# Rapid Formation of Massive Black Holes via Intense Lyman-Werner Radiation

Photo: Gail Guido

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# Outline

I. Forming massive BH: rapid gas infall in atomic cooling halo

II. Rapid gas infall requires absence of $H_2$: Lyman-Werner flux

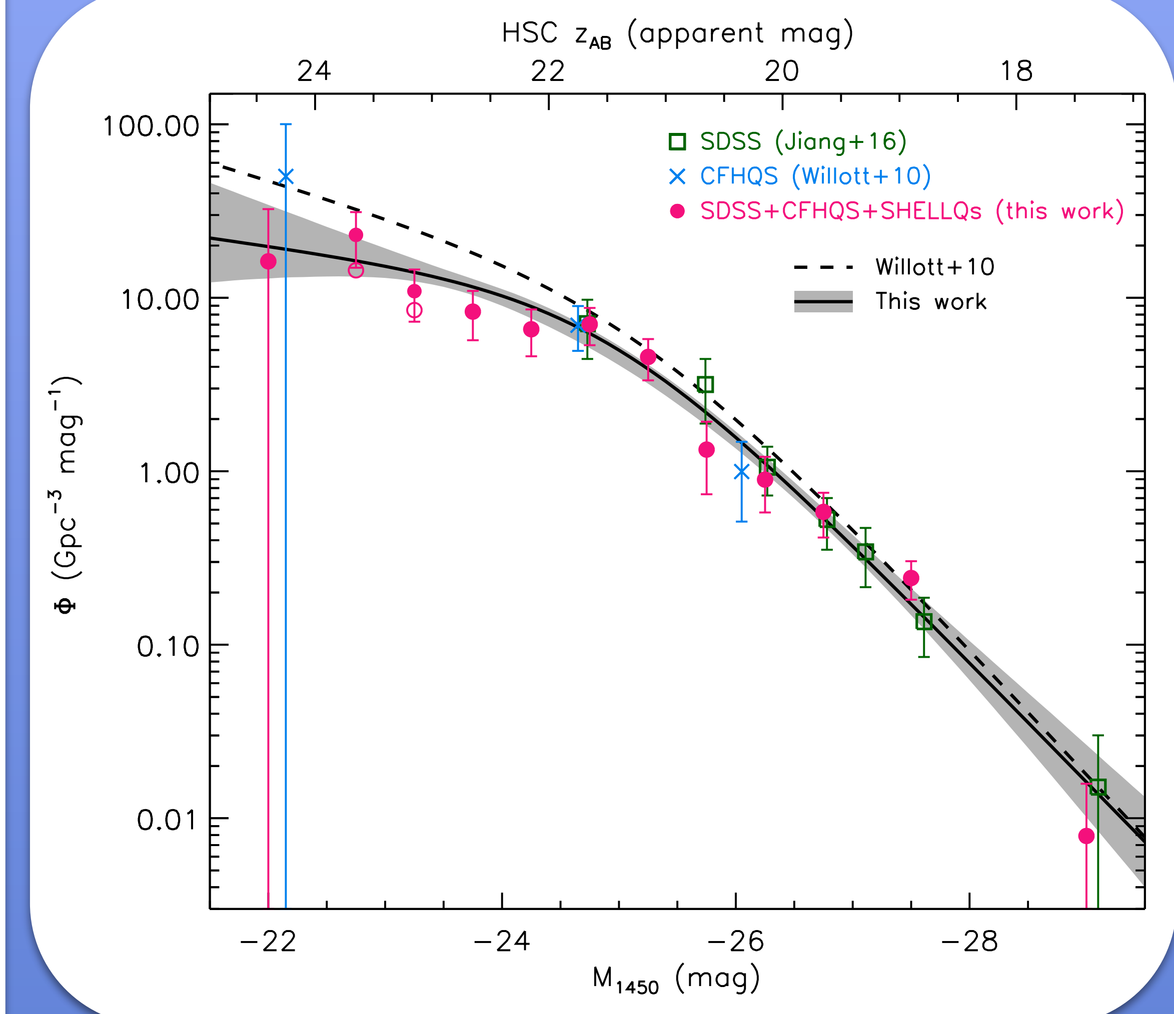
# Redshift z>6 Quasar BHs

- Rare (“$5\sigma$”) objects:
  - *~10 found in SDSS at z>6*
  - *~20 in CFHQS & ~10 others*

- Record: z = 7.54 *(t=0.7 Gyr)* *(Banados et al . 2018; UKIDDS+WISE+DECaLS)*

- Tip of the iceberg (?):
  - *space density ~1 $Gpc^{-3}$*

- Mass estimates:
  - $M_{bh} = L_{obs}/L_{Edd} \sim 10^{9\text{-}10}\ M_\odot$ (~Eddington luminosity)
  - $M_{halo} \sim 10^{12\text{-}13}\ M_\odot$ (matching space density)



Matsuoka et al. (201)

# A Promising Site: Atomic Cooling Halos

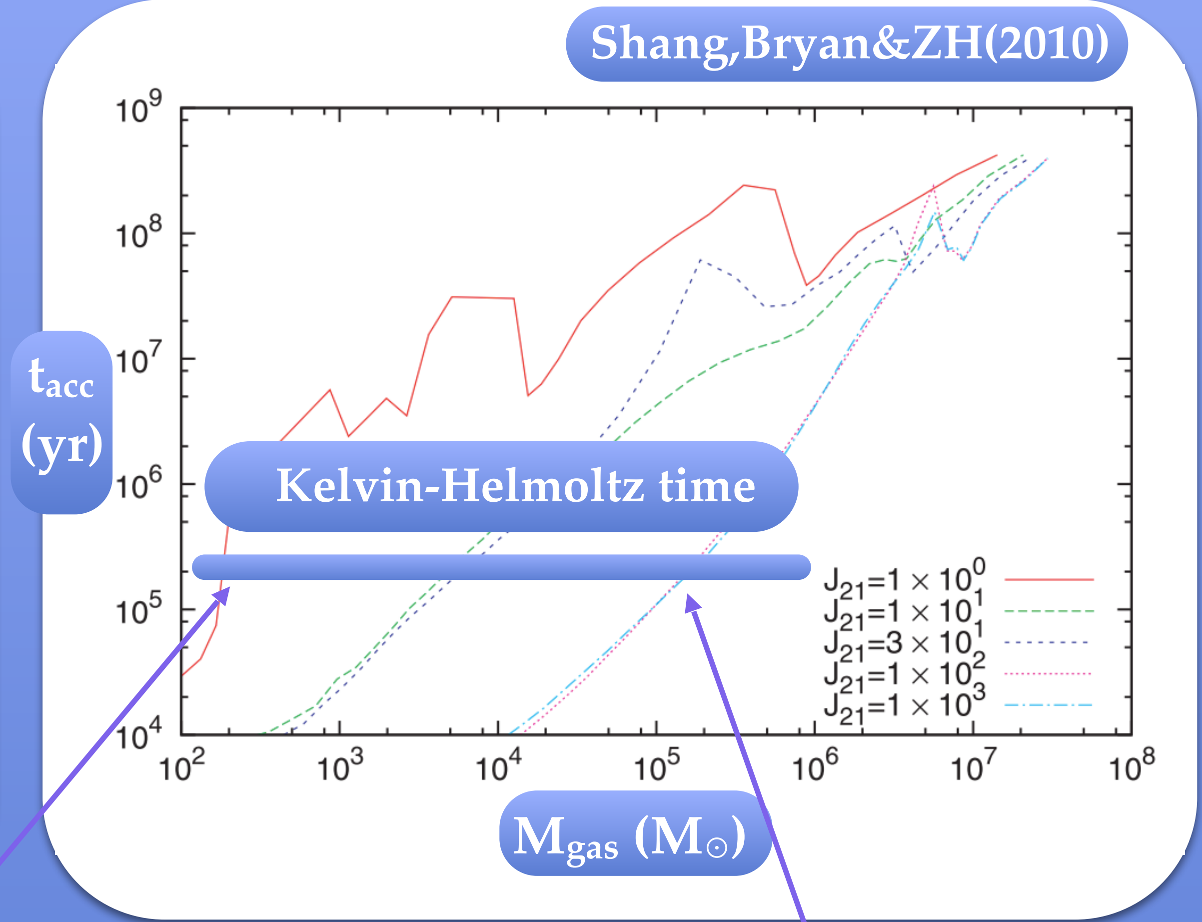
*Main assumption: gas remains at $T \approx 10^4$ K*
*(no $H_2$ or metals) and cools via atomic H*

- Second generation ("atomic-cooling") halos: $T_{vir} > 10^4$ K
- Deep potential - gas driven in rapidly: $M_{acc} \propto c_s^3/G \approx 0.1\text{-}1\ M_\odot\ \mathrm{yr}^{-1}$
- Jeans mass $M_J \propto T^{3/2} / \rho^{1/2} \approx 10^{5-6}\ M_\odot$ (—> Mo-Mao-White disk)
  with isothermal gas at $T = 10^4$ K ~ $T_{vir}$ is thick and *Toomre-stable*
  gas could avoid local fragmentation (Oh & Haiman 2002; Lodato+2007)
- No efficient fragmentation seen in simulations
  (Bromm & Loeb 2003; Wise & Abel 2007; Regan & Haehnelt 2009 …)
- A few fragments possible, but coalesce faster than forming stars
  (Regan et al 2014; Inayoshi & Haiman 2014; Becerra et al. 2015 )

# Mass of Central Object

- infall at sound speed $c_s \approx 10$ km/s
- mass accretion rate: 0.1-1$M_{\odot}$ $yr^{-1}$
- central object has mass $M \approx 10^5 M_{\odot}$
- what is it? SMS, BH, or star cluster
- Does not matter → all lead to BH
  - cf. $M \approx 10^2 M_{\odot}$ with $H_2$ ($c_s \approx$ 1-2 km/s)

➡ large $H_2$ dissociating flux required



$10^{2\text{-}3}$ $M_{\odot}$ Pop III Star (Abel et al., Bromm et al., Yoshida et al.)

$10^5$ $M_{\odot}$ SMBH seed
Fuller, Woosley & Weaver (1986)

Explicit modeling of rapidly accreting protostars: $M_{crit}$~0.05-0.1 $M_{\odot}yr^{-1}$

Hosokawa+2012,2015; Haemmerle+2017

# Getting rid of $H_2$: LW photodissociation

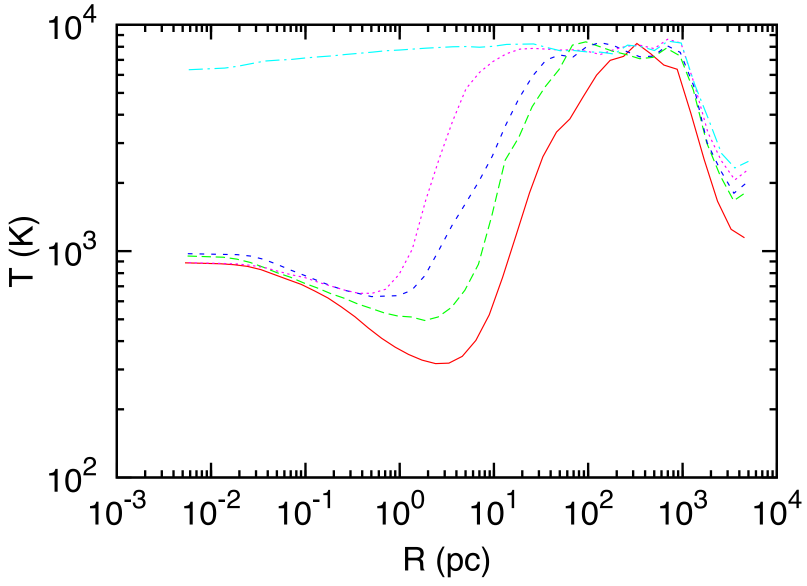
- Lyman-Werner (LW) radiation (11.1-13.6 eV) dissociates $H_2$

- [$H_2$-formation rate $\propto \varrho^2$]
  = [photodiss. rate $\propto J_{LW}\,\varrho$]
- Critical flux $\propto \varrho$ [$\propto T_{vir}^{3/2}$]

- $J_{21,crit}$ ~ 0.1-1 in minihalos
  (n~ 0.1-1cm$^{-3}$) < reionization
  (needed to avoid large CMB τ)

- Atomic cooling halos:
  Lyα cooling & self-shielding
  must avoid $H_2$-cooling up to
  n~ $10^4$ cm$^{-3}$
- $J_{21,crit}$ ~ $10^{3-4}$ in 3D simulations
  (Shang et al. 2009, etc. etc.)

- Formation:
  $H + e^- \longrightarrow H^- + \gamma(IR)$
  $H^- + H \longrightarrow H_2 + e^-$
- Destruction:
  $H_2 + \gamma(UV) \longrightarrow (^*)H_2$
  $(^*)H_2 \longrightarrow H + H + \gamma(IR)$

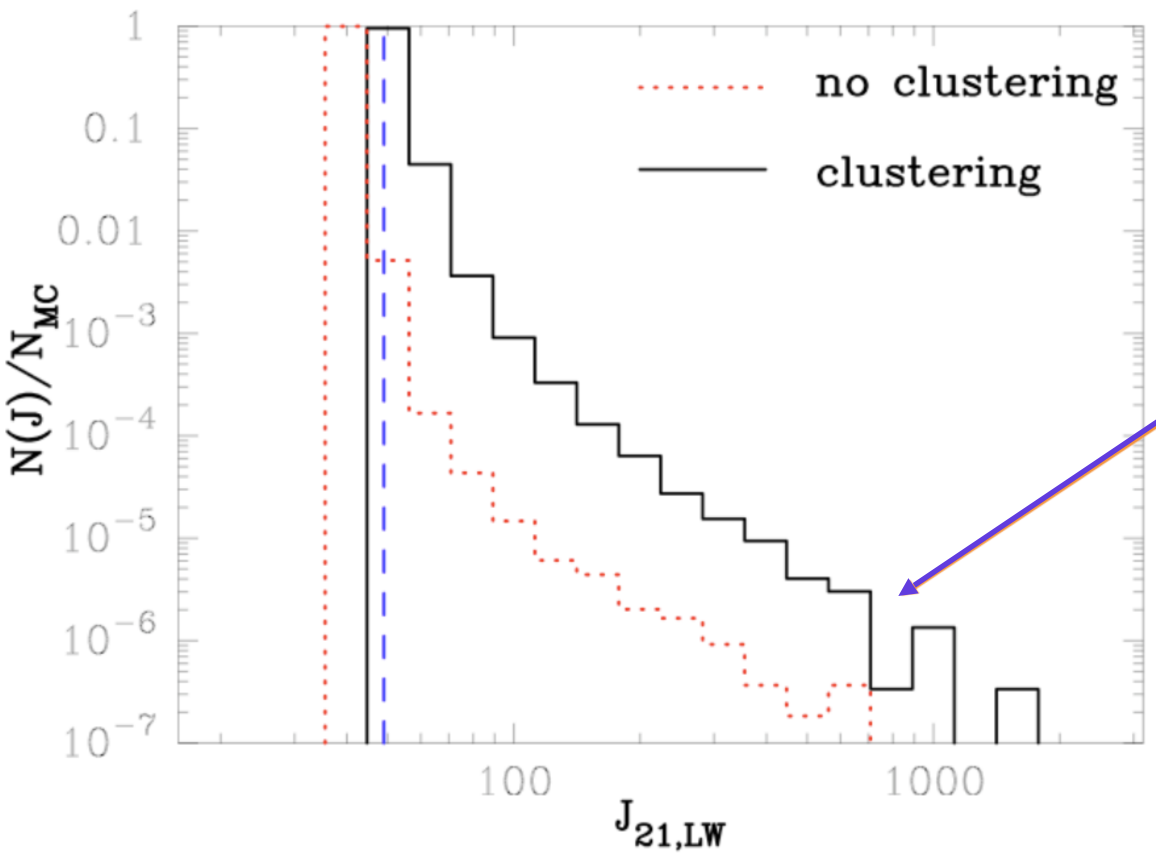


Shang, Bryan & ZH (2010)

# Large LW flux from bright nearby halo (?)

**Flux seen by halos varies**

- (non-linear) clustering of $\sim 10^{8\text{-}9} M_\odot$ halos
- Poisson fluctuations in # of neighbors
- UV luminosity scatter



Dijkstra, ZH, Mesinger & Wyithe (2008)

- **1 in ~ $10^6$ halos** has a close (~few kpc) bright neighbor, so it sees a flux ~30x mean background
- **N ~ $10^3$ Gpc$^{-3}$** halos, could all end up in z=6 QSO hosts
- *small changes in $J_{crit}$ → large change in # candidates*

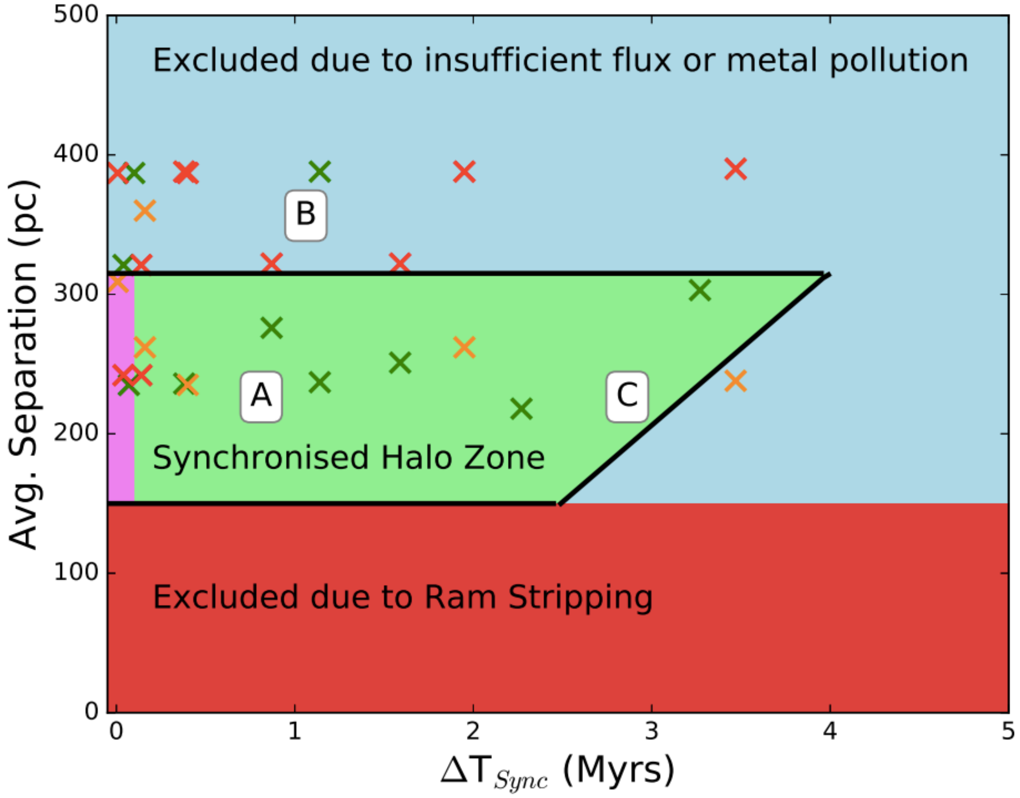
# Synchronized formation of subhalo: N-body

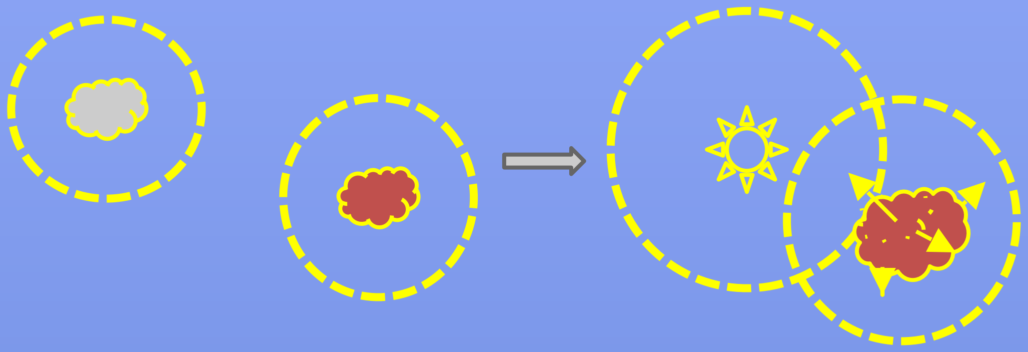
Visbal, ZH, & Bryan (2014)

- N-body needed to properly include clustering of halos on small scales
- Five Gadget-2 runs (768$^3$ particles, L = 15 cMpc)
- We found 2 synchronized pairs (<10 Myr, 0.5kpc)
- Abundance of z>6 SMBHs with $M_{bh}$ ~$10^9$ $M_\odot$ is n ~ 1 cGpc$^{-3}$
- Need ~1 candidate at z=10 per $60^3$ N-body boxes
- —> we overdid it by $10^4$
- Extrapolate w/analytic model: enough pairs with much tighter synchronization ($\Delta t_{sync}$~0.2 Myr)
- This can help to avoid external metal pollution: $10^5$ $M_\odot$ BH forms before stars in neighbor produce SNe and metals reach MBH host halo

# Synchronized Collapse: Hydro simulation

- Strong LW from a bright neighbor (+ background)
  - $\Delta t_{sync} < 4$ Myr
  - $d_{sep} \sim$ a few x 100 pc

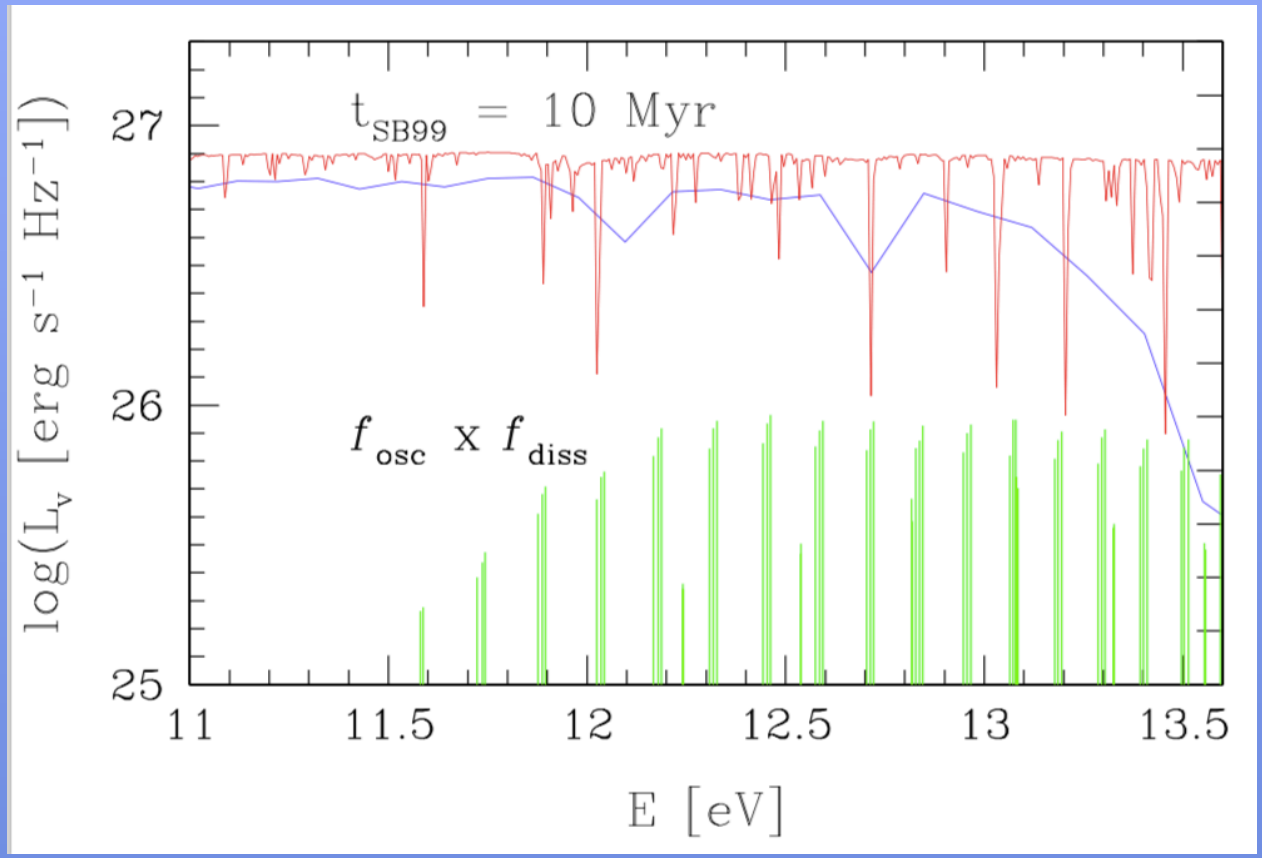


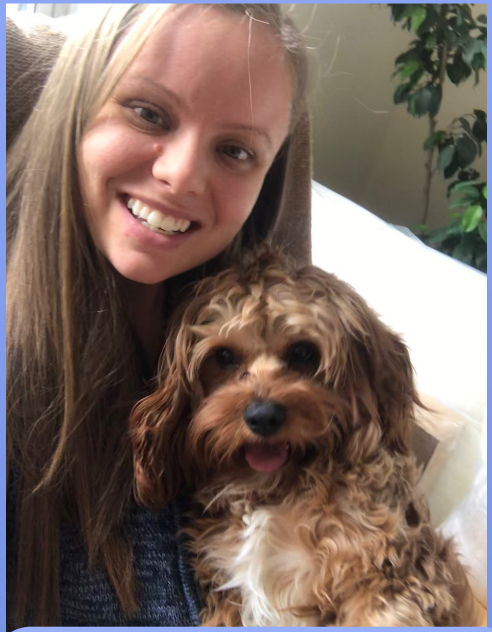


Danger: does starburst evaporate BH-forming gas?

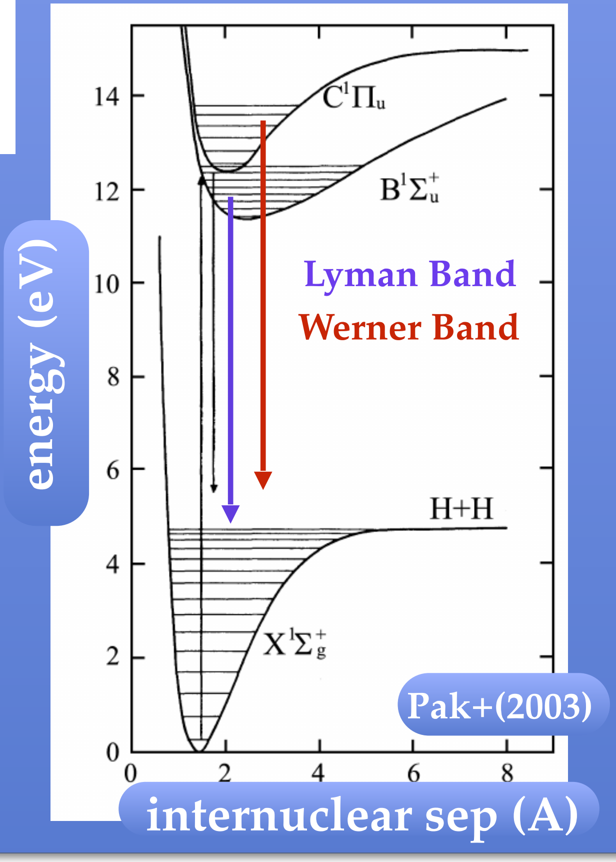
Regan, Visbal, Wise, ZH+2017

# Computing the $H_2$ dissociation rate





Jemma Wolcott-Green
grad student, Columbia



Pak+(2003)

**Lyman and Werner bands**

- 301 ground states
- 500,000 transitions

# Computing the $H_2$ dissociation rate

## Optically-thick diss rate: $k_{H2,diss}(N_{H2},n,T,J_{LW})$

- Challenges in calculating the optically-thick rate:

1. frequency-dependent optical depth: contributions from thousands of electronic transitions — expensive
2. $N_{H2}$ non-local — expensive in 3D simulations (ray-tracing)
3. $H_2$ level populations (v, J) — dep. on $N_{H2}$, n, T, $J_{LW}$ (time)
4. incident spectrum — Pop II/III galaxy SED not known

Two-step “Solomon” photodiss.

$$k_{\mathrm{diss},v,J} = \sum_{v',J'} \zeta_{v,J,v',J'} f_{\mathrm{diss},v',J'}$$

pumping rate

$$\zeta_{v,J,v',J'} = \int_{\nu_{\mathrm{th}}}^{\infty} 4\pi \sigma_\nu \frac{J_\nu}{h_{\mathrm{p}}\nu} \mathrm{d}\nu,$$

➡ $\sigma_v$ (v, J, v′, J′)

$$k_{\mathrm{diss}} = \sum_{v,J} k_{\mathrm{diss},v,J} f_{v,J},$$

➡ level pops

# Shielding factor – fitting formula

- <u>Challenges in calculating the optically-thick rate:</u>
  1. frequency dependent optical depth - expensive

## Parameterize with “shield factor”

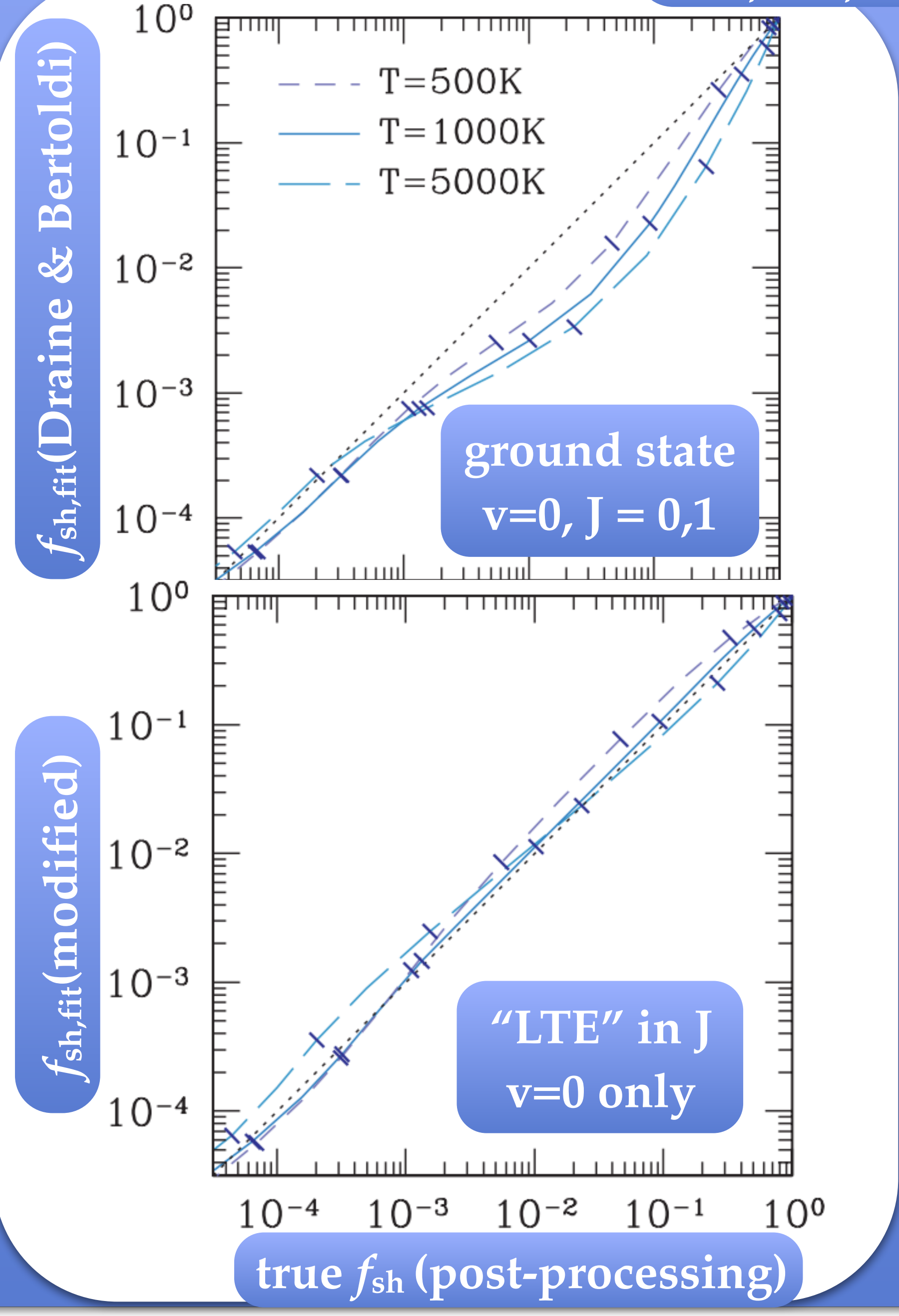
(Draine & Bertoldi 1996)

$$k_{\mathrm{diss}}(N_{\mathrm{H_2}}, T) = f_{\mathrm{sh}}(N_{\mathrm{H_2}}, T)\, k_{\mathrm{diss}}(N_{\mathrm{H_2}} = 0, T),$$

$$f_{\mathrm{sh}}\left(N_{\mathrm{H_2}}, T\right) = \frac{0.965}{(1 + x/b_5)^{\alpha}} + \frac{0.035}{(1+x)^{0.5}} \times \exp\left[-8.5 \times 10^{-4}\,(1+x)^{0.5}\right]$$

- ➡ D&B 1996 intended for low n, T
- ➡ fits well if $H_2$ in ground states only
- ➡ W-G+2011 modified ($\alpha$) assuming Boltzmann distribution for rotational pops in v=0 ground state, appropriate for n ~< $10^3$ cm$^{-3}$
- ➡ modified fit best for T ~ $10^3$ K

W-G, ZH, Bryan (2011)



# What is the correct column density $N_{H2}$ ?

- <u>Challenges in calculating the optically-thick exact rate:</u>

  2. $N_{H2}$ non-local — expensive in 3D simulations

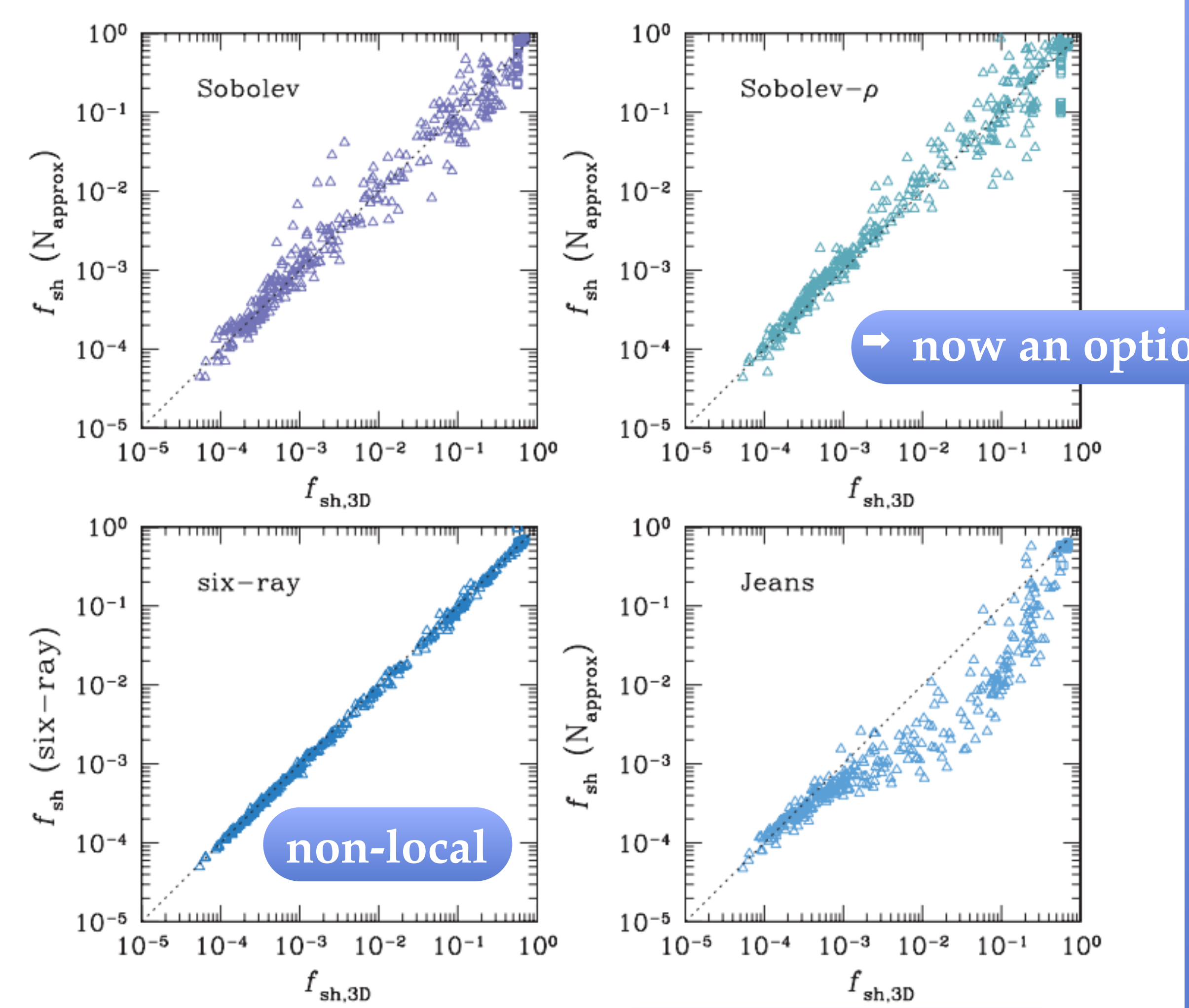
     - Typically Jeans length is used, but Sobolev or "Sobolev-like" lengths more accurate (using post-processed ENZO simulations)

**Local approximations**

$$N_{H_2} = n_{H_2} L_{\rm char},$$

$$L_{\rm Sob} \equiv \frac{v_{\rm th}}{|dv/ds|}$$

$$L'_{\rm Sob} \equiv \frac{\rho}{|\nabla \rho|},$$



➡ now an option in ENZO

non-local

W-G, ZH, Bryan '11

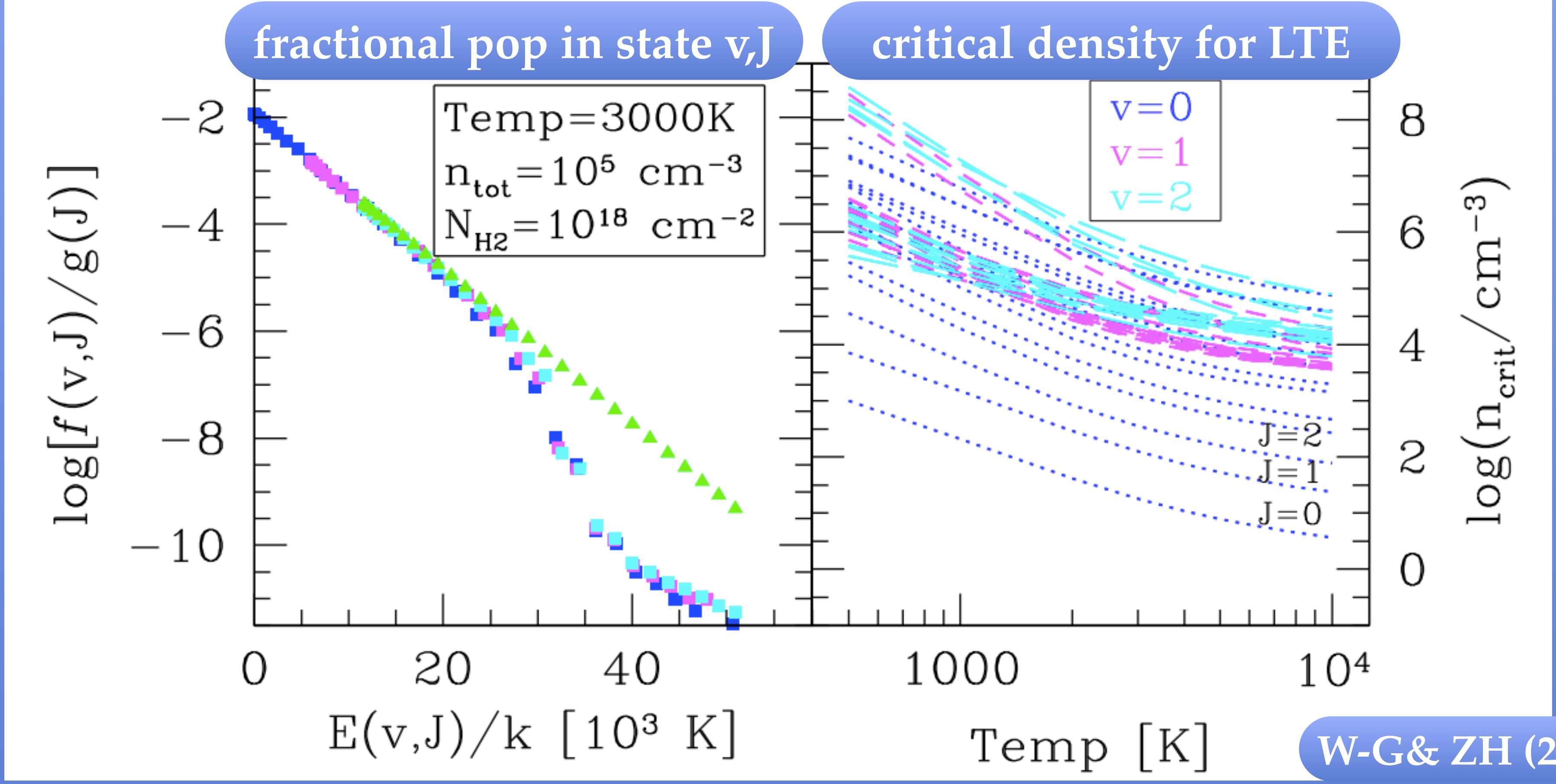
# $H_2$ level populations: not in (full) LTE

- Challenges in calculating the optically-thick exact rate:

  3.a $H_2$ level populations (v, J) — depend on $N_{H2}$, n, T (& time)

  ➡ Previous calculations included populations only in v=0

  (D&B'96, W-G,ZH,Bryan'11)



fractional pop in state v,J

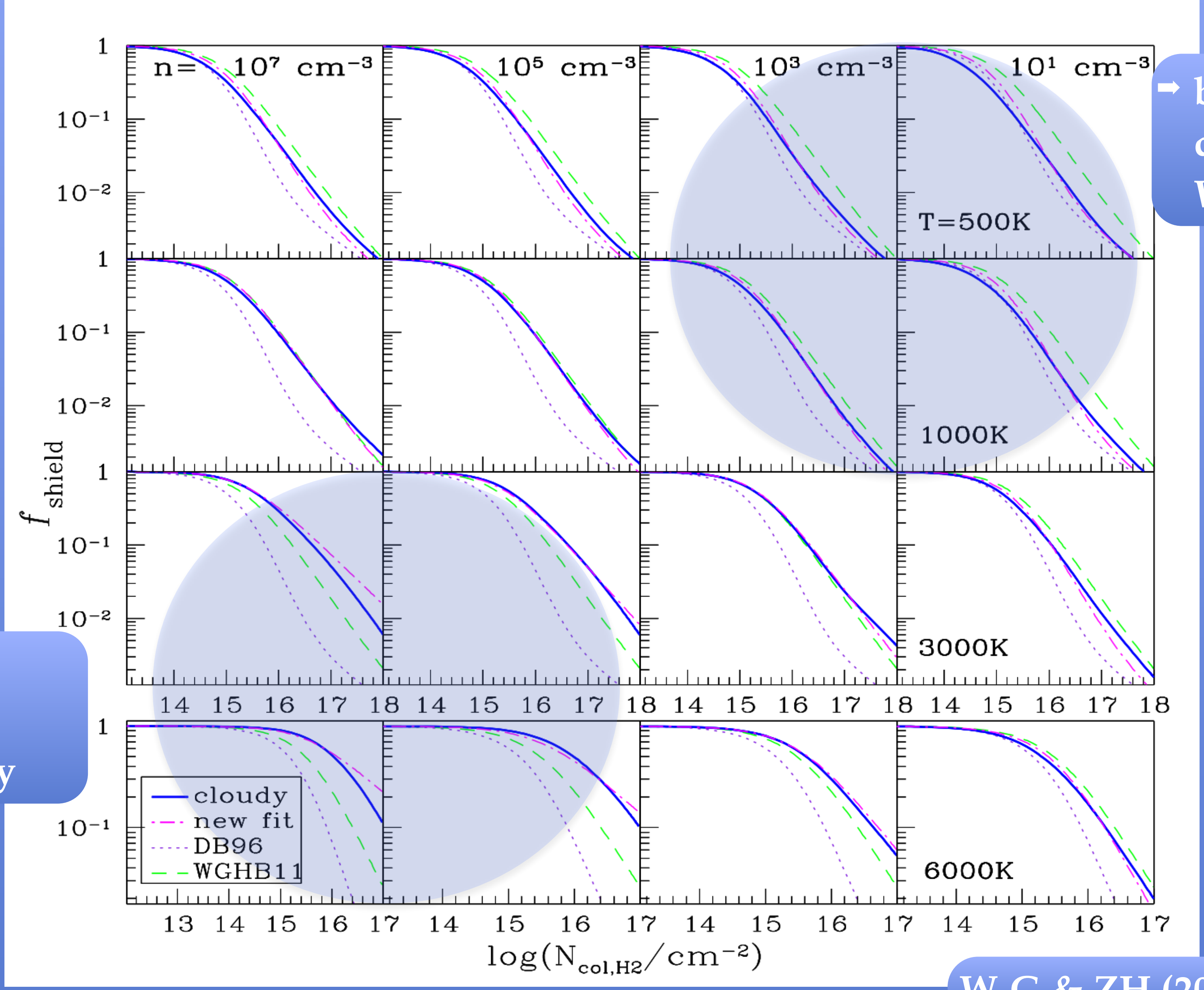
critical density for LTE

W-G& ZH (2019)

➡Even at moderate (n,T), first few v levels tend to LTE (CLOUDY)

# New “$f_{\text{shield}}$” fitting formula: use this…

- W-G & ZH ’19: use CLOUDY to fully resolve level populations
- calculate “true” frequency-dependent $H_2$ rate with resolved pops
- compare to previous fits & provide improved fitting formula



➡ better fit at low (n,T) bc doesn’t assume LTE as W-G, ZH, Bryan (2011)

—> more shielding

➡ accounts for more (v>0) level pops at higher temp, density

—> less shielding

W-G & ZH (2019)

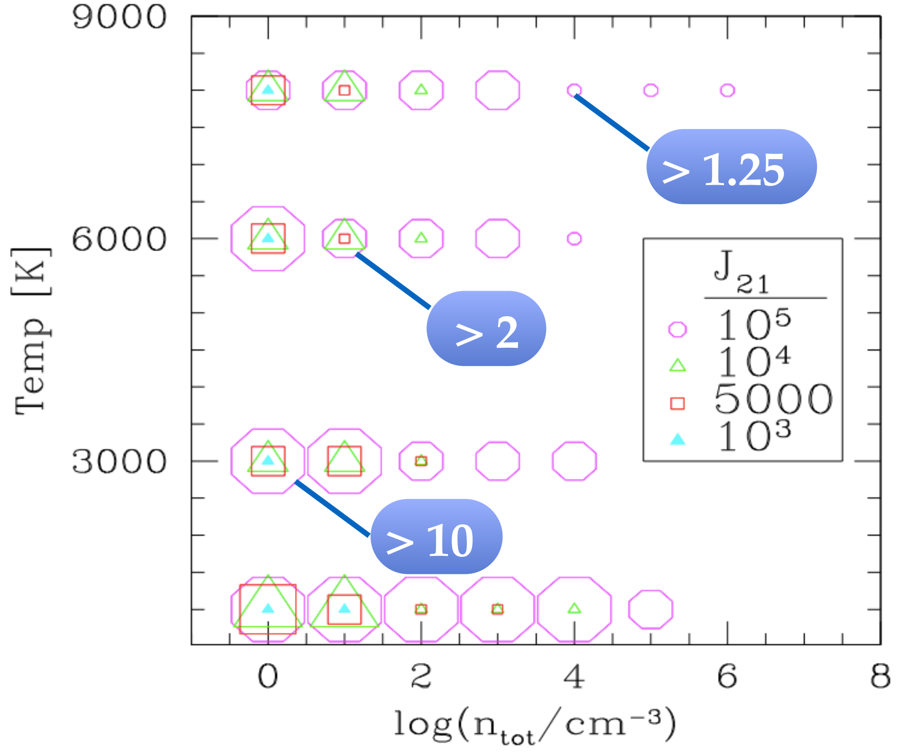
# New physics: UV "re-pumping" ?

Challenges in calculating the optically-thick rate: $k_{H2,diss}(N_{H2}, n, T, J_{LW})$

3.b $H_2$ level populations (v, J) — depend also on incident flux

LW "re-pumping" affects populations at high $J_{LW}$ by interrupting radiative cascade

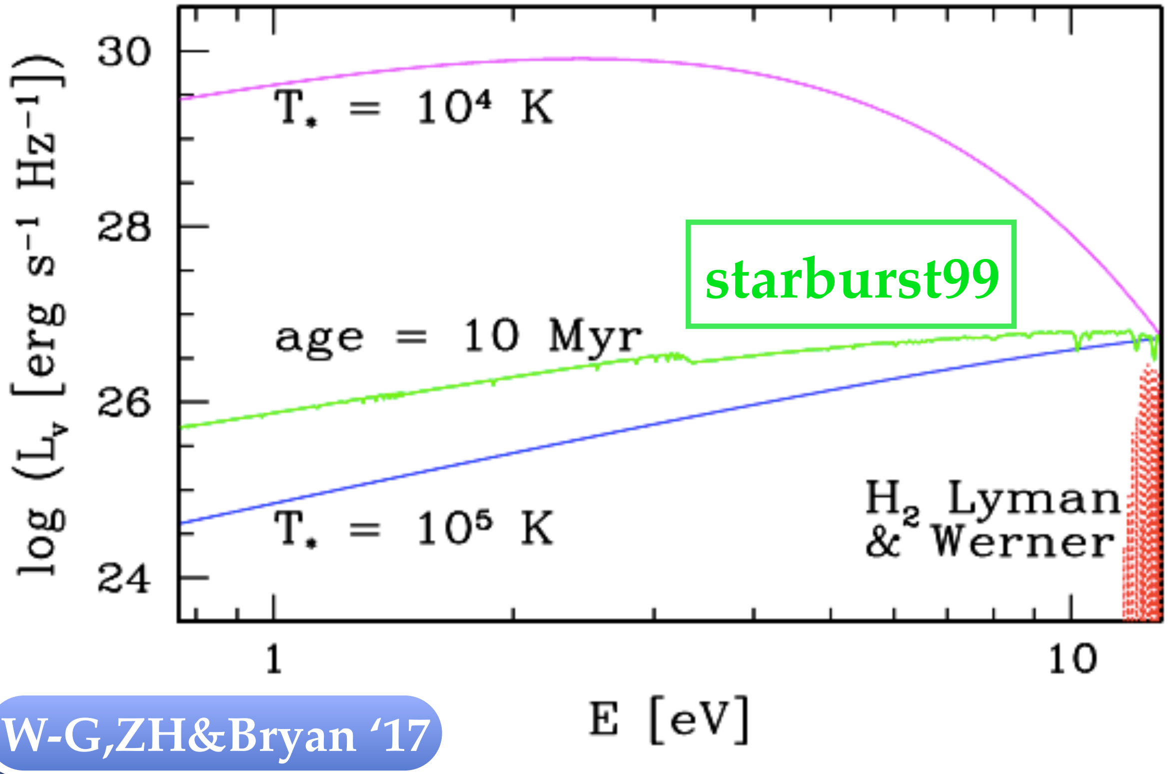
- ➡ re-pumping when $J_{LW} \sim 10^3$ ($\sim J_{crit}$!)
- ➡ re-pumping *more likely* than decay when $J_{LW} \sim 10^5$ (Shull '78)
- ➡ we find:
  - $f_{sh}$ changed by factor of > 10 with $J_{LW} >= 5\times10^3$
  - $f_{sh}$ changed by factor of > 1.25 with $J_{LW} \sim 10^3$
- ➡ may change $J_{crit}$ for direct collapse



W-G & ZH (2019)

# IR photodetachment of $H^-$ suppresses $H_2$

- <u>Challenges in calculating the optically-thick exact rate:</u>
  4. Incident spectrum from neighboring Pop III (III.2) galaxy



W-G,ZH&Bryan '17

- UV not only way to depress $H_2$-abundance!

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + h\nu$$

$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}^-$$

$$k_{\mathrm{H}^-} = 4\pi n_{\mathrm{H}^-} \int_{0.76\ \mathrm{eV}}^{13.6\mathrm{eV}} \sigma_{\nu,\mathrm{H}^-} \frac{J_\nu}{h\nu} \mathrm{d}\nu.$$

- $J_{crit}$ (T4) spectrum ~ 30 (!)
  *but requires much more efficient star formation* (T4-like $M_{char}$~ 1 $M_\odot$)
- starburst99 Pop III galaxy spectrum closer to T5

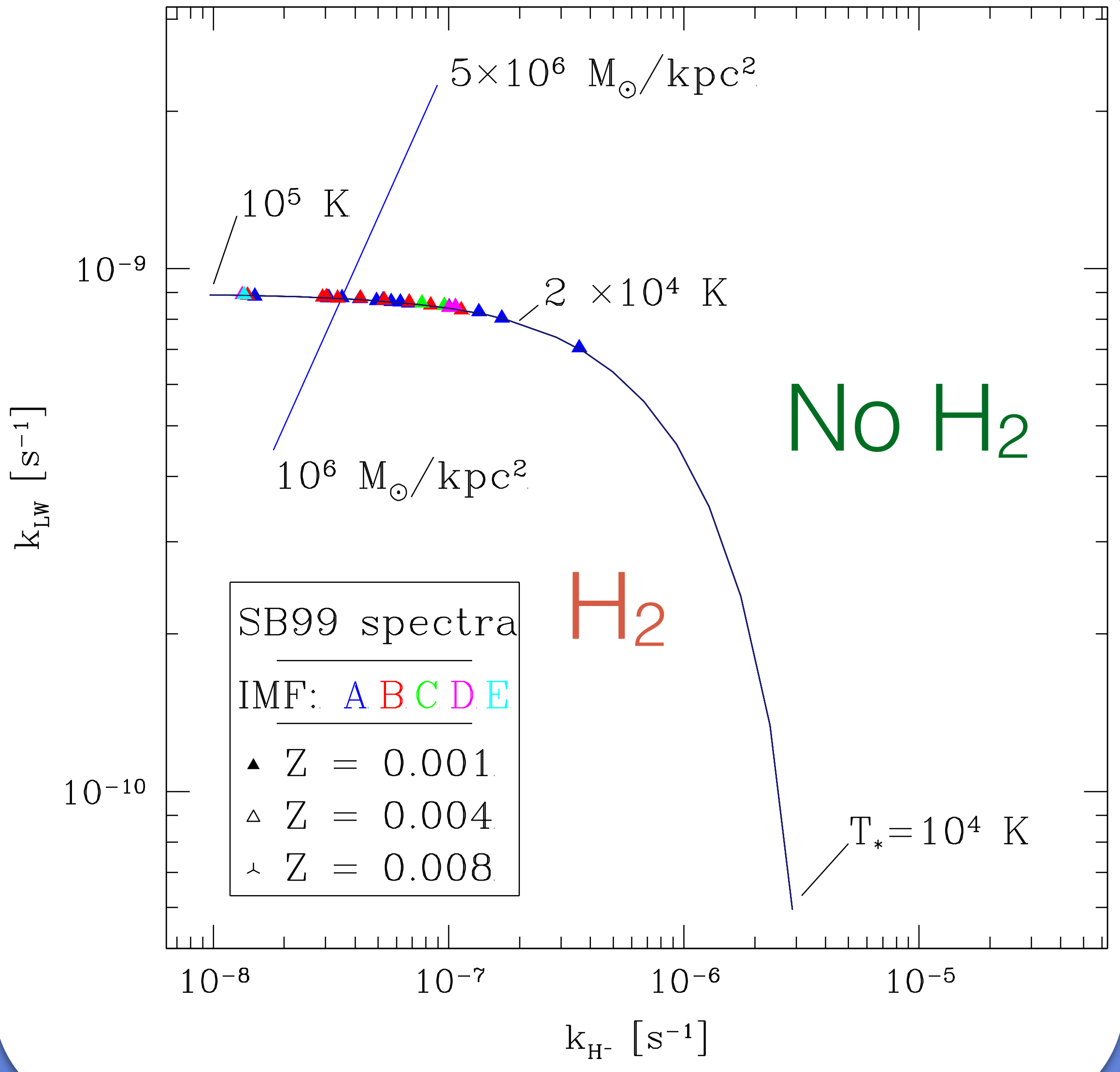
# No such thing as "Jcrit"

W-G, ZH & Bryan '17

$H_2$-cooling suppression determined by LW photodissociation and H- photodetachment rates

- ➡ $J_{crit}$ defined by choice of spectrum
- ➡ more general: CRITICAL CURVE showing combination of the two rates required to keep gas $H_2$ poor
- ➡ generic for any choice of spectrum

- ➡ we show $(M/d^2)_{crit}$ ($t_{starburst}$, Z)



➡ $J_{crit}$ =1100 with PopIII spectrum, new shielding, one-zone

# So what is the best estimate Jcrit?

- ➡ estimates have varied widely from 20-$10^5$, depending on assumed spectrum, model for self-shielding, chemistry network, etc.; however, most studies recently have found smaller $J_{crit}$ than initial estimates

- ➡ latest 1-zone models w/starburst99 Pop III (Z=0) spectra —> $J_{crit}$ ~1300 (W-G,ZH,Bryan 2017,Sugimura+2014) —> $J_{crit}$ ~1100 (with new shielding)

- ➡ one-zone with "Ly$\alpha$ trapping" —> $J_{crit}$ ~200-900 (Johnson & Dijkstra 2017)

- ➡ 3D simulations: $J_{crit}$(T5)~700-3000 (Glover 2015), $J_{crit}$(T5)~$10^3$ (Regan+14), $J_{crit}$($T_{BB}$=2x$10^4$)~2000-5000 (Latif+15); $J_{crit}$ (T5)~$10^4$ (Shang,Bryan&ZH+10*old $f_{sh}$)

- ➡ X-ray background, streaming velocity, compressional heating (..B-field) varies from halo to halo —> massive BH seeds form in corner of multi-D space

# Conclusions

I. Forming massive BH by rapid gas infall in atomic cooling halo is promising

II. The Large Lyman-Werner flux required to suppress $H_2$ cooling can be realized in rare subset of ACHs

III. The abundance of such rare halos is uncertain, because (a) we are in steep tail of $J_{LW}$-distribution and (b) precise value of critical flux varies from halo-to-halo, depending on halo accretion history, local UV/IR/X-ray backgrounds, and local streaming motions

IV. A global modeling of all of the above effects is needed to predict the high-z BH mass function