Ubiquitous generalizd ARPES signatures of electron fractionalization in quasi-low dimensional metals

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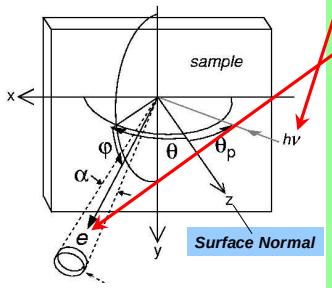
Angle resolved photoemission spectroscopy (ARPES) to measure ρ (k,ω)



- **Photon In**
- **(Photo-)Electron Out**
- **Electron KE, hν, ⇒ bind. en. ω**
- **Angles θ, ϕ → k-par, cons. at surf.**
- **k-perp -- not conserved, must model surface potential**
- **Electron Energy Distribution (ω) = ρ (k,ω) x Fermi function x (ARPES cross-section)**

MDC (fix ω, scan k) **EDC** (fix k, scan ω) **"FS" map** (ω=E_F, scan k region)

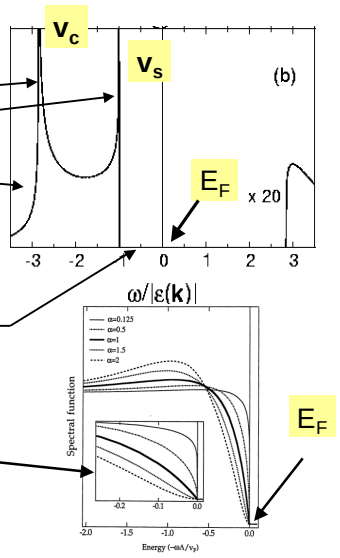
Photo-electron lifetime gives Δk-perp and extra Δω for 3d crystals → low-dimension better!

Luttinger liquid (Tomonaga-Luttinger model) spectral function much different from FL

Meden & Schönhammer '92, Voit '93,

TL lineshape

- two features- holon and spinon
- power law tails
- spinon:
  - $\alpha > \frac{1}{2}$ edge
  - $\alpha < \frac{1}{2}$ peak (shown)
- gap to E_F except for $k=k_F$



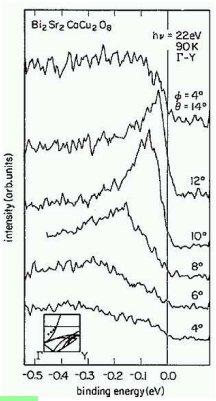
k-summed spectrum $\rho_{LOC}(\omega)$ approaches E_F as power law in α-- even though system metallic!!

CDW fluctuations can give NFL pseudogap & mimic $\Sigma_k A(k,E_F) \approx 0$

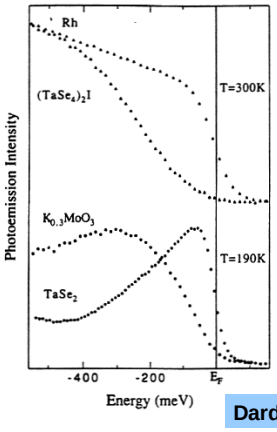
Early Experimental Motivations

Cuprate ARPES NFL lineshapes → Signal of LL?

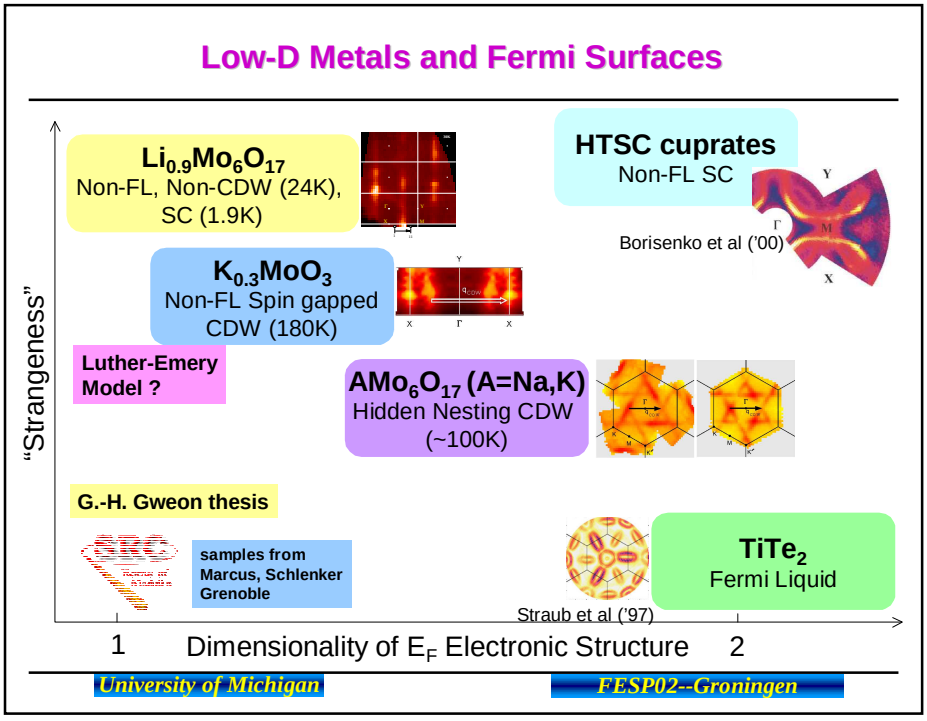
Quasi-1-d PES, $\sum_k A(k,0) \approx 0$ → LL? CDW pseudogap?



Olson ('90)



Dardel ('91)


Low-D Metals and Fermi Surfaces
$Li_{0.9}Mo_6O_{17}$
Non-FL, Non-CDW (24K), SC (1.9K)
HTSC cuprates
Non-FL SC
Borisenko et al ('00)
$K_{0.3}MoO_3$
Non-FL Spin gapped CDW (180K)
Luther-Emery Model ?
AMo_6O_{17} (A=Na,K)
Hidden Nesting CDW (~100K)
G.-H. Gweon thesis
samples from Marcus, Schlenker Grenoble
$TiTe_2$
Fermi Liquid
Straub et al ('97)
"Strangeness"
1
Dimensionality of E_F Electronic Structure
2
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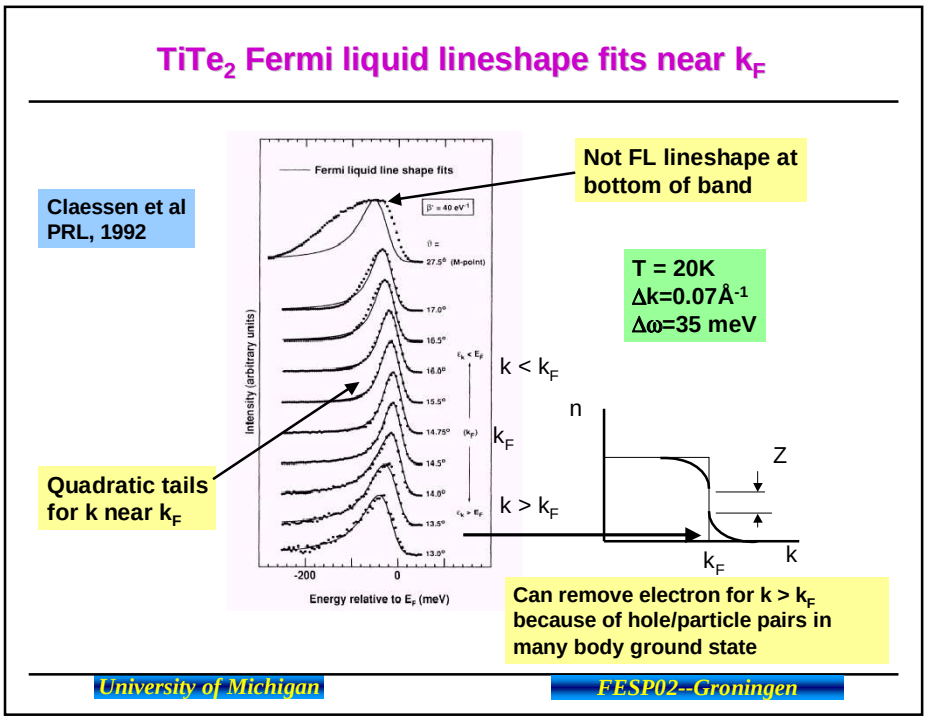
$TiTe_2$ Fermi liquid lineshape fits near k_F
Claessen et al PRL, 1992
Not FL lineshape at bottom of band
T = 20K
Δk=0.07Å^{-1}
Δω=35 meV
Fermi liquid line shape fits
Intensity (arbitrary units)
Energy relative to E_F (meV)
k < k_F
k_F
k > k_F
n
Z
k_F
k
Quadratic tails for k near k_F
Can remove electron for k > k_F because of hole/particle pairs in many body ground state
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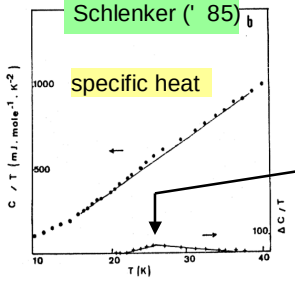
$Li_{0.9}Mo_6O_{17}$ properties consistent with LL above a mystery phase at 24K

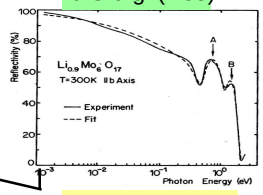
Schlenker (' 85)



Also 1.9 K SC

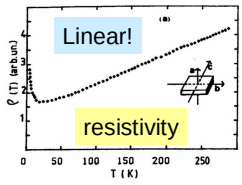
Mystery phase below 24 K
- ρ upturn
- weak C_V anomaly
- no gap > 1 meV
- no CDW, SDW in x-ray diffraction (Pouget, 2001)

diGiorgi (' 88)



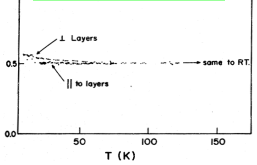
reflectivity 300K, 4K same

Schlenker ('93)



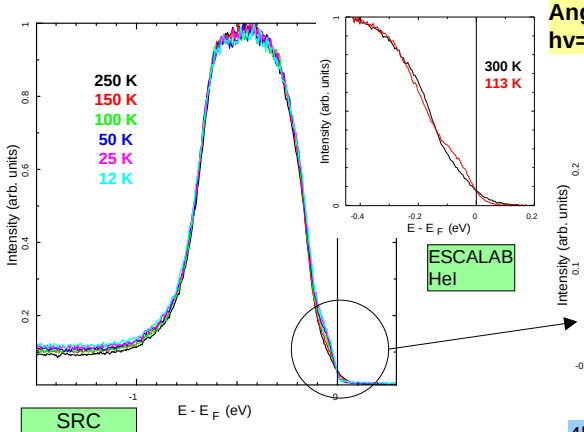
Above 24 K consistent with LL
- $C_V \propto T$ term exists
- $\chi \propto$ const
- $\rho \propto T$ (in one theory)

Greenblatt (' 84)

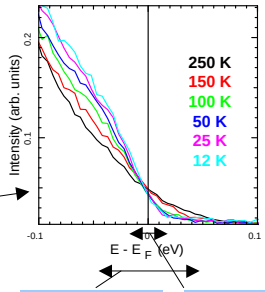


magnetic susceptibility

Temperature dependence in $Li_{0.9}Mo_6O_{17}$ PES no Fermi edge, no E_F gap opening

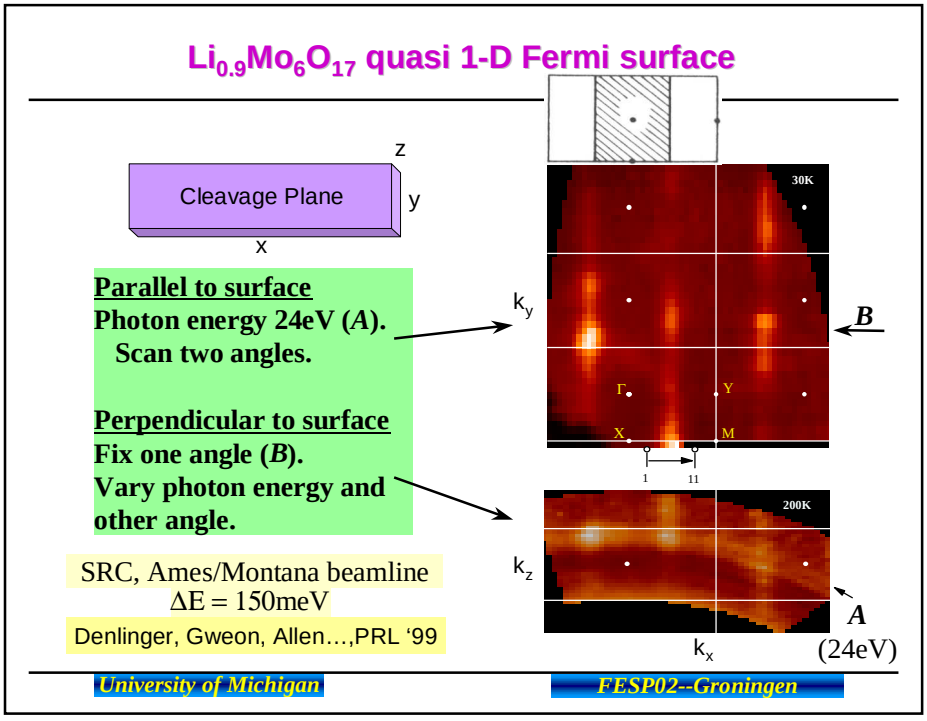


Angle integrated mode hv=33eV, ΔE=30meV



$4k_BT$ for 250K $4k_BT$ for 100K

Gradual change from 250K to 12K.
No Fermi edge. No gap. Only edge sharpening at small T


$Li_{0.9}Mo_6O_{17}$ quasi 1-D Fermi surface
z
Cleavage Plane
y
x
Parallel to surface
Photon energy 24eV (A).
Scan two angles.
Perpendicular to surface
Fix one angle (B).
Vary photon energy and other angle.
SRC, Ames/Montana beamline
ΔE = 150meV
Denlinger, Gweon, Allen…,PRL '99
k_y
k_z
k_x
30K
200K
Γ
Y
X
M
B
A
(24eV)
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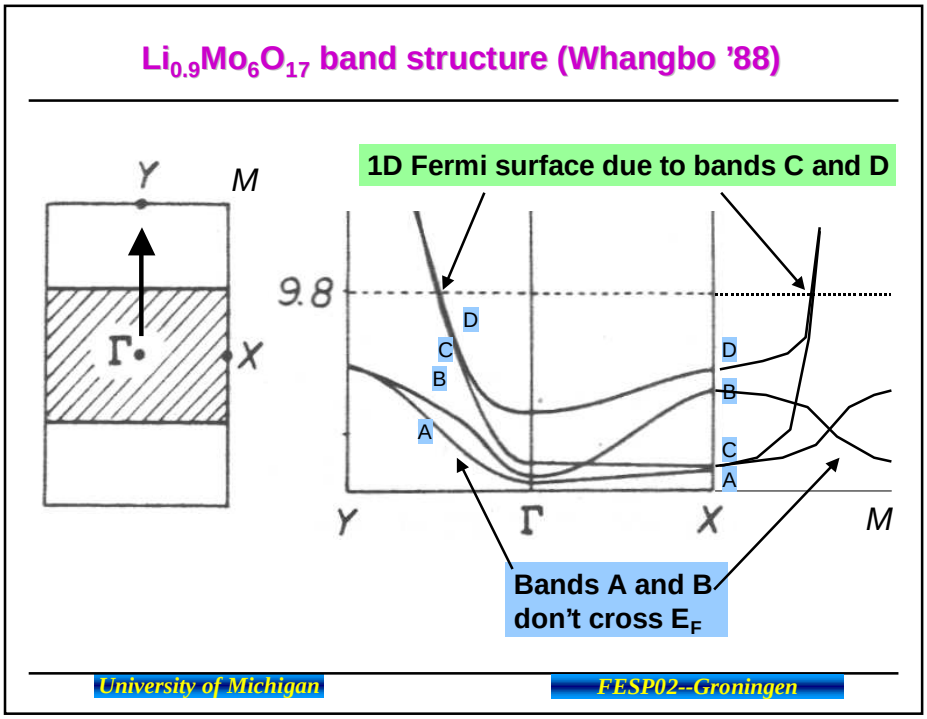
$Li_{0.9}Mo_6O_{17}$ band structure (Whangbo '88)
1D Fermi surface due to bands C and D
Y
M
Γ
X
9.8
D
C
B
A
Bands A and B don't cross E_F
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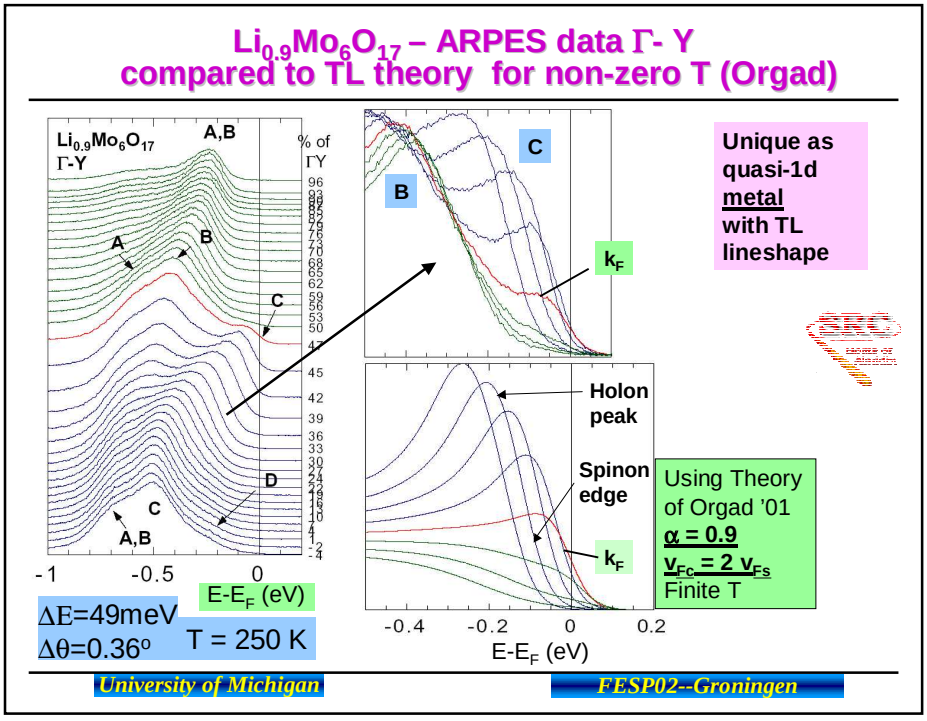
$Li_{0.9}Mo_6O_{17}$ – ARPES data Γ- Y
compared to TL theory for non-zero T (Orgad)
$Li_{0.9}Mo_6O_{17}$
Γ-Y
A,B
% of ΓY
A
B
C
D
C
A,B
-1
-0.5
0
E-E$_F$ (eV)
ΔE=49meV
Δθ=0.36°
T = 250 K
B
C
k_F
Holon peak
Spinon edge
k_F
-0.4
-0.2
0
0.2
E-E$_F$ (eV)
Unique as quasi-1d metal with TL lineshape
Using Theory of Orgad '01
α = 0.9
$v_{Fc} = 2\ v_{Fs}$
Finite T
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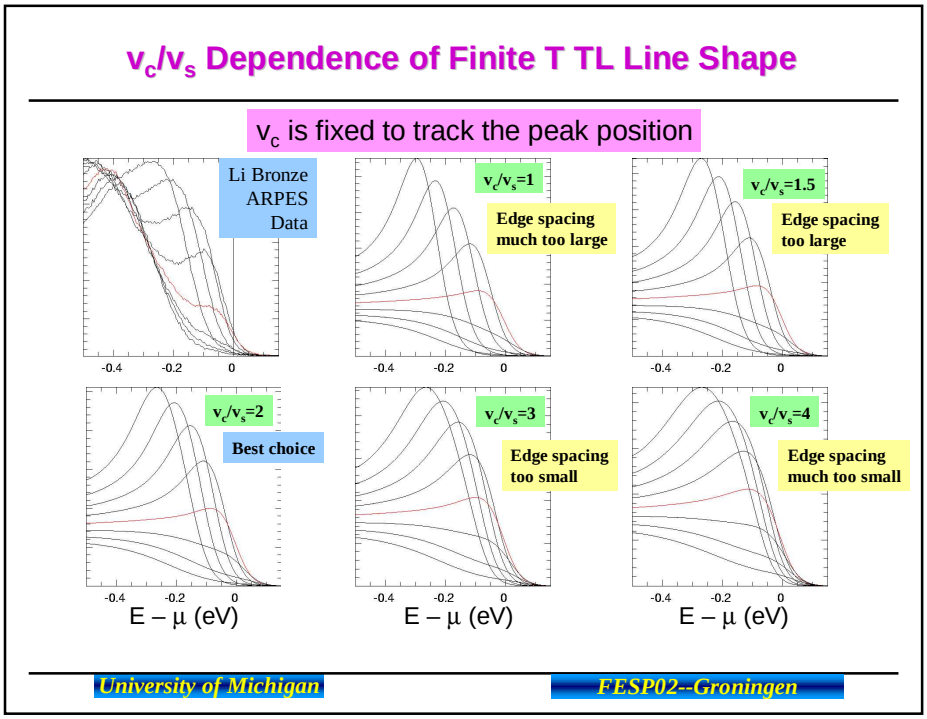
v_c/v_s Dependence of Finite T TL Line Shape
v_c is fixed to track the peak position
Li Bronze ARPES Data
v_c/v_s=1
Edge spacing much too large
v_c/v_s=1.5
Edge spacing too large
v_c/v_s=2
Best choice
v_c/v_s=3
Edge spacing too small
v_c/v_s=4
Edge spacing much too small
-0.4
-0.2
0
E – μ (eV)
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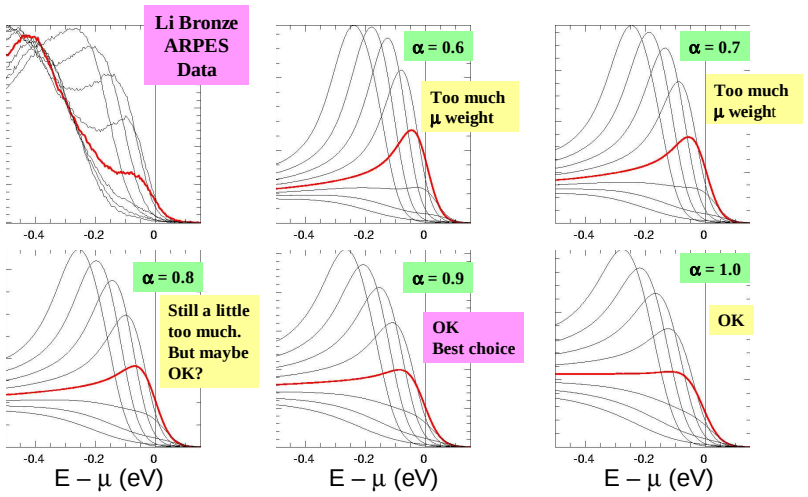
α Dependence of Finite T TL Line Shape



α limited to 1 in this theory

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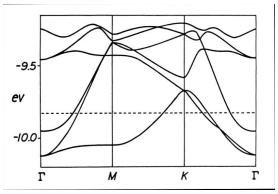
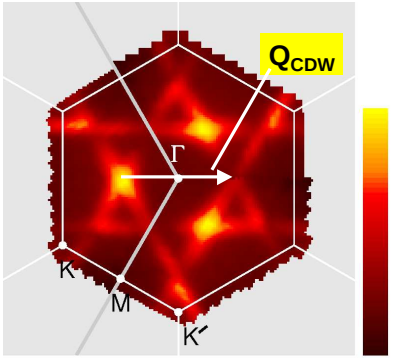
(K, Na) purple bronzes (quasi 2d, CDW) Fermi surface shows "hidden" one dimensionality

KMo_6O_{17} hν=22eV, ΔE=100meV, T=150K (T_{CDW}=80K)

3 weakly interacting quasi 1d chains 120 degrees apart





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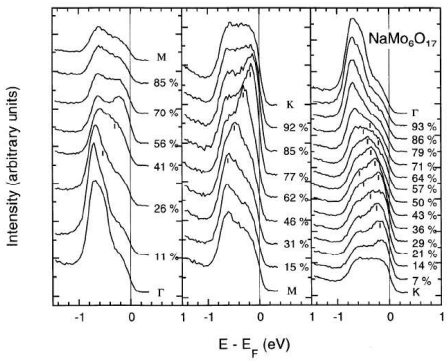
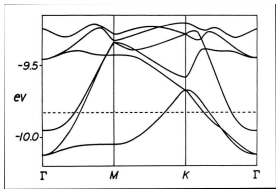
$NaMo_6O_{17}$ ARPES Lineshapes Strange





Couldn' t interpret data before taking FS map!

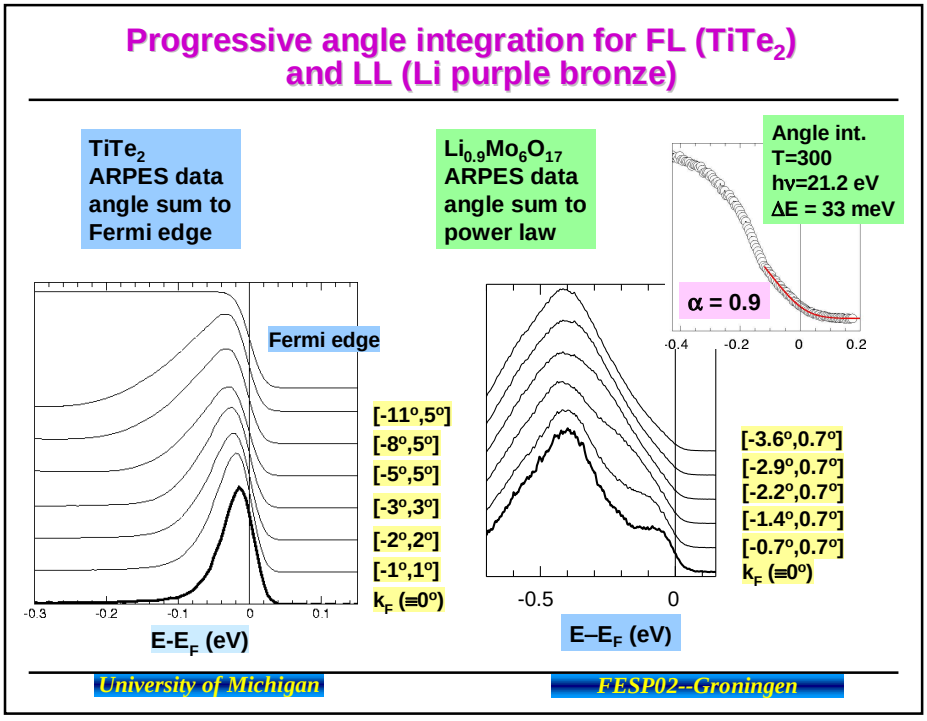
Generalized ARPES signatures of electron fractionalization into density waves

LL a paradigm theory for electron fractionalization.
But seldom find materials which map neatly onto any non-FL model

Example: Can' t describe NFLlineshapes of spin-gapped blue bronze with ANY model

Need to break free from "toy model straightjacket!"
Look for generalized signatures of fractionalization

- **Vanishing Weight at E_F (No QP)**
  e.g. Power Law (*Anomalous Dimension* α) of LL
- **Anderson-Ren Power Law Tail Line Shape (*Anom. Dim.*)**
- **Two (or More) Objects Moving At Different Speeds:**
  e.g. Holon (Peak) and Spinon (Peak or Edge) of LL
- **Sharp MDC, Broad EDC (Orgad et al '01)**


Progressive angle integration for FL ($TiTe_2$) and LL (Li purple bronze)
$TiTe_2$ ARPES data angle sum to Fermi edge
$Li_{0.9}Mo_6O_{17}$ ARPES data angle sum to power law
Angle int. T=300 hν=21.2 eV ΔE = 33 meV
α = 0.9
Fermi edge
[-11°,5°]
[-8°,5°]
[-5°,5°]
[-3°,3°]
[-2°,2°]
[-1°,1°]
k_F (≡0°)
[-3.6°,0.7°]
[-2.9°,0.7°]
[-2.2°,0.7°]
[-1.4°,0.7°]
[-0.7°,0.7°]
k_F (≡0°)
E-E_F (eV)
E–E_F (eV)
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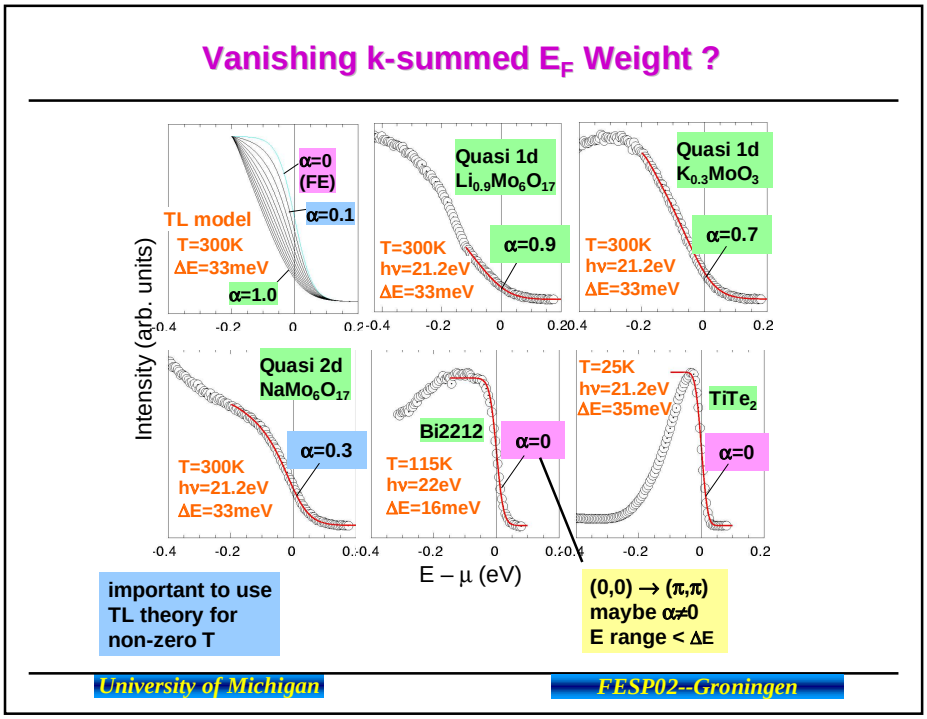
Vanishing k-summed E_F Weight ?
TL model
T=300K
ΔE=33meV
α=0 (FE)
α=0.1
α=1.0
Quasi 1d $Li_{0.9}Mo_6O_{17}$
T=300K
hν=21.2eV
ΔE=33meV
α=0.9
Quasi 1d $K_{0.3}MoO_3$
T=300K
hν=21.2eV
ΔE=33meV
α=0.7
Quasi 2d $NaMo_6O_{17}$
T=300K
hν=21.2eV
ΔE=33meV
α=0.3
Bi2212
T=115K
hν=22eV
ΔE=16meV
α=0
T=25K
hν=21.2eV
ΔE=35meV
$TiTe_2$
α=0
Intensity (arb. units)
E – μ (eV)
important to use TL theory for non-zero T
(0,0) → (π,π) maybe α≠0 E range < ΔE
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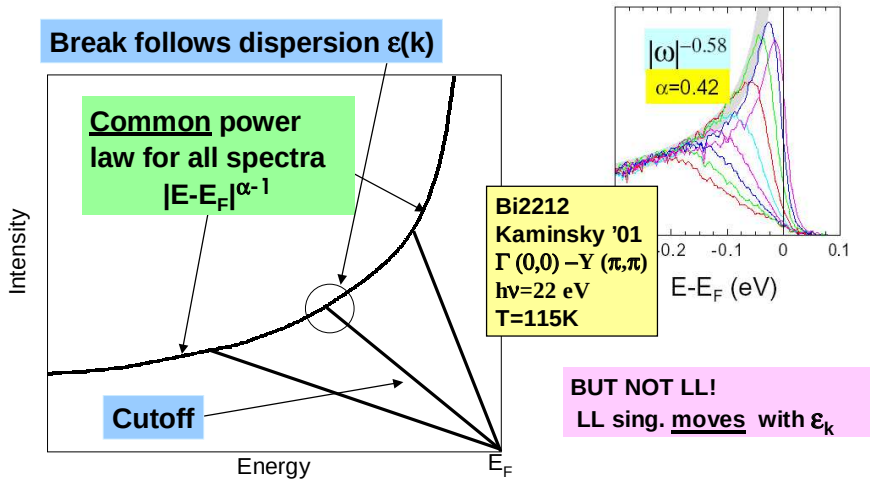
Anderson-Ren lineshape visualization

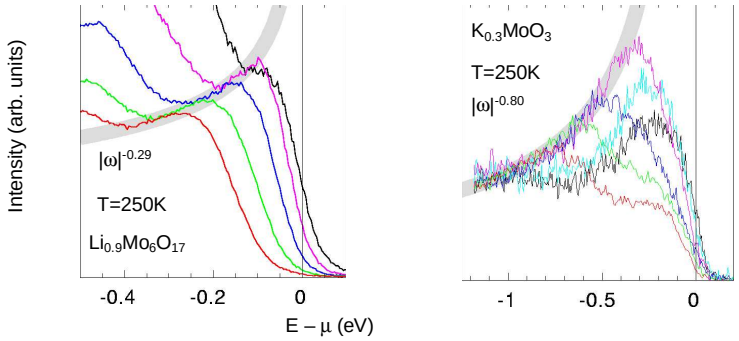


BUT NOT LL!
LL sing. moves with ε_k

VISUALIZATION of Bi2212 ARPES lineshape (Anderson/Ren, 1990)

NO for FL $TiTe_2$

AR lineshape for quasi 1-d systems



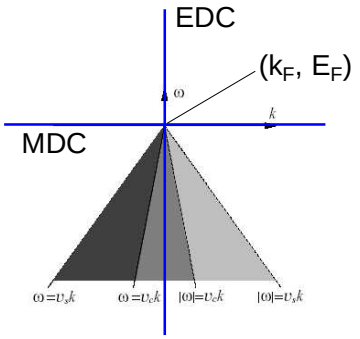
YES for $Li_{0.9}Mo_6O_{17}$
$|\omega|^{-0.29}$ α = 0.71
not 0.9 but > 0.5

YES for $K_{0.3}MoO_3$
$|\omega|^{-0.8}$ α = 0.2
≠ 0.7, blue bronze trouble
spin gap breaks
AR connection to α

Narrow MDC and Wide EDC

Orgad et al,
PRL **86**, 4362 (2001)

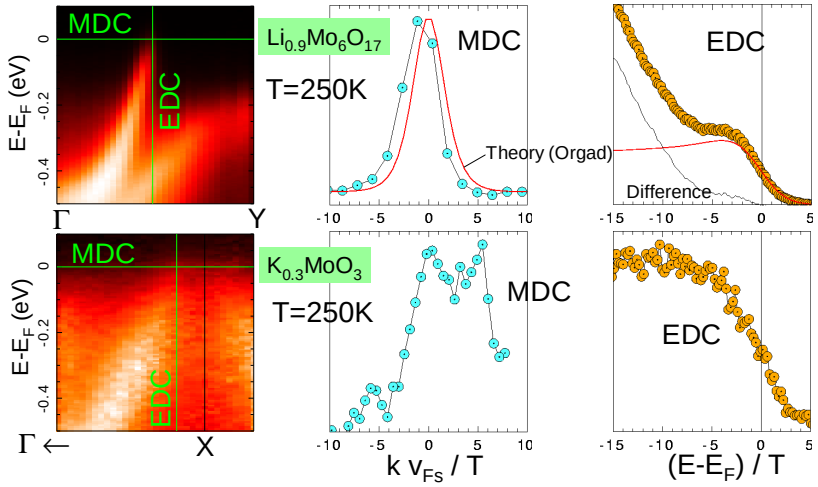
Reported for Bi2212 and static stripe cuprate



T=0, LL
Kinematic Constraint of
Decomposition of e- into Spinons and Holons

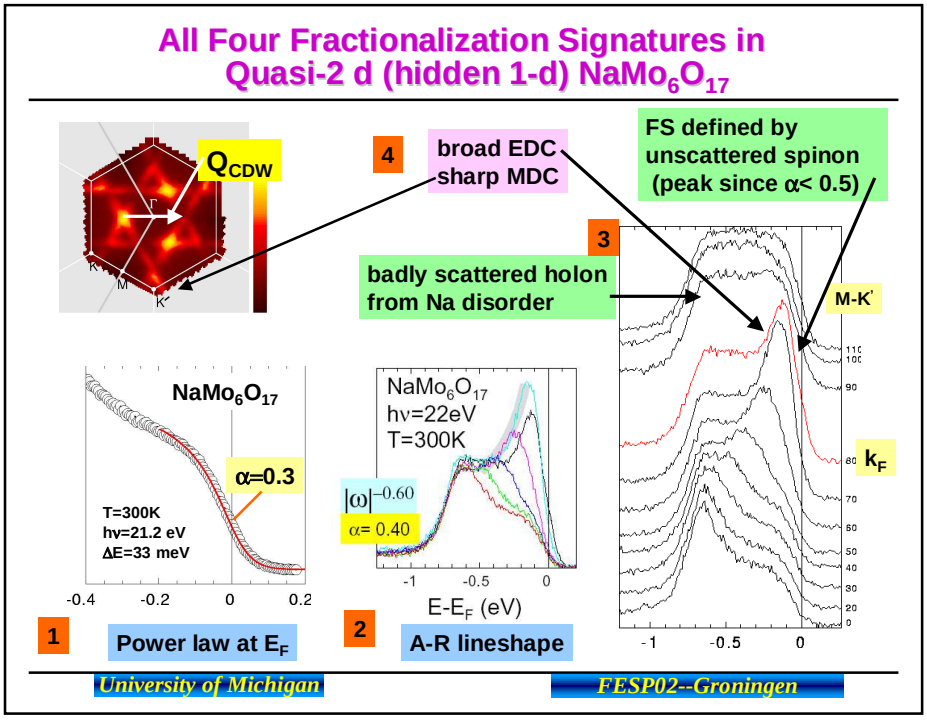
Holds for finite T and LE as well.
Generalized to other Density Waves?

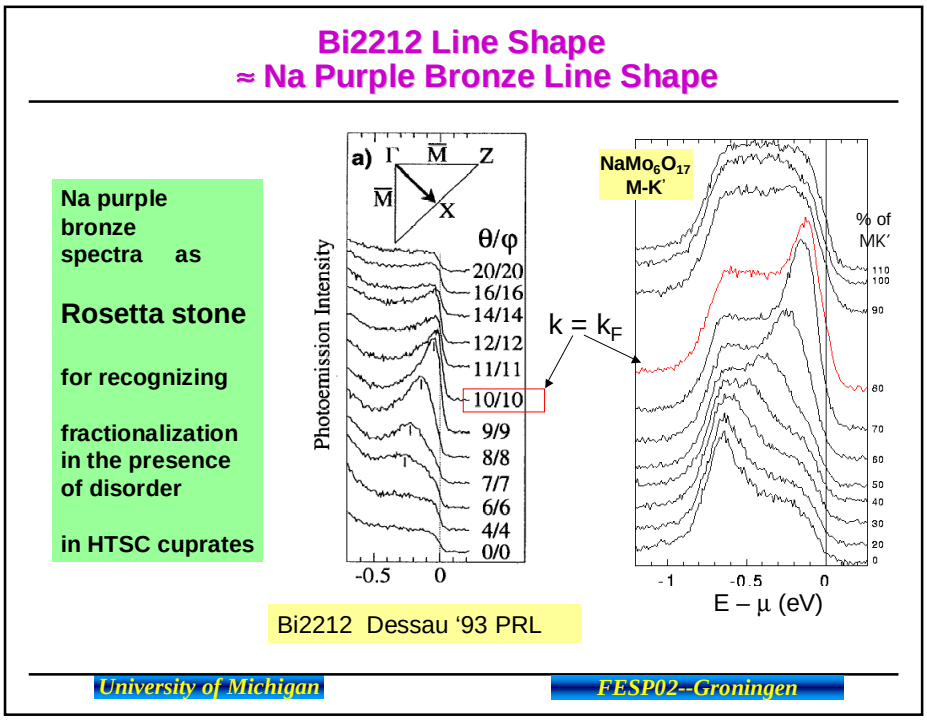
Sharp MDC and Broad EDC ?
For quasi-1d systems



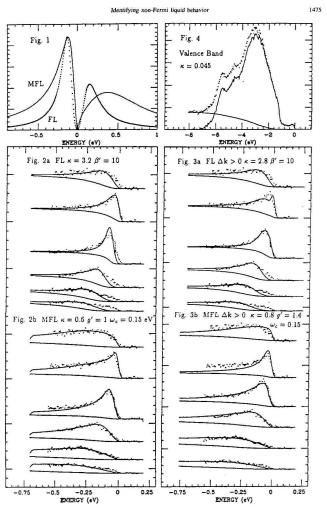
Both MDC Width and EDC Width **Intrinsic**

Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals



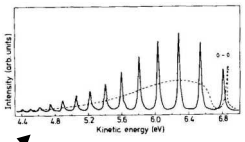


Early statements that the cuprate "background" is intrinsic



Can fit Olson et al Bi2212 data with MFL (FL) only if remove "background" 15 (60) times larger than implied by entire VB.

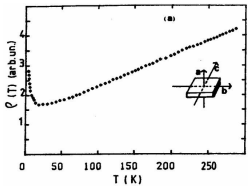
Liu, Anderson, Allen J Phys Chem Sol 1991



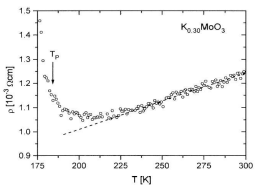
Vibronic analogy G.A. Sawatzky, Nature, 1989; Also, further arguments in LANL workshop proceedings, (Addison-Wesley, 1990).

T- linear resistivities in purple bronzes!

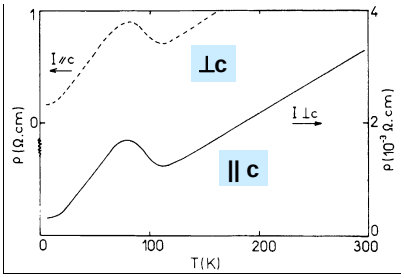
Quasi-1d Li purple Schlenker et al (' 93)



Quasi-1d K blue Brutting, ' 95



Quasi 2-d Hidden-1d Na,K purple



R. Buder et al J. Phys. Lett. **43**, L59 (1982)

Summary

Scorecard of generalized fractionalization signatures

• $TiTe_2$ no signatures	FL example
• quasi 1-d Li purple bronze (1, 2, 3, 4)	LL example
• quasi 1-d K blue bronze (1, 2,--, 4)	spin-gapped no lineshape works
• quasi 2-d (hidden 1-d) Na purple bronze (1, 2, 3, 4)	melted holon $\alpha < ½$ spinon peaky
• quasi 2-d Bi2212 SC cuprate (--, 2, 3, 4)	

note: no microscopic derivation of AR lineshape
HINTS OF A BIGGER PICTURE !

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