Supermassive star formation with detailed modelling of primordial-gas chemistry

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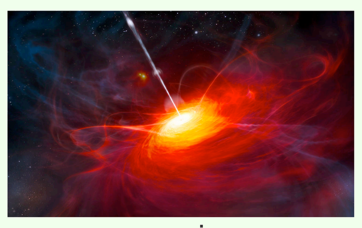
Abstract:

Direct-collapse black holes (DCBHs) formed at z > 10 are prominent candidates of the seeds for supermassive black holes (SMBHs). They are thought to be formed in pristine atomic cooling halos in which H_2 cooling is totally suppressed by strong external radiation. Here, we obtain the critical specific intensity at the Lyman-Werner (LW) bands J_{21}^{cr} (in units of 10^{-21} erg s^{-1} Hz^{-1} $sr^{-1} cm^{-2}$) required for DCBH formation, with detailed modelling of the primordial-gas chemistry. Specifically, we consider the non-local thermodynamic equilibrium(non-LTE) chemistry with the vibrationally resolved H_2^+ kinetics, as well as realistic radiation spectra of galaxies. We find the effects of non-LTE H_2^+ chemistry are negligible for hard spectra of young and/or metal-poor galaxies. However, for softer spectra, J_{21}^{cr} can be increased by a factor of a few due to the non-LTE effects. As a typical value of J_{21}^{cr} in the early Universe, we obtain almost constant J_{21}^{cr} with $J_{21}^{cr} \sim 1000$ for young (age $\lesssim$ 100 Myr) and/or extremely metal-poor ($Z \lesssim 5 \times 10^{-4} Z_\odot$) galaxies.

Introduction

Supermassive BH (SMBH) seeds



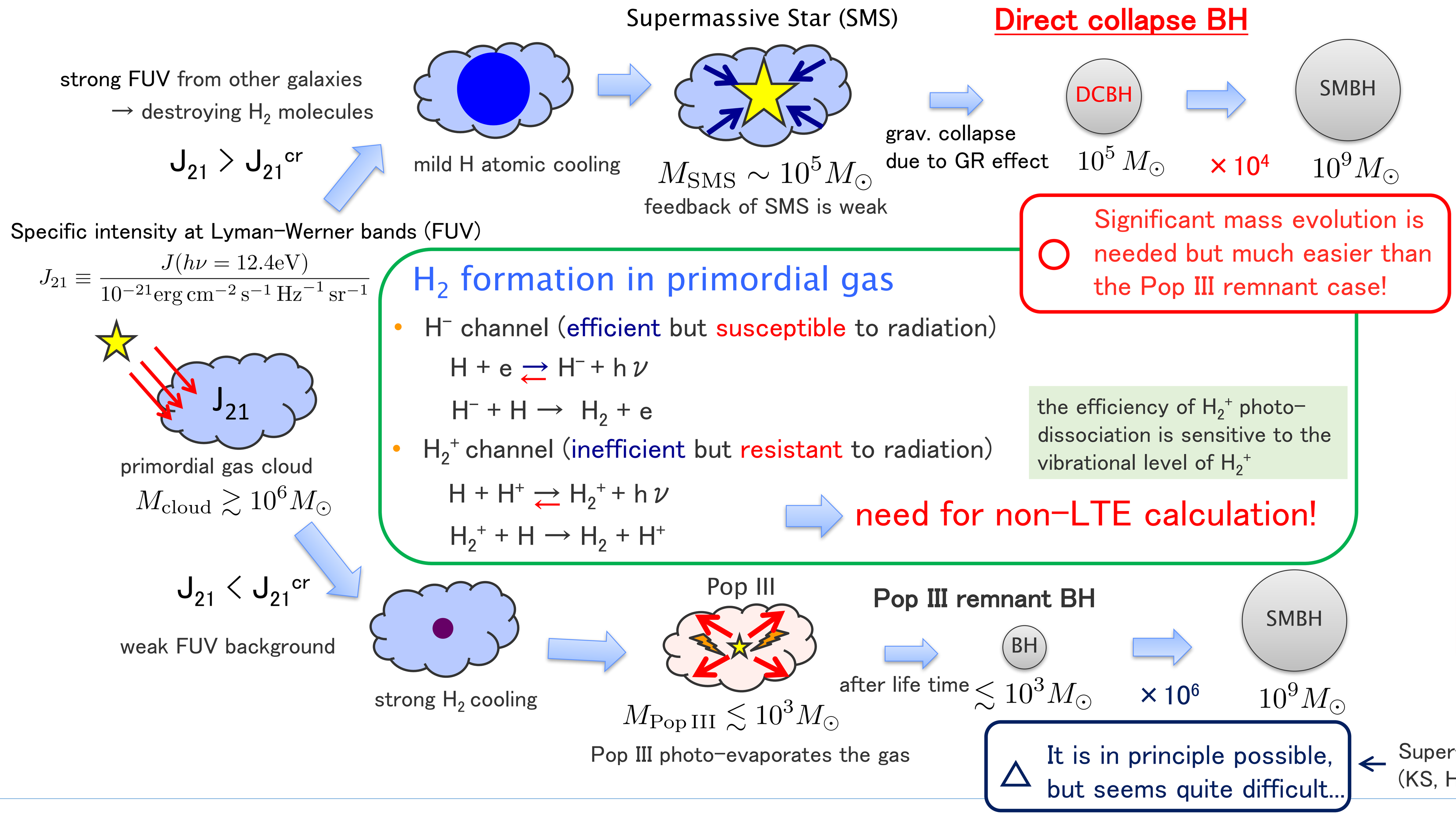
quasar image
(Credit: ESO/M. Kornmesser)

- About 40 high-z SMBHs ($M_{BH} \sim 10^9 M_{sol}$) have been found as quasars at with $z > 6$ ($t_{univ} < 1$Gyr) (cf. Mortlock+11)

Q: How such huge objects form in the first 1Gyr of the Universe?

We first need to reveal the SMBH seeds (= starting point of SMBH formation)

Direct Collapse BH (DCBH) vs Pop III remnant BH scenarios



Importance of J_{cr}^{21}

(critical J_{21} needed for DCBH formation)

- Growth of DCBHs to SMBHs is relatively easy
- # density of DCBHs is sensitive to J_{21}^{cr}
- Feasibility of DCBH scenario strongly depends on J_{21}^{cr}

Aim of this work

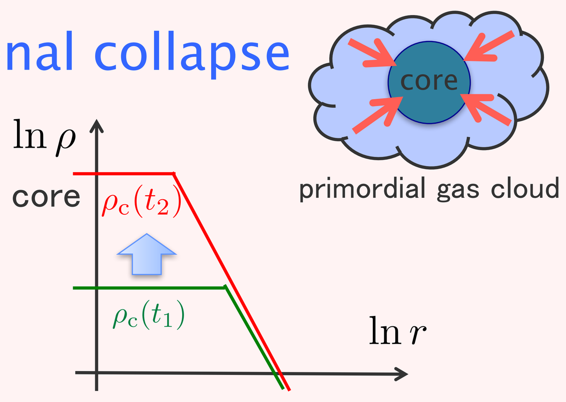
To determine J_{21}^{cr} considering all relevant radiative/chemical/thermal processes

In this work:

- we include the non-LTE chemistry of the H_2^+ vibrational state
- we consider realistic spectra of galaxies in the early Universe

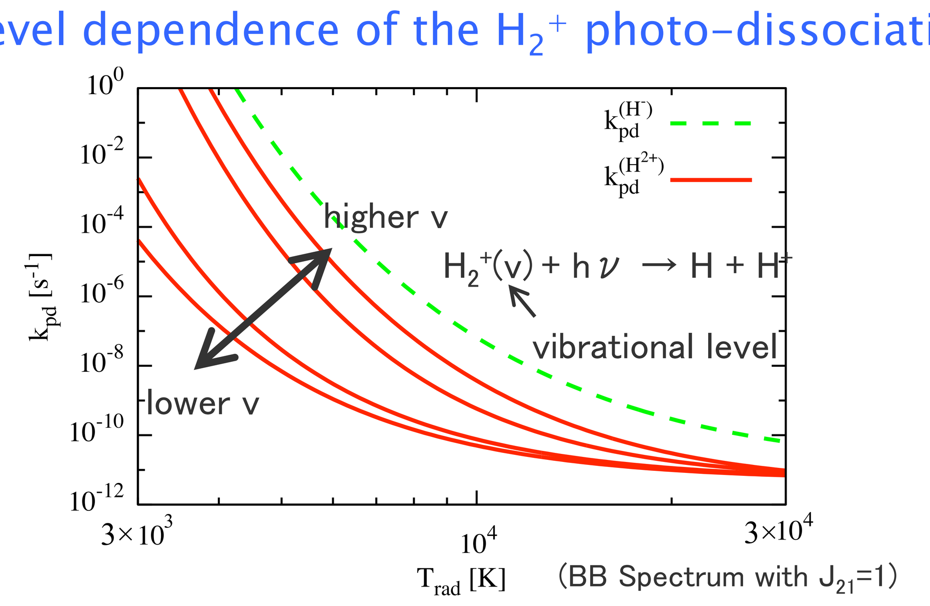
Model & Method

1-zone model for gravitational collapse

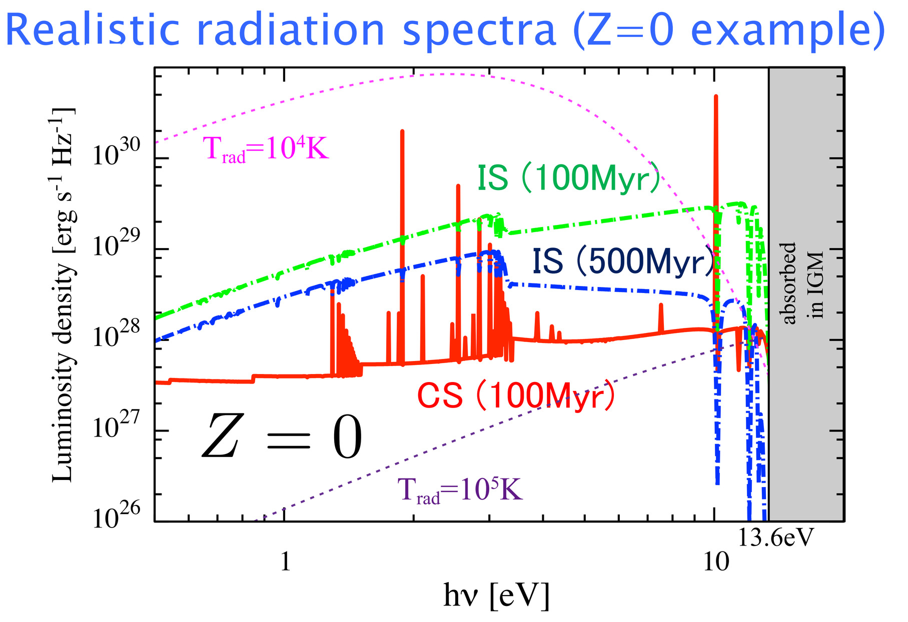


- Dynamics
  - density evolution is modeled by that of the self-similar solution
  - $d\rho_c/dt = \rho_c/t_{ff}$ $\left(t_{ff} = \sqrt{3\pi/32G\rho_c}\right)$
  - ⇨ evolution of density n (= ρ / μ m_p)
- Chemistry/thermodynamics
  - chemical network of molecules (w/ non-LTE chemistry of H_2^+)
    - H, H^+, H^-, e, H_2, $H_2^+(v=0,1, \cdots, 18)$, He, He^+, He^{2+}, HeH^+
    - ⇨ evolution of chemical fraction y_i (= n(i)/n)
  - energy equation (total energy conservation with emission/absorption)
    - ⇨ evolution the gas temperature T_{gas}
- External UV radiation model
  - Realistic spectra calculated with Starburst99 and Shaerer02
    - Z=0, $5\times10^{-4}Z_\odot$, $0.02Z_\odot$, $0.2Z_\odot$ t_{age}= 10Myr - 1Gyr (instantaneous SB (IS)/constant SF (CS))
    - Salpeter IMF 1-100 $M_\odot$
  - Black-body (BB) spectra with T_{rad}

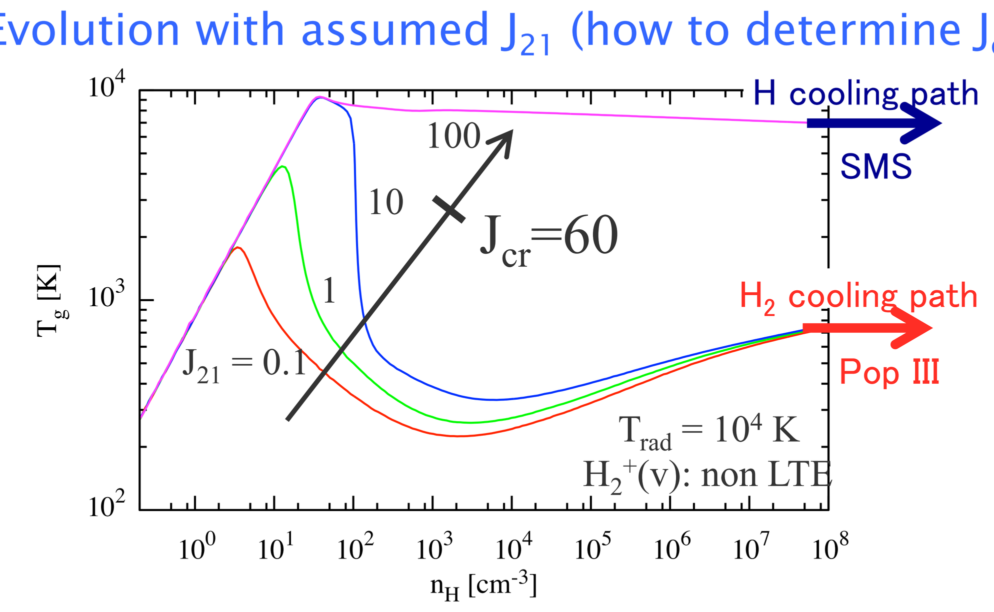
Level dependence of the H_2^+ photo-dissociation



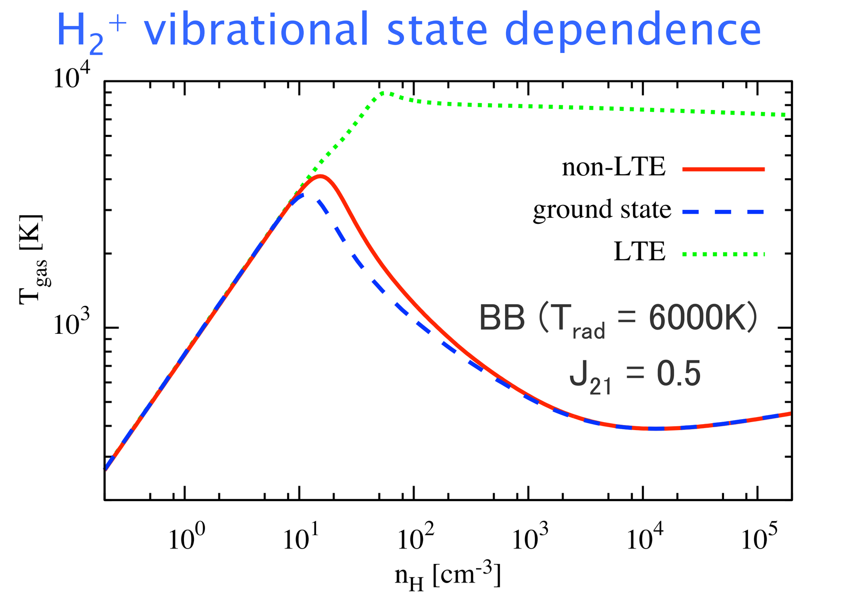
Realistic radiation spectra (Z=0 example)



Evolution with assumed J_{21} (how to determine J_{cr})

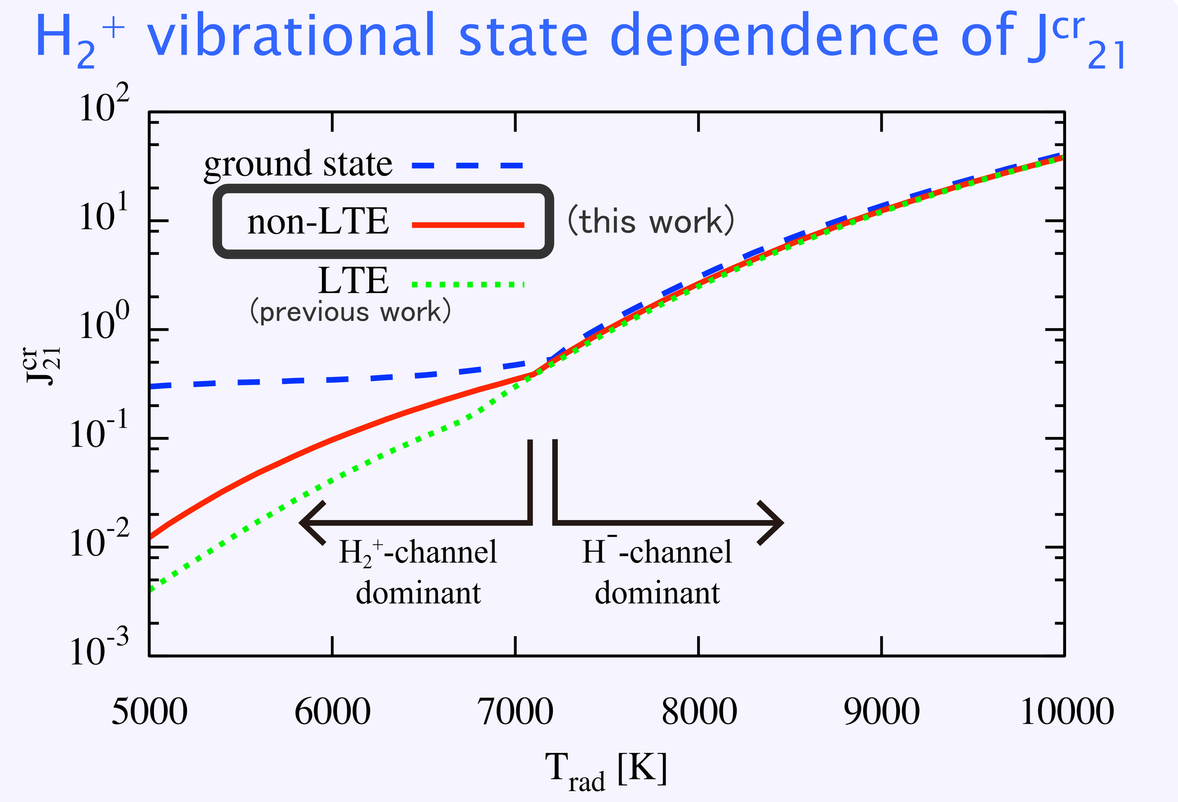


H_2^+ vibrational state dependence



Results & Conclusions

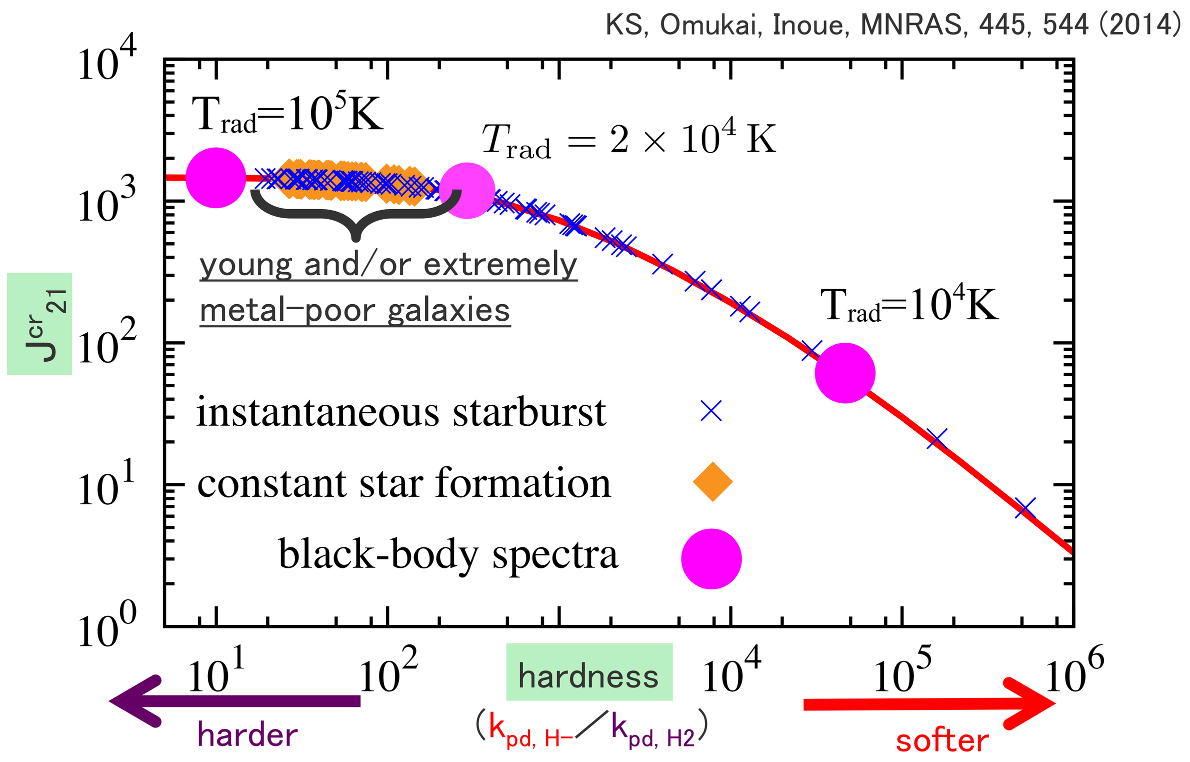
H_2^+ vibrational state dependence of J^{cr}_{21}



- Non-LTE chemistry of H_2^+ vibrational state is important for T_{rad} < 7000K
  - ⇨ J_{21}^{cr} is underestimated by a factor of a few if the LTE is assumed

J_{21}^{cr} for realistic spectra of galaxies

KS, Omukai, Inoue, MNRAS, 445, 544 (2014)



- For most of galactic spectra studied here, the hardness corresponds to $T_{rad} > 10^4$ K and non-LTE chemistry of H_2^+ does not affect J_{21}^{cr}
- For young (age < 100 Myr) and/or extremely metal-poor ($Z < 5 \times 10^{-4} Z_\odot$) galaxies, J_{21}^{cr} is almost constant with $J_{21}^{cr} \sim 1000$

Conclusions & Discussions

- We study the critical radiation intensity J_{21}^{cr} (in units of 10^{-21} erg s^{-1} Hz^{-1} $sr^{-1}cm^{-2}$) required for DCBH formation with consideration of non-LTE H_2^+ chemistry and realistic radiation spectra
- In the case the external radiation has soft spectrum (T_{rad} < 7000K), non-LTE chemistry of H_2^+ vibrational state is important and J_{21}^{cr} is underestimated by a factor of a few if LTE is assumed
- Young and/or extremely metal-poor galaxies, which are thought to be typical radiation sources in the early Universe, have hard spectra and their J_{21}^{cr} is almost constant with J_{21}^{cr} ~ 1000
- By extrapolating the result of Dijkstra, Ferrara & Mesinger (2014) with J_{21}^{cr} ~ 1000, we obtain n_{DCBH} ~ 10^{-10} $cMpc^{-3}$ at z = 10, which is roughly consistent with observed n_{SMBH} at z ~ 6
- Our result suggest that the non-LTE chemistry of H_2^+ becomes important when soft radiation strongly suppresses H_2 formation
- Such soft radiation can be emitted/caused by …
  - background galaxies at high-z/CMB at extremely high-z (z > 50?)
  - proto-supermassive stars, if they actually form