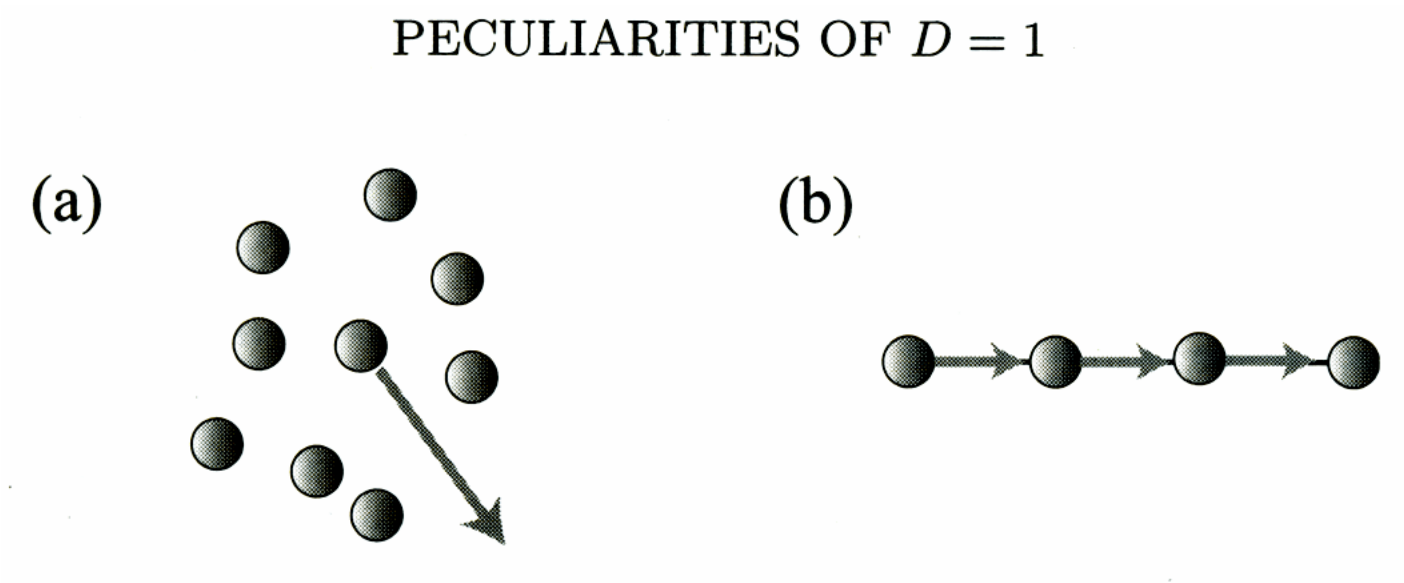
One-Dimensional Electron Systems at Surfaces

Physics in one dimension:

- Elegant and simple
- Lowest dimension with translational motion
- Electrons cannot avoid each other



2D,3D :

- Electrons avoid each other

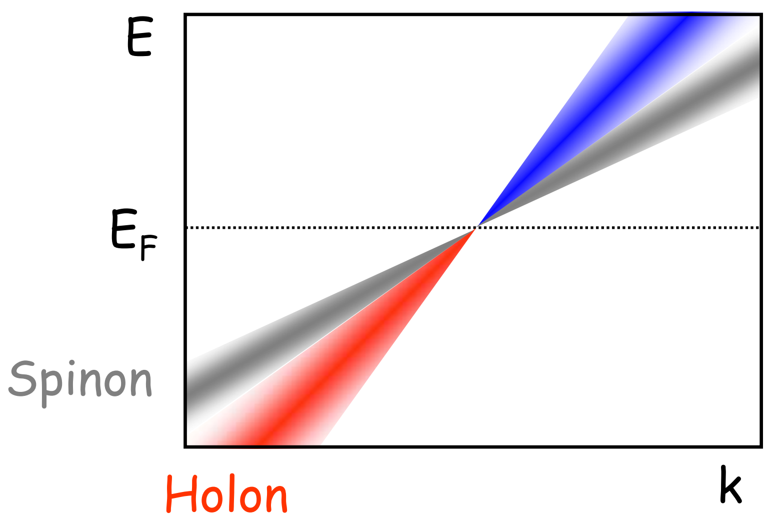
1D :

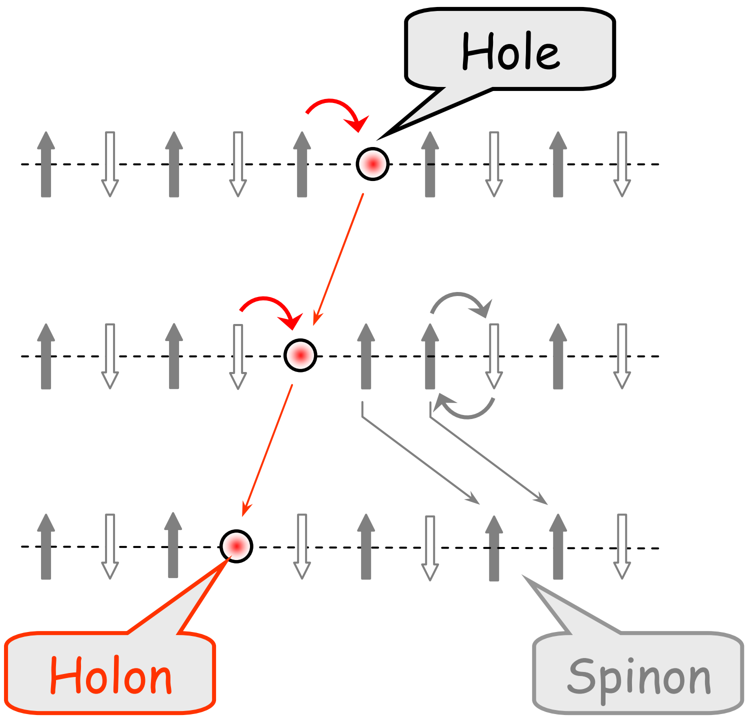
- Collective excitations
- Spin-charge separation

Giamarchi, *Quantum physics in one dimension*

Two Views of Spin Charge Separation

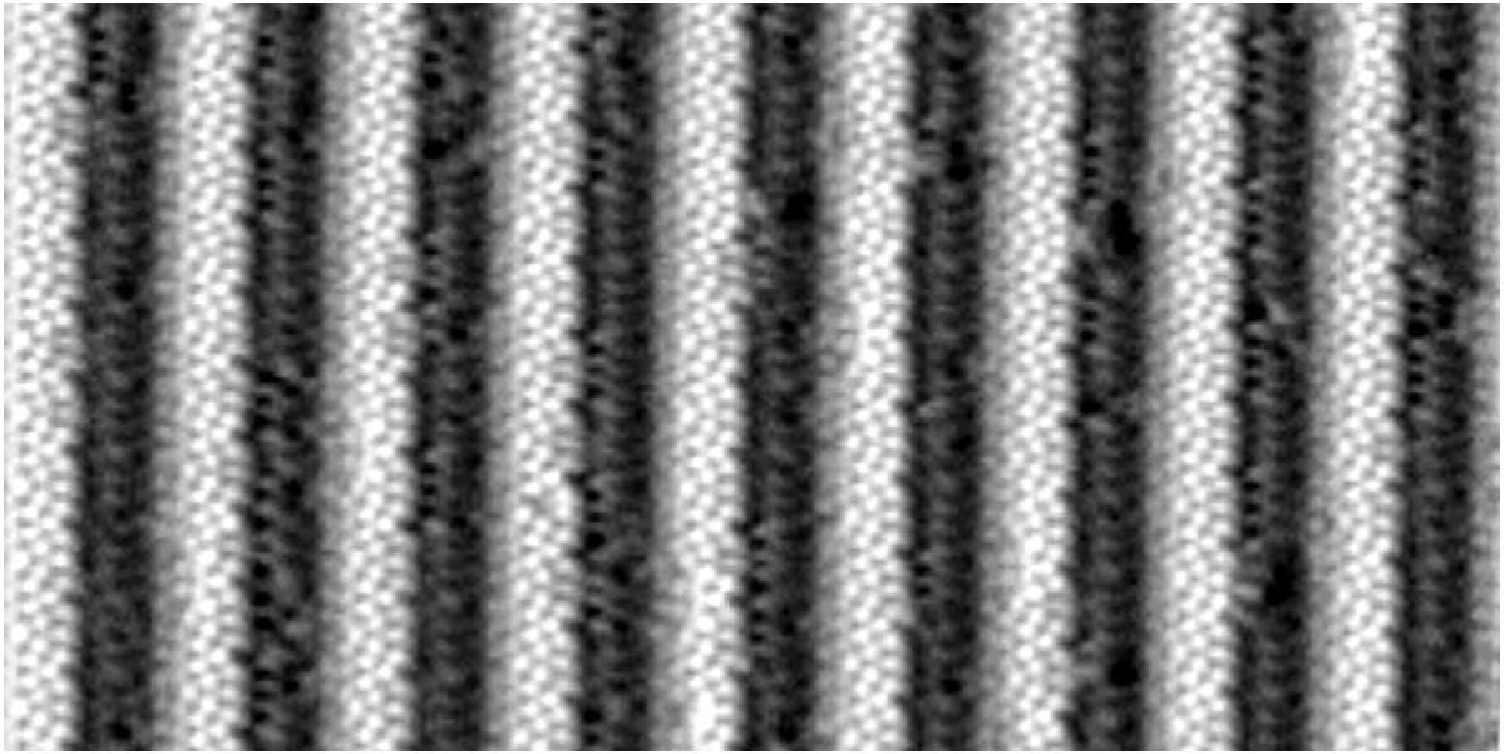
Delocalized e^- (k-space)	Localized e^- (real space)
Tomonaga-Luttinger Model	Hubbard, t-J Models





- Different velocities for spin and charge
- Holon and spinon bands intersect at E_F

Atomic Chains as the Ultimate Nanowires



- Straight steps at vicinal Si(111)7x7
  (1 kink in 20 000 edge atoms)

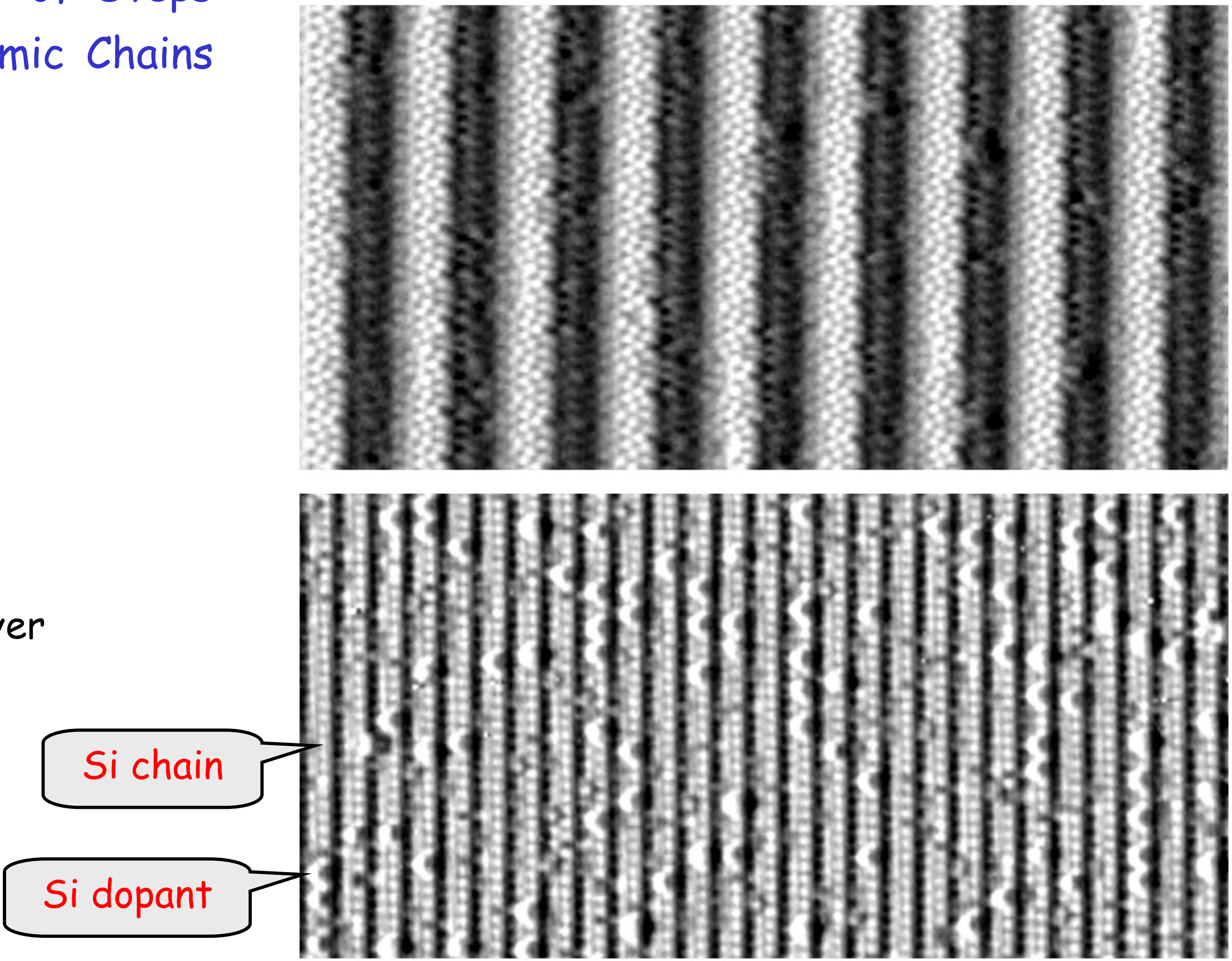
- Metallic surface states in the gap of silicon (truly 2D)

"Decoration" of Steps
⇒ 1D Atomic Chains

Clean

With Gold

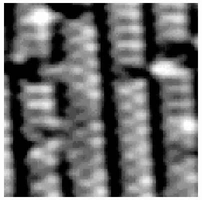
1/5 monolayer

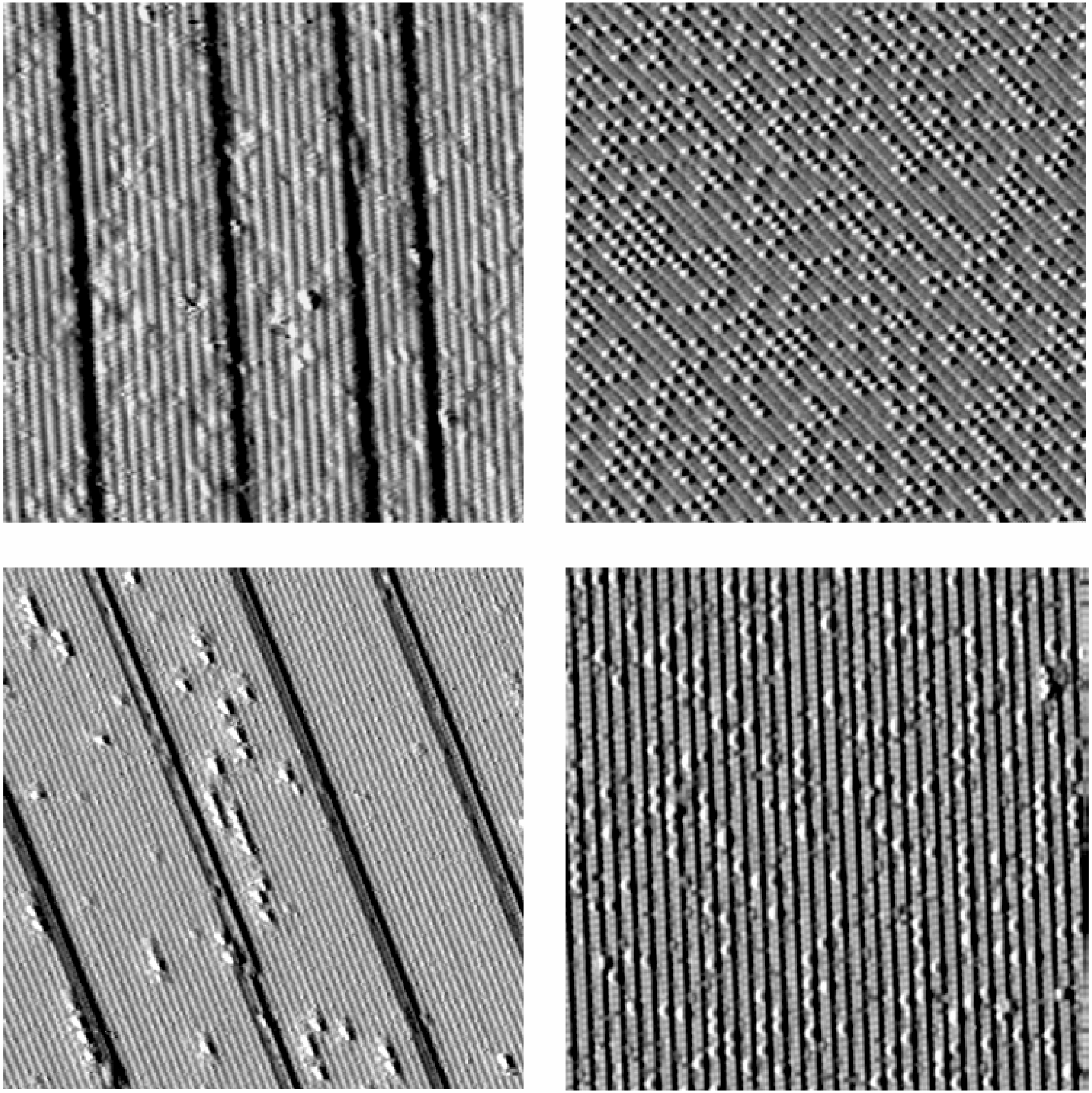


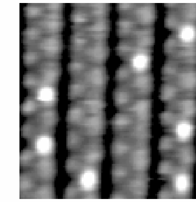
x-Derivative of the Topography, " Illumination from the Left "

Si(111) 5×2 - Gd

Si(111) 5×2 - Au



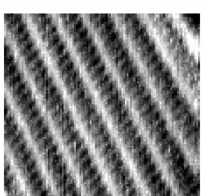


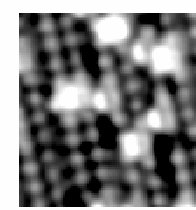


Many metals create chains

Li, Na,...
Ca,Ba,...
In
Ag, Au
Pt
Gd,Ho,Dy,Ce

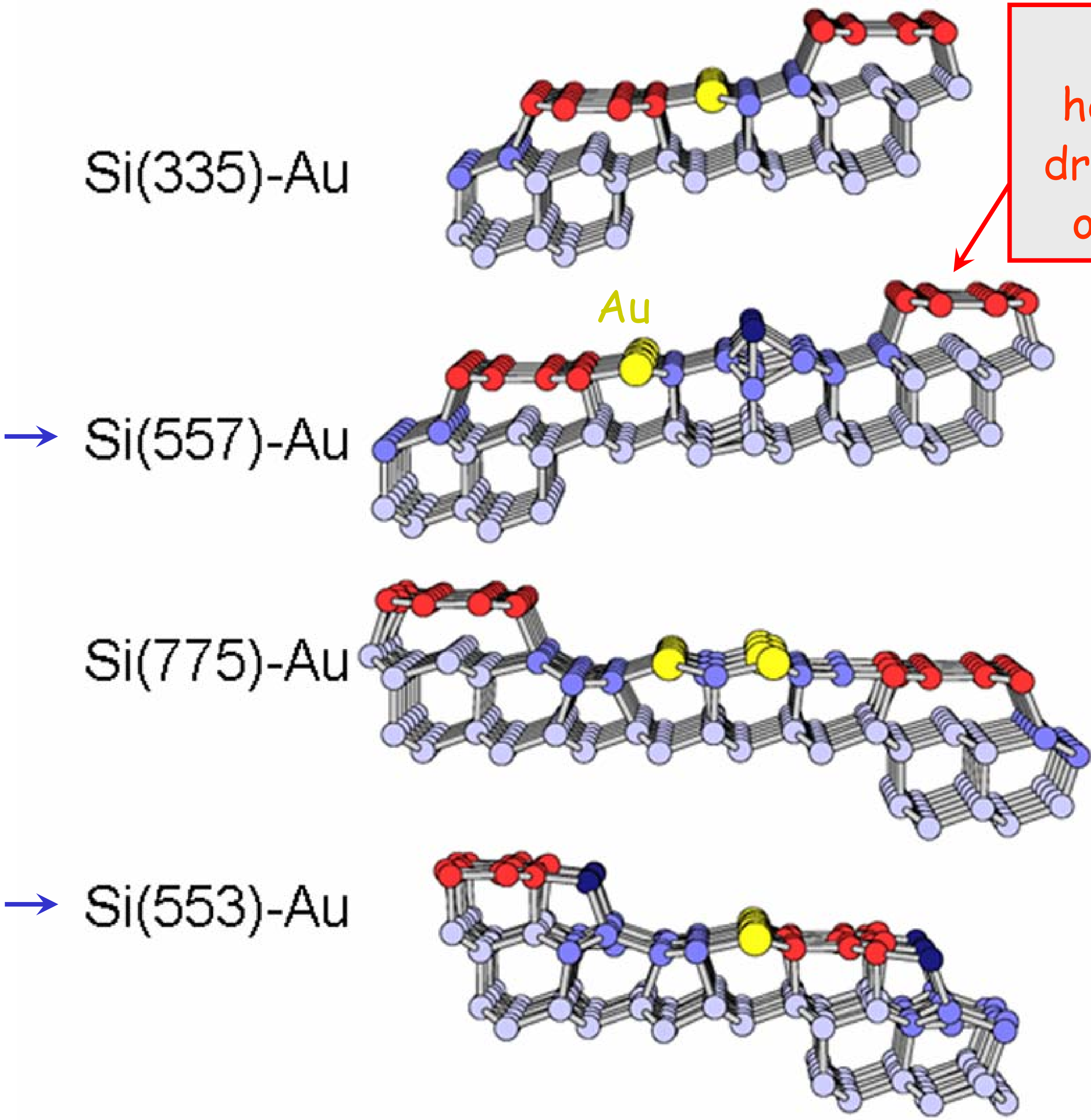
Also on Si(100), GaAs(110)





Si(111) 3×1 - Ag

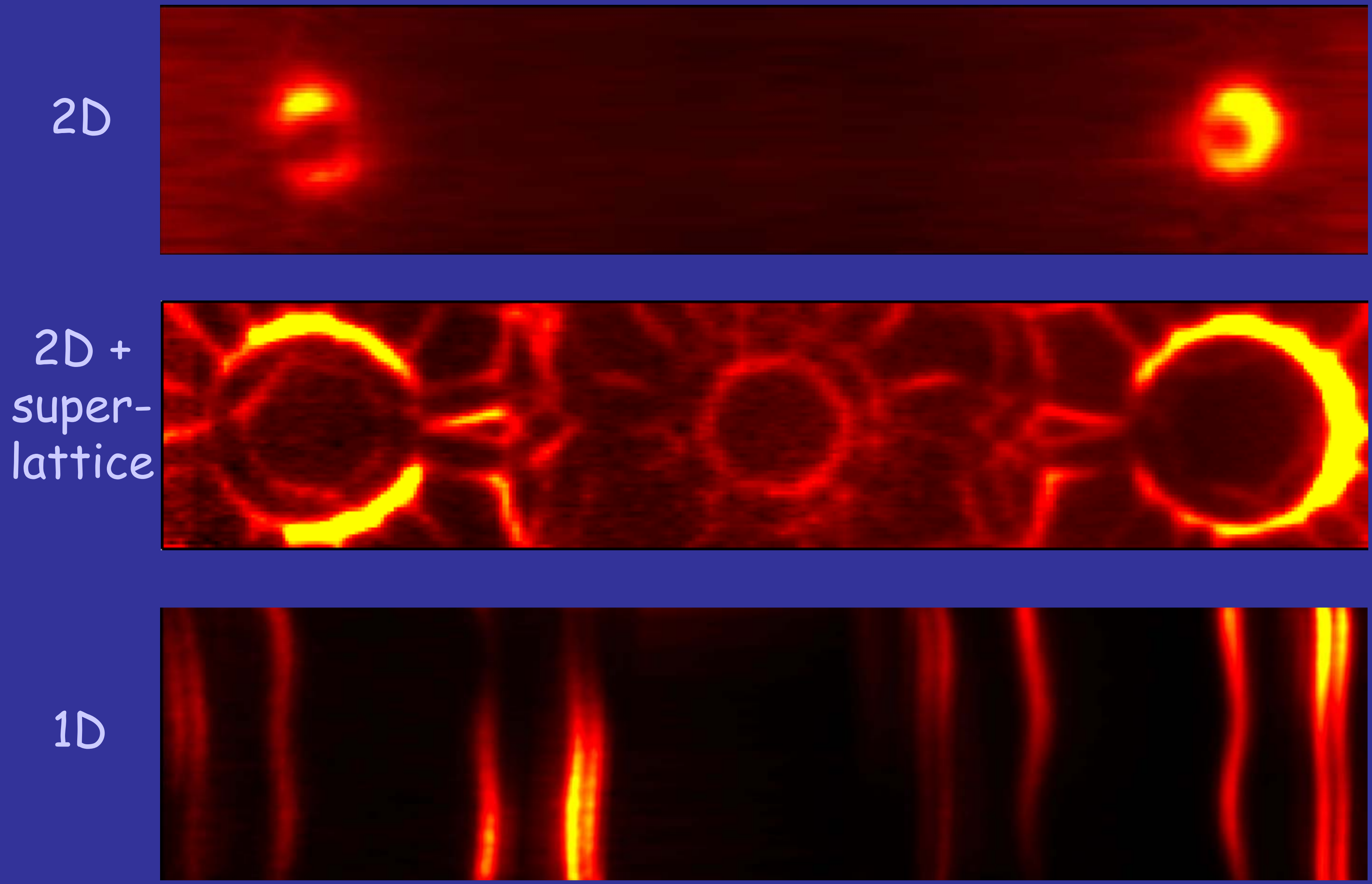
Si(557) - Au



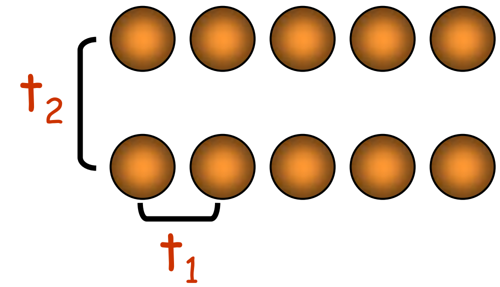
Graphitic honeycomb chain drives the surface one-dimensional

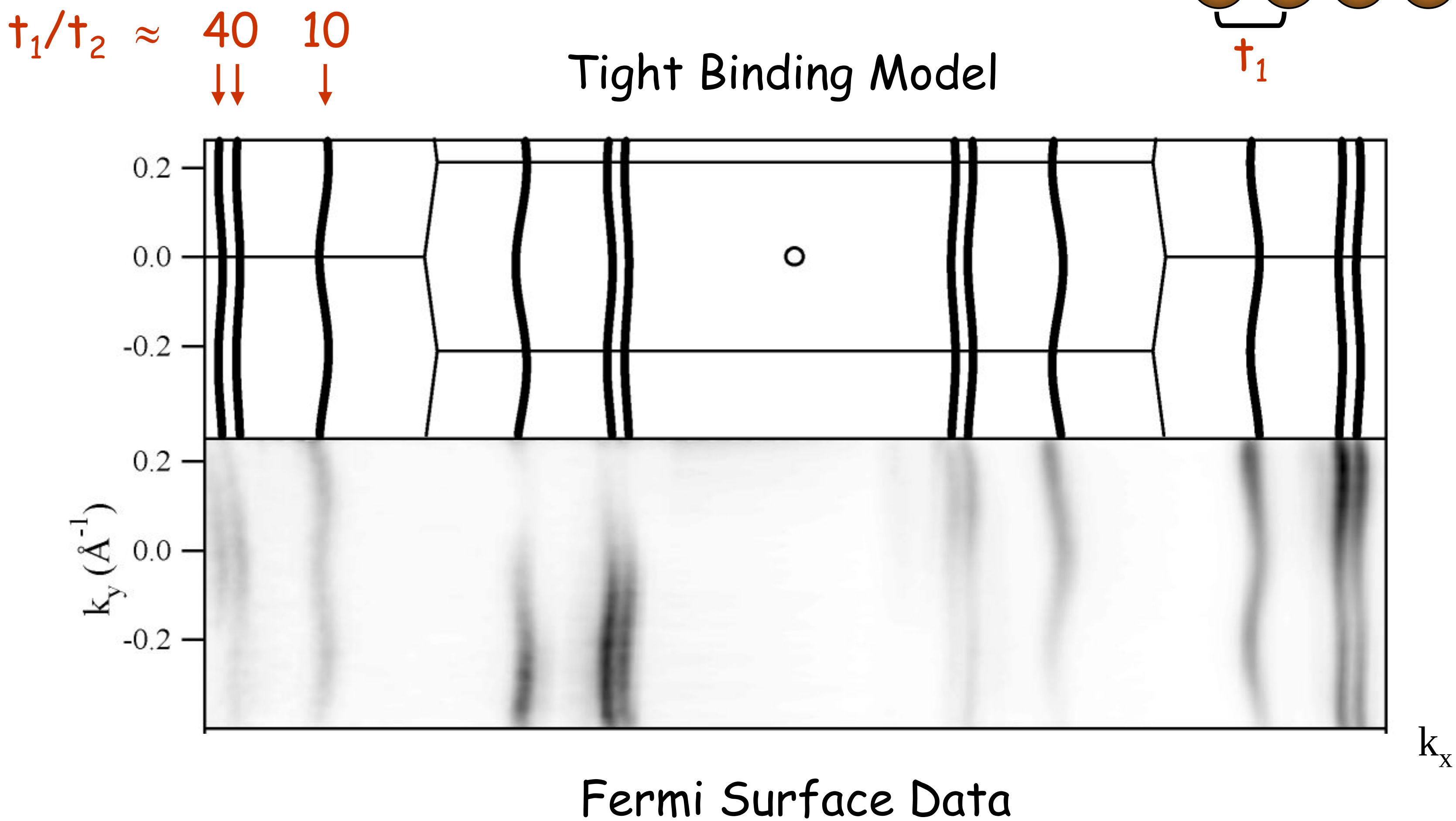
Variable chain spacing, coupling

Fermi Surfaces from 2D to 1D



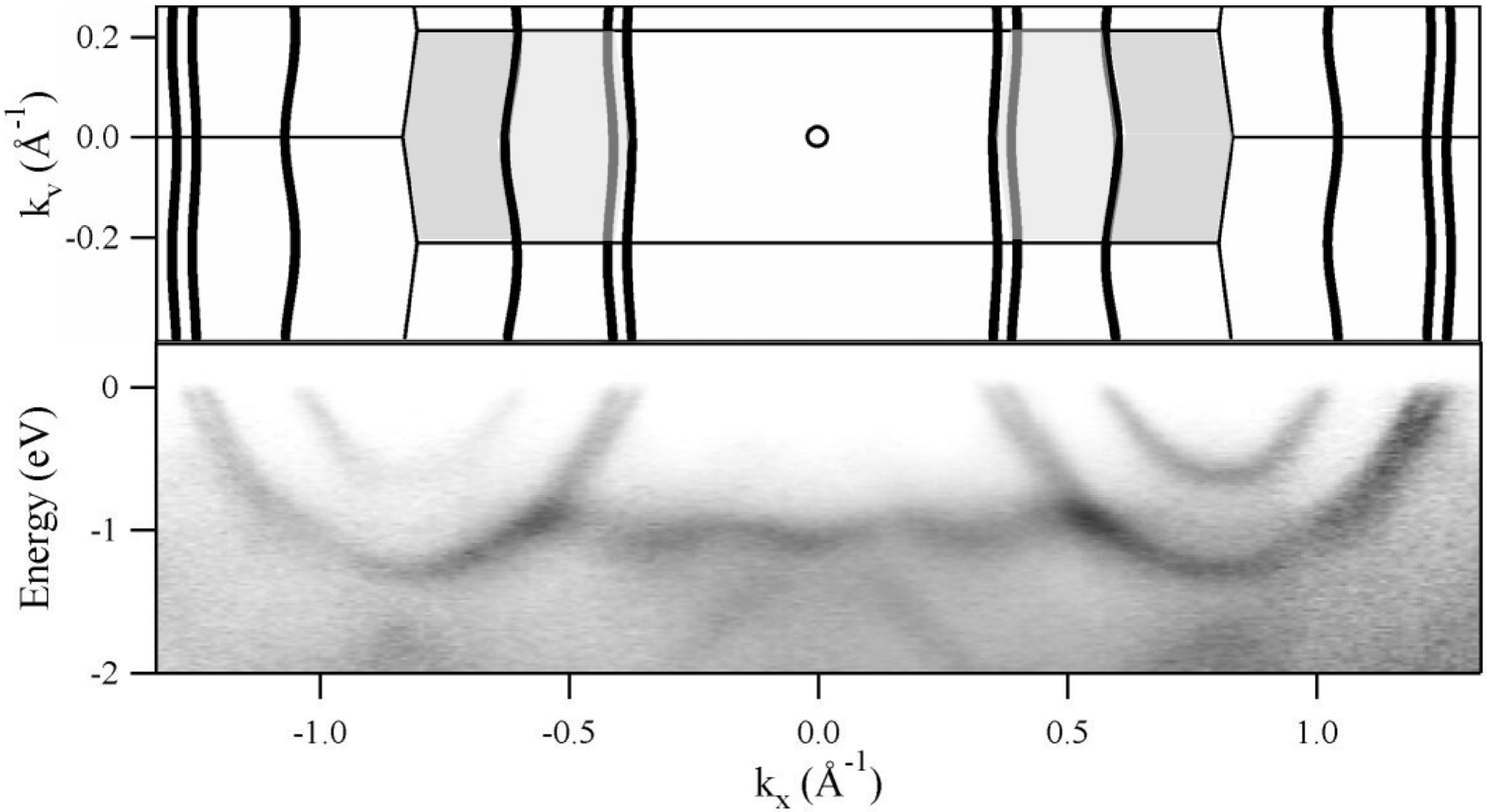
1D/2D Coupling Ratio





t_1/t_2 is variable from 10:1 to >70:1 via the step spacing

Fractional Filling

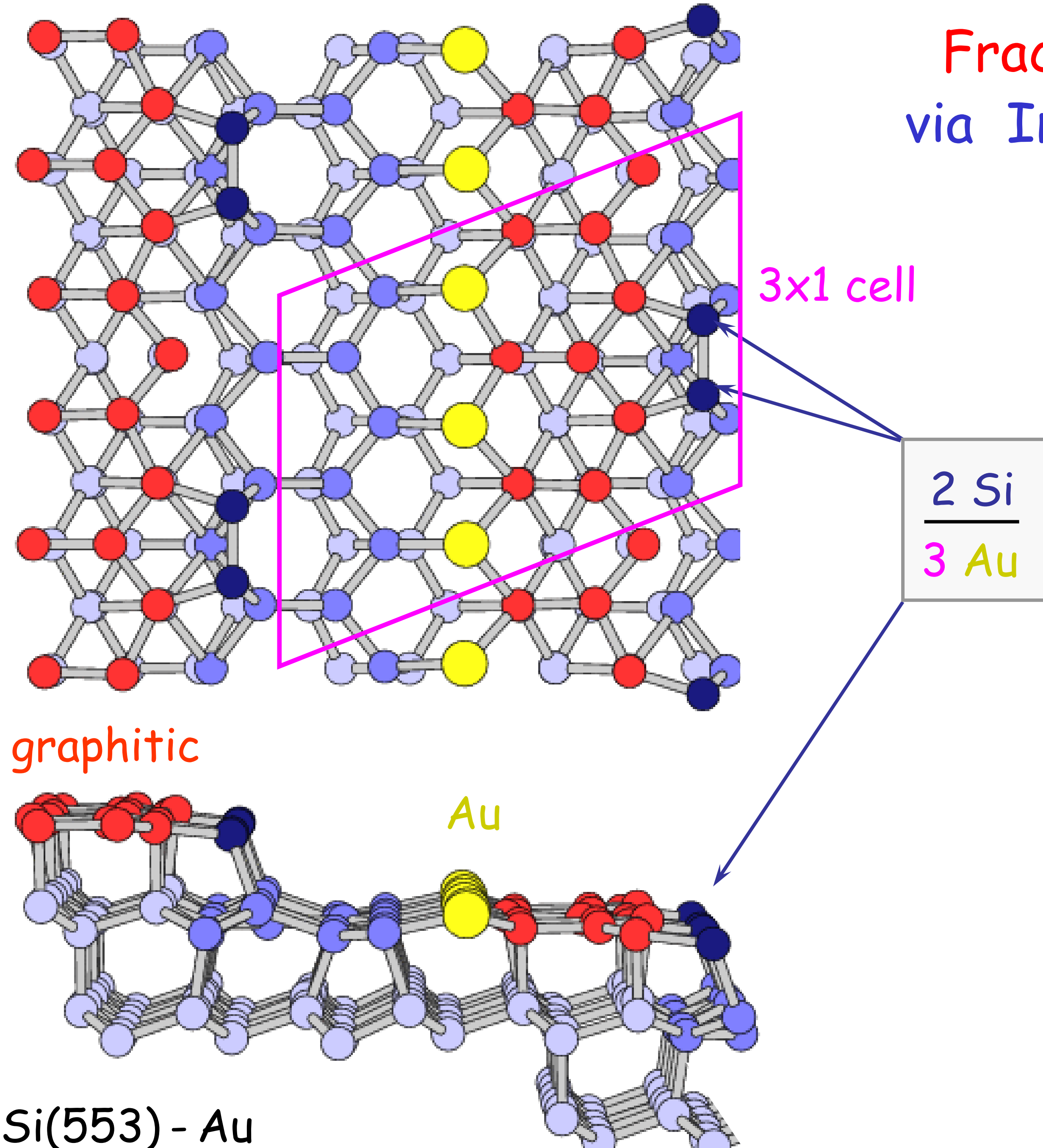


8/3 e^- per chain atom (spins paired)

5/3 e^- per chain atom (spin split)

Crain et al., PRL **90**, 176805 (2003)

Fractional Filling via Indirect Doping



Si(553) - Au

1D analog of HiTc doping

Fractional Charge

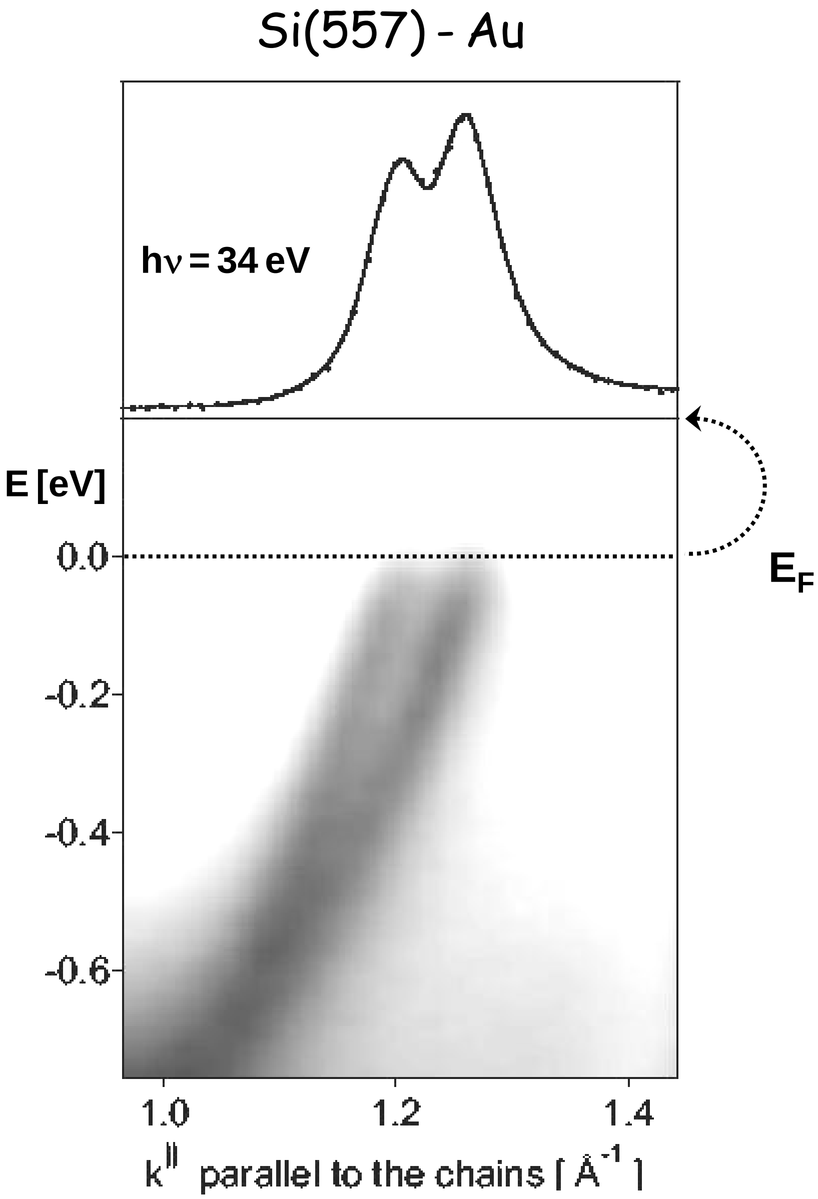
at the End of a CDW / Chain Segment

Seen for 2x1 (polyacetylene) : Su, Schrieffer, Heeger PR B **22**, 2099 (1980)

Predicted for 3x1 : Su, Schrieffer PRL **46**, 738 (1981)

Suggested for Si(553)3x1-Au : Snijders et al. PRL **96**, 076801 (2006)

Is there Spin-Charge Separation ?



Proposed by

Segovia et al., Nature **402**, 504 (1999)

Bands remain split at E_F

⇒ Not Spinon + Holon

Losio et al., PRL **86**, 4632 (2001)

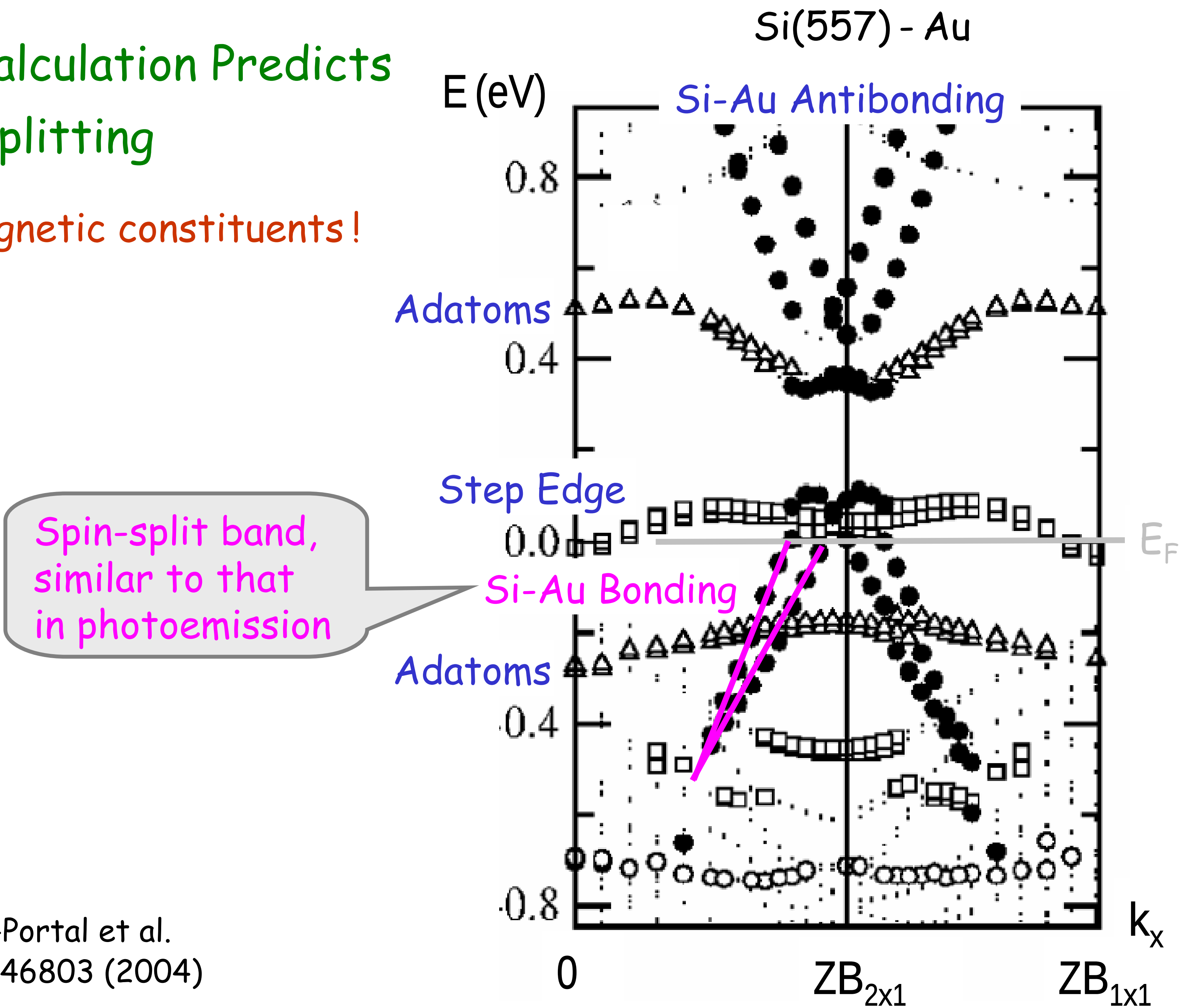
Why two half-filled bands ?

~ two half-filled orbitals

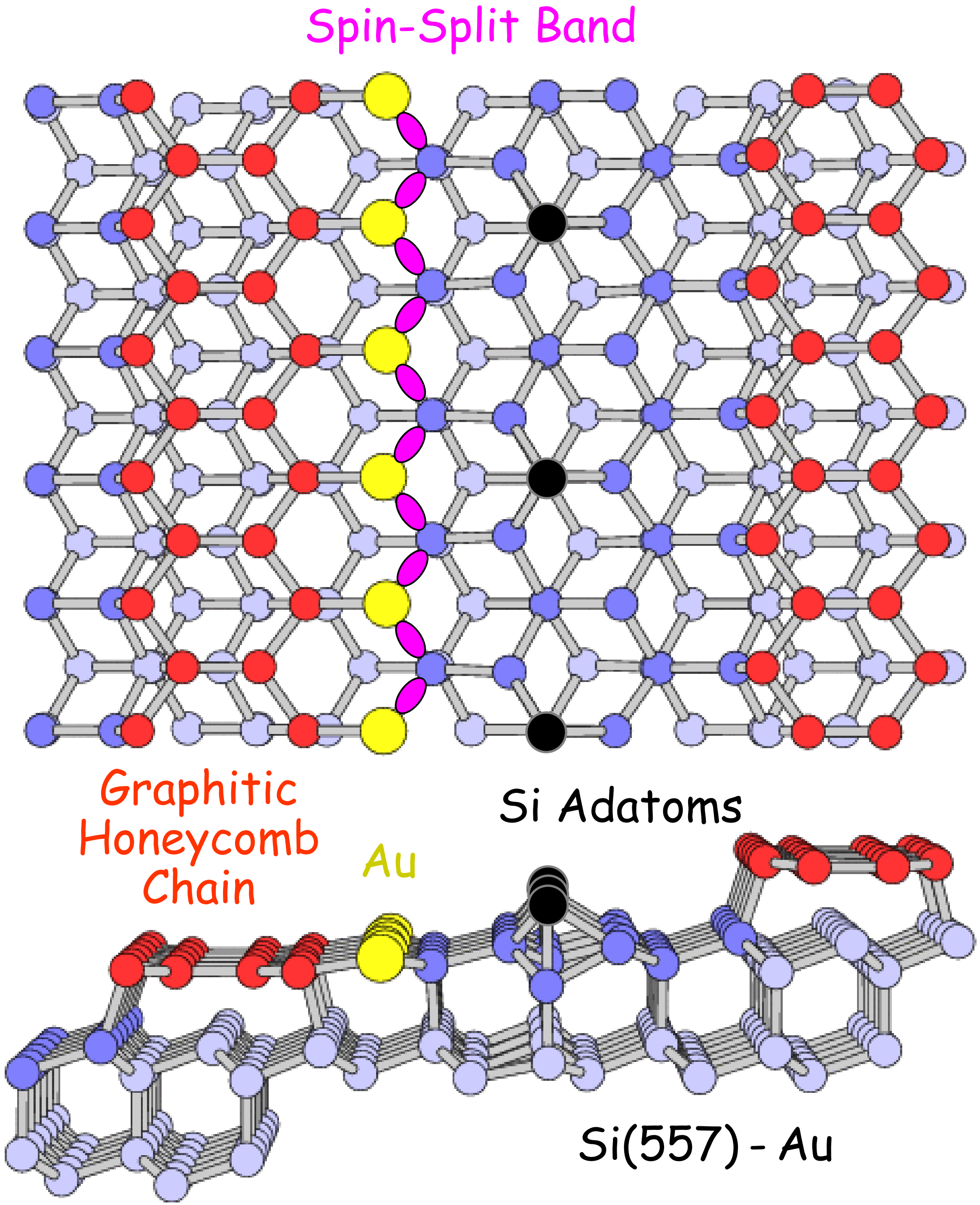
~ two broken bonds

LDA Calculation Predicts Spin Splitting

Non-magnetic constituents !



Sanchez-Portal et al.
PRL **93**, 146803 (2004)



First Principles Calculations:

Crain, Erwin, et al.,
PRB **69**, 125401 (2004)

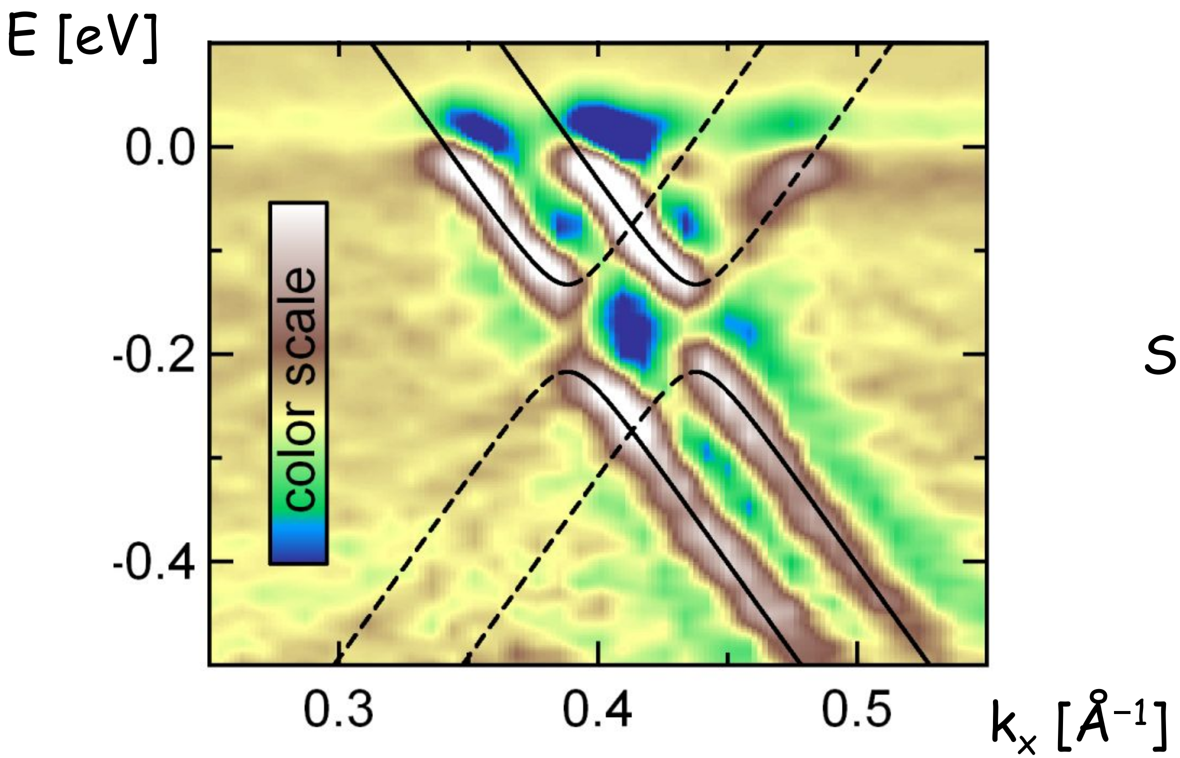
Sanchez-Portal et al.,
PRB **65**, 081401 (2002)

X-Ray Diffraction:

Robinson et al.,
PRL **88**, 096104 (2002)

Evidence for Spin-Splitting

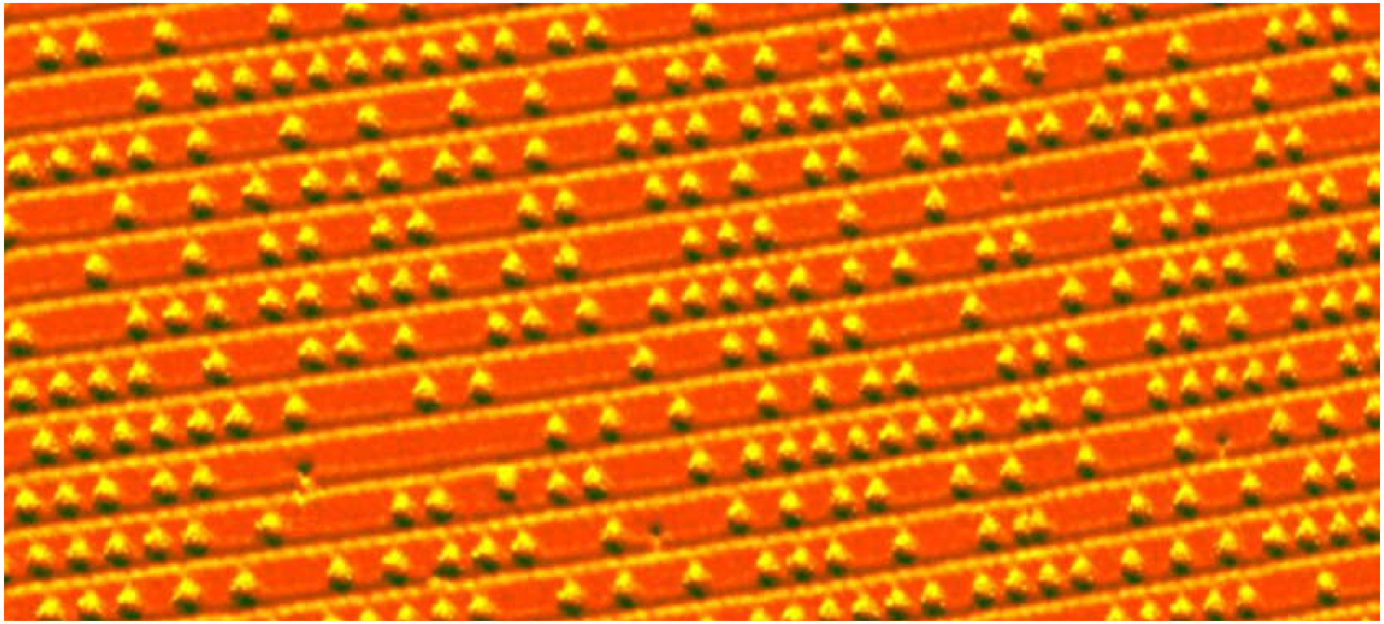
- Avoided crossings located left / right for spin-orbit (Rashba) splitting.
- Would be top / bottom for non-magnetic, (anti-)ferromagnetic splittings.



Si(553) - Au

Barke et al., PRL **97**, 226405 (2006)

Nanoscale Phase Separation in 1D



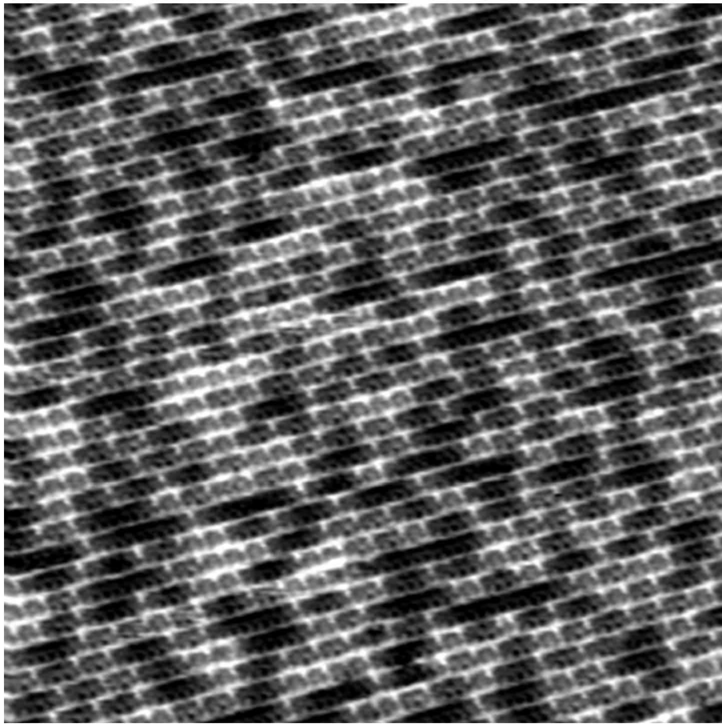
Si(111)5x2 - Au

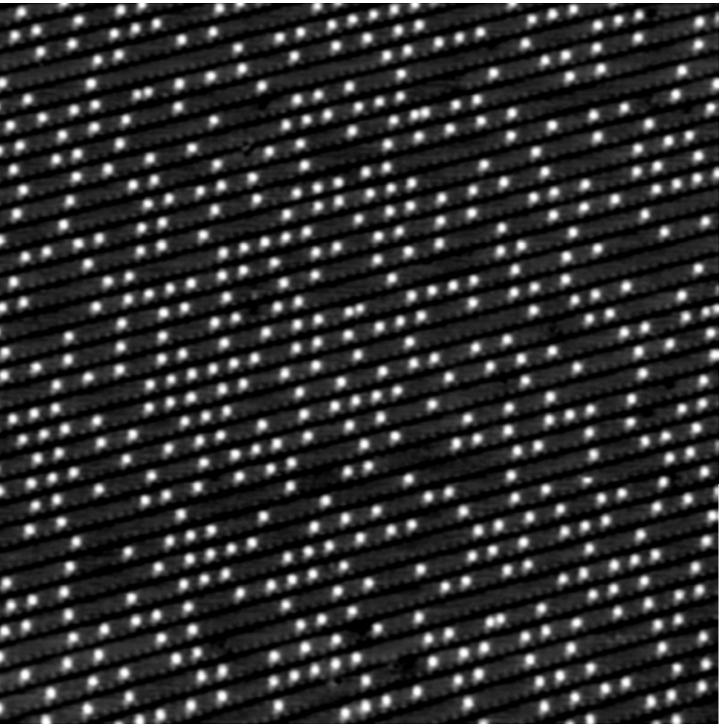
- Doped and undoped segments (1D version of "stripes")
  - Doped: gap !
  - undoped: metallic
- Competition between optimum doping[1] (5x8) and Fermi surface nesting[2] (5x4)
- Compromise: 50/50 filled/empty (5x4) sections

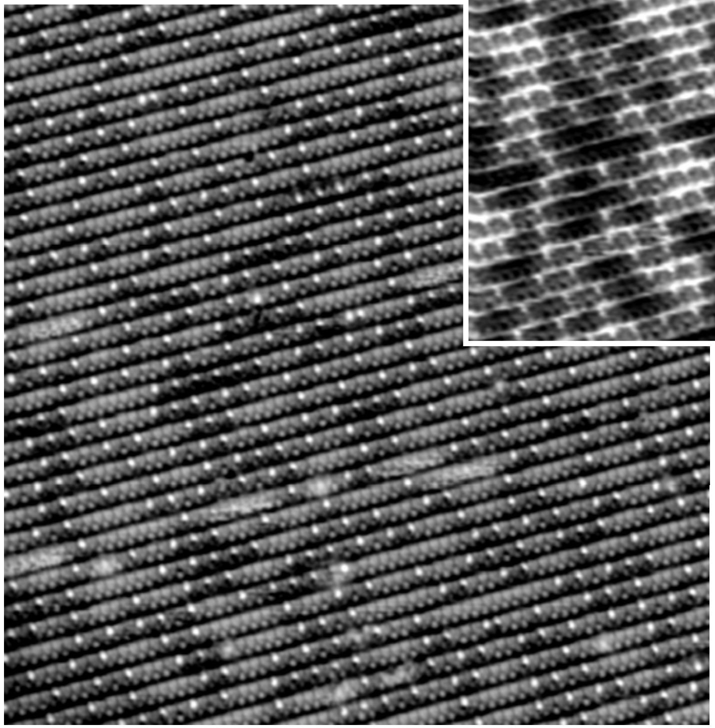
[1] Erwin, PRL **91**, 206101 (2003) [2] McChesney et al., Phys. Rev. B **70**, 195430 (2004)

What Determines the Length of the Segments ?

Spectroscopy +0.8V







-1.2V ⟵ Topography ⟶ +0.8V

Barke et al., unpublished

- Tunable band filling, fractional 5/3
- Tunable chain coupling, 10:1 to >70:1
- Tunable magnetic moment (rare earths)

$\Rightarrow$ New playground for low-dimensional physics

Use semiconductor substrates

- Metal atoms locked to the substrate
- Electrons at E_F decouple (in the gap)

Overview: Crain and Himpsel, Appl. Phys. A **82**, 431 (2006)