Title: Spinning black-hole binaries as gravitational and cosmological probes

Date: Jun 07, 2013 02:30 PM

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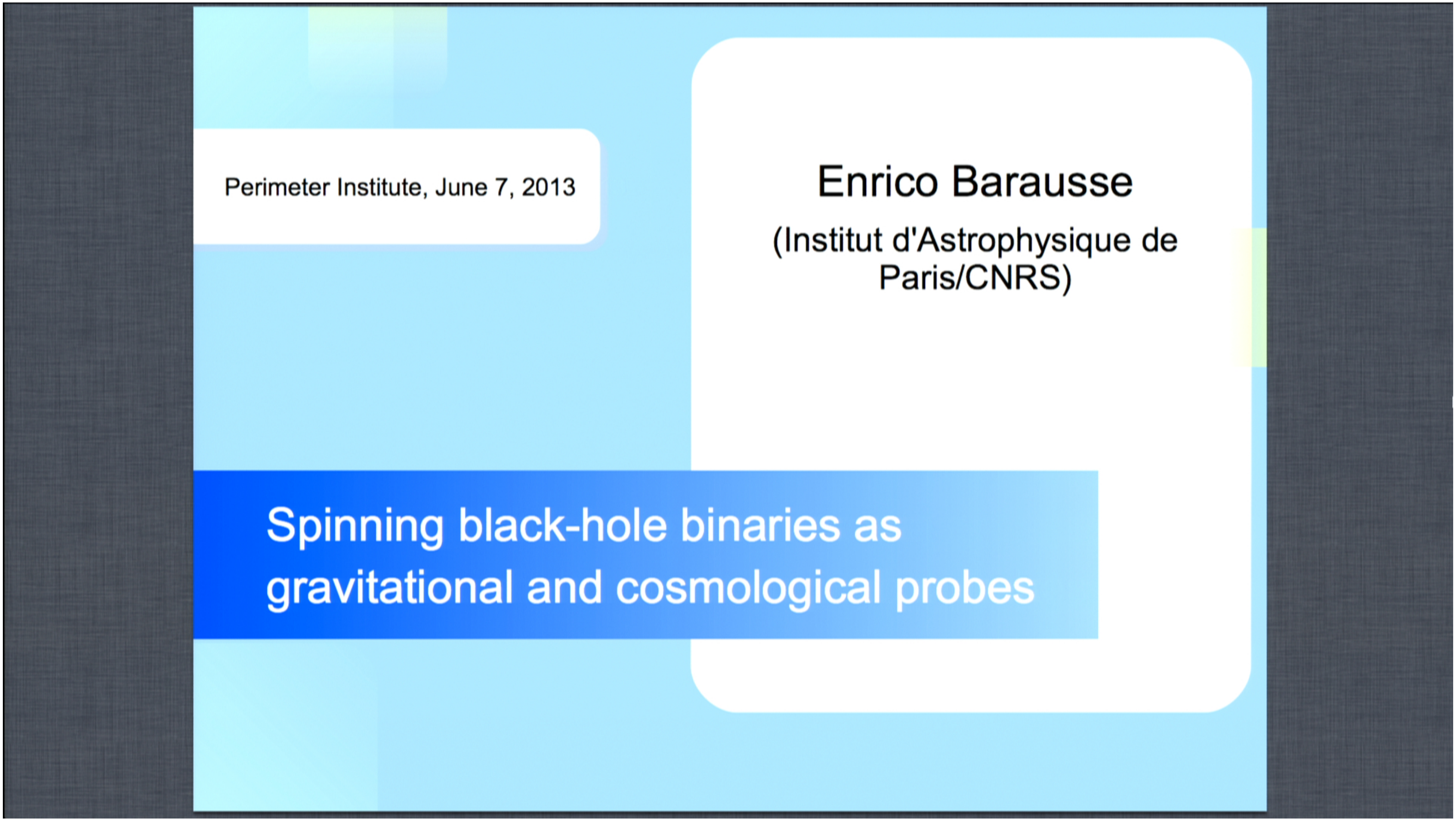
Abstract: Spins play a major role in the strong-field dynamics of
black-hole binaries and their gravitational-wave emission. By detecting spin
effects in the waveforms, existing and future gravitational-wave detectors
therefore provide a natural way to test gravity in strong-field, highly
dynamical regimes.

In the first part of my talk, I will show that the
inclusion of the spins in the gravitational templates for future space-based
detectors will permit testing scenarios for the formation and cosmological
evolution of supermassive black holes, and possibly shed light on models of
galaxy formation. In the second part, I will show that the effective-one-body
(EOB) model provides an efficient way to account for spin effects in both the
dynamics and waveforms, by combining information from post-Newtonian theory,
the self-force formalism, and numerical-relativity simulations.



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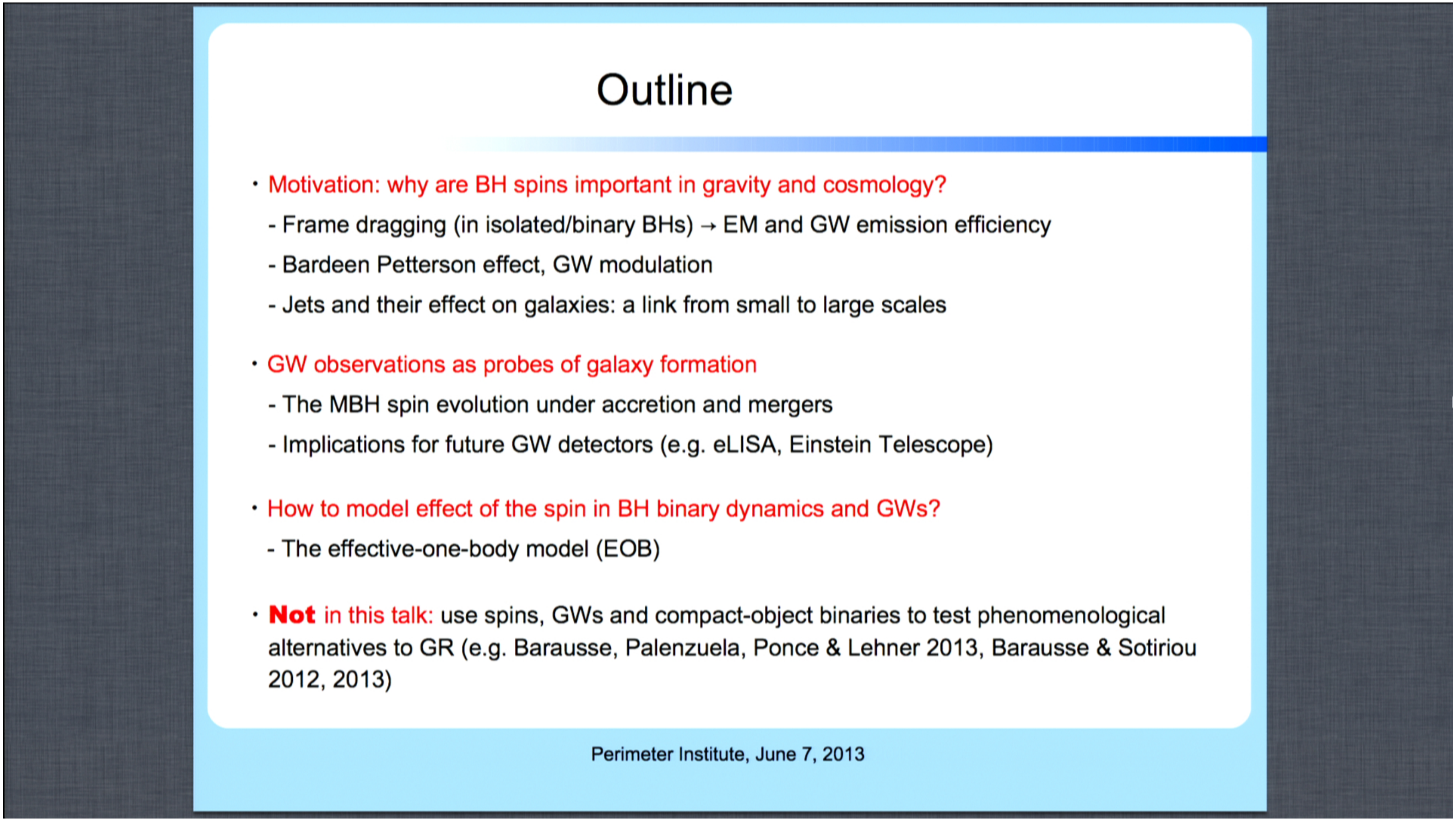
Enrico Barausse

(Institut d'Astrophysique de
Paris/CNRS)

Spinning black-hole binaries as gravitational and cosmological probes



Outline

- Motivation: why are BH spins important in gravity and cosmology?
  - Frame dragging (in isolated/binary BHs) → EM and GW emission efficiency
  - Bardeen Petterson effect, GW modulation
  - Jets and their effect on galaxies: a link from small to large scales
- GW observations as probes of galaxy formation
  - The MBH spin evolution under accretion and mergers
  - Implications for future GW detectors (e.g. eLISA, Einstein Telescope)
- How to model effect of the spin in BH binary dynamics and GWs?
  - The effective-one-body model (EOB)
- **Not** in this talk: use spins, GWs and compact-object binaries to test phenomenological alternatives to GR (e.g. Barausse, Palenzuela, Ponce & Lehner 2013, Barausse & Sotiriou 2012, 2013)

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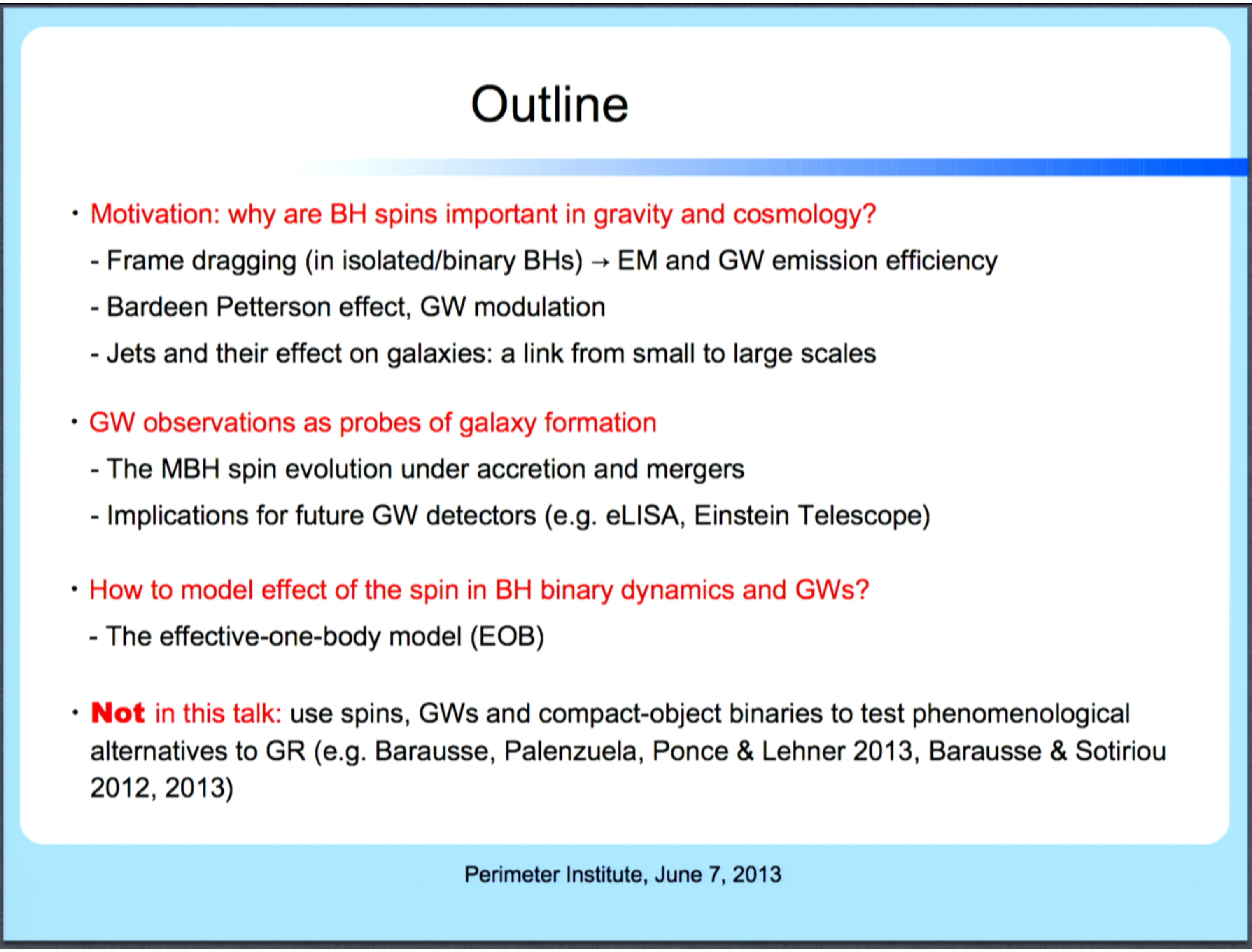

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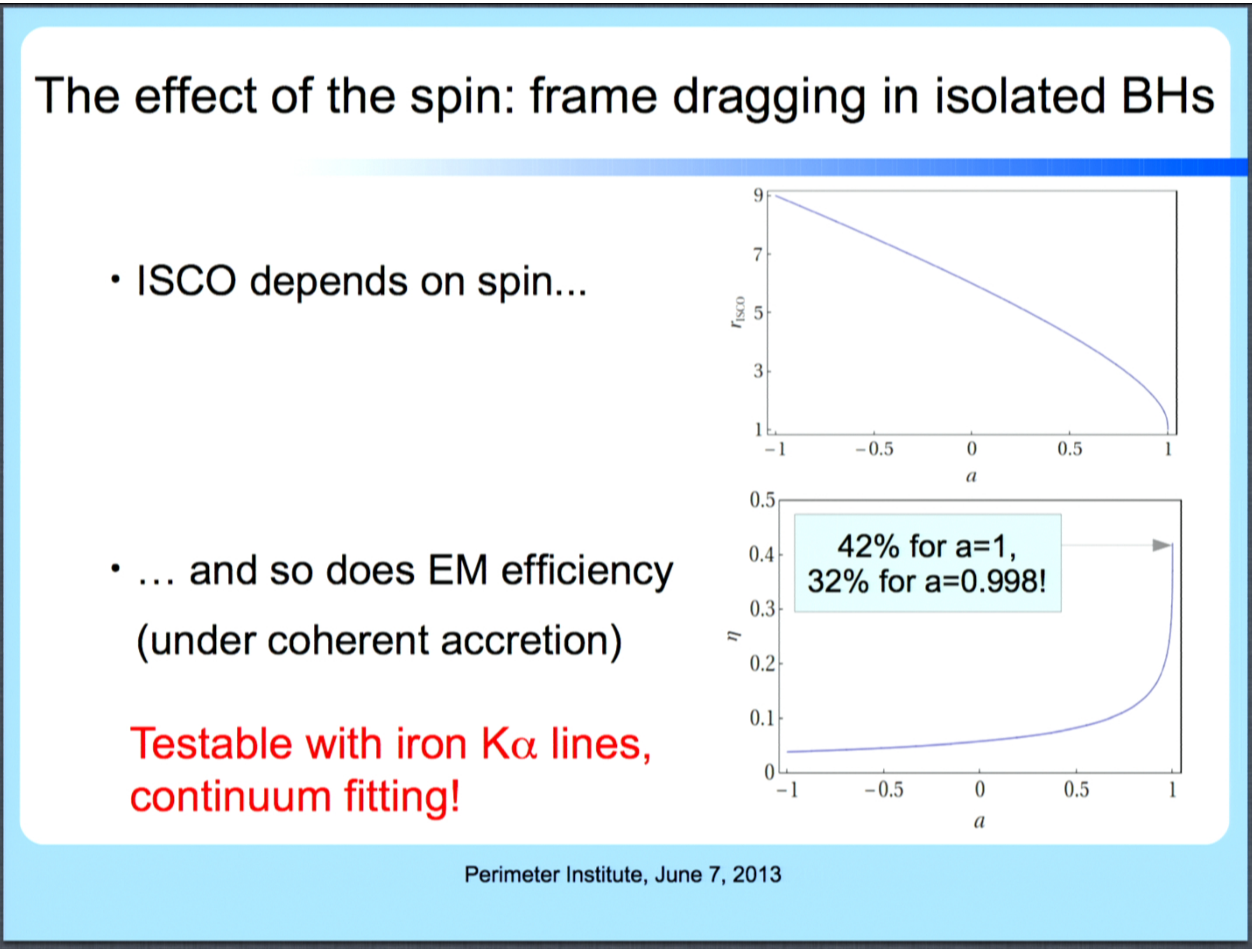


The effect of the spin: frame dragging in isolated BHs

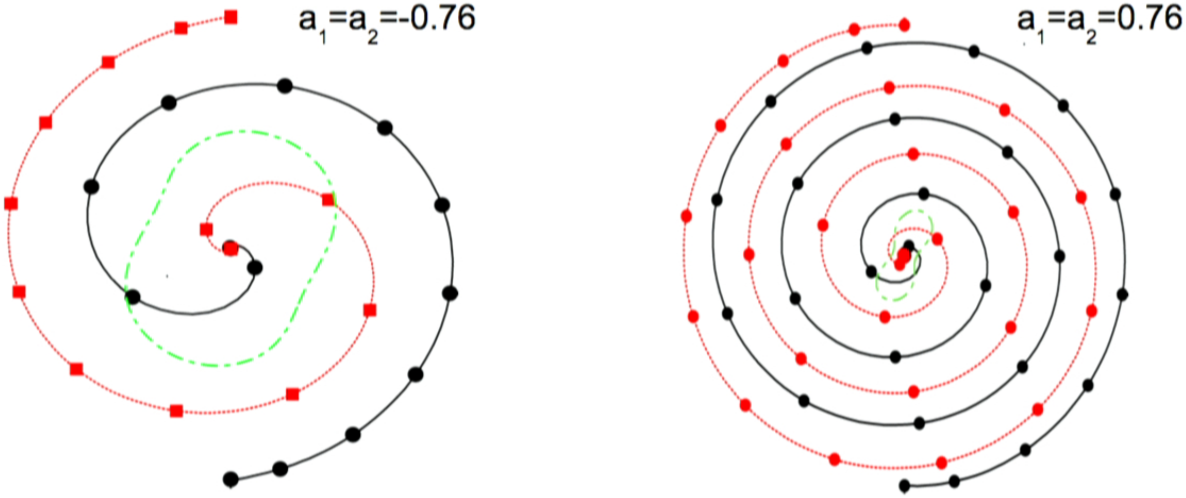
- ISCO depends on spin...
- … and so does EM efficiency (under coherent accretion)

Testable with iron Kα lines, continuum fitting!

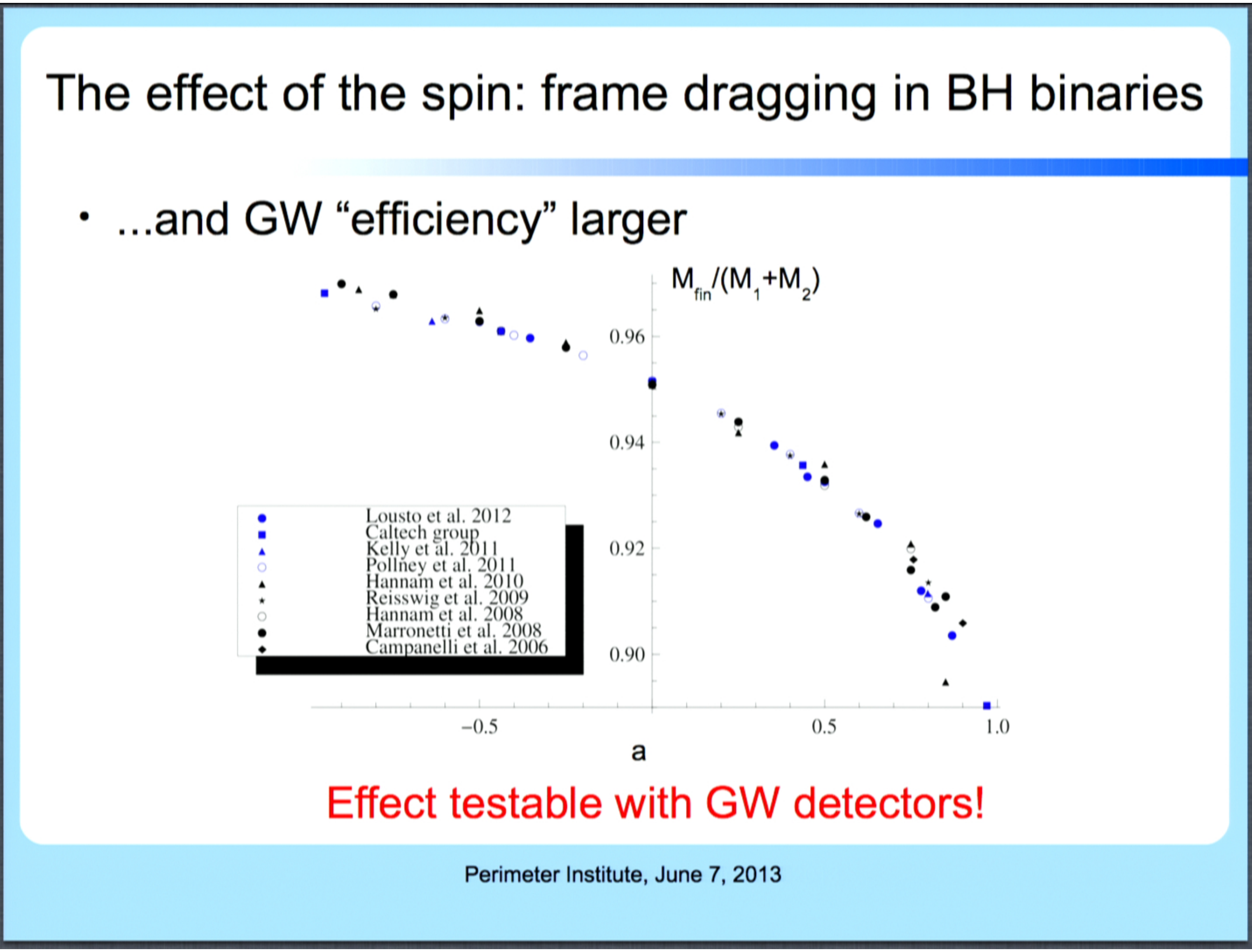
42% for a=1,
32% for a=0.998!

The effect of the spin: frame dragging in BH binaries

Spin-orbit coupling or “hang-up” effect: for large spins aligned with L, effective ISCO moves inward …



Figures from Campanelli, Lousto & Zlochower 2006



The effect of the spin: frame dragging in BH binaries

- ...and GW “efficiency” larger

Effect testable with GW detectors!

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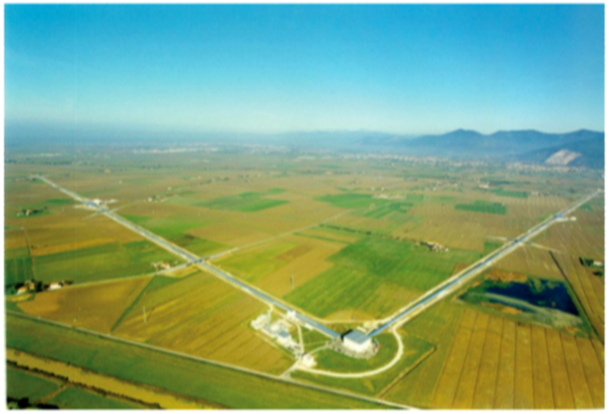
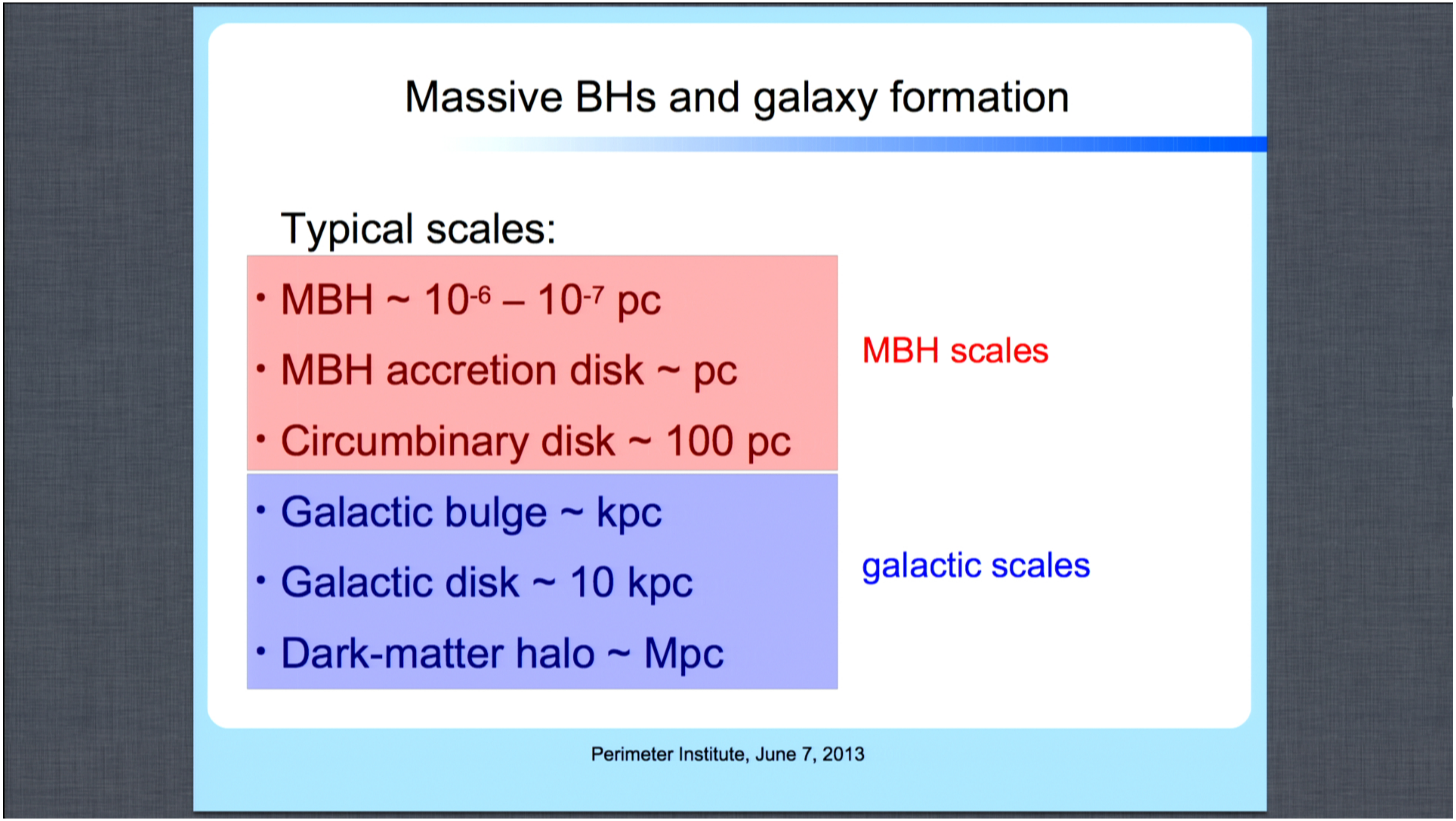
Gravitational waves from binary BHs

- GW detectors will
  - measure masses to within 0.1% and spins to within 1%
  - tell spin-aligned from precessing binaries thanks to spin induced modulation
- Today: sensitive to stellar-mass BHs (few events per yr at low z)





Massive BHs and galaxy formation

Typical scales:

- MBH ~ $10^{-6} – 10^{-7}$ pc
- MBH accretion disk ~ pc
- Circumbinary disk ~ 100 pc

MBH scales

- Galactic bulge ~ kpc
- Galactic disk ~ 10 kpc
- Dark-matter halo ~ Mpc

galactic scales

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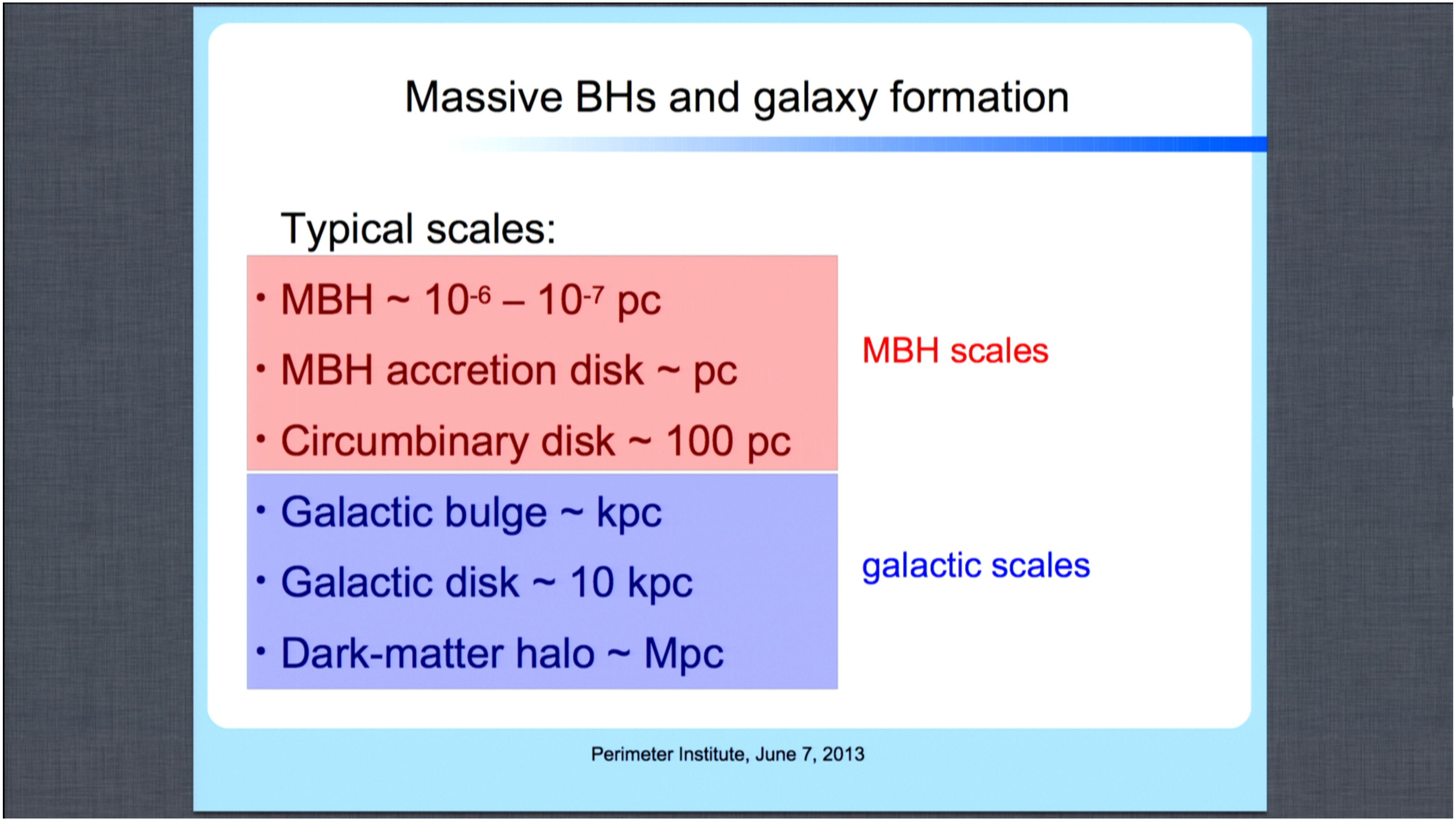

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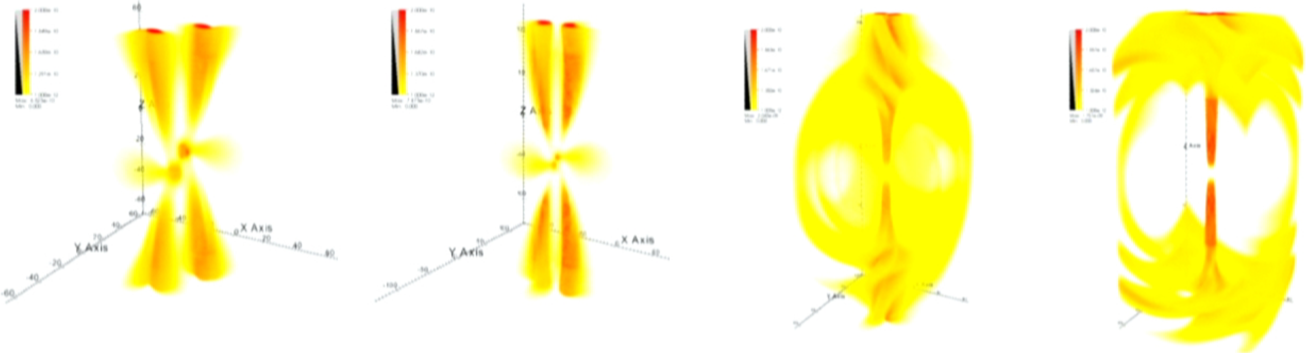
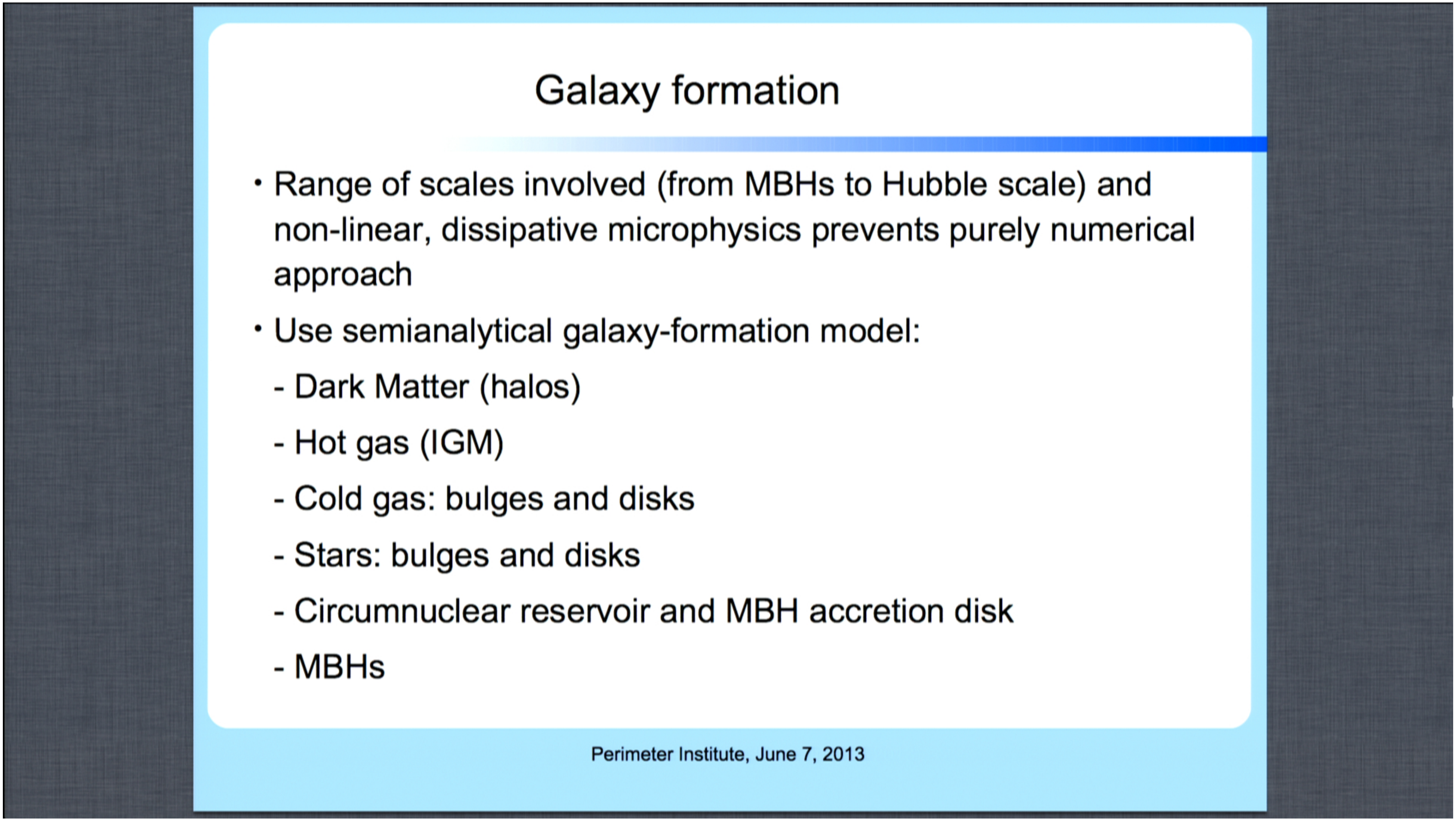
Why does galaxy formation care about MBHs?

- Jets can be produced by isolated spinnning BHs in a magnetic field anchored to accretion disk (Blandford & Znajek 1977)...
- … or by BHs (even non spinning ones) moving a magnetic fields anchored to circumbinary disk (Palenzuela, Lehner and Liebling 2010)



(a) $-11.0\,M_8$ hrs (b) $-3.0\,M_8$ hrs (c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs



Galaxy formation

- Range of scales involved (from MBHs to Hubble scale) and non-linear, dissipative microphysics prevents purely numerical approach
- Use semianalytical galaxy-formation model:

- Dark Matter (halos)
- Hot gas (IGM)
- Cold gas: bulges and disks
- Stars: bulges and disks
- Circumnuclear reservoir and MBH accretion disk
- MBHs

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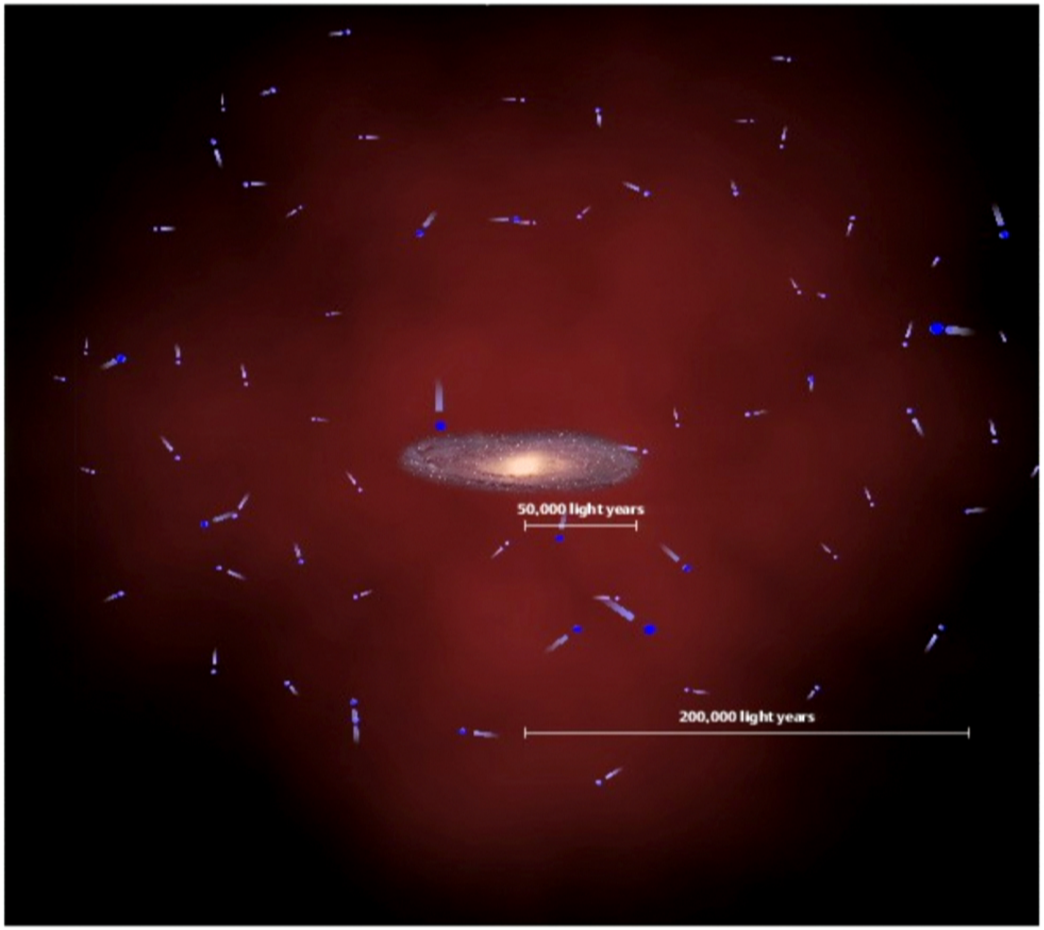

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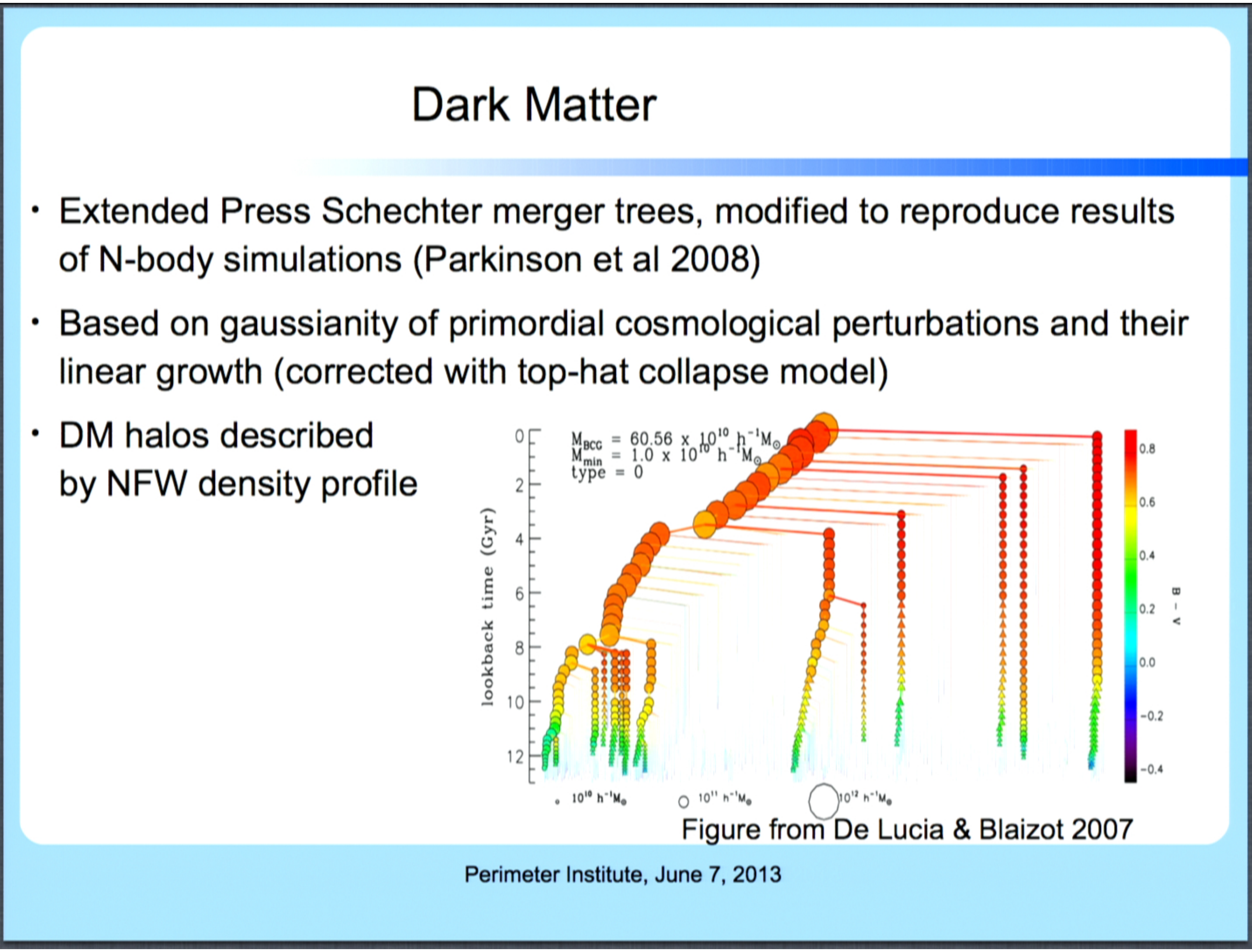
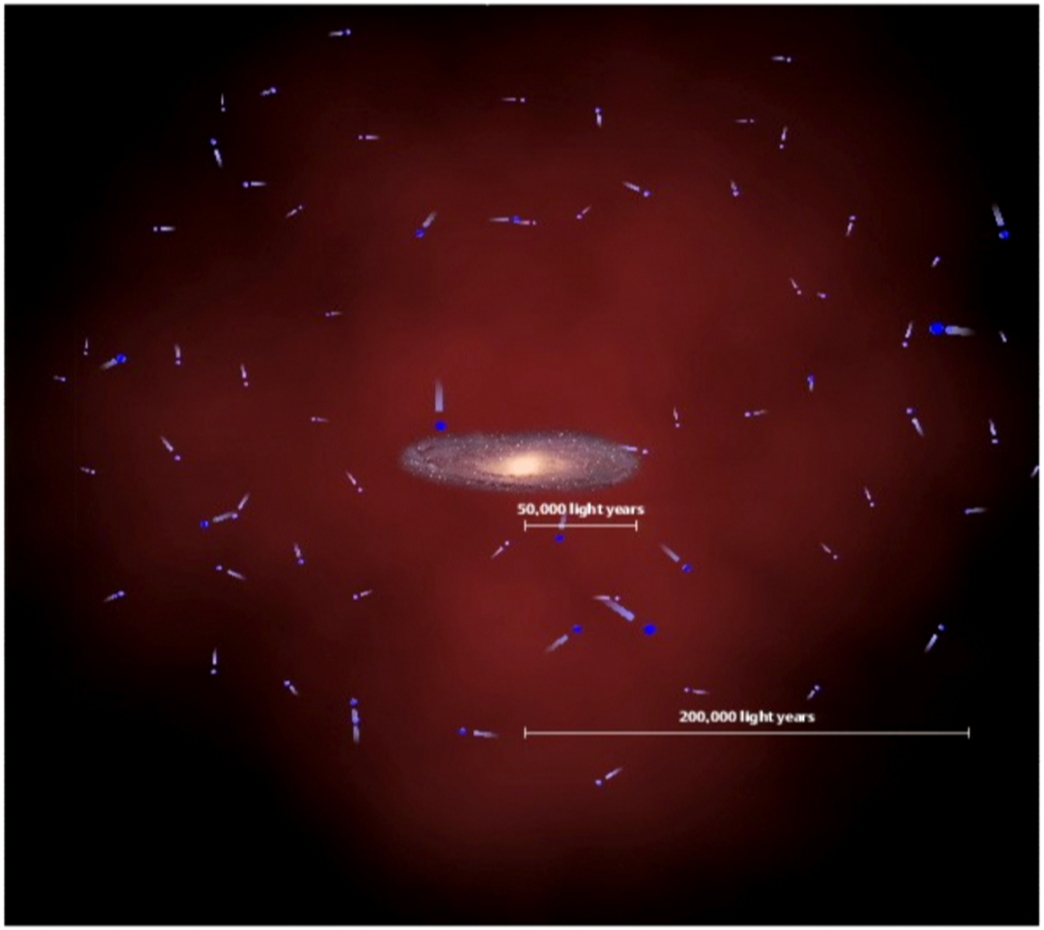


Dark Matter

- Extended Press Schechter merger trees, modified to reproduce results of N-body simulations (Parkinson et al 2008)
- Based on gaussianity of primordial cosmological perturbations and their linear growth (corrected with top-hat collapse model)
- DM halos described by NFW density profile

Figure from De Lucia & Blaizot 2007



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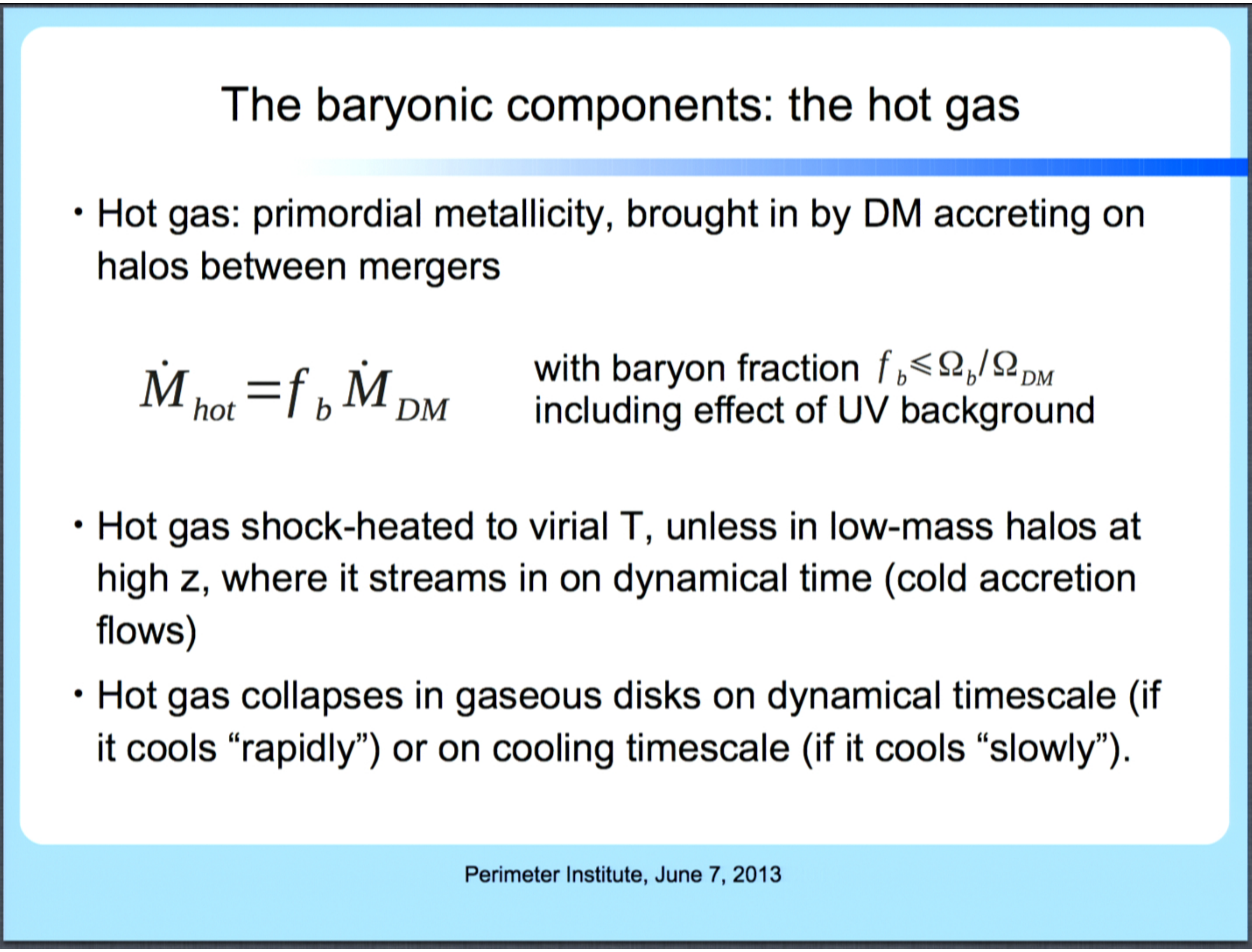

The baryonic components: the hot gas

- Hot gas: primordial metallicity, brought in by DM accreting on halos between mergers

$$\dot{M}_{hot} = f_b \dot{M}_{DM}$$

with baryon fraction $f_b \leqslant \Omega_b / \Omega_{DM}$
including effect of UV background

- Hot gas shock-heated to virial T, unless in low-mass halos at high z, where it streams in on dynamical time (cold accretion flows)
- Hot gas collapses in gaseous disks on dynamical timescale (if it cools “rapidly”) or on cooling timescale (if it cools “slowly”).

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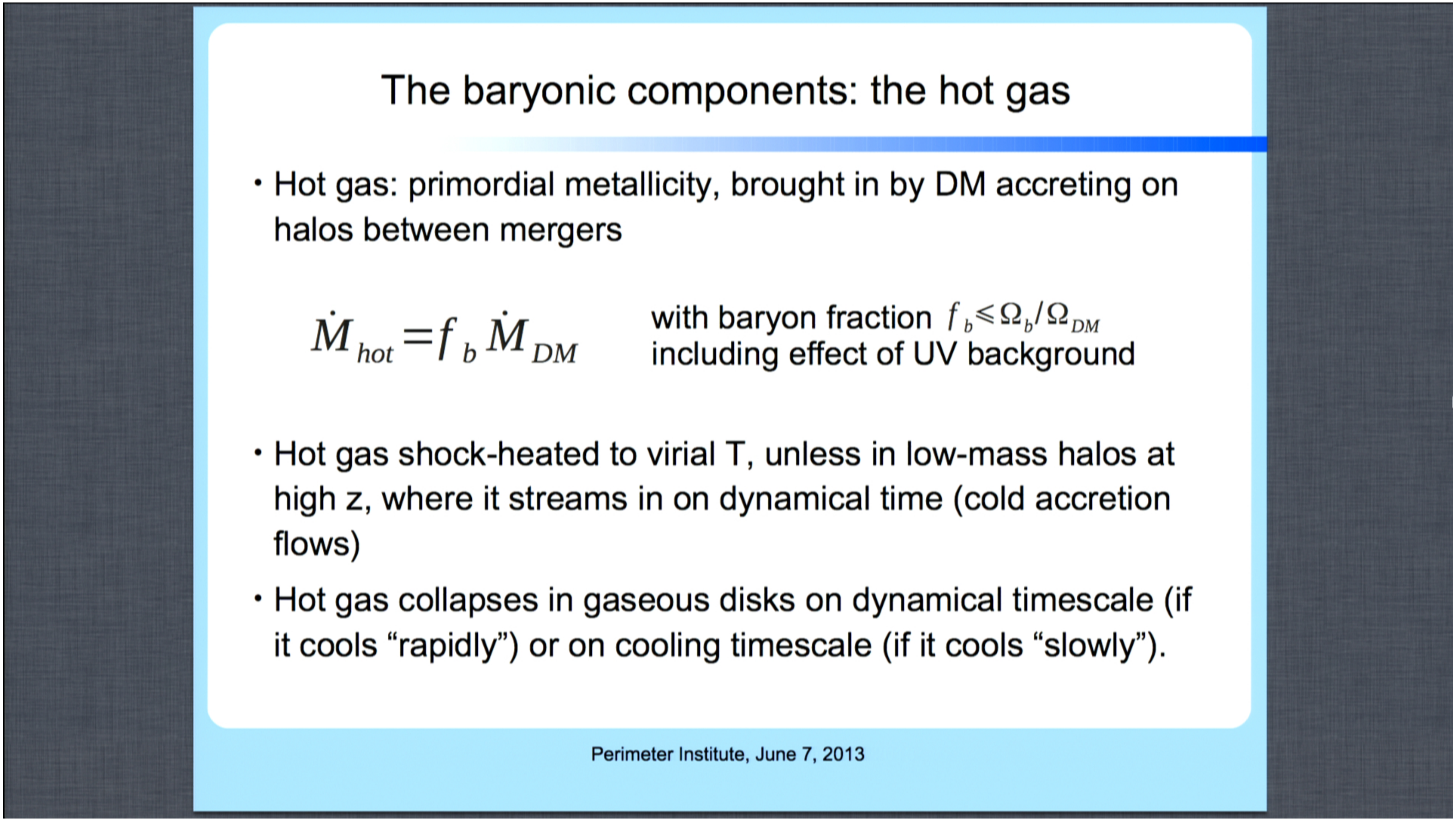

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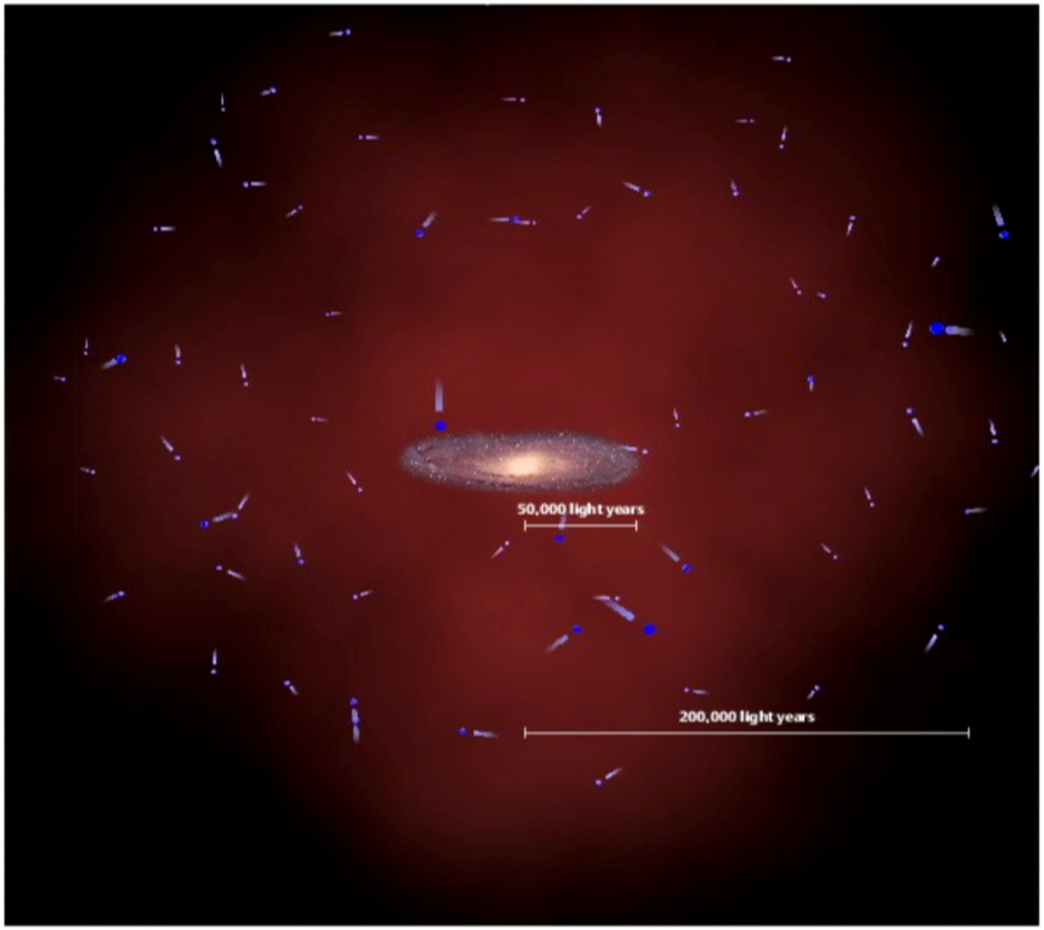
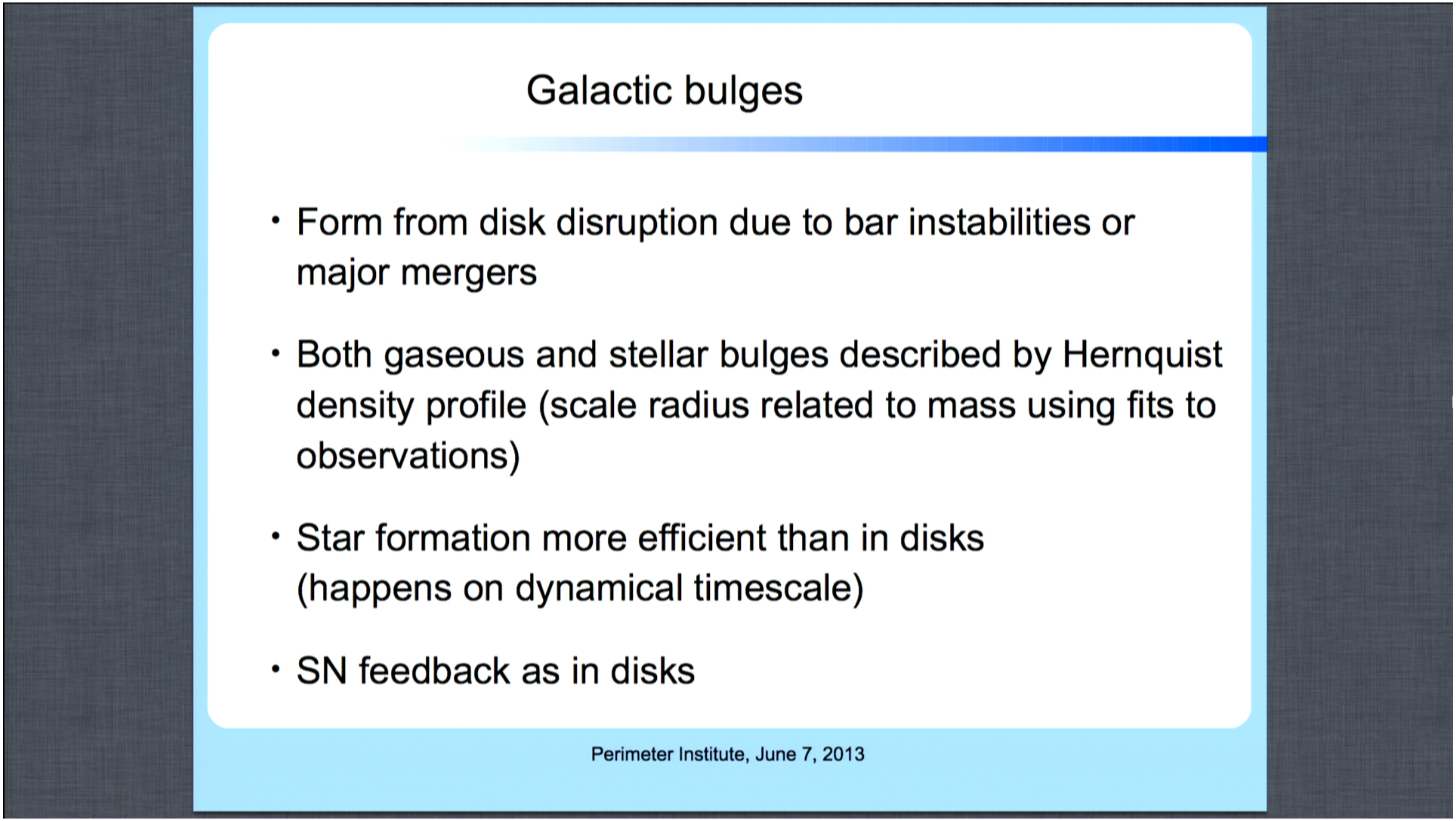

50,000 light years
200,000 light years



Galactic bulges

- Form from disk disruption due to bar instabilities or major mergers
- Both gaseous and stellar bulges described by Hernquist density profile (scale radius related to mass using fits to observations)
- Star formation more efficient than in disks (happens on dynamical timescale)
- SN feedback as in disks

Composite image of Centaurus A

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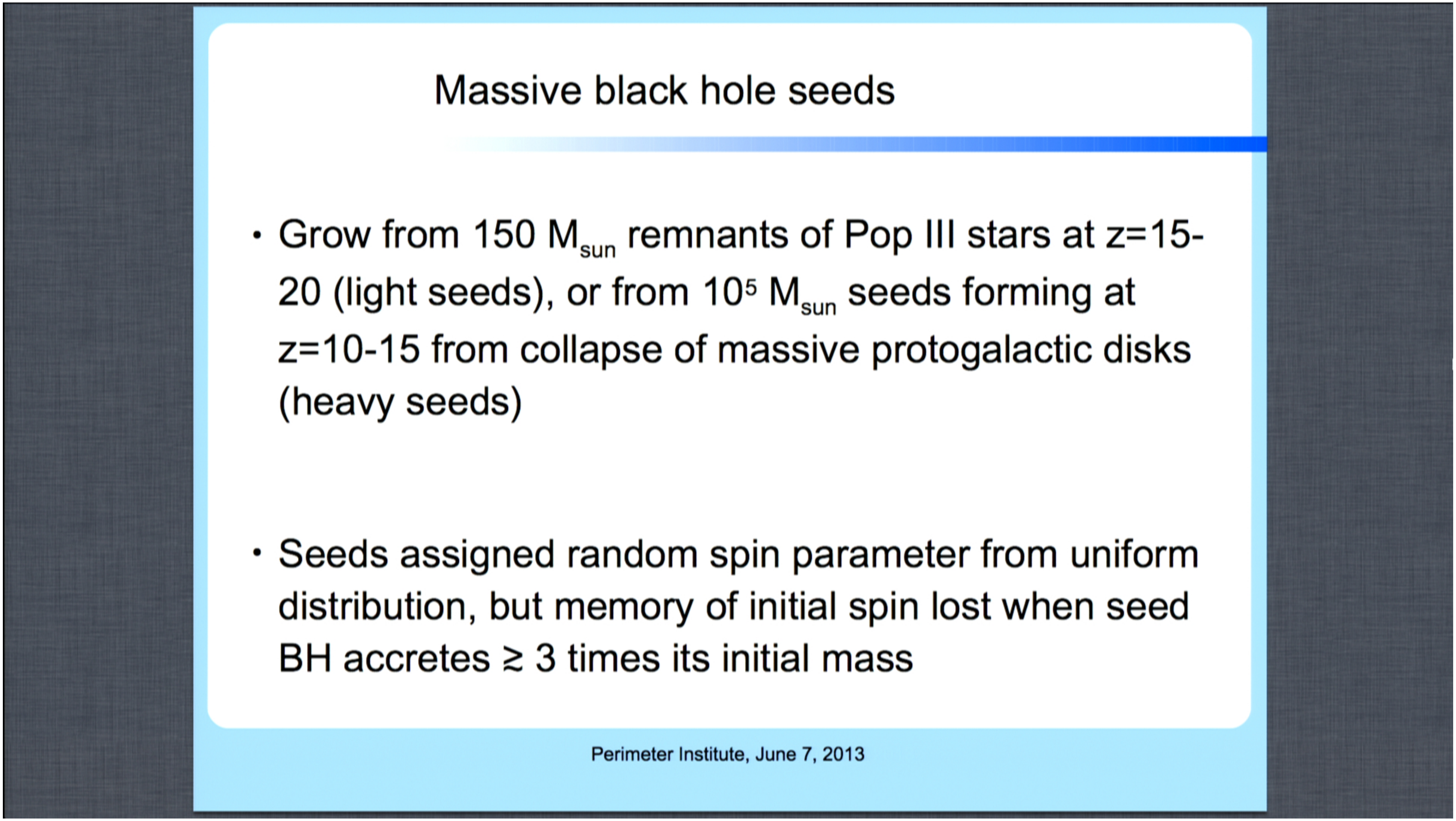

Massive black hole seeds

- Grow from 150 M_{sun} remnants of Pop III stars at z=15-20 (light seeds), or from 10^5 M_{sun} seeds forming at z=10-15 from collapse of massive protogalactic disks (heavy seeds)
- Seeds assigned random spin parameter from uniform distribution, but memory of initial spin lost when seed BH accretes ≳ 3 times its initial mass

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The QSO phase

- When SF happens in bulges (due to disk instabilities or major mergers), radiation drag forces cold gas into circumnuclear reservoir:

$$\dot{M}_{\rm res} = A_{\rm res}\psi_b(t)$$

- Circumnuclear reservoir accretes on MBH with rate

$$\dot{M}_{\rm QSO} = \frac{M_{\rm res}}{t_{\rm accr}}$$ t_{accr} is a free parameter

$$\dot{M}_{\rm bh,QSO} = \dot{M}_{\rm QSO}(1-\eta(a_{\rm bh}))$$

- $\dot{M}$ can be super-Eddington, but luminosity cannot

$$L_{\rm bh,QSO} = \min\left\{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2\,,\;L_{\rm Edd}\left[1+\ln\left(\frac{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2}{L_{\rm Edd}}\right)\right]\right\}$$

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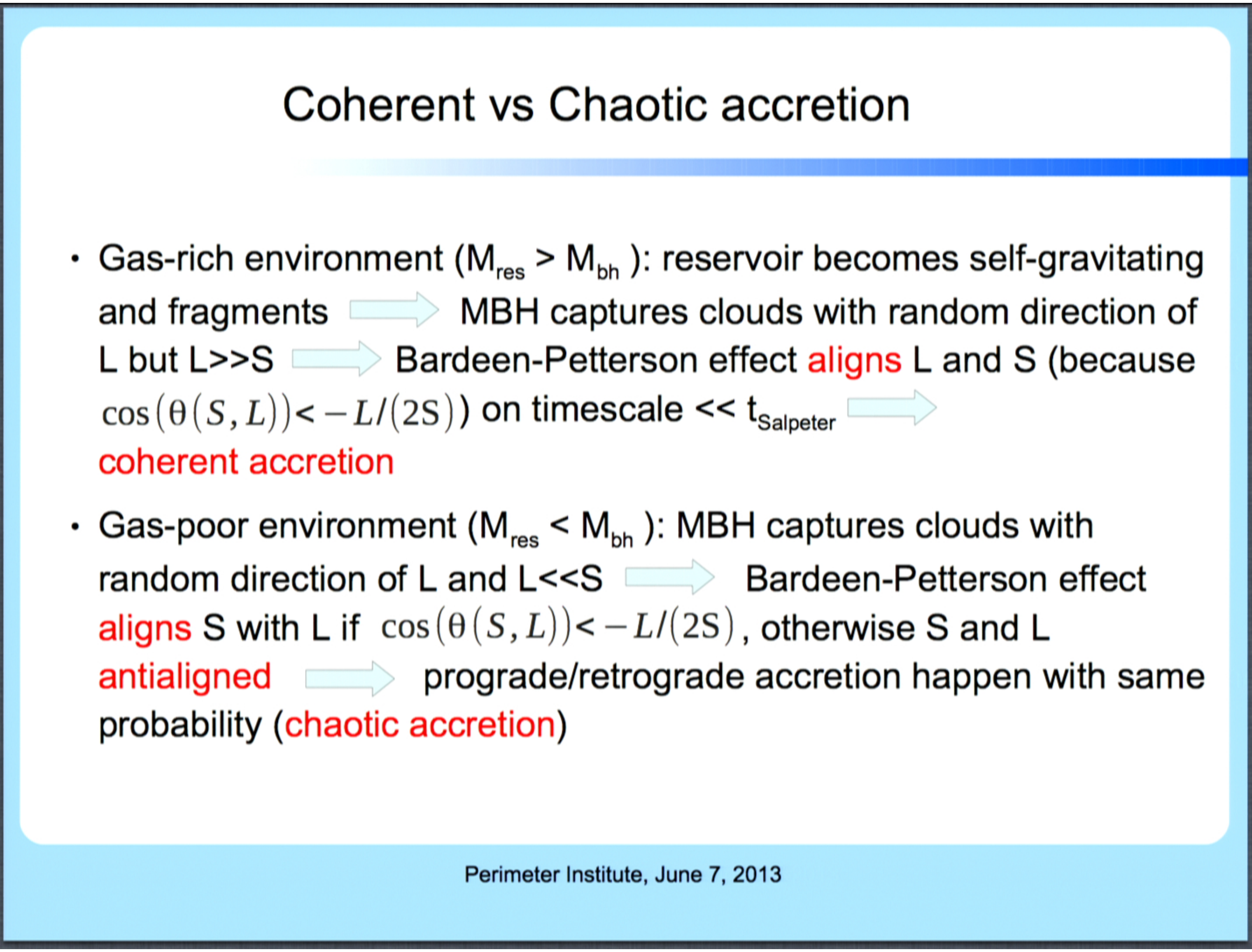
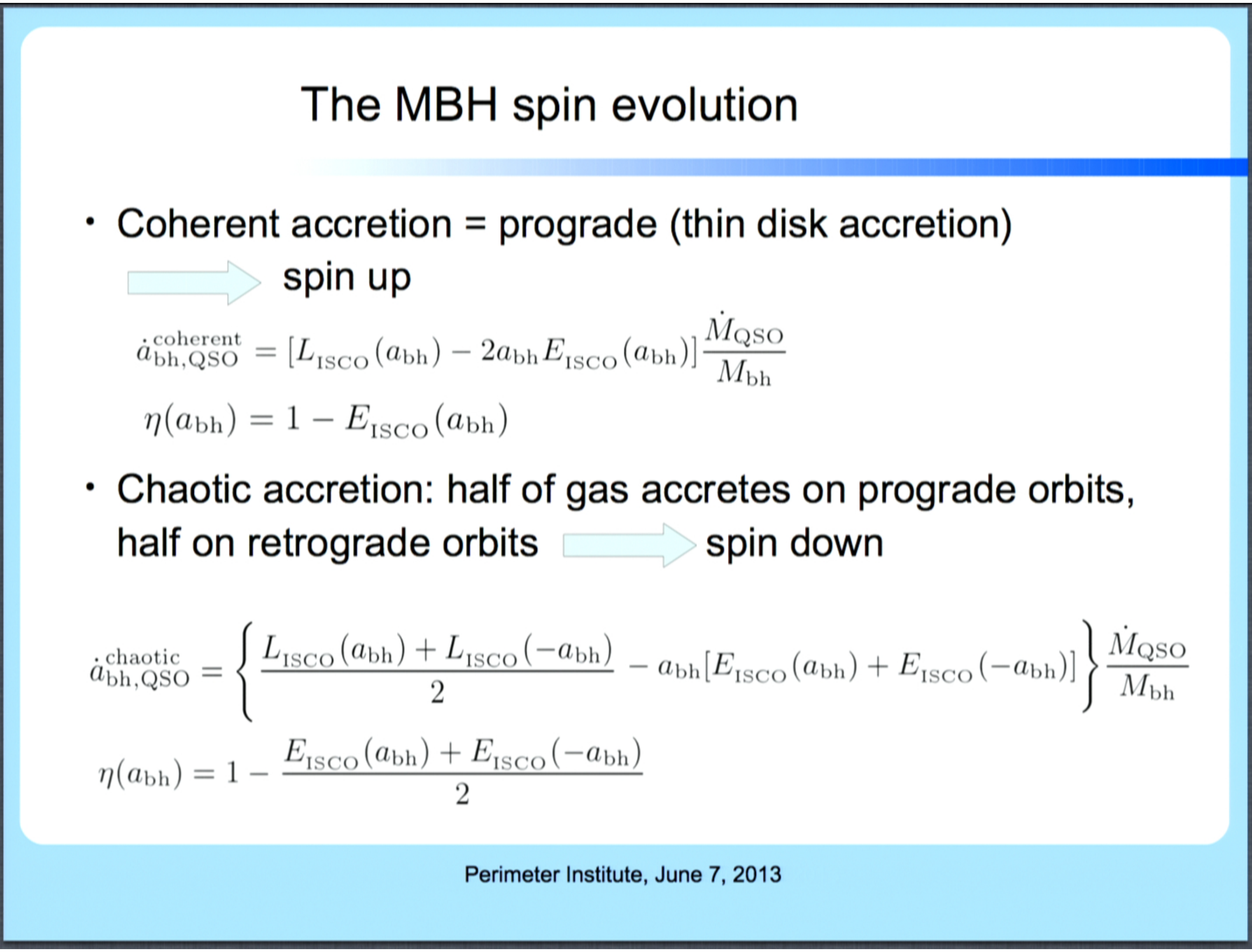


Coherent vs Chaotic accretion

- Gas-rich environment ($M_{res} > M_{bh}$): reservoir becomes self-gravitating and fragments $\Rightarrow$ MBH captures clouds with random direction of L but L>>S $\Rightarrow$ Bardeen-Petterson effect aligns L and S (because $\cos(\theta(S,L)) < -L/(2S)$) on timescale << $t_{Salpeter}$ $\Rightarrow$ coherent accretion
- Gas-poor environment ($M_{res} < M_{bh}$): MBH captures clouds with random direction of L and L<<S $\Rightarrow$ Bardeen-Petterson effect aligns S with L if $\cos(\theta(S,L)) < -L/(2S)$, otherwise S and L antialigned $\Rightarrow$ prograde/retrograde accretion happen with same probability (chaotic accretion)



The MBH spin evolution

- Coherent accretion = prograde (thin disk accretion)

→ spin up

$$\dot{a}^{\rm coherent}_{\rm bh,QSO} = [L_{\rm ISCO}(a_{\rm bh}) - 2a_{\rm bh}E_{\rm ISCO}(a_{\rm bh})]\frac{\dot{M}_{\rm QSO}}{M_{\rm bh}}$$

$$\eta(a_{\rm bh}) = 1 - E_{\rm ISCO}(a_{\rm bh})$$

- Chaotic accretion: half of gas accretes on prograde orbits, half on retrograde orbits → spin down

$$\dot{a}^{\rm chaotic}_{\rm bh,QSO} = \left\{\frac{L_{\rm ISCO}(a_{\rm bh}) + L_{\rm ISCO}(-a_{\rm bh})}{2} - a_{\rm bh}[E_{\rm ISCO}(a_{\rm bh}) + E_{\rm ISCO}(-a_{\rm bh})]\right\}\frac{\dot{M}_{\rm QSO}}{M_{\rm bh}}$$

$$\eta(a_{\rm bh}) = 1 - \frac{E_{\rm ISCO}(a_{\rm bh}) + E_{\rm ISCO}(-a_{\rm bh})}{2}$$

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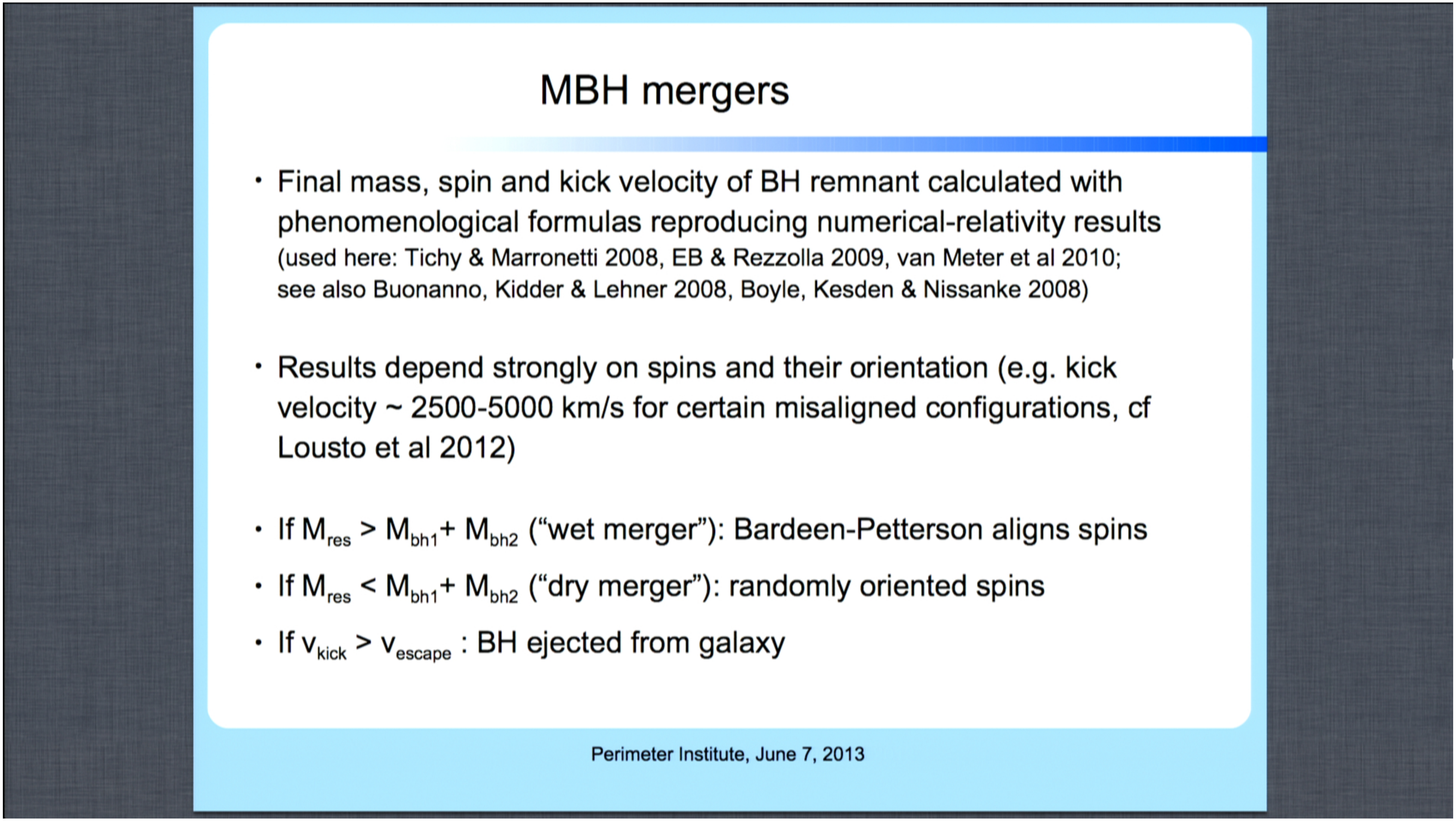

MBH mergers

- Final mass, spin and kick velocity of BH remnant calculated with phenomenological formulas reproducing numerical-relativity results (used here: Tichy & Marronetti 2008, EB & Rezzolla 2009, van Meter et al 2010; see also Buonanno, Kidder & Lehner 2008, Boyle, Kesden & Nissanke 2008)

- Results depend strongly on spins and their orientation (e.g. kick velocity ~ 2500-5000 km/s for certain misaligned configurations, cf Lousto et al 2012)

- If $M_{res} > M_{bh1} + M_{bh2}$ (“wet merger”): Bardeen-Petterson aligns spins
- If $M_{res} < M_{bh1} + M_{bh2}$ (“dry merger”): randomly oriented spins
- If $v_{kick} > v_{escape}$: BH ejected from galaxy

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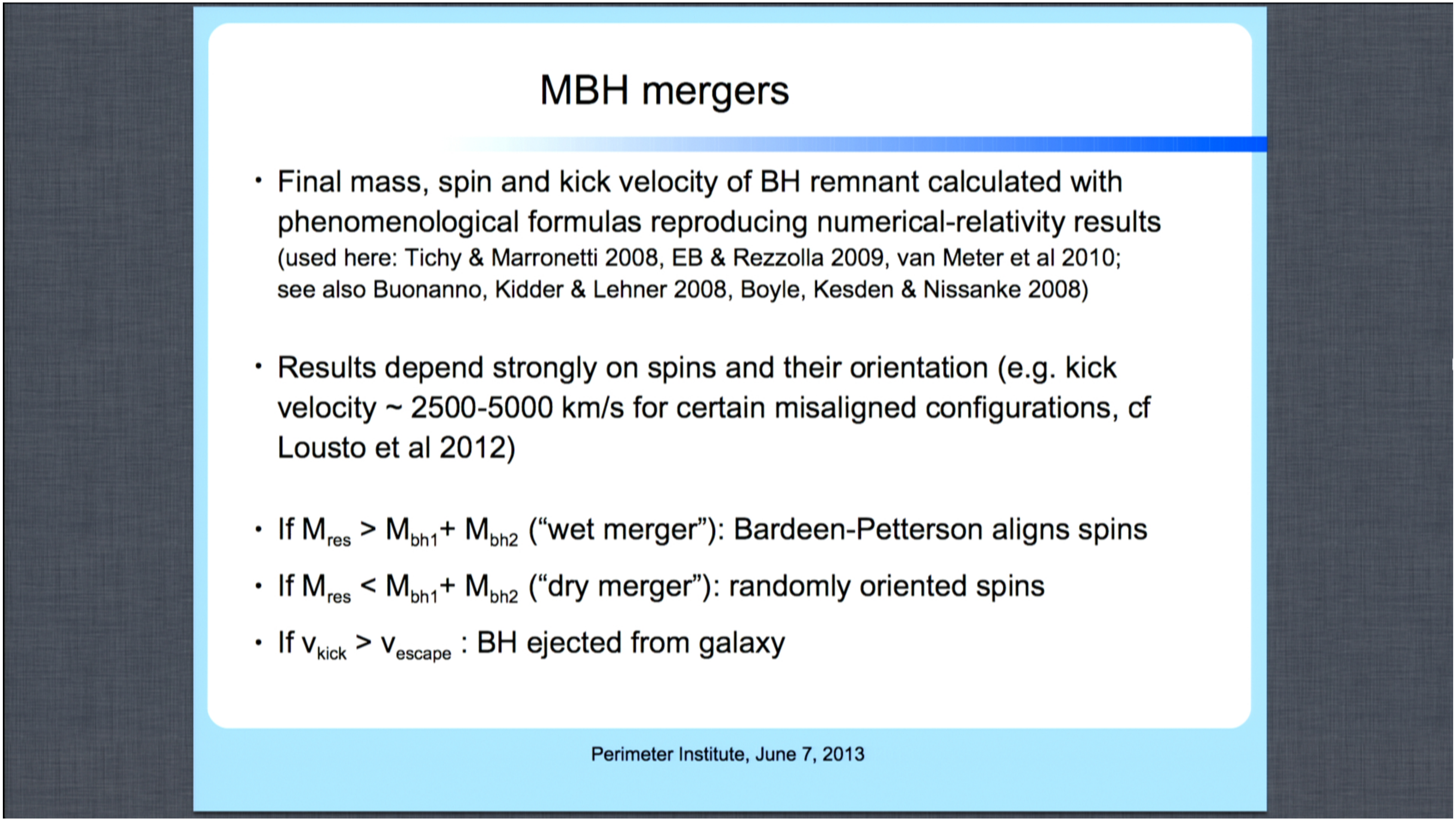

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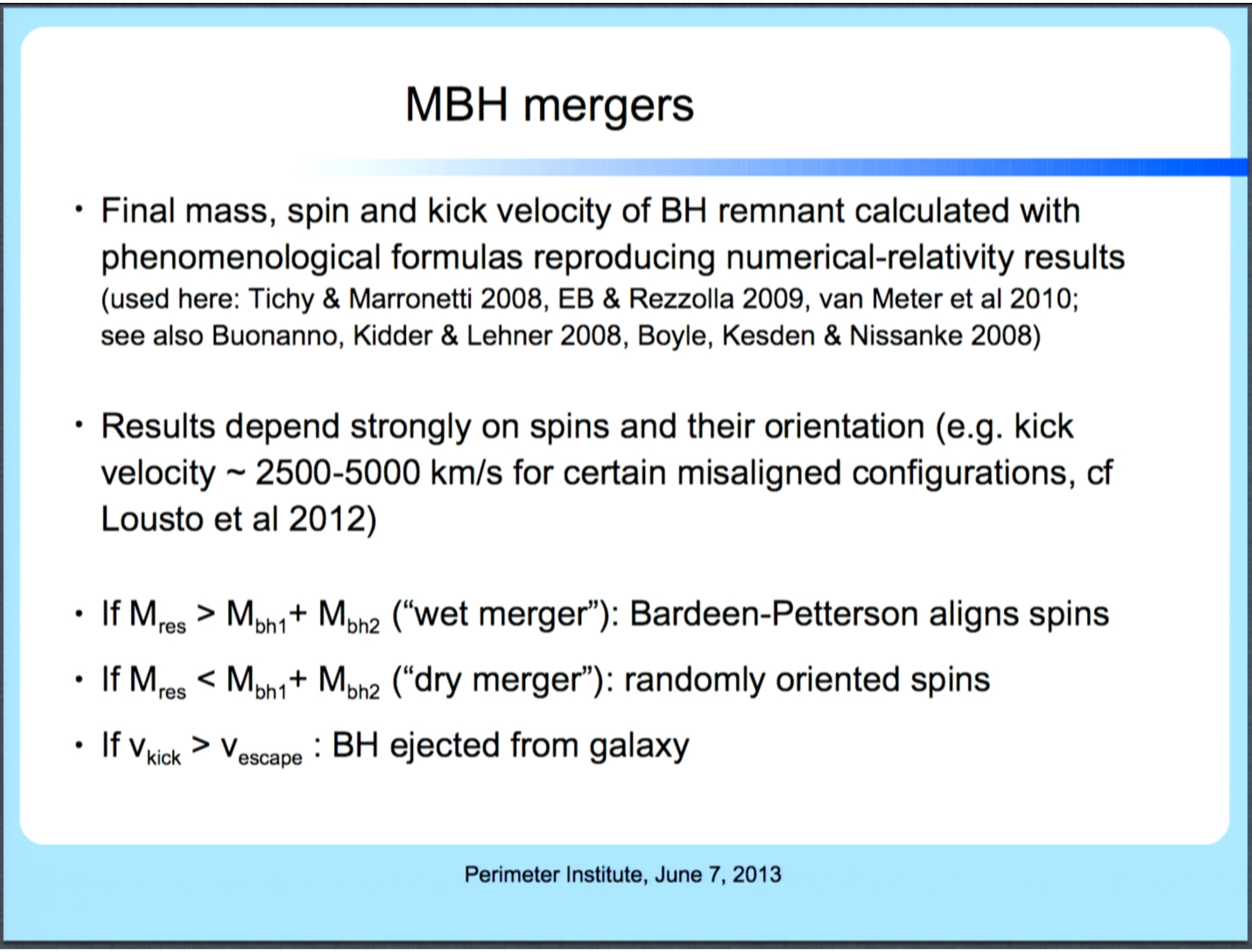

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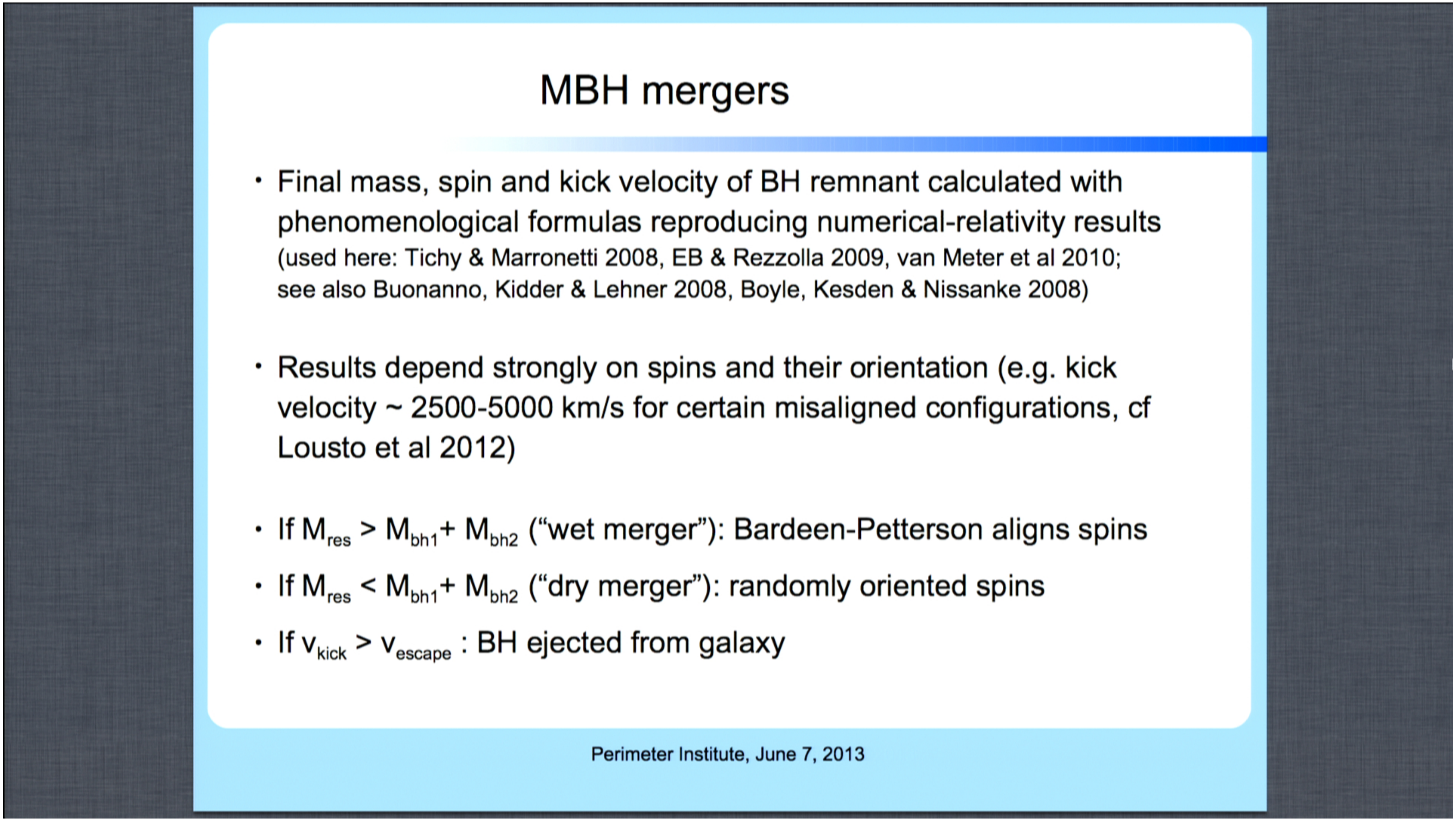

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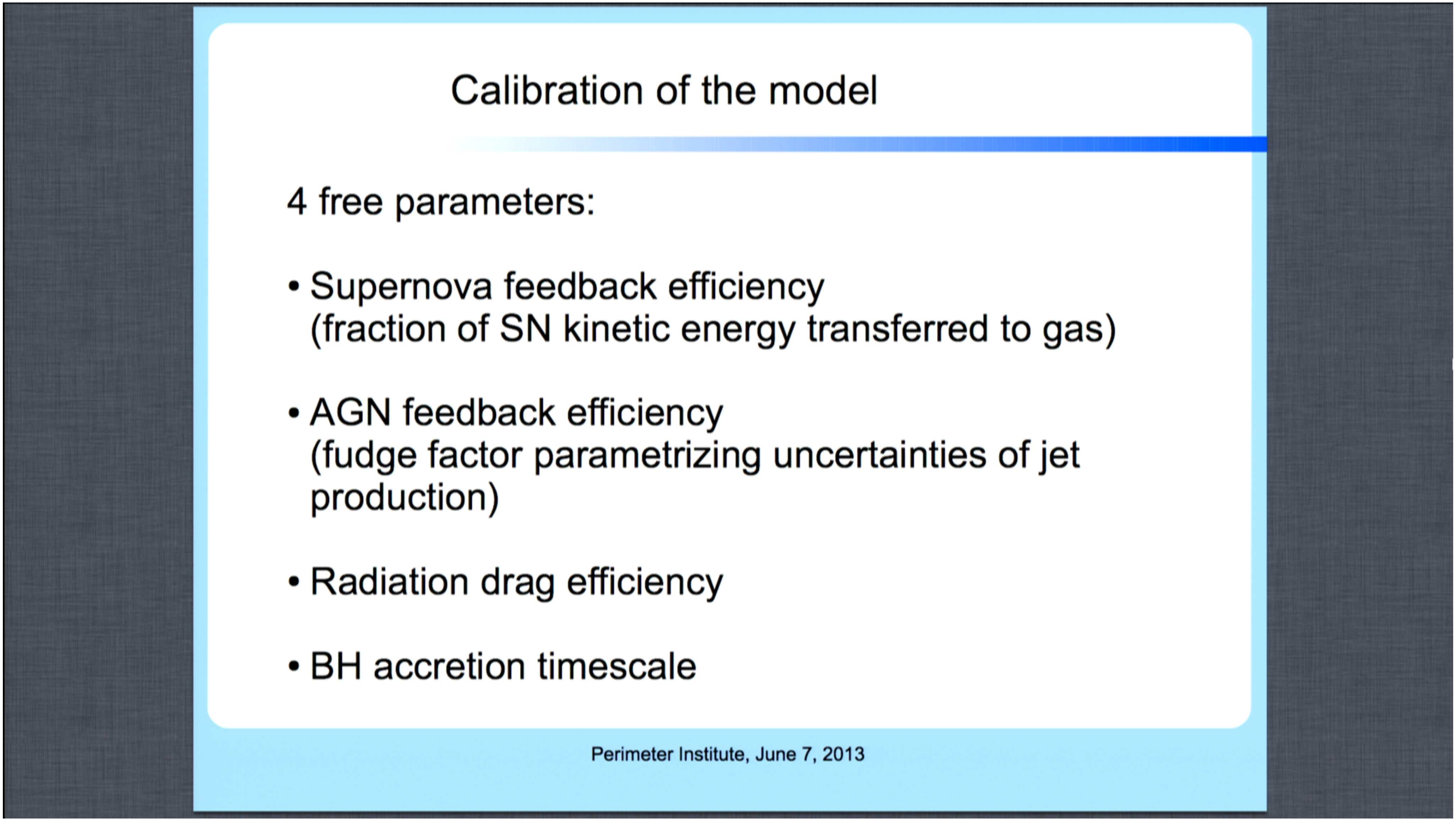
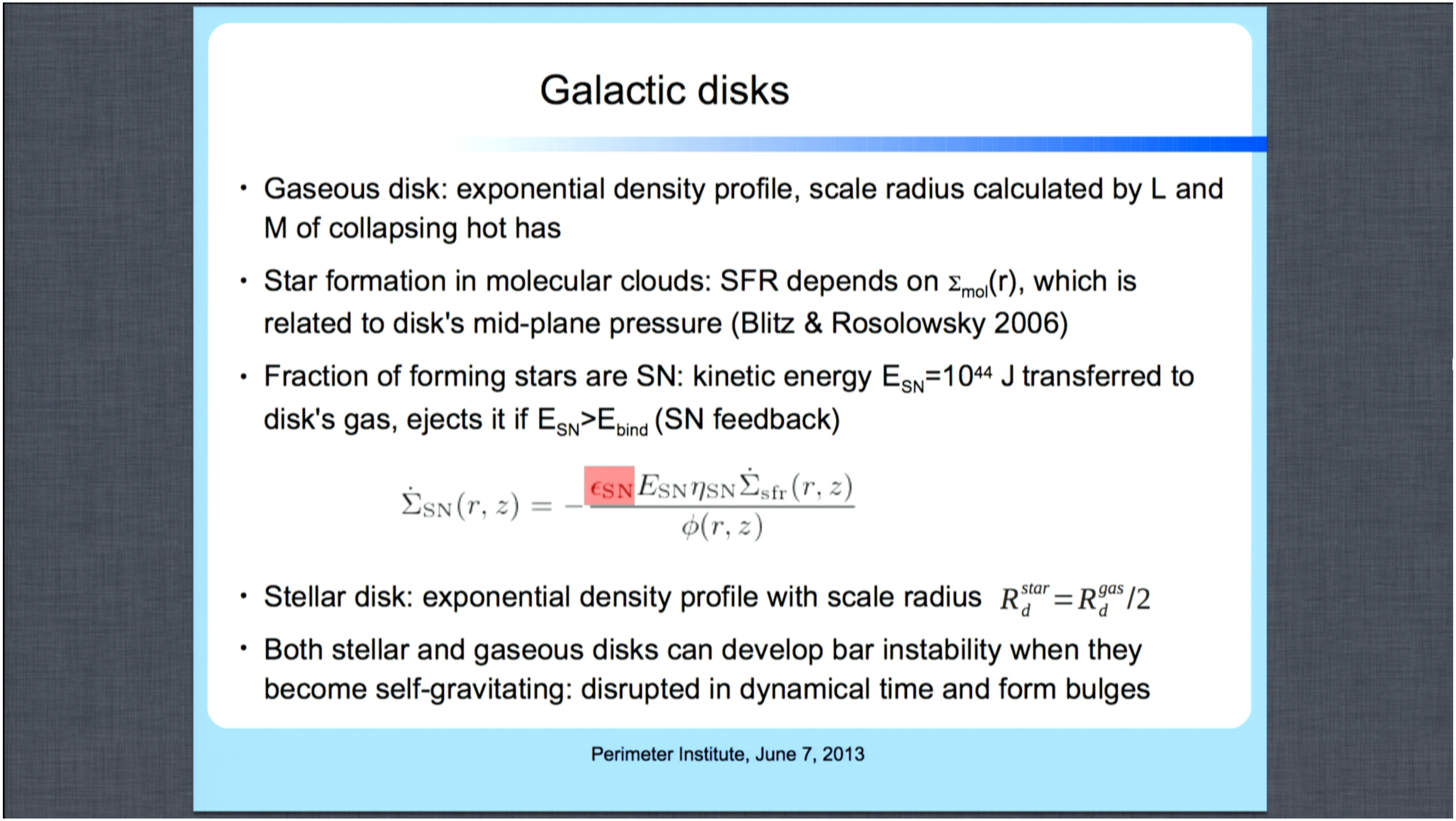


Calibration of the model

4 free parameters:

- Supernova feedback efficiency
  (fraction of SN kinetic energy transferred to gas)
- AGN feedback efficiency
  (fudge factor parametrizing uncertainties of jet production)
- Radiation drag efficiency
- BH accretion timescale

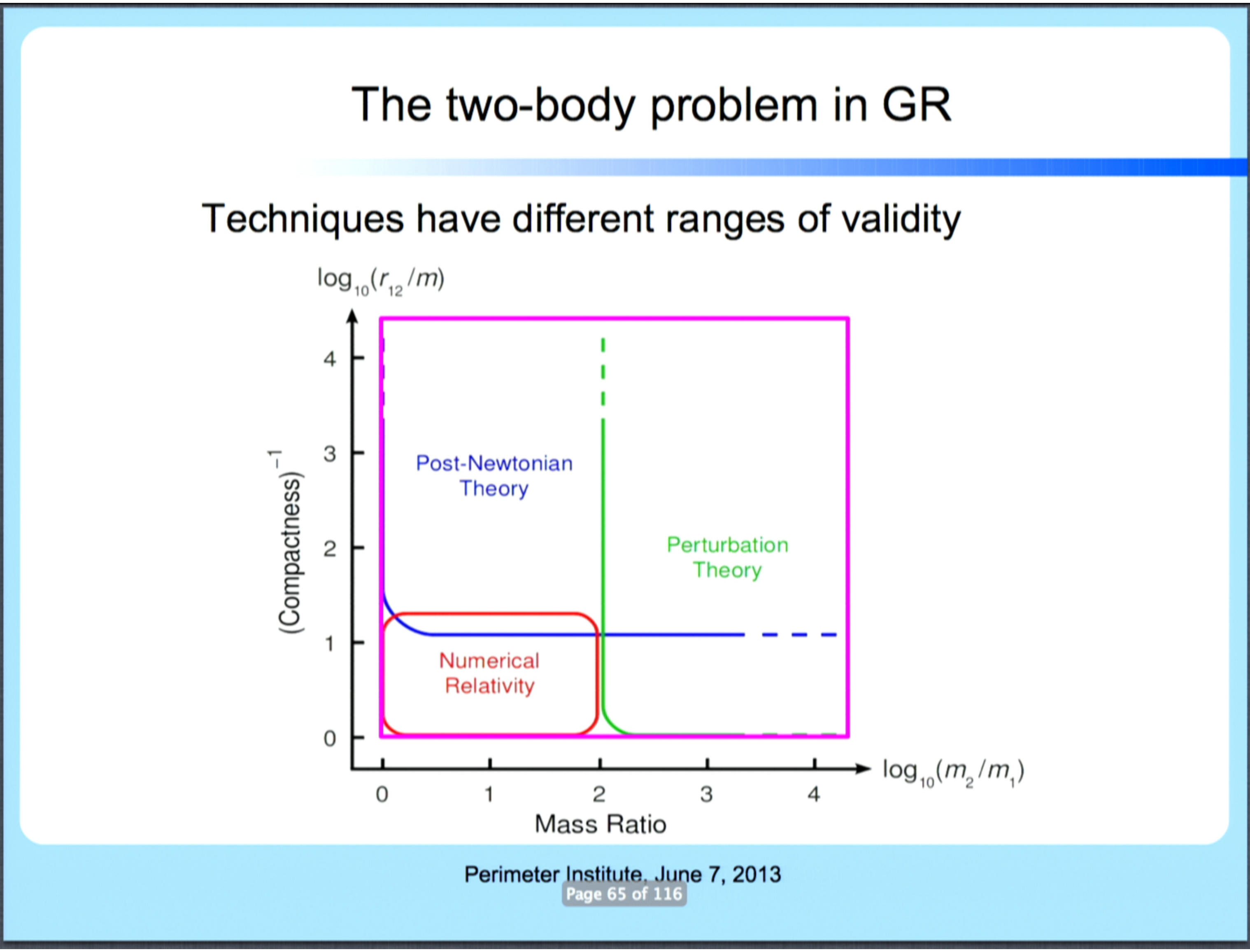


Galactic disks

- Gaseous disk: exponential density profile, scale radius calculated by L and M of collapsing hot has
- Star formation in molecular clouds: SFR depends on $\Sigma_{mol}(r)$, which is related to disk's mid-plane pressure (Blitz & Rosolowsky 2006)
- Fraction of forming stars are SN: kinetic energy $E_{SN}=10^{44}$ J transferred to disk's gas, ejects it if $E_{SN}>E_{bind}$ (SN feedback)

$$\dot{\Sigma}_{\rm SN}(r,z) = -\frac{\epsilon_{\rm SN} E_{\rm SN}\eta_{\rm SN}\dot{\Sigma}_{\rm sfr}(r,z)}{\phi(r,z)}$$

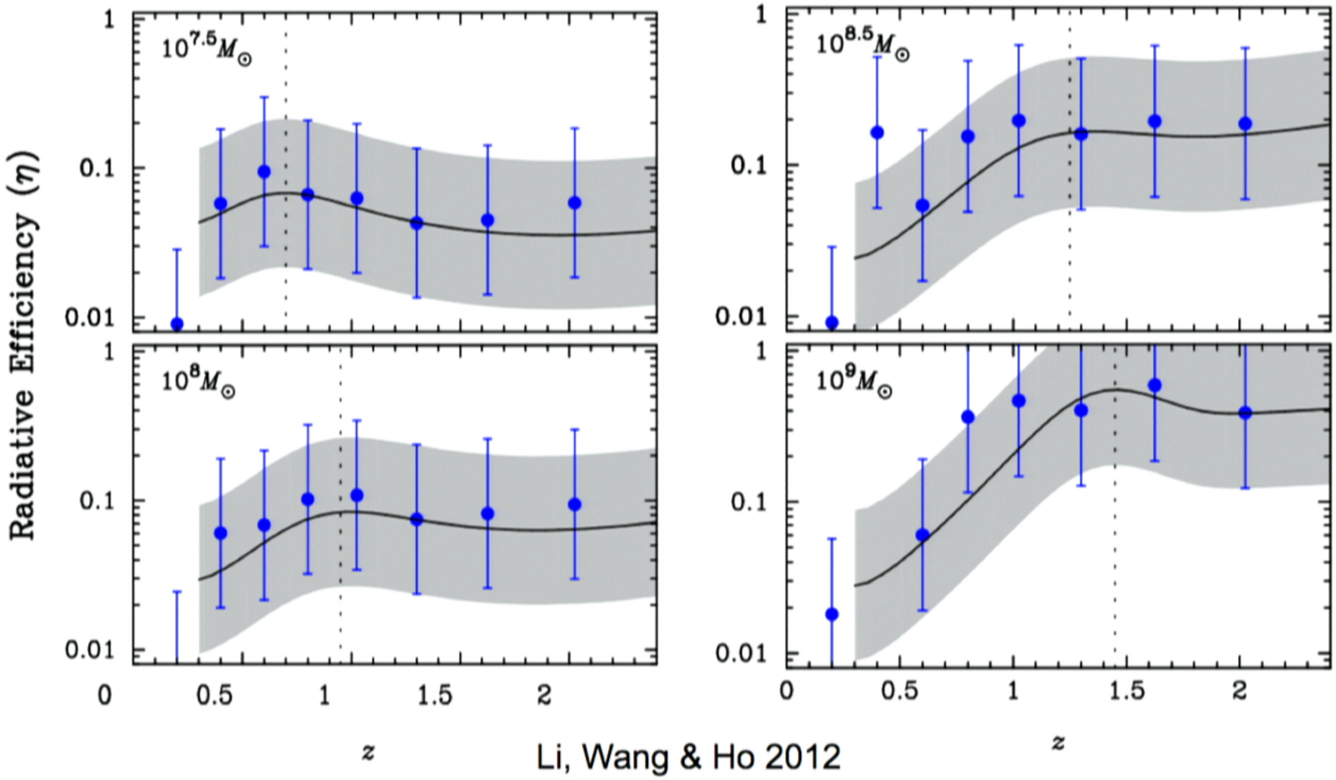
- Stellar disk: exponential density profile with scale radius $R_d^{star}=R_d^{gas}/2$
- Both stellar and gaseous disks can develop bar instability when they become self-gravitating: disrupted in dynamical time and form bulges



The two-body problem in GR

Techniques have different ranges of validity

Consistent with data?



Li, Wang & Ho 2012

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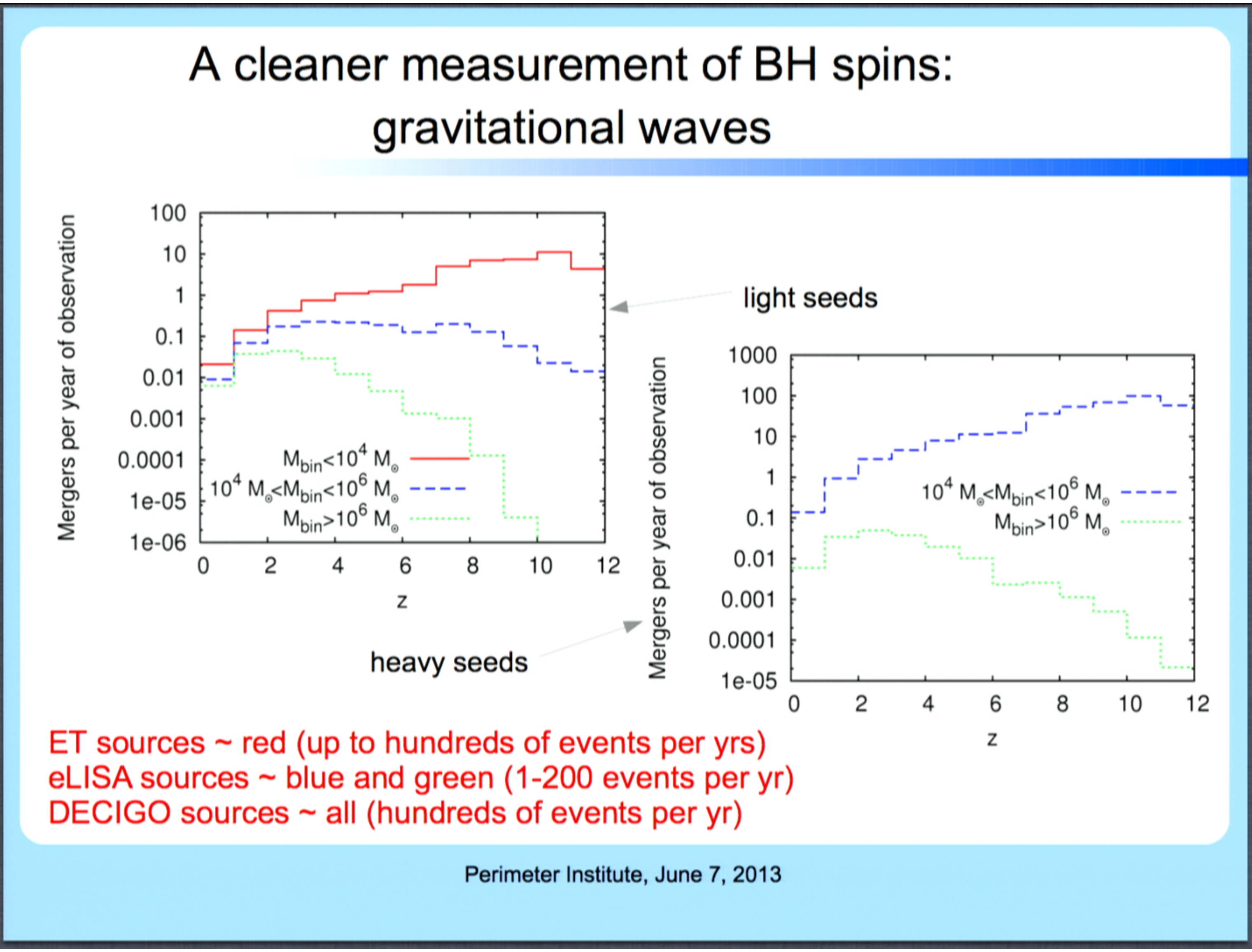

A cleaner measurement of BH spins: gravitational waves

ET sources ~ red (up to hundreds of events per yrs)
eLISA sources ~ blue and green (1-200 events per yr)
DECIGO sources ~ all (hundreds of events per yr)

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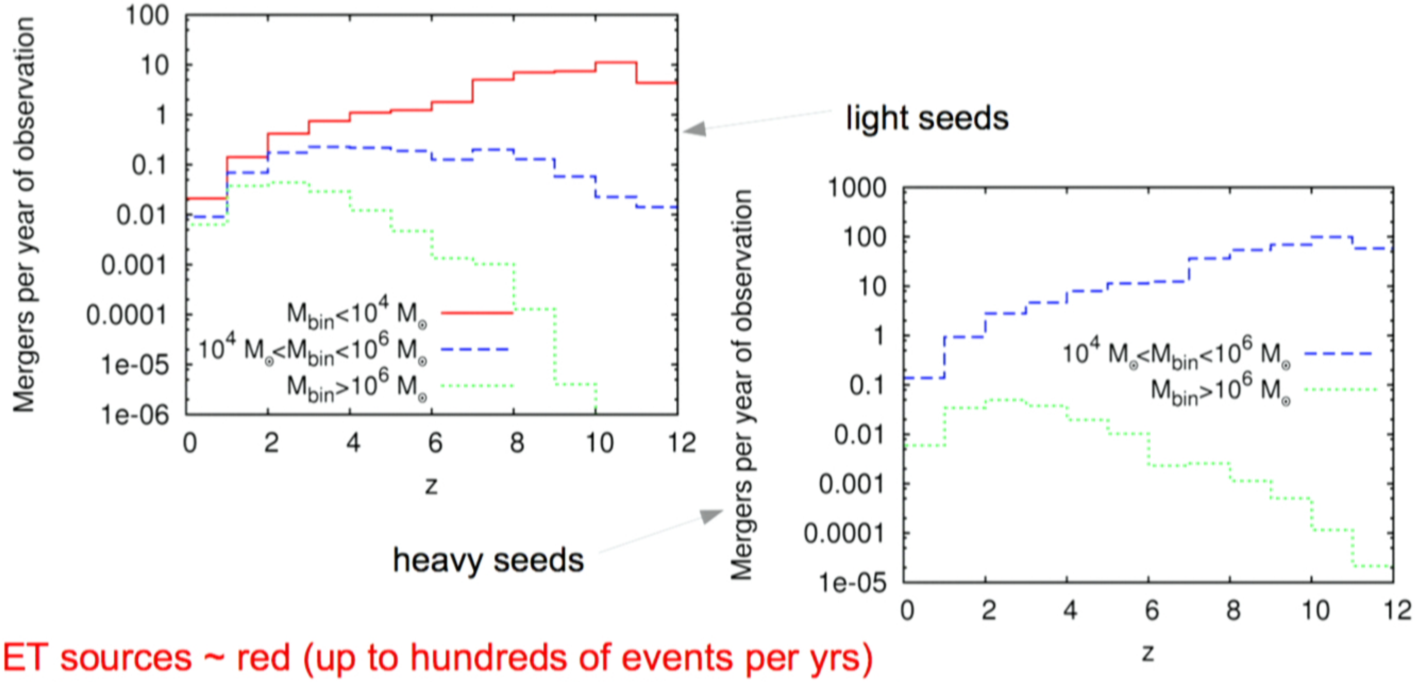

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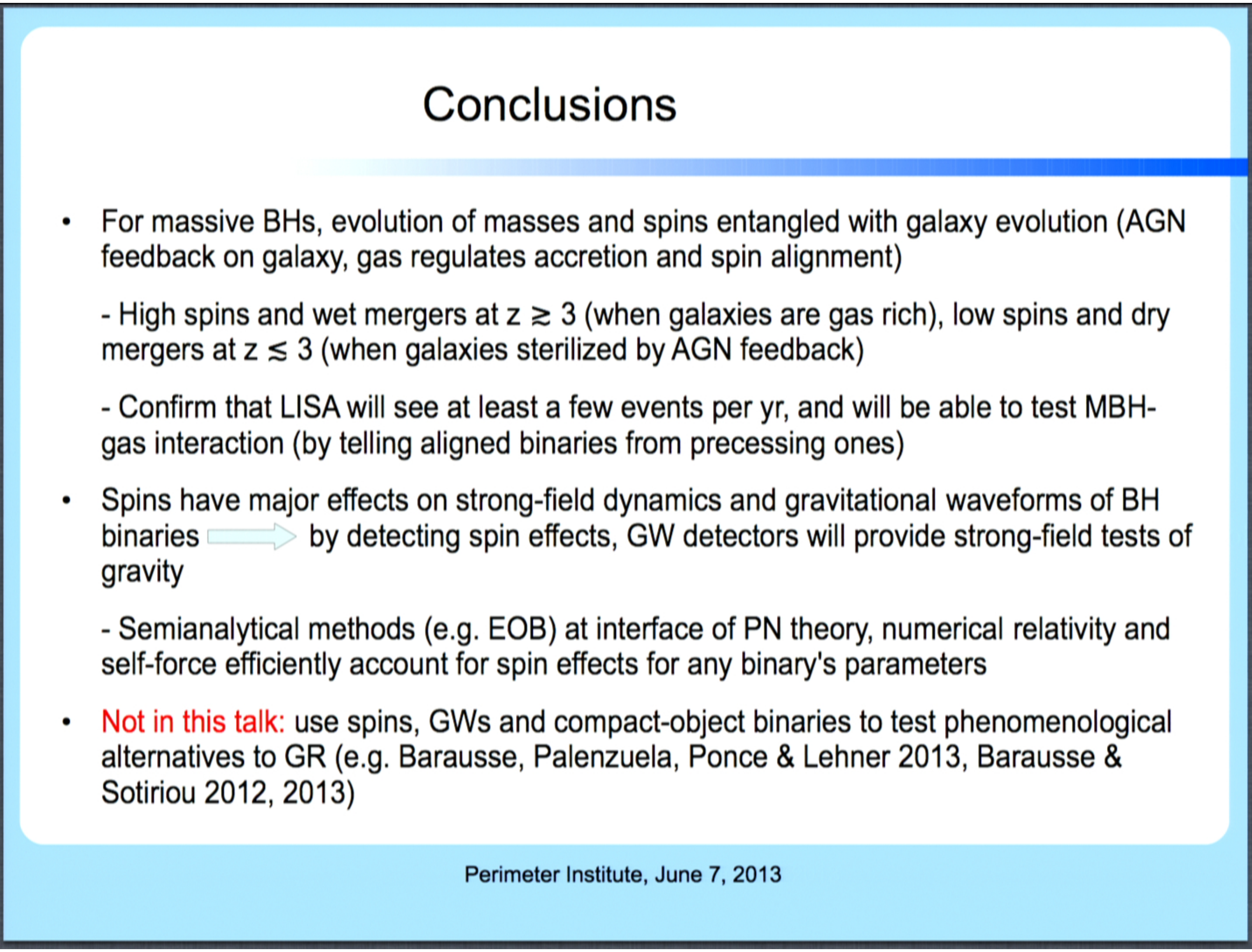

Conclusions

- For massive BHs, evolution of masses and spins entangled with galaxy evolution (AGN feedback on galaxy, gas regulates accretion and spin alignment)

  - High spins and wet mergers at $z \gtrsim 3$ (when galaxies are gas rich), low spins and dry mergers at $z \lesssim 3$ (when galaxies sterilized by AGN feedback)

  - Confirm that LISA will see at least a few events per yr, and will be able to test MBH-gas interaction (by telling aligned binaries from precessing ones)

- Spins have major effects on strong-field dynamics and gravitational waveforms of BH binaries ⇒ by detecting spin effects, GW detectors will provide strong-field tests of gravity

  - Semianalytical methods (e.g. EOB) at interface of PN theory, numerical relativity and self-force efficiently account for spin effects for any binary's parameters

- Not in this talk: use spins, GWs and compact-object binaries to test phenomenological alternatives to GR (e.g. Barausse, Palenzuela, Ponce & Lehner 2013, Barausse & Sotiriou 2012, 2013)

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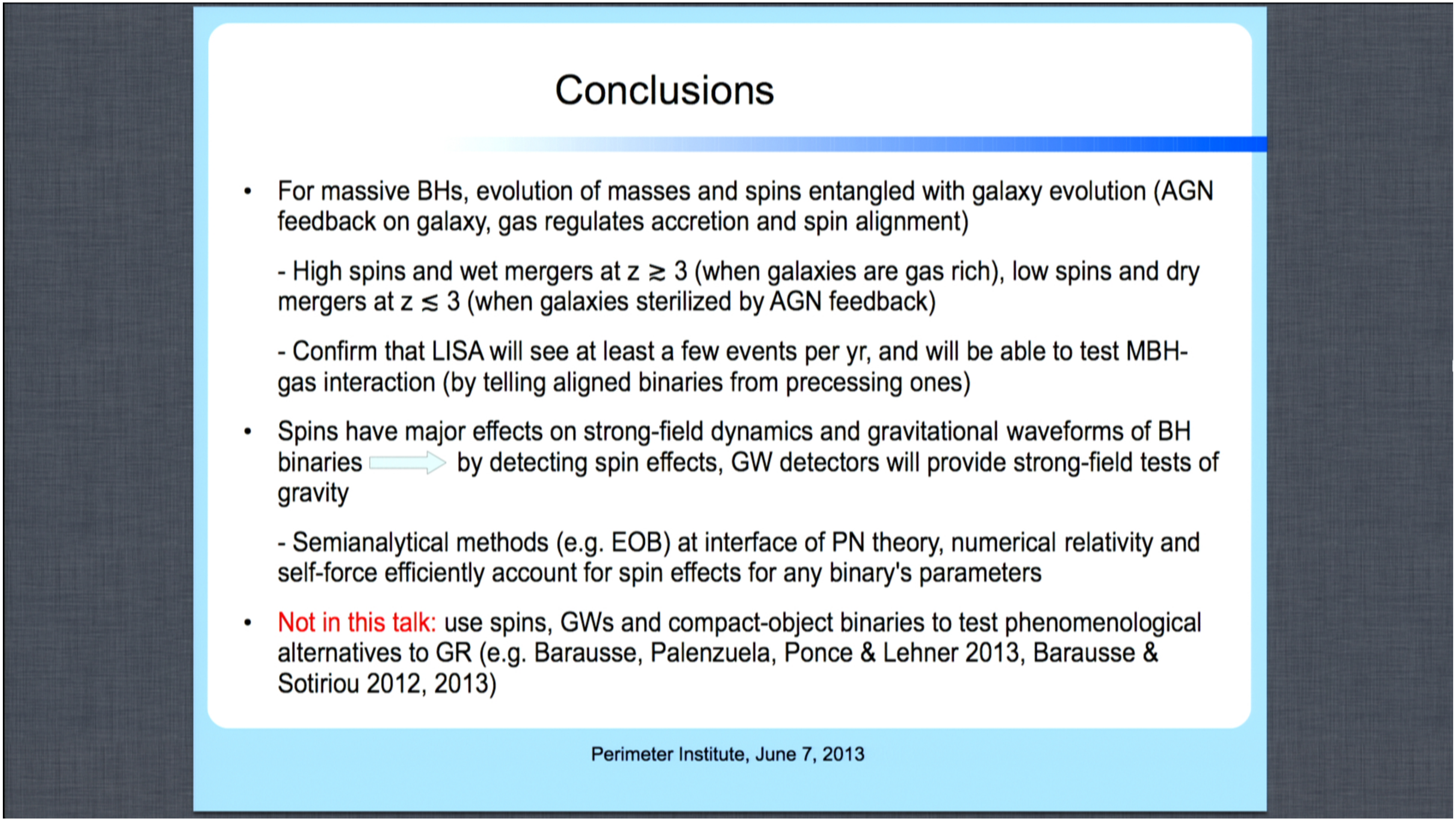

Conclusions

- For massive BHs, evolution of masses and spins entangled with galaxy evolution (AGN feedback on galaxy, gas regulates accretion and spin alignment)

  - High spins and wet mergers at $z \gtrsim 3$ (when galaxies are gas rich), low spins and dry mergers at $z \lesssim 3$ (when galaxies sterilized by AGN feedback)

  - Confirm that LISA will see at least a few events per yr, and will be able to test MBH-gas interaction (by telling aligned binaries from precessing ones)

- Spins have major effects on strong-field dynamics and gravitational waveforms of BH binaries ⇒ by detecting spin effects, GW detectors will provide strong-field tests of gravity

  - Semianalytical methods (e.g. EOB) at interface of PN theory, numerical relativity and self-force efficiently account for spin effects for any binary's parameters

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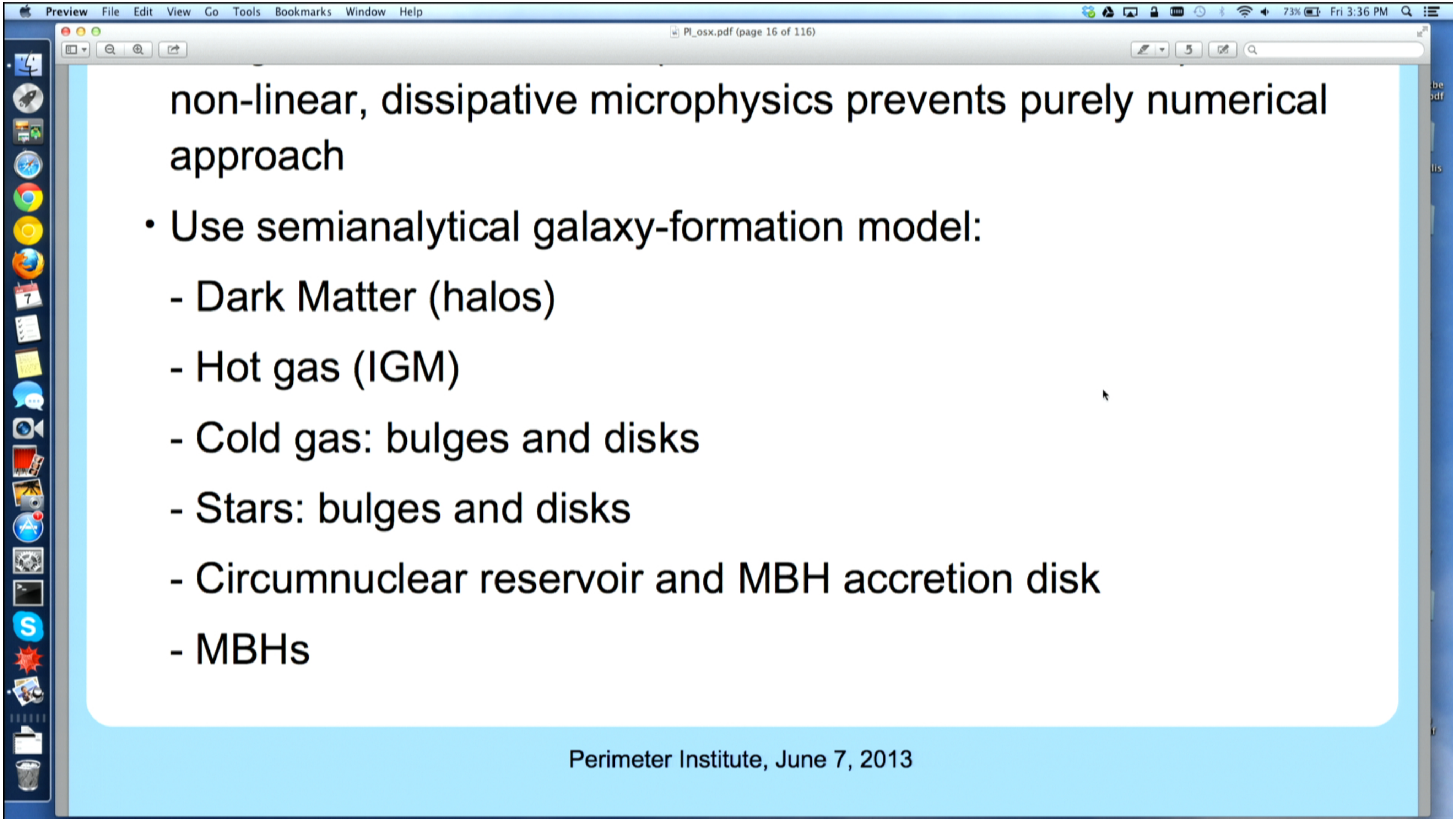

non-linear, dissipative microphysics prevents purely numerical approach

- Use semianalytical galaxy-formation model:
  - Dark Matter (halos)
  - Hot gas (IGM)
  - Cold gas: bulges and disks
  - Stars: bulges and disks
  - Circumnuclear reservoir and MBH accretion disk
  - MBHs

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