THE FIRST SUPERMASSIVE BLACK HOLES?

or…

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STARS: WHO NEEDS 'EM?

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NEED TO EXPLAIN:

- **Why BHs ubiquitous in present-day galaxies**
- **QSOs with $M>10^9 M_\odot$ at $z>6$**
  - **Age of Universe < 20 $t_{Salpeter}$** (for $\varepsilon \sim 0.1$)

⇩

Eddington-limited accretion would have to:

- **Start early**
- **Be nearly continuous**
- **Start with $M_{BH} > 10 - 100\ M_\odot$**

The Rees Flow Chart

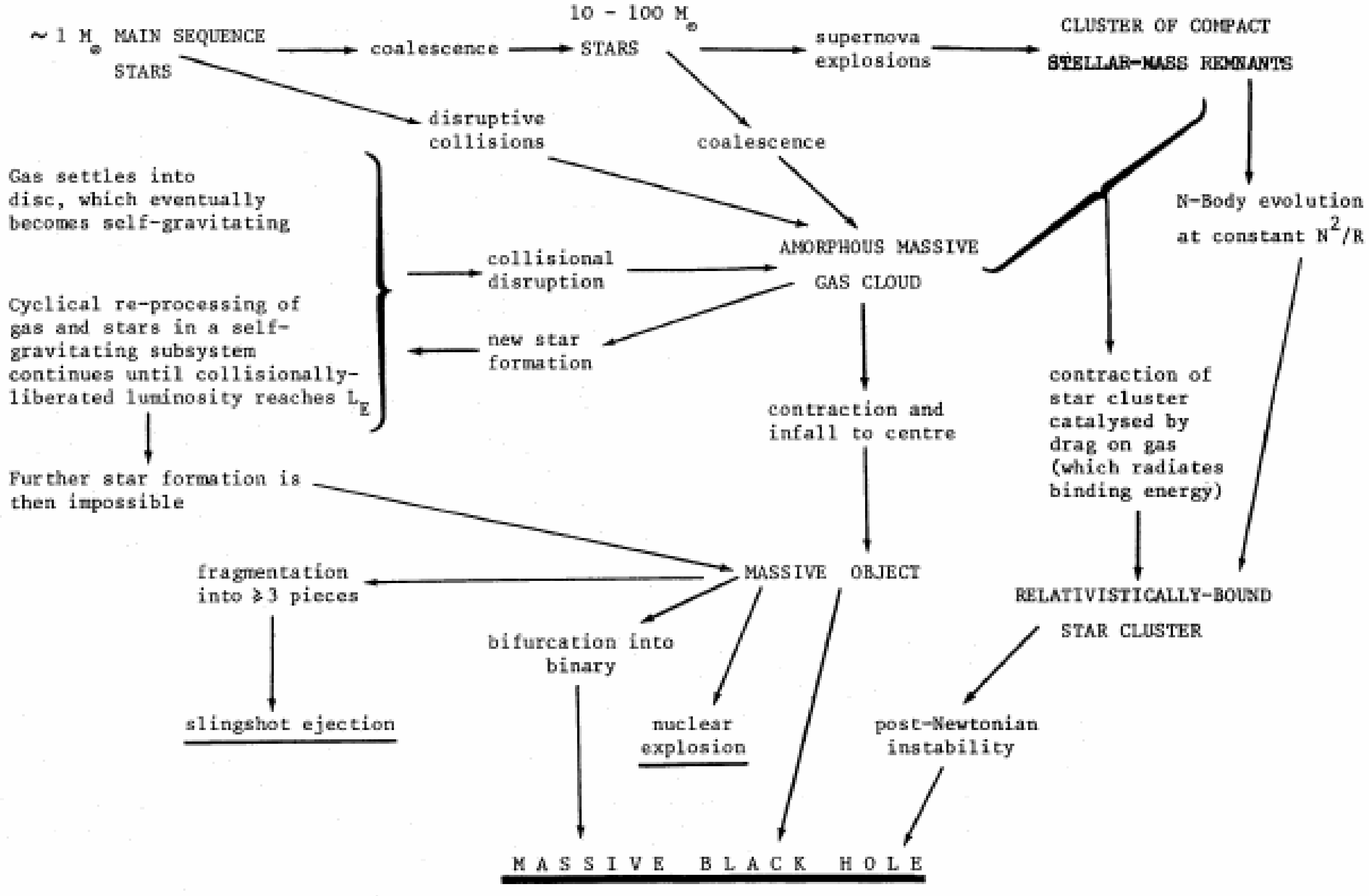
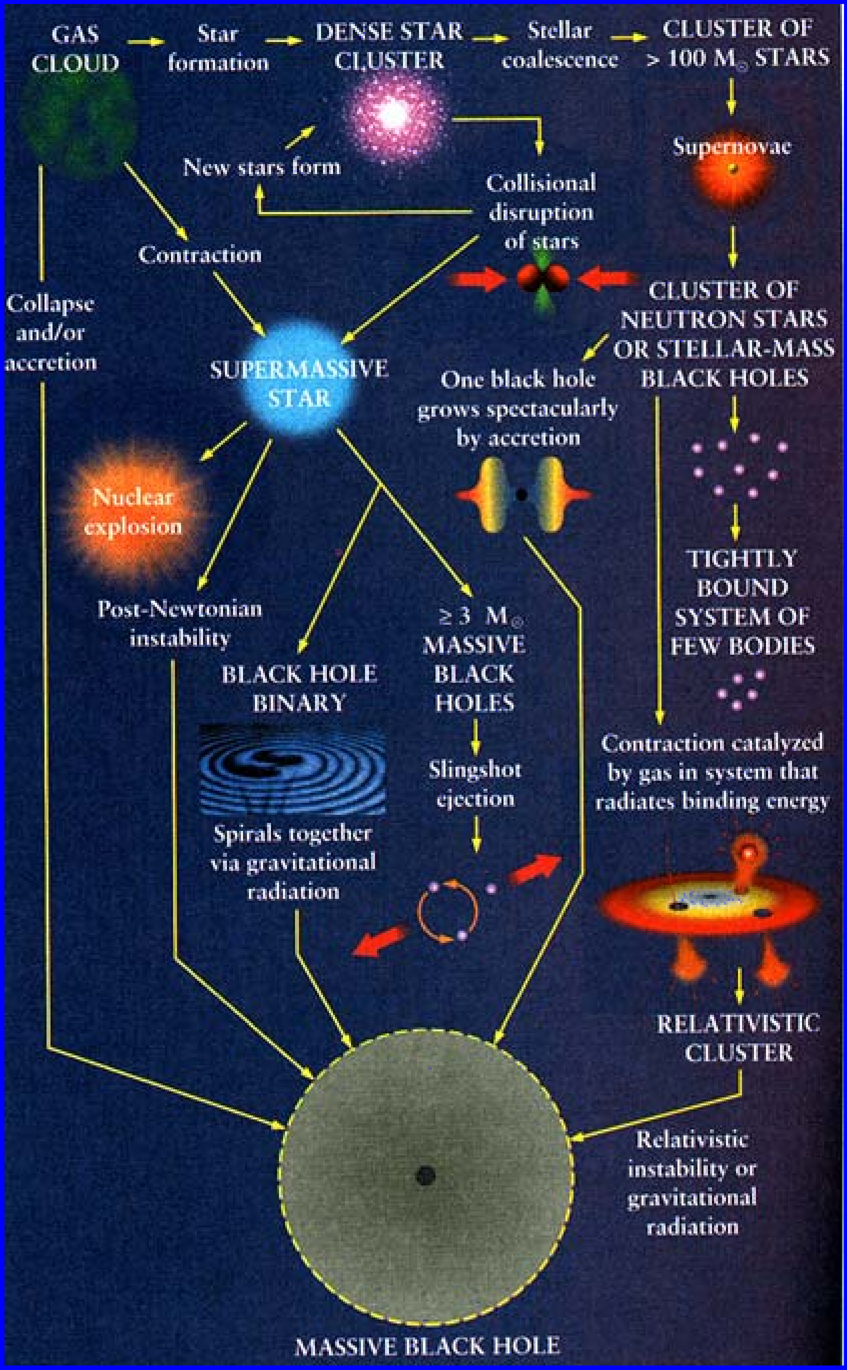


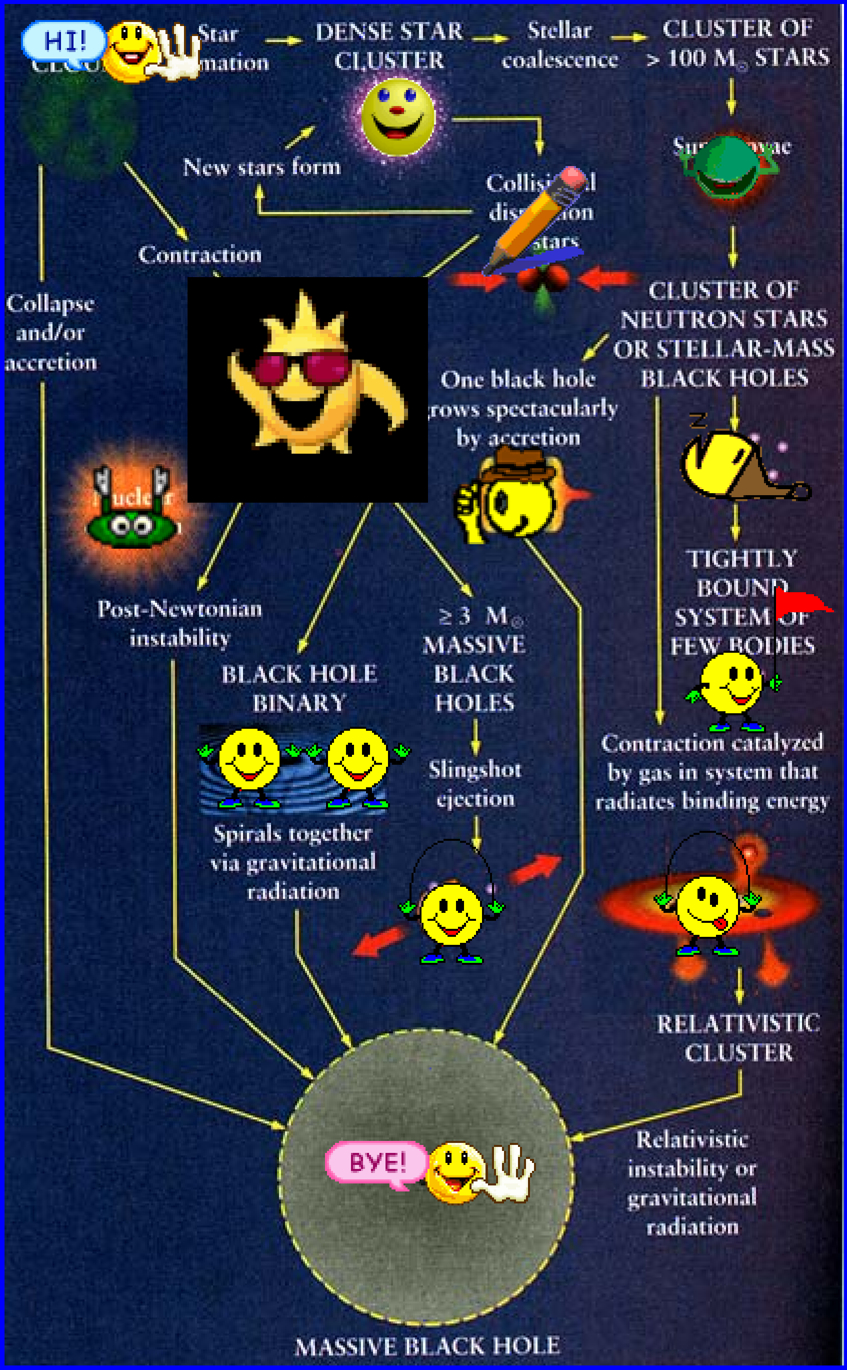
Figure 1

Begelman & Rees, MNRAS 1978

18 years later…
with 4-color printing!



Begelman & Rees,
"Gravity's Fatal Attraction" 1996



Begelman & Rees,
"Gravity's Fatal Attraction"
2nd Edition, coming 2009

CAN THE SEEDS OF SUPERMASSIVE BHs FORM BY DIRECT COLLAPSE?

…without a stellar precursor?

STARS FIRST

- $\dot{M} \sim 10^{-4}$-10^{-2} $M_\odot$ yr^{-1}
- Core contraction halted by nuclear ignition
- High-entropy throughout

DIRECT COLLAPSE

- $\dot{M} > 0.1$ $M_\odot$ yr^{-1}
- Potential too deep for nuclear ignition to halt contraction
- Low entropy core

  $p_{gas} \sim p_{rad}$

  High entropy envelope

  $p_{rad} >> p_{gas}$

ARE HIGH INFLOW RATES POSSIBLE?

- **"Natural" gravitational infall rate v^3/G**
  - **What v to use: v_{vir} of background or c_s?**
  - **Rotation weak: ~ radial infall, mediated by turbulence, "angular momentum segregation"**
  - **Rotating: global instability, "bars within bars"**
  - **Does fragmentation stop collapse?**
    - **Multiple thermal phases**
    - **How efficient is star formation?**

- **Possible sites of rapid infall**
  - **$T_{vir}>10^4$ K haloes: $\dot{M} > 0.1\ M_\odot\ yr^{-1}$**
  - **Aftermath of mergers (Di Matteo, Hernquist, Springel …)**
  - **Wherever quasars are fed (imagine the BH is missing)**

STRUCTURES LAID DOWN BY RAPID INFALL

- Self-gravity dominates
- Radiation-dominated, rotating
- Pre-BH:
  - Entropy small near center, increases with r
  - Very different from the supermassive stars postulated by Hoyle and Fowler
- Post-BH:
  - "Nuclear" energy source is BH accretion
  - Expands and becomes fully convective
  - Like radiation-dominated (metal-free) red giant

RAPID INFALL: NO BLACK HOLE

- **Mass m_* ($M_\odot$) increases with time** $0.1\,\dot{m}_{-1}$ **$M_\odot$ yr^{-1}**
- **Core with** $p_{gas} \sim p_{rad}$
- **Envelope** $p_{rad} / p_{gas} \propto r^{1/2} >> 1$
  - **Entropy increases outward – convectively stable**
  - **Rotation increases binding energy**
- **Outer radius** $r_* \sim 0.5\,\dot{m}_{-1}$ AU **constant**
- **Core radius** $r_c \sim r_* / m_*$ **shrinks**
  - **Nuclear burning inadequate to unbind star**
- **Core mass ~ 10 $M_\odot$ constant**
- **When** $m_* \sim 1800\,\dot{m}_{-1}$, **core temp.** $\sim 5 \times 10^8$ K

⇨ **rapid cooling by thermal neutrinos**

CORE COLLAPSE AND FORMATION OF ~10-20 $M_\odot$ SEED BH

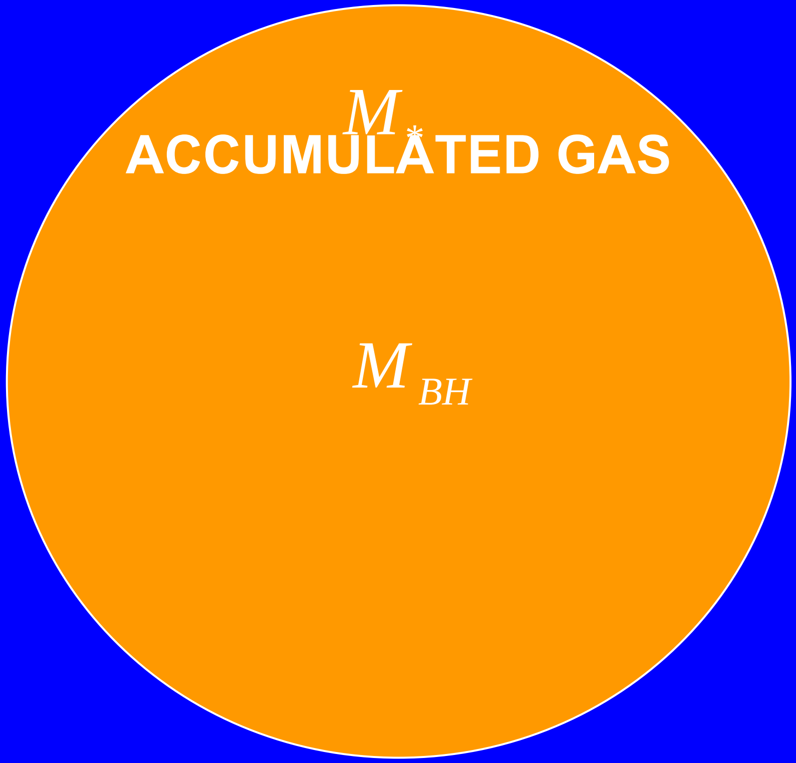
+

SUBSEQUENT ACCRETION AT EDDINGTON LIMIT

BUT WHOSE  LIMIT?

WHOSE  LIMIT?

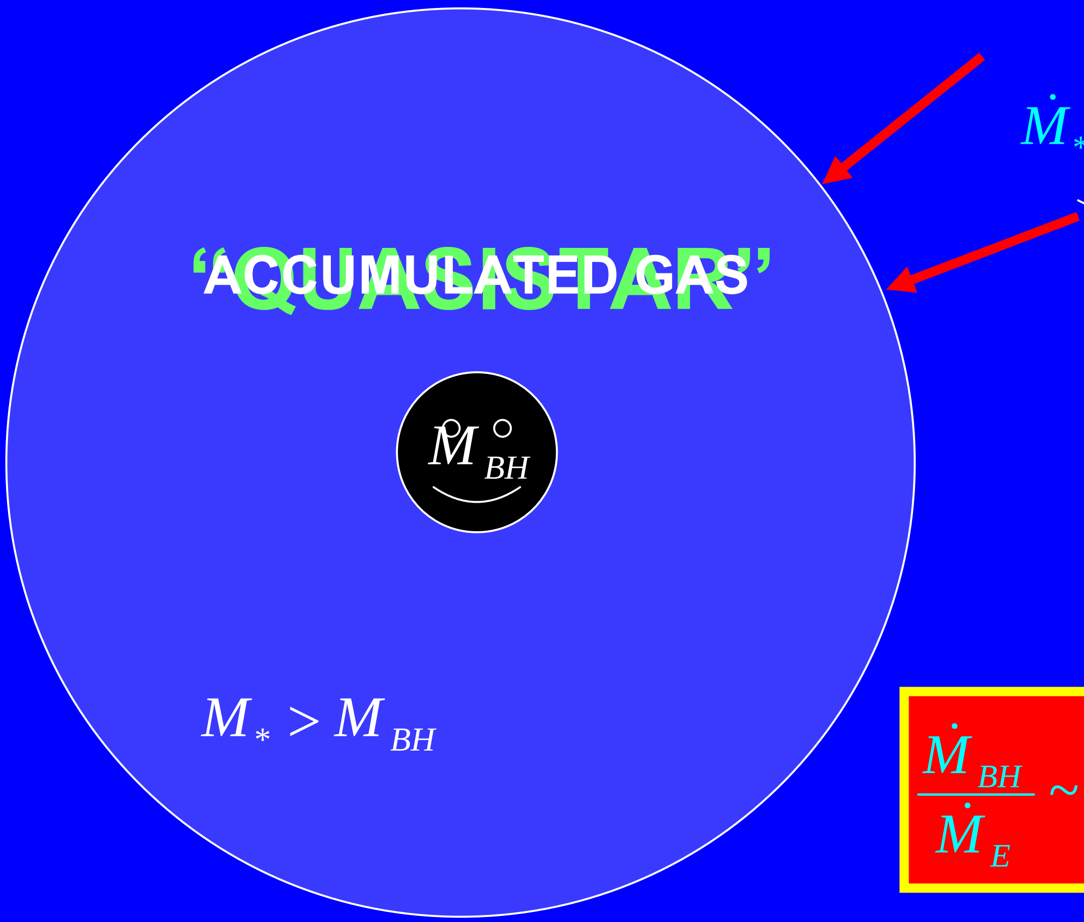
SUPPOSE A SEED BH SETTLES IN THE MIDDLE OF THE ACCUMULATED GAS



Max. BH accretion rate is $\dot{M}_E$ <u>for the mass of the ENVELOPE</u>

$$\dot{M}_{Max} \sim \left(\frac{M_*}{M_{BH}} \right) \dot{M}_E (M_{BH})$$

GROWTH OF AN EMBEDDED BH



$$\dot{M}_* \sim \frac{\alpha\sigma^3}{G} \sim 0.3\alpha\sigma_{10}^3 M_{Sol}\, yr^{-1}$$

$$\frac{\dot{M}_{BH}}{\dot{M}_E} \sim 3\times10^3 \left(\frac{\alpha\sigma_{10}^3}{\varepsilon_{0.1}}\right)^{1/2} \left(\frac{M_{BH}}{M_{Sol}}\right)^{-1/2}$$

Could seed BH grow from ~10 to >10^5 M_{Sol} at $\dot{M} >> \dot{M}_E$?

(Begelman, Volonteri & Rees 06)

STRUCTURE OF A QUASISTAR

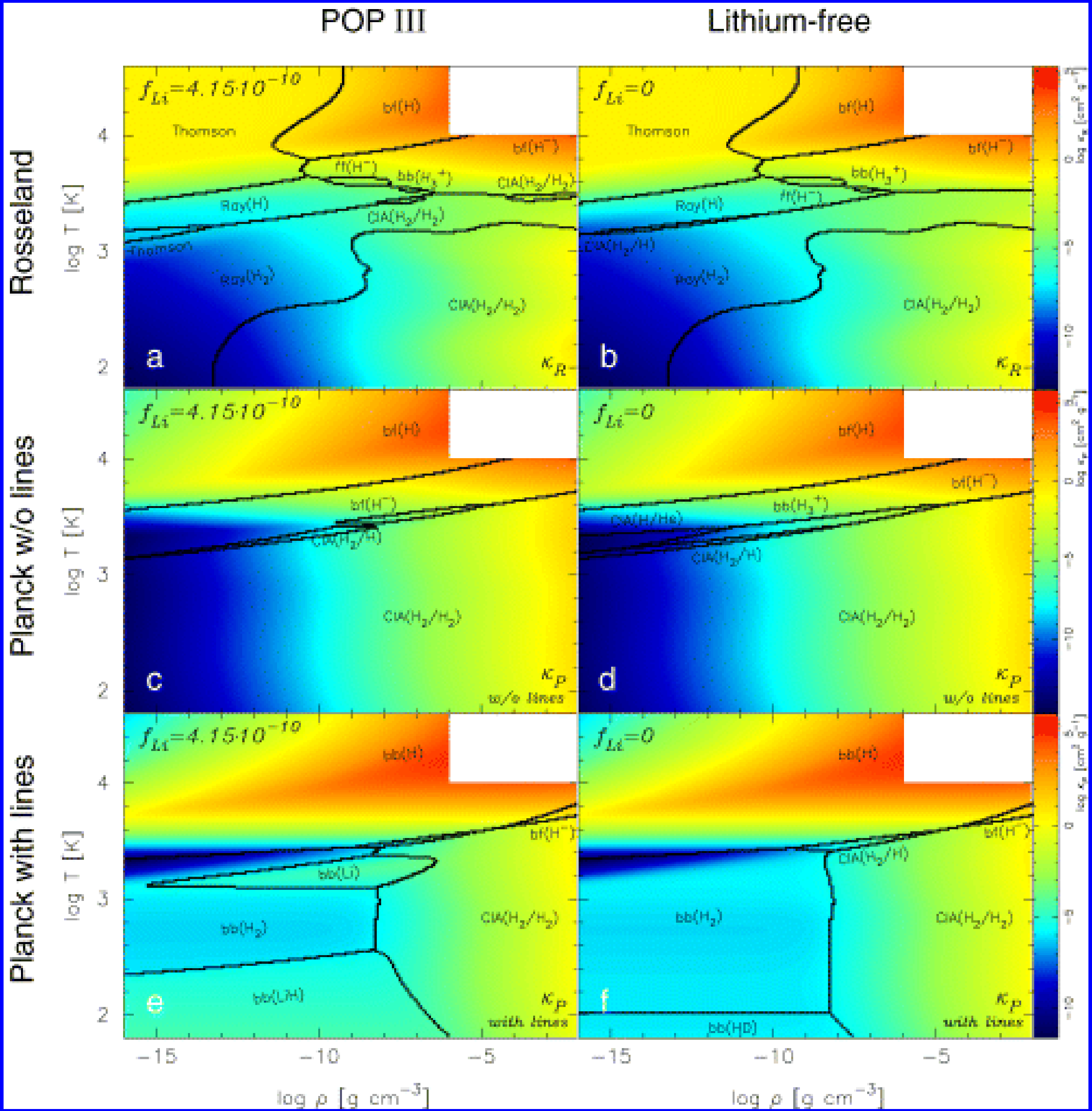
- **BH accretes adiabatically from quasistar interior**

$$\dot{M}_{BH} \sim \dot{M}_{Bondi}\left(\frac{c_s}{c}\right)^2$$

- **Adjusts so energy liberated** $\sim L_{Edd}(M_*)$
- **Radiation-supported convective envelope (w/rotation)**
  - **Central temp drops to ~ 10^6 K**
  - **Radius expands to ~ 100 AU**
  - **Photosphere temp. drops as BH grows**
- **T_{eff} < 4000 K ⇨ opacity crisis**

Mayer & Duschl 2005

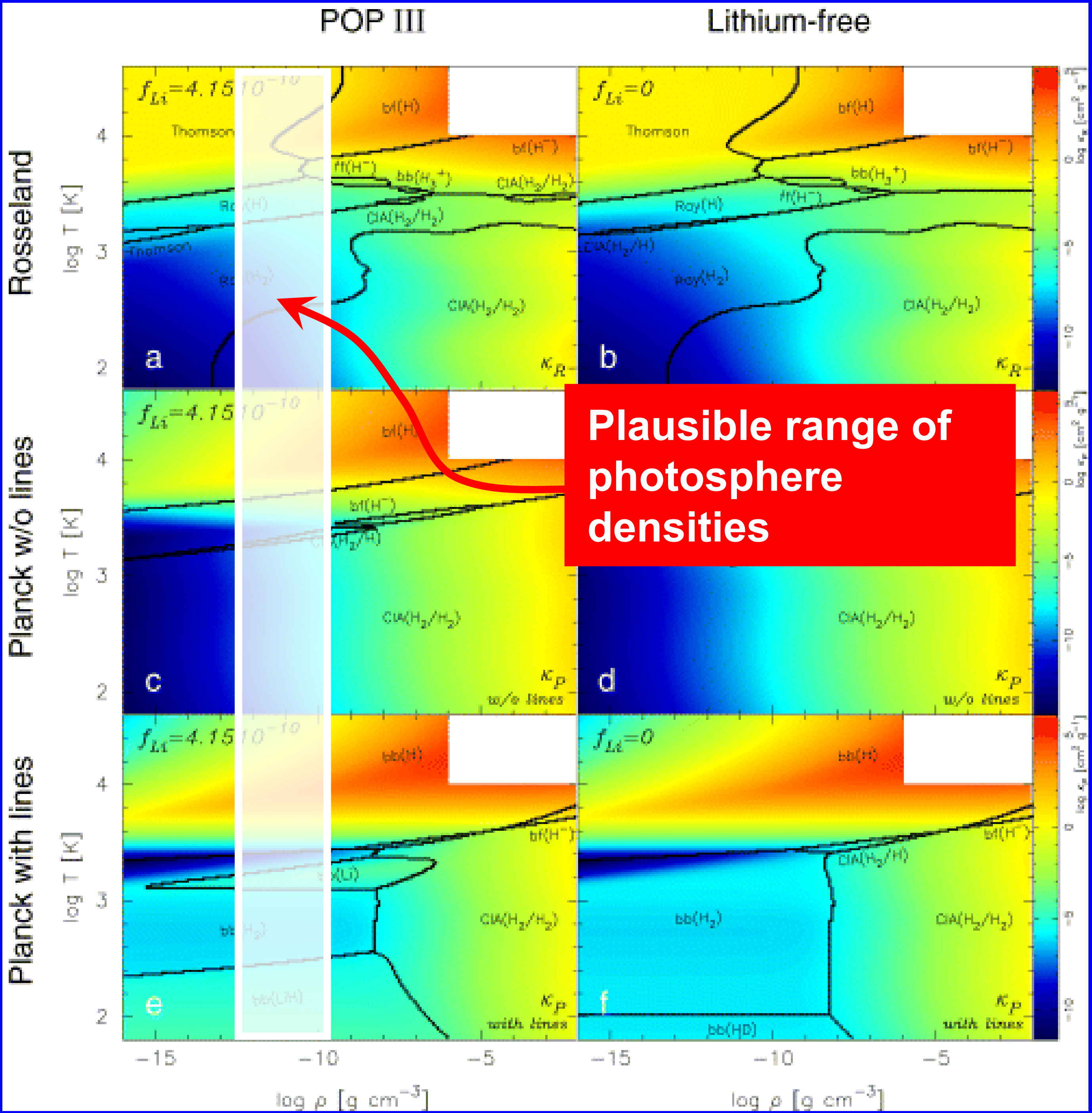
Metal-free opacities



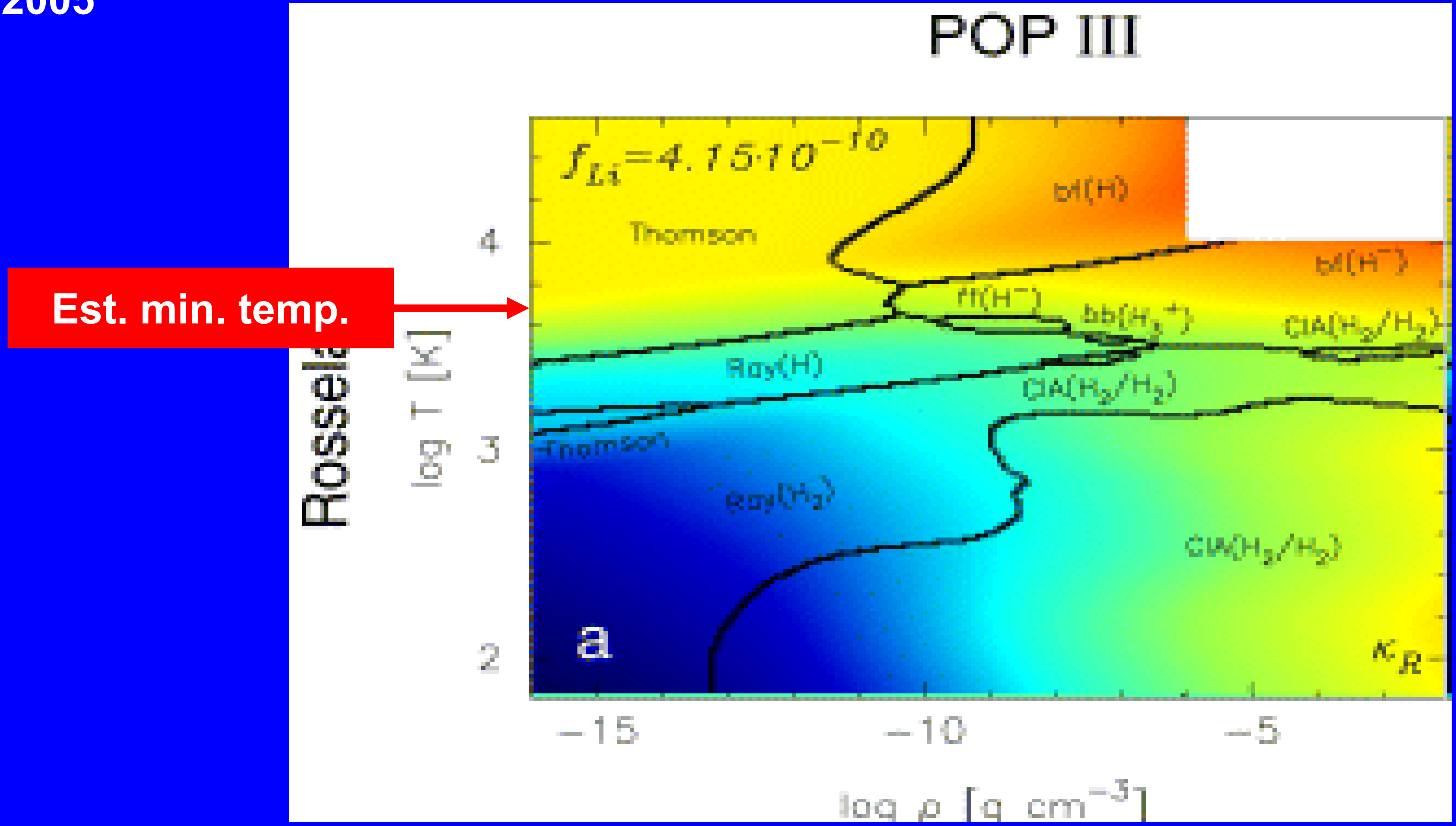
Mayer & Duschl 2005

Metal-free opacities

Analogous to Hayashi track, but match to radiation-dominated convective envelope



Mayer & Duschl
2005



If T_{phot} drops below minimum (~4000 K), flux inside quasistar exceeds Eddington limit, dispersing it.

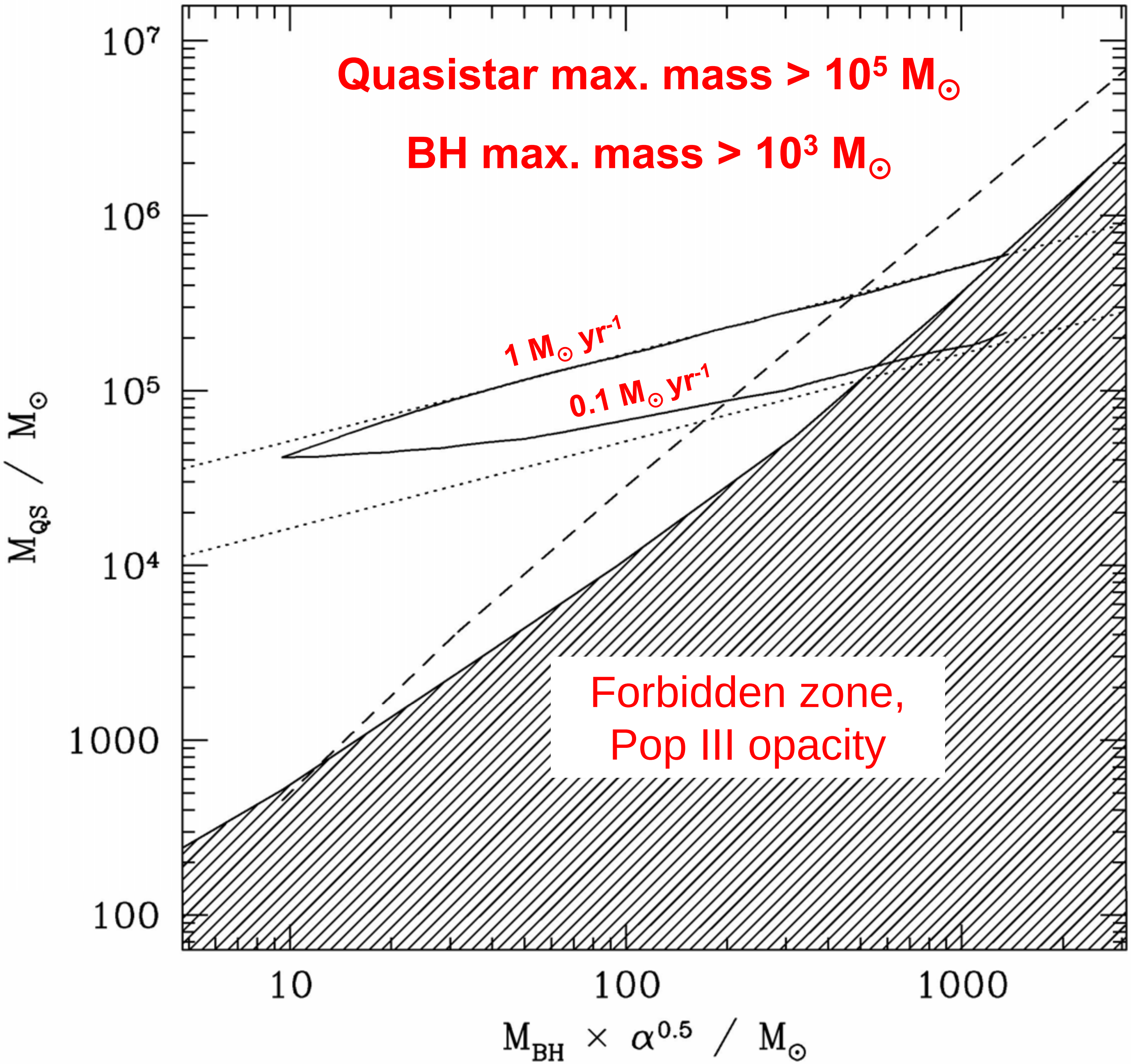
CONNECTION TO BH ACCRETION

$$\frac{T_{phot}}{4000\ \mathrm{K}} \sim 0.25\alpha^{-1/5}\left(\frac{L}{L_E}\right)^{9/20} m_*^{7/20} m_{BH}^{-2/5}$$

Once limiting temperature is reached,

$$\frac{L}{L_E} \sim m_*^{-7/9} m_{BH}^{8/9}$$

… dispersal is inevitable (and accelerates)


Quasistar max. mass > $10^5\ M_\odot$
BH max. mass > $10^3\ M_\odot$
$1\ M_\odot\ yr^{-1}$
$0.1\ M_\odot\ yr^{-1}$
Forbidden zone,
Pop III opacity
10^7
10^6
10^5
10^4
1000
100
$M_{QS}\ /\ M_\odot$
10
100
1000
$M_{BH} \times \alpha^{0.5}\ /\ M_\odot$

CAN QUASISTARS BE DETECTED?

…consider 10^4 K haloes as parent population

DETECTING A QUASISTAR

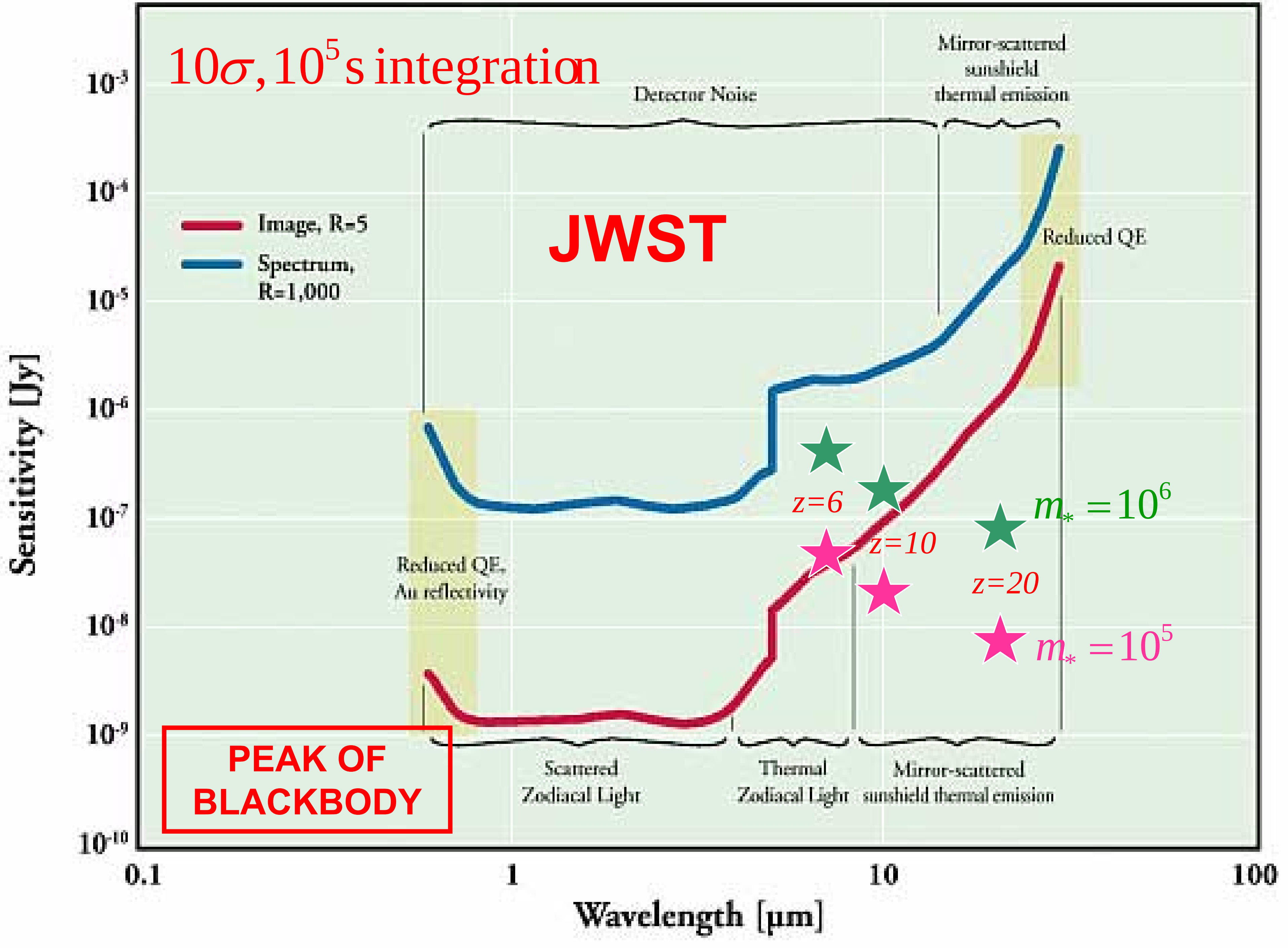
- **Most time spent as ~4000 K blackbody**
- **Radiates at Eddington limit for $10^5 m_5\ M_\odot$**

$$F_{\nu,\max} \sim 2.3\times10^{-5} m_5 T_{5000}^{-1}(1+z)D_{L,Gpc}^{-2}\ \mathrm{Jy}$$

$$\lambda_{\max} = (1+z)T_{5000}\ \mu m$$

- **Max flux ~**

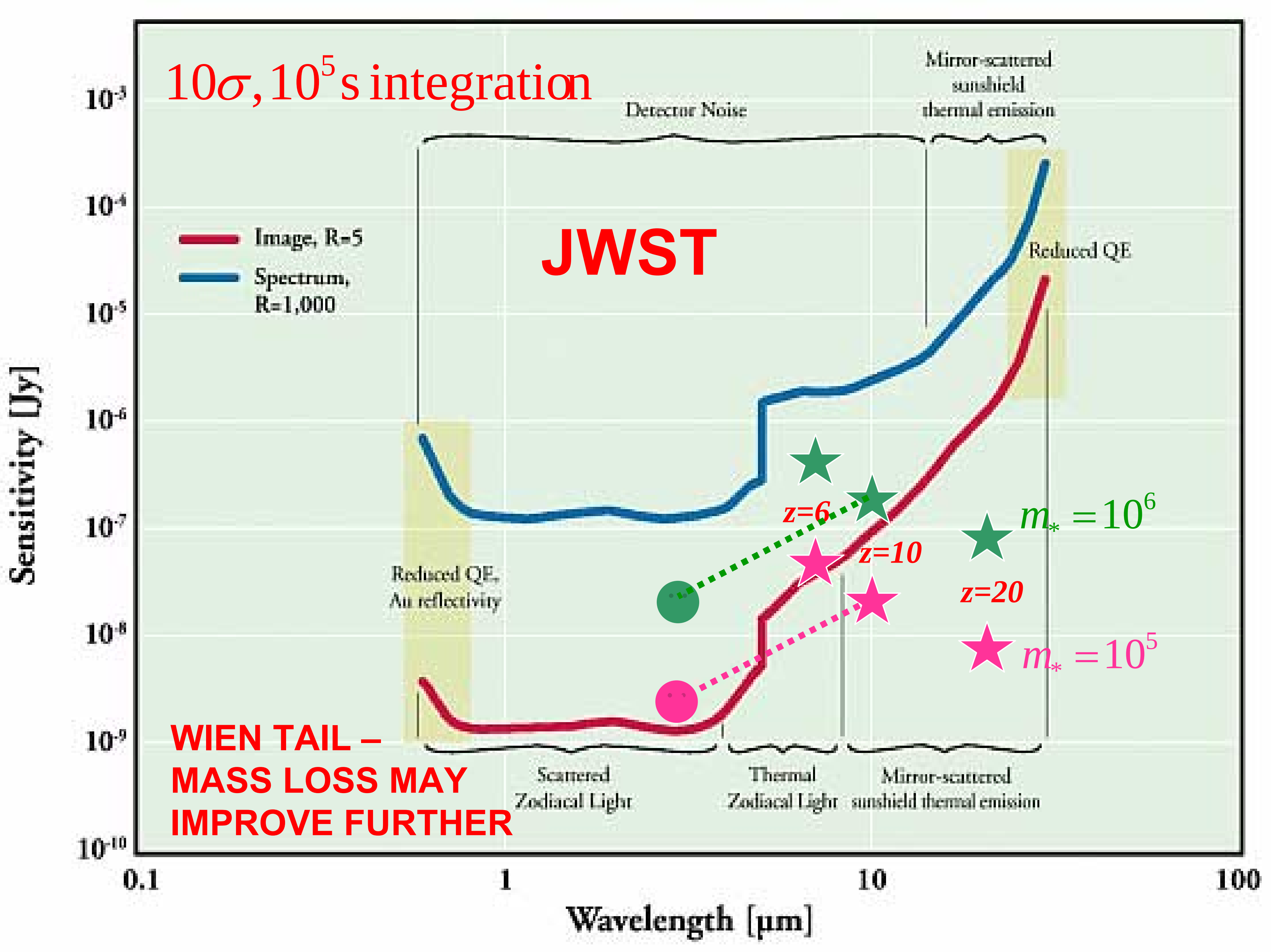
$10^{-8} - 5\times10^{-7}$ Jy for $z \sim 6-20$, $m_* \sim 10^5 - 10^6$



$10\sigma, 10^5$s integration
JWST
Detector Noise
Mirror-scattered sunshield thermal emission
Image, R=5
Spectrum, R=1,000
Reduced QE
Reduced QE, Au reflectivity
$z=6$
$z=10$
$z=20$
$m_* = 10^6$
$m_* = 10^5$
PEAK OF BLACKBODY
Scattered Zodiacal Light
Thermal Zodiacal Light
Mirror-scattered sunshield thermal emision
Sensitivity [Jy]
Wavelength [μm]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100

DETECTING A QUASISTAR

- Better to observe @ 3.5μm, on Wien tail
- Corona/mass loss/jet ⇨ hard tail, easier detection



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Reduced QE, Au reflectivity
z=6
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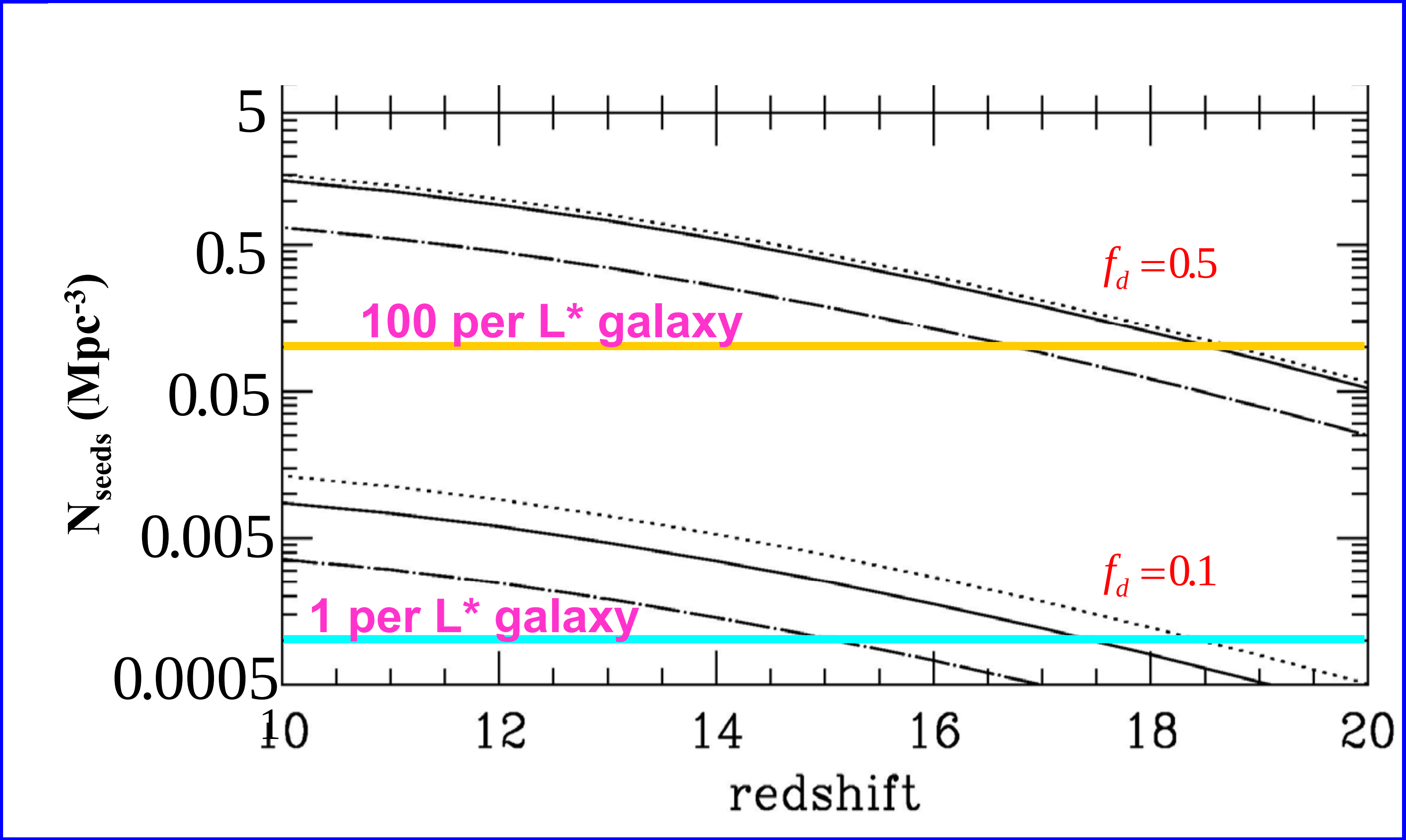
$m_* = 10^6$
$m_* = 10^5$
WIEN TAIL – MASS LOSS MAY IMPROVE FURTHER
Scattered Zodiacal Light
Thermal Zodiacal Light
Mirror-scattered sunshield thermal emision
Sensitivity [Jy]
Wavelength [μm]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100

HOW COMMON ARE QUASISTARS?

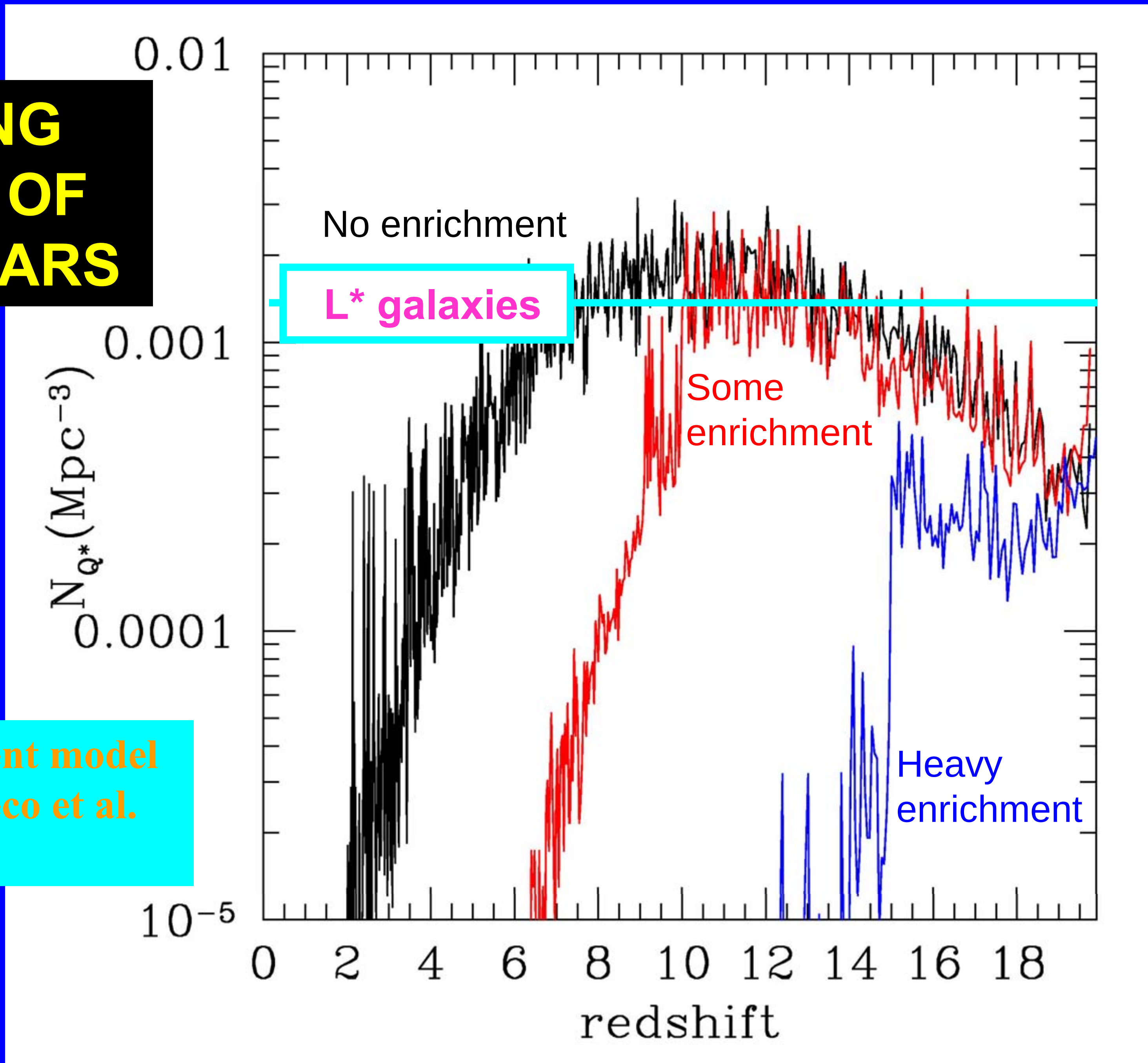


Cumulative comoving no. density of seeds

…but their lifetimes are short

COMOVING DENSITY OF QUASISTARS

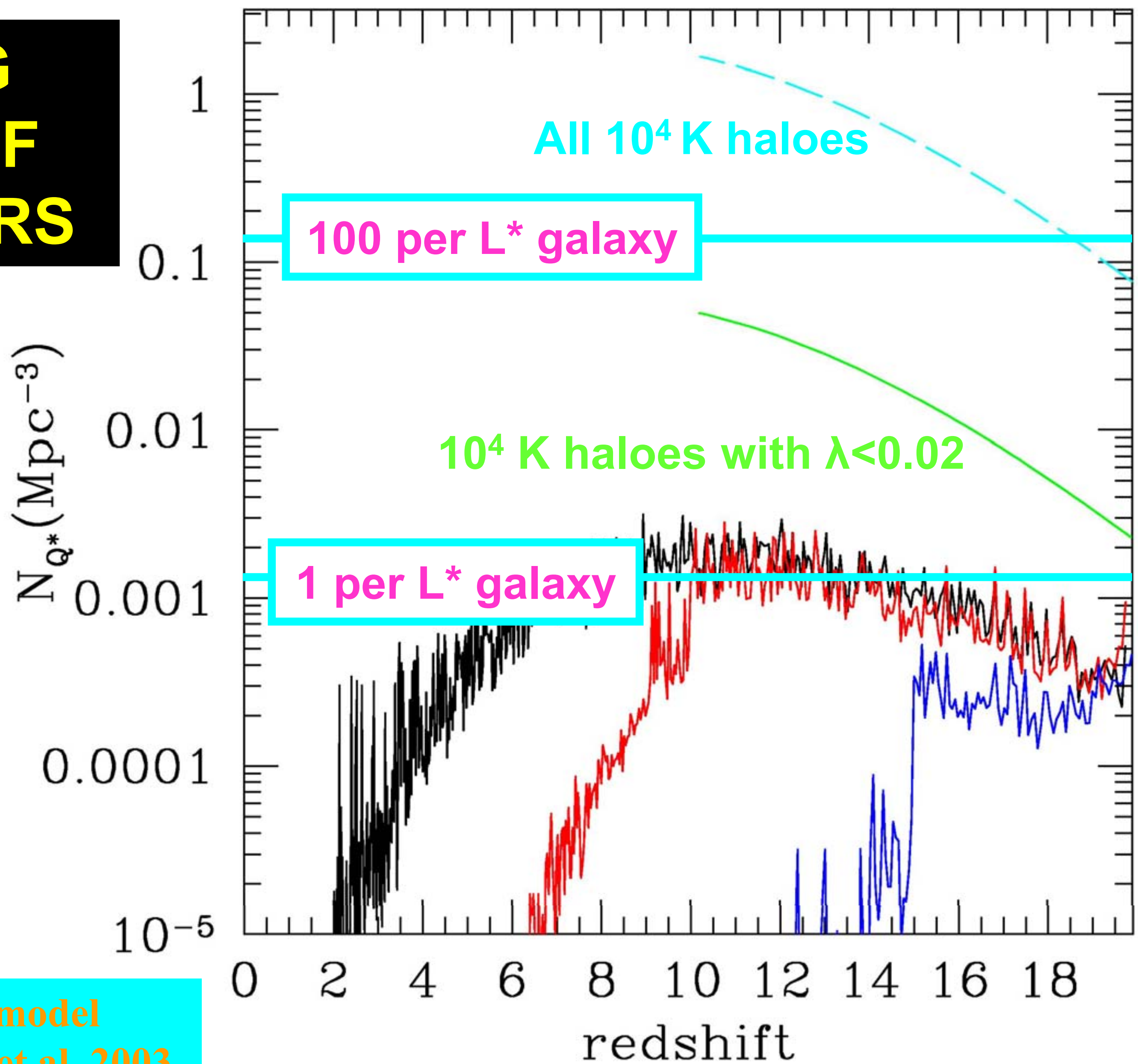
Lifetime = 10^6 yr



Metal enrichment model from Scannapieco et al. 2003

COMOVING DENSITY OF QUASISTARS

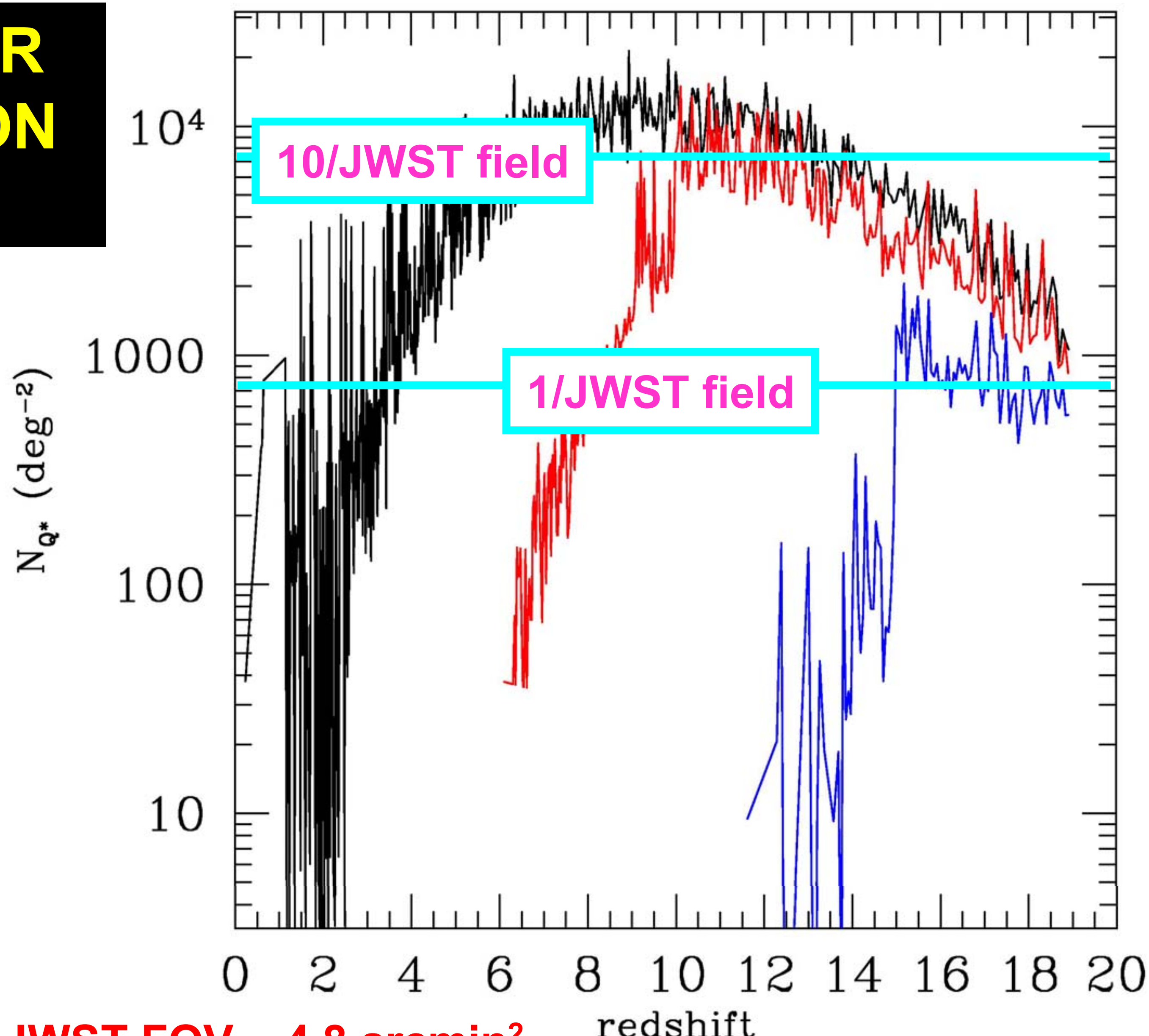
Lifetime = 10^6 yr



Metal enrichment model from Scannapieco et al. 2003

QUASISTAR DENSITY ON SKY

Lifetime = 10^6 yr



JWST FOV ~ 4.8 arcmin^2

HOW TO DISTINGUISH FROM OTHER OBJECTS?

- Colors: ~pure blackbody (not dust reddened)
  - Observe on Wien tail
  - No lines (distinguish from T dwarfs)
- Unresolved (distinguish from nearby starbursts)
- Clustering (like 10^4 K haloes)
- Detect protogalactic host
- Radiation from quasistar coronae/jets?

WHAT HAPPENS NEXT?

- If super-Edd. phase extends beyond opacity crisis, BH seeds could be as massive as $10^6\ M_\odot$
- Worst case: super-Edd. phase ends at $\sim 10^3\ M_\odot$
- 10 $t_{Salpeter}$ between z=10 and z=6 ⇨ growth by (only) 20,000

BUT

- – Exceeding L_{Edd} by factor 2 ⇨ squares growth factor!
- – Mergers can account for factor 10-100 of growth

CONCLUSIONS I

I. Star formation might be bypassed if inflow rate is high enough $(\dot{M} > 0.1 M_{Sol} yr^{-1})$

II. BH seed can form in situ from the infalling envelope itself (aided by ν cooling) or can be captured Pop III remnant

III. BH can grow at Eddington limit for the surrounding envelope, which can be $\gg \dot{M}_{Edd}$ for the BH

CONCLUSIONS II

IV. BH seeds grow inside a "quasistar" powered by BH accretion, with a radiation pressure-supported convective envelope

V. Min. T_{eff} of quasistar is ~4000 K, lifetime is > 10^6 yr

VI. Quasistars could be common and may be detectable by JWST