Two (Other) Episodes in the Life of a Quasar

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Outline of Talk

- Gravitational wave-emitting phase during the coalescence of a SMBH binary:
  - Can we identify the EM counterpart of a LISA source ?
  - Does GW kick produce an EM signal in circumbinary gas ?

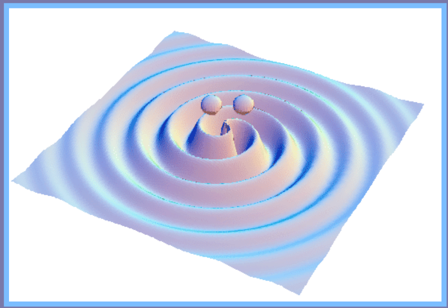
  Zoltan Lippai, Zsolt Frei, ZH (2008)

- Fossil HII region of a dead quasar
  - how does such a fossil look like (e.g. in 21cm) ?
  - what can we learn from them ?

  Steve Furlanetto, ZH & Peng Oh (2008)

Gravitational Waves from Coalescing BHs

- **LISA can detect low-frequency gravitational waves from super-massive black hole binaries**



— sensitive to $(10^5\text{-}10^7)/(1+z)\ M_\odot$
— will clarify build-up of $\sim 10^9\ M_\odot$ BHs at $z>6$

- **Revolution for cosmology and gravitational physics:**

— $f\,(df/dt)^{-1}$ →automatic 'standard siren' (Schutz 1980)
— can be used like Type Ia SNe, limited only by WL errors
— compare gravitons and photons: probe fundamental physics

- **Revolution for BH astrophysics / galaxy assembly:**

— Eddington ratio, spectrum, as a function of BH mass, spin, orbital parameters (eccentricity, alignment)

Can we find EM Counterpart?

- **Sky position error from LISA is poor (~0.3 deg^2)**

— $10^{4\text{-}5} \rightarrow 10^{2\text{-}3}$ galaxies with LISA redshift info (i.e.: 3D)
— perhaps a unique near-Eddington quasar **(Kocsis et al. 2005)**

- **EM signature produced by merger is not understood**

— hard problem, requires gas physics + GR + radiation

- **But 'last parsec problem' suggests gas needed**

— without gas, orbital decay / angular momentum loss time-scale exceeds Hubble time at r ~ 1 pc

(Begelman, Blandford, Rees 1984)

- **IF gas is still present at the GW-emitting phase**

— accretion onto one or both holes (or to post-merger binary)
— modulations on orbital time-scale? post-merger shocks?

(Kocsis et al. 2006; 2007)

Two Ways to Find EM Counterpart

- LISA sky position of coalescing SMBH binary accurate to precision ~10 deg^2 typically with 3 weeks advance notice. Monitor area for hourly-daily variables at 24-27 mag, hoping that binary periodically perturbs ambient gas.

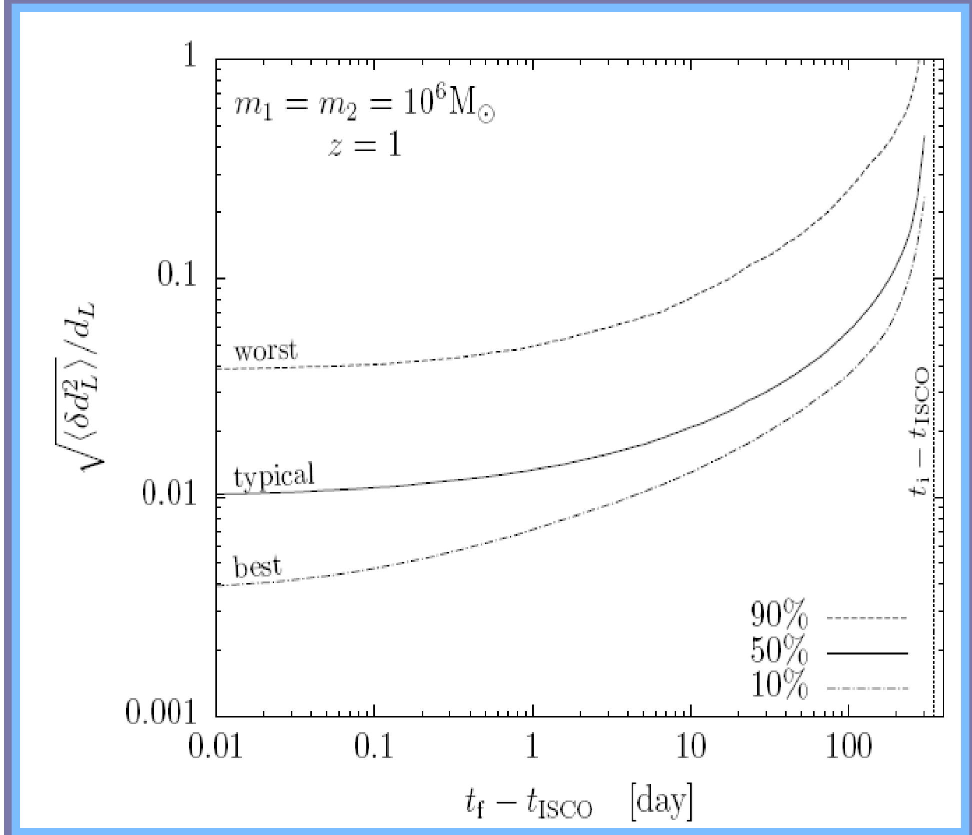
  (Kocsis, ZH & Menou 2007, 2008)

- Gravitational recoil at coalescence can produce shocks in the ambient gas. Monitor final LISA error box ~months after the merger, for a corresponding transient “afterglow”.

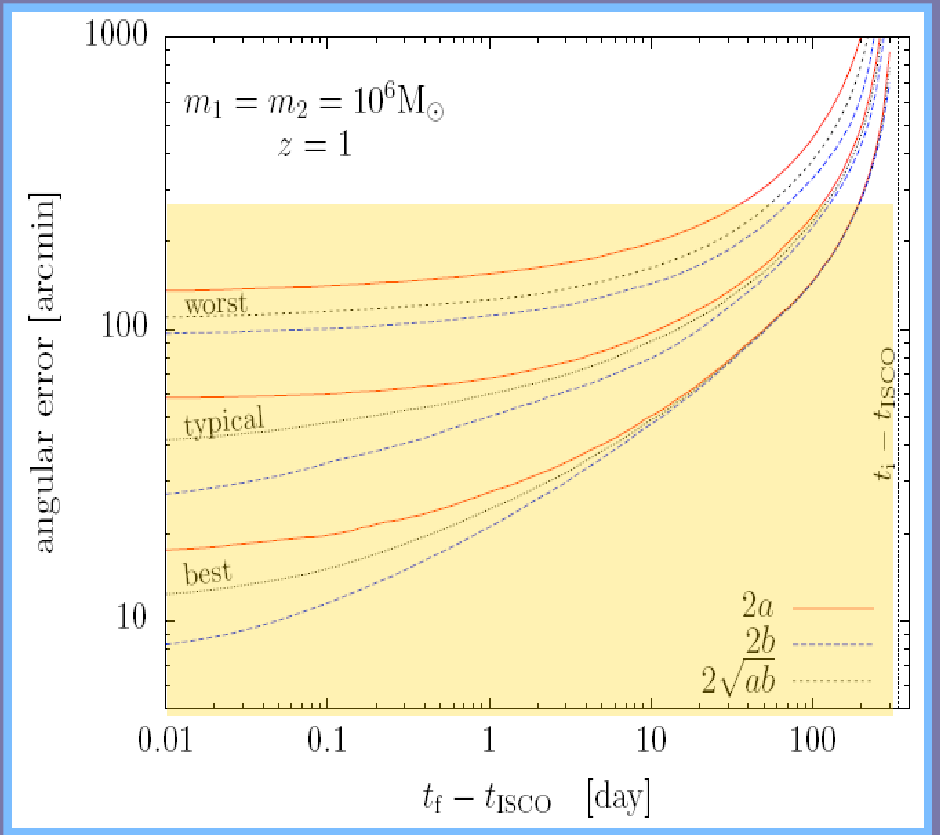
  (Lippai, Frei & ZH 2008)

Time dependence of localization

distance uncertainty



sky position uncertainty



Errors typically stop improving ~10 days before ISCO

The Effect of a Gravitational Kick

- **Gravitational radiation produces sudden recoil**

  — from conservation of linear momentum, near ISCO
  — kick velocity depends on mass ratio and on spin vectors
  — typical v(kick) ~ few × 100 km/s **(Baker et al. 2006, 2007**
  — maximum v(kick) ~ 4,000 km/s **Gonzalez et al. 2007)**

- **Most important at high redshift when halos are small**

  — escape velocities from z>6 halos is few × 10 km/s
  — major obstacle to building $\sim 10^9\ M_{\odot}$ BHs by z>6
  — requires a super-Eddington growth phase **(ZH 2004)**

- **Does the kick produce a prompt EM signal?**

  — perhaps, if there is circumbinary gas **(Lippai et al. 2008)**

Effect of Kick on Circumbinary Disk

Lippai, Frei & Haiman (ApJL 2008, in press)

- **Properties of disk:**

  — geometrically thin (cold) accretion disk, susceptible to shocks
  — inner cavity, evacuated by torques (out to ~100 R_s)
  — disk gravitationally unstable beyond ~10,000 R_s
  — v(orbit) ~ 20,000 km/s → 2,000 km/s
  — inner[outer] disk tightly[weakly] bound to kicked binary
  — disk mass low ($M_{disk} \sim 10^{-4} M_{BH}$): no effect on BH trajectory

- **Response of pressureless ("dark matter") disk:**

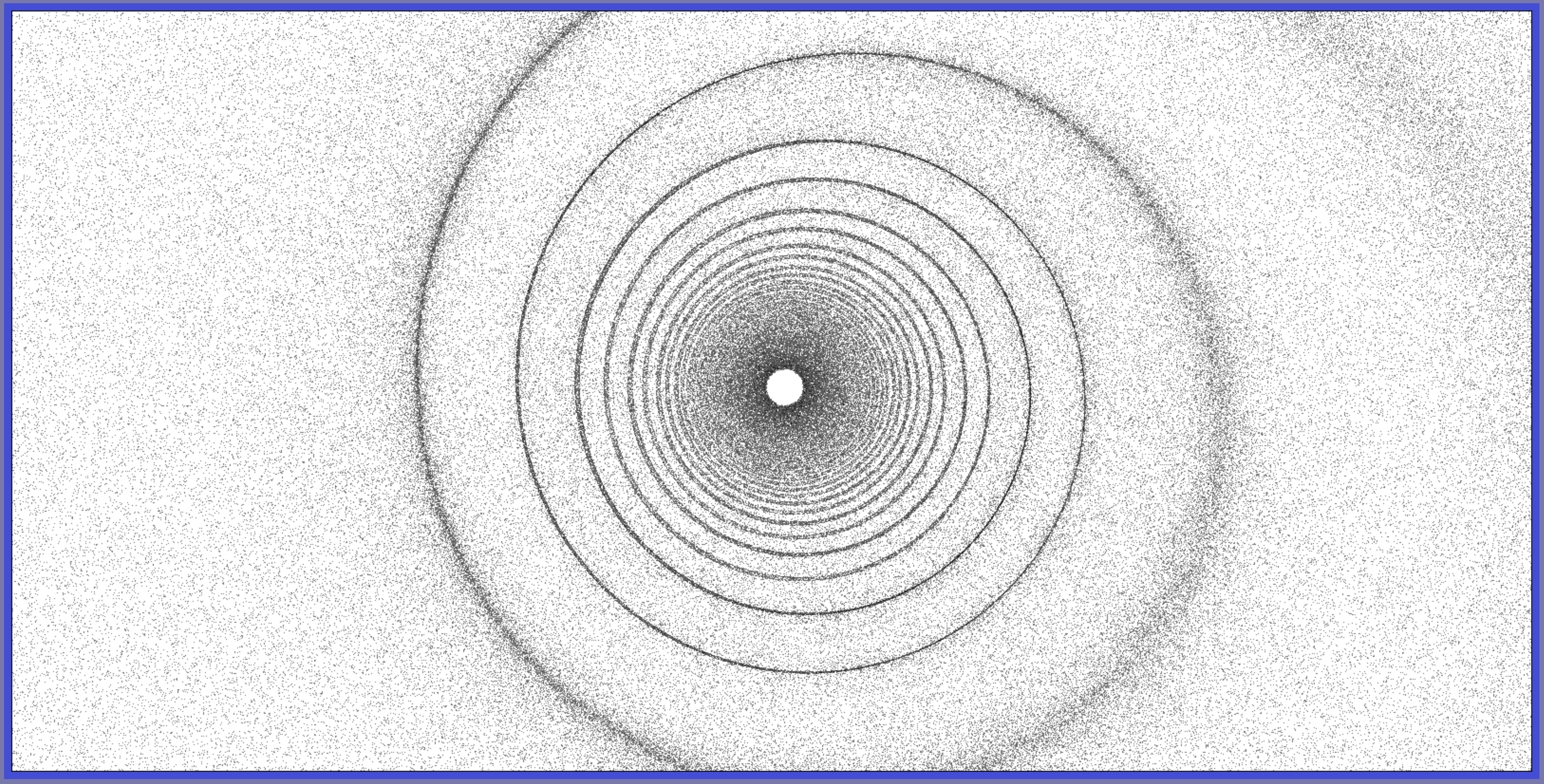
  — start with massless test particles on circular orbits
  — add instantaneous v(kick), parallel or perpendicular to disk
  — follow Kepler orbits (ellipses) for $N=10^6$ particles

Planar Kick Results in a Spiral Caustic

$M_{BH} = M_1 + M_2 = 10^6 M_\odot$ ($R_{cavity} = 100 R_s = 2$ AU)

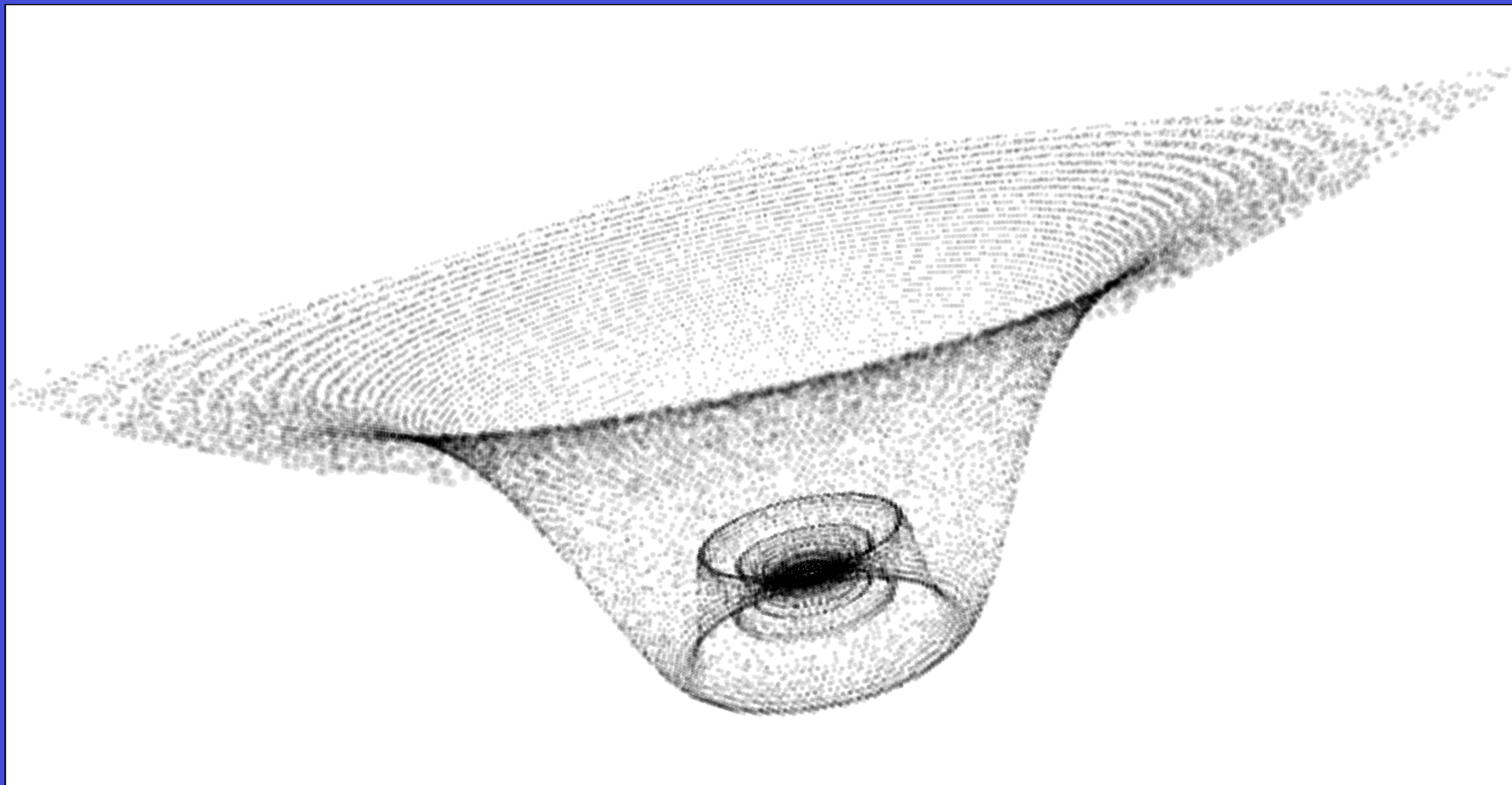
$v_{kick} = 500$ km/s (kick in the disk plane)

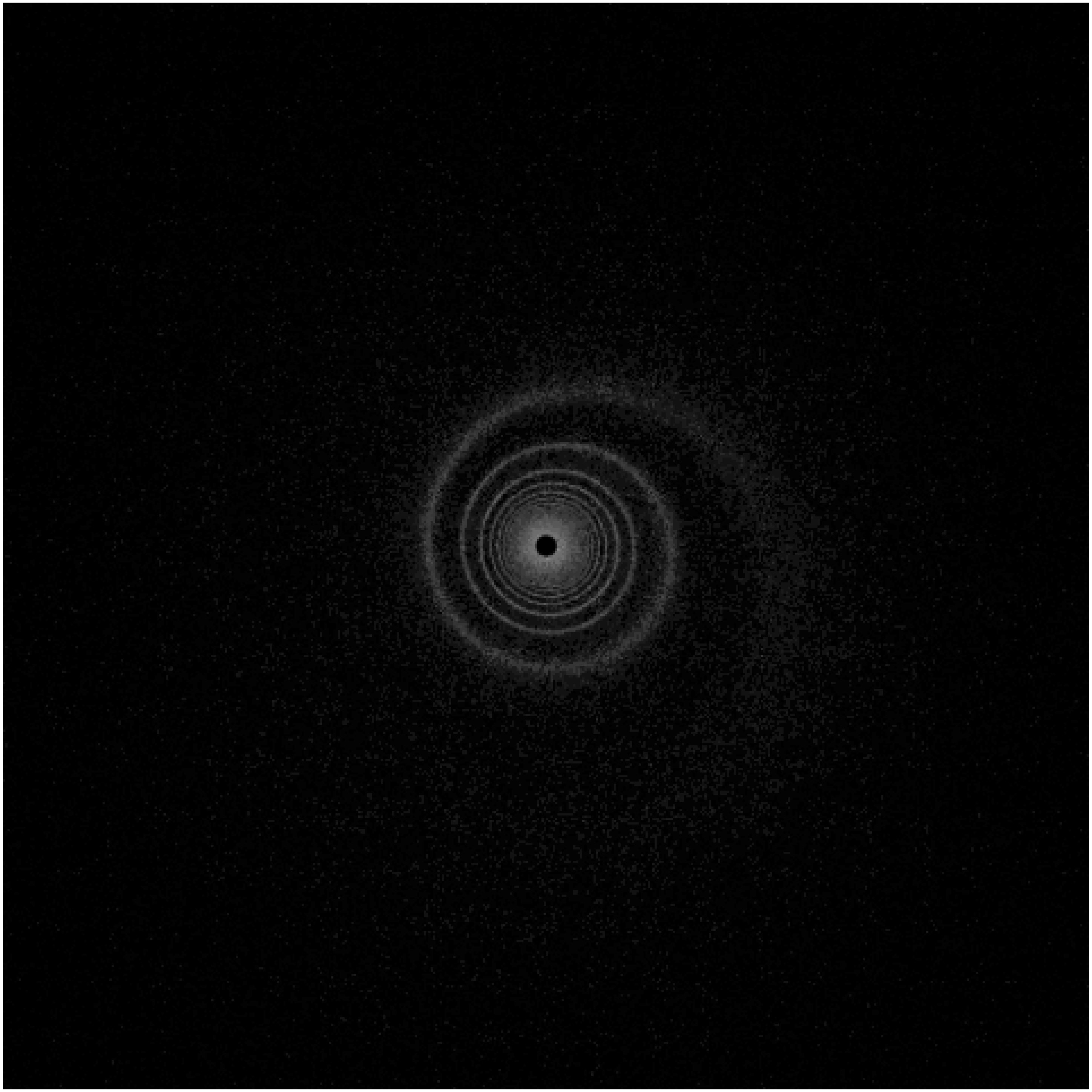
$t = 90$ days ($t_{cavity} = R_{cavity} / v_{kick} = 7$ days)



Perpendicular kick: Concentric Density Enhancements

(otherwise same parameters)





Why are the spiral caustics interesting?

- **Suggests prompt "afterglow" for SMBH coalescence:**

— caustic propagates outward with speed ~ v_{kick}

— infall speed into caustic is $v_{caustic} \sim v_{kick}^2/v_{orbit}$

— $v_{caustic}$ becomes supersonic beyond ~700 R_s (at > 25 km/s)

— gas shocks may produce strong emission (at >50 days)

- **Can speculate about properties of afterglow:**

— shocked gas heated to $v_{shock} \sim v_{caustic}$ ~ 25 - 80 km/s

— $L_{disk} \sim 1/2\, M_{disk}\, v_{shock}^2 \;/\; t_{shock}$

— $M_{disk} \sim$ 50-1,200 $M_\odot$ $t_{shock} \sim$ 50 days - 2 years

— $L_{disk} \sim 6 \times 10^{-4} - 2 \times 10^{-2}\, L_{edd}$ not negligible.

— Hardens from UV to soft X-ray (opposite of GRB afterglow)

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    Bence Kocsis, ZH, Kristen Menou (2007)
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Fossil Quasar Bubbles

- **Many pieces of evidence that bright quasar phase is short:**

  — 10^7 years $\lesssim$ $t_Q \lesssim 10^8$ years **(e.g. Martini 2004)**

- **Fiducial recombination time in z>6 IGM:**

  — $t_{rec} \approx t_{Hubble} \approx 5 \times 10^8$ years at mean density at z=8

  — fossils outnumber active bubbles by factor $t_{rec}/t_Q \approx$ 5-50

- **Fossils affect the IGM, and are useful probes:**

  — large (40-50 comoving Mpc), prime targets for 21cm imaging

  — probe quasar properties **(Wyithe, Loeb & Barnes 2005; Zaroubi & Silk 2005; Kramer & ZH 2007)**

  — probe IGM properties **(Lidz et al., Alvarez & Abel, Geil & Wyithe)**

  — entropy floor even in recombined fossils **(Oh & ZH 2003)**

  — H_2 formation **(Ricotti et al. 02; Kuhlen & Madau 05; Mesinger et al. 07)**

How does HII region recombine?

- **Recombination must be inhomogeneous:**

  — over-dense regions recombine quickly

  — under-dense regions remain ionized for longer than t_{rec}

- **Pre-existing galaxies:**

  — mean free path in fossil starts much higher than outside

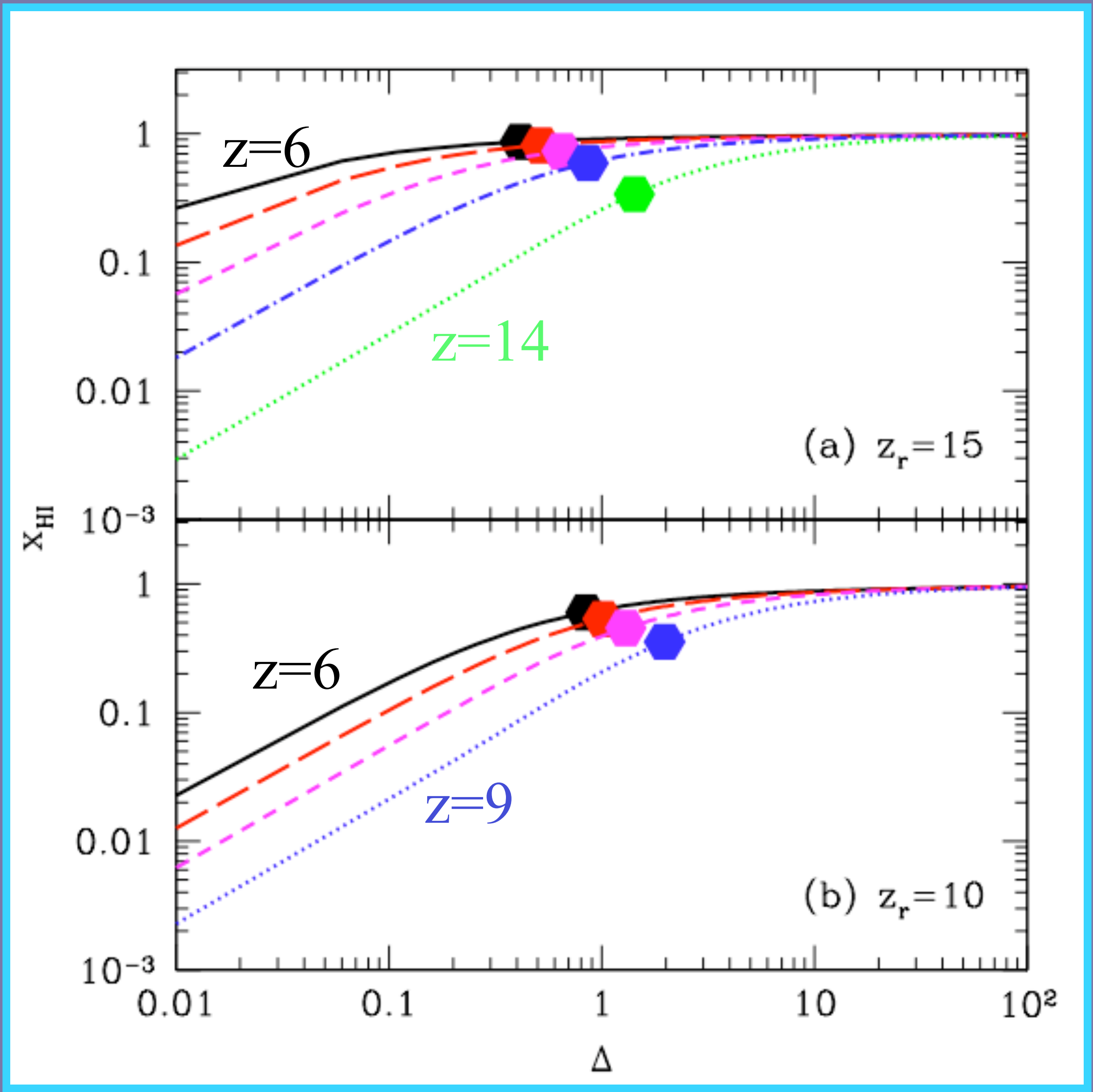
  — can pre-existing galaxies keep most of the fossil ionized? (easier than to ionize the region to begin with)

- **How do we distinguish fossils?**

  — "grey" bubble: reduced contrast relative to active bubbles but ionization nearly uniform

  — large size distinguishes them from rare large galaxy-bubbles

Fossil Recombination With Zero Flux

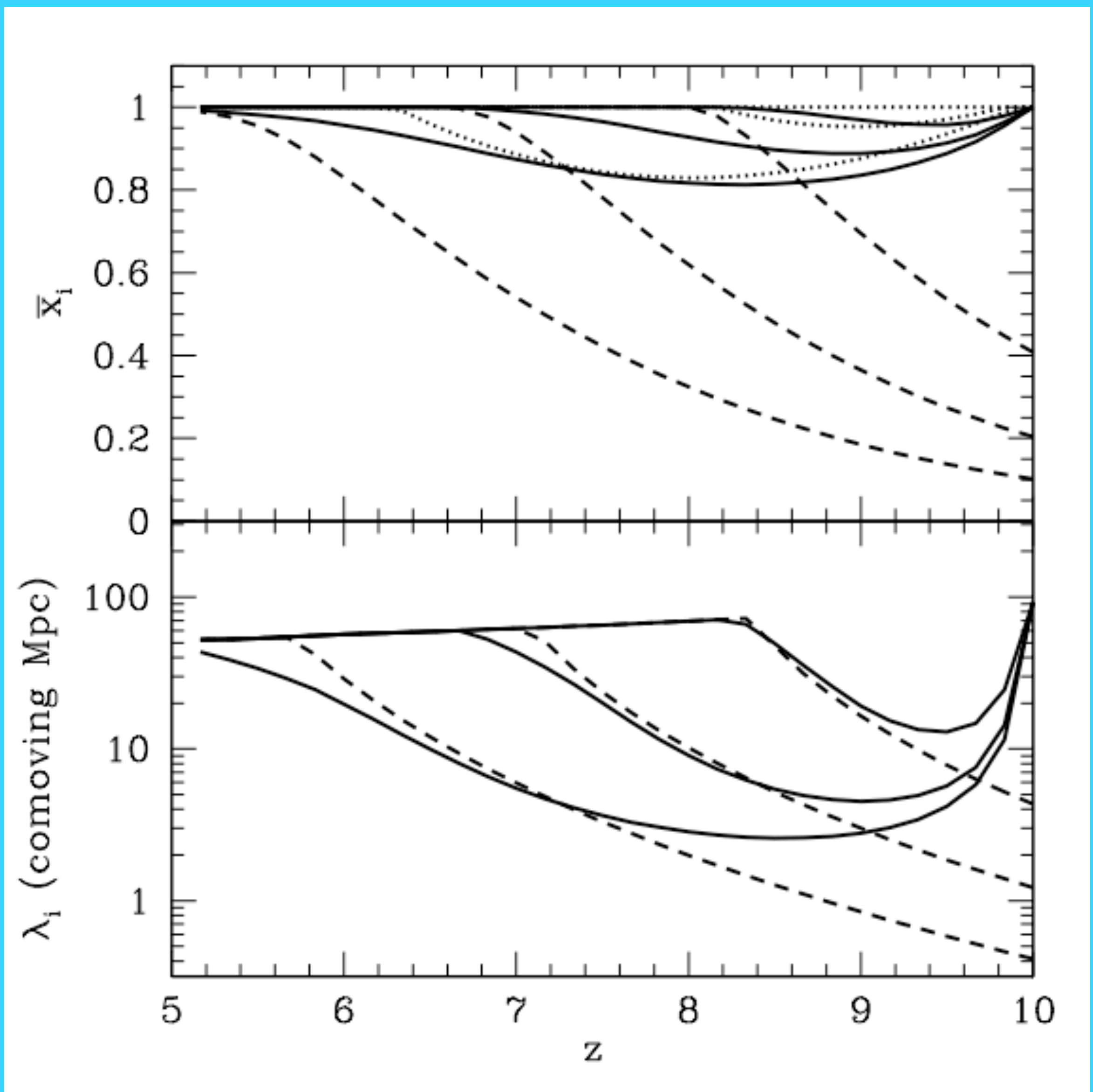


- Assume Γ_{bg}=0
- Follow Δ-dependent recombination
- cf: equivalent Δ_{crit} with P(Δ) from MHR00

Miralda-Escude, Haehnelt & Rees (2000)

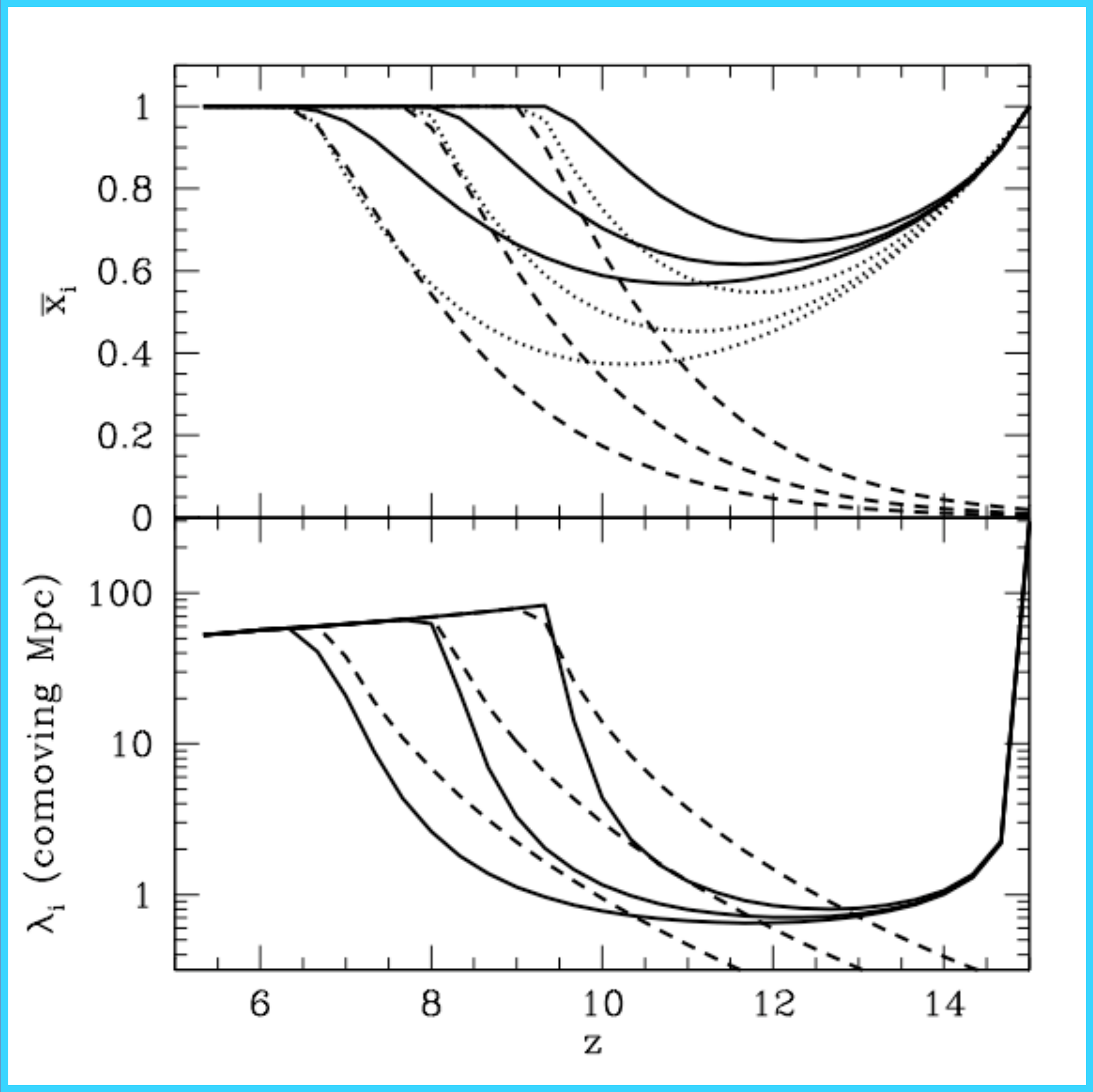
- Compute m.f.p. (including the under-dense voids)
- m.f.p. remains ~Mpc if $x_{HI} \lesssim 10^{-3}$ (at Δ~1)

Fossil Evolution vs Global Reionization



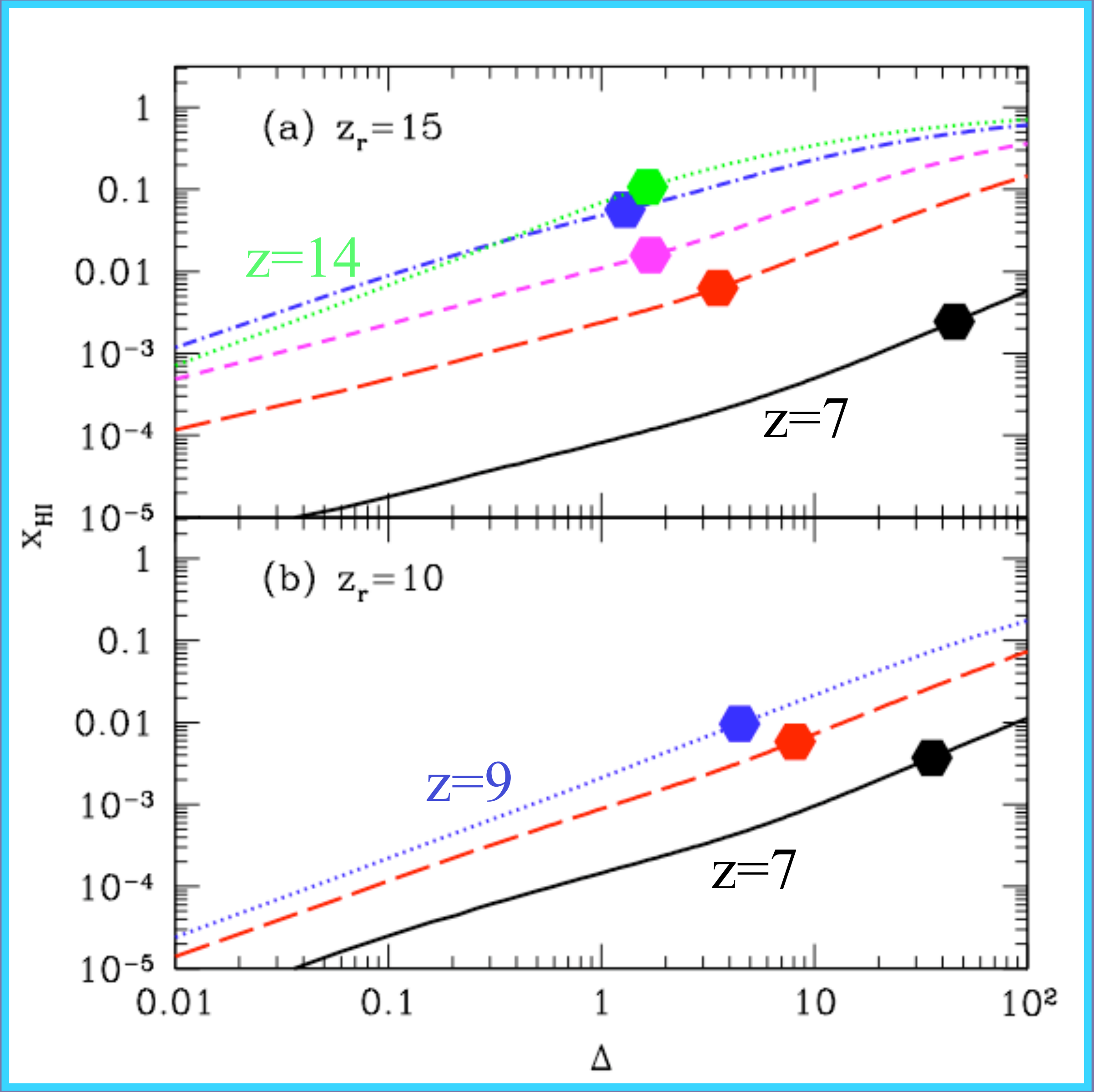
- Semi-analytical reionization model
- Follow mean $\langle x_{HI} \rangle$ in z=10 fossil *vs* globally
- Additionally: follow Δ-dependent x_{HI} inside fossils
- Compute m.f.p. using MHR00
- c.f. clustering length of pre-existing galaxies
- uniform, high ionization

An Early Fossil (z=15)



- Probably much rarer than fossils from z=10
- Still remains highly ionized
- different from z=10 fossil: m.f.p. drops below galaxy clustering length
- will develop (reduced contrast) swiss-cheese

Check validity of MHR00 m.f.p.



- Assume uniform Γ_{bg}
- neglect self-shielding
- Compute optical depth τ across one MHR00 m.f.p., including the under-dense voids
- z=10 fossil:
  $x_{HI} \lesssim 10^{-3}$
  τ=0.9, 0.5, 0.4
- z=15 fossil:
  τ=13, 4.5, 1.5, 0.7, 0.1

Conclusions

- Fossils outnumber active bubbles, last longer than t(rec)
- Fossils produced at $z \lesssim 10$ remain highly and uniformly ionized "grey zones": look similar in 21cm to active bubbles, but with a reduced contrast
- Example: $\langle X_{HI} \rangle$~ 10-20% in fossil, 70-80% outside.
- Nearly uniform ionization in fossil, swiss-cheese outside.

- Analogous fossils expected during helium reionization
- Makes "double-reionization" difficult to arrange