Universal Lower Limit on Vortex Creep in Superconductors

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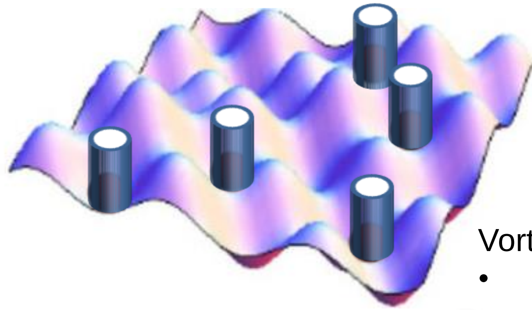
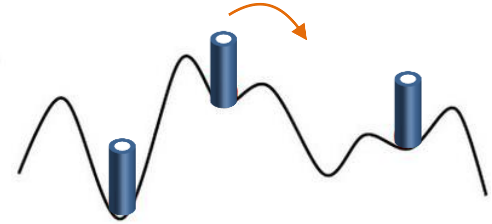
Outline

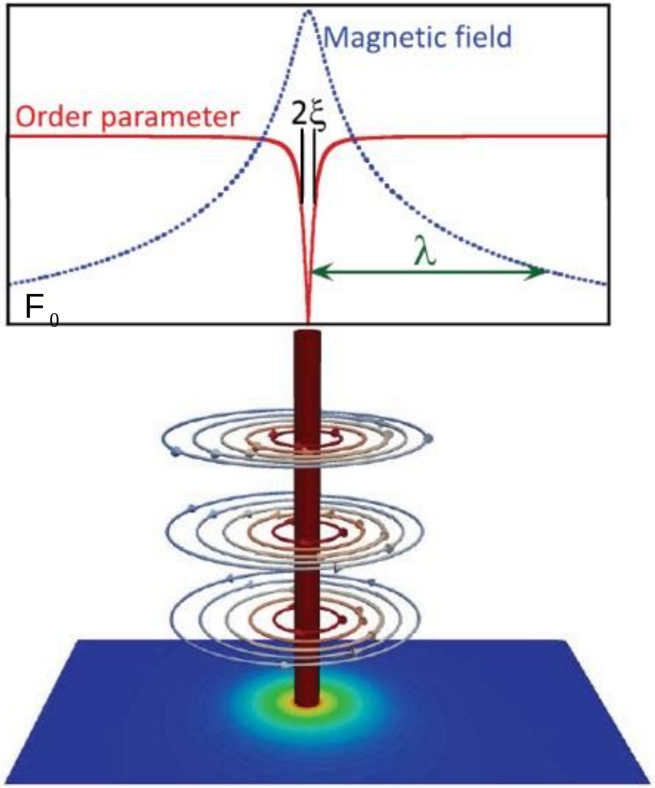
- Importance of considering flux creep
- Vortex creep in $YBa_2Cu_3O_{7-\delta}$ films & Fe-based superconductors
- Relationship between creep rate and material parameters

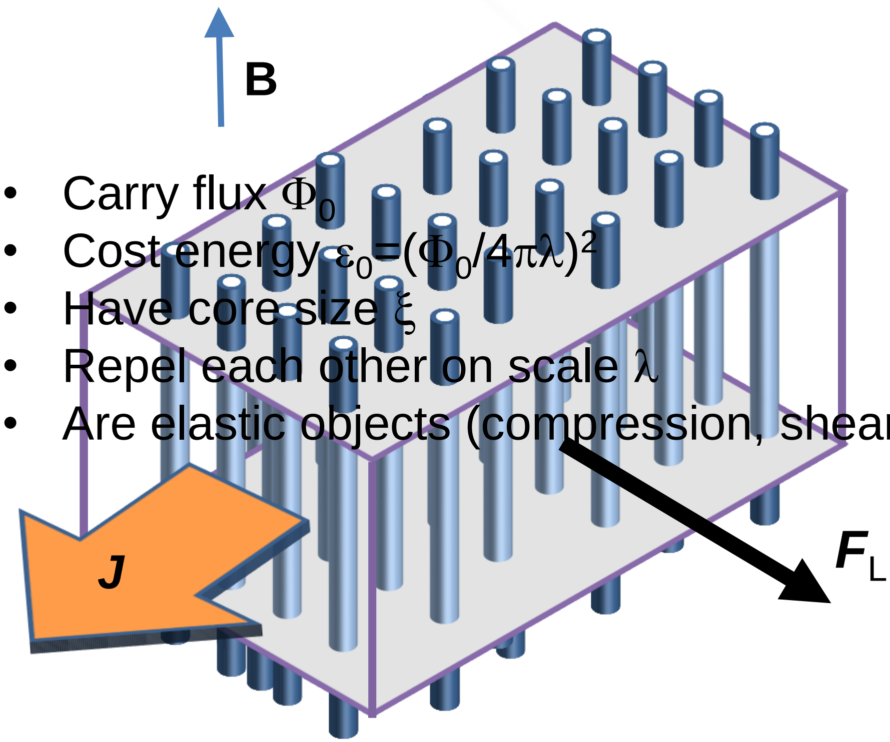
Vortices in the Mixed State





Vortex creep
- Thermally activated flux motion
- Decay in persistent current over time





- Carry flux Φ_0
- Cost energy $\varepsilon_0 = (\Phi_0/4\pi\lambda)^2$
- Have core size ξ
- Repel each other on scale λ
- Are elastic objects (compression, shear, tilt)

Figure from W.-K. Kwok et al, *Rep Prog Phys* **79**, 11 (2016)

Importance of Considering Flux Creep

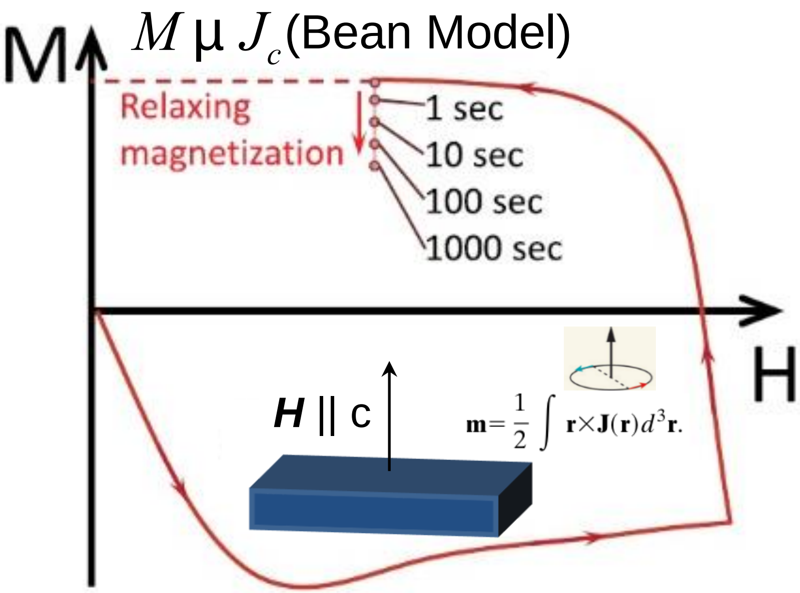
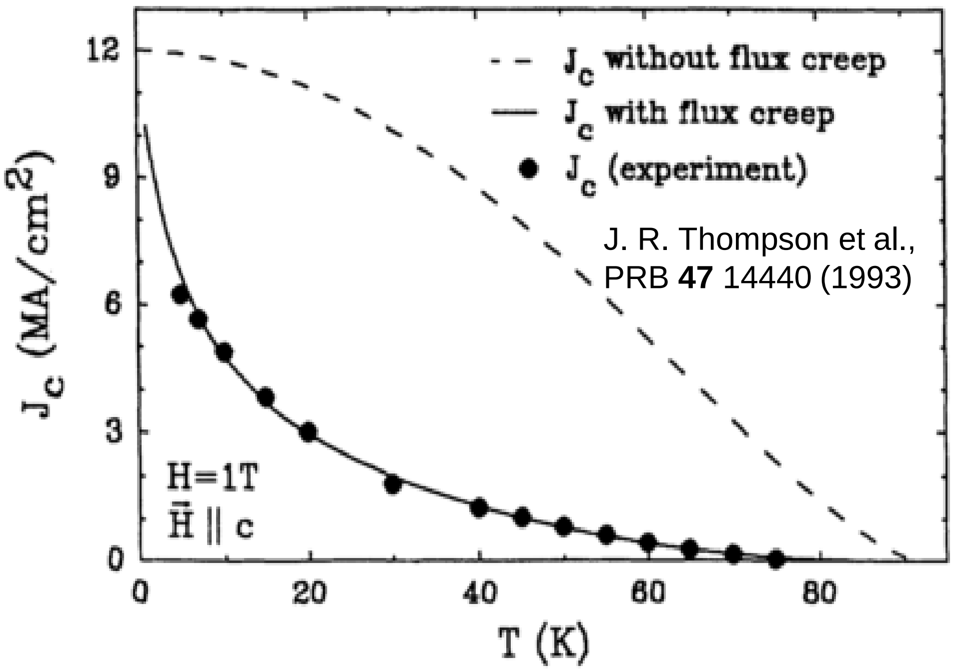


Fig. from W.-K. Kwok et al., *Rep Prog Phys* **79**, 11 (201

$YBa_2Cu_3O_{7-\delta}$ Single Crystal

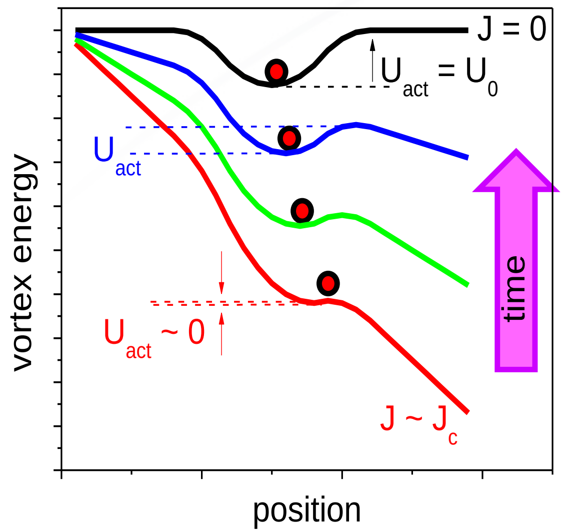


Large creep rates → measured J_c in high-T_c superconductors is significantly lower than initial J_c

Bad for applications

Engineer pinning to reduce creep

Models of Flux Creep



Anderson-Kim model:

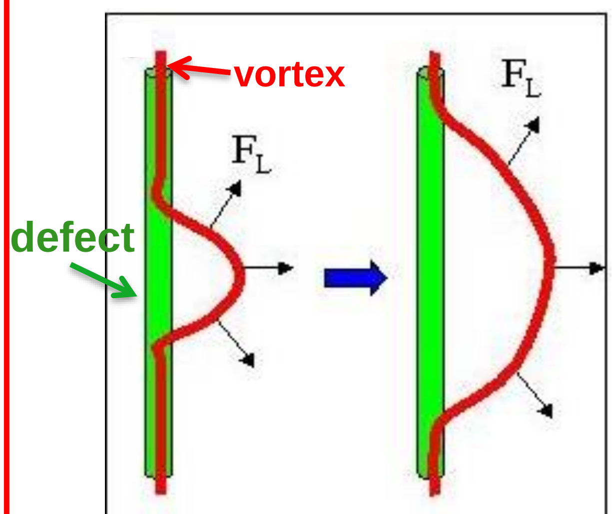
$$E \mu e^{-U_{act}(J)/k_B T}$$

$$U_{act} \mu U_0 \left|1 - J/J_c\right|$$

$$J(t) = J(t_0)\left[1 - \frac{k_B T}{U_0}\ln\left(\frac{t}{t_0}\right)\right]$$

$$U_{act}(J) \to U_0 \text{ as } J \to 0$$

$$S = \frac{-1}{J(t_0)} \frac{dJ}{d\ln(t/t_0)} \mu \frac{k_B T}{U_0}$$



Vortex elasticity $\Rightarrow$ as J decreases the vortex segment that jumps becomes longer $\Rightarrow$ U_{act} increases and ***diverges*** for $J \to 0$ (glassiness)

$$E \mu e^{-U_{act}(J,B,T)/k_B T}$$

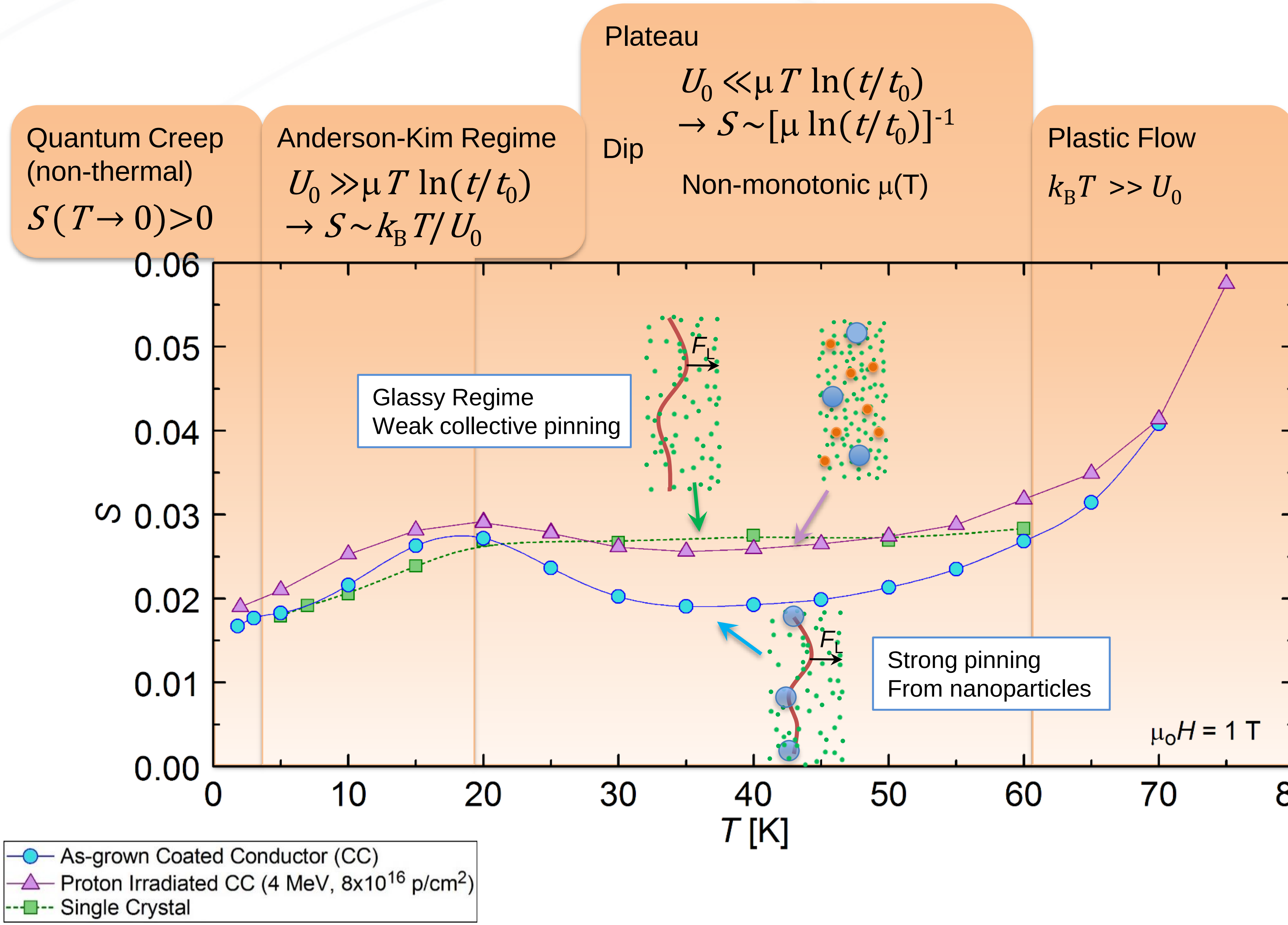
$$U_{act} \mu U_0 \left(J_c / J\right)^m$$

$$S = -\frac{d\ln J}{d\ln t} = \frac{k_B T}{U_0 + m k_B T \ln(t/t_0)}$$

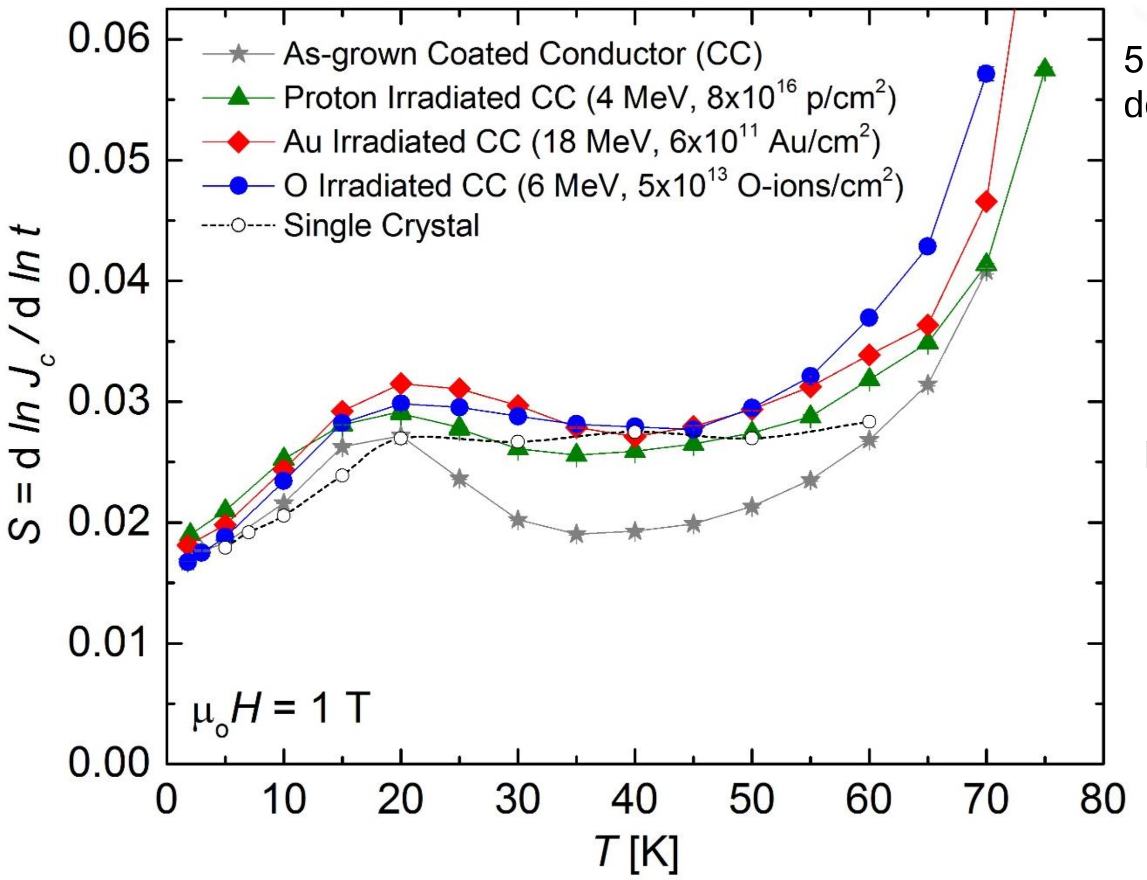
$$S \sim \frac{1}{m\ln(t/t_0)} \sim \frac{1}{30m}$$ High T plateau

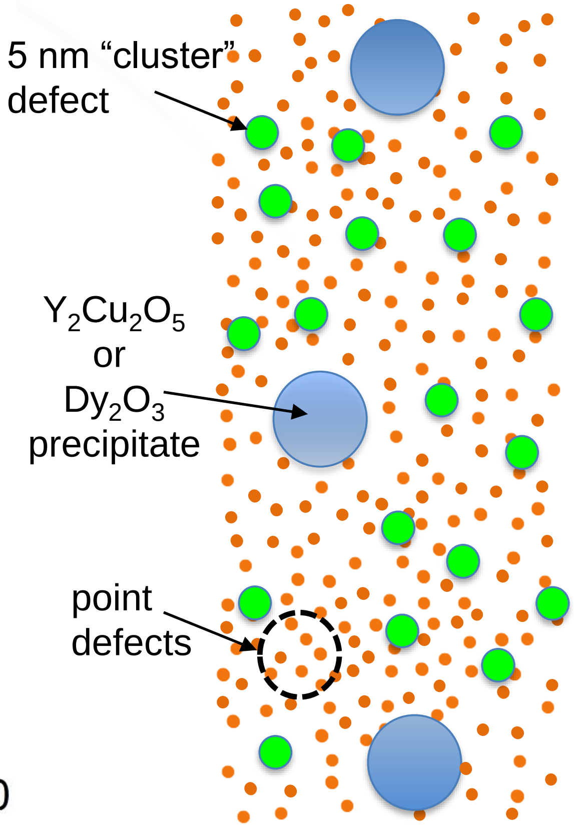
Creep in $YBa_2Cu_3O_{7-\delta}$

$$S = -\frac{d\ln(J)}{d\ln(t)} = \frac{k_B T}{U_0 + \mu k_B T \ln(t/t_0)}$$



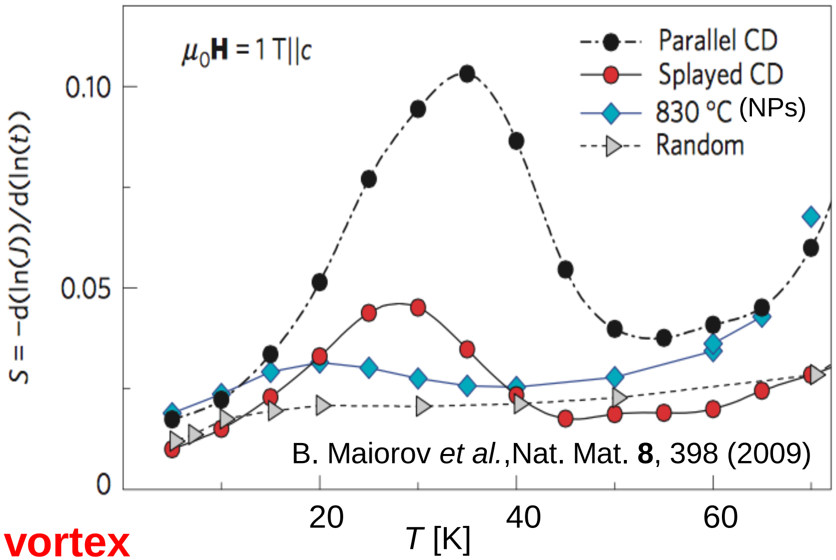
Irradiation Increases Creep in YBCO Coated Conductors (CCs)

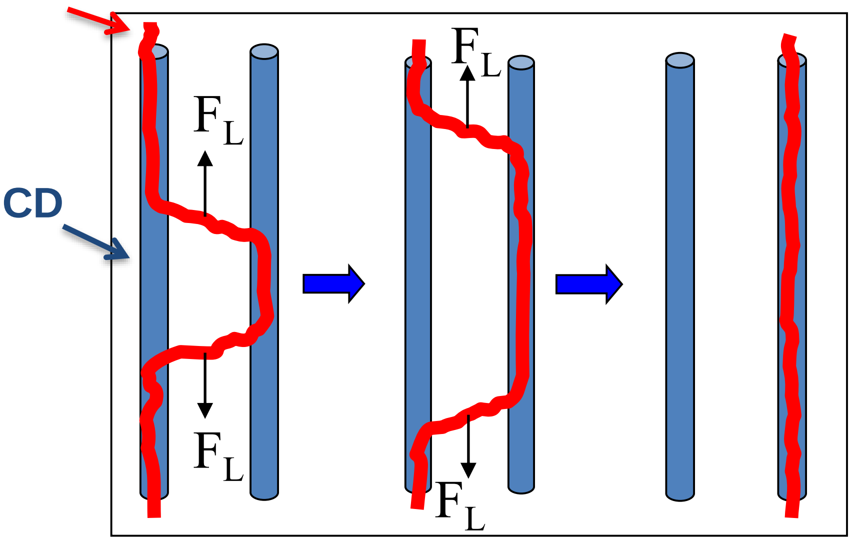




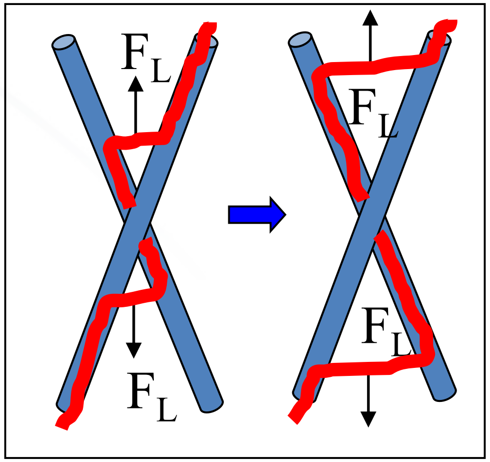
- S. Eley, et al., *SuST* **30** 015010 (2017)
- M. W. Rupich et al., *IEEE Trans. Appl. Superconductivity* **26** 3 (2016) (gold-irradiation)
- J. R. Thompson et al., *PRB* **47** 14440 (1993) (single crystal)

Vortex Depinning from Columnar Defects (CDs): YBCO

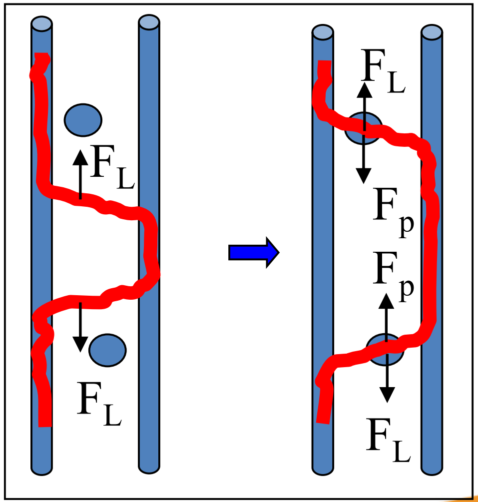




Splay



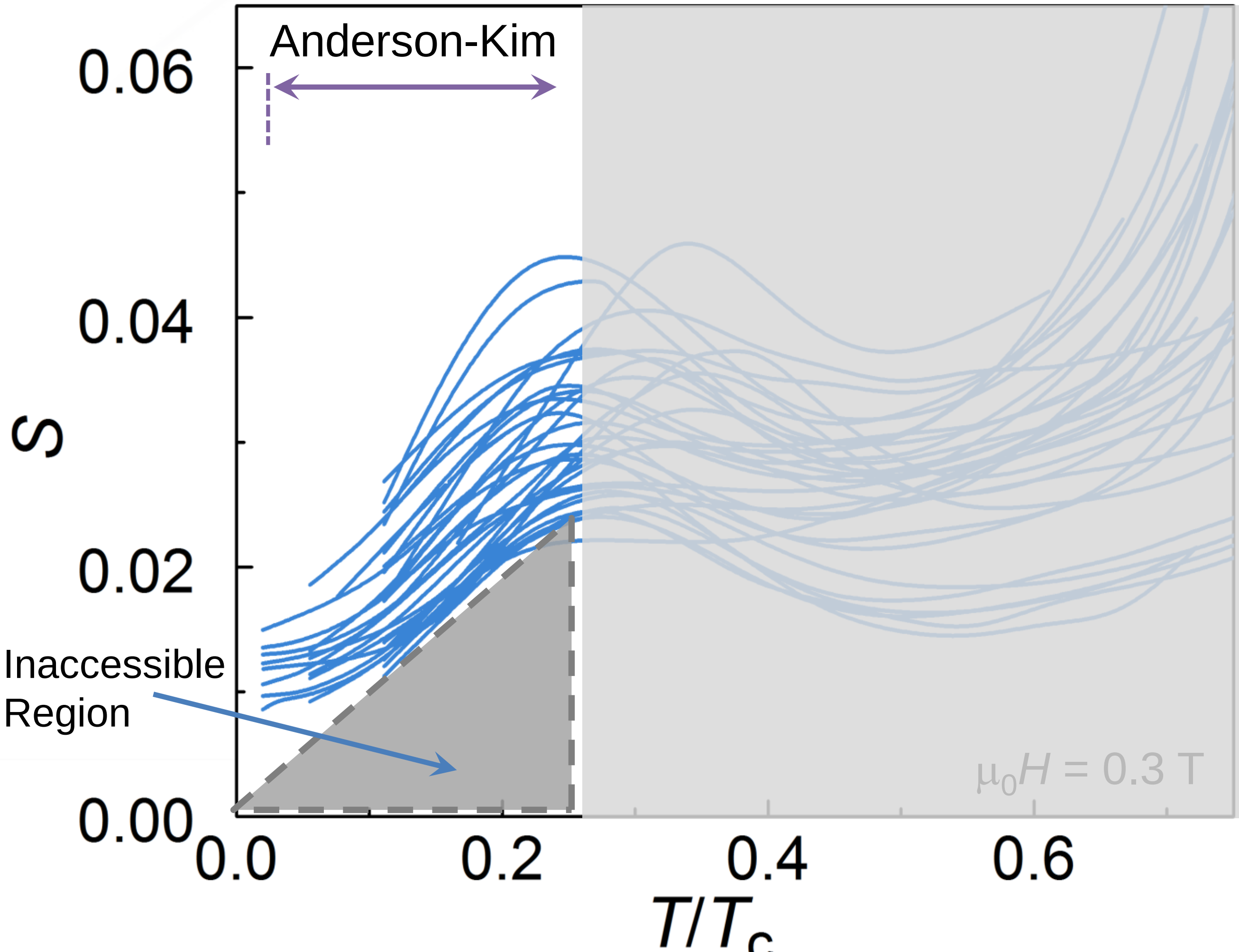
Random nanoparticles

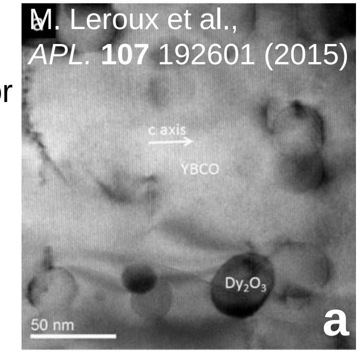


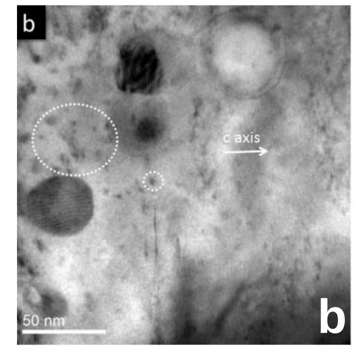
Creep in YBCO: Decades of microstructure modification

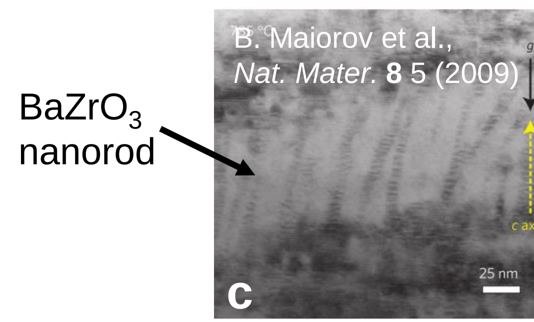
Examples (TEM images)
a, b, American Superconductor Corp, (images by D. Miller, Argonne NL)
c, d, Grown by M. Miura

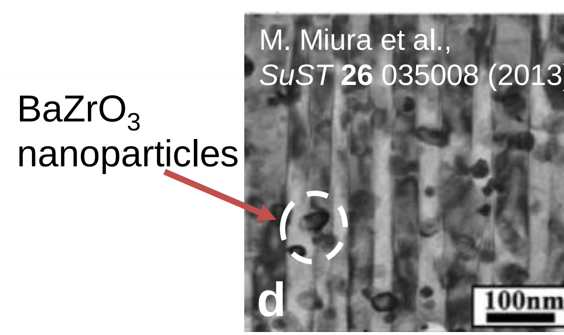
34 samples: Different microstructures





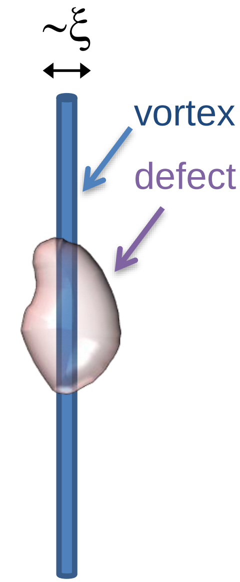






Expectations for Creep in Iron-based Superconductors

Creep is faster in high-T_c SC than in low-T_c SC
We expected S in iron-based superconductors to lie in between



- Anderson-Kim regime: $S \sim k_B T / U_P$
- Low T: $U_P \sim (H_c^2/8\pi) V_P \sim \xi^2$
- High T_c SC: Small ξ → Small U_P (?) → Large S → How large?
- Magnitude of S should somehow positively correlate with Gi

Ginzburg number: $$Gi = \frac{\gamma^2}{2}\left[\frac{m_0 k_B T_c}{4\pi B_c^2(0)\xi_{ab}^3(0)}\right]^2 \propto \frac{\gamma^2 T_c^2 \lambda^4}{\xi^2}$$

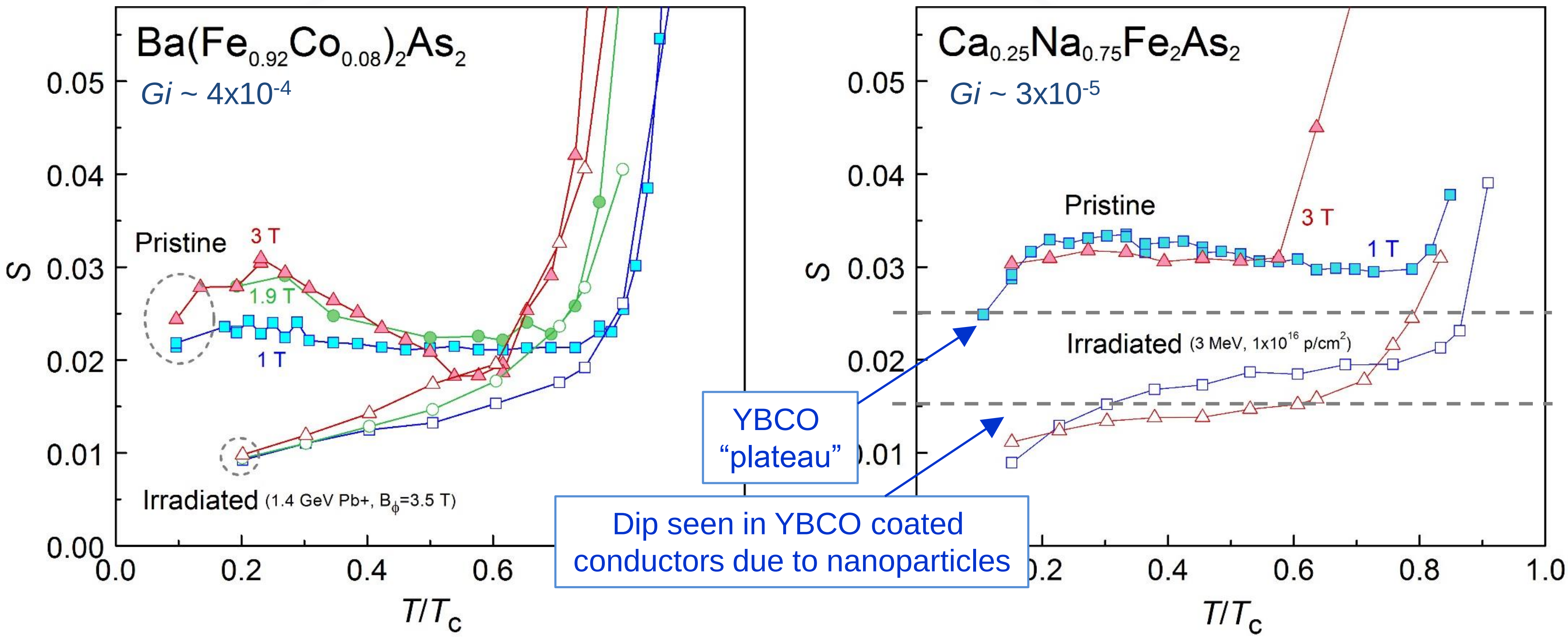
parameterizes scale of thermal fluctuations in a superconductor

Material	*Gi*
Nb	10^{-9}
Fe-based	$\sim 10^{-5}$-10^{-4}
YBCO	10^{-2}

Creep in Iron-Based Superconductors
Irradiation can reduce *S* in Fe-based superconductors

N. Haberkorn et al. SUST **28** 055011 (2015)

N. Haberkorn et al. PRB **84** 094522 (2011)



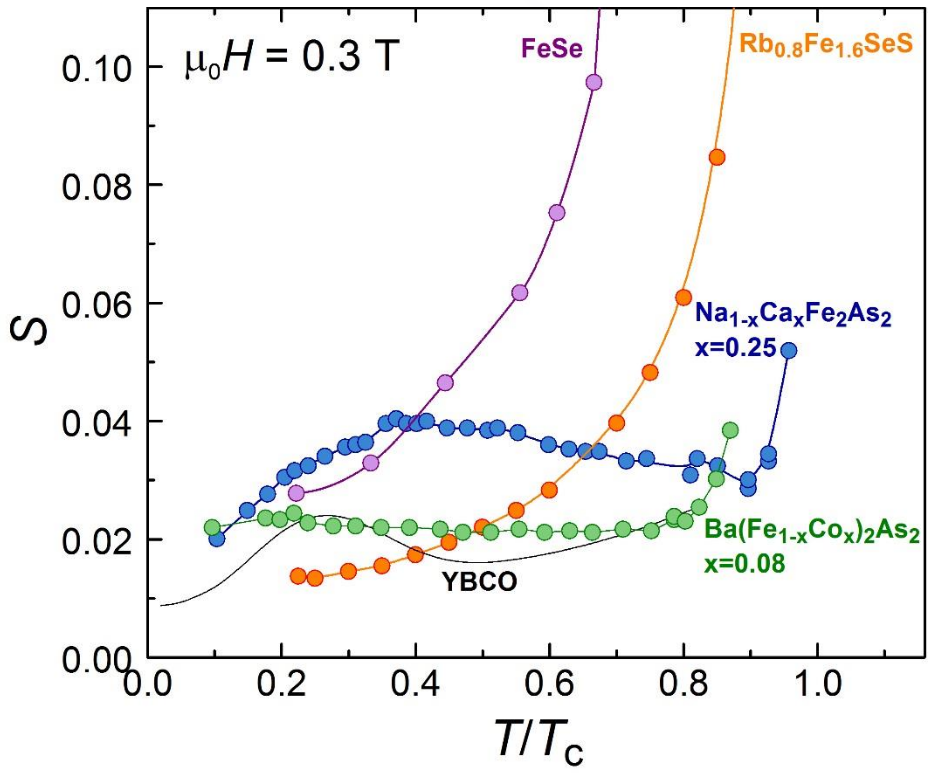
Creep still not much slower than in YBCO (*Gi*~10^{-2})

Note that Tamegai et al, [*PRB* **82** 220504 (2010), *SuST* **25** (2012) 084008] have extensively studied the effects of irradiation on iron-based superconductors.

Why is creep so fast in iron-based superconductors?

Material	*Gi*
Nb	10^{-9}
$Ca_{1-x}Na_xFe_2As_2$	10^{-5}
FeSe	10^{-4}
$Ba(Fe_{1-x}Co_x)_2As_2$	$4x10^{-4}$
YBCO	10^{-2}

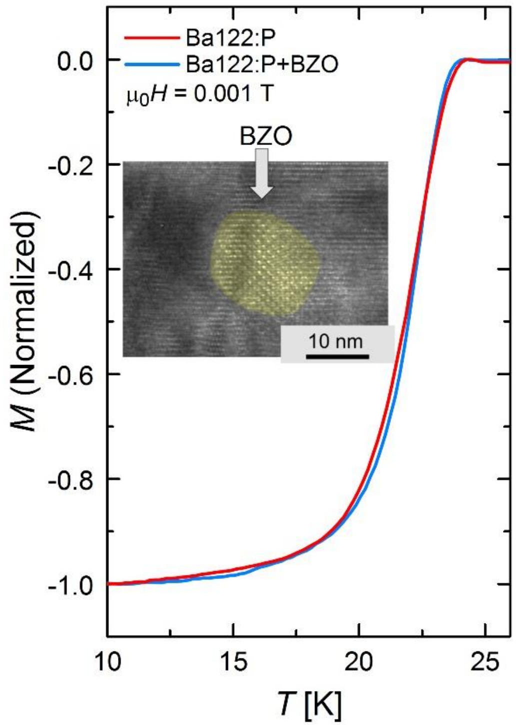
Y. Sun, APEX 8 113102 (2015); J. Yang (in prepration); N. Haberkorn, PRB 84 (2011); N. Haberkorn, SUST 28 55011 (2011); S. Eley, Nature Materials (2017)

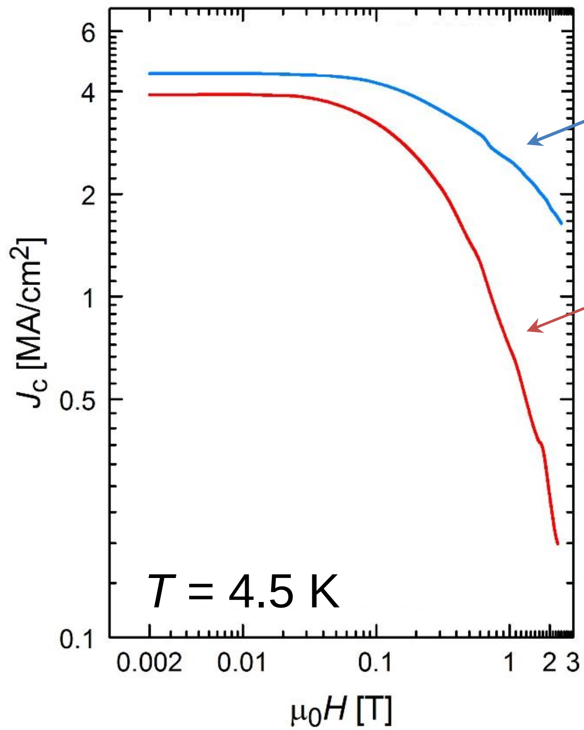


P-doped 122 films with Nanoparticle Inclusions

$BaFe_2(As_{0.67}P_{0.33})_2$

- High J_c that can be enhanced by $BaZrO_3$ nanoparticle inclusions





M. Miura et al., *Nat. Commun.* **4** 2499 (2013)

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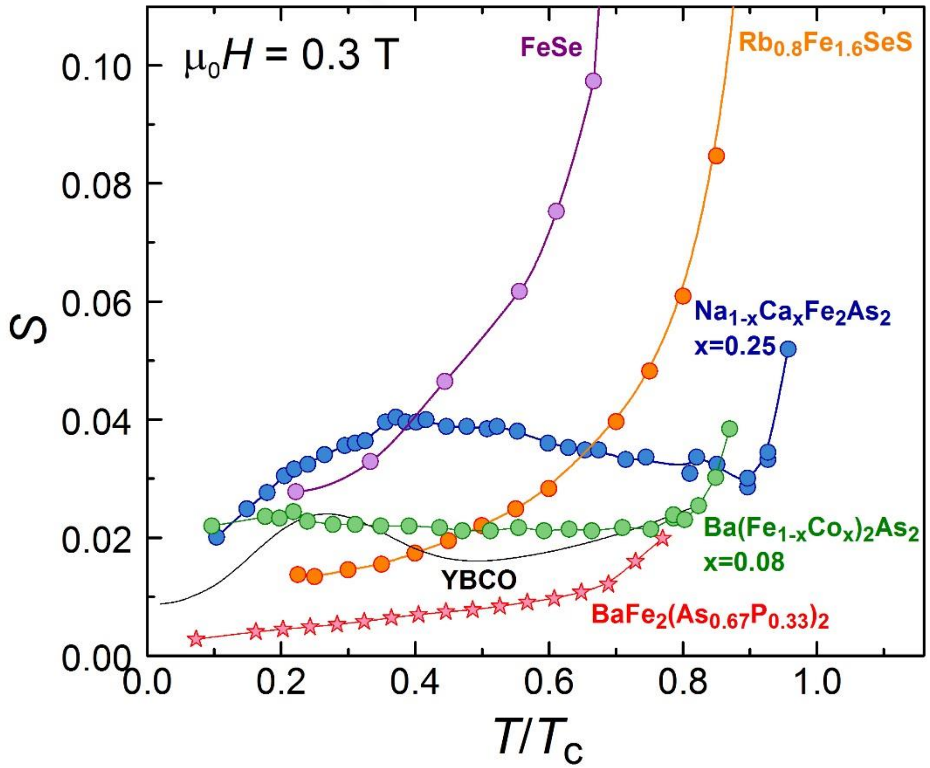
Material	*Gi*
Nb	10^{-9}
$Ca_{1-x}Na_xFe_2As_2$	10^{-5}
FeSe	10^{-4}
$Ba(Fe_{1-x}Co_x)_2As_2$	$4x10^{-4}$
$BaFe_2(As_{0.67}P_{0.33})_2$	$9x10^{-5}$
YBCO	10^{-2}



- *Gi* is orders of magnitude higher in YBCO than in most Fe-based superconductors / We grew and measured S and J_c in $BaFe_2(As_{0.67}P_{0.33})_2$ film
  - Has slowest S of any iron-based superconductor measured to date / Has slowest S yet, comparable to YBCO
- What should we have expected? How much lower can we go?
- Can we predict creep rates based on material parameters?

Lower Limit to Vortex Creep in Superconductors (at low temperatures)

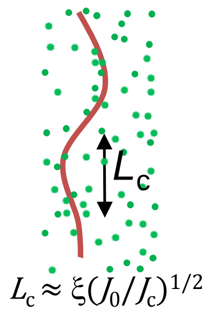
Limitations to Analysis

- Anderson-Kim regime: $S \sim k_B T / U_P,\ J \sim J_c$
- Low H: Single vortex
- Low T: $U_P \sim (H_c^2/8\pi) V_P$, $\sim T$ independent

$$Gi = \frac{\gamma^2}{2}\left[\frac{\mu_0 k_B T_c}{4\pi B_c^2(0)\xi_{ab}^3(0)}\right]^2 \propto \frac{\gamma^2 T_c^2 \lambda^4}{\xi^2}$$

Point defects (weak collective)

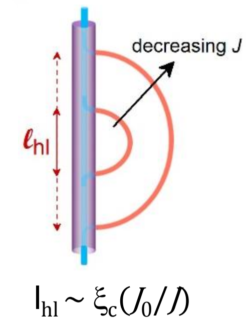
$$U_P \sim H_c^2(\xi_{ab}^3/\gamma)(J_c/J_0)^{1/2}$$



Columnar Defects

Half-loop formation

$$V_P \sim 2\pi\xi_{ab}^2 \ell_{hl}$$

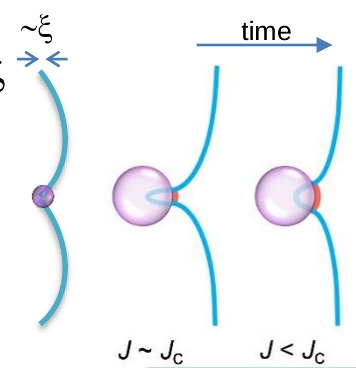


Nanoparticles $R \sim \xi$

$$V_P \sim (4\pi/3)(\xi_{ab}^3/\gamma)$$

Half-loop formation

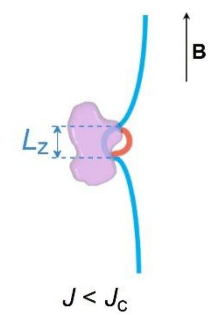
$$V_P \sim 2\pi\xi_{ab}^2 \ell_{hl}$$



Arbitrary shape/size

Half-loop formation

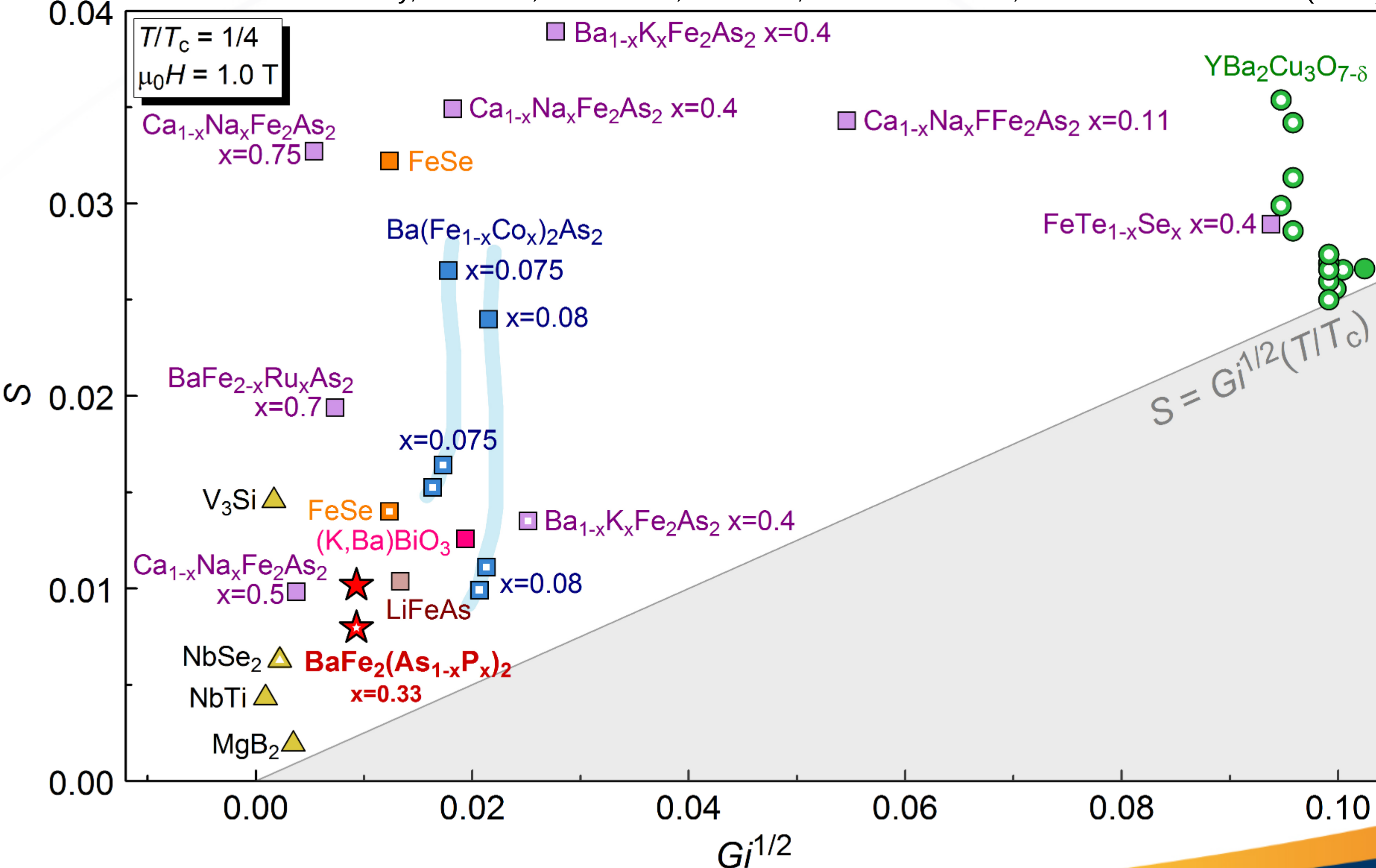
$$V_P \sim 2\pi\xi_{ab}^2 \ell_{hl}$$



$$S \gtrsim Gi^{1/2}(T/T_c)$$

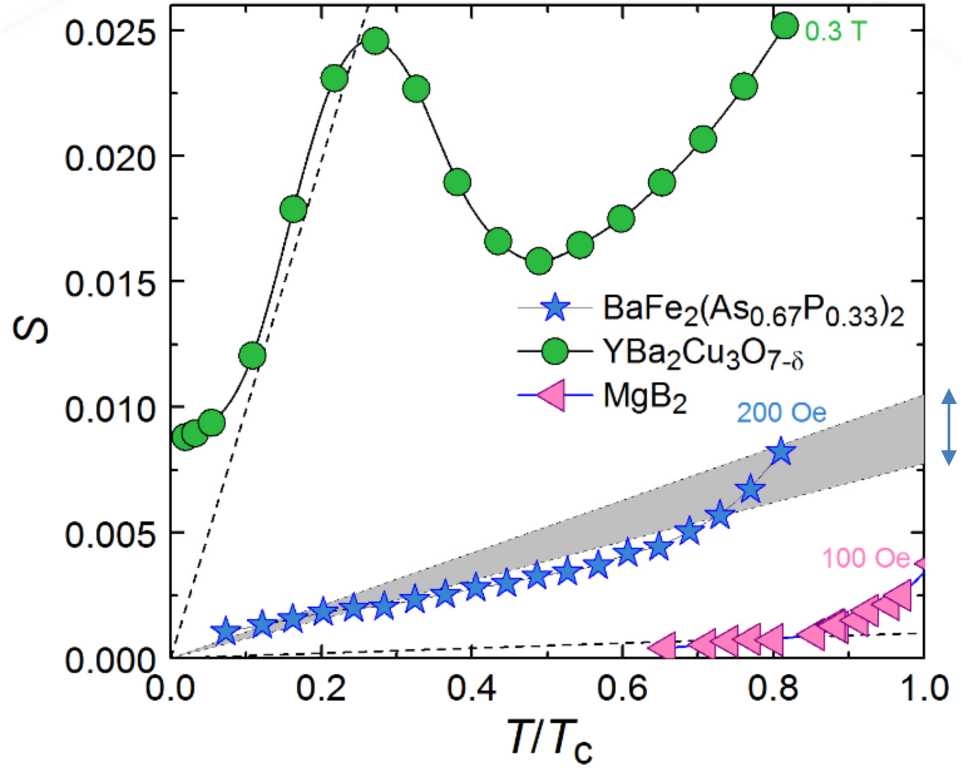
No Materials Violate Lower Limit

S. Eley, M. Miura, B. Maiorov, L. Civale, *Nature Materials*, doi:10.1038/nmat4840 (2017)



Few Materials Have Reached Limit

S. Eley, M. Miura, B. Maiorov, L. Civale,
Nature Materials, doi:10.1038/nmat4840 (2017)
Featured in Fitzgerald, *Physics Today*, doi:10.1063/PT.5.7347

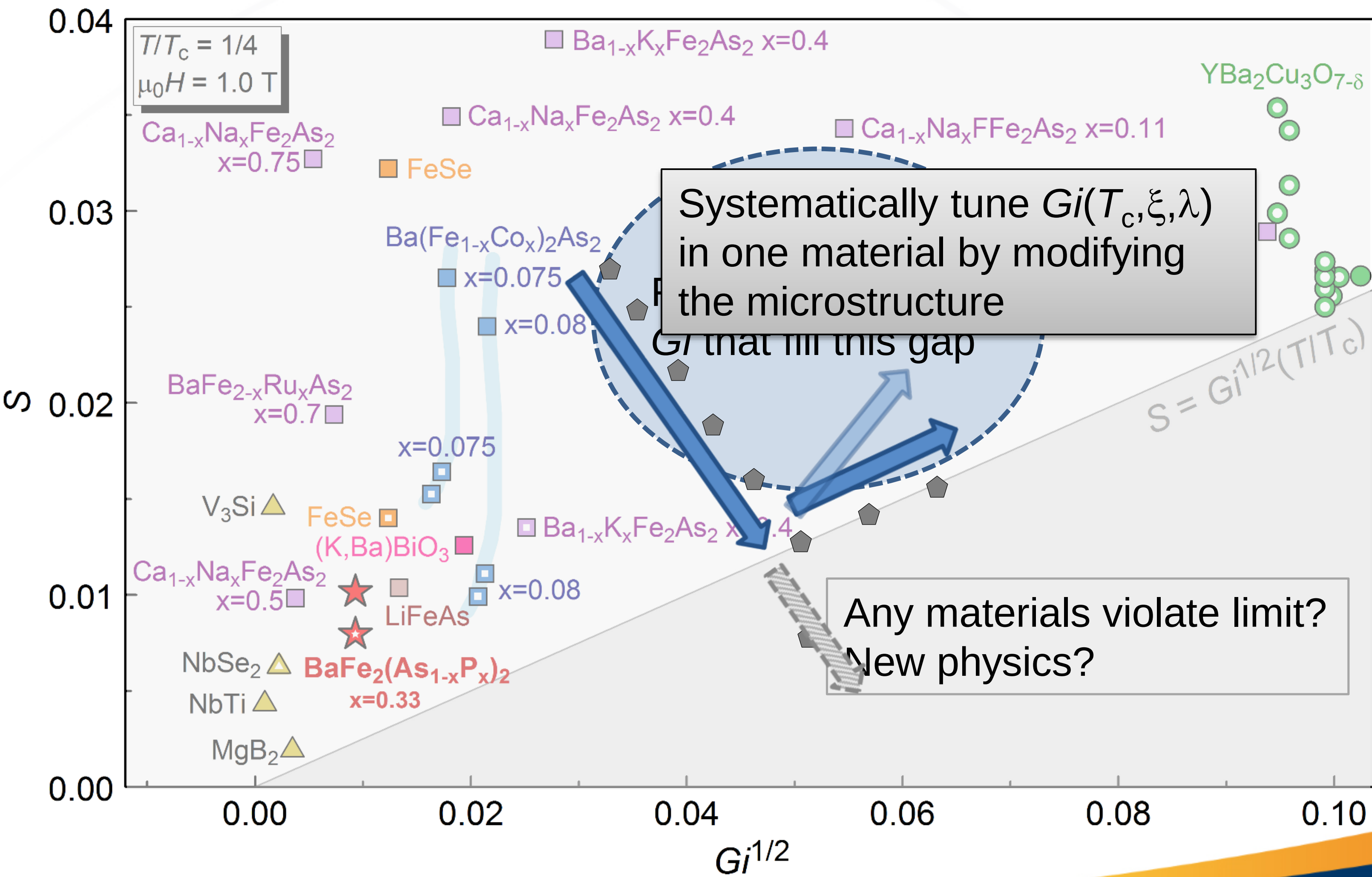


gray region captures uncertainty in $Gi^{1/2}(T/T_c)$, due to the uncertainty in λ

P-doped 122, $YBa_2Cu_3O_{7-\delta}$, MgB_2 (all films)

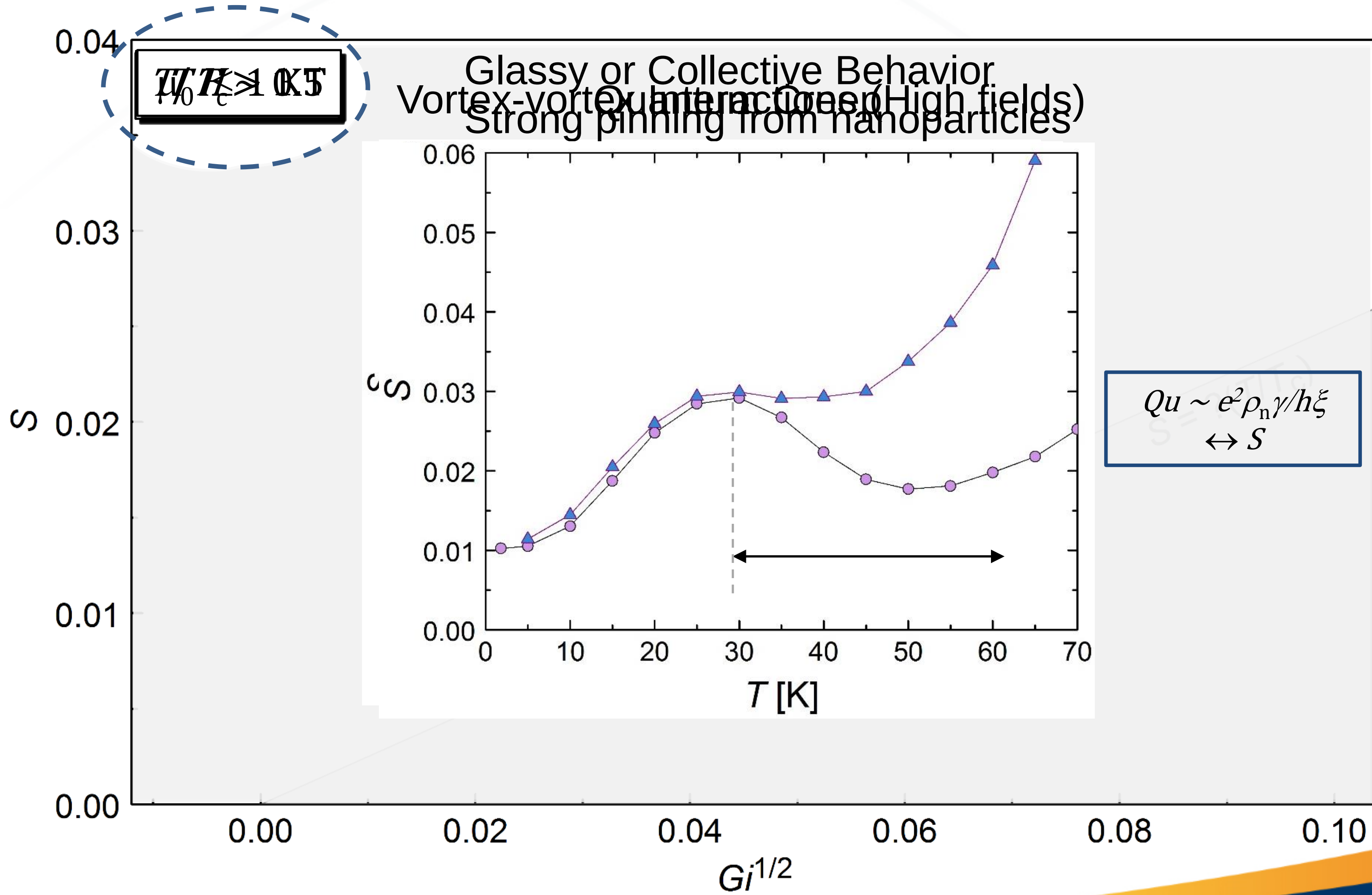
- Indicated fields (lowest *B* used that is above self-field)
- Dashed line shows $Gi^{1/2}(T/T_c)$ limit for each film

Future Work



T/T_c = 1/4
$\mu_0 H$ = 1.0 T
$Ba_{1-x}K_xFe_2As_2$ x=0.4
$Ca_{1-x}Na_xFe_2As_2$ x=0.4
$Ca_{1-x}Na_xFFe_2As_2$ x=0.11
$YBa_2Cu_3O_{7-\delta}$
$Ca_{1-x}Na_xFe_2As_2$ x=0.75
FeSe
$Ba(Fe_{1-x}Co_x)_2As_2$
x=0.075
x=0.08
$BaFe_{2-x}Ru_xAs_2$ x=0.7
x=0.075
V_3Si
FeSe
$(K,Ba)BiO_3$
$Ba_{1-x}K_xFe_2As_2$
$Ca_{1-x}Na_xFe_2As_2$ x=0.5
LiFeAs
x=0.08
$NbSe_2$
$BaFe_2(As_{1-x}P_x)_2$ x=0.33
NbTi
MgB_2
$S = Gi^{1/2}(T/T_c)$
that fill this gap
Systematically tune $Gi(T_c,\xi,\lambda)$ in one material by modifying the microstructure
Any materials violate limit? New physics?
S
0.00
0.01
0.02
0.03
0.04
0.00
0.02
0.04
0.06
0.08
0.10
$Gi^{1/2}$

Future Work



Glassy or Collective Behavior
Vortex-vortex interactions (High fields)
Quantum Creep
Strong pinning from nanoparticles
0.04
0.03
0.02
0.01
0.00
S
0.00
0.02
0.04
0.06
0.08
0.10
$Gi^{1/2}$
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
10
20
30
40
50
60
70
T [K]
S
$Qu \sim e^2\rho_n\gamma/h\xi$
$\leftrightarrow S$

Conclusions

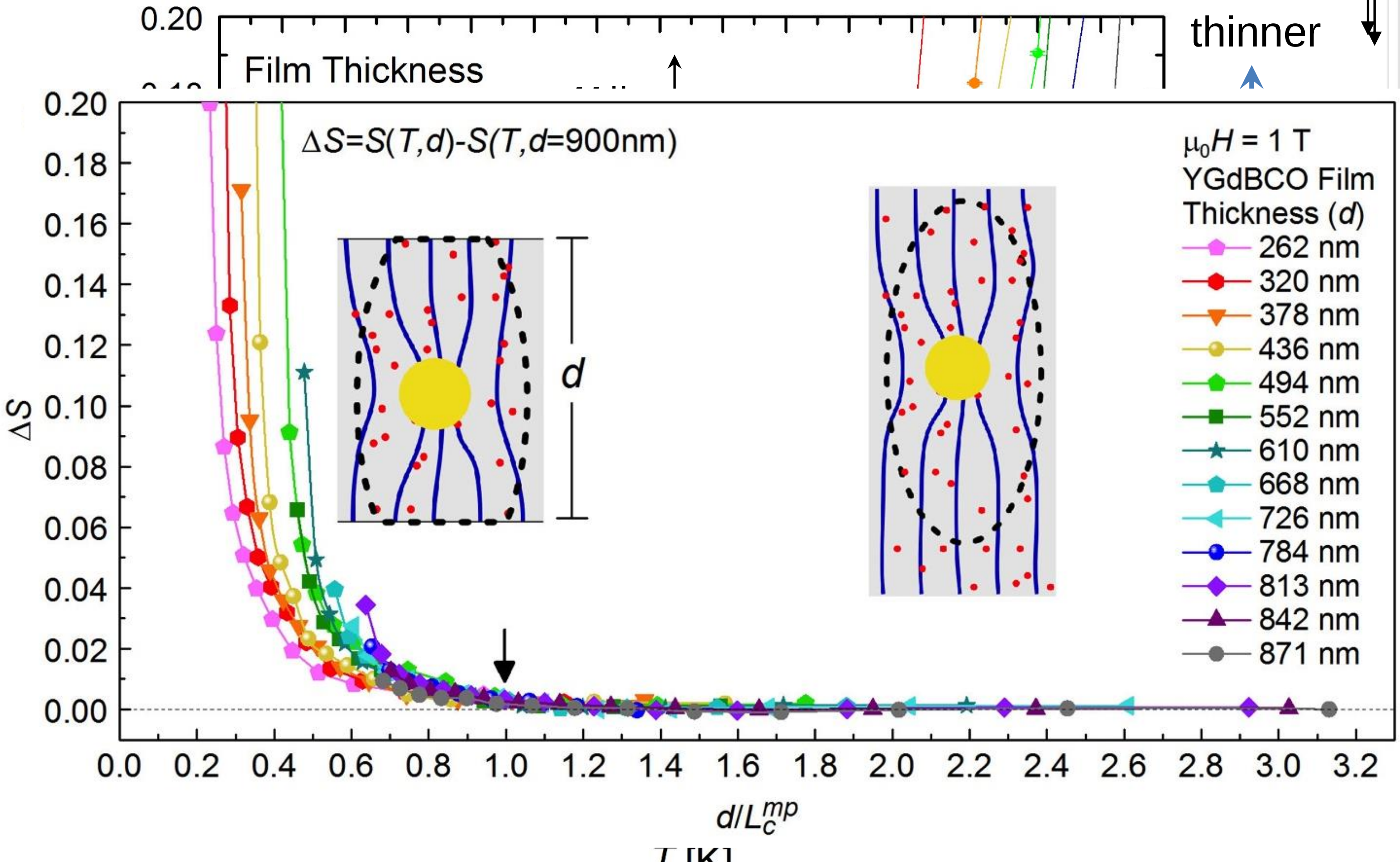
- $S(T)$ cannot be smaller than $Gi^{1/2}(T/T_c)$ in any material (in the Anderson-Kim regime)
  - Fundamental limitation to how much creep can be slowed through modification of the microstructure
  - Serve as a guide for when further improvements can be achieved
- Creep problem in high-T_c superconductors can not be fully eliminated
  - Limit to how much it can be ameliorated
- Any yet-to-be-discovered high-T_c superconductors will have fast creep
- Sheds light on designing materials with slow creep

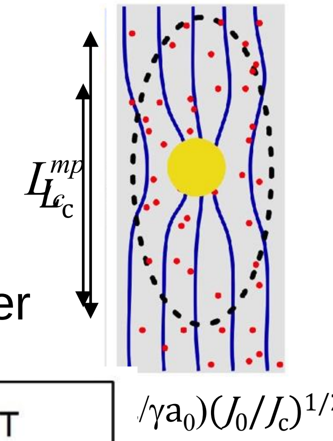
Future Work

- Precise tuning of Gi and limits to creep outside Anderson-Kim regime
- Creep is fast in very thin films! (systematic study: arXiv:1709.02776)

Creep Rate Very Sensitive to Film Thickness

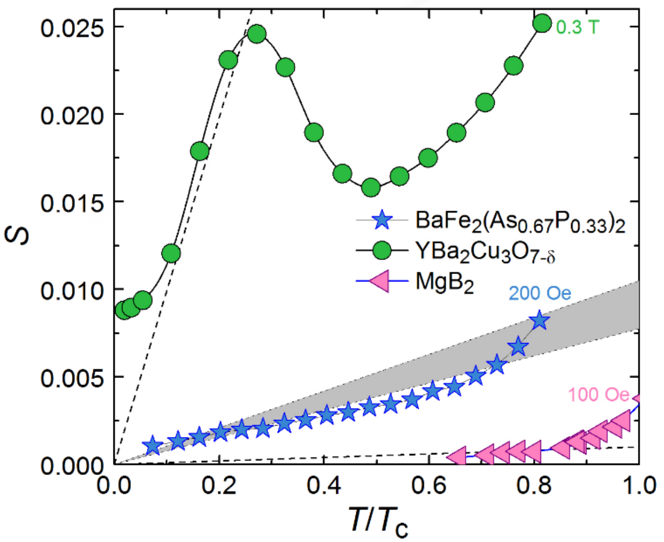
(Y,Gd)$Ba_2Cu_3O_{7-\delta}$





S. Eley, R. Willa, M. Miura, M. Sato, M.D. Henry, L. Civale, arXiv:1709.02776

Few Materials Have Reached Limit



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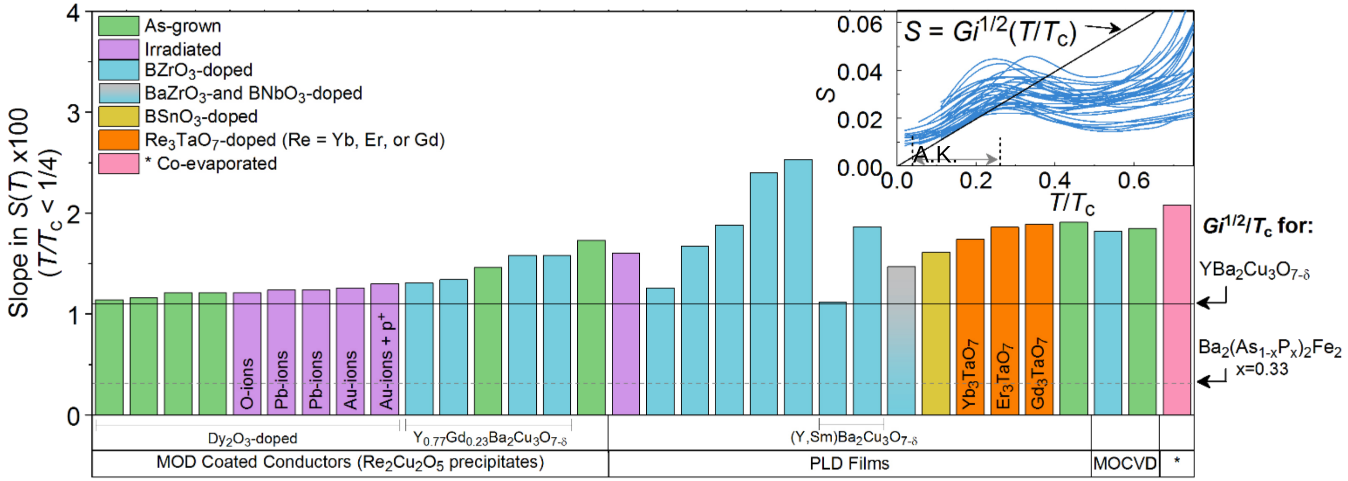
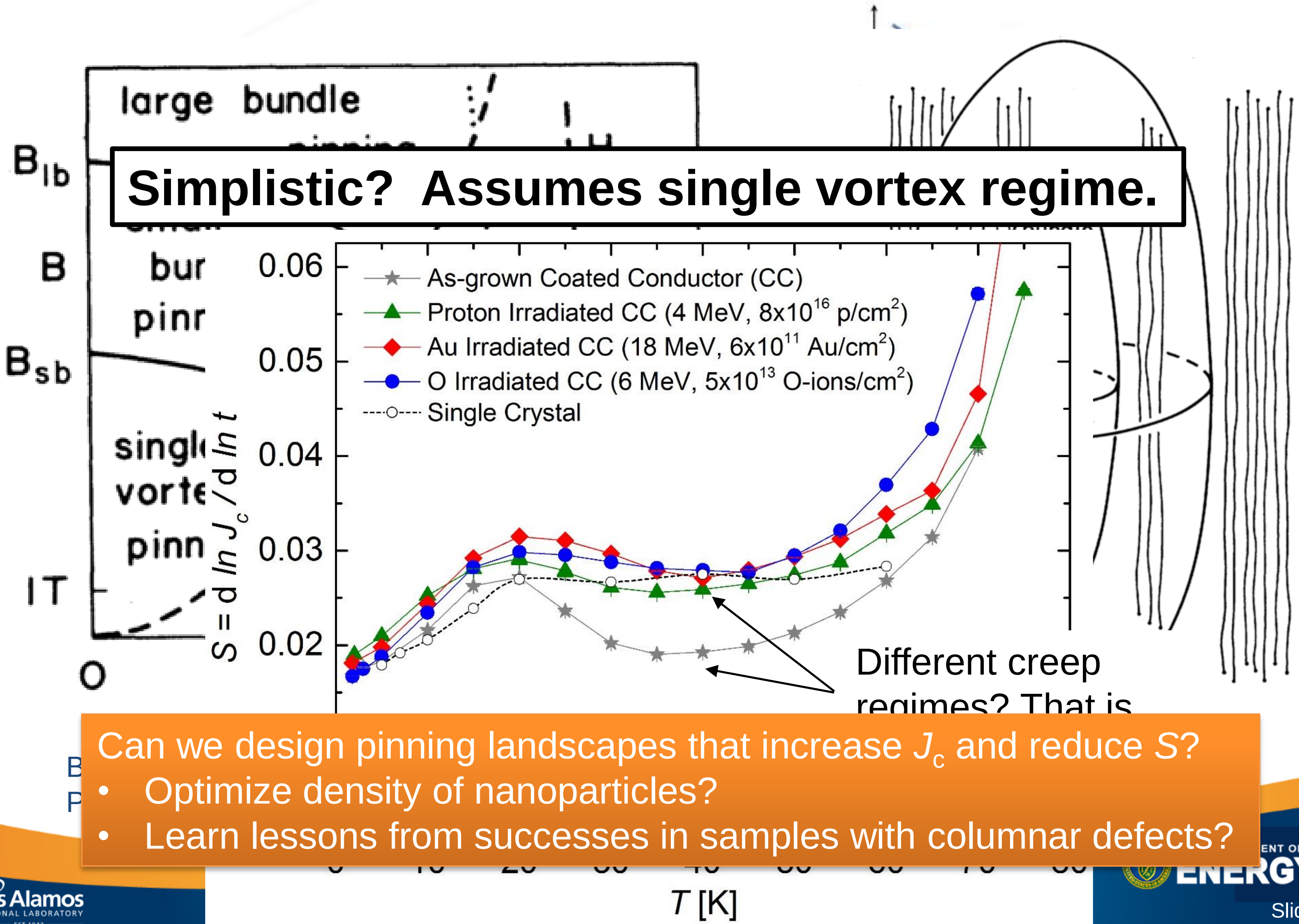


Why Does Irradiation Sometimes Increase Creep?



Can we design pinning landscapes that increase J_c and reduce S?

- Optimize density of nanoparticles?
- Learn lessons from successes in samples with columnar defects?