

# VASP - Best Practices Workshop

Weine Olovsson

National Supercomputer Centre (NSC), Linköping University

NAISS-ENCCS training, online 17-18<sup>th</sup> Apr 2024

# VASP - Best Practices Workshop



**NAISS**



<https://www.nsc.liu.se/>

<https://www.naiss.se/>

<https://encacs.se/>

# National Supercomputer Centre (NSC)

NSC is part of:

- **NAISS** National Academic Infrastructure for Supercomputing in Sweden
- **li.u** LINKÖPING UNIVERSITY liu.se

NSC partners: SAAB, SMHI, MET Norway



**SMHI**



# NSC academic clusters

**Tetralith** (2018 - ) 1908 x 2 x 16 cores, Intel Xeon Gold 6130

**NAISS**

Top500 no. 282 (74)

**Sigma** (2018 - ) 110 x 2 x 16 cores, Intel Xeon Gold 6130



**BerzeLiUs** (2021 - ) Nvidia DGX SuperPOD, 60 x 8 A100 GPUs

- increased with 34 nodes in 2023



*Knut and Alice  
Wallenberg  
Foundation*

Top500 no. 151 & 178 (82)

# About myself

- PhD in Physics 2005 @Uppsala Univ.
- PostDoc @Kyoto Univ. 4y, @Leoben Univ. 1y
- **Application Expert @NSC**, 2011 (50%), 2016 (90%)
- 10% theoretical spectroscopy @IFM, LiU
- Electronic structure calculations
- @NSC: VASP, QE, WIEN2k, GPAW, ...





# Information / Schedule

[https://www.nsc.liu.se/support/Events/VASP\\_workshop\\_2024/](https://www.nsc.liu.se/support/Events/VASP_workshop_2024/)

<https://enccs.se/events/vasp-best-practices-workshop/>

*Wednesday 17th April*

**10:00 -11:00** Introduction & Basic Theory

**11:00 -12:00** VASP - Basics

**12:00 -13:00** L u n c h

**13:00 -15:00** Hands-on session (guided)

**15:00 -17:00** Hands-on session

*Thursday 18th April*

**10:00 -11:00** Running & Performance

**11:00 -12:00** Cont., Utilities & Summary

**12:00 -13:00** L u n c h

**13:00 -15:00** Hands-on session (guided)

**15:00 -17:00** Hands-on session

10-15 min breaks every hour

# Workshop organization

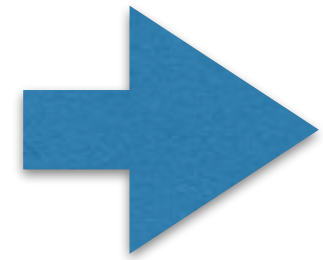
- Weine Olovsson (NSC) - organizer & presentations
- Yonglei Wang (ENCSS) - organizer & helper
- Diana Iusan (UPPMAX) - helper
- Pavlin Mitev (UPPMAX) - helper
- Wei Li (ENCSS) - helper
- Qiang Li (ENCSS) - helper
- Luis Casillas Trujillo (NSC) - helper

# VASP - Best Practices Workshop

- Basic theory (PAW)
- General considerations ...at specific supercomputer centres
- Focus on practical aspects of running VASP
- Influential parameters, NPAR/NCORE, ALGO, NSIM, KPAR, ...
- Benchmarks, examples
- Common problems ... clickable links are underlined



# Resources



- Wiki and Manual  
**Check in detail!**
- Examples, tutorials
- Presentations
- Forum



Find all the links:  
<https://vasp.at/>

- Also other resources, materials and tools for VASP (see presentation 4.)
- Peter Larsson's old blog at NSC: <https://www.nsc.liu.se/~pla/>
- NSC VASP installations: <https://www.nsc.liu.se/software/installed/tetralith/vasp/>

**Questions / trouble @NSC clusters? [support@nsc.liu.se](mailto:support@nsc.liu.se)**



# 1. Introduction & Basic Theory

Weine Olovsson

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# VASP - Best Practices Workshop



**NAISS**



<https://www.nsc.liu.se/>

<https://www.naiss.se/>

<https://encacs.se/>

# VASP: short background

- PAW-method
- DFT, **post-DFT** (HSE06, GW, ...)
- Born-Oppenheimer Molecular Dynamics
- **widely used** in Academia/Industry
  - Efforts from [Intel](#) & [Nvidia](#) for optimization
- 20-25% of Tetralith usage

... clickable links are [underlined](#)



<https://vasp.at/>



# Schrödinger Equation

Time-independent SE

$$H\Psi = E\Psi,$$

Born-Oppenheimer approx.  
= 0

$$H = T + T_n + V_{int} + V_{nn} + V_{ext} = -\frac{\hbar^2}{2m_e} \sum_i \nabla_i^2 - \boxed{\sum_I \frac{\hbar^2}{2M_I} \nabla_I^2} +$$
$$+ \sum_{i \neq j} \frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|} + \frac{1}{2} \sum_{I \neq J} \frac{Z_I Z_J \cdot e^2}{|\mathbf{R}_I - \mathbf{R}_J|} - \sum_{i,J} \frac{Z_J \cdot e^2}{|\mathbf{r}_i - \mathbf{R}_J|},$$

solid  $\sim 10^{23}$  particles...

# How to solve it?

“The general theory of quantum mechanics is now almost complete, ...”

“The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to **equations much too complicated to be soluble.**”

“It therefore becomes desirable that **approximate practical methods of applying quantum mechanics should be developed**, which can lead to an explanation of the main features of complex atomic systems without too much computation”

# Density Functional Theory (DFT)

Use electron probability density  $n(\mathbf{r})$  instead of  $\Psi \dots$

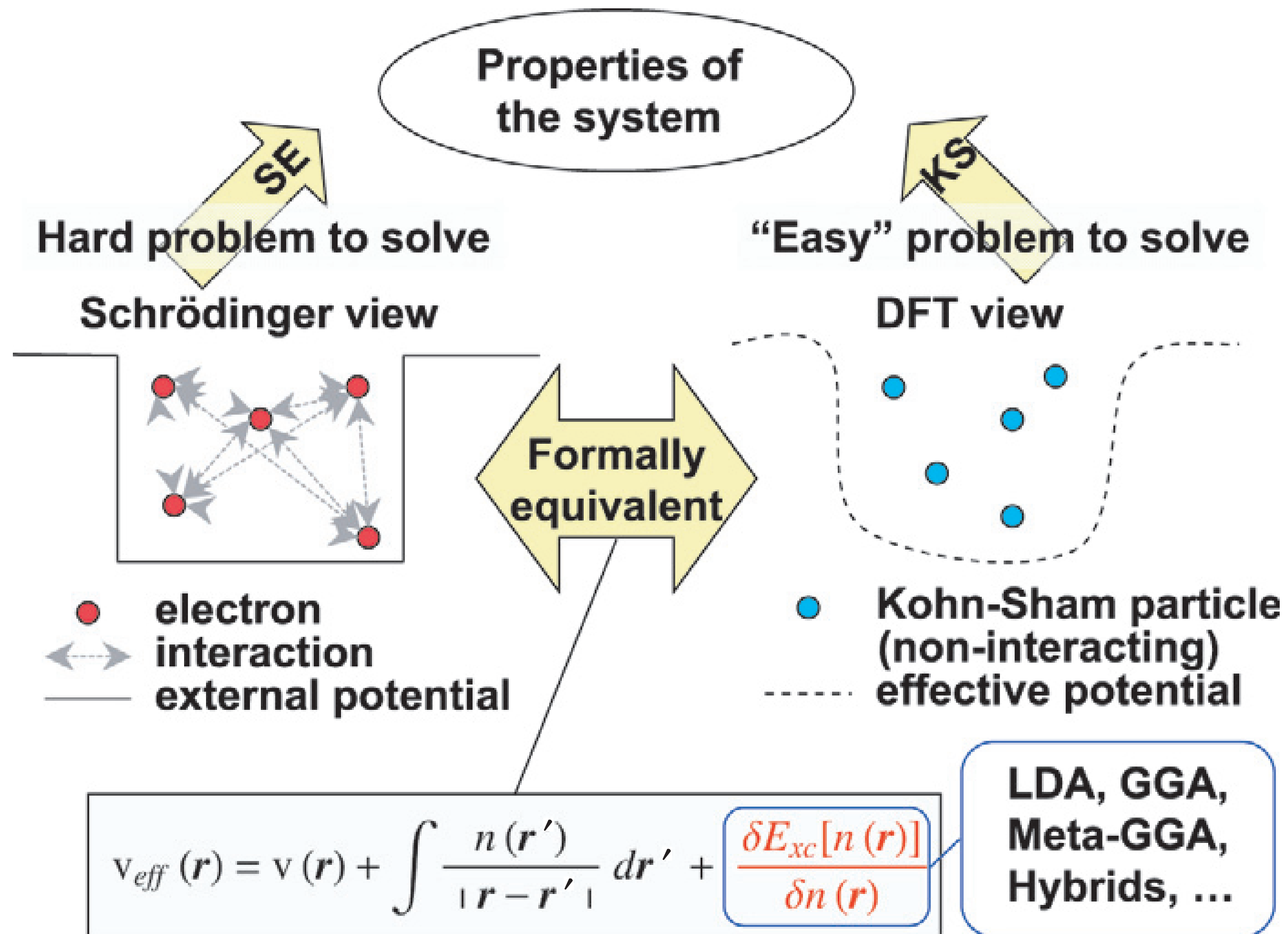
- (1) The potential  $V_{\text{ext}}$  of a system is determined uniquely, except for a constant by the ground state density  $n(\mathbf{r})$
- (2) The total energy functional  $E[n]$ , for a given  $V_{\text{ext}}$ , assumes its minimal value for the correct electron density  $n(\mathbf{r})$  of the ground state

**Ansatz:** 
$$E_{KS}[n] = \int d^3r V_{\text{ext}}(\mathbf{r})n(\mathbf{r}) + T_s[n] + E_{xc}[n] + \iint d^3r d^3r' \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|},$$

for *independent* electrons (mean field theory)

Hohenberg & Kohn, PRL **136**, B864 (1964)

Kohn & Sham, PRL **140**, A1133 (1965)



# Exchange-Correlation Functional

All difficulties now included in the XC-functional, need to find an approximation...

$$E_{xc}^{LDA}[n] = \int dr^3 n(\mathbf{r}) \epsilon_{xc}(n(\mathbf{r})),$$

Local Density Approximation (LDA)  
homogeneous electron gas

$$E_{xc}^{GGA}[n] = \int d^3r n(\mathbf{r}) \epsilon_{xc}(n(\mathbf{r}), |\nabla n|),$$

Generalized Gradient Approximation (GGA)

**GGA:** PBE, AM05, PBEsol, ...

**meta-GGA:** SCAN, ...

**mixing with exact-X:** HSE06, ...

many choices, commonly used are e.g. PBE, HSE06, ...



# Using periodicity

- The Bloch theorem states that the one-electron wavefunctions obey the equation:

$$\psi_{n\mathbf{k}}(\mathbf{r} + \mathbf{R}) = \psi_{n\mathbf{k}}(\mathbf{r})e^{i\mathbf{k}\mathbf{R}}$$

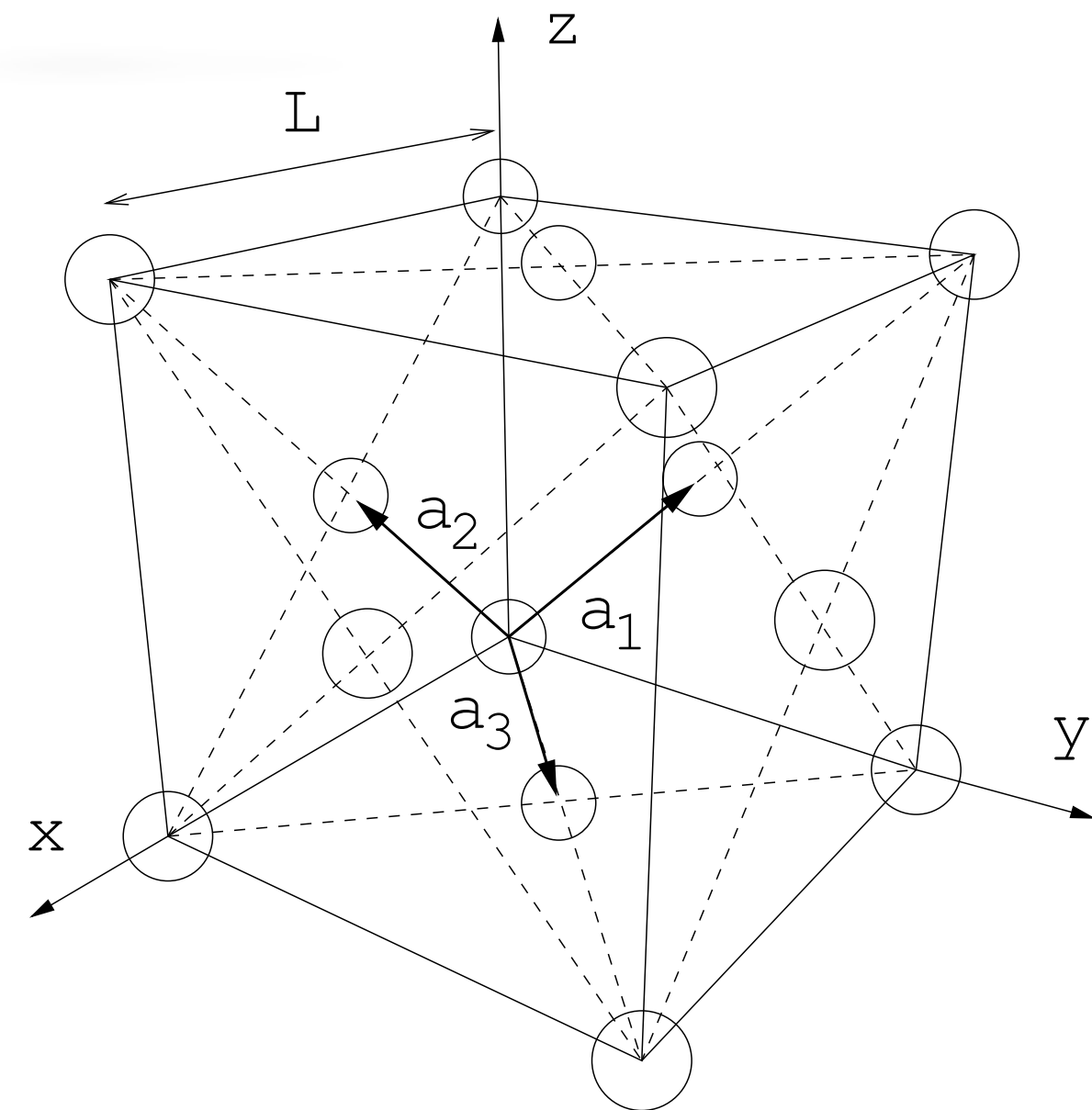
where  $\mathbf{R}$  is any translational vector leaving the Hamiltonian invariant.

- $\mathbf{k}$  is usually constrained to lie within the first Brillouin zone in reciprocal space.

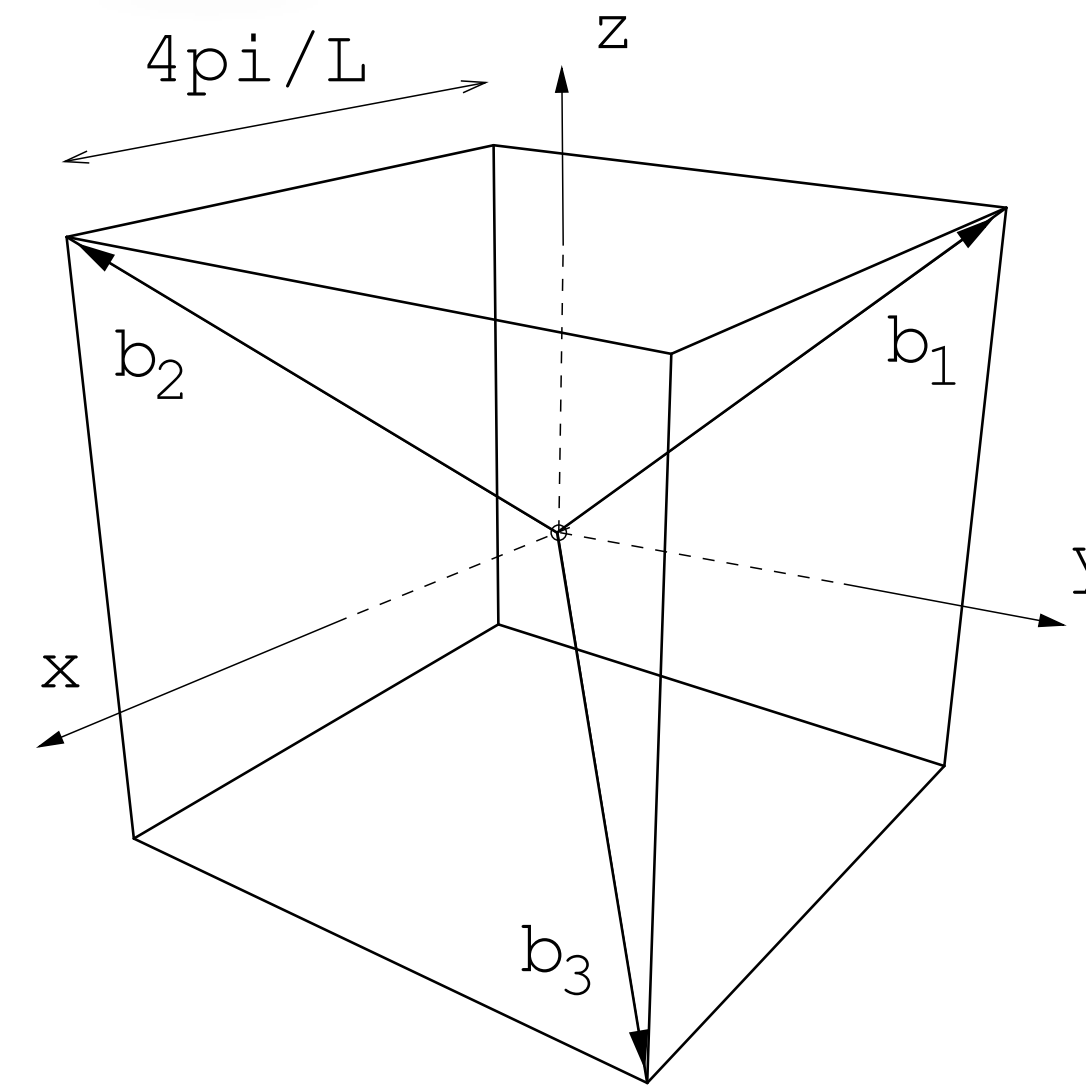


The intractable task of determining  $\Psi(\mathbf{r}_1, \dots, \mathbf{r}_N)$  (for  $N \sim 10^{23}$ ) has been reduced to calculating  $\psi_{n\mathbf{k}}(\mathbf{r})$  at a discrete set of points  $\{\mathbf{k}\}$  in the first BZ, for a number of bands that is of the order of the number of electrons *per unit cell*.

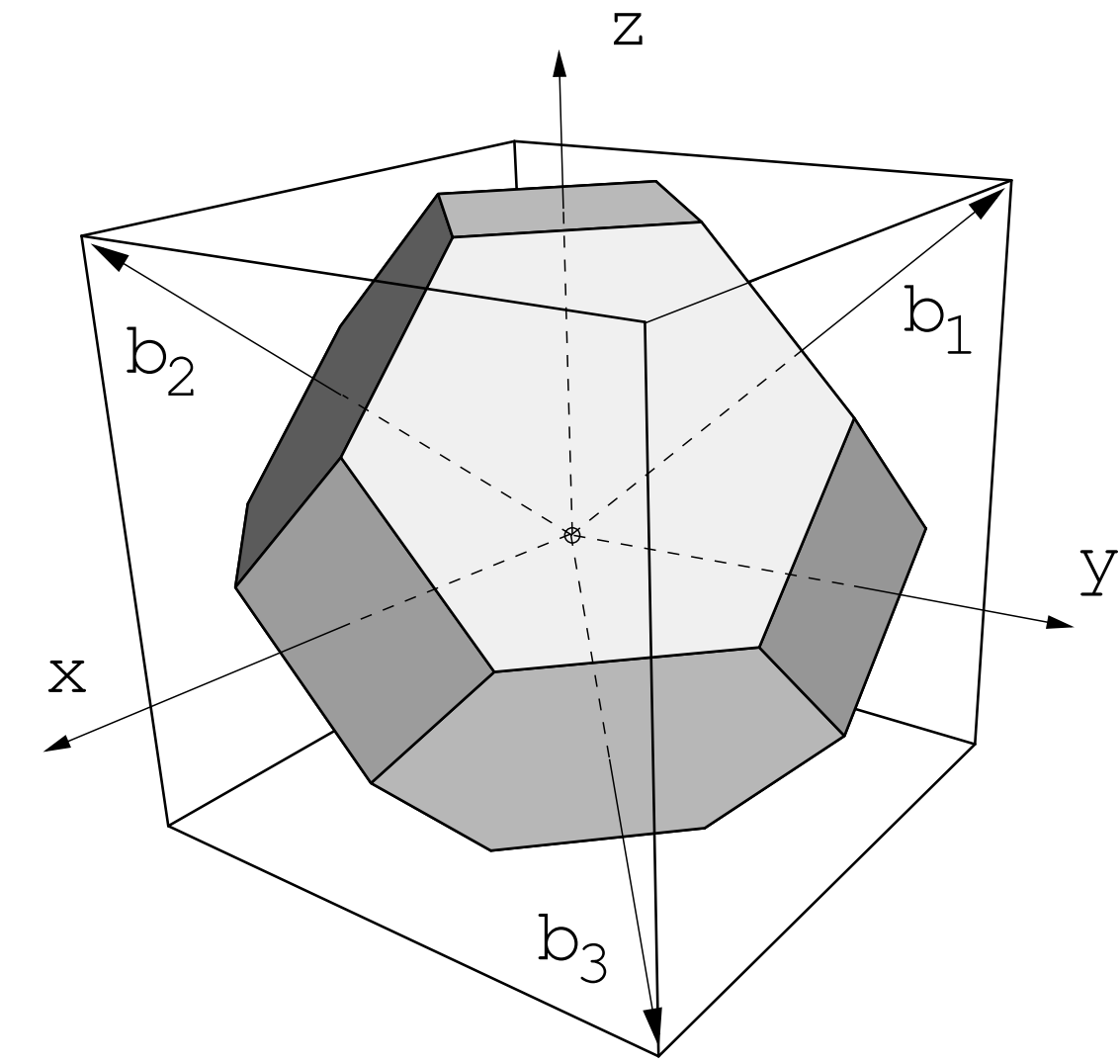
# Using periodicity



A



B

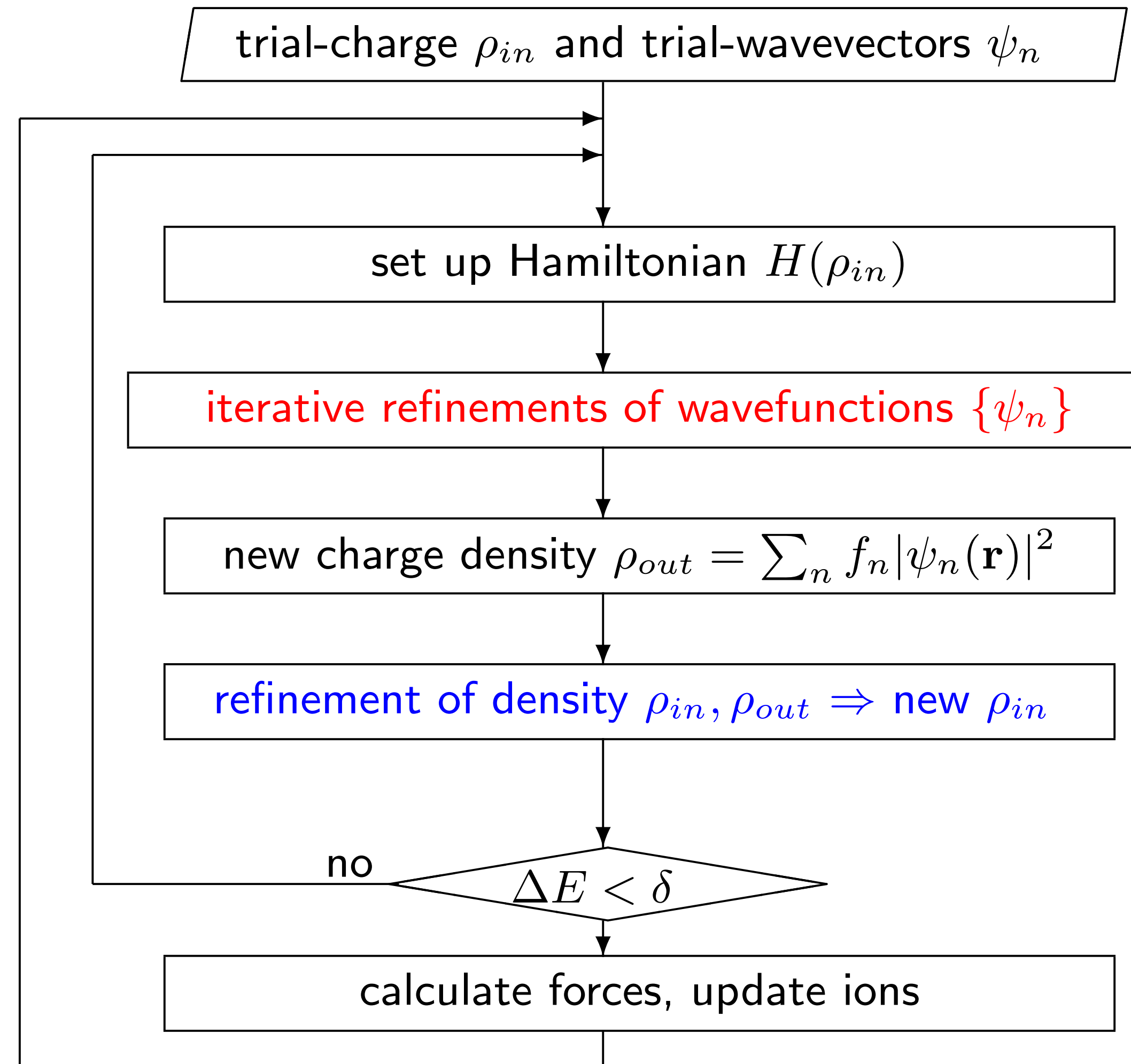


C

$$\mathbf{b}_1 = \frac{2\pi}{\Omega} \mathbf{a}_2 \times \mathbf{a}_3 \quad \mathbf{b}_2 = \frac{2\pi}{\Omega} \mathbf{a}_3 \times \mathbf{a}_1 \quad \mathbf{b}_3 = \frac{2\pi}{\Omega} \mathbf{a}_1 \times \mathbf{a}_2$$

$$\Omega = \mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3 \quad \mathbf{a}_i \cdot \mathbf{b}_j = 2\pi \delta_{ij}$$

# Self-consistent iterations



- two subproblems optimization of  $\{\psi_n\}$  and  $\rho_{in}$
- refinement of density: DIIS algorithm  
P. Pulay, Chem. Phys. Lett. 73, 393 (1980)
- refinement of wavefunctions: DIIS or Davidson algorithm

# Why PAW?

- **Goal:** both **accurate** (LAPW) and **fast** (e.g. USPP) method
- Want to *keep* all-electron (AE) wave function
- Focus on *valence electrons* (frozen core) - chemical bonding
- Fast calculation in *reciprocal space* using FFT (plane waves)
- **Solution:** Projector Augmented Wave (PAW) method

# Plane waves & Augmentation

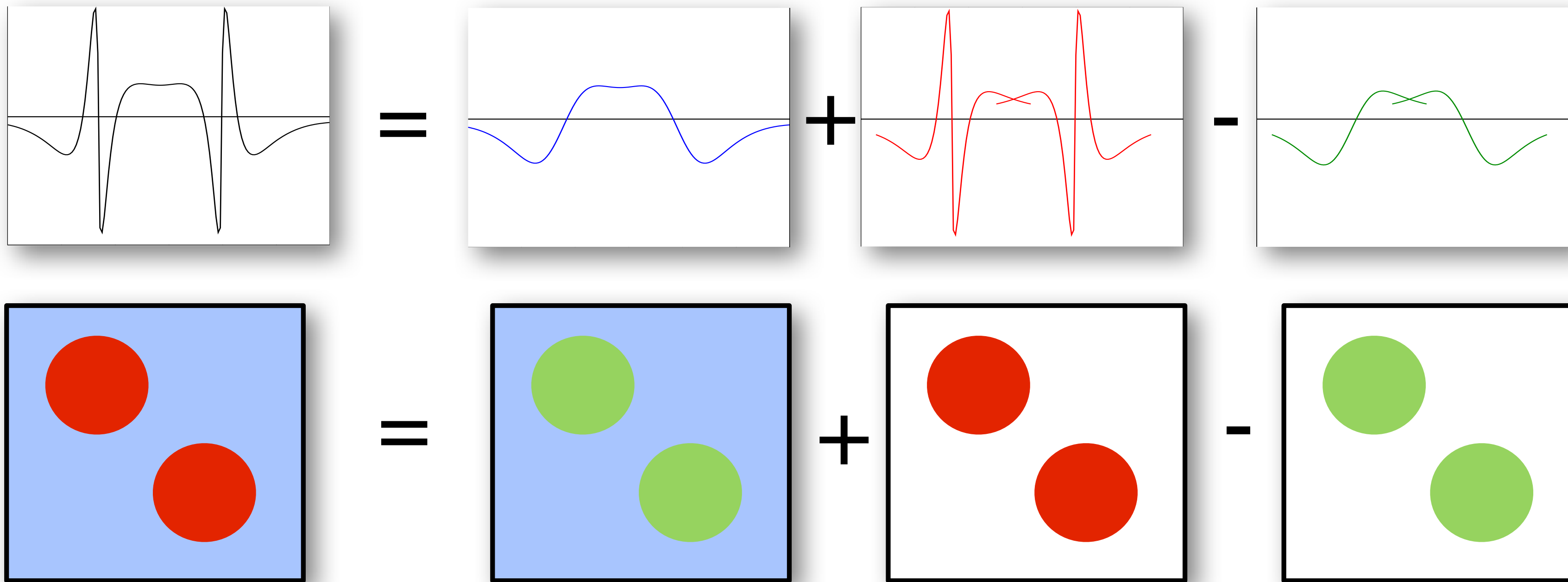
- Rapid wave oscillations close to nucleus  
need too many plane waves!
- Strongly localised states at atoms  
therefore ->
- Split into *interstitial* and *augmentation* (sphere) regions  
smooth pw
- No overlap between spheres (one-centre expansion)
- PAW: Energy and potential *independent* wave functions



# PAW Augmentation

$$\underbrace{|\psi\rangle}_{\text{all-electron}} = \underbrace{|\tilde{\psi}\rangle}_{\text{pseudo}} + \underbrace{|\psi^1\rangle}_{\text{1-center, all-el.}} - \underbrace{|\tilde{\psi}^1\rangle}_{\text{1-center, pseudo}}$$

$\sum_{\alpha} |\phi_{\alpha}\rangle \langle \tilde{p}_{\alpha} | \tilde{\psi}\rangle$        $\sum_{\alpha} |\tilde{\phi}_{\alpha}\rangle \langle \tilde{p}_{\alpha} | \tilde{\psi}\rangle$



# Transformation theory

True AE wave function and *auxiliary* PS wf related via **transformation operator**:

$$|\Psi_n\rangle = \mathcal{T}|\tilde{\Psi}_n\rangle$$

Kohn-Sham equation:

$$H|\Psi_n\rangle = |\Psi_n\rangle\epsilon_n$$

Can write Schrödinger-like equation:

$$\mathcal{T}^\dagger H \mathcal{T}|\tilde{\Psi}_n\rangle = \mathcal{T}^\dagger \mathcal{T}|\tilde{\Psi}_n\rangle\epsilon_n$$

$$\langle A \rangle = \sum_n f_n \langle \Psi_n | A | \Psi_n \rangle = \sum_n f_n \langle \tilde{\Psi}_n | \mathcal{T}^\dagger A \mathcal{T} | \tilde{\Psi}_n \rangle$$

**Expectation values** can be evaluated for *true* AE or *auxiliary* PS waves

# Transformation operator

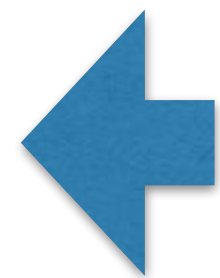
$$\mathcal{T} = 1 + \sum_R \mathcal{S}_R$$

TO unity in *interstitial*, outside *augmentation sphere*  $R$

$$\Psi(\mathbf{r}) = \sum_{i \in R} \phi_i(\mathbf{r}) c_i \quad \text{for} \quad |\mathbf{r} - \mathbf{R}_R| < r_{c,R}$$

Inside sphere  $R$ , describe by **AE partial waves**, undetermined coefficients  $c_i$

$$\begin{aligned} |\phi_i\rangle &= (1 + S_R) |\tilde{\phi}_i\rangle \quad \text{for} \quad i \in R \\ S_R |\tilde{\phi}_i\rangle &= |\phi_i\rangle - |\tilde{\phi}_i\rangle \end{aligned}$$



Relate AE partial wave with **PS partial wave**, through *local* transformation operator  $S$

$$\tilde{\Psi}(\mathbf{r}) = \sum_{i \in R} \tilde{\phi}_i(\mathbf{r}) \langle \tilde{p}_i | \tilde{\Psi} \rangle \quad \text{for} \quad |\mathbf{r} - \mathbf{R}_R| < r_{c,R} \quad \text{Expand PS wf in PS partial waves}$$

projector function

$$\langle \tilde{p}_i | \tilde{\phi}_j \rangle = \delta_{i,j} \quad \text{for} \quad i, j \in R \quad \text{requirement for above to hold}$$

# Transformation operator

$$S_R|\tilde{\Psi}\rangle = \sum_{i \in R} S_R|\tilde{\phi}_i\rangle\langle\tilde{p}_i|\tilde{\Psi}\rangle = \sum_{i \in R} \left( |\phi_i\rangle - |\tilde{\phi}_i\rangle \right) \langle\tilde{p}_i|\tilde{\Psi}\rangle \quad \text{From using the previous relations}$$

$$\mathcal{T} = 1 + \sum_i \left( |\phi_i\rangle - |\tilde{\phi}_i\rangle \right) \langle\tilde{p}_i| \quad \leftarrow \text{Final expression for the transformation operator}$$

$$|\Psi\rangle = |\tilde{\Psi}\rangle + \sum_i \left( |\phi_i\rangle - |\tilde{\phi}_i\rangle \right) \langle\tilde{p}_i|\tilde{\Psi}\rangle = |\tilde{\Psi}_n\rangle + \sum_R \left( |\Psi_R^1\rangle - |\tilde{\Psi}_R^1\rangle \right)$$

$$|\Psi_R^1\rangle = \sum_{i \in R} |\phi_i\rangle\langle\tilde{p}_i|\tilde{\Psi}\rangle$$

$$|\tilde{\Psi}_R^1\rangle = \sum_{i \in R} |\tilde{\phi}_i\rangle\langle\tilde{p}_i|\tilde{\Psi}\rangle$$

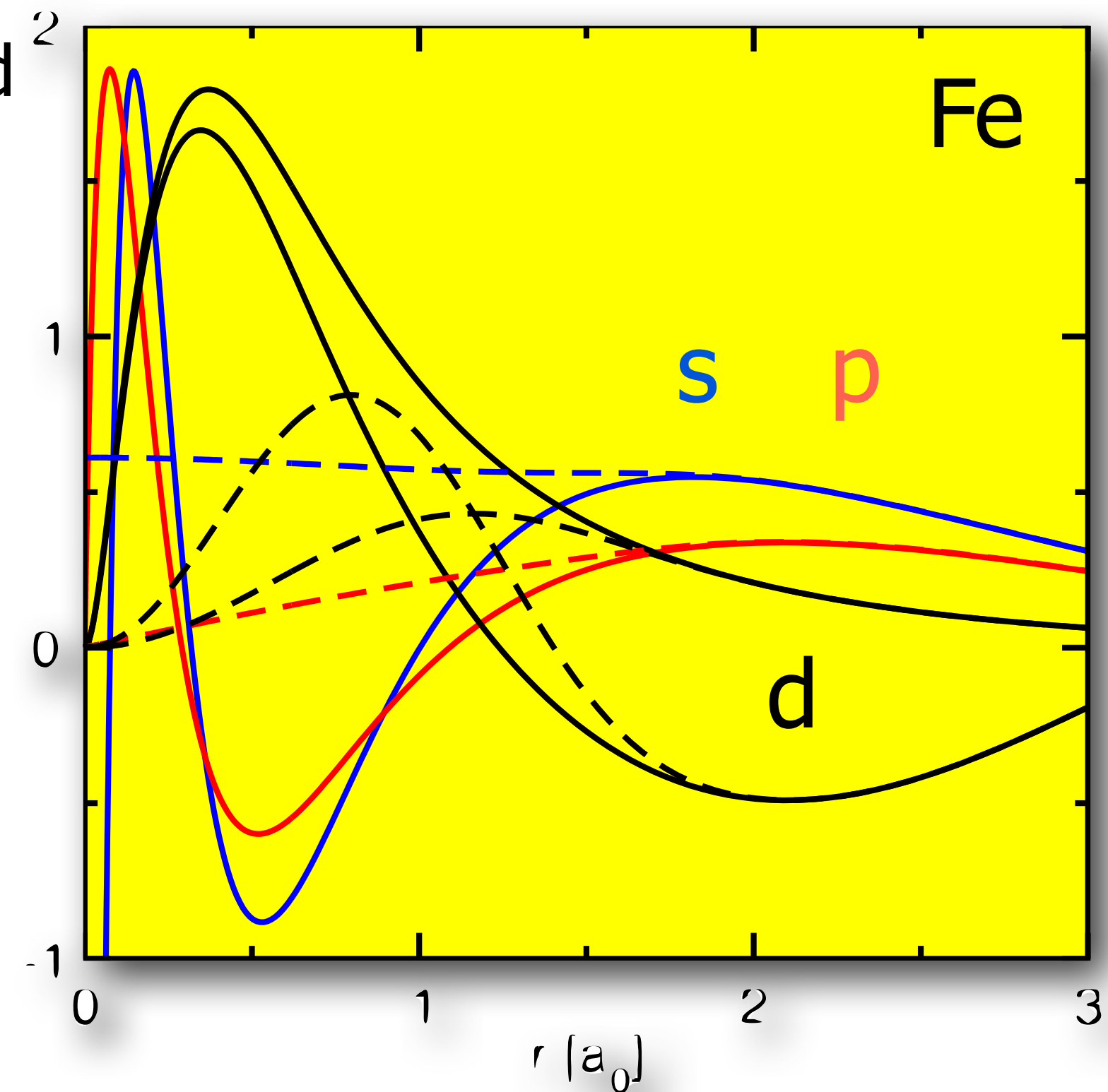
**Final expression for the *true* AE wf:**

- one PS wf expanded in plane waves

- two atom centred localised functions

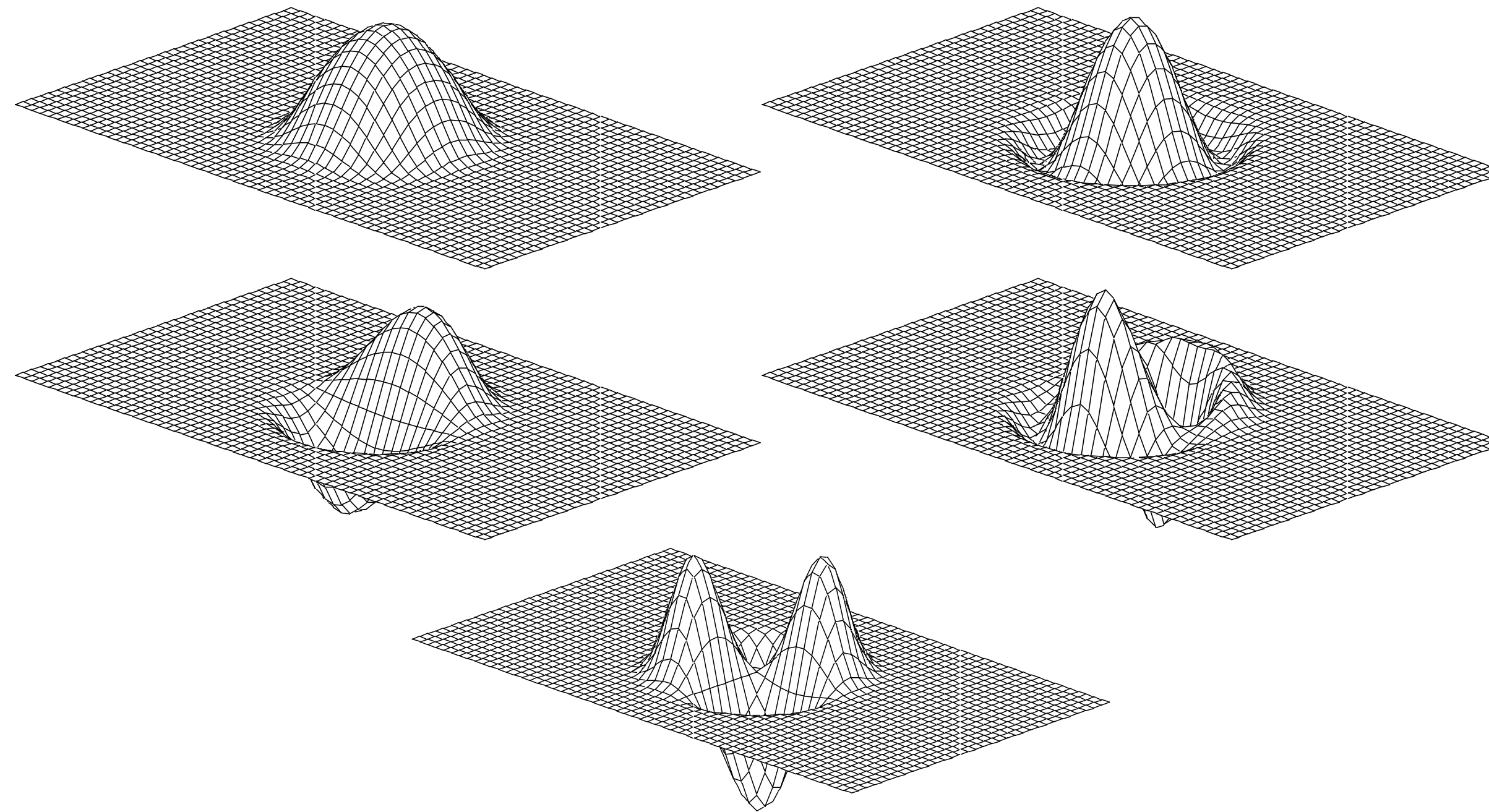
# Partial waves

- all-electron partial waves  $|\phi_\alpha\rangle$ 
  - integrate Schrödinger equation outward
  - have the correct nodal structure
- pseudo partial waves  $|\tilde{\phi}_\alpha\rangle$ 
  - smooth inside
  - identical to ae partial waves outside
  - $n-n_{\text{core}}$  nodes
  - usually constructed by adjusting an dependent potential





# Projector functions



- Localised
- Angular momentum of partial waves

Figure 1: Top: projector functions of the Cl atom for two s-type partial waves, middle: p-type, bottom: d-type.



# Wave functions

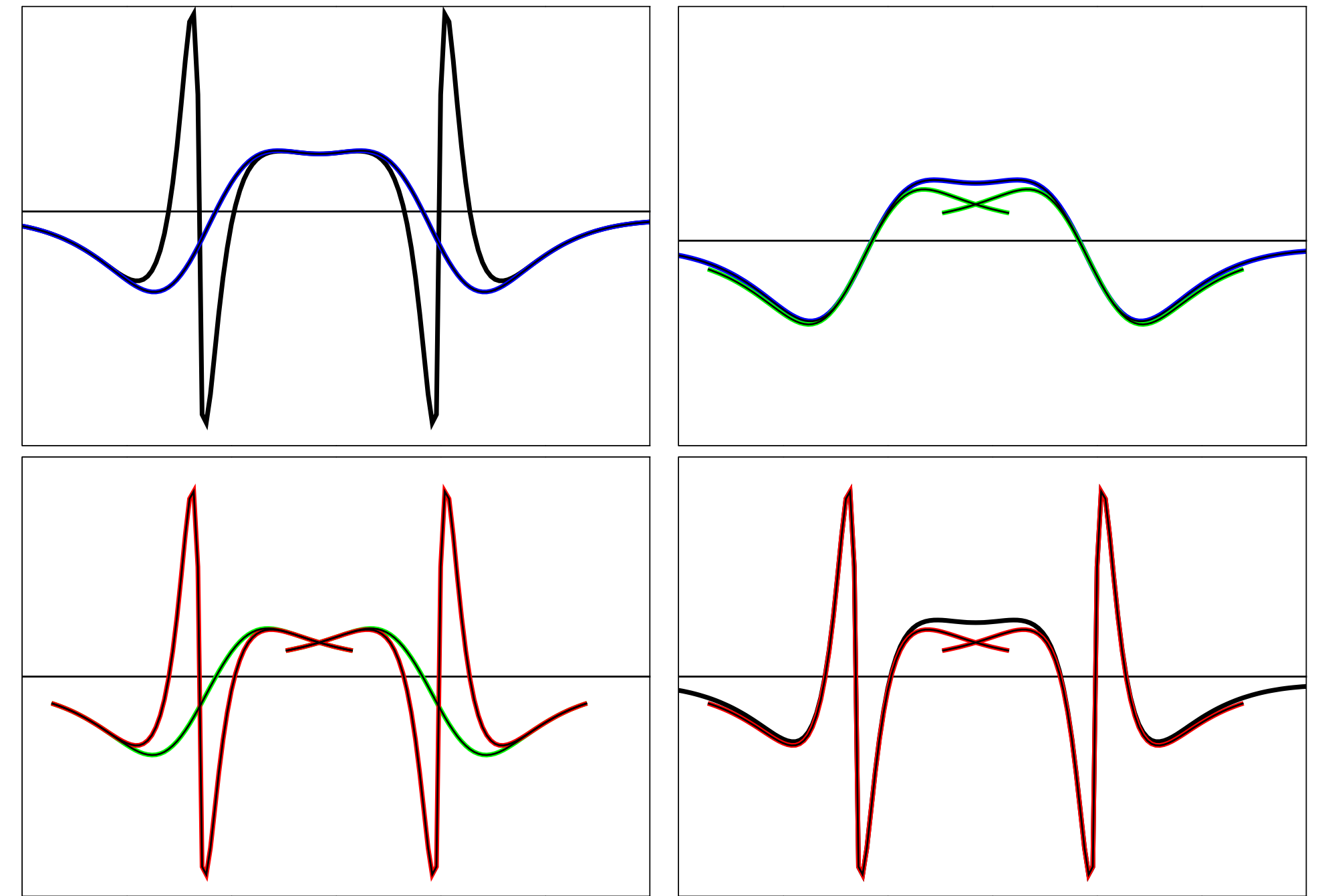
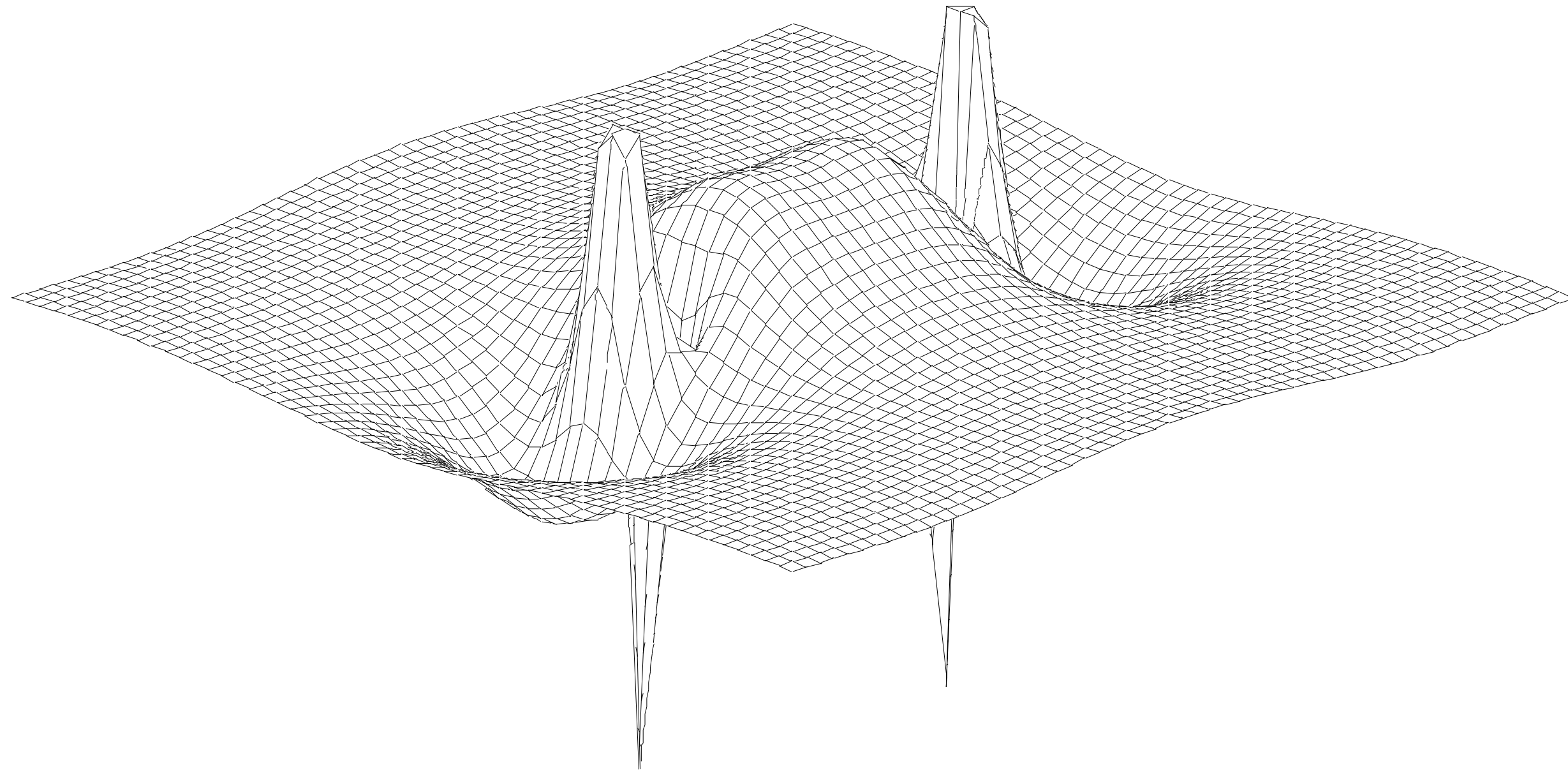
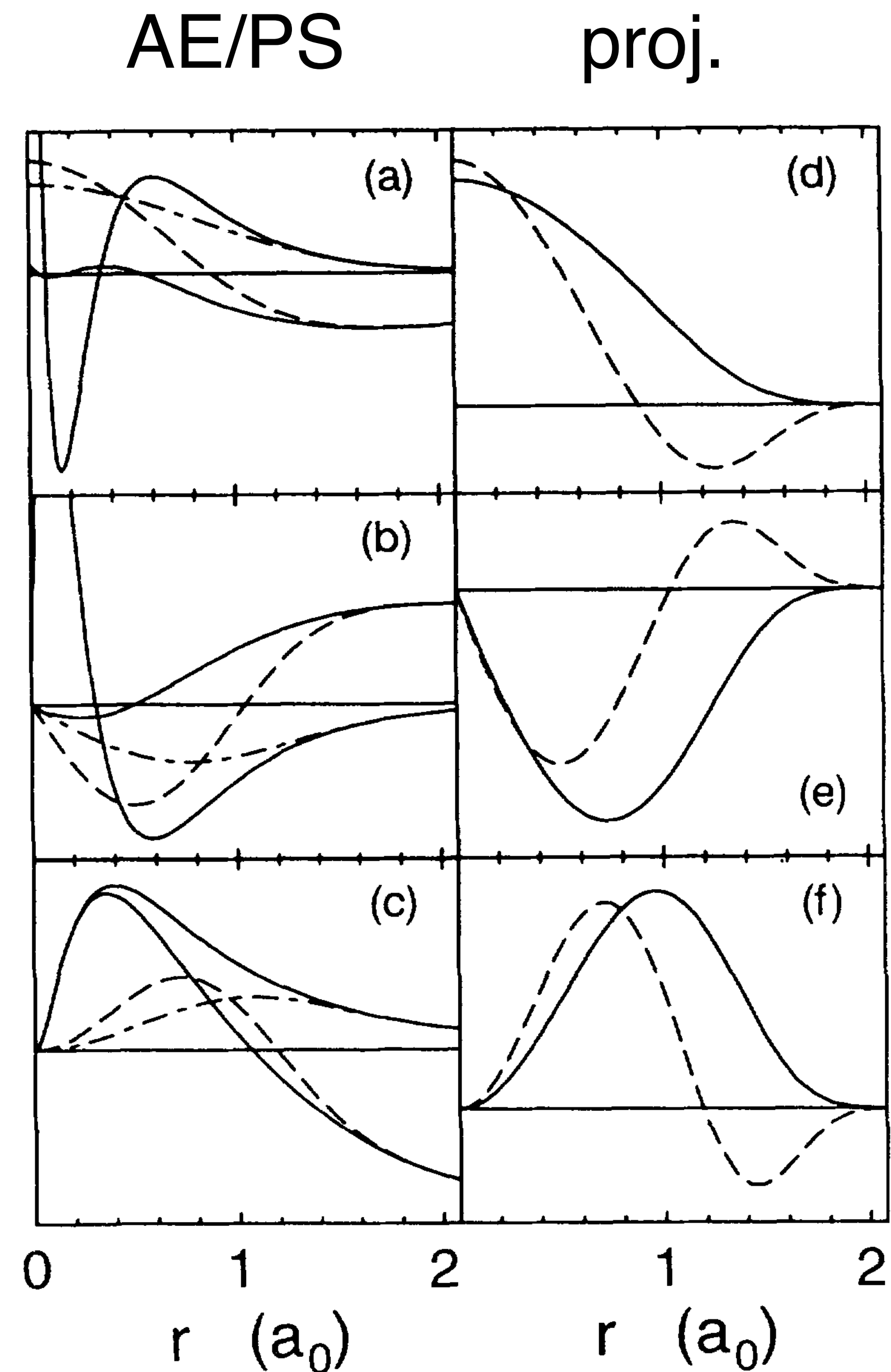


Figure 2: Bonding  $p\text{-}\sigma$  orbital of the  $\text{Cl}_2$  molecule and its decomposition of the wave function into auxiliary wave function and the two one-center expansions. Top-left: True and auxiliary wave function; top-right: auxiliary wave function and its partial wave expansion; bottom-left: the two partial wave expansions; bottom-right: true wave function and its partial wave expansion.

# More examples

FIG. 1. Partial waves and projectors for Mn. Left panel: AE partial waves (solid lines) and PS partial waves (dashed and dash-dotted lines). The “first” PS partial wave is a dash-dotted line. Right panel: first (solid line) and second (dashed line) projector functions. (a) and (d) show the results for the first and the second partial wave of the  $s$  angular momentum channel, respectively, (b) and (e) for the  $p$  channel, and (c) and (f) for the  $d$  channel.  $3s$  and  $3p$  functions are treated as valence states. Functions are scaled individually.

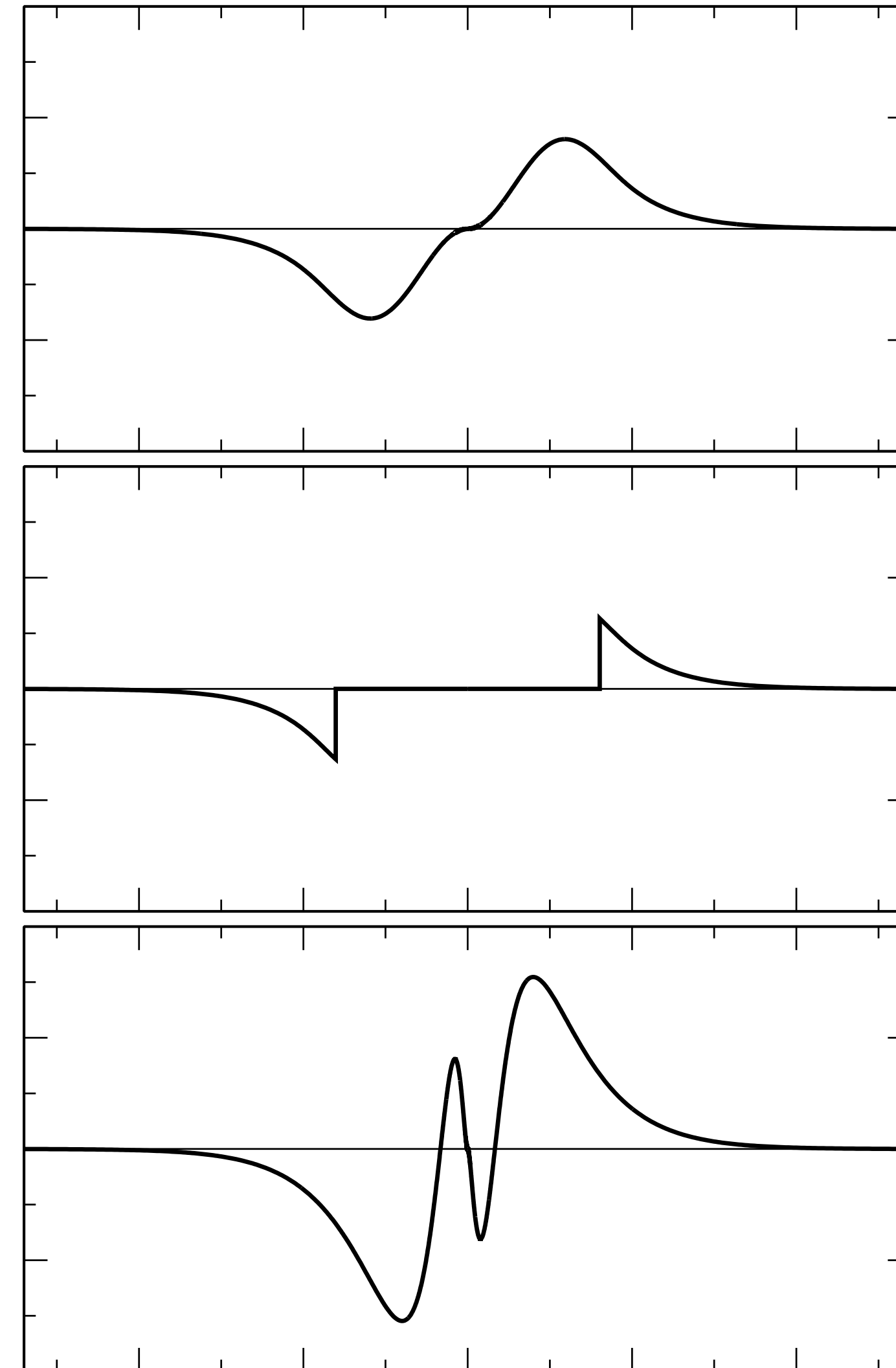


# PAW Augmentation

$$|\tilde{\psi}_n\rangle$$

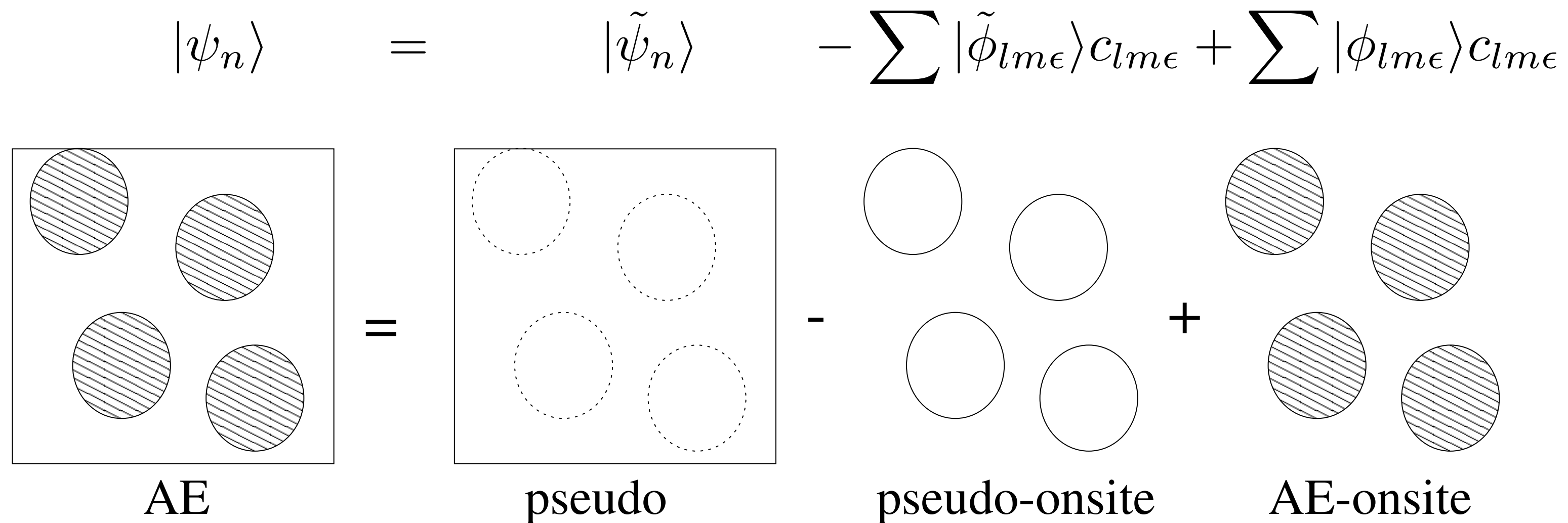
$$|\tilde{\psi}_n\rangle - \sum_i |\tilde{\phi}_i\rangle \langle \tilde{p}_i | \tilde{\psi}_n \rangle$$

$$|\tilde{\psi}_n\rangle - \sum_i |\tilde{\phi}_i\rangle \langle \tilde{p}_i | \tilde{\psi}_n \rangle + \sum_i |\phi_i\rangle \langle \tilde{p}_i | \tilde{\psi}_n \rangle$$



# PAW Augmentation

- Character of wavefunction:  $c_{lm\epsilon} = \langle \tilde{p}_{lm\epsilon} | \tilde{\psi}_n \rangle$



- Same trick works for

- Wavefunctions
- Charge density

- Kinetic energy
- Exchange correlation energy
- Hartree energy

# Total Energy

$$E = \tilde{E} + E^1 - \tilde{E}^1$$

three terms

PW grid

$$\tilde{E} = \sum_n f_n \langle \tilde{\psi}_n | -\frac{1}{2} \Delta | \tilde{\psi}_n \rangle + E_{xc}[\tilde{\rho} + \hat{\rho} + \tilde{\rho}_c] + E_H[\tilde{\rho} + \hat{\rho}] + \int v_H[\tilde{\rho}_{Zc}] (\tilde{\rho}(\mathbf{r}) + \hat{\rho}(\mathbf{r})) d^3\mathbf{r} + U(\mathbf{R}, Z_{\text{ion}})$$

local radial grid

$$\tilde{E}^1 = \sum_{\text{sites}} \left\{ \sum_{(i,j)} \rho_{ij} \langle \tilde{\phi}_i | -\frac{1}{2} \Delta | \tilde{\phi}_j \rangle + \overline{E_{xc}[\tilde{\rho}^1 + \hat{\rho} + \tilde{\rho}_c]} + \overline{E_H[\tilde{\rho}^1 + \hat{\rho}]} + \int_{\Omega_r} v_H[\tilde{\rho}_{Zc}] (\tilde{\rho}^1(\mathbf{r}) + \hat{\rho}(\mathbf{r})) d^3\mathbf{r} \right\}$$

local radial grid

$$E^1 = \sum_{\text{sites}} \left\{ \sum_{(i,j)} \rho_{ij} \langle \phi_i | -\frac{1}{2} \Delta | \phi_j \rangle + \overline{E_{xc}[\rho^1 + \rho_c]} + \overline{E_H[\rho^1]} + \int_{\Omega_r} v_H[\rho_{Zc}] \rho^1(\mathbf{r}) d^3\mathbf{r} \right\}$$

from Marsman: <https://www.vasp.at/mmars/day1.pdf>

# What are the approximations?

- Frozen core can be relaxed: Marsman & Kresse, JCP 125, 104101 (2006)
- Plane wave expansion, energy cut-off  $\frac{1}{2}|\mathbf{G} + \mathbf{k}|^2 < E_{\text{cutoff}}$
- Partial wave expansion (1-2 per angular momentum)



# PAW: Things to note

- *All-electron method* (valence states orthogonal to core)
- Frozen core approximation
- Plane waves: FFT in reciprocal space, **fast calculations**
- **Forces** from total energy expression
- PAW point-of-view: LAPW *special case*, PP an *approximation*

# Accuracy

Compare with FPLAPW method (WIEN2k):

$\Delta(\text{PAW})_{(\text{VASP})} = 1.9 \text{ meV/atom}$

H																		He
0.1																		0.0
Li	Be											B	C	N	O	F		Ne
0.2	0.1											0.3	0.3	10.6	8.3	1.5		0.1
Na	Mg											Al	Si	P	S	Cl		Ar
0.0	0.7											0.3	2.0	3.8	3.3	4.0		0.1
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br		Kr
0.1	0.2	0.4	0.9	1.3	3.1	1.4	3.4	3.4	2.0	0.4	0.3	0.2	2.4	1.7	1.5	1.5		0.1
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I		Xe
0.1	0.1	0.5	2.7	7.3	5.5	8.3	2.3	5.4	4.4	4.1	1.4	0.4	0.2	0.1	0.5	0.9		0.1
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At		Rn
0.3	0.7	4.3	1.2	1.0	3.5	4.3	3.8	1.9	2.5	5.9	0.5	0.4	0.6	0.4	0.4			0.0

# Lejaeghere et al. Science 351, 1415 (2016)

	AE													PAW								USPP						NCPP													
	Elk	exciting	FHI-aims/tight	FHI-aims/really_tight	FHI-aims/tier2	FLEUR	FPLO/default	FPLO/T+F	FPLO/T+F+s	RSpt	WIEN2k/default	WIEN2k/enhanced	WIEN2k/acc	GBRV12/ABINIT	GPAW06/GPAW	GPAW09/ABINIT	GPAW09/GPAW	JTH01/ABINIT	JTH02/ABINIT	PSlib031/QE	PSlib100/QE	VASP2007/VASP	VASP2012/VASP	VASPGW2015/VASP	GBRV12/QE	GBRV14/CASTEP	GBRV14/QE	OTFG7/CASTEP	OTFG9/CASTEP	SSSP/QE	Vdb/CASTEP	Vdb2/DACAO	FHI98pp/ABINIT	HGH/ABINIT	HGH-NLCC/BigDFT	MBK2013/OpenMX	ONCVSP (PD0.1)/ABINIT	ONCVSP (SG15)1/CASTEP	ONCVSP (SG15)1/QE	ONCVSP (SG15)2/CASTEP	
AE	Elk	0.3	0.6	0.6	0.3	0.6	3.9	1.0	1.0	0.9	1.7	1.8	0.3	0.9	3.8	1.3	1.5	1.2	0.6	1.6	0.9	2.1	0.7	0.4	1.1	1.1	1.0	2.5	0.4	0.4	6.4	6.3	13.5	2.2	1.1	2.1	0.7	1.5	1.4	1.4	
	exciting	0.3		0.5	0.5	0.1	0.5	3.9	1.0	0.9	0.8	1.7	1.8	0.2	0.8	3.8	1.3	1.5	1.2	0.6	1.6	0.8	2.1	0.6	0.4	1.0	1.1	1.0	2.5	0.5	0.3	6.4	6.3	13.4	2.2	1.1	2.1	0.7	1.4	1.3	1.4
	FHI-aims/tight	0.6	0.5		0.0	0.5	0.7	3.8	0.9	1.1	0.7	1.8	1.8	0.5	1.0	3.8	1.3	1.6	1.3	0.7	1.7	1.0	2.2	0.8	0.6	1.1	1.2	1.1	2.6	0.7	0.6	6.4	6.3	13.6	2.2	1.2	2.0	0.8	1.5	1.4	1.5
	FHI-aims/really_tight	0.6	0.5	0.0		0.5	0.7	3.8	0.9	1.1	0.8	1.8	1.8	0.5	1.0	3.8	1.3	1.6	1.3	0.7	1.7	1.0	2.2	0.8	0.6	1.1	1.2	1.1	2.6	0.7	0.6	6.5	6.3	13.6	2.2	1.2	2.0	0.8	1.5	1.4	1.5
	FHI-aims/tier2	0.3	0.1	0.5	0.5		0.5	3.9	0.9	0.9	0.8	1.7	1.8	0.2	0.8	3.8	1.3	1.5	1.2	0.6	1.6	0.8	2.0	0.6	0.4	0.9	1.0	0.9	2.5	0.5	0.3	6.4	6.3	13.4	2.2	1.1	2.1	0.7	1.4	1.3	1.4
	FLEUR	0.6	0.5	0.7	0.7	0.5		3.6	0.8	0.8	0.6	1.4	1.5	0.4	0.9	3.5	1.3	1.5	1.0	0.6	1.5	0.8	1.9	0.7	0.6	1.0	1.0	1.0	2.6	0.7	0.5	6.5	6.3	13.2	2.0	1.0	1.9	0.6	1.3	1.3	1.3
	FPLO/default	3.9	3.9	3.8	3.8	3.9	3.6		3.1	3.6	3.3	2.9	2.5	3.9	4.0	3.1	4.1	4.1	3.4	3.6	3.3	3.9	2.8	3.9	4.0	4.0	4.0	4.1	5.8	4.1	3.9	7.9	7.2	13.0	4.9	3.6	3.2	3.7	4.1	4.1	4.1
	FPLO/T+F	1.0	1.0	0.9	0.9	0.9	0.8	3.1		0.8	0.7	1.4	1.4	0.9	1.3	3.4	1.7	1.9	1.0	0.9	1.5	1.3	1.9	1.2	1.0	1.3	1.3	1.3	3.1	1.1	1.0	6.6	6.4	13.7	2.4	1.2	1.8	1.0	1.6	1.6	1.6
	FPLO/T+F+s	1.0	0.9	1.1	1.1	0.9	0.8	3.6	0.8		0.9	1.5	1.5	0.9	1.3	3.5	1.7	1.8	1.2	0.9	1.4	1.3	1.9	1.2	1.0	1.4	1.4	1.4	2.9	1.0	0.9	6.4	6.4	13.0	2.3	1.2	1.8	1.0	1.6	1.6	1.6
	RSpt	0.9	0.8	0.7	0.8	0.8	0.6	3.3	0.7	0.9		1.3	1.3	0.8	1.1	3.4	1.5	1.7	0.9	0.7	1.6	1.1	1.9	1.0	0.8	1.2	1.3	1.3	3.0	1.0	0.8	6.7	6.5	13.2	2.2	1.1	1.8	0.8	1.5	1.5	1.5
	WIEN2k/default	1.7	1.7	1.8	1.8	1.7	1.4	2.9	1.4	1.5	1.3		0.9	1.7	1.9	3.2	2.2	2.3	1.3	1.5	1.8	1.8	1.7	1.8	1.8	1.9	1.9	1.9	3.8	1.8	1.6	7.1	7.0	13.0	2.8	1.7	1.9	1.6	2.1	2.1	2.1
	WIEN2k/enhanced	1.8	1.8	1.8	1.8	1.8	1.5	2.5	1.4	1.5	1.3	0.9		1.8	2.0	2.6	2.1	2.2	1.1	1.5	1.6	1.8	1.4	1.9	2.0	2.0	2.0	2.0	3.8	2.0	1.7	6.9	6.9	12.3	2.8	1.6	1.5	1.7	1.9	1.9	1.9
WIEN2k/acc	0.3	0.2	0.5	0.5	0.2	0.4	3.9	0.9	0.9	0.8	1.7	1.8		0.8	3.8	1.3	1.5	1.2	0.5	1.6	0.8	2.0	0.7	0.3	0.9	1.0	1.0	2.5	0.5	0.3	6.4	6.2	13.4	2.1	1.0	2.0	0.6	1.4	1.3	1.4	
PAW	GBRV12/ABINIT	0.9	0.8	1.0	1.0	0.8	0.9	4.0	1.3	1.3	1.1	1.9	2.0	0.8		4.1	1.5	1.6	1.5	1.1	2.0	1.1	2.3	1.0	0.9	0.7	0.8	0.7	2.8	1.0	0.7	6.4	6.3	15.1	2.5	1.5	2.4	1.1	1.8	1.7	1.8
	GPAW06/GPAW	3.8	3.8	3.8	3.8	3.8	3.5	3.1	3.4	3.5	3.4	3.2	2.6	3.8	4.1		3.6	3.5	3.2	3.5	3.0	3.8	2.8	3.7	3.8	4.0	3.8	4.0	5.6	3.9	3.6	7.4	7.6	12.3	4.5	3.0	3.0	3.6	3.7	3.8	3.7
	GPAW09/ABINIT	1.3	1.3	1.3	1.3	1.3	1.3	4.1	1.7	1.7	1.5	2.2	2.1	1.3	1.5	3.6		0.6	1.5	1.4	2.0	1.5	2.4	1.4	1.3	1.6	1.6	1.6	2.5	1.4	1.3	6.5	6.1	13.6	2.3	1.7	2.3	1.2	1.7	1.7	1.7
	GPAW09/GPAW	1.5	1.5	1.6	1.6	1.5	1.5	4.1	1.9	1.8	1.7	2.3	2.2	1.5	1.6	3.5	0.6		1.6	1.5	2.1	1.6	2.5	1.6	1.5	1.7	1.7	1.7	2.7	1.5	1.4	6.5	6.1	13.6	2.5	1.8	2.3	1.5	1.8	1.8	1.8
	JTH01/ABINIT	1.2	1.2	1.3	1.3	1.2	1.0	3.4	1.0	1.2	0.9	1.3	1.1	1.2	1.5	3.2	1.5	1.6		0.9	1.5	1.4	1.9	1.4	1.3	1.5	1.5	1.5	3.0	1.4	1.1	6.5	6.5	13.0	2.2	1.3	1.5	1.2	1.4	1.4	1.4
	JTH02/ABINIT	0.6	0.6	0.7	0.7	0.6	0.6	3.6	0.9	0.9	0.7	1.5	1.5	0.5	1.1	3.5	1.4	1.5	0.9		1.4	0.9	1.9	0.7	0.7	1.2	1.2	1.2	2.6	0.7	0.6	6.3	6.2	13.4	2.2	1.2	1.9	0.7	1.4	1.4	1.4
	PSlib031/QE	1.6	1.6	1.7	1.7	1.6	1.5	3.3	1.5	1.4	1.6	1.8	1.6	1.6	2.0	3.0	2.0	2.1	1.5	1.4		1.6	1.5	1.6	1.6	2.0	1.9	2.0	3.1	1.6	1.5	6.1	5.8	12.8	2.4	1.6	1.7	1.5	2.1	2.2	2.1
	PSlib100/QE	0.9	0.8	1.0	1.0	0.8	0.8	3.9	1.3	1.3	1.1	1.8	1.8	0.8	1.1	3.8	1.5	1.6	1.4	0.9	1.6		1.7	1.0	0.8	1.1	1.2	1.2	2.2	0.9	0.7	6.1	5.9	13.5	2.1	1.4	1.9	0.9	1.6	1.6	1.6
	VASP2007/VASP	2.1	2.1	2.2	2.2	2.0	1.9	2.8	1.9	1.9	1.9	1.7	1.4	2.0	2.3	2.8	2.4	2.5	1.9	1.9	1.5	1.7		1.8	2.1	2.1	2.2	2.1	3.5	2.1	1.9	6.5	6.1	12.4	3.0	2.2	1.7	1.9	2.5	2.4	2.5
	VASP2012/VASP	0.7	0.6	0.8	0.8	0.6	0.7	3.9	1.2	1.2	1.0	1.8	1.9	0.7	1.0	3.7	1.4	1.6	1.4	0.7	1.6	1.0	1.8		0.7	1.1	1.2	1.1	2.5	0.8	0.6	6.5	6.3	13.4	2.2	1.2	2.1	0.9	1.6	1.5	1.6
	VASPGW2015/VASP	0.4	0.4	0.6	0.6	0.4	0.6	4.0	1.0	1.0	0.8	1.8	2.0	0.3	0.9	3.8	1.3	1.5	1.3	0.7	1.6	0.8	2.1	0.7		1.1	1.1	1.1	2.6	0.5	0.4	6.6	6.2	13.7	2.2	1.1	2.2	0.7	1.5	1.4	1.5
USPP	GBRV12/QE	1.1	1.0	1.1	1.1	0.9	1.0	4.0	1.3	1.4	1.2	1.9	2.0	0.9	0.7	4.0	1.6	1.7	1.5	1.2	2.0	1.1	2.1	1.1	1.1		0.4	0.1	2.6	1.0	0.8	6.3	6.4	15.3	2.3	1.4	2.1	1.2	1.6	1.5	1.6
	GBRV14/CASTEP	1.1	1.1	1.2	1.2	1.0	1.0	4.0	1.3	1.4	1.3	1.9	2.0	1.0	0.8	3.8	1.6	1.7	1.5	1.2	1.9	1.2	2.2	1.2	1.1	0.4		0.3	2.6	0.9	0.9	6.2	6.3	15.0	2.4	1.6	2.1	1.1	1.5	1.5	1.5
	GBRV14/QE	1.0	1.0	1.1	1.1	0.9	1.0	4.1	1.3	1.4	1.3	1.9	2.0	1.0	0.7	4.0	1.6	1.7	1.5	1.2	2.0	1.2	2.1	1.1	1.1	0.1	0.3		2.6	1.0	0.8	6.3	6.3	15.2	2.3	1.4	2.1	1.2	1.6	1.5	1.5
	OTFG7/CASTEP	2.5	2.5	2.6	2.6	2.5	2.6	5.8	3.1	2.9	3.0	3.8	3.8	2.5	2.8	5.6	2.5	2.7	3.0	2.6	3.1	2.2	3.5	2.5	2.6	2.6	2.6	2.6		2.2	2.4	4.8	5.7	14.5	2.7	2.9	3.4	2.4	2.6	2.6	2.6
	OTFG9/CASTEP	0.4	0.5	0.7	0.7	0.5	0.7	4.1	1.1	1.0	1.0	1.8	2.0	0.5	1.0	3.9	1.4	1.5	1.4	0.7	1.6	0.9	2.1	0.8	0.5	1.0	0.9	1.0	2.2		0.6	6.3	6.2	13.6	2.2	1.1	2.1	0.8	1.5	1.4	1.5
	SSSP/QE	0.4	0.3	0.6	0.6	0.3	0.5	3.9	1.0	0.9	0.8	1.6	1.7	0.3	0.7	3.6	1.3	1.4	1.1	0.6	1.5	0.7	1.9	0.6	0.4	0.8	0.9	0.8	2.4	0.6		6.4	6.2	13.6	2.1	1.0	2.0	0.7	1.4	1.2	1.3
	Vdb/CASTEP	6.4	6.4	6.4	6.5	6.4	6.5	7.9	6.6	6.4	6.7	7.1	6.9	6.4	6.4	7.4	6.5	6.5	6.5	6.3	6.1	6.1	6.5	6.5	6.6	6.3	6.2	6.3	4.8	6.3	6.4		9.6	16.3	6.6	6.1	6.6	6.4	5.7	5.8	5.7
	Vdb2/DACAO	6.3	6.3	6.3	6.3	6.3	6.3	7.2	6.4	6.4	6.5	7.0	6.9	6.2	6.3	7.6	6.1	6.1	6.5	6.2	5.8	5.9	6.1	6.3	6.2	6.4	6.3	6.3	5.7	6.2	6.2	9.6		17.9	6.2	5.9	6.4	6.1	6.5	6.5	6.5
NCPP	FHI98pp/ABINIT	13.5	13.4	13.6	13.6	13.4	13.2	13.0	13.7	13.0	13.2	13.0	12.3	13.4	15.1	12.3	13.6	13.6	13.0	13.4	12.8	13.5	12.4	13.4	13.7	15.3	15.0	15.2	14.5	13.6	13.6	16.3	17.9		14.3	8.5	13.0	13.3	13.3	13.6	13.4
	HGH/ABINIT	2.2	2.2	2.2	2.2	2.2	2.0	4.9	2.4	2.3	2.2	2.8	2.8	2.1	2.5	4.5	2.3	2.5	2.2	2.2	2.4	2.1	3.0	2.2	2.2	2.3	2.4	2.3	2.7	2.2	2.1	6.6	6.2	14.3		0.9	2.6	2.0	2.0	2.0	2.0
	HGH-NLCC/BigDFT	1.1	1.1	1.2	1.2	1.1	1.0	3.6	1.2	1.2</																															

# DFT codes using PAW

- VASP license
- Abinit free
- Quantum Espresso free
- GPAW free
- + more

Importance of good **potential database**

# Refs.

- Good presentations by [Marsman](#) and [Blöchl](#)
- Blöchl PRB **50**, 17953 (1994)
- Blöchl *et al.* <https://arxiv.org/abs/cond-mat/0201015v2>
- Kresse & Joubert PRB **59**, 1758 (1999)
- Holzwarth *et al.* PRB **55**, 2005 (1997)
- Martin, *Electronic Structure*, Chapter 11.1, 13.2

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