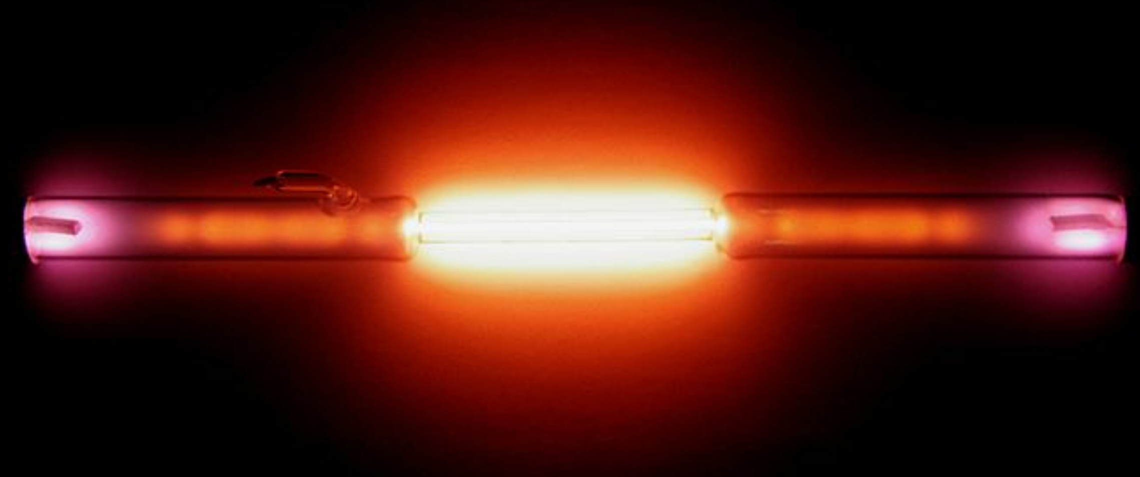
Some aspects of cosmological helium



Eric R. Switzer (KICP)

Fermilab, Dec. 7

Cosmological helium recombination (Switzer&Hirata and Hirata&Switzer 2008)

Small-scale anisotropy measurements (ACT, Dunkley et al. 2010, my contribution: Switzer et al. 2008)

New atomic tracers of helium reionization (McQuinn & Switzer 2009, 2010)

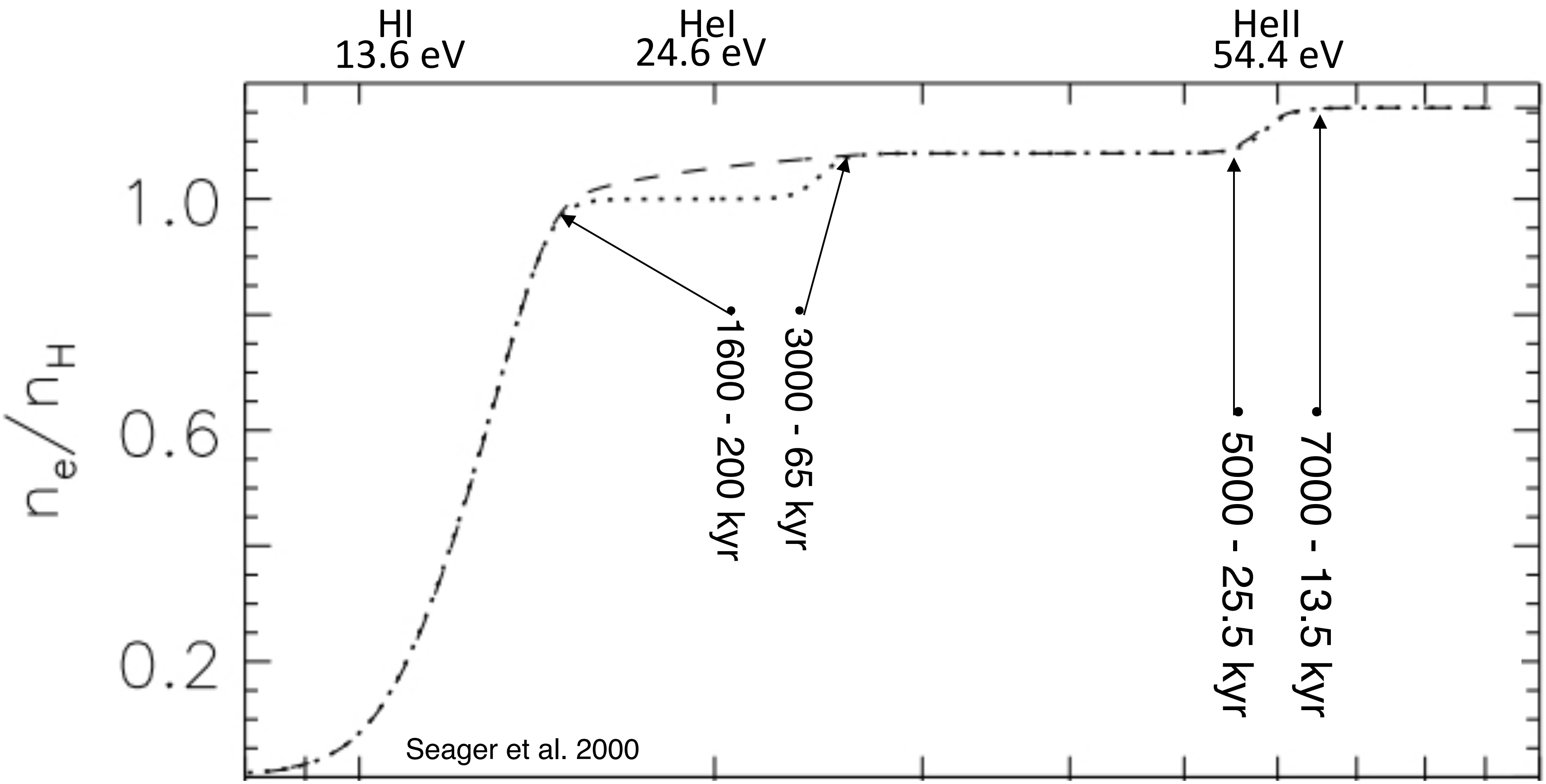
Life of a typical helium atom

- Born: t≈3 minutes (HeIII, Nuclear scale ~ MeV: Helium formation)
- Capture one electron: t≈20 kyr (HeII, 54.4 eV)
- Capture a second electron: t≈100 kyr (HeI, 24.6 eV)
- Singly ionized: t~1 Gyr (HeII)
- Doubly ionized: t~2 Gyr (HeIII)
- Humans discover helium in the sun (*helios*) through its $2^3P°$ - 2^3D transition: 1868 AD, on earth in 1882 with the same transition in Mt. Vesuvius. (but primarily not primordial)

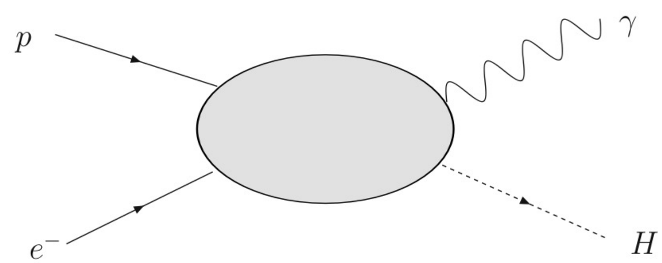
Outline

- The helium recombination history, new processes, and impact on the CMB.
- Atacama Cosmology Telescope inference of the helium abundance.
- Helium in the more recent universe and new observational prospects.

The recombination history

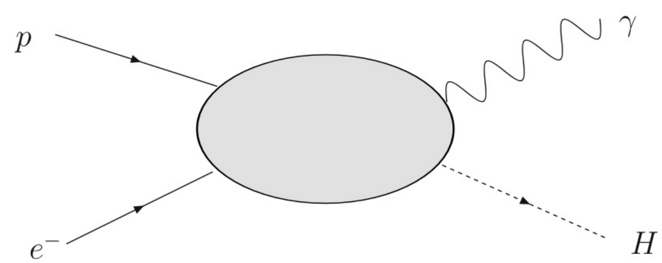


How?



p+e ←→ H + γ

How?



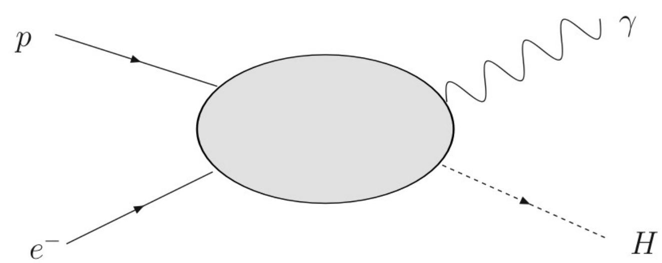
p+e ←→ H + γ

But once the universe is cool enough:

p+e → H(1s) + γ(E>13.6 eV)
γ(E>13.6 eV) + H(1s) → p+e

p+e →p+e?

How?



p+e ⇔ H + γ

But once the universe is cool enough:

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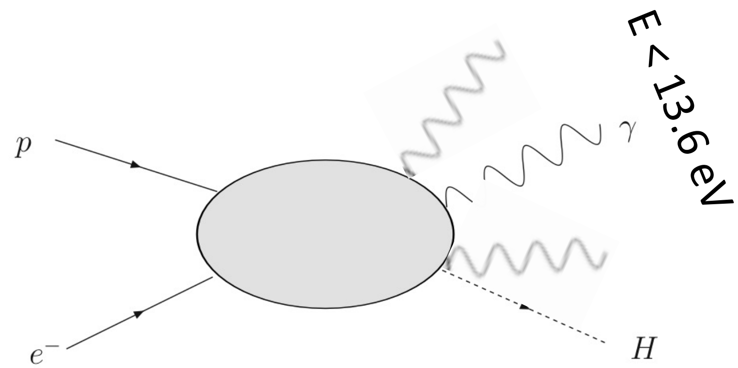
γ(E>13.6 eV) + H(1s) ➔ p+e

p+e ➔p+e?

So how do we form the neutral species?

How?



p+e ⇔ H + γ

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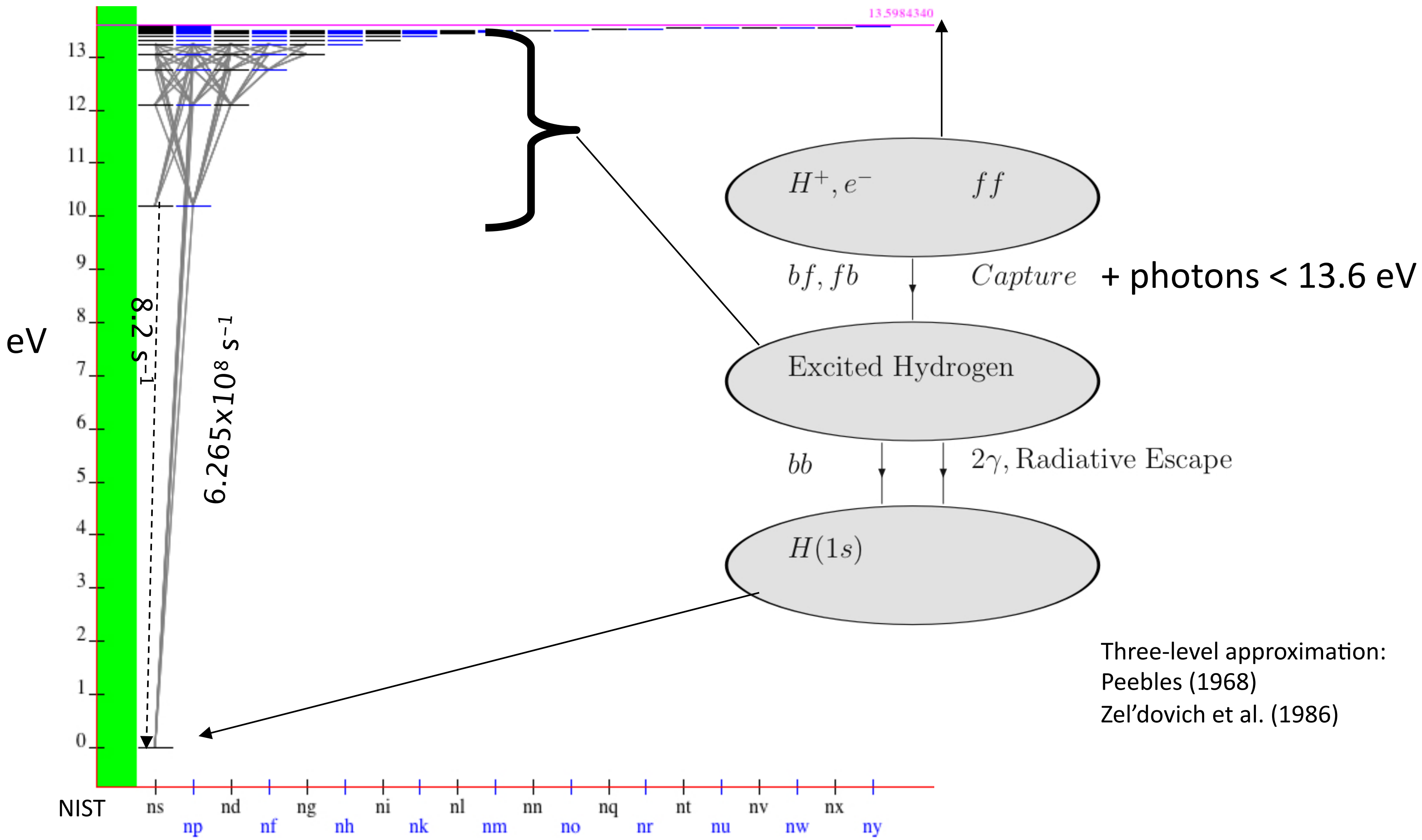
γ(E>13.6 eV) + H(1s) ➔ p+e

p+e ➔p+e?

So how do we form the neutral species?
(degrade the energy into **multiple** photons)

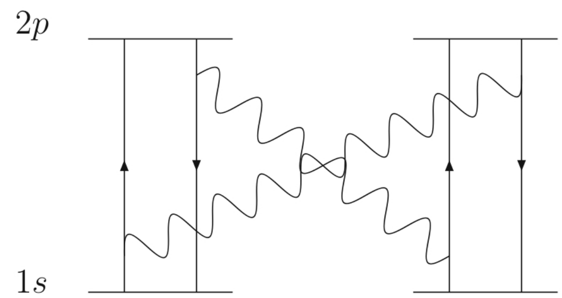
Hydrogen recombination



Three-level approximation:
Peebles (1968)
Zel'dovich et al. (1986)

Rate(1s) = P(excited ➔ n=1) * capture rate to excited

The traffic jam



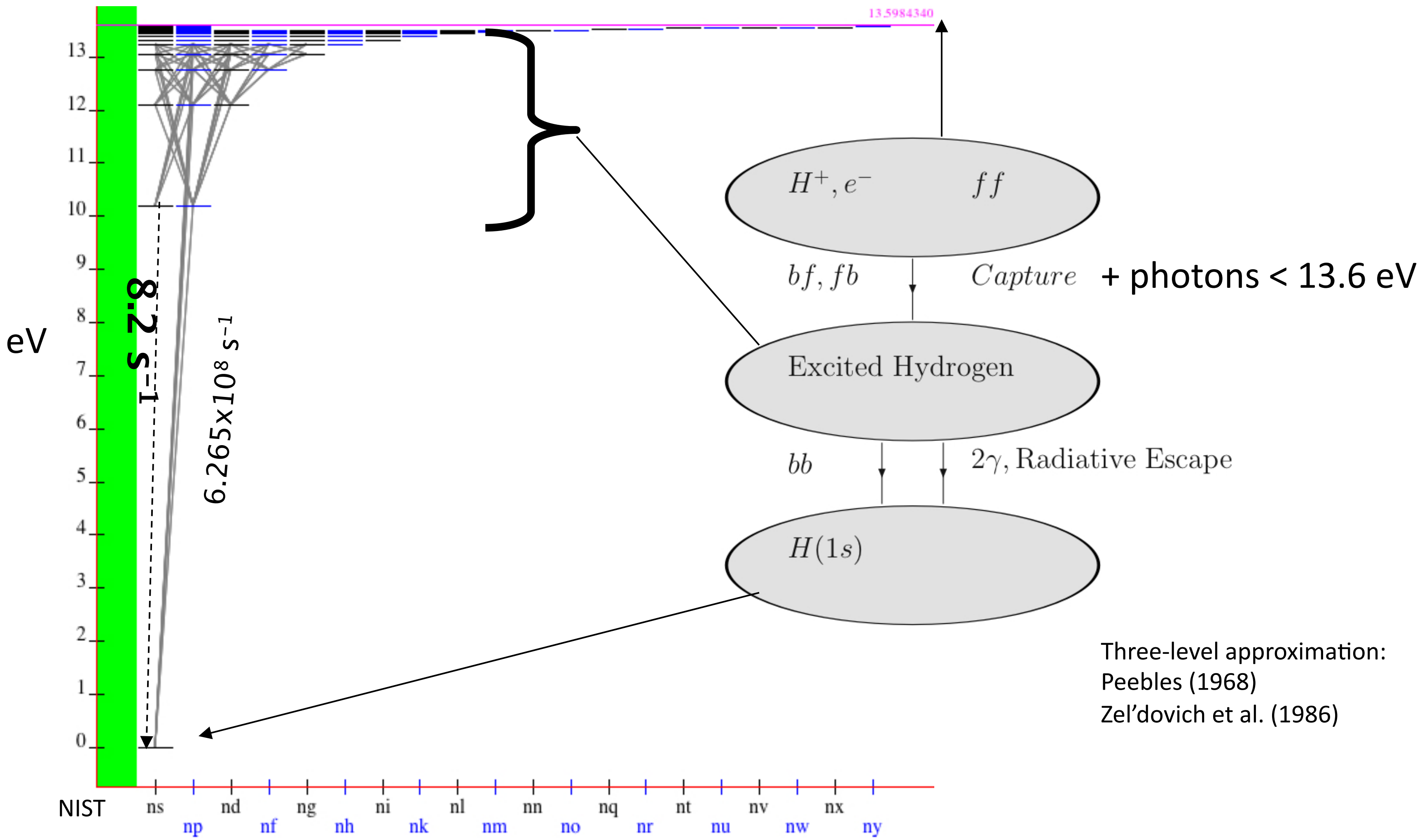
The Traffic Jam

H(2p) ➔ H(1s) + γ(Lyα)
H(1s) + γ(Lyα) ➔ H(2p)

H(2p) ➔H(2p)

So how do we form the neutral species?!

Hydrogen recombination



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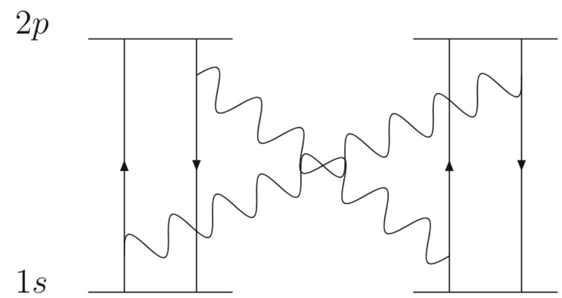


The Traffic Jam

H(2p) ➔ H(1s) + γ(Lyα)
H(1s) + γ(Lyα) ➔ H(2p)

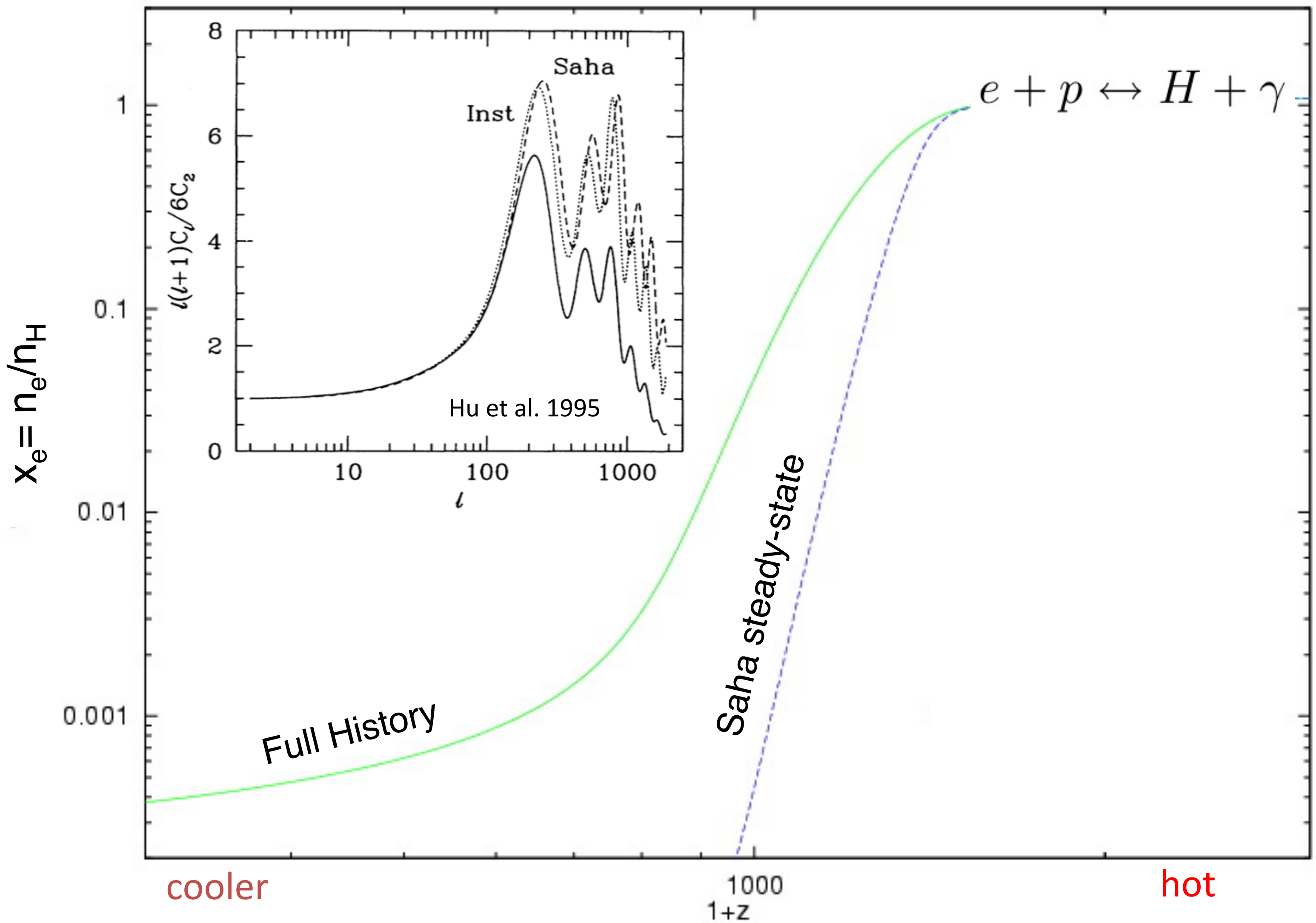
H(2p) ➔H(2p)

So how do we form the neutral species?!
Instead decay from 2s ➔ 1s through two photons
Or… redshift! (Sobolev Escape)

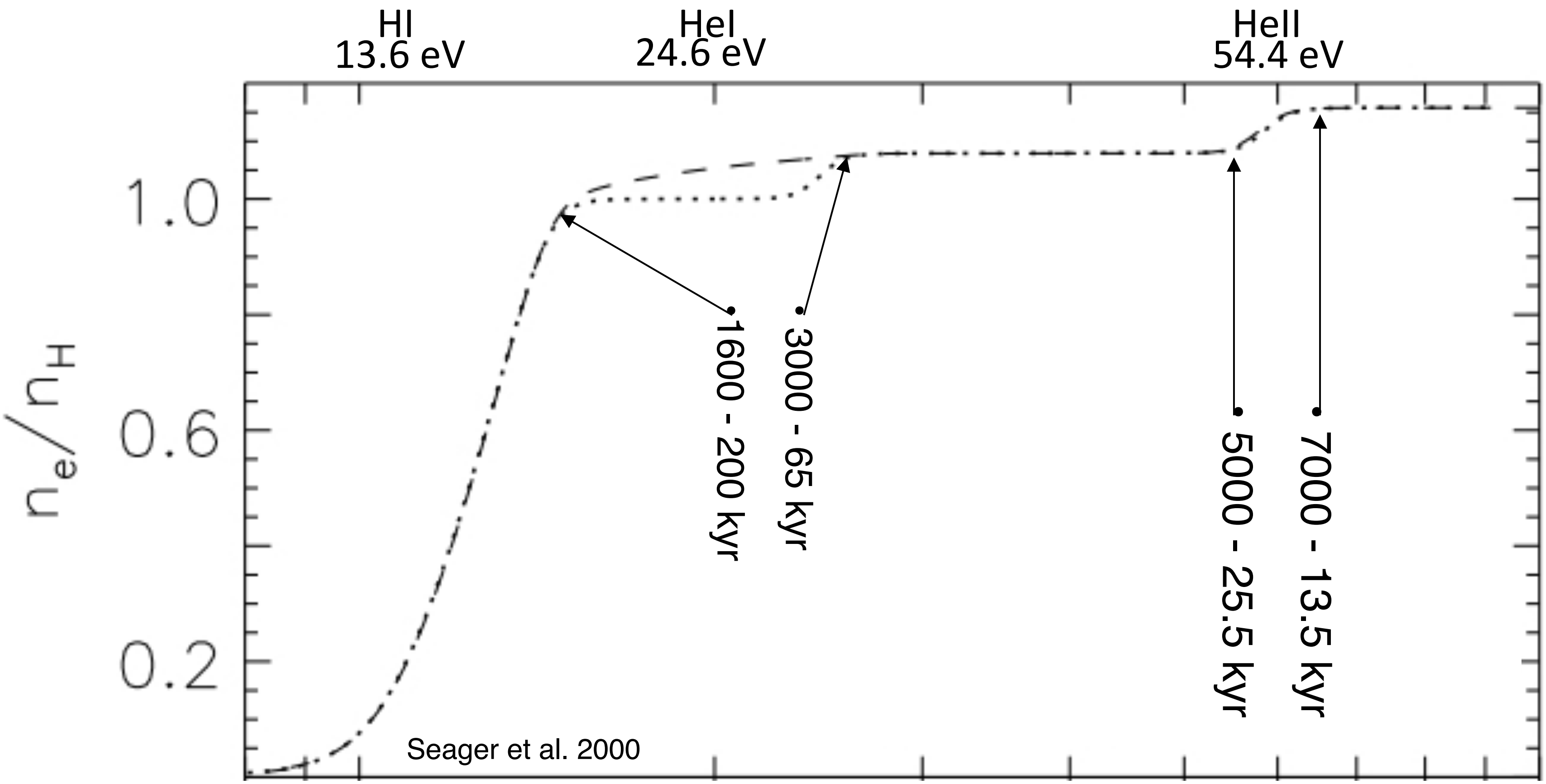
H(2p) ➔ H(1s) + γ(Lyα)
γ(Lyα) ➔γ(<Lyα) Escapes!
And then, H(2p) ➔H(1s) + γ(<Lyα)

Recombination to the ground state is difficult, and rare processes and unusual radiative transport dominate the dynamics!

Schematic of recombination

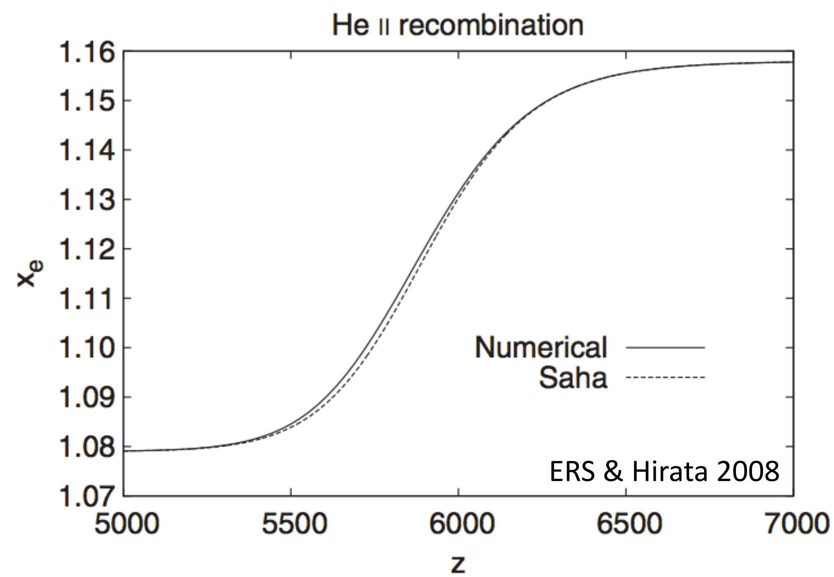


The recombination history

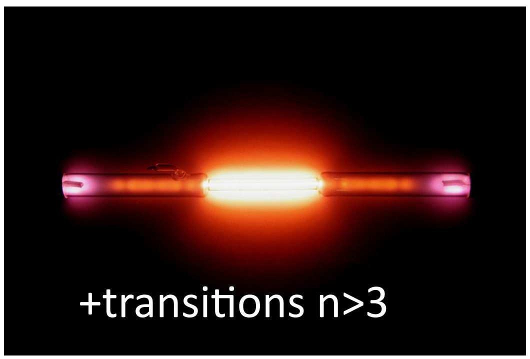


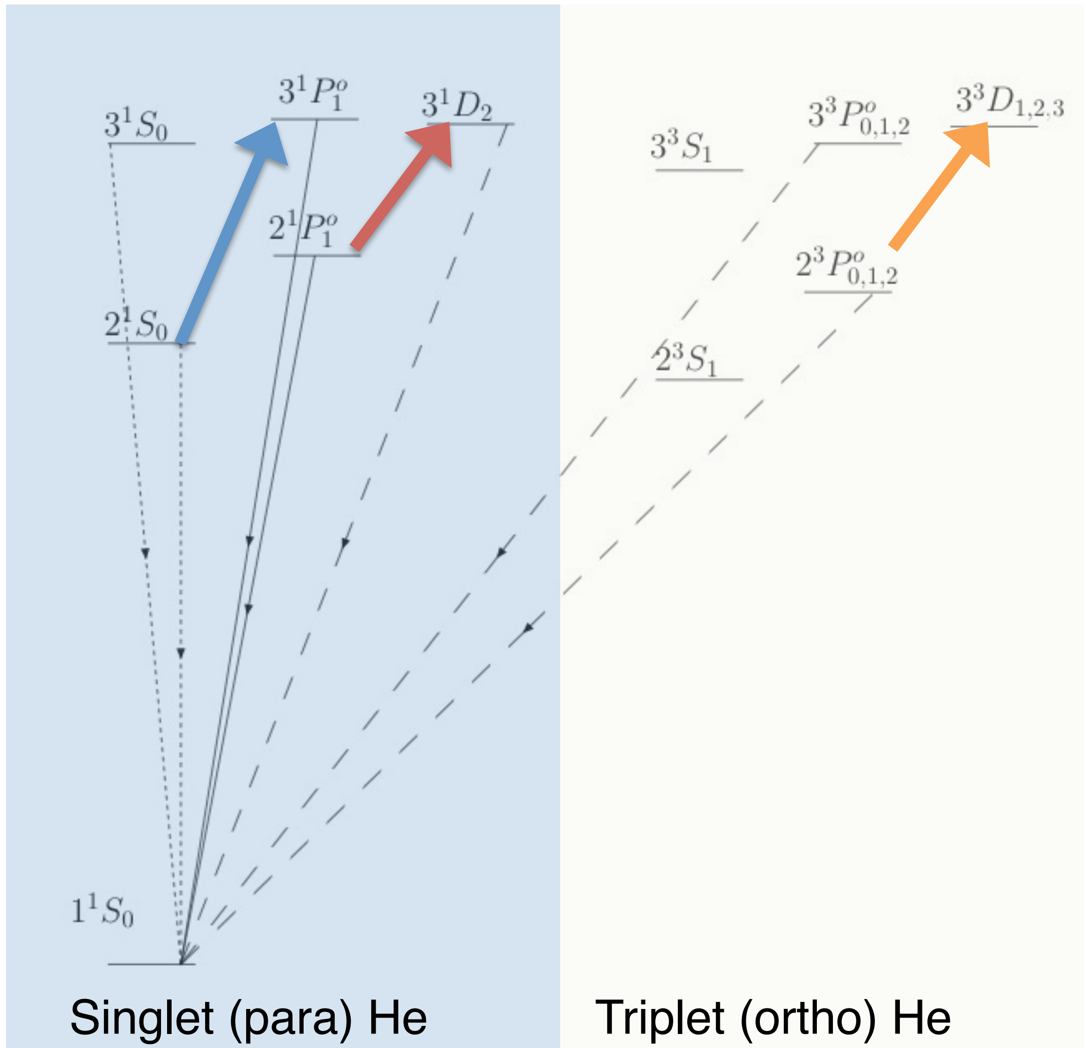
Recombination to HeII

- ***Hydrogenic***
- Multiply energies by $Z^2=4$, bound-bound rates by $Z^4=16$, and two-photon rate $Z^6=64$.
- Saha evolution is an excellent approximation.

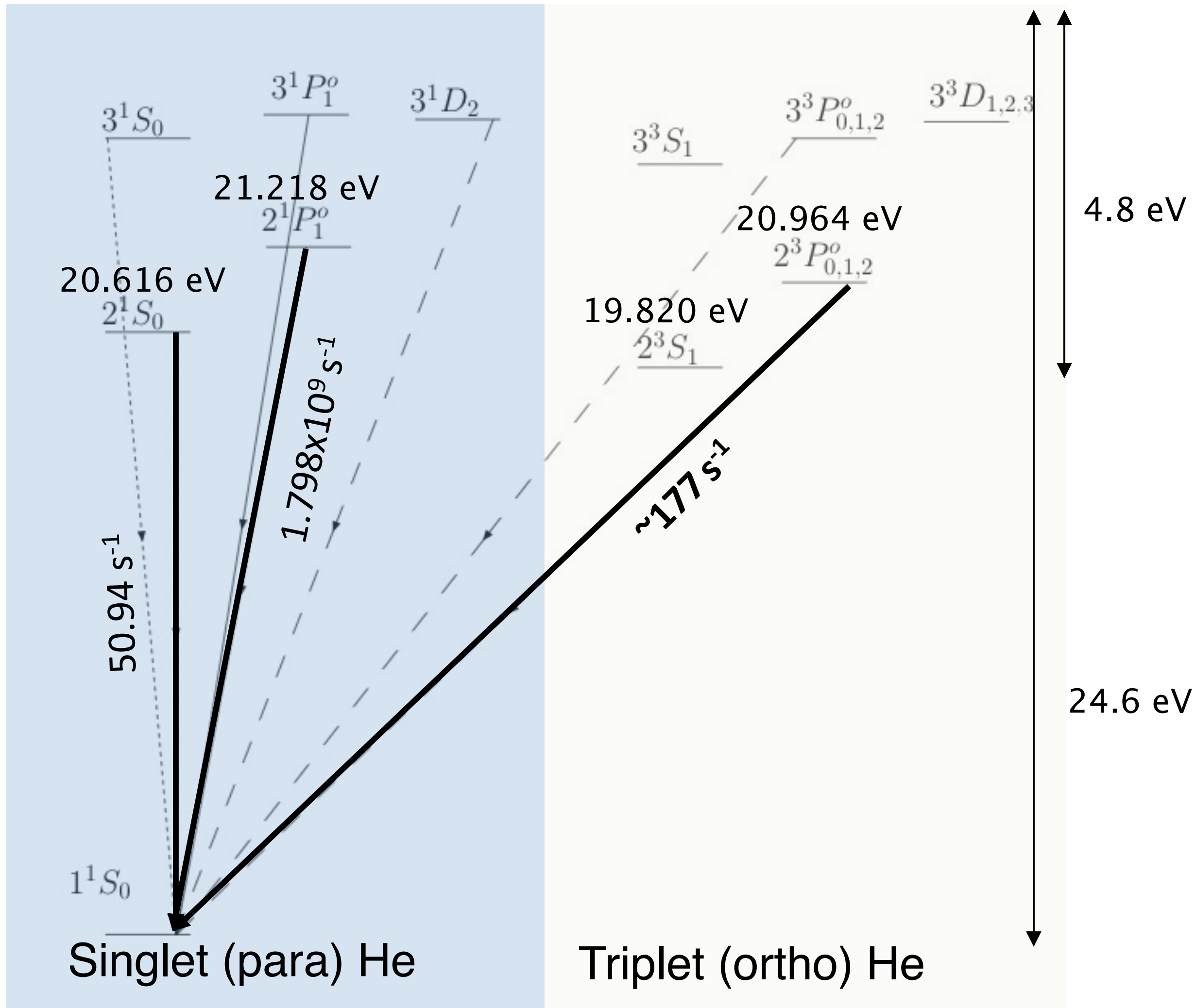


HeI: Grotrian diagram (n < 4)

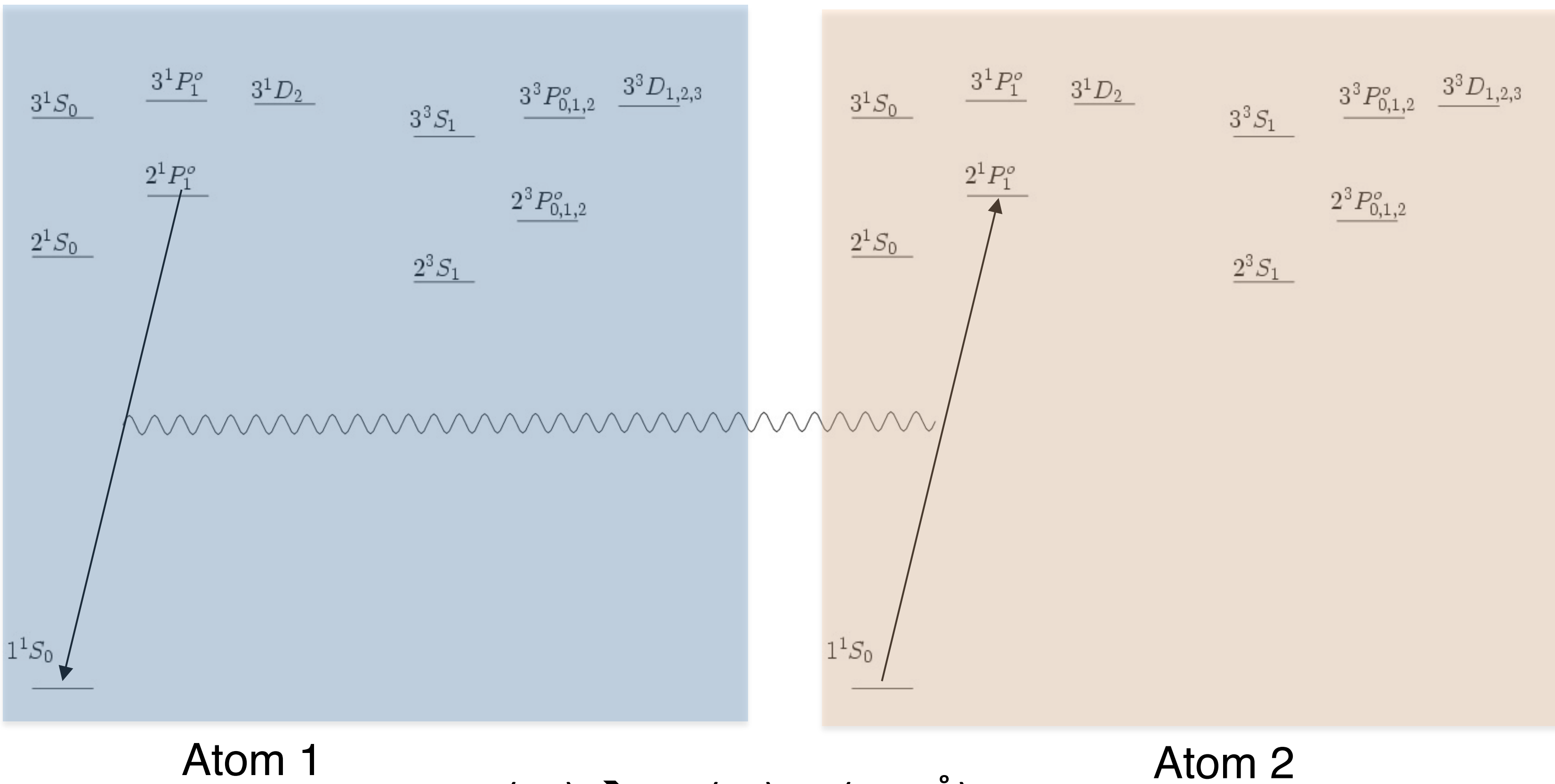




Helium states: n<4



Helium: re-excitation



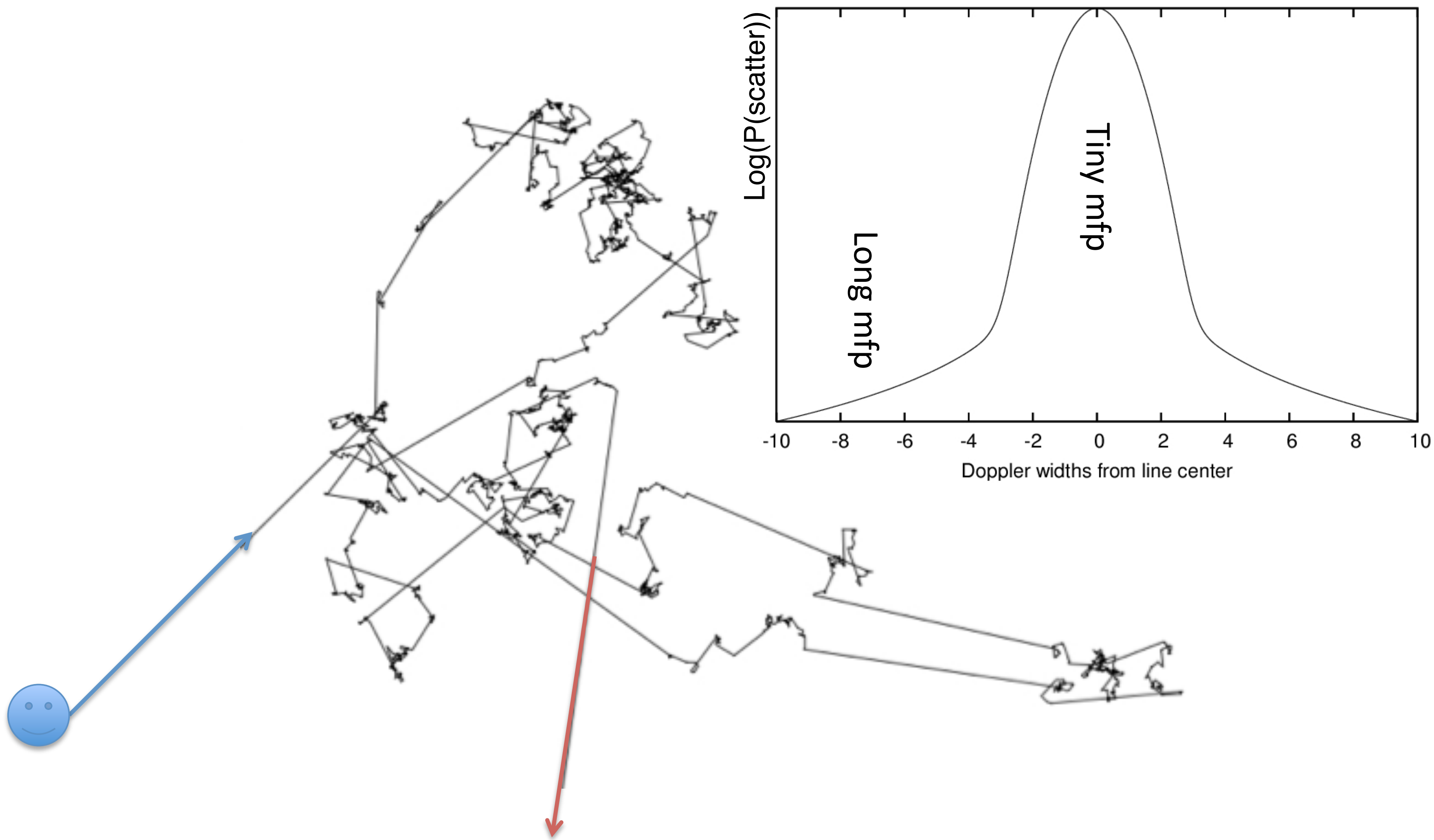
HeI(2P) ➔ HeI(1S) + γ(584 Å)

HeI(1S) + γ(584 Å) ➔ H(2P)

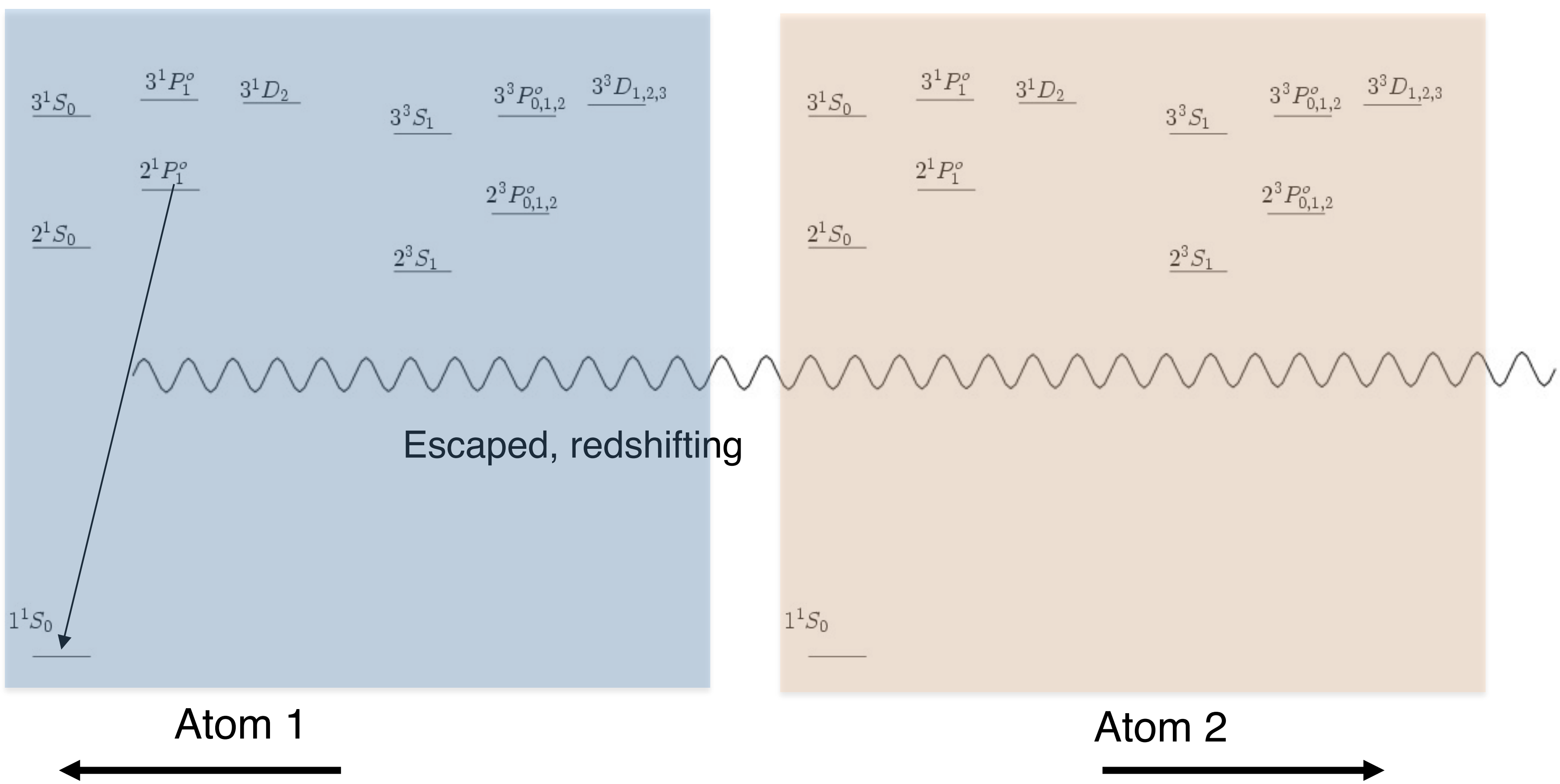
H(2P) ➔H(2P)

Slows recombination, (standard model)

Resonant scatter and escape

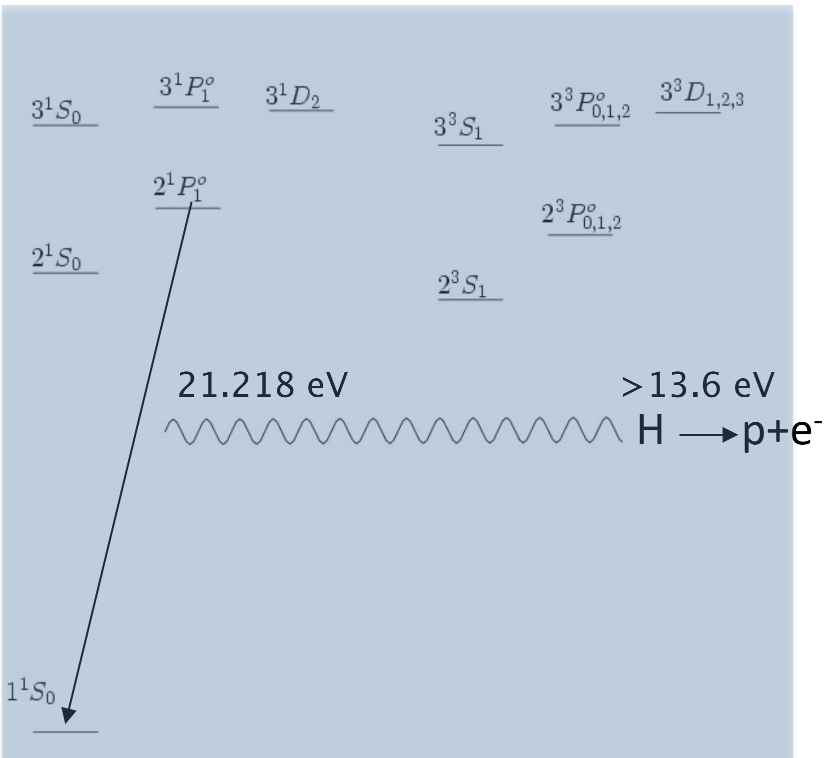


Helium: resonant escape

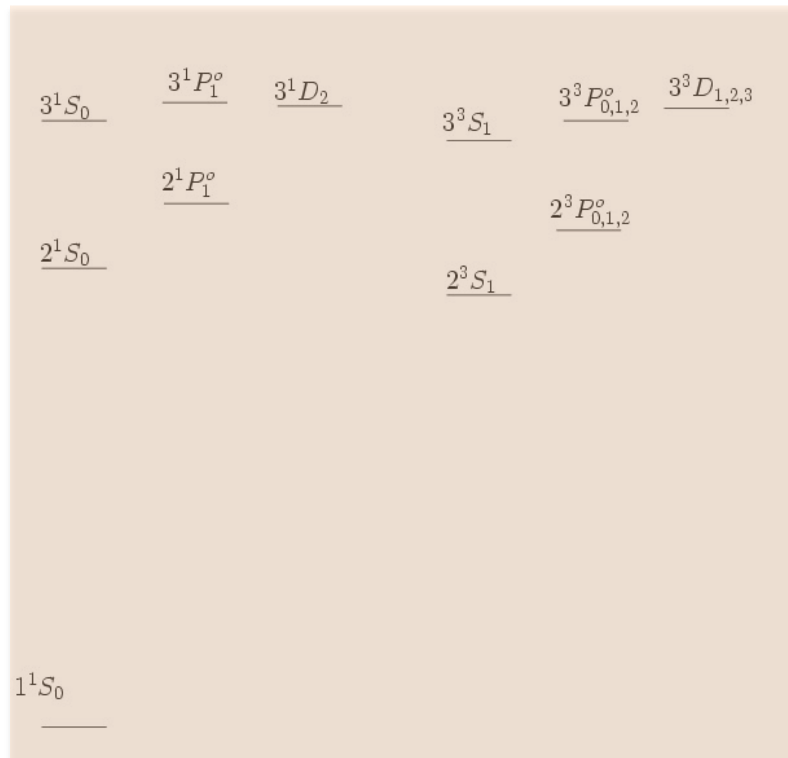


Accelerates recombination (standard model)

Helium: Continuum HI opacity



Atom 1



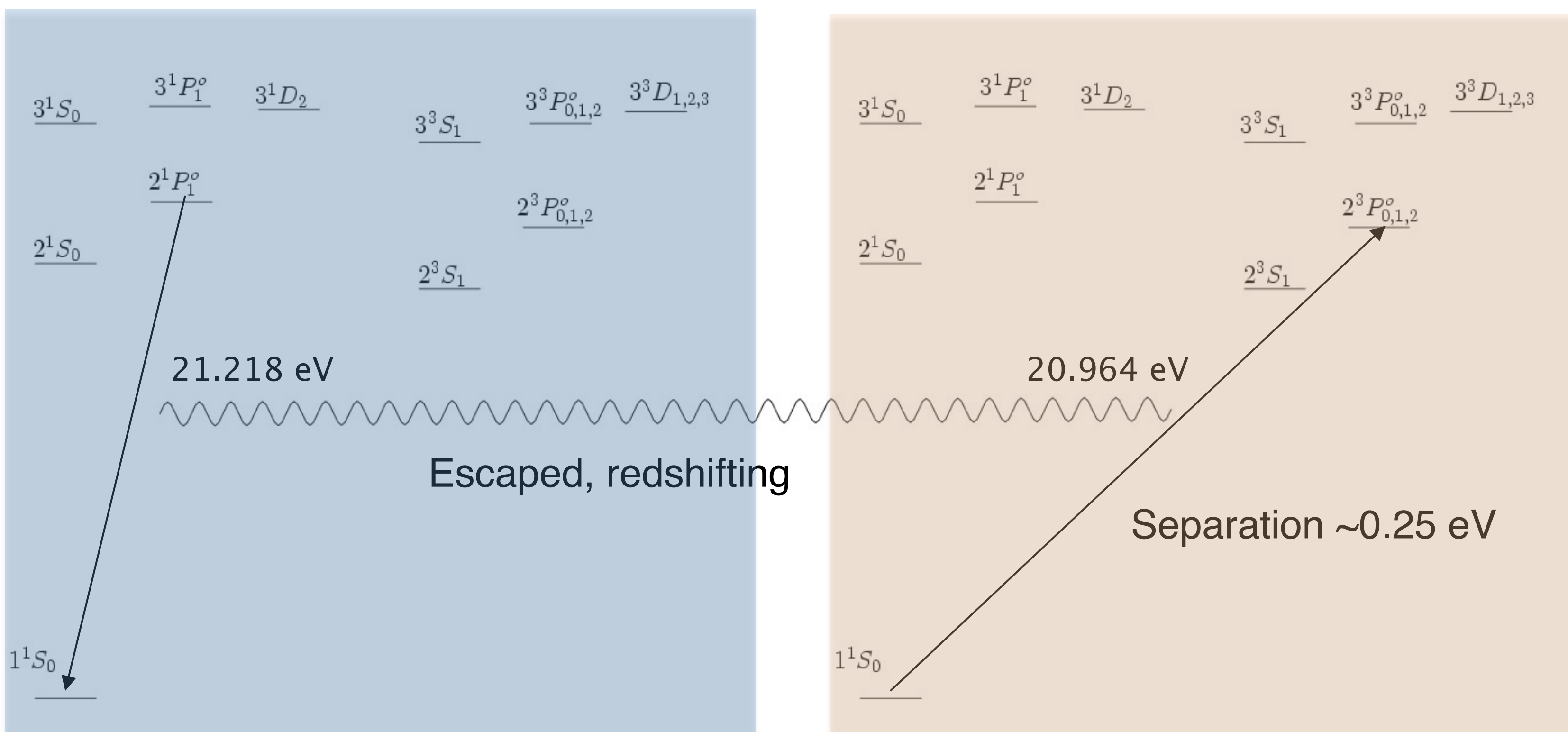
Atom 2

Accelerates recombination **(new process)**

$$\eta_c = \frac{d\tau}{d\nu}\bigg|_{\text{continuum}} = \frac{n_H x_{1s} \sigma_{c1} c}{H\nu}$$

(Suggested in Hu et al. 1995 based on private communication with J. Peebles.)

Helium: radiative feedback

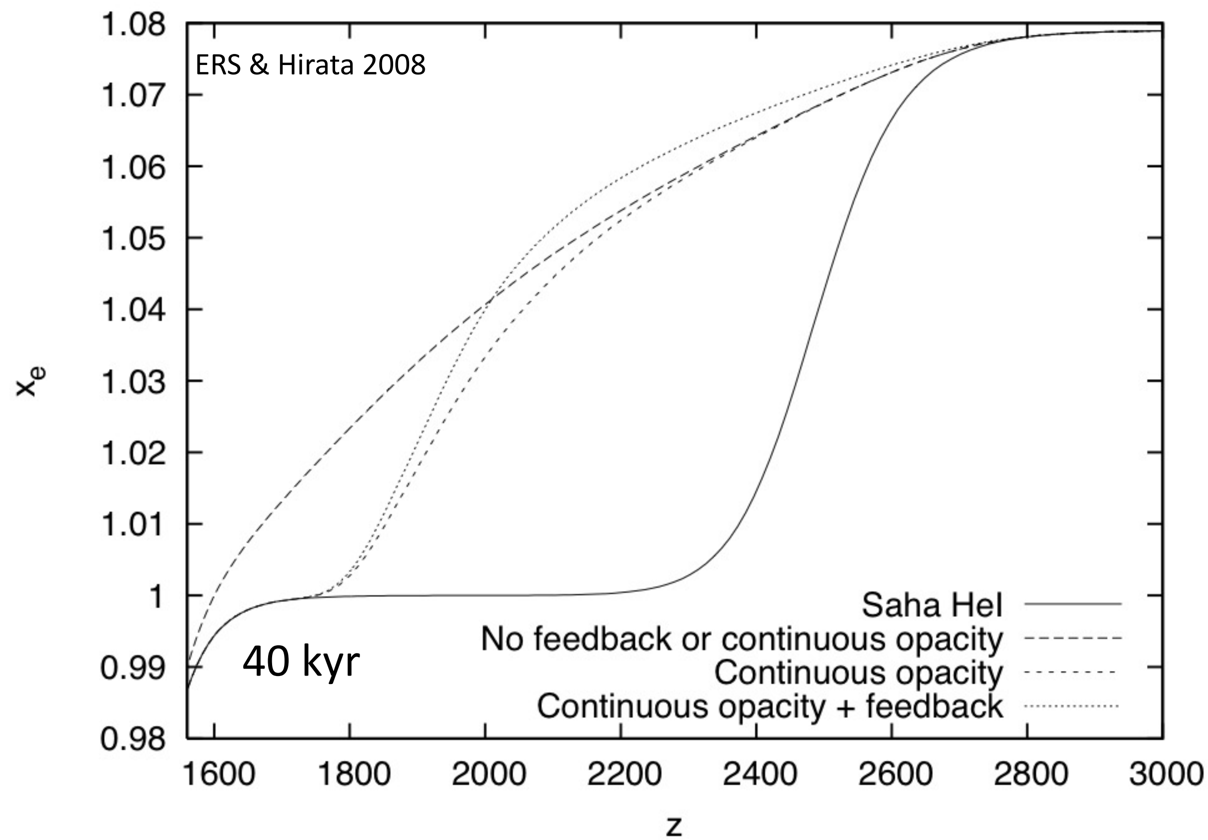


Atom 1
z=2000

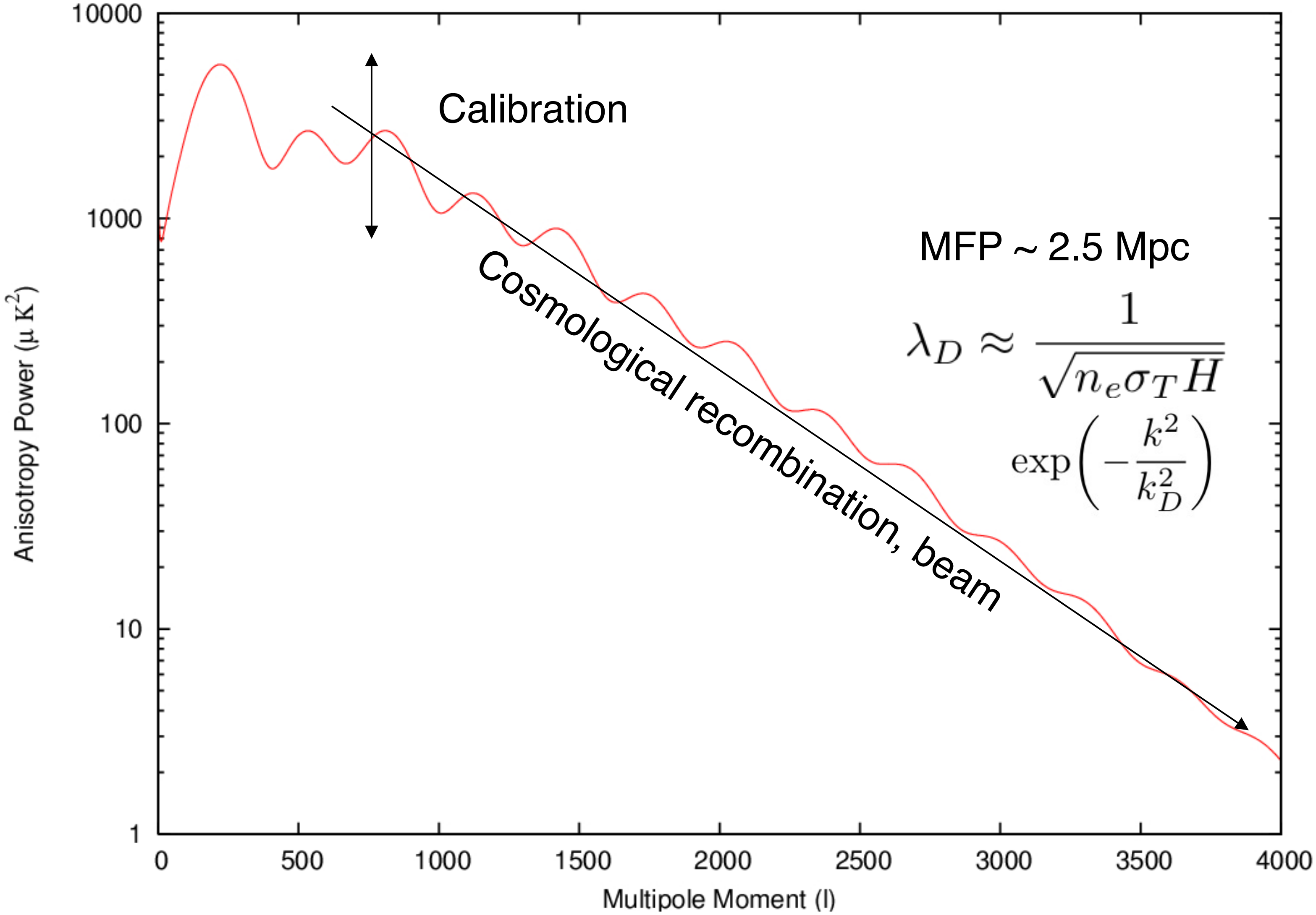
Atom 2
z=1976

Slows recombination **(new process)**

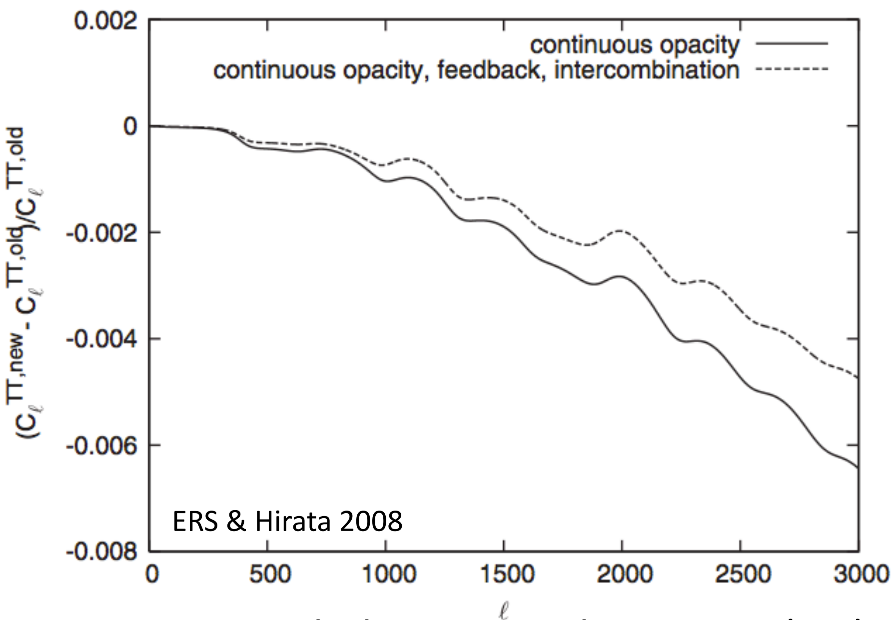
Impact of new effects



Impact on the CMB



Impact on the CMB



Corrections to helium recombination O(1%)

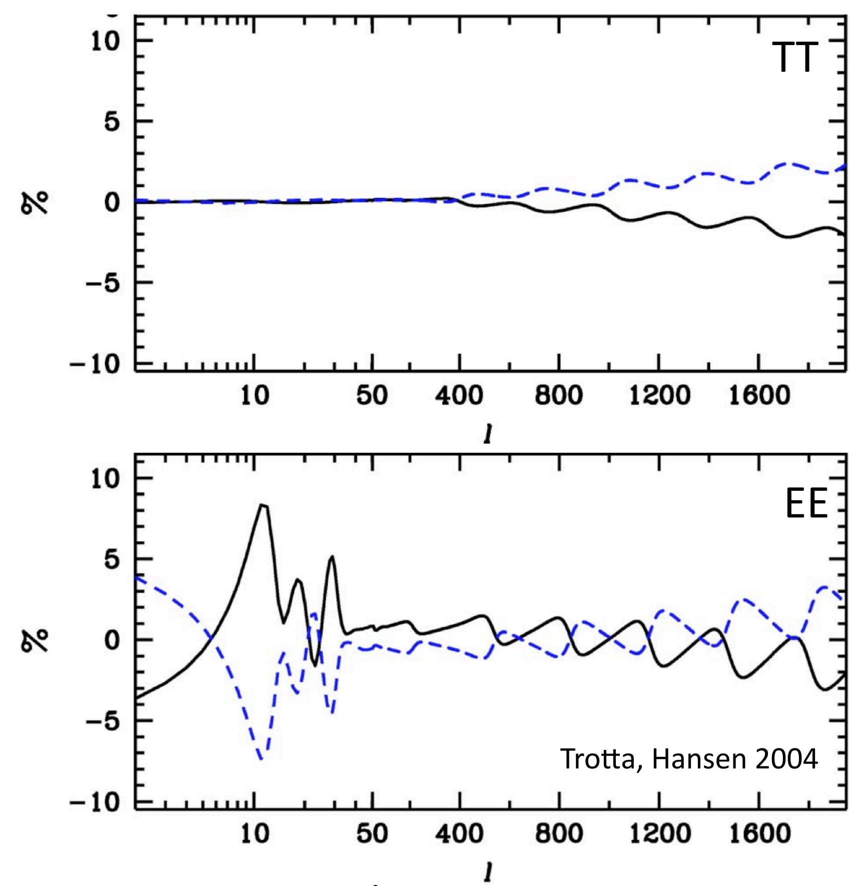
~1σ for Planck (Fisher)

Corrections relative to recfast (inc. hydrogen):

n_s, Ω_b biased at ~2 σ (Rubiño-Martin et al. 2010)

See Hirata and Chluba 2010 for complete discussion.

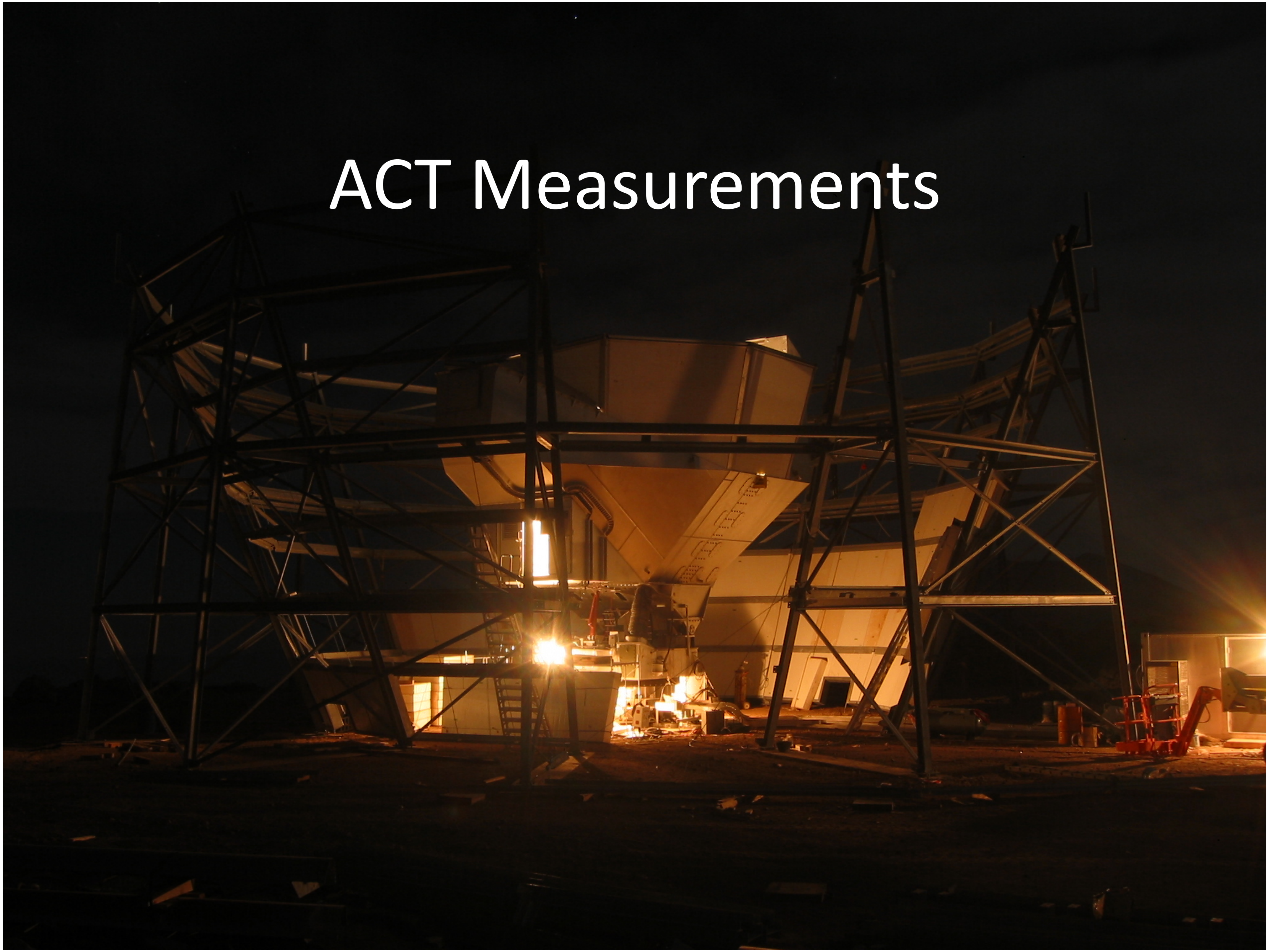
Bias



10% inc/dec in Y_p from 0.24

Measurement

ACT Measurements



Atacama Cosmology Telescope

- Barcelona ICE
- Univ of British Columbia (Canada)
- Univ of Cape Town (S Africa)
- Cardiff University (UK)
- Columbia University (USA)
- Haverford College (USA)
- INAOE (Mexico)
- Univ of Kwa-Zulu Natal (S Africa)
- Univ of Massachusetts (USA)
- NASA/GSFC (USA)
- NIST (USA)
- Univ of Oxford (UK: Dunkley, Hlozek)
- Univ of Pennsylvania (USA)
- *Princeton University (USA) (PI L. Page)
- Univ of Pittsburgh (USA)
- Pontifica Universidad Catolica (Chile)
- Rutgers University (USA)
- Univ of Toronto (Canada)
- Collaborators at La Sapienza, MPI, Miami, Stanford, Berkeley, Chicago, CfA, LLNL, IPMU Tokyo

- ~ 90 collaborators

ACT bibliography

Hardware and analysis:

- **Swetz et al. 2010, “The Receiver and Instrumentation” – also SPIE series in 2008**
- Hajian et al. 2010, “Calibration with WMAP Using Cross-Correlations”

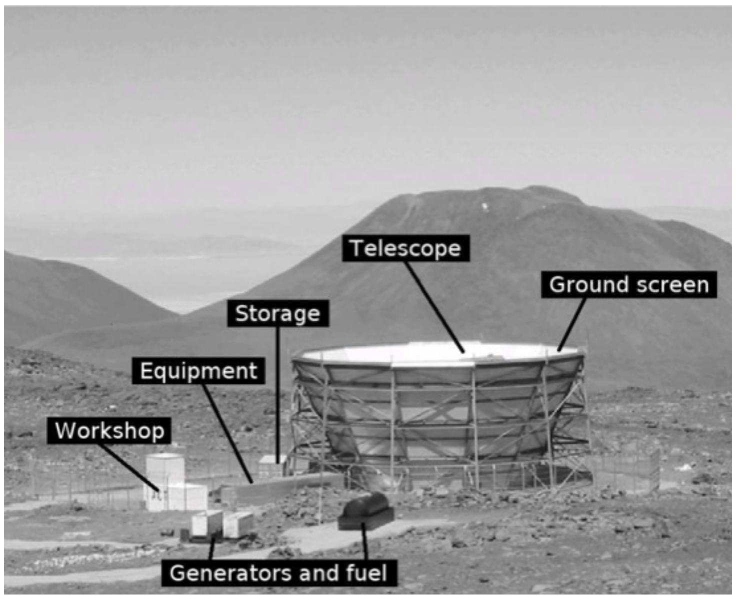
CMB:

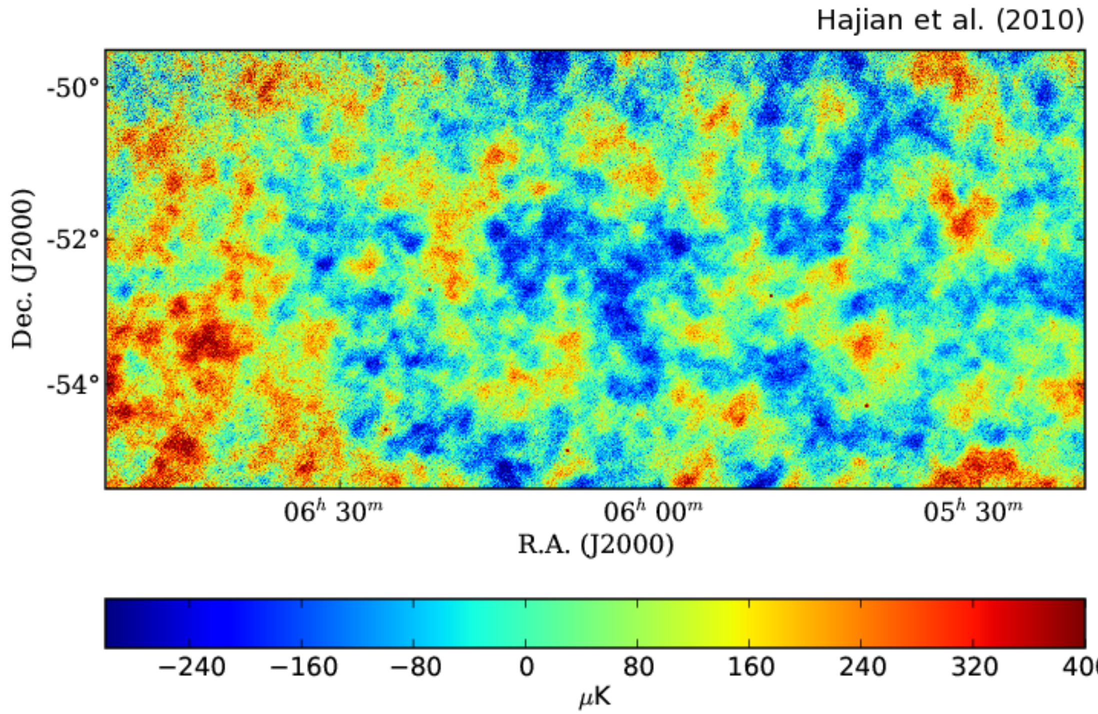
- Fowler et al. 2010, “A Measurement of the 600< ell <8000 Cosmic Microwave Background Power Spectrum at 148 GHz”
- Das et al. 2010, “A Measurement of the CMB Power Spectrum at 148 and 218 GHz from the 2008 Southern Survey”
- **Dunkley et al. 2010, “Cosmological Parameters from the 2008 Power Spectra”**

SZ and point sources:

- Hincks et al. 2009, “Beam Profiles and First SZ Cluster Maps”
- Marriage et al. 2010, “Extragalactic Sources at 148 GHz in the 2008 Survey”
- Menanteau et al. 2010, “Physical Properties and Purity of a Galaxy Cluster Sample Selected via the Sunyaev-Zel'dovich Effect”
- Marriage et al. 2010, “Sunyaev Zel’dovich Selected Galaxy Clusters at 148 GHz in the 2008 Survey”
- Sehgal et al. 2010, “Cosmology from Galaxy Clusters Detected via the Sunyaev-Zel’dovich Effect”

Telescope site and map

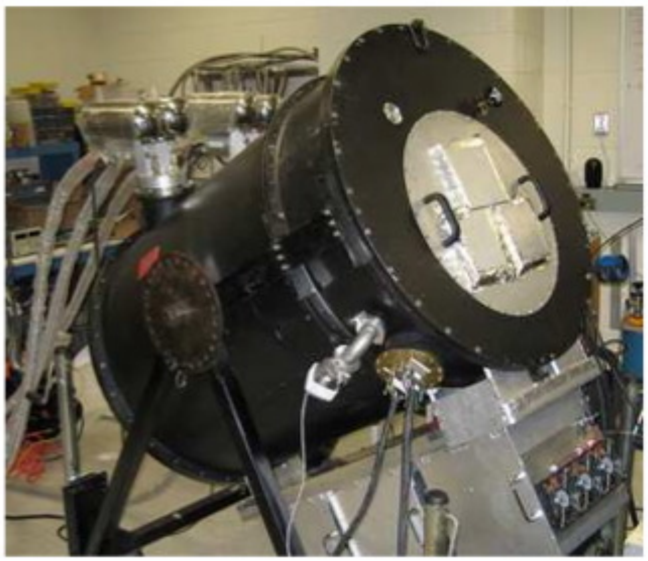


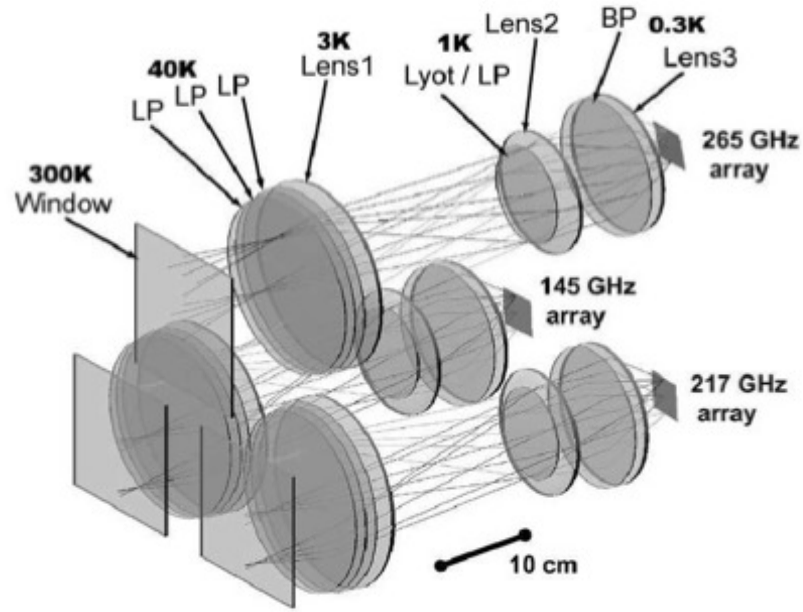


Elevation: 5200 m, Atacama Desert, 6m primary, 2m secondary, ~1.4’
3x1024 TES detectors at 148 GHz, 220 GHz (SZ null) and 270 GHz

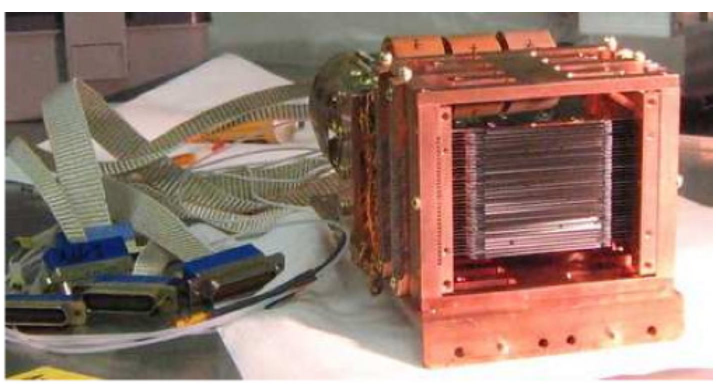
Figures: A. Hincks, A. Hajian, ERS

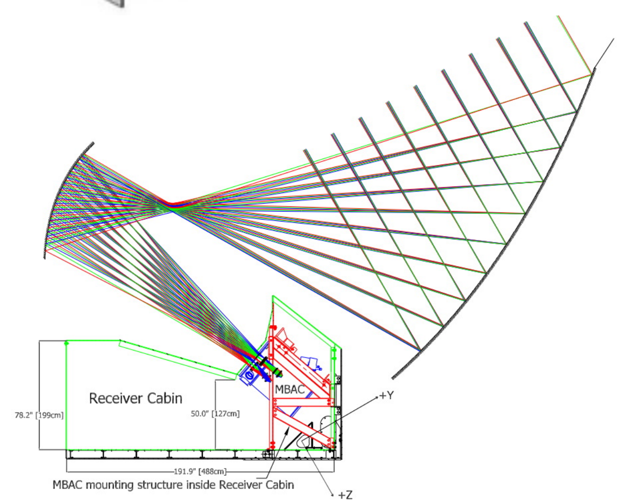
The MBAC camera and array



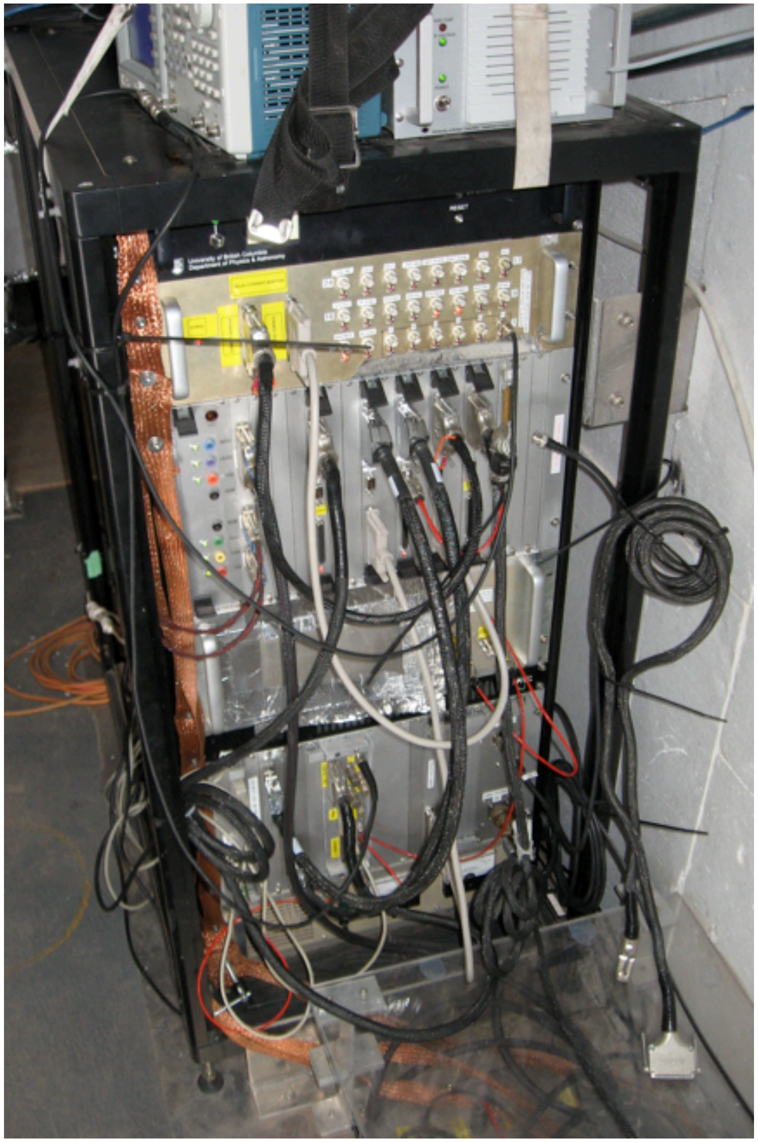


Figures: S. Dicker, B. Thornton, M. Niemack, D. Swetz





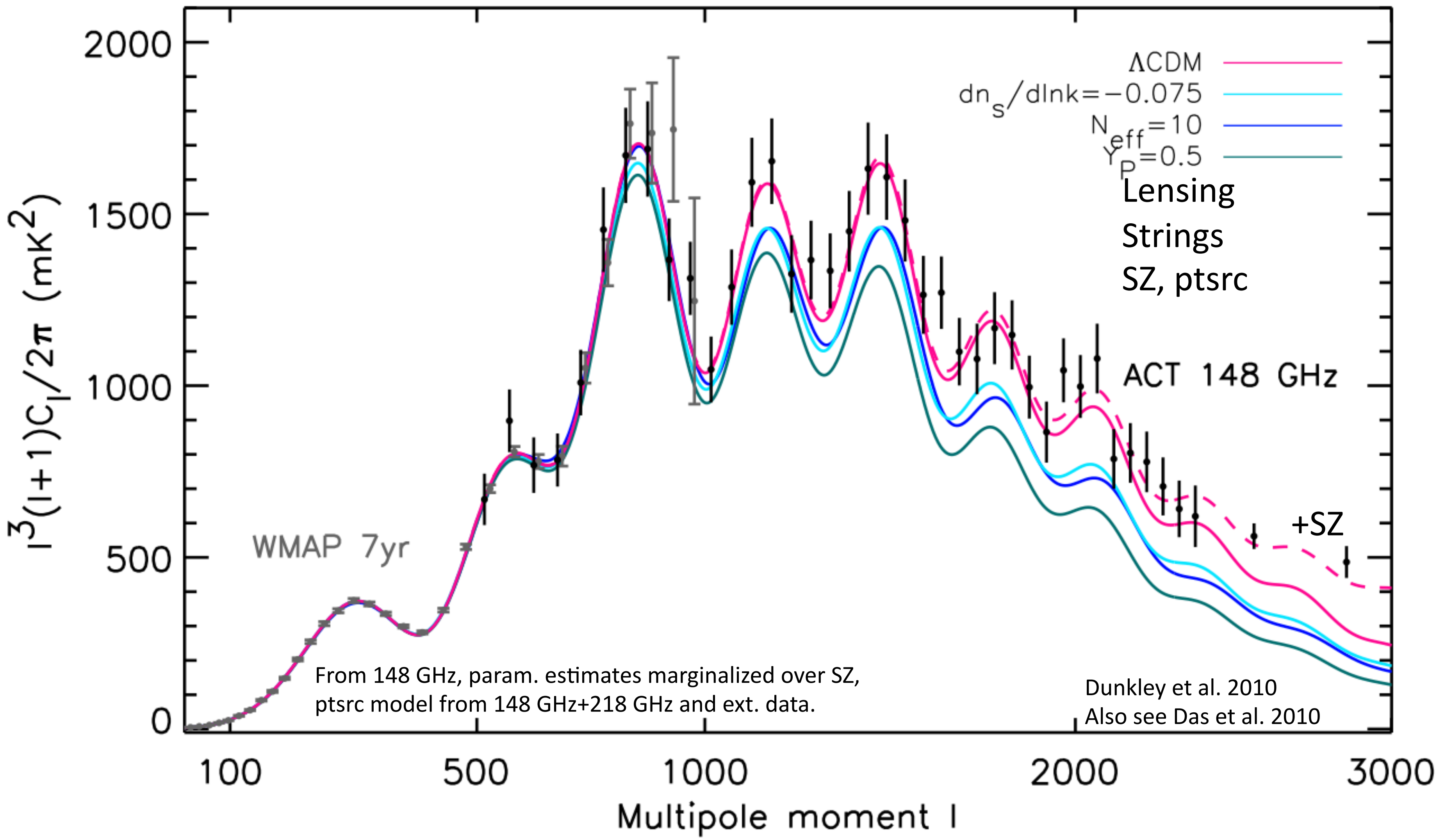
ACT Systems, Control, Calibration



"Systems and control software for the Atacama Cosmology Telescope" Switzer et al. 2008, SPIE
Calibration using the planets and atmosphere; see ERS thesis.

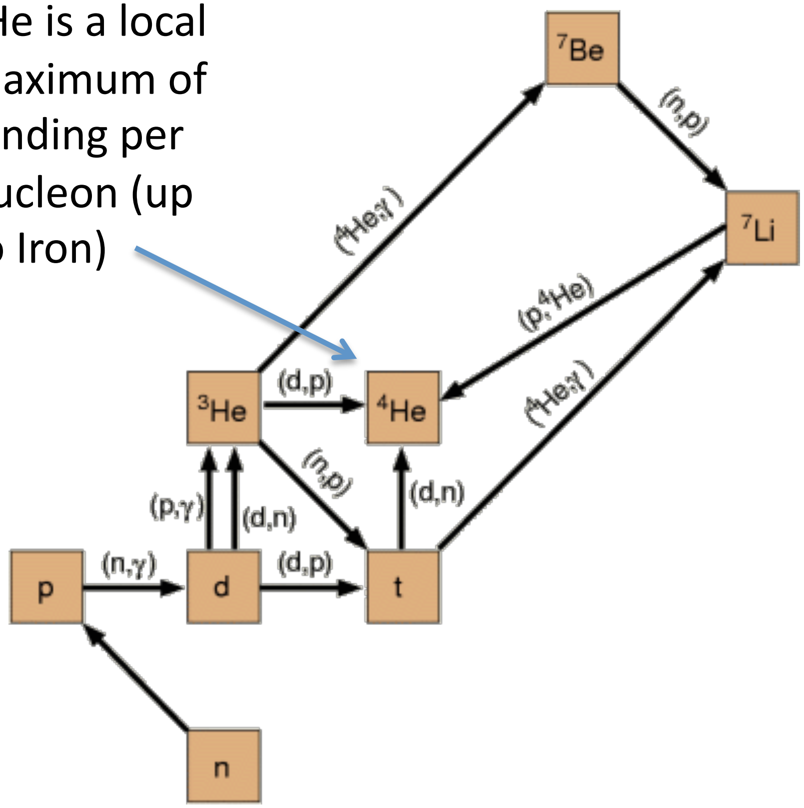
Working at the site

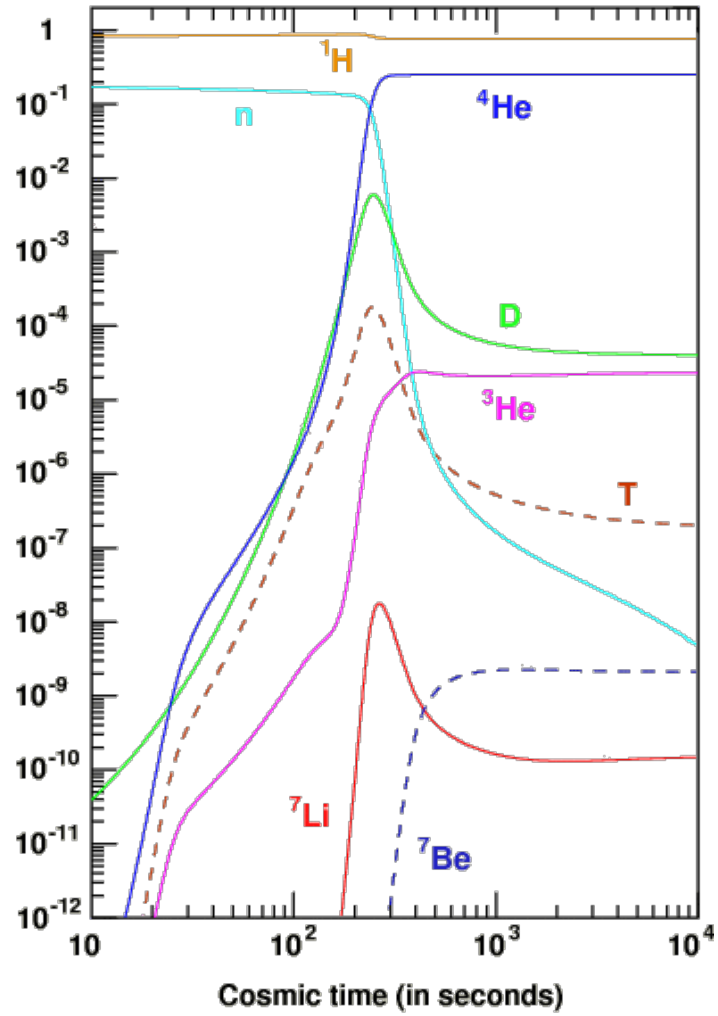
ACT power spectrum



Prehistory: creating helium

^{4}He is a local maximum of binding per nucleon (up to Iron)

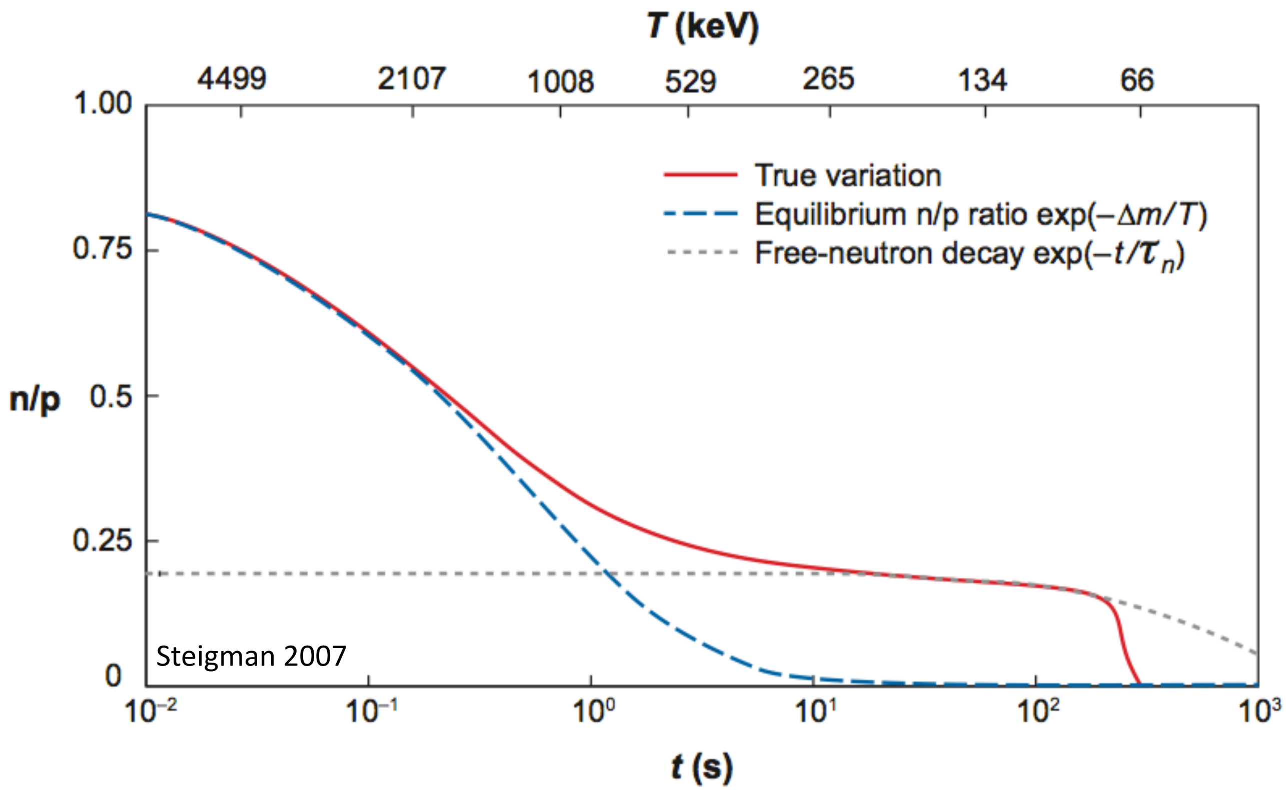




Deuterium binding energy = 2.2 MeV; baryon to photon ratio inhibits nuclei production until T < 0.1 MeV, but then opens the pipeline to convert neutrons and protons into helium.

Figures: Achim Weiss, *Einstein Online* **Vol. 2** (2006), 1018

Prehistory: neutron budget

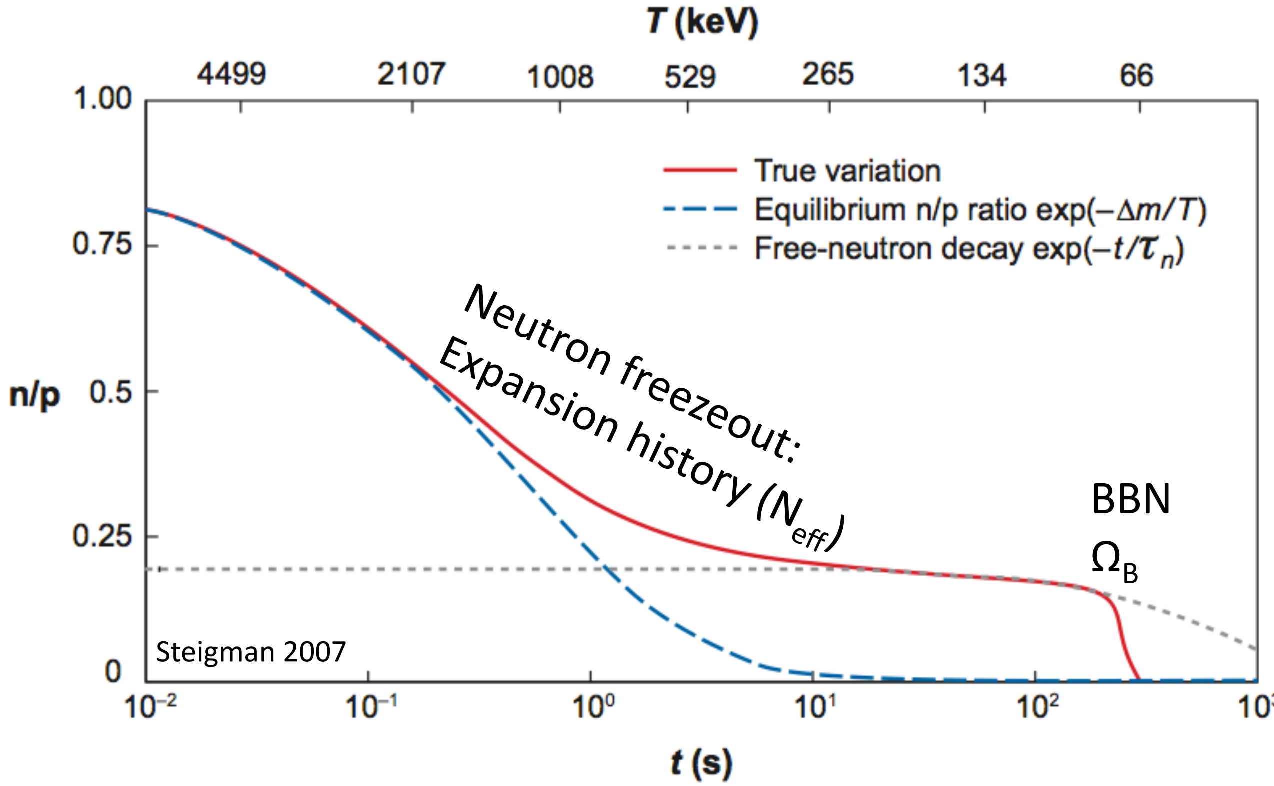


Neutron-proton mass difference = 1.3 MeV

Neutron τ=886 sec

2 neutrons per 14 protons gives one ^{4}He and 12 protons, or Y_p≈0.25

Prehistory: neutron budget



Neutron-proton mass difference = 1.3 MeV

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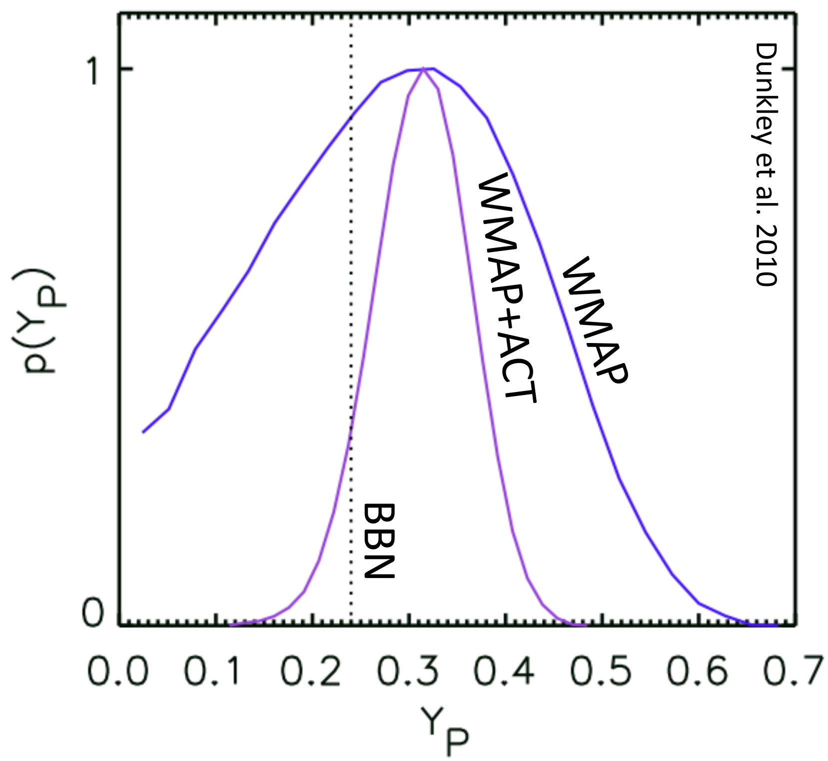
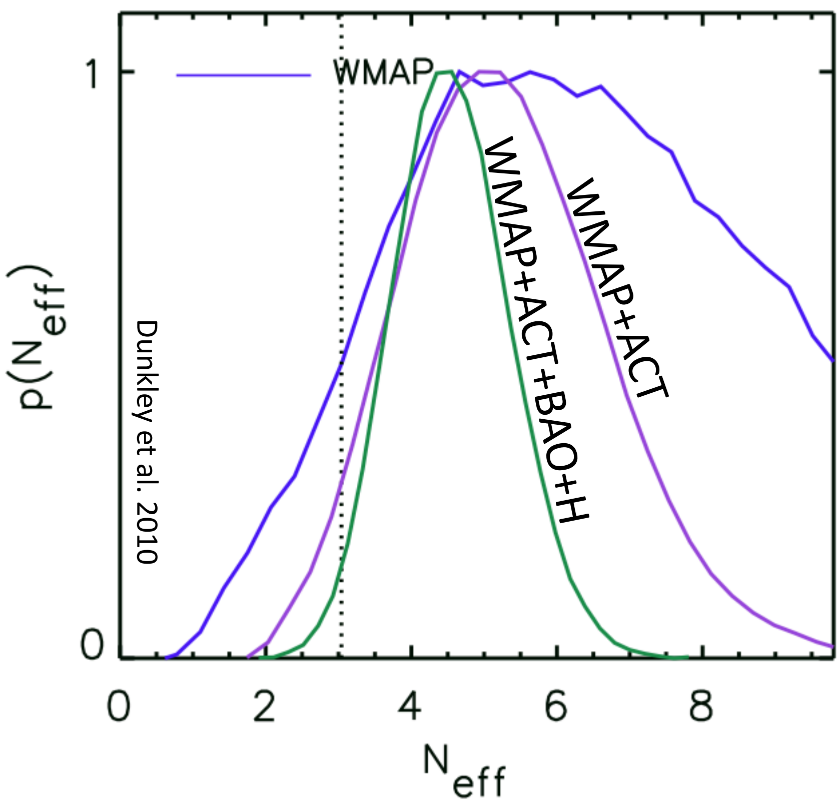
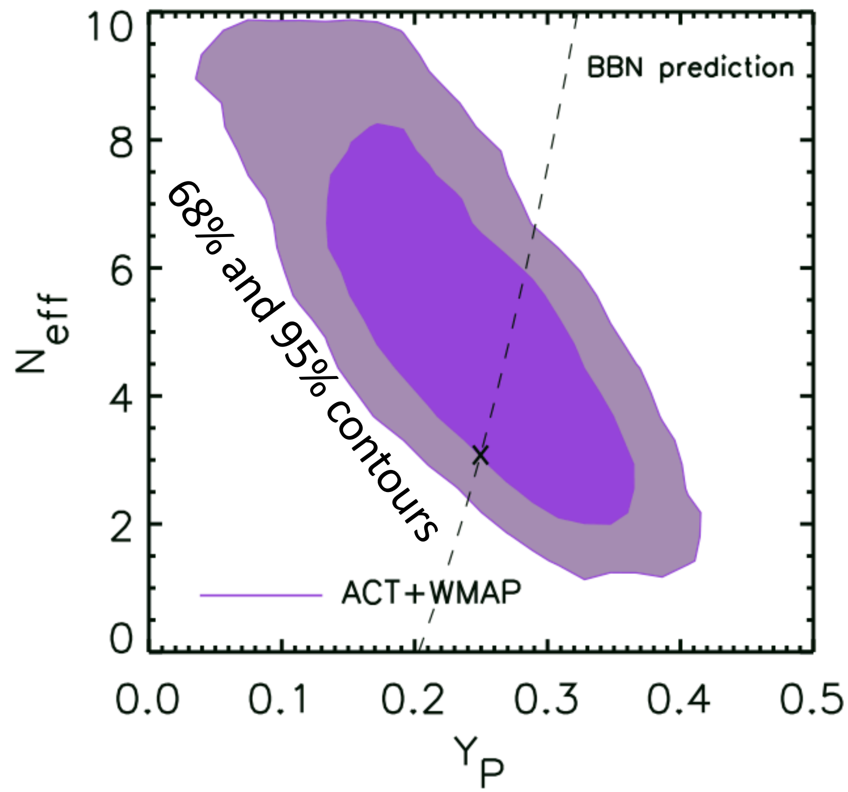
ACT: CMB constraint on helium



Is the recombination calculation sufficiently converged?: update produces a 2% shift at l~2000 vs. the 7% shift at 1σ for Y_p

Relation to neutrinos





Obs. degeneracy: increasing Y_p gives more damping; increasing N_{eff} gives more damping
Theory: increasing N_{eff} gives faster expansion, more frozen-out neutrons, larger Y_p

Strong evidence for both helium and neutrinos from CMB alone!

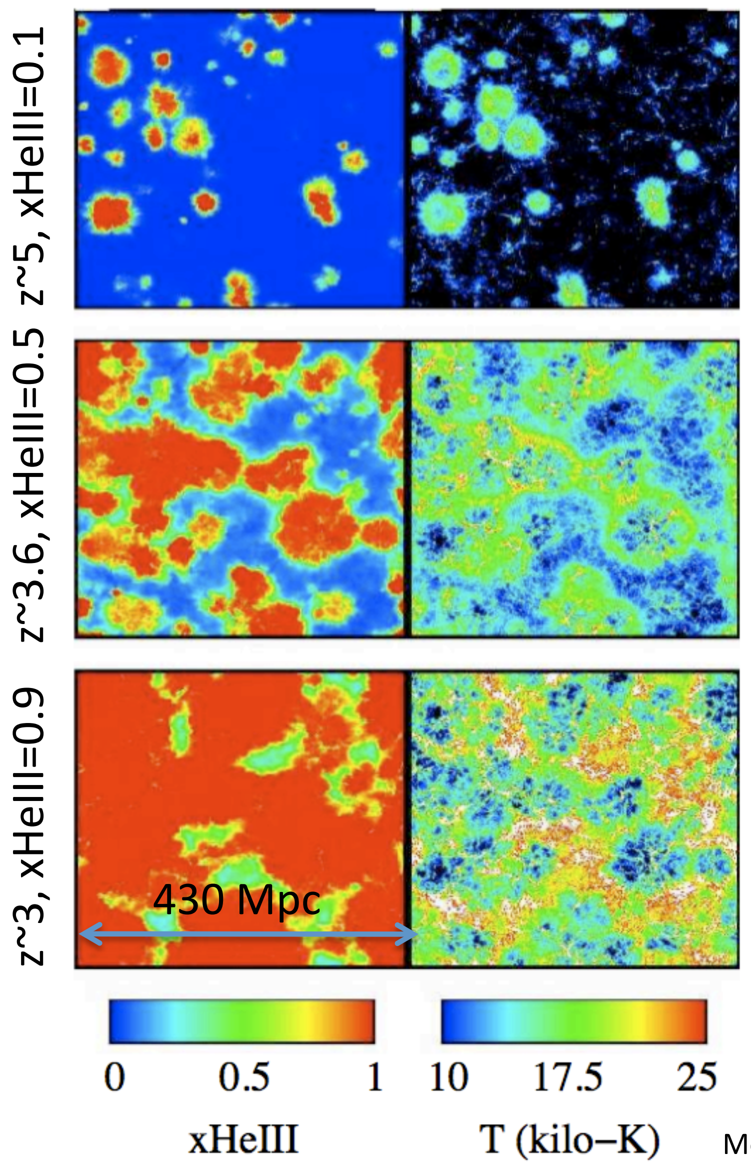
Many roads lead to helium

- Measure directly from CMB (Silk damping)
  ➔ACT08+WMAP07 CMB bound is Y_p = 0.313±0.044
- Measure deuterium (quasar absorption)➔ lower bound on primordial abundance➔ baryon/photon ratio➔ SBBN helium abundance Y_p (SBBN,D)=0.2482±0.0007
- Measure baryon abundance using the CMB
  ➔Y_p (SBBN,CMB) = 0.2488±0.0006
- Metal-poor, extragalactic HII regions, measuring another proxy for metallicity, extrapolate to zero metallacity (proxy for stellar nuc. Rates) ➔ Y_p=0.2565±0.001 (stat) ±0.005 (sys)
- Helium is least sensitive to reaction rates and baryon density; instead, to energy density, by the expansion rate.

Dunkley et al. 2010, Steigman 2010, Izotov & Thuan 2010

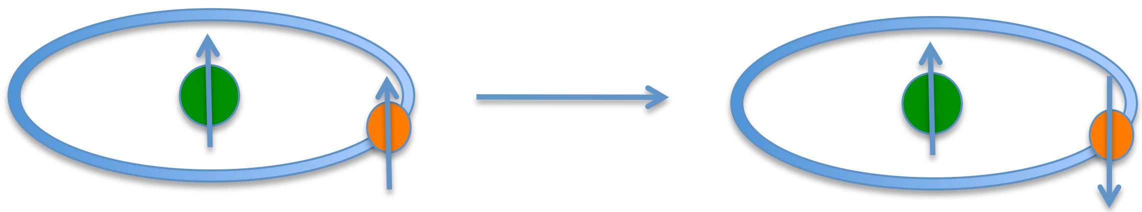
Helium reionization

HeII reionization



McQuinn et al. 2009

Hyperfine lines



New splitting on F = J + I, or: need nonzero J=L+S and I=nuclear spin.

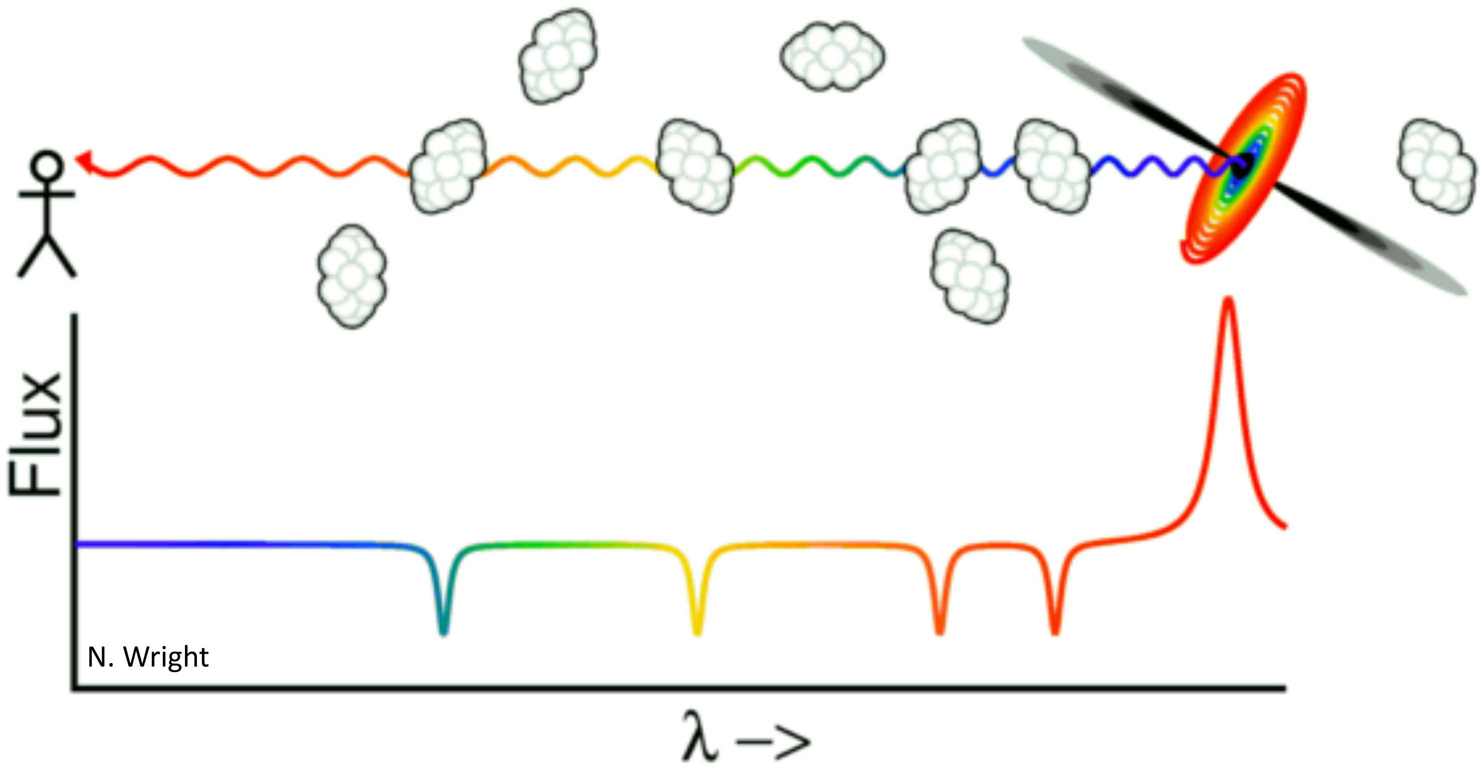
~115 stable nuclei with non-zero spin, I; ionic states that have nonzero J
Spontaneous rate ~ Z^9!

$^3He^+$ has a hyperfine splitting – can we probe HeII reionization?

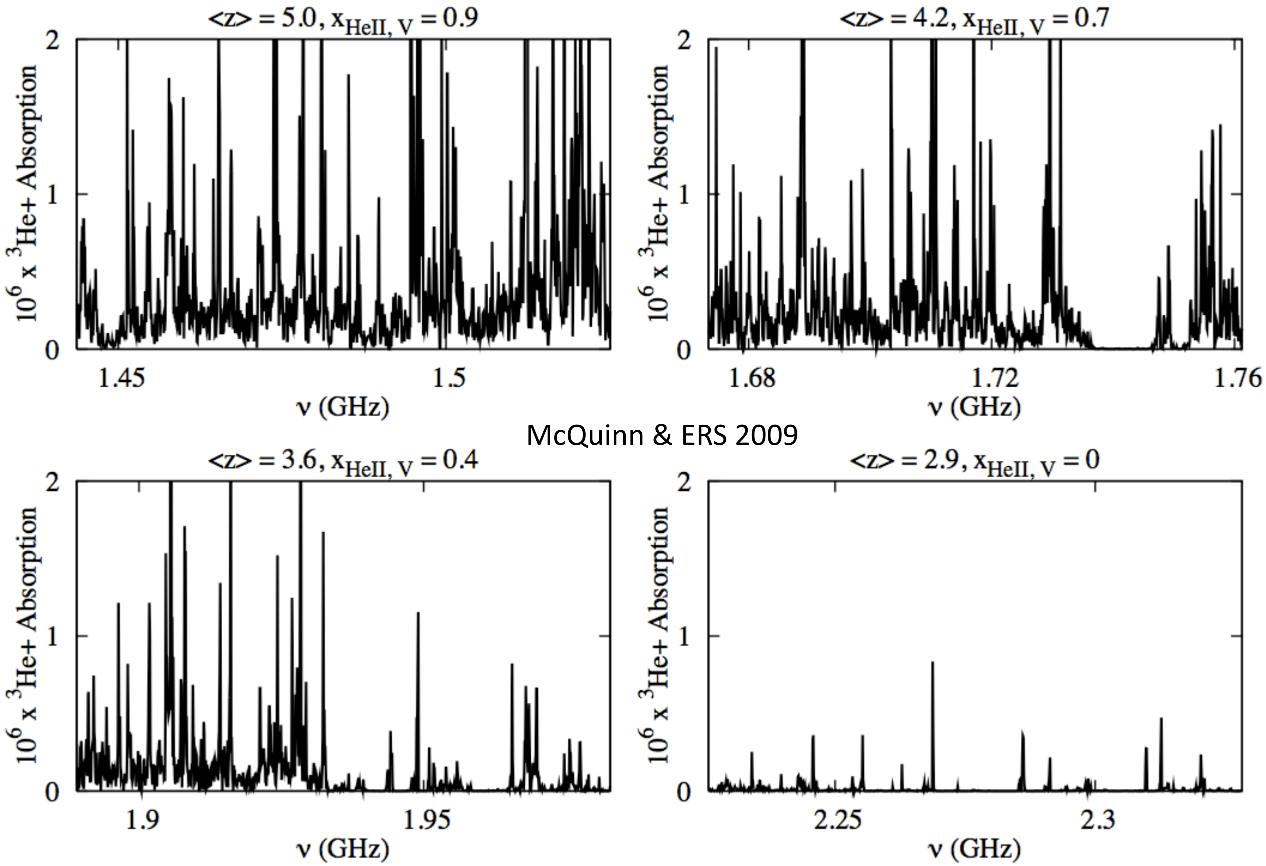
$^3He^+$ as an observable

- Abundance is down by 10^5 from hydrogen, but Einstein-A is 680 times larger than 21 cm!
- For us, 8.666 GHz at z=3.6 fiducial (where xHeII mean is thought to be ~0.5 based on quasar luminosity), becomes 1.84 GHz. (slide available)
- $^3He^+$ hyperfine from HII in galaxy constrains ^3He abundance (subject to modeling of those regions) to $\sim(1.5\times10^{-5})^{+1}_{-0.5}$ (Rood et al. 1998) consistent with BBN; also stars should reprocess ^3He in a way not fully understood.
- Cosmological ^3He: Sunyaev et al. 1966, 1984, 2007; Sigurdson and Furlanetto 2006. McQuinn&ERS 2009: First consideration in practical detail.
- Radiative and collisional coupling are inefficient (high A, low UV): $T_{spin} \sim T_{CMB}$ ➔ look for absorption! (except at >100x mean density, including ISM, slide available)

Observing absorption



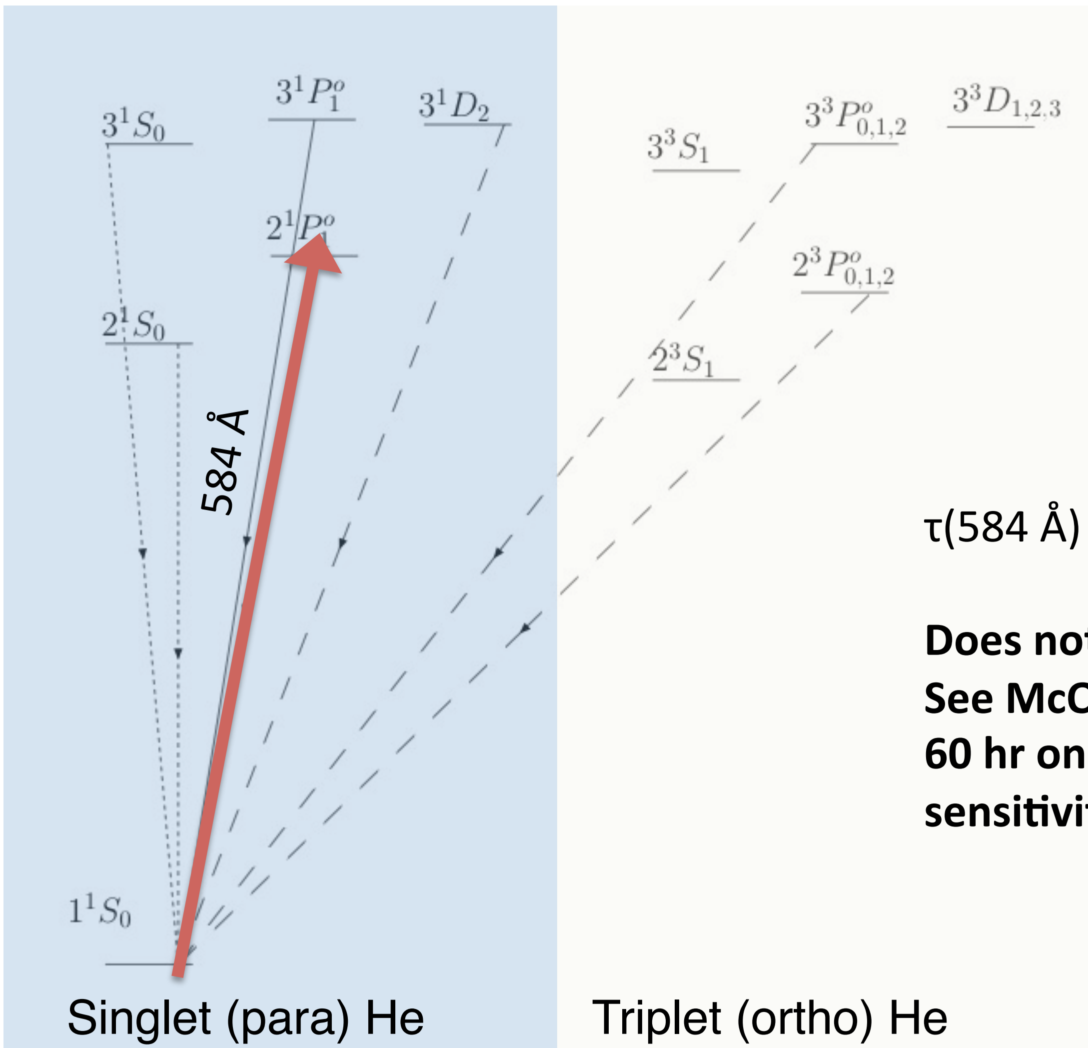
The $^{3}He^{+}$ hyperfine forest



McQuinn & ERS 2009

Sensitivity: 1 μJy/1 MHz bin direct, 30 μJy/0.1 MHz statistical, dense regions?
Best observed: 100 μJy/1 MHz at 1.7 GHz (VLA OH study, Omar et al. 2002)
Brightest (1.4 GHz) quasar: 2 Jy, z=3.53 (J1445+0958)
Challenges: ***integration, passband calibration and stability, RFI***

HeI: Grotrian diagram (n < 4)



τ(584 Å) ~ 0.025 x_{HeII} $(\Gamma_{HI}/\Gamma_{HeI})$ τ (HI Lyα)

Does not saturate, but is weak.
See McQuinn & ERS 2010.
60 hr on HST/COS NUV with pre-flight sensitivity.

Importance of the history of helium

- Helium has a rich electronic structure.
- Well-understood physics explains the helium recombination epoch to high accuracy.
- Helium impacts the CMB anisotropy, and small-angular scale measurements can be used to determine helium abundance (n/p at t < 1 min).
- There are good prospects for characterizing the second helium reionization. The $^3He^+$ and HeI 584 Å line are potential linear tracers.