

Electron screening of nuclear reactions

C.A. Bertulani

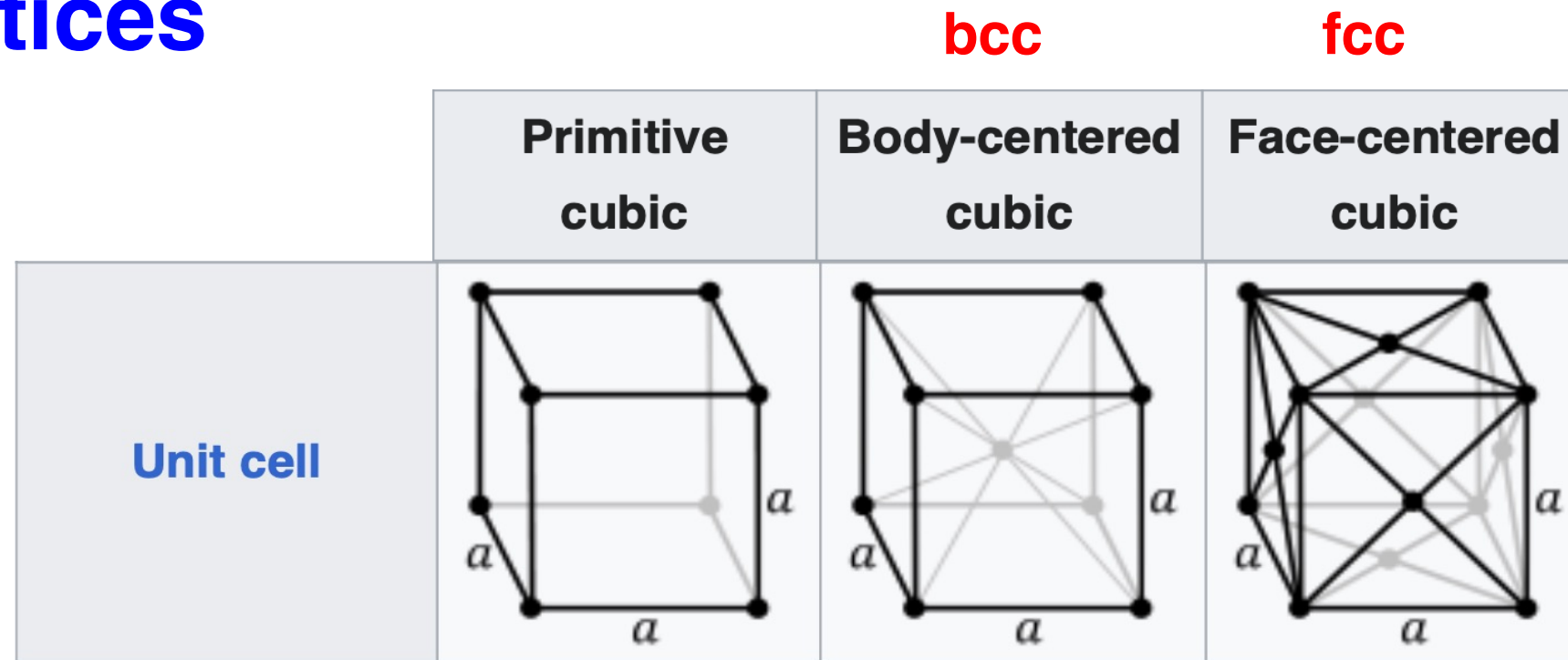
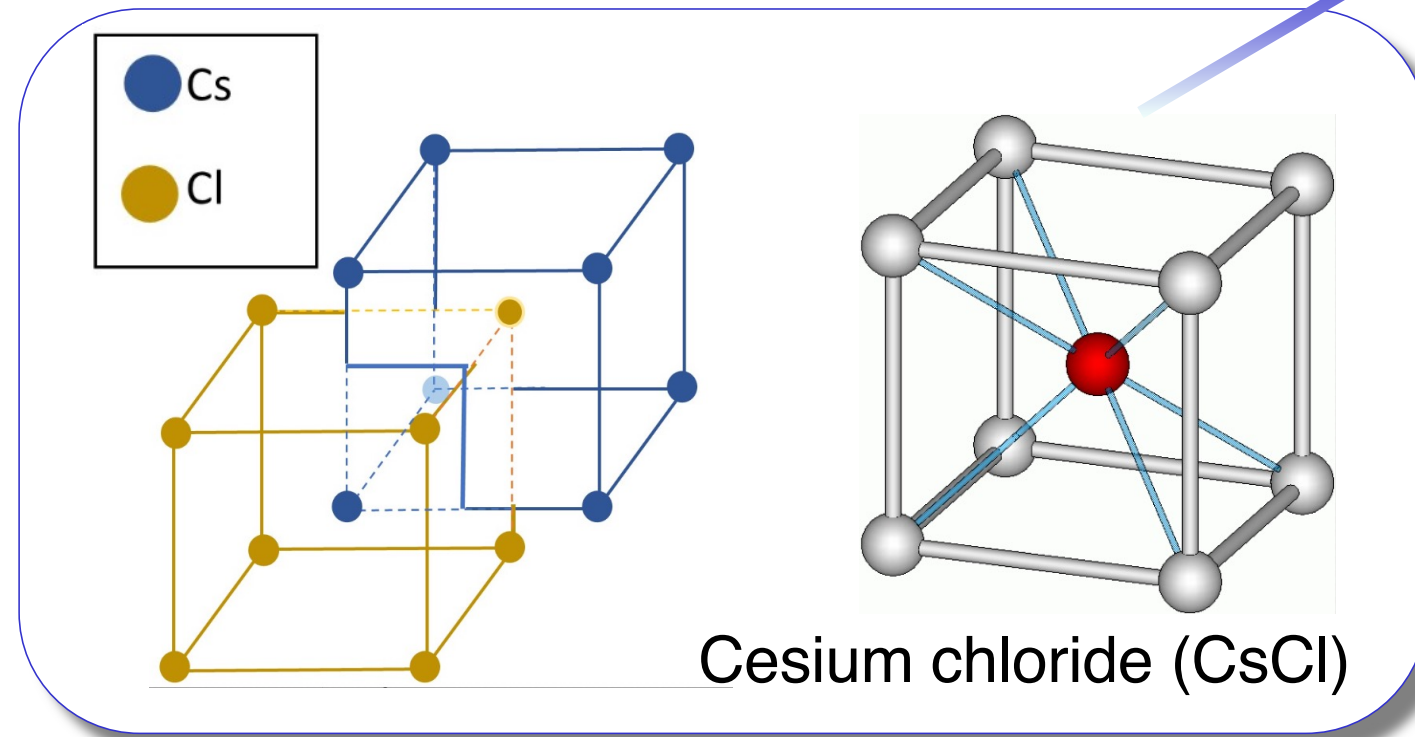
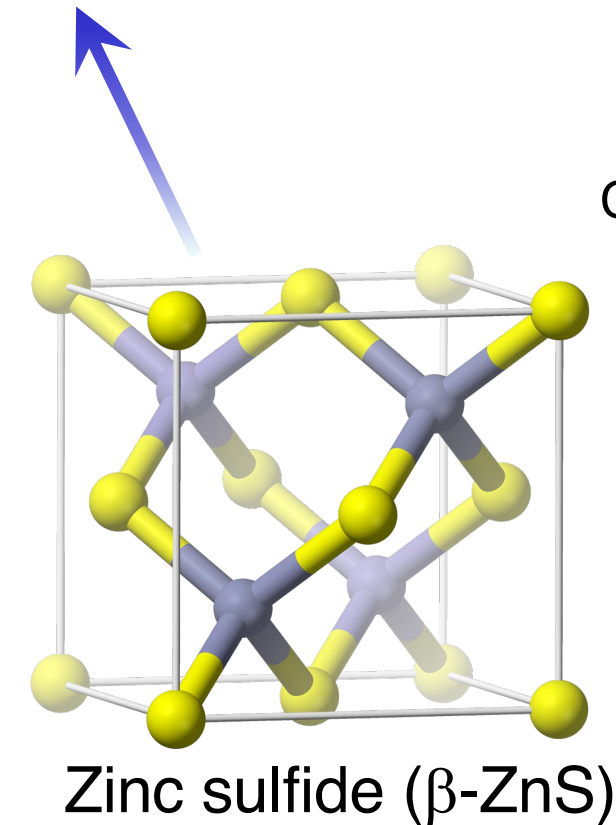


TEXAS A&M UNIVERSITY
COMMERCE

Wherever you go, there you are!

Groucho Marx

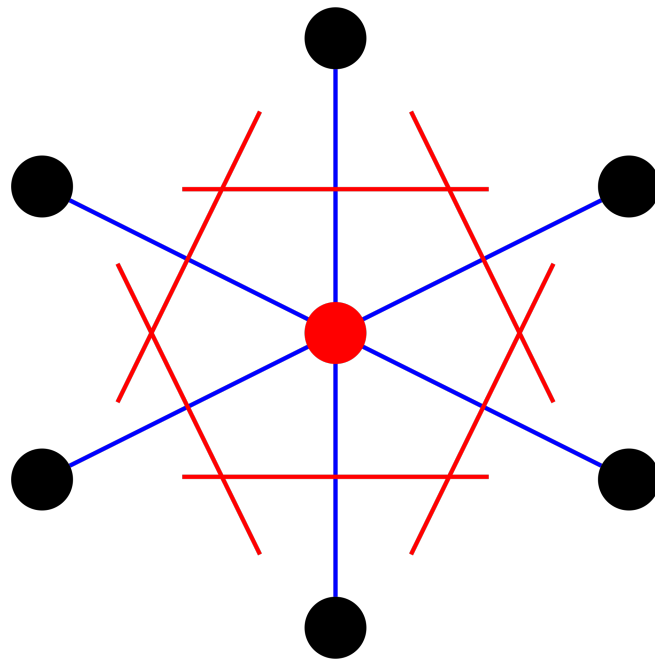
Cubic lattices



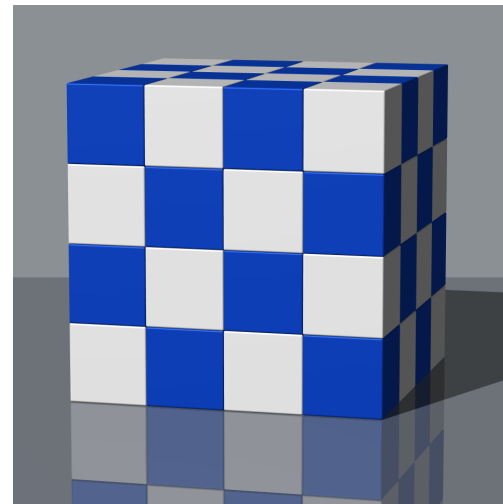
Credit: *Wikipedia*

Wigner-Seitz cell

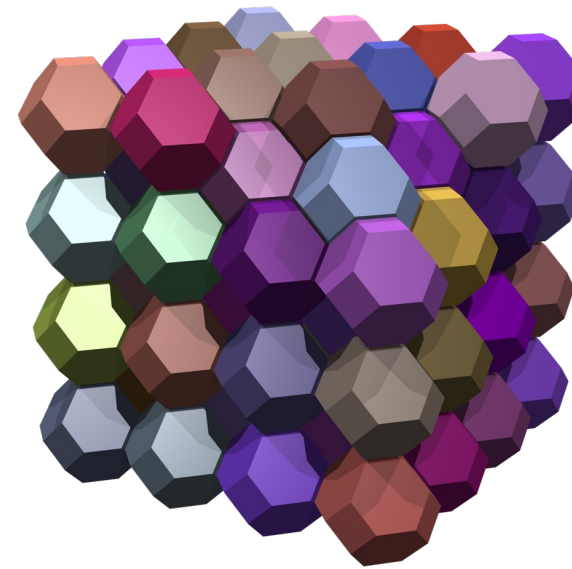
- Useful for studying discrete translational symmetries of crystalline materials.
- Contains exactly one lattice point (a point shared by all neighboring cells) – *a primitive cell*.
- Constructing the cell:



Credit: Wikipedia



WS cell of the primitive cubic lattice is a cube



WS cell of bcc lattice is a truncated octahedron

WS cell of fcc lattice is a rhombic dodecahedron



Salpeter-Van Horn treatment of dense plasmas

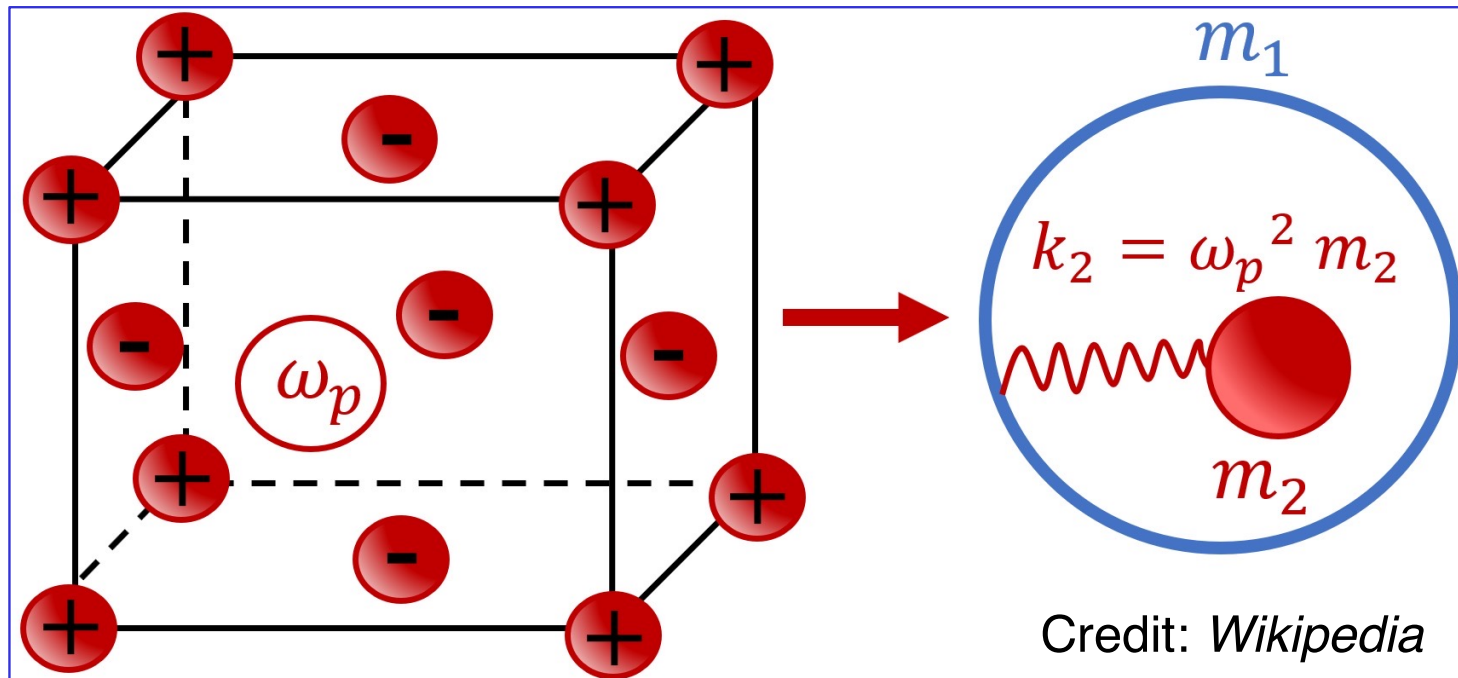
- Electrons as a uniform distribution of negative background charge in which the nuclei (larger charge) move.
- Electrostatic interaction of the ions can in certain regimes cause the nuclei to “freeze” into a Coulomb lattice structure.

$$E_{coul} \sim \rho^{1/3} Z^2$$

- (bcc) structure, has the greatest binding energy per nucleus and is adopted → corresponding Wigner-Seitz cell is used.

- Plasma frequency, zero point energy:

$$\omega_p \sim \rho^{1/6} A^{1/2} Z^3$$



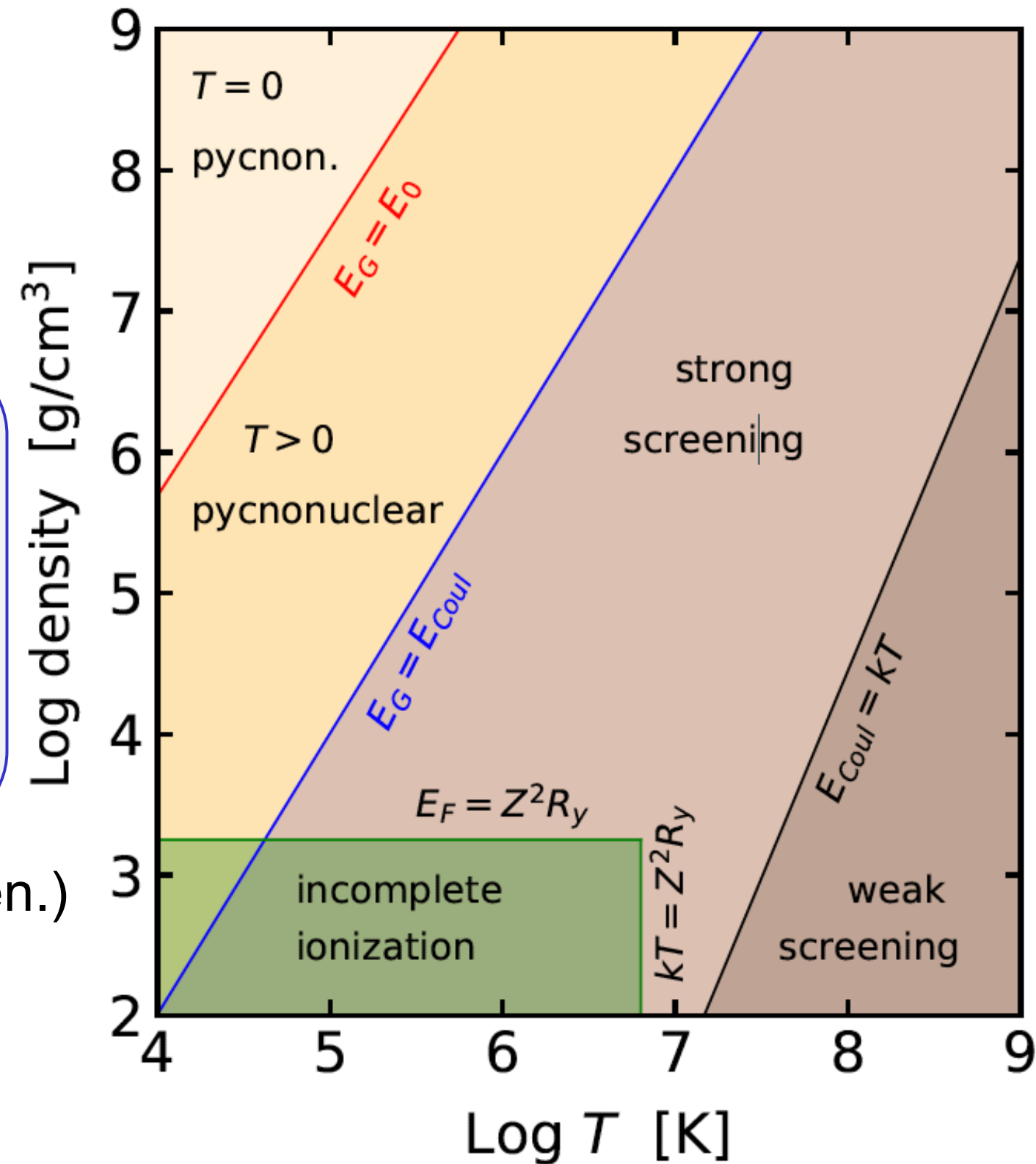
- m_1 = shell of ionic lattice
- m_2 = electron

Screening regimes

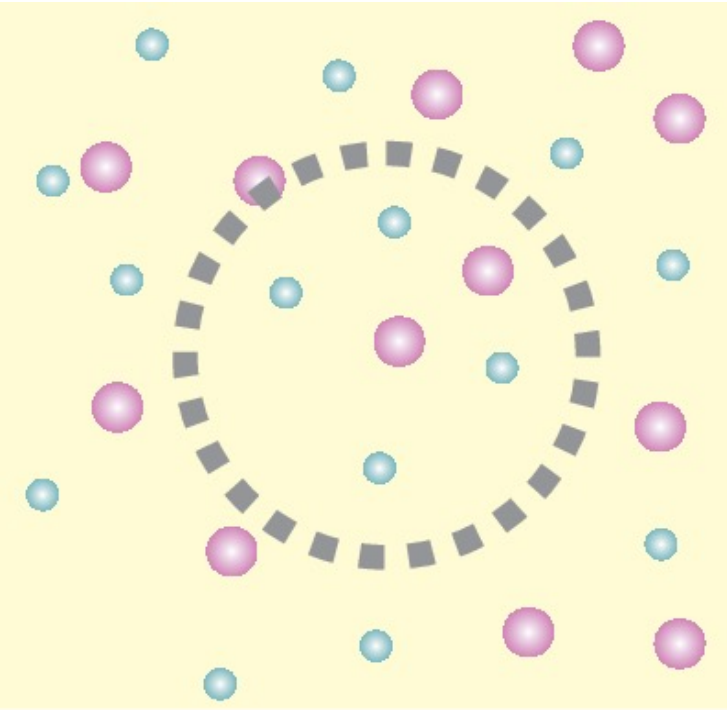
Coulomb coupling parameter

$$\Gamma = \frac{Z^2 e^2}{akT} \sim \frac{\rho^{1/3} Z^2}{T}$$

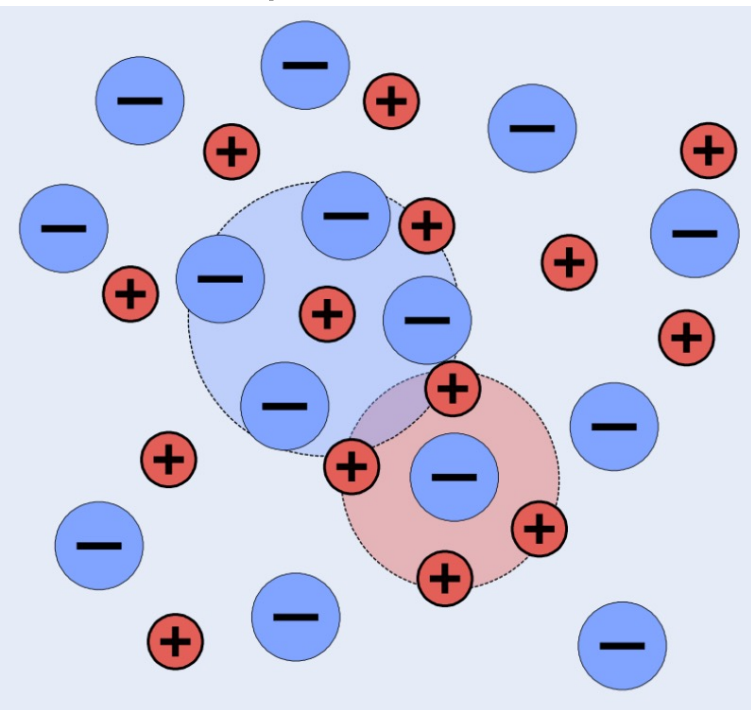
- $\frac{E_{coul}}{T} \sim \Gamma \ll 1 \rightarrow$ *weak screening*
- $E_{Gamow} \gg E_{coul}$ ($\Gamma \gg 1$) $\rightarrow$ *strong screening* (“liquid” phase, $\Gamma \lesssim 100$)
- $T \sim 0$, $E_{Gamow} \sim E_0$ (zero point energy)
- Classical thermonuclear regime (weak screen.)
- Strong plasma screening regime
- Thermo-pycnonuclear regime
- Thermally enhanced pycnonuclear regime
- Zero-temperature pycnonuclear regime



Weak screening – Debye-Hückel theory (low ρ , high T)



Credit: Wikipedia



- *Debye-Hückel sphere*: ions of opposite signs tend to be closer

- *Concentration* of ions in a charge neutral solution: $\sum_i Z_i e c_{i0} = 0$
($i = +$ or $-$)

- *Interaction* $\rightarrow c_{i0}$ are not spatially uniform

- *Boltzmann* $\rightarrow c_{\pm}(r) = c_{\pm 0} \exp[-Z_{\pm} e V(r)/kT]$

- $V(r)$ to be found Coulomb potential

Around positive ion, $V(r) > 0 \rightarrow c_{+}(r) < c_{+0}$ and $c_{-}(r) < c_{-0}$

- *Charge density*:

$$\rho(r) = \sum_i Z_i e c_i = \sum_i Z_i e c_{i0} \exp[-Z_i e V(r)/kT]$$

- Weak screening

$$Z_i e V(r)/kT \ll 1 \rightarrow$$

$$\rho(r) = - \frac{e^2 V(r)}{kT} \sum_i Z_i^2 c_{i0}$$

Weak screening – Debye-Hückel theory (low ρ , high T)

• What is $V(r)$? *Poisson equation*

$$-\frac{1}{r^2} \frac{d}{dr} \left[r^2 \frac{dV}{dr} \right] = 4\pi\rho(r)/\epsilon$$

→ $V(r) = \frac{Z_i e}{r} \exp\left(-\frac{r}{R_D}\right)$

$$R_D^2 = \frac{\epsilon k T}{4\pi e^2 \sum_i Z_i^2 c_{i0}}$$

Debye sphere radius

Debye, Hückel, Z. Phys 24, 185 (1923)

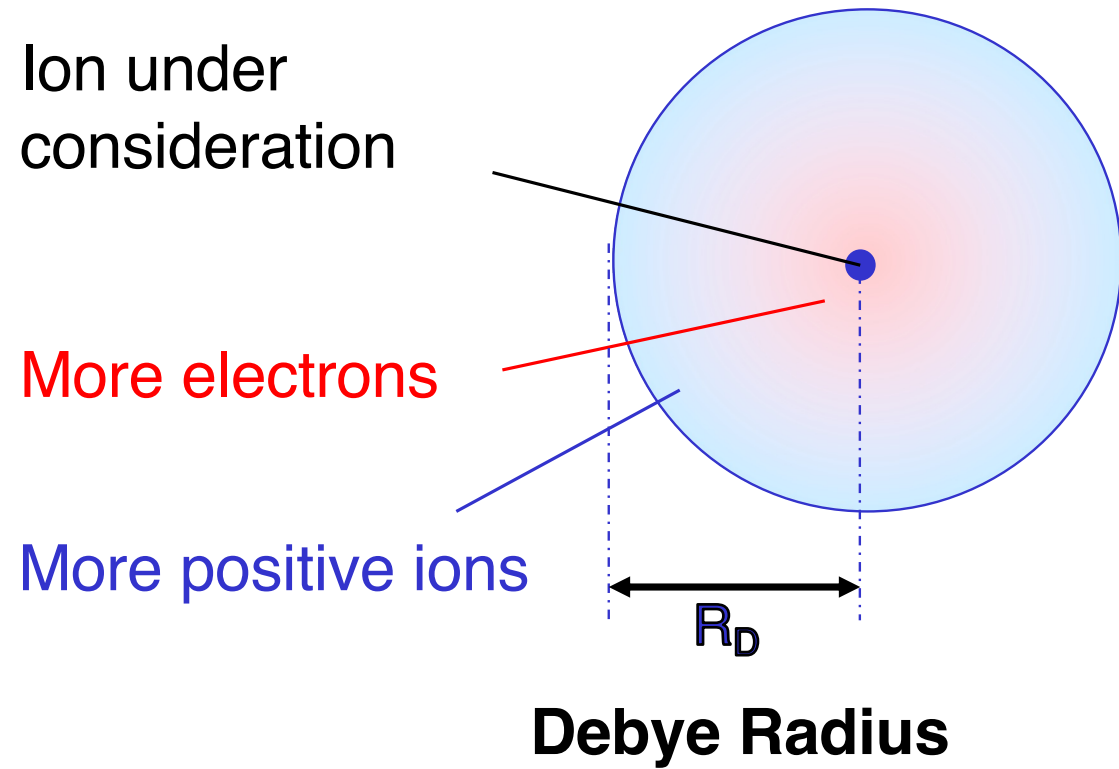
Screening potential $V(r)$:

(a) Decreases with T , (b) increases with ion concentration c_{i0}

(c) Based on mean field approximation → # particles large within R_D

NOTE: condition $\rho R_D^3 \gg 1$ not always satisfied

Stellar plasmas – Weak screening (low ρ , high T)



$$\langle \sigma v \rangle_{\text{plasma}} = f(E) \langle \sigma v \rangle_{\text{bare}}$$
$$V_{12}(r) = \frac{Z_1 Z_2 e^2}{r} e^{-\frac{r}{R_D}} \approx \frac{Z_1 Z_2 e^2}{r} + U_e(r)$$
$$U_e(r) = -\frac{Z_1 Z_2 e^2}{R_D}$$

Solar core: $X=0.7$, $Y=0.3$, $T=1.5 \times 10^7$ K, $\rho=160$ g/cm³

coupling
parameter
 $\Gamma \sim 0.04$

$$f(E) = e^{U_e/kT}, \quad R_D \sim \sqrt{kT / \rho} \sim 0.218 \text{ \AA (Sun)}$$

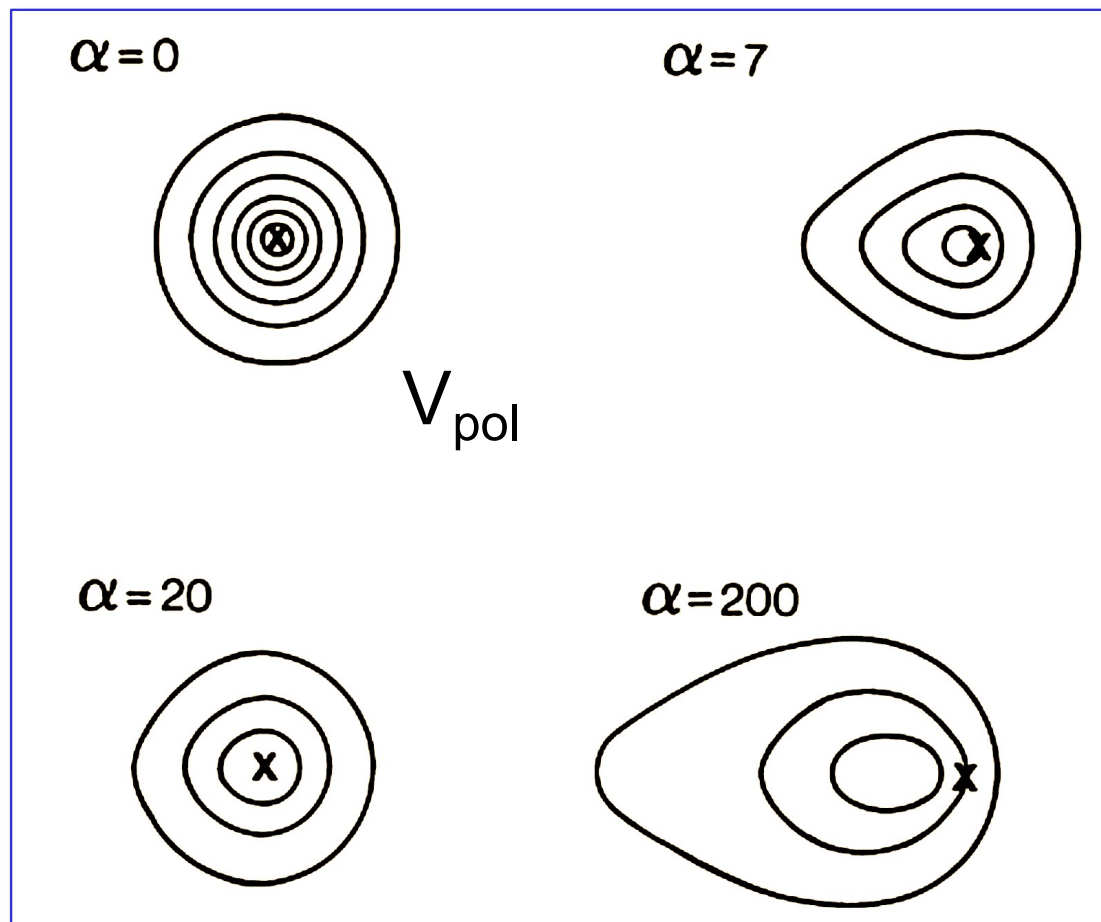
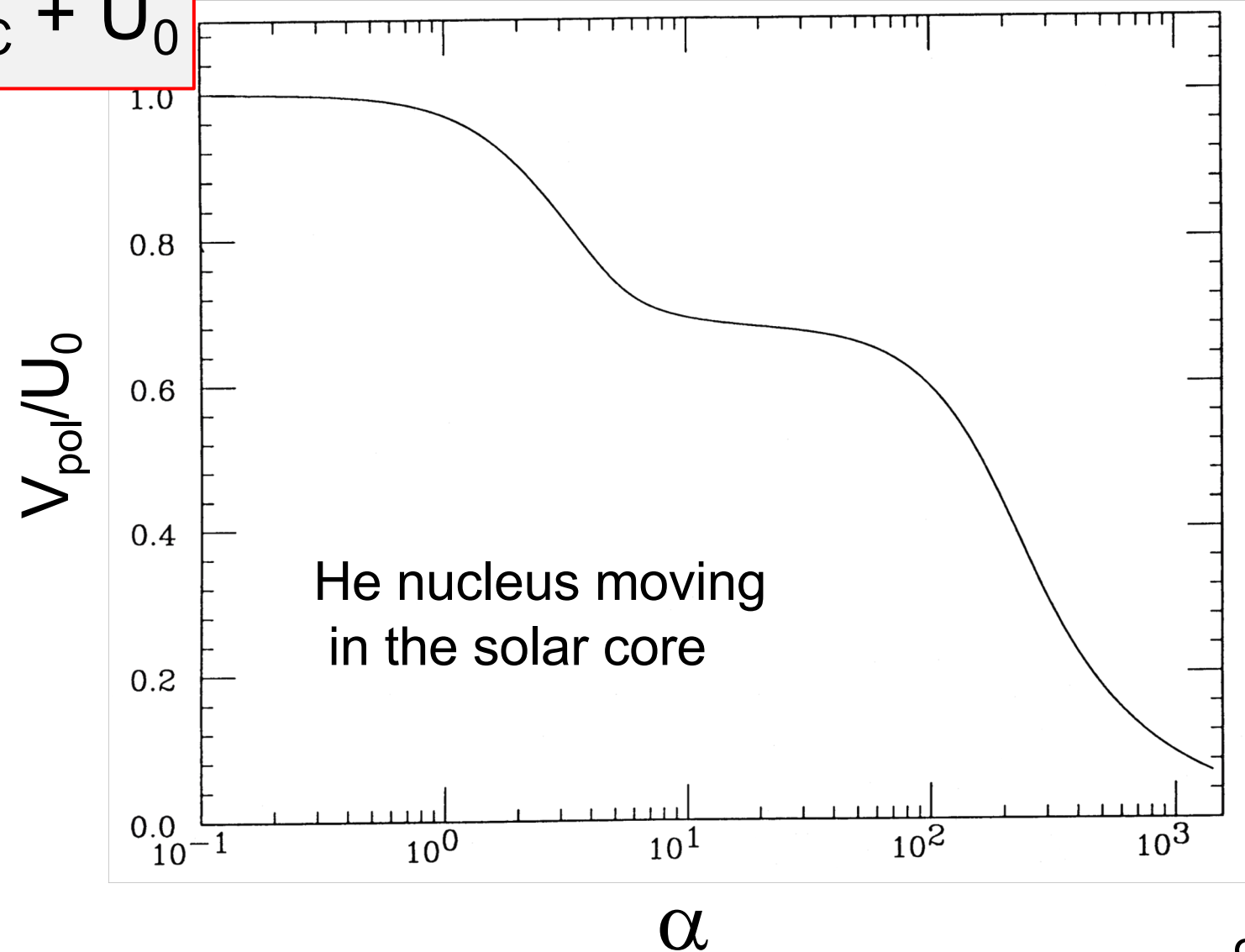
${}^7\text{Be}(p, \gamma){}^8\text{B}$ ($T \sim 10^7$ K): $f(E) \sim 1.2$ (20 % effect)

Dynamic weak screening

Carraro, Schaefer, Koonin, ApJ 331, 565 (1988)

$$\nabla^2 V = -4\pi(\rho_{ion} + \rho_{pol}), \quad \rho_{ion} = Ze\delta(\mathbf{r} - \mathbf{v}t), \quad \alpha = (mv^2/T)^{1/2}$$

$$\alpha = 0 \rightarrow V(r) = \frac{Ze}{r} \exp\left(-\frac{r}{R_D}\right) \sim V_C + U_0$$

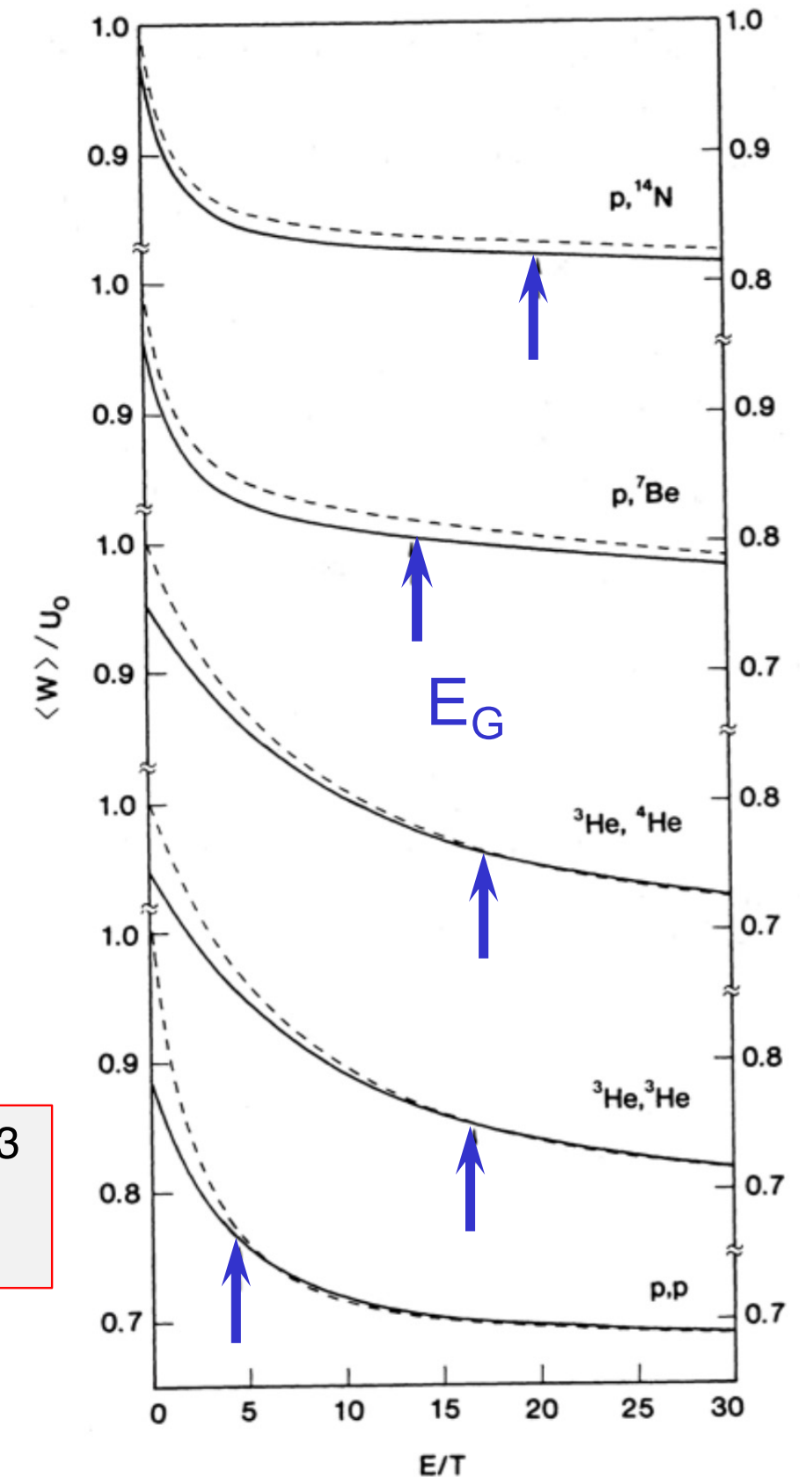


Dynamic weak screening

Change in the reaction rate r_{12}

Reaction	E_G/T	U_{pol}/U_0	r_{12}/r_{12}^0
$p + p$	4.6	0.76	0.992
${}^3\text{He} + {}^3\text{He}$	16.6	0.75	0.966
${}^3\text{He} + {}^4\text{He}$	17.3	0.76	0.968
$p + {}^7\text{Be}$	13.9	0.80	0.973
$p + {}^{14}\text{N}$	20.6	0.82	0.958

Carbon + carbon burning at $T = 1.5 \times 10^8 \text{ K}$, $\rho = 10^5 \text{ g/cm}^3$
 $\rightarrow$ 15% decrease of U_{pol}/U_0



Dynamic weak screening

Shaviv & Shaviv, ApJ. 529, 1054 (2000), ApJ. 558, 925 (2001)

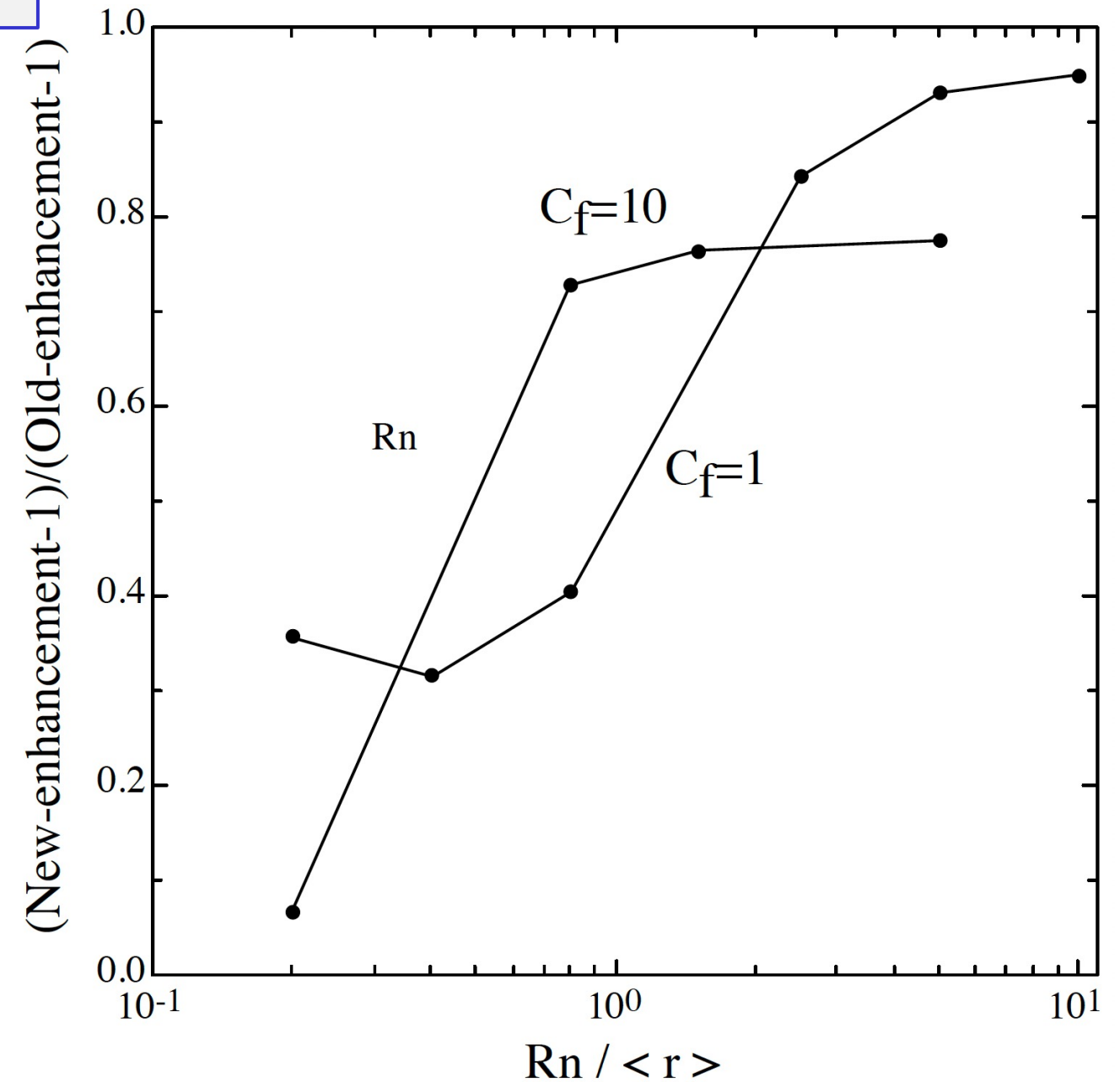
Fluctuations in the Debye sphere

$$n R_D^3 \sim 3 - 5$$

- One cannot derive the screening from thermodynamics but one has to resort to kinetic equations.
- Deviations from Debye-Hückel can be large.

Molecular dynamics calculation
Parameters of short range potential
 $R_n \sim$ Debye radius
 $\langle r \rangle$ = average distance

for stars along the main sequence



Weak screening in stars – Dynamic vs Adiabatic

Lowell, Brown, Rev. Mod. Phys 69, 411 (1997)

$$r_{12} = \int_{-\infty}^{\infty} dt \int d\mathbf{r} e^{iQt} \langle \psi_1^\dagger(\mathbf{r}, t) \psi_2^\dagger(\mathbf{r}, t) W(\mathbf{r}, t) \psi_1(0, t) \psi_r(0, t) \rangle_\beta$$

Q = energy transfer
 W = operator in the
plasma state space

- (a) reduction in the fusion rate of about 10% of the Salpeter enhancement term
- (b) no “dynamical screening” modification of the Salpeter result

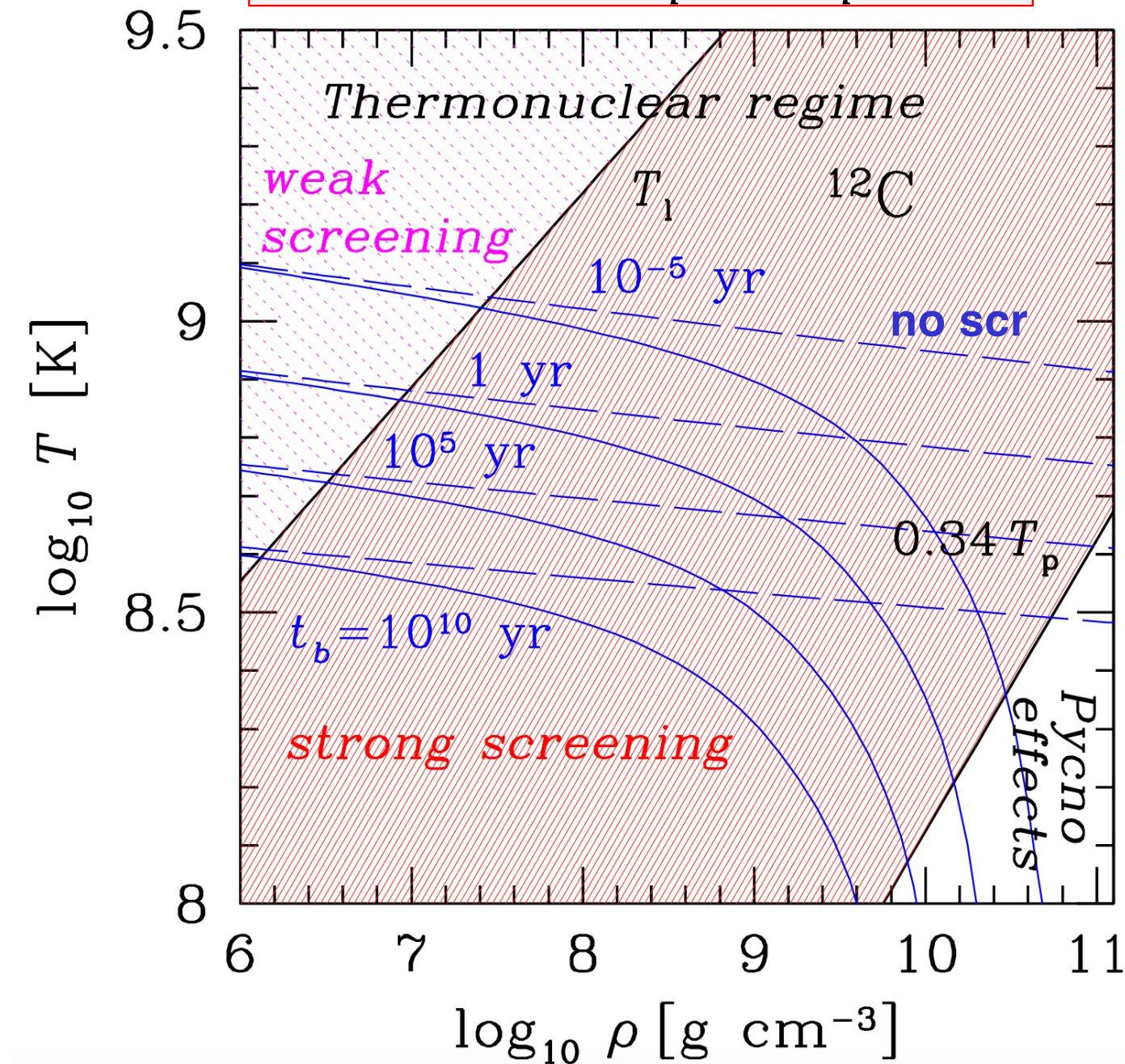
Bahcall, Brown, Gruzinov, Sawyer, A&A 383, 291 (2002)

- (a) Salpeter formula correct in 5 different approaches
- (b) no “dynamical screening” necessary
- (c) Carraro et al. 1988; Shaviv & Shaviv 1996, 1997, 2000; Savchenko 1999, 2001; Tsytovich 2000; Opher & Opher 2000a, 2000b; Lavagno & Quarati 2000; Weiss et al. 2001

all wrong! ???????

Strong plasma screening

$$T_l(\Gamma \sim 1), \quad T_p \sim \hbar \omega_p / k$$



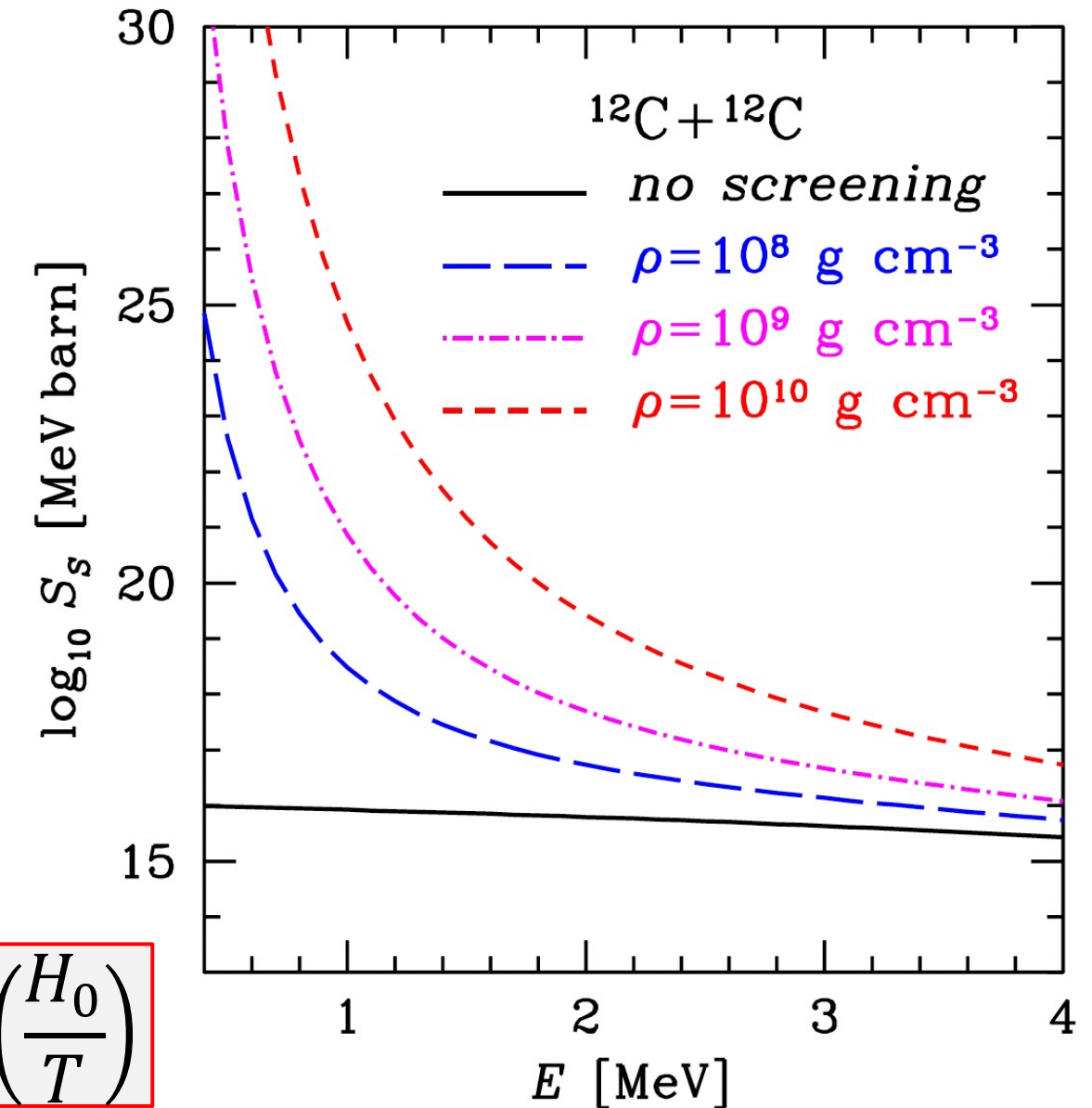
Kravchuk, Yakovlev, PRC 89, 015802 (2014)

- Mean-field models:
 $H = \text{background potential}$

$$V(r) = \frac{Ze^2}{r} - H(r)$$

Salpeter,
Aust J. Phys.
7, 373 (1954)
 $H = H_0$

$$f_{scr} = \exp\left(\frac{H_0}{T}\right)$$



$$H_0 = 1.0573 Z^2 e^2 \left(\frac{4\pi n_e}{3Z} \right)^{1/3}$$

Strong plasma screening

Jancovici, Physica 91A, 152 (1978)

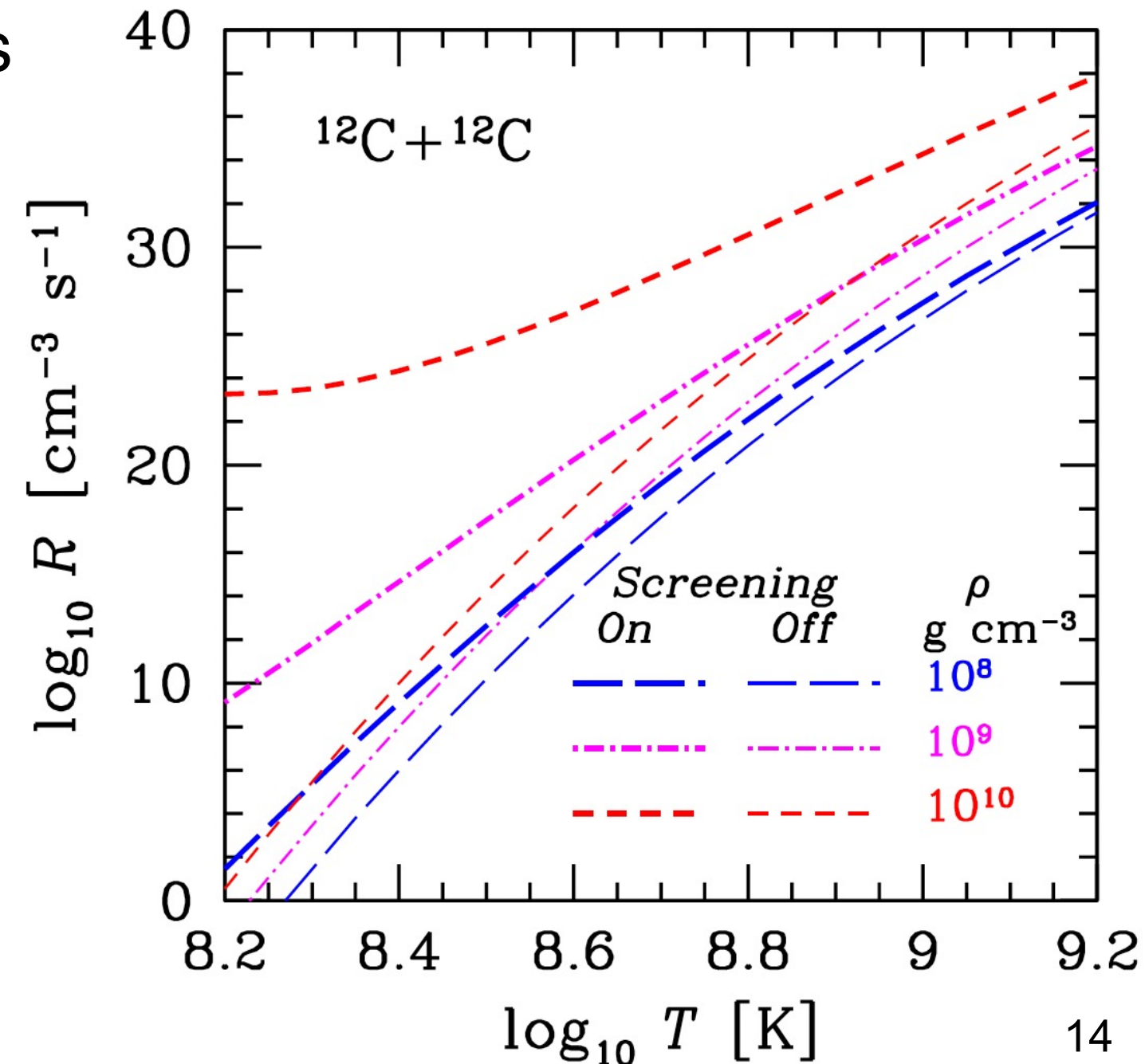
$$\beta F = -\ln \left[\frac{1}{N!} \int \langle \mathbf{r}_1 \mathbf{r}_2 \mathbf{r}_3 \cdots \mathbf{r}_N | \exp(-\beta H) | \mathbf{r}_1 \mathbf{r}_2 \mathbf{r}_3 \cdots \mathbf{r}_N \rangle \right] + \text{exchange terms}$$

Solved with path integral MC methods

$$H(r) = \frac{Z_1 Z_2 e^2}{a} h(x)$$

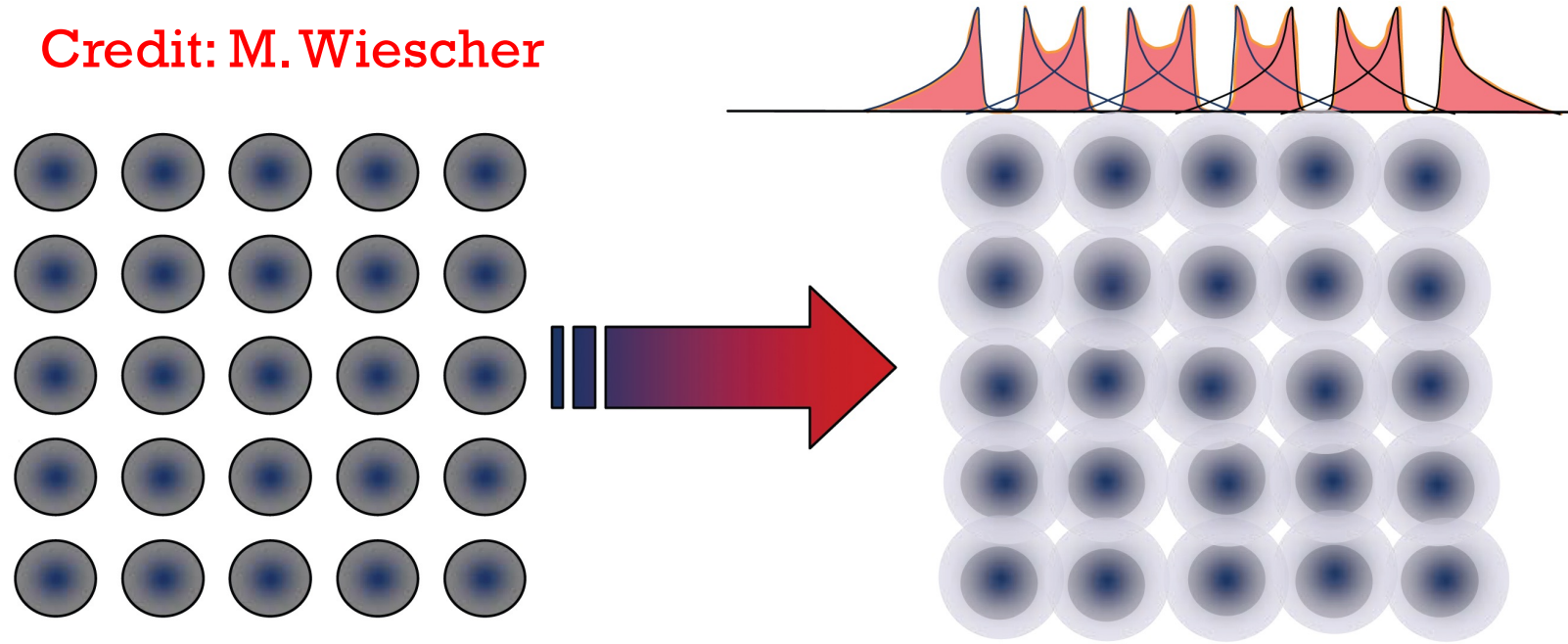
$$h(x) = b_0 + b_2 x^2 + b_4 x^4 + \cdots$$

- Numerous methods:
 - *Electron drop model*
Kravchuk, Yakovlev, PRC 89, 015802 (2014)
 - *Monte-Carlo sampling*
DeWitt, Graboske, Cooper, ApJ. 181, 439 (1973)
Ogata, ApJ. 481, 883 (1997)
Pollock, Militzer, PRL 92, 021101 (2004), etc.
- A still contentious subject, with P_{scr} different by factors of ~ 50
- NOTE: $f_{\text{scr}} \sim 10^{70}$ for $\Gamma \sim 170$



Pycnonuclear reactions at $T \sim 0$

Credit: M. Wiescher



Penetrability through zero point motion vibrations

$$R_{12} \sim S(E_G) P_{pyc} F_{pyc}$$

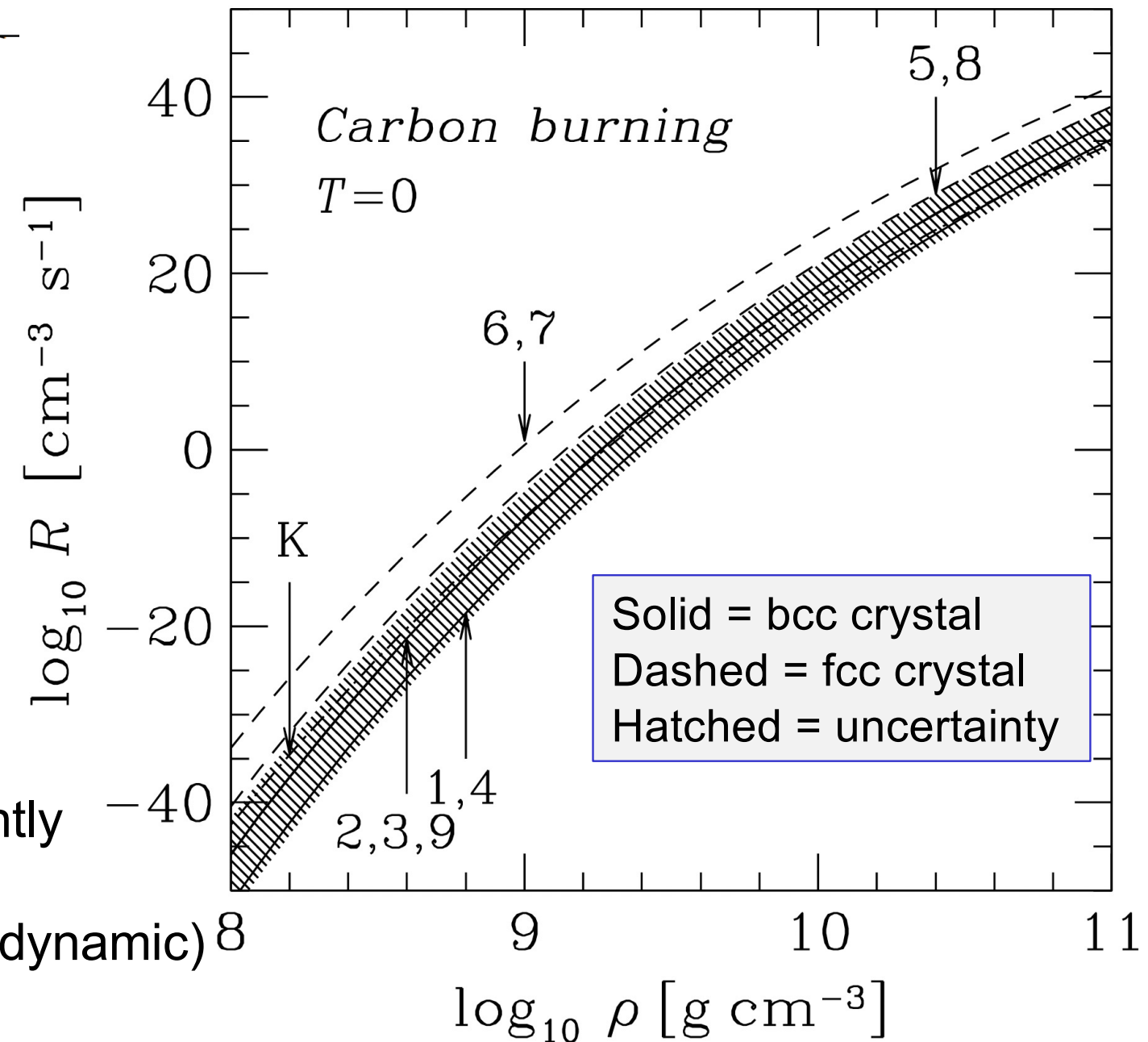
$$P_{pyc} \sim \exp(-C_1 \rho^{-1/6})$$

$$F_{pyc} \sim C_2 \rho^{C_3}$$

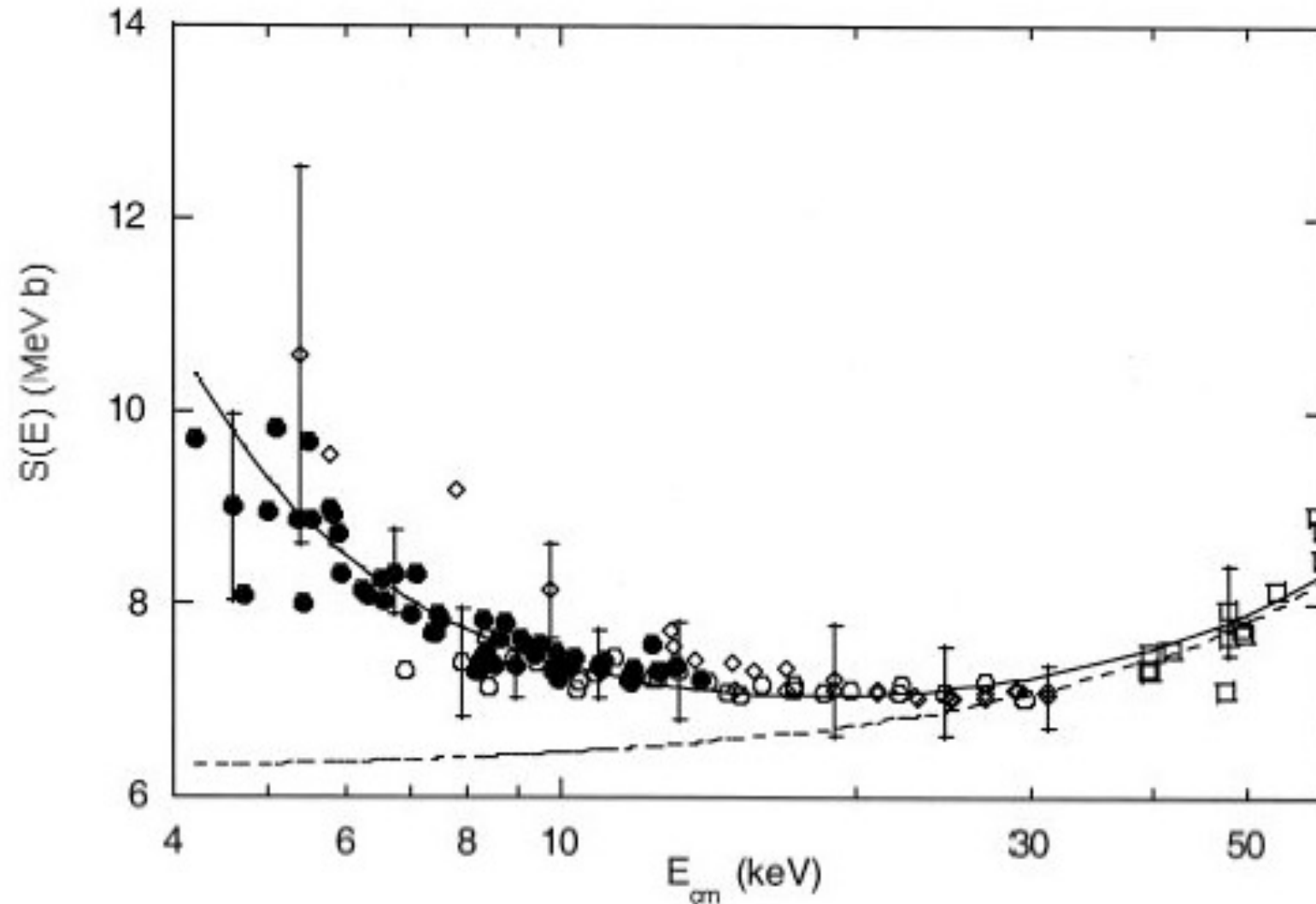
Uncertainties:

- bcc lattice more tightly bound than fcc
- Static and relaxed (dynamic) lattices
- Extrapolation models

Gasques et al, PRC 72, 025806 (2005)



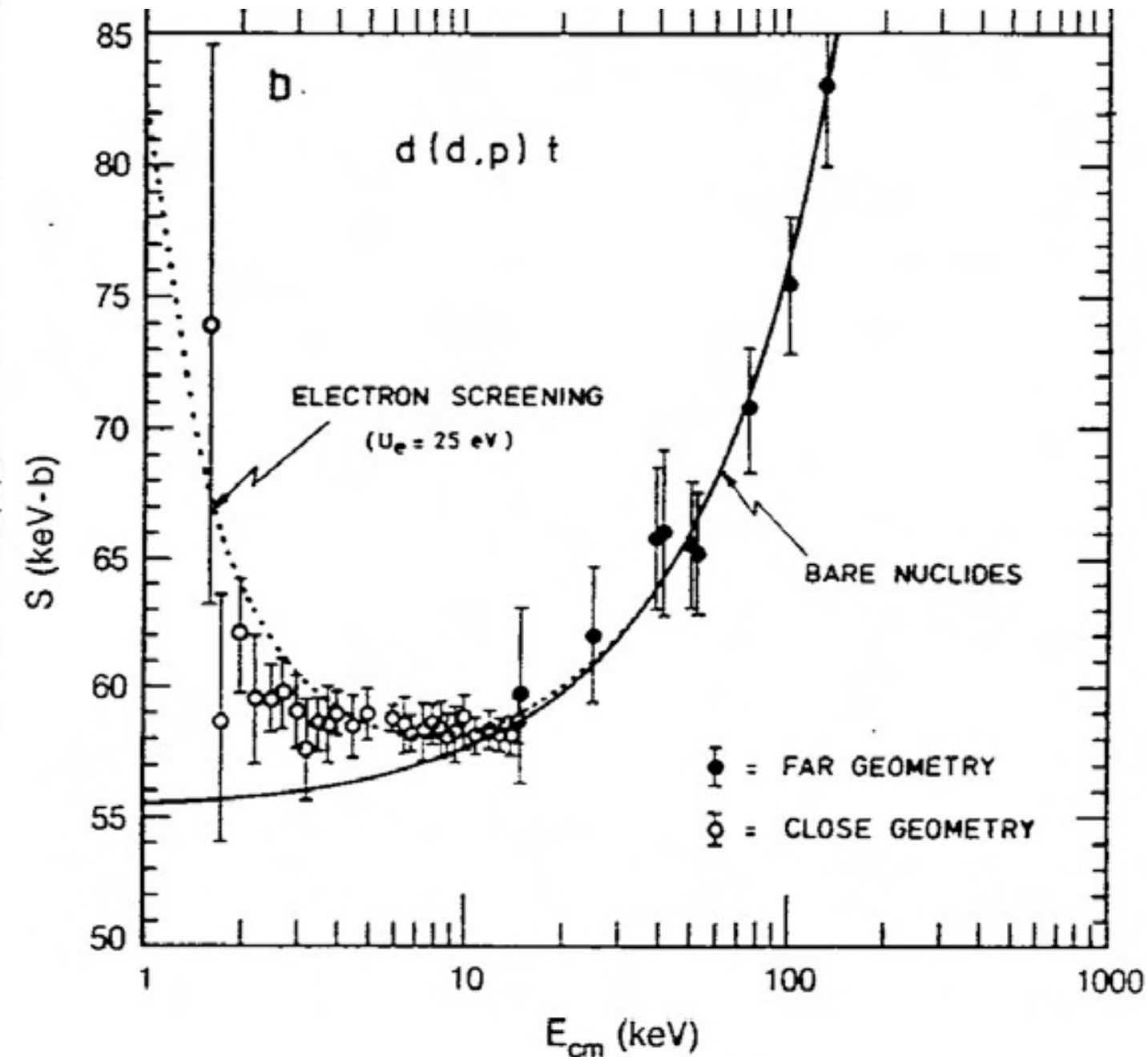
Screening of nuclear reactions in laboratory



Costantitni et al, PLB 482, 43 (2000)

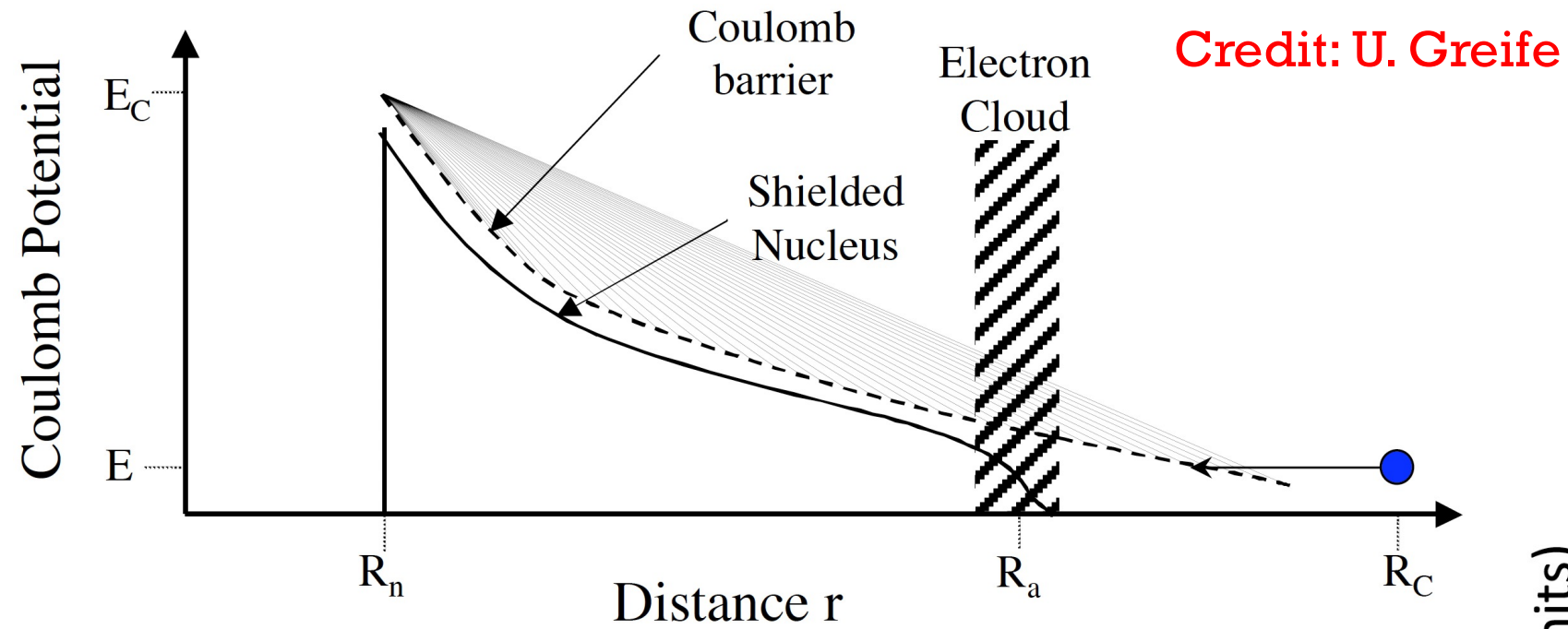
Unheard of before 1987!

Assenbaum, Langanke, Rolfs: Z.Phys.327(1987)461

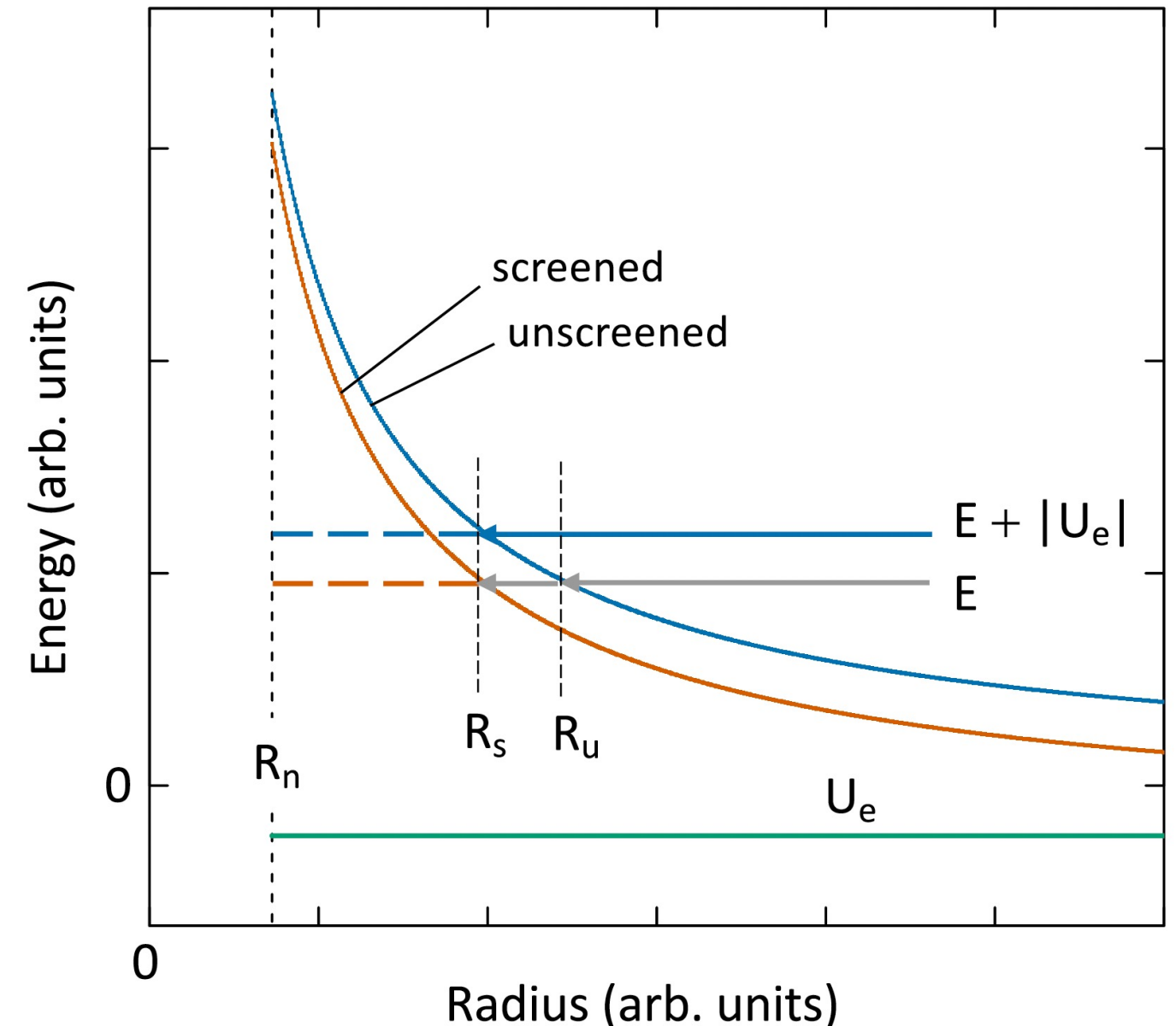
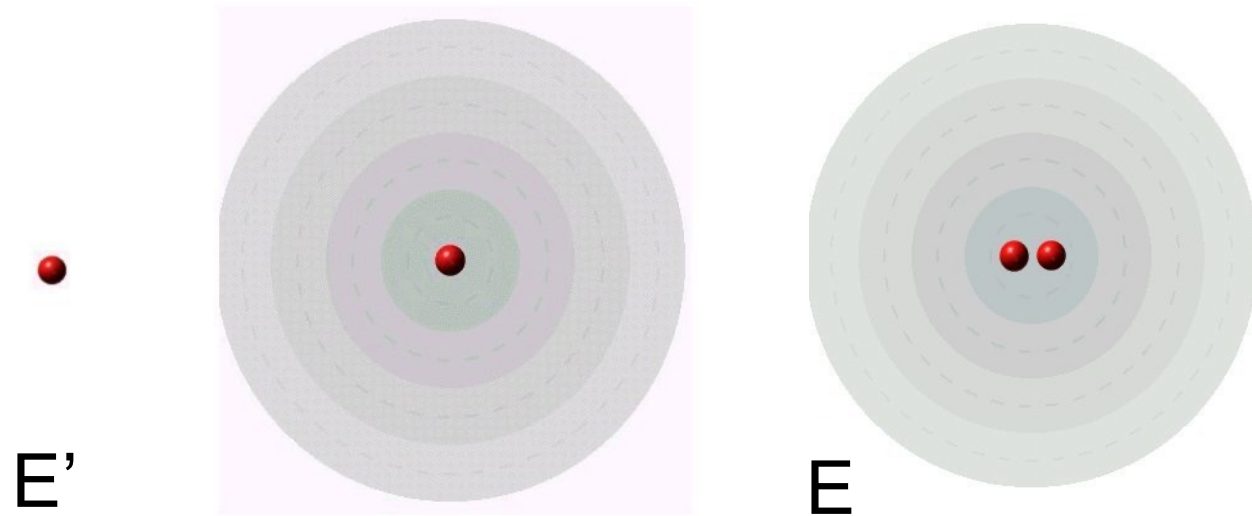


Greife et al, Z. Phys. A 351, 107 (1995)

Screening of nuclear reactions in laboratory

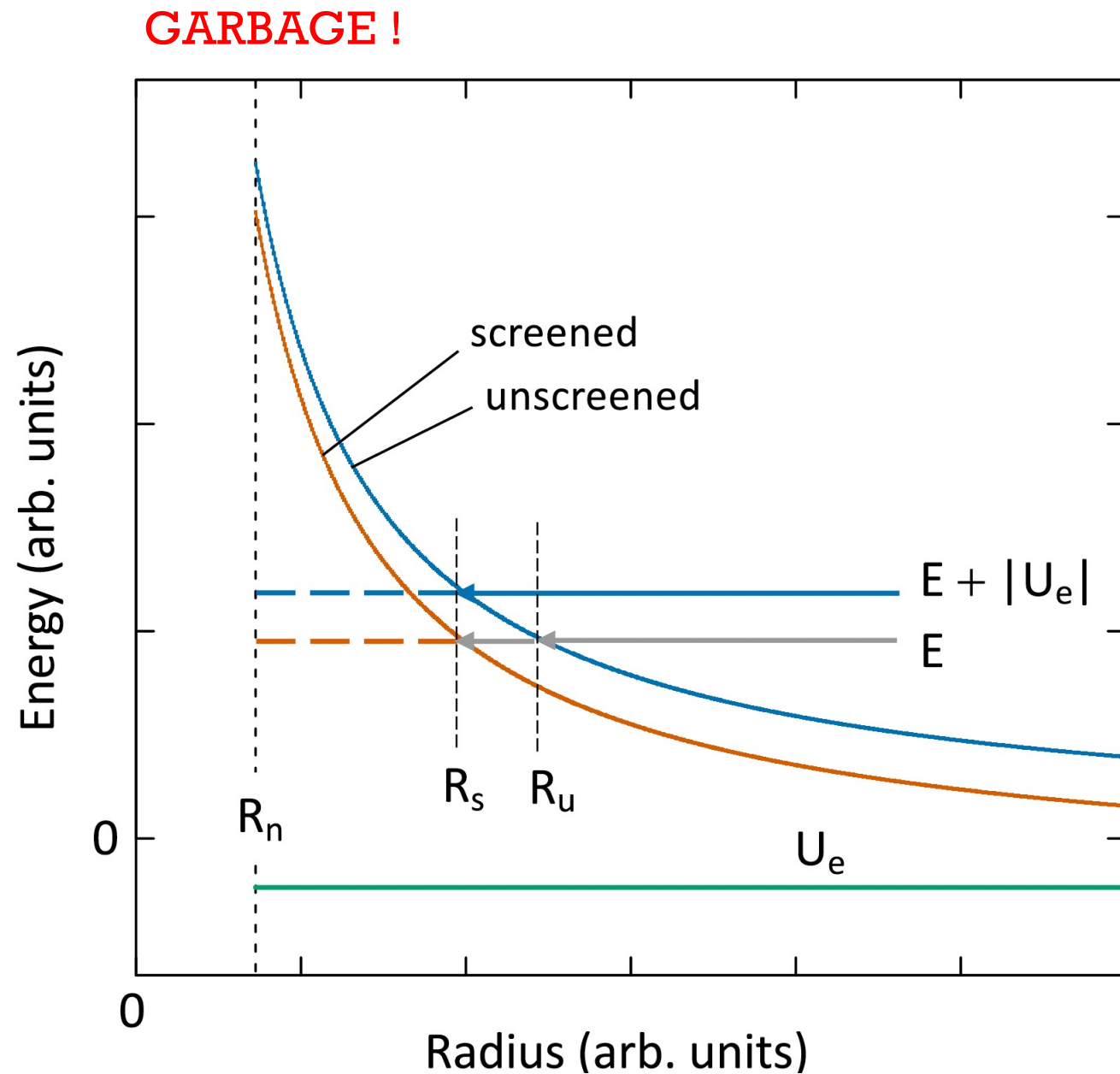


Credit: C. Iliadis

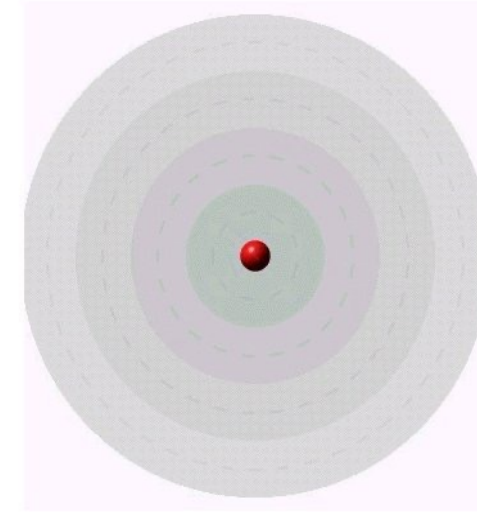


Much better view: energy conservation

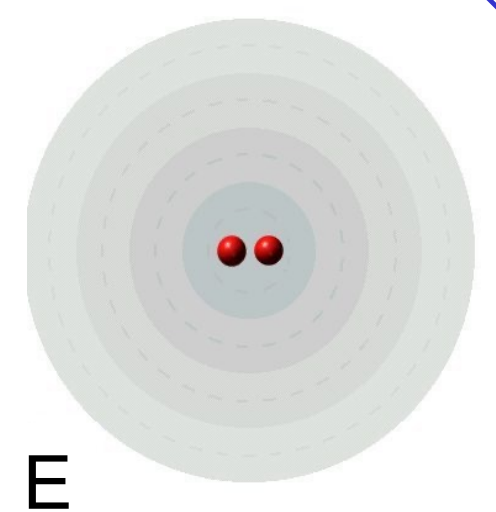
Screening of nuclear reactions in laboratory



E'



E



Adiabatic model

$$\Delta E = U_e = E' - E$$

Electron screening enhancement

$$\sigma_{lab}(E) = \sigma_{bare}(E + U_e) \sim \exp \left[\pi \eta(E) \frac{U_e}{E} \right] \sigma_{bare}(E)$$

Screening in laboratory – Dynamic vs Adiabatic

Shoppa, Koonin, Langanke, Seki, PRC 48, 837 (1993)

TDHF

$$i \frac{\partial \psi(\mathbf{r}, t)}{\partial t} = -[\Phi(\mathbf{r}, t) + \nabla^2] \psi(\mathbf{r}, t)$$

Anti-symmetrization g.s.

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, t) = \psi(\mathbf{r}_1, t) \psi(\mathbf{r}_2, t) \frac{1}{\sqrt{2}} [\alpha(1)\beta(2) - \alpha(2)\beta(1)]$$

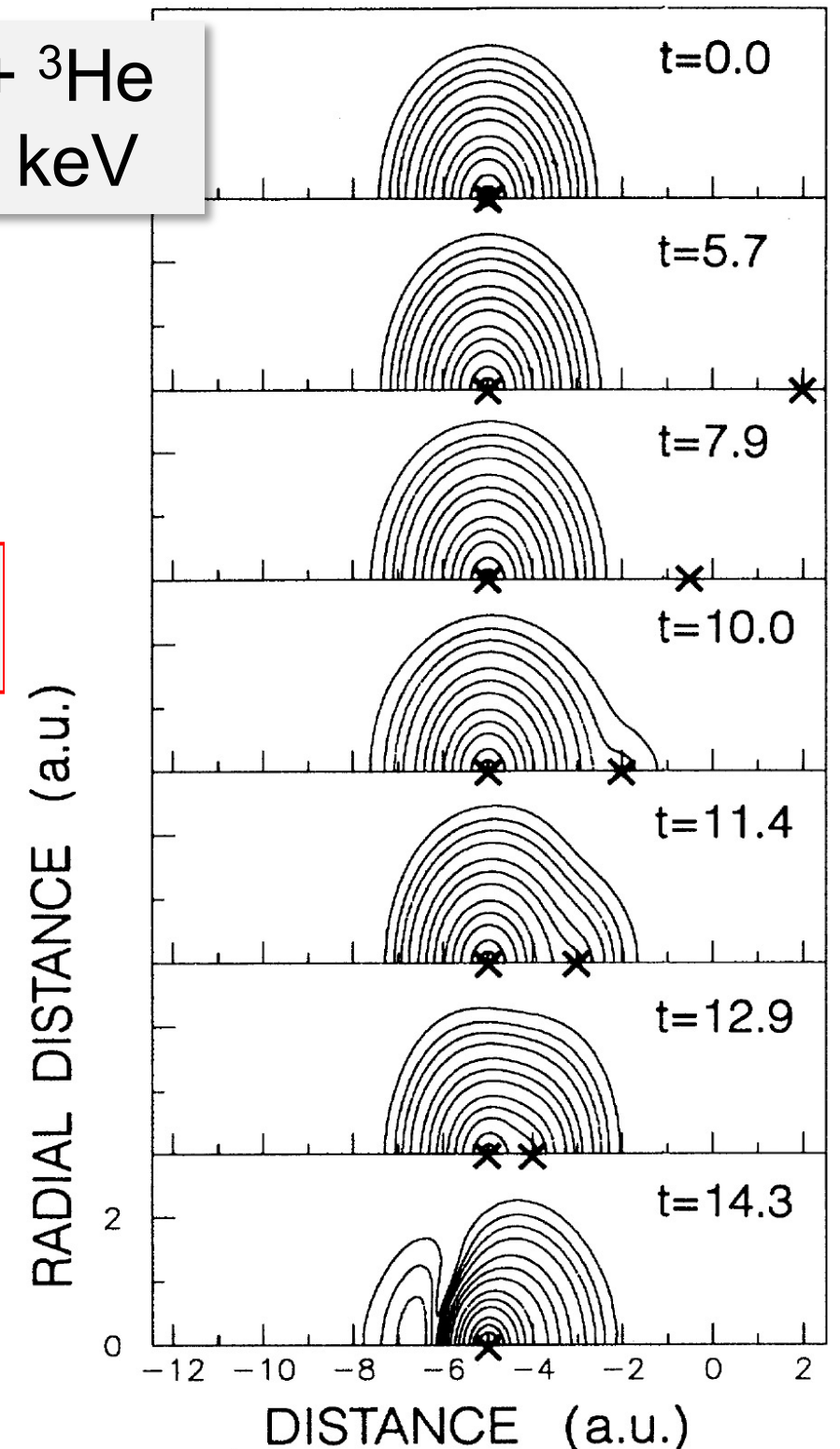
Time-dependent potential

$$\Phi(\mathbf{r}, t) = \frac{Z_1}{|\mathbf{r} - \mathbf{R}_1(t)|} + \frac{Z_2}{|\mathbf{r} - \mathbf{R}_2(t)|} - \int d^3r' \frac{|\psi(\mathbf{r}', t)|^2}{|\mathbf{r} - \mathbf{r}'|}$$

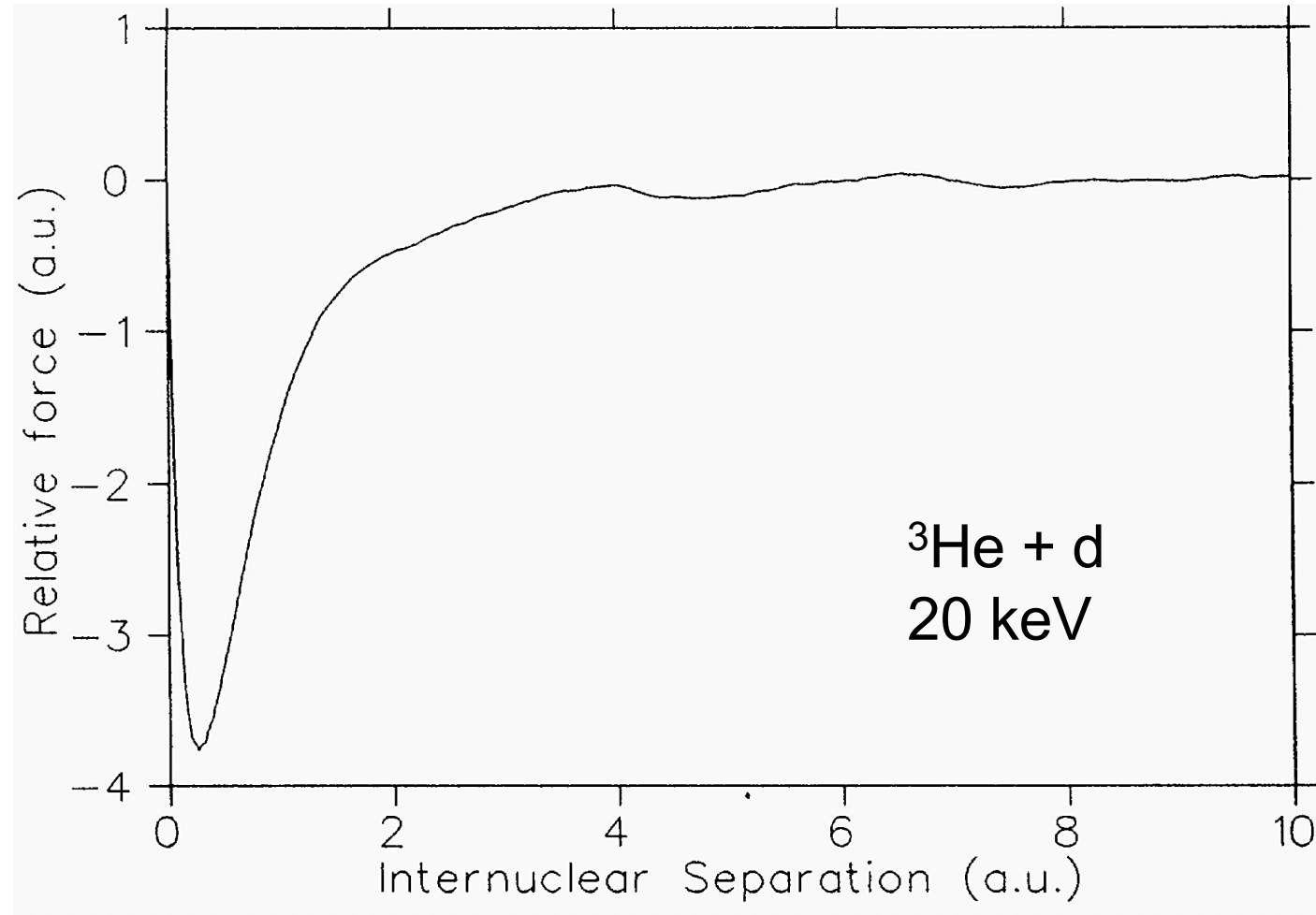
Electronic force on nuclei

$$F_i(t) = \int d^3r' \frac{\rho(\mathbf{r}', t) [(\mathbf{R}_i(t) - \mathbf{r}') \cdot \hat{\mathbf{z}}]}{|\mathbf{R}_i(t) - \mathbf{r}'|^3}$$

d + ³He
20 keV



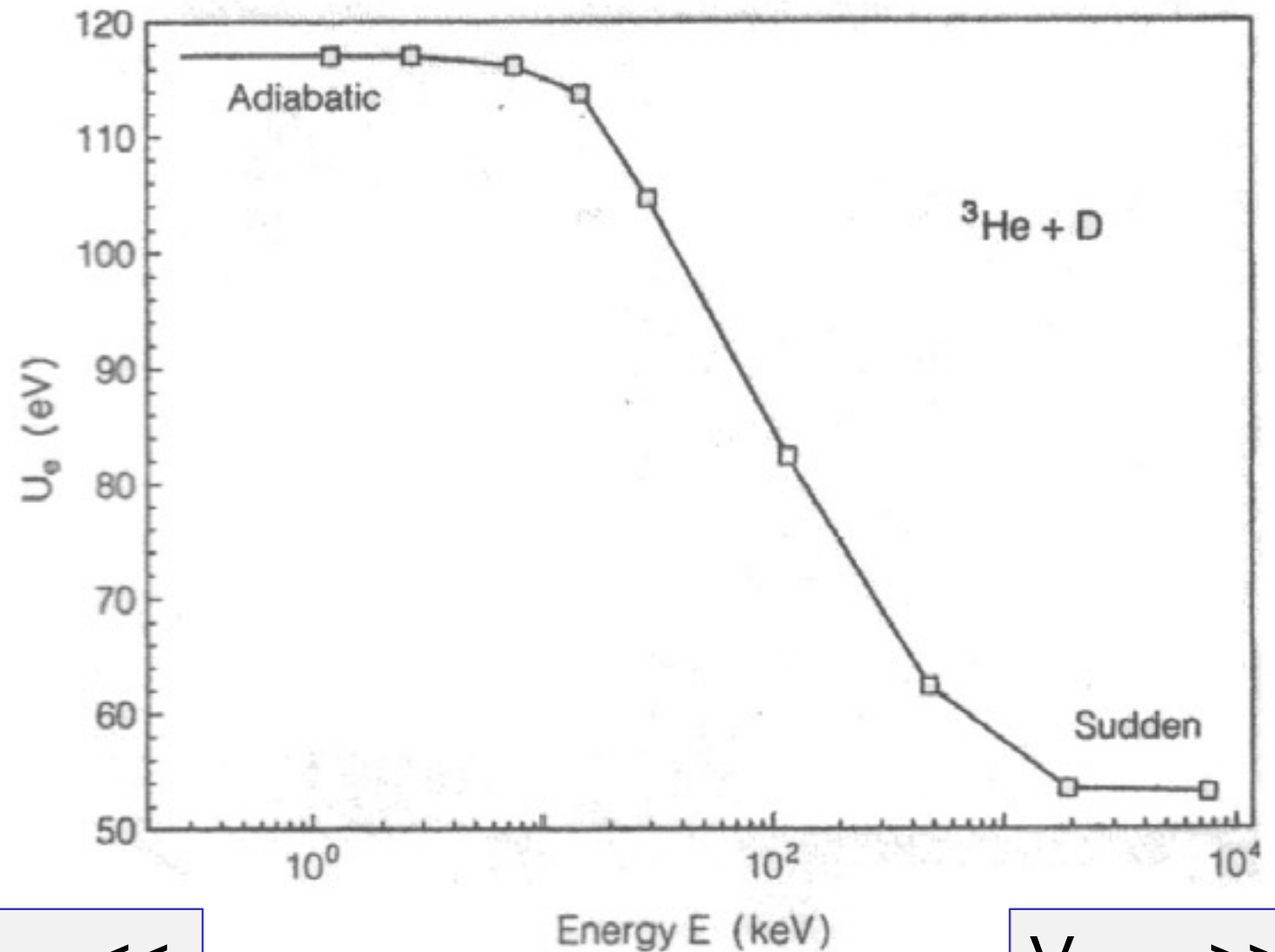
Screening in laboratory – Dynamic vs Adiabatic



Relative force applied by
the electrons on nuclei

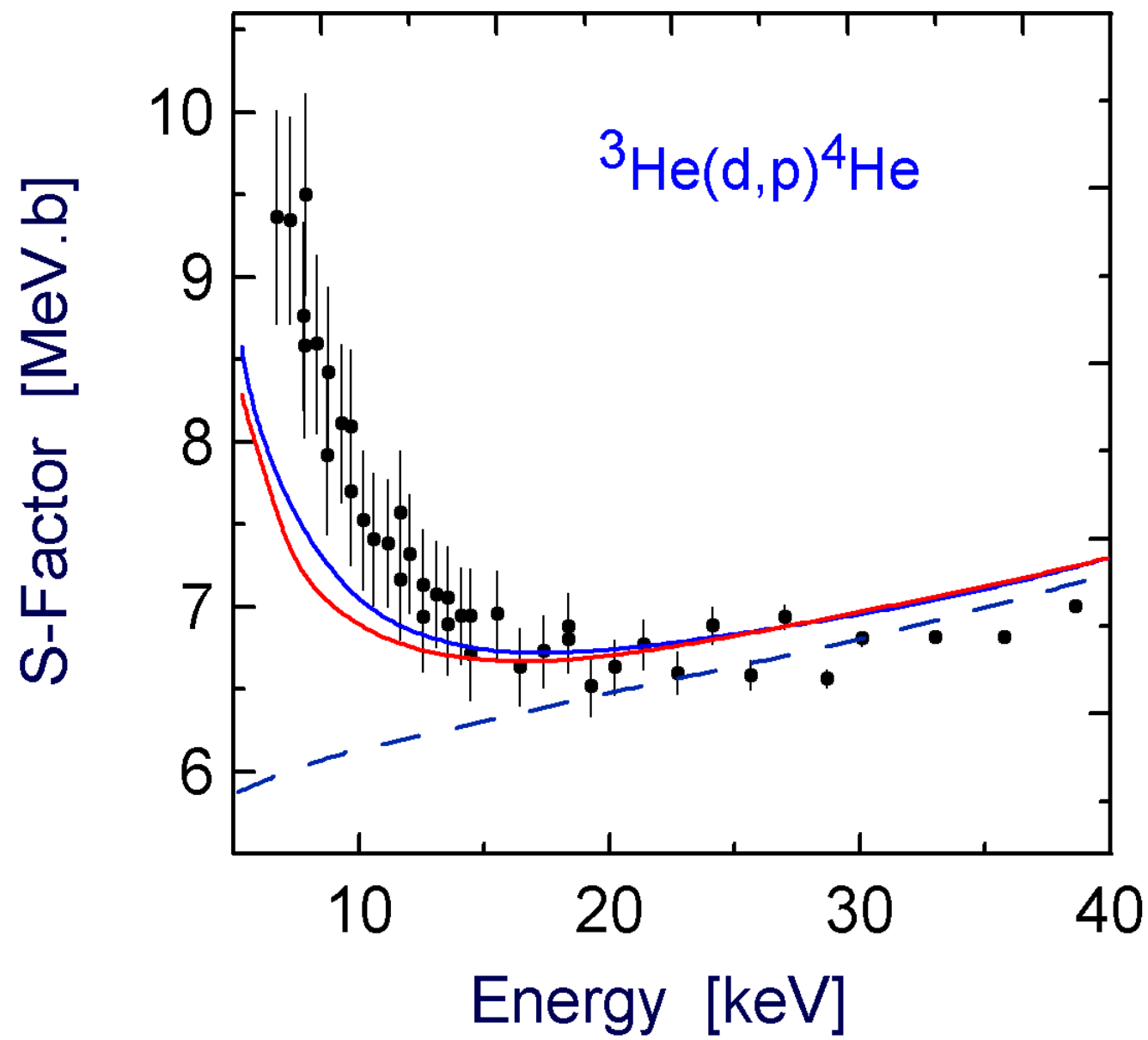
$V_{\text{nuclei}} \ll$
 $V_{\text{electrons}}$

Shoppa, Koonin, Langanke, Seki,
PRC 48, 837 (1993)



$V_{\text{nuclei}} \gg$
 $V_{\text{electrons}}$

Screening of nuclear reactions in laboratory



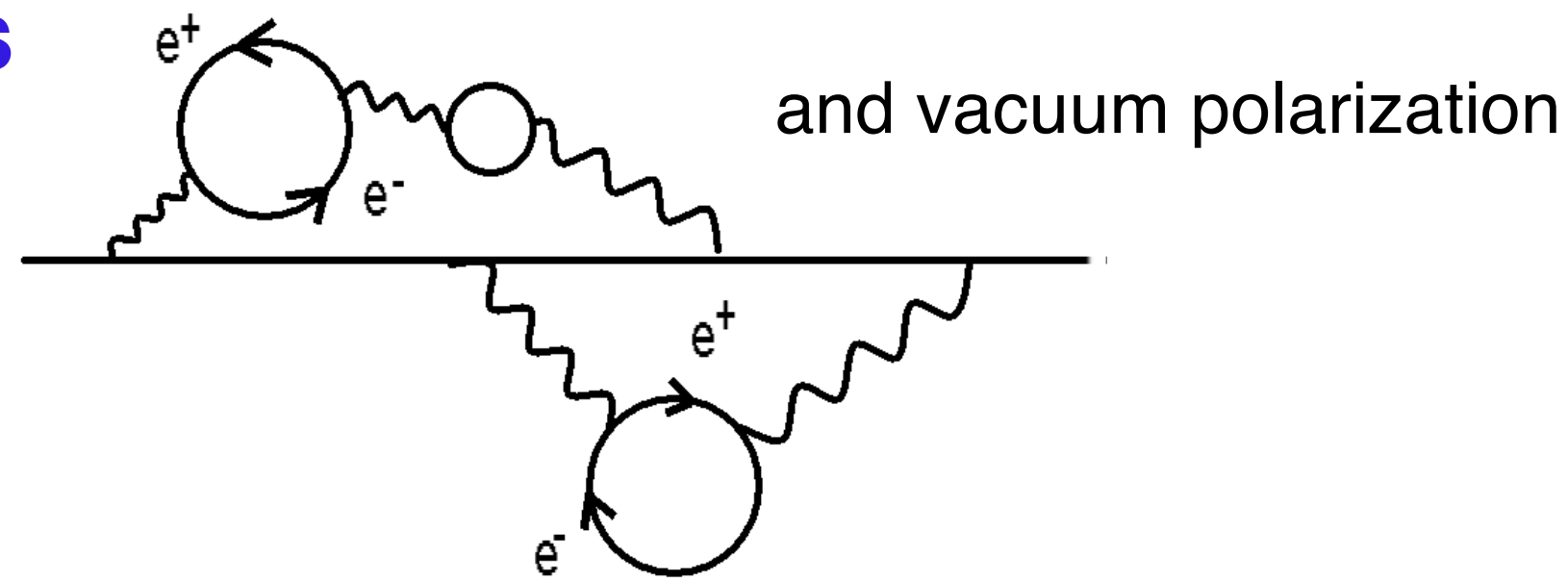
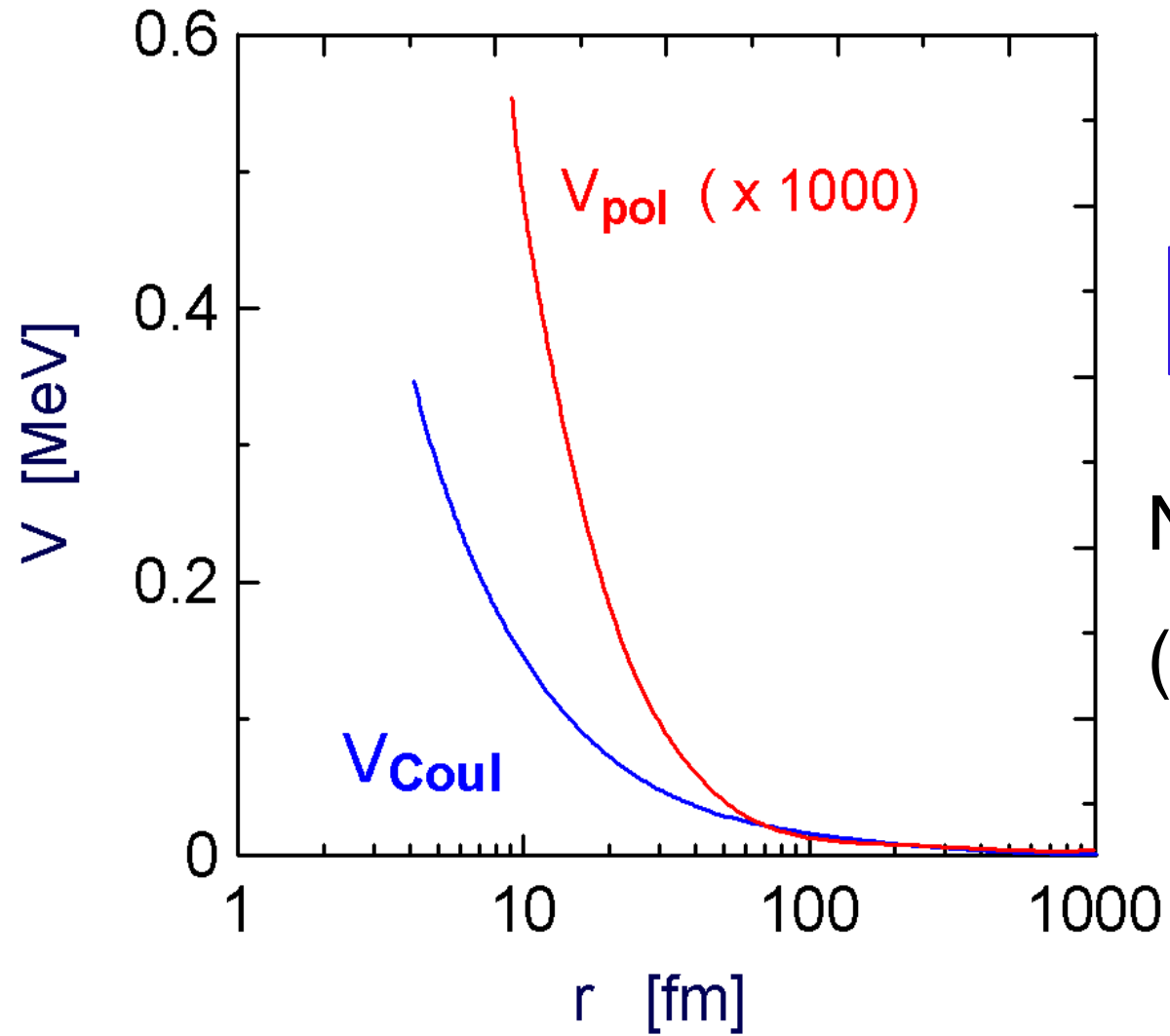
Aliotta et al, NPA 690, 790 (2001)

--- S_{bare}
— Dynamic
— Adiabatic

Reaction	U_{ad}	U_{exp}	Ref.
d(d,p)t	14	25±5	Greife et al (1995)
$^3\text{He}(\text{d,p})^4\text{He}$	120	186±12	Prati et al (1994)
d($^3\text{He,p})^4\text{He}$	65	123±9	Prati et al (1994)
$^7\text{Li}(\text{p},\alpha)^4\text{He}$	182	300±280	Engstler et al (1992)
$^{11}\text{B}(\text{p},\alpha)^8\text{Be}$	148	430±80	Angulo et al (1993)

Beyond-screening effects

- Thermal motion, lattice vibrations
beam energy spread
- Nuclear breakup channels
- Dynamics of tunneling



Balantekin, CB, Hussein, NPA 627, 324 (1997)

all $\leq 1\%$

Not a solution!
(need $\sim 100\%$)

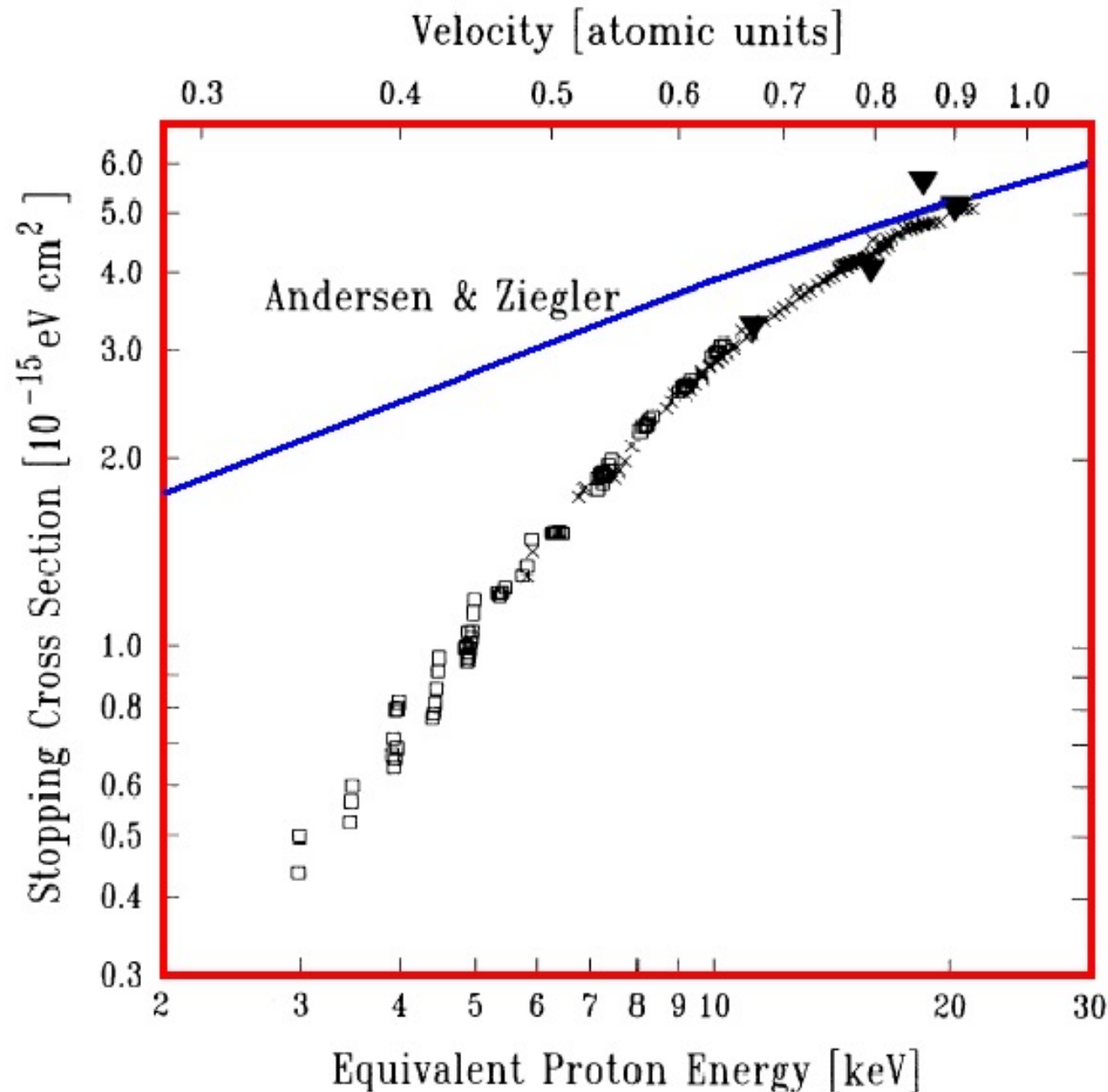
Corrections	
Vaccuum Polarization	$\sim 1\%$
Relativity	10^{-3}
Bremsstrahlung	10^{-3}
Atomic porarization	10^{-5}
Nuclear polarization	$< 10^{-10}$

Stopping power at very low energy

Bang, PRC 53, R18 (1996)

Langanke, PLB 369, 211 (1996)

Data needs to be corrected for
stopping power



$$E' = E - S_p \cdot \Delta x$$

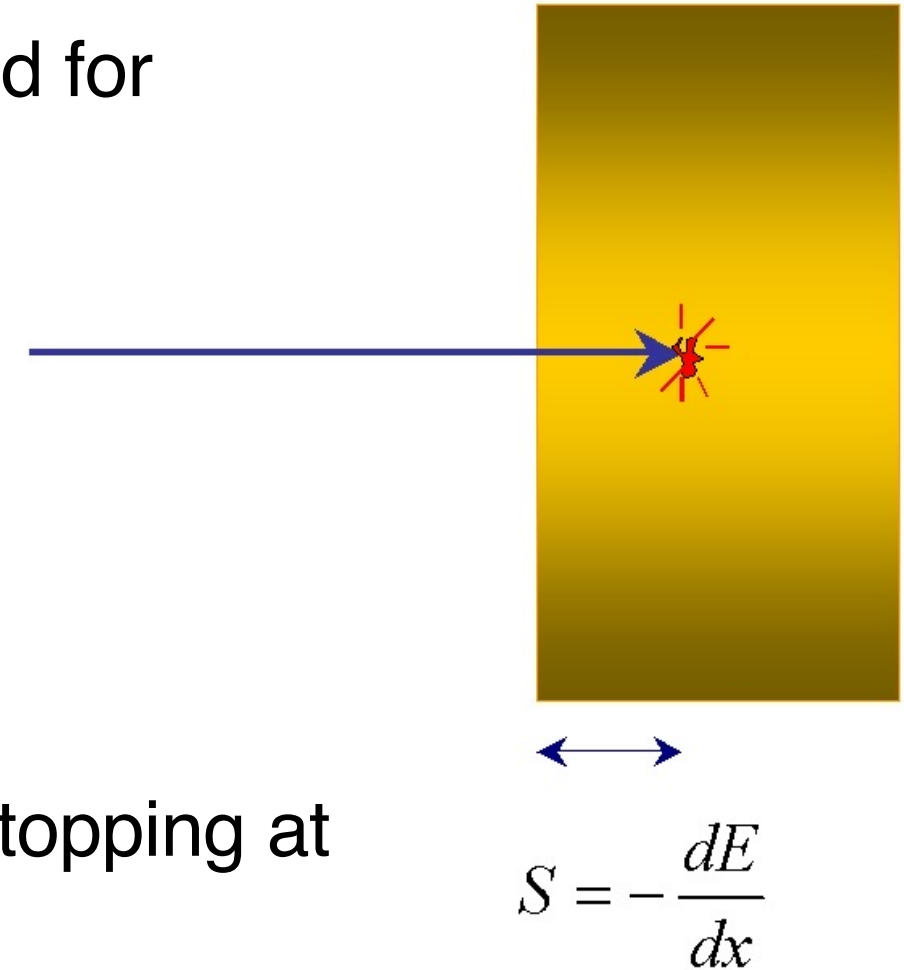
$$S_p = -\frac{dE}{dx}$$

Very few data on stopping at
ultra-low energies

H + He

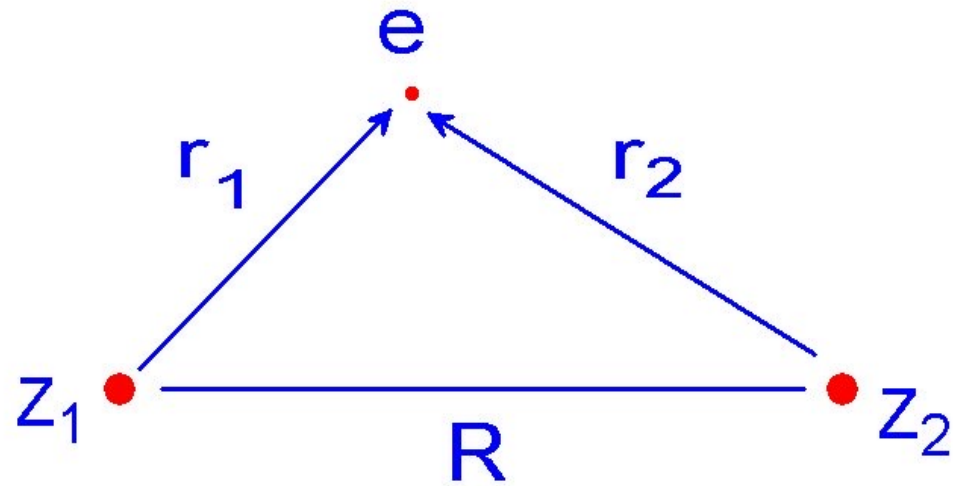
Golser, Semrad, PRL 14 (1991) 1831

Mainly charge-exchange between ions



Stopping power - dynamics calculations

Bertulani, de Paula, PRC 62, 045802 (2000)
PLB 585, 35 (2004)



Elliptic coordinates

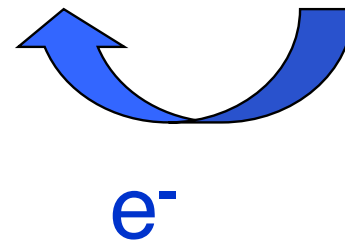
Change of variables

$$\xi = \frac{r_1 + r_2}{R}; \quad \eta = \frac{r_1 - r_2}{R}; \quad \phi$$

$$\Psi = F(\xi)G(\eta)e^{im\phi}$$

$p + H$

$p + d$



Charge exchange (pickup)

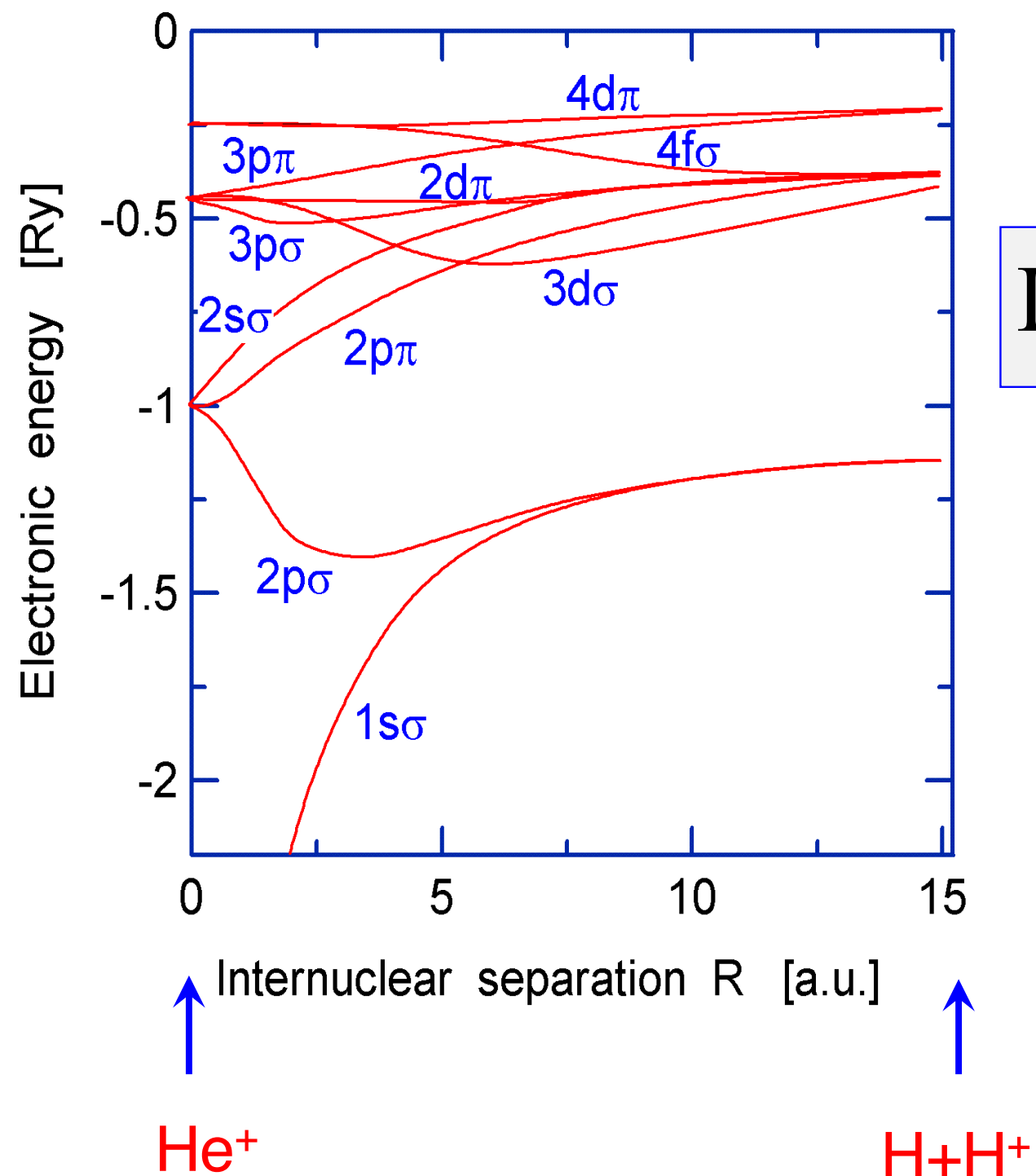
Projectile slows down to carry electron with

Two-center wfs (molecular orbitals):

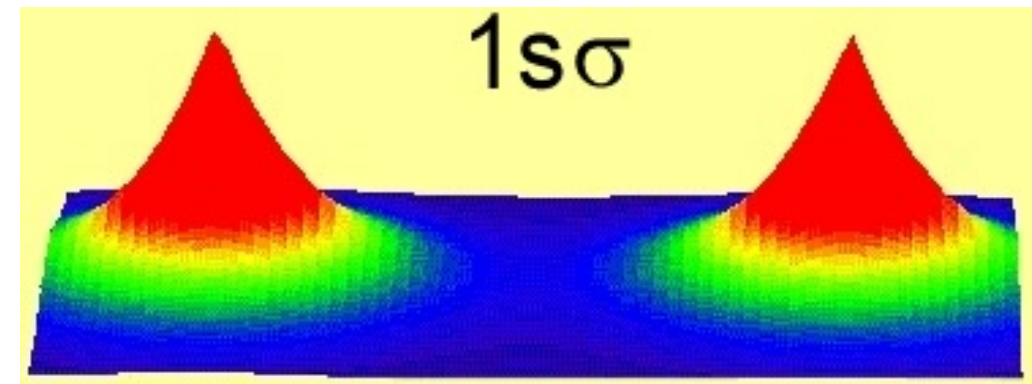
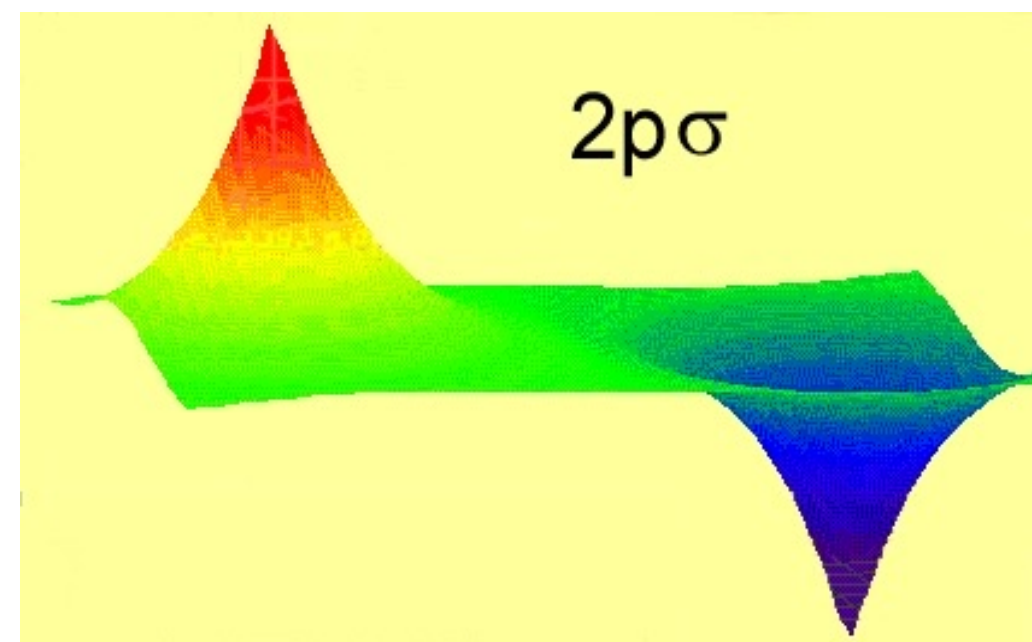
$$\frac{d}{d\xi} \left[(\xi^2 - 1) \frac{dF}{d\xi} \right] + \left[\frac{R^2 \xi^2}{2} E + 2R\xi - \frac{m^2}{\xi^2 - 1} \right] F(\xi) = 0$$

$$\frac{d}{d\eta} \left[(1 - \eta^2) \frac{dG}{d\eta} \right] - \left[\frac{R^2 \xi^2}{2} E + 2R\xi + \frac{m^2}{\eta^2 - 1} \right] G(\eta) = 0$$

Expansion basis: molecular orbitals for p + H



$$L_z \Phi_s = \pm \lambda \Phi_s$$



Value of λ	0	1	2	3
Symbol	σ	π	δ	$\phi, \dots$

Coupled-channels calculation

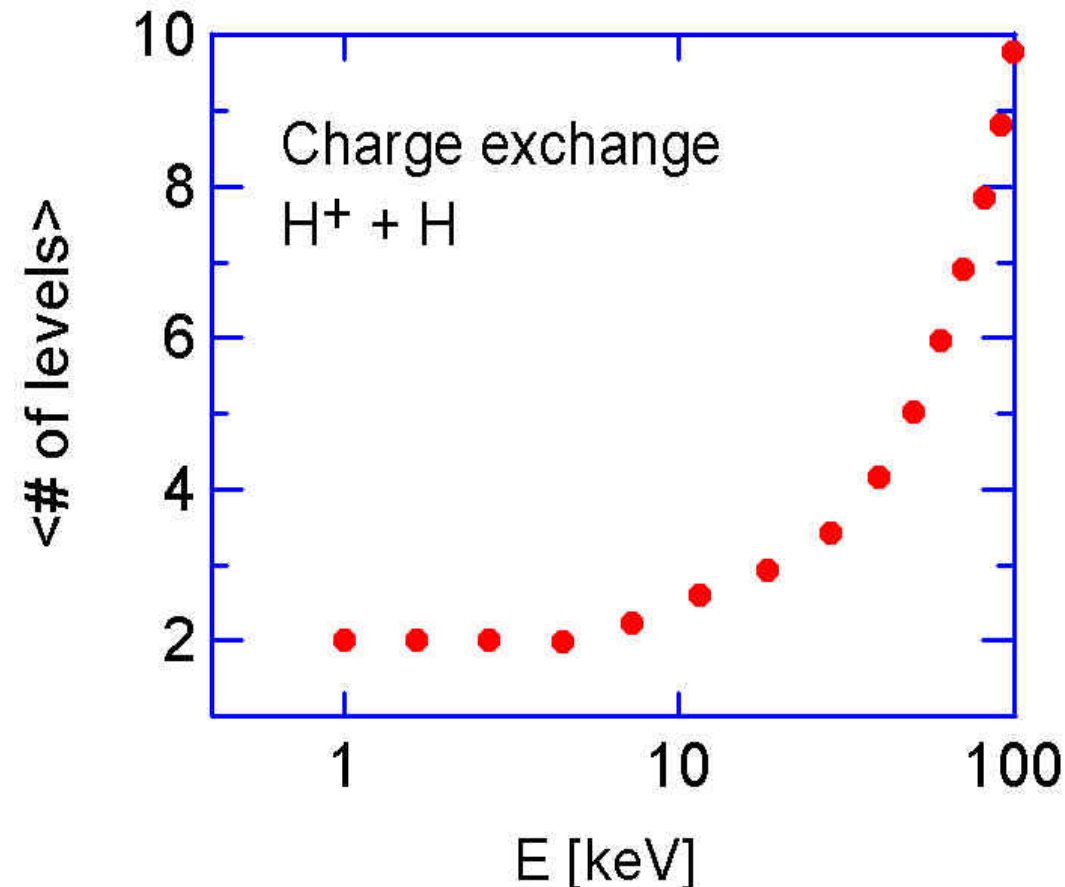
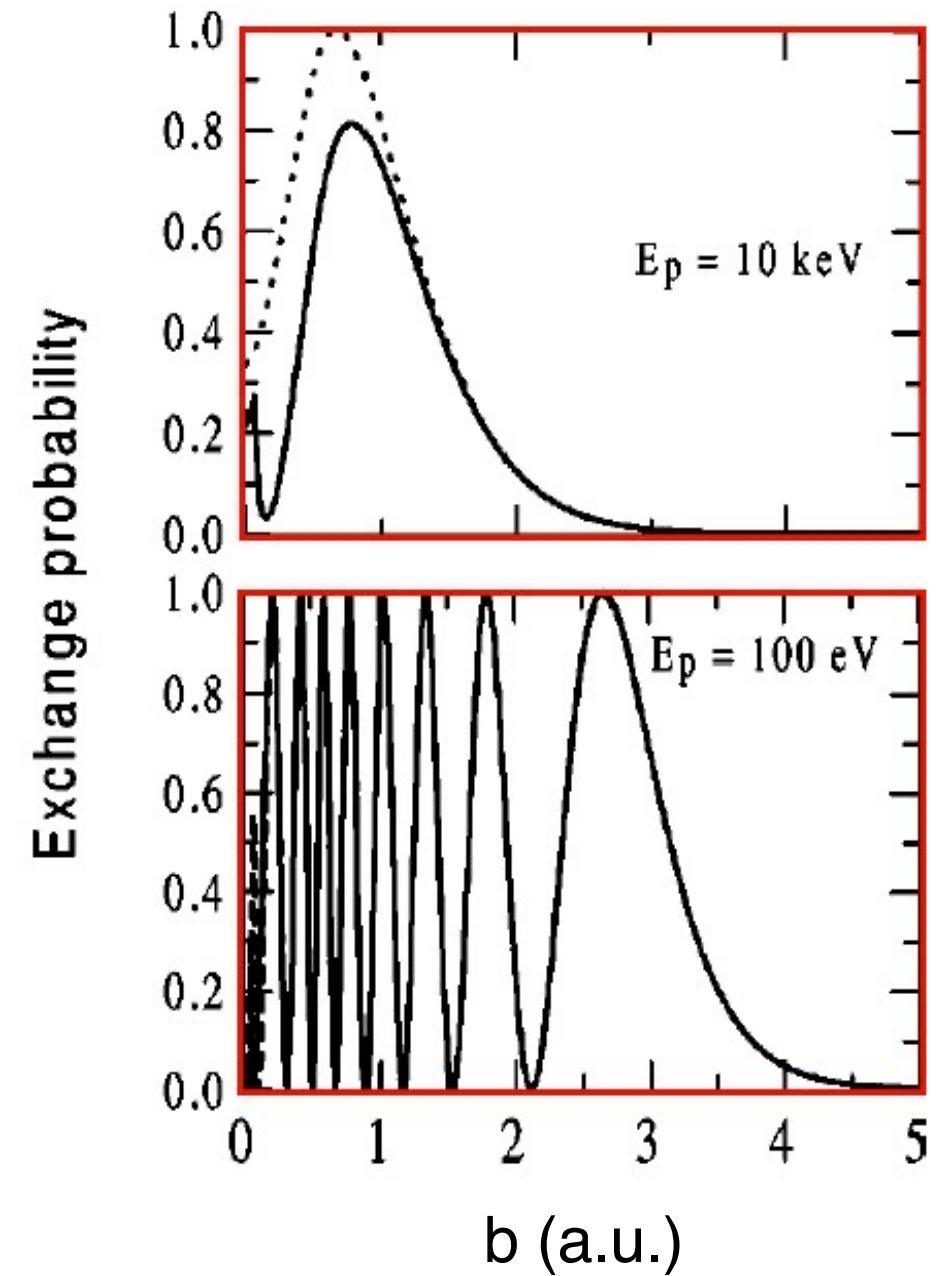
$$i\hbar \frac{d}{dt} a_m(t) = E_m(t) a_m(t) - i\hbar \sum_n a_n(t) \left\langle m \left| \frac{d}{dt} \right| n \right\rangle$$

$$\left\langle m \left| \frac{d}{dt} \right| n \right\rangle = \frac{\left\langle m \left| dV_p / dt \right| n \right\rangle}{E_n(t) - E_m(t)},$$

(Hellman-Feynmann relation)

For $E_p < 10$ keV,
only $1s\sigma$ and $2p\sigma$

2-level problem
resonant exchange



$$P_{\text{exch}} \approx \frac{1}{2} + \frac{1}{2} \cos \left\{ \frac{1}{\hbar} \int_{-\infty}^{\infty} [E_{2p}(t) - E_{1\sigma}(t)] dt \right\}$$

H⁺ + He collisions - two-active electrons

CB, PLB 585, 35 (2004)

Expand in Slater-type orbitals

$$\phi = N r^{n-1} e^{-\xi r} Y_{lm}(\theta, \phi)$$

Two-center basis for two-electrons Hartree-Fock equations 

$$\Phi_i = \sum_{j=1}^n \left[c_{ji}^A \phi_i^A + c_{ji}^B \phi_i^B \right]$$

$$F_{\mu\nu} = H_{\mu\nu} + \sum_{\lambda\rho} P_{\lambda\rho} \left[(\mu\nu | \lambda\rho) - \frac{1}{2} (\mu\rho | \lambda\nu) \right]$$

F . C = O . C . E

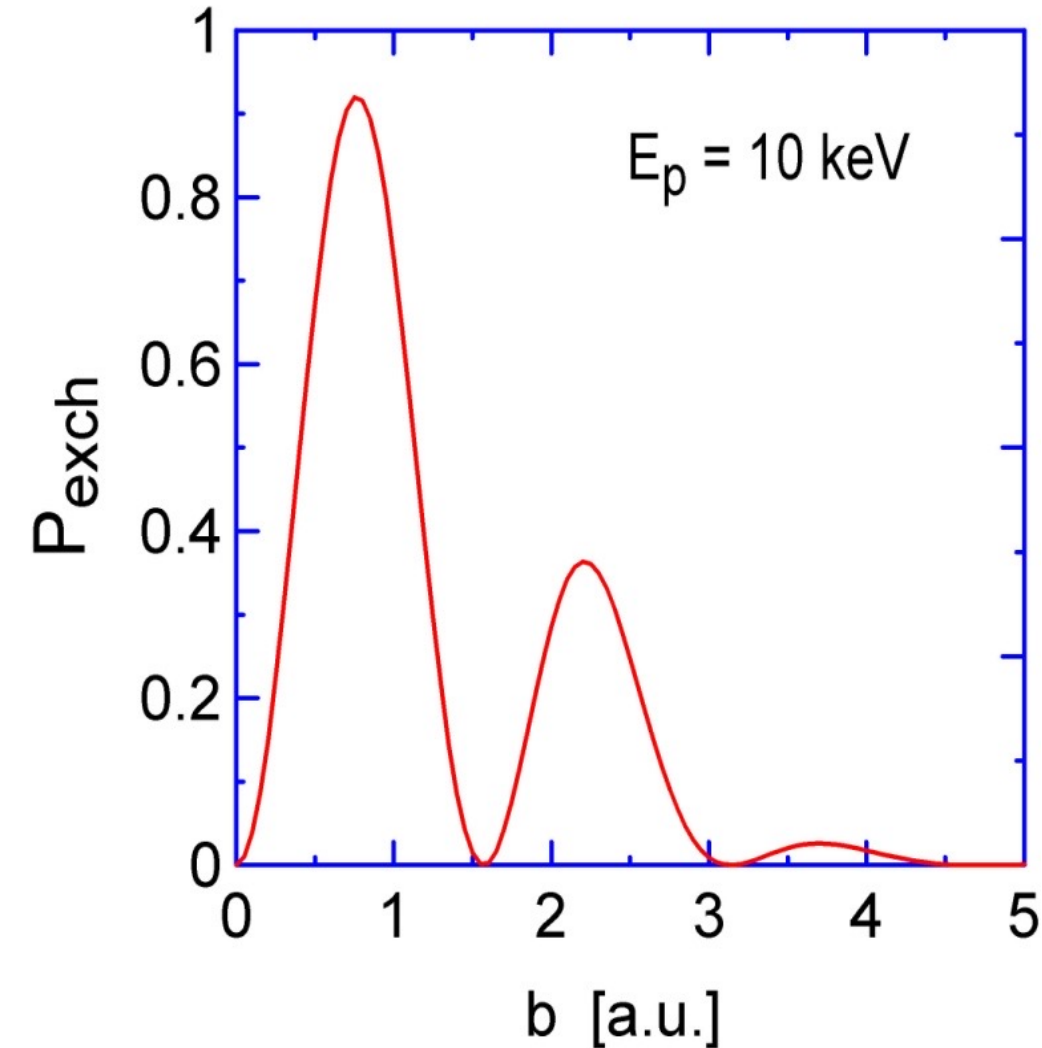
$$H_{\mu\nu} = \iint \phi_{\mu}^*(1) \left[-\frac{1}{2} \nabla_1^2 - \sum_A \frac{1}{r_{1A}} \right] \phi_{\nu}^*(1) d\tau_1, \quad P_{\lambda\rho} = 2 \sum_{i=1}^{\text{occ}} c_{\lambda i} c_{\rho i}$$

$$(\mu\nu | \lambda\rho) = \iint \phi_{\mu}(1) \phi_{\nu}(1) \frac{1}{r_{12}} \phi_{\lambda}(2) \phi_{\rho}(2) d\tau_1 d\tau_2, \quad O_{\mu\nu} = \int \phi_{\mu}(1) \phi_{\nu}(1) d\tau_1$$



t. d. coupled-channels equations

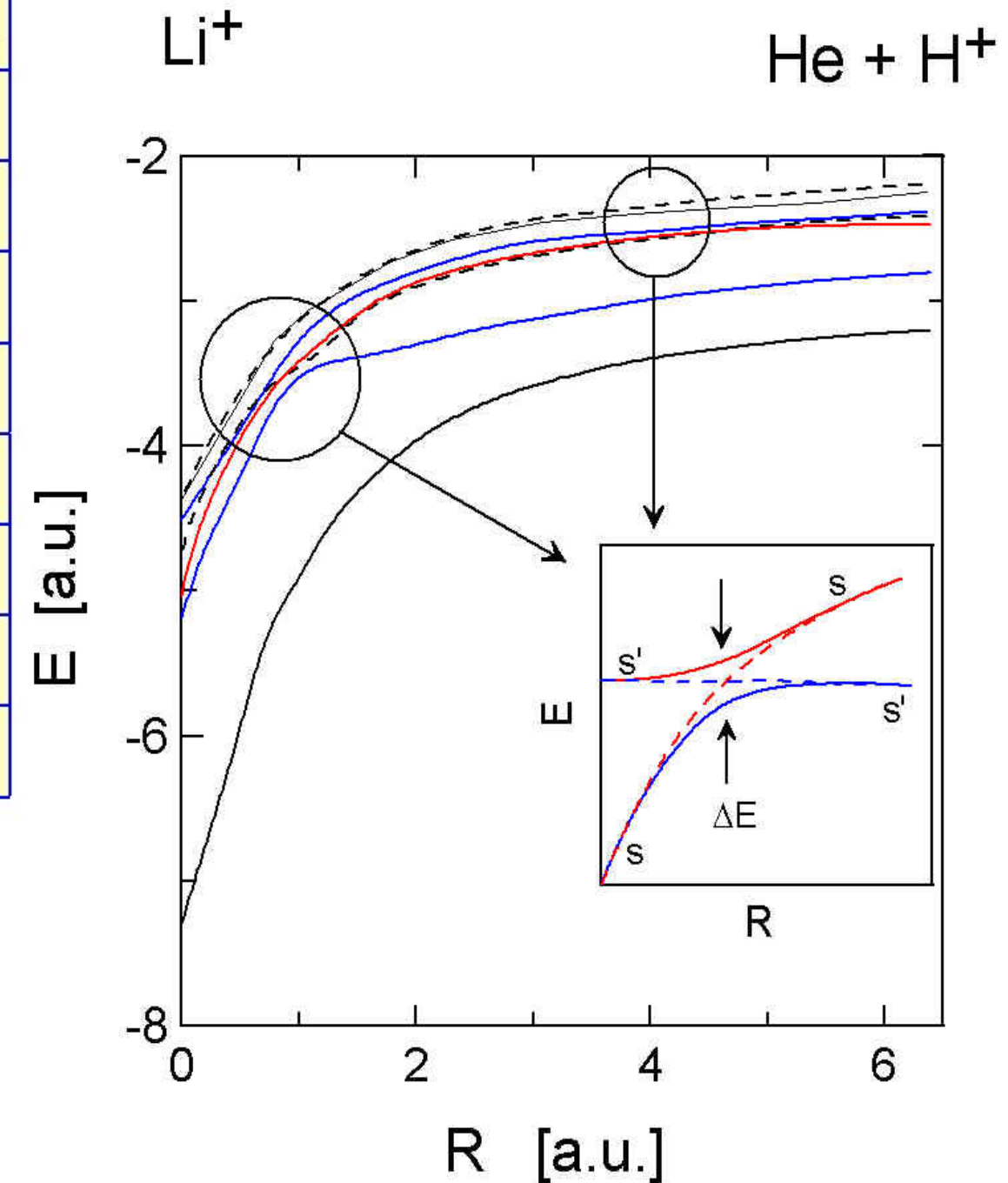
Damping of resonant exchange



Separated atom	United atom
$\text{H}^+ + \text{He}(1s^2)$	0Σ
$\text{H}(1s) + \text{He}^+(1s)$	1Σ
$\text{H}^+(1s) + \text{He}(1s2s)$	2Σ
$\text{H}(n=2) + \text{He}^+(1s)$	1Π
$\text{H}(n=2) + \text{He}^+(1s)$	3Σ
$\text{H}(n=2) + \text{He}^+(1s)$	4Σ
$\text{H}^+ + \text{He}(1s1p)$	5Σ
$\text{H}^+ + \text{He}(1s1p)$	2Π

Landau-Zener
effect + dissipation

$$P = e^{-\Gamma \Delta t_{\text{coll}}} \cos^2 \left[\frac{H_{12} a}{2v} \right]$$

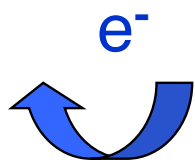
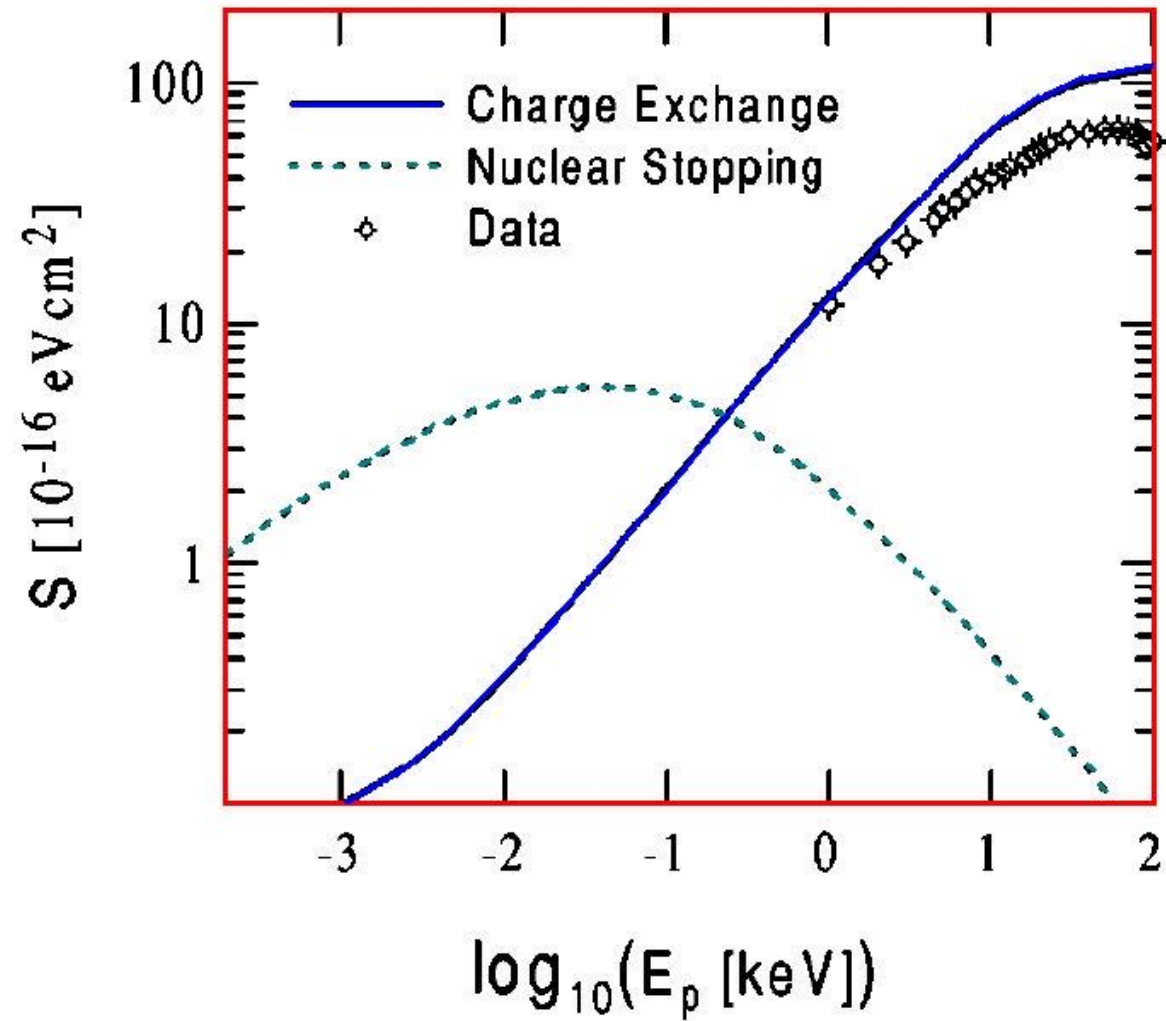


Stopping power at very low energies

p + H

P + D

CB, de Paula
PRC 62, 045802 (2000)



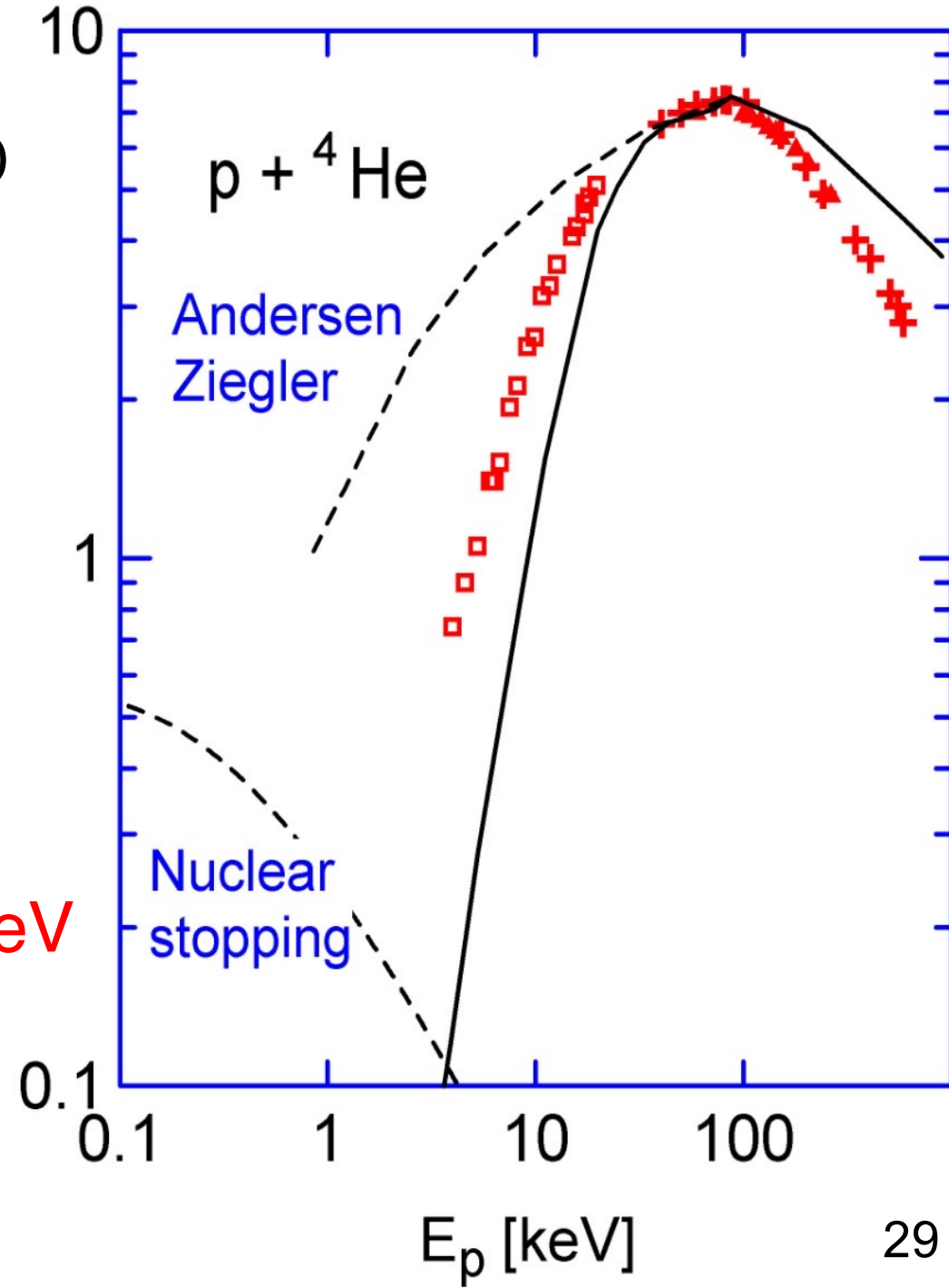
Threshold effect

CB, PLB 585, 35 (2004)

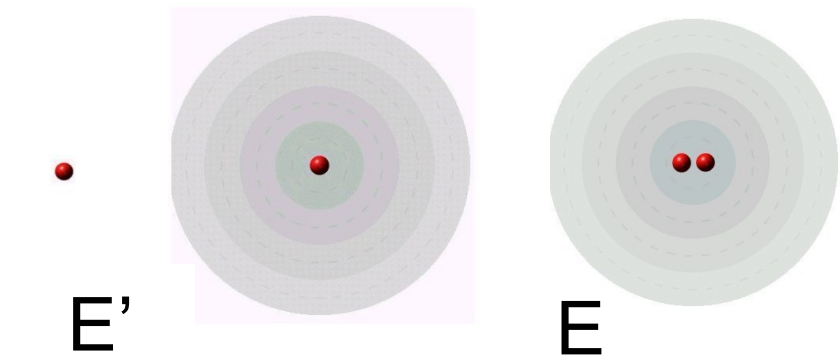
He:
 $1s^2 \rightarrow 1s2s: 19.8 \text{ eV}$

$$E_p \geq \frac{\mu^2}{4M_p m_e} \Delta E \geq 8 \text{ keV}$$

$S [10^{-15} \text{ eV cm}^2]$



Screening effect on resonances



Adiabatic model:

$$\Delta E = U_e = E' - E$$

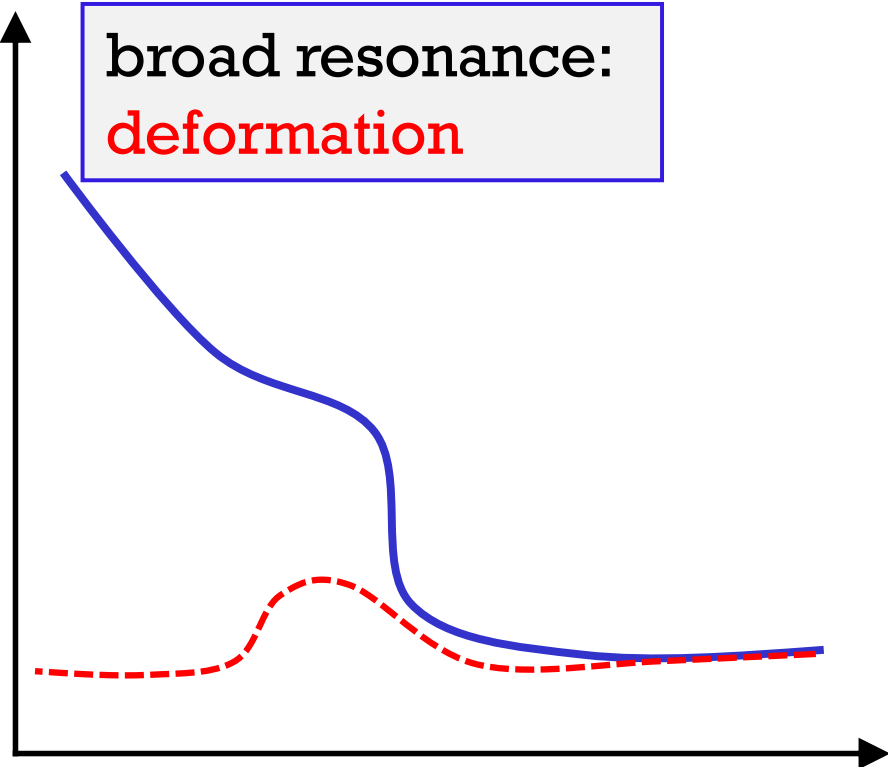
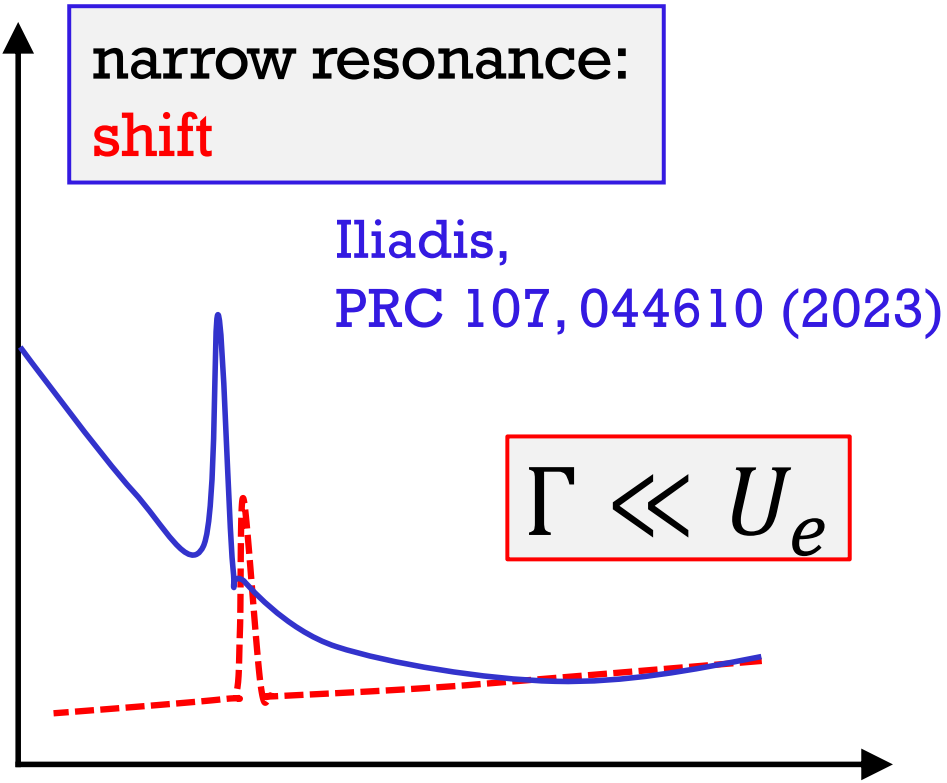
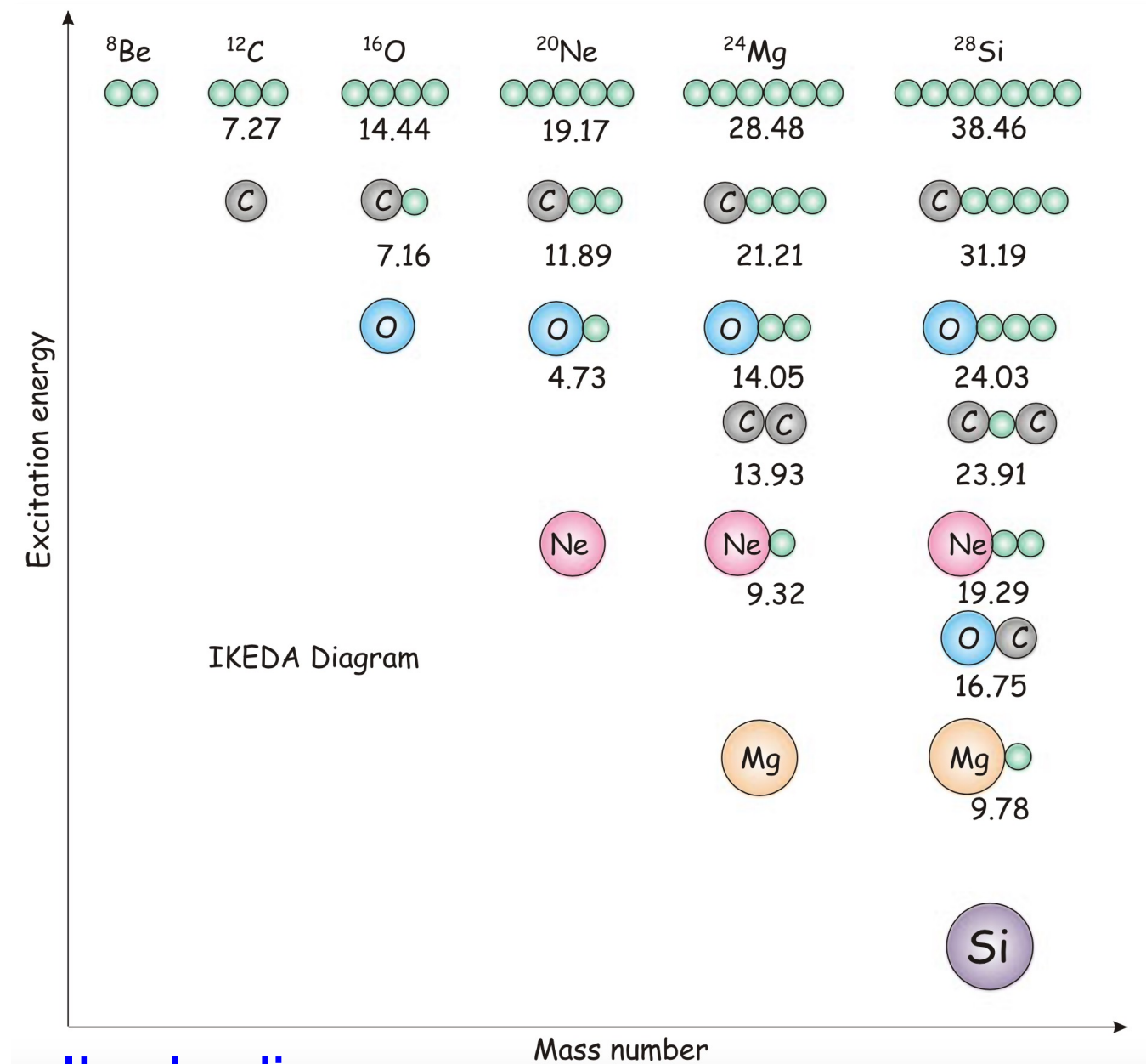


TABLE I. Electron screening factors, f_r , and related quantities, for reported measured narrow resonances.

Reaction	$E_r^{\text{c.m.}}$ (keV)	Γ (eV)	Target	r_K (fm) ^a	L_{TF} (fm) ^b	R_s (fm) ^c	U_e (keV) ^d	U_{ad} (keV) ^e	f_r ^f	Literature	
										f_{Lit}	Ref.
$^{17}\text{O}(p, \alpha)^{14}\text{N}$	64.5	$130 \pm 5^{\text{h}}$	$\text{Ta}_2\text{O}_5^{\text{l}}$	21160		178.6	−0.54	−0.68	0.9996	1.15	[12]
$^{18}\text{O}(p, \gamma)^{19}\text{F}$	90.0	$121 \pm 5^{\text{i}}$	$\text{Ta}_2\text{O}_5^{\text{l}}$	21160		128.0	−0.54	−0.68	0.9998	1.10	[32]
$^{18}\text{O}(p, \alpha)^{15}\text{N}$	90.0	$121 \pm 5^{\text{i}}$	$\text{Ta}_2\text{O}_5^{\text{l}}$	21160		128.0	−0.54	−0.68	0.9998	1.09	[33,34]
$^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$	149.4	$<60^{\text{j}}$	Ne gas	15870		96.4	−0.91	−0.91	0.9998	1.07	[11]
$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$	92.2	$<30^{\text{j}}$	Mg metal	12484	55315	187.4	−1.7	−1.2	0.9976	1.25	[13]
$^{27}\text{Al}(p, \gamma)^{28}\text{Si}$	956	$70 \pm 14^{\text{k}}$	Al metal	11310	49044	19.6	−2.0	−1.3	0.9999		
$^{176}\text{Lu}(p, n)^{176}\text{Hf}$	805 ^g		Lu metal								[25]

Clustering in light nuclei



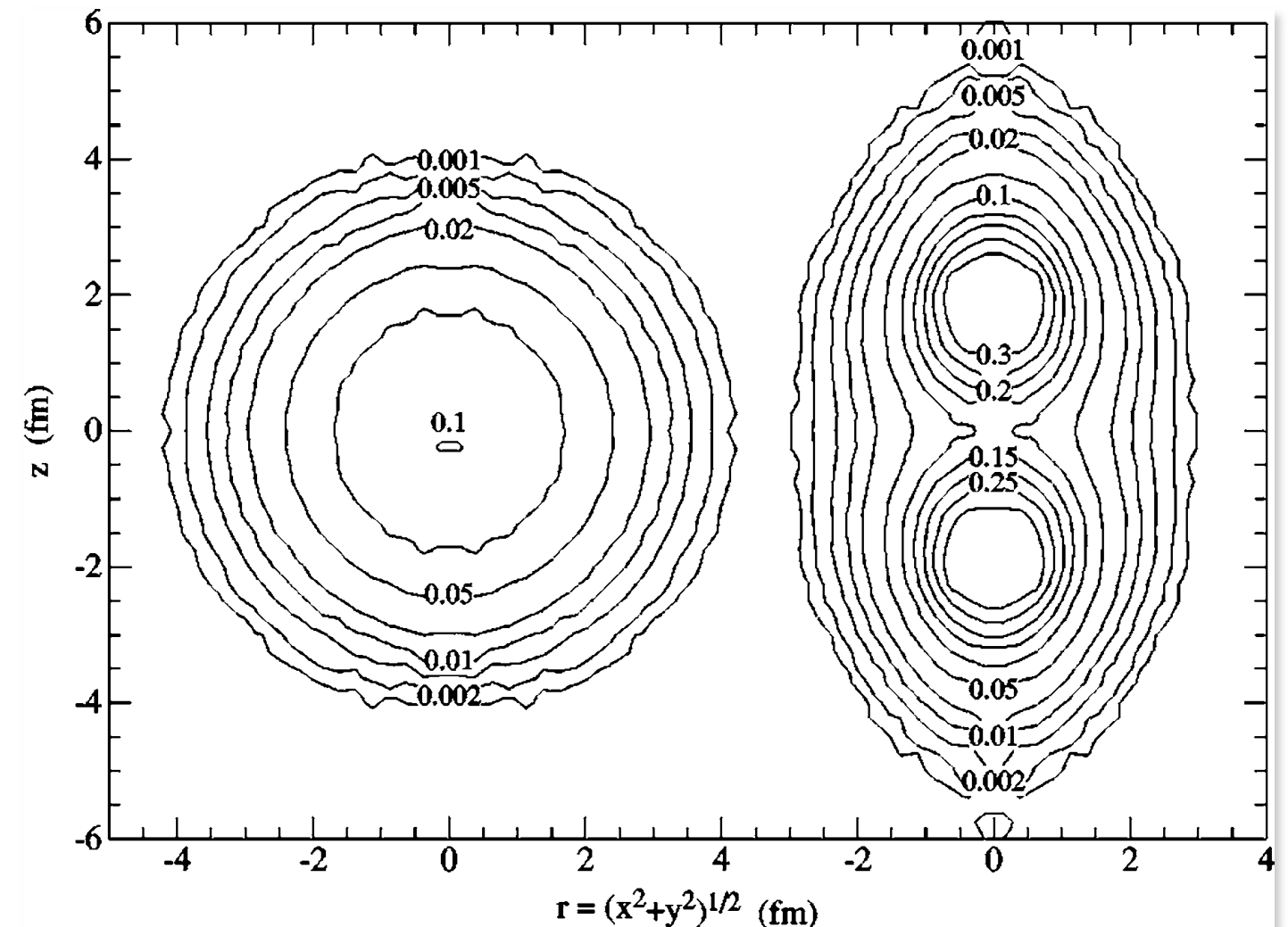
Ikeda diagram

Cluster degree of freedom as the excitation energy increases

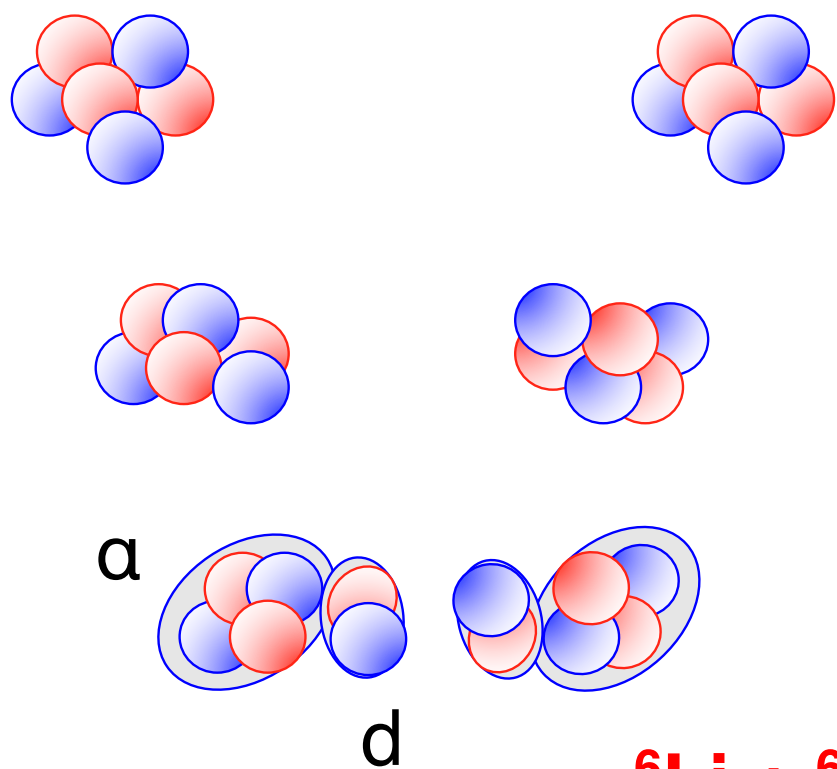
Density of ^8Be :

(a) laboratory, (b) intrinsic frame

Wiringa, Pieper, Carlson, Pandharipande,
PRC 62, 014001 (2000)



Clustering in nuclear reactions



${}^6\text{Li} + {}^6\text{Li}$ puzzle

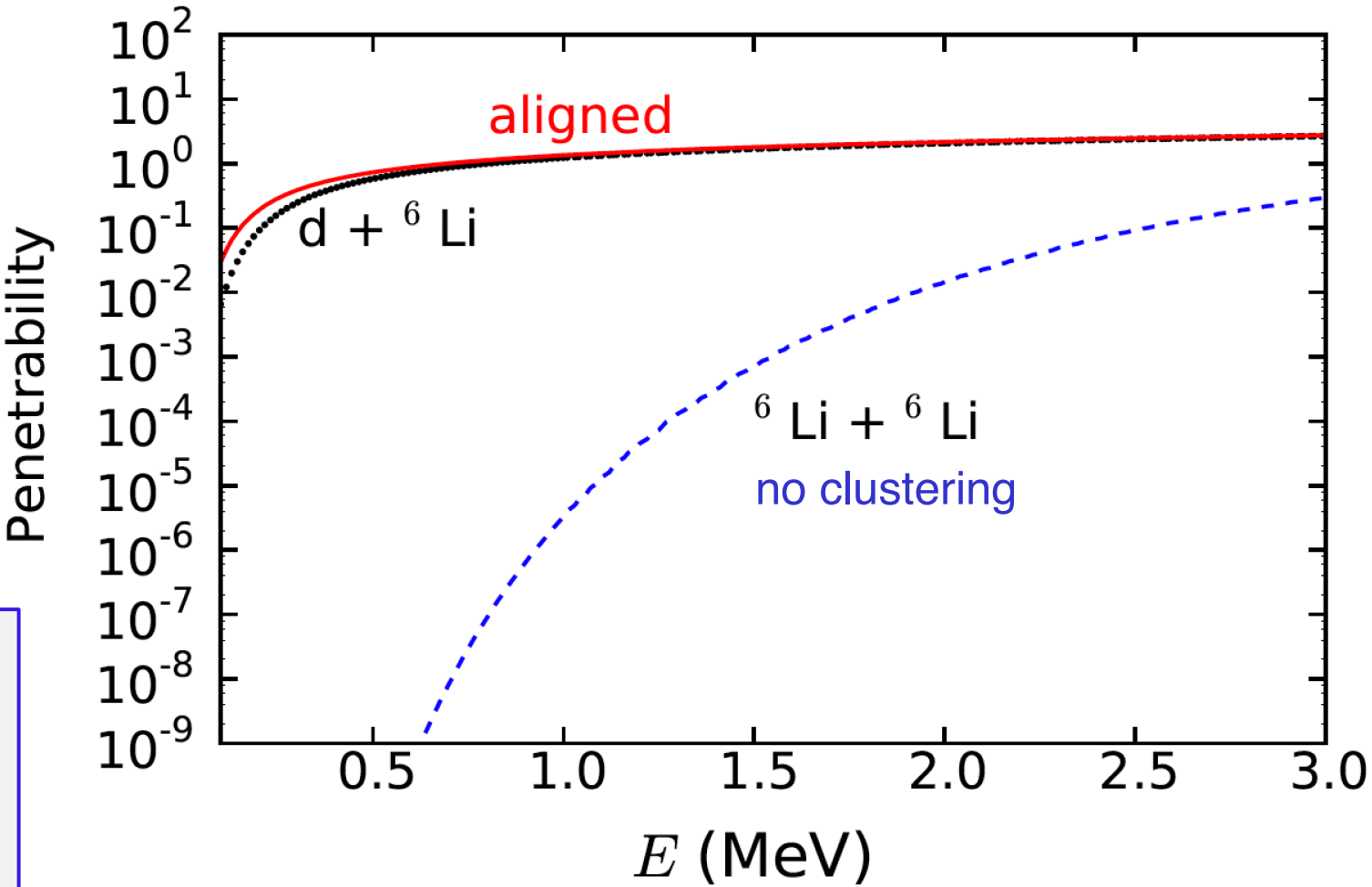
$$\sigma\left({}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha\right) \neq 0$$

Lattuada, et al.,
Z. Phys. A 330, 183 (1988)

$$\frac{P_{{}^6\text{Li}+{}^6\text{Li}}}{P_{\text{d}+{}^6\text{Li}}} \xrightarrow{k \rightarrow 0} 0$$

$$|\psi\rangle = \alpha|\psi_A\rangle + \beta|\psi_a\psi_B\rangle + \gamma|\psi_c\psi_D\rangle + \cdots$$

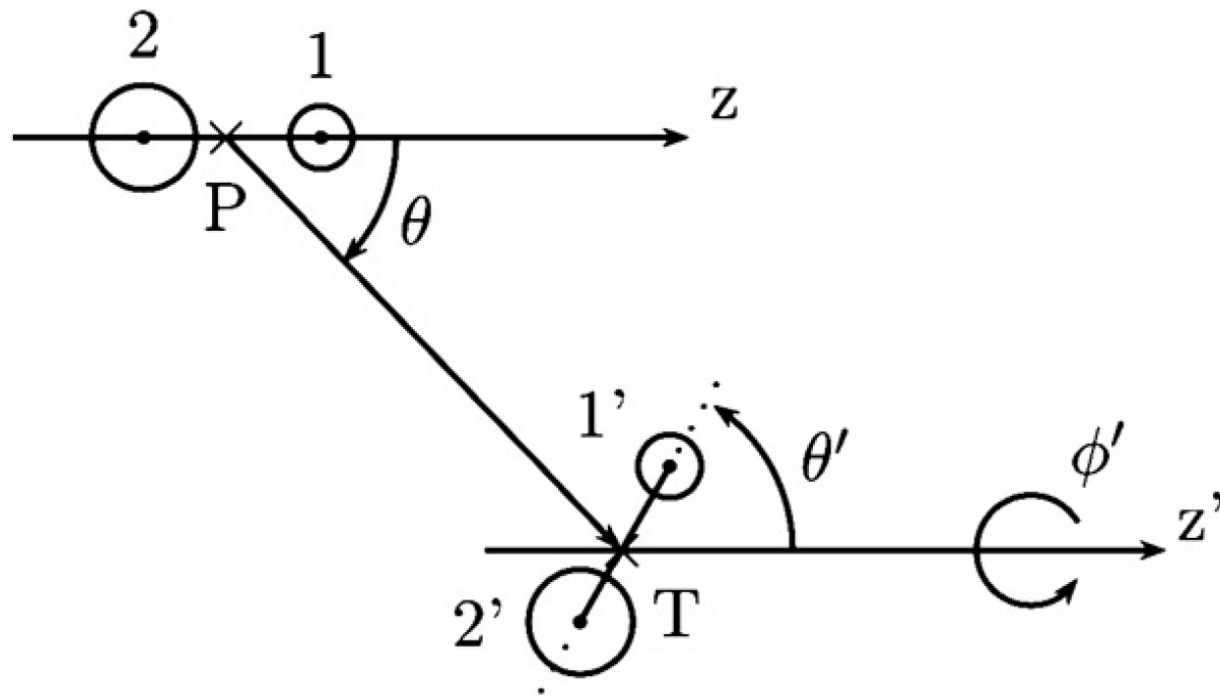
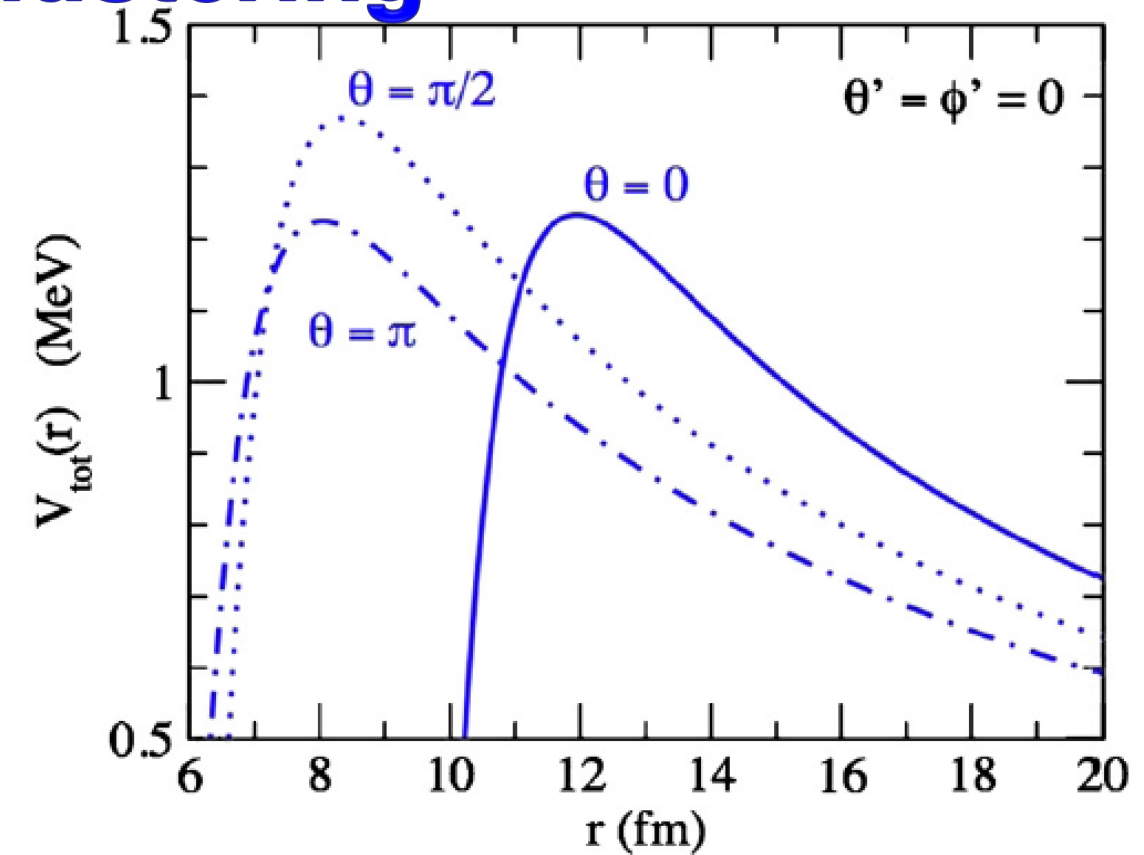
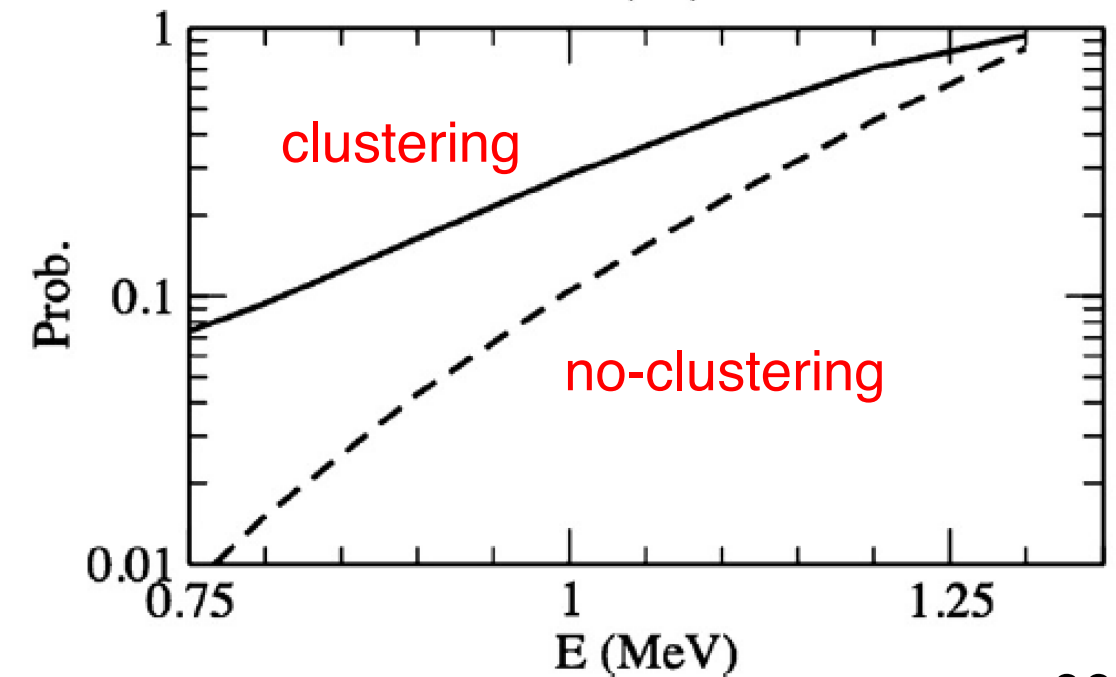
$$\sigma_L = C_{66}P_{{}^6\text{Li}+{}^6\text{Li}} + C_{26}P_{\text{d}+{}^6\text{Li}} + \cdots$$



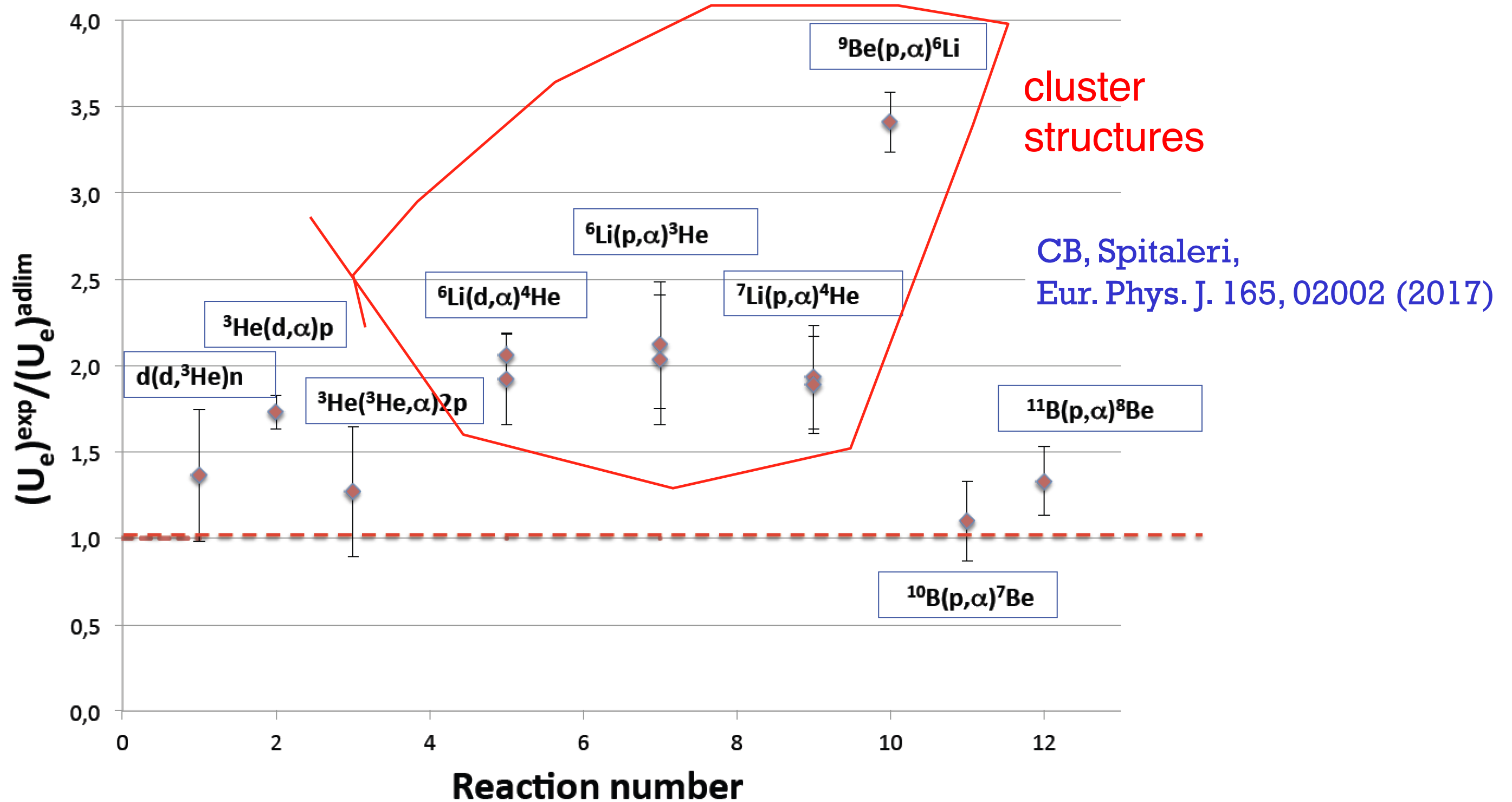
Electron screening puzzle & nuclear clustering

${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ experimentally much larger than penetrability estimates $\rightarrow$ suggests clustering + alignment

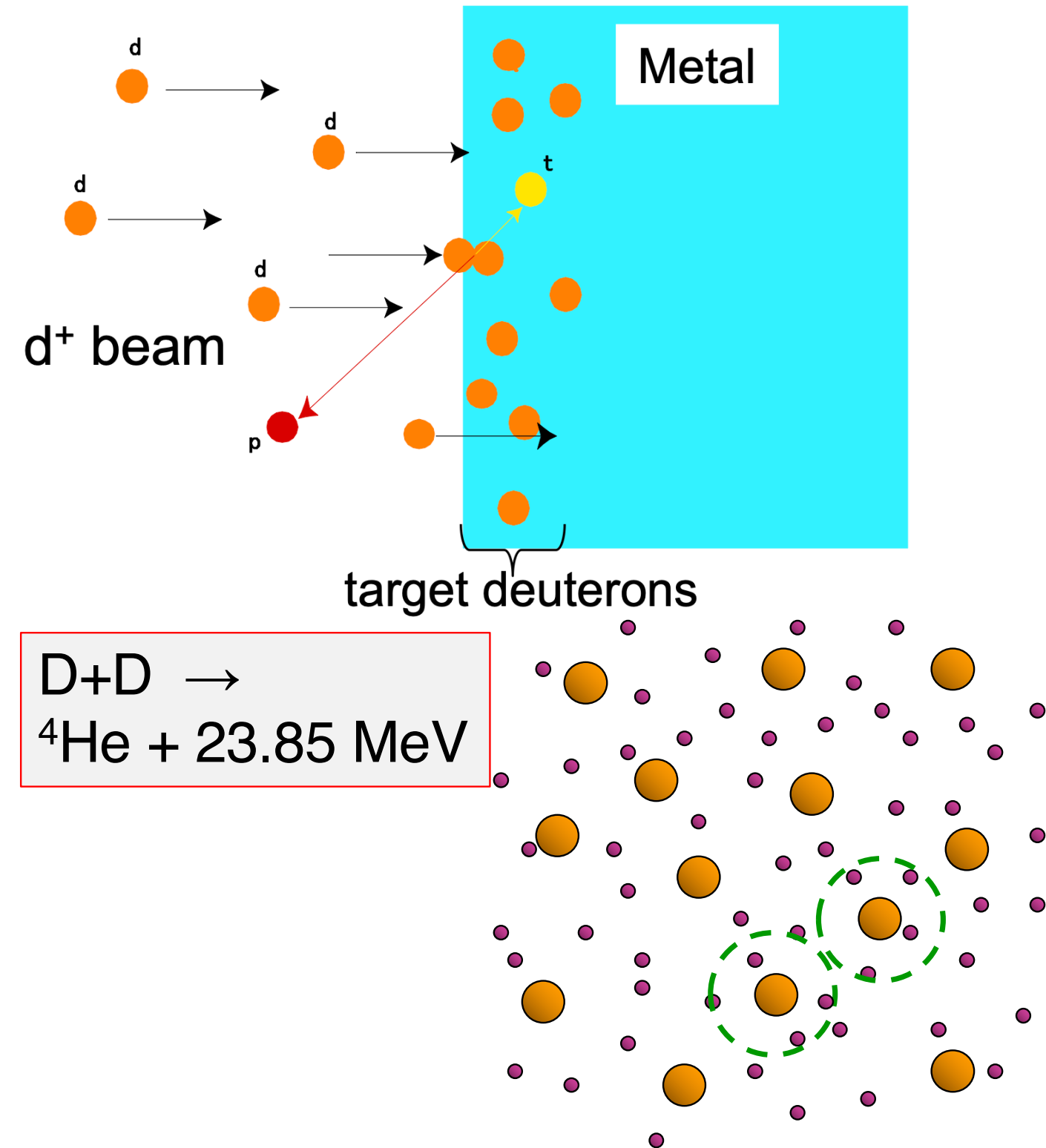
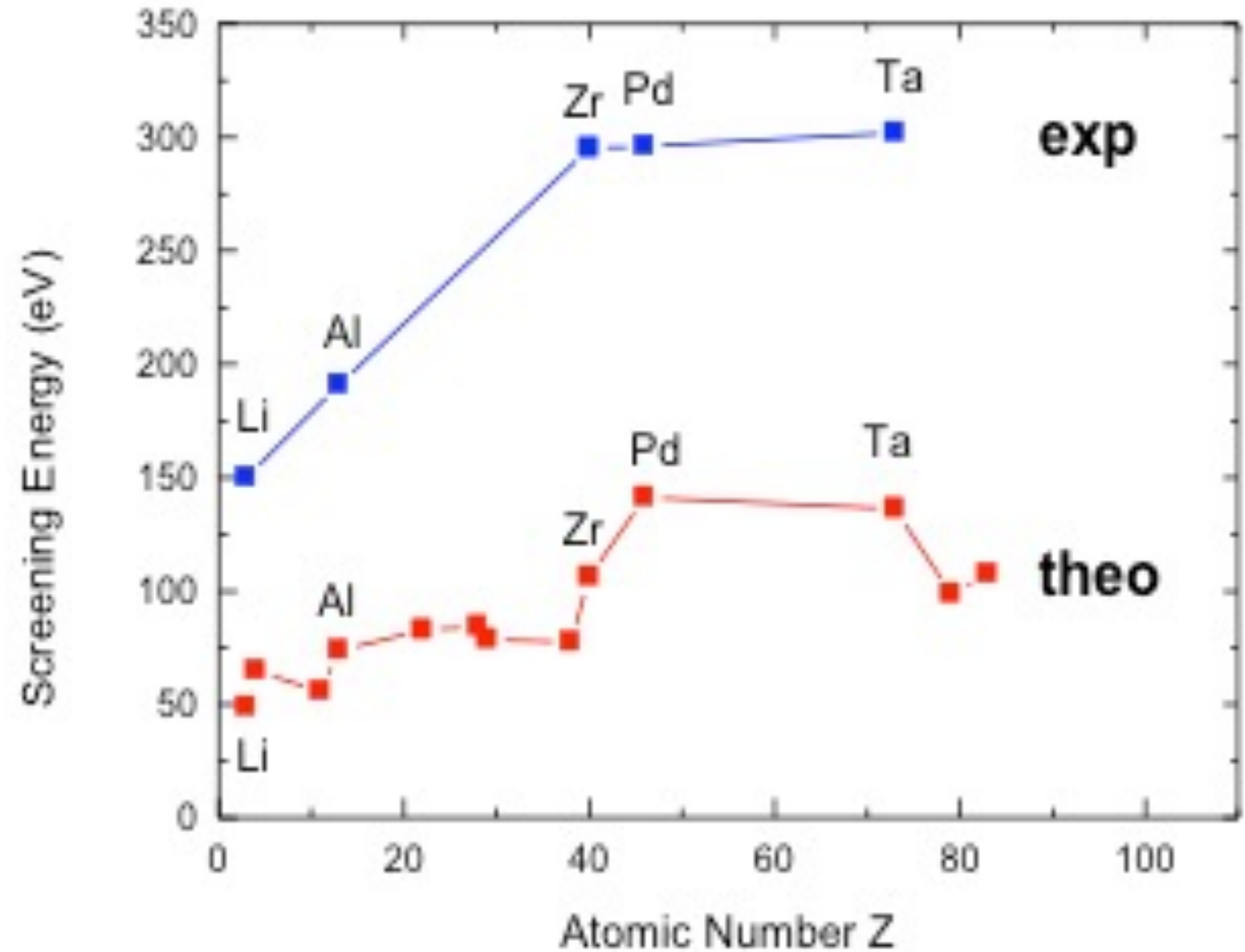
Spitaleri, CB, Fortunato, Vitturi
PLB 755 (2016) 275



Electron screening puzzle & nuclear clustering



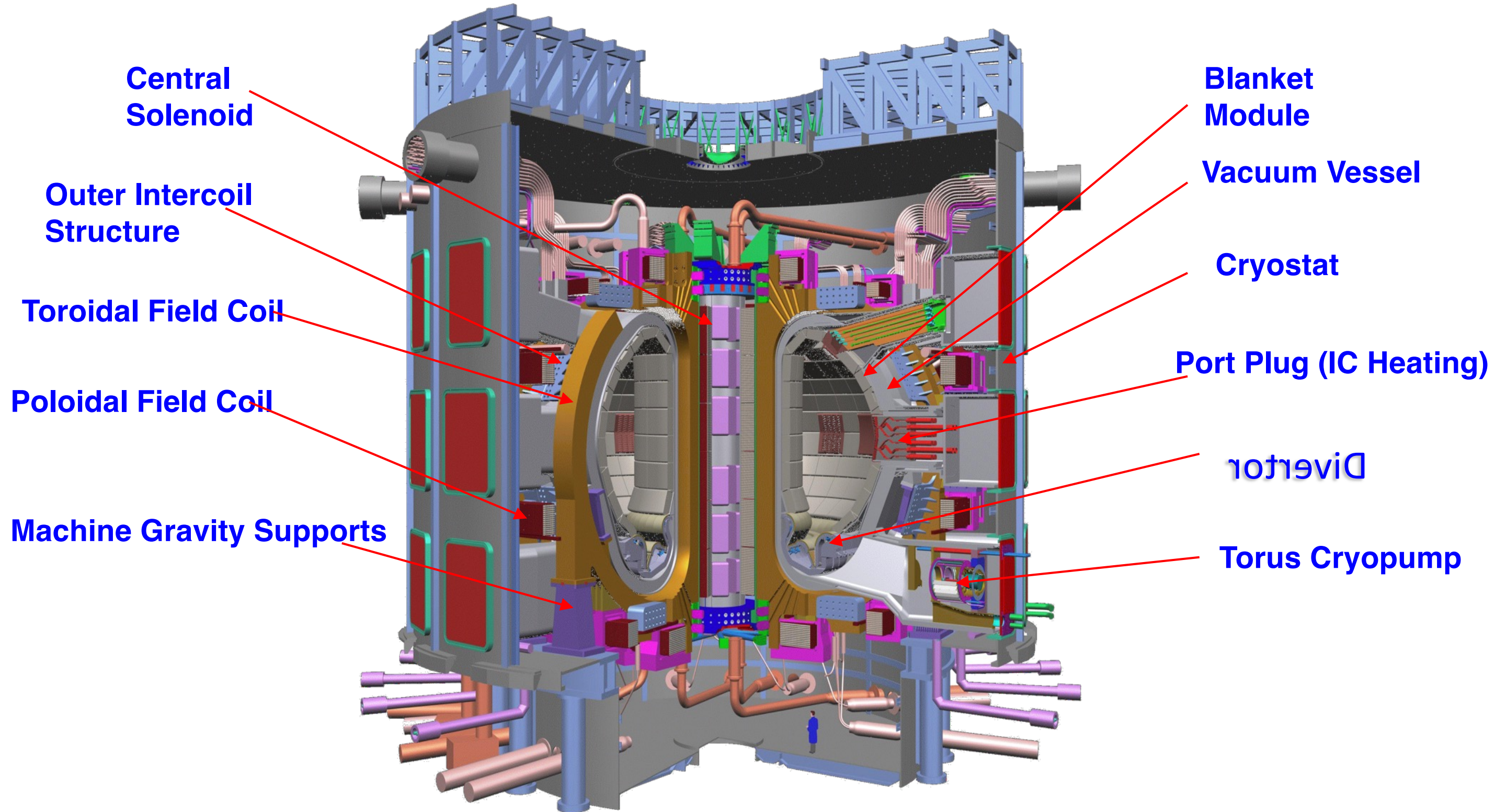
Enhanced electron screening in deuterated metals



Czerski, EPJ Web Conf. 154, 01024 (2017)

J. Kasagi, Surf. Coat. Tech. 201, 8574 (2007)

Future laboratory experiments: ITER nuclear fusion



ITER nuclear fusion



- Lots of money (> 20 billion EUROS, as of 2023)
- Need additional ITERs for nuclear science (maybe in 2050)

Courtesy: R. Boyd

**NIF concentrates all
the energy in a football
stadium-sized facility
into a mm³**

Matter
Temperature $>10^8$ K
Radiation
Temperature $>3.5 \times 10^6$ K
Densities $>10^3$ g/cm³
Pressures $>10^{11}$ atm



Screening in NIF

t = 0

Low-z Ablator for efficient absorption

2 mm

DT gas

Cryogenic Fuel for efficient compression

Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel

t = 15 ns

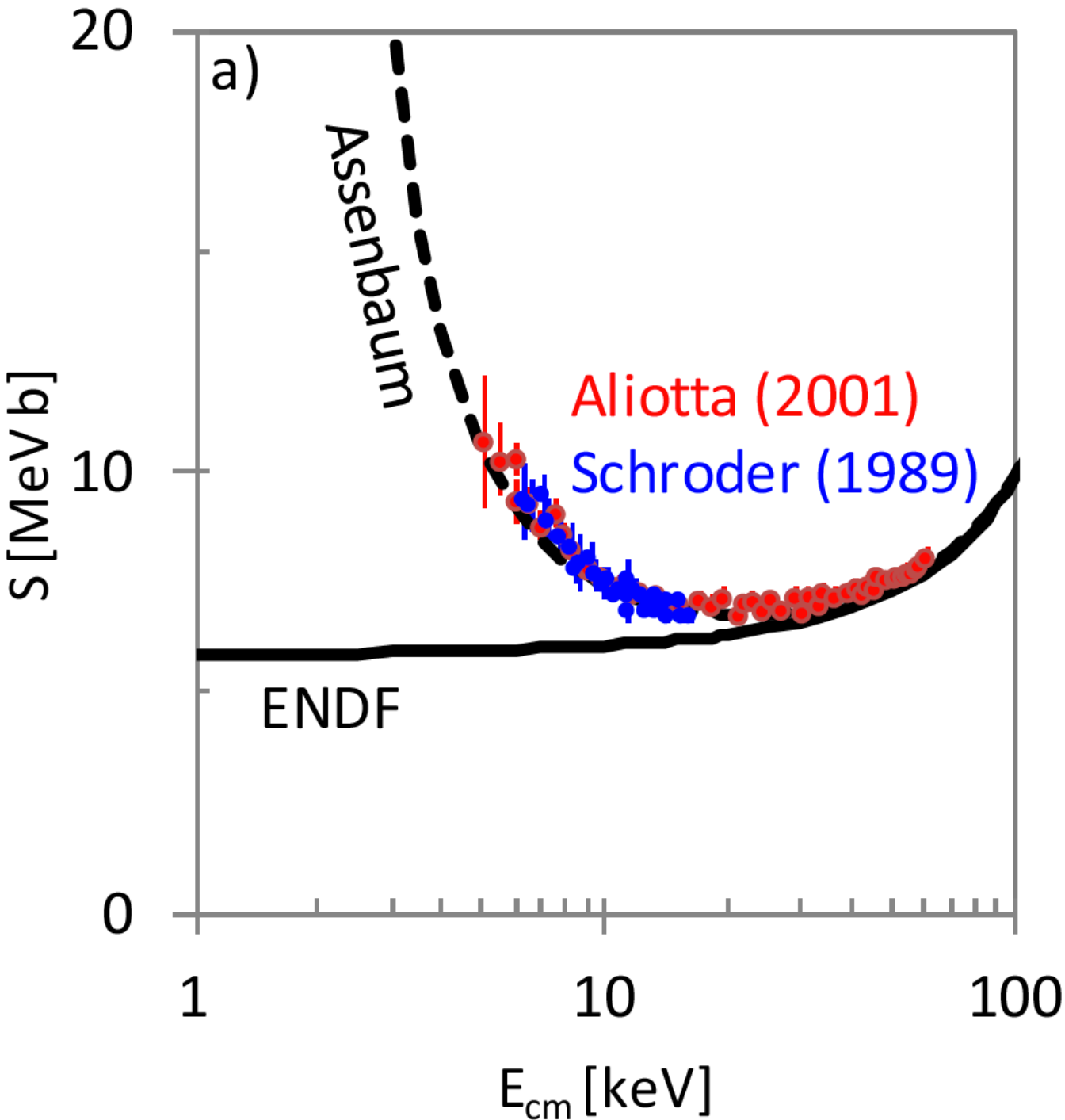
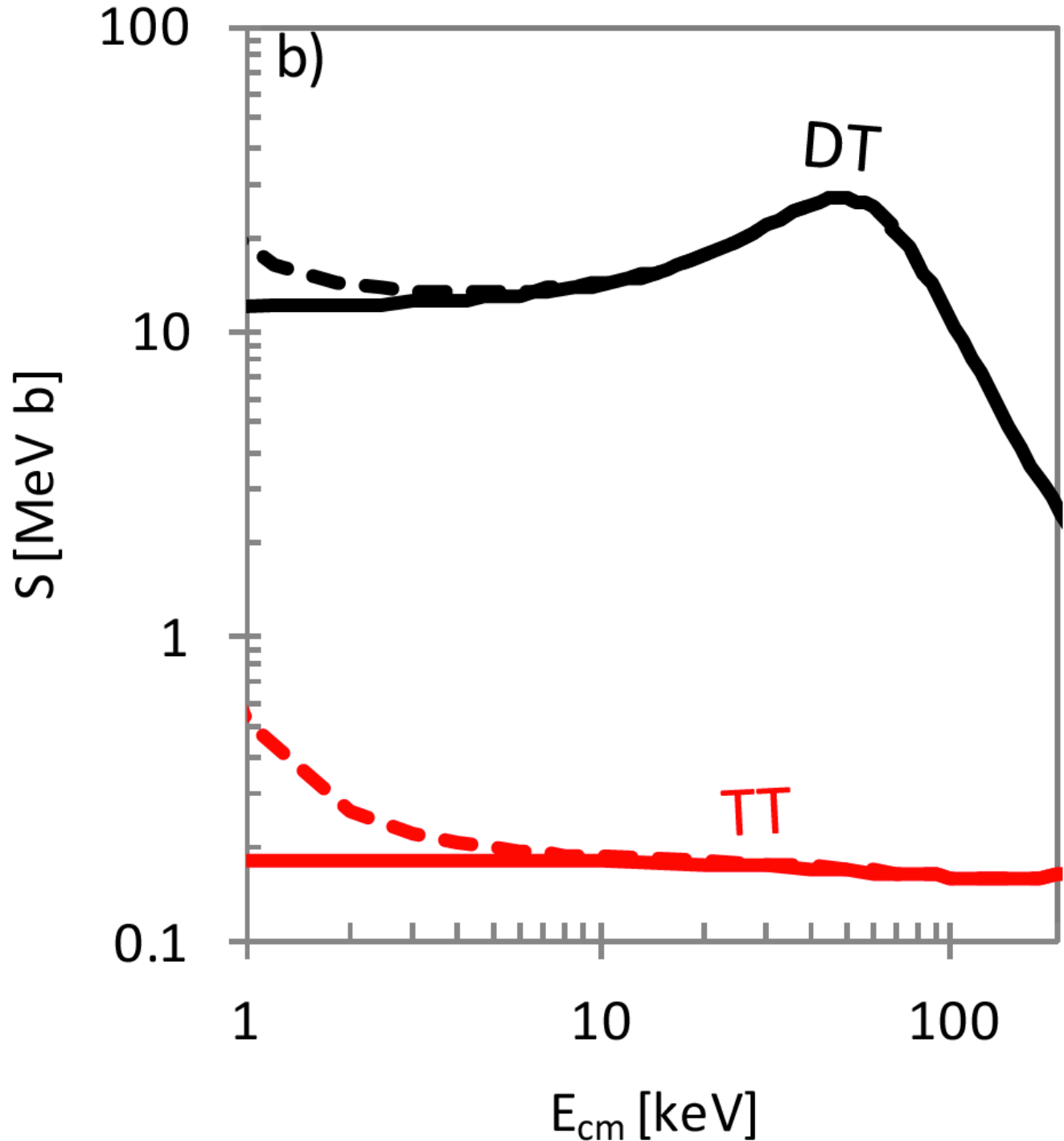
Cold, dense main Fuel (1000 g/cm³)

100 μm

Hot spot (10 keV)

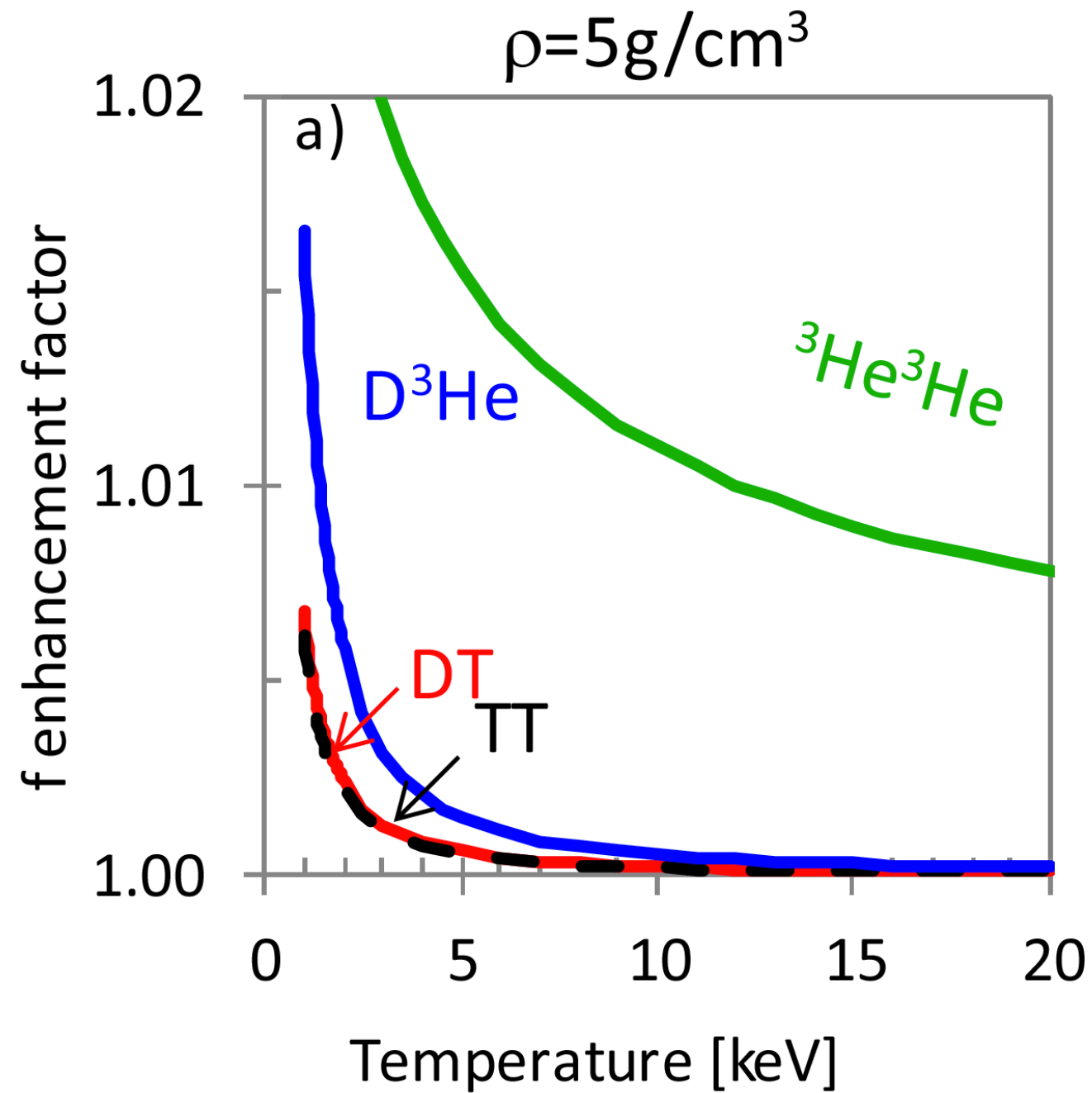
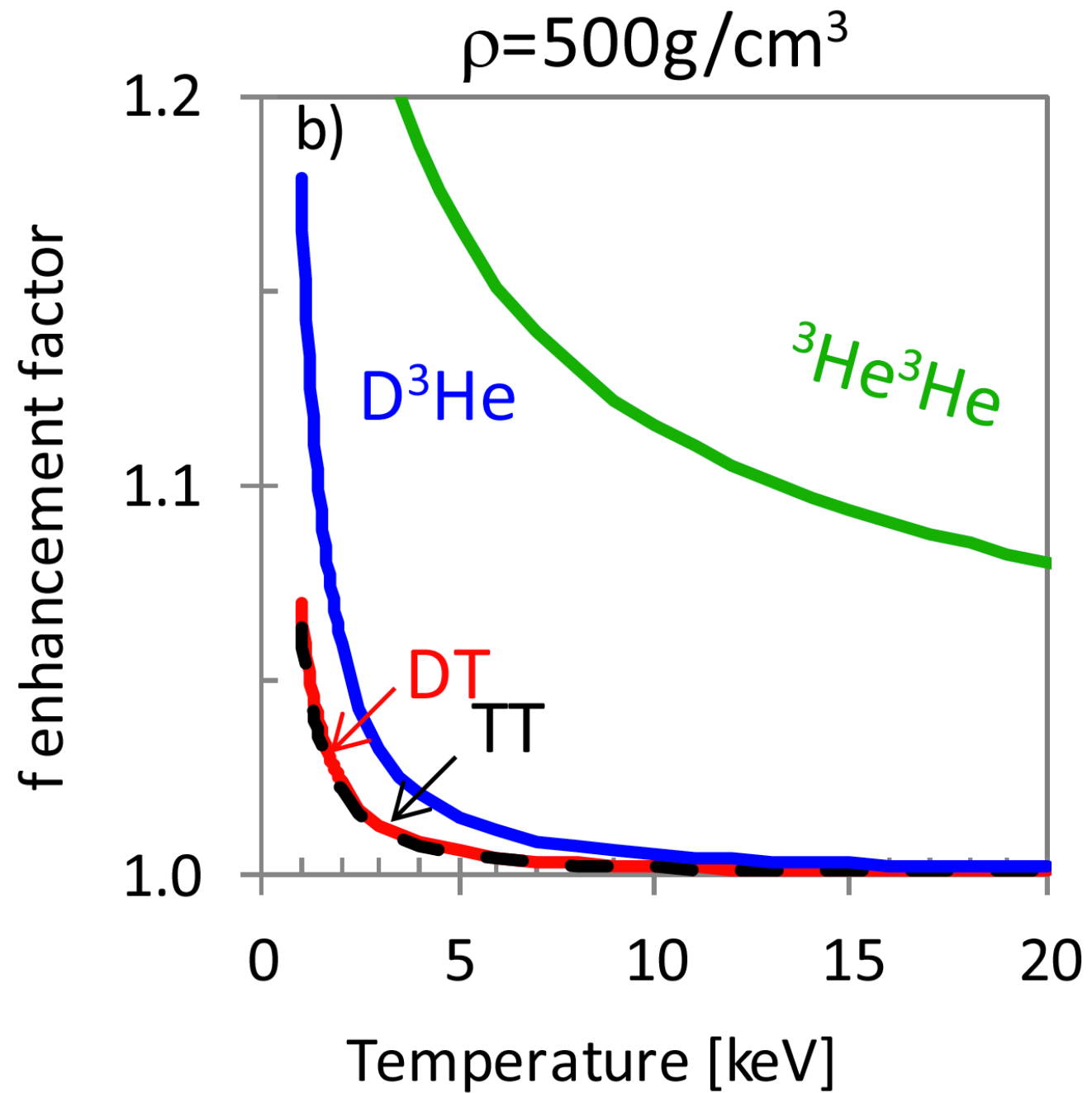
Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel

Possible screening studies in NIF

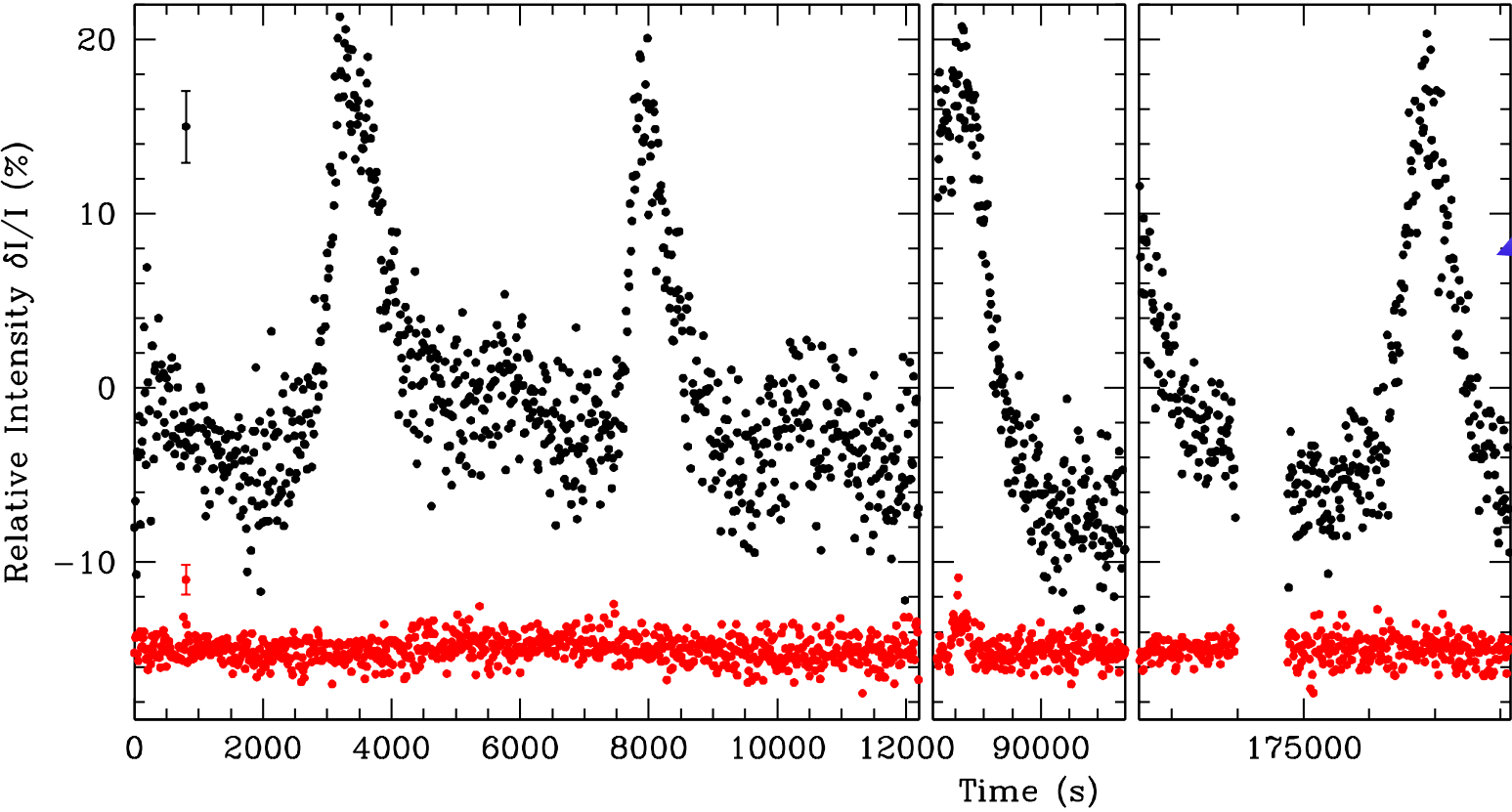


Possible screening studies in NIF

D. Casey et al.,
Front. Phys., 05 January 2023



Screening in Astronomy Observations

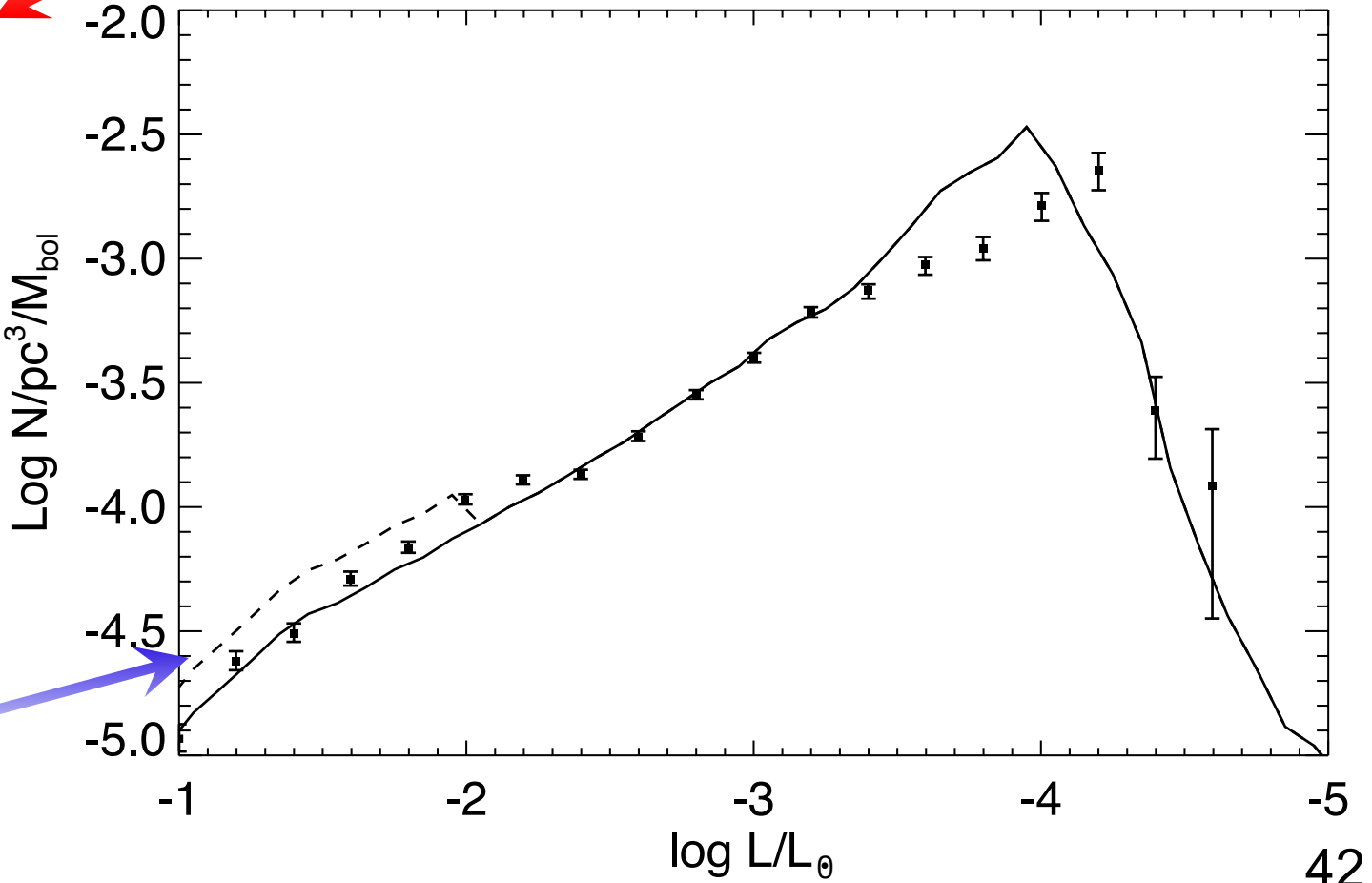


Extremely Low Mass (ELM)
white dwarfs
($M < 0.2 M_{\odot}$)
pulsators
($2000 \text{ s} < P < 5000 \text{ s}$)

Neighboring star

Hermes et al.,
MNRAS 436,, 3573 (2013)

WD luminosity function



Electron screening of nuclear reactions

- It should be simple. It is just atomic physics.
- Laboratory experiments can't be done at high ρ and/or T (not yet)
- Theory predicts enhancement covering a huge range of $1 - 10^{100}$, depending on ρ and T (yes, 10^{100} , my friends!)
- Weak screening easier to understand. But theories based on dynamic modifications and mean field approximations are not fully understood
- Some laboratory screening experimental data disagree with basic principles in atomic physics
- More help on these problems will be highly appreciated