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Compact objects as probes of astrophysics, gravity and fundamental physics

IAP seminar, March 7, 2014

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Outline

- Why bother about compact objects?
  The astrophysicist's vs relativist's view
- What can we learn from EM observations?
  Example: the spin evolution of supermassive BHs (models vs observations)
- Existing and future GW observations and what we can learn from them
  Examples: the spins of supermassive BHs (again!), tests of gravity theories (e.g. Lorentz violation)

CO's: the astrophysicist's view

- Stellar evolution theory & observations: stellar-mass BHs, neutron stars & white dwarfs exist
- Supermassive BHs observed at the center of galaxies and co-evolve with them
- Intermediate mass BHs may exist, but no dynamical measurements so far

CO's: the relativist's view

- GR tested only in systems with v << c (quasi-static) and/or weak gravitational fields and spacetime curvatures
- CO's provide strong fields and curvatures, and close CO binaries also have v ~ c

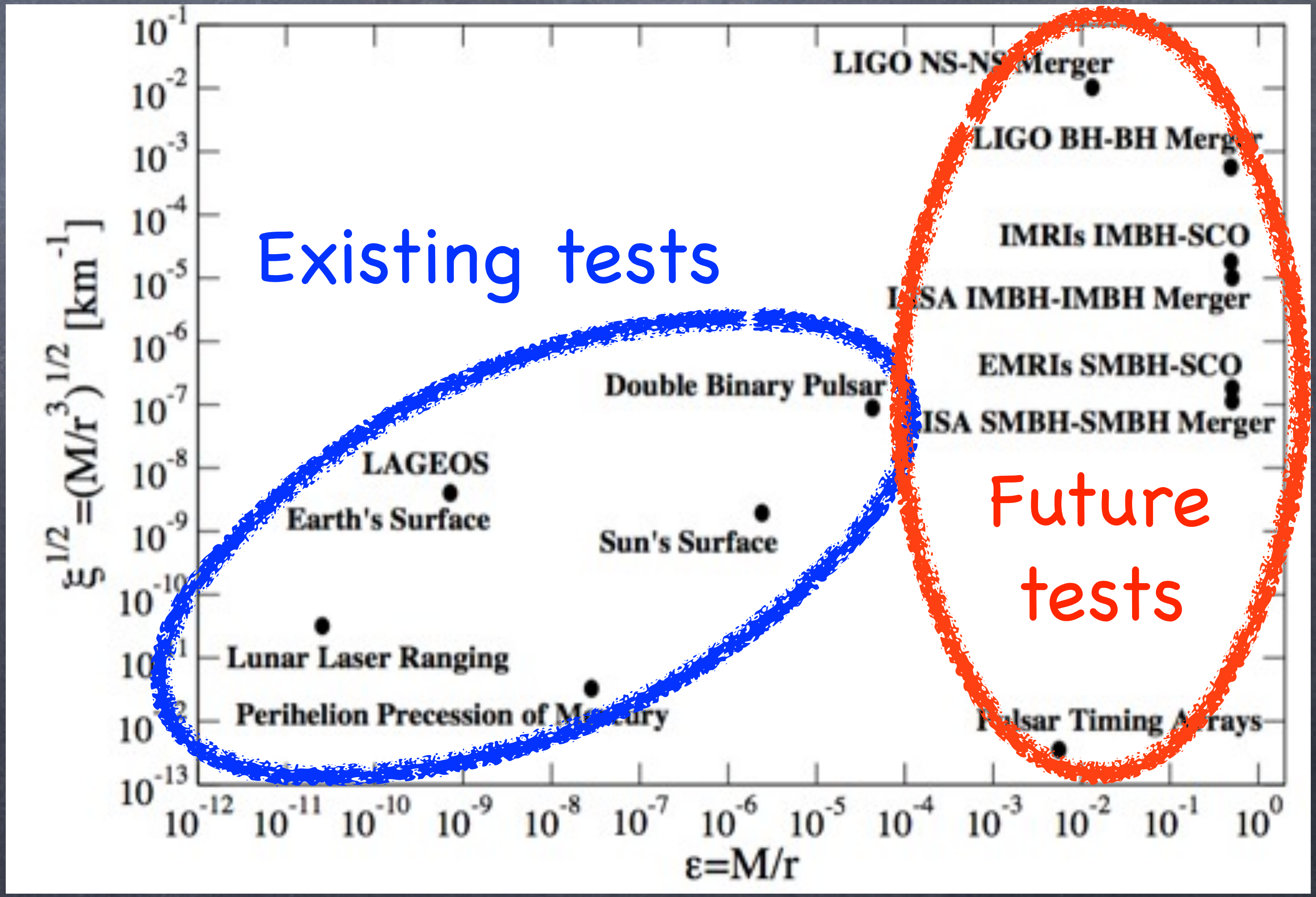


Figure courtesy of N. Yunes, adapted from D. Psaltis Living Rev. Relativity 11 (2008), 9 (see also Yunes & Siemens 2013)

Part I:

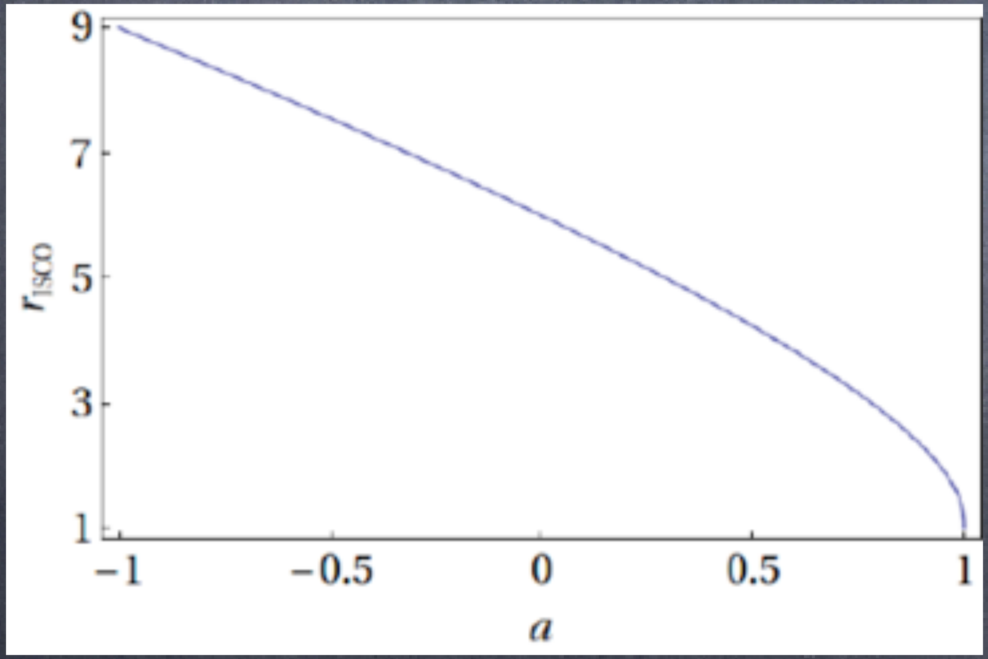
What can we learn from EM observations (of massive BHs)

What is a BH?

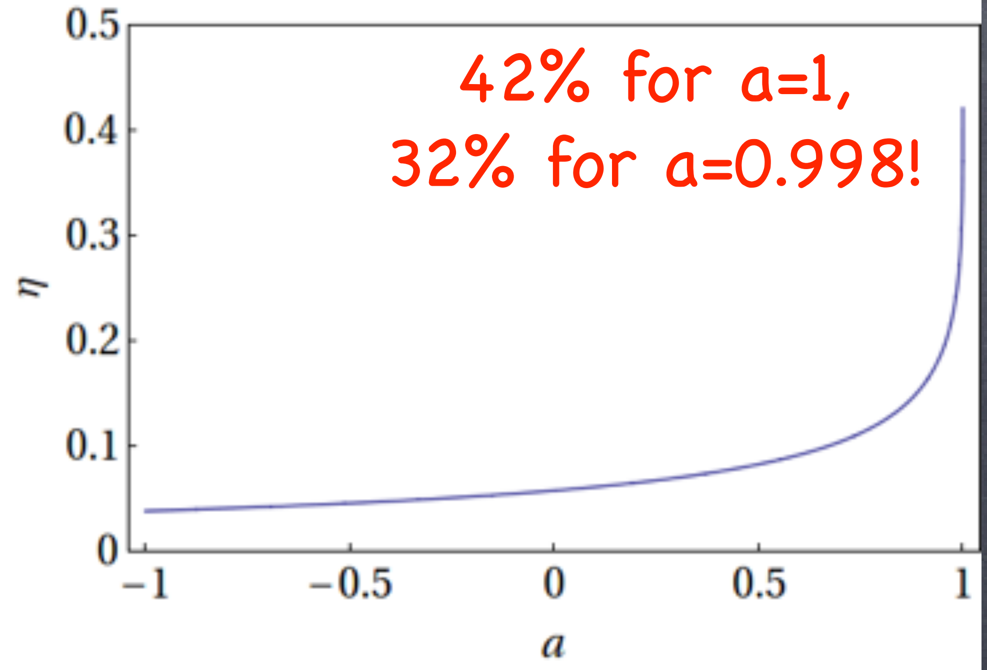
- A vacuum solution to the field equations that is regular outside an event horizon (located at $R \sim GM/c^2$)
- In GR, characterized by mass M, electric charge Q (= 0 astrophysically) and spin S ...
- ... but more exotic charges present if gravity not described by GR

Astrophysical consequences of BH charges

- Mass behaves qualitatively like in Newtonian gravity
- Spin affects motion around BHs ("frame dragging" or "spin-orbit coupling"):



ISCO radius

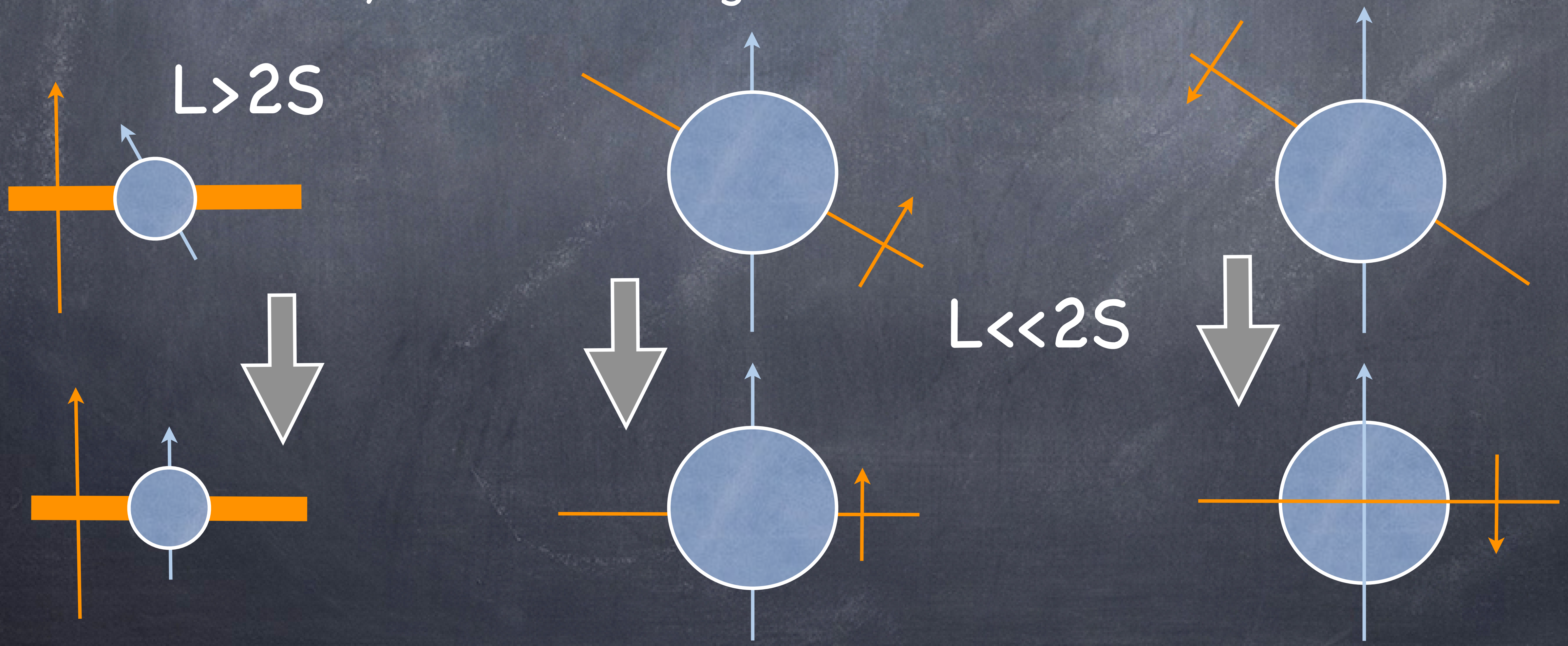


Efficiency of EM emission from thin disks

The Bardeen Petterson effect

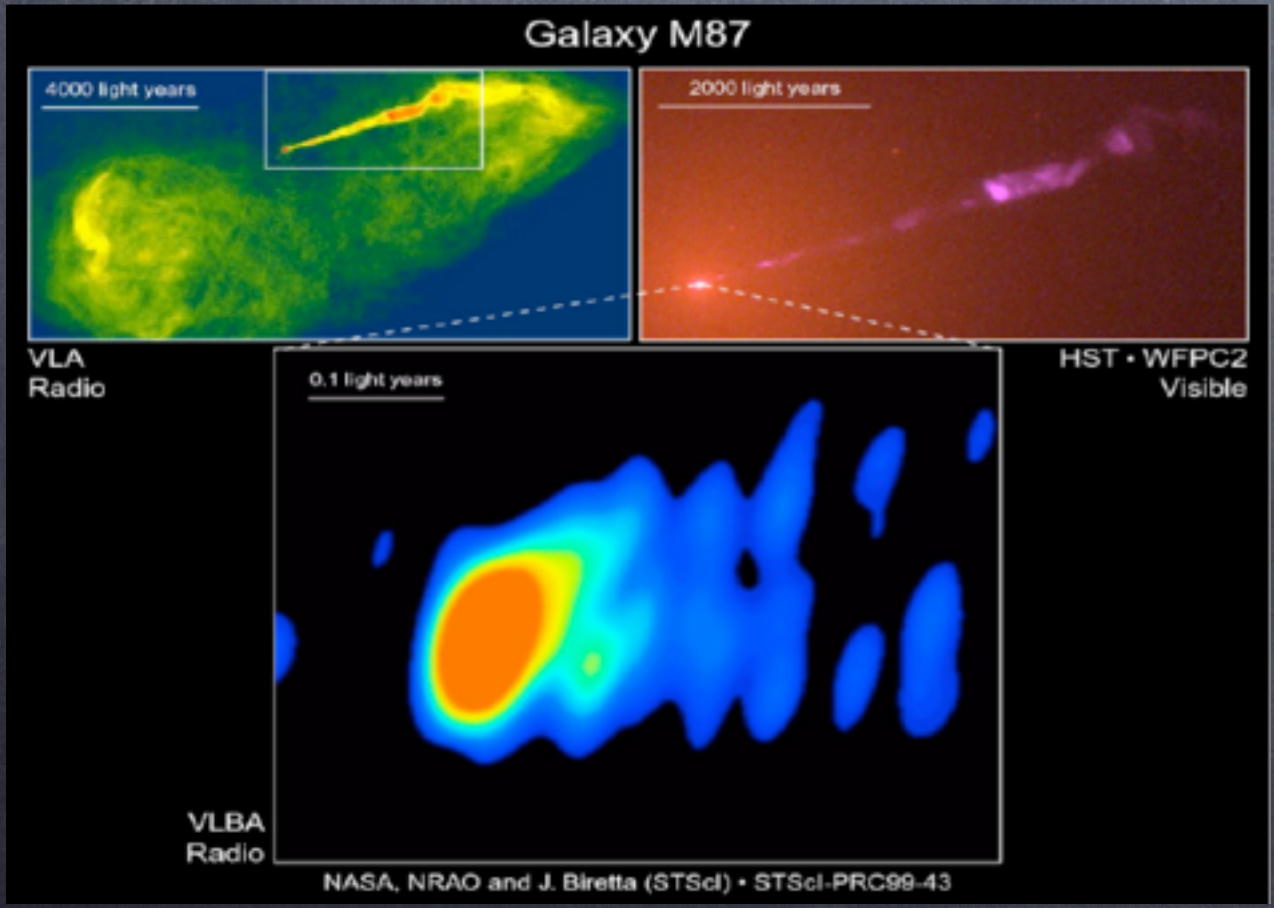
(see also King, Pringle, Dotti, Volonteri, Perego, Colpi, ...)

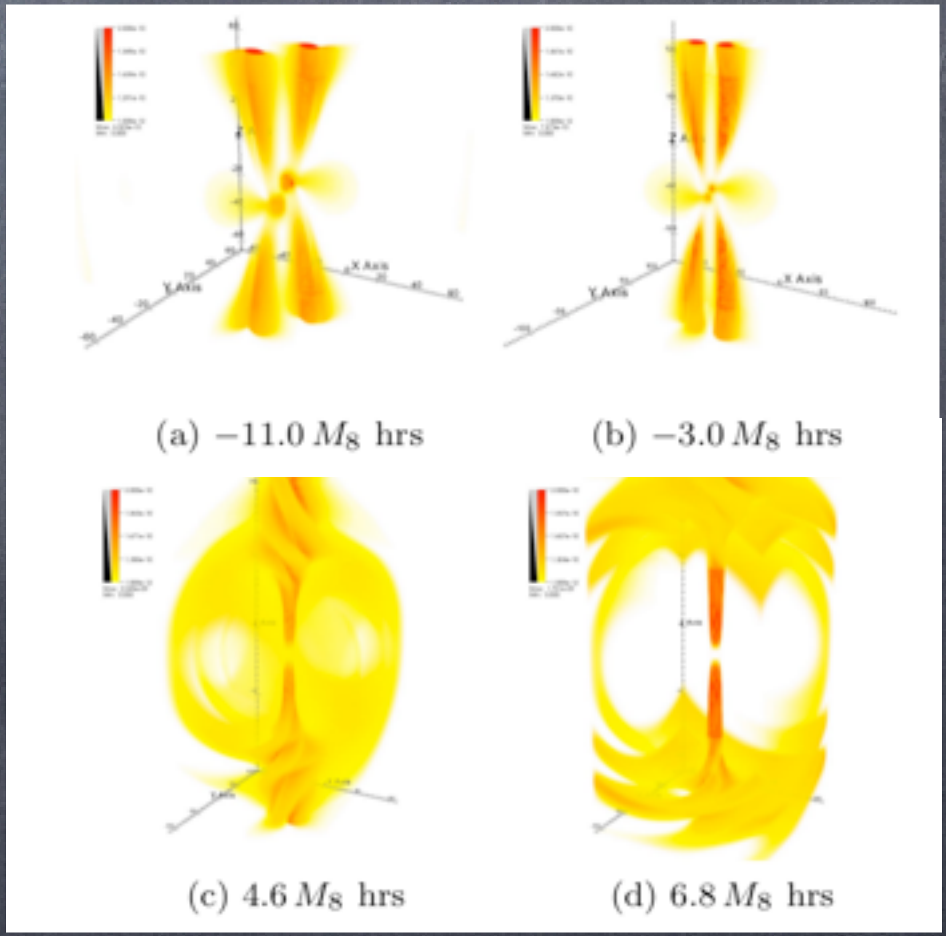
- Coupling between BH spin S and angular momentum L of misaligned accretion disk + dissipation
- Either aligns or antialigns S and L in ~10^5 yrs (for MBHs) << accretion timescale
- Antialignment only if disk carries little angular momentum (L < 2S) and is initially counterrotating



Spin (and mass) evolution depends on environment!

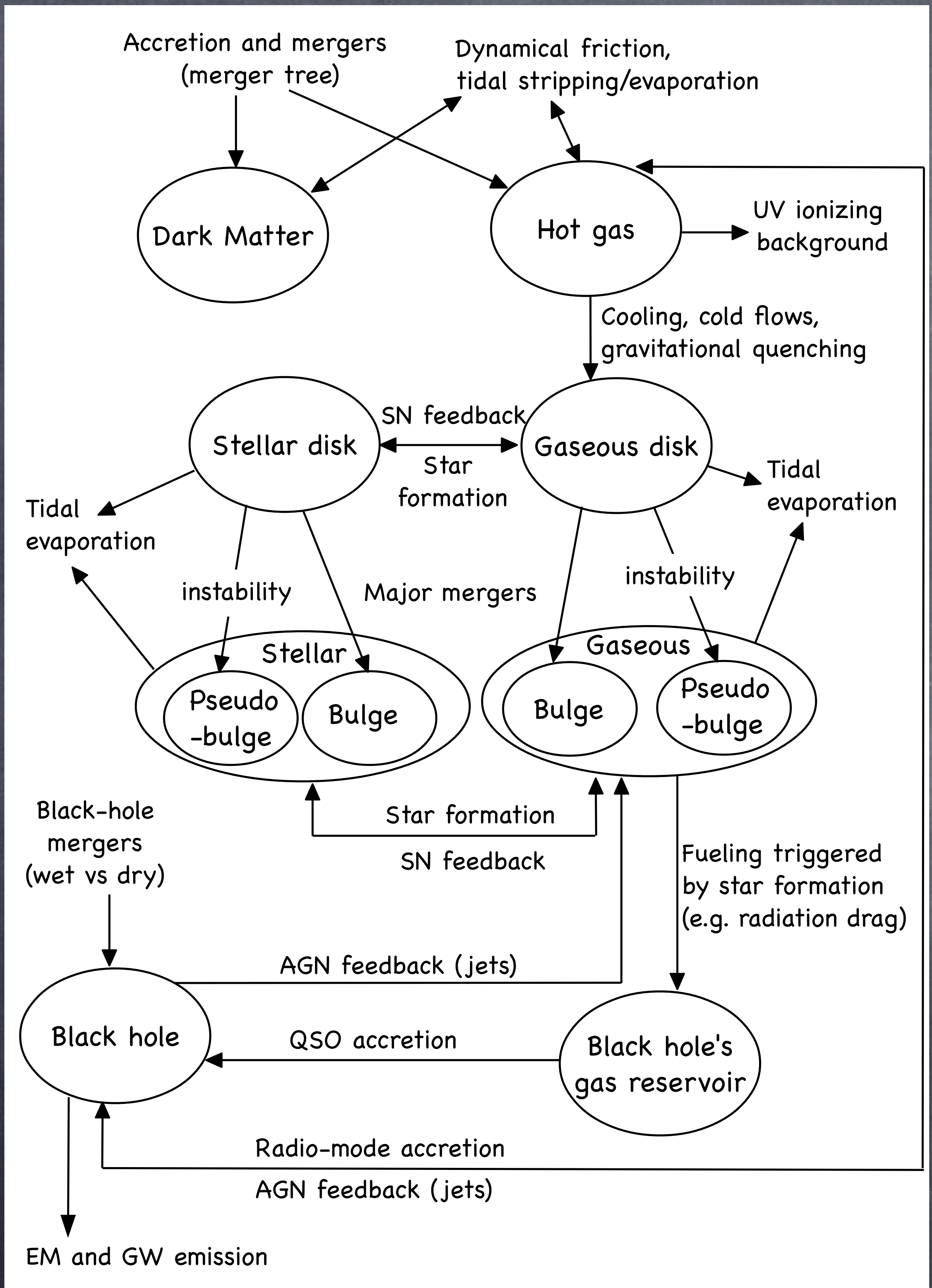
- Accretion & Bardeen Petterson effect depend on local availability of gas
- BHs transfer energy to galaxy through jets (trigged by spin and/or binary motion + magnetic field) and quench star formation (AGN feedback)
    - Surprising due to scales (BHs ~10^{-6} pc vs galaxy ~1-100s kpc)
    - Invoked to explain "cosmic downsizing" (most massive galaxies, where strongest AGNs live, have older stars and weaker star formation than smaller galaxies)





simulation by Palenzuela, Lehner and Liebling 2010; cf also Blandford & Znajek (1977)

A semi-analytical galaxy formation model

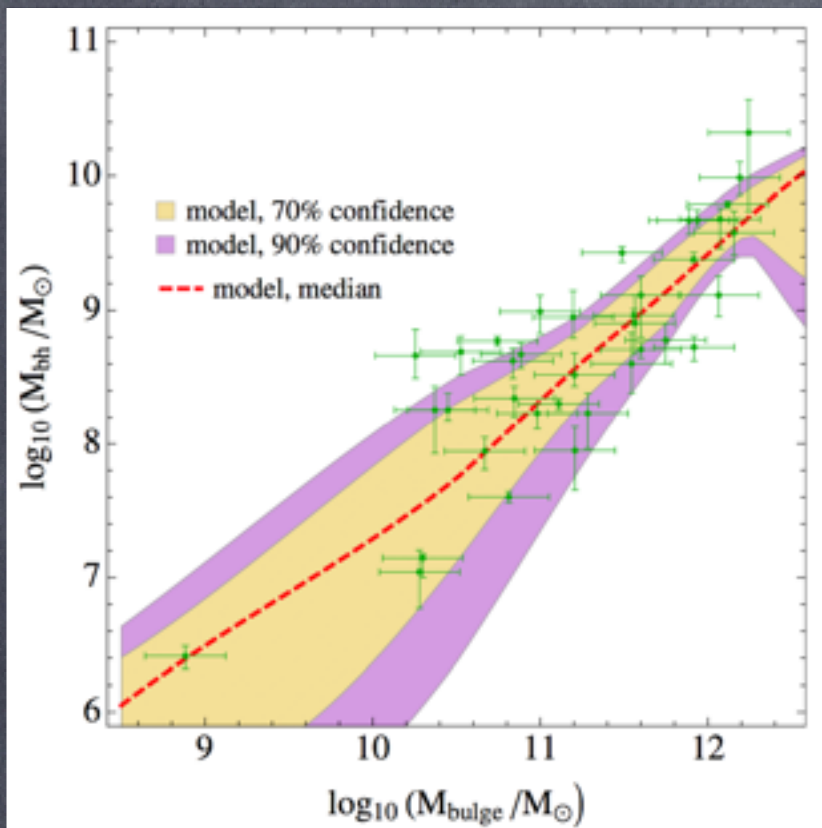


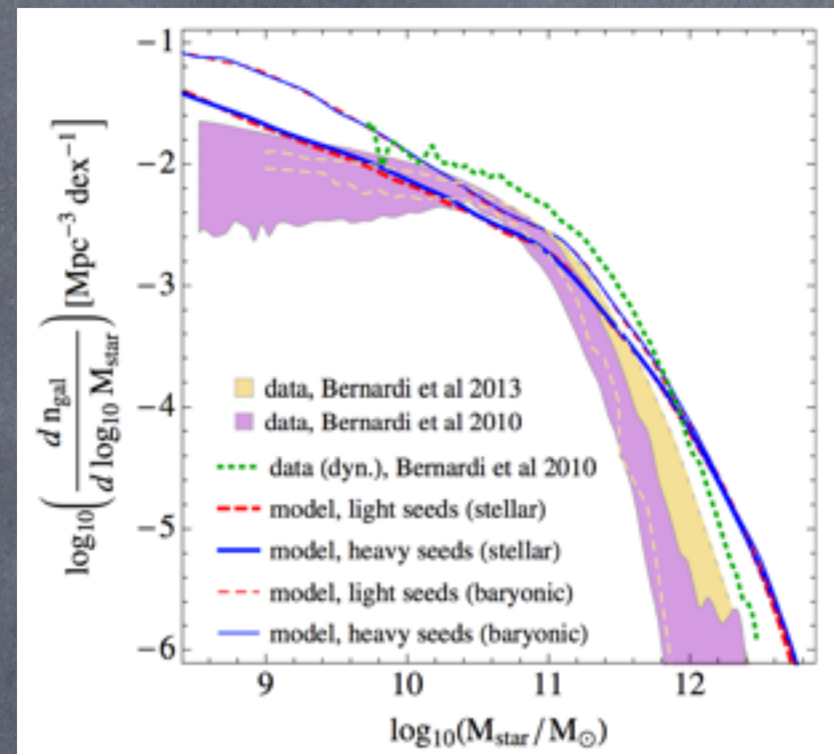
- Purely numerical simulations impossible due to sheer separation of scales (10^{-6} pc to Mpc) and dissipative/nonlinear processes at sub-grid scales
- 7 free parameters calibrated vs observables at z = 0 and z > 0 (e.g. BH luminosity & mass function, stellar/baryonic mass function, SF history, M – σ relation, etc)

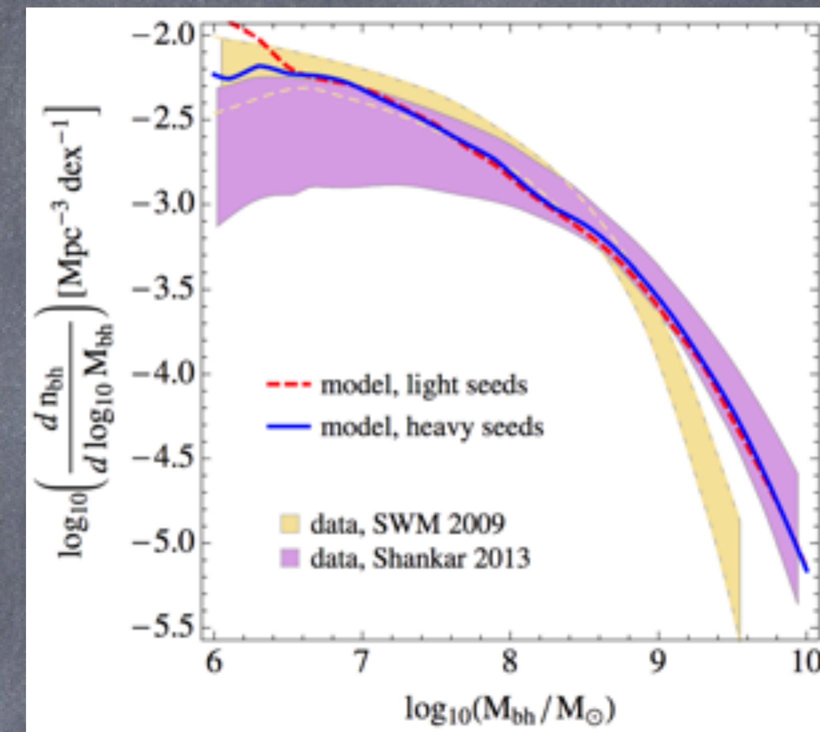
	light seeds	heavy seeds
$M_{\rm cloud}$	$3 \times 10^4 M_\odot$	$3 \times 10^4 M_\odot$
$\epsilon_{\rm SN,b}$	0.4	0.4
$\epsilon_{\rm SN,d}$	0.1	0.1
$f_{\rm jet}$	10	10
$A_{\rm res}$	6×10^{-3}	5.75×10^{-3}
$A_{\rm Edd}$	2.2	1
$k_{\rm accr}$	10^{-3}	10^{-3}

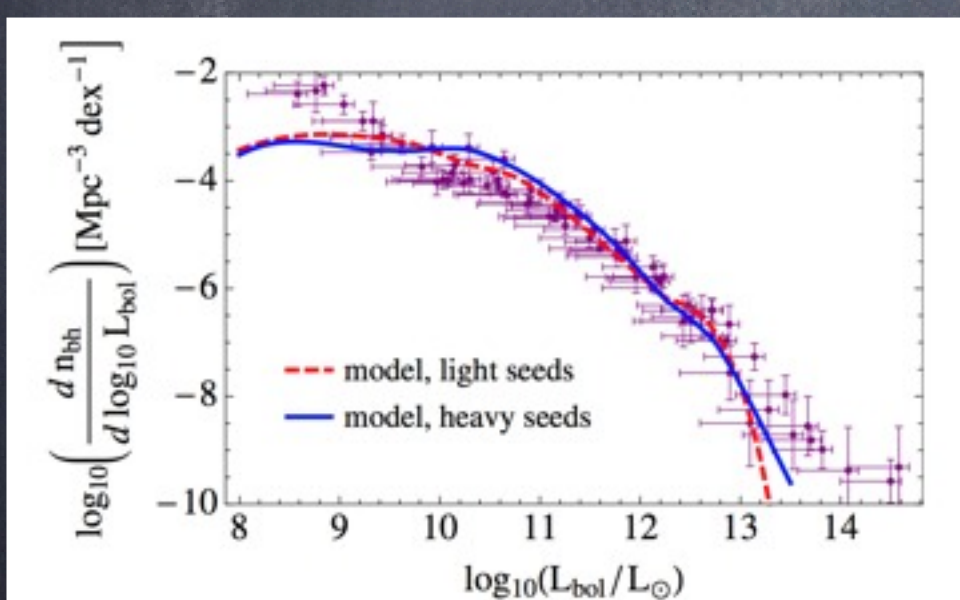
EB (2012); Sesana, EB, Dotti & Rossi (2014)

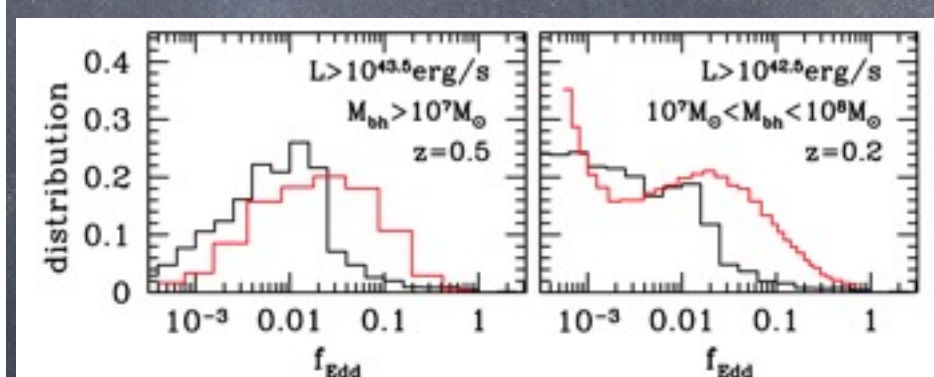
Calibration: a few examples

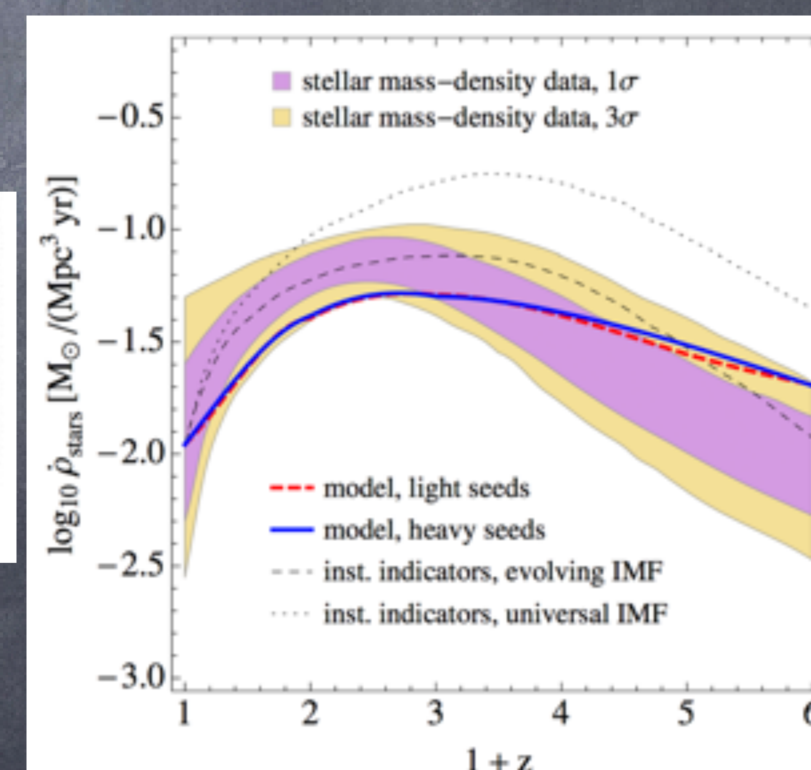










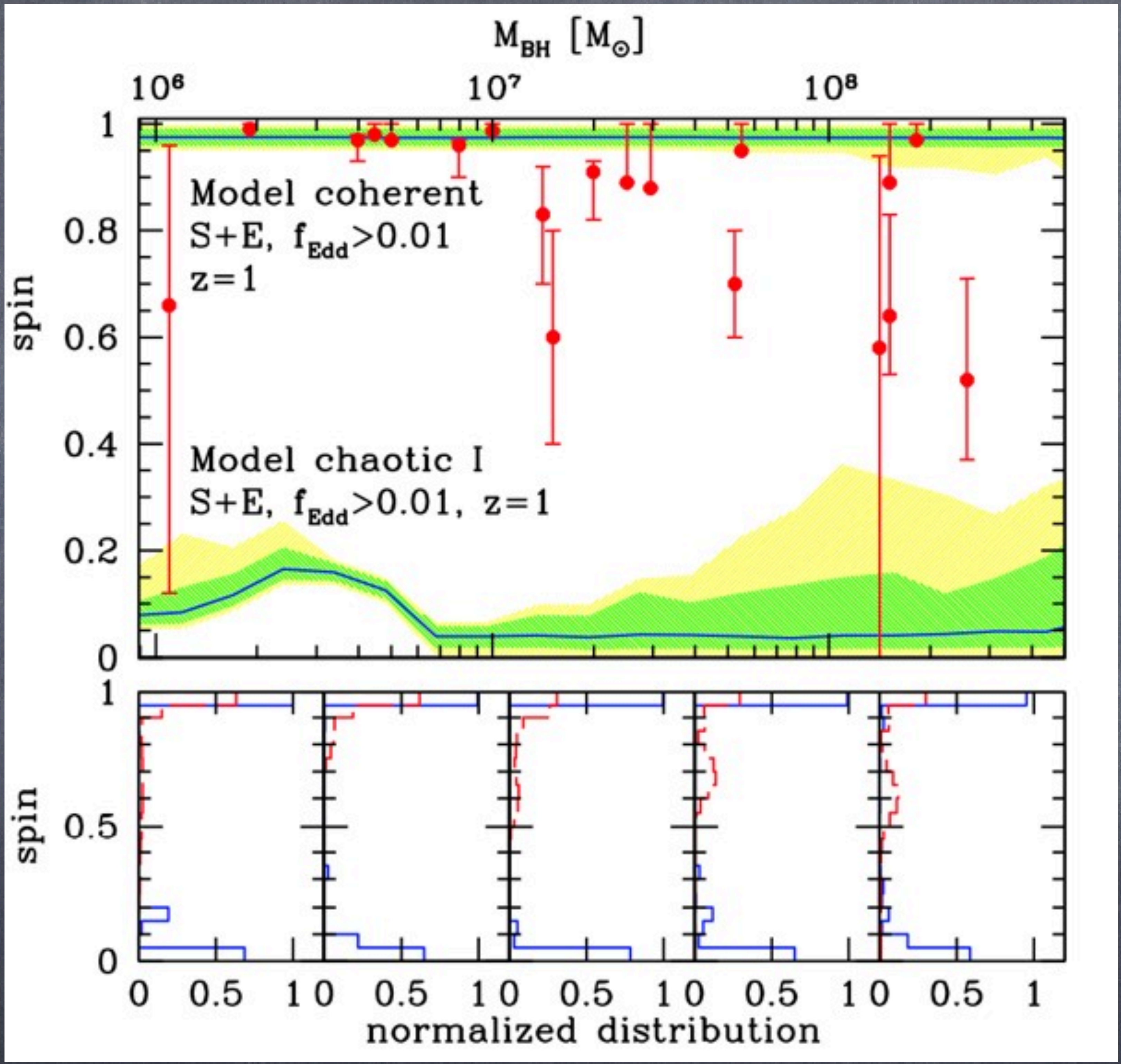


EB (2012); Sesana, EB, Dotti & Rossi (2014)

How about spin evolution?

- Observations: growing number of spin measurements using relativistic iron lines
- Theory (King, Pringle, Volonteri, Berti, ...): main driver of spin evolution is accretion and **not** mergers:
  - Coherent accretion (with fixed L)
  - Chaotic accretion (of clouds with randomly oriented L)

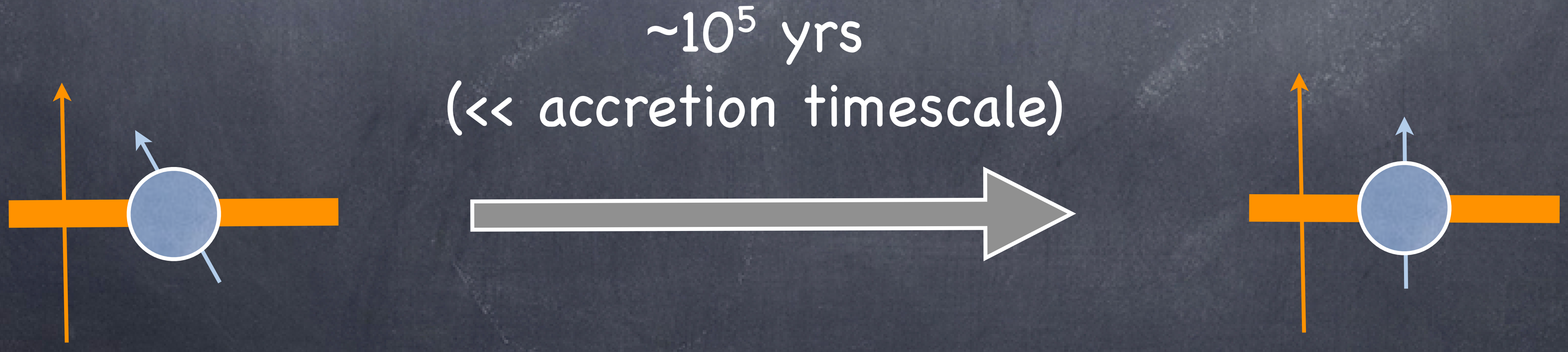
Neither works!



Sesana, EB, Dotti & Rossi (2014)

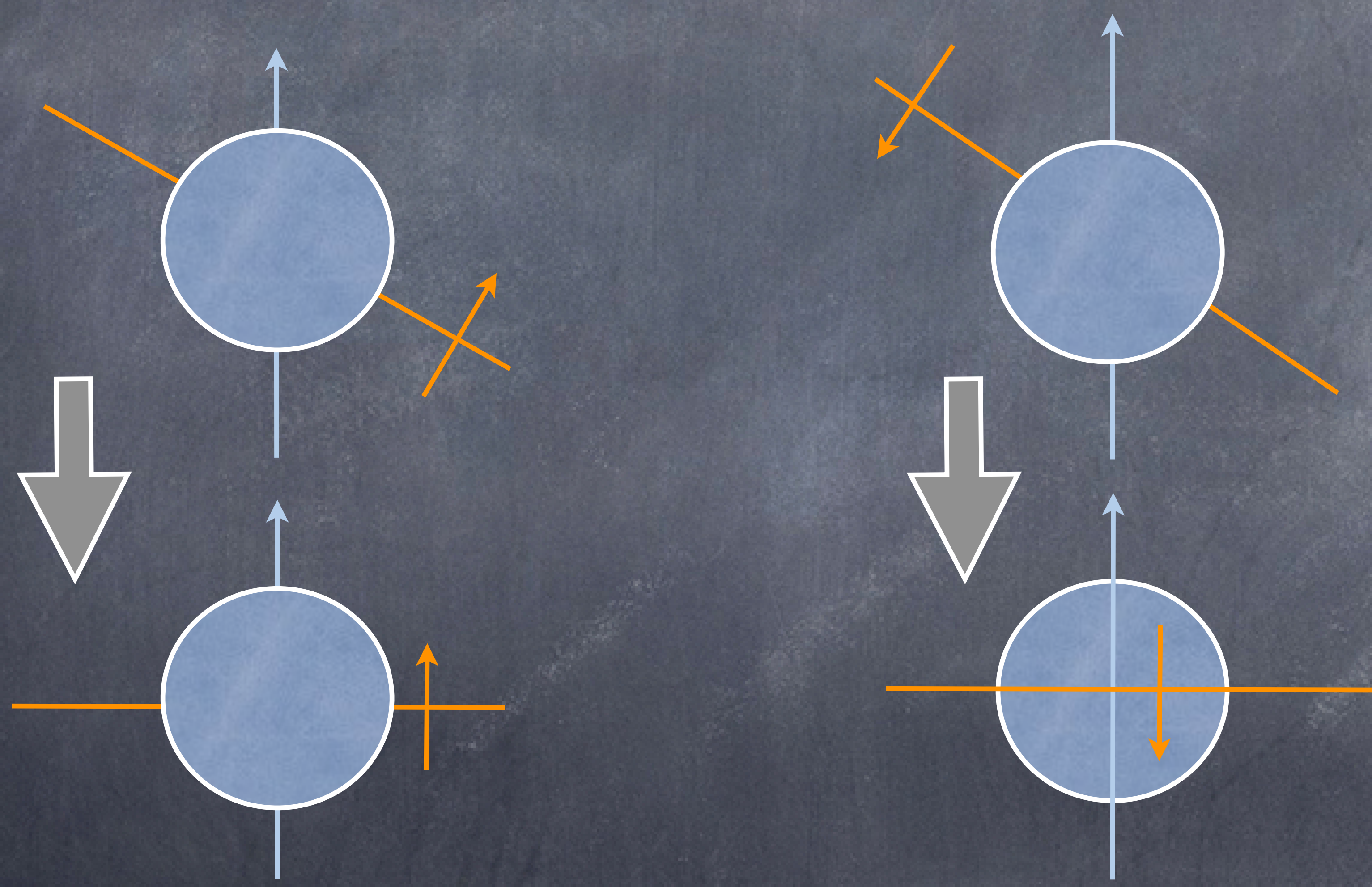
A mix of coherent and chaotic? (Dotti et al 2012)

- Accretion by clouds, with mass set by minimum of a "typical" cloud mass ~10^4 - 10^5 M_{sun}, and "fragmentation" mass scale set by self gravity
- If $J_{cloud} > 2 J_{bh}$, Bardeen Petterson effect aligns BH spin to accretion disk: coherent accretion



A mix of coherent and chaotic? (Dotti et al 2012)

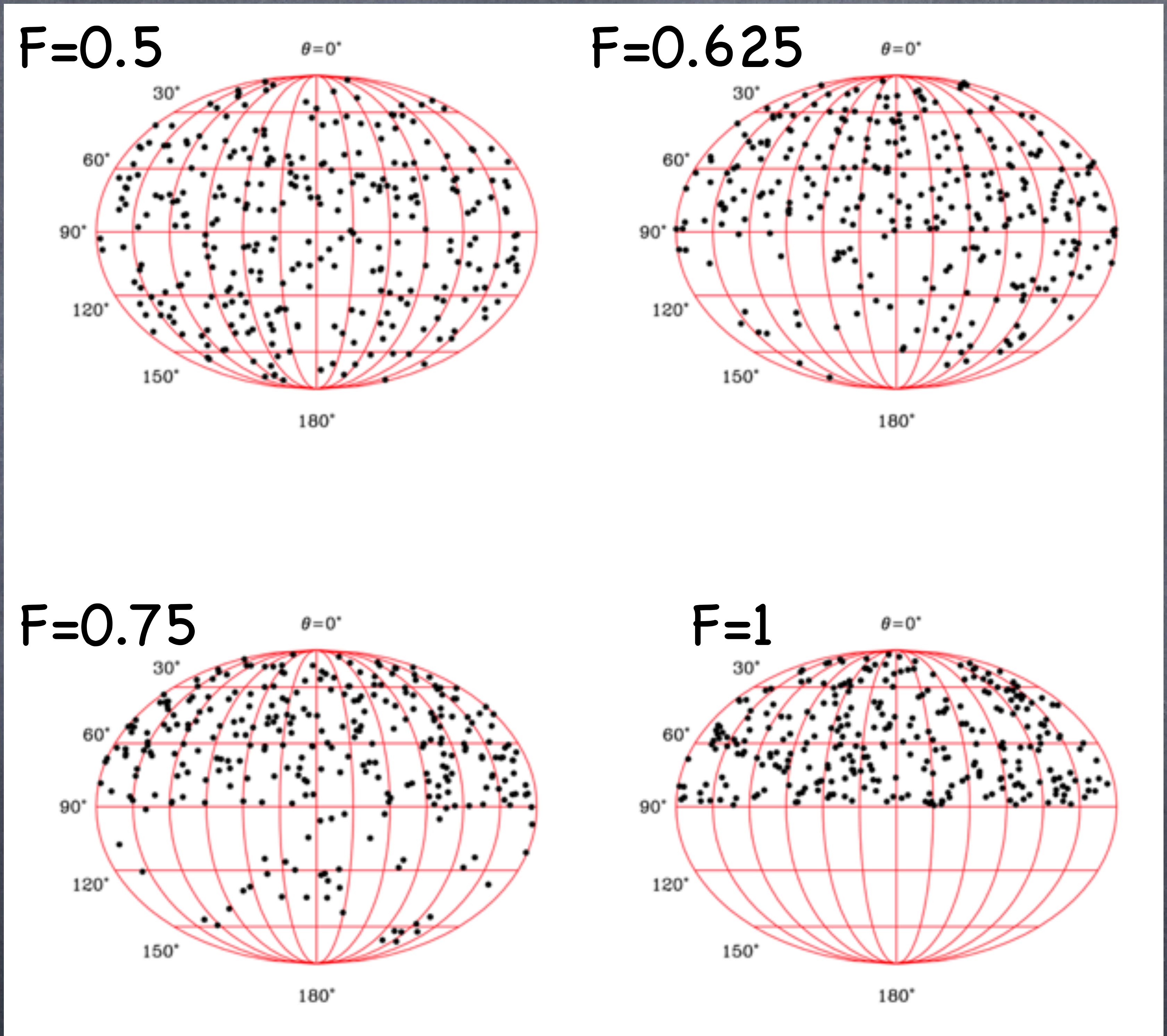
- If J_{cloud} < 2 J_{bh}, either alignment or anti-alignment can happen, depending on initial orientation of J_{cloud}:
spin evolution depends on "isotropy" of J_{cloud} distribution



~10^5 yrs
(<< accretion timescale)

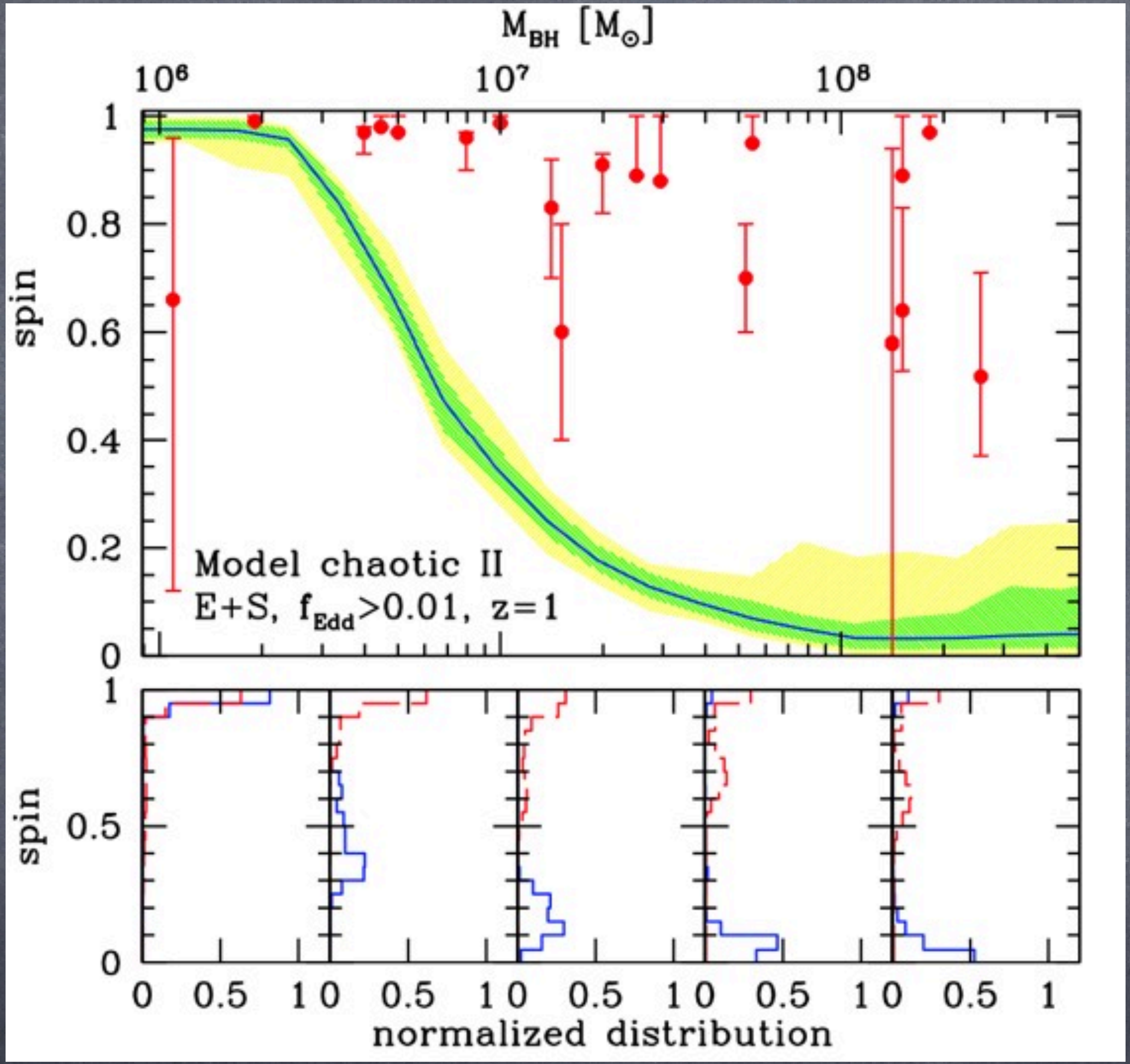
- "Isotropy" parameter F (= fraction of clouds with $J_{bh} \cdot J_{cloud} > 0$)

The "isotropy" parameter



Dotti et al (2012)

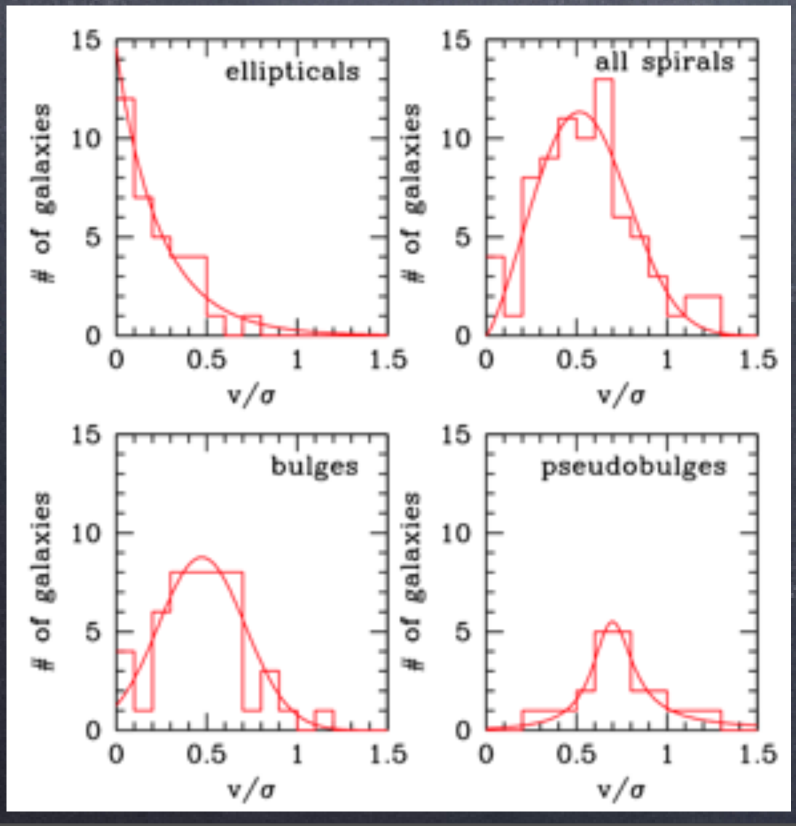
Randomly oriented clouds (F=1/2)



Sesana, EB, Dotti, Rossi (2014)

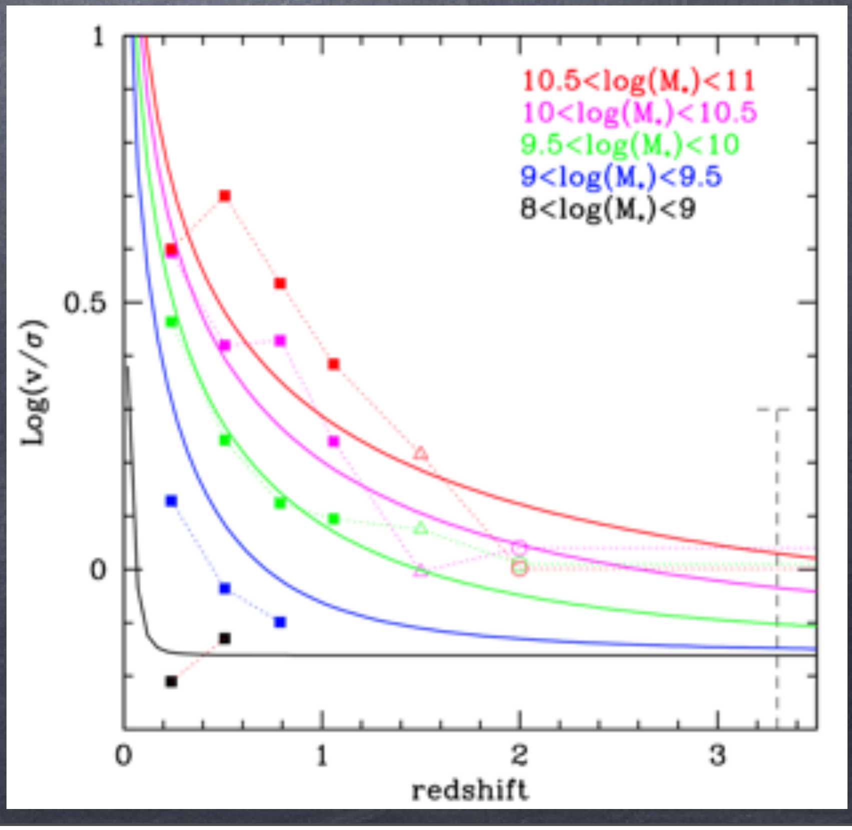
Linking accretion to galactic morphology (Sesana, EB, Dotti & Rossi 2014)

- J_{cloud} has "coherent" part (due to rotational velocity v) and "chaotic" part (due to velocity dispersion σ)
- Extract from observations of v / σ for
  - Stars in ellipticals
  - Bulge/pseudobulge stars in spirals ("bulge" model) OR disk gas in spirals ("disk" model)

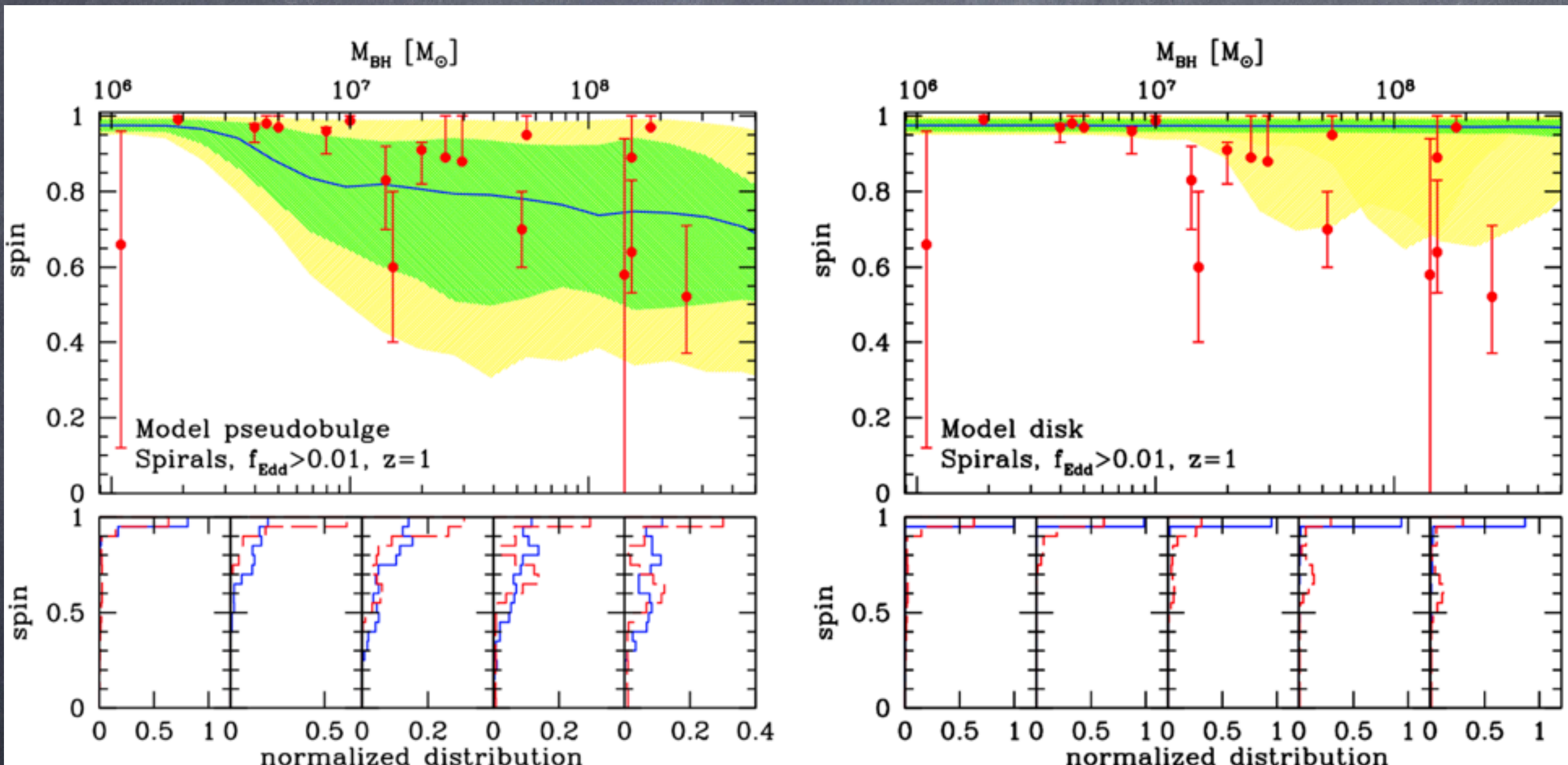


Stars

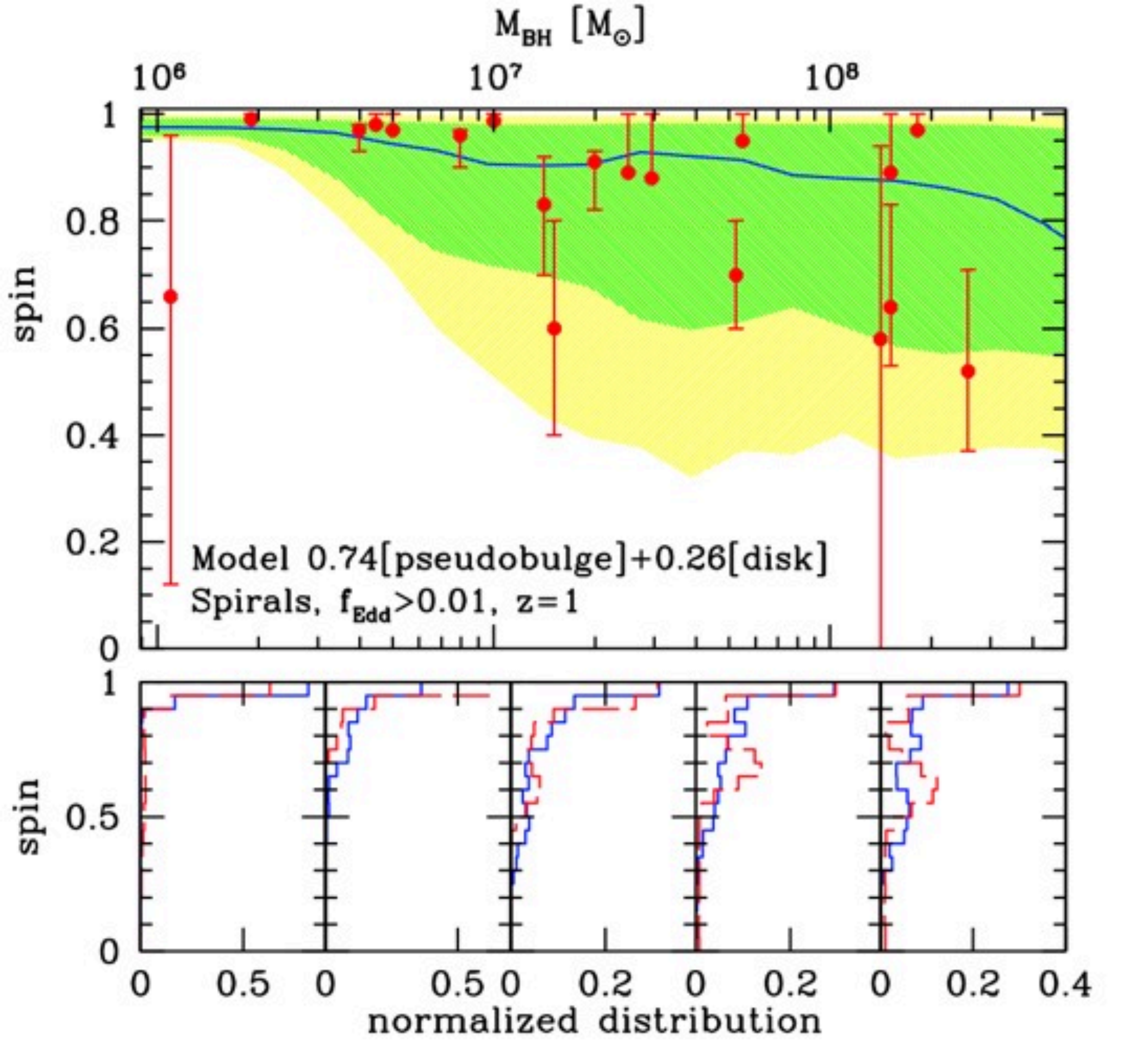
Gas



Disk vs Bulge model

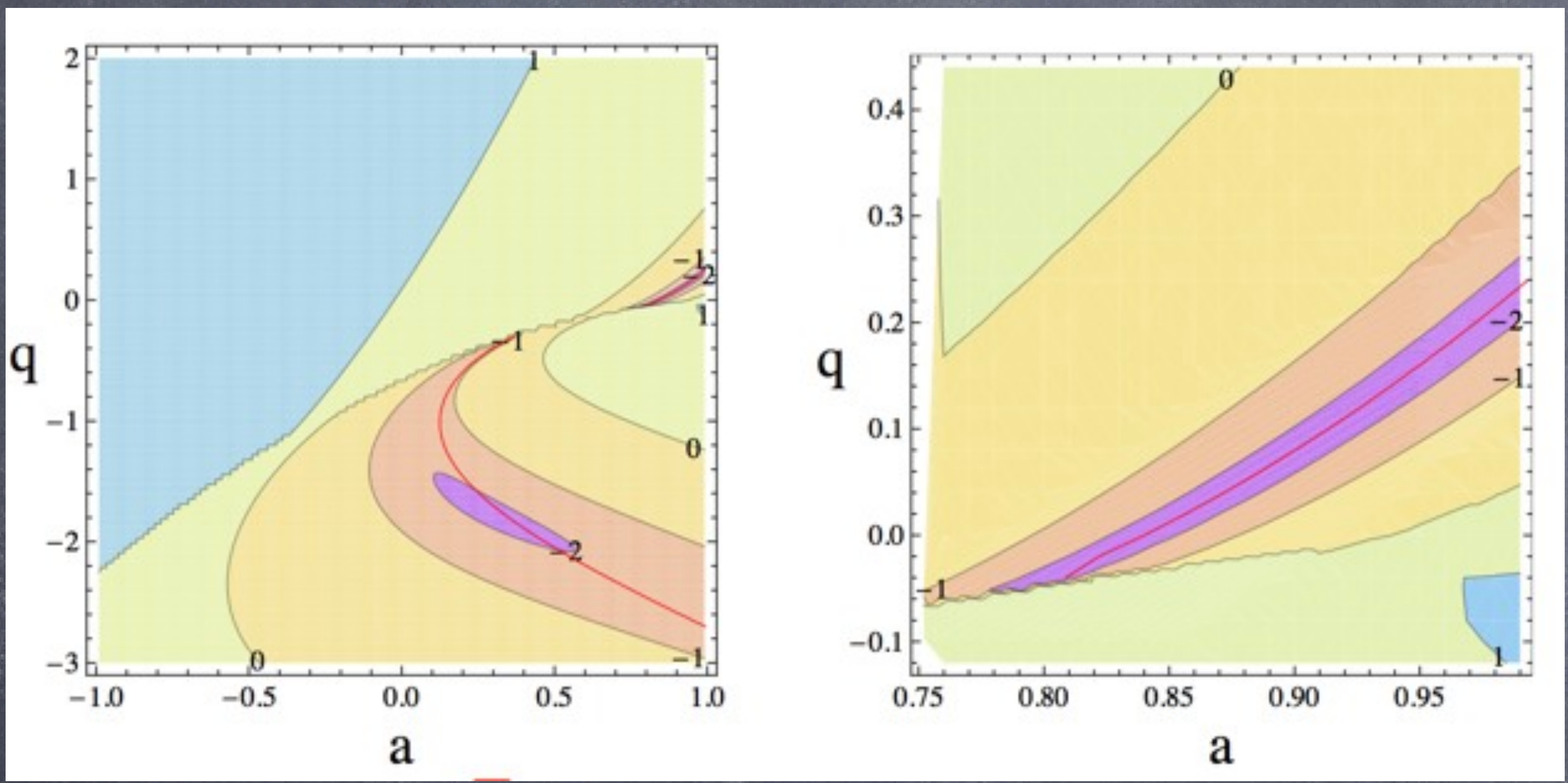


A mixed model



Are there 2 fueling channels (bulge stars + disk gas)?

Can EM observations detect exotic BH hairs?



Color code = $\log10(\chi^2_{red})$

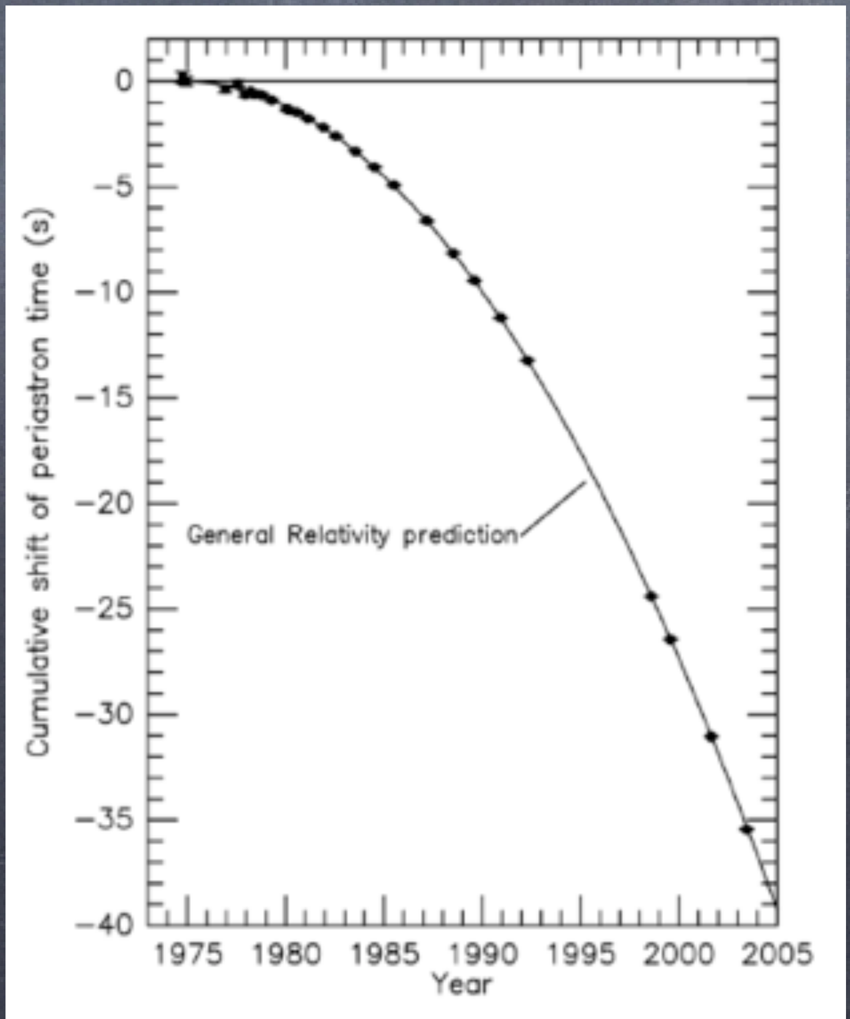
allowed region: $\chi^2_{red} < 1$

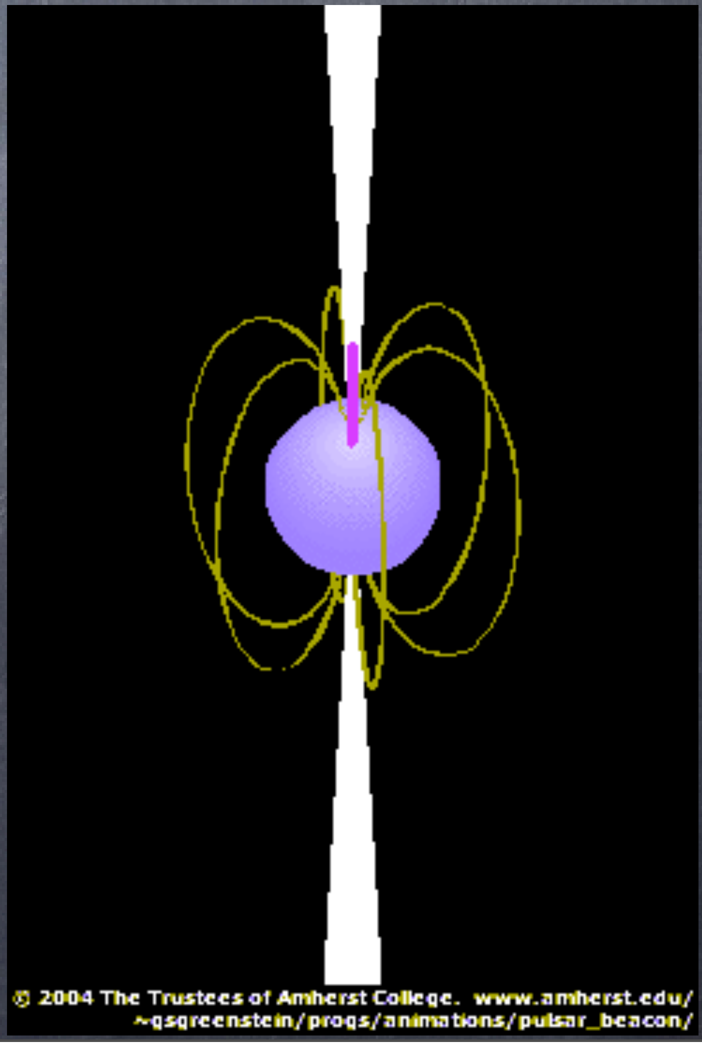
- Continuum fitting of microquasar M33 X-7 ($M = 15.65 \pm 1.45\ M_{sun}$, $a = 0.84 \pm 0.05$) with an extra parameter q measuring deviations from Kerr BH's quadrupole (Bambi & EB 2011)

Part II:
GW observations of compact objects

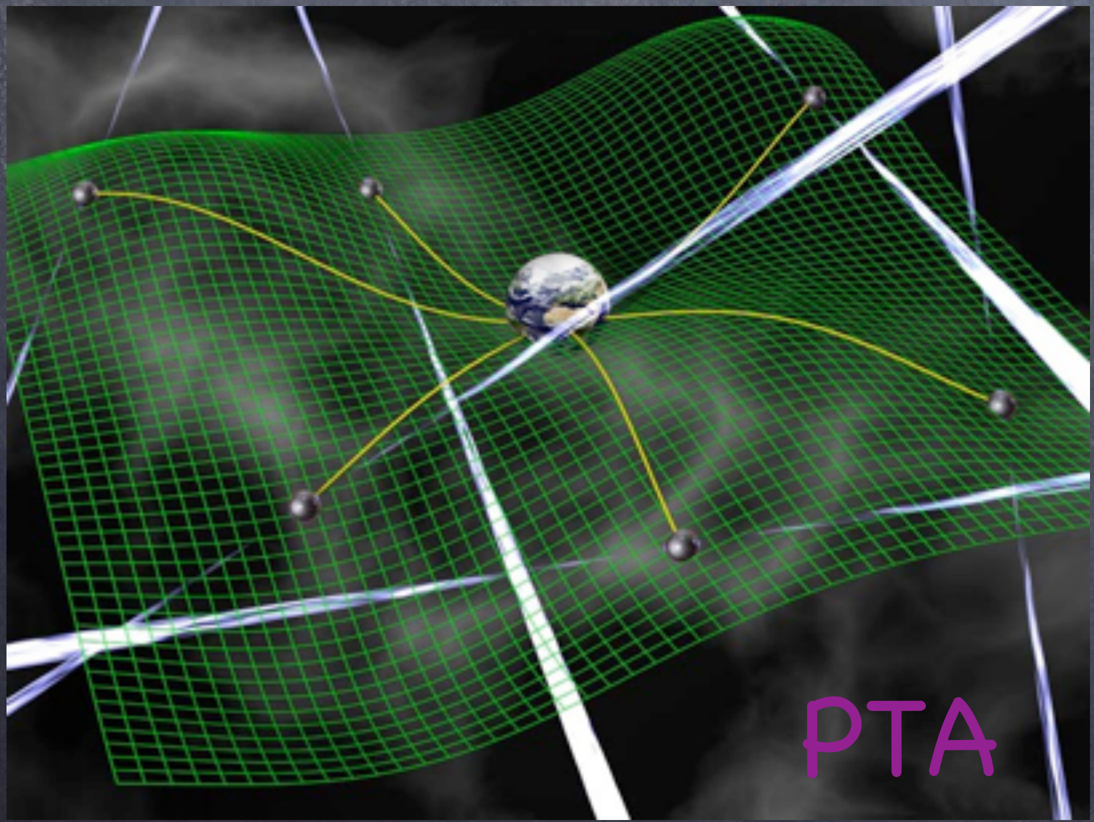
Indirect evidence of GWs

- Binary in circular orbits has time changing mass quadrupole ⟶ GW emission
- GWs carry energy and angular momentum away from system ⟶ binding energy gets more and more negative and binary shrinks
- Indirect detection: Hulse-Taylor binary (and other binaries where one star is a pulsar)

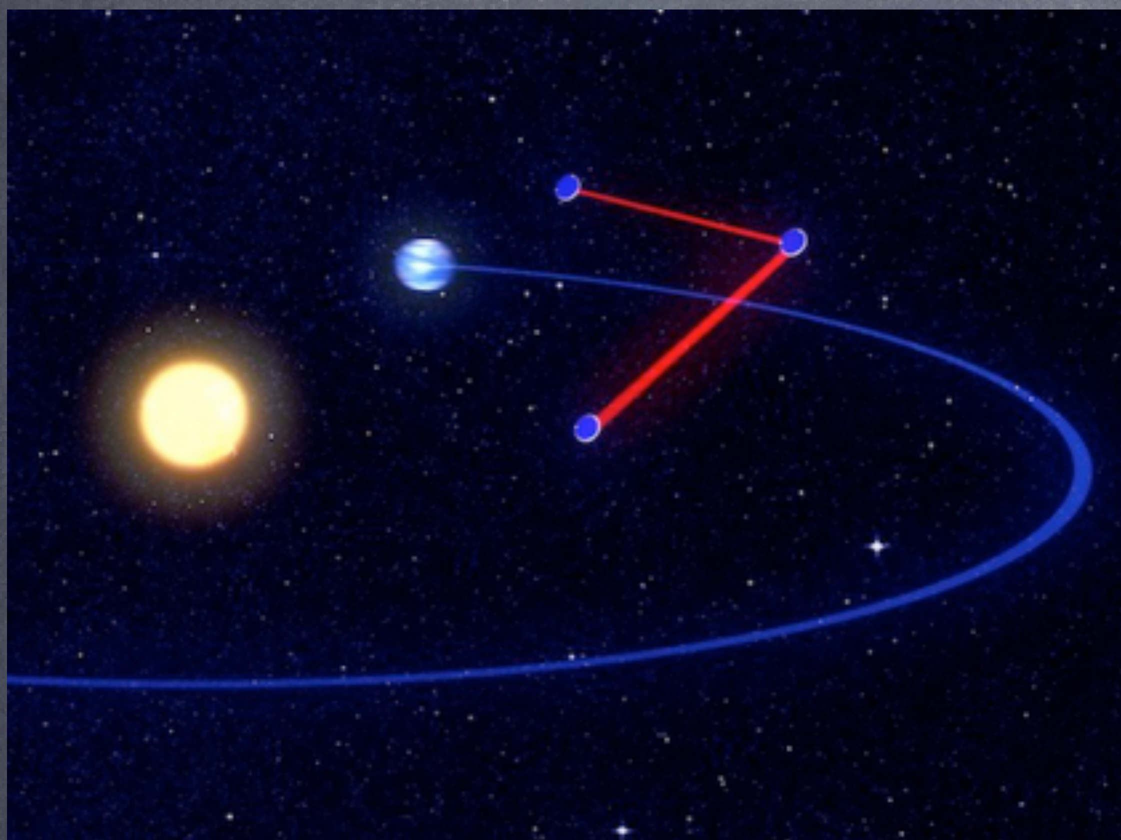




A direct detection before the end of the decade?



Next-generation detectors



eLISA: selected as ESA's L3 mission (exploratory mission 2016; launch 2028-2034)

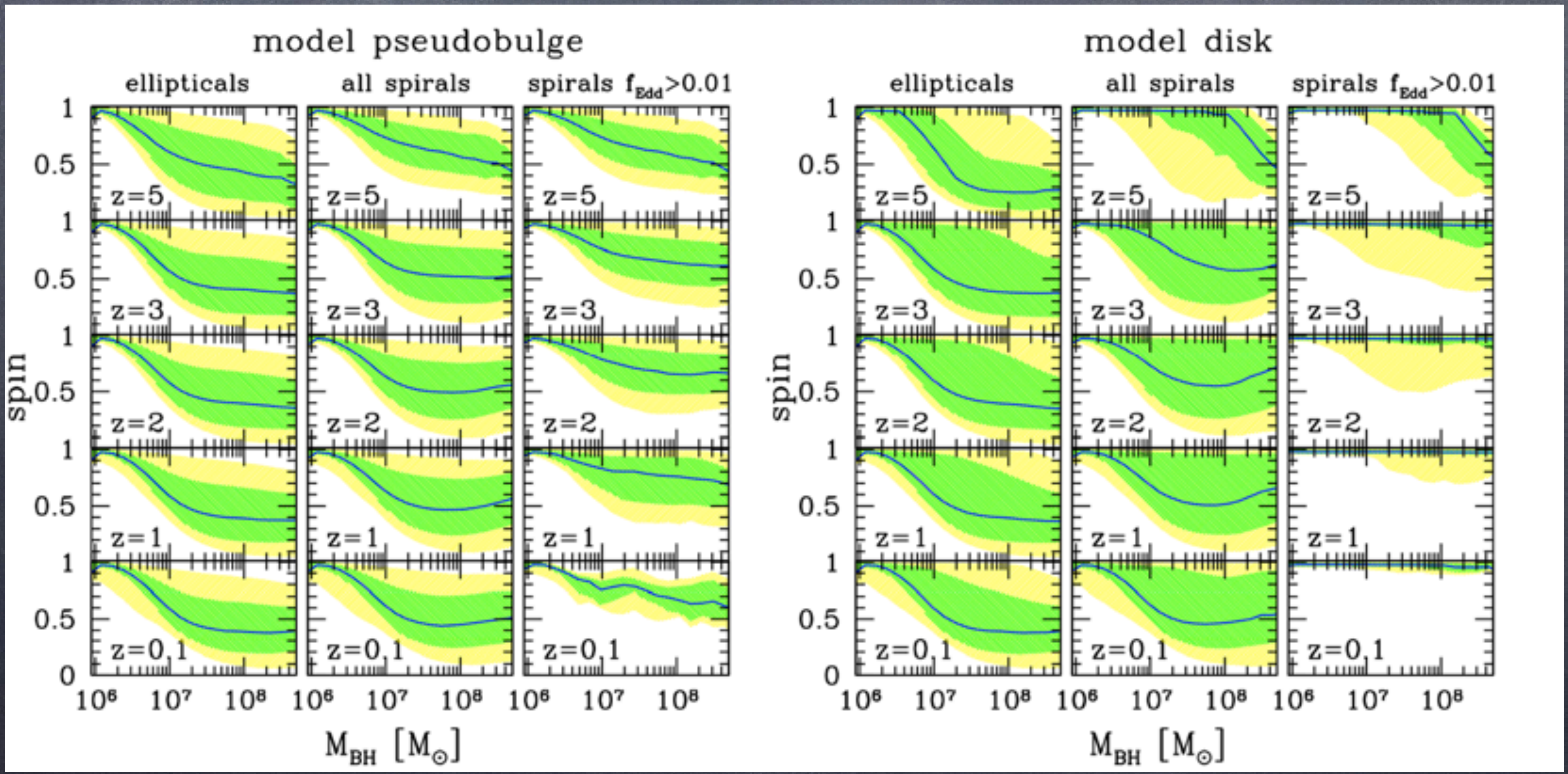
ET: design study funded; 2020s?

Compact-object binaries as GW sources

- Adv LIGO/Virgo: stellar-mass range, i.e. NS-NS up to $z \sim 0.1$, NS-BH, BH-BH up to $z \sim 0.5 - 1$
- ET: stellar and intermediate mass range, i.e. NS-NS, BH-NS, NS-NS at $z < 5$, IMBH-IMBH, BH-IMBH, NS-IMBH at $z < 10 - 15$
- PTA: supermassive range, i.e. SMBH-SMBH at $z < 1$
- eLISA: supermassive range, i.e. SMBH-SMBH at $z < 10 - 15$; IMBH-SMBH at $z < 5$, BH-SMBH, NS-SMBH at $z < 1$

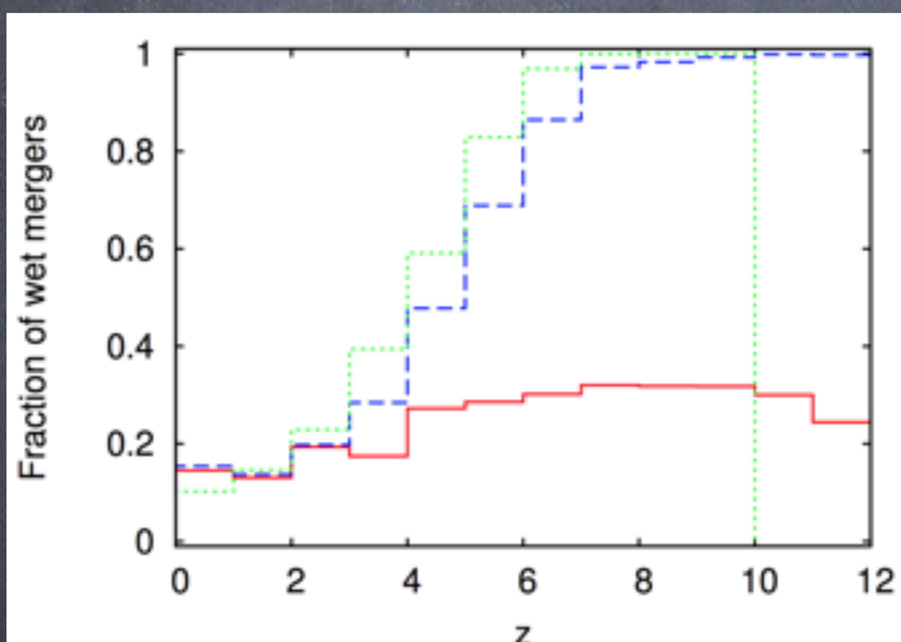
GW cosmology/astrophysics

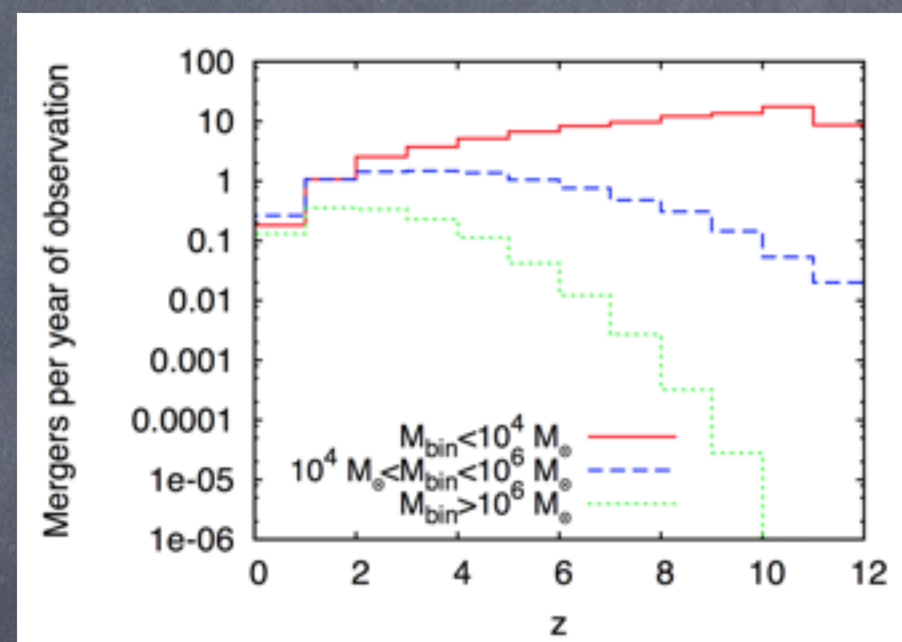
- eLISA/ET will measure masses to within 0.1% and spins to within 0.01-0.1
- Clean measurements (no environmental effects; see e.g. EB, Pani & Cardoso 2014)
- Will test correlation between BH spins & morphology



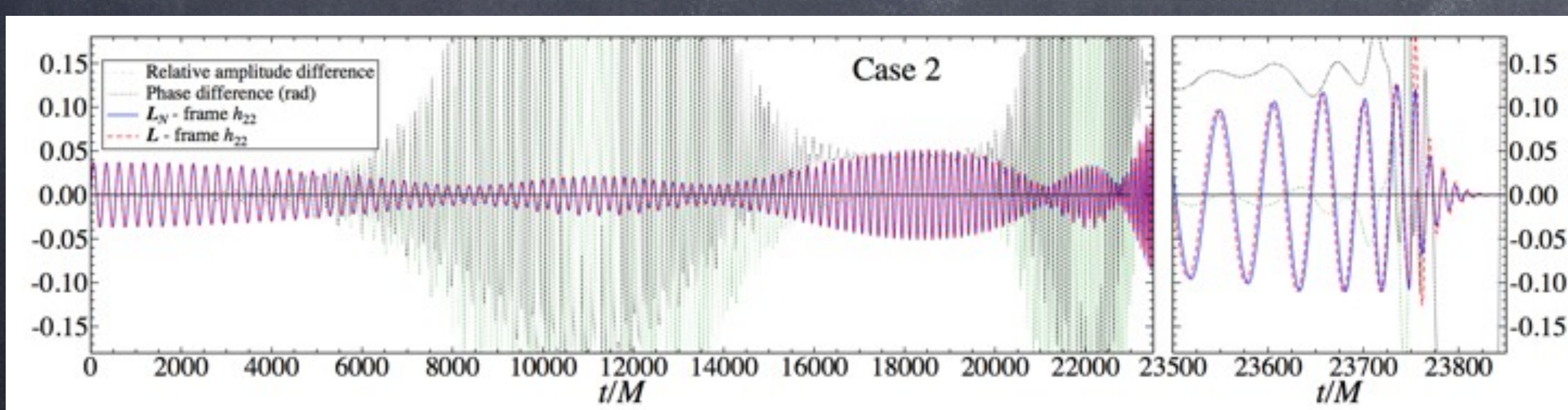
GW cosmology/astrophysics

- eLISA will observe modulation in GW amplitude due to spin precession...
- .. and will tell "wet" SMBH mergers (spins aligned by Bardeen Petterson effect) from "dry" SMBH mergers (randomly oriented spins)





EB (2012)



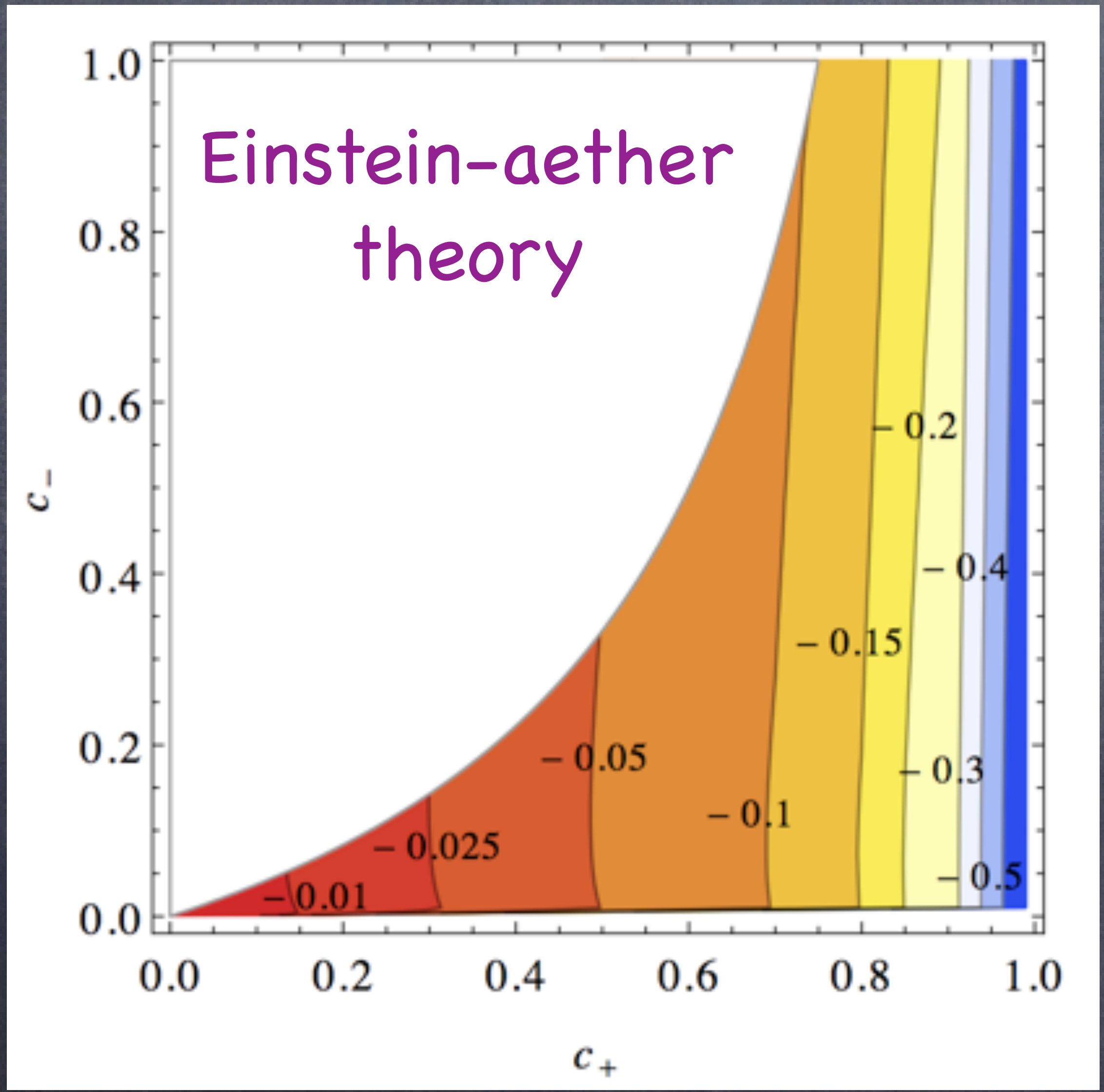
EOB waveforms for BH binary with mass ratio 1:6 and spins 0.6 and 0.8, from Pan et al (2013), produced with EOB Hamiltonian of EB & Buonanno (2010,2011)

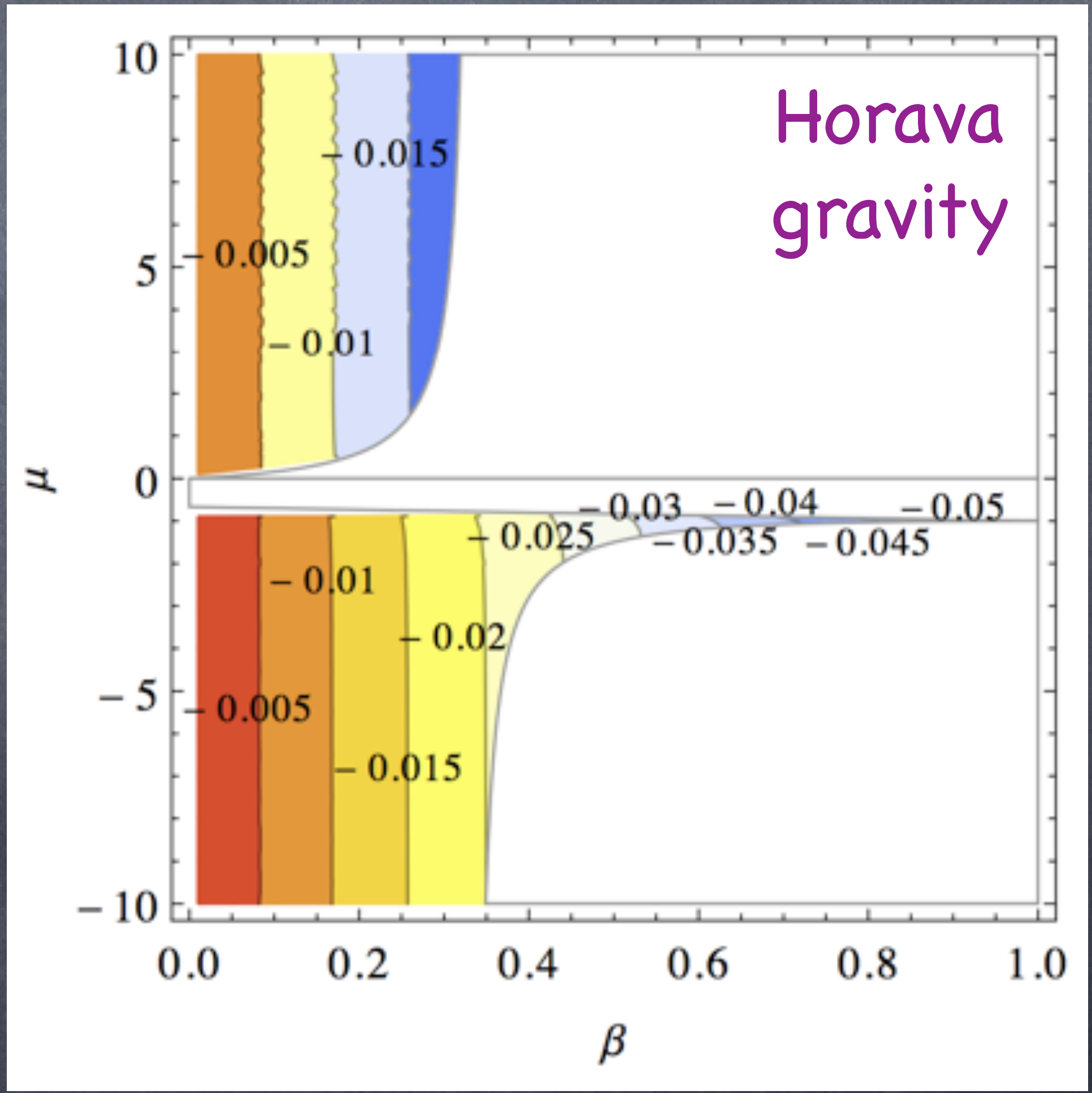
Tests of fundamental physics with GWs?

- An example: test Lorentz invariance in gravity
  - Is there an absolute time in gravitational observations?
  - Do gravitons have non-linear dispersion relation $\omega^2 = \kappa^2 + \alpha \kappa^4 + \dots$?
- Motivation
  - Lorentz invariance tested with high precision in matter sector (e.g. cosmic rays), but not in gravity
  - Lorentz violations ubiquitous in quantum gravity, e.g. they allow to construct power-counting renormalizable gravity theories (e.g. Horava gravity)

BHs in Lorentz-violating gravity

- Fractional deviation of $\omega_{isco} \cdot M$ from GR
- Color = viable region of coupling constants when stability and solar systems tests are imposed

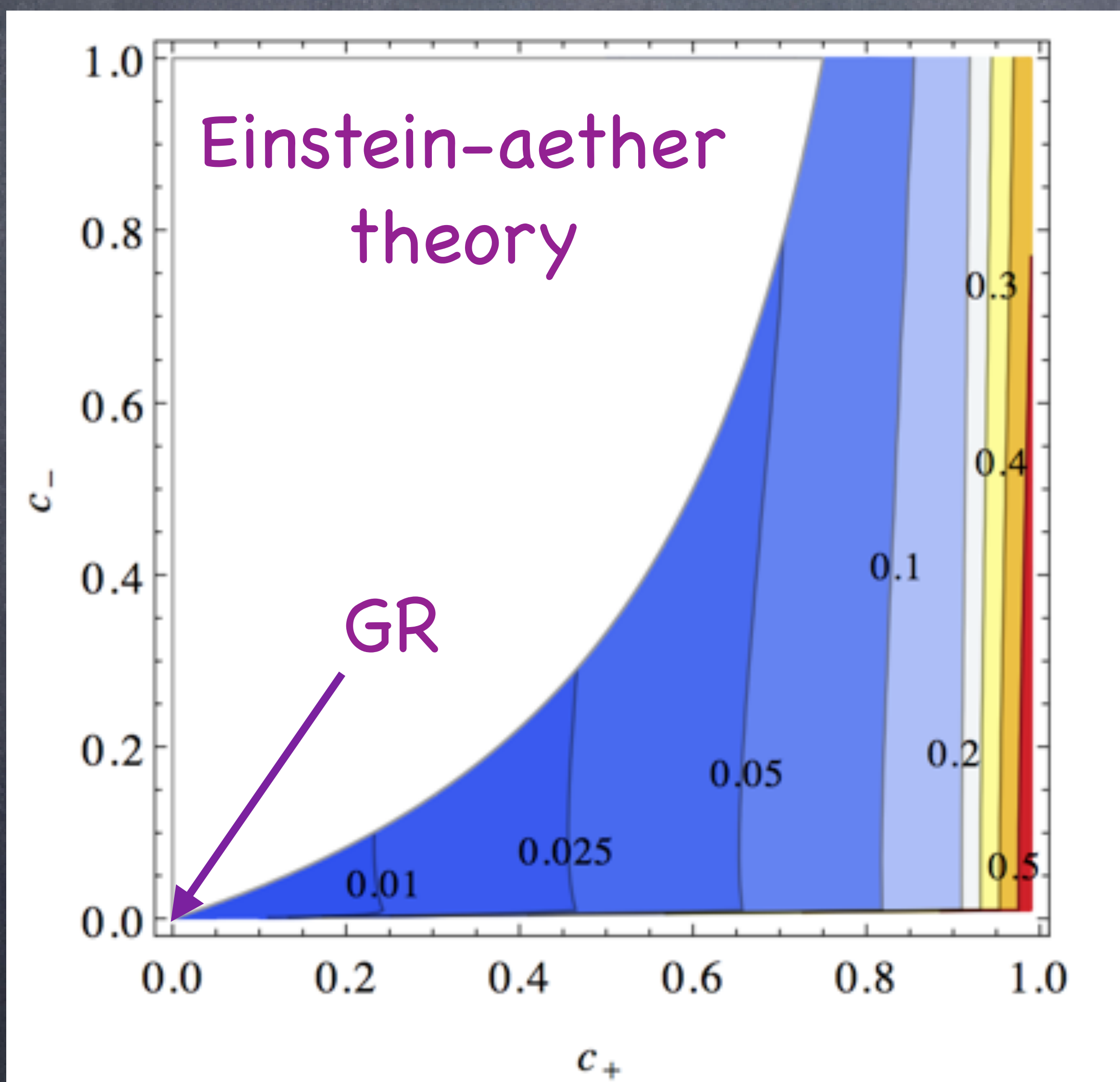


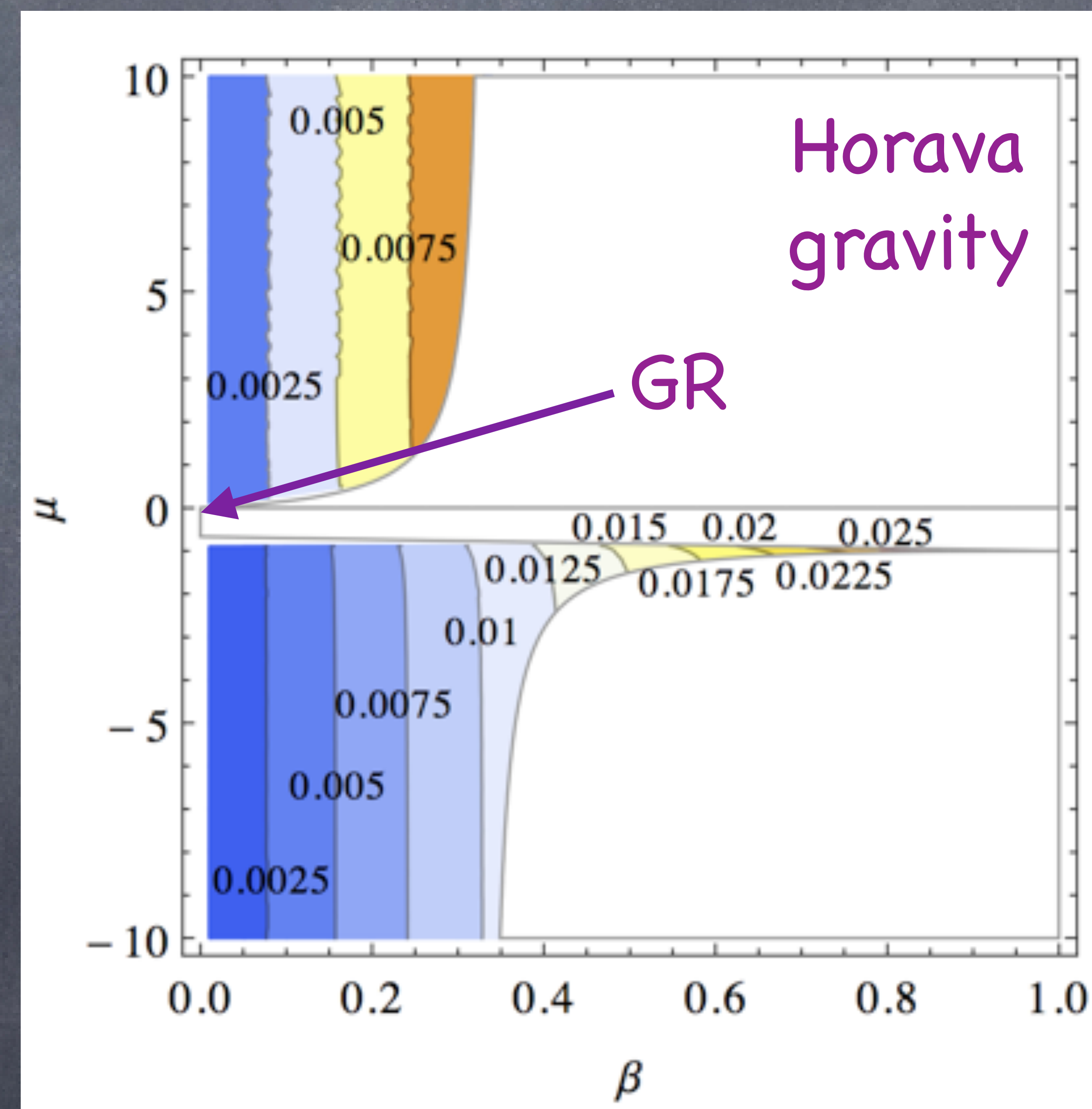


EB, Jacobson & Sotiriou (2011), EB & Sotiriou (2013)

BHs in Lorentz-violating gravity

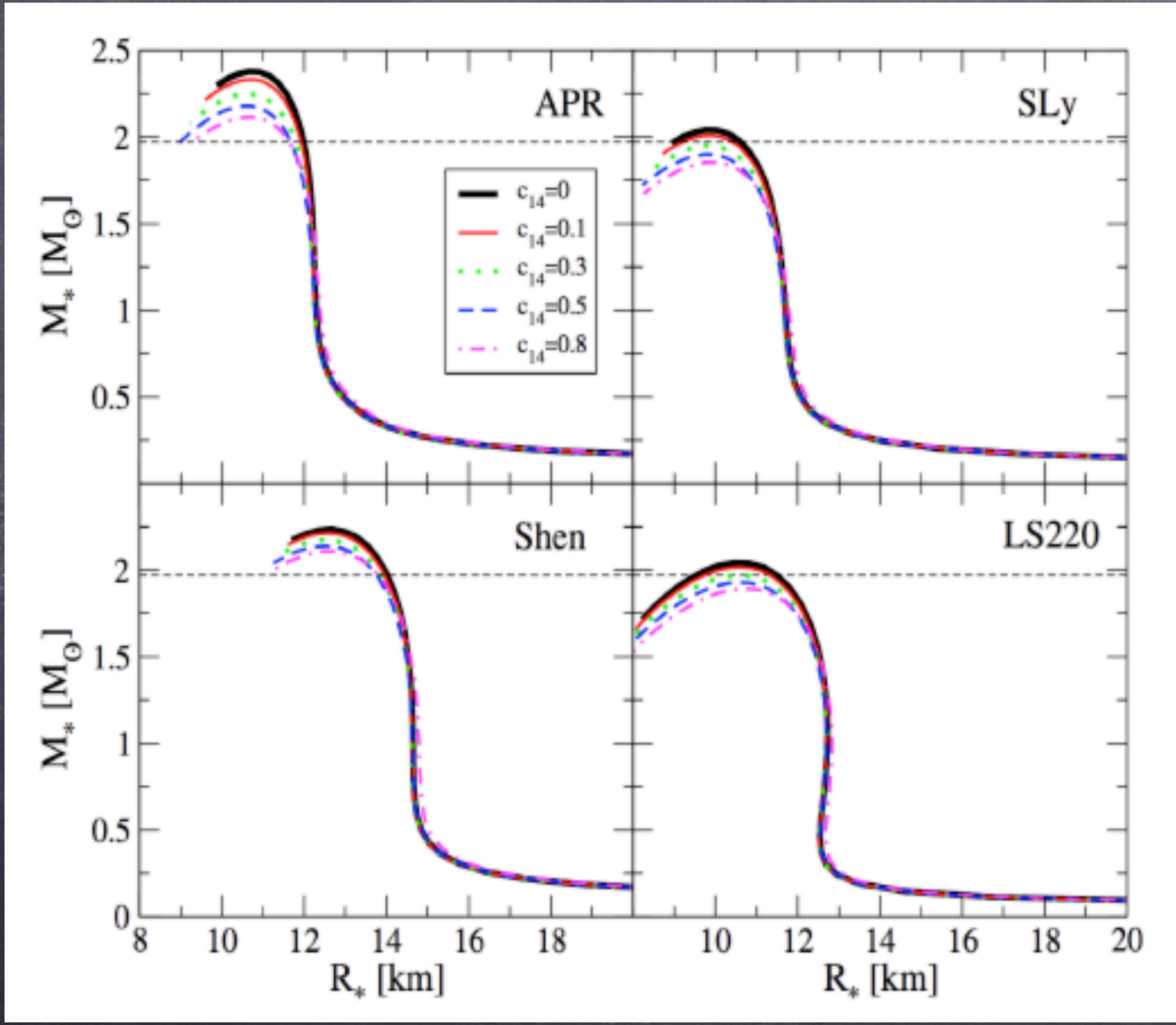
- Fractional deviation of b_{photon}/M from GR
- Deviations from GR too small for EM observations, but not for GWs!





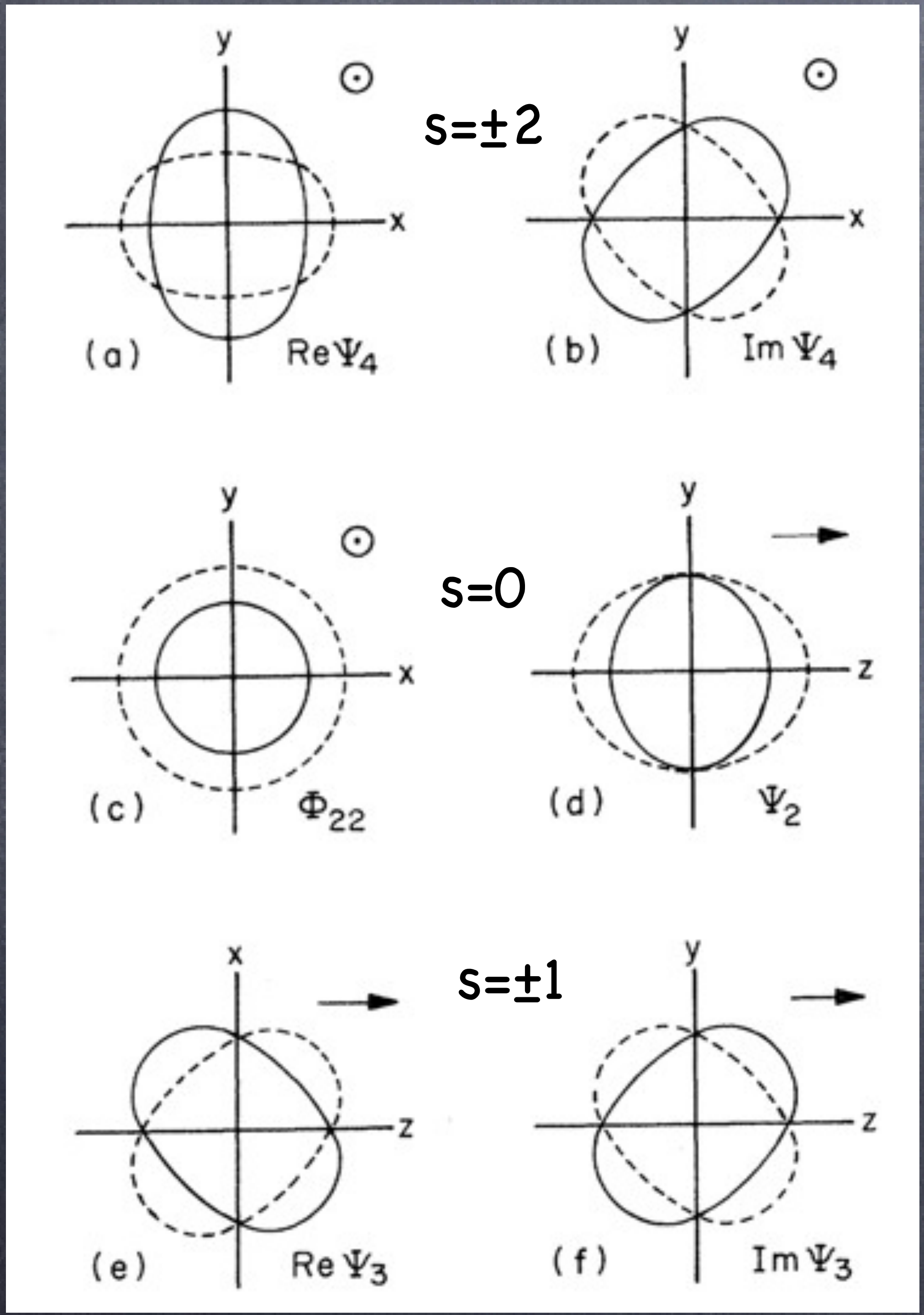
EB, Jacobson & Sotiriou (2011), EB & Sotiriou (2013)

Neutron stars in Lorentz-violating gravity



Eling, Jacobson, Miller (2007); Yagi, Blas, EB & Yunes (2013)

Extra GW polarizations in modified gravity

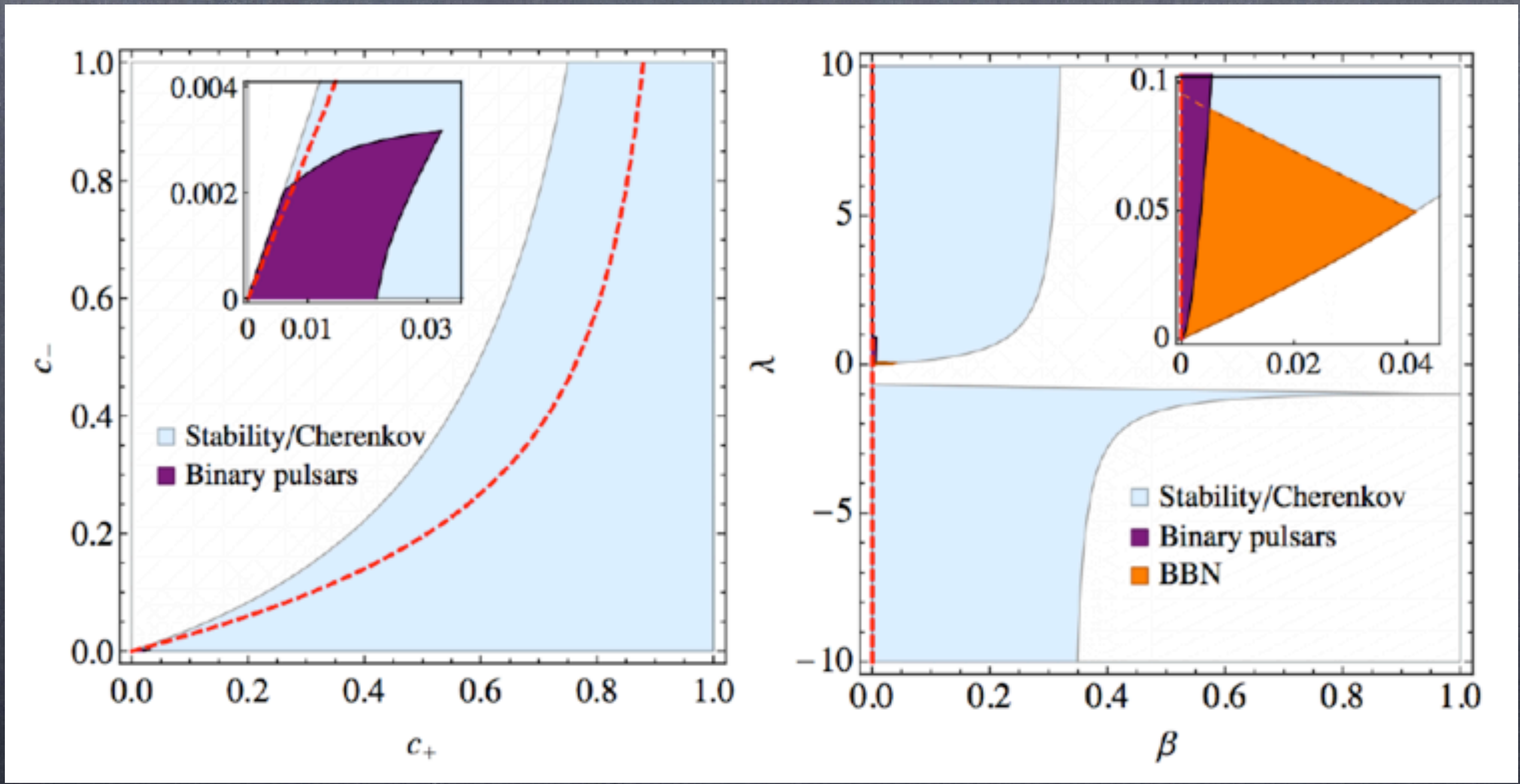


Eardley et al (1973)

- Only ψ_4 (quadrupole) in GR
- Extra polarizations sourced by extra "charges" of NS's and BHs
- May not be observable directly (may be weakly coupled to GW detector)...
- ... but visible in quadrupolar waves due to backreaction on system (extra modes carry extra energy and angular momentum away from binary)

Constraints on Lorentz violation from binary pulsars

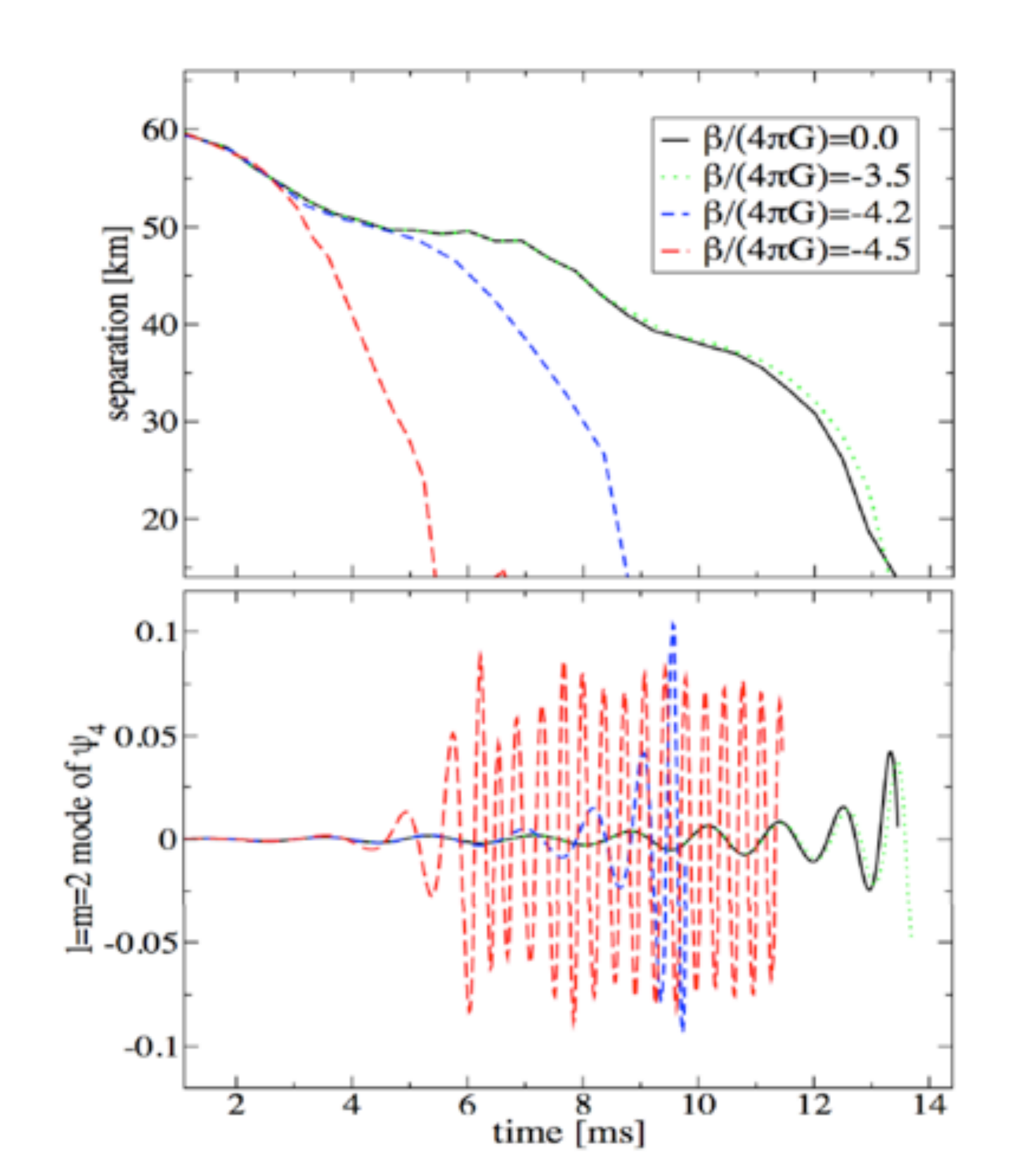
- Combined constraints from almost-circular WD-pulsar and pulsar-pulsar systems (PSR J1141-6545, PSR J0348+0432, PSR J0737-3039, PSR J1738+0333)
- Includes observational uncertainties (masses, spins, eccentricity, EOS)



Yagi, Blas, EB & Yunes (2013); Yagi, Blas, Yunes & EB (2013)

A smoking gun for deviations from GR?

- Lorentz violating gravity produces gradual "drift" away from GR during binary's inspiral, due to dipolar emission
- In a class of scalar tensor theories (Damour & Esposito Farese 1996), deviations from GR can be made arbitrarily small during inspiral ...
- ... but deviations from GR behavior can still occur for NS-NS near merger
- Effects observable with Adv LIGO/ Virgo, cannot be mistaken for exotic equation of state



EB, Palenzuela, Ponce, Lehner (2013); Palenzuela, EB, Ponce, Lehner (2013)

Conclusions

- BHs in GR characterized by mass and spin alone ("no hair theorem"); modified gravity theories introduce extra "charges" (e.g. anomalous quadrupole moment)
- NSs/WDs have more degrees of freedom (mass, radius, spin, deformability, equation of state, etc), but modifications of gravity still introduce extra "charges"
- Mass/spin can be measured with EM probes, gives information e.g. about coevolution between galaxy and massive BHs
- GWs can measure mass and spin, but also extra exotic "charges" produced by gravity modifications (e.g. Lorentz violations, scalar-tensor gravity)

Thank you!