Visualizing Electronic Structures of Quantum Materials
– By Angle Resolved Photoemission Spectroscopy (ARPES)

PART B: New Frontier in ARPES

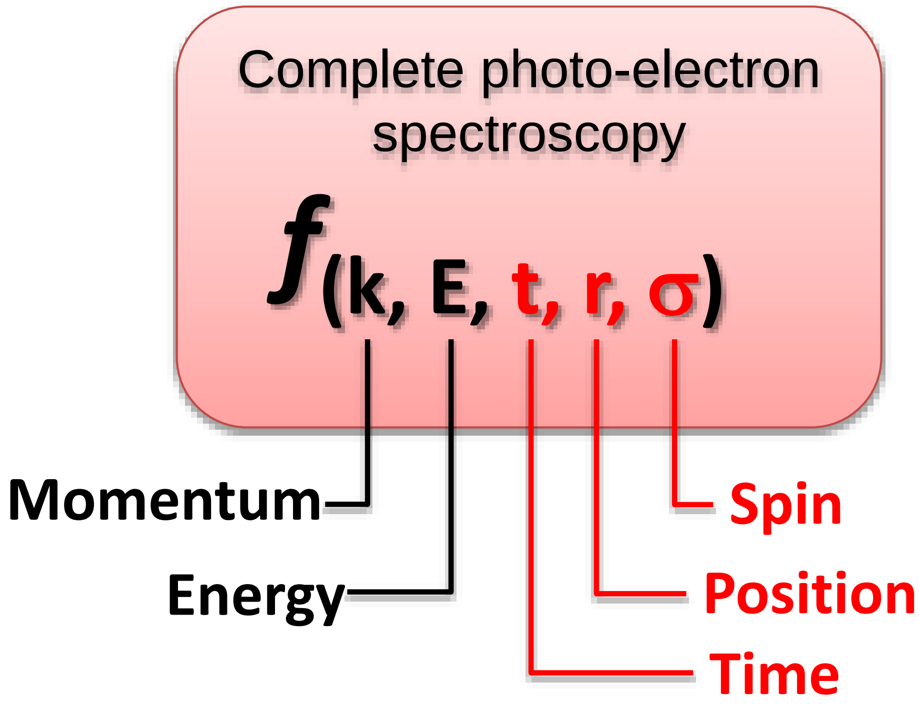
Yulin Chen

Oxford University / Tsinghua University

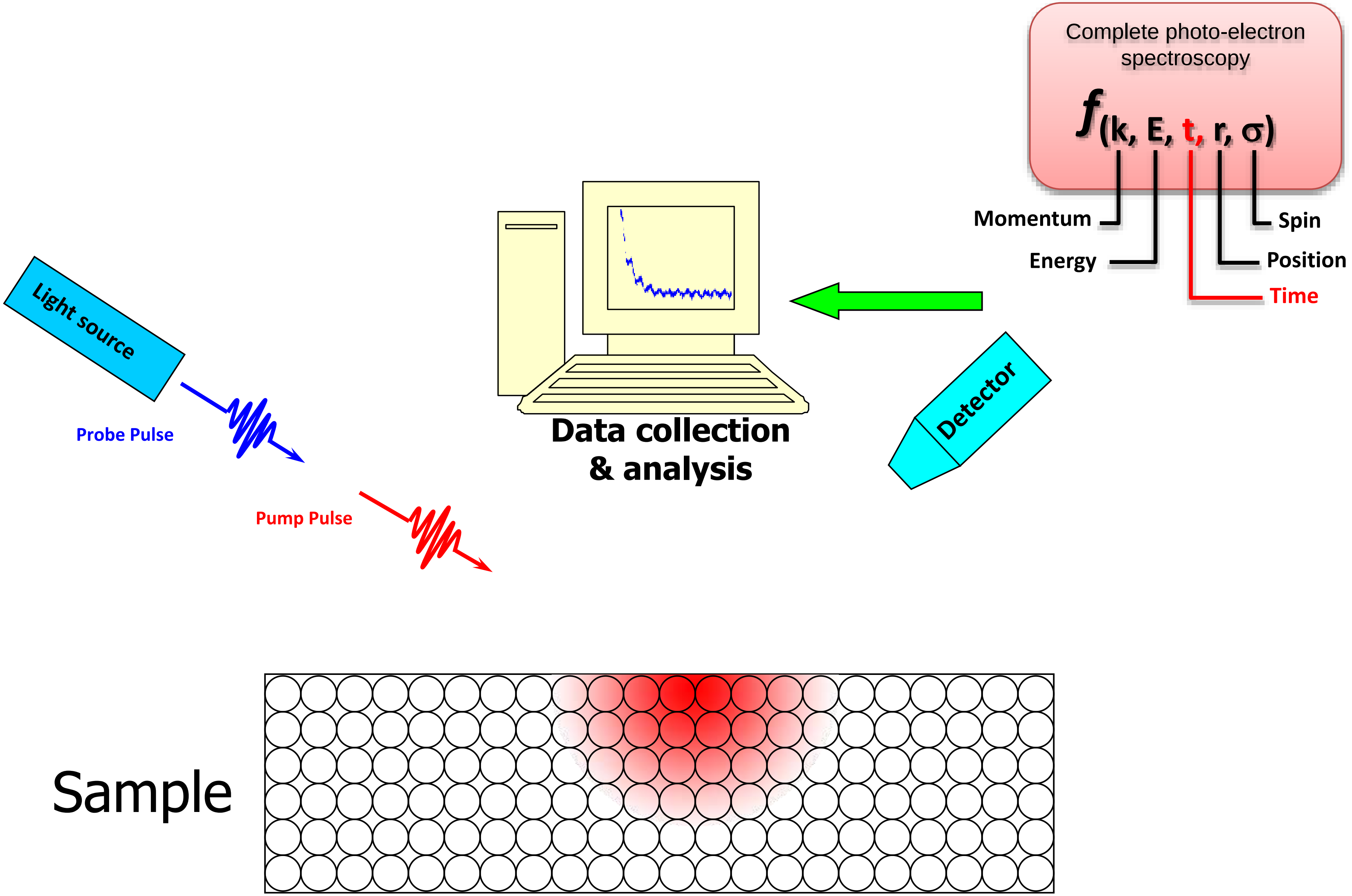
www.arpes.org.uk

Yulin.Chen@physics.ox.ac.uk ; yulinchen@mail.tsinghua.edu.cn

New Frontiers



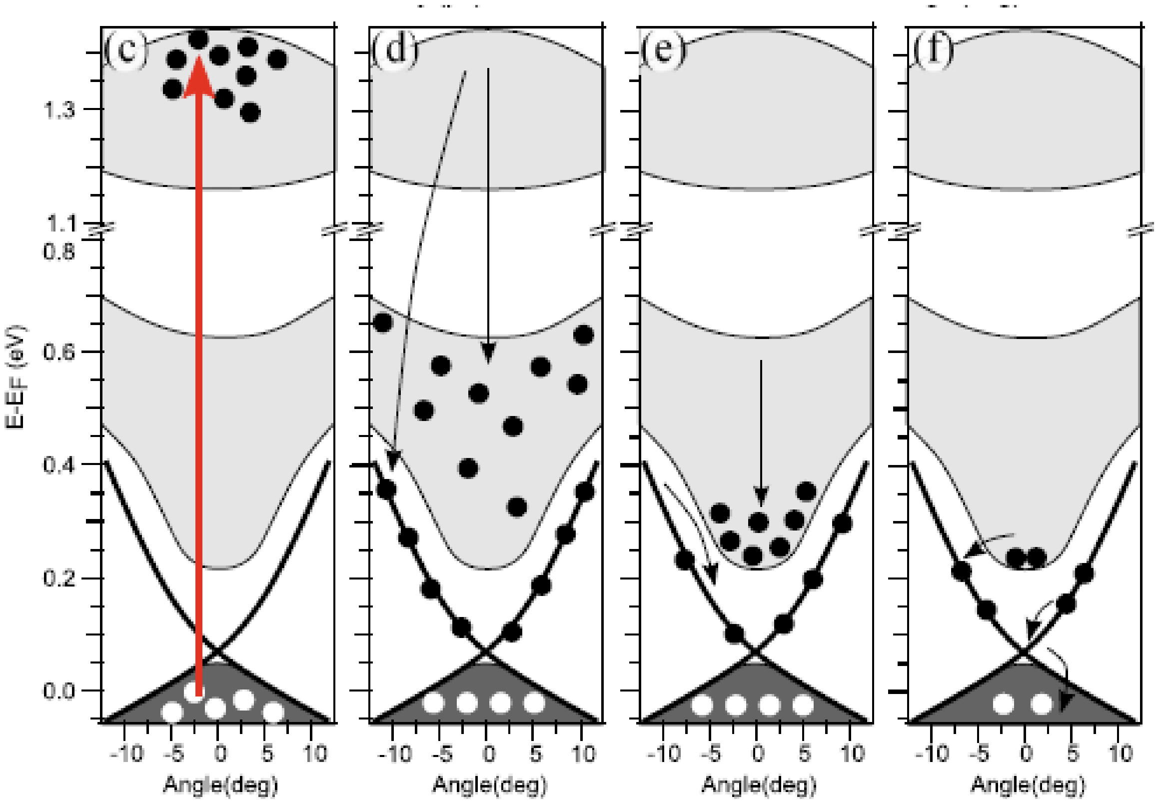
Explore electron dynamics



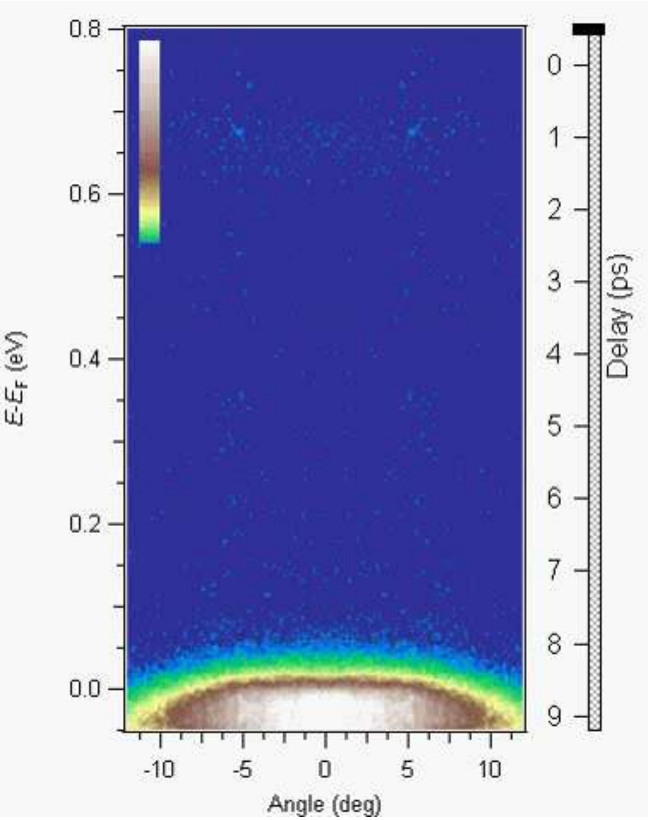
Long lived surface electrons of Bi_2Se_3

J. Sobota, *et al. Phys. Rev. Lett.* **108,** 117403 (2012)

Physical process



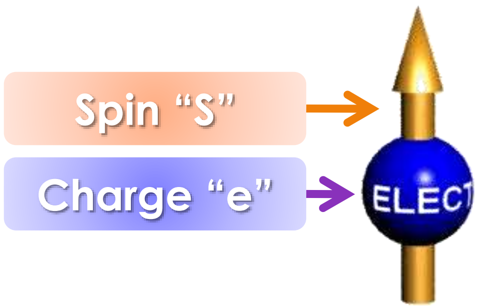
Measurement

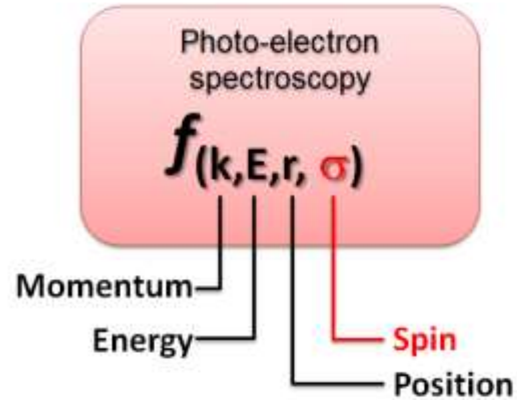


Spin resolved ARPES

New frontier

Explore electron spin





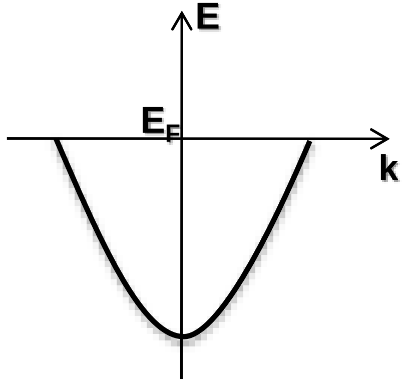
Spin information is important for:

- ❑ Topological quantum materials
- ❑ CMR materials
- ❑ Novel superconductivities
- ❑ Multiferroic materials
- ❑ Heavy fermion systems
- ❑ Spintronics applications

…

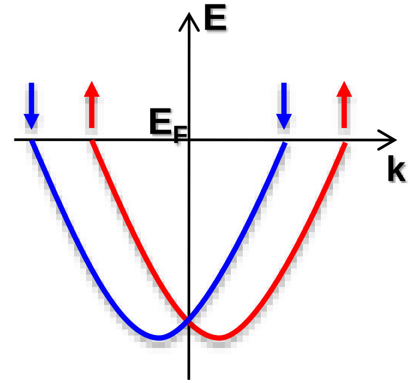
Materials with spin-dependent electronic structure

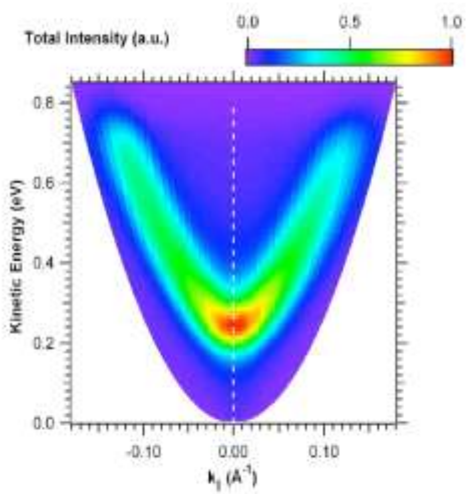
Free electron dispersion

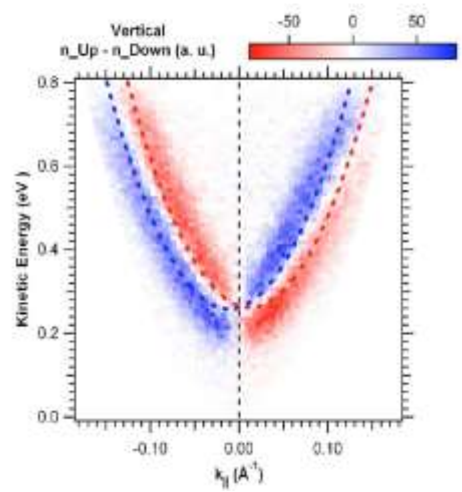


SOC

Free electron dispersion

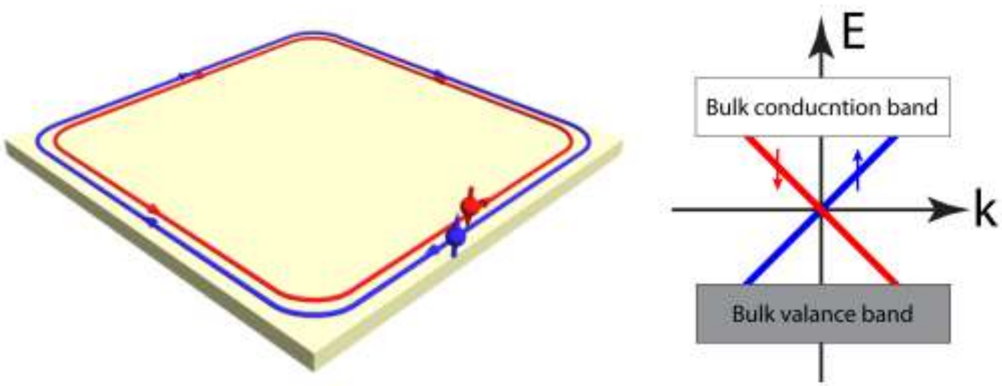




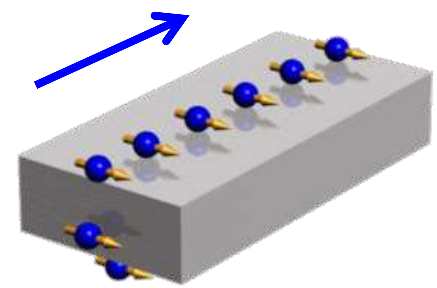


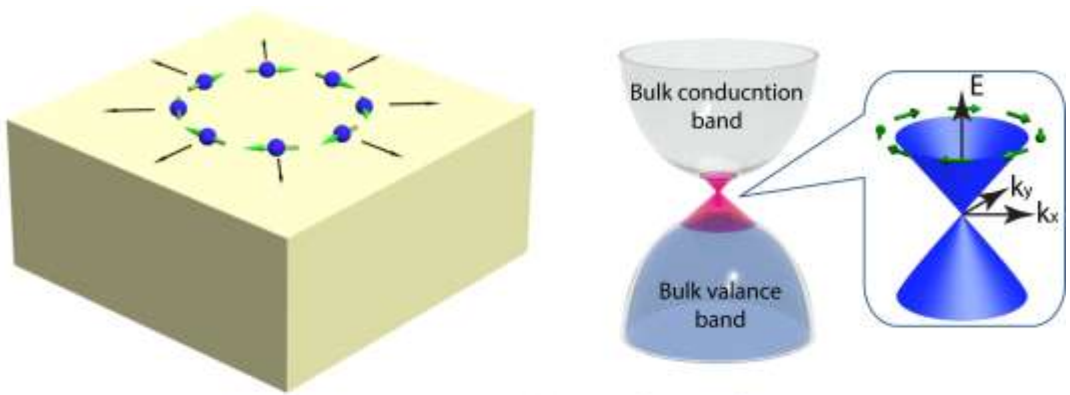
Exotic spin states: Topological insulators

“Locking” of current & spin

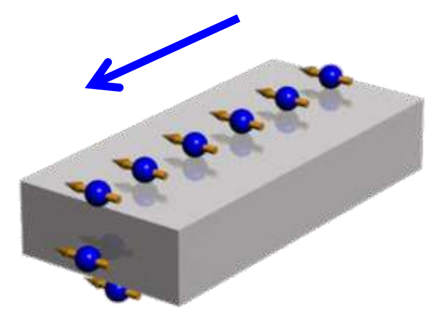


2D Topological insulator (QSH insulator)





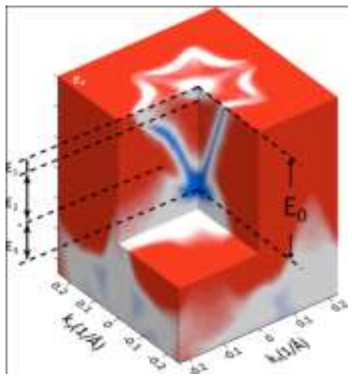
3D Topological insulator



Understand the spin of topological surface electrons

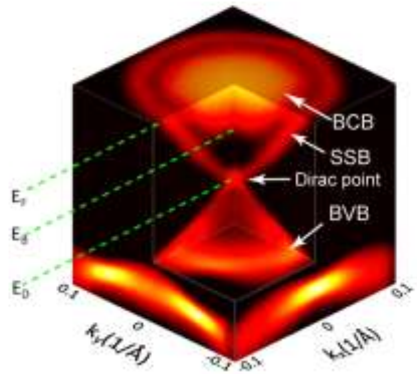
Regular ARPES
3D structure

Bi_2Te_3



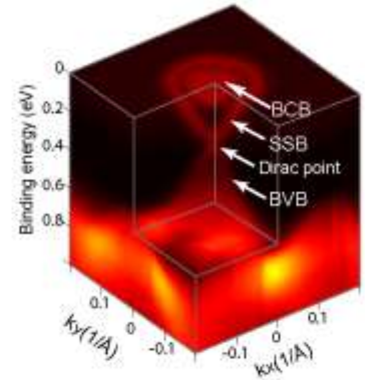
Y. L. Chen, *et. al.*,
Science 325, 178 (2009)

Bi_2Se_3



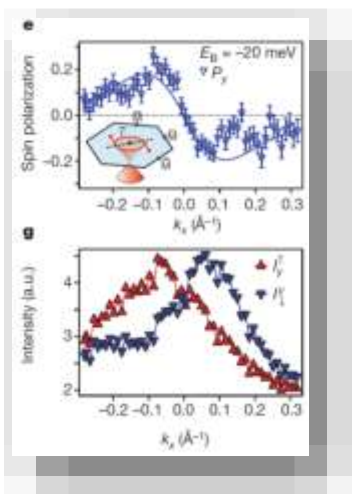
Y. L. Chen, *et. al.*,
Science 329, 659 (2010)

$TlBiSe_2$

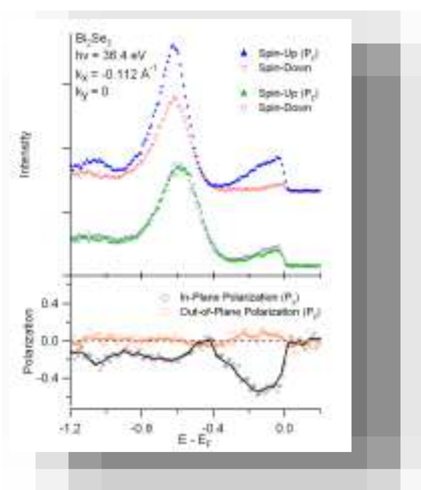


Y. L. Chen, *et. al.*,
Phys. Rev. Lett., 105 266401 (2010)

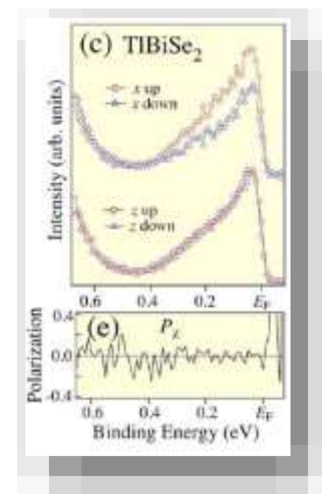
Spin-ARPES
1D structure



D. Hsieh, *et. al.*,
Nature 460, 1101 (2009)



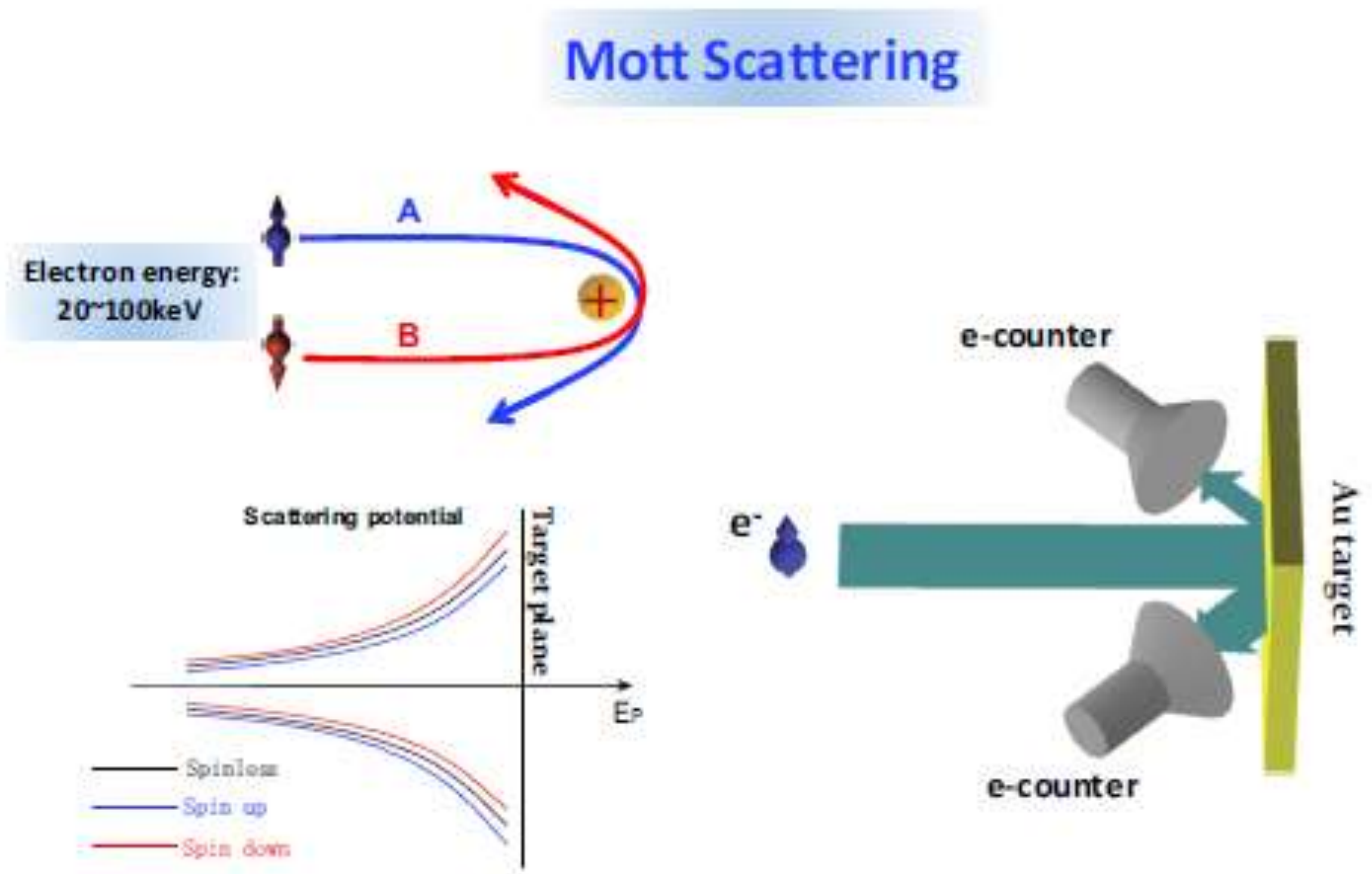
C. Jozwiak, et al.
Phys. Rev. B. **84,** 165113 (2011)



Souma, *et. al.*,
Phys. Rev. Lett., 106, 216803 (2011)

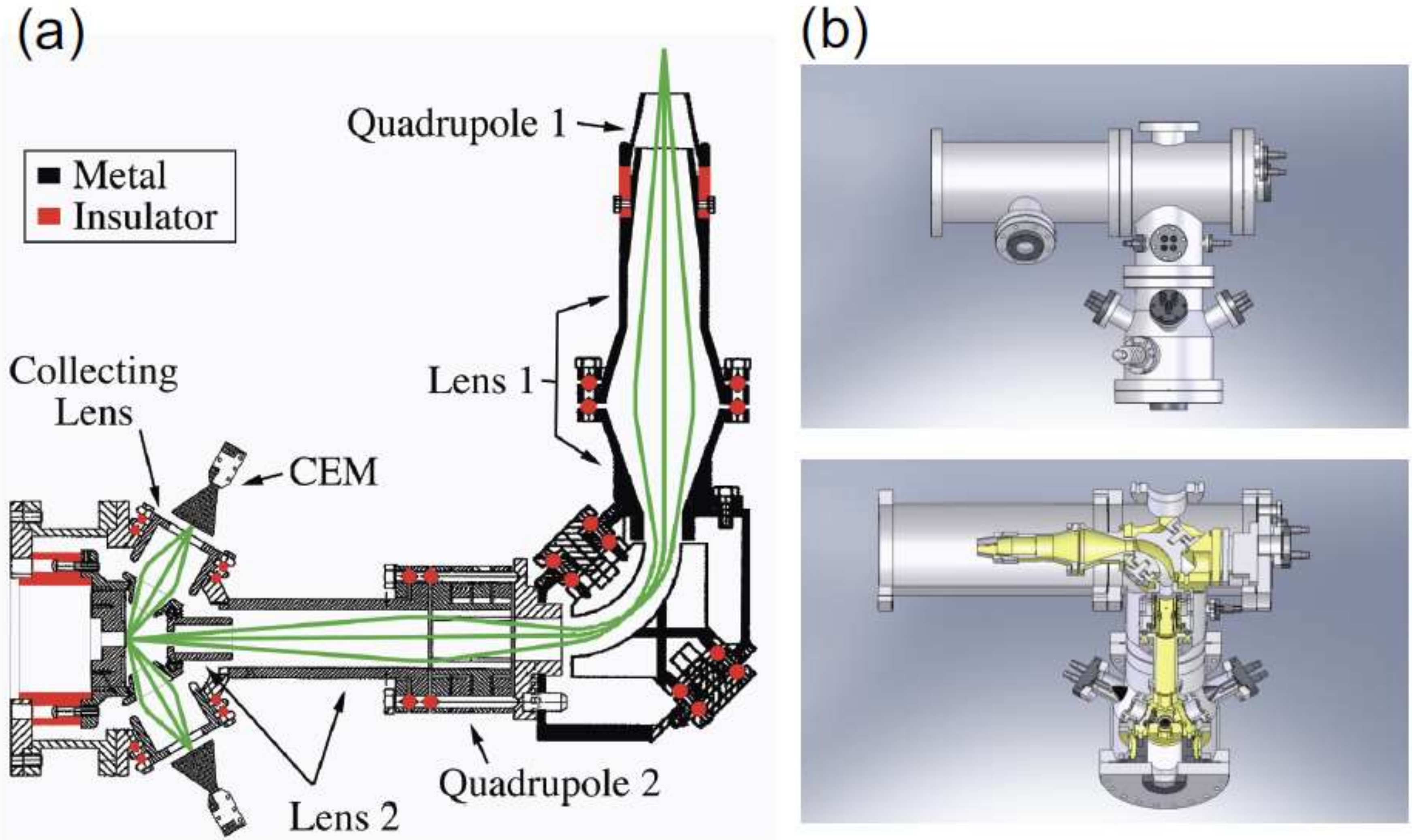
Detecting Electron Spin

Mott scattering spin polarimeter



Detecting Electron Spin

Mott scattering spin polarimeter



Detecting Electron Spin

Figure of Merit

$$A = \frac{I_{left} - I_{right}}{I_{left} + I_{right}} = PS$$ => $$P = \frac{A}{S} \Rightarrow \Delta P = \frac{\Delta A}{S} = \sqrt{\frac{1}{IS^2}}$$

$$\Delta A = \sqrt{(\frac{\partial A}{\partial I_{left}})^2(\Delta I_{left})^2 + (\frac{\partial A}{\partial I_{right}})^2(\Delta I_{right})^2}$$

$$= \sqrt{(\frac{2I_{right}}{(I_{left} + I_{right})^2})^2 I_{left} + (-\frac{2I_{left}}{(I_{left} + I_{right})^2})^2 I_{right}}$$

as $I = I_{left} + I_{right}$

$$= \sqrt{\frac{4I_{left}I_{right}}{I^3}}$$

$$4I_{left}I_{right} = I^2(1 - P^2S^2)$$ => $$4I_{left}I_{right} \approx I^2$$

$$\approx \sqrt{\frac{1}{I}}$$

=> $$\Delta P = \frac{\Delta A}{S} = \sqrt{\frac{1}{IS^2}}$$

Detecting Electron Spin

Figure of Merit

$$\Delta P = \frac{\Delta A}{S} = \sqrt{\frac{1}{IS^2}}$$

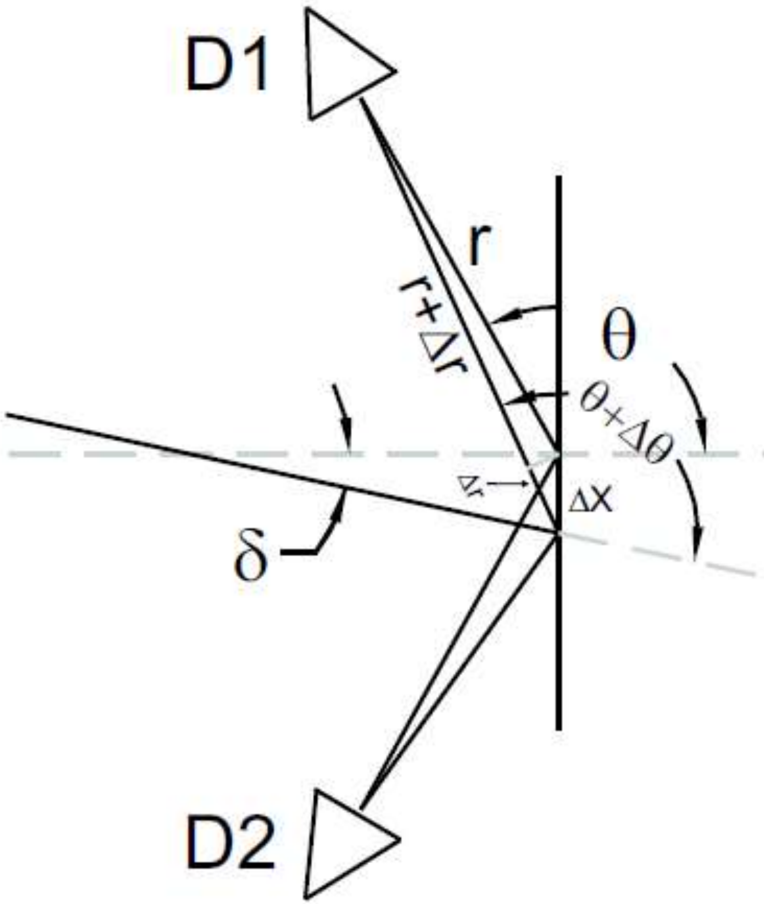
To minimize ΔP, we need to maximize IS^2

So normalized by the total initial flux I_0, the index is defined as "Figure of Merit" (FOM)

$$FOM = S^2 \frac{I}{I_0}$$

Detecting Electron Spin

Mott scattering spin polarimeter



$$N^+ = \sqrt{L_\uparrow R_\downarrow} \qquad N^- = \sqrt{R_\uparrow L_\downarrow}$$

$$L_\uparrow = nNE_l\Omega_l(\Delta r, \Delta\theta)\sigma(\theta+\Delta\theta)(1 + PS(\theta) + P\frac{\partial S}{\partial\theta}\Delta\theta)$$

$$R_\uparrow = nNE_r\Omega_r(\Delta r, \Delta\theta)\sigma(\theta+\Delta\theta)(1 - PS(\theta) + P\frac{\partial S}{\partial\theta}\Delta\theta)$$

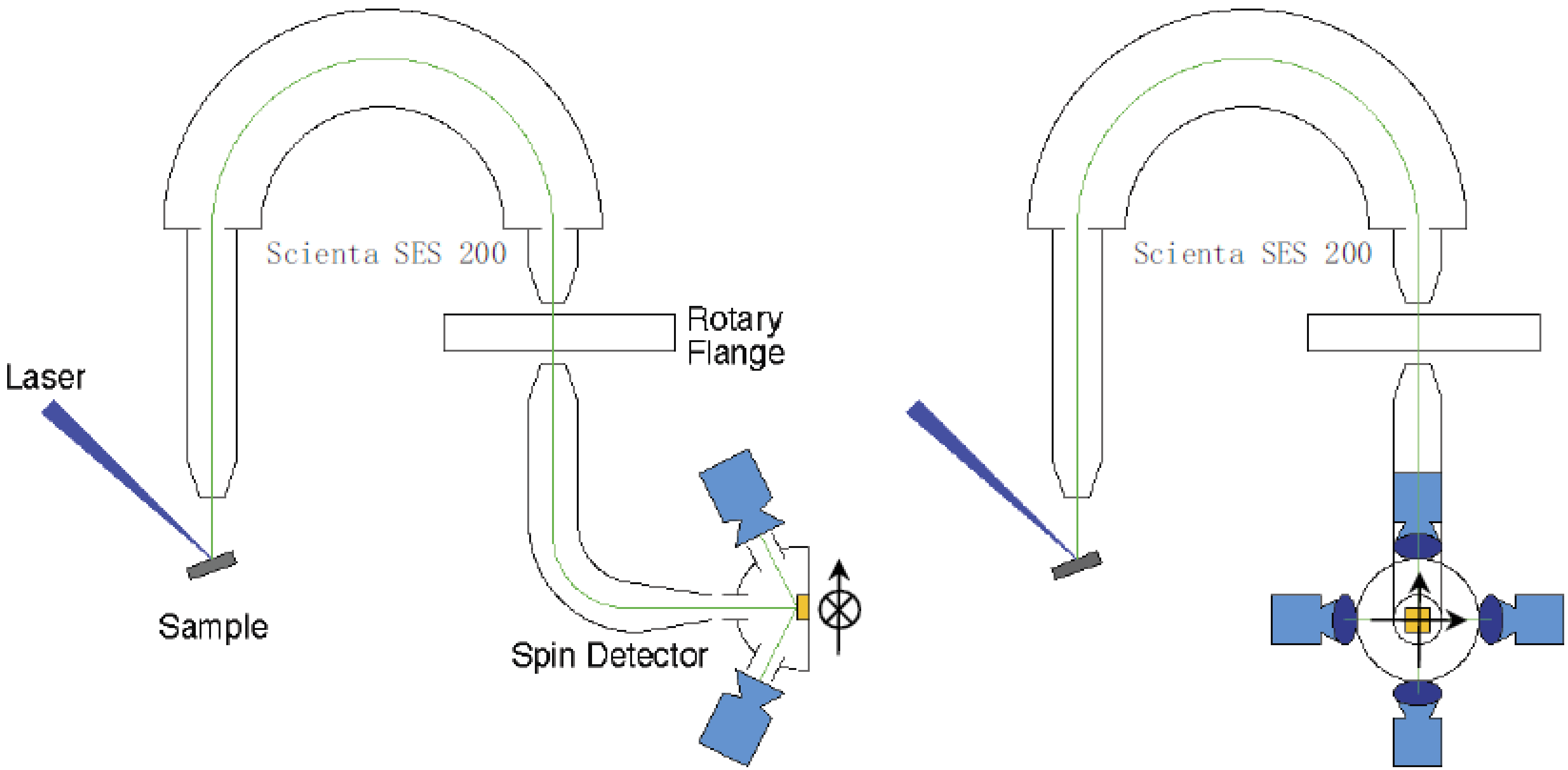
$$L_\downarrow = n'NE_l\Omega_l(\Delta r, \Delta\theta)\sigma(\theta+\Delta\theta)(1 - PS(\theta) - P\frac{\partial S}{\partial\theta}\Delta\theta)$$

$$R_\downarrow = n'NE_r\Omega_r(\Delta r, \Delta\theta)\sigma(\theta+\Delta\theta)(1 + PS(\theta) - P\frac{\partial S}{\partial\theta}\Delta\theta)$$

$$A = \frac{N^+ - N^-}{N^+ + N^-} = PS$$

Detecting Electron Spin

Mott scattering spin polarimeter

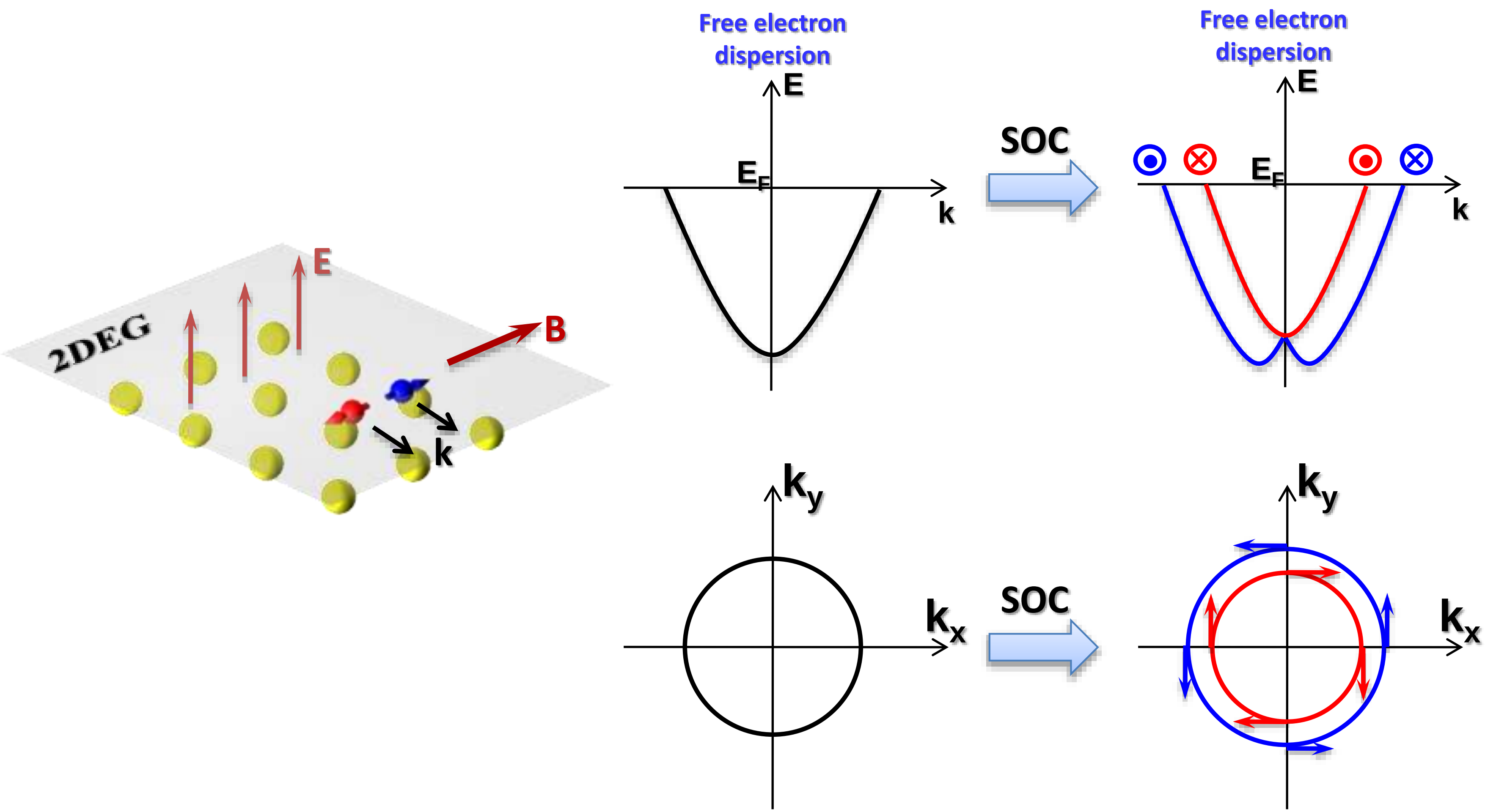


First Arrangement:
Measures $P_{\otimes}$ and $P_{\uparrow}$

Second Arrangement:
Measures $P_{\uparrow}$ and $P_{\rightarrow}$

Spin-resolved laser ARPES

Spin-orbital splitting of the surface state band

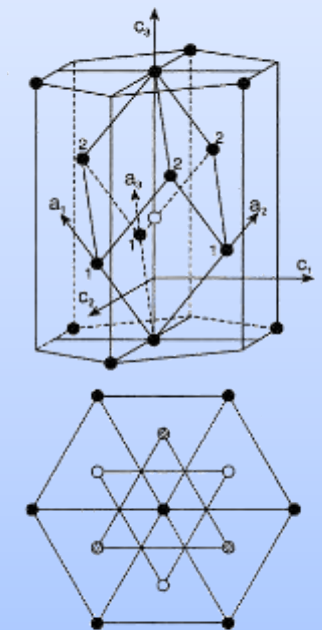


Spin-resolved laser ARPES

Sb(111) Surface state

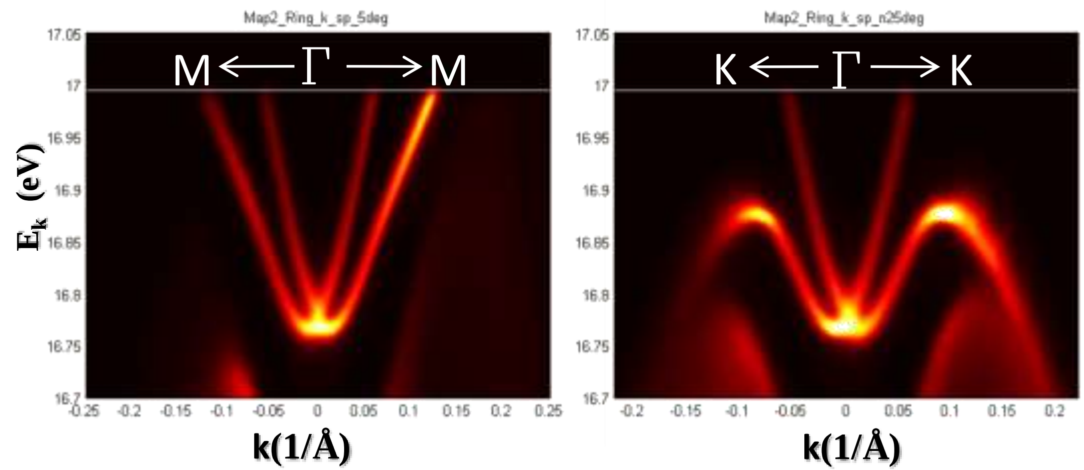
Structural Aspect

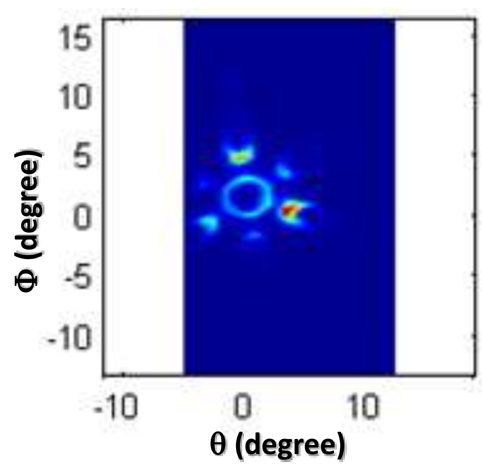
Rhombohedral Lattice



Top View

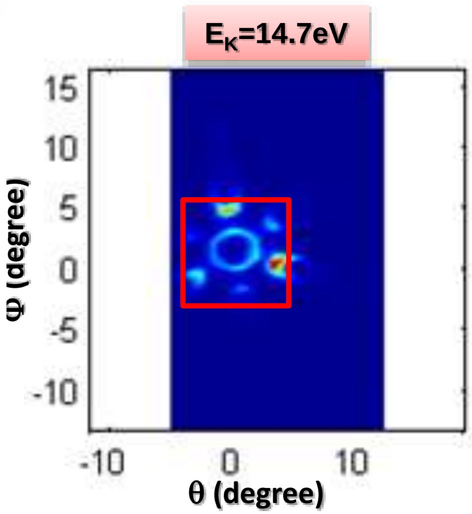
Regular ARPES

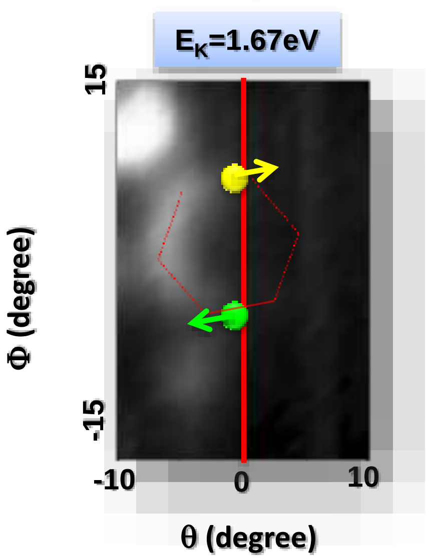


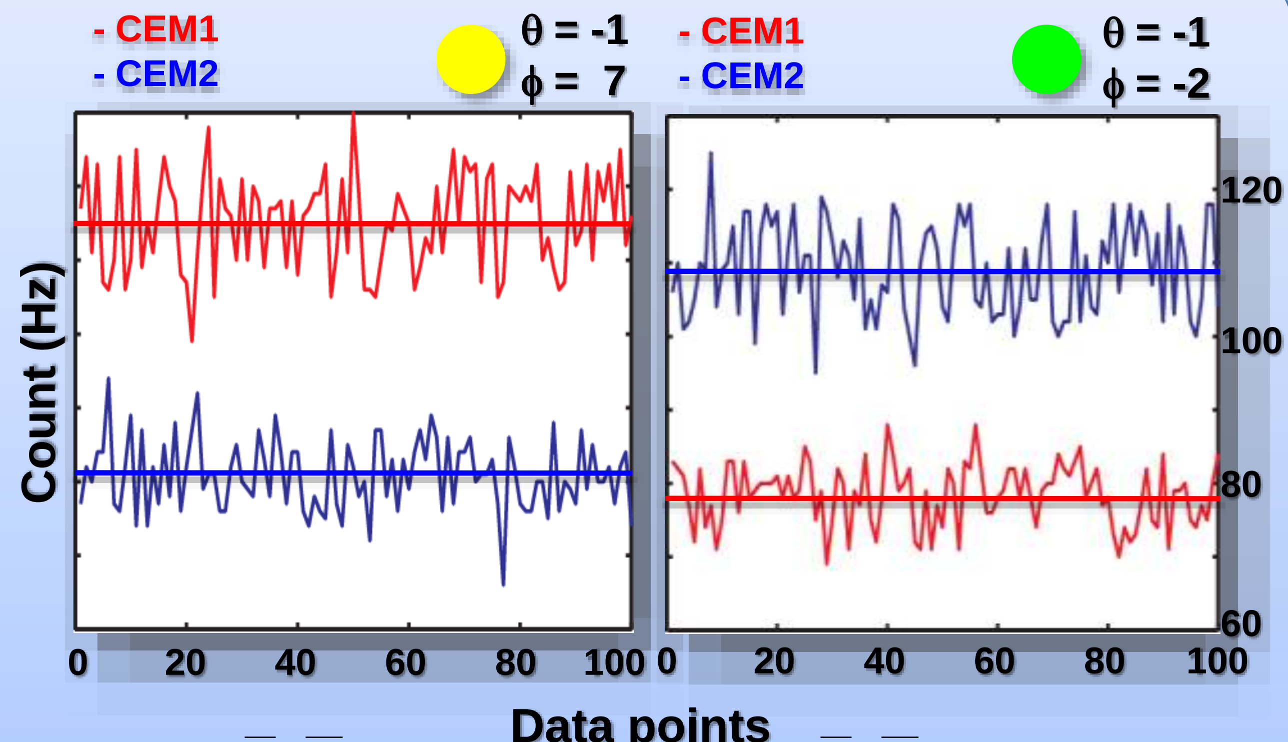


Spin-resolved laser ARPES

Spin direction of the FS







$$A = \frac{\overline{C1} - \overline{C2}}{\overline{C1} + \overline{C2}} = 0.175$$

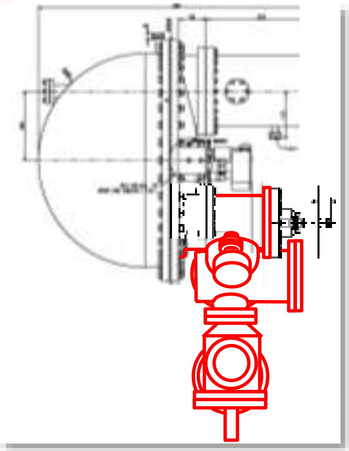
$$P = \frac{A}{S} = 84.7 \pm 8.7\%$$

$$A = \frac{\overline{C1} - \overline{C2}}{\overline{C1} + \overline{C2}} = -0.163$$

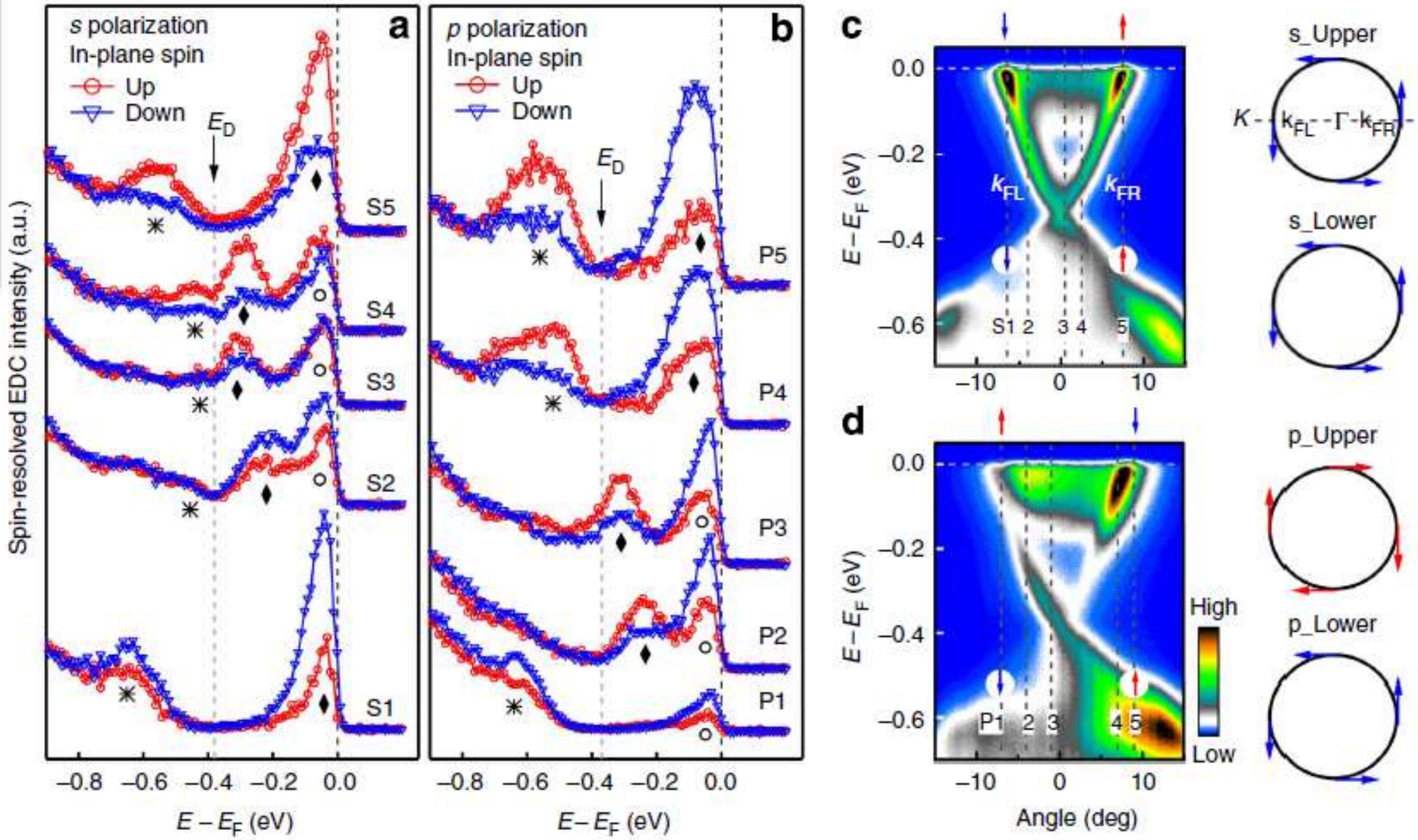
$$P = \frac{A}{S} = -78.9 \pm 8.1\%$$

Understand the spin of topological surface electrons

Z. Xie, et. al., Nature Comm 5:3382 (2014)

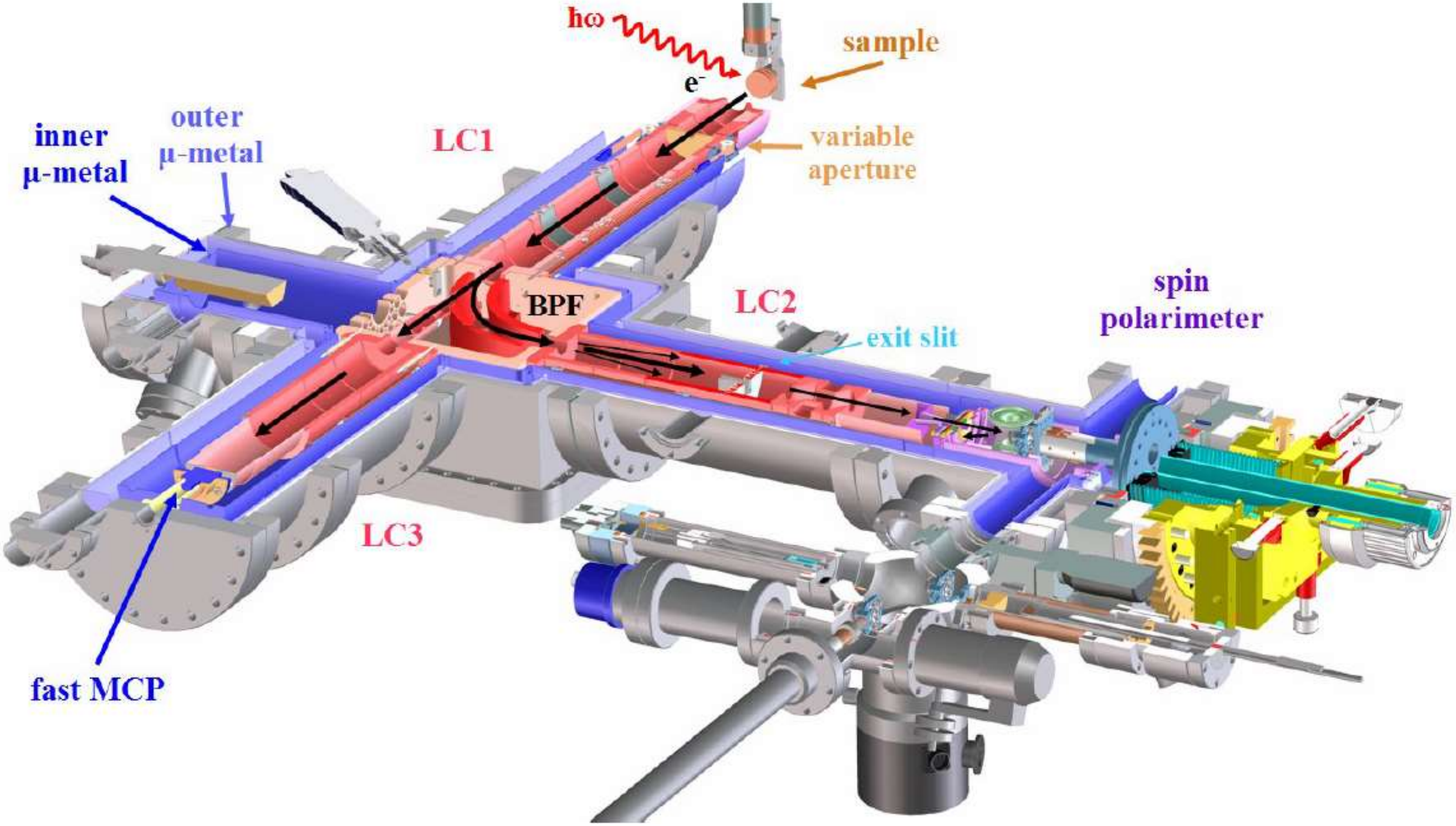


0D Spin detection



Understand the spin of topological surface electrons

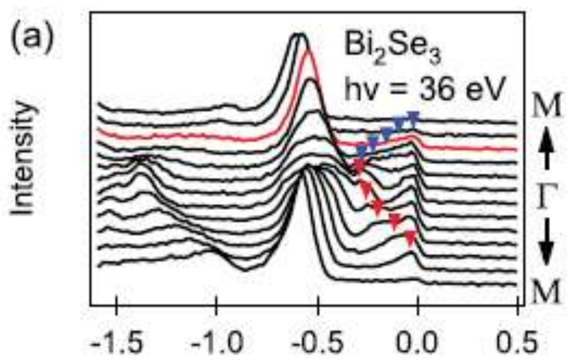
1D Spin detection

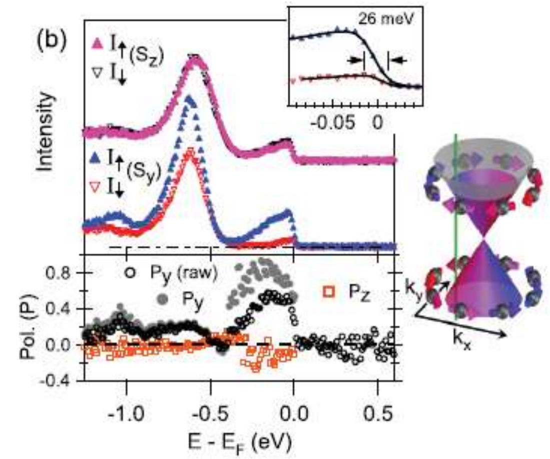


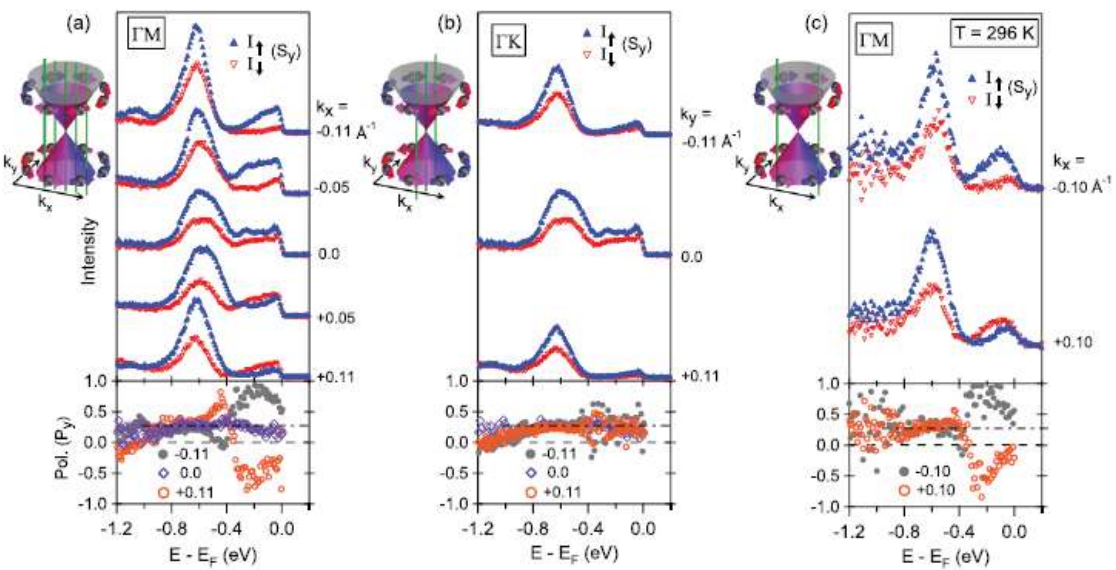
Understand the spin of topological surface electrons

C. Jozwiak, *et. al., Phys. Rev. B. 84, 165113 (2011)*

1D Spin detection



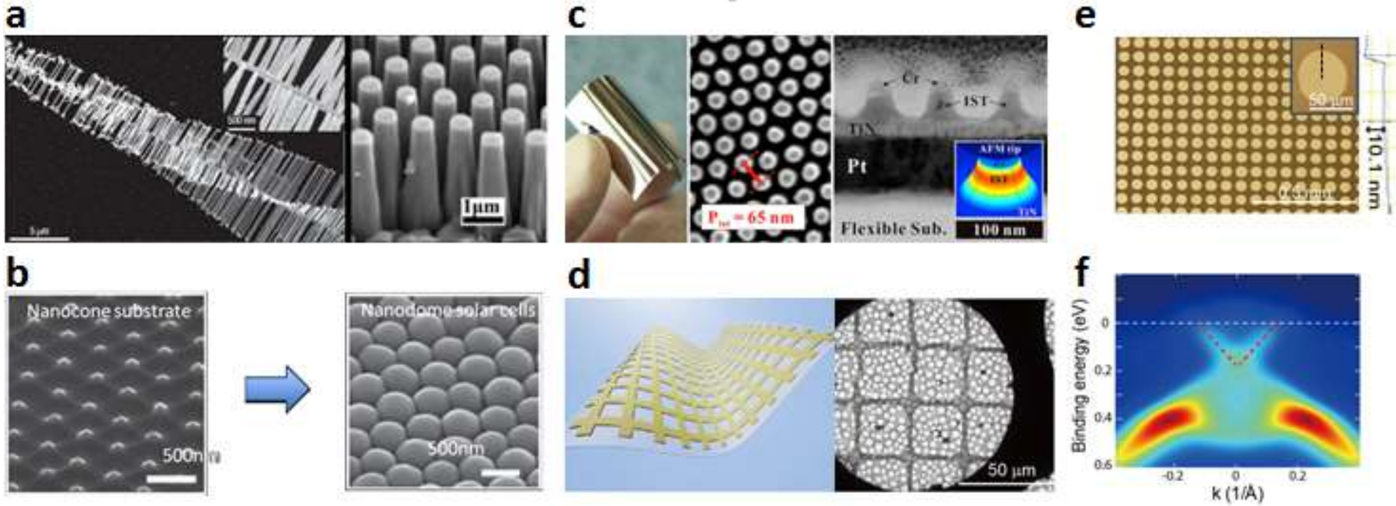




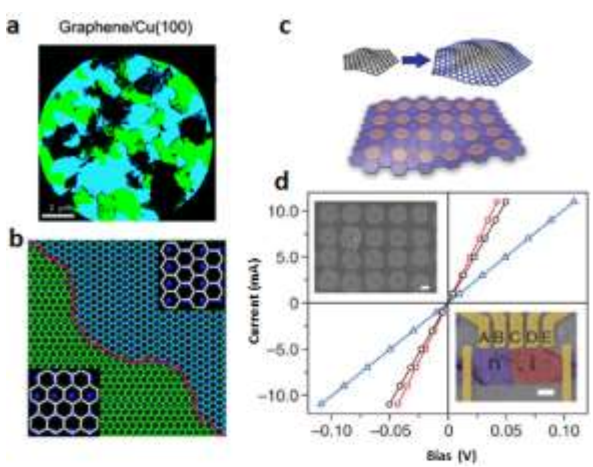
Spatially resolved ARPES

Explore electronic structure with spatial resolution

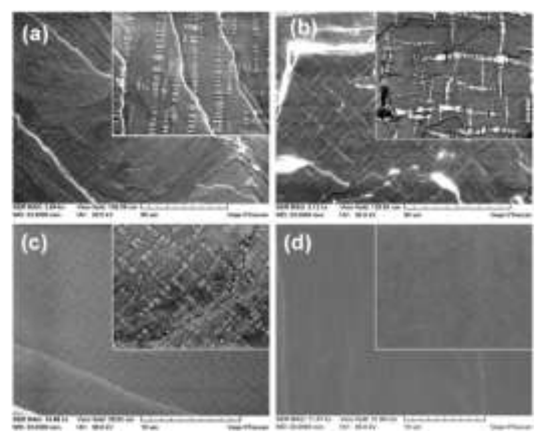
New mesoscopic materials



Materials with local compositional inhomogeneity



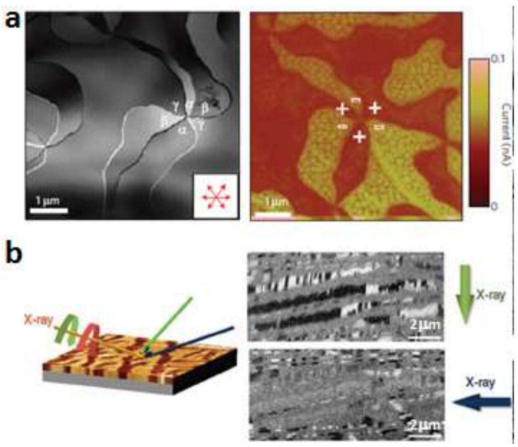
Graphene p-n junction



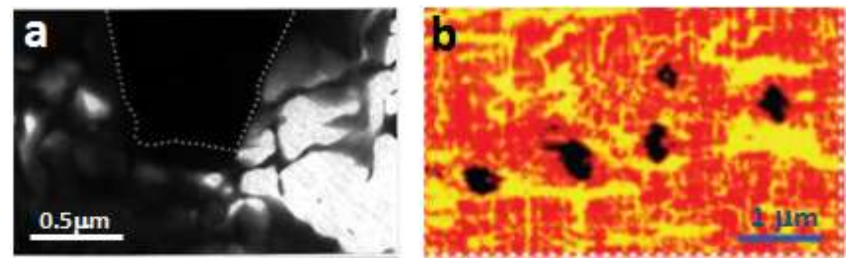
Fe-based superconductor

Explore electronic structure with spatial resolution

Materials with domains

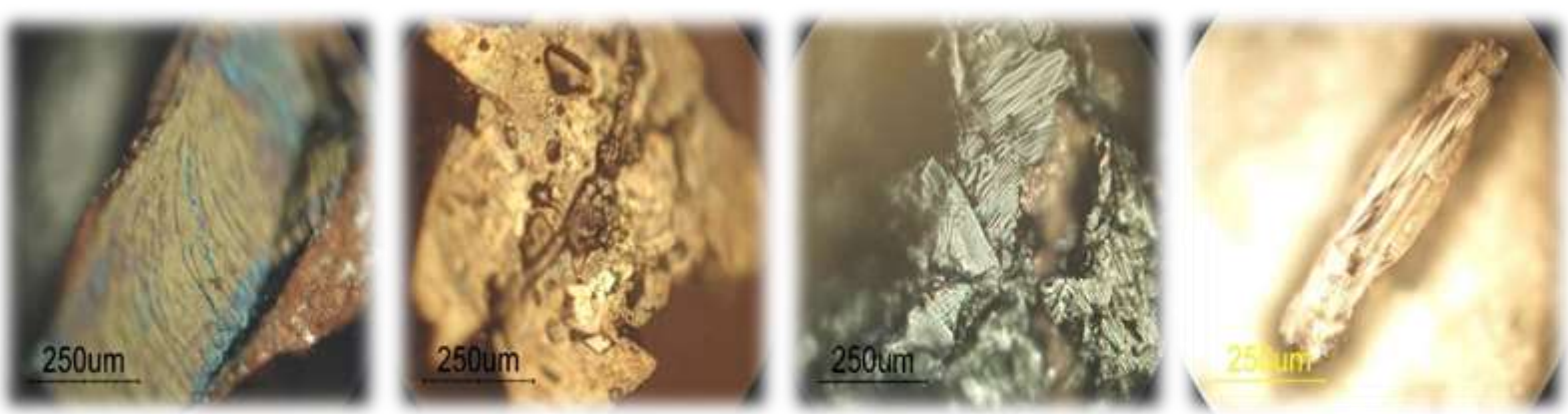


Multi-ferroic materials



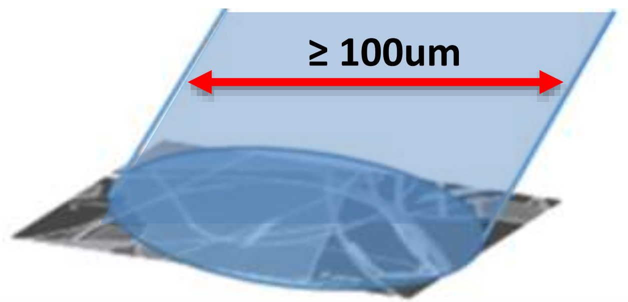
CMR materials

Unfriendly sample surface for traditional ARPES

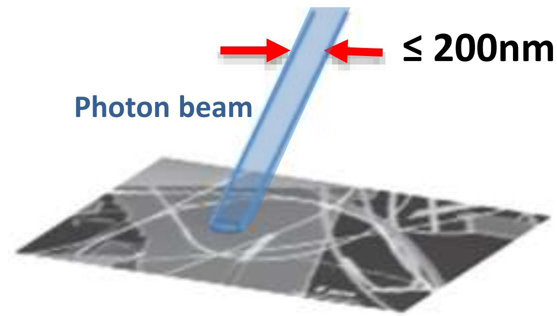


How to achieve nm scale spatial resolution

Regular ARPES

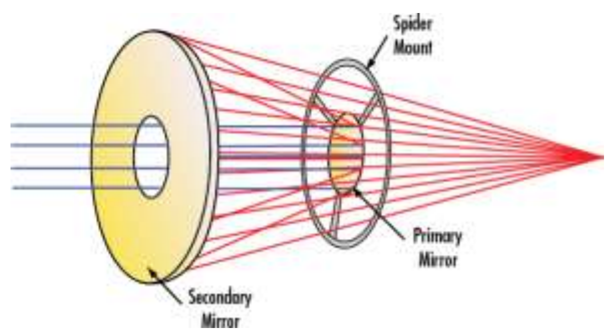


Spatially-resolved ARPES

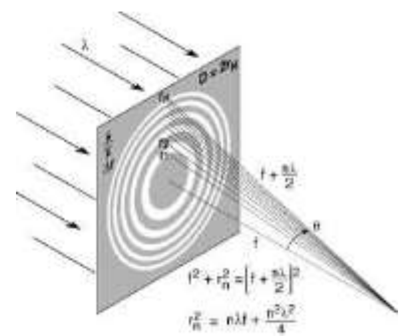


Focus with lens

Schwarzschild objective

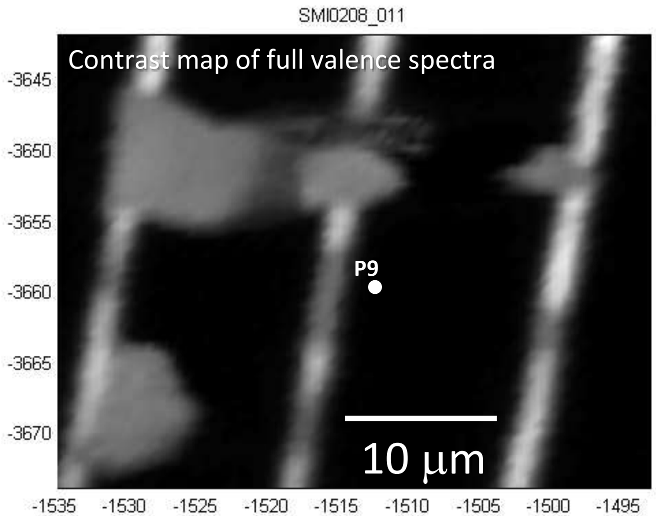


Zone plate



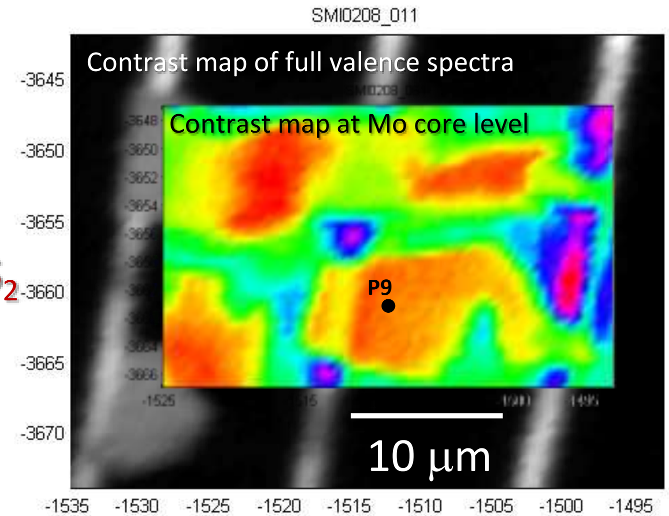
λ_{100eV} ~ 13nm

Preliminary study – element enhanced mapping

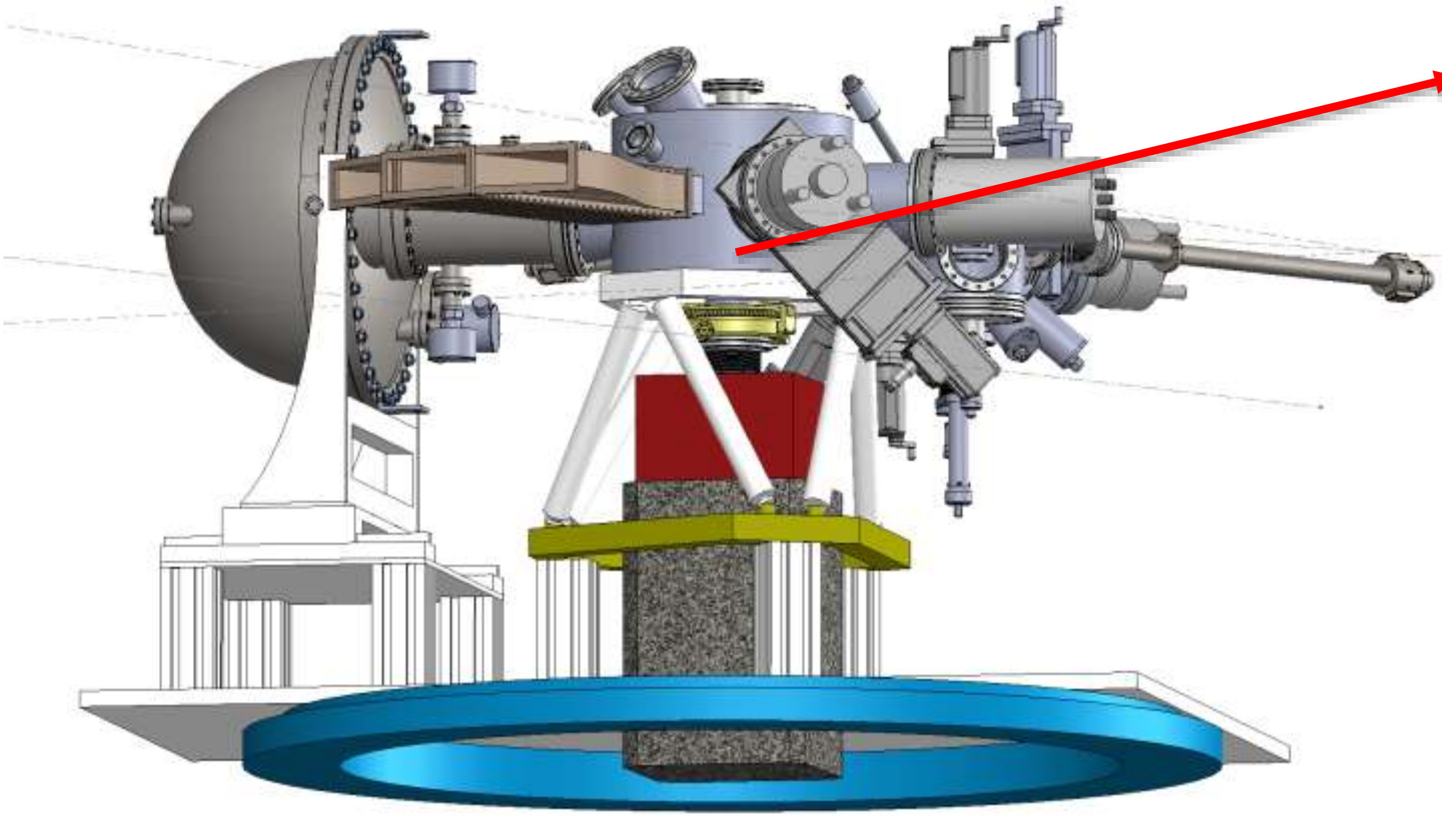


Core level enhanced contrast image

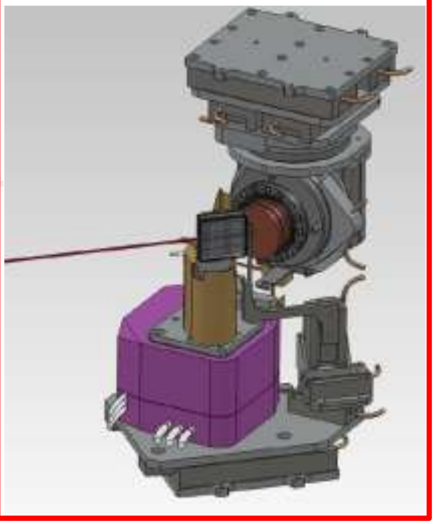
Reveals single layer MoS_2



Conceptual design

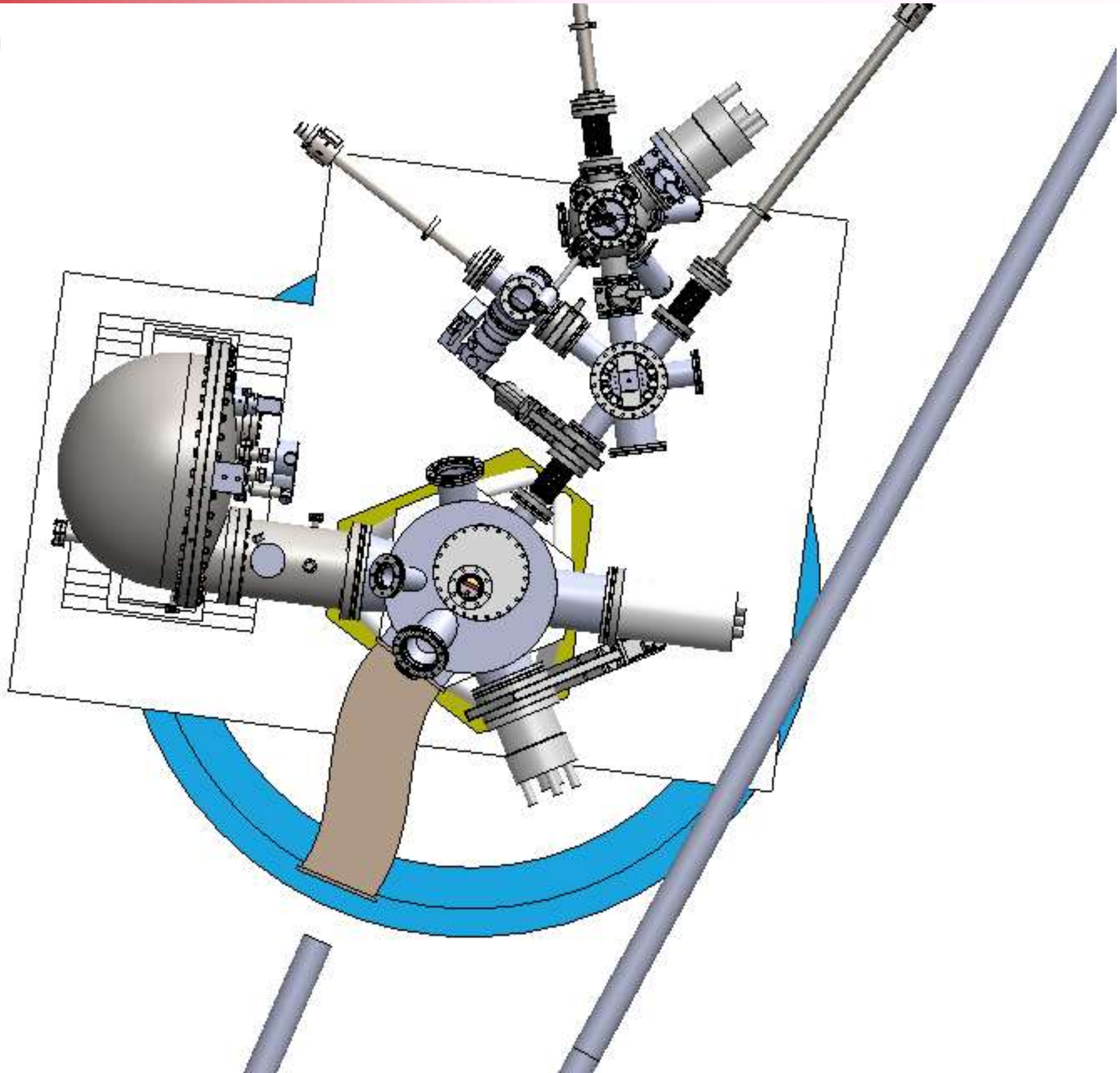


Sample manipulator
& Zone plate holder



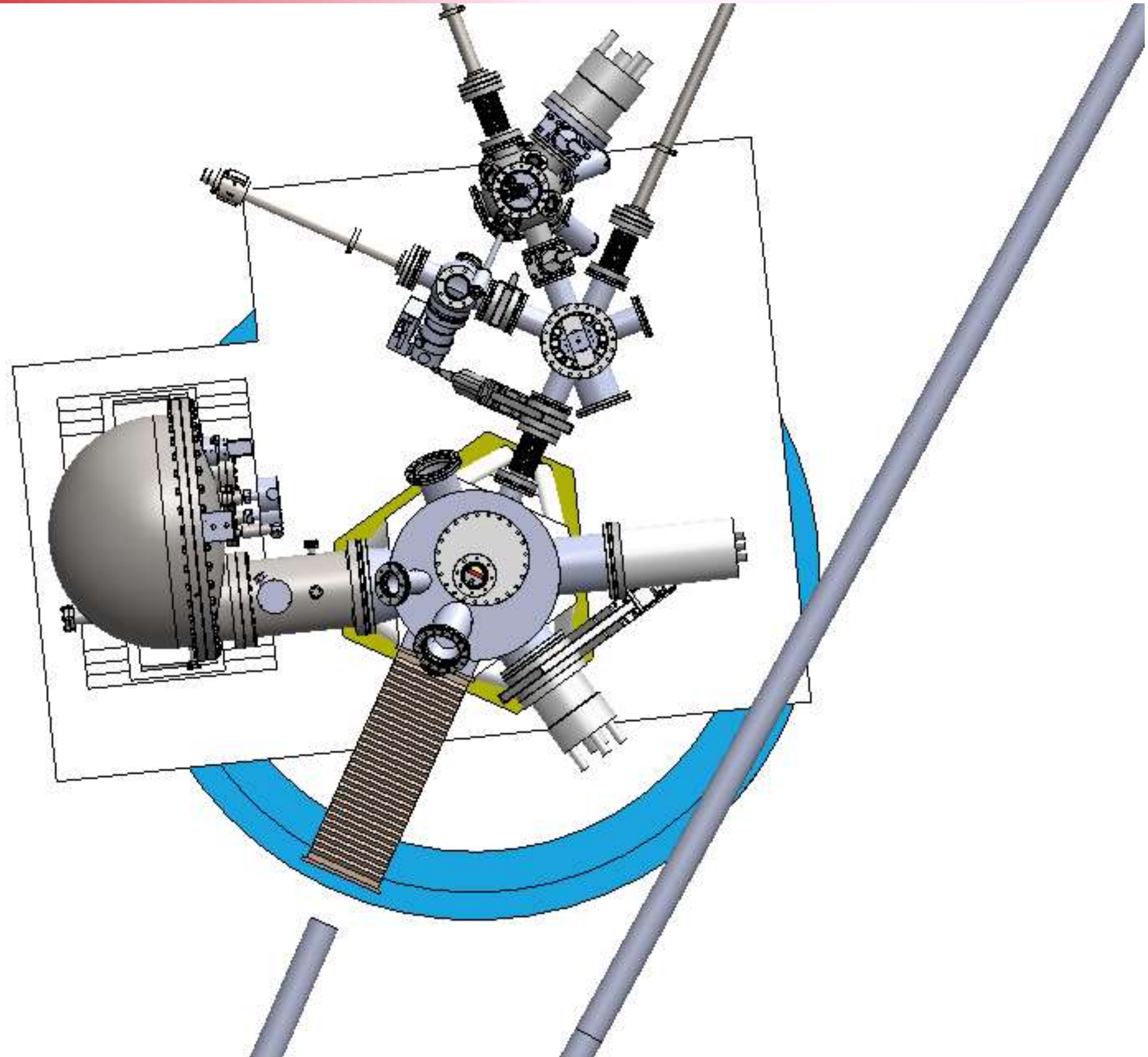
Conceptual design

$\theta = -15^{o}$



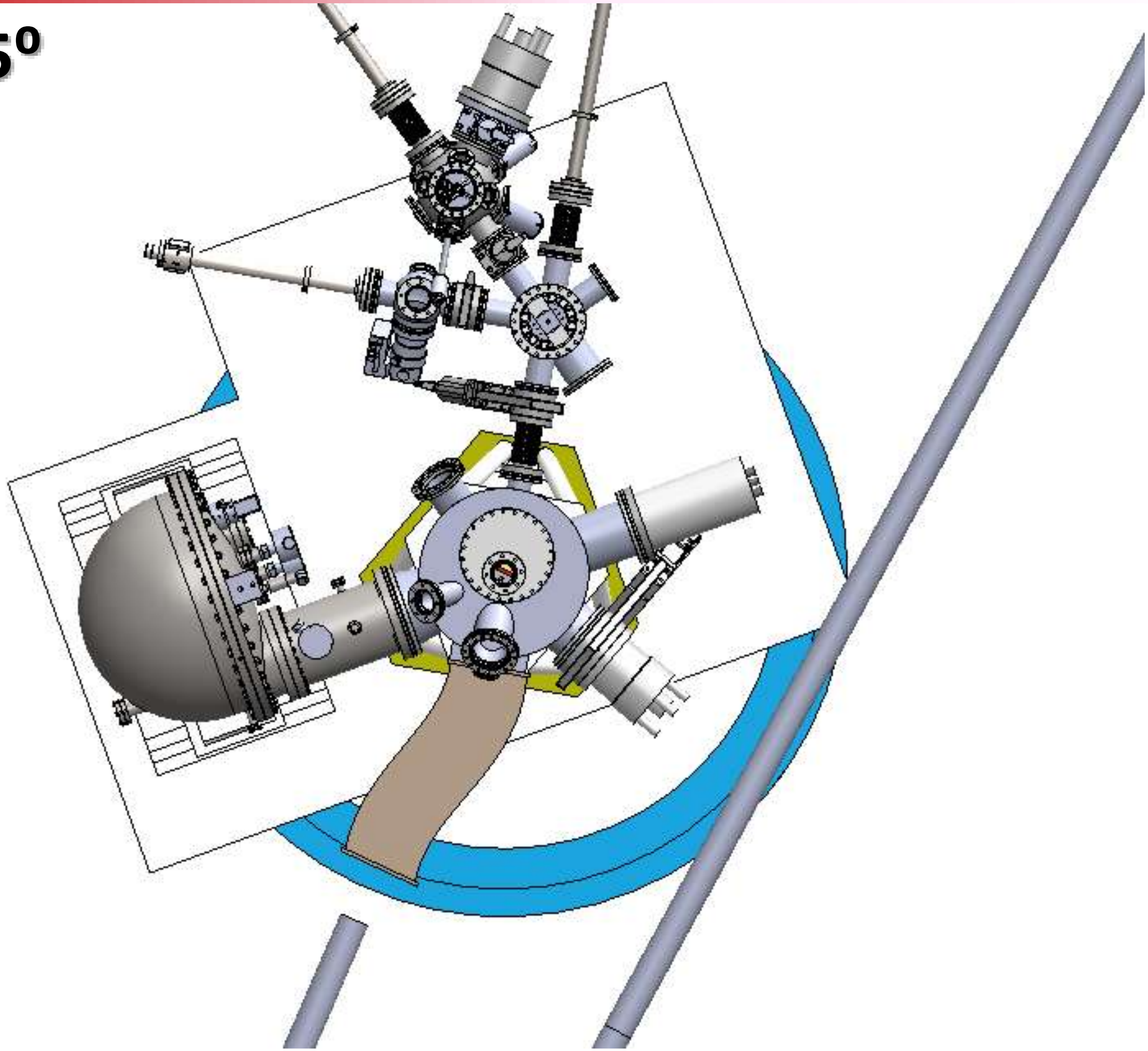
Conceptual design

$\theta = 0^o$



Conceptual design

$\theta = 15^o$



Thank you!