What is the temperature of an ultra-cold Rydberg plasma?

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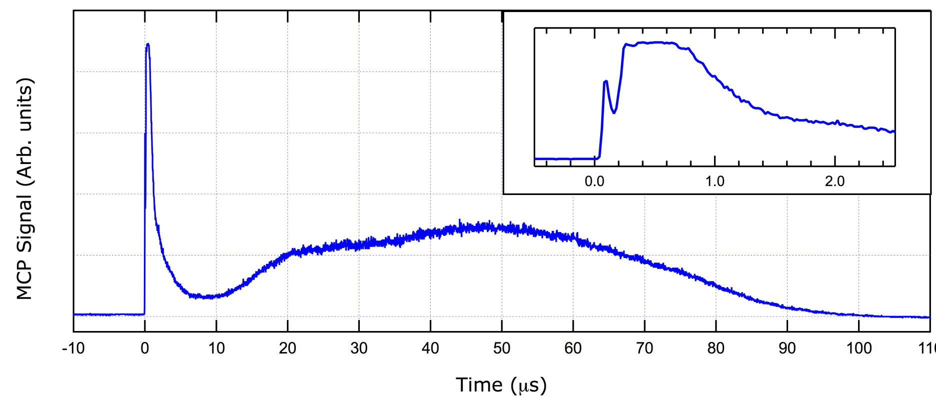
* In collaboration with Gabe Forest, Yin Li, Edwin Ward, and Anne Goodsell

Overview



Ultra-cold (neutral) plasmas (UNPs)

- What is an ultra-cold neutral plasma?
- How do you make a UNP?
- What is an ultra-cold Rydberg plasma?
- Our experiment
- UNP diagnostics
- Recent results – what is the electron temperature?
- Conclusion

What have we done?

Experiment:

$$\text{Cold Rydberg atoms} \rightarrow \text{UNP}$$

1. Look at time-of-flight spectra of Rb^+ ions as a diagnostic for plasma asymptotic expansion velocity, v_0.

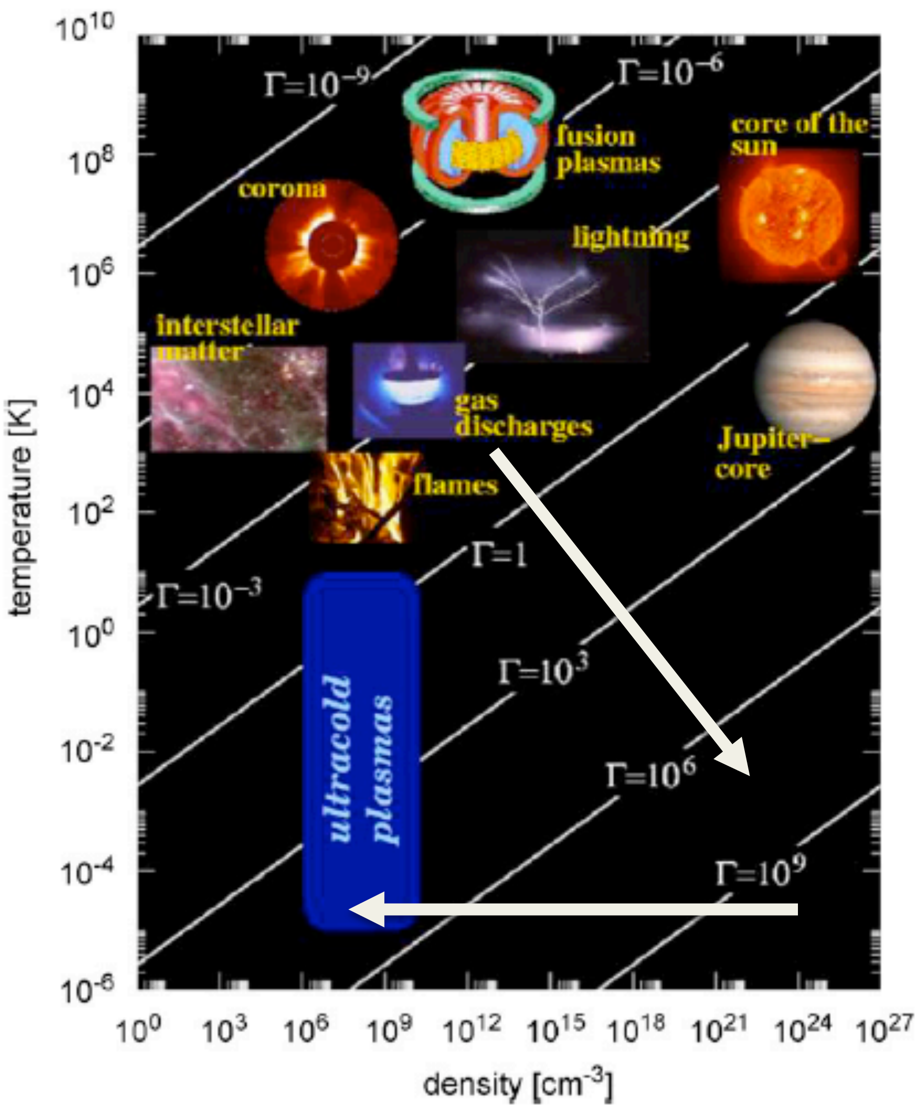
2. How is the "effective electron temperature",

$$T_{e,0} = \frac{m_i v_0^2}{k_B}$$

   affected by the initial Rydberg binding energy, E_b, and the Rydberg atom density?

What makes a plasma a plasma?

T.C. Killian et al. / Physics Reports 449 (2007) 77–130



$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}}$$

$$\ll \text{plasma size}, \ \sigma$$

$$\left(\frac{4}{3}\pi\lambda_D^3\right) n_e \geq 1$$

Coulomb coupling parameter:

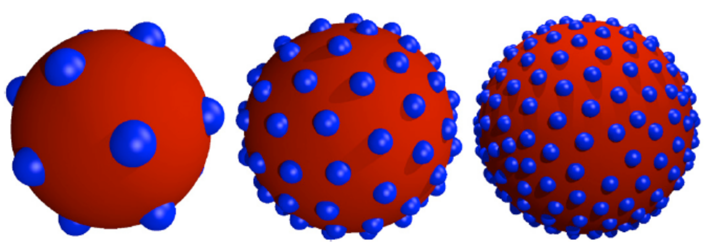
$$\Gamma_e = \frac{e^2}{4\pi\epsilon_0 a k_B T_e}$$

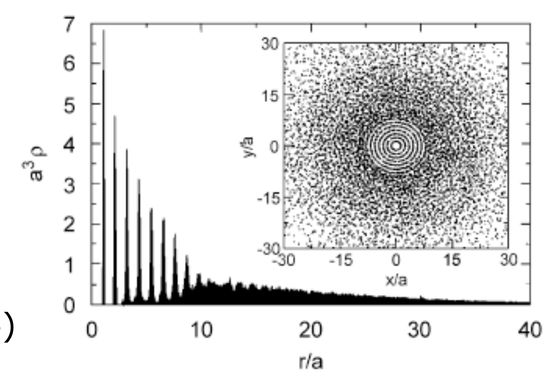
- Most plasmas are hot!

$\Rightarrow$ Electron collisions need to be able to ionize atoms to replenish electrons lost by recombination

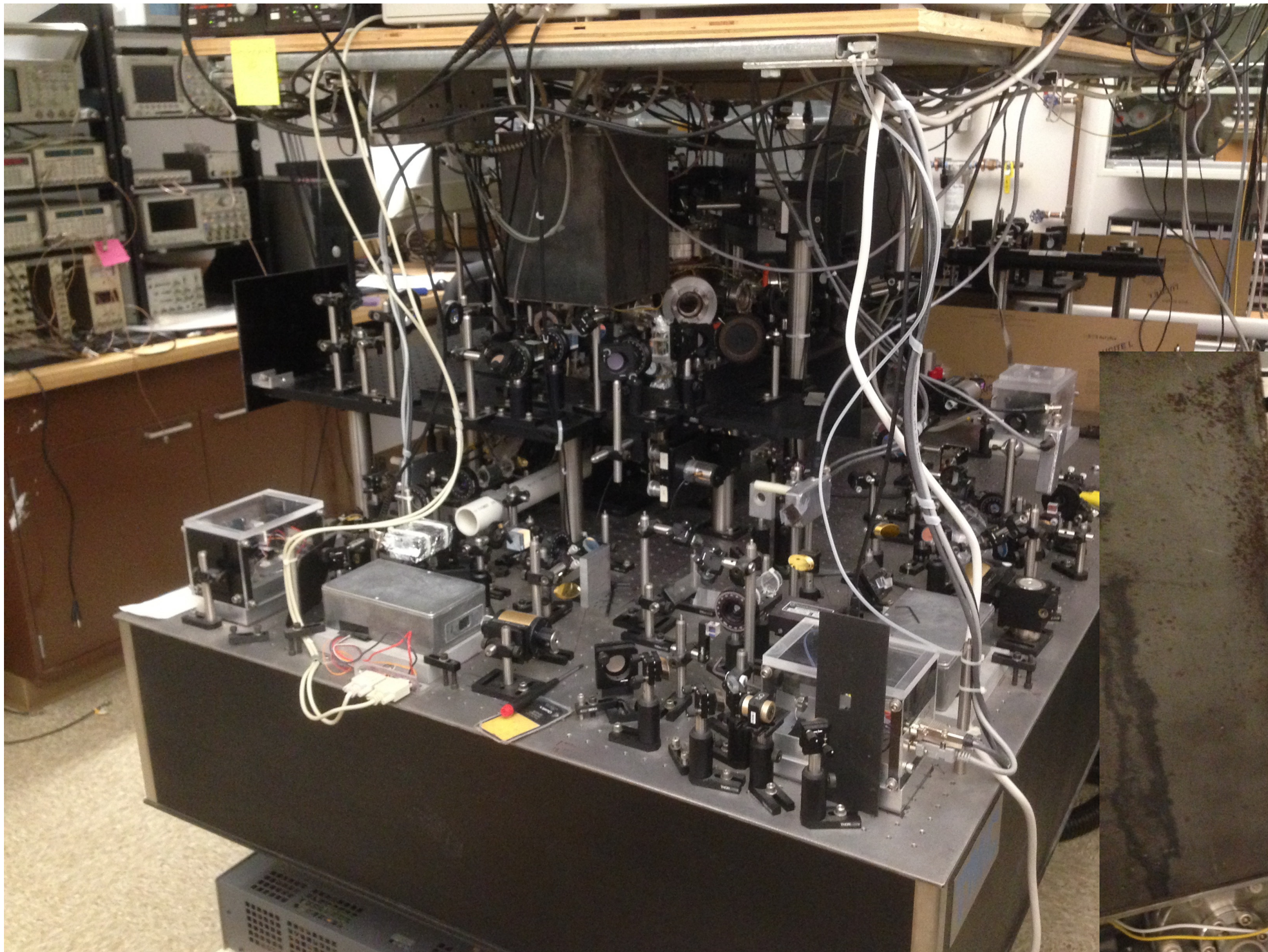
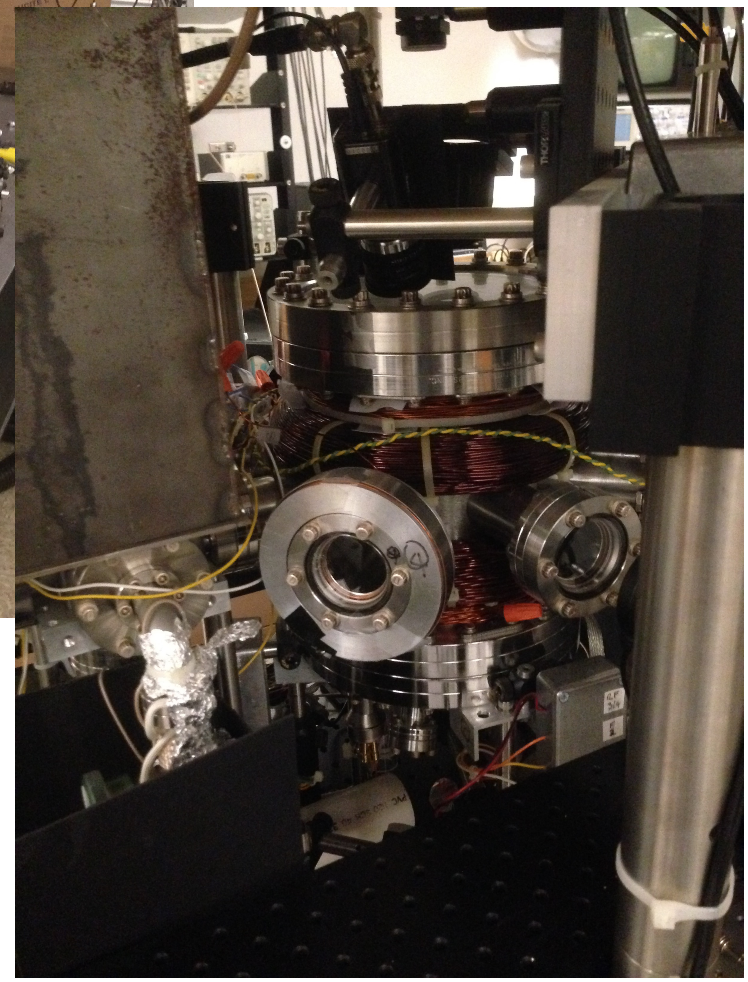
- Atomic physics affects plasma dynamics

- Cold plasmas – a route to the "strongly coupled regime"? ($\Gamma > 1$)





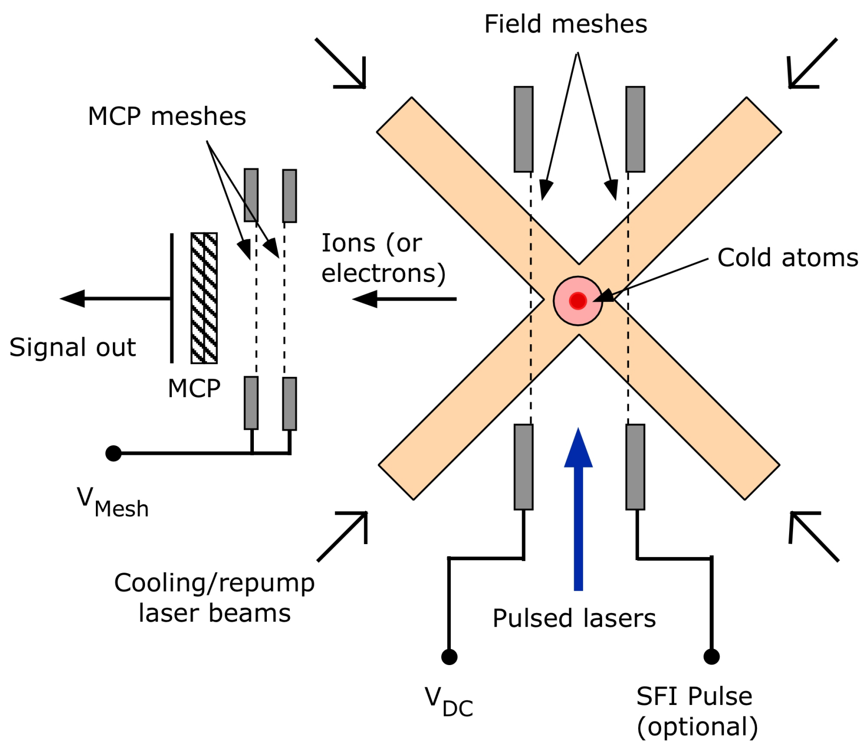
Pohl et al, Phys. Rev. Lett., **92**, 155003 (2004)

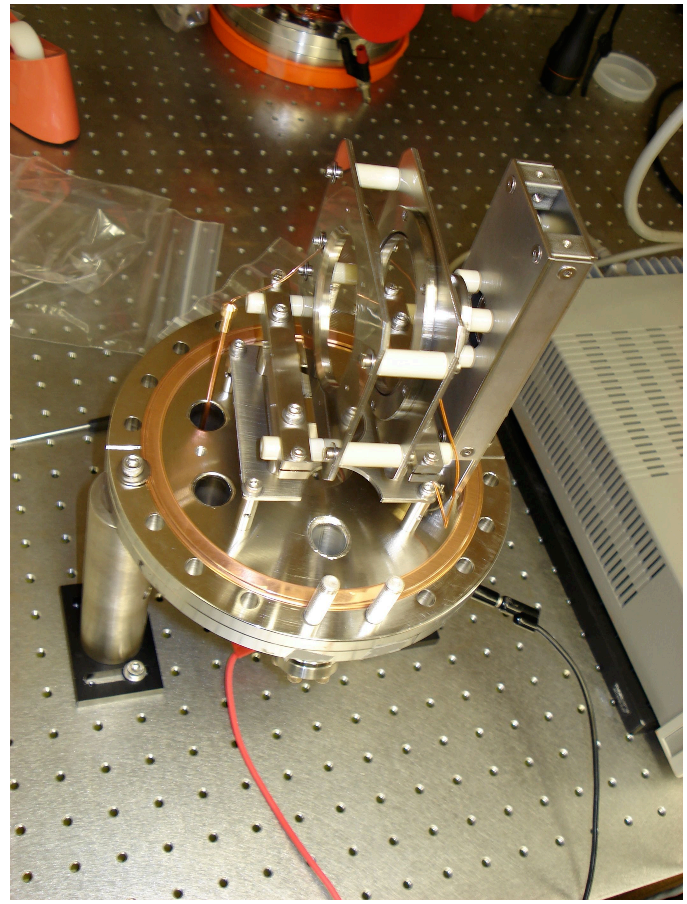



Colby Apparatus
(September 2015)

Inside MOT vacuum chamber

Observe electrons (or ions) that "leak" out of UNP made from cold **Rb** atoms using a micro-channel plate (MCP)

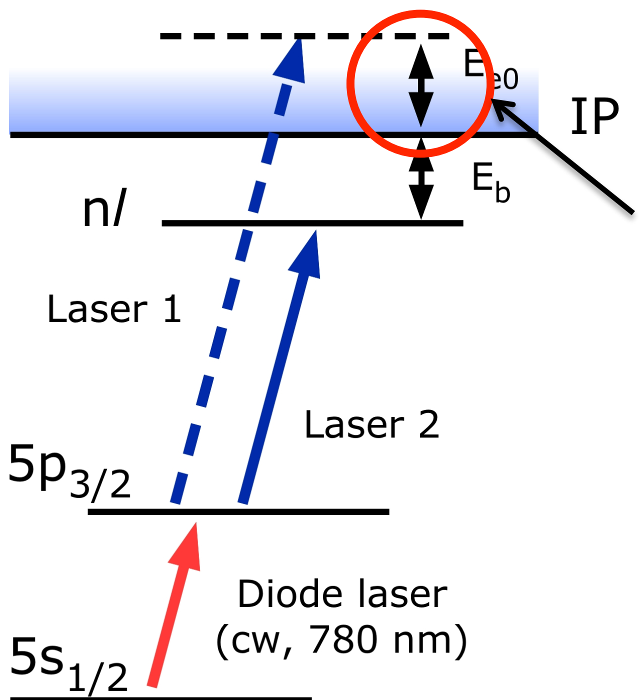




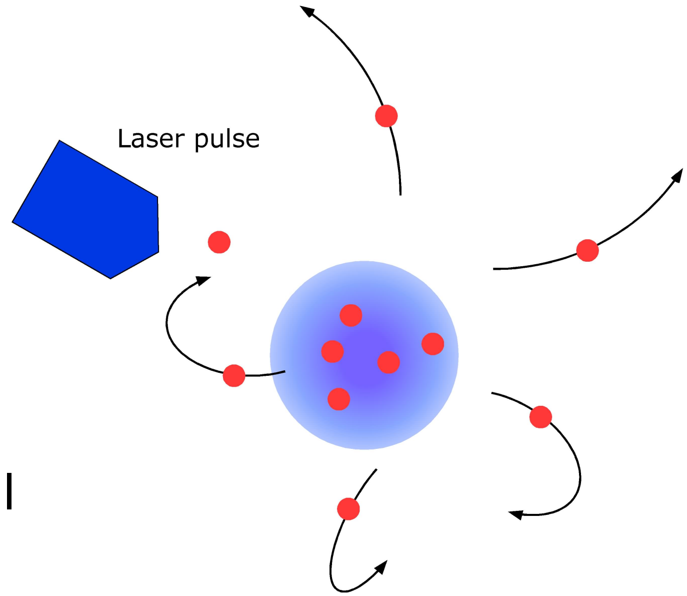
(Rb^+ has no transitions that are suitable for laser Doppler velocimetry.)

Making a UNP

(Rb; "Laser 1" only)



Control initial electron temperature



$$E_{e,0} \equiv \frac{3}{2} k_B \underline{T_{e,0}} = h\nu - E_{IP}$$

$$\Gamma_e = \frac{e^2}{4\pi\epsilon_0 \underline{a} k_B T_e}$$

$$T_{e,0} = \ 0.1 - 1000 \text{ K}$$

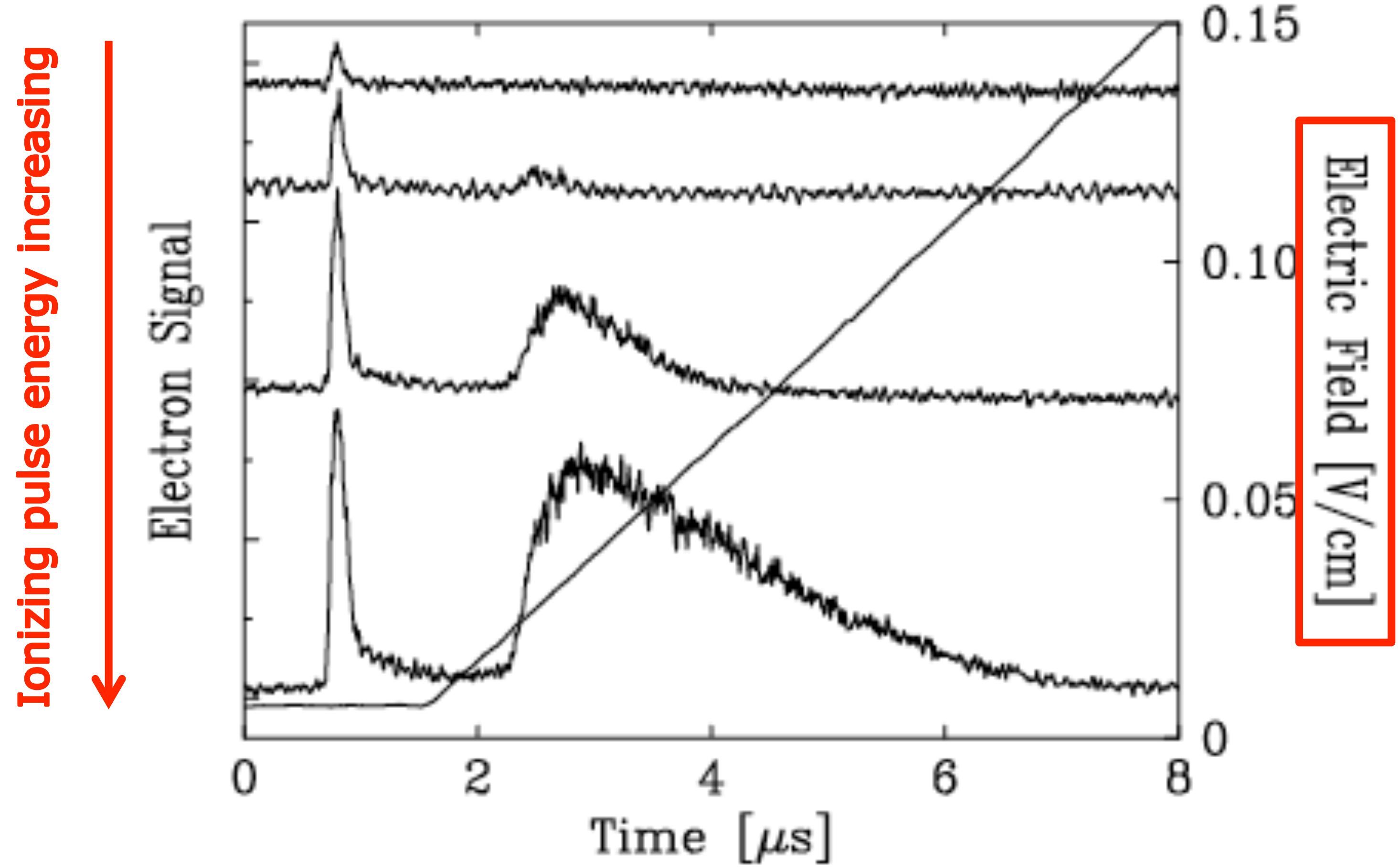
Laser 1 excess photon energy all goes to electron

VOLUME 83, NUMBER 23 PHYSICAL REVIEW LETTERS 6 DECEMBER 1999

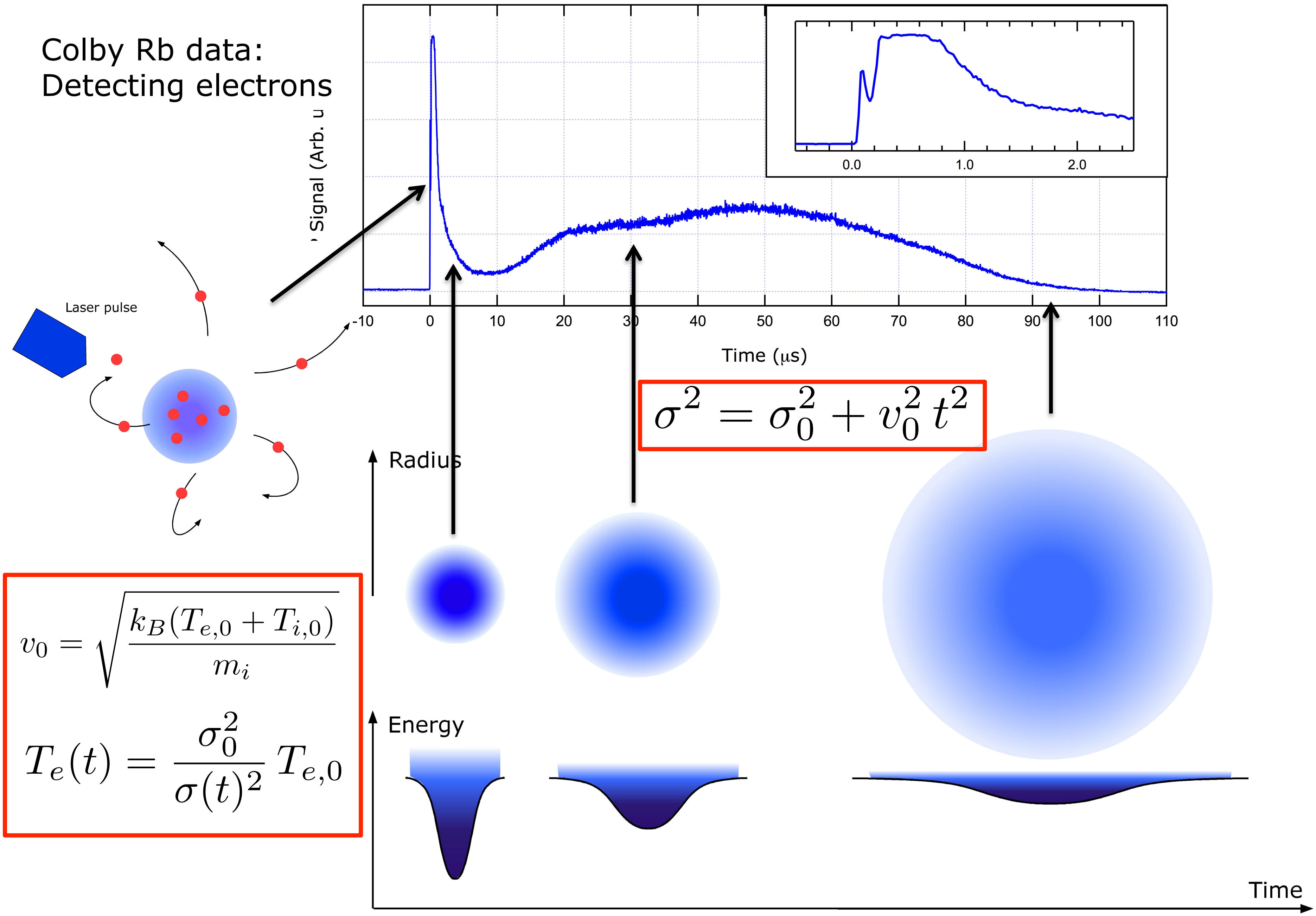
Creation of an Ultracold Neutral Plasma

T. C. Killian, S. Kulin, S. D. Bergeson,* L. A. Orozco,† C. Orzel, and S. L. Rolston
National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8424
(Received 30 July 1999)

Xe $6s[3/2]_2$
$\tau = 43$ s
$\lambda = 882$ nm



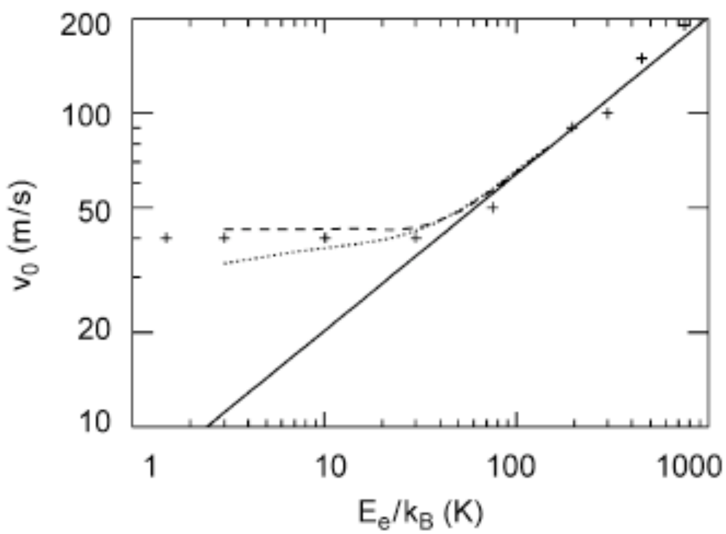
Colby Rb data:
Detecting electrons



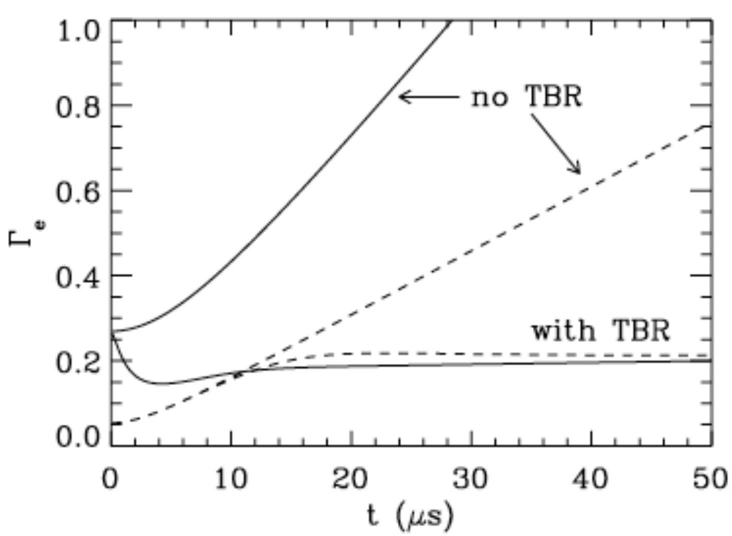
$$\sigma^2 = \sigma_0^2 + v_0^2\, t^2$$

$$v_0 = \sqrt{\frac{k_B(T_{e,0} + T_{i,0})}{m_i}}$$

$$T_e(t) = \frac{\sigma_0^2}{\sigma(t)^2}\, T_{e,0}$$



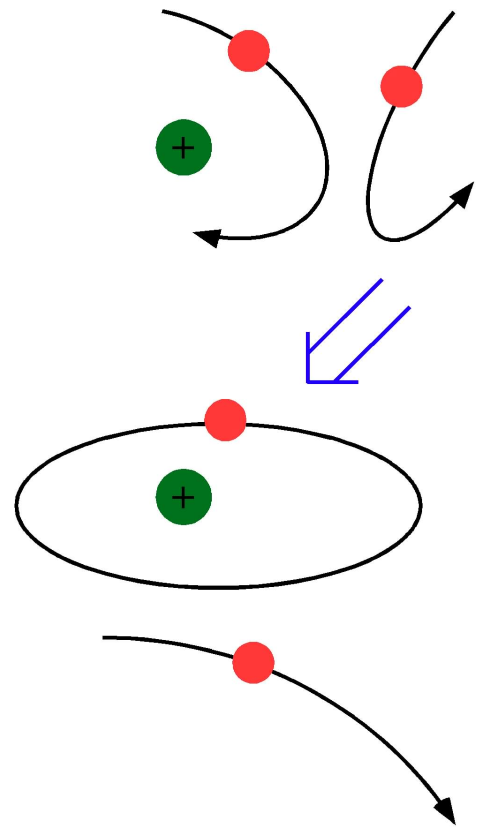
Experiment: Kulin et al., PRL, **85**, 318 (2000)
Theory: Robicheaux and Hansen, PRL, **88**, 055002 (2002)



Problems in reaching the Strongly-coupled regime

TBR heating (+ DIH, CL)

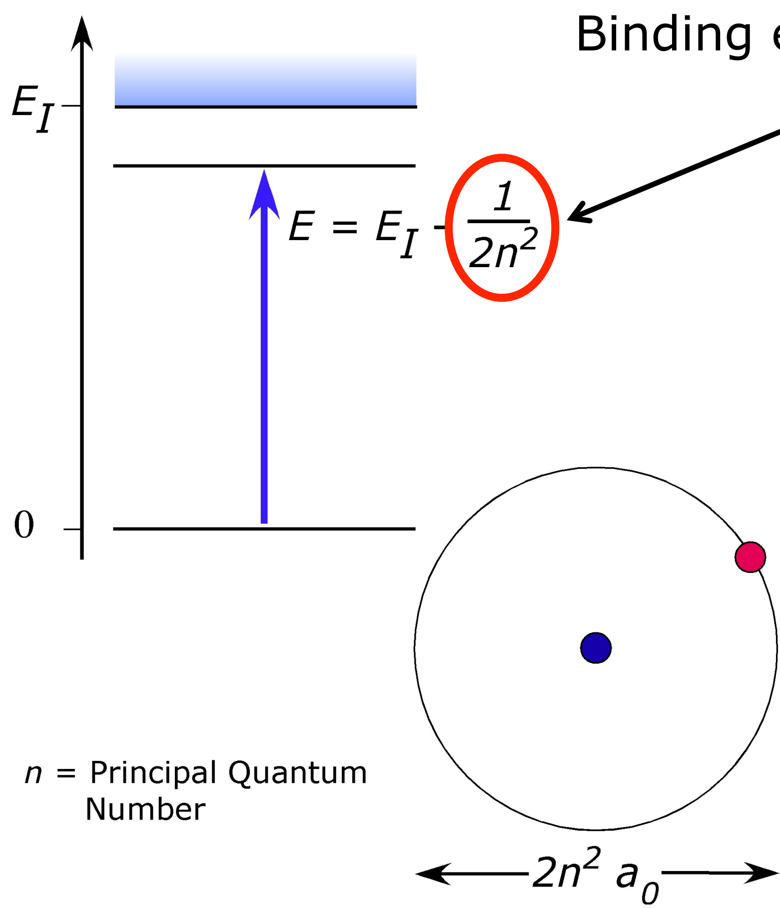
$$\mathrm{Rate} \propto T^{-9/2}$$



Rydberg atoms

Large size, electron weakly bound – "planetary atoms"
Properties depend on *n* (or *n**) in a regular manner

Binding energy, E_b (in atomic units)



Rydberg state properties

Cross section $\propto n^4$

Polarizability $\propto n^7$

Dipole moment $\propto n^2$

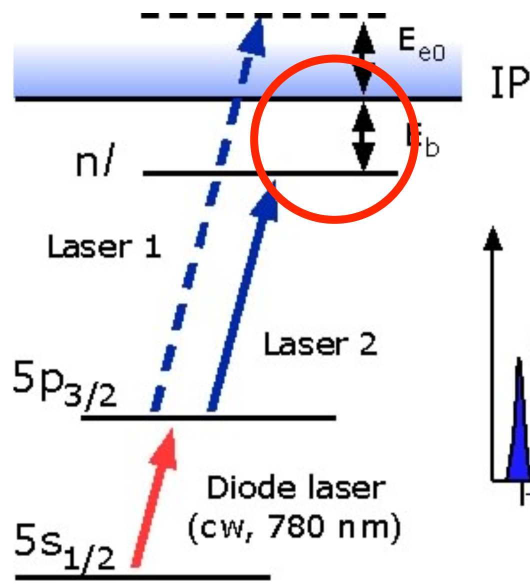
Radiative lifetime $\propto n^3$

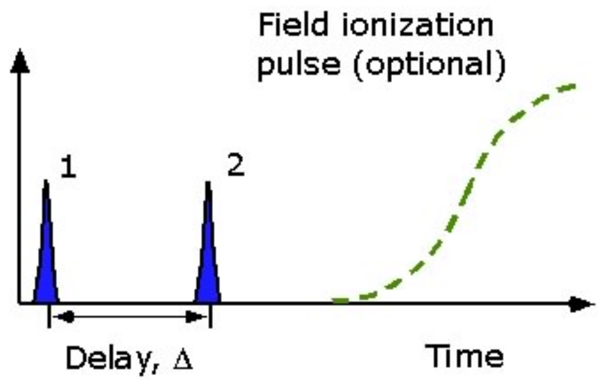
$\boxed{\text{Field ionization threshold } \propto n^{-4}}$

What is a Rydberg plasma?

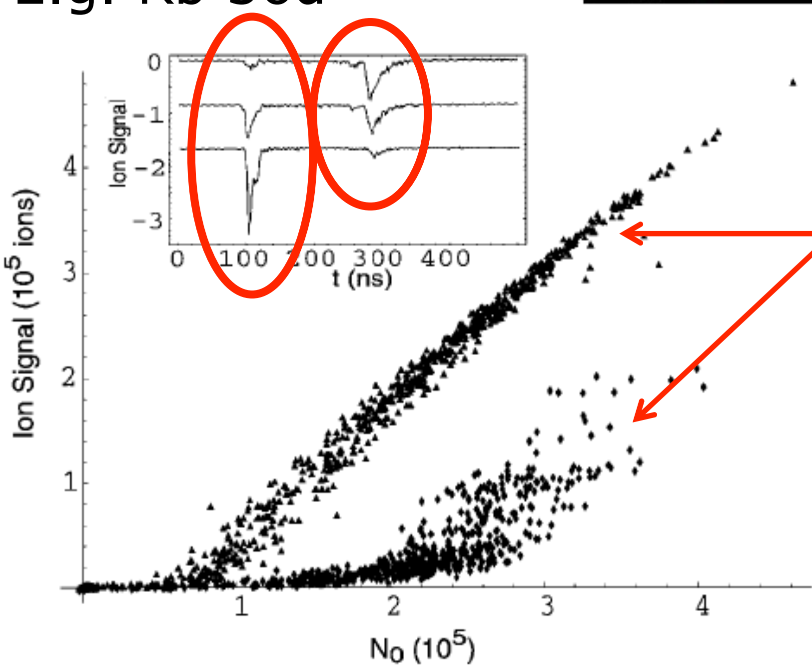
(and, how do you make one?)

(Laser 2 only)





E.g. Rb 36d



"Avalanche"

Somehow, cold, dense samples of Rydberg atoms spontaneously evolve to plasma!
(Discovered at UVA)

(Robinson et al, Phys. Rev. Lett., 85, 4466, 2000)

How does this happen?

Seeding mechanism:

Dipole-dipole forces – attractive and repulsive interatomic energy curves (e.g. Cabral et al., New J. Phys., **12**, 093023, 2010)

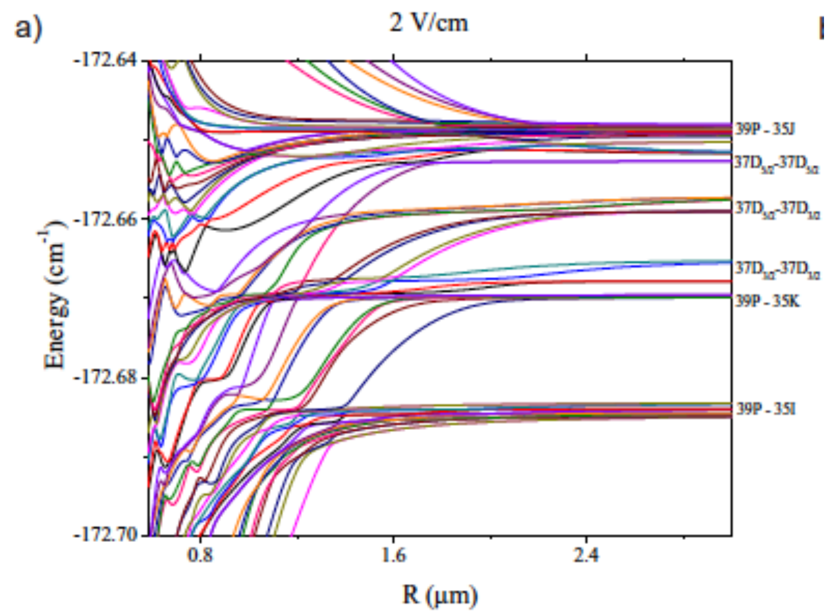
Penning ionization due to attractive potentials (e.g., Robicheaux, J. Phys. B, **38**, S333, 2005)

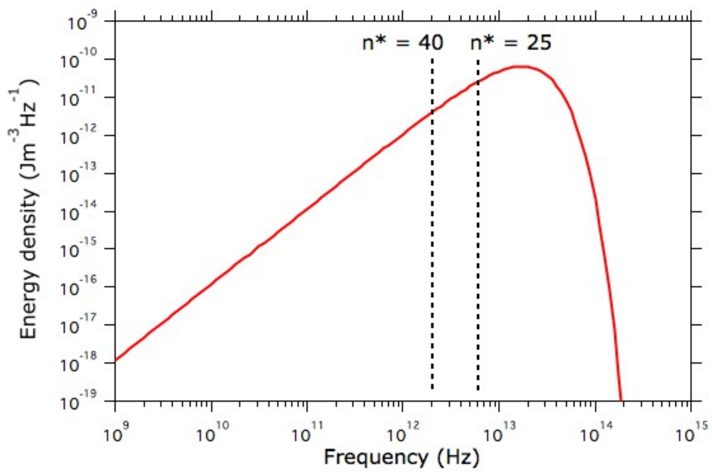
Or:

Photoionization by black body radiation (BBR)

Hot-cold Rydberg collisions

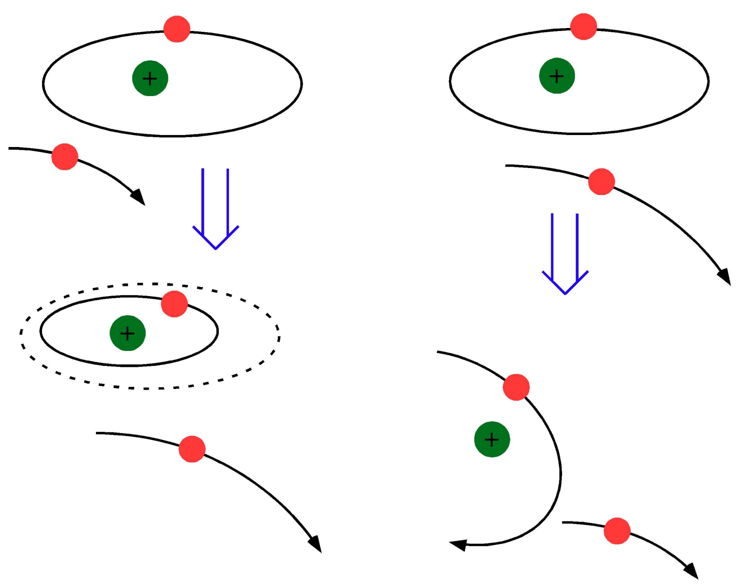
Li et al., Phys. Rev. A, **70**, 042713 (2004)





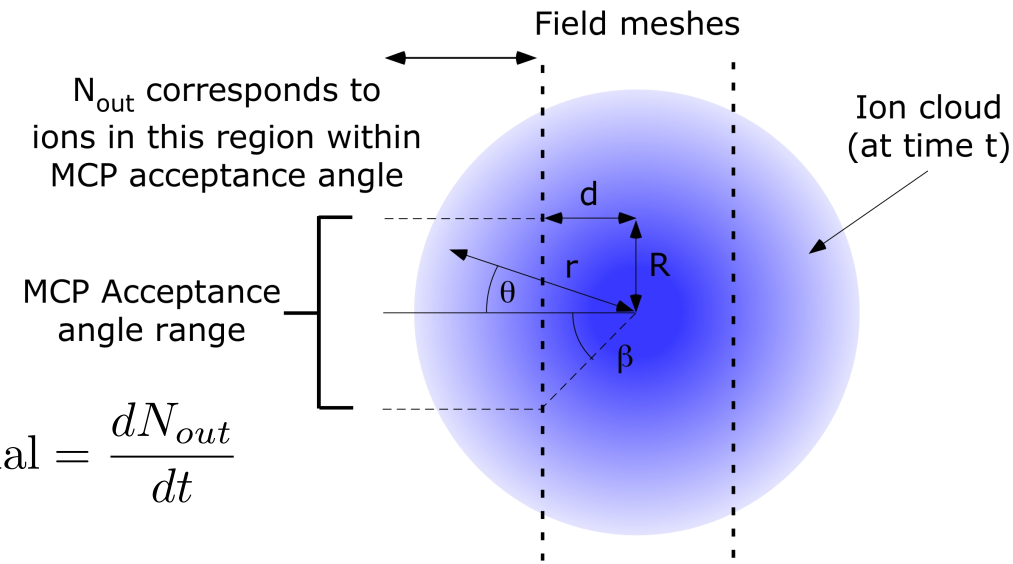
Then: avalanche regime

- Electron-Rydberg collisions ionize up to approximately 75% of Rydberg atoms
- Remaining Rydberg atoms are scattered to lower energy states
- **When does avalanche regime end, and what determines the plasma electron temperature?**



Experiment – finding v_0 from Rb^+ ion TOF signal

Kevin Twedt, PhD thesis, University of Maryland, 2012



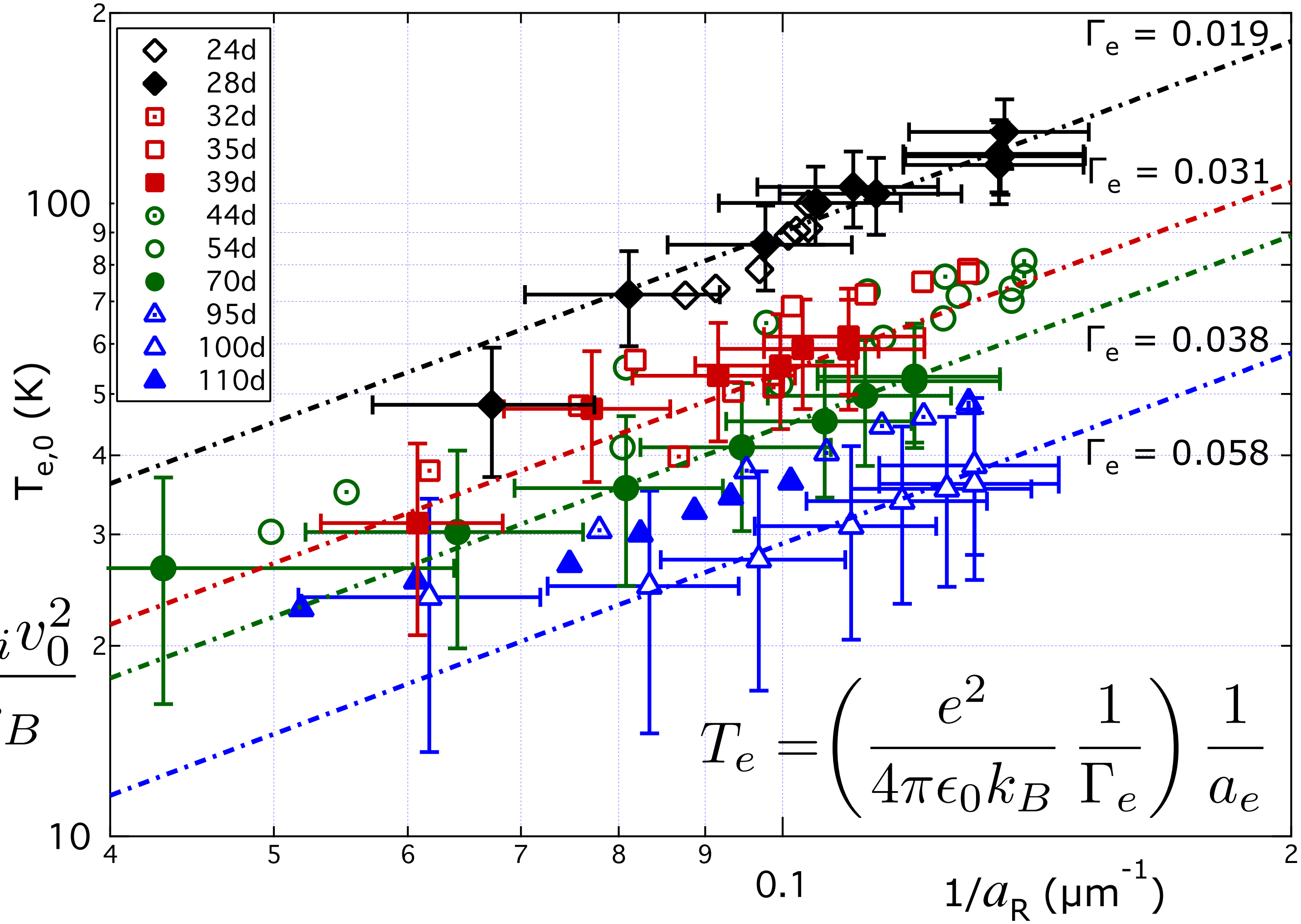
$$\text{MCP Signal} = \frac{dN_{out}}{dt}$$

$$N_{out}(t) = 2\pi \int_{\theta=0}^{\beta} \int_{r=d/cos\theta}^{\infty} n_i(t,r) r^2 sin\theta \, d\theta \, dr$$

$$\sigma^2 = \sigma_0^2 + v_0^2 t^2$$

$$\boxed{n_i(r,t) = \frac{N_i}{(2\pi\sigma^2)^{3/2}} e^{-\frac{r^2}{2\sigma^2}}}$$

Selected results



$$T_{e,0} = \frac{m_i v_0^2}{k_B}$$

Idea: use scaled quantities:

$$E_b = \frac{1}{2}\frac{e^2}{4\pi\epsilon_0 a_0}\frac{1}{n^{*2}}$$

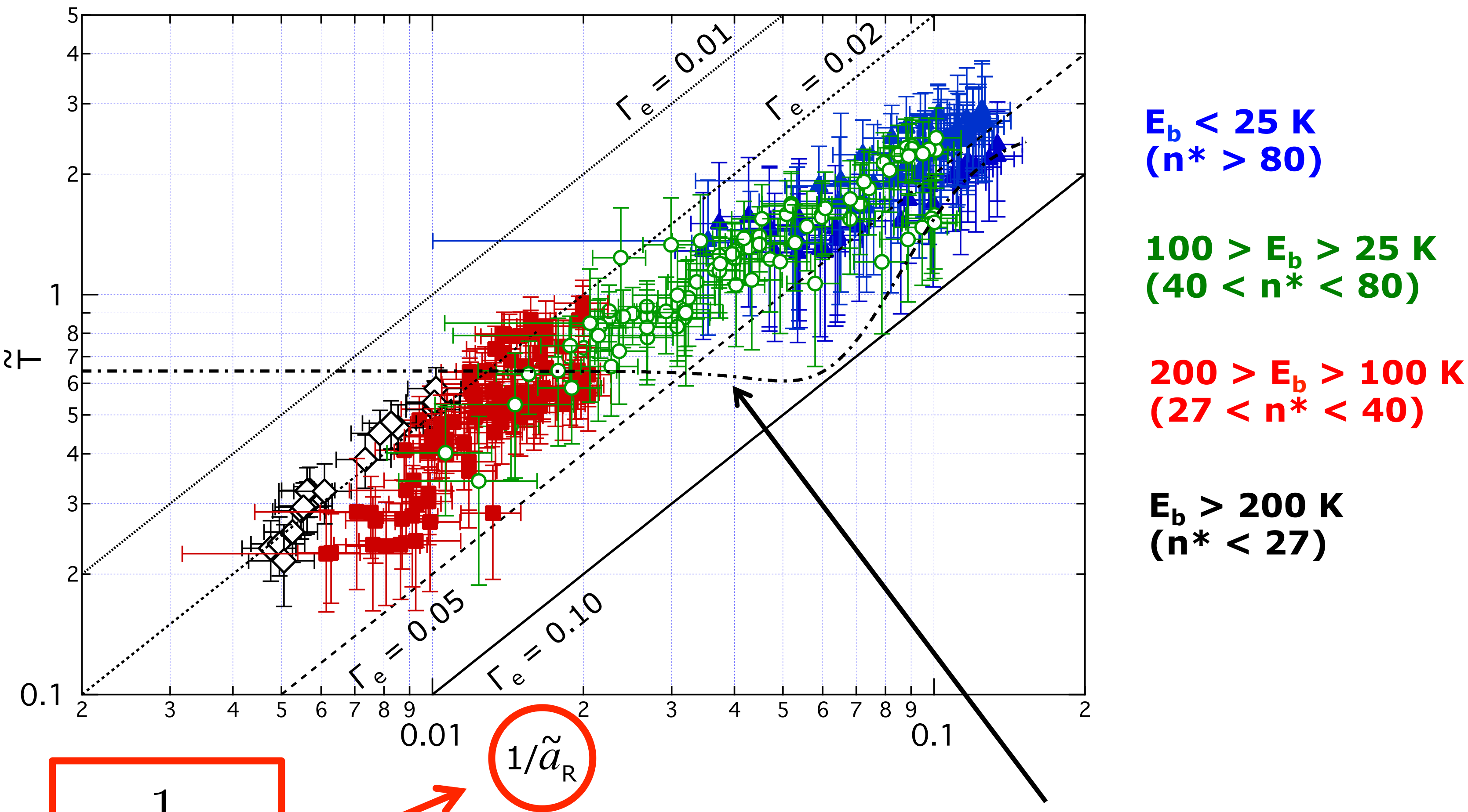
$$\tilde{T} = \frac{k_B\,T_e}{E_b} \qquad\qquad \tilde{a}_e = \frac{a_e}{2n^{*2}a_0}$$

$$\Gamma_e = \frac{e^2}{4\pi\epsilon_0 a_e k_B T_e} = \frac{1}{\tilde{a}_e\,\tilde{T}}$$

But: we can’t measure a_e, just a_R (*f* = ionization fraction)

$$\tilde{a}_e = \frac{\tilde{a}_R}{f^{1/3}}$$

Data fall on a universal curve!



$$\frac{1}{f^{1/3}\,\tilde{a}_e}$$

Theory (later!)

Analysis – what do the data mean?

Simulated expansion of an ultra-cold, neutral plasma

F. Robicheaux[a] and James D. Hanson
Department of Physics, Auburn University, Alabama 36849-5311

Physics of Plasmas, **10**, 2217 (2003)

$$n_i(r,t)=N_i[\beta(t)/\pi]^{3/2}\exp[-\beta(t)r^2]$$

$$v_i(r,t)=r\gamma(t)$$

$$\frac{d\gamma}{dt}+\gamma^2=2k_bT_e(t)\beta(t)/M_i\,,$$

$$\beta(t)=\beta(0)\,\exp\left[-2\int_0^t\gamma(\bar{t})d\bar{t}\right],$$

$$\frac{3}{2}k_BT_e(0)=\frac{3}{2}k_BT_e(t)+\frac{3}{4}M_i\frac{\gamma^2(t)}{\beta(t)}+E_{Ryd}\,,$$

f = Probability of excitation

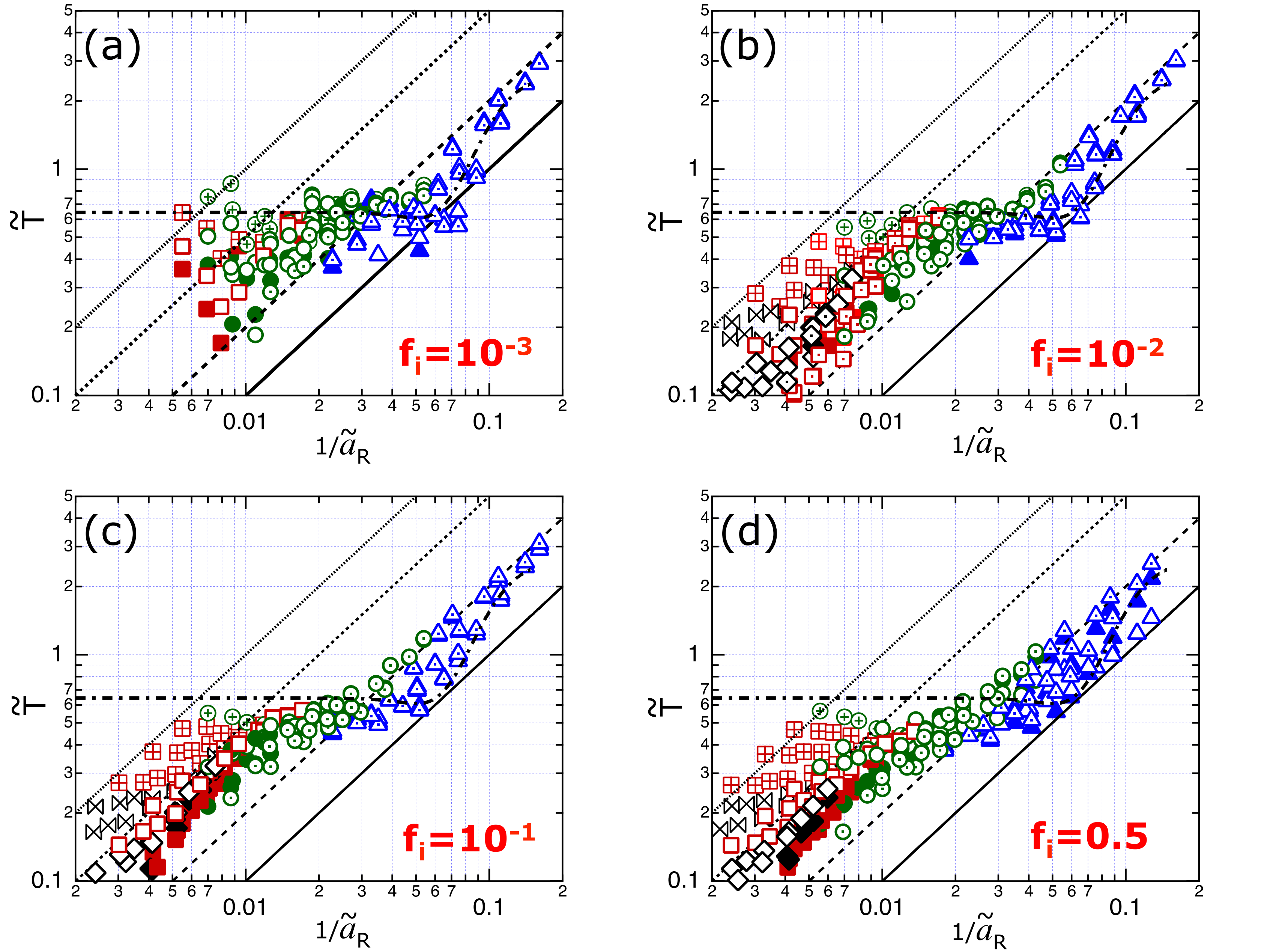
$$f=\frac{1}{1+\frac{|E_R|}{3.83k_BT_e}}$$

$$A_d=n_e(r)7.2\left(\frac{27.2\text{ eV}}{k_bT_e}\right)^{0.17}\nu^{2.66}a_0^2\alpha c$$

$$A_e=n_e(r)55\left(\frac{k_bT_e}{27.2\text{ eV}}\right)^{0.83}\nu^{4.66}a_0^2\alpha c$$

$$\Delta E_R=E_R\cdot\left(\left[\frac{1-f}{1-y}\right]^{0.2611}-1\right)$$

$$=-k_BT_e\ln\left(\frac{y}{f}\right)$$



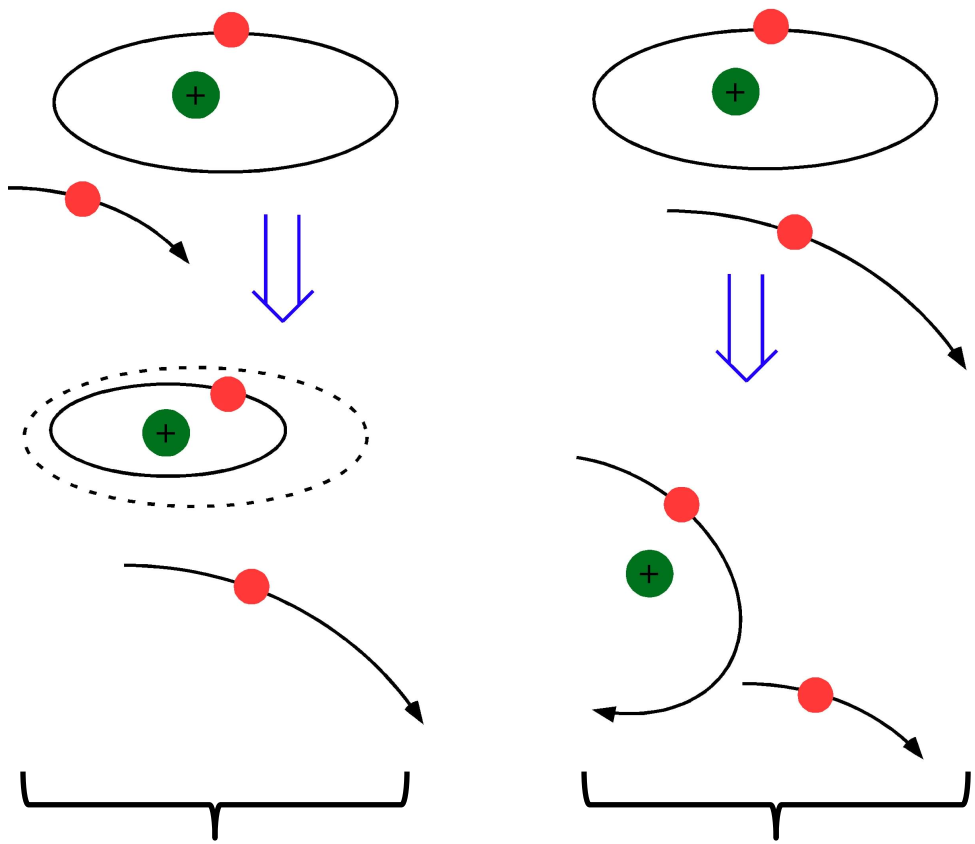
Now: f_i = initial ionization fraction

Intuition – what do the simulation results mean?

Effect of Rydberg atoms on electron temperature

Heating

Cooling



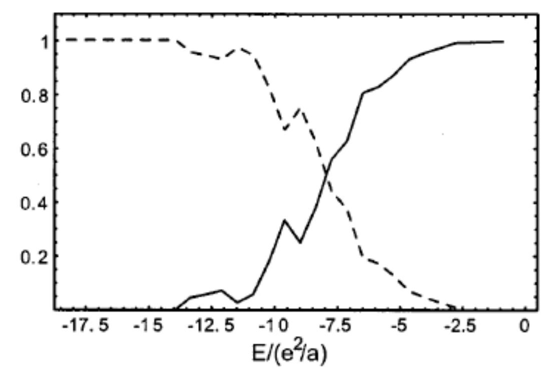
Atom may be "lost" due to radiative decay

May recombine via TBR

Heating/cooling Boundary

("bottle neck")

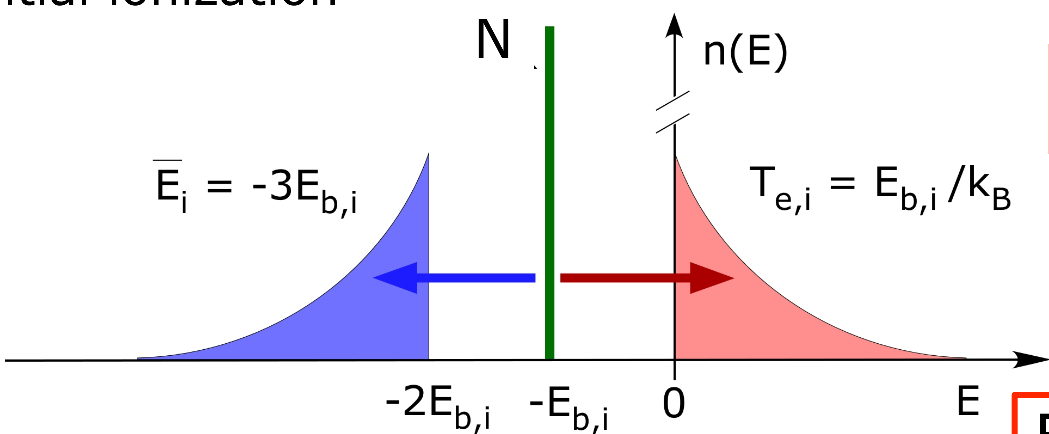
$$E_b = 4k_B T_e$$



Kuzmin et al., Phys. Plasmas, 9, 3743, 2002

Cold dipole collisions (Robicheaux, *J. Phys. B*, **38**, S333, 2005)

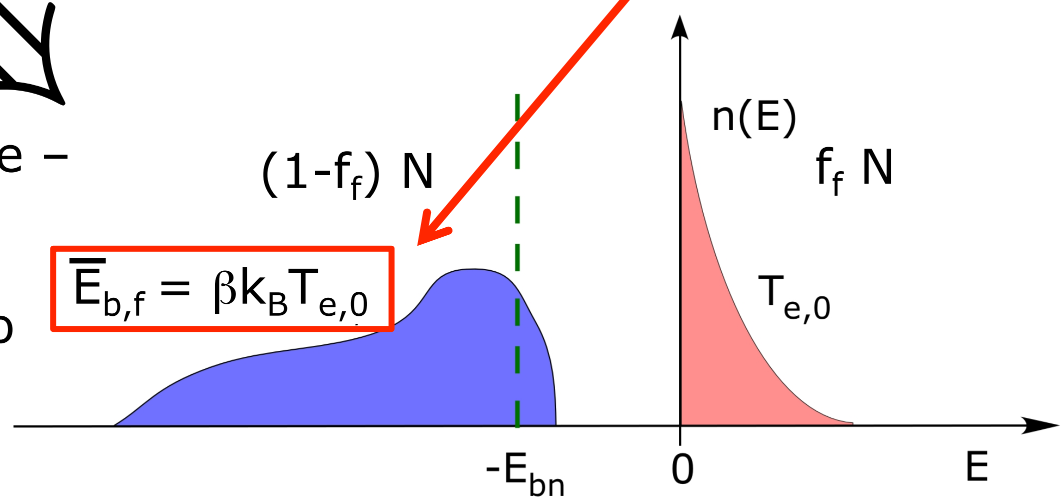
Initial ionization



Bottleneck energy:

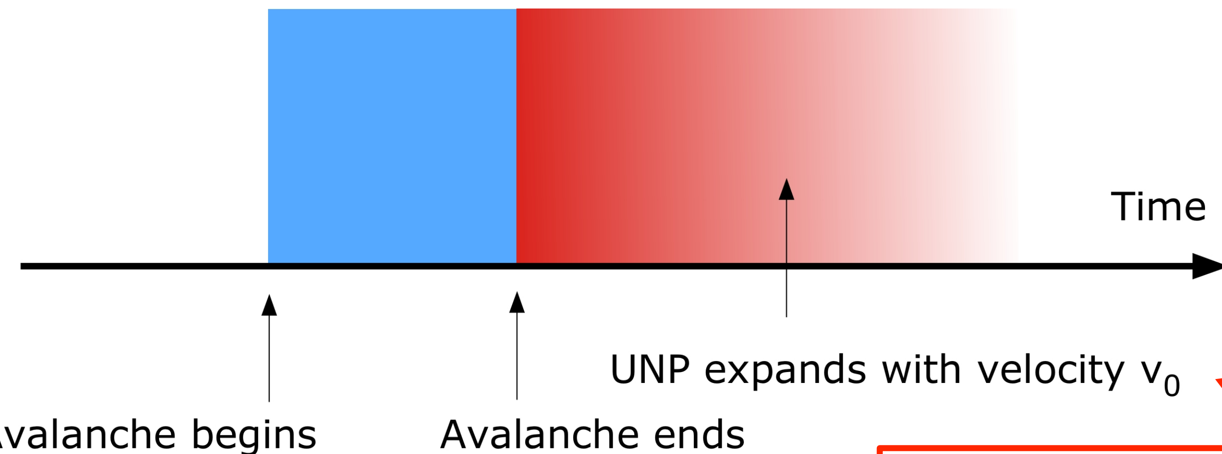
$$\boxed{E_{bn} \approx 4k_B T_e}$$

$\boxed{\text{Expect } \beta \approx 4?}$



End of avalanche regime – UNP decouples from Rydberg atoms when electrons are too cold to ionize remaining atoms

What can we predict?



$$-(1-f_i)\,N\,E_{b,i} + f_i\,N\,\frac{3}{2}\,k_B\,T_{e,i}$$

$$= -(1-f_f)\,N\,\bar{E}_{b,f} + f_f\,N\,\frac{3}{2}\,k_B\,T_{e,f}$$

Rydbergs

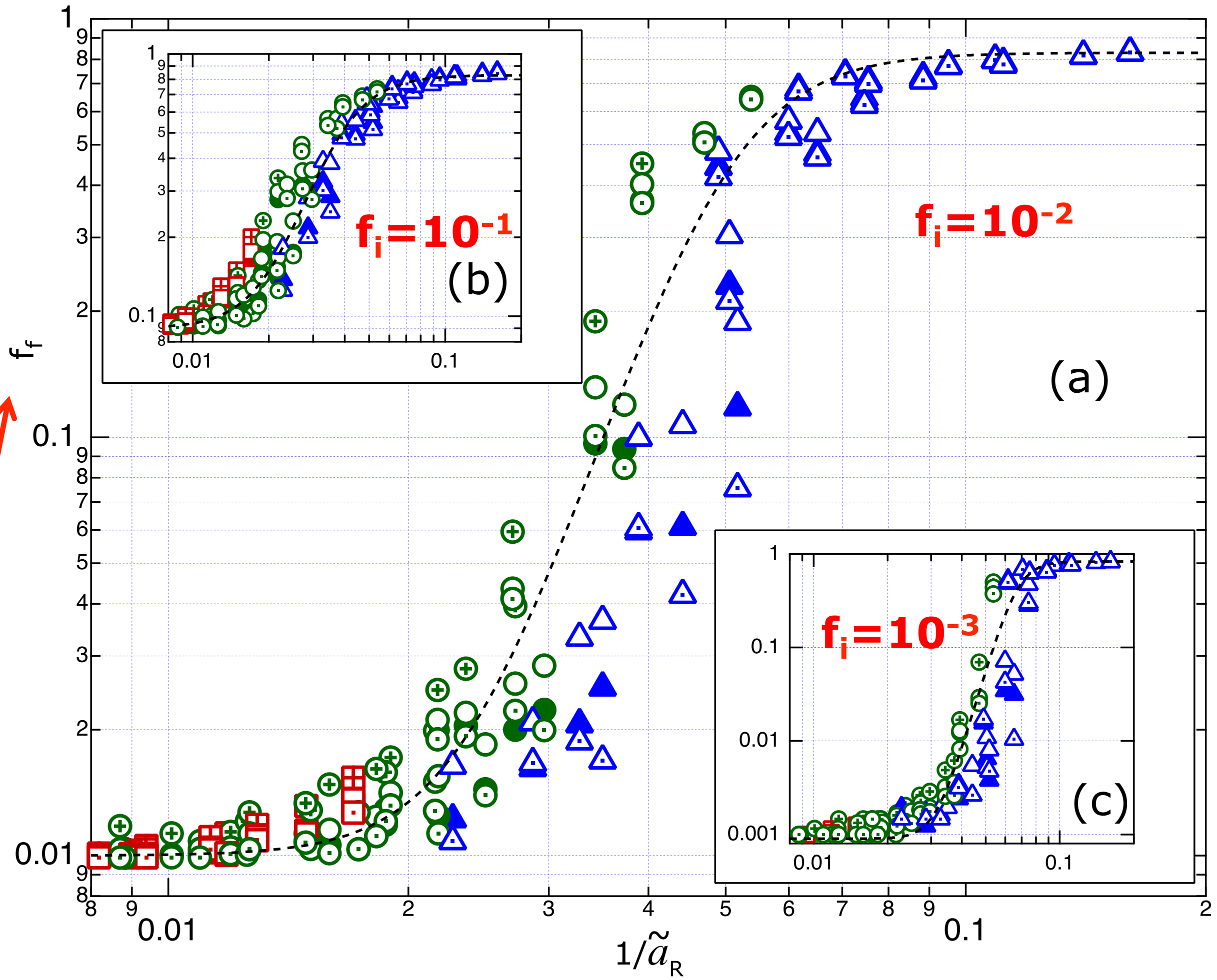
Electrons

$$\boxed{T_{e,f} = T_{e,0} = \frac{m_{ion} v_0^2}{k_B}}$$

$$\boxed{\bar{E}_{b,f} = \beta k_B T_{e,0}}$$

$$\left(\frac{3}{2}k_B T_e(0) = \frac{3}{2}k_B T_e(t) + \frac{3}{4}\cancel{M\frac{\gamma^2(t)}{\beta(t)}} + E_{\mathrm{Ryd}} \right)$$

Final ionization fraction, f_f



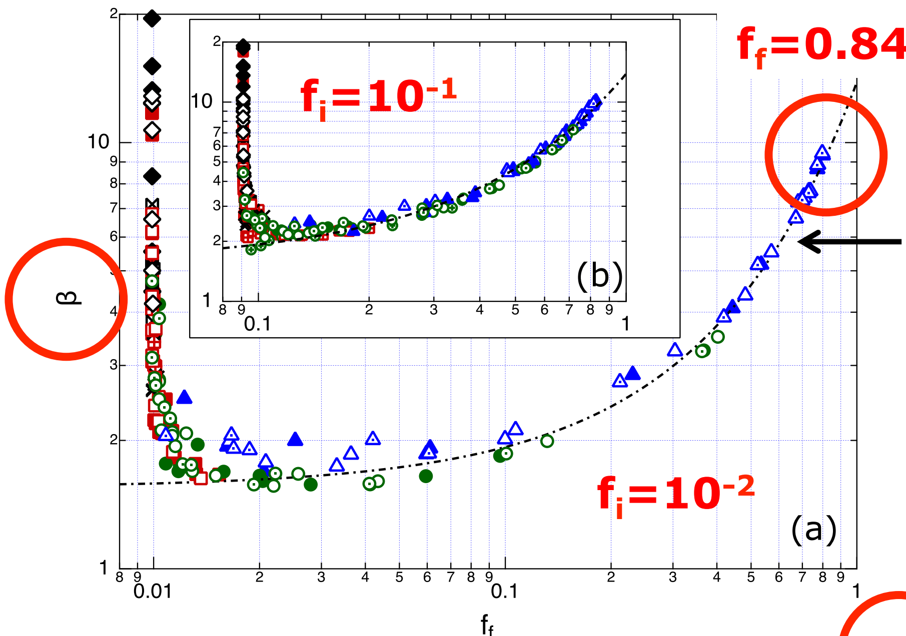
E_b < 25 K
(n* > 80)

100 > E_b > 25 K
(40 < n* < 80)

200 > E_b > 100 K
(27 < n* < 40)

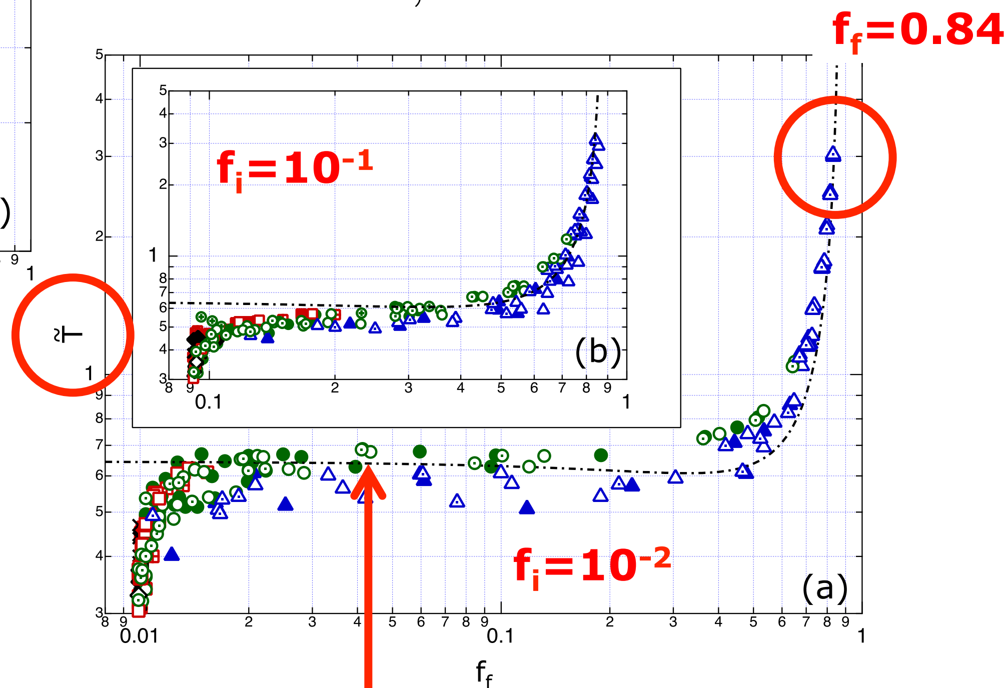
E_b > 200 K
(n* < 27)

f_f = final ionization fraction (at 40 μs evolution time)



Heuristic:

$$\beta \equiv \frac{\bar{E}_{b,f}}{k_B T_{e,0}} = 1.55\, e^{2.19\, f_f}$$



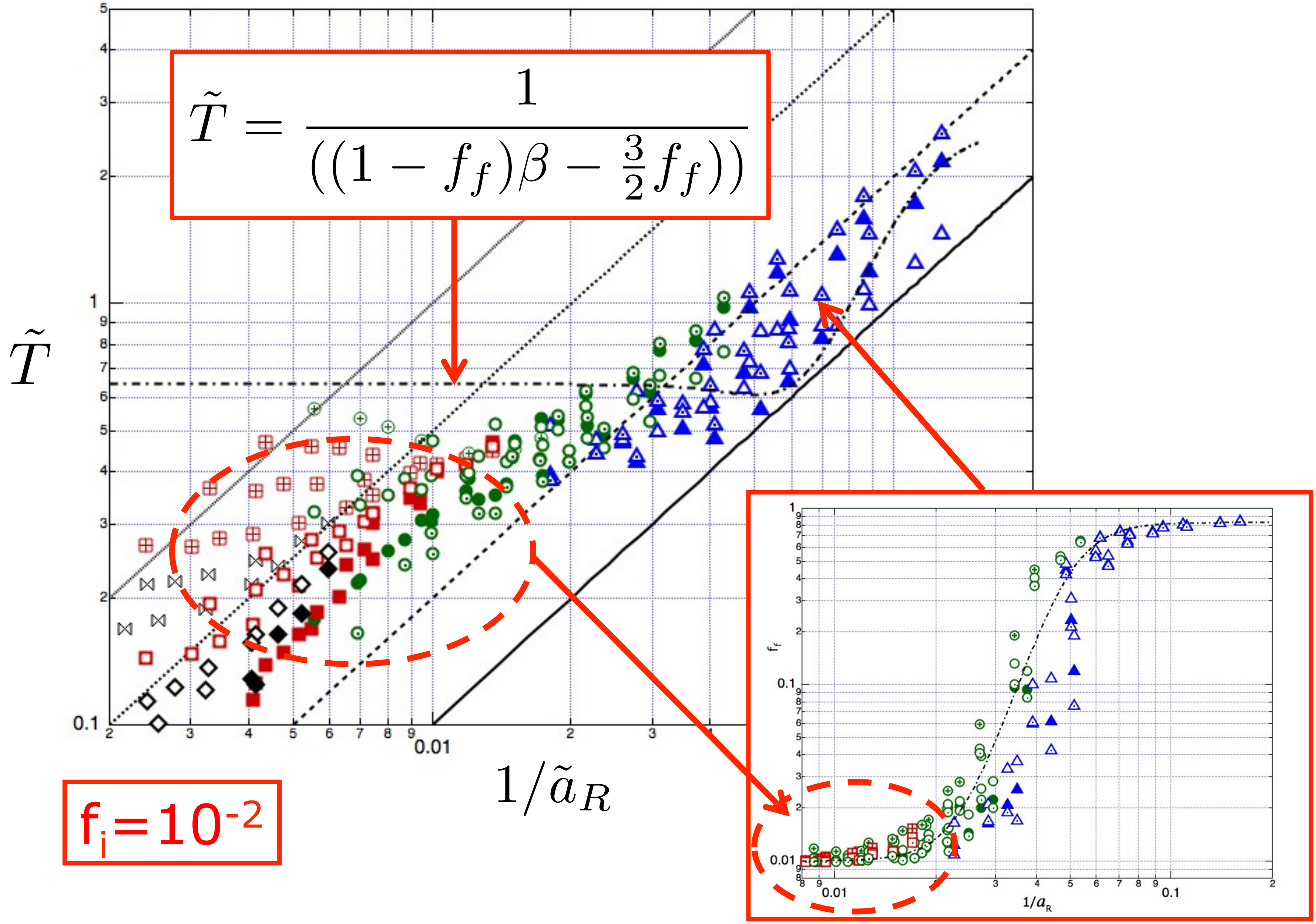
Energy conservation:

$$-(1-f_i)\, N\, E_{b,i} + f_i\, N\, \frac{3}{2}\, k_B\, T_{e,i}$$

$$= -(1-f_f)\, N\, \bar{E}_{b,f} + f_f\, N\, \frac{3}{2}\, k_B\, T_{e,f}$$

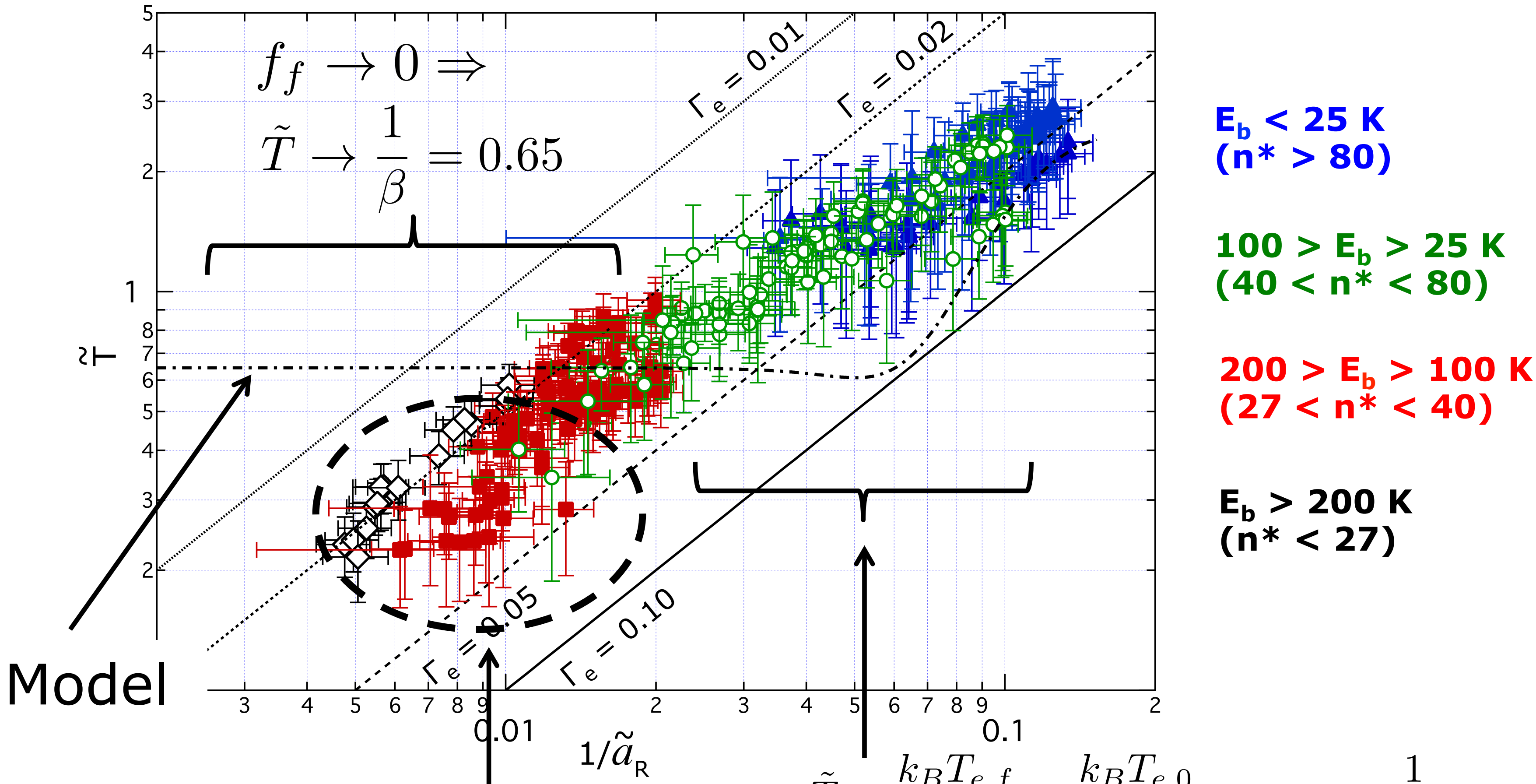
$$\Rightarrow$$

$$\boxed{\tilde{T} = \frac{k_B T_{e,f}}{E_{b,i}} = \frac{k_B T_{e,0}}{E_{b,i}} \approx \frac{1}{\left((1-f_f)\beta - \frac{3}{2} f_f\right)}}$$



$$\tilde{T} = \frac{1}{((1 - f_f)\beta - \frac{3}{2} f_f))}$$

$f_i = 10^{-2}$



$$\tilde{T} = \frac{k_B T_{e,f}}{E_{b,i}} = \frac{k_B T_{e,0}}{E_{b,i}} \approx \frac{1}{((1-f_f)\beta - \frac{3}{2} f_f)}$$

Initial UNP electrons too cold to ionize Rydberg atoms – main interaction is Rydberg de-excitation:

$$\Delta E_R \propto -|E_R| \Rightarrow \tilde{T} \propto E_{b,i}$$

Conclusions

- Plasma electron temperature is determined by decoupling point between UNP and Rydberg atoms. This happens when electrons cool (as plasma adiabatically expands) so much that they cannot ionize Rydberg atoms
- For n > 40, electron temperature depends on final ionization fraction, f_f
- For n < 30, ionization fraction is small. Initial seed electrons have too low an energy to ionize Rydberg atoms. Electrons heat by an amount proportional to E_b due to collisions which de-excite Rydbergs.
- An earlier version of this work is available at https://arxiv.org/abs/1702.01463
- Will be resubmited for publication (soon!)

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