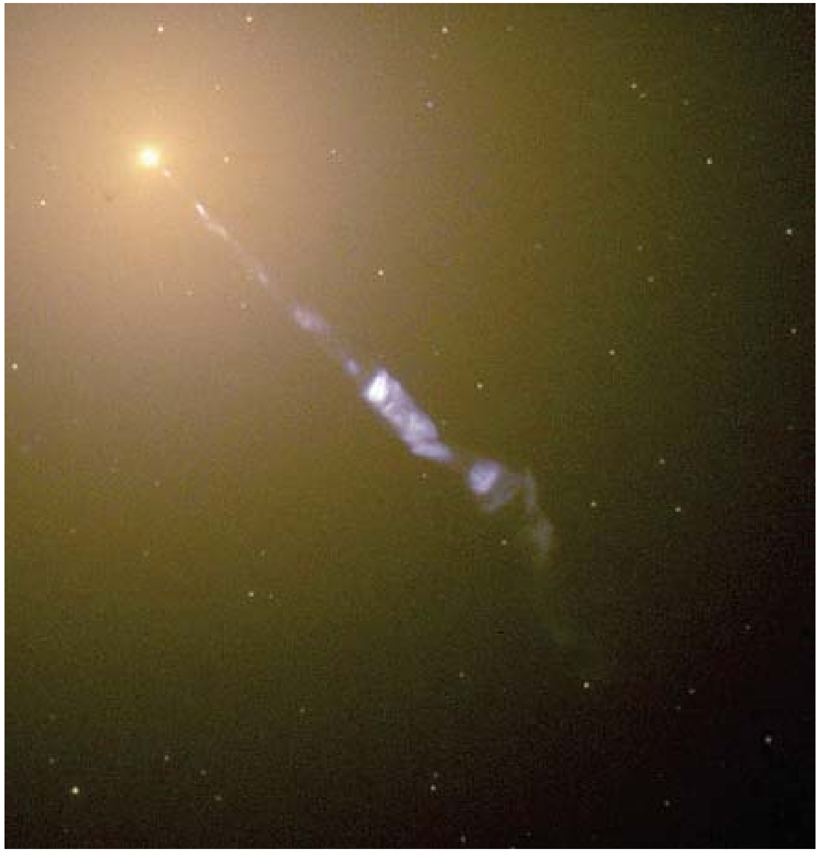
- Stellar dynamics



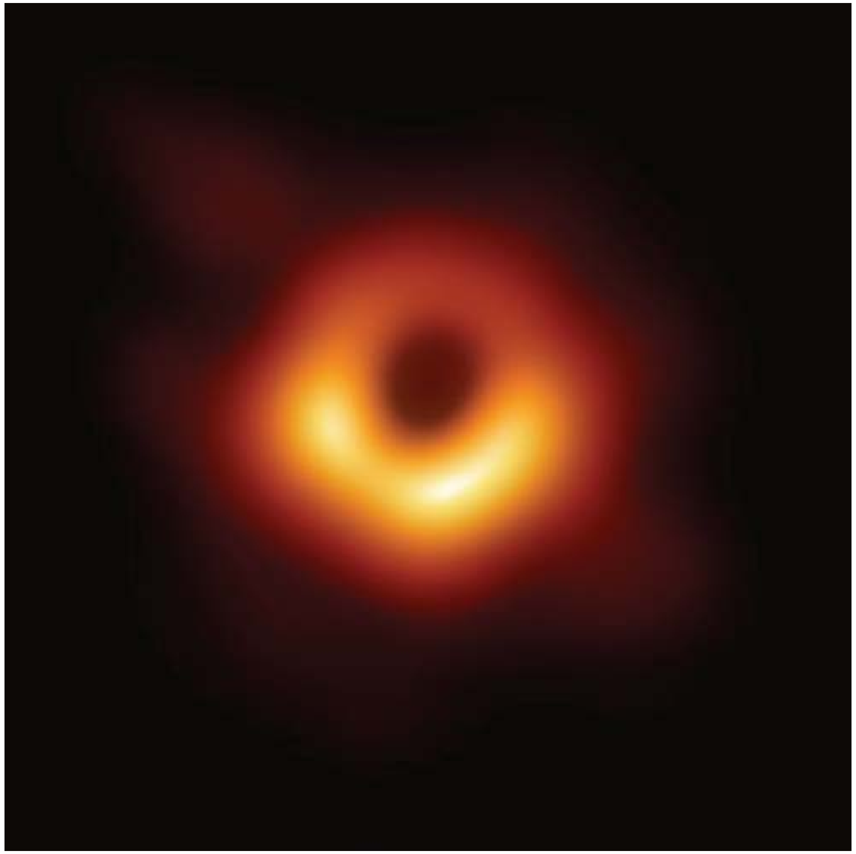

(Magorrian et al. 1998)

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

# Seeing the BH in M87



Hubble Space Telescope



Event Horizon Telescope

$M_{BH}=6.5\times10^{9}\,M_{sun}$

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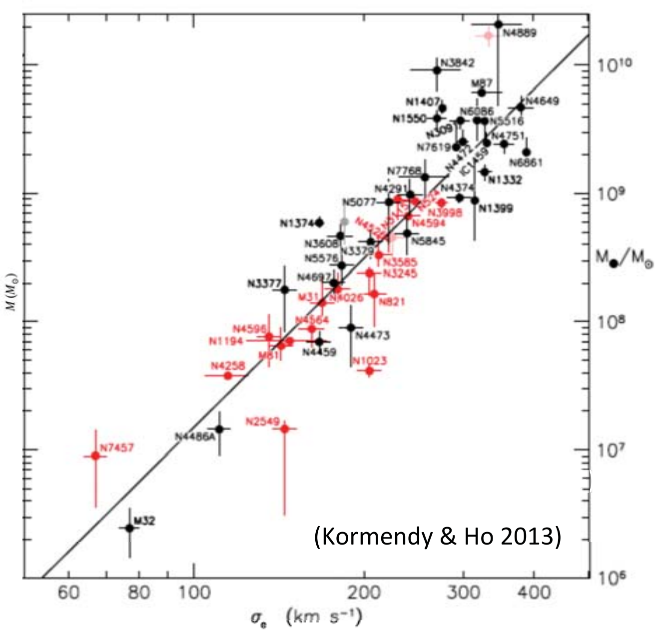
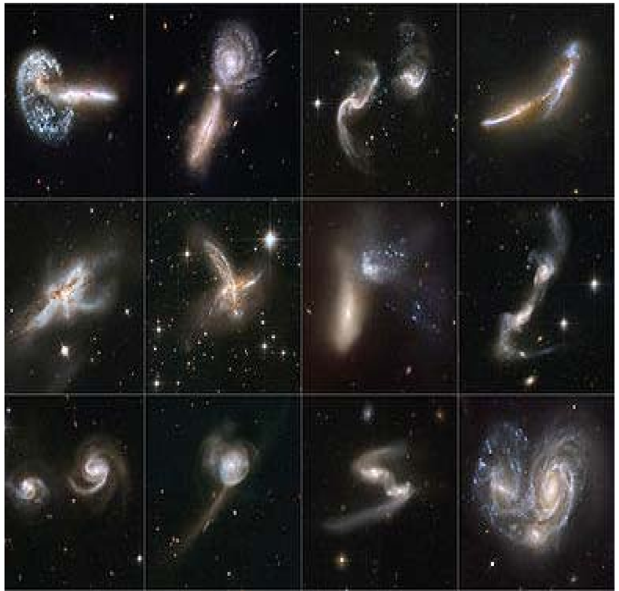
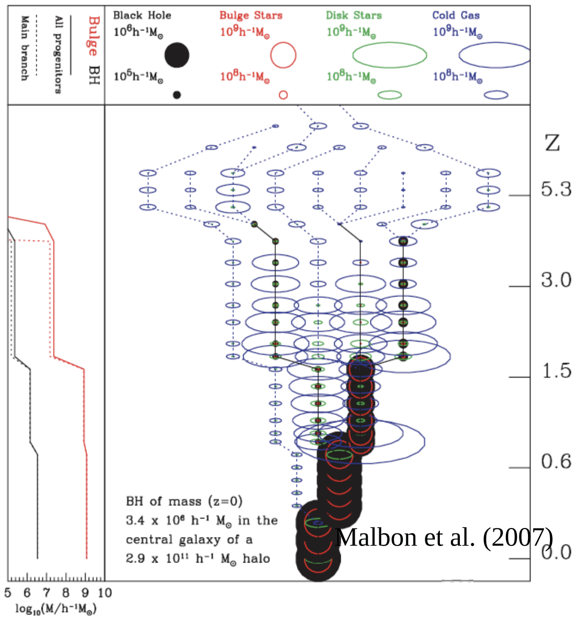
# Massive BBHs/dual AGNs

- Massive black holes (MBHs) exist in the centers of most, if not all, galaxies.
- Mergers of galaxies play the central role in the hierarchical galaxy formation model, and we do see many galaxies that experienced major mergers.
- Binary/paired MBHs are natural products of mergers of galaxies.

- Mergers of galaxies can drive gaseous material to the very center of the merged galaxies and are believed to be responsible for the AGN/QSO phenomenon.
- Binary/dual/paired AGNs are expected products of the mergers of galaxies.



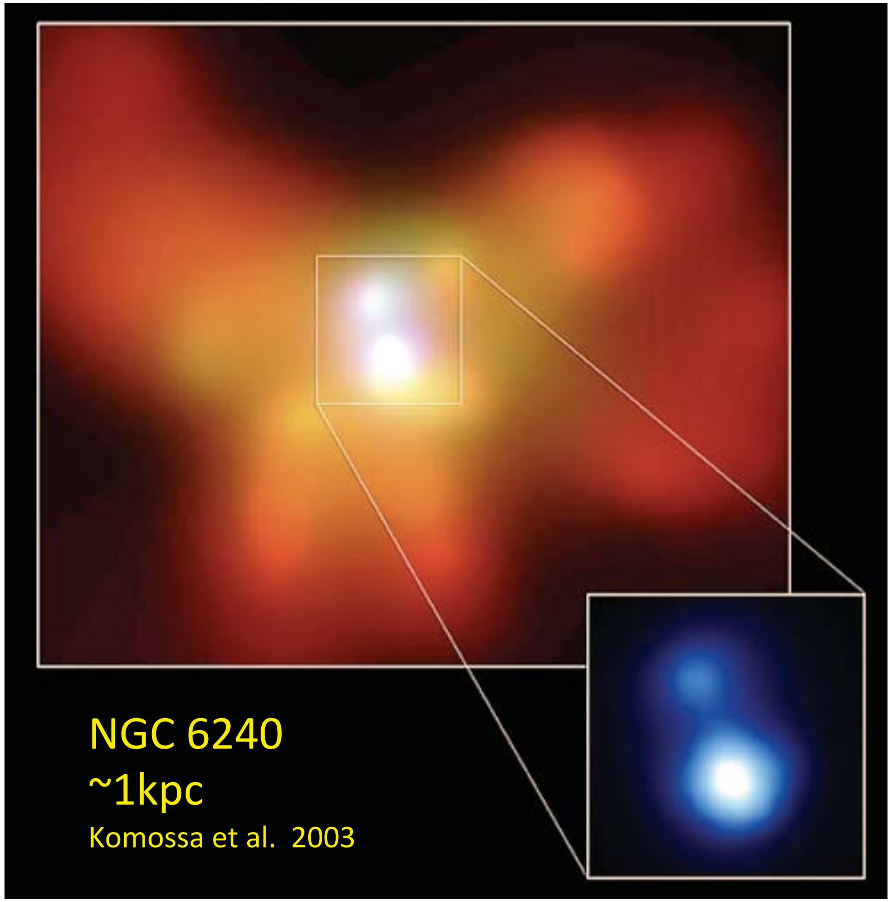


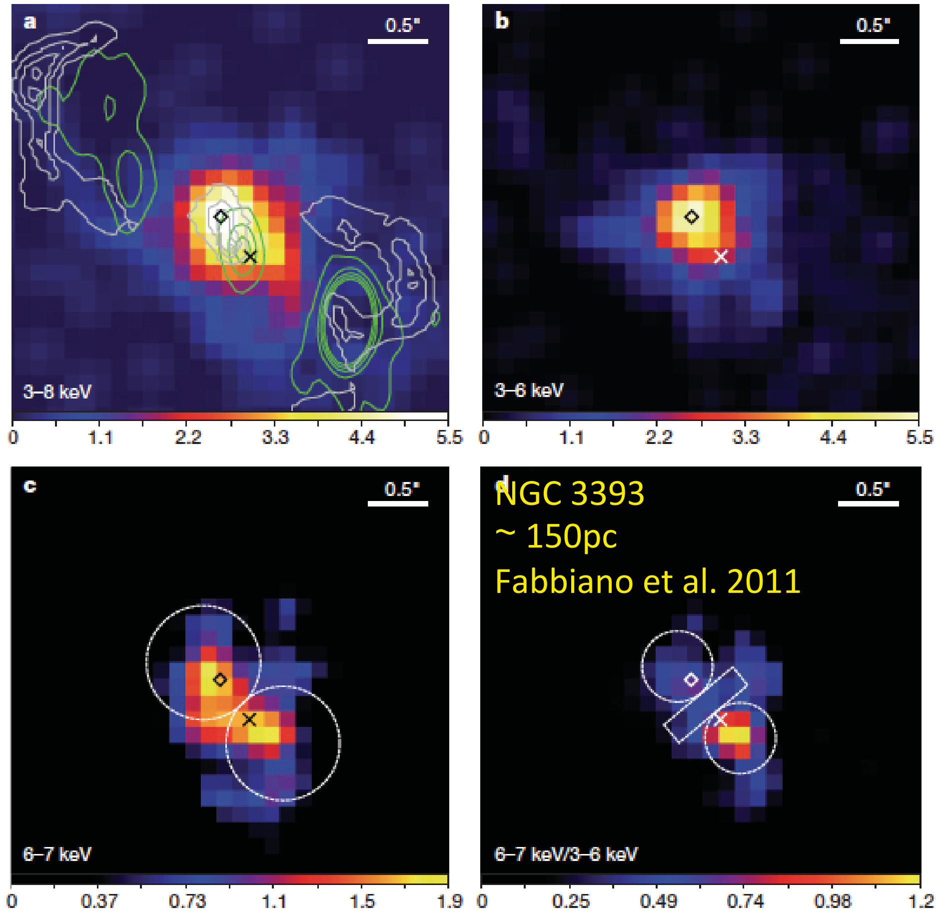
Malbon et al. (2007)

Constraining the big pictures / approaching the long-standing questions in astrophysics, cosmology, and fundamental physics:

- Hierarchical galaxy and structure formation
- Triggering mechanisms of nuclear activities
- Black hole physics
- Gravitational wave detection, testing gravity theory

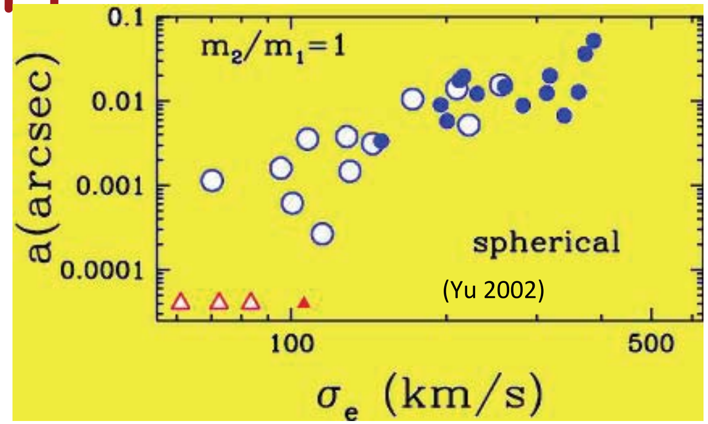
# kpc-scale dual AGNs

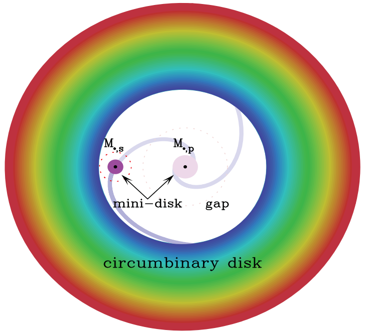


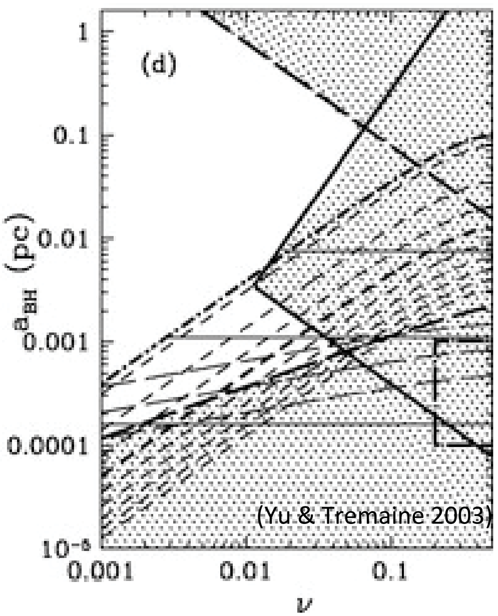
# BBHs: observational appearance?

- Gas-poor mergers
- Gas-rich mergers
- BH companion to Sgr A* (GC)?




Examples… …

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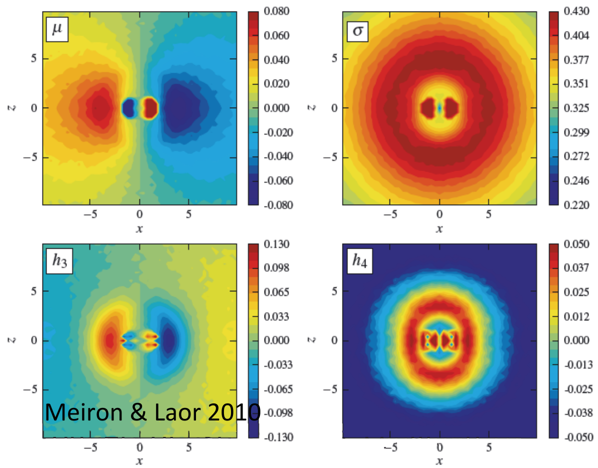
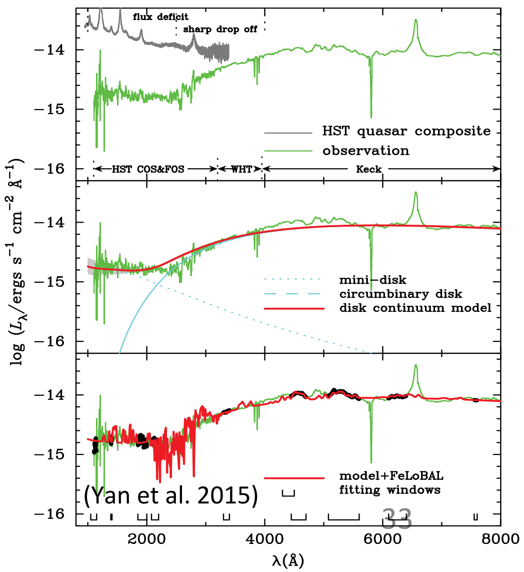
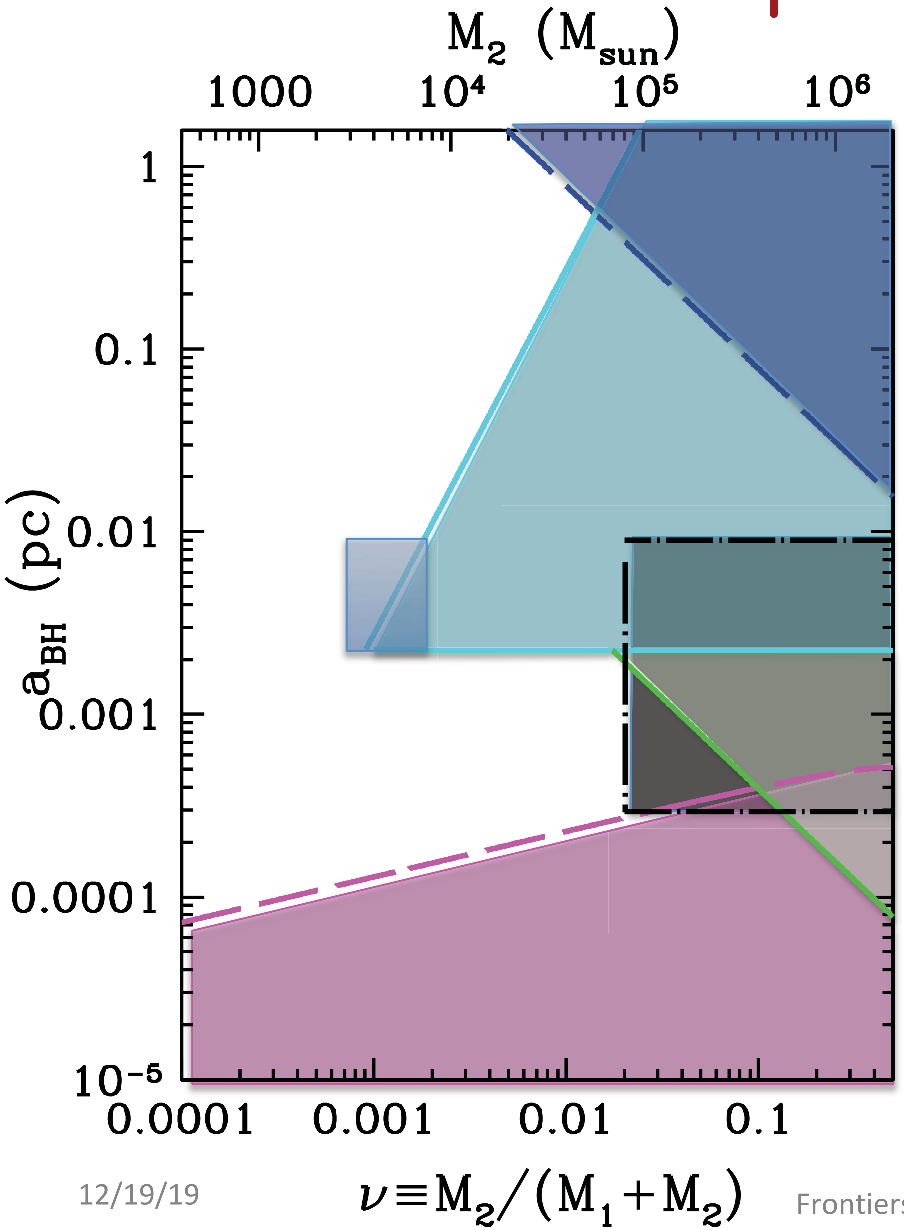


# A BH companion to Sgr A*?

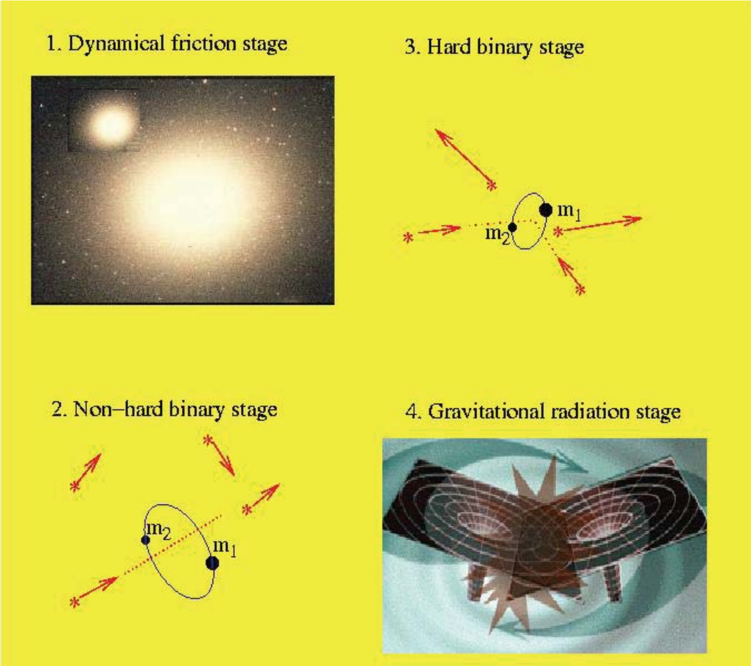



Existence of a BH companion in the Galactic center serves as one of the ways to explain the puzzling existence and distributions of the young stellar disk(s) and S stars, and also hypervelocity stars discovered in the Galactic halo.

- Peak of stellar surface density;
- Gravitational wave radiation;
- Proper motion of Sgr A*:
  - Upper limit of peculiar motion perpendicular to the Galactic plane;
  - Position residual from motion;
- Eccentric Keplerian orbits of S stars at radii r~0.1-1mpc around a point mass;
- Long-term perturbations ($10^7$yr) on the inclination and eccentricity distributions of S stars due to an IMBH:

# Orbital evolution of massive BBHs: gas-poor mergers

- **Dynamical friction stage (several ten kpc down to ten pc or pc scale)**
- **Gravitationally bound BBHs**
  - Non-hard binary stage (10 pc or pc-scale):
    —three-body interactions with stars
    —dynamical friction
  - Hard-binary stage (pc or sub-pc scale)
    —three-body interactions with stars
    —depending on galaxy shapes and galaxy properties
- **Gravitational wave radiation stage ($<\sim 10^{-2}$ pc scale)**




(Yu 2002)

**Are low-*J* stars depleted before the gravitational radiation stage?**

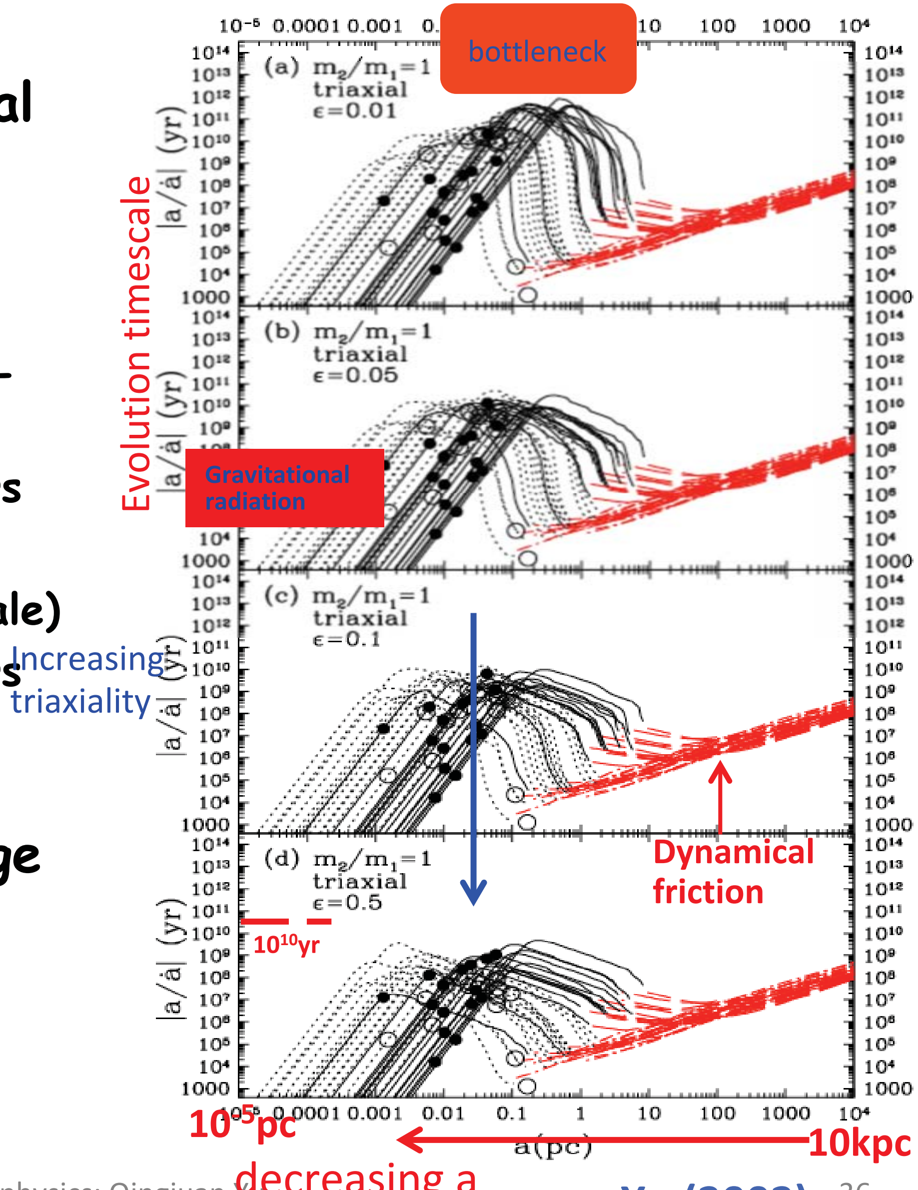
sperical: $\rho(r)$

triaxial: $\rho\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)$

Begelman et al. 1980; Yu 2002; Milosavljevic & Merritt 2005; Preto et al. 2011; Kahn et al. 2011 etc.

# Orbital evolution of massive BBHs: gas-poor mergers

- **Dynamical friction stage (several ten kpc down to ten pc or pc scale)**
- **Gravitationally bound BBHs**
  - Non-hard binary stage (10 pc or pc-scale):
    - —three-body interactions with stars
    - —dynamical friction
  - Hard-binary stage (pc or sub-pc scale)
    - —three-body interactions with stars
    - —**depending on galaxy shapes and galaxy properties**
- **Gravitational wave radiation stage (<~$10^{-2}$ pc scale)**




Yu (2002)

# Role of galaxy triaxiality

- Semimajor axis evolution
  - Decreasing bottleneck timescale
- Orbital orientation evolution
  - Alignment erasing effects in rotating systems

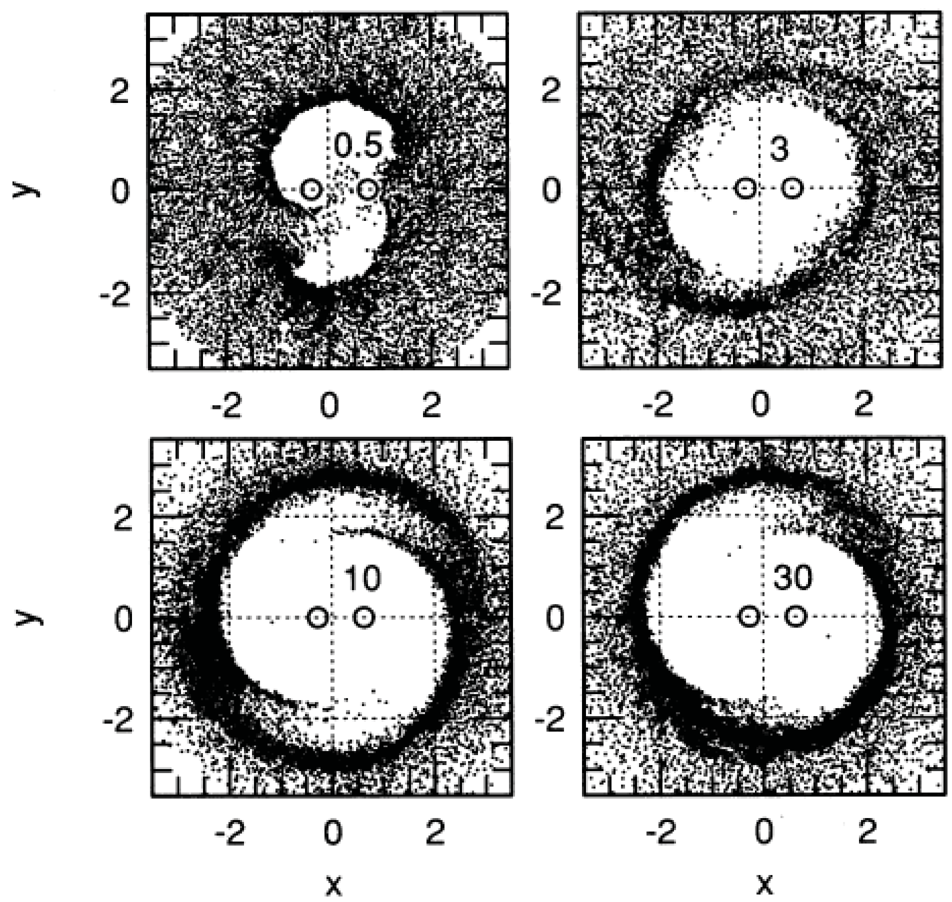
(Cui & Yu 2014)

- Eccentricity evolution
  - Decreasing eccentricity in counter-rotating systems

# Orbital evolution of binary MBHs: gas-rich mergers

- Dynamical friction stage (seve ten kpc down to ten pc or pc scale)
- Gravitationally bound BBHs
  - Gas-rich mergers
    - Dynamical friction/migration to circum-nuclear gas reservo (10-1pc-scale)
    - BBHs embedded in accretion (sub-pc-scale): gap opening
      - Viscosity driven;
      - Migration:

        similar to the type 2 migration of planets in planetary disks
- Gravitational wave radiation stage (<~$10^{-2}$ pc scale)



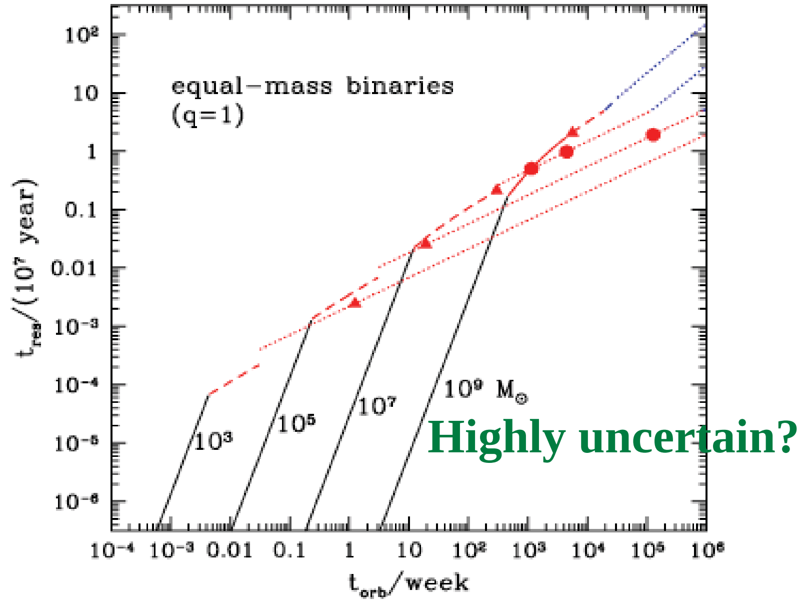

Goldreich & Tremaine 1979
Lin & Papaloizou 1979
Artymowicz & Lubow 1994
Artymowicz 1998

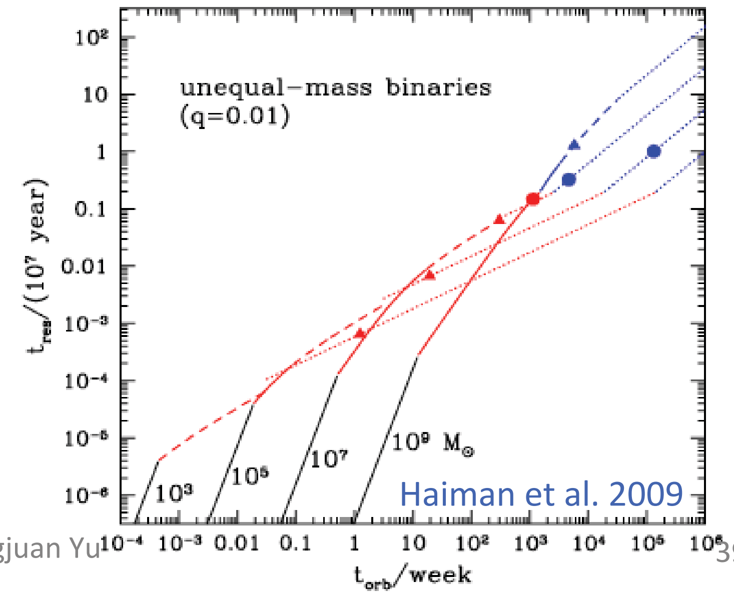
# Orbital evolution of massive BBHs: gas-rich mergers

- Dynamical friction stage (several ten kpc down to ten pc or pc scale)

- Gravitationally bound BBHs
  - Gas-rich mergers
    - Dynamical friction/migration due to circum-nuclear gas reservoir (10-1pc-scale)
    - BBHs embedded in accretion disk (sub-pc-scale):
      - Viscosity driven;
      - Migration:
        similar to the type 2 migration of planets in planetary disks

- Gravitational wave radiation stage (<~$10^{-2}$ pc scale)



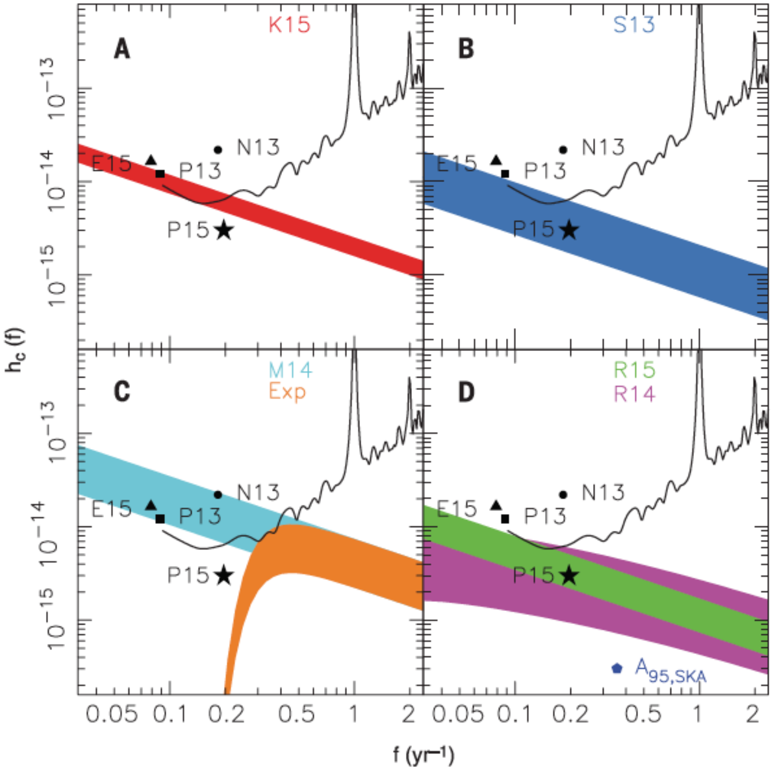



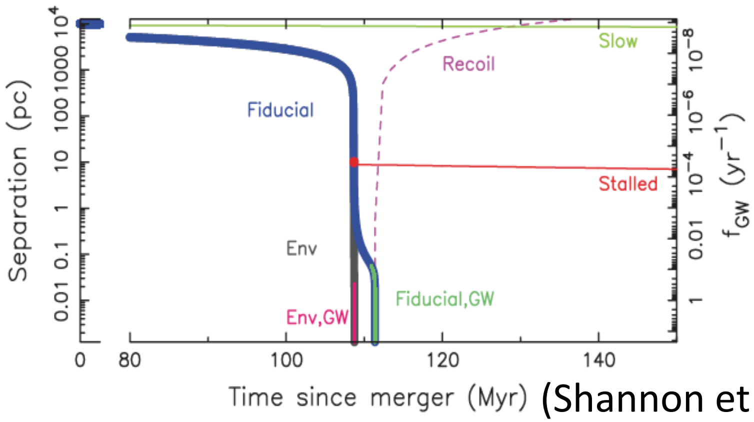
# Possible sources at the PTA bands

- Supermassive binary black holes
  - Stochastic backgrounds
  - Individual sources

- Cosmic strings
- QCD-scale phase transitions in the early universe

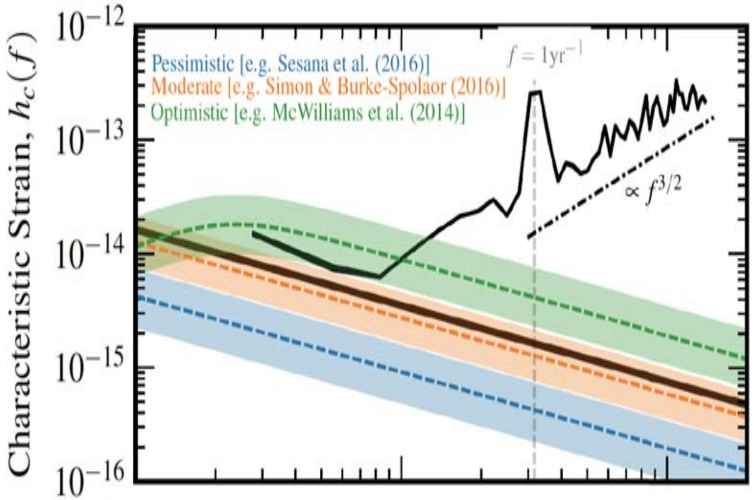
# Problems in GWB contributed by BBHs




(Shannon et al. 2015)

- galaxy merger rates
- BH-galaxy properties relations
- BBH evolution
  - Hardening timescale

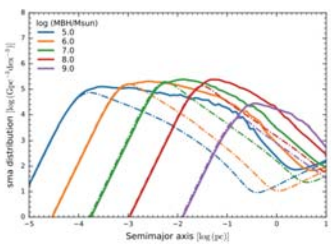
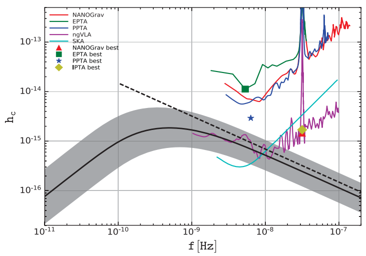
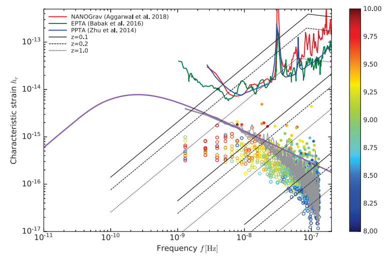
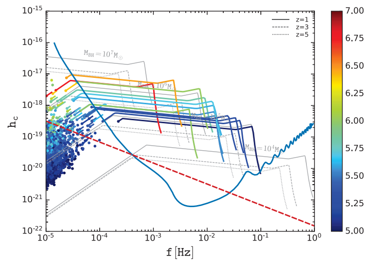



$$h_c(f) = A_{\mathrm{GWB}} \frac{(f/\mathrm{yr}^{-1})^{\alpha}}{(1+(f_{\mathrm{bend}}/f)^{\kappa})^{1/2}}$$

(Arzoumanian et al. 2018)

# BBHs in realistic galaxy distributions

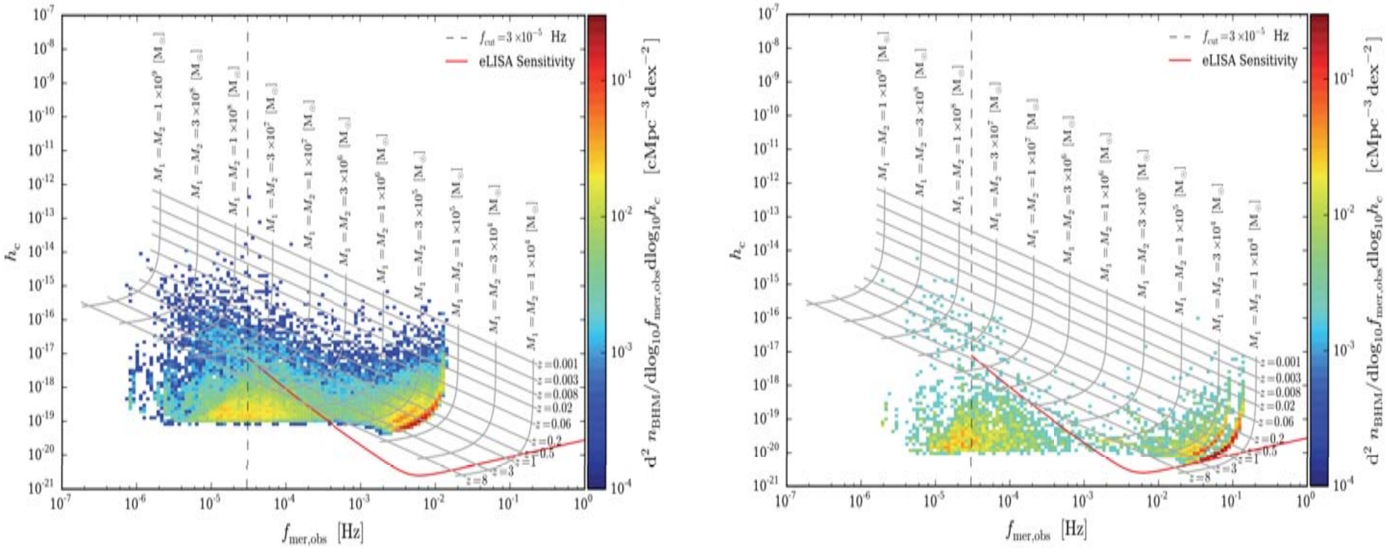
- Realistic intrinsic shape distributions
  - triaxiality
- Realistic light/mass distributions
- Distributions of surviving BBHs
- Expected stochastic GWB at PTA bands
- Prospects for GWs from individual sources
  - PTA bands
  - LISA bands (including EMRIs)

# BBH mergers at eLISA bands: depending on seeding BH models

EAGLE simulations, eLISA bands
Different black hole seeding models

Seed black holes:
Remnants of the first generation of stars
Collapsing nuclear star clusters
Direct collapse of supermassive stars



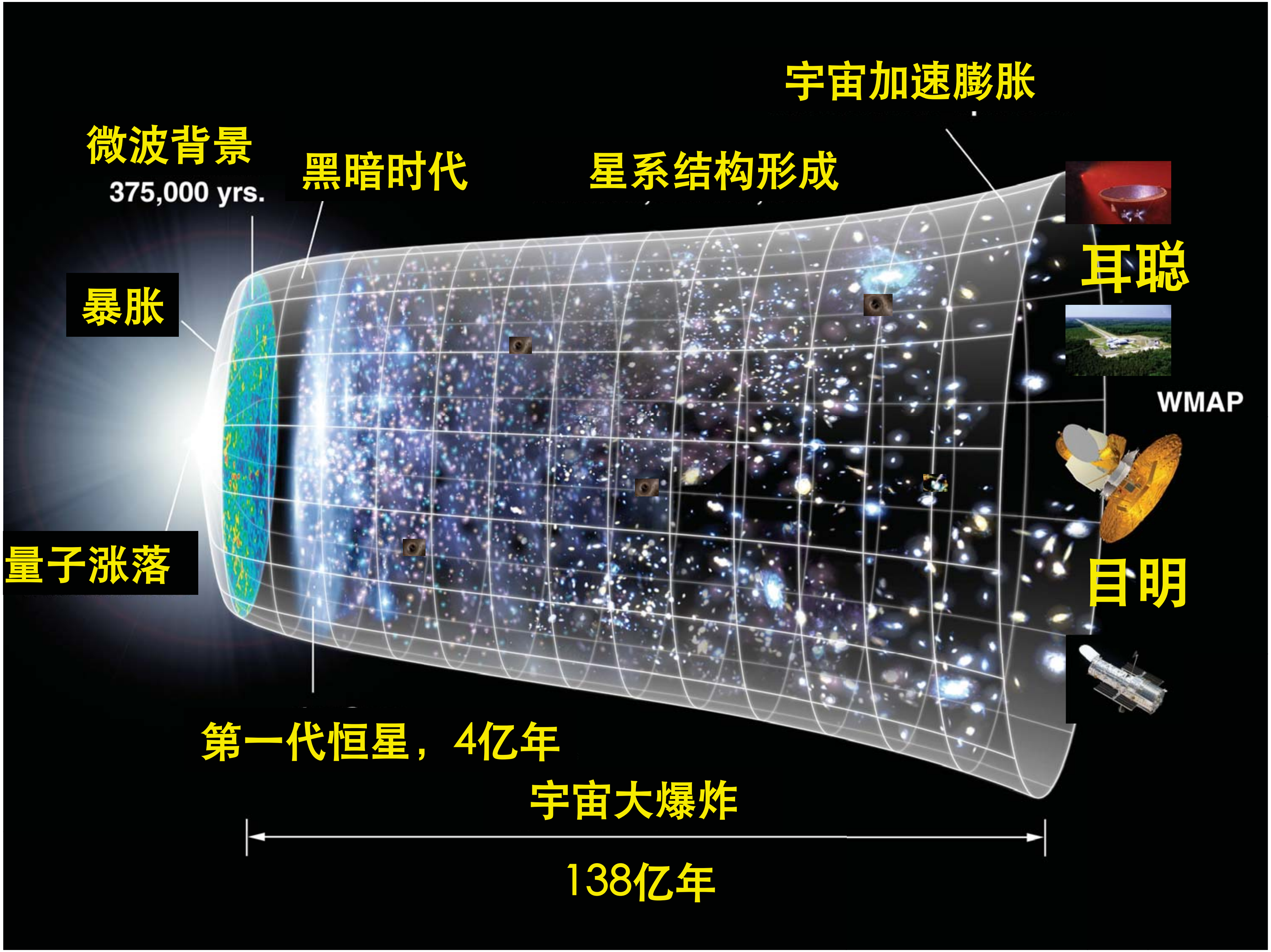

- Dominated by mergers between seed mass black holes merging at redshifts between z ~ 2 and z ~ 1.
- Predicted event rate of GWs for the inspiral and merger phases: ~2 events/year.



Salcido et al. 2016

# Summary

- Massive binary black holes are natural products of galaxy mergers.
- Observational appearance of a BBH depends on the evolutionary stage of the BBH.
- Evolution of BBHs depends on BH masses, and velocity dispersions and shapes, and gas environment of host galaxies
  - Triaxiality: Overcoming evolution timescale bottleneck
- Evolution of BBHs in realistic galaxy distributions determines
  - Distribution of surviving BBHs
  - Strength of stochastic GWB from mergers of BBHs
    - compatible with current PTA observations and to be tested in the near future **(FAST, ngVLA, SKA)**
  - Mergers of individual sources**(FAST, ngVLA, SKA,LISA),** EMRIs **(LISA)**
- **Events: testing black hole physics, gravity theory in a new regime etc.**
- **Streng & Event rates: Probing structure formation and evolution, formation and evolution of BHs and galaxies**


宇宙加速膨胀
微波背景
375,000 yrs.
黑暗时代
星系结构形成
暴胀
耳聪
WMAP
量子涨落
目明
第一代恒星，4亿年
宇宙大爆炸
138亿年

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  - Galaxy evolution
  - Semi-analytical models
- Opportunities, Challenge & Summary

# The luminosity function of QSOs as a function of redshift traces the accretion history of the local MBHs. (Soltan 1982)

- **Accreted:**

$L_{\rm bol}$: bolometric luminosity;

$\varepsilon$ : mass-to-energy efficiency;

$$\dot{M} = \frac{(1-\varepsilon)L_{\rm bol}}{\varepsilon c^2} \text{ : mass accretion rate;}$$

$$\int_0^{t_0} \mathrm{d}t \int_0^{\infty} \mathrm{d}L \frac{(1-\varepsilon)L_{\rm bol}}{\varepsilon c^2} \psi(L,t)$$

$\psi(L,t)$ : QSO luminosity function

bolometric correction: $L \rightarrow L_{\rm bol}$.

?

- **Local:**

$$\int_0^{\infty} M_0 n(M_0, t_0) dM_0$$

BH mass function

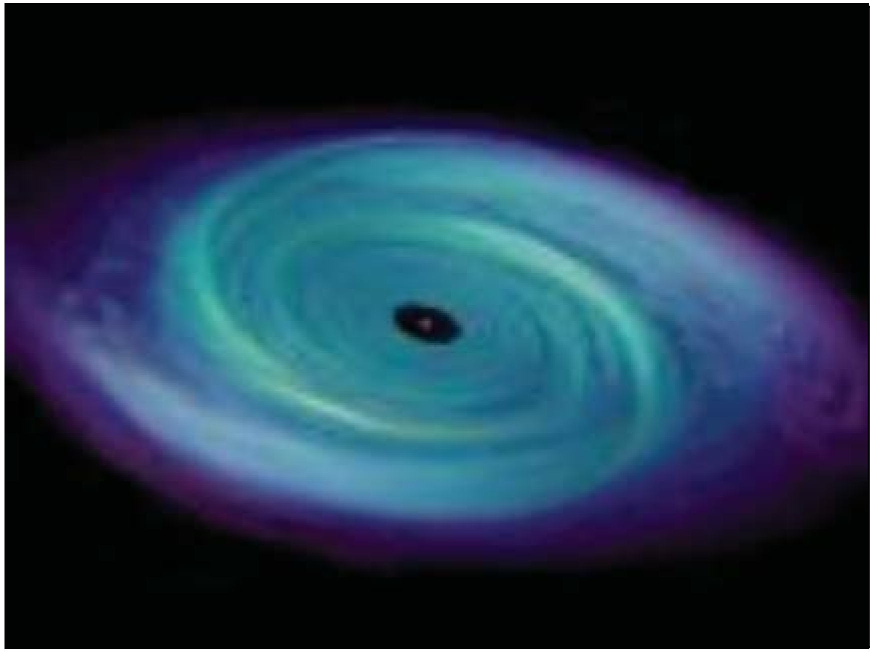
$n(M_0, t_0)$

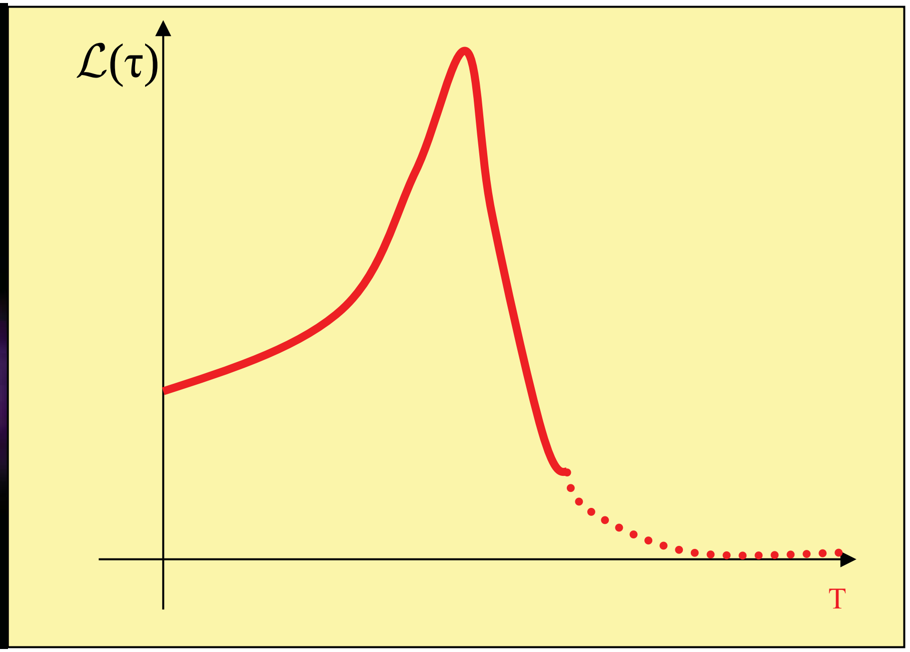
- BH mass M-sigma or M-L relation
- galaxy sigma or L distribution

Total local BH mass density is consistent with the expected density of QSO/AGN remnants if ε≈0.1-0.3. (consistent with GR expectation)

Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2004,2008; Yu & Lu 2004, 2008; Merloni & Heinz 2008

- Mass growth of massive BHs comes mainly from accretion due to bright QSO phases. (Dark accretion ruled out.)
- How does the accretion/luminosity of individual QSOs evolve?



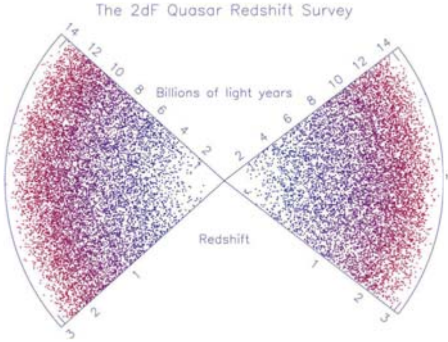



Evolution after the nuclear activity of a QSO/AGN is triggered

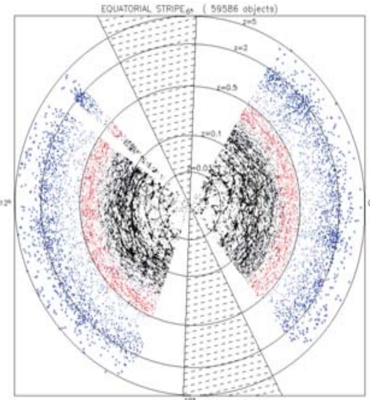
$$\dot{\mathcal{M}}(\tau) = \frac{(1-\varepsilon)\mathcal{L}(\tau)}{\varepsilon c^2}$$

$$M(\tau) = M_i + \int_0^{\tau} \dot{\mathcal{M}}(\tau')d\tau'$$

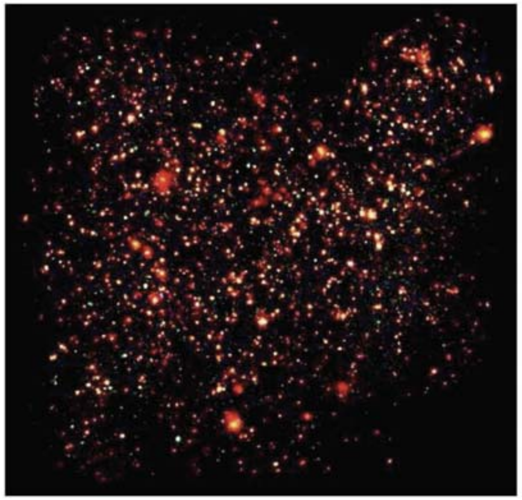
# Extracting evolution of accretion from observations



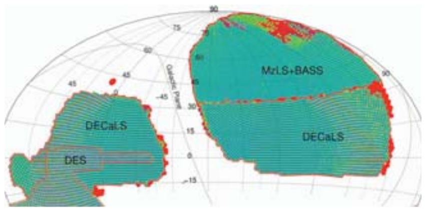

2dF

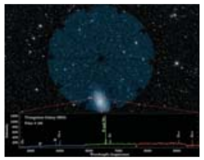


SDSS



X-ray survey



DESI

Prime Focus Spectrograph

SuMIRe

Statistical methods involving a large sample of QSOs/AGNs are required.

- A single AGN may only represent one specific period in a prolonged phase of nuclear activity.
- A large sample of AGNs with different ages will span all phases of this activity and allow us to extract information about evolution.

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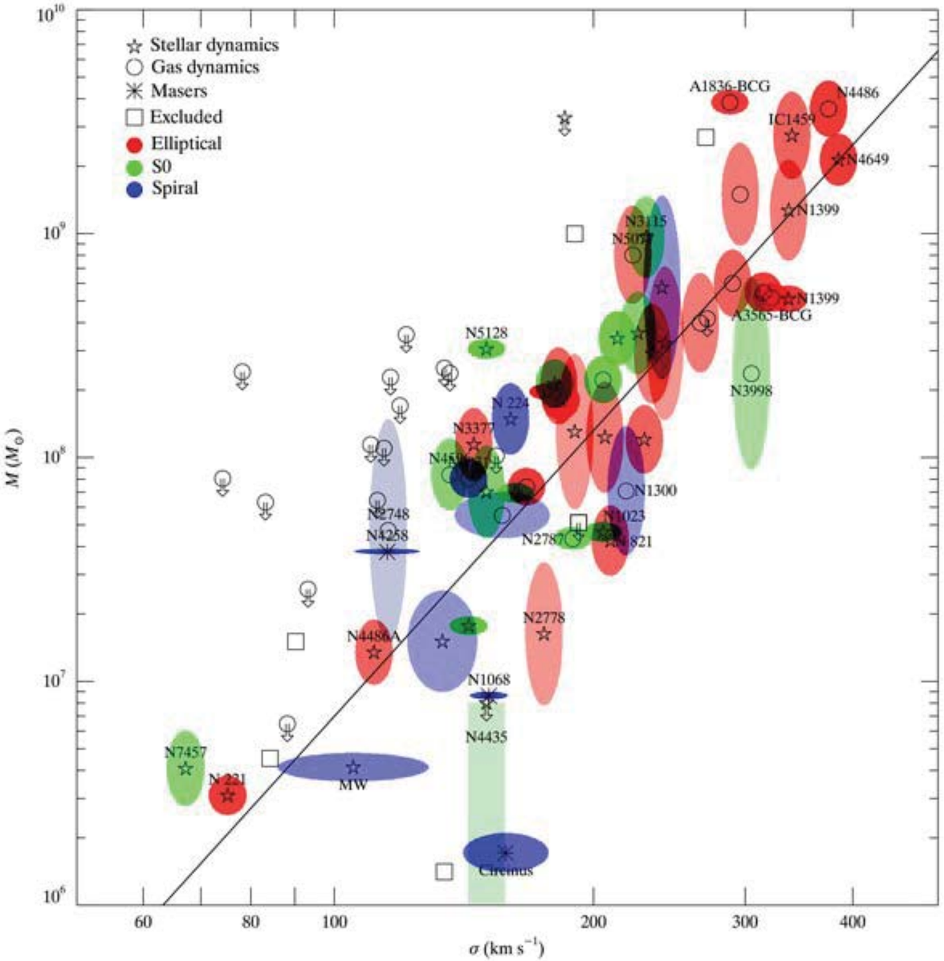
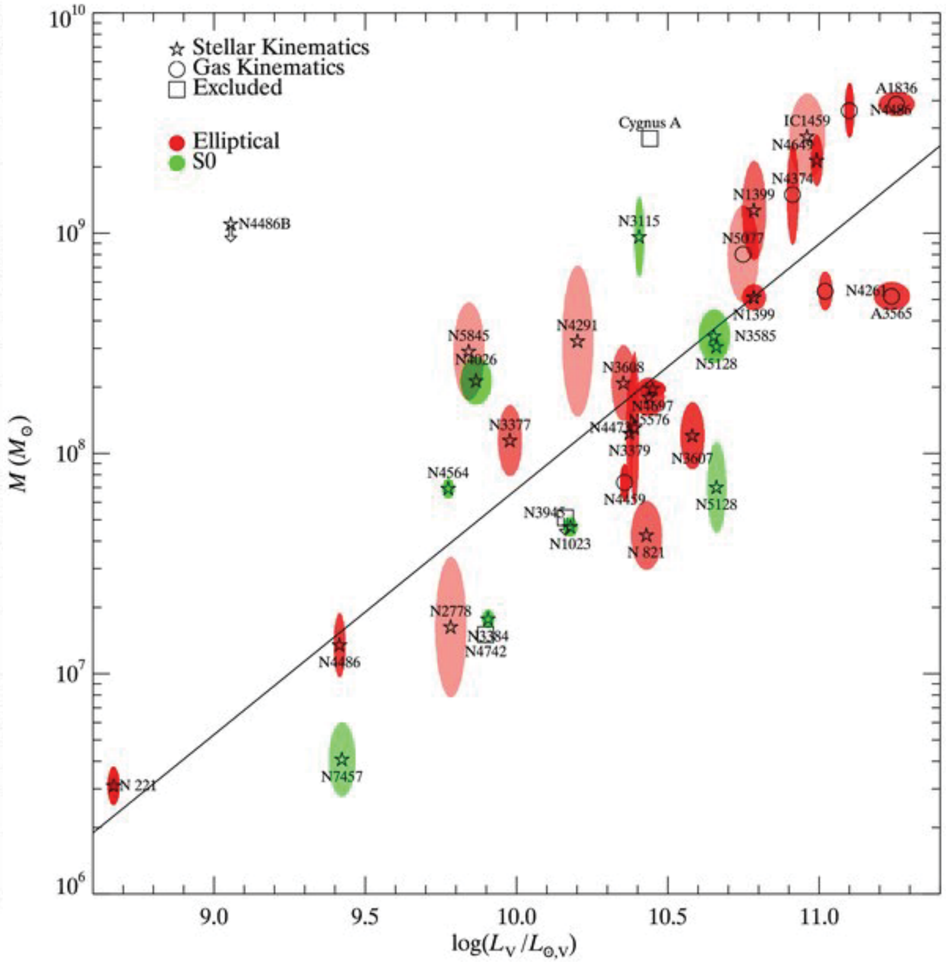
# Correlations between MBH masses and galaxy properties

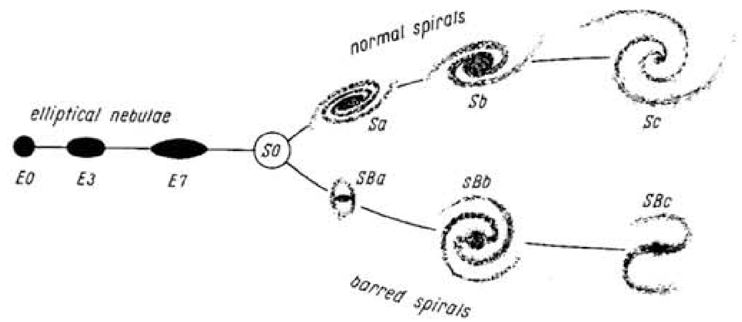


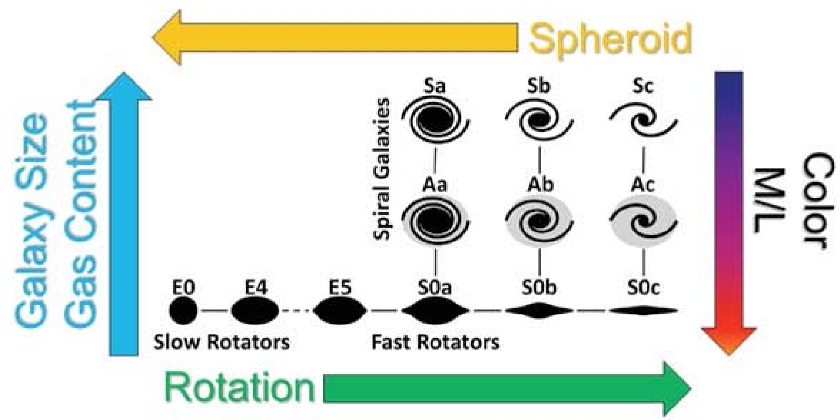

$$\log\left(\frac{M}{M_\odot}\right) = (8.12 \pm 0.08) + (4.24 \pm 0.41)\log\left(\frac{\sigma_e}{200\ \mathrm{km\ s^{-1}}}\right)$$

$$\log\left(\frac{M}{M_\odot}\right) = (8.95 \pm 0.11) + (1.11 \pm 0.18)\log\left(\frac{L_V}{10^{11}\ L_{\odot,V}}\right)$$

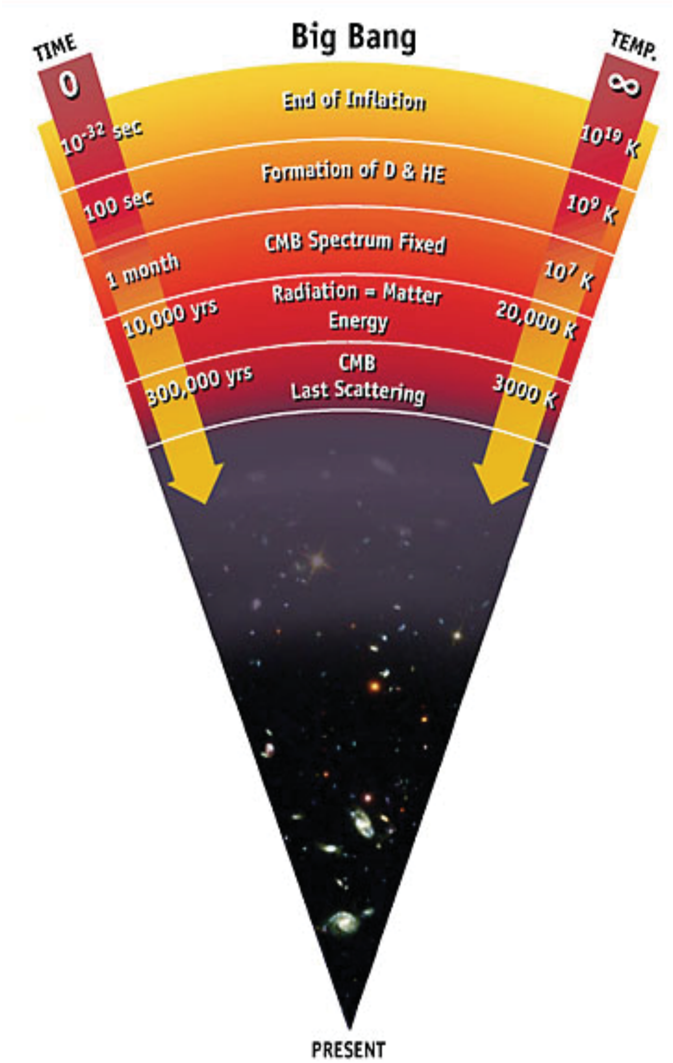
Gültekin et al. 2009

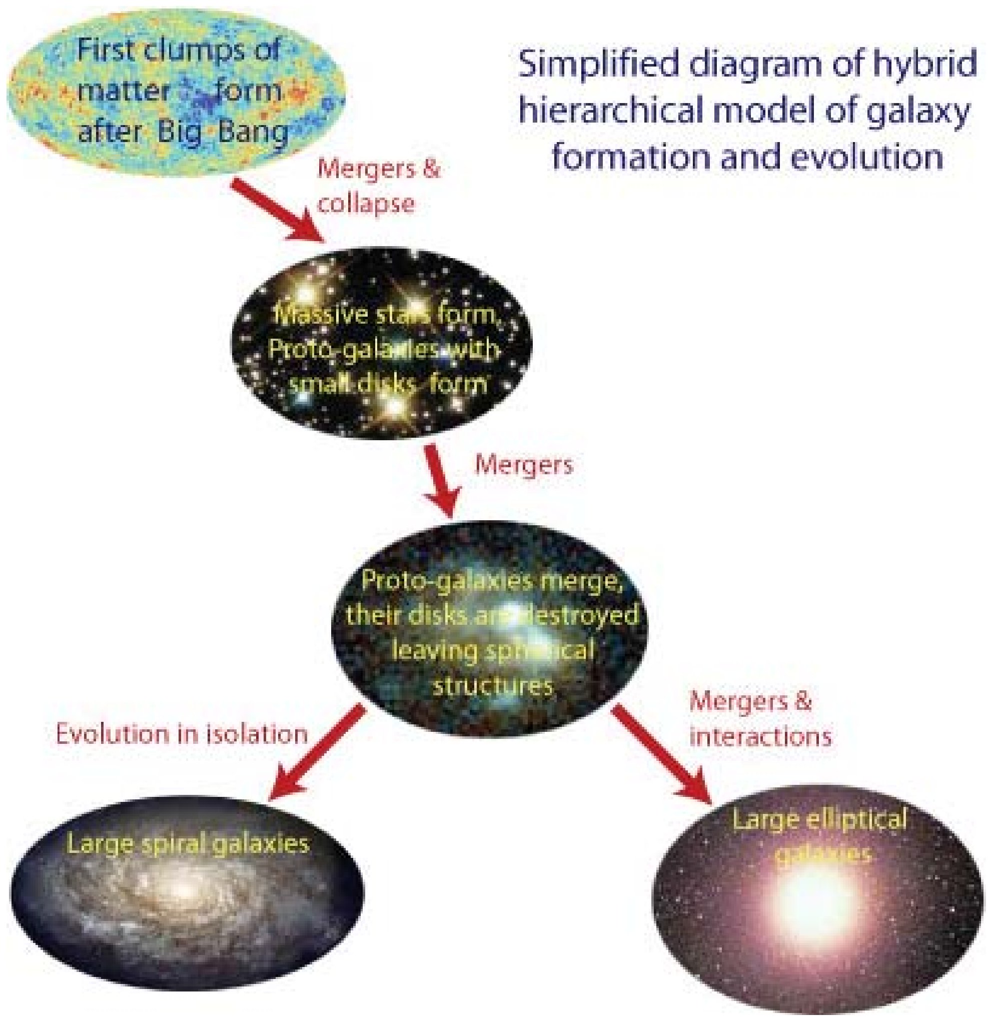



Hubble (1936) tuning fork



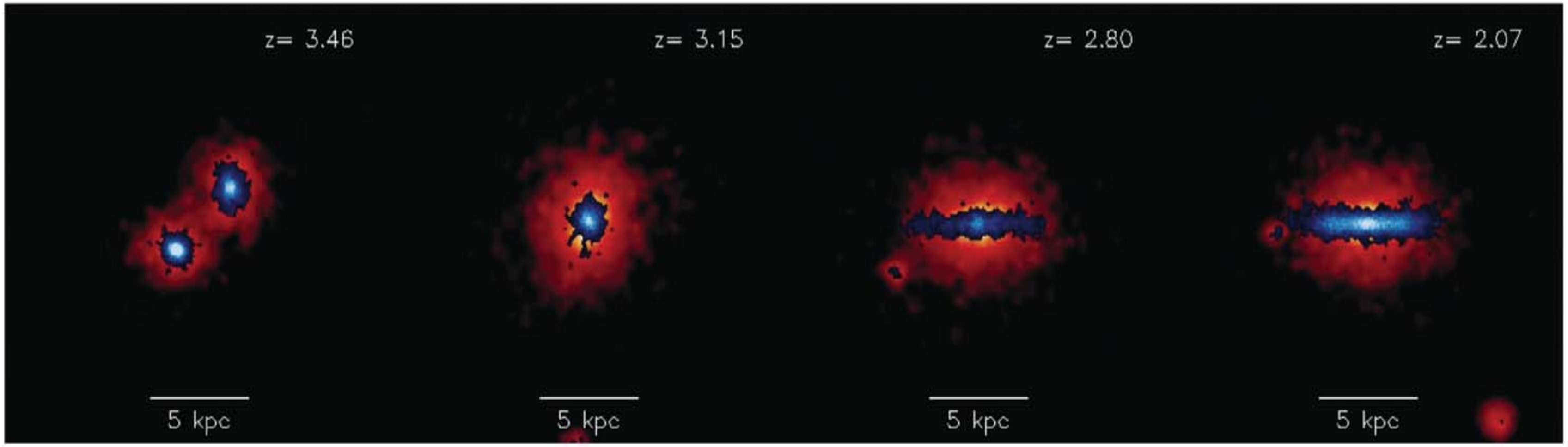

The ATLAS$^{3D}$ comb (2011)


Big Bang
TIME
0
10-32 sec
100 sec
1 month
10,000 yrs
300,000 yrs
TEMP.
∞
10¹⁹ K
10⁹ K
10⁷ K
20,000 K
3000 K
End of Inflation
Formation of D & HE
CMB Spectrum Fixed
Radiation = Matter Energy
CMB Last Scattering
PRESENT

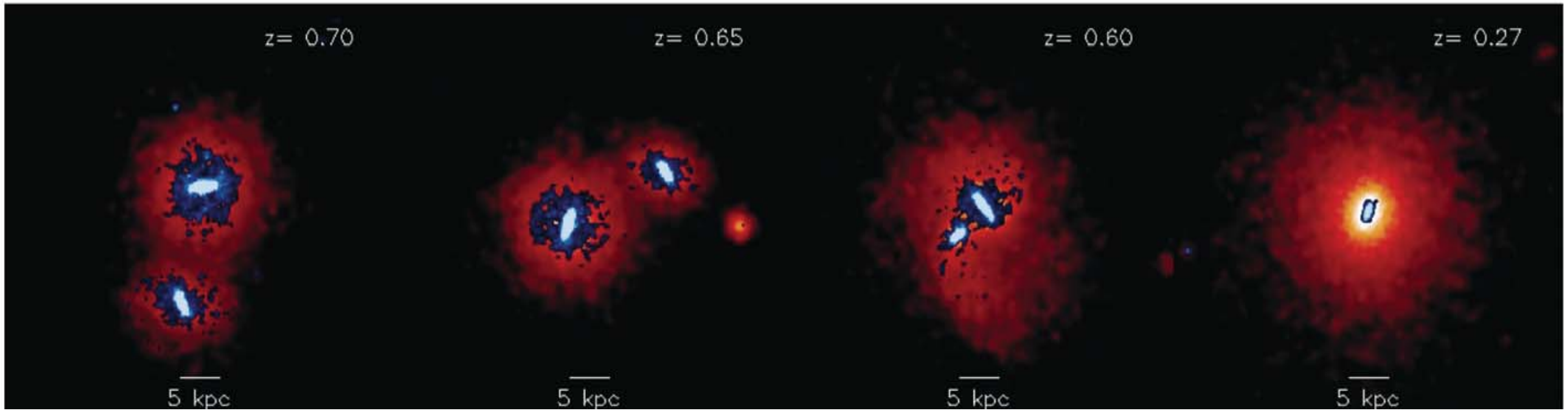

Simplified diagram of hybrid hierarchical model of galaxy formation and evolution
First clumps of matter form after Big Bang
Mergers & collapse
Massive stars form, Proto-galaxies with small disks form
Mergers
Proto-galaxies merge, their disks are destroyed leaving spherical structures
Evolution in isolation
Mergers & interactions
Large spiral galaxies
Large elliptical galaxies

# Major mergers of galaxies: morphological and color transformation

The formation of bulge and rebirth of a disk




A major merger and the formation of an elliptical galaxy




(Steinmetz & Navarro 2002)

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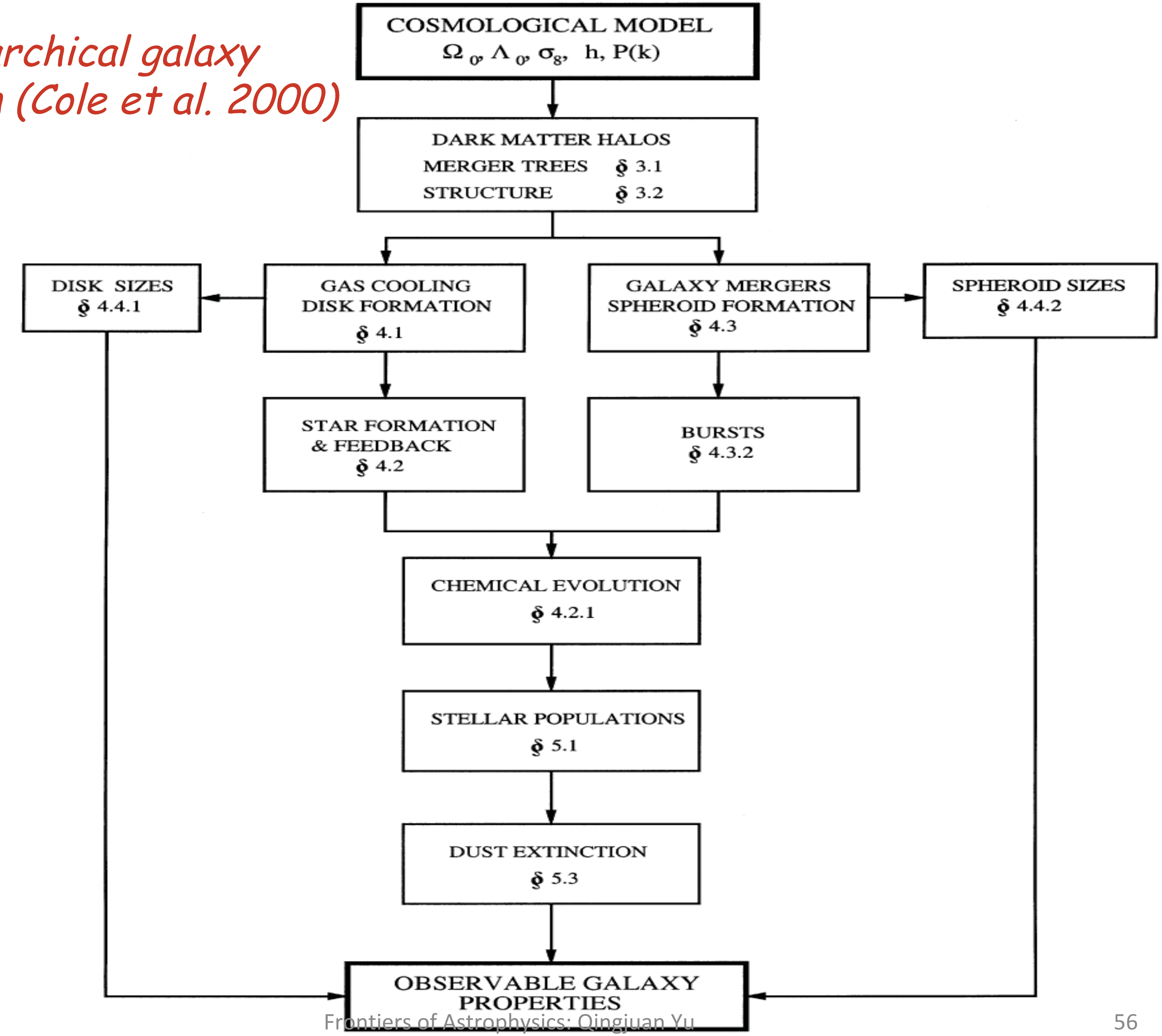
## *Hierarchical galaxy formation (Cole et al. 2000)*



# Background: structure formation

- Press-Schechter mass function:
  - Halo mass distribution at a given cosmic time t

$$\frac{\mathrm{d}n(M,t)}{\mathrm{d}M}\mathrm{d}M = \left(\frac{2}{\pi}\right)^{1/2}\frac{\bar{\rho}_0}{M^2}\frac{\delta_\mathrm{c}(t)}{\sigma(M)}\left|\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M}\right|\exp\left[-\frac{\delta_\mathrm{c}^2(t)}{2\sigma^2(M)}\right]\mathrm{d}M$$

- Extended Press-Schechter mass function (conditional distribution mass function):
  - The fraction of mass in haloes of mass $M_2$, at time $t_2$, which at an earlier time, $t_1$, was in haloes of mass in the range $M_1$ to $M_1+dM_1$

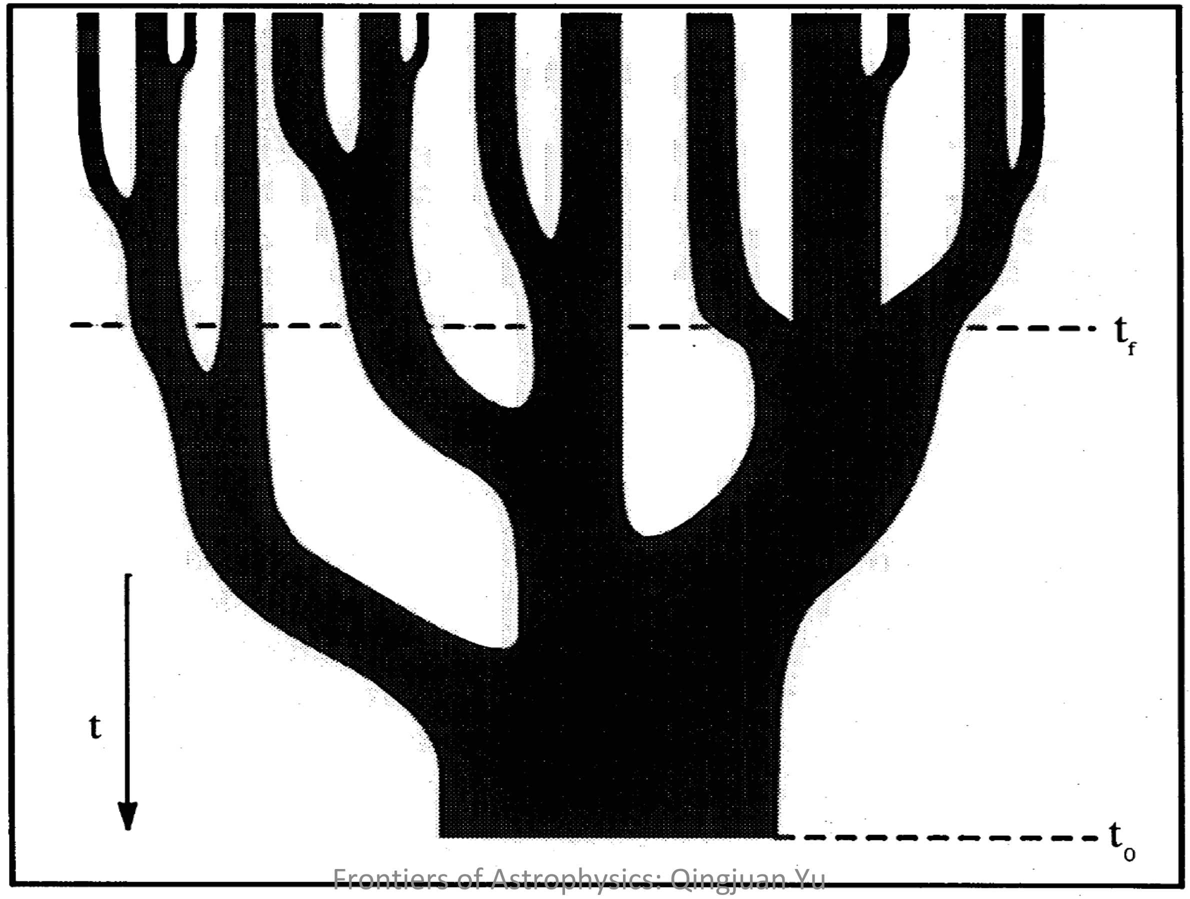
$$f_{12}(M_1,M_2)\,\mathrm{d}M_1 = \frac{1}{\sqrt{2\pi}}\frac{(\delta_{c1}-\delta_{c2})}{(\sigma_1^2-\sigma_2^2)^{3/2}}$$

$(M_1<M_2)$

$$\times\exp\left[-\frac{(\delta_{c1}-\delta_{c2})^2}{2(\sigma_1^2-\sigma_2^2)}\right]\frac{\mathrm{d}\sigma_1^2}{\mathrm{d}M_1}\mathrm{d}M_1$$

# Merger trees from conditional Mass distribution function

- Using Monte Carlo method (or directly using numerical simulations)



# Recipes for Galaxy formation

- Cooling of the hot gas in haloes

$$\tau_{\rm cool} = \frac{3}{2}\frac{\rho_{\rm gas}(r)}{\mu m_{\rm H}}\frac{k_{\rm B}T_{\rm gas}}{n_{\rm e}^2(r)\Lambda(T_{\rm gas}, Z_{\rm gas})}$$

(example)

- Star formation from cold gas (formation of disk)

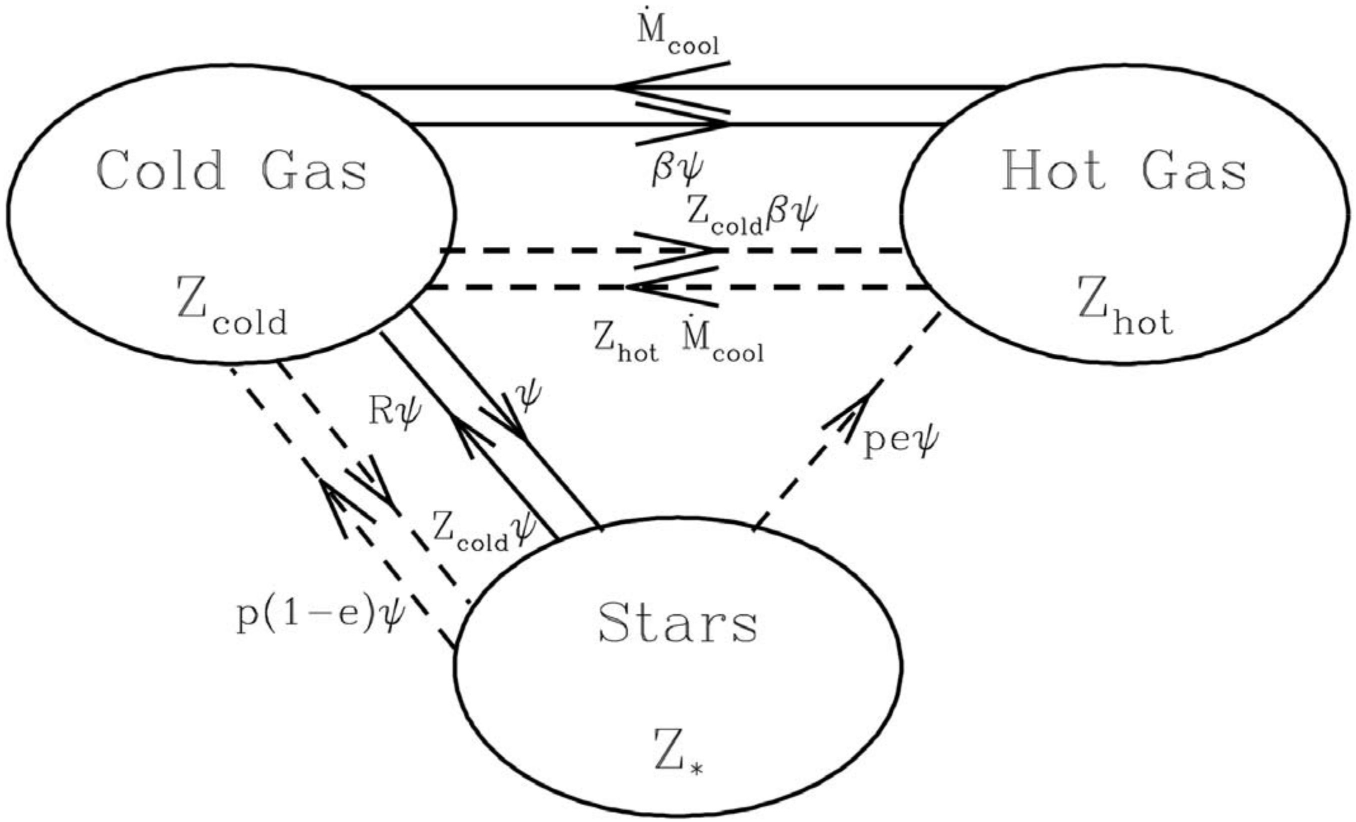
$$\psi = M_{\rm cold}/\tau_{\star}.$$

$$\tau_{\star} = \epsilon_{\star}^{-1}\,(V_{\rm disk}/200\,{\rm km\,s^{-1}})^{\alpha_{\star}}\,\tau_{\rm disk}$$

(example)

# Recipes for Galaxy formation

- Supernovae feedback, metal enrichment



# Recipes for Galaxy Formation

- Galaxy merging

  1) dynamical friction

$$\tau_{\rm mrg} = f_{\rm df}\, \Theta_{\rm orbit}\, \tau_{\rm dyn} \frac{0.3722}{\ln(\Lambda_{\rm C})} \frac{M_{\rm H}}{M_{\rm S}}$$

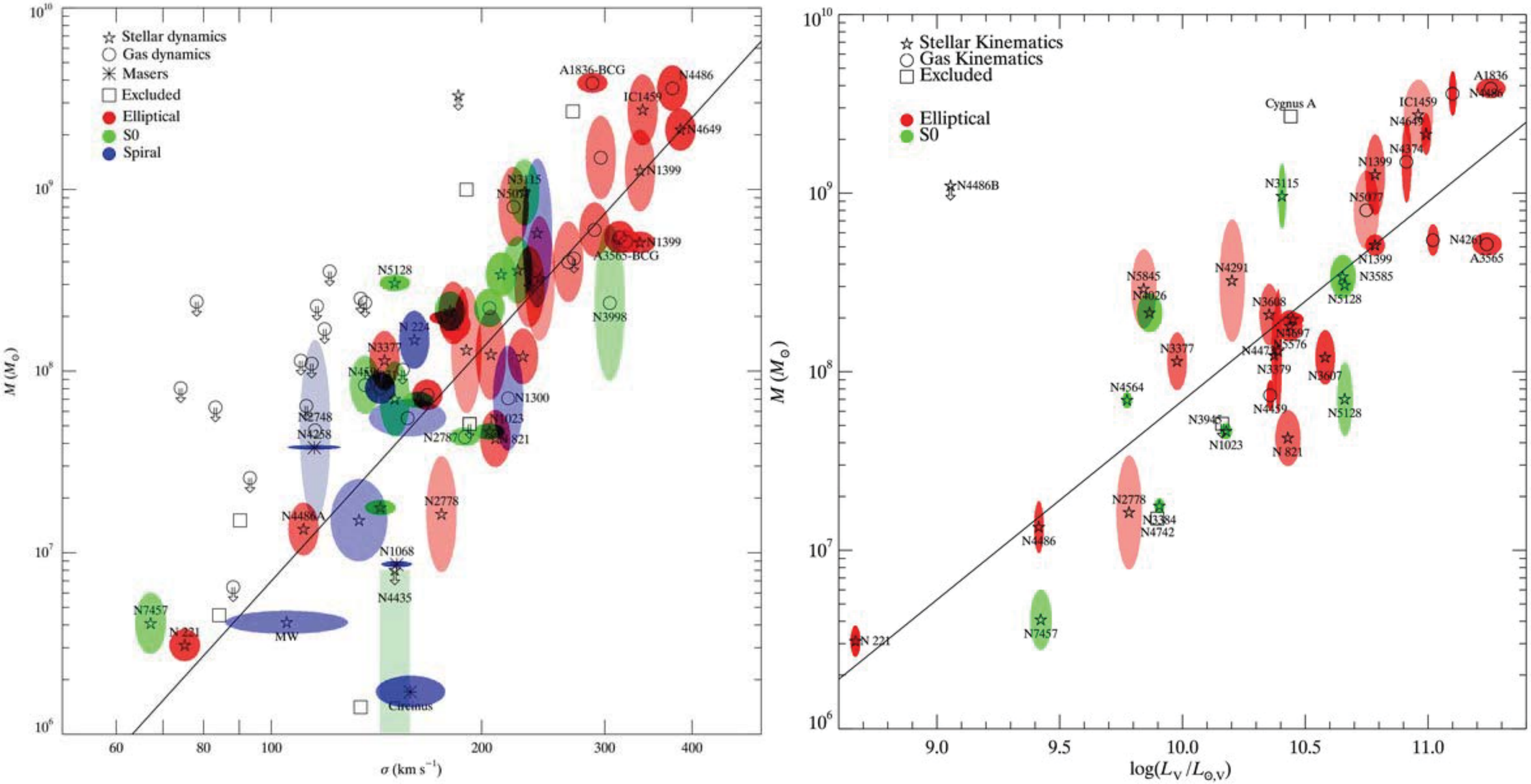
(example)

  2) Spheroid formation (major mergers / minor mergers)
     disk and bulge size
     mainly determined by the angular momentum and
     mass in the formed stars; trigger star bursts

- Spectral synthesis model
  and dust extinction

Galaxies formed

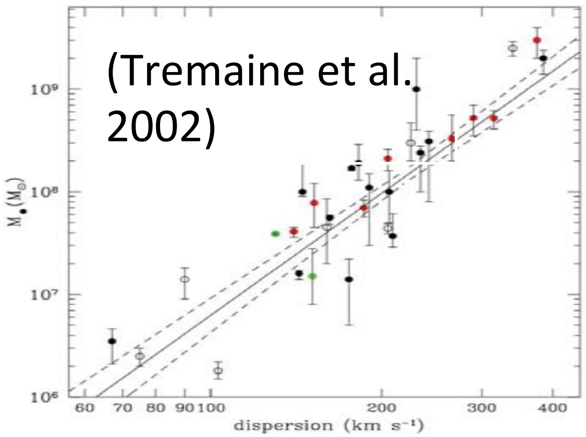
# Correlations between MBH masses and galaxy properties




These correlations strongly suggest a close link between the formation and evolution of galaxies and their central BHs. What is the physical origin?

# AGN Feedback

- Relations between SMBH mass and velocity dispersion, bulge luminosity or bulge mass



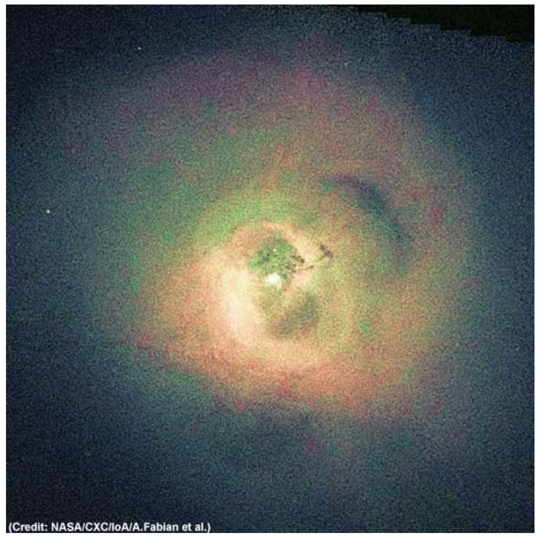

Total energy output from a QSO:

$$E_{output} \approx \epsilon M_{\bullet} c^2 \approx 10^{62} \left(\frac{\epsilon}{0.1}\right)\left(\frac{M_{\bullet}}{10^9 M_{sun}}\right) erg$$

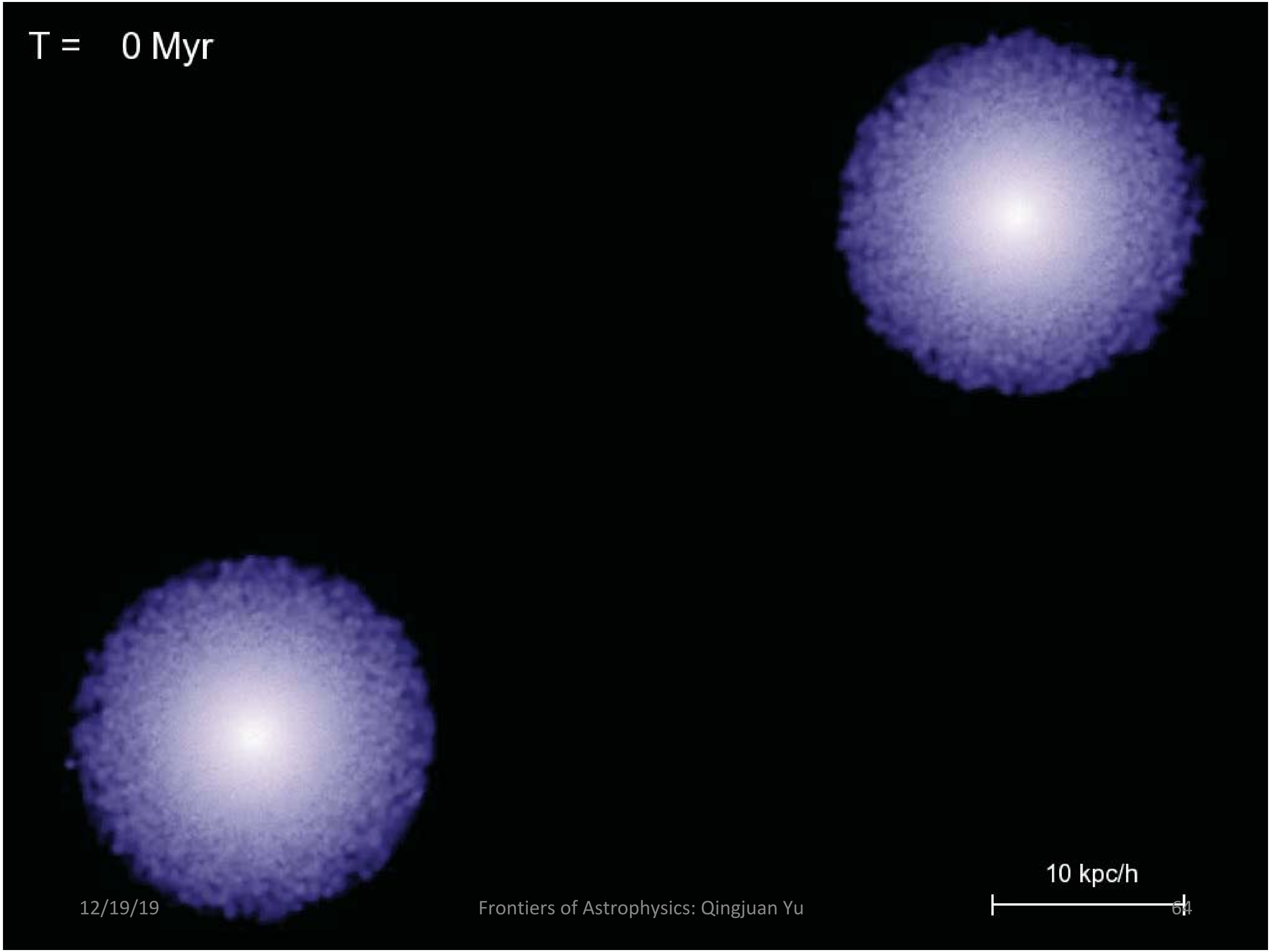
Total bounding energy of the galaxy:

$$E_{binding} \approx C M_{Gal} \sigma^2 \approx 10^{60} \left(\frac{C}{1}\right)\left(\frac{M_{Gal}}{10^{12} M_{sun}}\right) erg$$

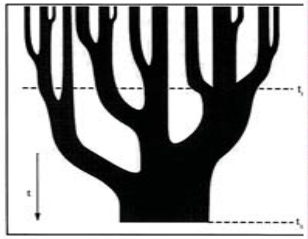
Even a small fraction of QSO energy incorporated into galactic medium may expels all the medium out of the galaxy

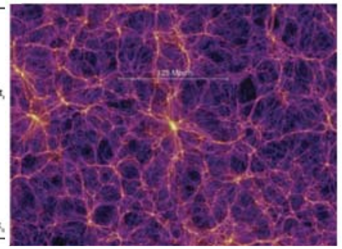



Fabian et al. 2003


T = 0 Myr
10 kpc/h

# Formation and evolution of BHs and galaxies



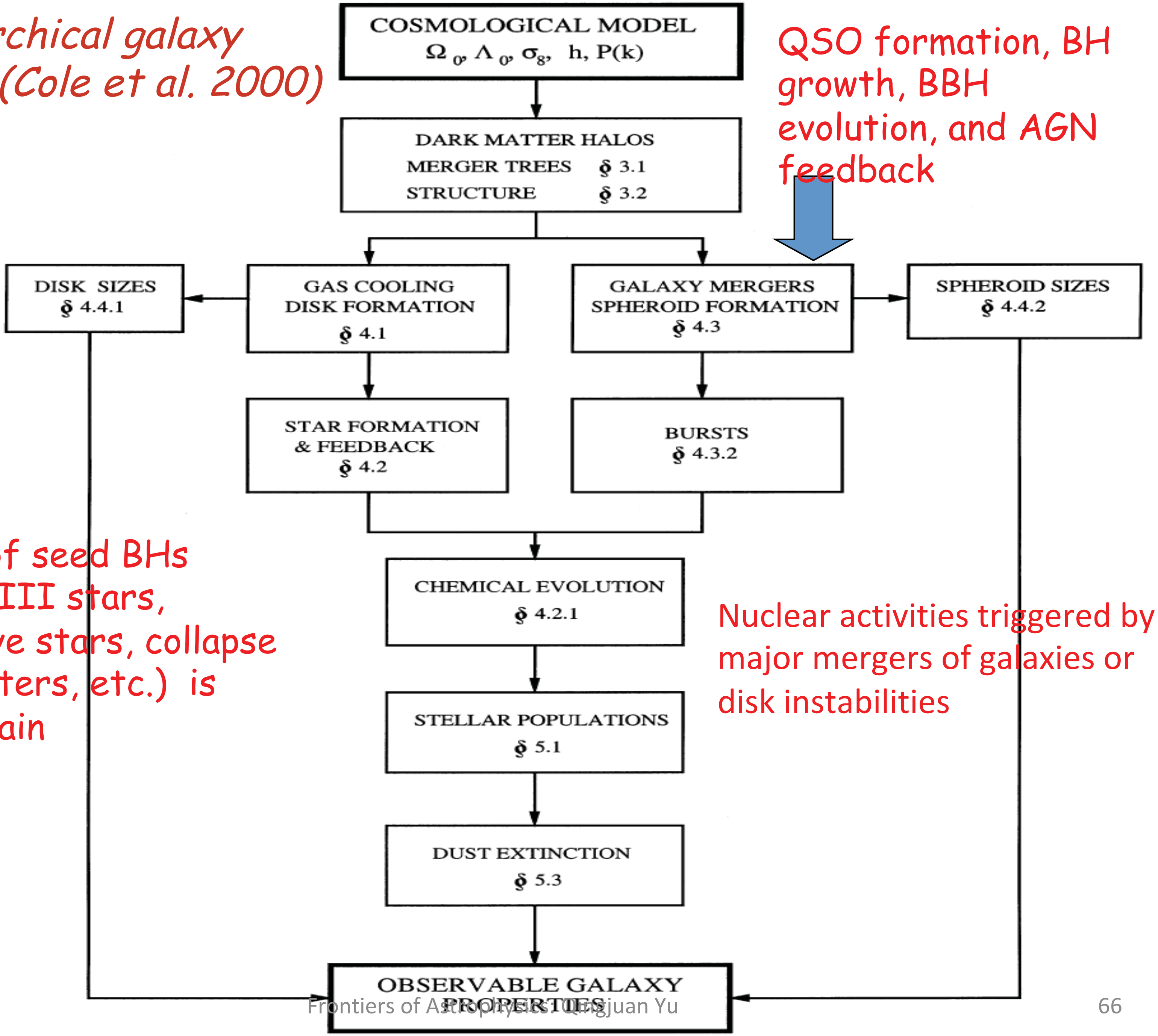


- Structure formation: halo merger tree
- Recipes for galaxy formation
- Recipes for formation and evolution of BHs and QSOs, gas accretion
  - QSOs: triggered by major mergers of galaxies/halos or disk instability
  - BH growth: BH mergers + gas accretion during major mergers of galaxies/halos or disk instability
  - AGN feedback: suppressing star formation and BH growth (QSO mode & Radio mode)
  - Seed BH formation and dynamics of BBHs and triple BH interaction
- Model output
  - QSO luminosity function, BH mass function, SFRs, galaxy properties etc.
  - BBHs, binary quasars/dual AGNs, wandering BHs in halos, BHs in IGM

Involving many uncertain parameters and assumptions (though some even controversial). Any progress in the mechanisms involved may help to improve the understanding.

*Hierarchical galaxy formation (Cole et al. 2000)*

QSO formation, BH growth, BBH evolution, and AGN feedback

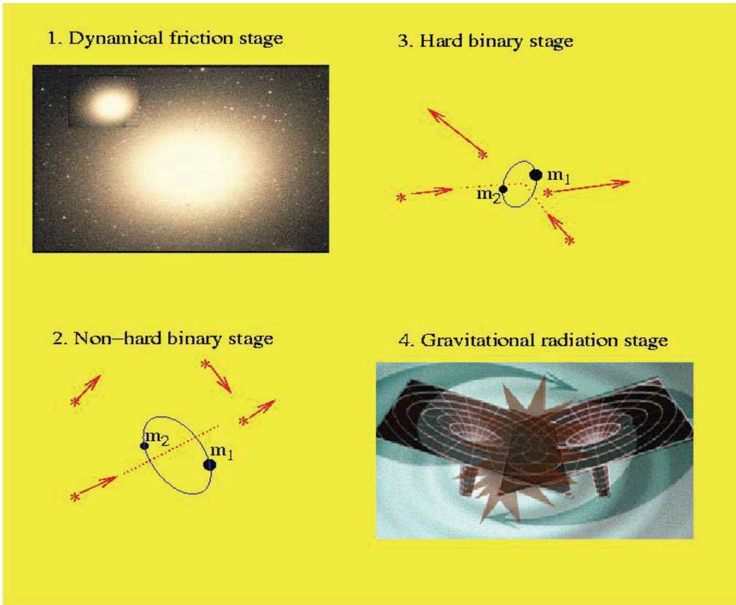


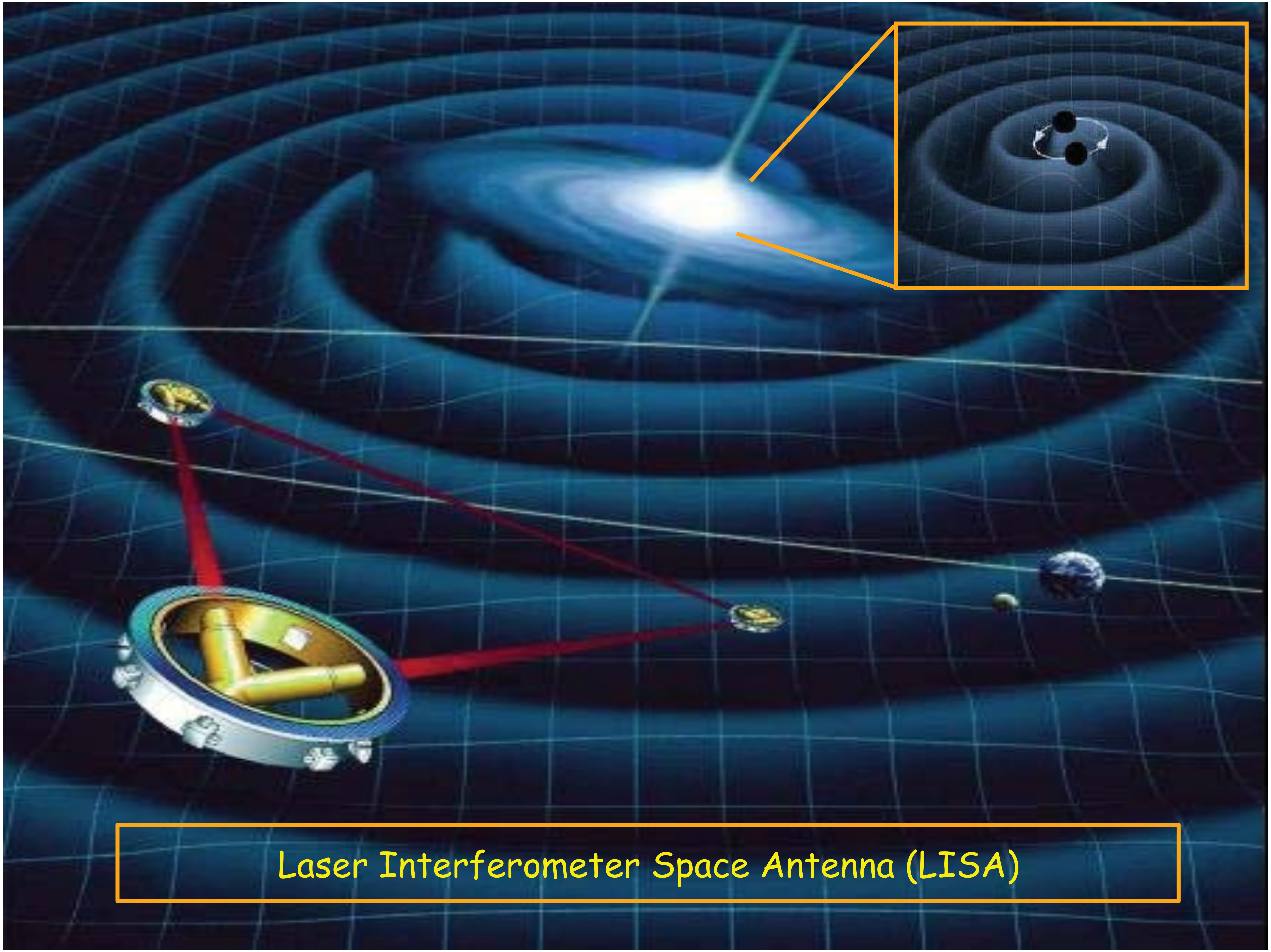

Formation of seed BHs (population III stars, supermassive stars, collapse of star clusters, etc.) is very uncertain

Nuclear activities triggered by major mergers of galaxies or disk instabilities

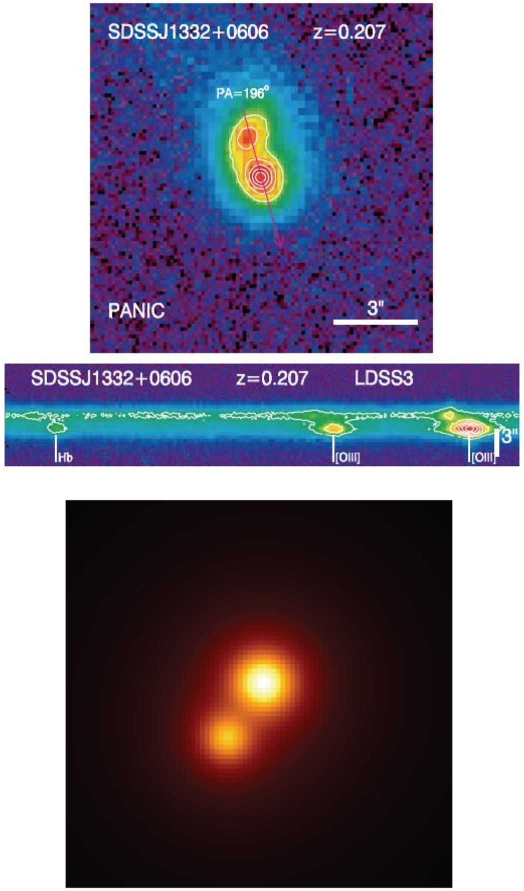
# Seed BHs and dynamics of BBH evolution

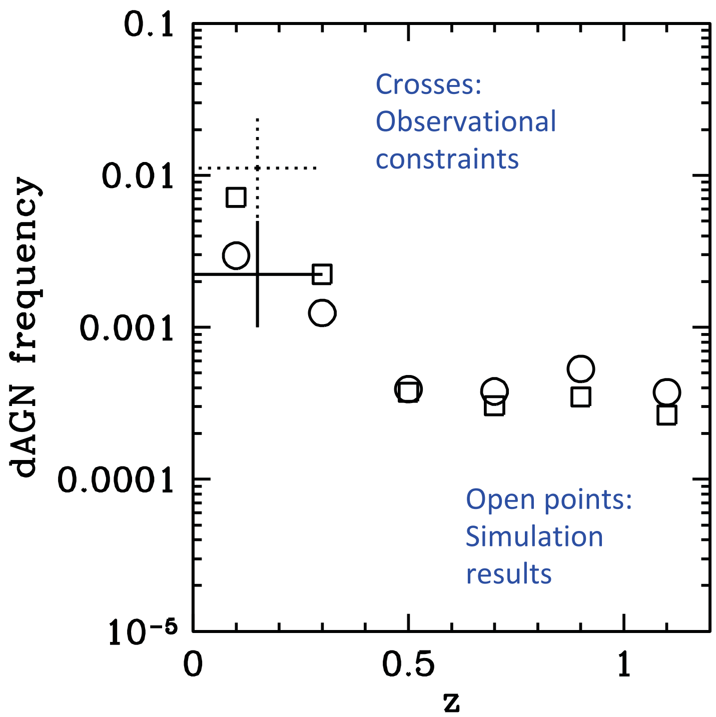
- Seed BHs:
  - Mass, redshift, over-density of haloes (little effect if the mass of seed BHs is small)
- BH mergers?
  - Dynamical evolution of BBHs
    - BH masses
    - Velocity dispersions, shapes, stellar densities of galaxies
    - Amount of gas in galactic nuclei
  - Three-body interactions of BHs (gravitational slingshot)
    - scattering or exchange
  - Recoil by gravitational radiation
  - Products of BH mergers




Laser Interferometer Space Antenna (LISA)

# Dual AGNs:
# frequency consistent with major merger rates of galaxies?




(Yu et al. 2011)

# Summary

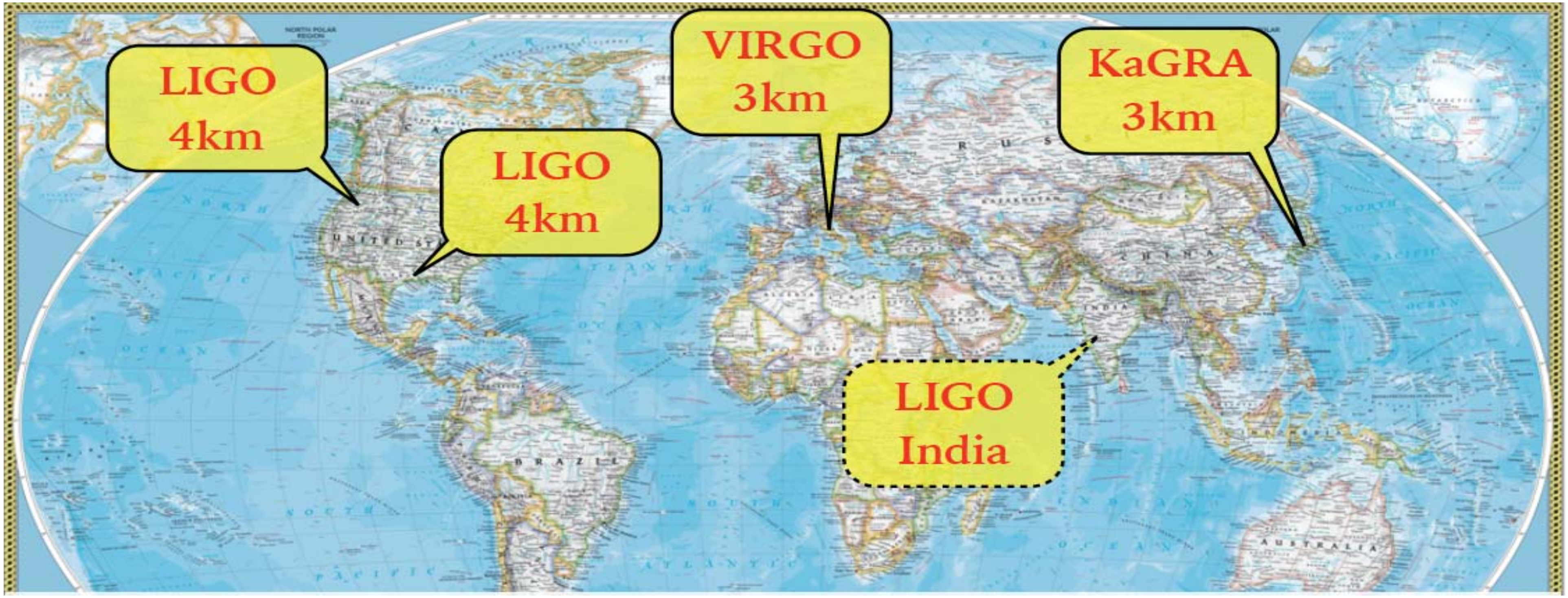
- We are entering an epoch to learn the formation and evolution of massive BHs from large observational samples and understand the role of BHs in the framework of galaxy formation and evolution and in the cosmological context.

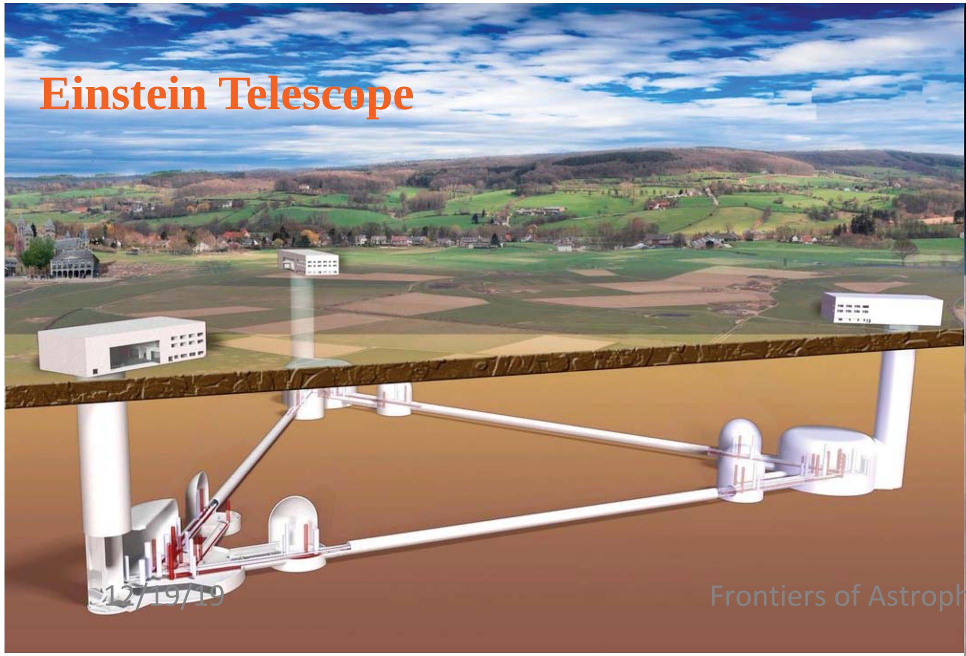
- The semi-analytical model provides a framework for understanding the co-evolution of galaxies and SMBHs and can well explain many current observations, although involving many assumptions.
- Further progress in the mechanisms involved may help to improve the understanding.

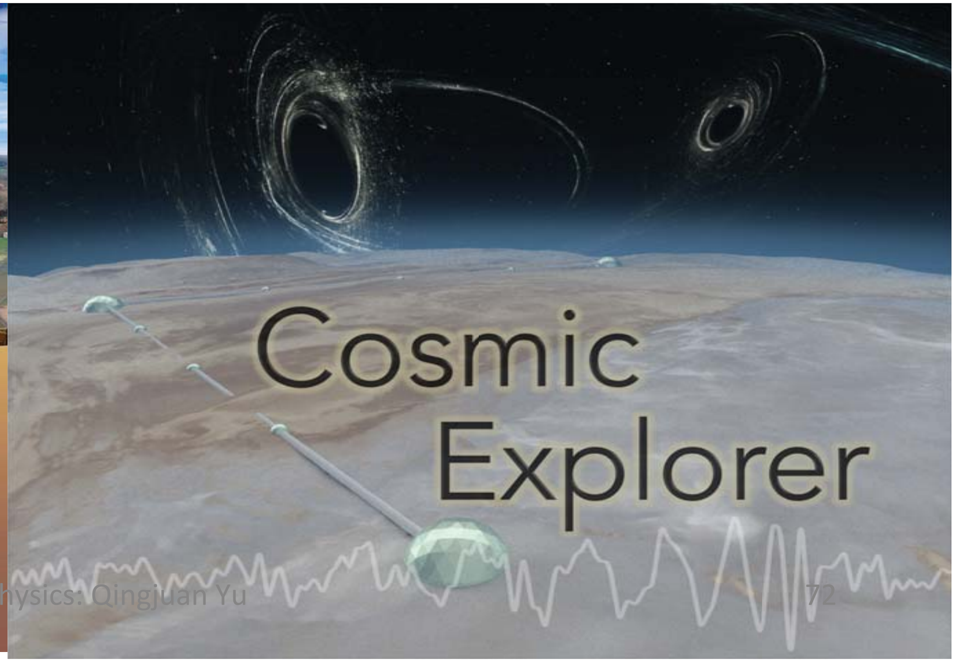
- GW detection results ⇄ insights on the model components
  - Massive stellar-mass BHs at LIGO band
  - GWR at PTA, LISA bands?
  - ....

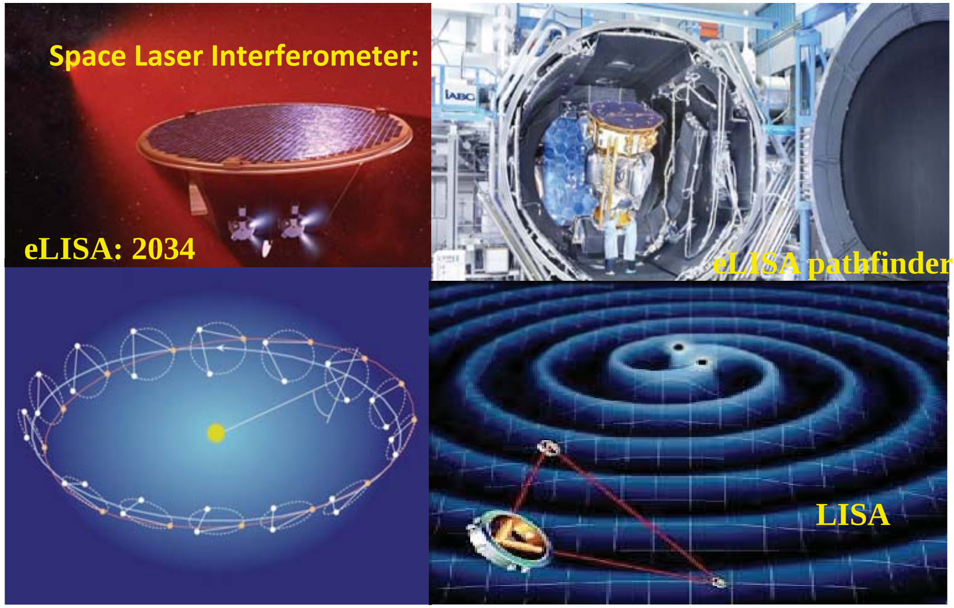
# Outline

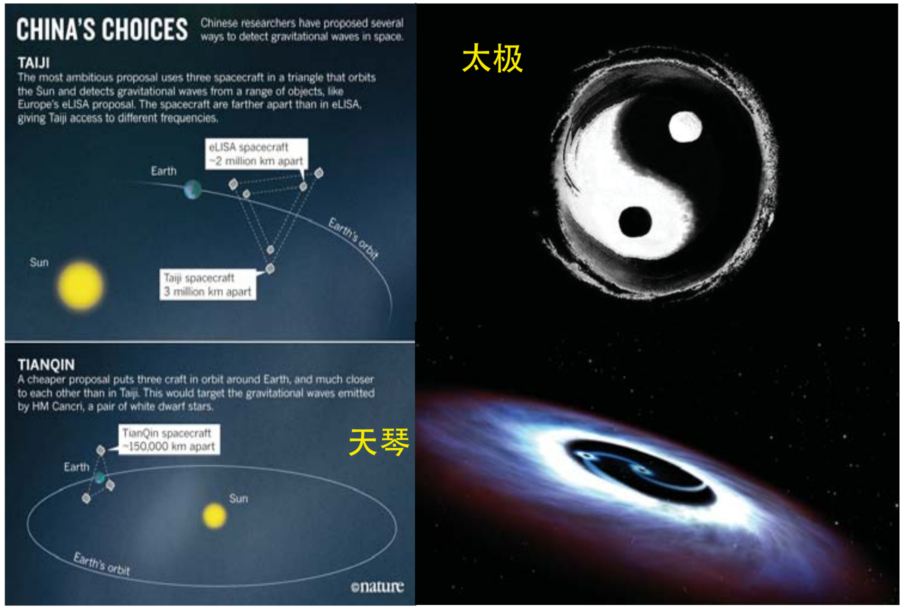
- Gravitational waves (GWs)
  - Basics
  - detection
  - significance
- Supermassive binary black holes (BBHs)
  - BHs
    - Stellar-mass BHs
    - Supermassive at galactic centers
      - Evidence: AGNs & Nearby galaxies
      - Galactic center
  - Supermassive BBHs
    - Observational characteristics, BH companion to Sgr A*?
    - Orbital evolution
    - Detection prospects
- Formation and evolution of galaxies and supermassive (BHs)
  - BH growth
  - Galaxy evolution
  - Semi-analytical models
- Opportunities, Challenge & Summary

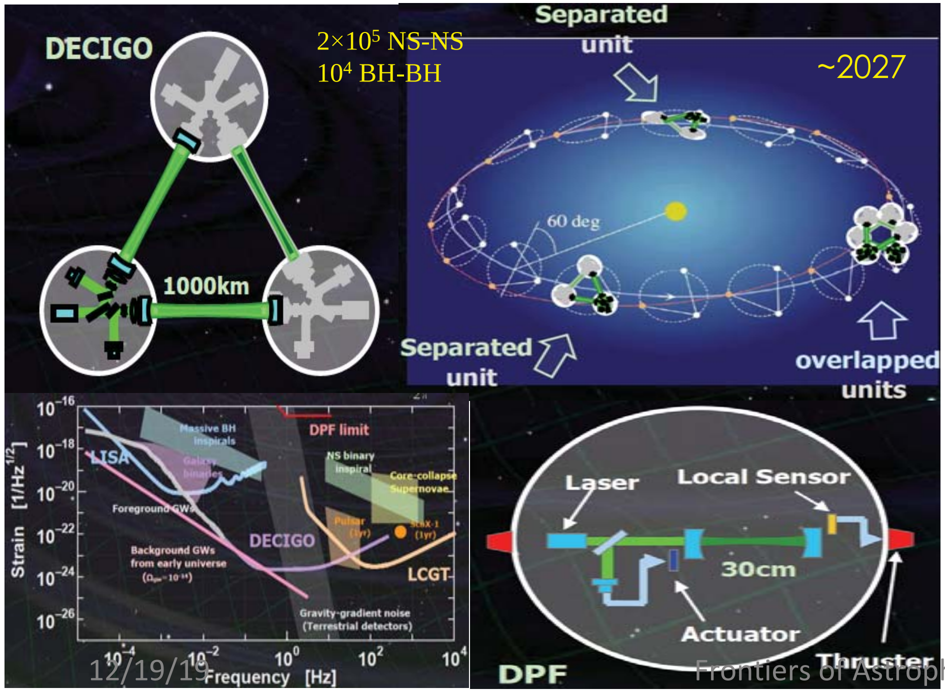

LIGO
4km
LIGO
4km
VIRGO
3km
KaGRA
3km
LIGO
India

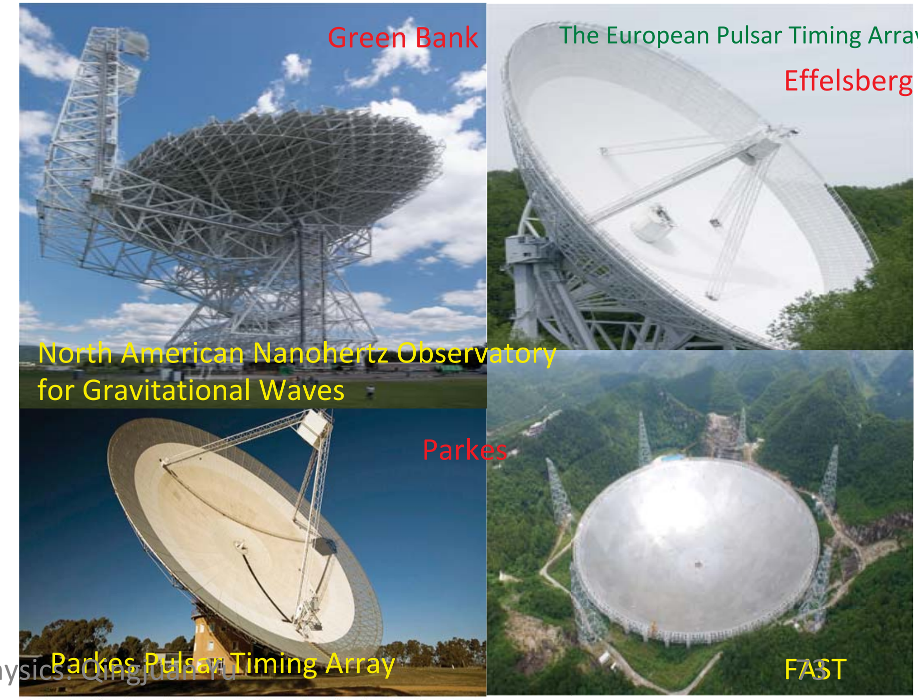

Einstein Telescope


Cosmic
Explorer




Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

# Big Questions

- 黑洞自旋及其演化？
- ~~引力波存在？~~ 新发现、新现象？
- 引力的本质？
- 宇宙中其它类型物态、天体？
- 宇宙的创生？

# Summary

- A new/great era to learn gravitational physics,
- A new/great era to re-learn astrophysics

- New insights for connection between math, physics, and astronomy?
- Huge stimulations for technology developments

- Interdisciplinary field

Fascinating
Challenging
Exciting
Revolutionary?!

Thank You!

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