The QUASI-STAR CHANNEL of SUPERMASSIVE BLACK HOLE FORMATION
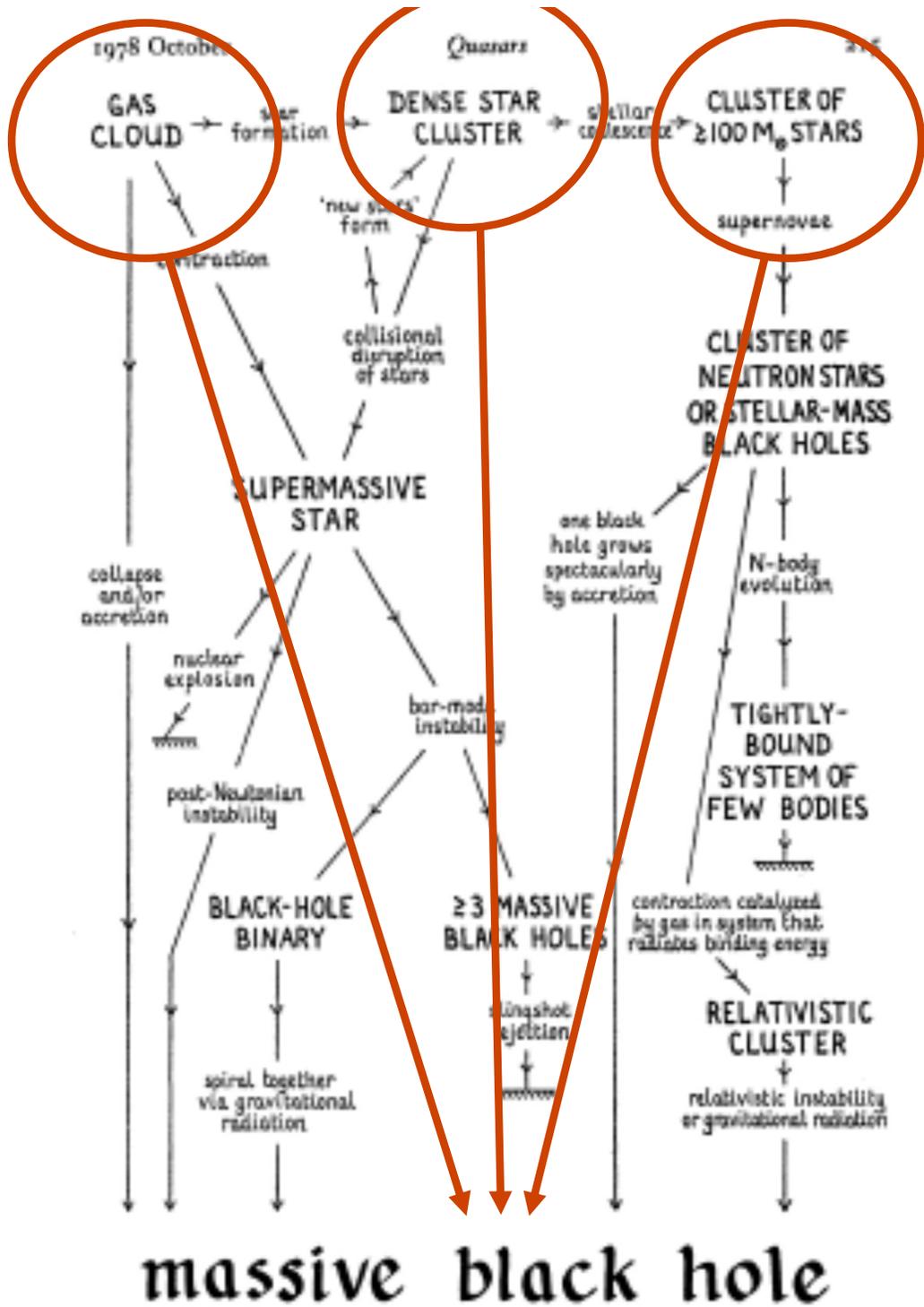
Mitch Begelman

JILA, University of Colorado

Martin Rees's flow chart

Rees, Physica Scripta, 1978

FIG. 2
Possible modes of formation of a massive black hole in a galactic nucleus.

42 years later …

…not much has changed

Begelman & Rees,
"Gravity's Fatal Attraction"
3rd Edition, 2020

BH seed channels

- Remnants of early (Pop III) stars
  - Stars form, evolve and collapse
  - BHs and/or NSs merge and/or grow by accretion
  - $M_{seed} \sim 10^2 \, M_\odot$
- Cluster collapse
  - Stars form in dense cluster
  - Stars merge to form massive stars, which collapse
    - …or, core collapse of a cluster of compact objects
  - $M_{seed} \sim 10^{3-4} \, M_\odot$
- "Direct collapse"
  - Massive gas cloud accumulates
  - Collapses directly, or first forms supermassive star, core collapse creates black hole seed
  - Rapid accretion from further infall or massive envelope
  - $M_{BH} > 10^4 - 10^6 \, M_\odot$ **HOW CAN IT HAPPEN?**
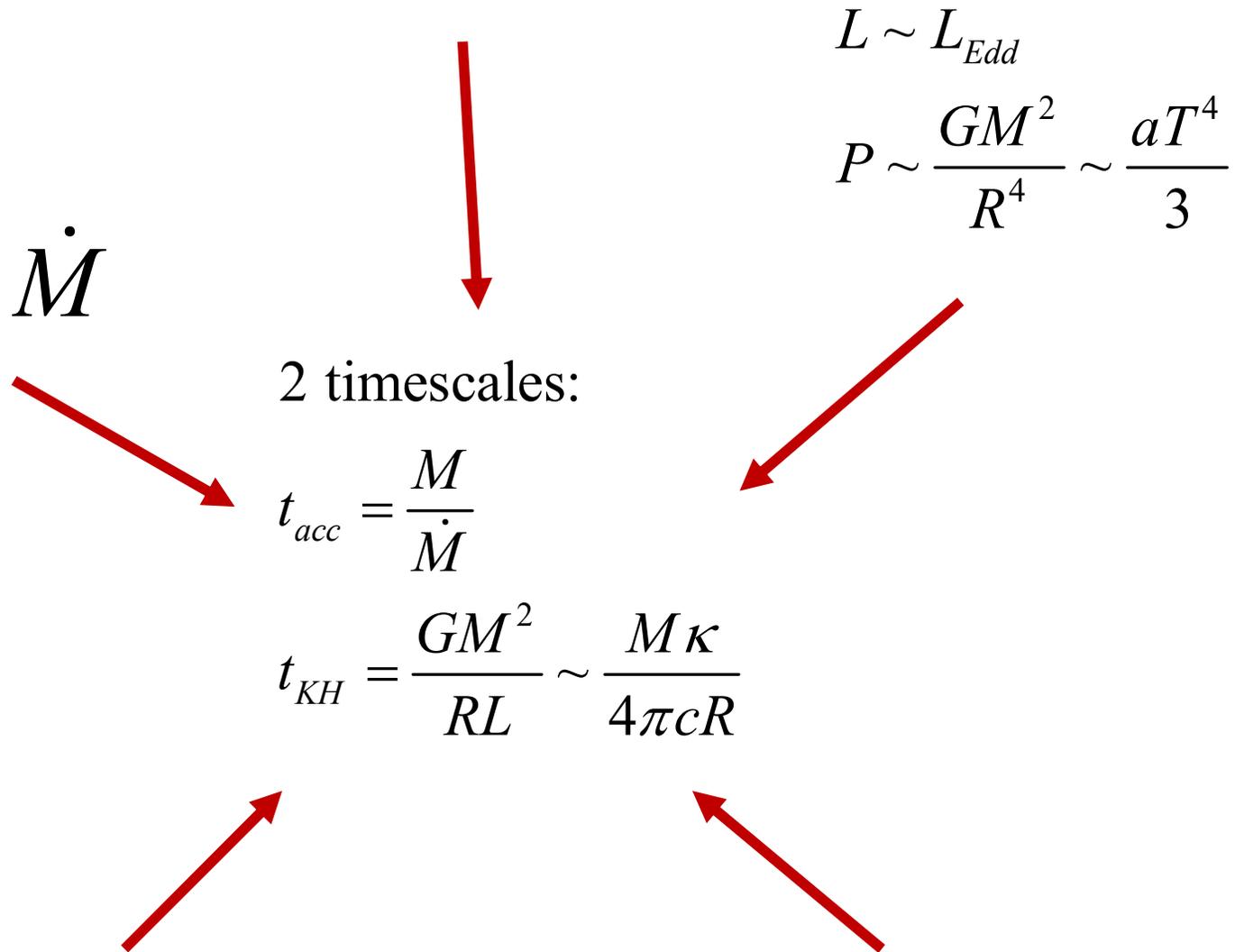
How "direct" is direct collapse?

- Infalling gas traps radiation:
  - $\Rightarrow$ heats to ~ 10^8 K $\Rightarrow$ thermonuclear hiatus
  - Core collapse after ~ 2 Myr as Supermassive Star (SMS)

- Core gas has modest rotation:
  - Core collapse creates small initial BH seed
  - BH formation energy expands envelope
  - Doesn't disperse $\Rightarrow$ rapid accretion from massive envelope: "Quasi-Star" (QS)
  - Swallows most/all envelope in ~ 20-80 Myr (~$t_{Salpeter}$)

- To get total mass:
  - $\gtrsim 10^5$ $M_\odot$ after SMS stage
  - $\gtrsim 10^6$-10^7 $M_\odot$ after QS stage

Need $\dot{M} \gtrsim 0.1$ $M_\odot$ yr^{-1}

A paradox ...

If enough of the SMS collapses initially to disperse envelope, final BH mass might be smaller!

Massive star formation (M ≳100 M⊙)

$$L \sim L_{Edd}$$

$$P \sim \frac{GM^2}{R^4} \sim \frac{aT^4}{3}$$

$\dot{M}$

2 timescales:

$$t_{acc} = \frac{M}{\dot{M}}$$

$$t_{KH} = \frac{GM^2}{RL} \sim \frac{M\kappa}{4\pi cR}$$

Massive star formation (M $\gtrsim$ 100 M$_\odot$)

$\dot{M}$

At ignition: $T \sim 10^8$ K

$t_{acc} \sim t_{KH}$

$M_{SMS} \sim 10^3 \dot{M}_{0.1}^2 M_\odot$

$t \sim 10^4 \dot{M}_{0.1}$ yr

Low-entropy core gas $\Rightarrow$ Ignition is late in an SMS

How to get the required infall rate?

SELF-GRAVITATING INFALL

Max infall rate set by virial temperature of halo $T_{vir} \Leftrightarrow$ infall speed v at radius where gas becomes self-gravitating relative to DM

$$\dot{M} \sim \frac{v^3}{G} \propto \frac{T^{3/2}}{G}$$

- "Normal" star formation

$$T_{vir} \sim 10 - 100\,\mathrm{K}, \ \dot{M} \sim 10^{-5} - 10^{-4}\,\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$$

- Pop III remnants

$$T_{vir} \sim 100 - 1000\,\mathrm{K}, \ \dot{M} \sim 10^{-4} - 10^{-2}\,\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$$

- Direct collapse

$$T_{vir} > 10^{4}\,\mathrm{K}, \ \dot{M} > 0.1\,\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$$

Issues with direct collapse

- To build up $\gtrsim 10^5$ M$_\odot$ need:
  - $\dot{M} > 0.1$ M$_\odot$/yr $\Rightarrow$ T$_{vir} > 10^4$ K $\Rightarrow$ big enough DM halos
- Why doesn't the infalling gas just form stars?
  - Could fragment if T$_{gas} \ll$ T$_{vir}$ but:
    - Metal-free atomic gas can't cool below ~ 10^4 K
    - Need strong UV background, otherwise gas is *molecular* (H$_2$) and cools to ~10^3 K
    - Speculation is that Pop III stars form from molecular gas, direct collapse is with atomic gas
    - Requires special "rare" conditions (metal-free + UV background)

OR

  - Could fragment if T$_{gas} \ll$ T$_{vir}$ but:
    - Turbulence
    - Magnetic fields

STAGE I:

SUPERMASSIVE STAR

SUPERMASSIVE STARS

Hoyle & Fowler 1963

- Proposed as energy source for radio galaxies, quasars
- Burn H for ~10^6 yr
- Supported by radiation pressure ➡ fragile
- Small P_g stabilizes against GR to $10^5\,M_\odot$
- Small rotation stabilizes to 10^8-$10^9\,M_\odot$

Photos: AIP – Emilio Segré Archives

3 THINGS HOYLE & FOWLER DIDN'T KNOW ABOUT SUPERMASSIVE STARS

… because they didn't worry about how they formed

- They are not thermally relaxed
- They are not fully convective
- If made out of pure Pop III material they quickly create enough C to trigger CNO

A BLACK HOLE FORMS

COULD BE SMALL ($< 10^3$ M$_\odot$) AT FIRST …

… BUT SOON TO GROW FAST

Energy released insufficient to disperse envelope, which expands but remains bound

STAGE II:

QUASI-STAR

QUASI-STAR

- Remnant envelope around newly formed SMBH seed
- Black hole accretes from envelope, releasing energy
- Envelope absorbs energy and expands
- Accretion rate adjusts until energy output $\geq$ Eddington limit of envelope – supports the "star"
- BH can swallow entire mass in ~ 40 Myr

MCB, Volonteri & Rees 2006; MCB, Rossi & Armitage 2008; Coughlin & MCB 2024
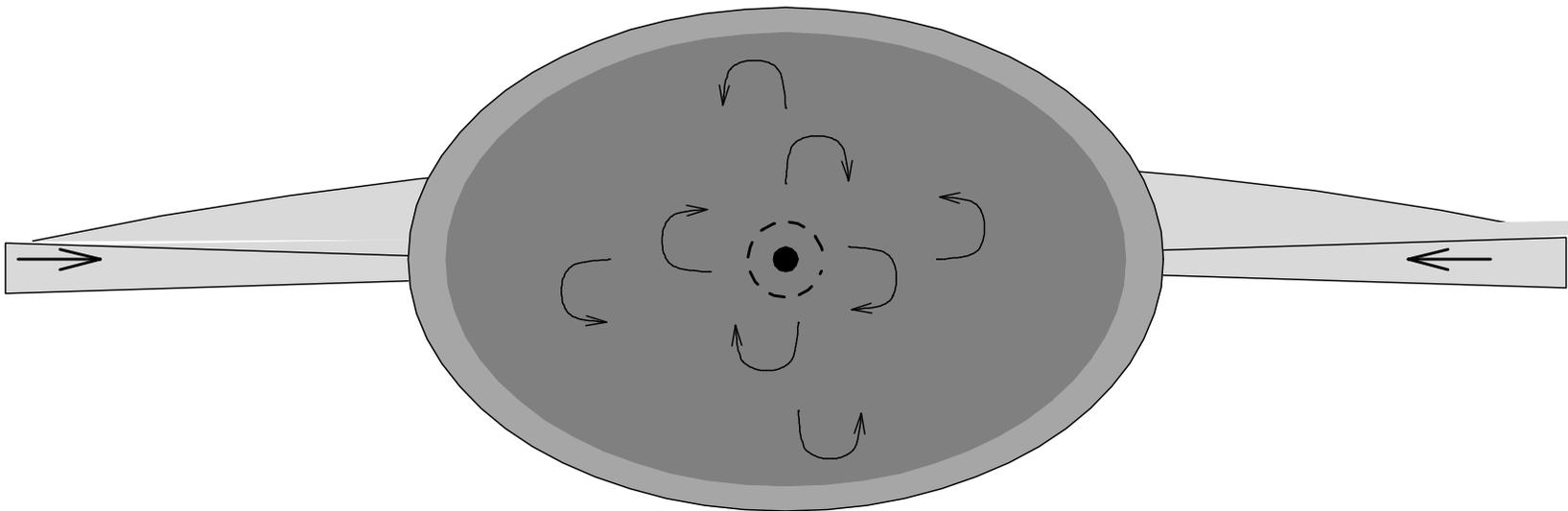
SO THE BLACK HOLE GROWS AT THE EDDINGTON LIMIT, RIGHT?

BUT WHOSE **LIMIT?**

EDDINGTON

- Eddington-limited growth of isolated BH: exponential
- Eddington-limited growth of in BH inside QS : ~ linear
- QS lifetime ~ 1-2 $t_{salpeter}$ independent of mass

QUASI-STAR

- Resembles a red giant (or Thorne-Żytkow object)
- Radiation pressure-supported convective envelope

As $M_\bullet / M_*$ increases:

Central temp. drops

Radius expands

T_{phot} drops very weakly
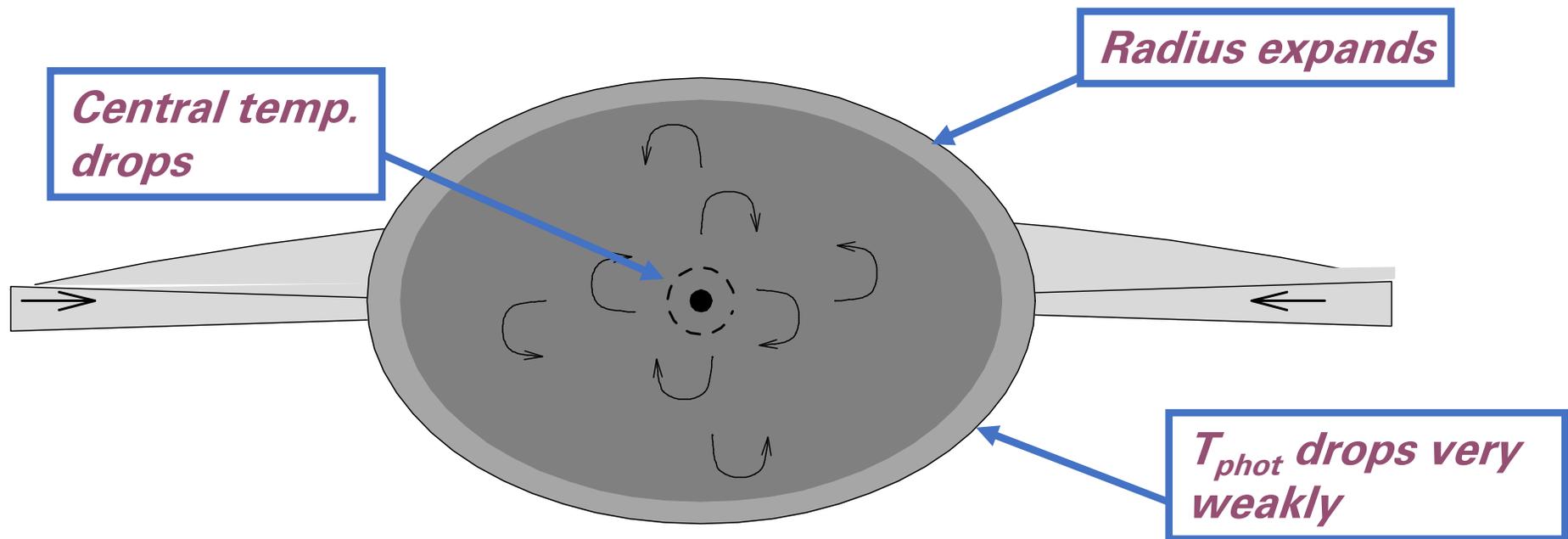
QUASI-STAR INTERIOR

Inner: saturated convection:

$$L \sim \beta P_{rad} c_s r^2 \sim \beta P_{rad}^{3/2} \rho^{-1/2} r^2$$

Outer: weak convection

$\sim$ adiabatic, $\gamma \approx 4/3$

Models insensitive to

efficiency factor β
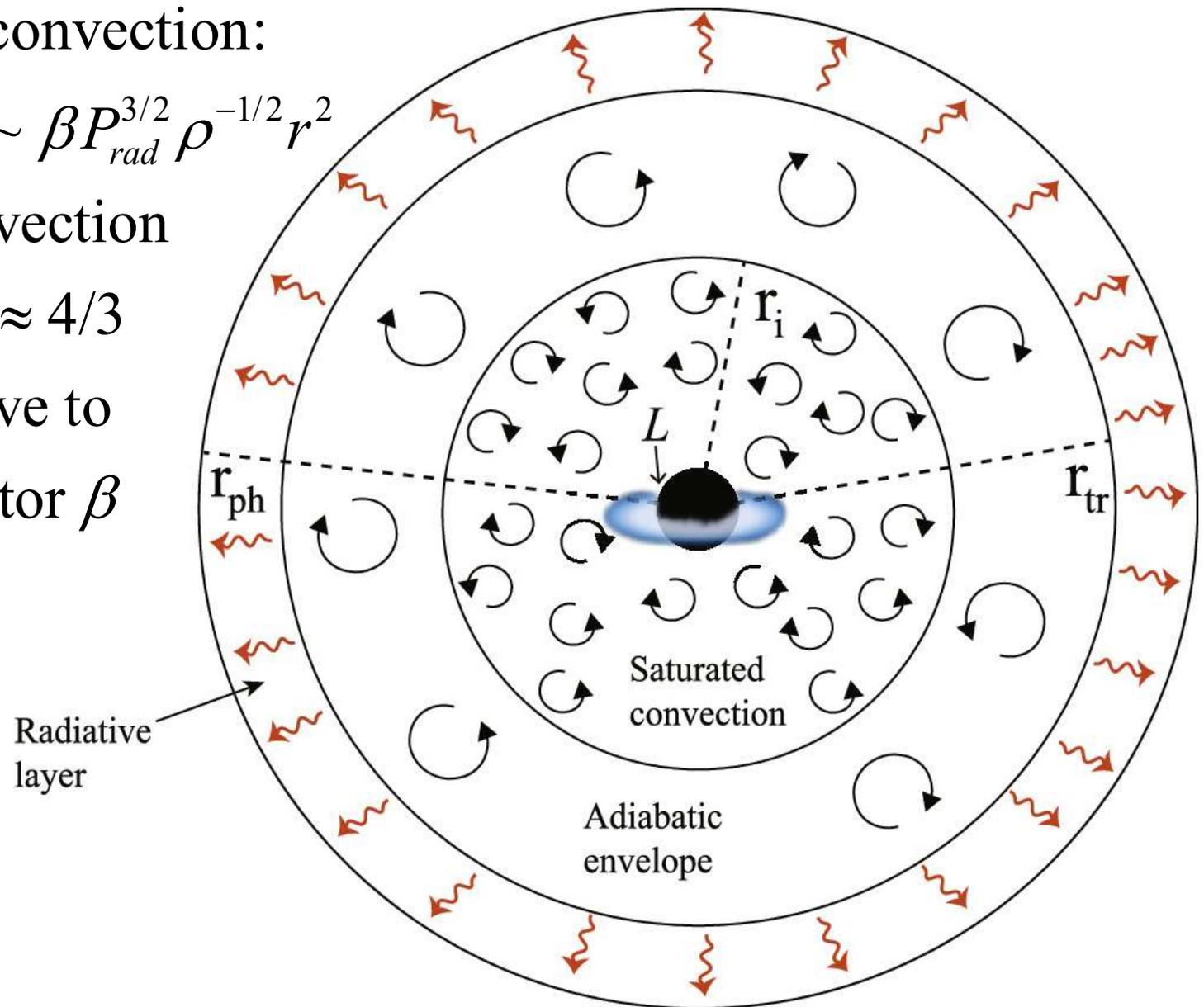
Radiative layer

r_{ph}

r_i

L

Saturated convection

Adiabatic envelope

r_{tr}

Coughlin & MCB 2024

QUASI-STAR EVOLUTION

Coughlin & Begelman

$$M_* = 10^5 M_\odot$$
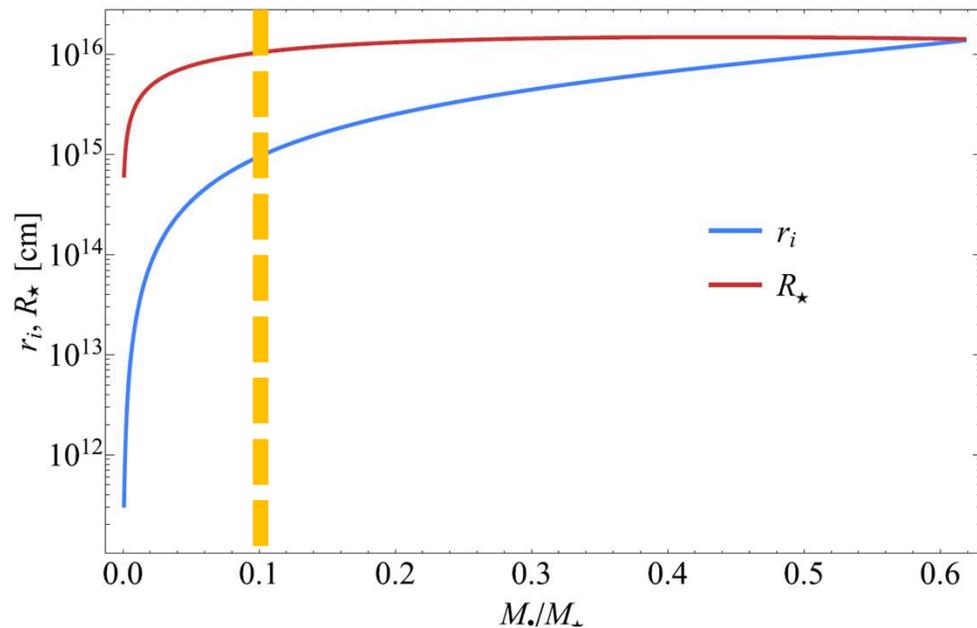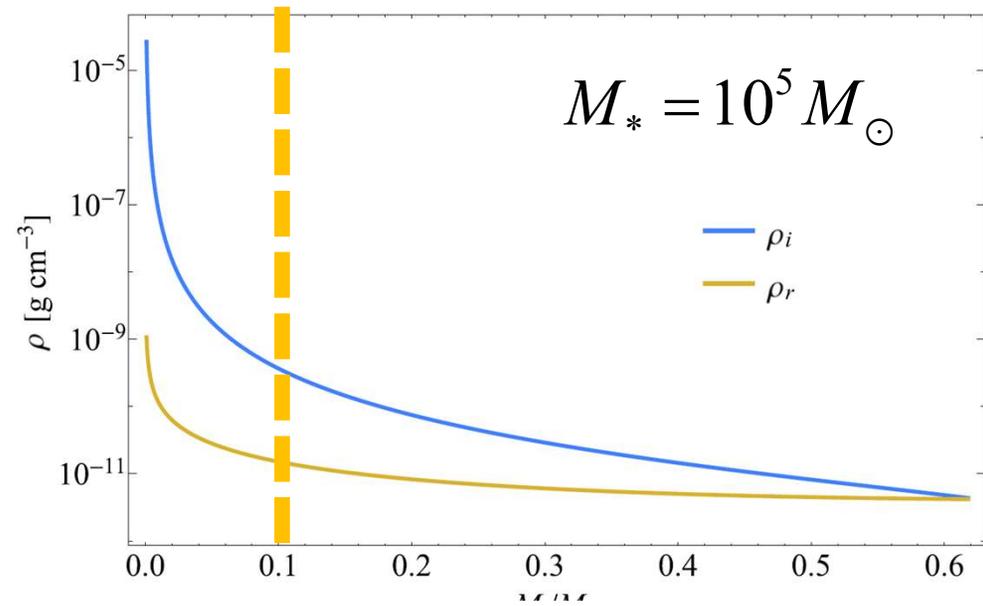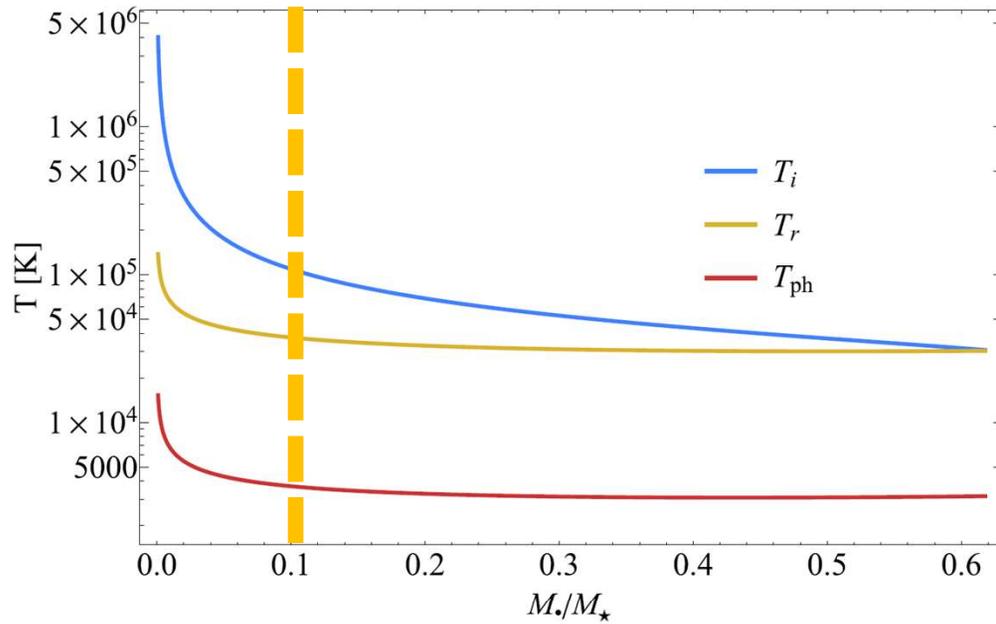
Early QS: M$_{BH}$ < 0.1 M$_*$
Sensitive to M$_{BH}$/M$_*$
Late QS: M$_{BH}$ > 0.1 M$_*$
Insensitive to M$_{BH}$/M$_*$

Little Red Dots (LRDs)
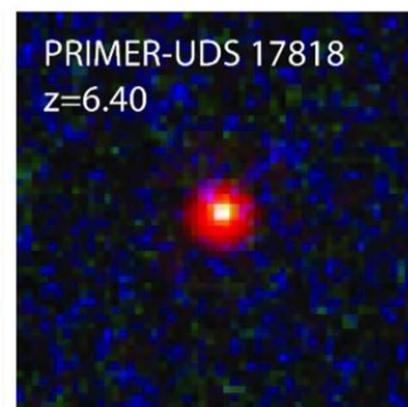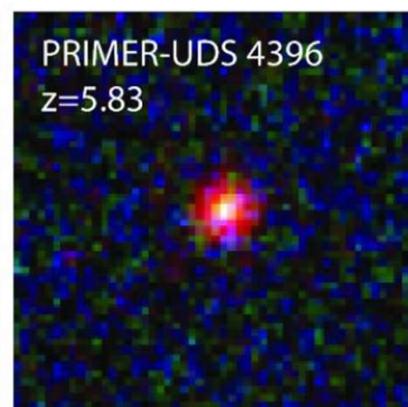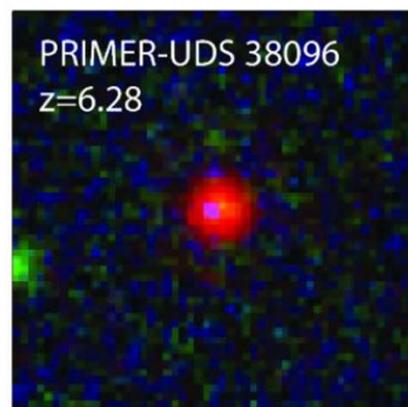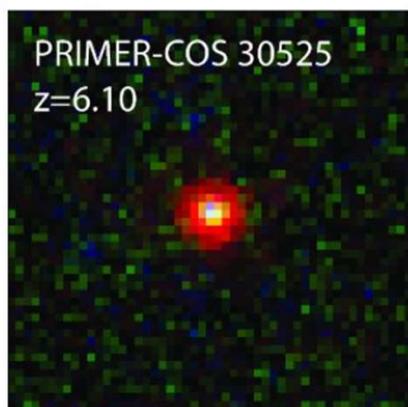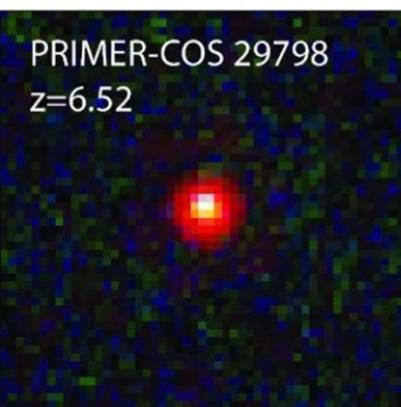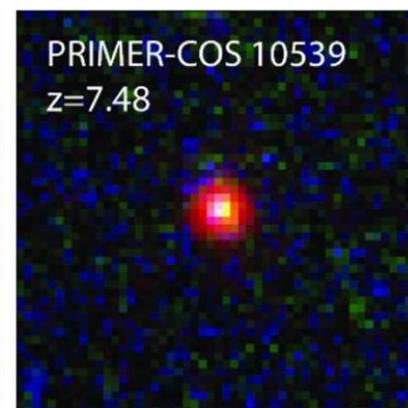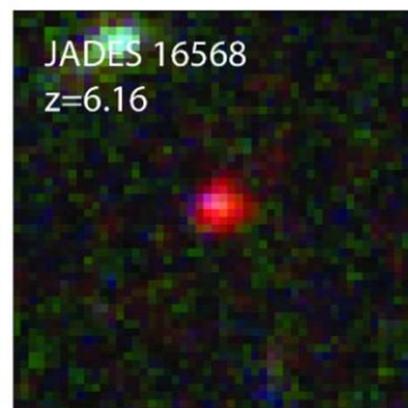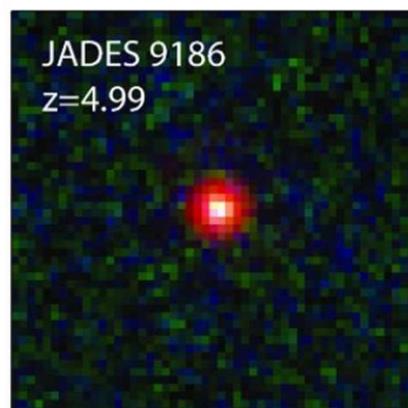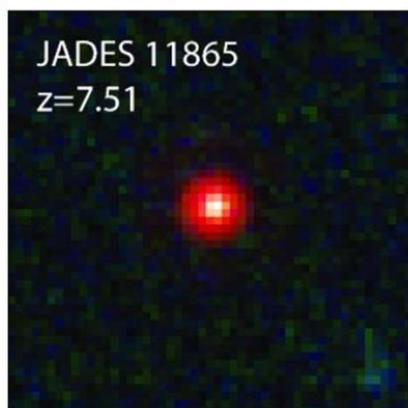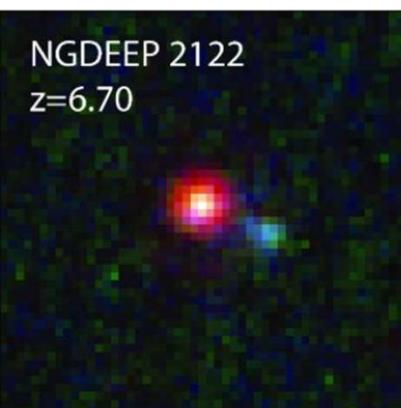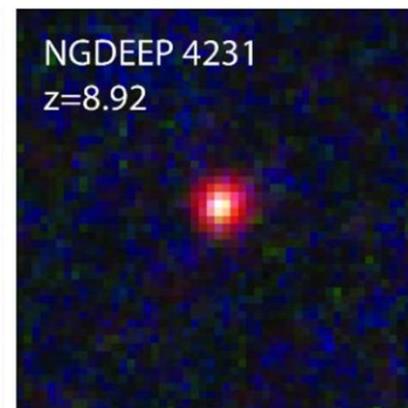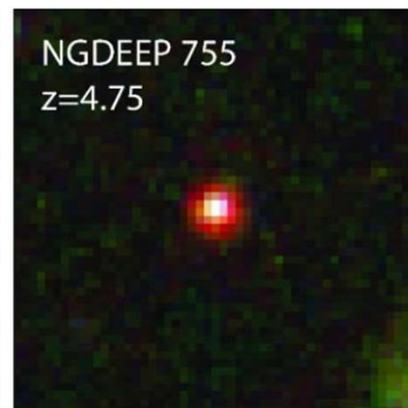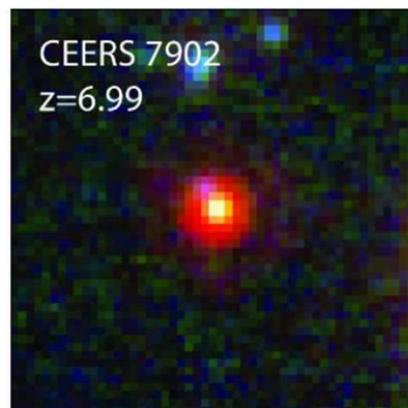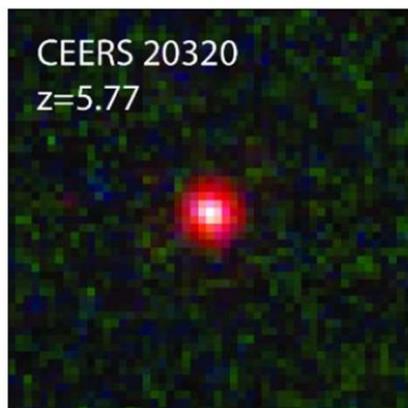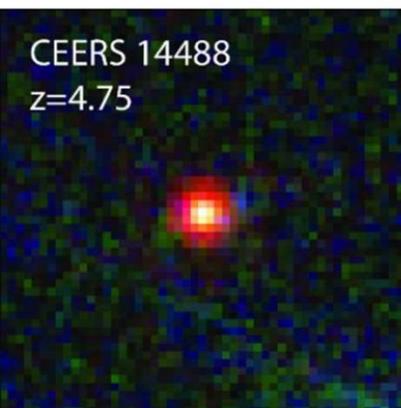
Little Red Dots (LRDs)

- Population of mainly high-z (~ 4 - >11) sources from JWST surveys
- "v-shaped" spectrum
  - Red in the red, blue in the blue
  - Strong Balmer break
    too strong for any stellar population
  - Broad Balmer emission *and* absorption
  - Large Balmer decrement
- No X-rays or radio
- No dust (from FIR/sub-mm)
- Extremely compact ($\lesssim$ 100 pc)
  - If made of stars they would self-destruct

Naidu et al 25
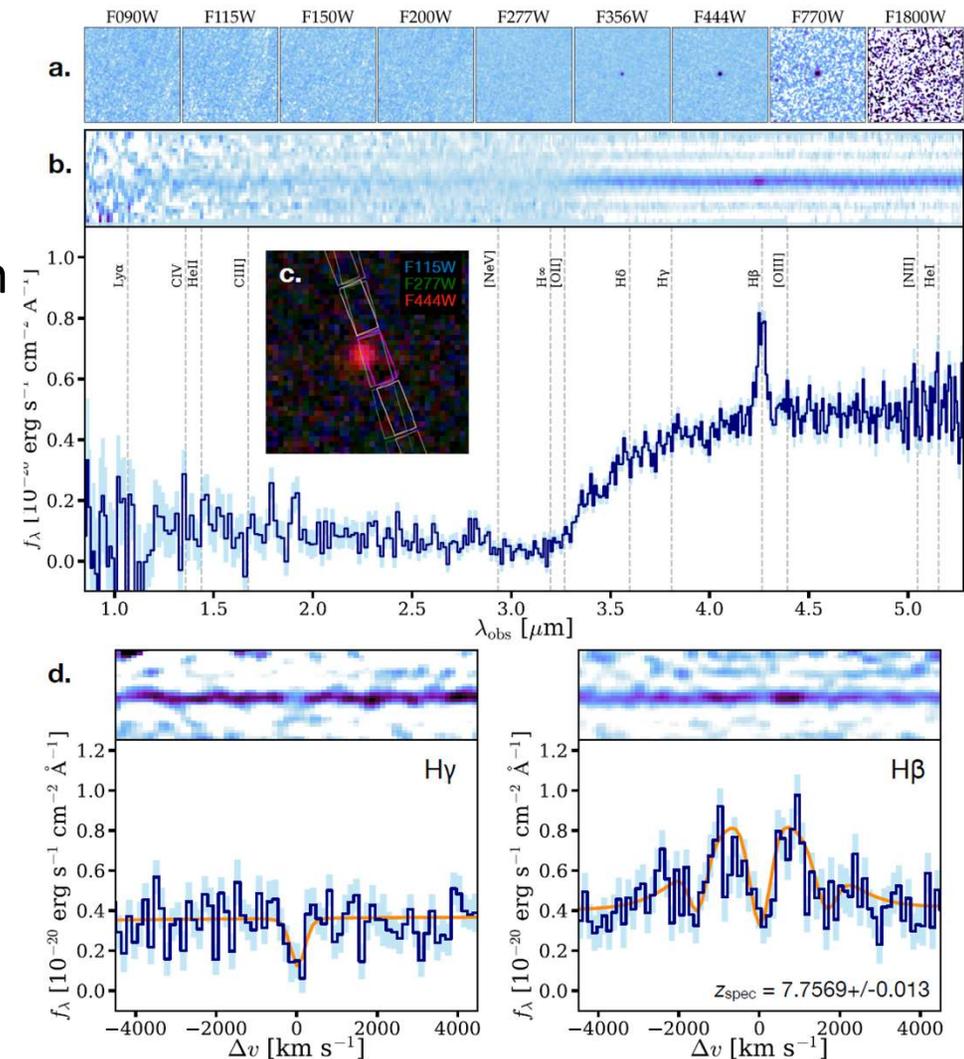
Predicted Late QS atmosphere properties similar to LRD spectra

- QS atmospheres very different from stars
  - T_{color} ~ 6000 K, roughly blackbody shape
  - However, T_{eff} ~ 3000 K $\Rightarrow$ dilute blackbody
    - Non-LTE, scattering dominated, $\tau_{sc} \gg 1$ kills X-rays
    - More like accretion disk spectrum
  - Emission lines form because Balmer lines thermalized in the non-LTE zone
  - Strong Balmer break from large n=2 column
  - v_{Kep} ~ 300 km/s, so lines scatter-broadened

Hypothesis: LRDs are late-stage quasistars

Begelman & Dexter 2025

Properties of Late QS Atmospheres: inefficient convection zone

- Transition to inefficient convection:
  - $t_{\text{diffusion}} \sim t_{\text{buoyancy}}$ across pressure scale height
  - Convection still operates but very inefficient
    - Strong negative entropy gradient, density inversion in spherical symmetry?
    - More realistic? Hypothesize neutral buoyancy with uniform mean density
- At base of layer:

$$R \sim 6 \times 10^{16} M_6^{3/5} \text{ cm}$$

$$T \sim 15000 \text{ K (insensitive to } M_\bullet)$$

$$\rho \sim 2 \times 10^{-13} M_6^{-4/5} \text{ g cm}^{-3}$$

$$\Delta R / R \sim 0.2, \quad \Delta M / M \sim 0.1$$

Begelman & Dexter 2025

Radiative layer

r_{ph}

L

Satu
conv

Adiaba
envelop
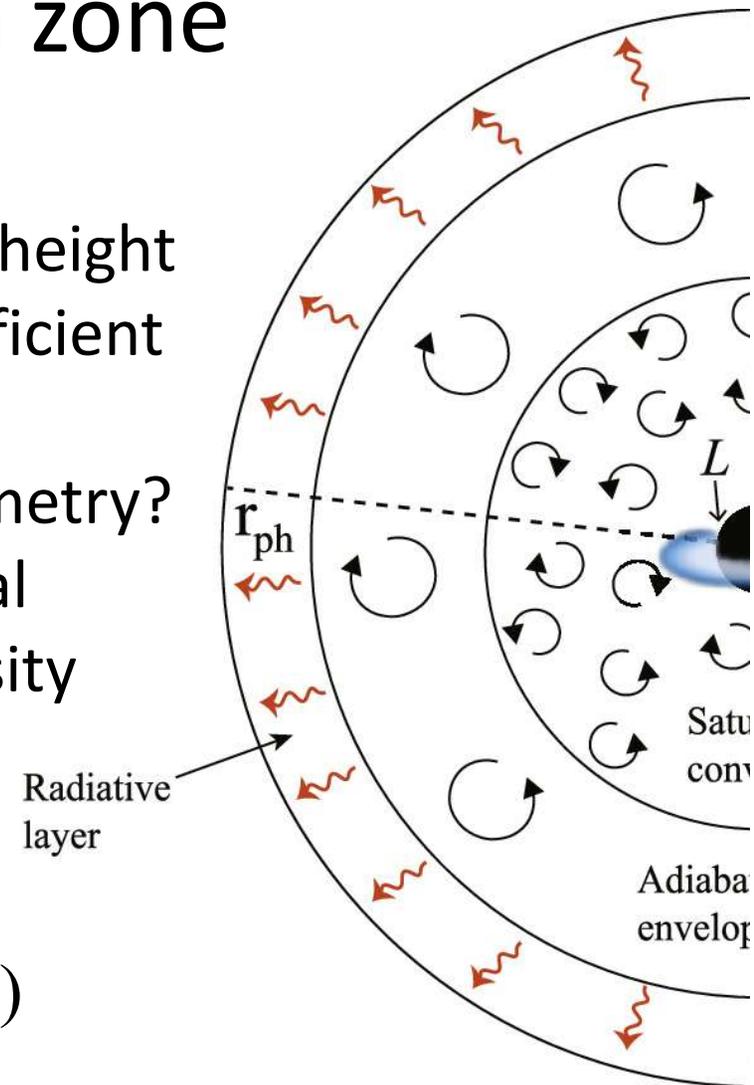
Properties of Late QS Atmospheres: spectrum formation

- LTE zone
  - Low density $\Rightarrow$ fully ionized to 5800 K
  - Abundant electrons $\Rightarrow$ H$^-$ determined by H alone, no need for metals
- Transition to NLTE:
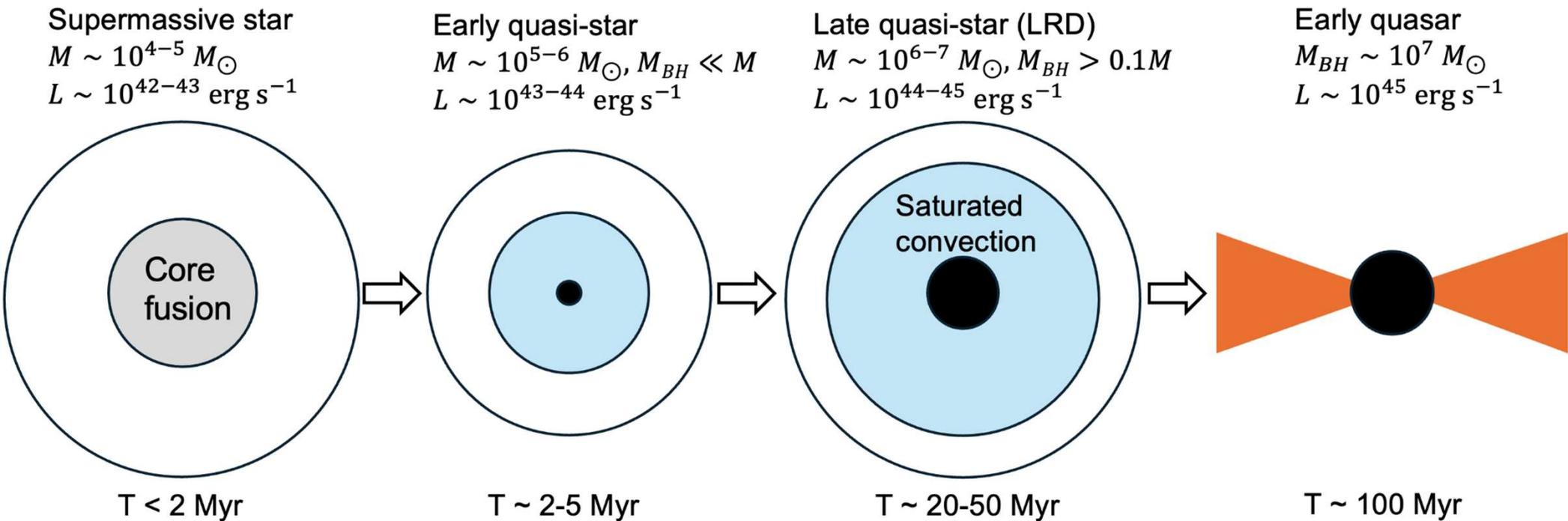 - $\kappa_{ff} < \kappa_{H-} < \kappa_{scatt}$
  - $\tau_{H-} \tau_{scatt} \sim 1 \Rightarrow T_{color} \sim 6000$ K
  - $\tau_{scatt} \sim 20$
  - $T_{eff} \sim 3000$ K

Begelman & Dexter 2025

IMPLICATIONS FOR SMBH FORMATION

- LRDs are common!
  - ~ 10^{-5} cMpc^{-3} @ z~5-7
  - 1% of early UV-selected galaxies
- But Quasi-Stars are shortlived
  - ~ 30-50 Myr, with most time spent in late stage
- ∴ if LRD = QS
  - ~ all galaxies pass through a single QS/LRD stage
  - if $\dot{M} \gtrsim 0.1$ M$_\odot$ yr^{-1} then M$_{BH}$~10^{6-7} at end of QS stage
  - Not much room to form SMBH seeds by other mechanisms

Stages of SMBH formation/growth

Supermassive star
$M \sim 10^{4-5} M_\odot$
$L \sim 10^{42-43}$ erg s^{-1}

Core
fusion

T < 2 Myr

Early quasi-star
$M \sim 10^{5-6} M_\odot, M_{BH} \ll M$
$L \sim 10^{43-44}$ erg s^{-1}

T ~ 2-5 Myr

Late quasi-star (LRD)
$M \sim 10^{6-7} M_\odot, M_{BH} > 0.1M$
$L \sim 10^{44-45}$ erg s^{-1}

Saturated
convection

T ~ 20-50 Myr

Early quasar
$M_{BH} \sim 10^7 M_\odot$
$L \sim 10^{45}$ erg s^{-1}

T ~ 100 Myr

Begelman & Dexter 2025

Some recent developments

- MESA models of quasi-stars *(Hassan…MCB… '26, Santarelli + '26)*
  - Evolutionary tracks, effects of winds…
  - Confirm basic analytic model, refine mass limits
- Atmosphere, spectrum formation models ⇒ in progress
  - Hassan +, other groups
- Fleshing out LRD properties:
  - An "X-ray dot" discovered? *(Hviding + '26)*
  - Low-z LRDs? *(Ji + '26, Lin + '26)*
  - UV emission is extended ⇒ stars?
    (Naidu + '25, Zhuang + '26)
  - LRDs not variable on *JWST* timescales …
  - … but may show decades-century variability!
    (Zhang + '25 – Einstein cross)
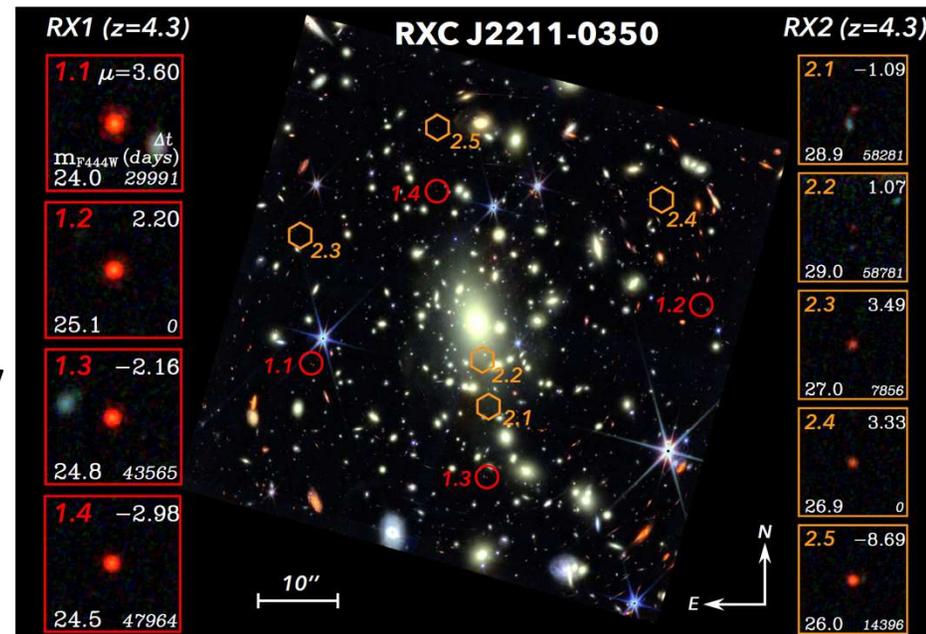
Pulsational Instability of Quasi-Stars

(Cantiello … MCB … '26)

- Driven by κ-mechanism for He II ionization zone – supermassive analog of Cepheids
- Strong mass loss?
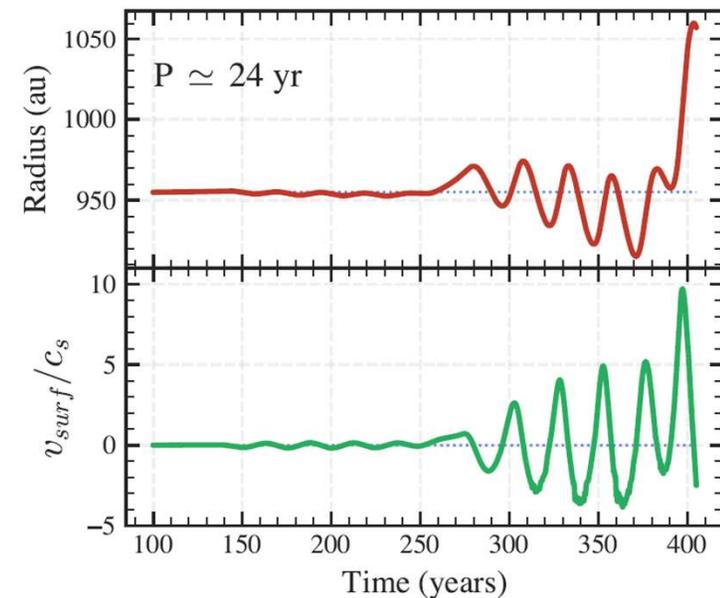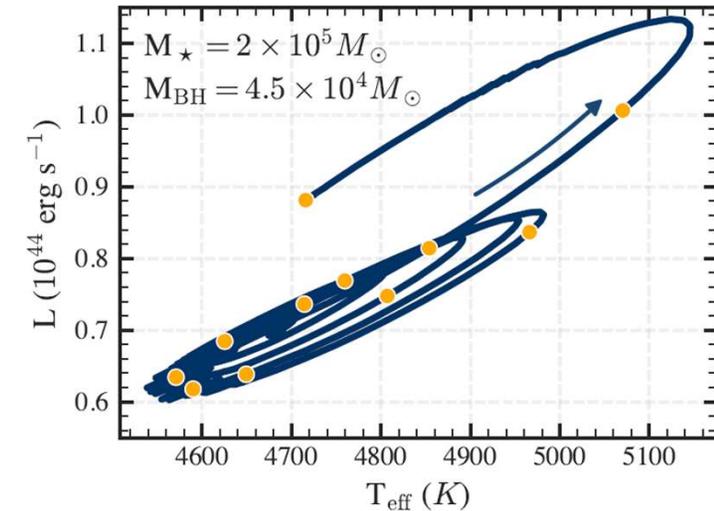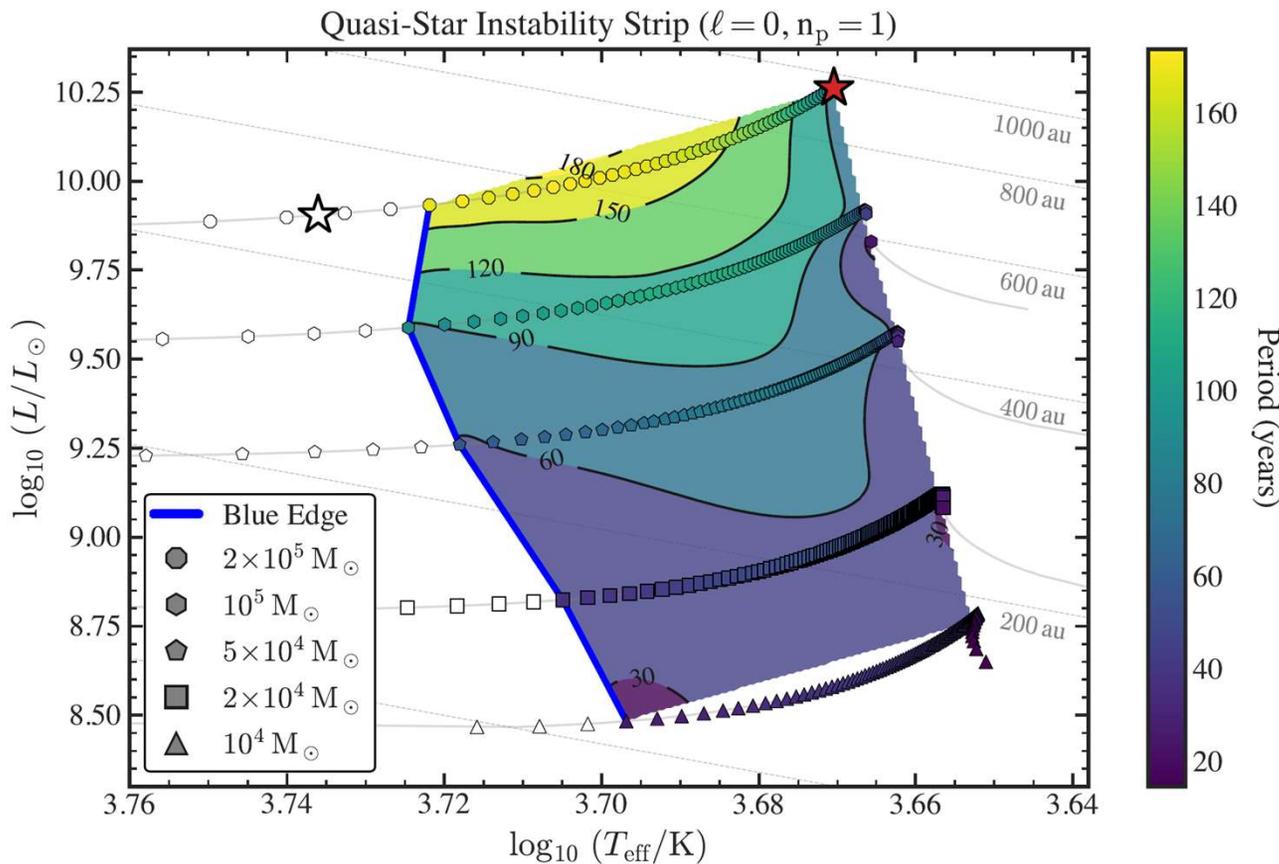
Quasi-Star Instability Strip ($\ell = 0$, $n_p = 1$)

Some *very* unsolved QUASI-STAR problems

- Role of ang. mom. in core
  - Binding energy of accreted gas (accretion efficiency)
  - Transition to saturated convection (like CDAF, $\rho \propto r^{-1/2}$)
- Role of ang. mom. in envelope
  - Freshly accreted gas joins with some J
  - Internal ang. mom. transport in envelope
- Jets from quasi-stars?
- Inefficient convection zone
  - How does Nature resolve density inversion?
  - Is strong mass loss inevitable?
    - If so, how much?
    - Sensitivity to v. small deviations from L_{Edd} – how does the core "know" how to respond
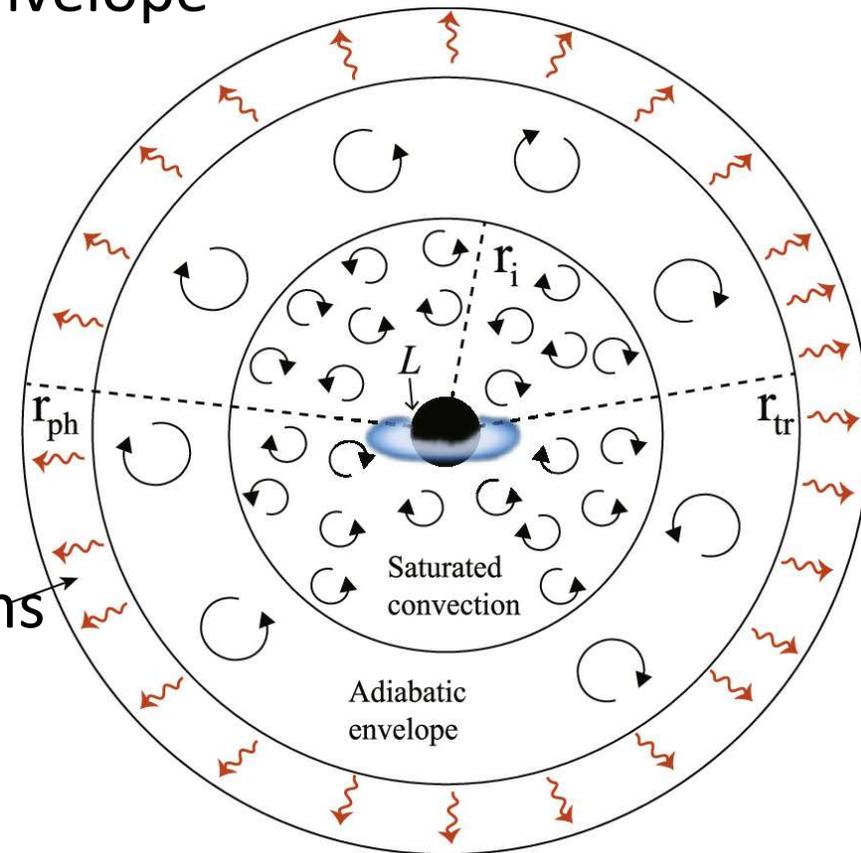
Some *very* unsolved QUASI-STAR problems

- Role of ang. mom. in core
  - Binding energy of accreted gas (accretion efficiency) *
  - Transition to saturated convection (like CDAF, $\rho \propto r^{-1/2}$)
- Role of ang. mom. in envelope
  - Freshly accreted gas joins with some J
  - Internal ang. mom. transport in envelope
- Jets from quasi-stars? *
- Inefficient convection zone
  - Does BH swallow entire envelope or expel a remnant? *

* Factors that can increase BH growth rate and/or decrease QS lifetime
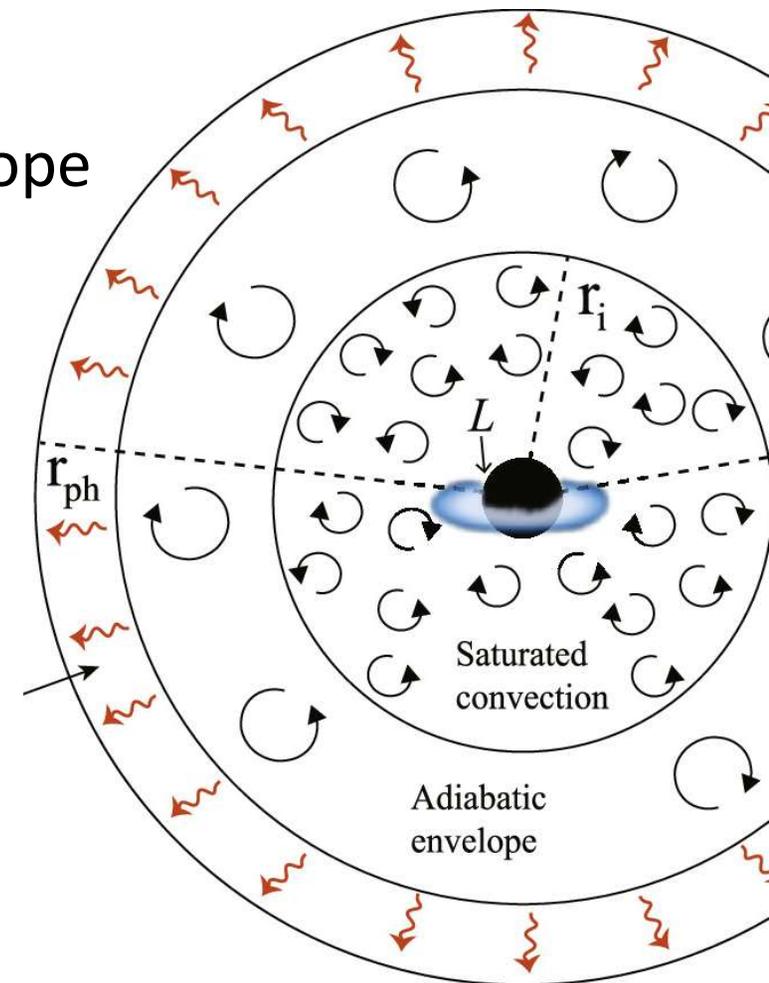
Observational Tests

Low-z LRDs:

- A few examples found in SDSS at ~ 0.1-0.2
  - How can they form? – why is infall occurring so late?
  - Environment?
  - Relation to nearby star formation?
  - Effects of metallicity?

Find the precursors and descendants:

- Rarer and fainter SMSs and early-stage QSs
- How does the transition to AGN occur, can the intervening stages be seen?

Beamed LRDs? (if quasi-stars have jets or funnels):

- How could they be identified?
- X-rays down the funnel?
- Emergent jets in radio? (deep search, esp. at low-z and for extremely lensed LRDs)

IMPLICATIONS FOR SMBH FORMATION

- LRDs are common!
  - $\sim 10^{-5}$ cMpc^{-3} @ z~5-7
  - 1% of early UV-selected galaxies
- But Quasi-Stars are shortlived
  - ~ 30-50 Myr, with most time spent in late stage
- $\therefore$ if LRD = QS
  - ~ all galaxies pass through a single QS/LRD stage
  - if $\dot{M} \gtrsim 0.1$ M$_\odot$ yr^{-1} then M$_{BH}$~10^{6-7} M$_\odot$ at end of QS stage
  - Not much room to form SMBH seeds by other mechanisms

IMPLICATIONS FOR GALAXY FORMATION

- Stellar mass limited to a few times M$_\bullet$
- BHs form before galaxies!
    - Infall at high rate without efficient star formation – WHY?
    - But mature massive disks (and bulges) appear soon after

- Are BHs needed to stimulate initial burst of star formation? - i.e. positive feedback (Silk et al 24)
- Rare low-z LRDs may indicate late baryon infall into compact DM halos

SUMMARY

- Late-stage quasi-stars a promising explanation for LRDs
- If so they are the dominant channel for SMBH formation, implying …
  - Large infall rates into protogalactic nuclei without extensive star formation
  - BHs reach ~10^{6-7} M$_\odot$ in 10s of Myr

Can the flow chart finally be simplified?