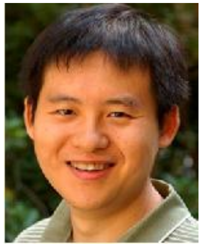
Learning to design superconductivity at and out equilibrium

Antonio M. García-García
Cavendish Laboratory, Cambridge University

Pedro Ribeiro
Lisbon

Tezuka
Kyoto



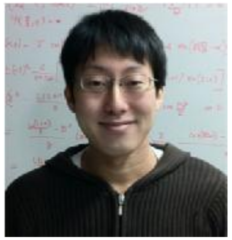
Hong Liu
MIT

Paul Chesler
Harvard

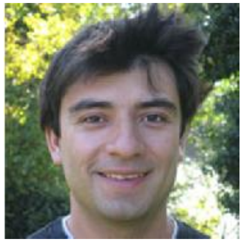
Bermudez
Cambridge

Naidon
Tokyo Riken

Cazalilla
Tsinghua



Endo
Paris, ENS



Lobos
Maryland

Mayoh
Cambridge

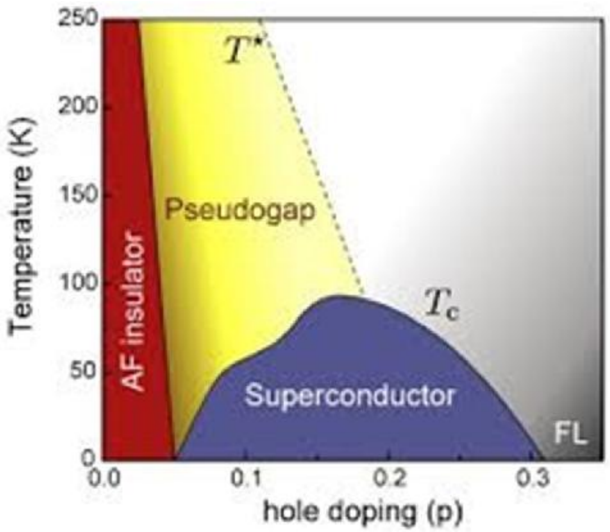
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

MARIE CURIE ACTIONS

EPSRC
Engineering and Physical Sciences
Research Council

Superconductivity

Mavericks



Quantum critical points ©

Cuprates	~100K	1986	Mueller & Bednorz
MgB_2	39K	2001	Akimitsu
FeSC	~50K	2006	Hotsono

Pb ~7K Al ~1K Sn ~3.7K Nb ~9.3K

Librarians

Thinner

Cleaner

Smaller

BCS + ….

Abeles, Tinkham, Devoret, Goldman, Xue, Kern, Di Fazio, Schoen, Halperin, Leggett,Blatt….

Thin films

Josephson Junctions

Nanowires

Control

No Control → Theory Drifts / Trial and error

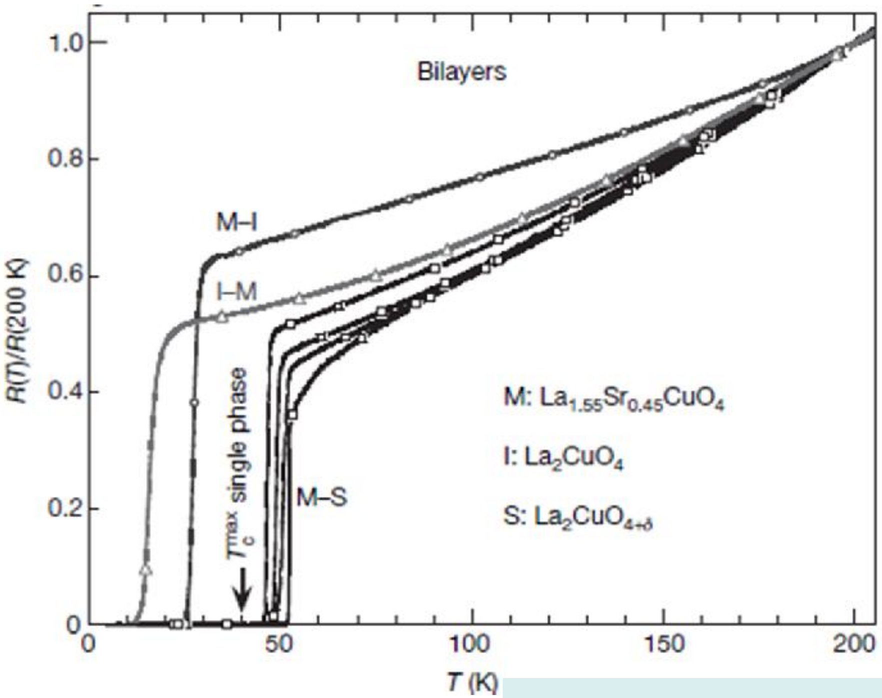
Experimental Control → Enhancement Tc? / Understanding Tc?

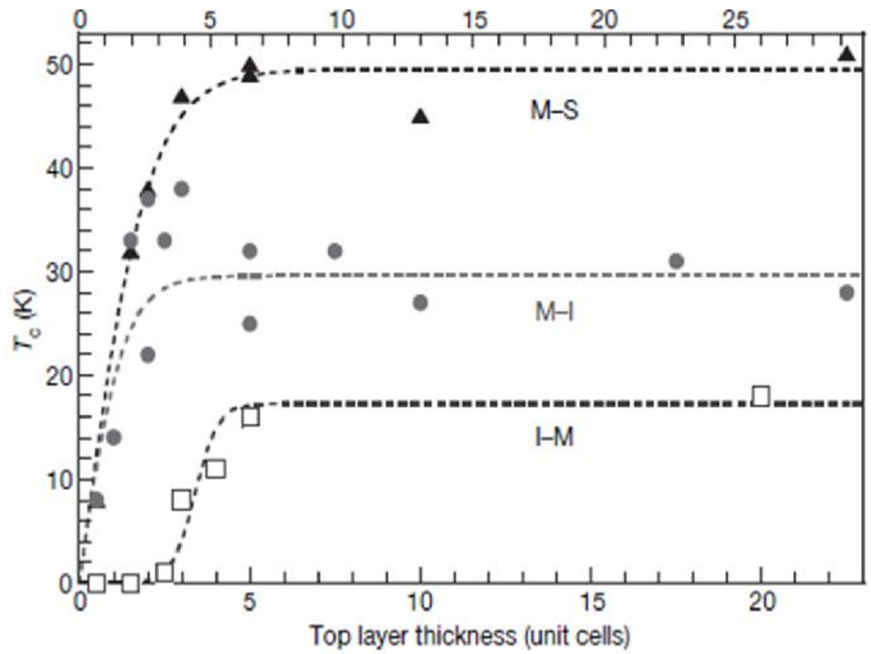
Mavericks meet Librarians

Learning to design SC

- Conventional SC in low dimensions
- Artificial heterostructures LAO/STO…
- Refined high Tc

Cuprates high T_c Heterostructures

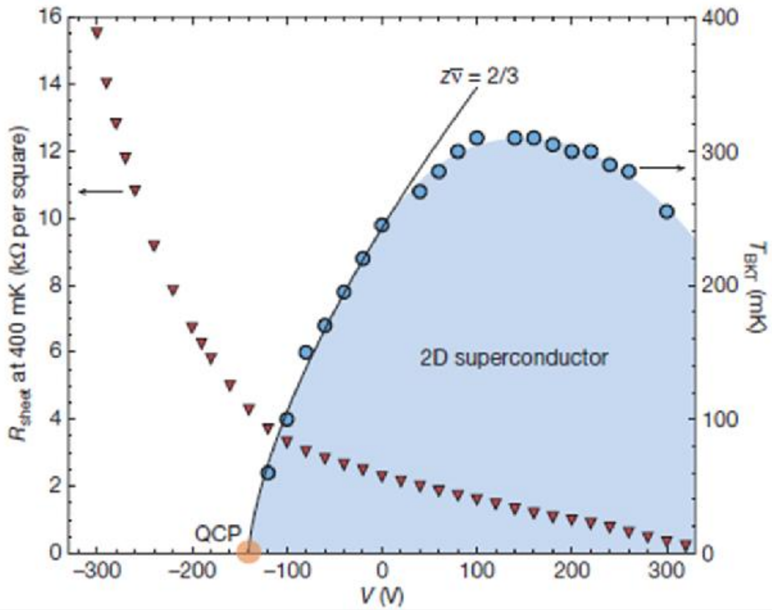




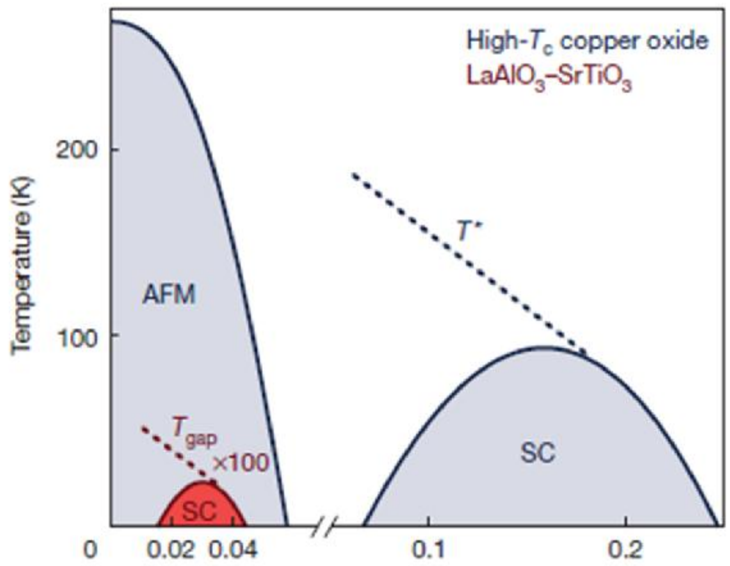
Bozovic et al., Nature 455, 782 (2008)

Higher T_c!!

$LaAlO_3$ /$SrTiO_3$ Heterostructures



Triscone et al. , Nature 456 624 (2008)



Mannhart et al., Nature 502, 528 (2013)

Control

Tunability

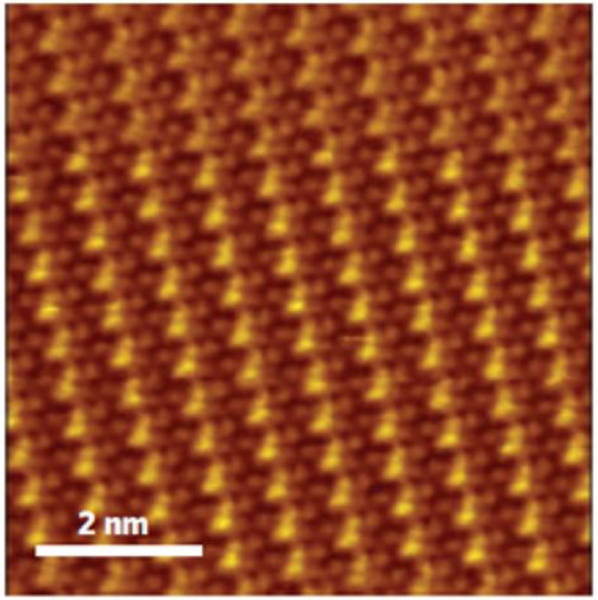
Electric Field Effect

No chemical doping

LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI:10.1038/NPHYS1499
nature physics

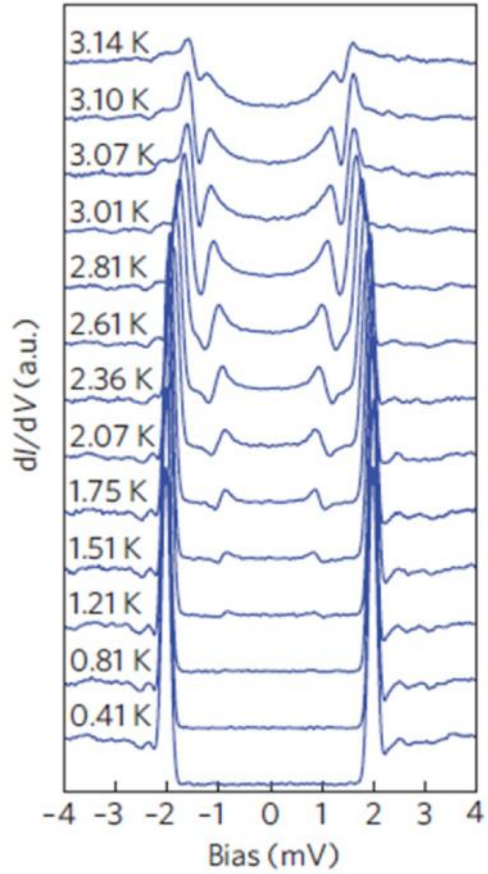
Superconductivity in one-atomic-layer metal films grown on Si(111)

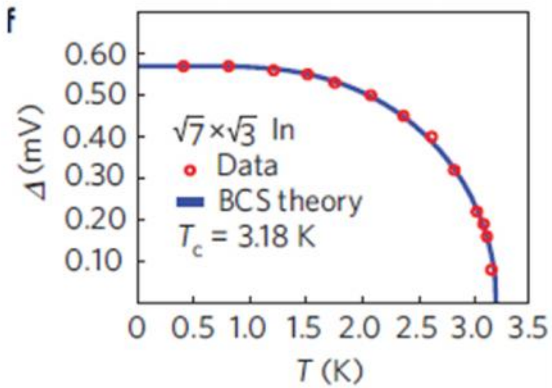
Epitaxial growth



STM

No impurities





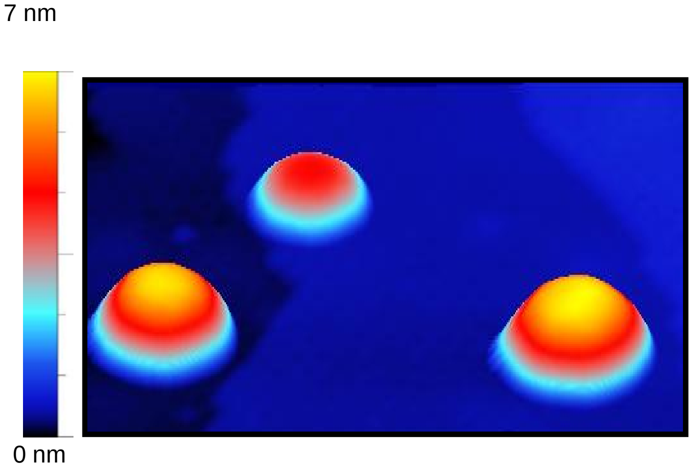
nature materials

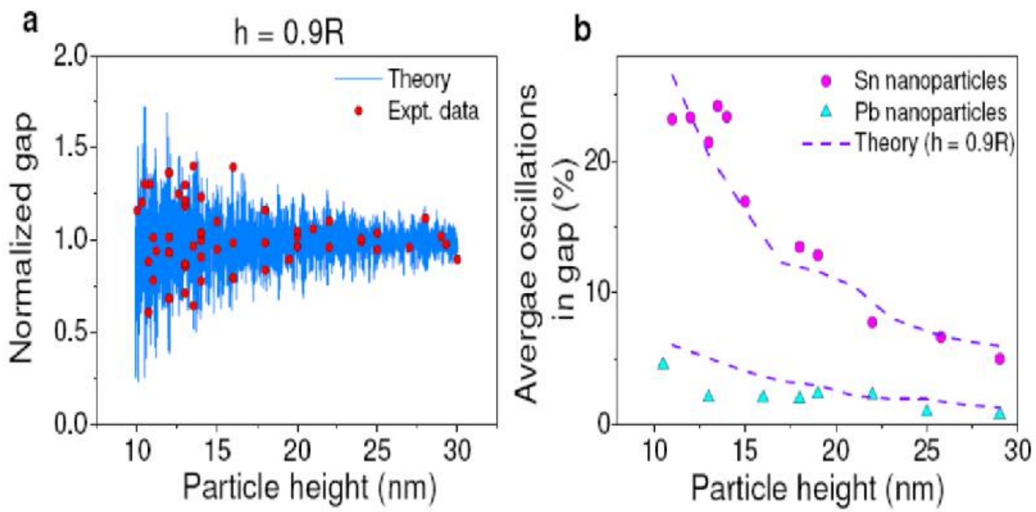
LETTERS

PUBLISHED ONLINE: 30 MAY 2010 | DOI:10.1038/NMAT2768

Observation of shell effects in superconducting nanoparticles of Sn

Sangita Bose[1]*, Antonio M. García-García[2]*, Miguel M. Ugeda[1,3], Juan D. Urbina[4], Christian H. Michaelis[1], Ivan Brihuega[1,3]* and Klaus Kern[1,5]





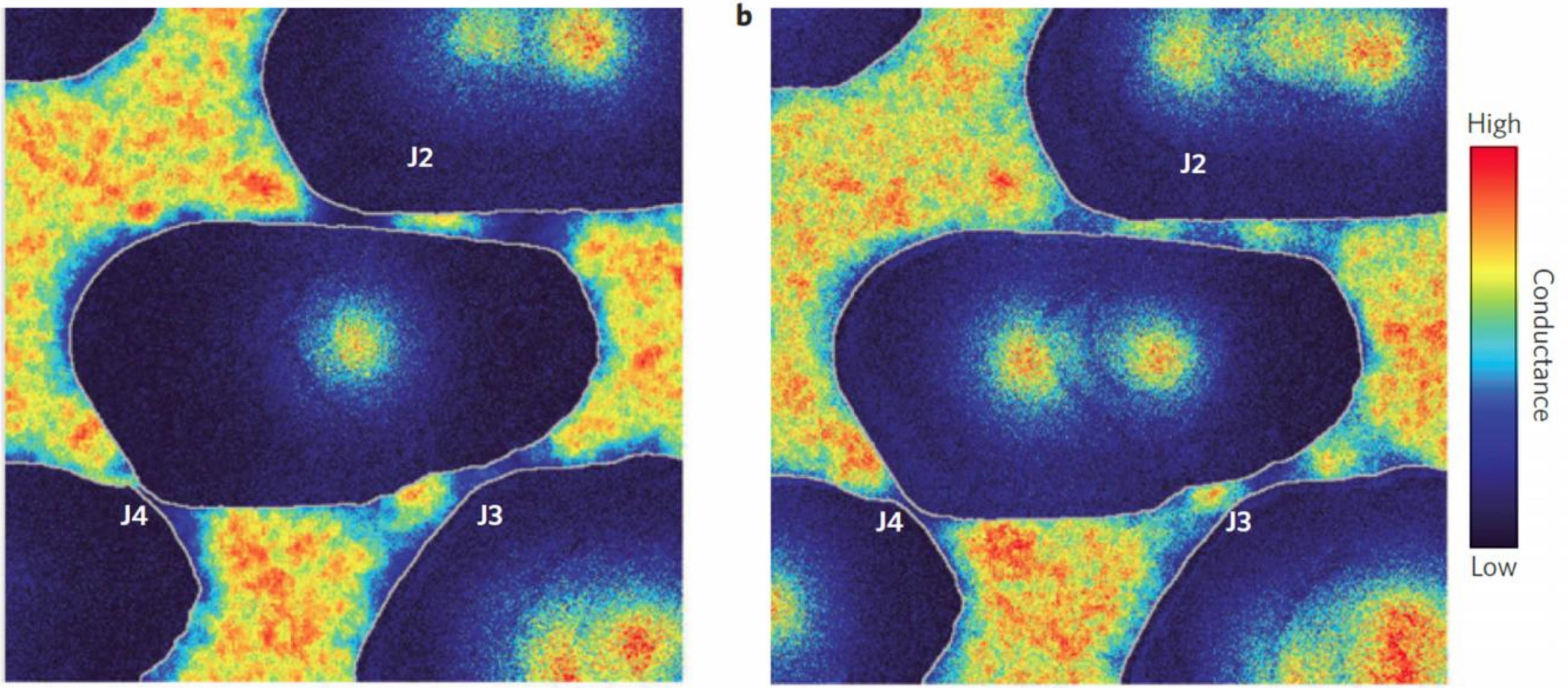
nature physics

LETTERS

PUBLISHED ONLINE: 23 FEBRUARY 2015 | DOI: 10.1038/NPHYS3240

Direct observation of Josephson vortex cores

Dimitri Roditchev[1,2], Christophe Brun[1], Lise Serrier-Garcia[1], Juan Carlos Cuevas[3], Vagner Henrique Loiola Bessa[4], Milorad Vlado Milošević[4,5], François Debontridder[1], Vasily Stolyarov[1] and Tristan Cren[1]*



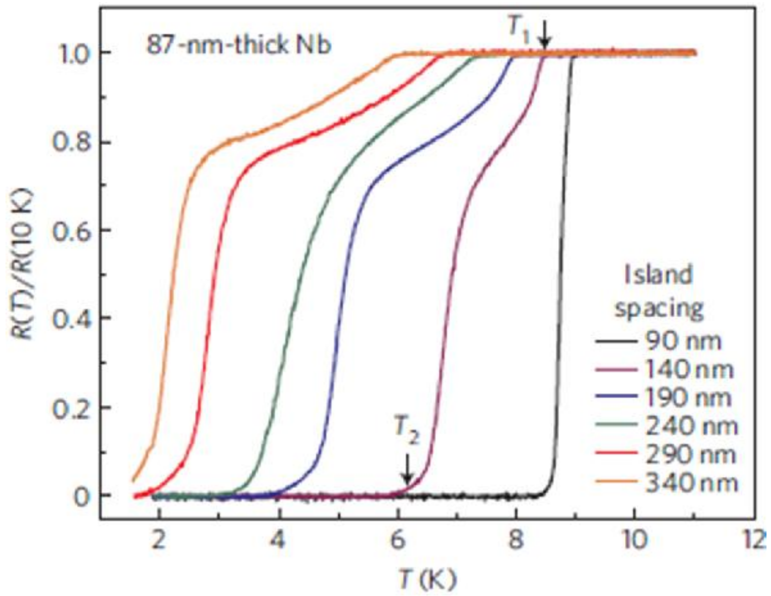
nature physics

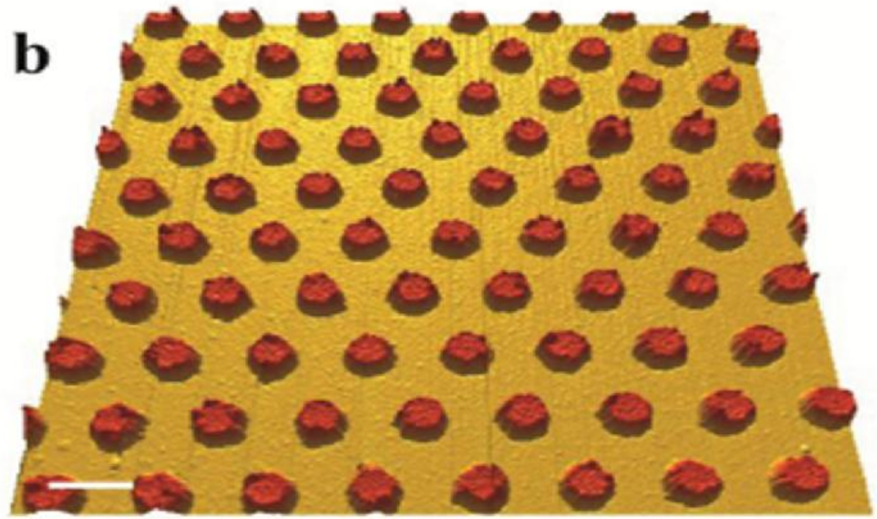
LETTERS

PUBLISHED ONLINE: 4 DECEMBER 2011 | DOI: 10.1038/NPHYS2154

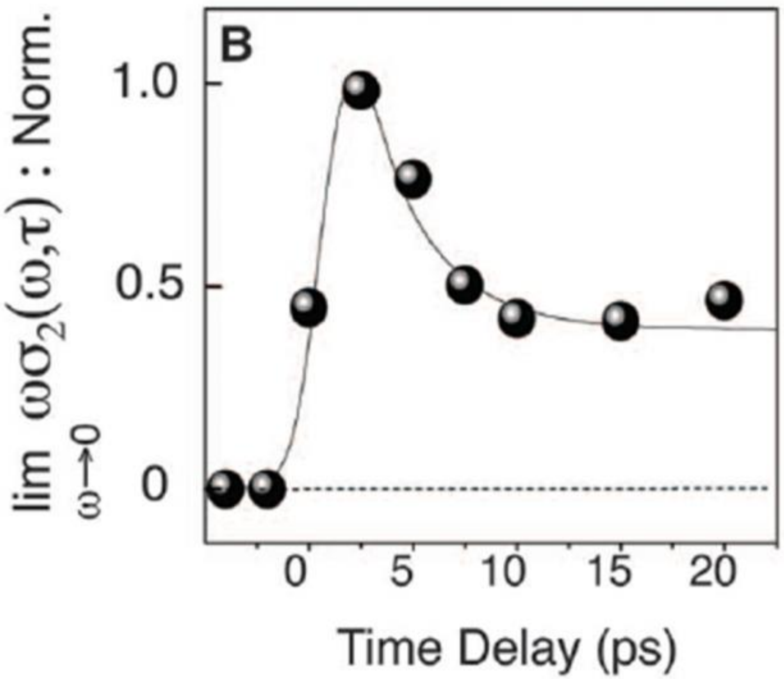
Approaching zero-temperature metallic states in mesoscopic superconductor–normal–superconductor arrays

Serena Eley[1], Sarang Gopalakrishnan[1], Paul M. Goldbart[2] and Nadya Mason[1]*





Transient Superconductivity



Pump & Probe

Femtosecond Pulses

ARPES

PRL **110**, 267003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Transient Increase of the Energy Gap of Superconducting NbN Thin Films Excited by Resonant Narrow-Band Terahertz Pulses

Light-Induced Superconductivity in a Stripe-Ordered Cuprate
D. Fausti *et al.*
Science **331**, 189 (2011);
DOI: 10.1126/science.1197294

Far from equilibrium

Cazalilla
Tsinghua

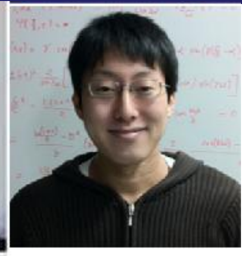
Tezuka
Kyoto

Chesler
Harvard

Liu
MIT

Novel pairing

Naidon
Tokyo



Endo
Paris

Research

Ribeiro
Lisboa

Mayoh
Cambridge

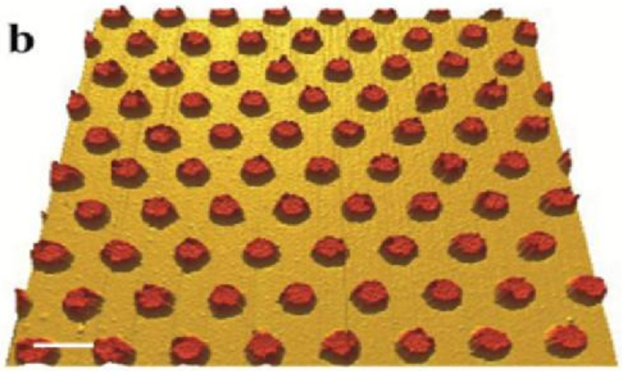
Nano Engineering

Kern
Sttutgart

Bermudez
Cambridge

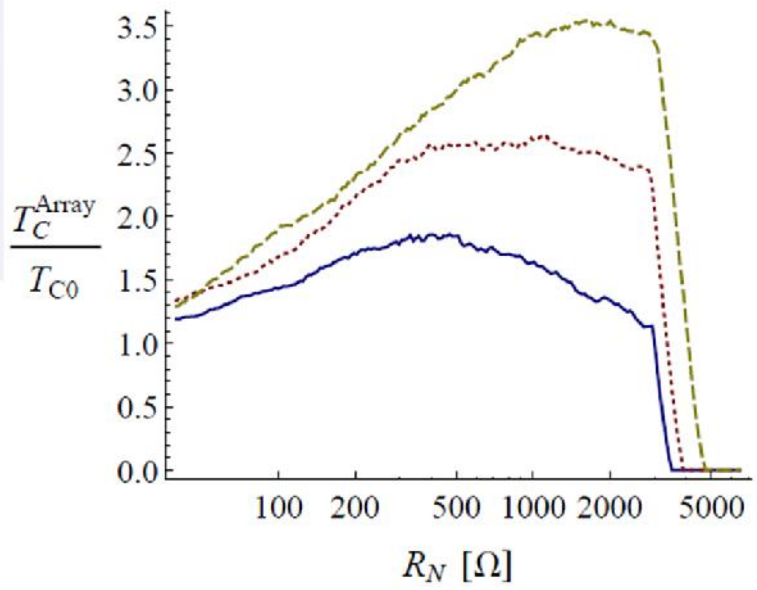
Engineering granular materials

Optimal but realistic



Size | Variance | Packing

$Tc=1.3Tc^{bulk}$
$Tc=1.5Tc^{bulk}$
$Tc=3.0Tc^{bulk}$!!!



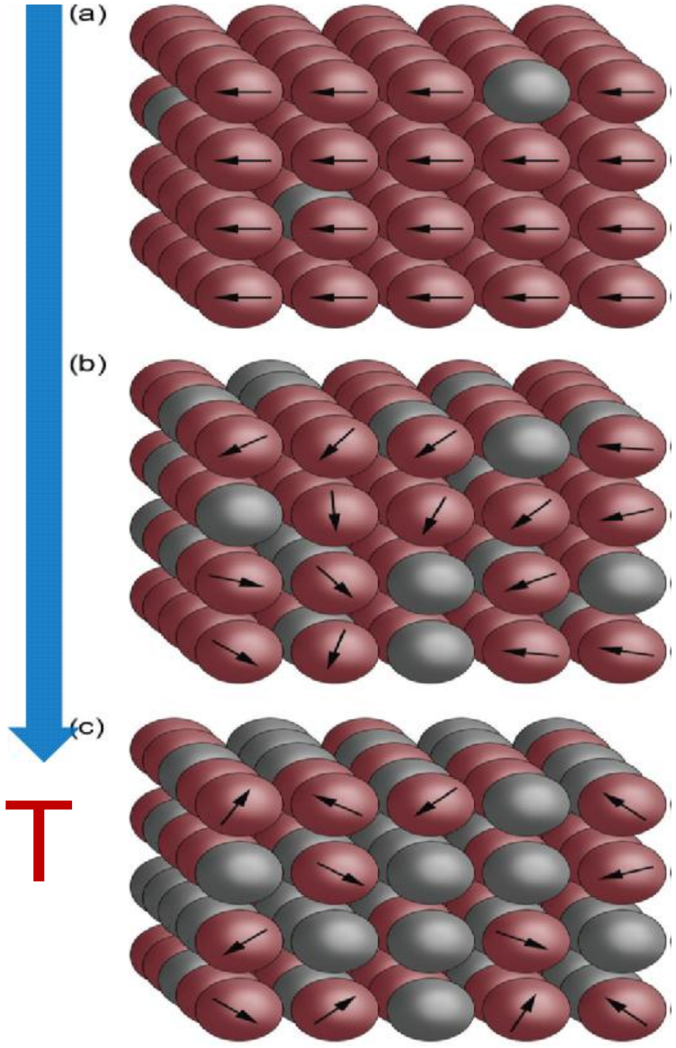
James Mayoh
Cambridge

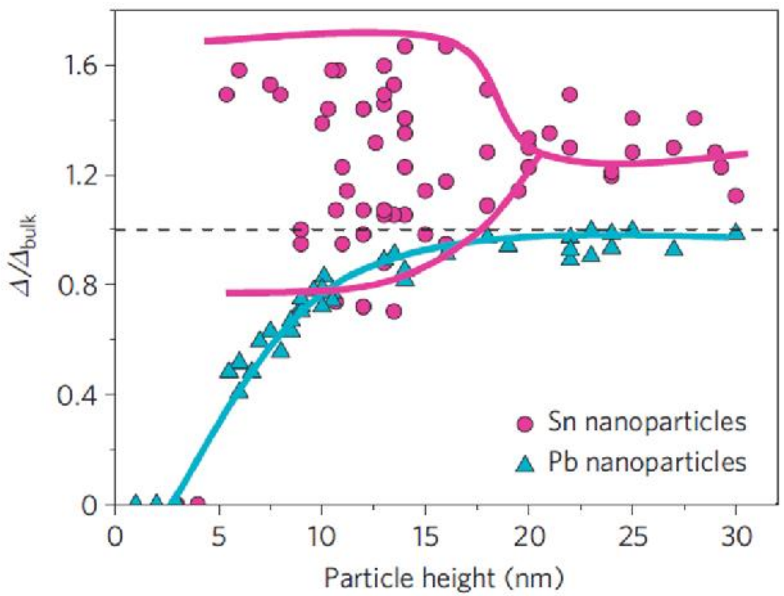
Mayoh, AGG. Phys. Rev. B 90, 134513 (2014)

Grey = No SC

Global T_c ?

L ~ 5nm





AGG et al. Nature materials 9 (2010) 550

Open grain

JJ Array

BCS

Mean field

Semiclassical

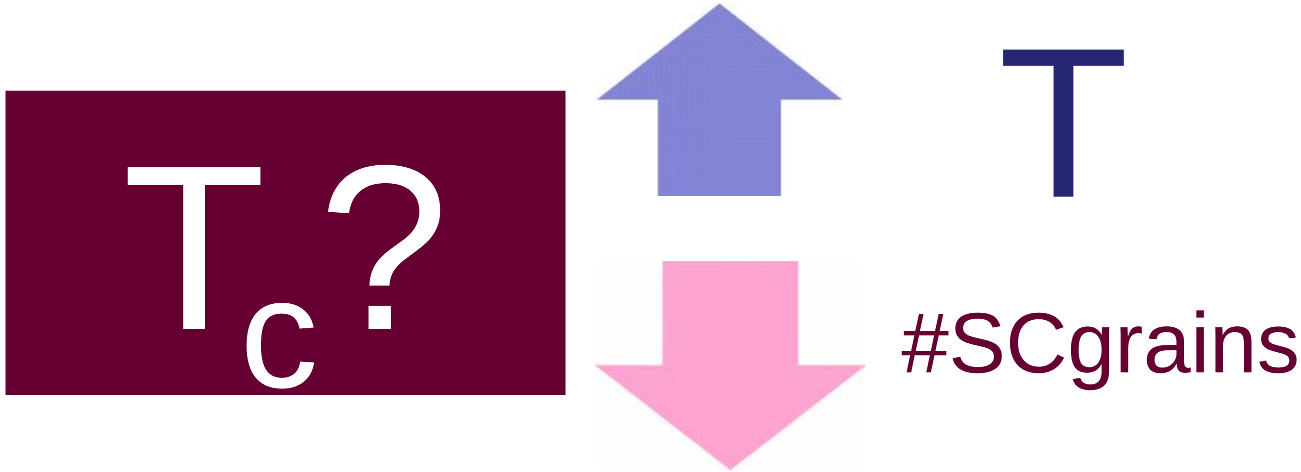
Percolation

Charging effects

Inhomogeneities

Percolation?

Phase fluctuations?



Packing = Cubic, BCC, FCC

$= 1$

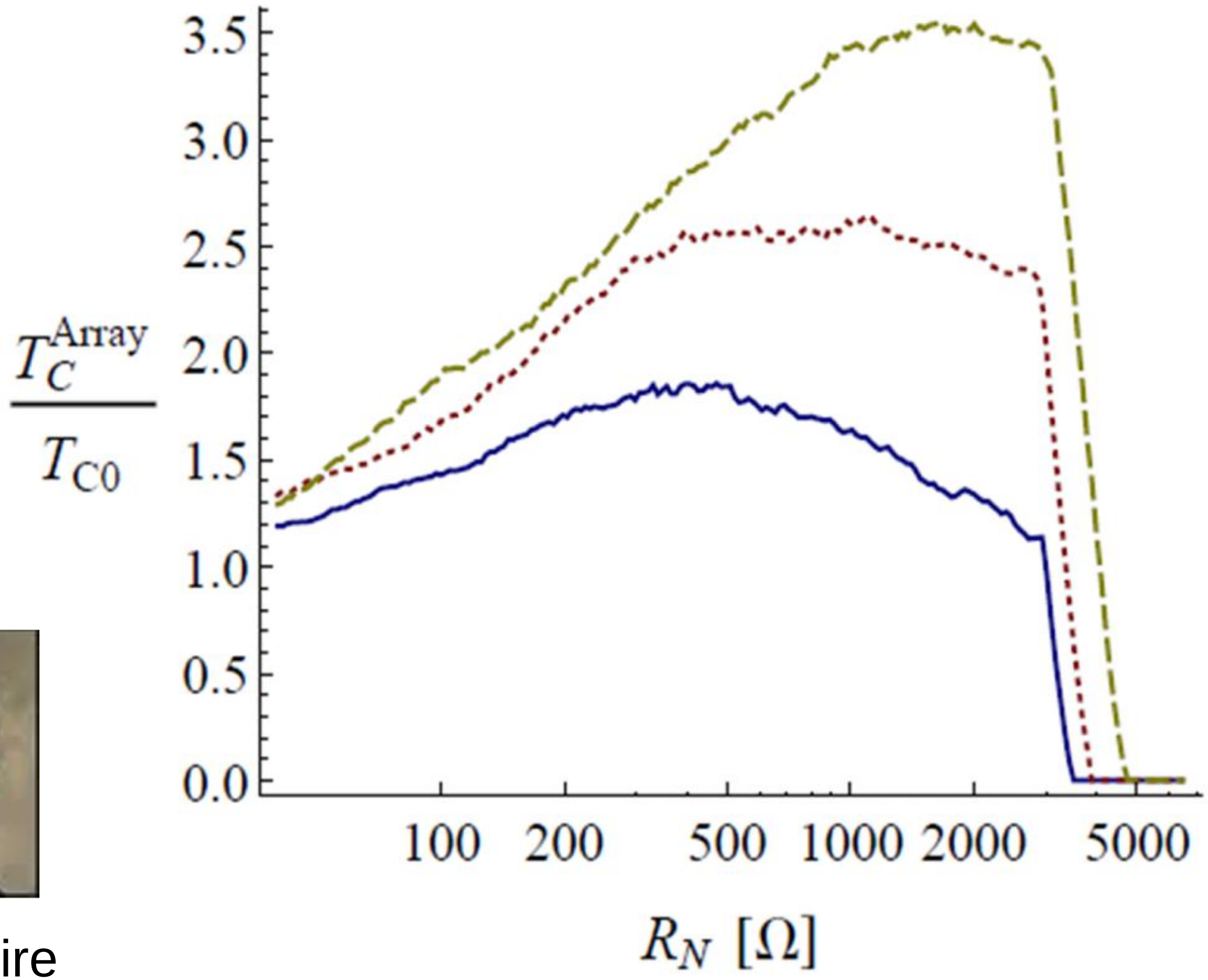
$= 5$

$= 0.25$

Enhancement!

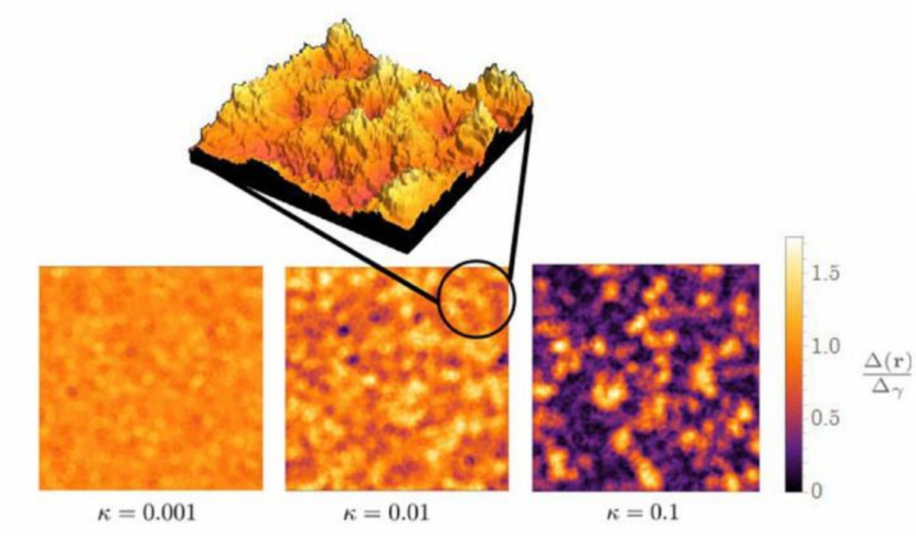
Patent

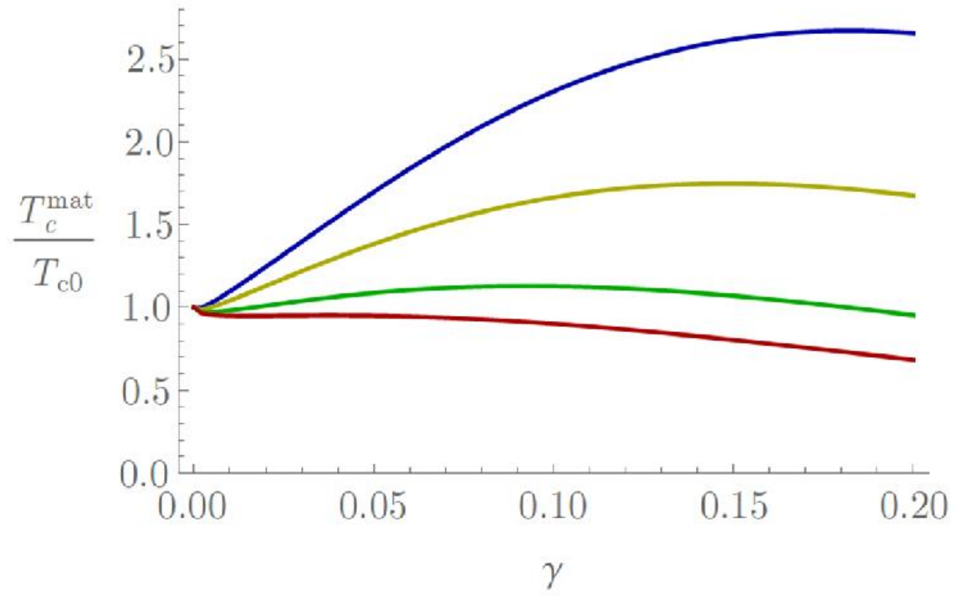
Mark Blamire
Cambridge

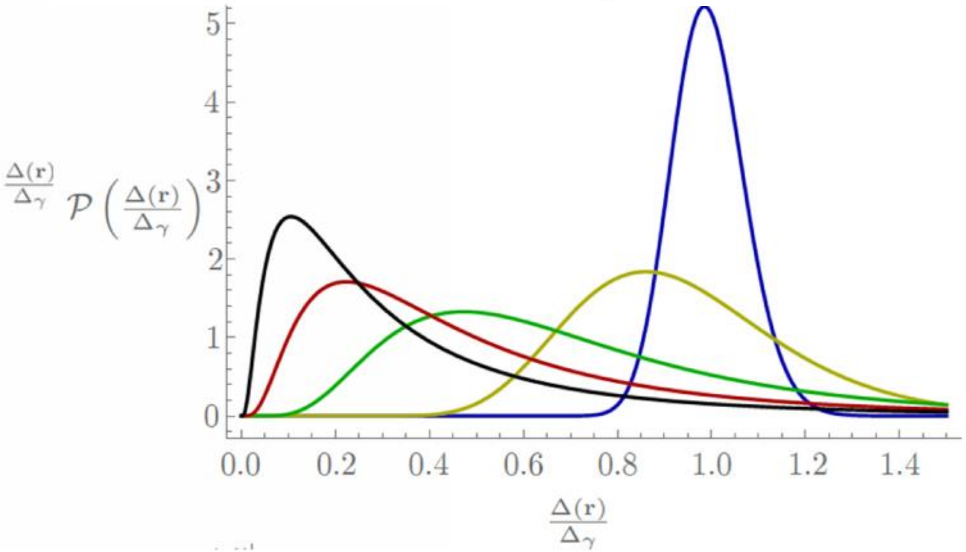


Global T_c in disordered thin films?

Mayoh, AGG, arXiv:1412.0029





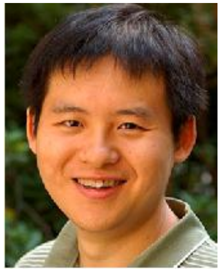


Solution for Al puzzle?

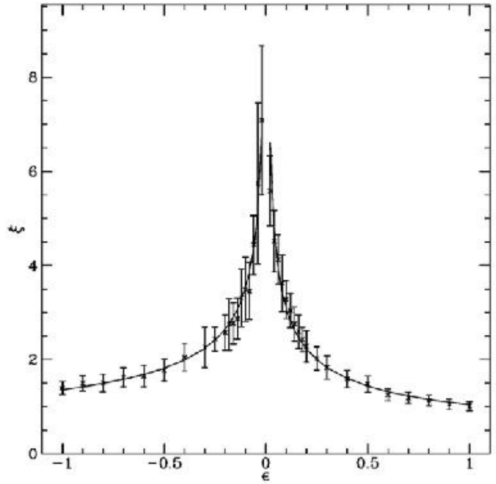
$$\mathcal{P}\left(\frac{\Delta(\mathbf{r})}{\Delta_\gamma}\right) = \frac{\Delta_\gamma}{\Delta(\mathbf{r})\sqrt{2\pi}\sigma}\exp\left[-\frac{\left(\ln\left(\frac{\Delta(\mathbf{r})}{\Delta_\gamma}\right)-\mu\right)^2}{2\sigma^2}\right]$$

The out of equilibrium birth of a superfluid

Phys, Rev. X, Accepted, arXiv:1407.1862


Hong Liu
MIT


Paul Chesler
Harvard



$= \quad | \; |$

$= \quad | \; |$

Unbroken Phase | Broken phase

T(t) $\langle \quad \rangle = 0$ | T_c | $\langle \quad \rangle \neq 0$

$\langle \quad \rangle = \Delta(\; , \;)$ $(\; , \;)$?

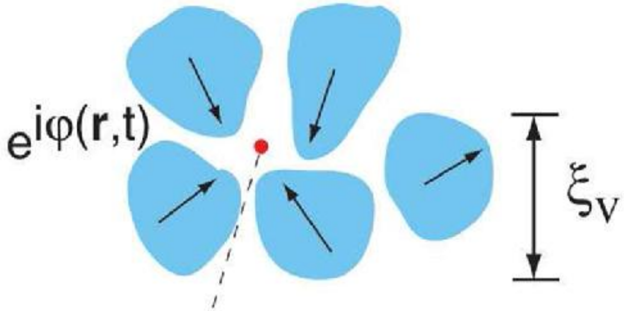
Kibble

J. Phys. A: Math. Gen. 9: 1387. (1976)

Causality

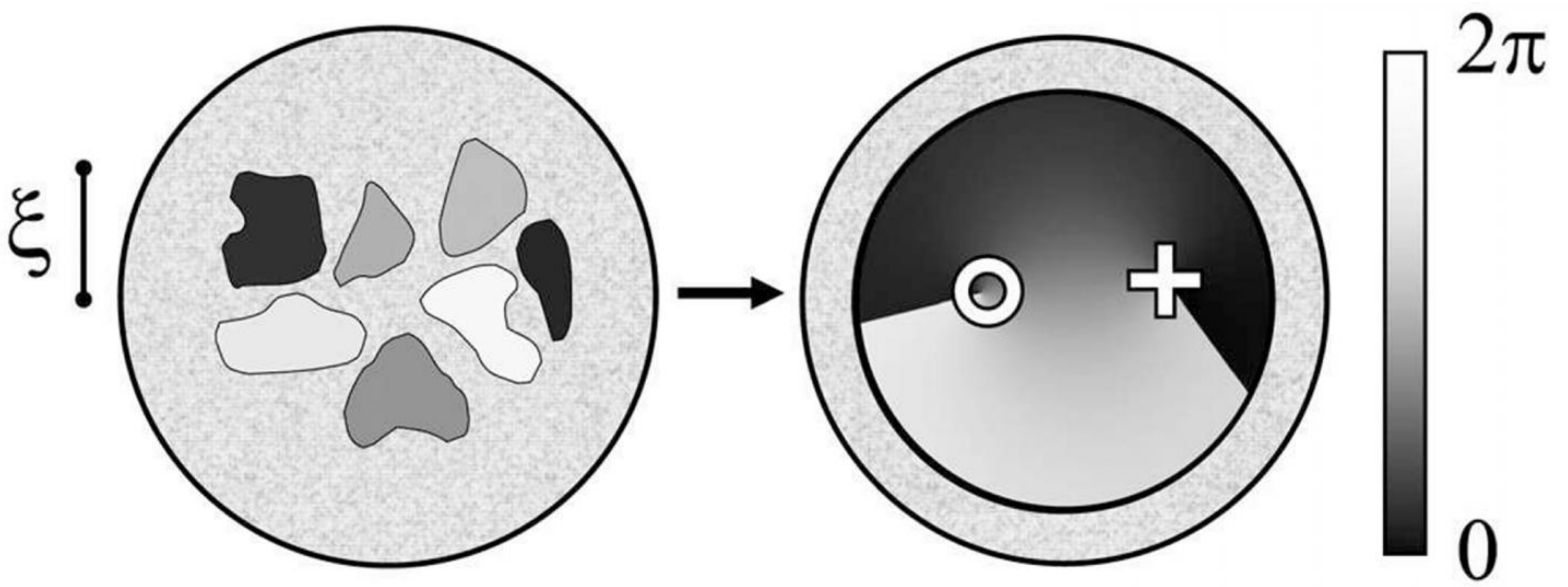
Vortices in the sky

Cosmic strings



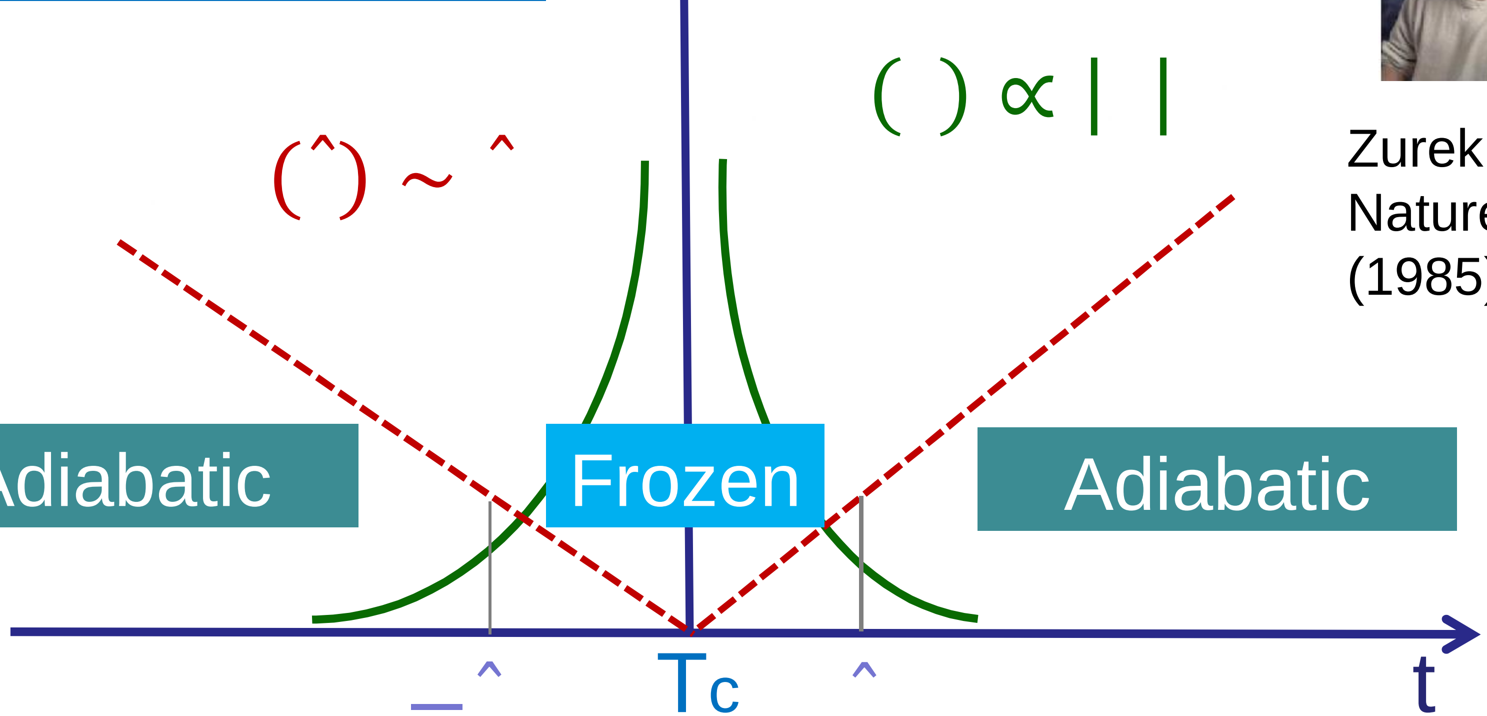
Krusius, 2006

Generation of Structure



Weyler, Nature 2008

$1 - \frac{(\ )}{\ } = (\ ) = \ /$



Zurek
Nature 317
(1985) 505

$= \ |\hat{\ }| \ = \ (\ /\ )^{/(\ \ )}$

Kibble-Zurek mechanism

$\sim \quad \sim \quad /(\ \ )$

nature COMMUNICATIONS

ARTICLE

Received 25 Mar 2013 | Accepted 11 Jul 2013 | Published 7 Aug 2013 DOI: 10.1038/ncomms3290

Observation of the Kibble-Zurek scaling law for defect formation in ion crystals

S. Ulm[1], J. Roßnagel[1], G. Jacob[1], C. Degünther[1], S.T. Dawkins[1], U.G. Poschinger[1], R. Nigmatullin[2,3], A. Retzker[4], M.B. Plenio[2,3], F. Schmidt-Kaler[1] & K. Singer[1]

nature Vol 455|16 October 2008|doi:10.1038/nature07334

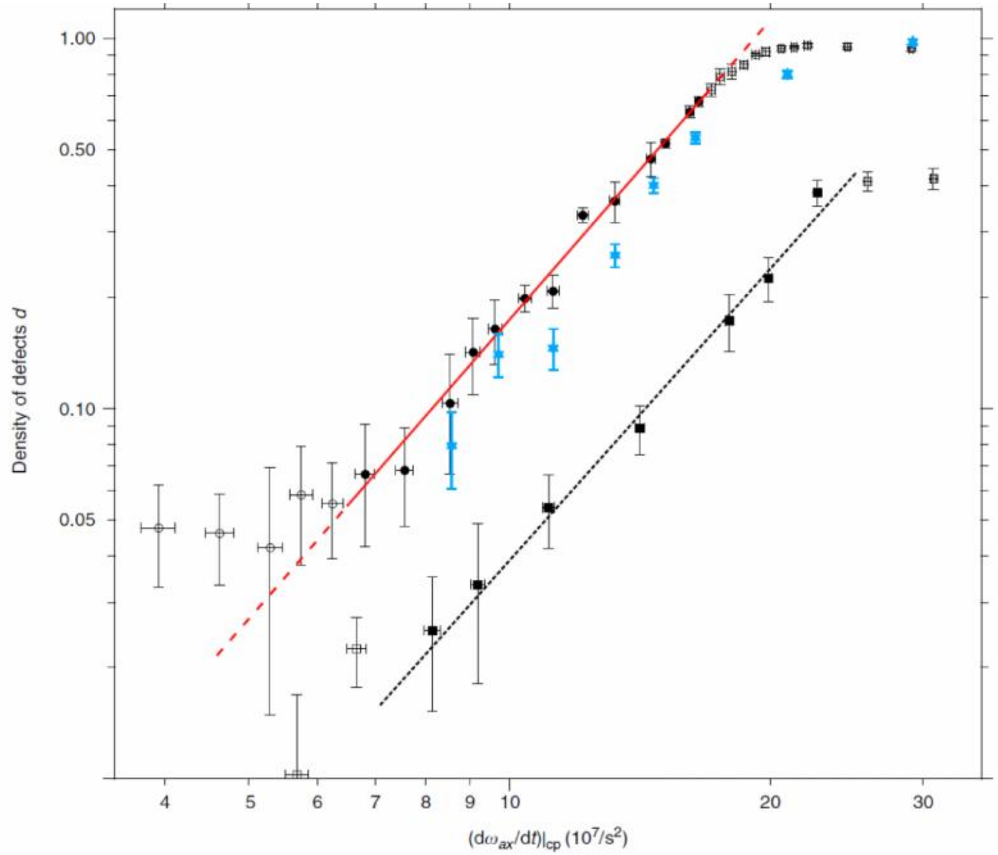
LETTERS

Spontaneous vortices in the formation of Bose–Einstein condensates

Chad N. Weiler[1], Tyler W. Neely[1], David R. Scherer[1], Ashton S. Bradley[2]†, Matthew J. Davis[2] & Brian P. Anderson[1]

KZ scaling with the quench speed

Too few defects



Issues with KZ | Too many defects

Adiabatic at t_{freeze}?

Defects without a condensate?

$>$ $>$ is relevant

PRX, Accepted

Chesler, AGG, Liu

Slow Quenches	Linear response
>	Scaling

KZ	Frozen	Adiabatic	
US	Frozen	Coarsening	Adiabatic

$$\sim (\quad)$$

$$(\quad) \sim [\log \quad]$$

$$| \; | (\,) \propto$$

$$\sim \quad /$$

$$= \frac{1 + (\; - 2)}{2(1 + \;)}$$

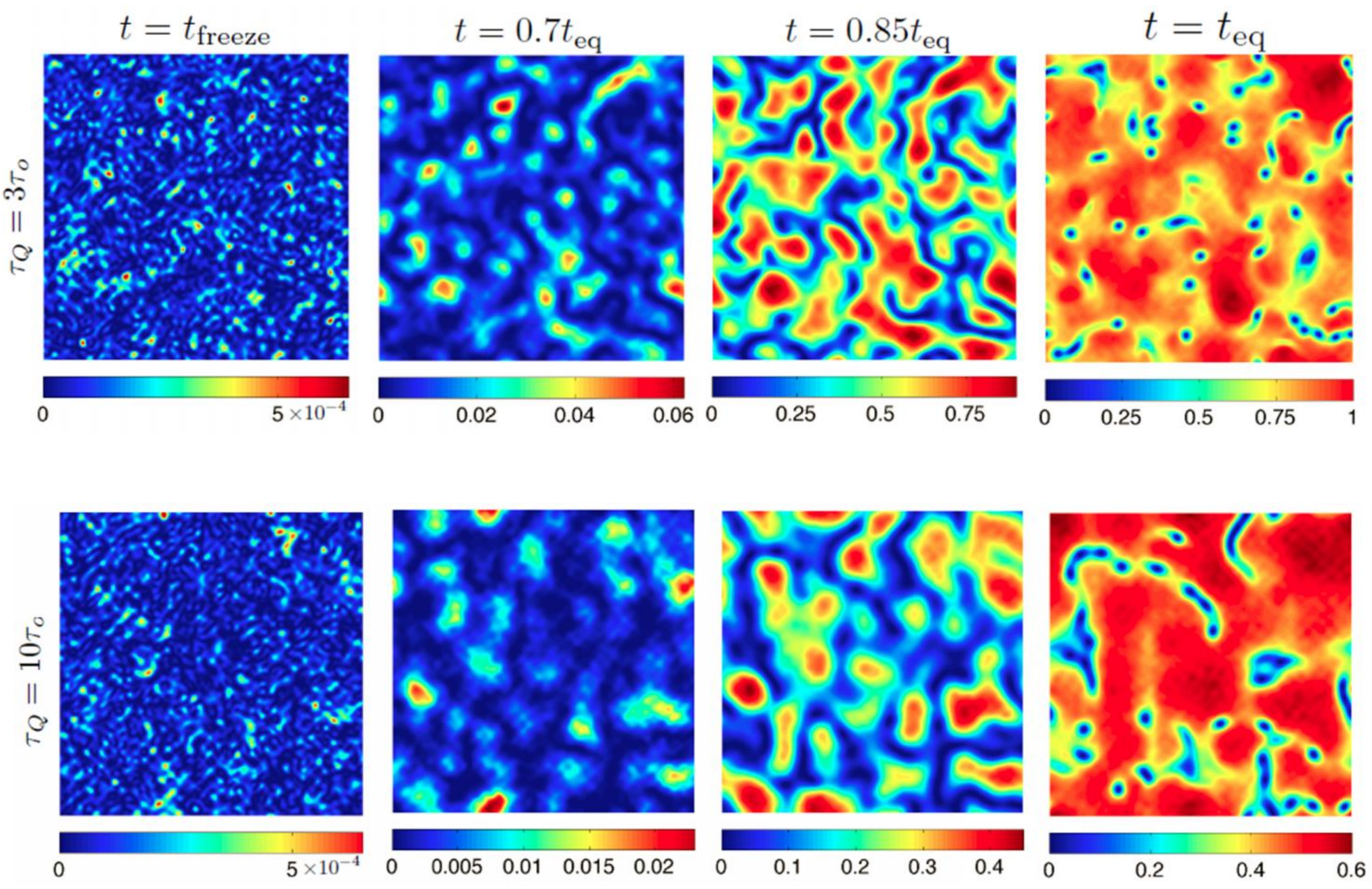
$$\Lambda = (\; - \;) \; - 2$$

AdS/CFT Maldacena1997

Strongly coupled field theory in d	↔	Weakly coupled gravity in d+1
N=4 Super-Yang Mills CFT		Anti de Sitter space AdS

2003	QCD Quark gluon plasma
2008	Holographic superconductivity
2012	Quantum criticality, non-equilibrium..

Easy to compute in the gravity dual & Detailed dictionary

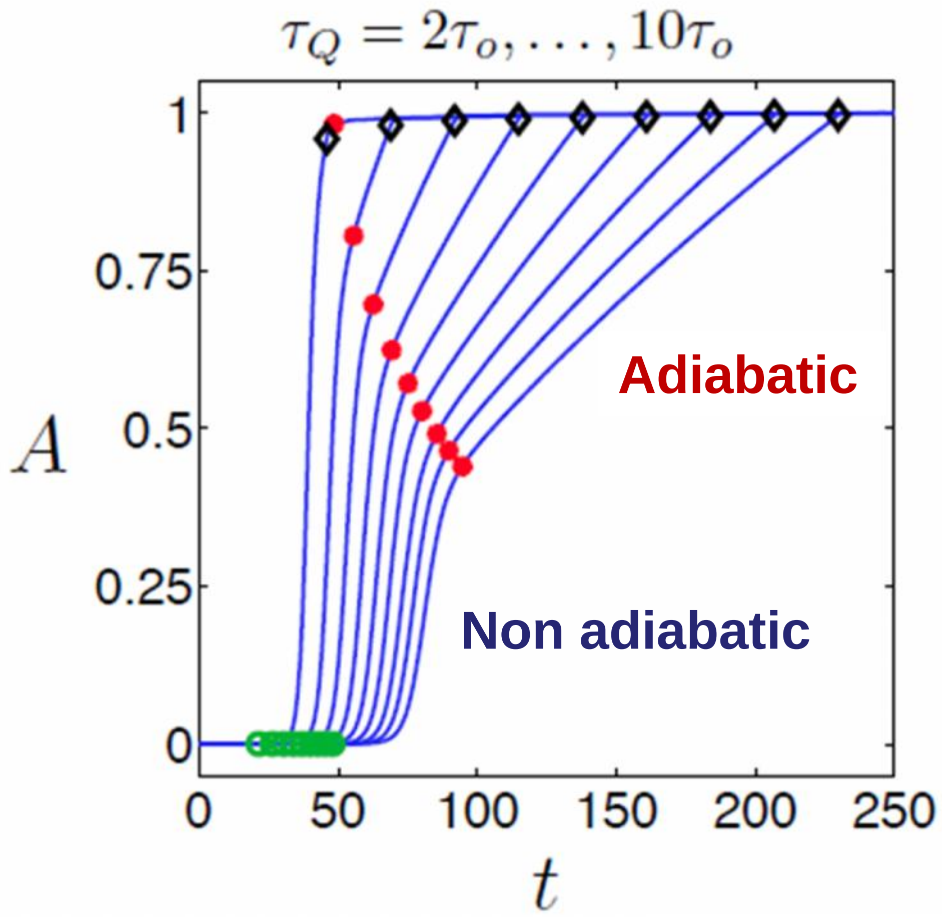


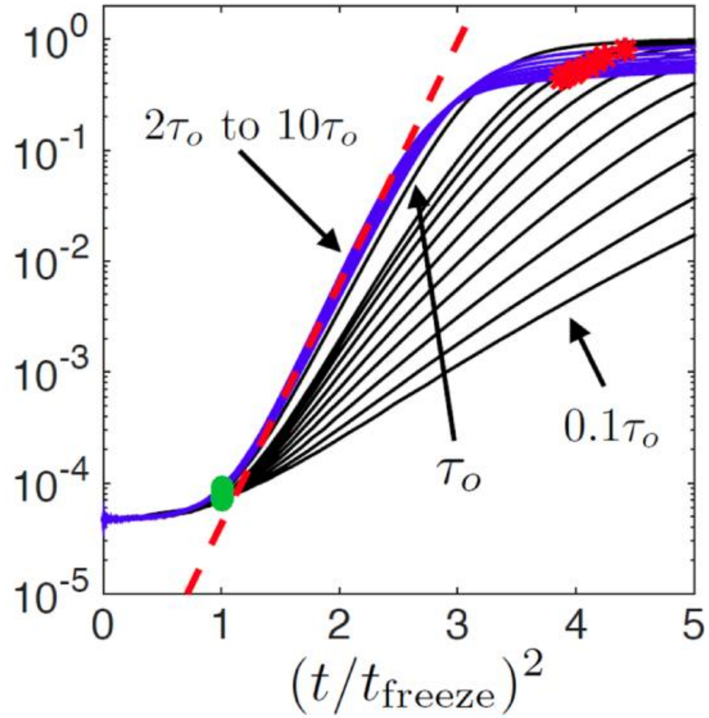
$t = t_{\text{freeze}}$
$t = 0.7t_{\text{eq}}$
$t = 0.85t_{\text{eq}}$
$t = t_{\text{eq}}$
$\tau_Q = 3\tau_o$
$\tau_Q = 10\tau_o$
0
5×10^{-4}
0 0.02 0.04 0.06
0 0.25 0.5 0.75
0 0.25 0.5 0.75 1
0
5×10^{-4}
0 0.005 0.01 0.015 0.02
0 0.1 0.2 0.3 0.4
0 0.2 0.4 0.6

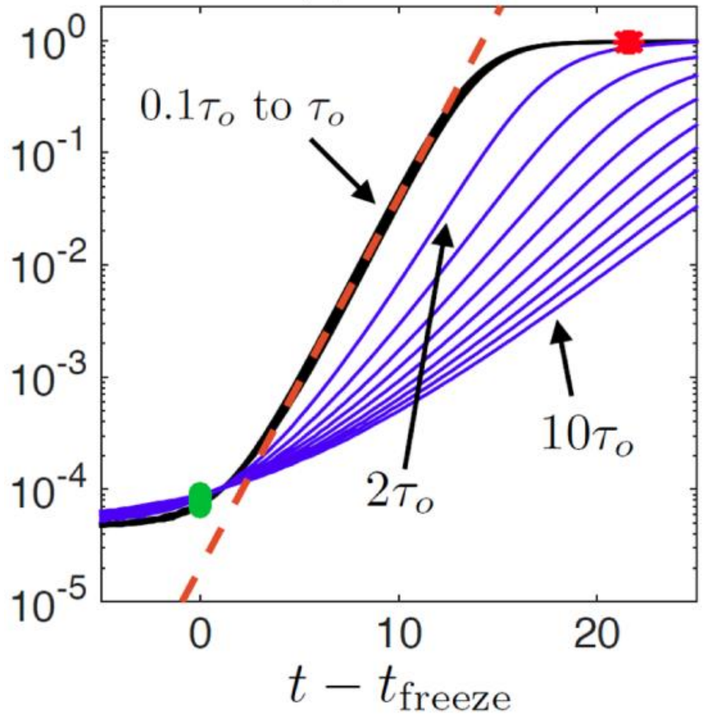
h

$$A(t) = \frac{1}{M} \sum_{i=1}^{M} \frac{a_i(t)}{a_i(\infty)}$$

$$a_i(t) \equiv \int d^2x \, |\psi_i(t, \boldsymbol{x})|^2$$







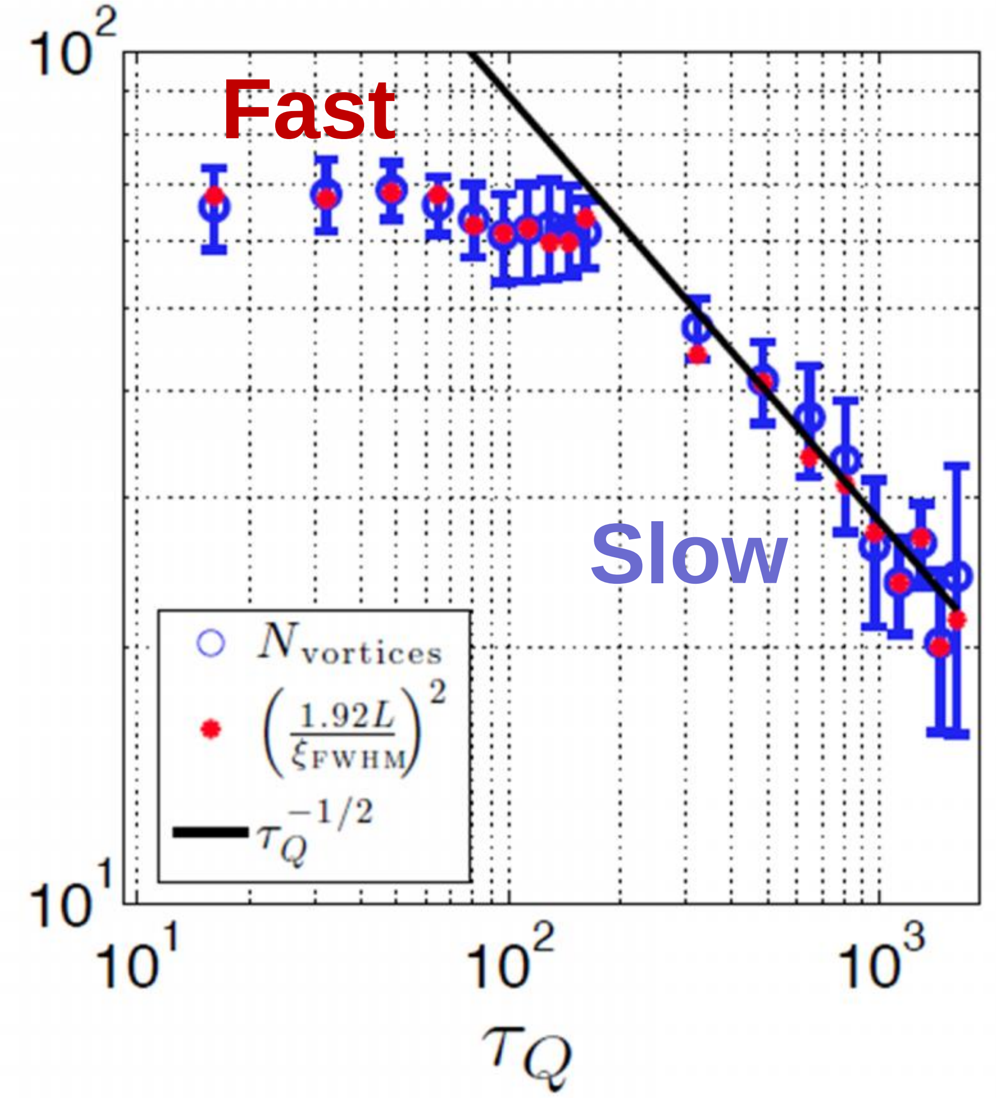
Slow

$\sim \frac{\quad}{(\quad(\quad/\,))^{\,/}}$

Fast

$\sim \frac{\quad}{\log(\frac{\quad}{\quad})}$

$= 1 - \quad /$



Relevant for ^{4}He ?

~25 times less defects than KZ prediction!!

Inhomogeneous correlated matter

Interfaces

Heterostructures

Out of equilibrium

Novel ground states

Optimization of SC

Disorder, many-body localization

Intrinsic topological SC at and out equilibrium

Thermalization and steady non-thermal states

Bounds on transport properties

Many-body Efimov

Lorentz center

Superconductivity on the Verge

from 27 Jul 2015 through 31 Jul 2015

Scientific organizers:

Lara Benfatto (Rome, Italy)

Andrea Caviglia (Delft, The Netherlands)

Antonio García-García (Cambridge, United Kingdom)

Jérôme Lesueur (Paris, France)

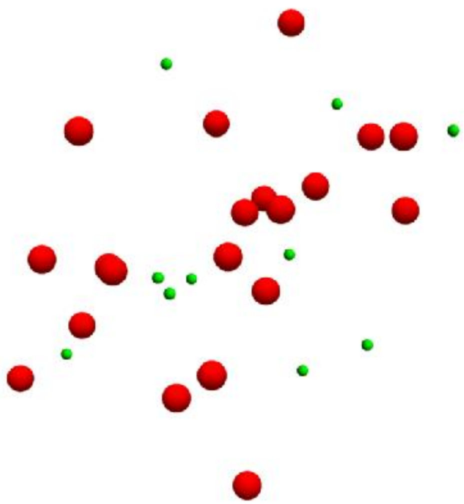
Pratap Raychaudhuri (Colaba, Mumbai, India)

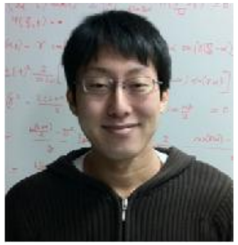
EU network

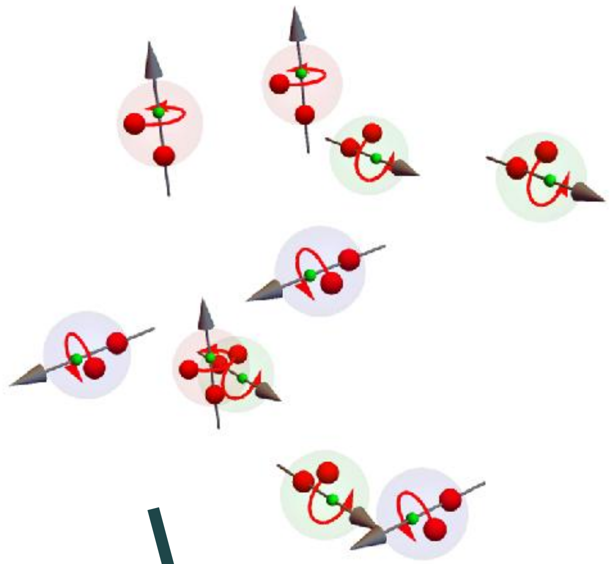
EPSRC funding

ERC funding

Thanks!





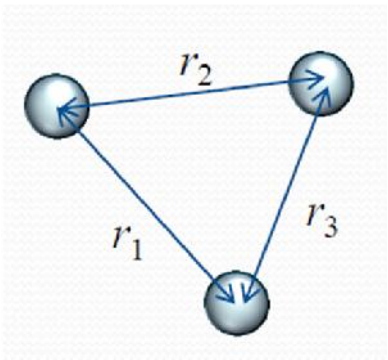


Many body Efimov Physics

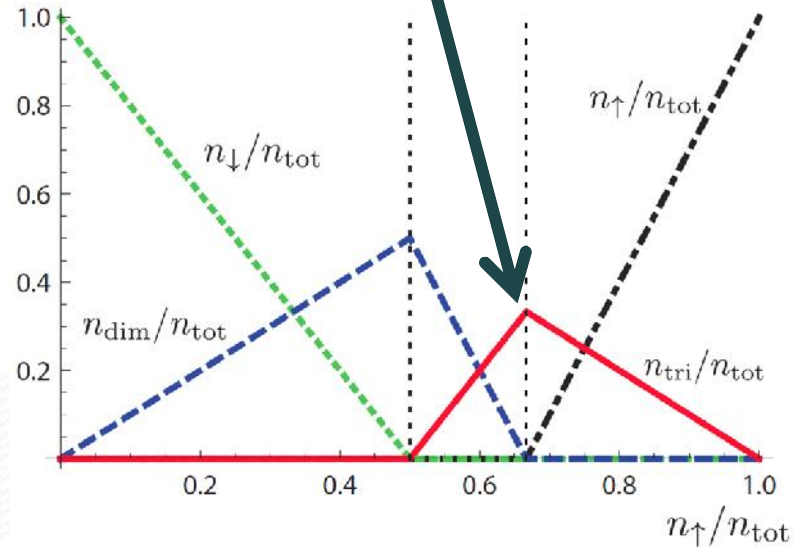
Efimov 70's

Bound states

Scaling

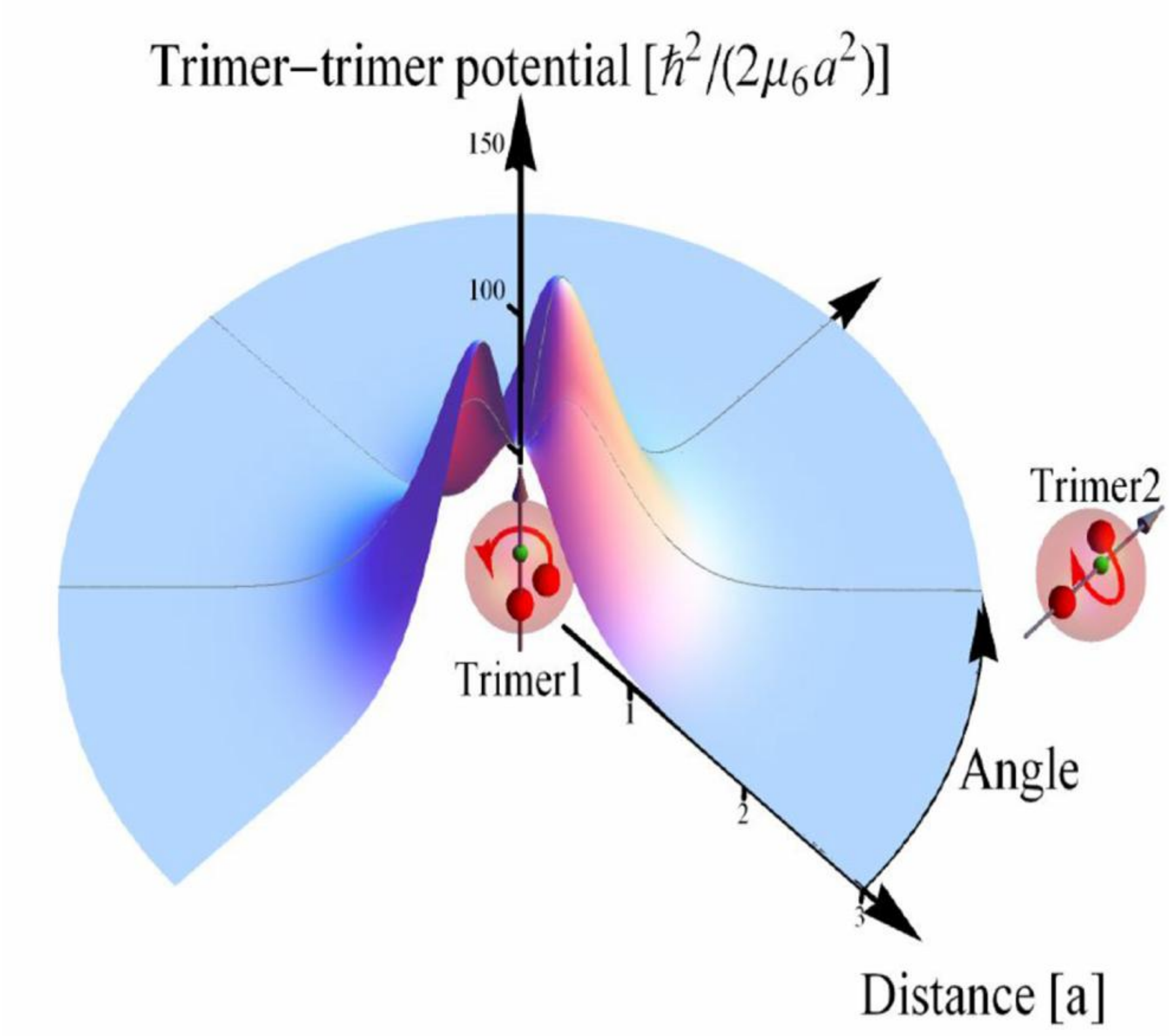


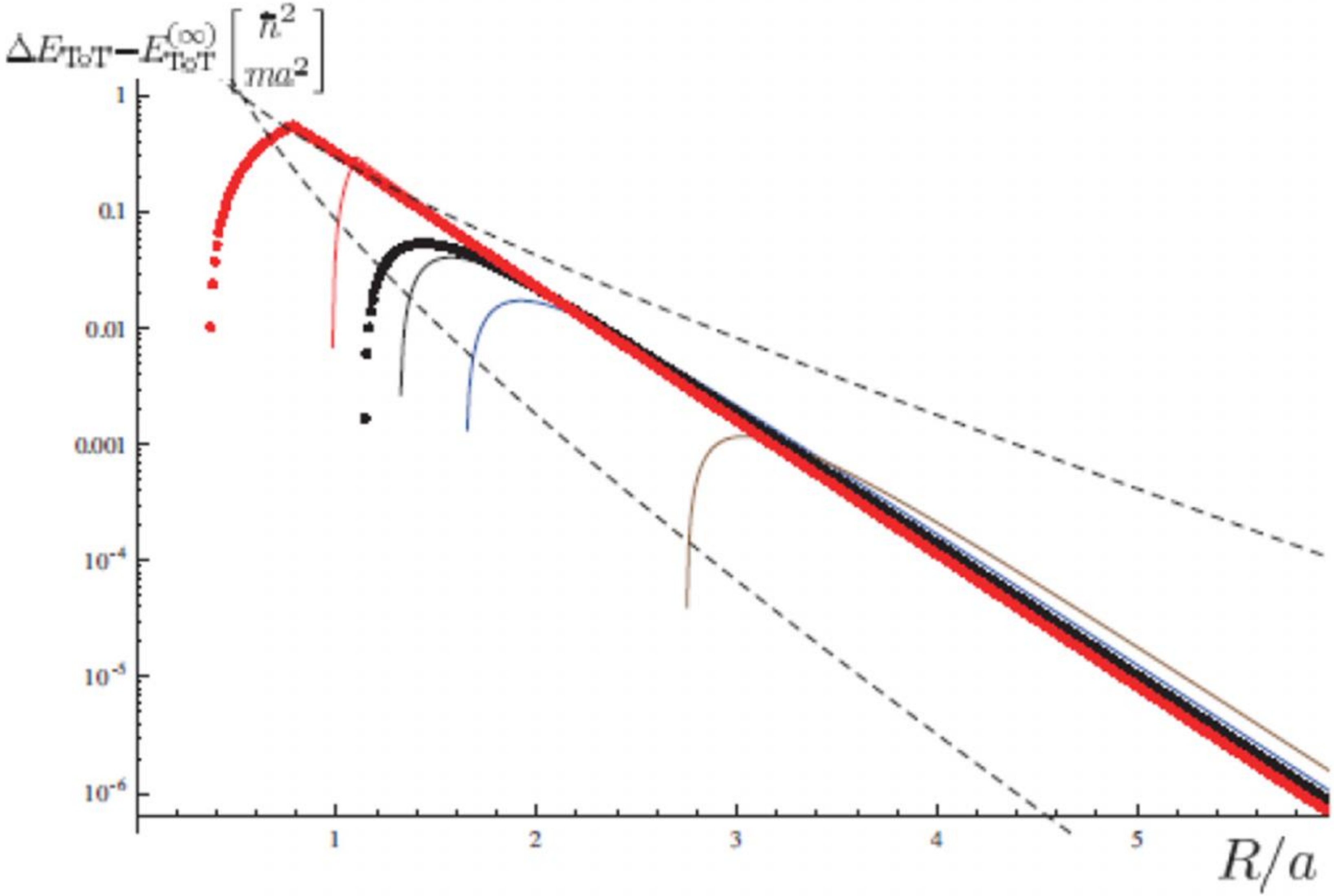
$$R^2 = \frac{1}{3}({r_1}^2 + {r_2}^2 + {r_3}^2)$$



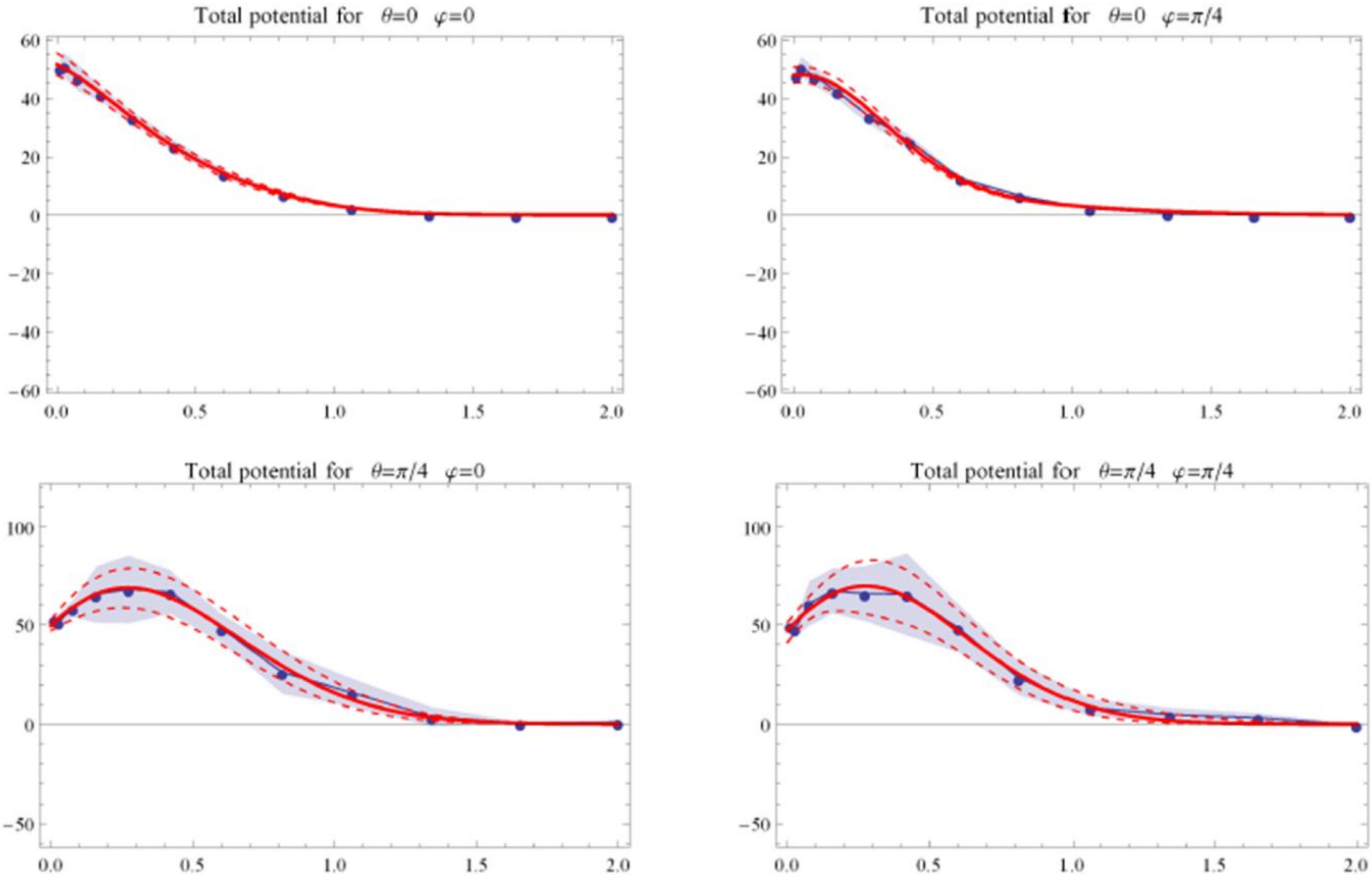
RGM

Born-Oppenheimer





$\Delta E_{\mathrm{T \circ T}} - E^{(\infty)}_{\mathrm{T \circ T}} \left[\frac{\hbar^2}{ma^2}\right]$
1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5
R/a


Total potential for θ=0 φ=0
Total potential for θ=0 φ=π/4
Total potential for θ=π/4 φ=0
Total potential for θ=π/4 φ=π/4
60
40
20
0
−20
−40
−60
100
50
0
−50
0.0
0.5
1.0
1.5
2.0