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Laboratoire de Chimie et Physique Quantiques

Green's function methods for quantum chemistry

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https://lcpq.github.io/PTEROSOR

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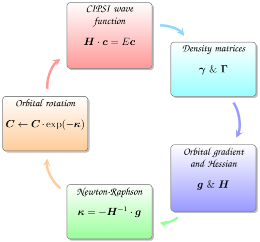
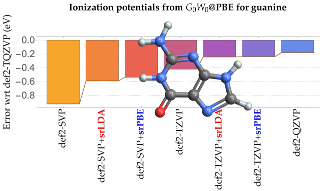




Config-uration Interaction

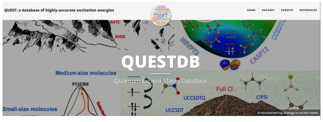
Coupled Cluster

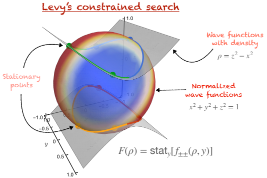
Excited-State Methods

QUEST database

Green's Function Methods

Density Functional Theory





https://lcpq.github.io/PTEROSOR/

Antoine Marie (PhD)

Xavier Blase (Grenoble)

Pina Romaniello (Toulouse)

Wave Function Theory

$$\overset{\text{Hamiltonian}}{\hat{H}}\ \underbrace{\Psi(\boldsymbol{r}_1, \ldots, \boldsymbol{r}_N)}_{\text{Wave function}} = \overset{\text{Energy}}{E}\ \underbrace{\Psi(\boldsymbol{r}_1, \ldots, \boldsymbol{r}_N)}_{\text{Wave function}}$$

$$\hat{H} = \overset{\text{kinetic}}{\hat{T}} + \underbrace{\hat{W}_{\text{ee}}}_{\text{electron repulsion}} + \overset{\text{external potential}}{\hat{V}_{\text{ext}}} \quad \Rightarrow \quad \boxed{E = E_T + E_W + E_V}$$

Density Functional Theory

$$N \int \cdots \int \Psi^*(\boldsymbol{r}, \dots, \boldsymbol{r}_N)\Psi(\boldsymbol{r}, \dots, \boldsymbol{r}_N)\mathrm{d}\boldsymbol{r}_2 \cdots \mathrm{d}\boldsymbol{r}_N = \overbrace{\boxed{n(\boldsymbol{r})}}^{\text{electron density}}$$

Wave Function Theory (WFT) $\rightsquigarrow$ Density Functional Theory (DFT)

$$E = \underset{✗}{E_T} + \underset{✗}{E_W} + \underset{✓}{E_V}$$

Hohenberg & Kohn, Phys. Rev. 1964 (B864) 136

Density Matrix Functional Theory

1st-order reduced density matrix

$$N \int \cdots \int \Psi^*(\boldsymbol{r}, \ldots, \boldsymbol{r}_N)\Psi(\boldsymbol{r}', \ldots, \boldsymbol{r}_N) \mathrm{d}\boldsymbol{r}_2 \cdots \mathrm{d}\boldsymbol{r}_N = \boxed{n_1(\boldsymbol{r}, \boldsymbol{r}')}$$

Wave Function Theory (WFT) $\rightsquigarrow$ Reduced Density Matrix Functional Theory (RDMF)

$$E = \underset{\checkmark}{E_T} + \underset{\times}{E_W} + \underset{\checkmark}{E_V}$$

Gilbert, Phys. Rev. B 12 (1975) 2111

Density Matrix Functional Theory (2nd order)

2nd-order reduced density matrix

$$\frac{N(N-1)}{2}\int\cdots\int \Psi^*(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_N)\Psi(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_N)\mathrm{d}\mathbf{r}_3\cdots\mathrm{d}\mathbf{r}_N = \boxed{n_2(\mathbf{r}_1,\mathbf{r}_2)}$$

$$E = \underset{\checkmark}{E_T} + \underset{\checkmark}{E_W} + \underset{\checkmark}{E_V}$$

$$E = -\frac{1}{2}\int \nabla_r^2 n_1(\mathbf{r},\mathbf{r}')\Big|_{\mathbf{r}'=\mathbf{r}}\mathrm{d}\mathbf{r} + \int\int \frac{n_2(\mathbf{r}_1,\mathbf{r}_2)}{r_{12}}\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2 + \int v(\mathbf{r})n(\mathbf{r})\mathrm{d}\mathbf{r}$$

One-Body Propagator in the Time Domain

$$\underbrace{G(\mathbf{r}t,\mathbf{r}'t')}_{\text{one-body Green's function}} = -\mathrm{i} \underbrace{\left\langle \Psi_0^N \right|}_{} \underbrace{\hat{T}}_{\text{time-ordering}} \Big[\underbrace{\hat{\psi}(\mathbf{r}t) \quad \hat{\psi}^\dagger(\mathbf{r}'t')}_{\text{Field operators}} \Big] \underbrace{\left| \Psi_0^N \right\rangle}_{N\text{-electron ground state}}$$

$$G(\mathbf{r}t,\mathbf{r}'t') = \begin{cases} -\mathrm{i} \left\langle \Psi_0^N \middle| \hat{\psi}(\mathbf{r}t)\hat{\psi}^\dagger(\mathbf{r}'t') \middle| \Psi_0^N \right\rangle & \text{for} \quad t > t' \\ +\mathrm{i} \left\langle \Psi_0^N \middle| \hat{\psi}^\dagger(\mathbf{r}'t')\hat{\psi}(\mathbf{r}t) \middle| \Psi_0^N \right\rangle & \text{for} \quad t' < t \end{cases}$$

- $\left\langle \Psi_0^N \middle| \hat{\psi}(\mathbf{r}t)\hat{\psi}^\dagger(\mathbf{r}'t') \middle| \Psi_0^N \right\rangle$ measures the propagation of an electron (electron branch)
- $\left\langle \Psi_0^N \middle| \hat{\psi}^\dagger(\mathbf{r}'t')\hat{\psi}(\mathbf{r}t) \middle| \Psi_0^N \right\rangle$ measures the propagation of a hole (hole branch)

Martin, Reining & Ceperley, *"Interacting Electrons"*

One-Body Propagator in the Frequency Domain

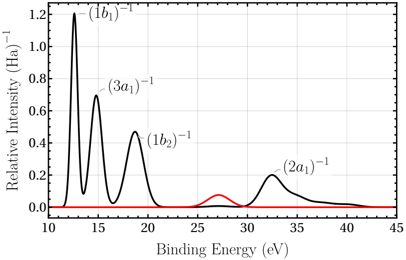
$$G(\mathbf{r},\mathbf{r}';\omega) = \sum_\nu \frac{\mathcal{I}_\nu(\mathbf{r})\mathcal{I}_\nu^*(\mathbf{r}')}{\omega - \underbrace{(E_0^N - E_\nu^{N-1})}_{\nu\text{th ionization potential (IP)}} - i\eta} + \sum_\nu \frac{\mathcal{A}_\nu(\mathbf{r})\mathcal{A}_\nu^*(\mathbf{r}')}{\omega - \underbrace{(E_\nu^{N+1} - E_0^N)}_{\nu\text{th electron affinity (EA)}} + i\eta}$$

Spectral function

$$\boxed{A(\omega) = \frac{1}{\pi}\left|\mathrm{Im}\, G(\omega)\right|}$$

Marie & Loos, JCTC 20 (2024) 4751

Photoemission spectrum of water



Link to RDMFT & DFT

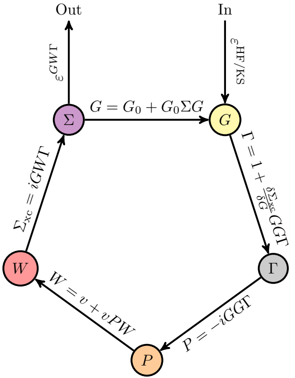
$$n_1(\mathbf{r},\mathbf{r}') = -\mathrm{i}\lim_{t'\to t} G(\mathbf{r}t,\mathbf{r}'t') \qquad n(\mathbf{r}) = -\mathrm{i}\lim_{t'\to t}\lim_{\mathbf{r}'\to\mathbf{r}} G(\mathbf{r}t,\mathbf{r}'t')$$

Galitskii-Migdal Energy Functional

$$\begin{aligned} E &= \frac{\mathrm{i}}{2}\int \mathrm{d}\mathbf{r} \lim_{t'\to t}\lim_{\mathbf{r}'\to\mathbf{r}} \nabla_{\mathbf{r}}^2 G(\mathbf{r}t,\mathbf{r}'t') + \frac{1}{2}\int \mathrm{d}\mathbf{r} \lim_{t'\to t}\lim_{\mathbf{r}'\to\mathbf{r}} \left[\frac{\partial}{\partial t} + \mathrm{i}\hat{h}(\mathbf{r})\right] G(\mathbf{r}t,\mathbf{r}'t') + E_V \\ &= \frac{1}{2}\int \mathrm{d}\mathbf{r} \lim_{t'\to t}\lim_{\mathbf{r}'\to\mathbf{r}} \left[\frac{\partial}{\partial t} - \mathrm{i}\hat{h}(\mathbf{r})\right] G(\mathbf{r}t,\mathbf{r}'t') \end{aligned}$$

Wave Function Theory (WFT) $\rightsquigarrow$ Green's Function Functional Theory (GFFT) ?!

Galitskii & Migdal, JETP 7 (1958) 96



Hedin, Phys. Rev. 139 (1965) A796

Hedin's Equations

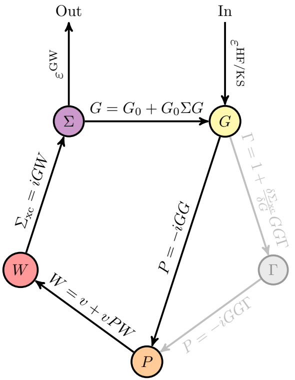
$$\underbrace{G(12)}_{\text{Green's function}} = G_0(12) + \int G_0(13)\Sigma(34)G(42)d(34)$$

$$\underbrace{\Gamma(123)}_{\text{vertex}} = \delta(12)\delta(13) + \int \frac{\delta \Sigma_{xc}(12)}{\delta G(45)} G(46)G(75)\Gamma(673)d(4567)$$

$$\underbrace{P(12)}_{\text{polarizability}} = -\mathrm{i} \int G(13)\Gamma(342)G(41)d(34)$$

$$\underbrace{W(12)}_{\text{screening}} = v(12) + \int v(13)P(34)W(42)d(34)$$

$$\underbrace{\Sigma_{xc}(12)}_{\text{self-energy}} = \mathrm{i} \int G(14)W(13)\Gamma(423)d(34)$$



Hedin, Phys. Rev. 139 (1965) A796

The GW Approximation

$$\underbrace{G(12)}_{\text{Green's function}} = G_0(12) + \int G_0(13)\Sigma(34)G(42)d(34)$$

$$\underbrace{\Gamma(123)}_{\text{vertex}} = \delta(12)\delta(13)$$

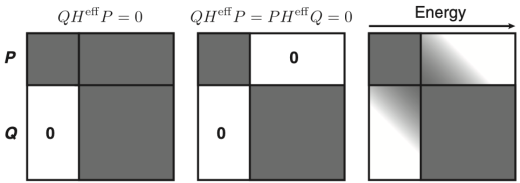
$$\underbrace{P(12)}_{\text{polarizability}} = -\mathrm{i}G(12)G(21)$$

$$\underbrace{W(12)}_{\text{screening}} = v(12) + \int v(13)P(34)W(42)d(34)$$

$$\underbrace{\Sigma_{\text{xc}}(12)}_{\text{self-energy}} = \mathrm{i}G(12)W(12)$$

Golze et al. Front. Chem. 7 (2019) 377; Marie et al. Adv. Quantum Chem. 90 (2024) 157

Regularization via the Similarity Renormalization Group (SRG)

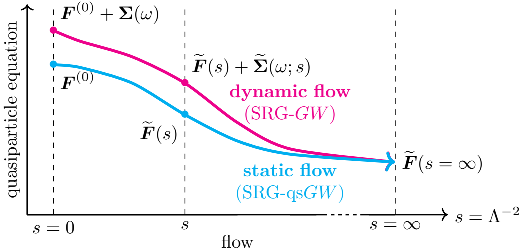


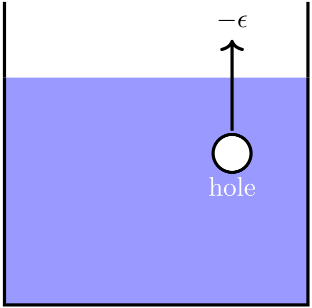
$\Leftarrow$ Continuous (unitary) SRG transformation

Idea based on Evangelista's DSRG method

Chenyang Li & Evangelista, Annu. Rev. Phys. Chem. 70 (2019) 275

Monino & Loos, JCP 156 (2022) 231101; Marie & Loos, JCTC 19 (2023) 3943

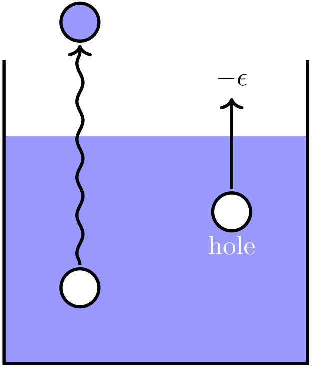




electron removal

- Link to electron-boson Hamiltonian:
  Langreth, PRB 1 (1970) 471
  Hedin, JPCM 11 (1999) R489

- Link to coupled-cluster theory:
  Lange & Berkelbach, JCTC 14 (2018) 4224
  Quintero-Monsebaiz et al. JCP 157 (2022) 231102
  Tolle & Chan, JCP 158 (2023) 124123



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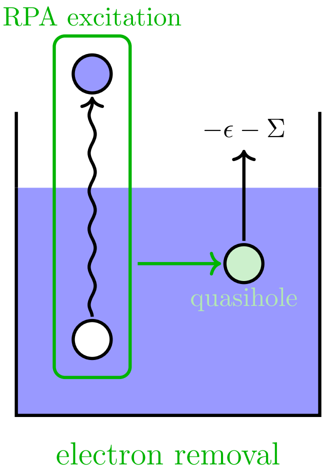

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  Quintero-Monsebaiz et al. JCP 157 (2022) 231102
  Tolle & Chan, JCP 158 (2023) 124123

Propagation Can be Longer Than Expected

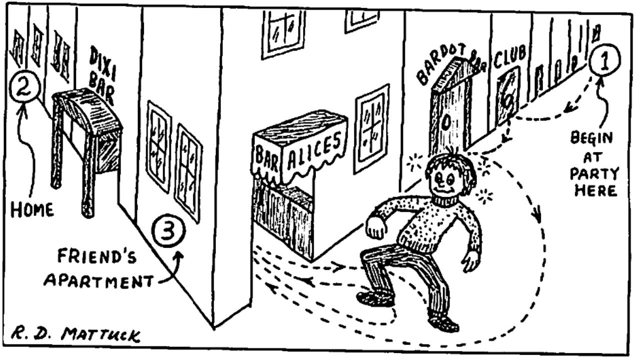


Fig. 1.1 ***Propagation of Drunken Man***

(Reproduced with the kind permission of *The Encyclopedia of Physics*)

Mattuck, *"A Guide to Feynman Diagrams in the Many-Body Problem"*

Two-Body Propagator in the Time Domain

two-body Green's function

$1 = (r_1, t_1)$

$$G_2(12;1'2') = (-\mathrm{i})^2 \left\langle \Psi_0^N \middle| \hat{T}\left[\hat{\psi}(2)\hat{\psi}^\dagger(2')\right]\hat{T}\left[\hat{\psi}(\;1\;)\hat{\psi}^\dagger(1')\right] \middle| \Psi_0^N \right\rangle$$

Propagation of electron-hole pairs ($t_{1'} > t_1$ and $t_{2'} > t_2$)

$$G_2^{\text{eh}}(12;1'2') = (-\mathrm{i})^2 \left\langle \Psi_0^N \middle| \hat{\psi}^\dagger(1')\hat{\psi}(1)\hat{\psi}^\dagger(2')\hat{\psi}(2) + \hat{\psi}^\dagger(2')\hat{\psi}(2)\hat{\psi}^\dagger(1')\hat{\psi}(1) \middle| \Psi_0^N \right\rangle$$

Propagation of electron-electron and hole-hole pairs ($t_{1'} > t_{2'}$ and $t_1 > t_2$)

$$G_2^{\text{ee}}(12;1'2') = (-\mathrm{i})^2 \left\langle \Psi_0^N \middle| \hat{\psi}(1)\hat{\psi}(2)\hat{\psi}^\dagger(1')\hat{\psi}^\dagger(2') \middle| \Psi_0^N \right\rangle$$

$$G_2^{\text{hh}}(12;1'2') = (-\mathrm{i})^2 \left\langle \Psi_0^N \middle| \hat{\psi}^\dagger(1')\hat{\psi}^\dagger(2')\hat{\psi}(1)\hat{\psi}(2) \middle| \Psi_0^N \right\rangle$$

Electron-Hole Correlation Function

eh correlation function

$$\boxed{L(12;1'2')} = -G_2(12;1'2') + G(11')G(22')$$

$$L(\mathbf{r}_1\mathbf{r}_2;\mathbf{r}_{1'}\mathbf{r}_{2'};\omega) = \sum_{\nu>0} \frac{L_\nu^N(\mathbf{r}_2\mathbf{r}_{2'})R_\nu^N(\mathbf{r}_1\mathbf{r}_{1'})}{\omega - (E_\nu^N - E_0^N - i\eta)} - \sum_{\nu>0} \frac{L_\nu^N(\mathbf{r}_2\mathbf{r}_{2'})R_\nu^N(\mathbf{r}_1\mathbf{r}_{1'})}{\omega - (E_0^N - E_\nu^N + i\eta)}$$

νth excitation energy

Electron-Hole Bethe-Salpeter Equation (eh-BSE)

$$L(12;1'2') = \underbrace{L_0(12;1'2')}_{G(12')G(21')} + \int \mathrm{d}(33'44')\, L_0(13';1'3)\, \boxed{\Xi^{\text{eh}}(34';3'4)}\, L(42;4'2')$$

eh kernel

Strinati, Riv. Nuovo Cimento 11 (1988) 1; Blase et al. JPCL 11 (2020) 7371

Effective Interaction Kernel

$$\Xi^{\text{eh}}(12;1'2') = \frac{\delta\Sigma(11')}{\delta G(2'2)} \qquad \overbrace{\boxed{\Sigma_{\text{xc}}}}^{\text{exchange-correlation}} = \mathrm{i}GW \quad \Rightarrow \quad \frac{\delta\Sigma_{\text{xc}}}{\delta G} = \mathrm{i}\frac{\delta G}{\delta G}W + \mathrm{i}G\underbrace{\frac{\delta W}{\delta G}}_{=0} = \mathrm{i}W$$

Casida Equations for eh-BSE

$$\begin{pmatrix} A & B \\ -B & -A \end{pmatrix} \begin{pmatrix} X_\nu \\ Y_\nu \end{pmatrix} = \Omega_\nu^N \begin{pmatrix} X_\nu \\ Y_\nu \end{pmatrix}$$

If no correlation, $W_{ij,ab} = \langle ib|ja\rangle$, then
eh-BSE becomes RPAx (or TDHF)!

Matrix Elements With Static Screening

$$A_{ia,jb} = \overbrace{(\epsilon_a^{GW} - \epsilon_i^{GW})}^{\text{quasiparticle energies}} \delta_{ij}\delta_{ab} + \underbrace{\langle ib|aj\rangle}_{\text{Hartree}} - \underbrace{W_{ij,ab}}_{\text{exchange-correlation}}$$

$$B_{ia,jb} = \langle ij|ab\rangle - W_{ib,aj}$$

Particle-Particle Correlation Function

pp correlation function

anomalous propagators

$$\underbrace{K(12;1'2')}_{\text{pp correlation function}} = -G_2(12;1'2') + \underbrace{G^{\text{hh}}(12)G^{\text{ee}}(2'1')}_{\text{anomalous propagators}}$$

$$K(\mathbf{r}_1\mathbf{r}_2;\mathbf{r}_{1'}\mathbf{r}_{2'};\omega) = \sum_\nu \frac{L_\nu^{N+2}(\mathbf{r}_1\mathbf{r}_2)R_\nu^{N+2}(\mathbf{r}'_1\mathbf{r}'_2)}{\omega - (\underbrace{E_\nu^{N+2} - E_0^N}_{\nu\text{th double EA (DEA)}} - i\eta)} - \sum_\nu \frac{L_\nu^{N-2}(\mathbf{r}'_1\mathbf{r}'_2)R_\nu^{N-2}(\mathbf{r}_1\mathbf{r}_2)}{\omega - (\underbrace{E_0^N - E_\nu^{N-2}}_{\nu\text{th double IP (DIP)}} + i\eta)}$$

Particle-Particle Bethe-Salpeter Equation (pp-BSE)

$$K(12;1'2') = \underbrace{K_0(12;1'2')}_{\frac{1}{2}[G(21')G(12')-G(11')G(22')]} - \int d(33'44')K(12;44')\underbrace{\Xi^{\text{pp}}(44';33')}_{\text{pp kernel}}K_0(33';1'2')$$

Marie, Romaniello, Loos, PRB 110 (2024) 115155; Marie et al. (in preparation)

Effective Interaction Kernel

$$\Xi^{\mathrm{pp}}(11';22') = \frac{\delta\Sigma^{\mathrm{ee}}(22')}{\delta G^{\mathrm{ee}}(11')}\bigg|_{U=0} \quad \underbrace{\boxed{\Sigma^{GW}_{\mathrm{Bc}}}}_{\text{Bogoliubov-correlation}} = -\mathrm{i}G^{\mathrm{ee}}W \quad \Rightarrow \quad \mathrm{i}\frac{\delta\Sigma^{GW}_{\mathrm{Bc}}(11')}{\delta G^{\mathrm{ee}}(22')} = \frac{1}{2}[W(11';22') - W(11';2'2)]$$

Essenberger, PhD thesis (2014)

Casida Equations for pp-BSE

$$\begin{pmatrix} C & B \\ -B^{\dagger} & -D \end{pmatrix}\begin{pmatrix} X_\nu \\ Y_\nu \end{pmatrix} = \Omega_\nu^{N\pm 2}\begin{pmatrix} X_\nu \\ Y_\nu \end{pmatrix}$$

If no correlation, $W_{pq,rs} = \langle ps|qr\rangle$, then pp-BSE becomes pp-RPA!

Matrix Elements With Static Screening

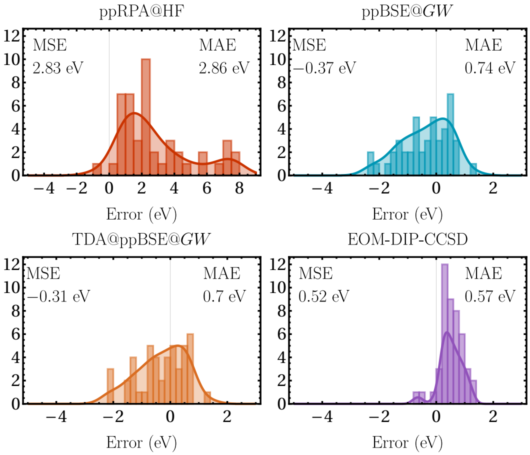
$$C_{ab,cd} = \overbrace{(\epsilon_a + \epsilon_b)}^{\text{quasiparticle energies}} \delta_{ac}\delta_{bd} + \underbrace{W_{ac,bd} - W_{ad,bc}}_{\text{Bogoliubov-correlation}}$$

$$B_{ab,ij} = W_{ai,bj} - W_{aj,bi}$$

$$D_{ij,kl} = -(\epsilon_i + \epsilon_j)\delta_{ik}\delta_{jl} + W_{ik,jl} - W_{il,jk}$$

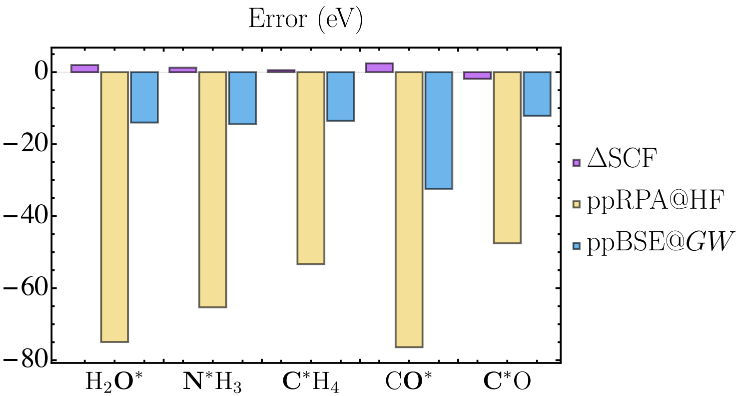
Deilmann, Drüppel & Rohlfing, PRL 116 (2016) 196804

Singlet and Triplet DIPs (aug-cc-pVTZ) for 23 small molecules (FCI reference)



Marie & Loos, JCTC 20 (2024) 4751; Marie et al. (in preparation)

(Single-Site) Double Core Holes (aug-cc-pCVTZ & CVS-FCI reference)



Cederbaum et al. JCP 85 (1986) 6513; Marie et al. (in preparation)

- Antoine Marie
- Pina Romaniello
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