Direct formation of high-z Supermassive Black Holes from Supermassive Disks (SMDs) in galaxy mergers

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The puzzle of the high-z Quasars

Bright Quasars (L > 10^{47} erg/s) < 650-700 million years after Big Bang (z ~ 6-7.65)

M_{BH} > 10^9 Mo from Eddington limit *(Banados et al. 2017;Wang et al. 2021)*

PROBLEM: is there enough time to grow these early SMBHs?

$$\boxed{\dot{M}_{\rm Edd} = \frac{4\pi G M_\bullet}{\eta \kappa c}}$$

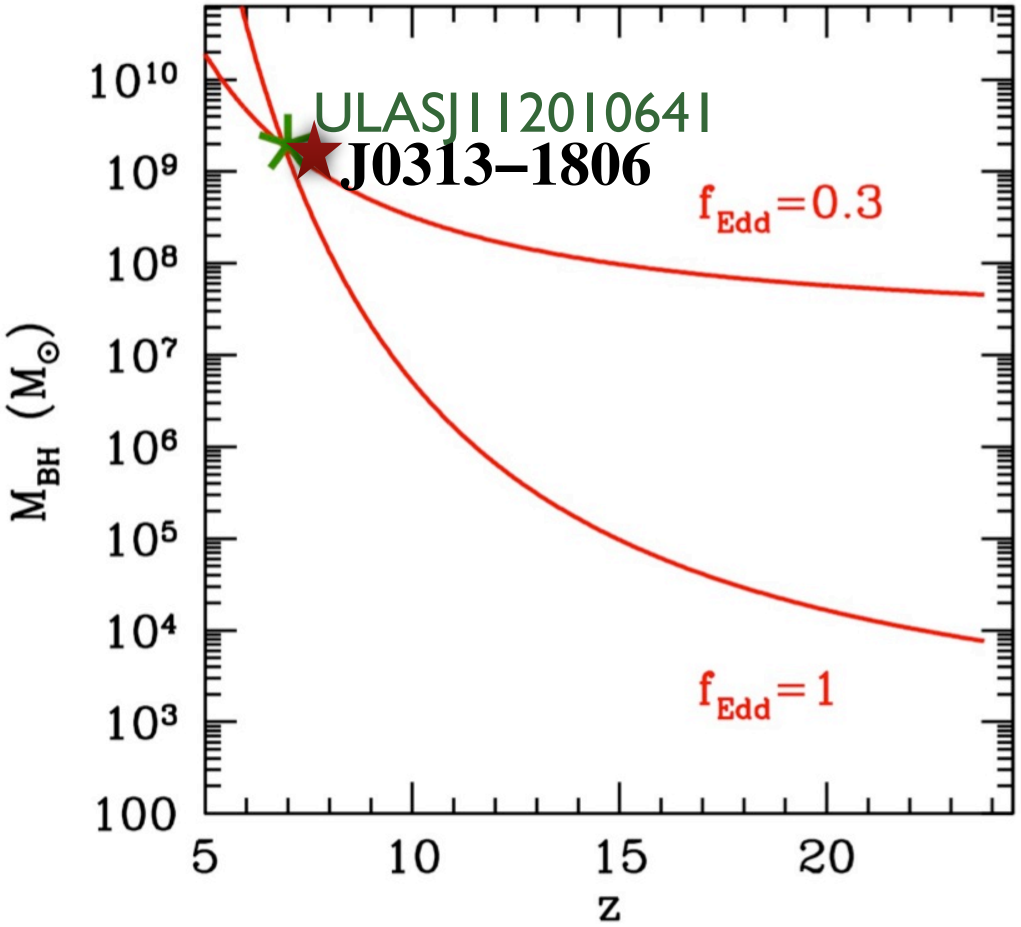
radiative efficiency

Eddington rate: maximum (spherical) accretion rate set by balance between gravity and pressure force of radiation

"Growth equation"

$$\boxed{M_\bullet(t) = M_\bullet(t_0)\, e^{(t-t_0)/\tau_{\rm Salp}}}$$

$$\boxed{\tau_{\rm Salp} \approx 4.4 \times 10^7 \left(\frac{f_{\rm Edd}}{1}\right)^{-1} {\rm yr}} \ \text{x} \ (\eta/0.1)$$



(Courtesy of Marta Volonteri)

High-z QSO rare (>~10^{-9} h^3 Mpc^{-3}), 4 orders of magnitude less abundant than their z=0 counterparts. Abundance and clustering suggests their hosts rare massive halos, M_{halo} >~ 10^{12} Mo at z ~ 6-7, (see Volonteri & Rees 2006; Sijacki et al. 2010)

Standard BH seed formation pathways

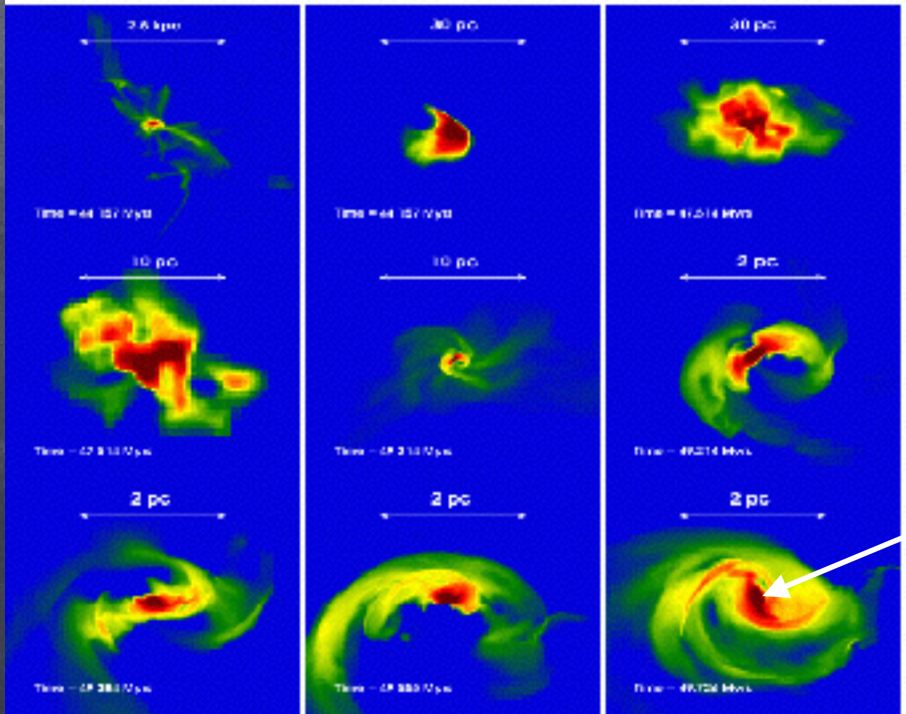
(eg review Inayoshi, Haiman & Visbal 2020, ARAA)

- I. Pop III seeds (M_{BH}~ 10-1000 Mo, z >~ 30). Would need subsequent Super-Eddington accretion, unlikely due to strong effect of radiative feedback in low mass host halos.

- II. Direct collapse seeds (M_{BH} >~10^4 Mo, z ~ 15-25). Gas inflow followed by supermassive star formation (SMS) in protogalxy. Require fine-tuning of environmental conditions; **suppression of cooling via H_2. dissociation by external LW radiation + metal free-gas to avoid fragmentation and star formation —-> isothermal collapse (T ~ a few 1000 K) Alternatively increase dynamical PdV/shock heating in highly accreting halos** (Wise et al. 2019) or **turbulence in supersonic accretion flows** (Hirano et al. 2018;Latif et al. 2022). Note: BH seed of ~ 10^4 Mo, might still need to grow Super-Eddington.

Both start early, at z ~ 15-30 — halo masses low (< 10^{10} Mo). NOTE: radial gas infall in a (isolated) halo potential well is **$dM/dt \sim V_c^3/G$, $V_c \sim V_{ff} \sim M_{vir}^{1/3}$** in CDM. In atomic cooling halos <~ **1 Mo/yr (M_{vir} <~ 10^9 Mo**) But at z <~ 10 in ~ 10^{12} Mo halos **dM/dt ~ 1000 Mo/yr**

Latif et al. (2022)



Latif et al. (2013)
Jeans unstable clump (M >~ 10^4 Mo)

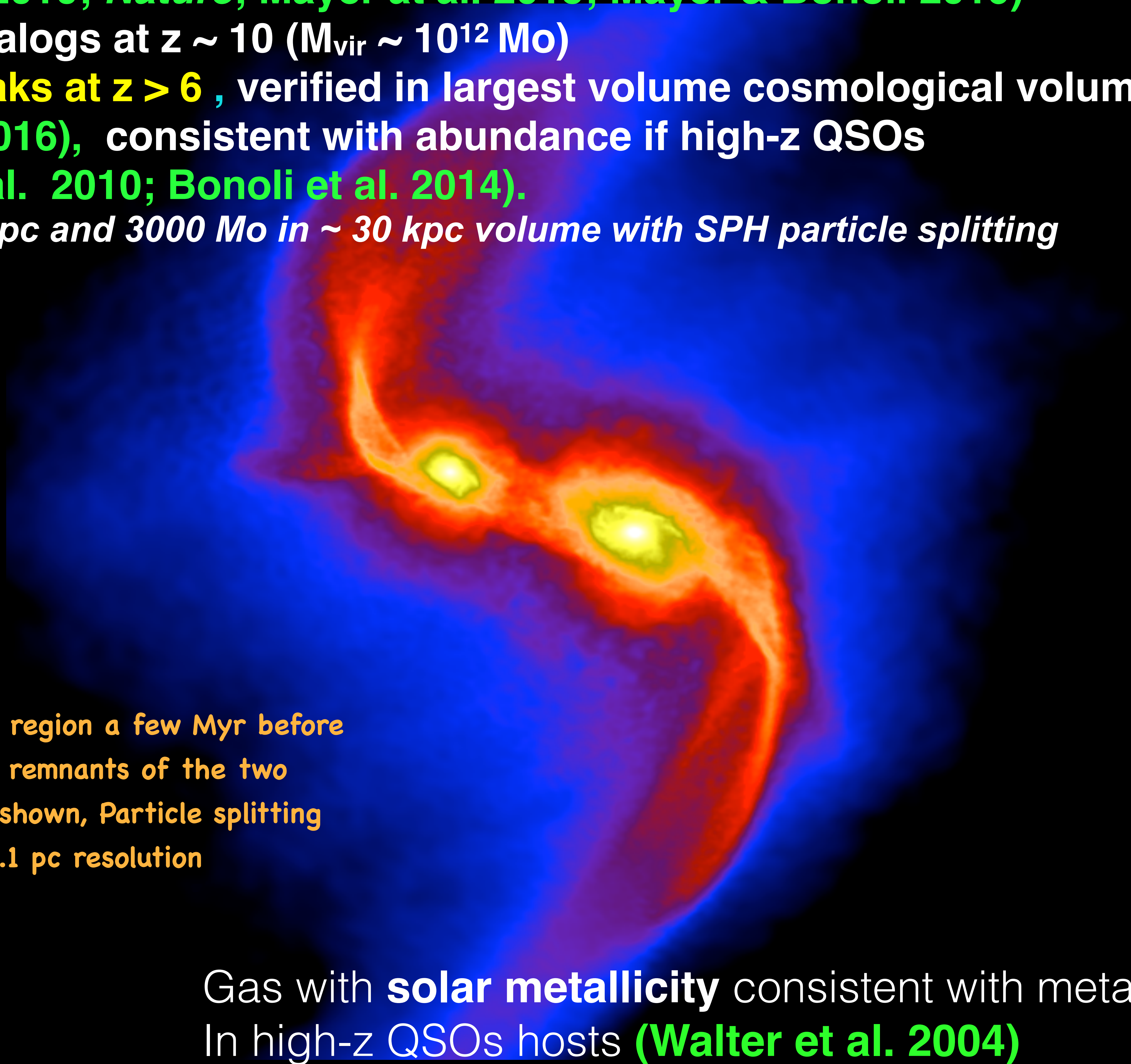
MAJOR MERGERS (>1:4) of most massive galaxies at $z \sim 8$-10

(Mayer et al. 2010; *Nature*; Mayer at al. 2015; Mayer & Bonoli 2019)

Milky Way analogs at $z \sim 10$ ($M_{vir} \sim 10^{12}$ Mo)

Rare 3-4σ peaks at $z > 6$, verified in largest volume cosmological volume (Feng et al. 2016), consistent with abundance if high-z QSOs (Mortlock et al. 2010; Bonoli et al. 2014).

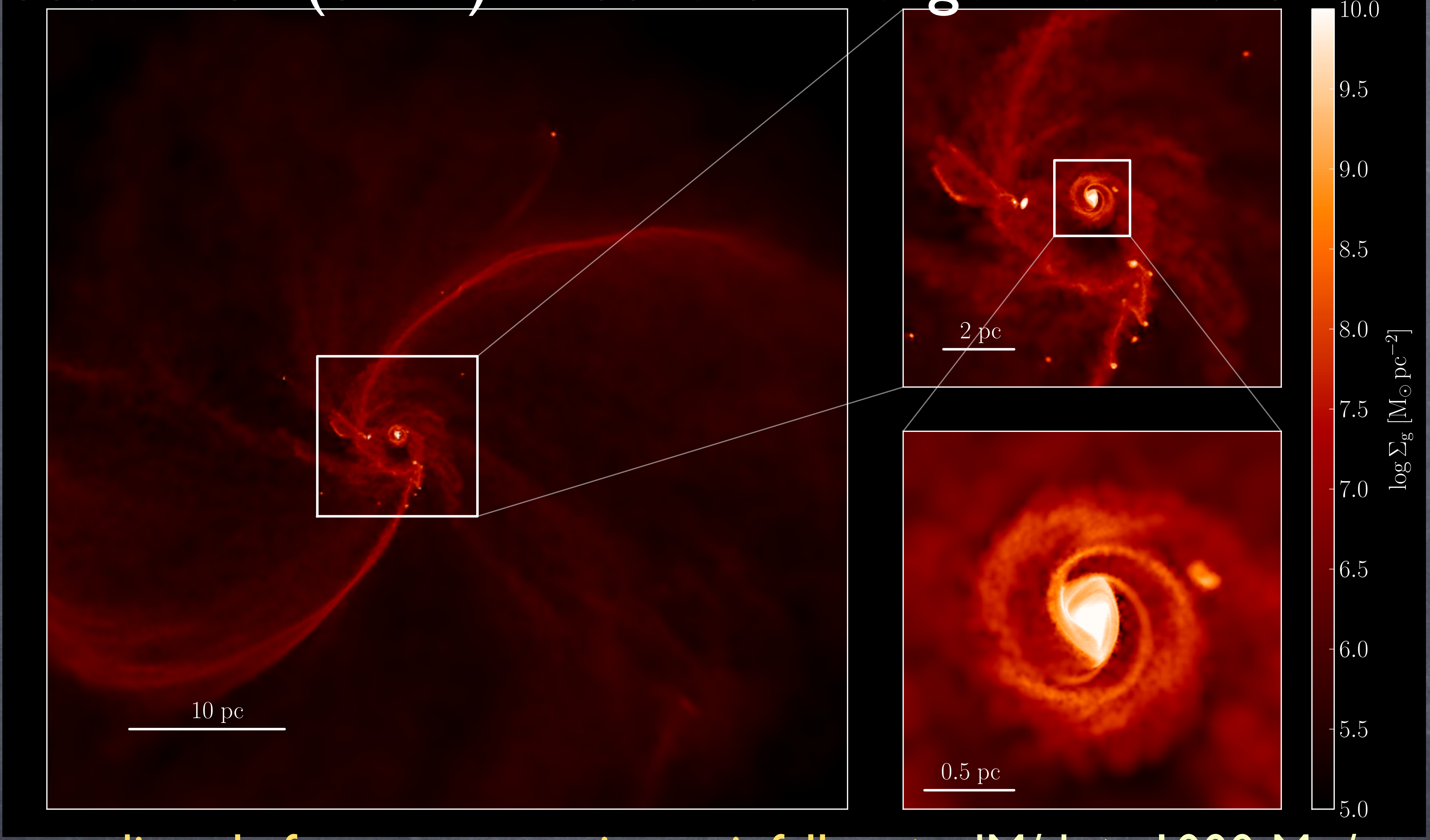
Resolution 0.1 pc and 3000 Mo in ~ 30 kpc volume with SPH particle splitting



The inner 200 pc region a few Myr before final merger: the remnants of the two galaxy cores are shown, Particle splitting allows to reach 0.1 pc resolution

Gas with **solar metallicity** consistent with metallicity In high-z QSOs hosts **(Walter et al. 2004)**

Formation of heavily mass loaded central supermassive pc-scale disk (SMD) in core of merger remnant



SMD forms directly from supersonic gas infall —> dM/dt > 1000 Mo/yr triggered by collision of the two galaxy cores

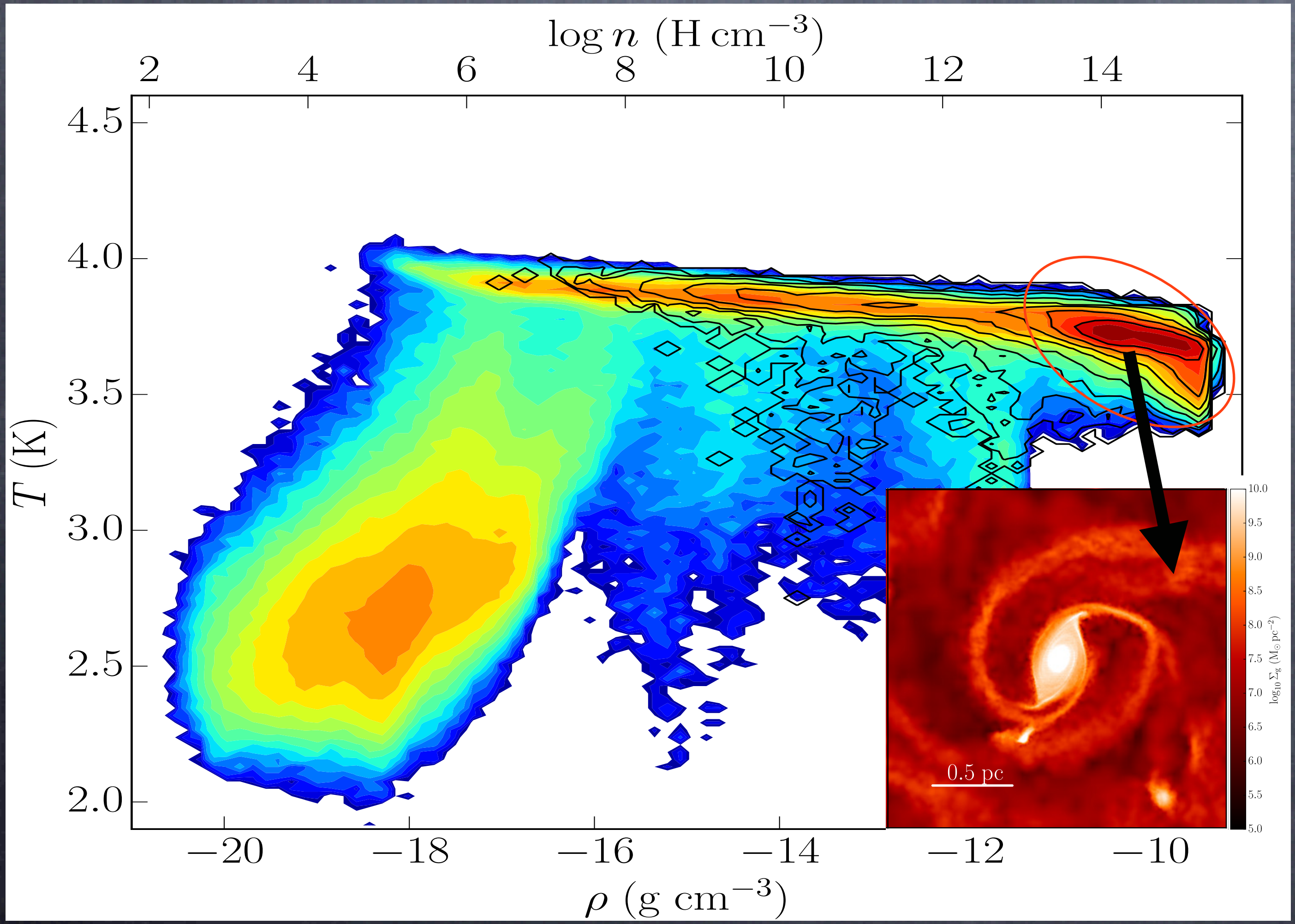
>~10^9 Mo accumulated inside ~2 pc in only < 10^5 yr after merger is completed
ρ_{max} ~ 10^{-10} g/cm^3 within 0.2 pc (comparable to outer regions of a protoplanetary disk at 100 AU scales!)

The SMD core: precursor of direct collapse BH seed?

Nearly isothermal, T ~ 3000-7000 K. Fine structure metal line and molecular cooling offset by dynamical heating from accretion and gravitoturbulence.

No star formation possible in core because of high T

Photon diffusion timescale at r ~ 2 pc (~ initial size of central compact disk after merger) large due to high optical depth ($\tau_{es} > 10^4$, $\tau_{H-} > 10^5$)
(1) **$t_{diff} \sim 10^{4-5}$ yr >> t_{orb} (~ 10^3 yr)** ----> disk expected to be stable to fragmentation (Gammie criterion; Gammie 2001; Deng et al. 2017)
(2)From accretion shock + turbulence $t_{heat} \sim t_{diff}$ —.> nearly isothermal core.



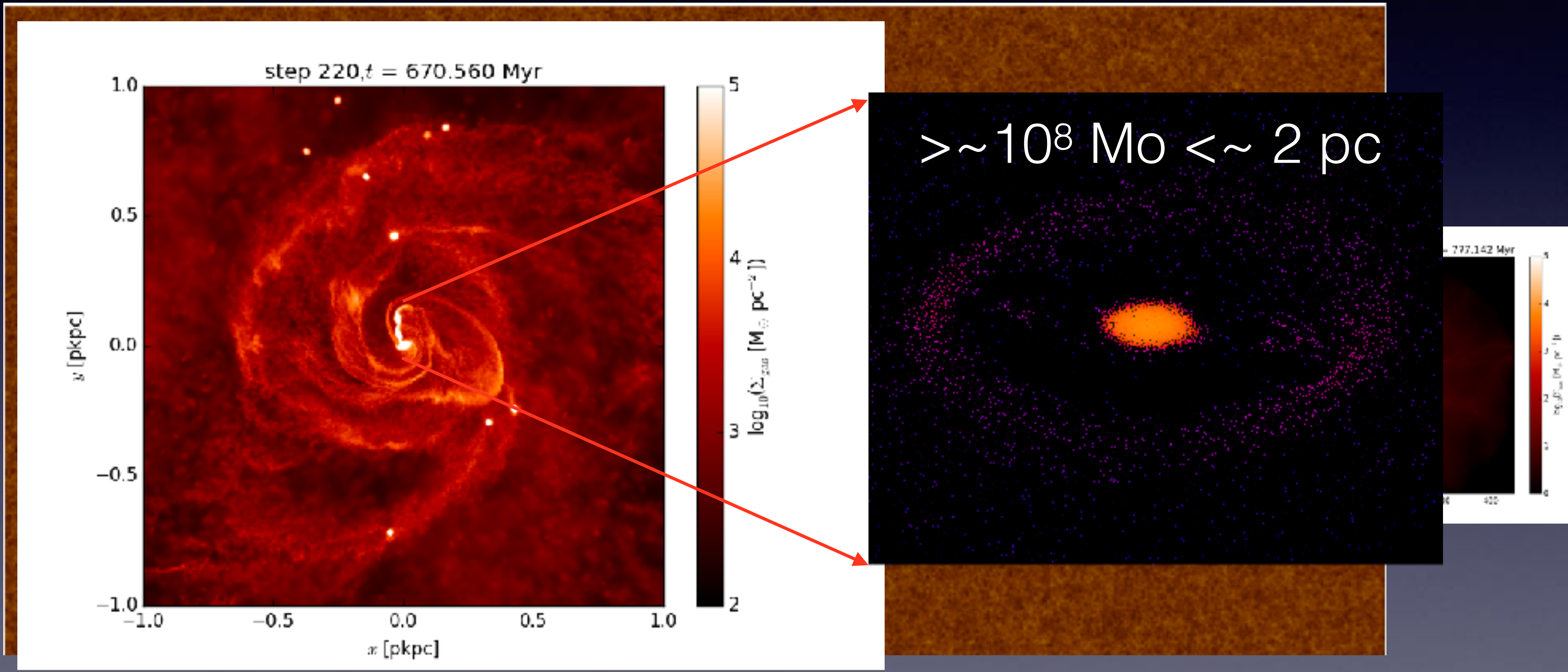
Note: dense optically thick gas cocoon could also accrete Hyper-Eddington on a pre-existing light MBH seed (Inayoshi et al. 2016; Takeo et al. 2018 — see Mayer 2019)

Validating scenario in full cosmological context:

MassiveBlackHR ‘zooms of zooms’ simulations

0.4 billion particles (SPH+dm), reach 1700 Mo, 0.1 pc hydro resolution

Capelo, Mayer et al.in prep. **Host halo:** $M_{vir} \sim 2 \times 10^{12}$ Mo at z=7.



$>\sim 10^8$ Mo $<\sim$ 2 pc

3 re-simulations of the zoom-in run of “HALO3” of **Feng et al. 2014, with GASOLINE2 SPH code**
Mass resolution 1x, 8x, and 64x the original MassiveBlack PGADGET zoom-ins
Highest resolution run: **300 million SPH particles within R_{vir} at z = 7**. No BH/AGN feedback

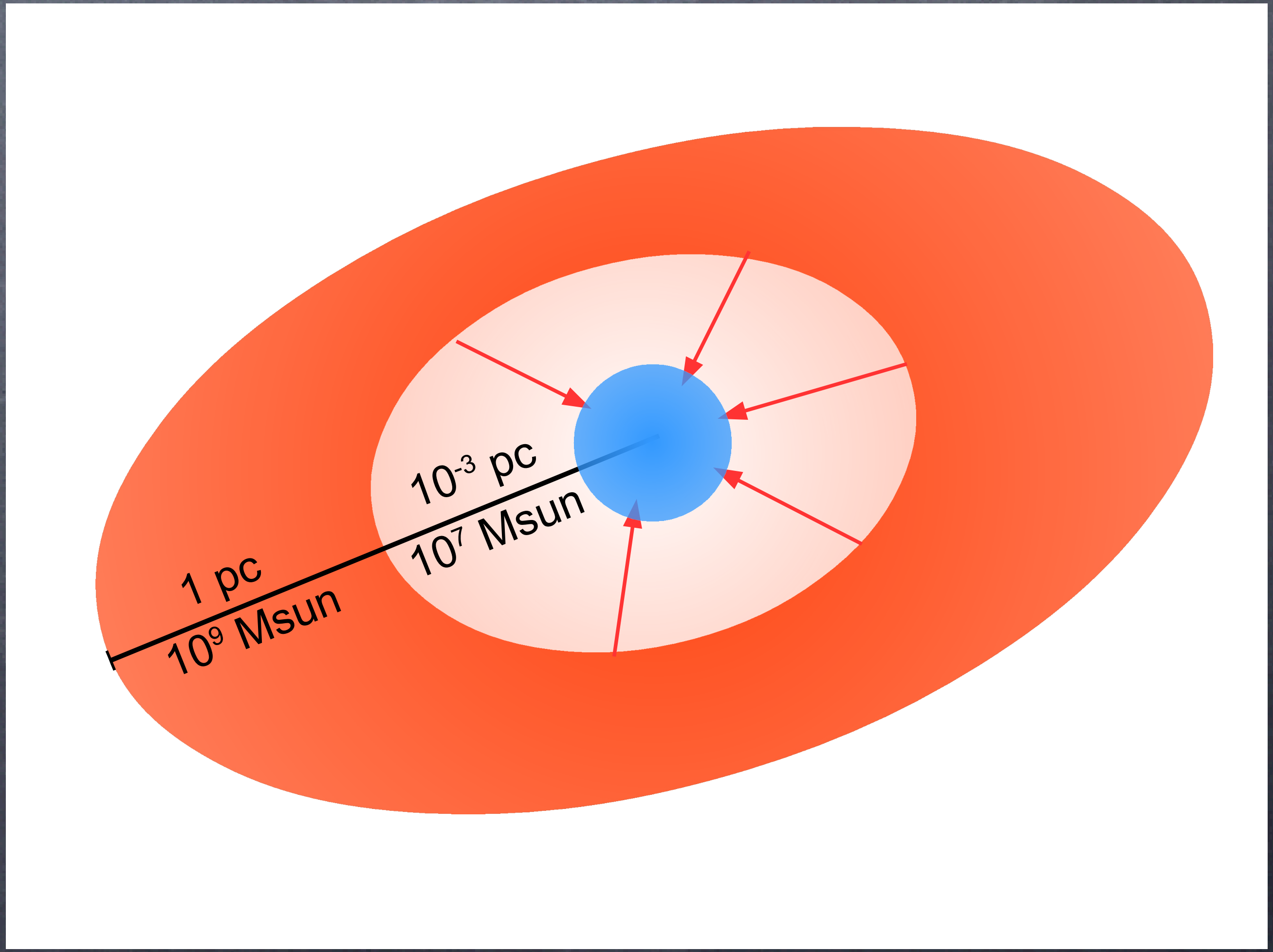
Evolution of the supermassive circumnuclear disk (SMD)

Zwick, Mayer, Haemmerle & Klessen, 2022

Analytical approach: treat the disk as a 2-component system with a (initially tiny) central spherically symmetric "core" plus an extended rotationally supported component — the actual SMD.

I. **Initial Configuration.** Suggested by end results of our hydro simulations. A centrally concentrated profile is natural consequence of angular momentum transport in self-gravitating disks (eg **Lin & Pringle 1987; Lodato & Natarajan 2006**)

To model transport in self-gravitating SMD use "effective alpha" viscosity $\alpha \sim 0.1$.



$$\frac{t_{\rm diff}}{t_{\rm visc}} \sim \alpha \mathcal{A}^2 \frac{\mathcal{A} R_{\rm d}}{\lambda_{\rm ph}} \frac{c_{\rm s}}{c}, \sim \mathcal{A}^2 10^4 \left(\frac{M_{\rm d}}{10^9\,{\rm M_\odot}}\right) \left(\frac{1\,{\rm pc}}{R_{\rm d}}\right)^2$$

aspect ratio

From equation above **t_{diff} >~ t_{visc} (A ~ 0.01-0.1, α~ 0.1), t_{visc} <~ 10^5 yr**
Also t_{dyn} at R ~ 1 pc << t_{diff} ~ 500 yr (“dynamical” angular momentum transport, eg via bar instability) —-> **angular momentum transport adiabatic**

$$M_{\rm r} = M_{\rm d} \left(\frac{r}{R_{\rm d}}\right)^{3-n}.$$

Rotationally supported self-gravitating disk with **power law mass profile, n=0-2**

Now find **the radius for which enclosed internal energy is equal to gravitational energy.** Consider both radiation and thermal pressure, and different characteristic temperatures for the SMD. —-> ***“core radius”*, can be interpreted as region containing hydrostatic core** that could contract into a radiation pressure-supported supermassive star (SMS);

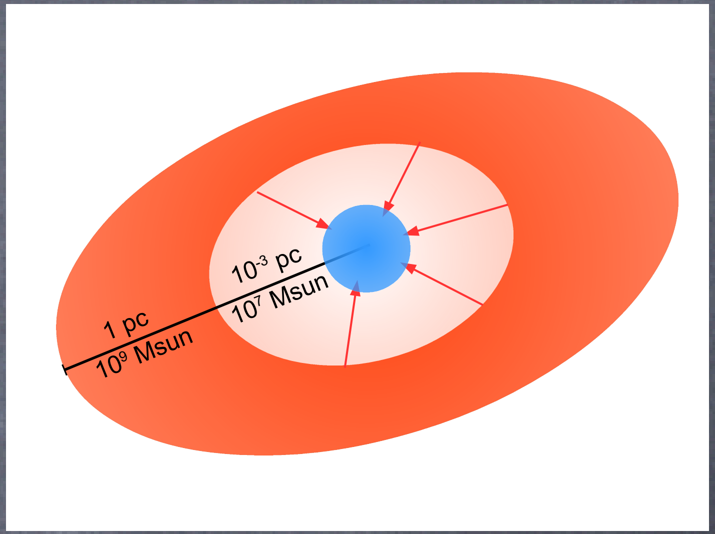
$$R_C/R_D \sim \approx 8.8\times10^{-3}\,\frac{5-2n}{3-n}\left(\frac{10^9\,{\rm M_\odot}}{M}\right)^2\left(\frac{R_{\rm d}}{\rm pc}\right)^4\left(\frac{T}{7000\,{\rm K}}\right)^4$$

II. Growth of the core by (quasi-static) disk accretion

Fluid elements at any initial radius r_o in the disk can be accreted as long as they dissipate their angular momentum via viscous or dynamical transport.

Once a fluid element joins the core the energy liberated at some location *x*, which adds to internal energy of the core, is given by;

$$\mathcal{E}(x) = \mathcal{E}_{\rm gas}\left(\frac{r_0}{x}\right)^2 + \mathcal{E}_{\rm rad}\left(\frac{r_0}{x}\right) + \int_x^{r_0} \frac{GM_{\rm r}}{r^2}\,dr,$$



The last term accounts for the dissipation of kinetic energy (=rotational energy, would apply even if part of the kinetic energy is in turbulence).

A new equilibrium will be achieved (contraction stops) when

$$\mathcal{E}(x) \sim \frac{GM_x}{x}$$

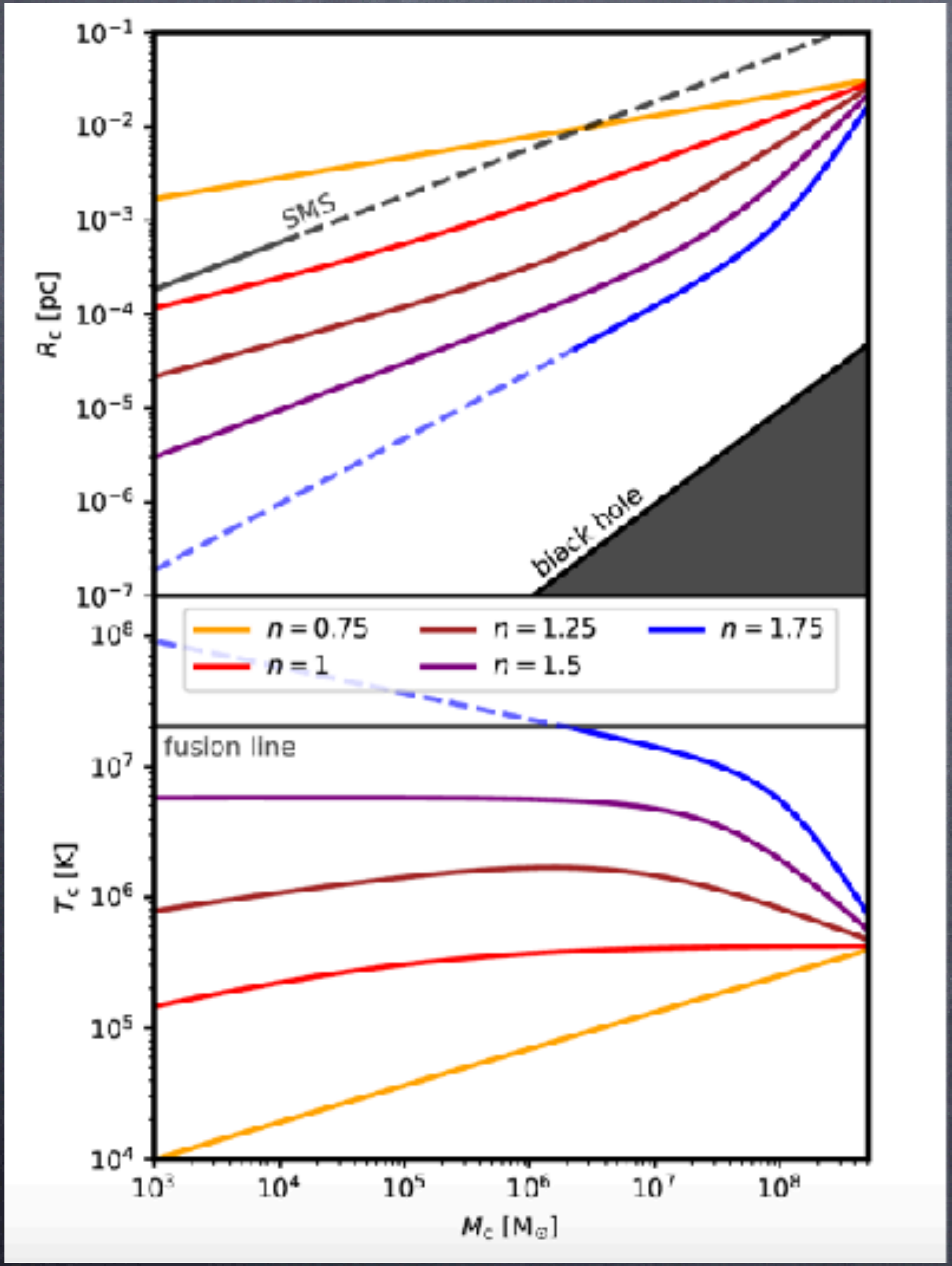
Equilibration equation

Implicit solution of above equation gives the new equilibrium radius of accreted fluid elements

For SMD to lose its entire rotational support, it should contract by factor ~ 10^2

⟶ ***if $R_d \sim 1$ pc initially, at end of the contraction phase $R_d \sim R_c \sim 0.01$ pc***

Using the solutions of the equilibration equation one can find mass-radius relation for the core for a given initial mass profile **(—> dependence on “n”)**



Note: temperature never high enough to ignite nuclear burning because density does not increase enough before BH forms (see next slide)

No SMS, only a proto-SMS!

III. Onset of general relativistic radial instability (GRI) and *direct* formation of supermassive black hole

As the disk contracts and accretes onto the core, the mass of the core might become large enough for its radius that it becomes susceptible to the GRI. Indeed eventually 10^9 Mo will end up in 0.01 pc !
This would **trigger the GLOBAL COLLAPSE of the core into a massive BH**
Numerical GR simulations tell us the resulting BH is ~ mass of the progenitor cloud/supermasssive star **(Saijio & Hawke 2009, Reisswig et al. 2013.)**.

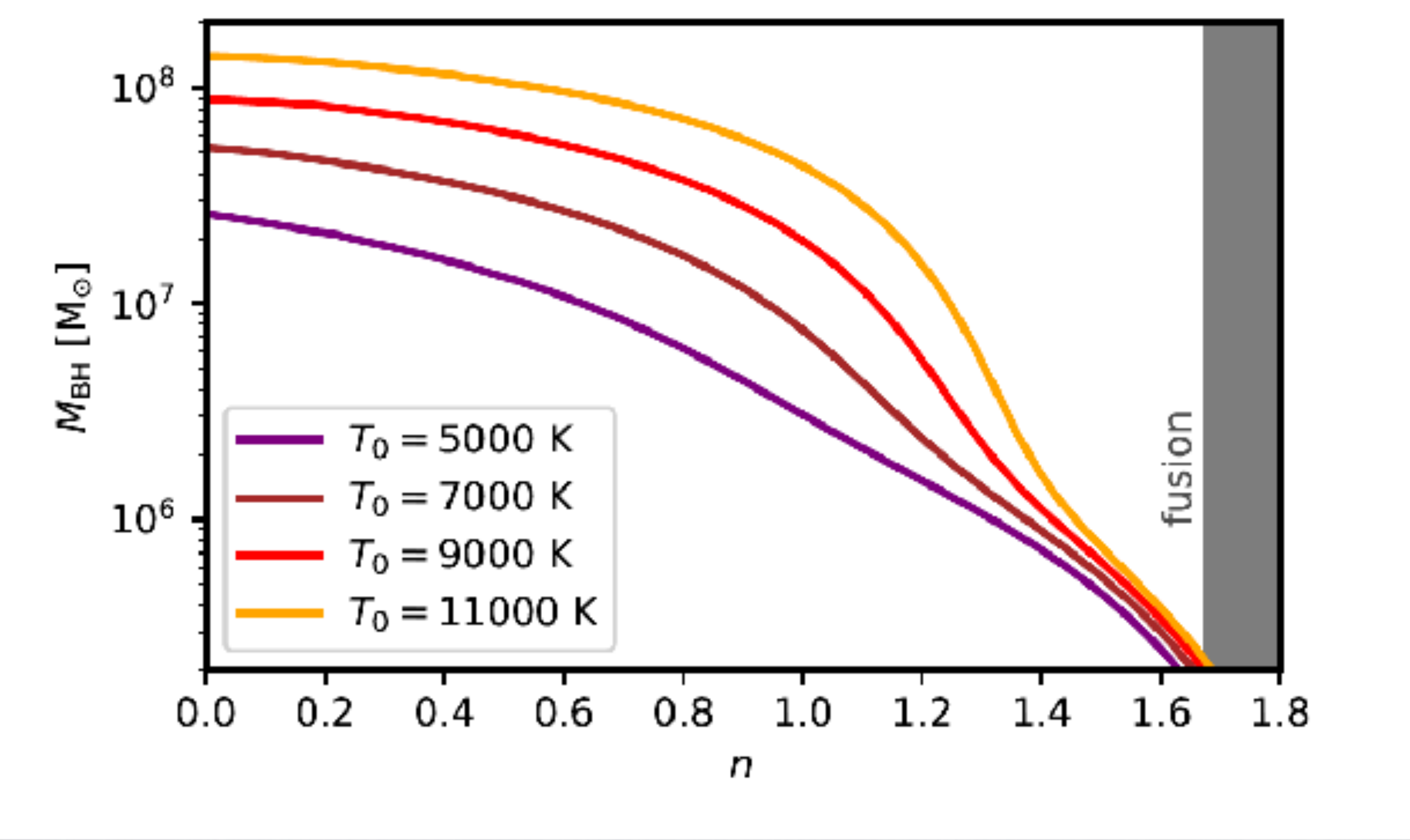
The condition for the GRI is set by the adiabatic index threshold;

$$\Gamma_1 = \frac{32-27\beta}{24-21\beta} \approx \frac{4}{3} + \frac{\beta}{6}. \quad < \quad \gamma_{\rm p} = 4/3 + \frac{1}{2}\frac{2GM_{\rm c}}{c^2 R_{\rm c}};$$

First order PN correction

β = thermal pressure/total pressure

Note the factor of 1/2 I strictly valid for an homogeneous density distribution, hence it is meaningful for mean density of the core (for a radial density profile pre-factors vary but not much)



$$\frac{M_{\rm BH}}{{\rm M}_\odot} \sim 3 \times 10^7 f(T_0, n)$$

$$f(T_0, n) = \left(1 - \frac{n}{2}\right)^{2.8} + \frac{2}{3}\left(\frac{T_0}{7000\,{\rm K}}\right)^4 \left(1 - \left(\frac{4n}{5}\right)^2\right)^{1.8}.$$

Fitting formula for M_{BH}

More concentrated profiles gives rise to lower mass SMBHs because the GR instability occurs at smaller radius (—> smaller enclosed mass)

From the formation of SMD the SMBH formation occurs in <~ 10^5 yr — upper limit set by the viscous transport timescale , while core collapse timescale is <~ months!
——> *naturally explains rapid formation of SMBHs powering* high-z QSOs

Note that assuming an angular momentum transport timescale of 10^5 yr yields an accretion rate of 10^4 Mo/yr, consistent with the >~ pc scales infall rates in our numerical simulations (cab be larger if accretion dynamical)

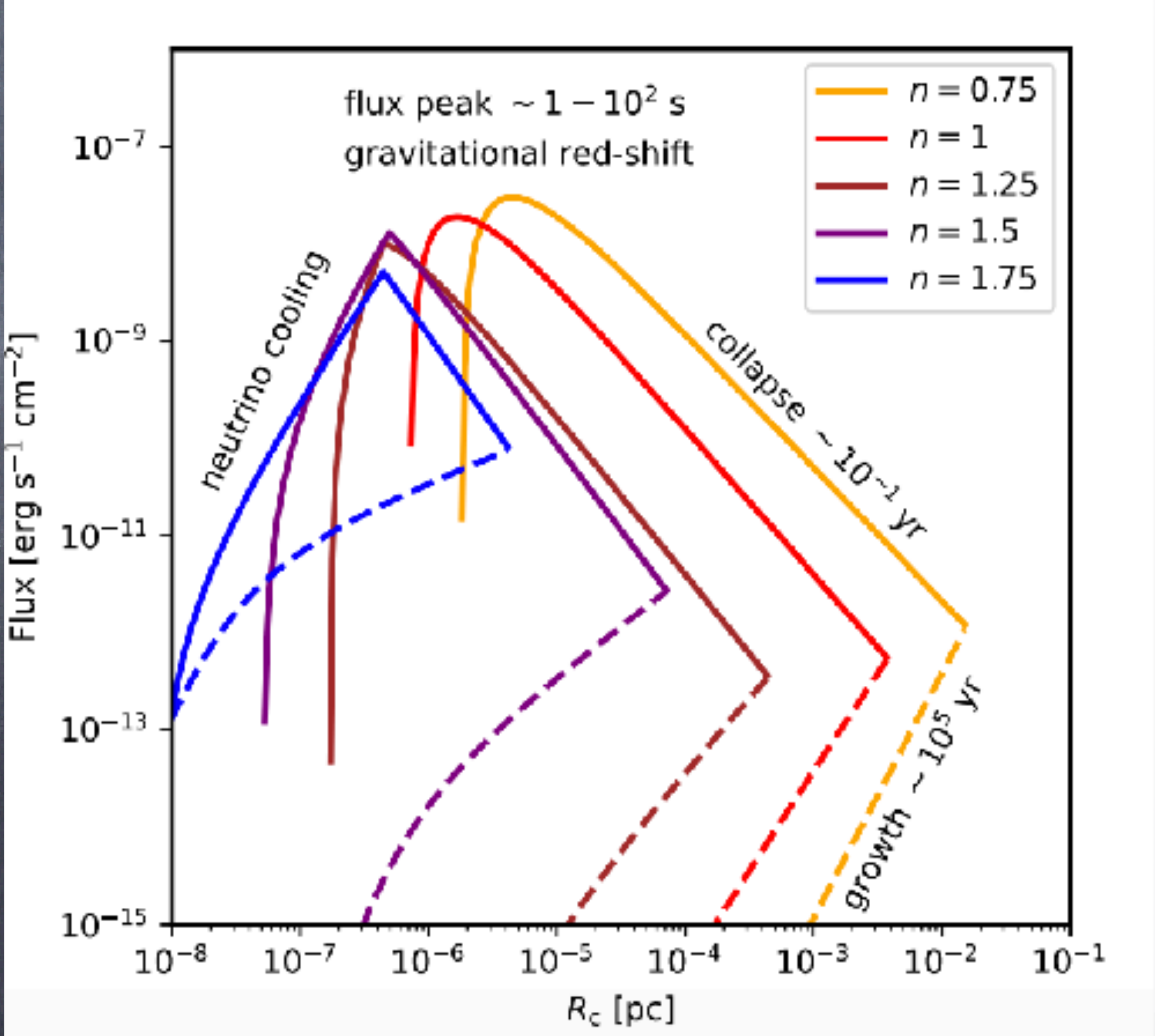
Detectability in EM and neutrino domain

SMD's cores are optically thick. Assume simple blackbody "photosphere".

I. In the **growth phase** the luminosity **L grows ~ R_c^2**, then after SMD enters the **contraction phase** due to the GR instability **L diminishes as R_c^{-2}** (because $T \sim R^{-1}$ in a contracting adiabatic system and $L \sim T^4 Rc^2$ in a BB). UV and soft X-rays

II. In contracting phase T grows to ~10^9 K —> neutrino emission via pair annihilation and URCA process important cooling mechanism (see Begelman et al. 2006 — similar to his *Quasi-Star* model). Flux at peak in hard X-rays.

III. As the core collapses to its own Schwarzschild radius gravitational redshift must be accounted for



Since Rc evolves differently for different density profile power law index ***n,*** different luminosity tracks for different ***n***

Flux plot assumes a source at z = 10

Detectability in the GW domain

GR-driven core collapse not exactly spherically symmetric, eg because of small residual flattening due to rotation
—-> ***non-vanishing quadrupole moment of the collapsing core***

Assume homologous contraction, namely **a/b = constant** during collapse (a,b = semi-major and semi-minor axis of core) —-> compute quadrupole moment of homologous spheroid —-> then **GW strain** is;

$$h \sim \epsilon^2 \frac{GM_c}{c^2 D_l} \left(\frac{v}{c}\right)^2 \qquad \approx 4 \times 10^{-21} \left(\frac{\epsilon}{10^{-2}}\right)^2 \left(\frac{M_c}{10^7\,\mathrm{M}_\odot}\right) \left(\frac{10\,\mathrm{Gpc}}{D_l}\right) \left(\frac{v}{c}\right)^2$$

radial infall velocity, v/c <~1 just before M_{BH} forms

Most of the energy released at the end in GW burst because of quadratic dependence on velocity. Burst has characteristic frequency;

$$f_b \sim \frac{c^3}{2GM_c} \approx 10^{-2} \left(\frac{10^7\,\mathrm{M}_\odot}{M_c}\right) \,[\mathrm{Hz}]$$

well within LISA band, + strain sensitivity ok!