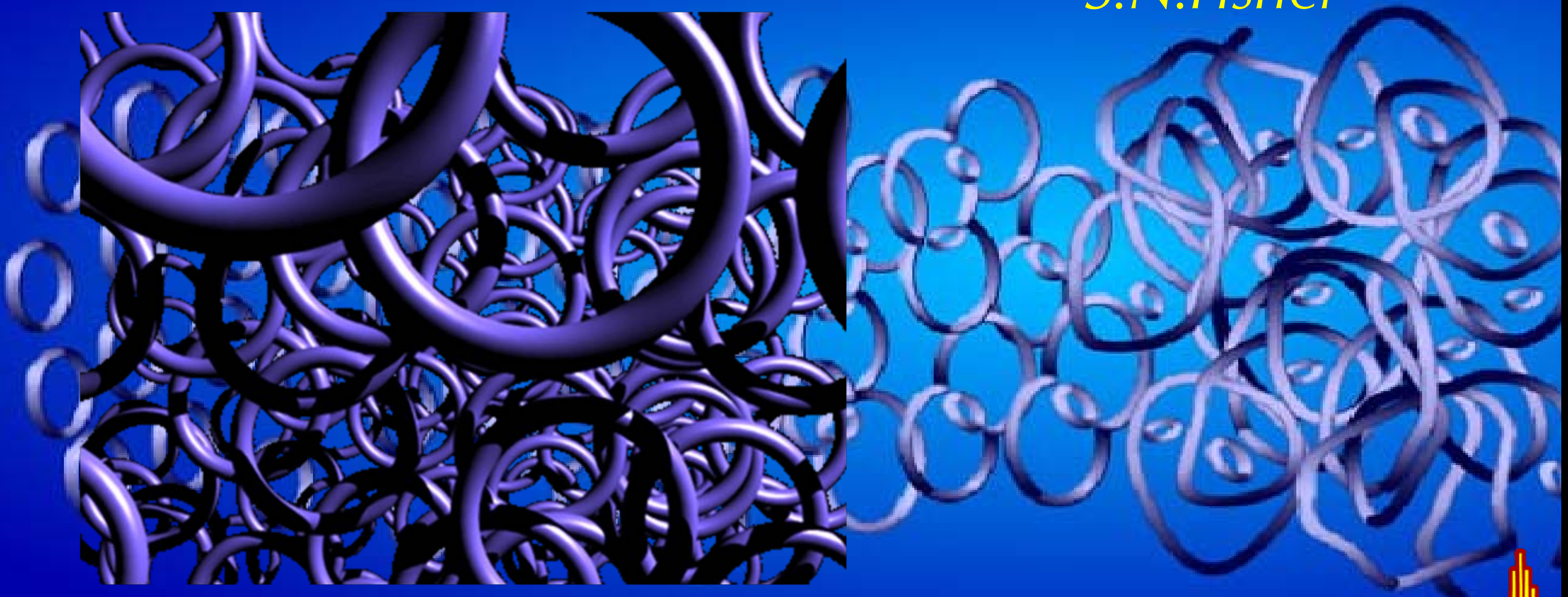
Experiments on quantum vortices in a pure superfluid condensate, ^{3}He-B at ultralow temperatures.

S.N.Fisher



SEVENTH FRAMEWORK PROGRAMME
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Lancaster Quantum Fluids

Ian Bradley	*Pam Crookston*	*Viktor Efimov*
Matt Fear	*Shaun Fisher*	*George Foulds*
Deepak Garg	*Mark Giltrow*	*Andrei Ganshyn*
Tony Guénault	*Richard Haley*	*Matthew Holmes*
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Peter McClintock	*Ian Miller*	*Alan Stokes*
Samantha O'Sullivan	*Roch Schanen*	*David Potts*
George Pickett	*Viktor Tsepelin*	*Nikolai Vasilev*
Martin Ward	*Paul Williams*	*Louise Wheatland*

Peter Skyba (Kosice) *Joe Vinen (Birmingham)*

SEVENTH FRAMEWORK PROGRAMME
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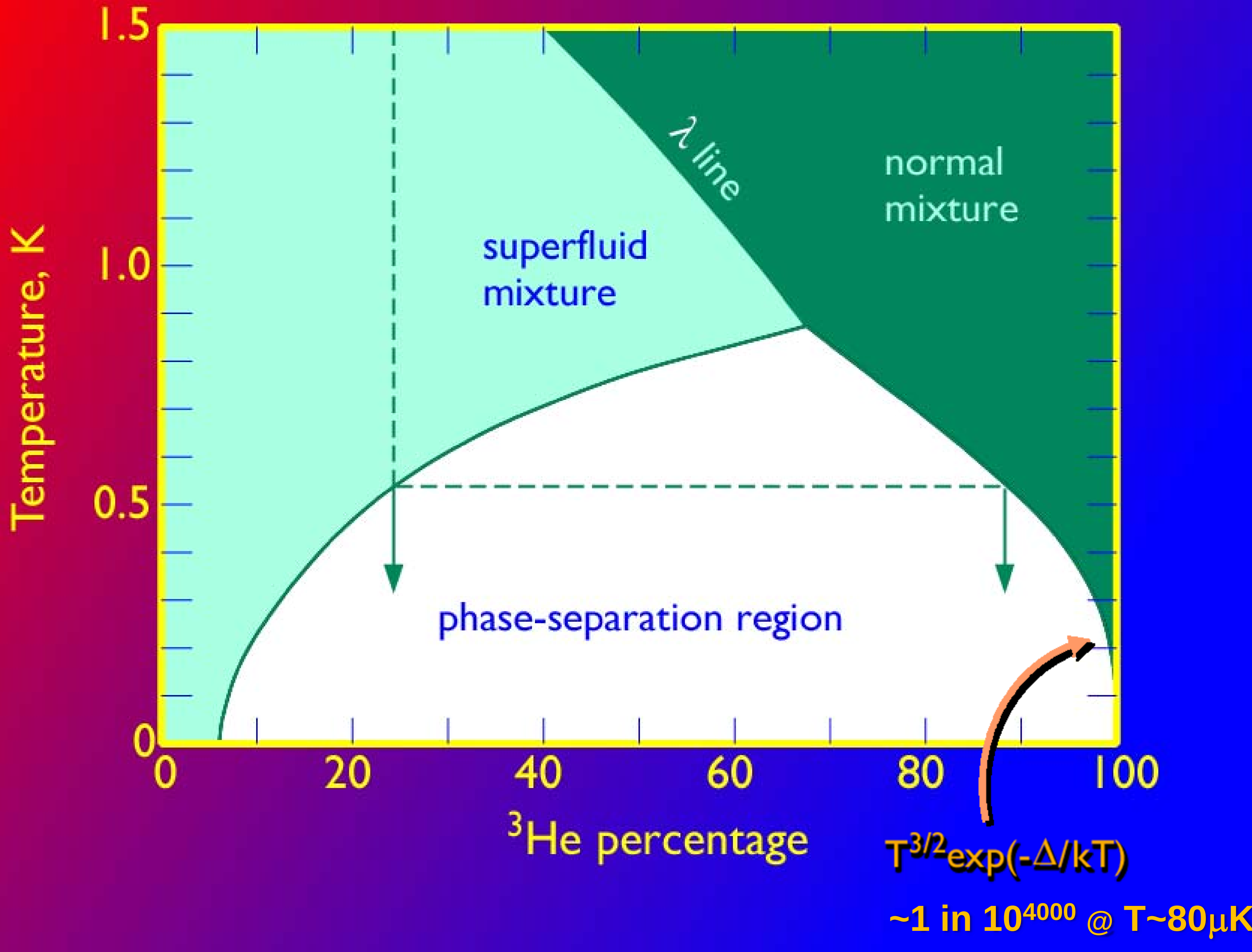

1.5
1.0
0.5
0
Temperature, K
0
20
40
60
80
100
3He percentage
λ line
normal mixture
superfluid mixture
phase-separation region
T3/2exp(-Δ/kT)
~1 in 104000 @ T~80μK

Classical Vortices (eddies)

can have a wide range of shapes and sizes.

Quantum Vortices (^{3}He-B and ^{4}He)

2π phase change around core
Gives circulating superfluid flow,

$$v_S = \kappa/2\pi r$$

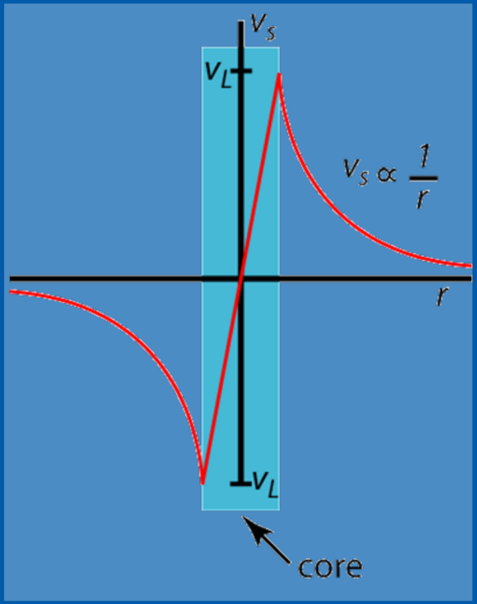
circulation : $\kappa_4 = h/m_4$

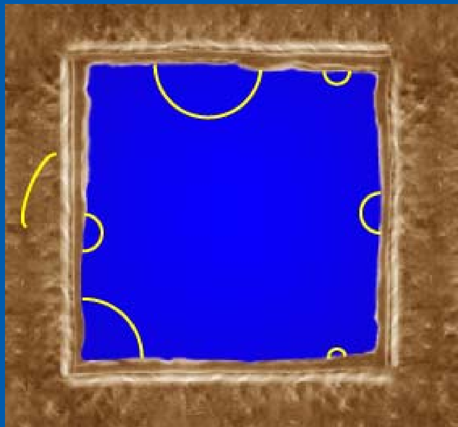
$\kappa_3 = h/2m_3$

core size:

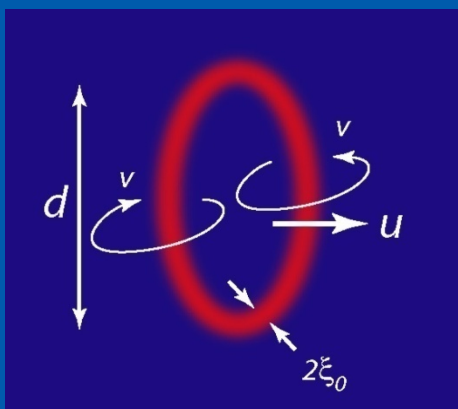
^{4}He : $\xi_0 \sim 0.1$ nm

^{3}He : $\xi_0 \sim 65$ - 15 nm (pressure dep.)





Vortices can end on cell walls



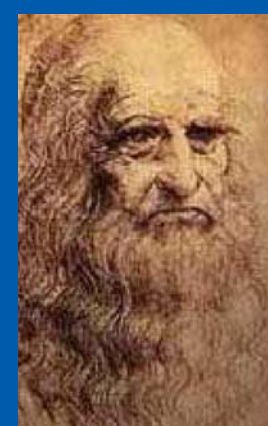
Form self propagating Rings

$$u = \frac{\kappa}{2\pi d} \ln\left(\frac{d}{2\,\xi}\right)$$

d~5μm $\Rightarrow$ u~10mm s^{-1}

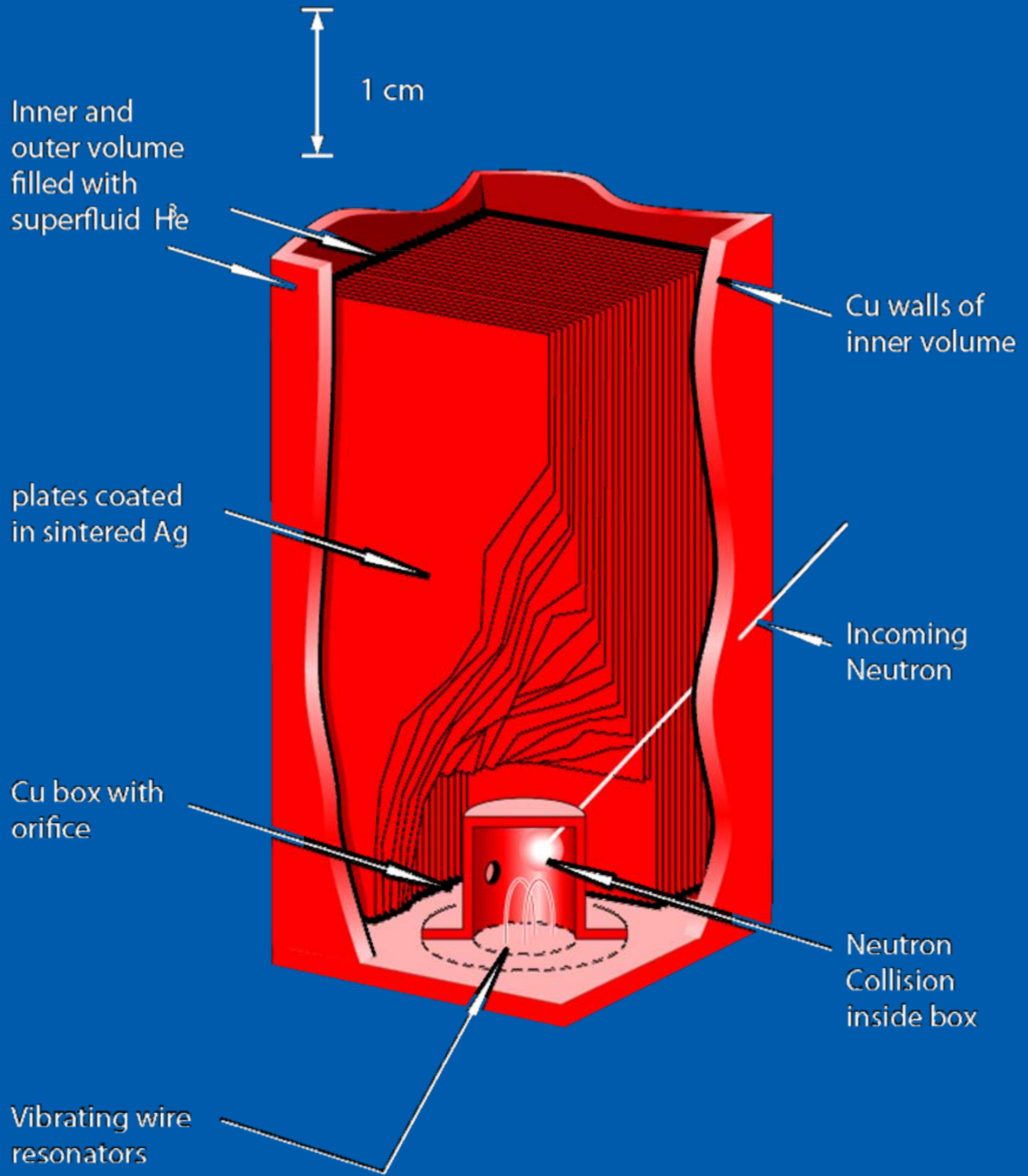
Or form a tangle
(Quantum Turbulence)

Inter-vortex spacing l
Line Density L=$1/l^2$
(line length per unit volume)

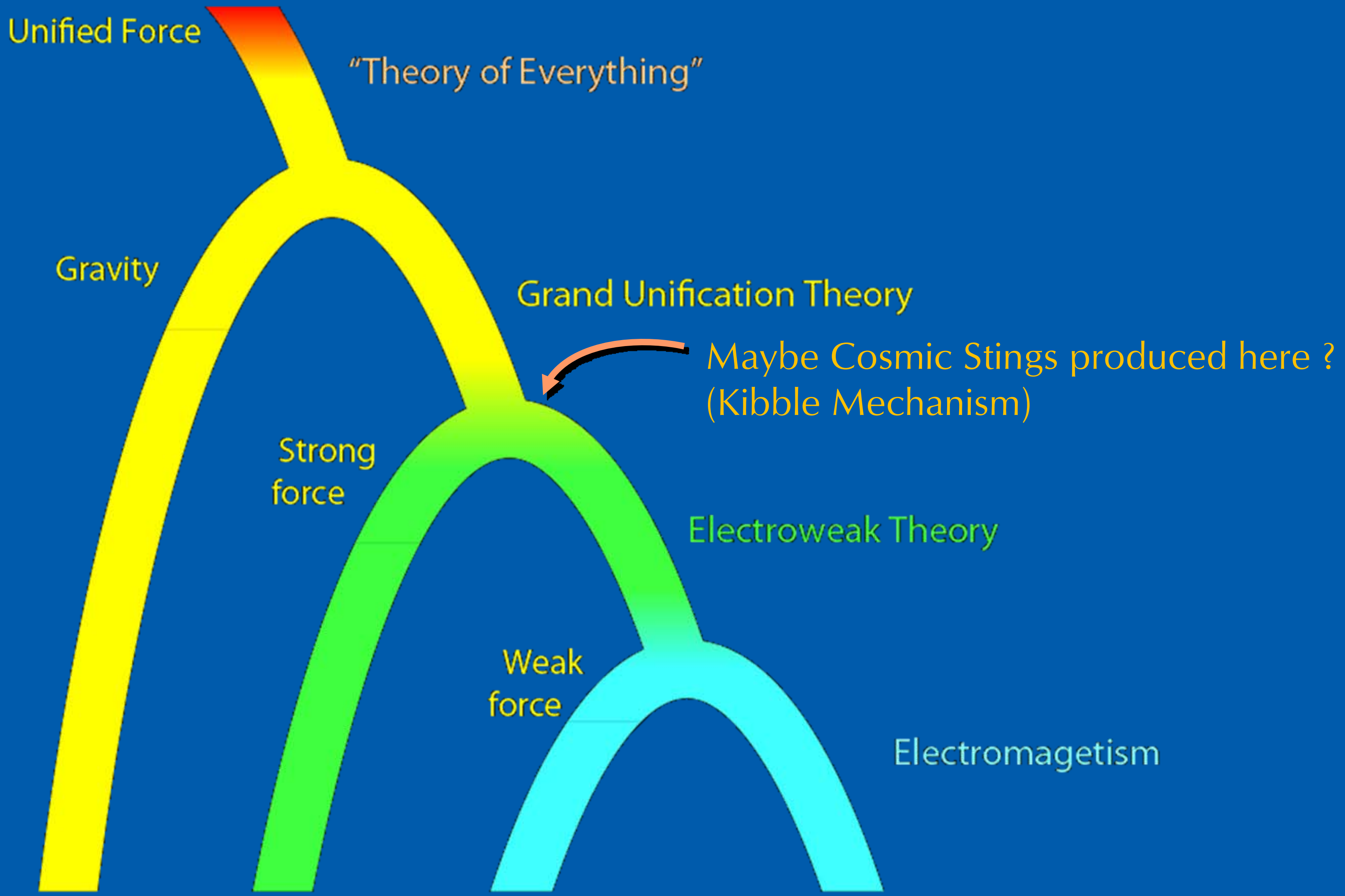


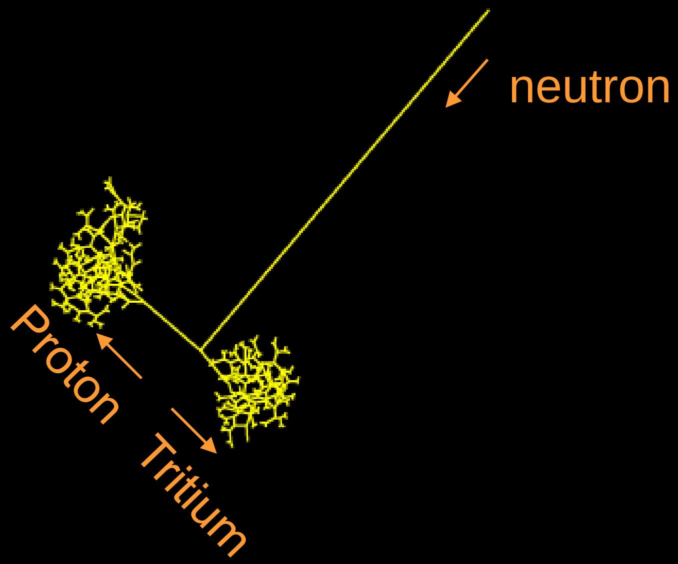
Leonardo
da Vinci
1515

Vortices produced by a rapid phase transition



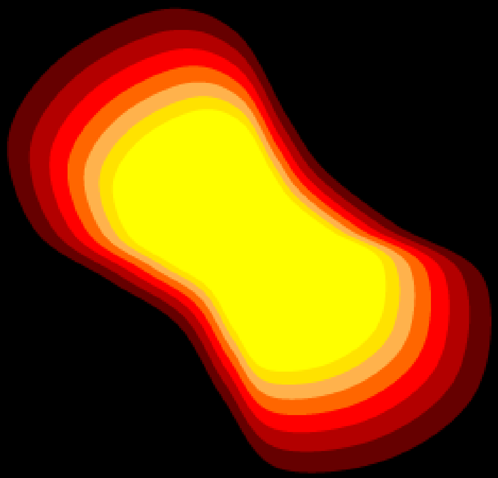
Cosmological Analogue:
Phase Transitions after the Big Bang





$$n + {}^{3}He \longrightarrow p + {}^{3}H + 764keV$$

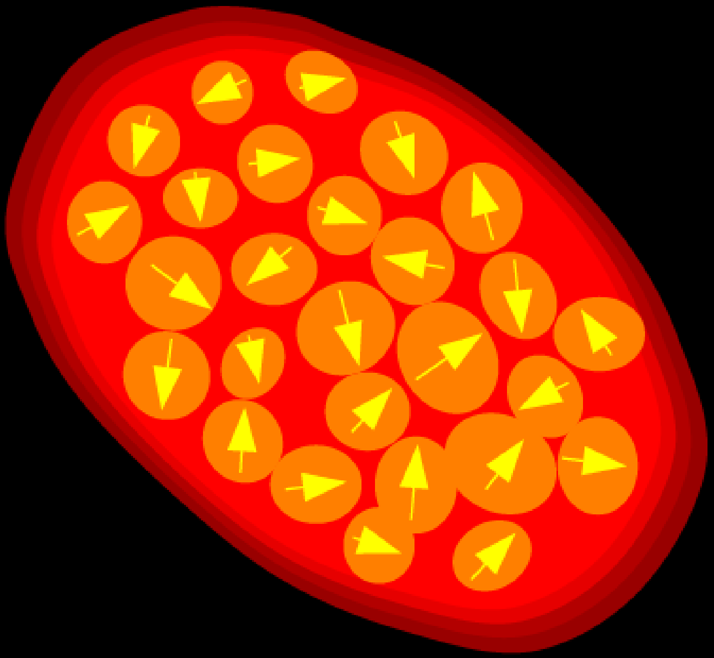
The “Big Bang”



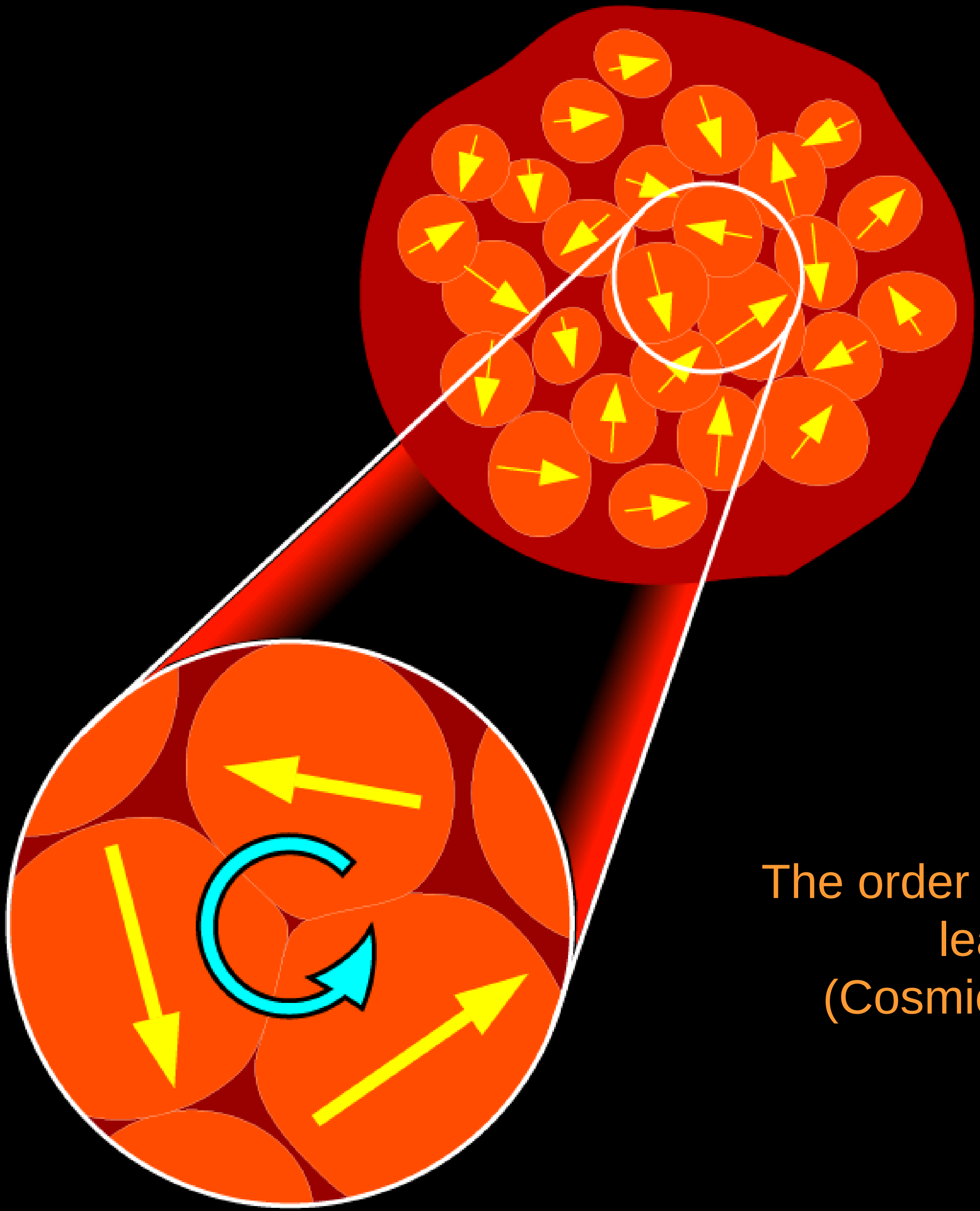
Hot Expanding Universe
(normal ^3He)

The Phase Transition

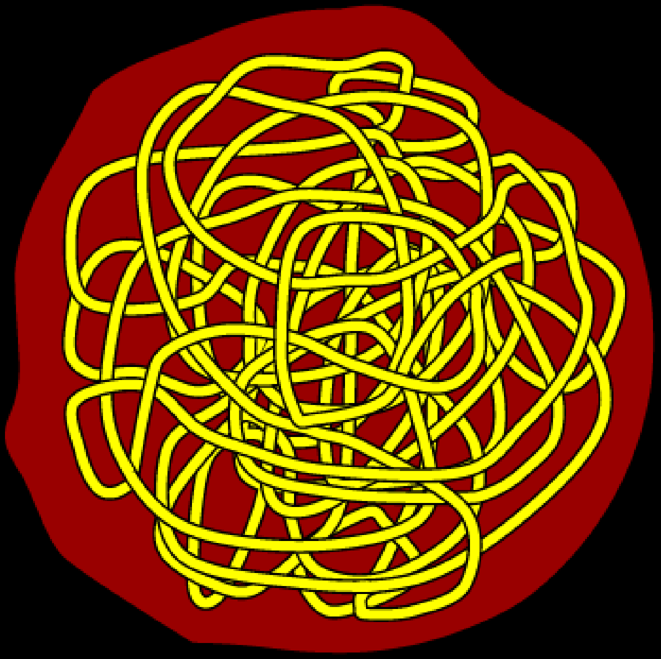
(to superfluid ^3He)



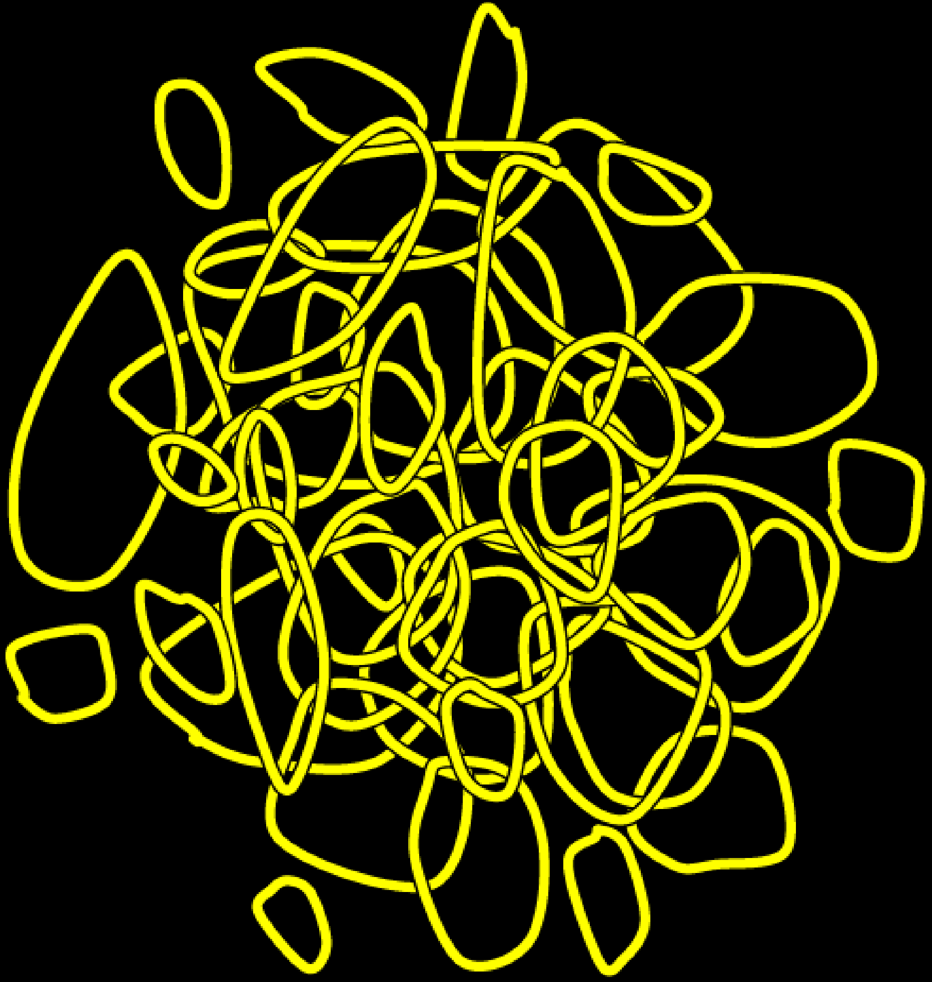
Ordering produces domains, limited by causality
(fast transition gives small domains)



The order parameter smoothes,
leaving defects
(Cosmic strings / vortices)

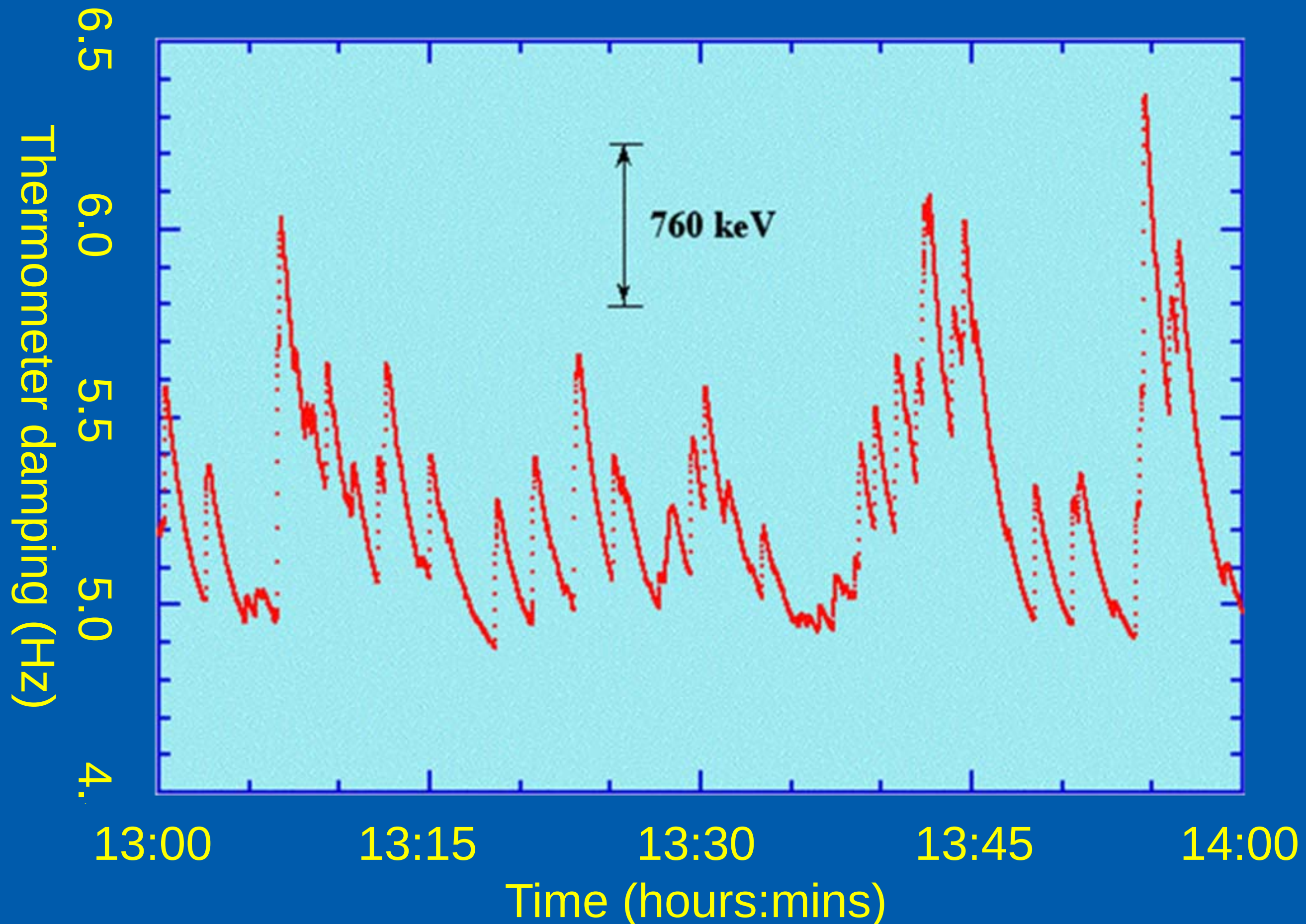


Line defects form a random tangle
(Quantum Turbulence)

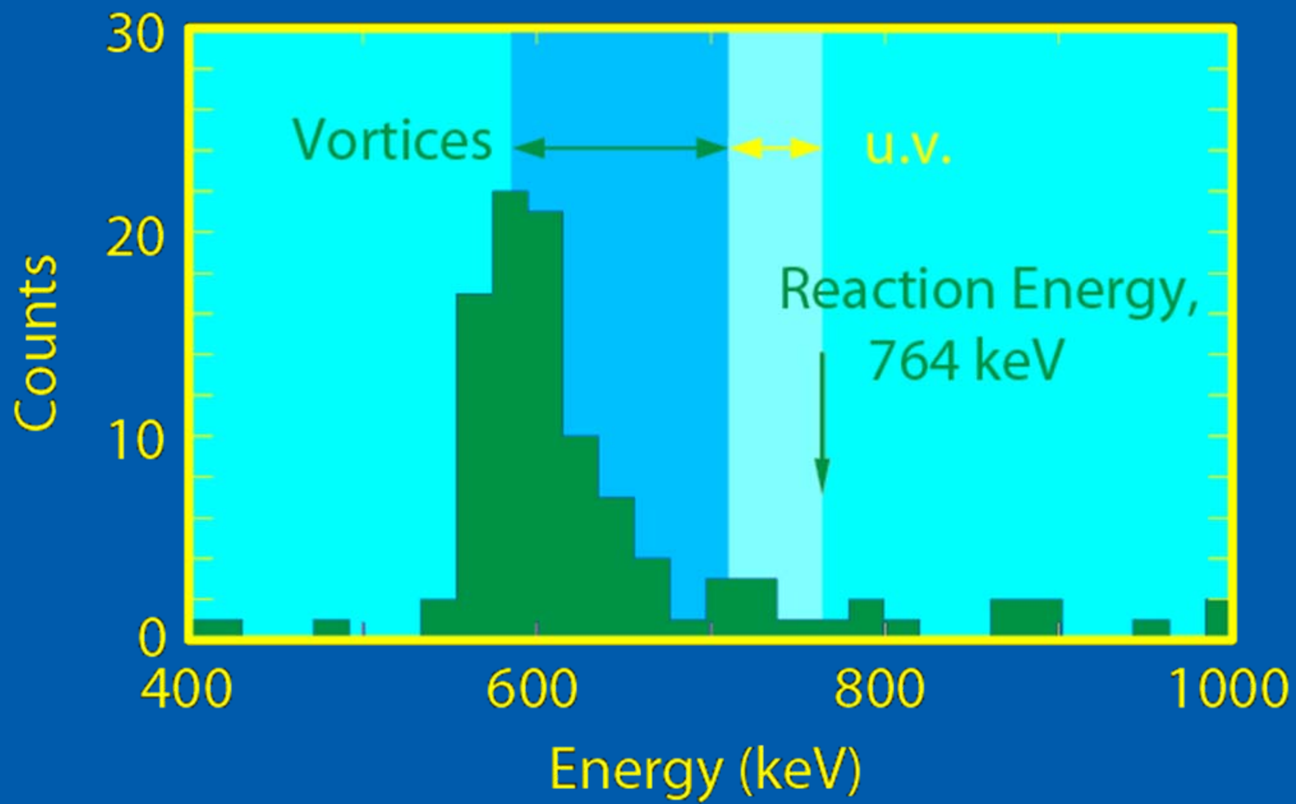


The tangle may evolve very slowly
(and may store a lot of energy)

The damping of the thermometer wire in the box with an external neutron source.



The detector is calibrated (using the heater wire to input a known energy) which then allows us to determine the energies of individual events.

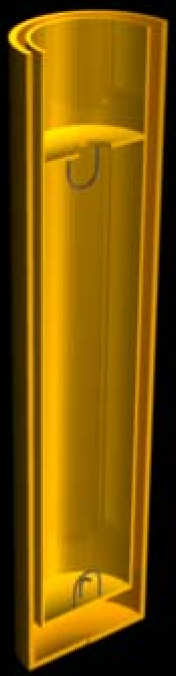


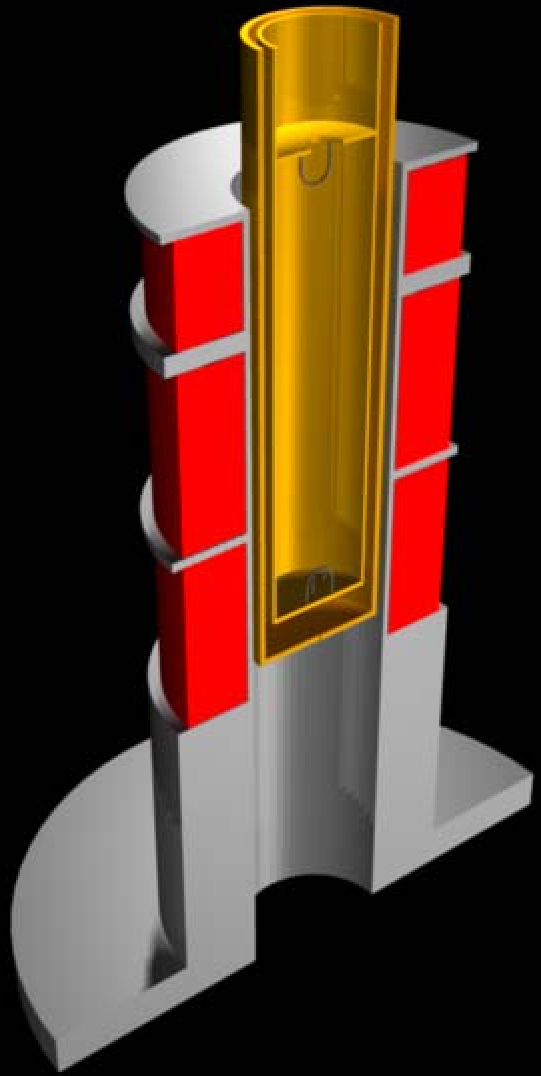
Energy deficit measures the amount of vortices produced

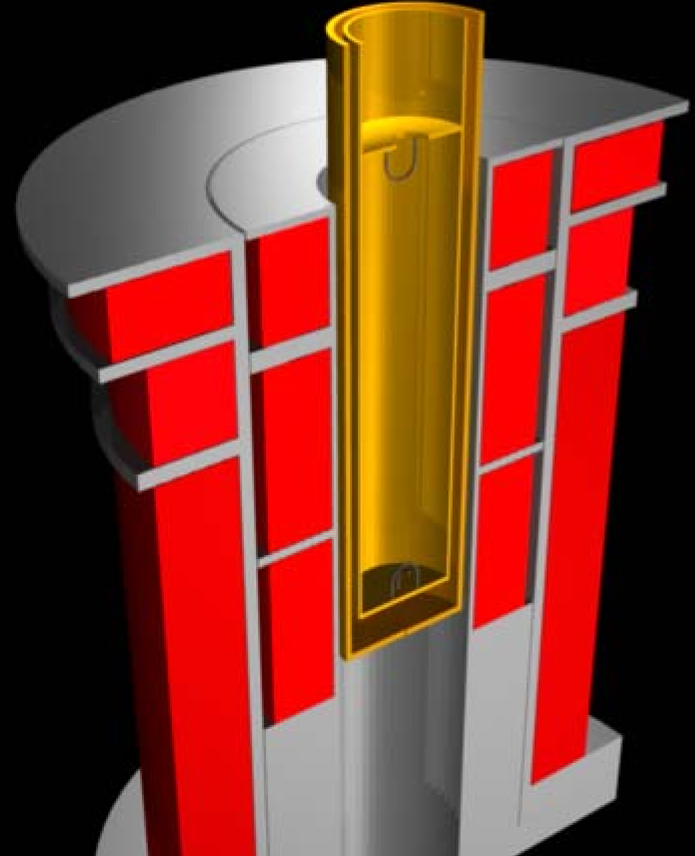
Good agreement with the `Cosmological' model
(Kibble-Zurek mechanism)

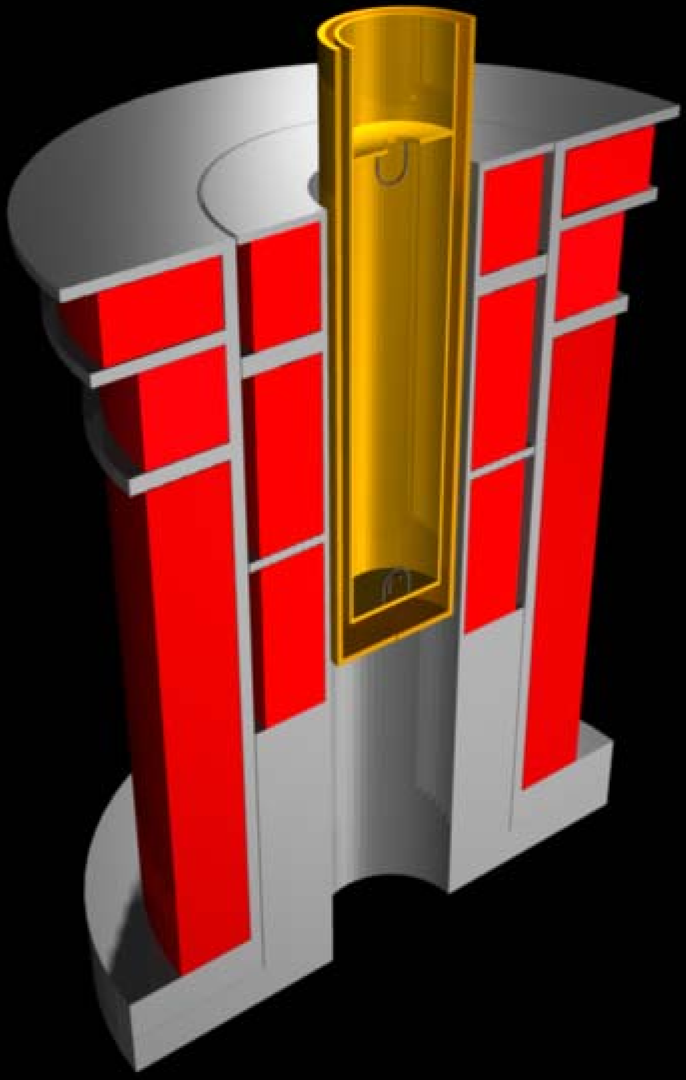
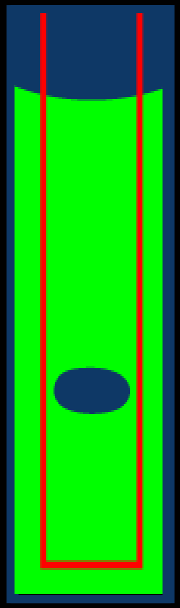
Vortices produced by annihilation of phase boundaries

(analogous to Brane-collisions in cosmology, which may have triggered inflation)





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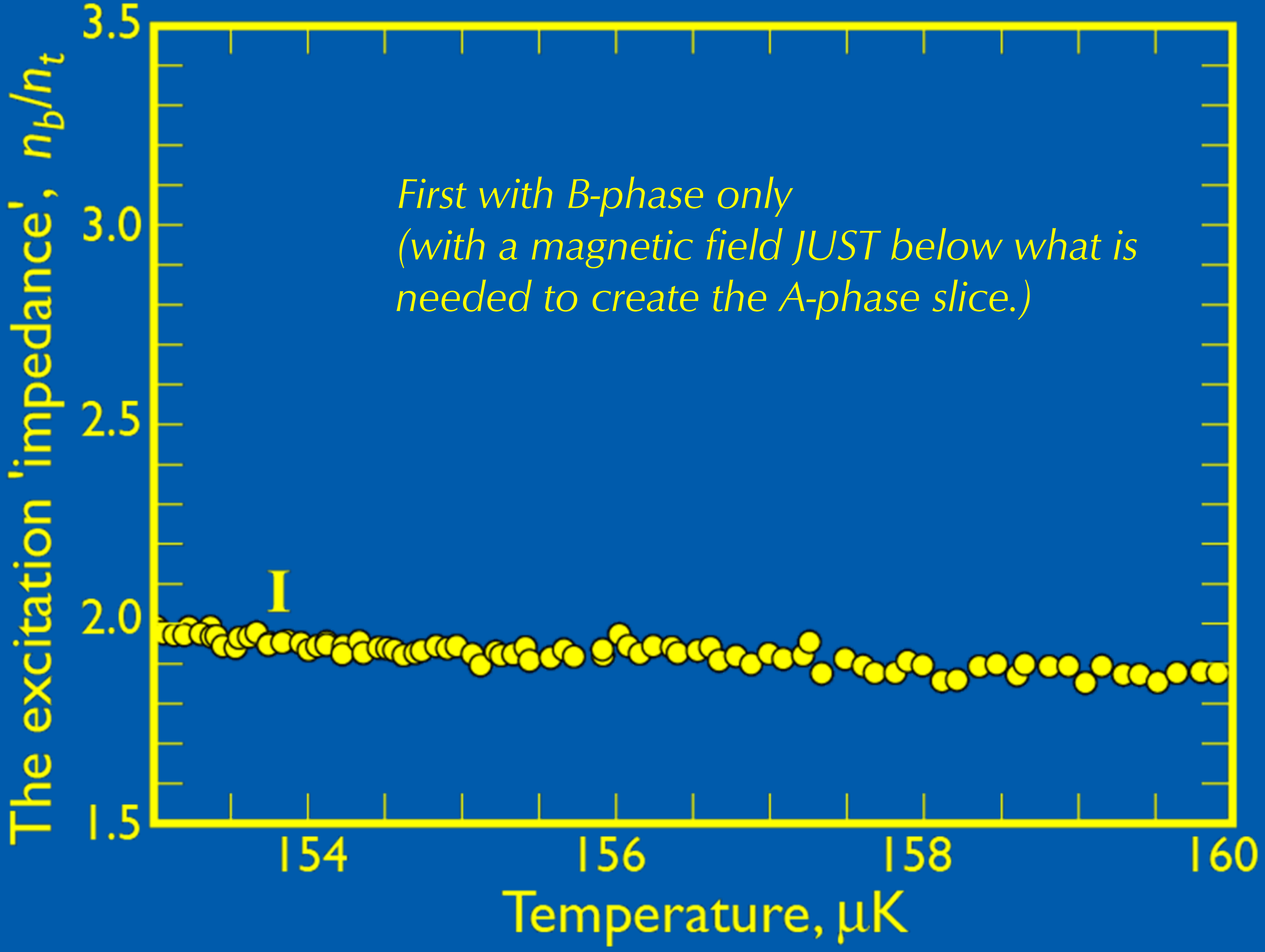
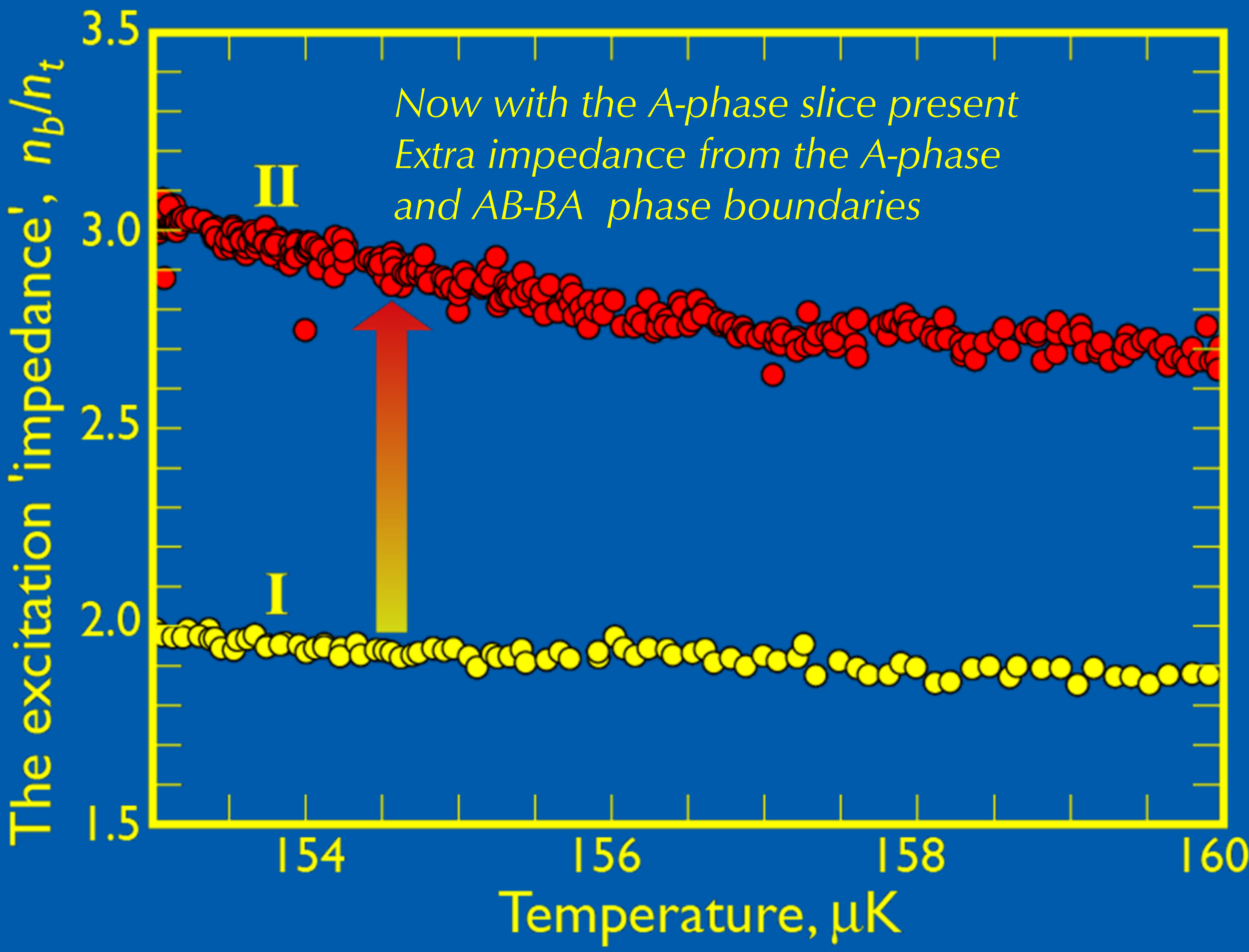
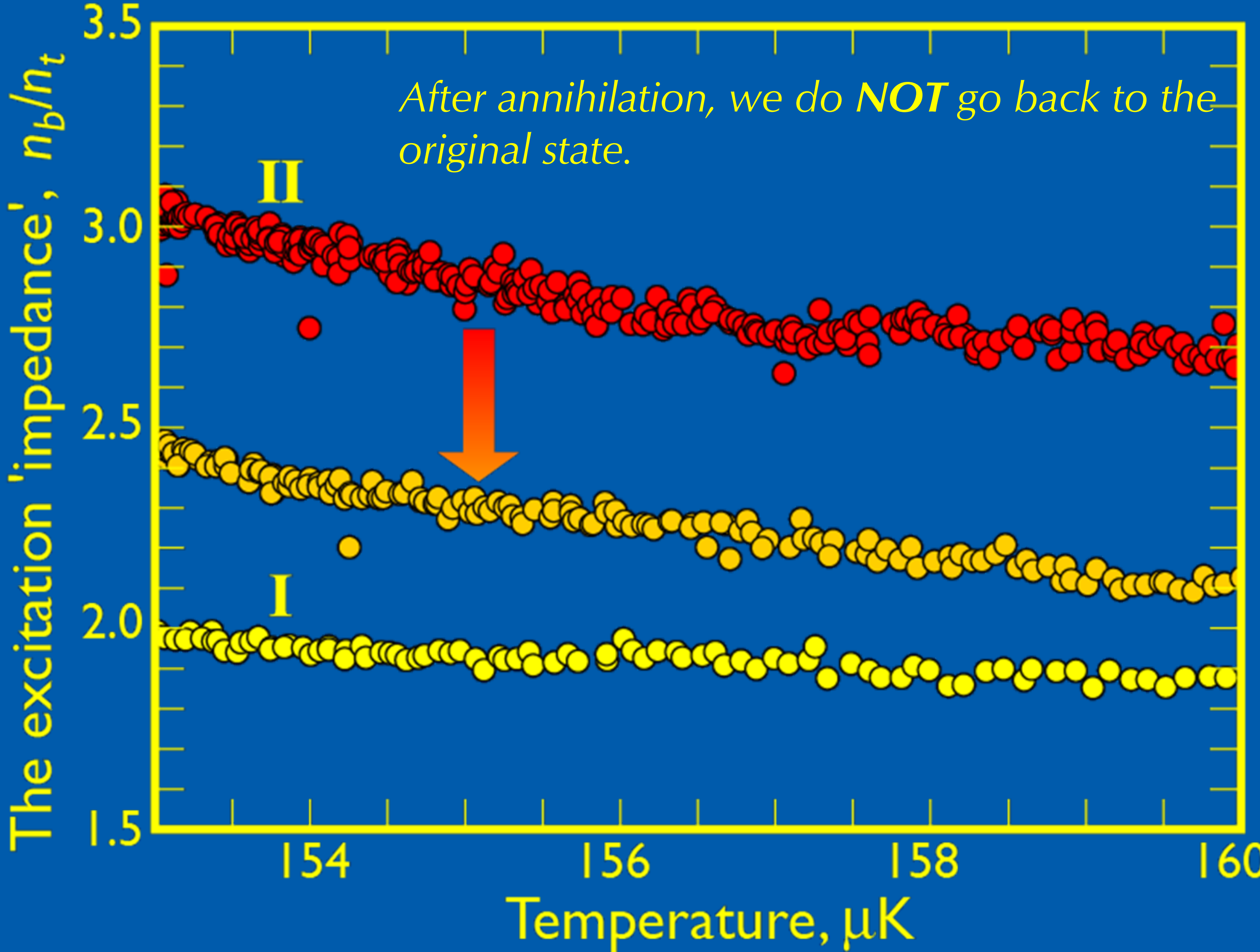
QUANTUM OPTICS
Few-photon fluorescence
SUPERCONDUCTIVITY
Charge without spin
QUANTUM MOLECULAR DYNAMICS
Explosive simulations



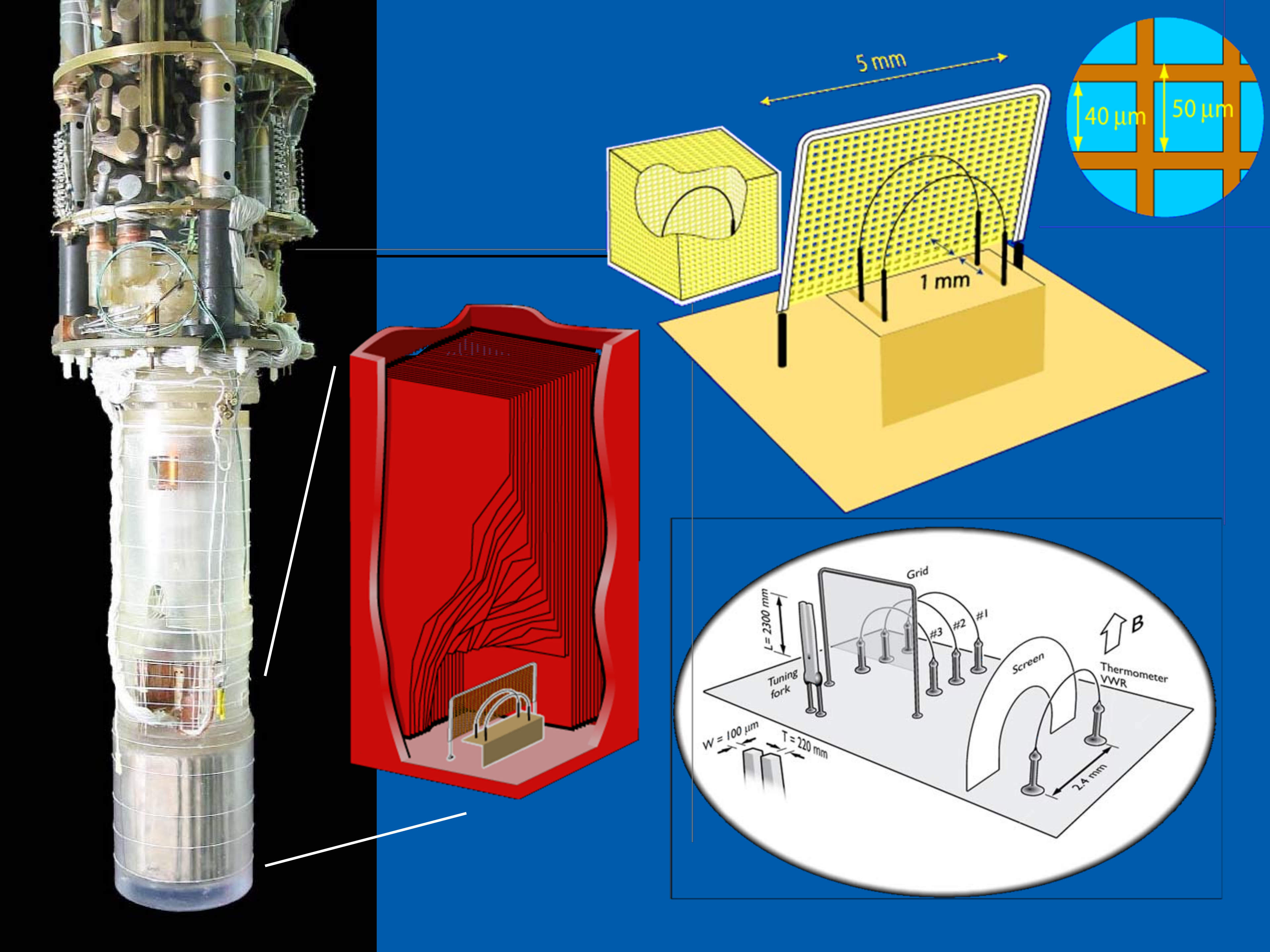
3.5
3.0
2.5
2.0
1.5
The excitation 'impedance', n_b/n_t
First with B-phase only
(with a magnetic field JUST below what is
needed to create the A-phase slice.)
I
154
156
158
160
Temperature, μK



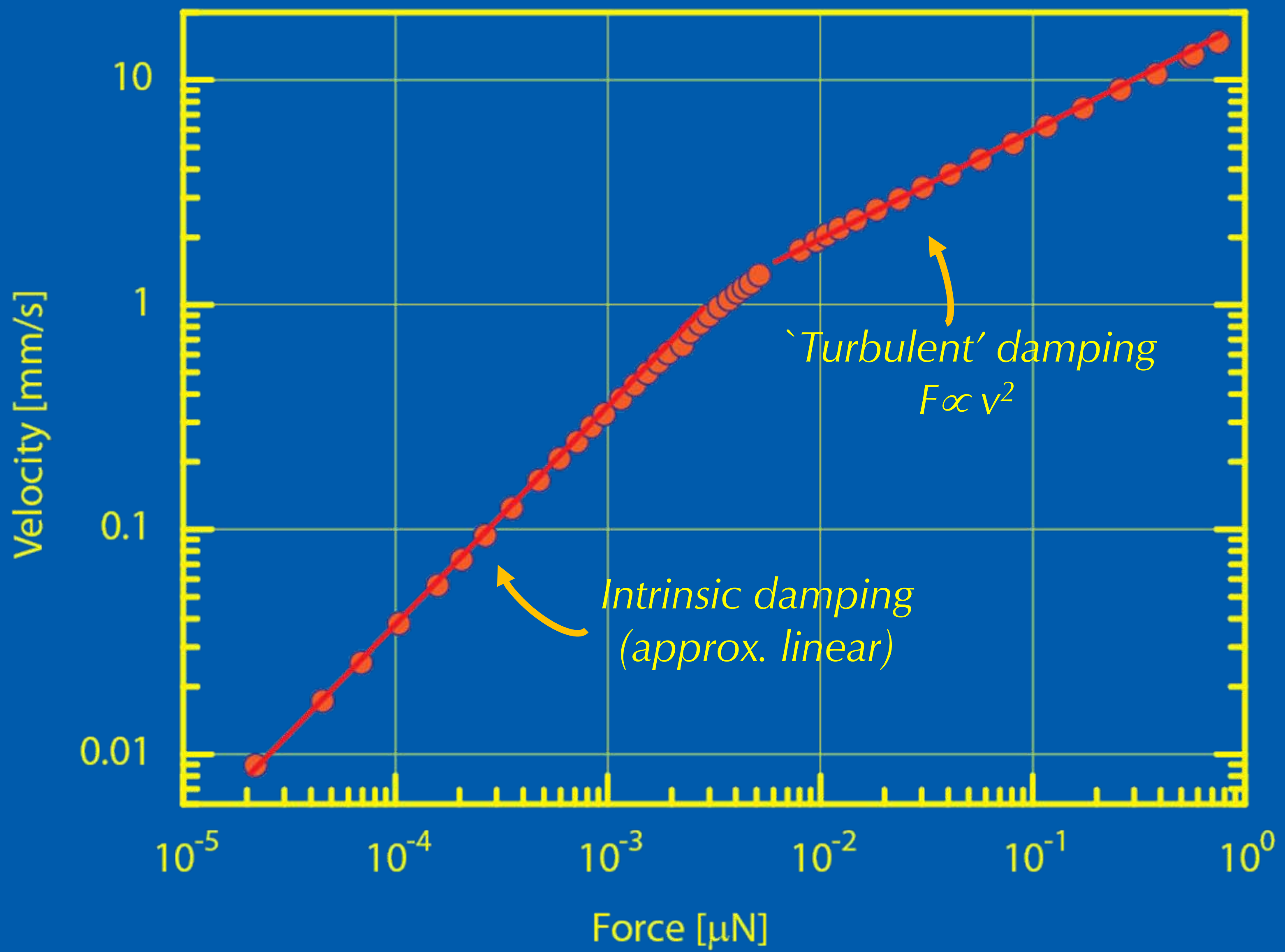
Now with the A-phase slice present
Extra impedance from the A-phase
and AB-BA phase boundaries
II
I
3.5
3.0
2.5
2.0
1.5
154
156
158
160
The excitation 'impedance', n_b/n_t
Temperature, μK



After annihilation, we do **NOT** go back to the original state.
II
I
3.5
3.0
2.5
2.0
1.5
154
156
158
160
The excitation 'impedance', n_b/n_t
Temperature, μK

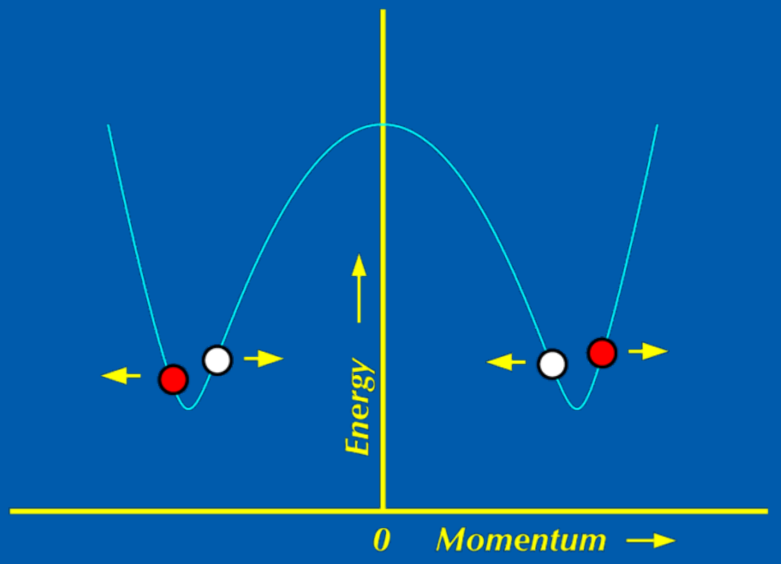

5 mm
40 μm
50 μm
1 mm
Grid
L = 2300 mm
#3
#2
#1
B
Tuning fork
Screen
Thermometer VWR
W = 100 μm
T = 220 mm
2.4 mm

Vortex Production by a vibrating Grid in 3He-B

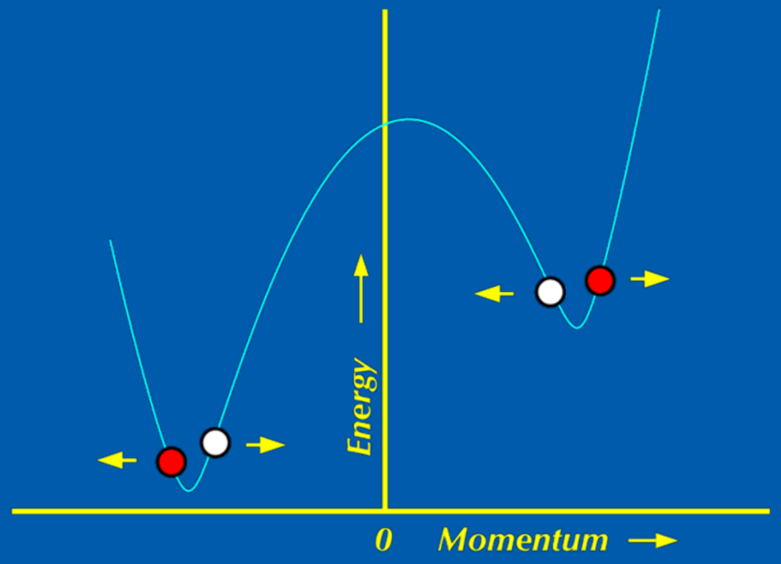


The excitation dispersion curve is tilted by superflow
(energies are shifted by $p_F.v$).

Liquid static

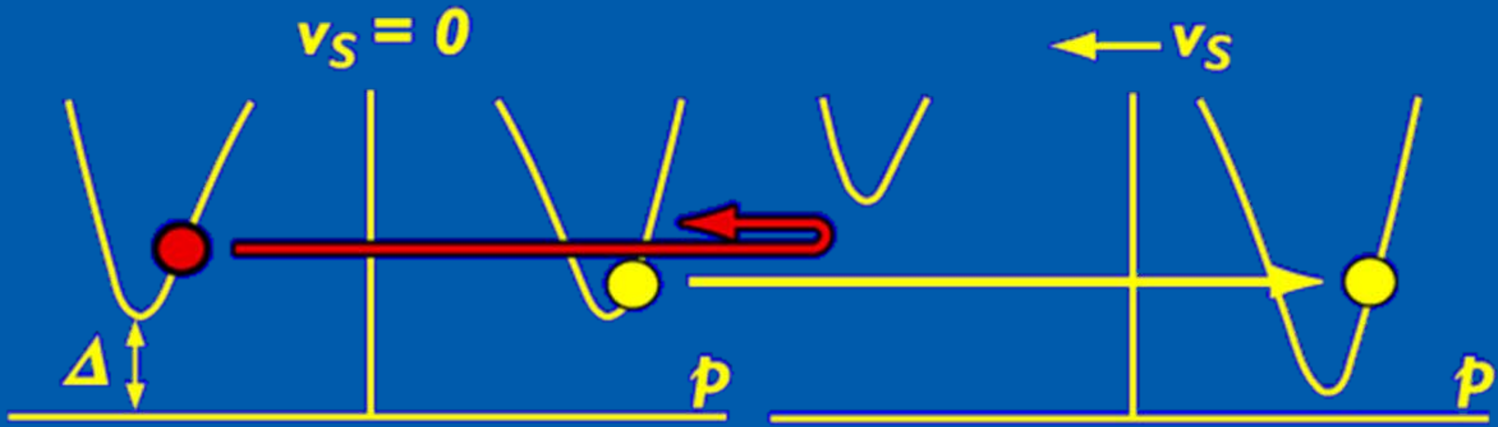


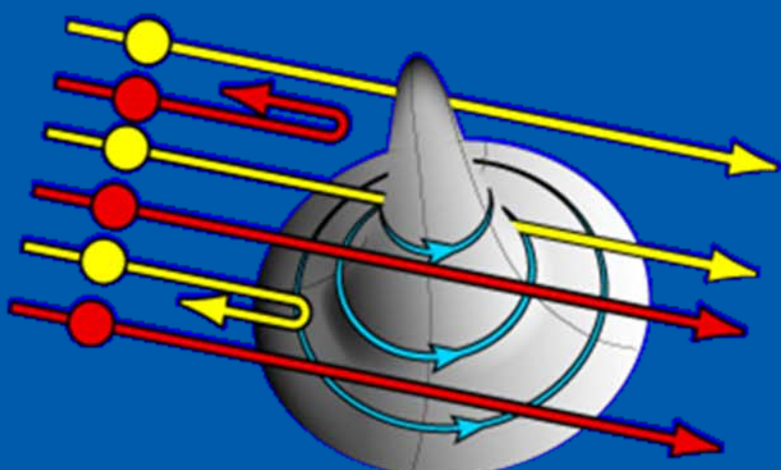
Liquid moving

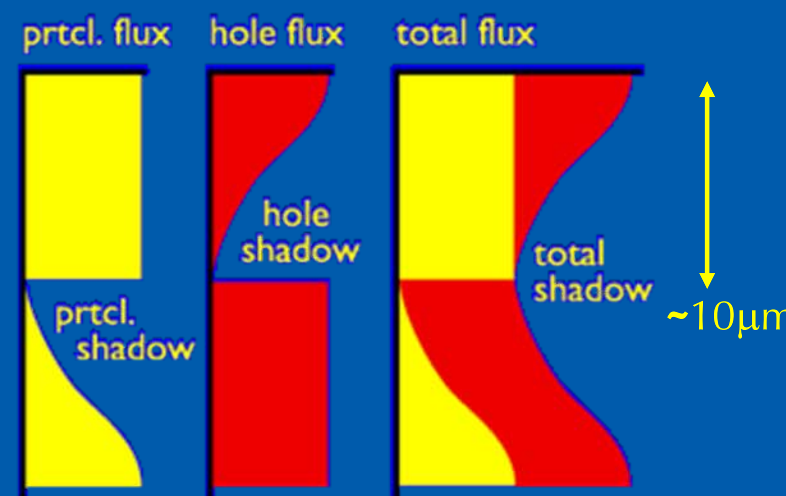


Andreev Scattering by vortex lines

The flow around a vortex, Andreev reflects excitations (particles on one side and holes on the other side).

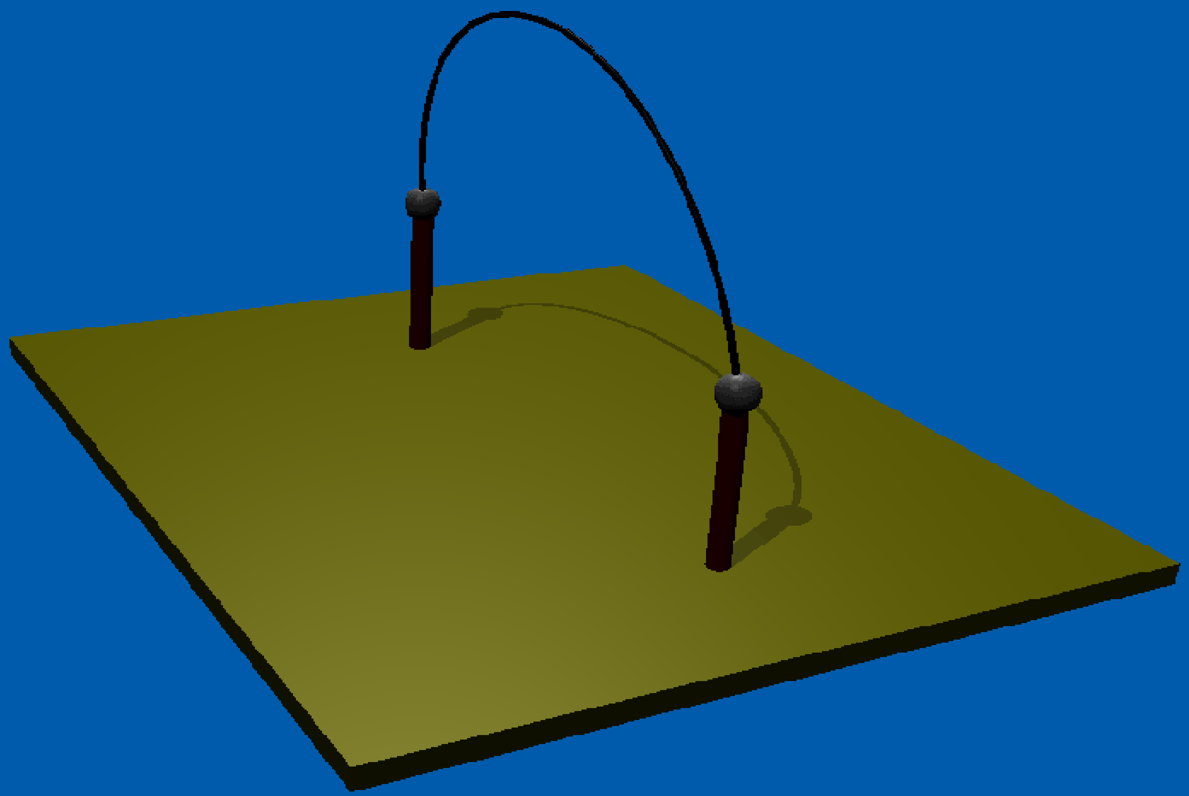






Vibrating Wire Resonator

a loop of superconducting wire is placed in a magnetic field and set into motion by passing an ac current through it .



Vibrating Wire Resonator

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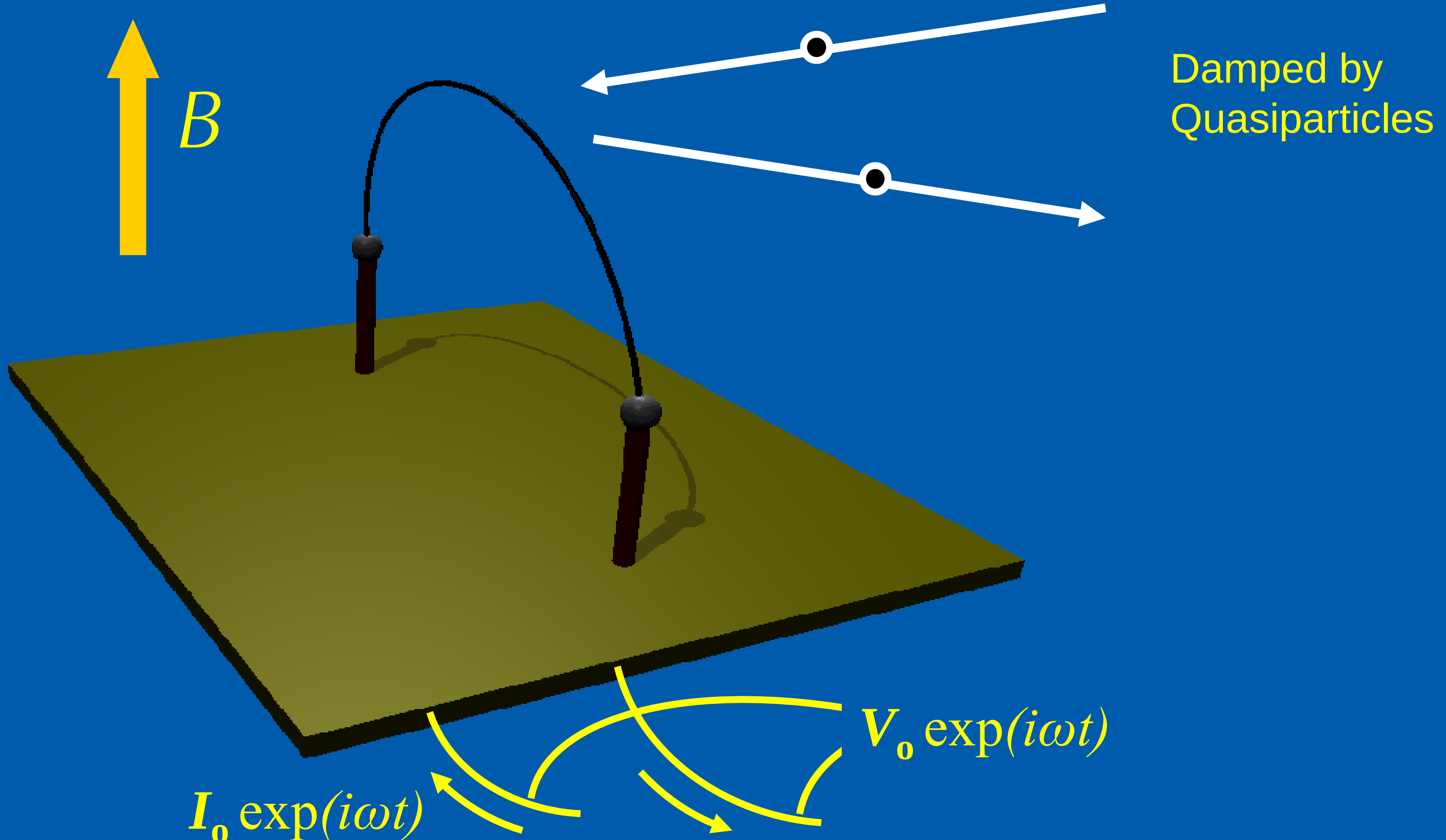
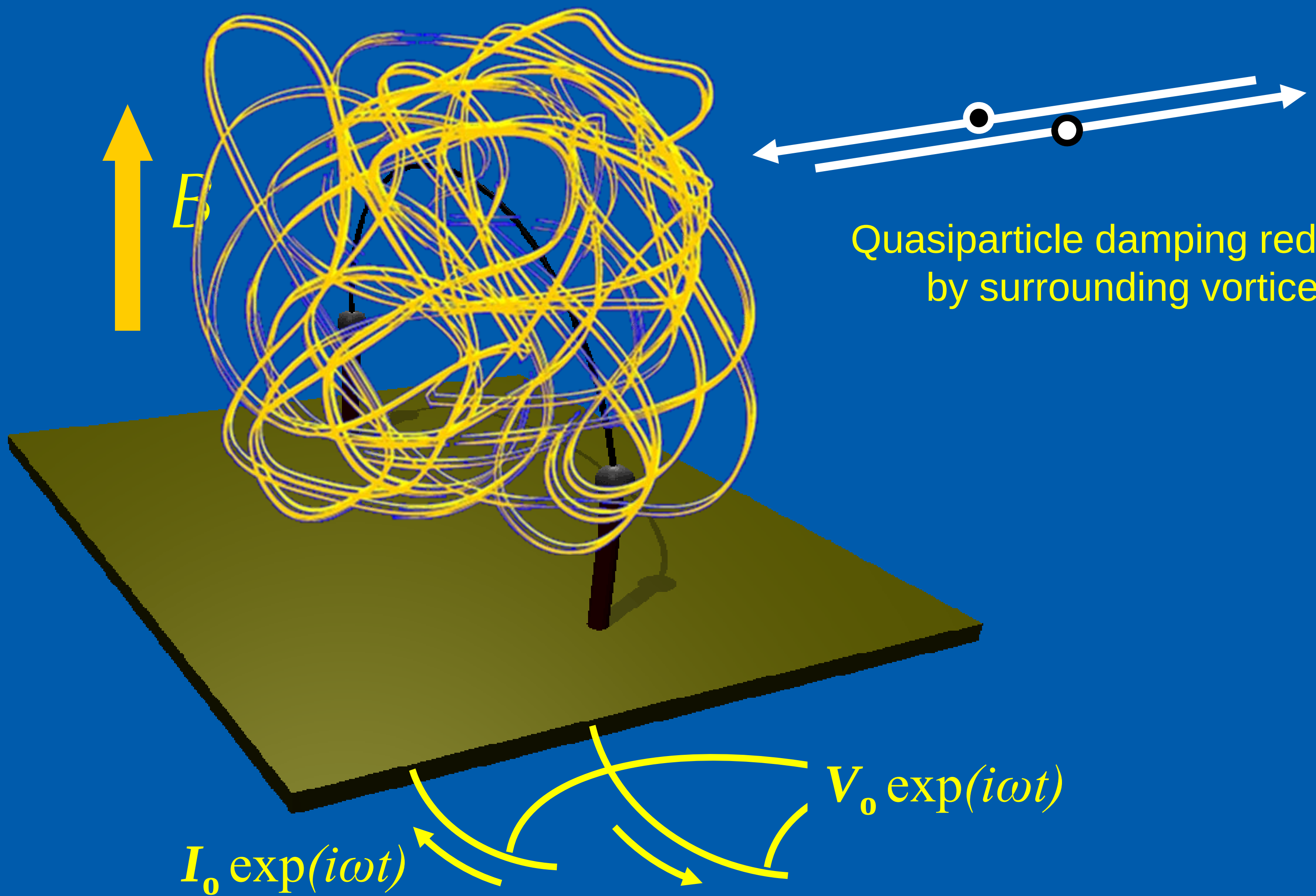
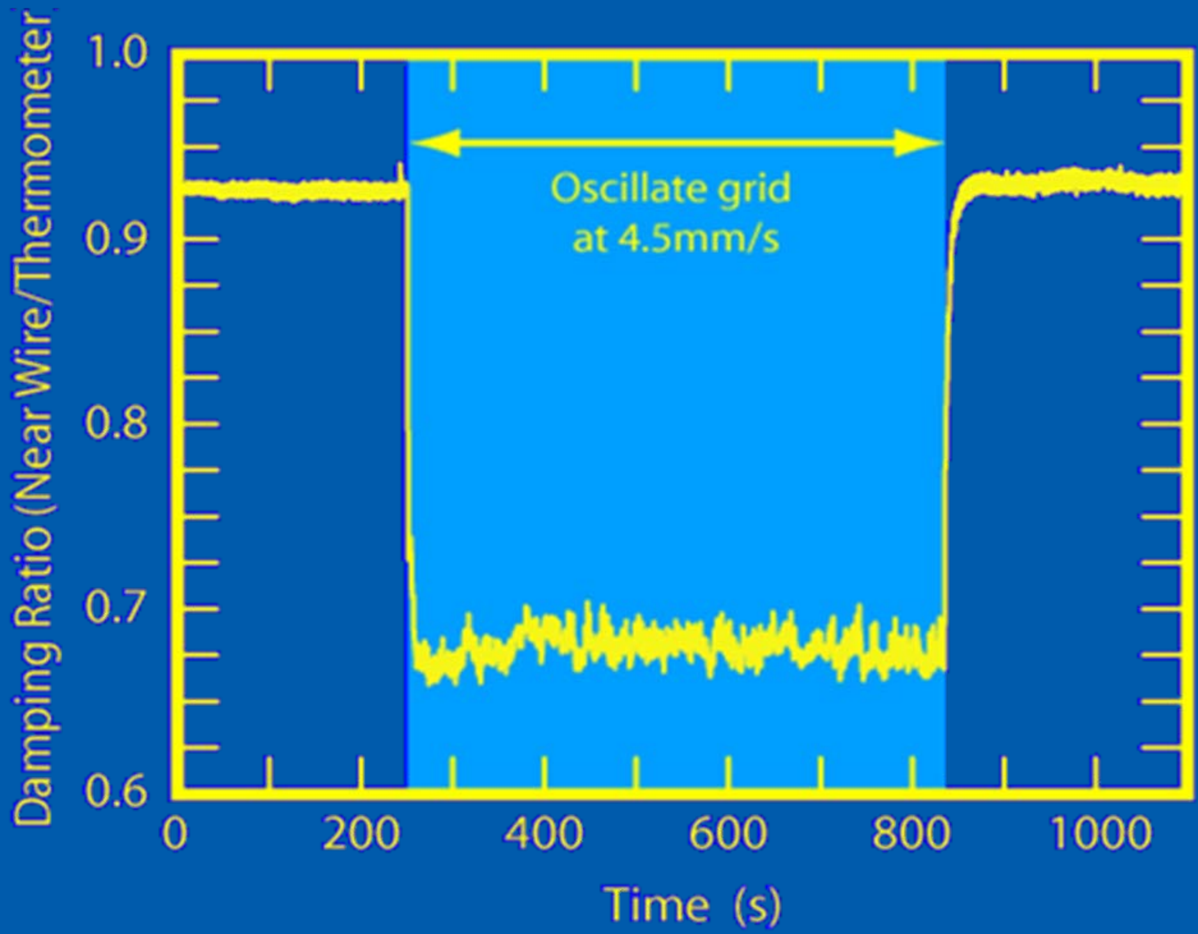


Vibrating Wire Resonator

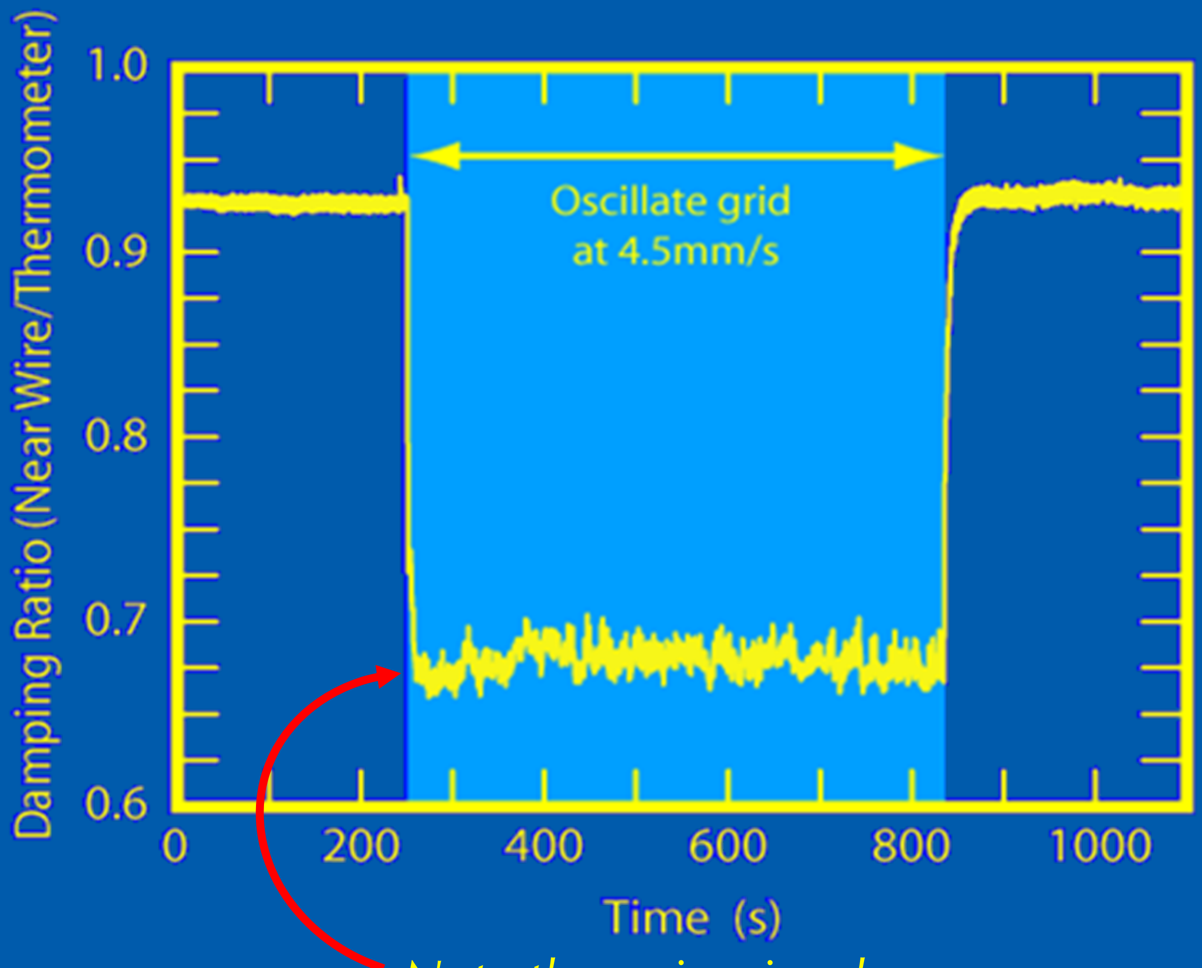
a loop of superconducting wire is placed in a magnetic field and set into motion by passing an ac current through it .



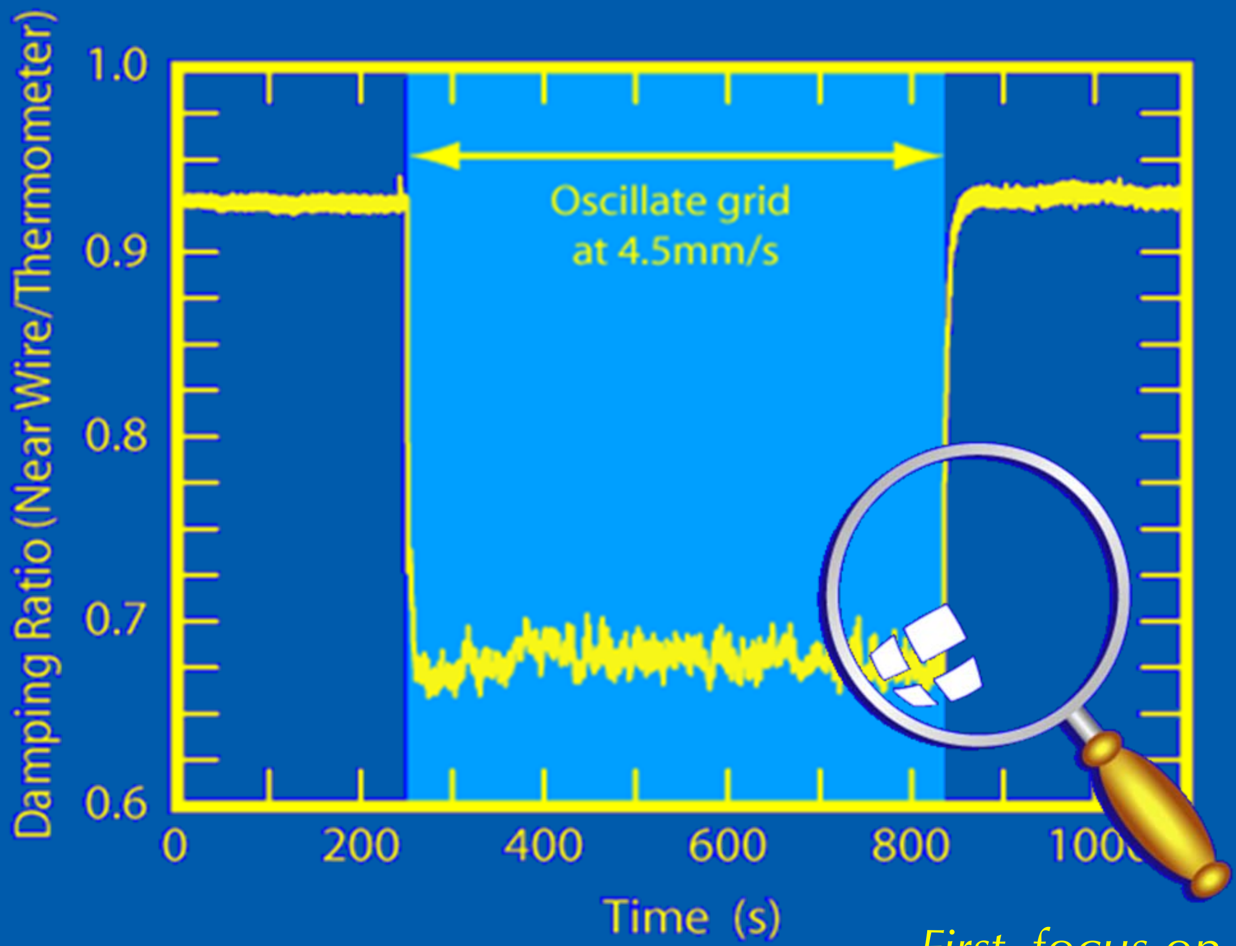
The wire damping is suppressed when the grid is oscillated.



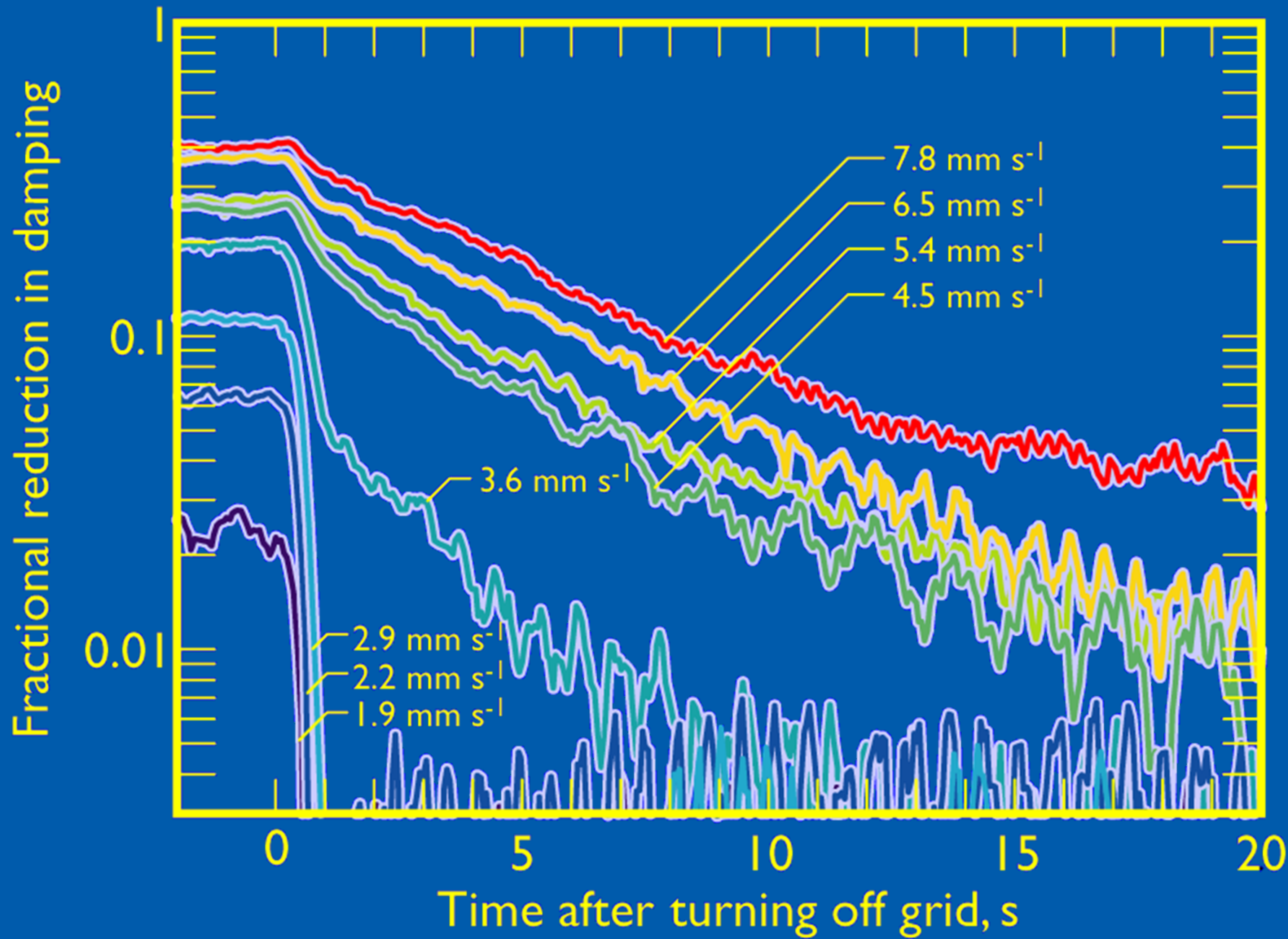
This is our `vortex signal'.



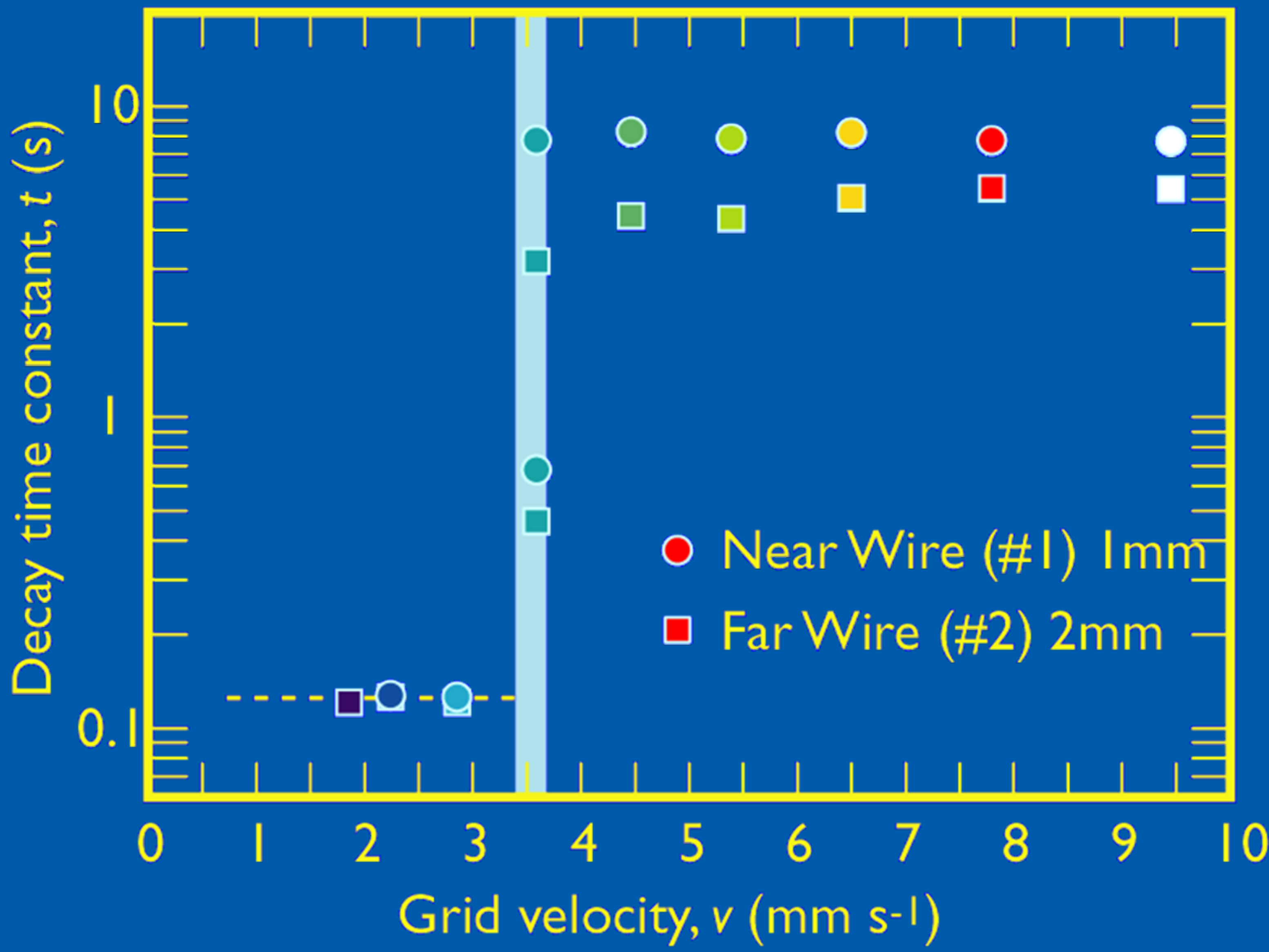
Note the noisy signal
– we see fluctuations in the vortex configuration.



First, focus on the decay of the vorticity after we switch off the grid.



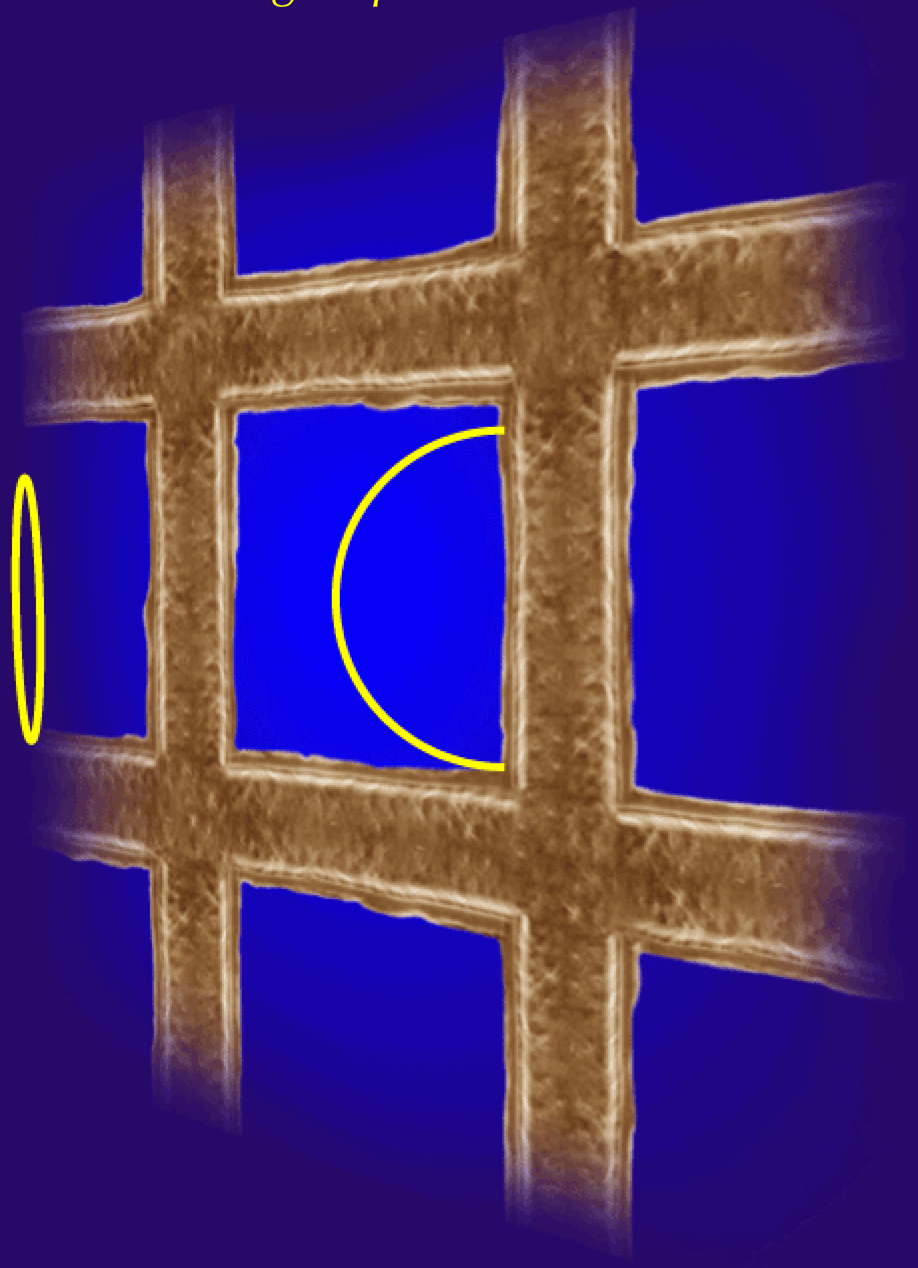
Fractional reduction in damping
1
0.1
0.01
0
5
10
15
20
Time after turning off grid, s
7.8 mm s^{-1}
6.5 mm s^{-1}
5.4 mm s^{-1}
4.5 mm s^{-1}
3.6 mm s^{-1}
2.9 mm s^{-1}
2.2 mm s^{-1}
1.9 mm s^{-1}



10
1
0.1
Decay time constant, t (s)
Near Wire (#1) 1mm
Far Wire (#2) 2mm
0
1
2
3
4
5
6
7
8
9
10
Grid velocity, v (mm s-1)

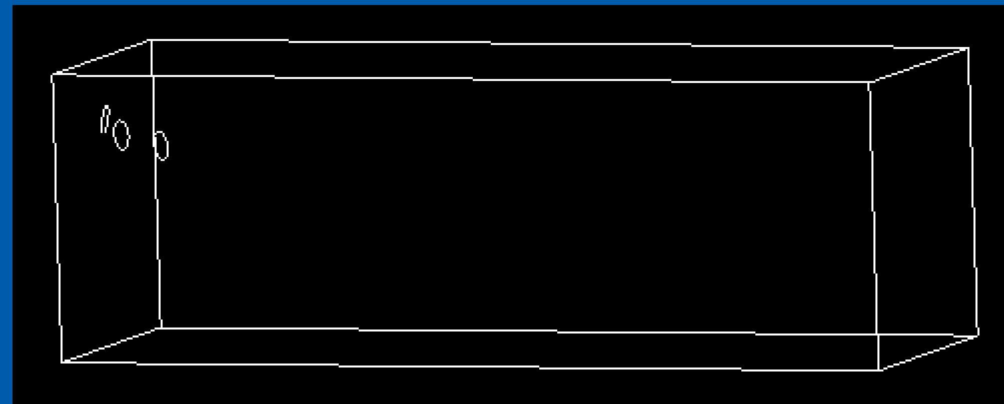
Based on simulations by Makoto Tsubota's group.

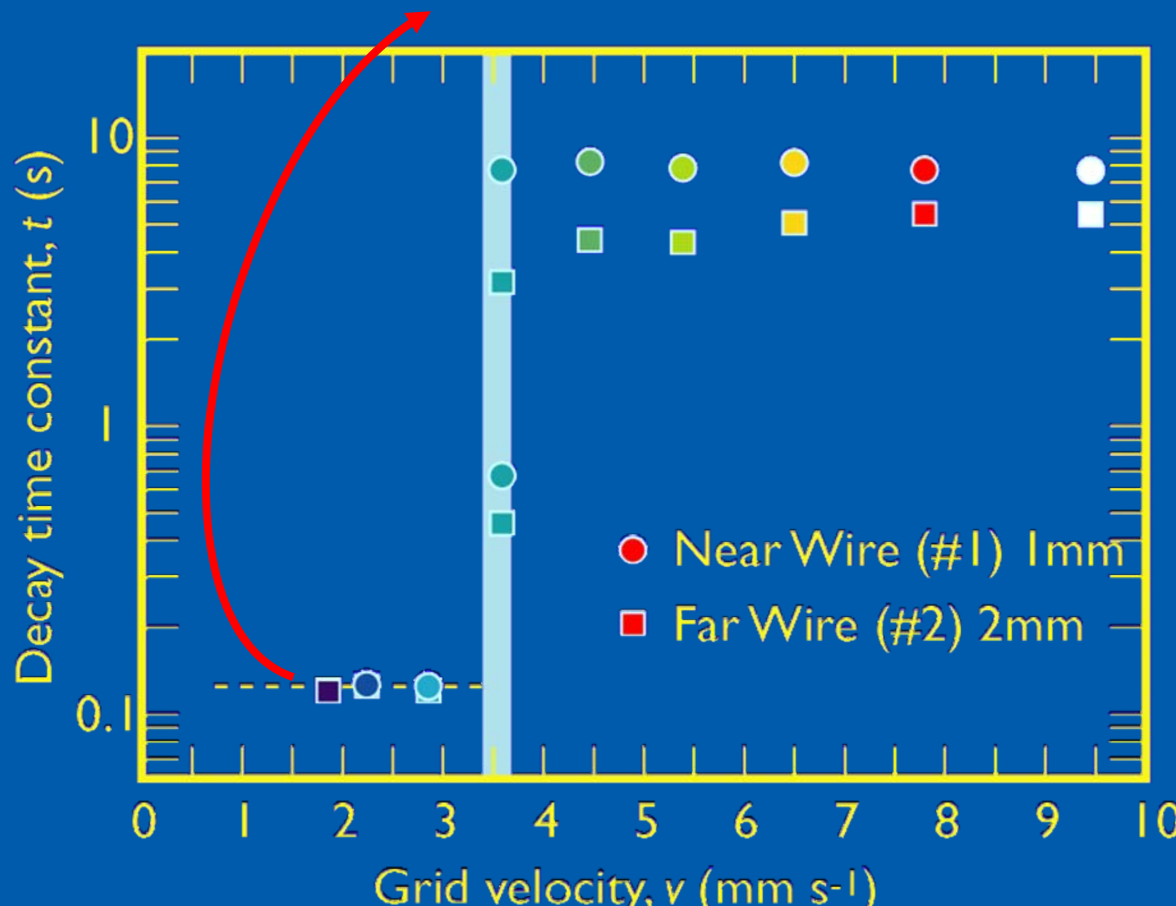
The grid frequency, 1300Hz, predominantly excites 5μm diameter loops.



Simulations by Makoto Tsubota's group.

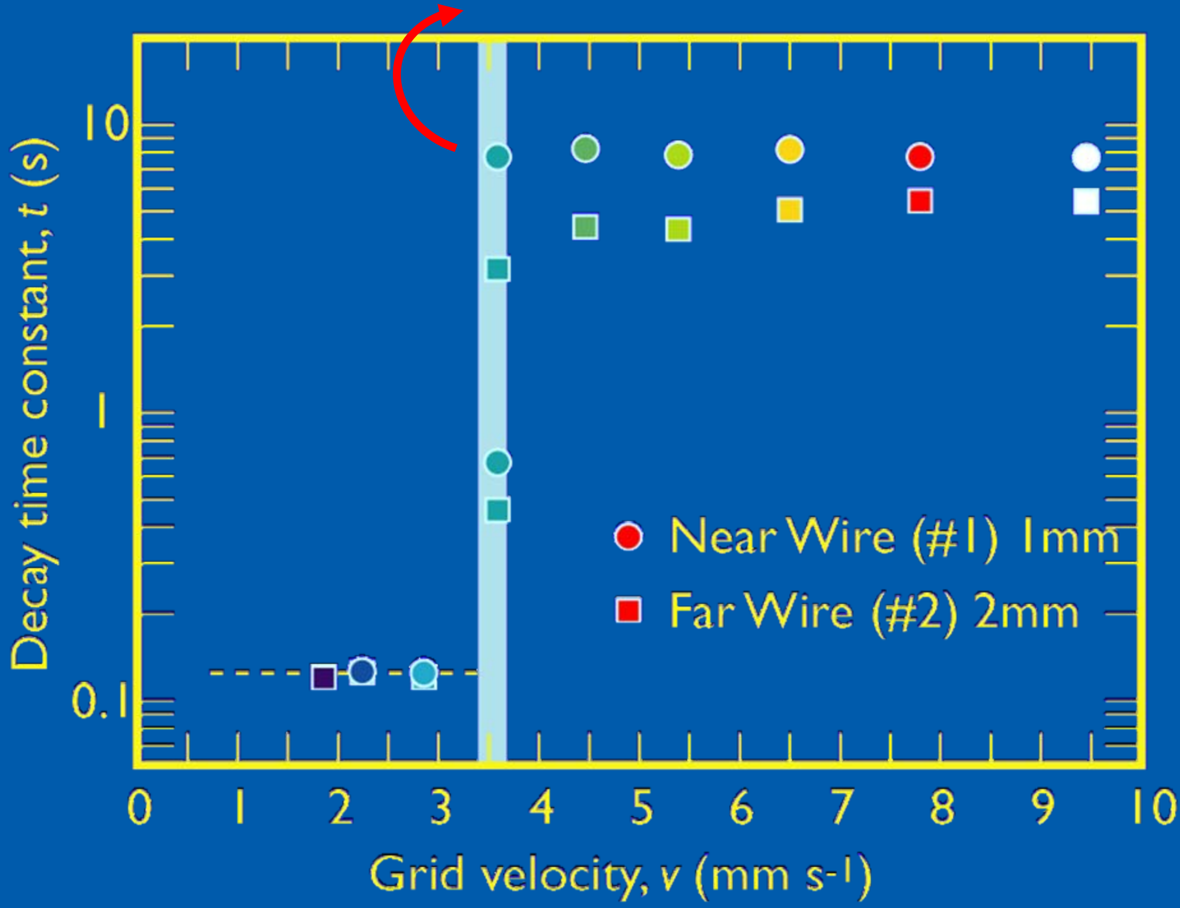
At low ring production rates, the rings are ballistic and travel with their self-induced velocity with almost no interaction.





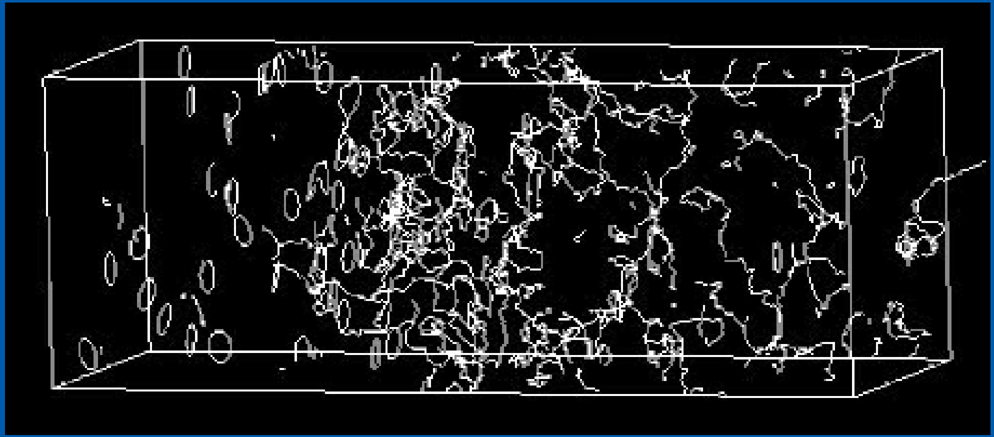
Simulations by Makoto Tsubota's group.

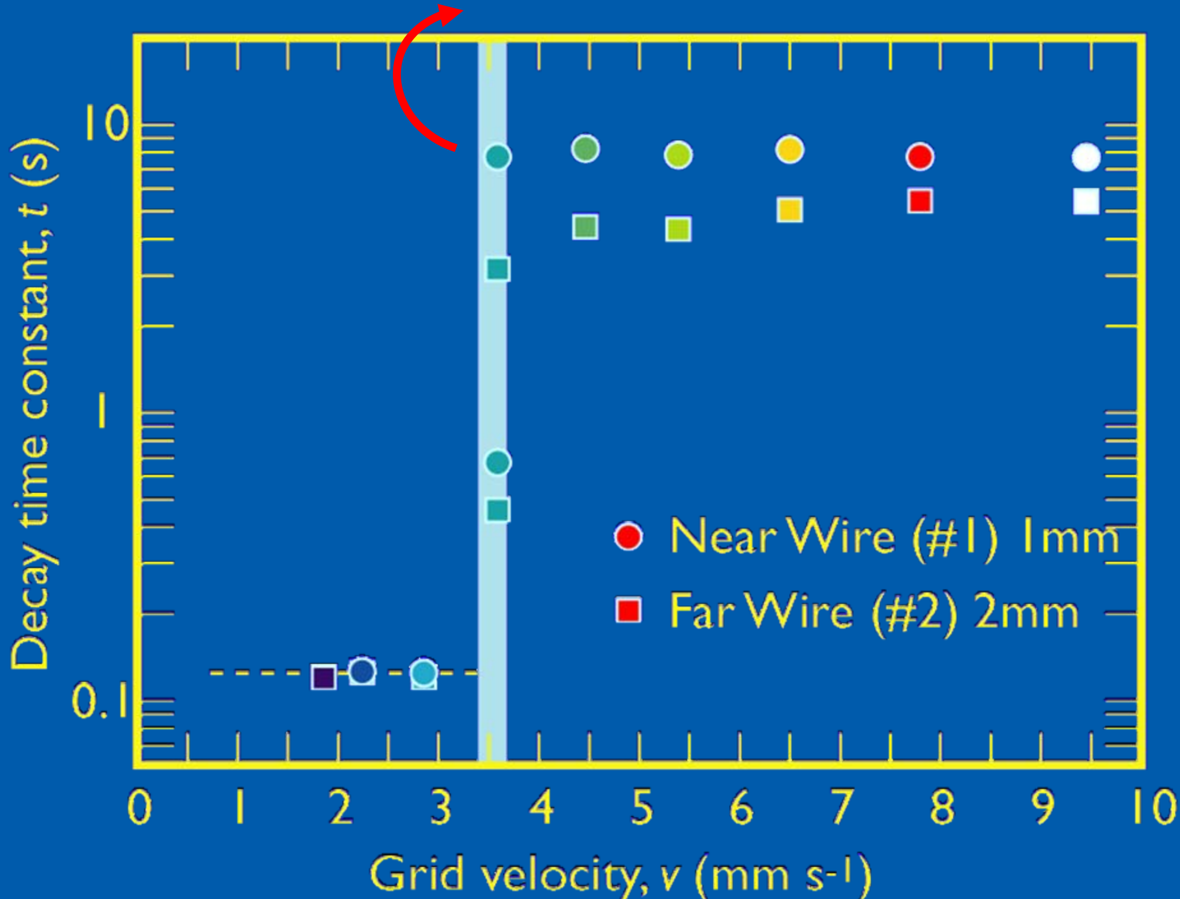
At higher ring production rates, the rings collide to produce a vortex tangle (quantum turbulence).



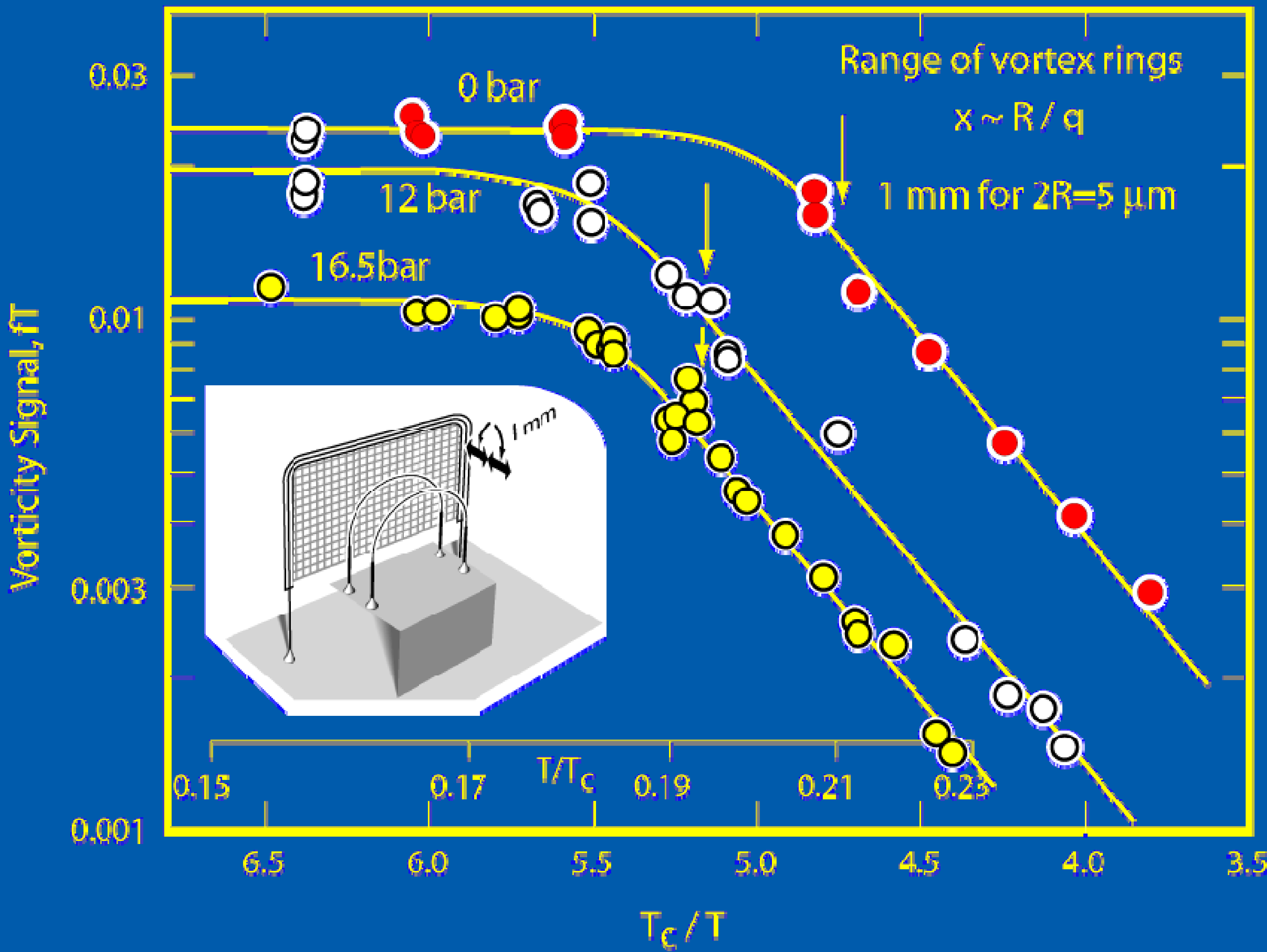
Simulations by Makoto Tsubota's group.

The quantum turbulence then decays relatively slowly.



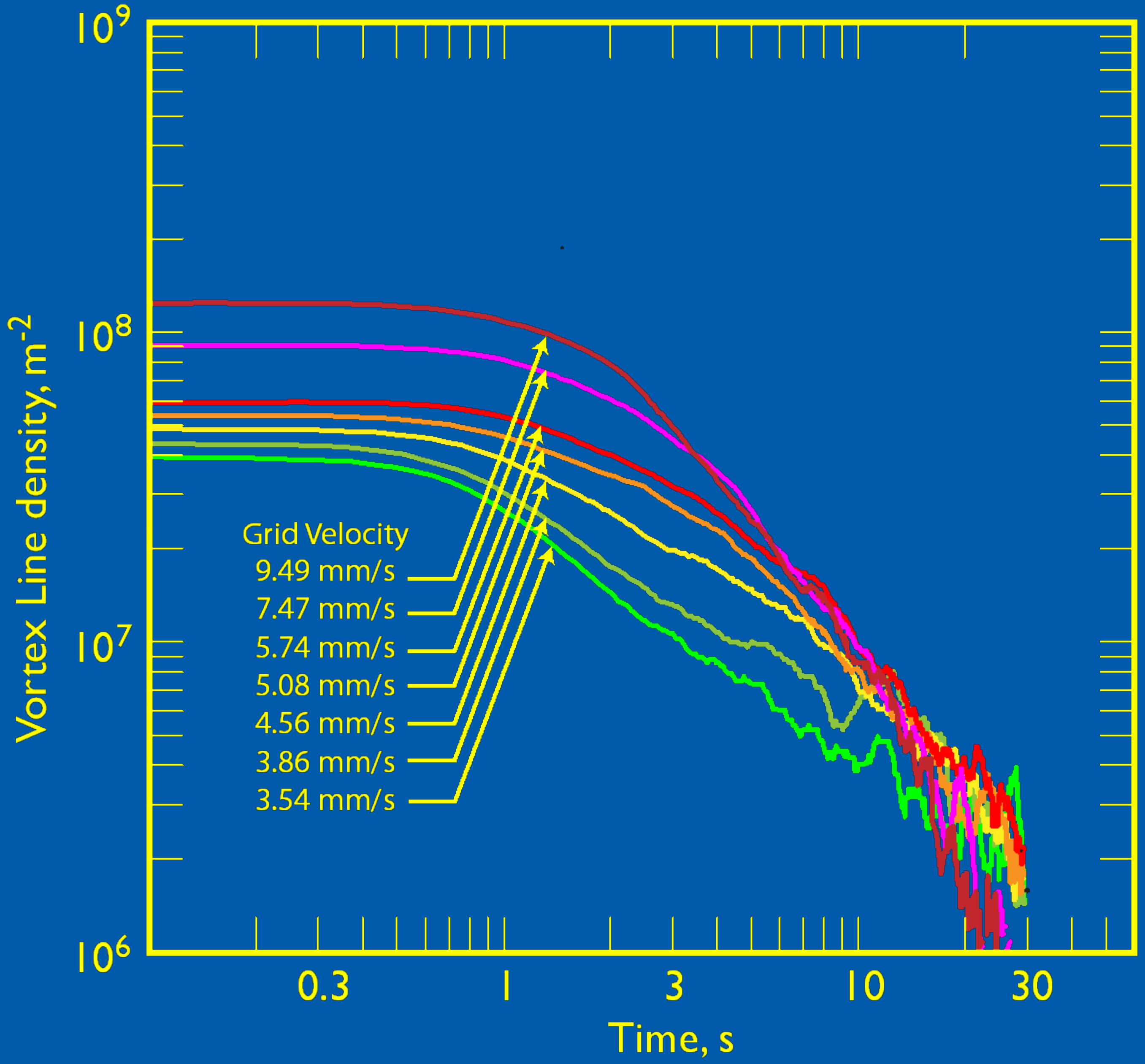


Thermal decay of vortex rings

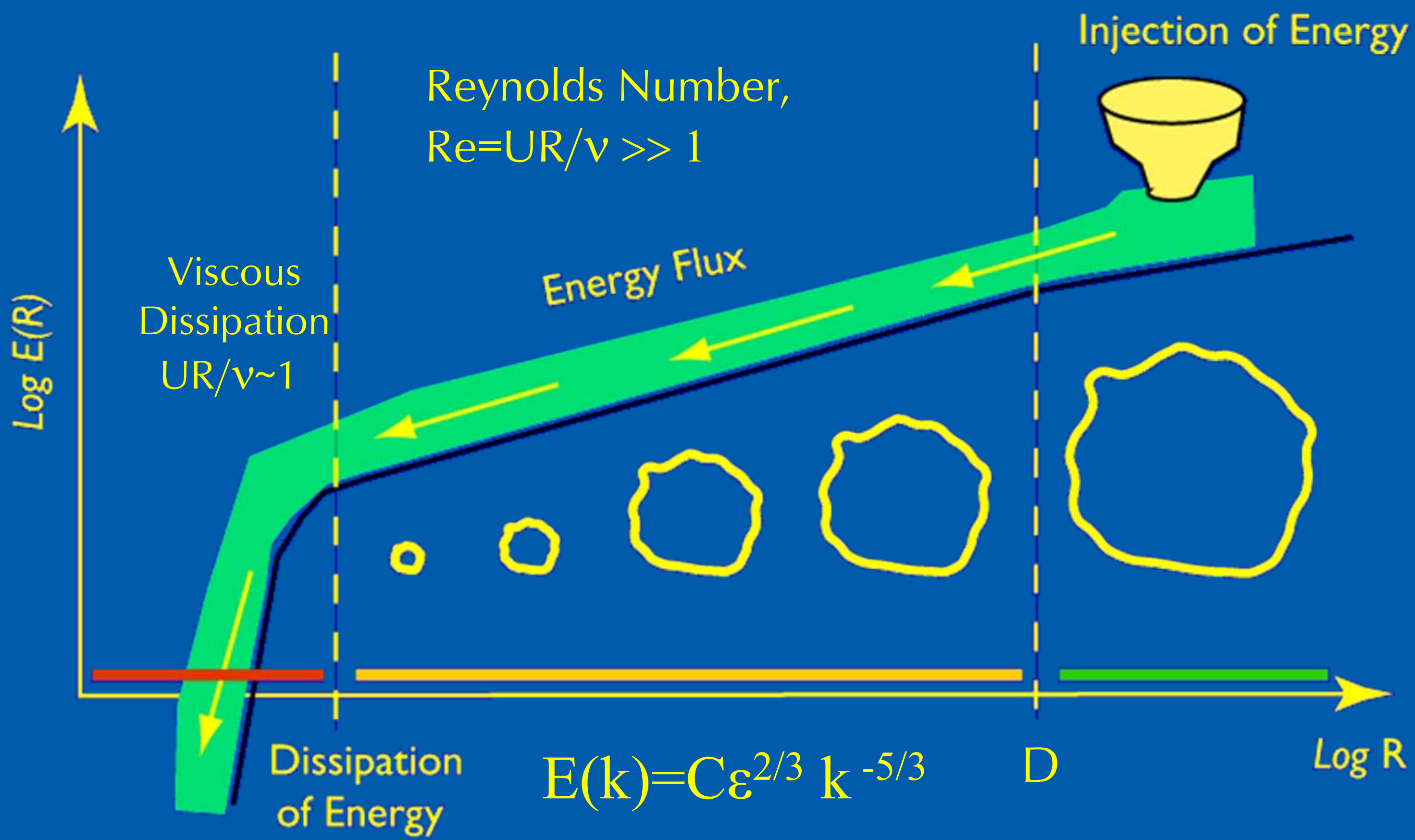


Arrows give ange of 5 micron rings based on mutual friction measurements by Bevan *et. al.* JLTP **109**, 243 (1997).

Decay of Pure Quantum Turbulence



Richardson cascade - Kolmogorov spectrum

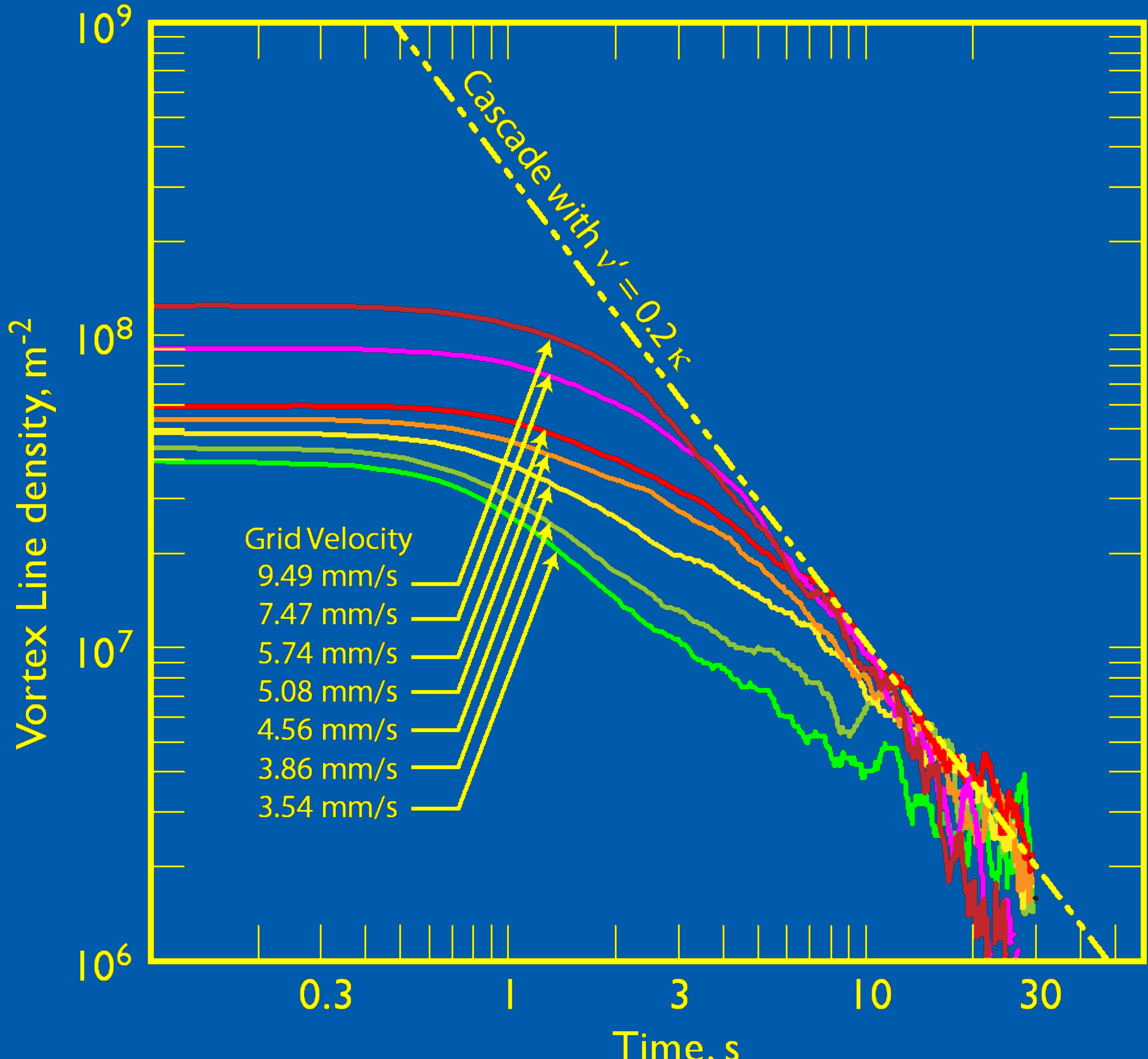


Classical cascade model (assuming $\omega=\kappa L$) predicts:

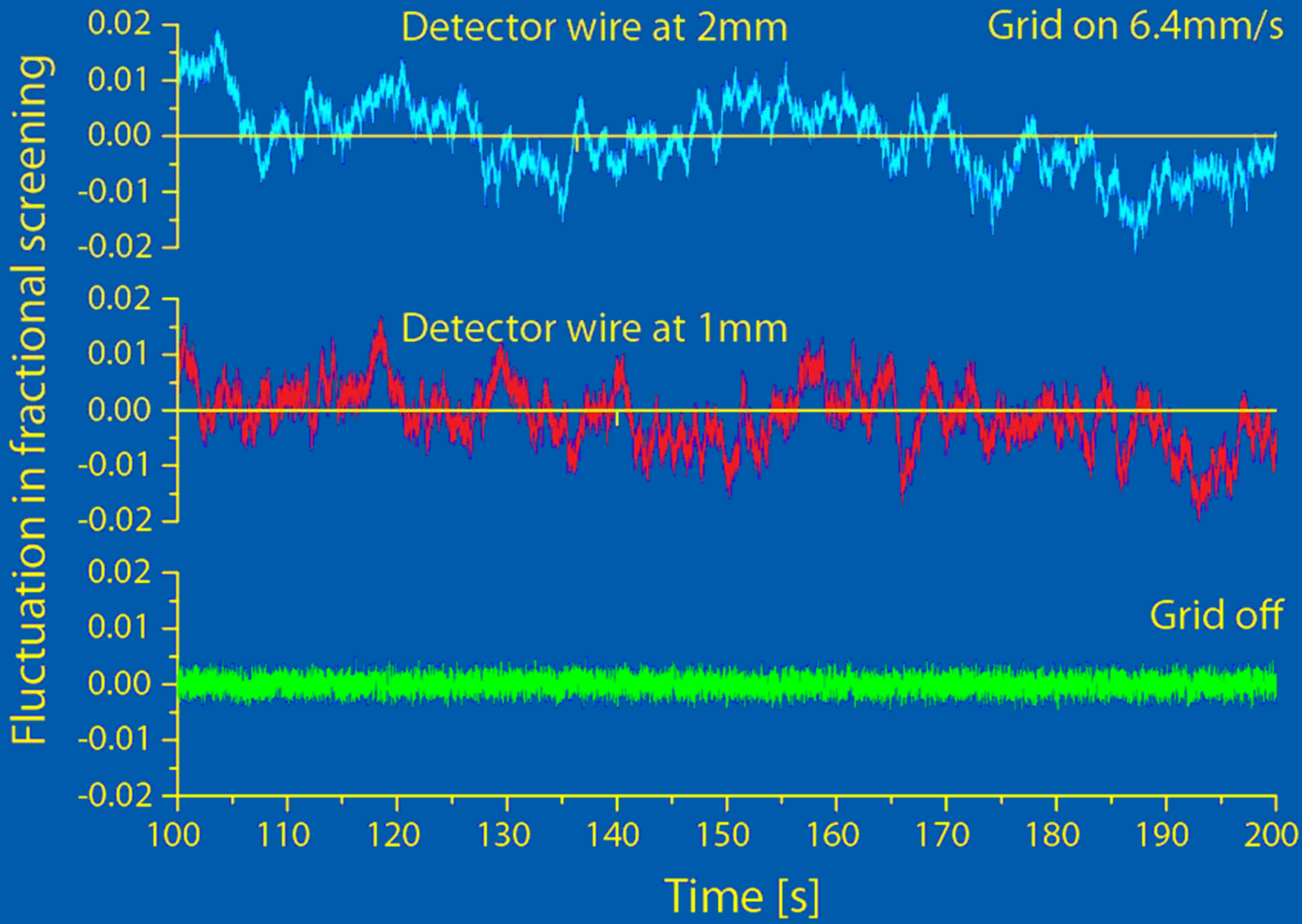
Vortex Line Density at late times, $L=D/2\pi\kappa\,(27C/\nu)^{1/2}\,t^{-3/2}$

ν = `effective' kinematic viscosity.

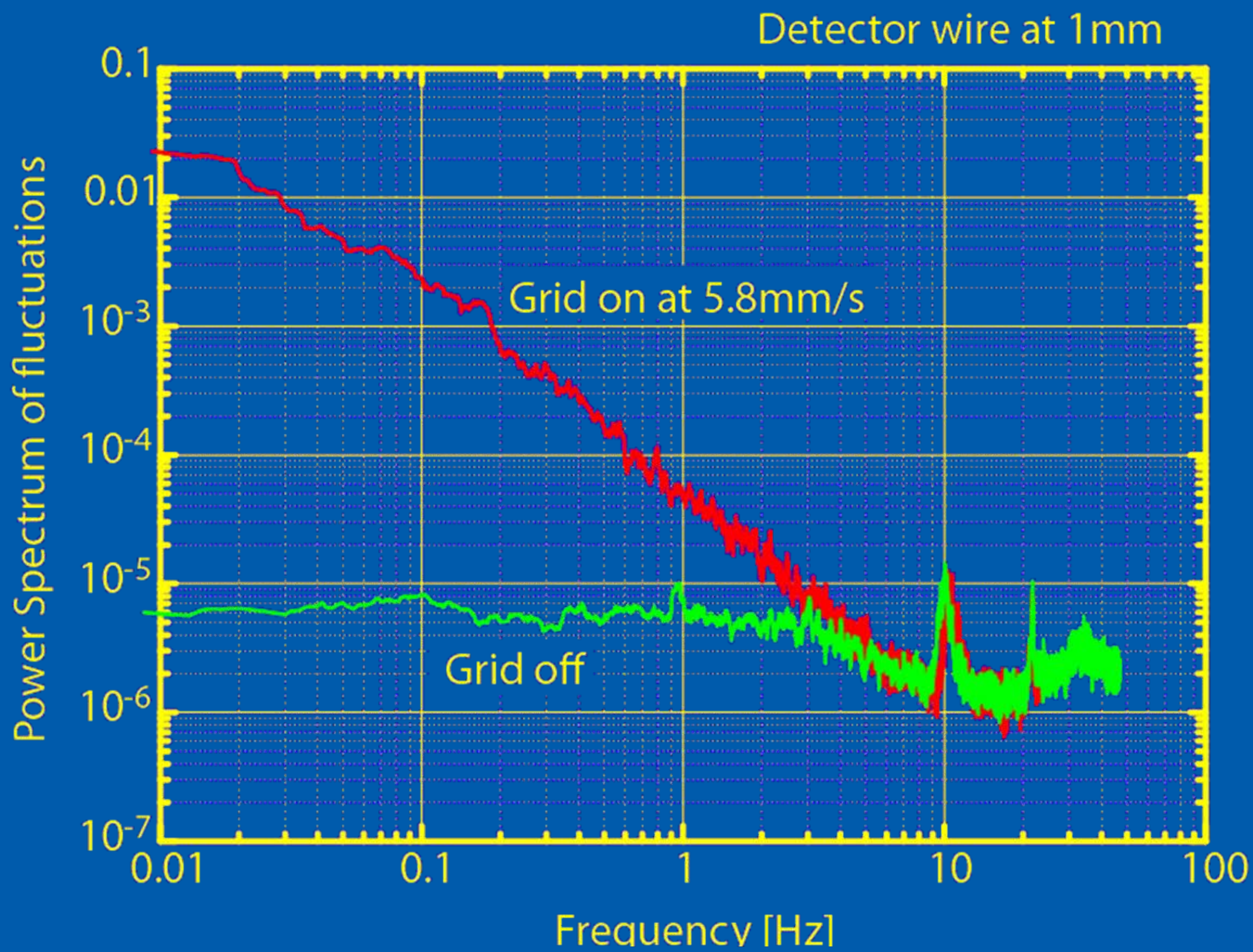
Decay of Pure Quantum Turbulence



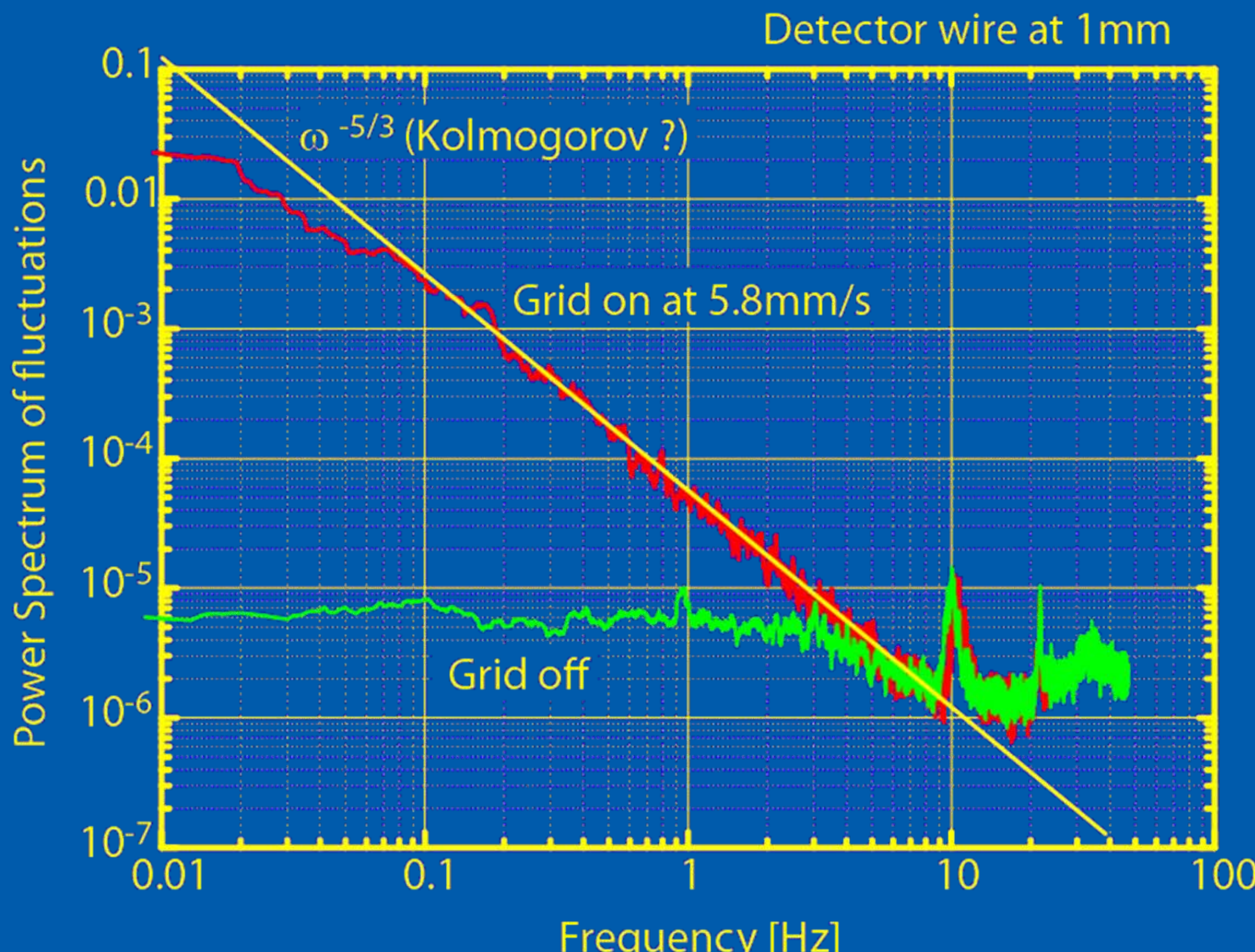
Turbulent Fluctuations



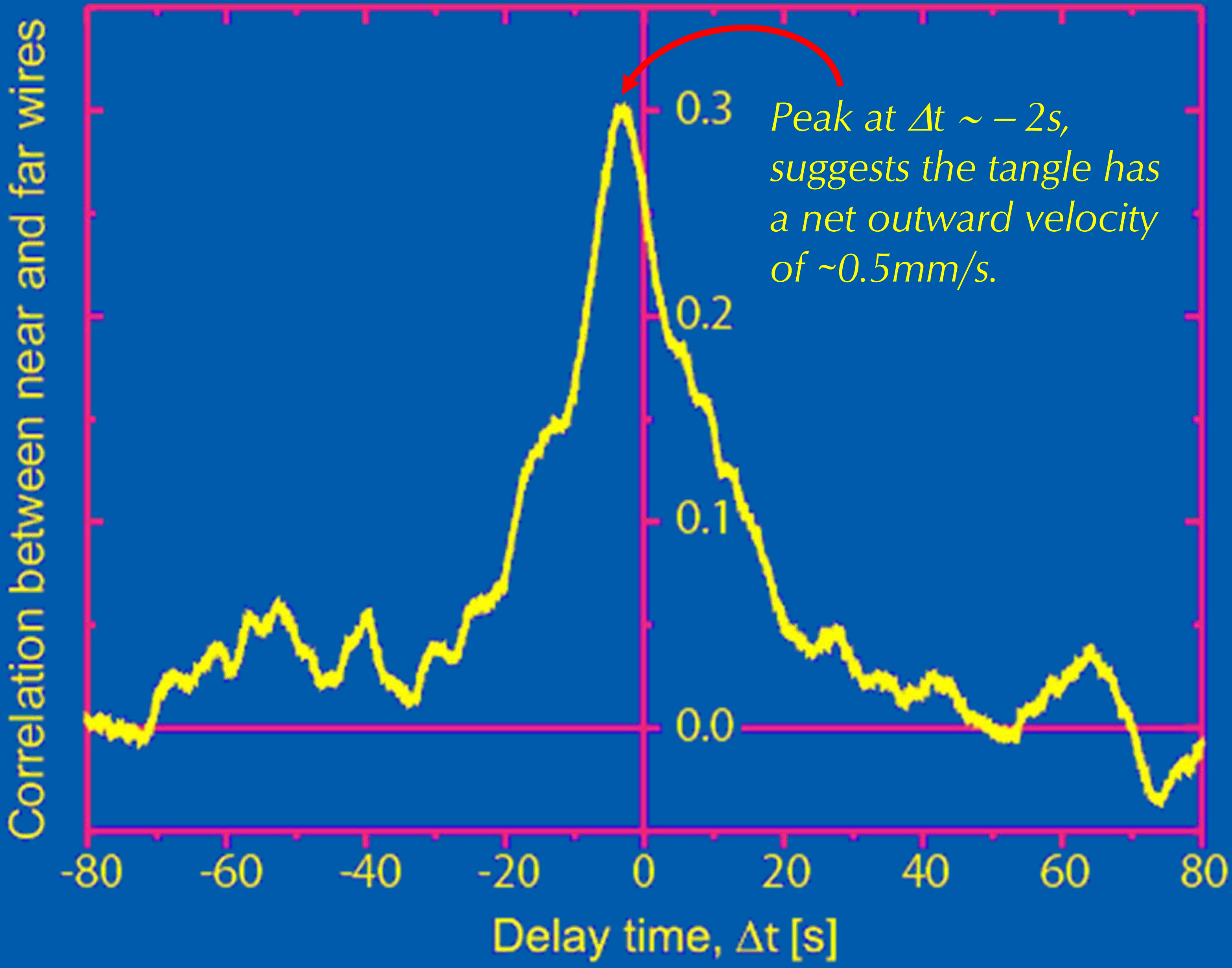
Power spectrum of turbulent fluctuations



Power spectrum of turbulent fluctuations

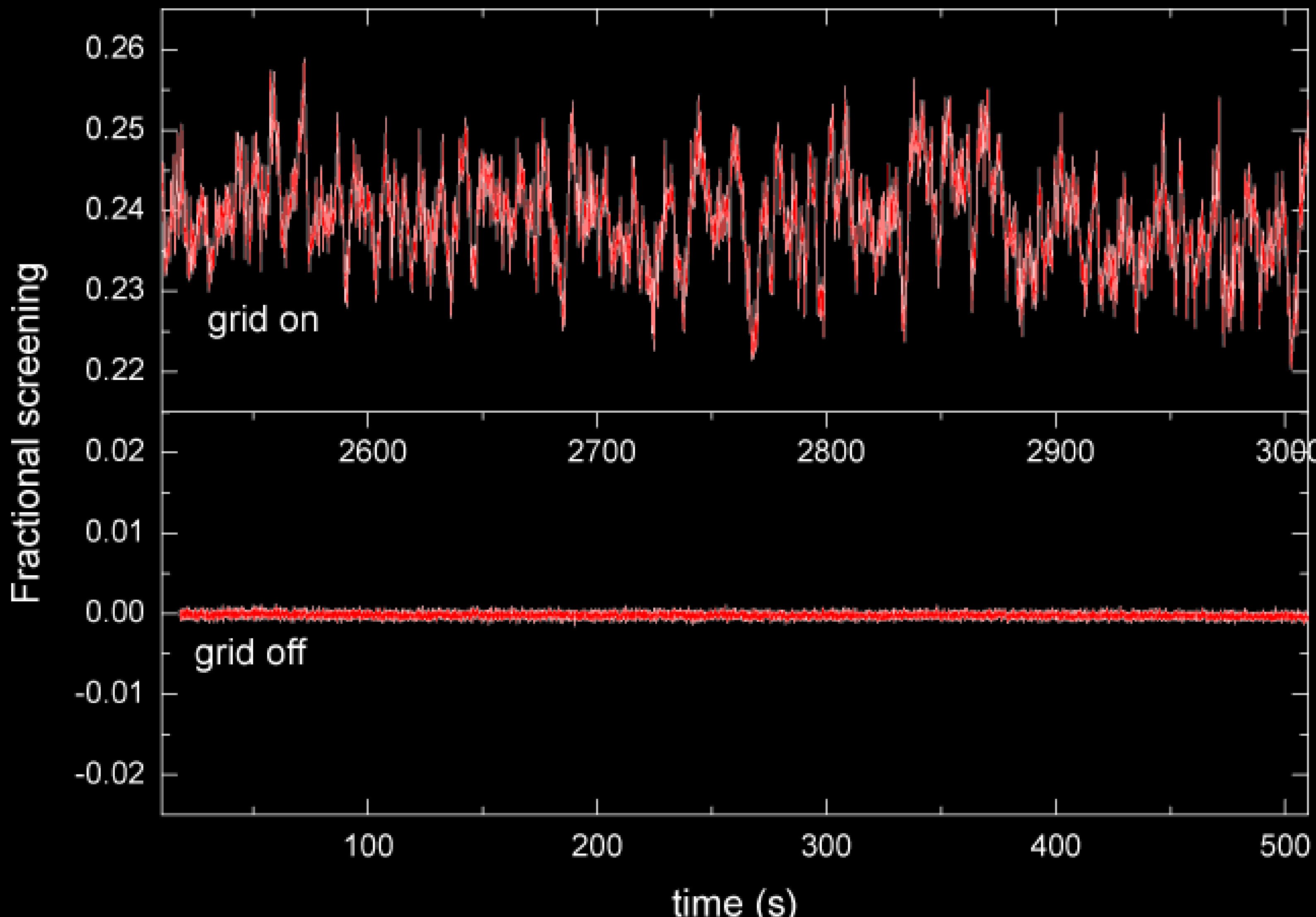


Cross-correlation of turbulent fluctuations

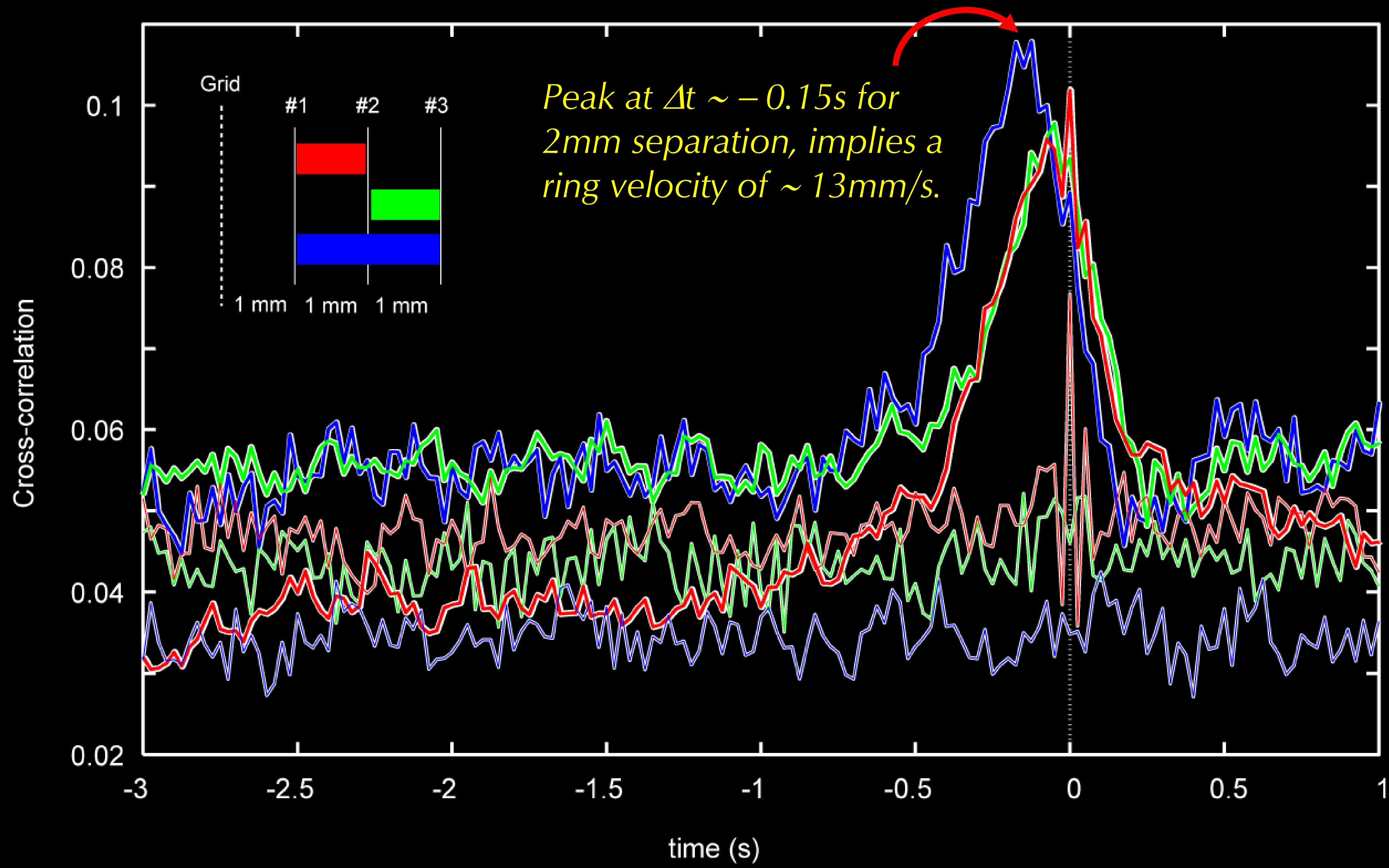


Peak at $\Delta t \sim -2s$, suggests the tangle has a net outward velocity of ~0.5mm/s.

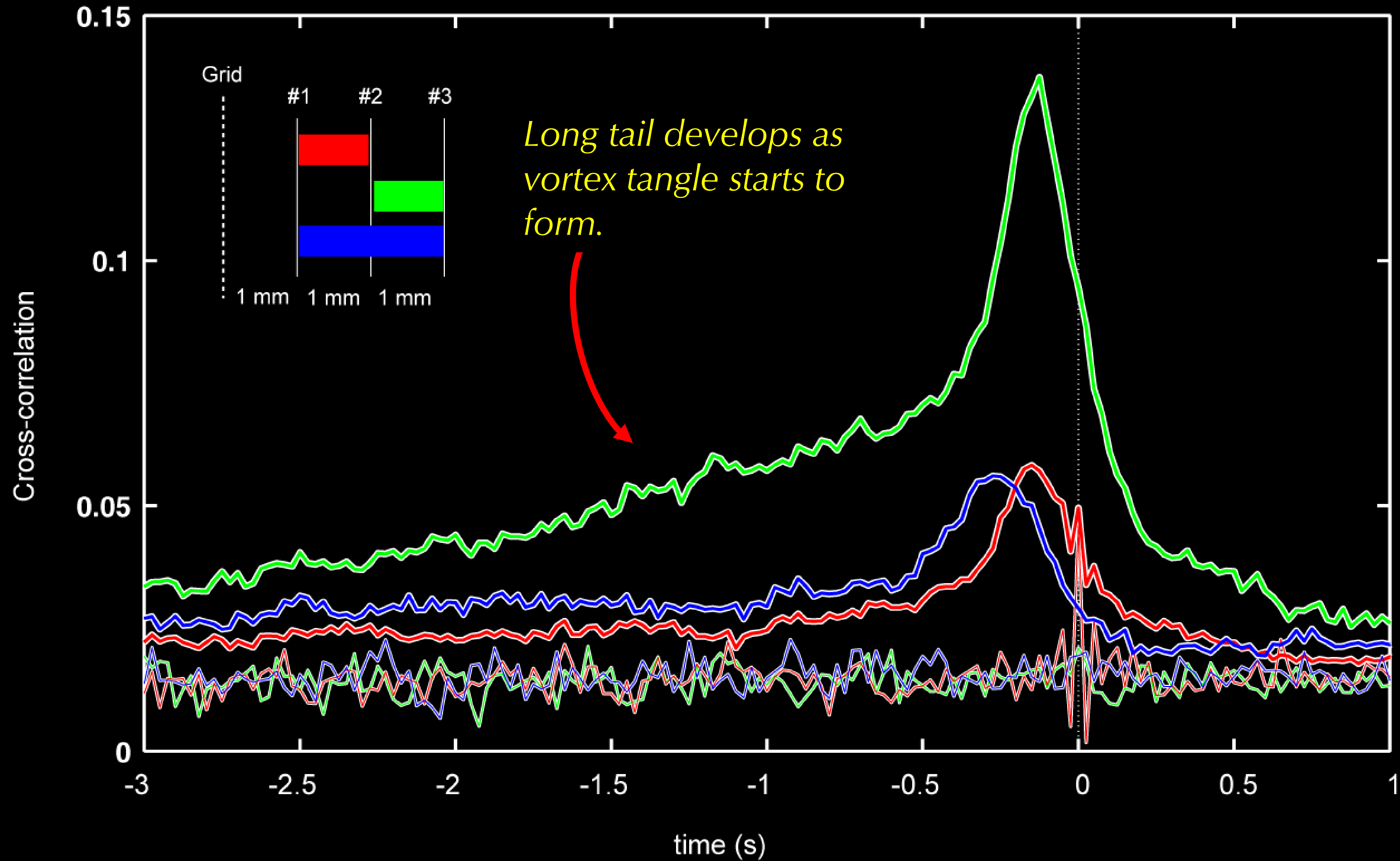
Turbulent fluctuations observed in the most recent experiment



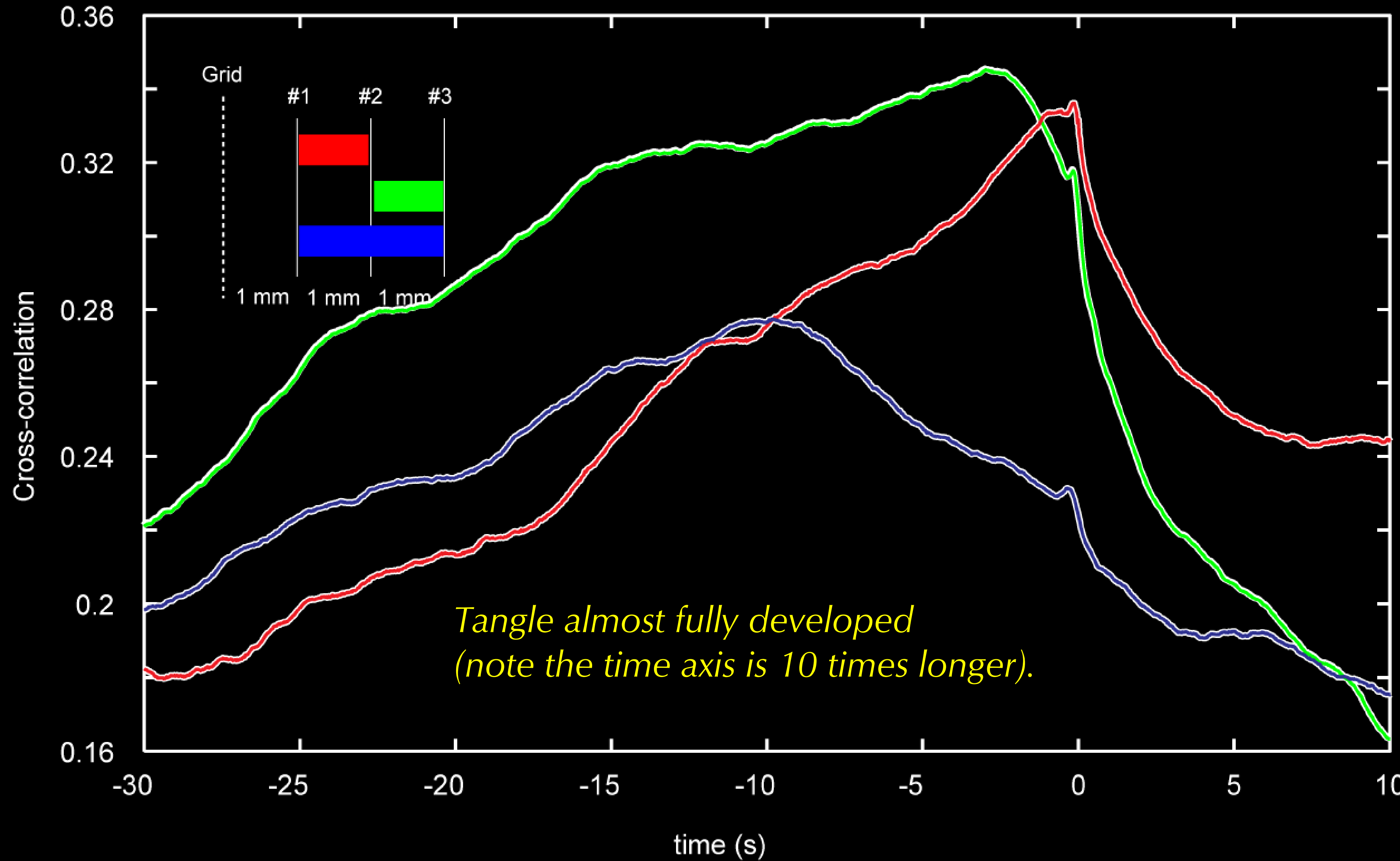
Cross-correlation of vortex ring signal (grid v=1.8mm/s)



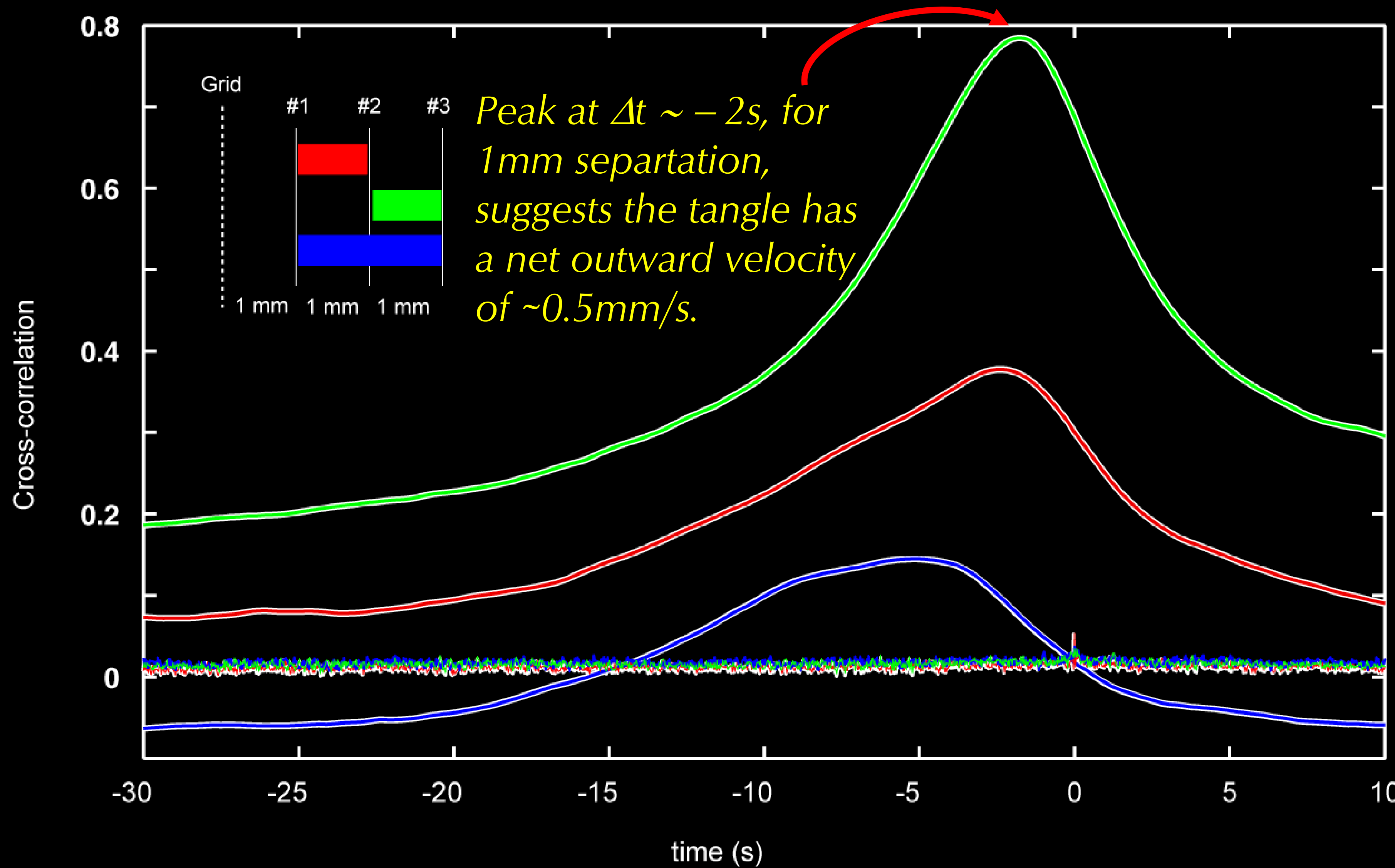
Cross-correlation of vortex signal (grid v=2.6mm/s)



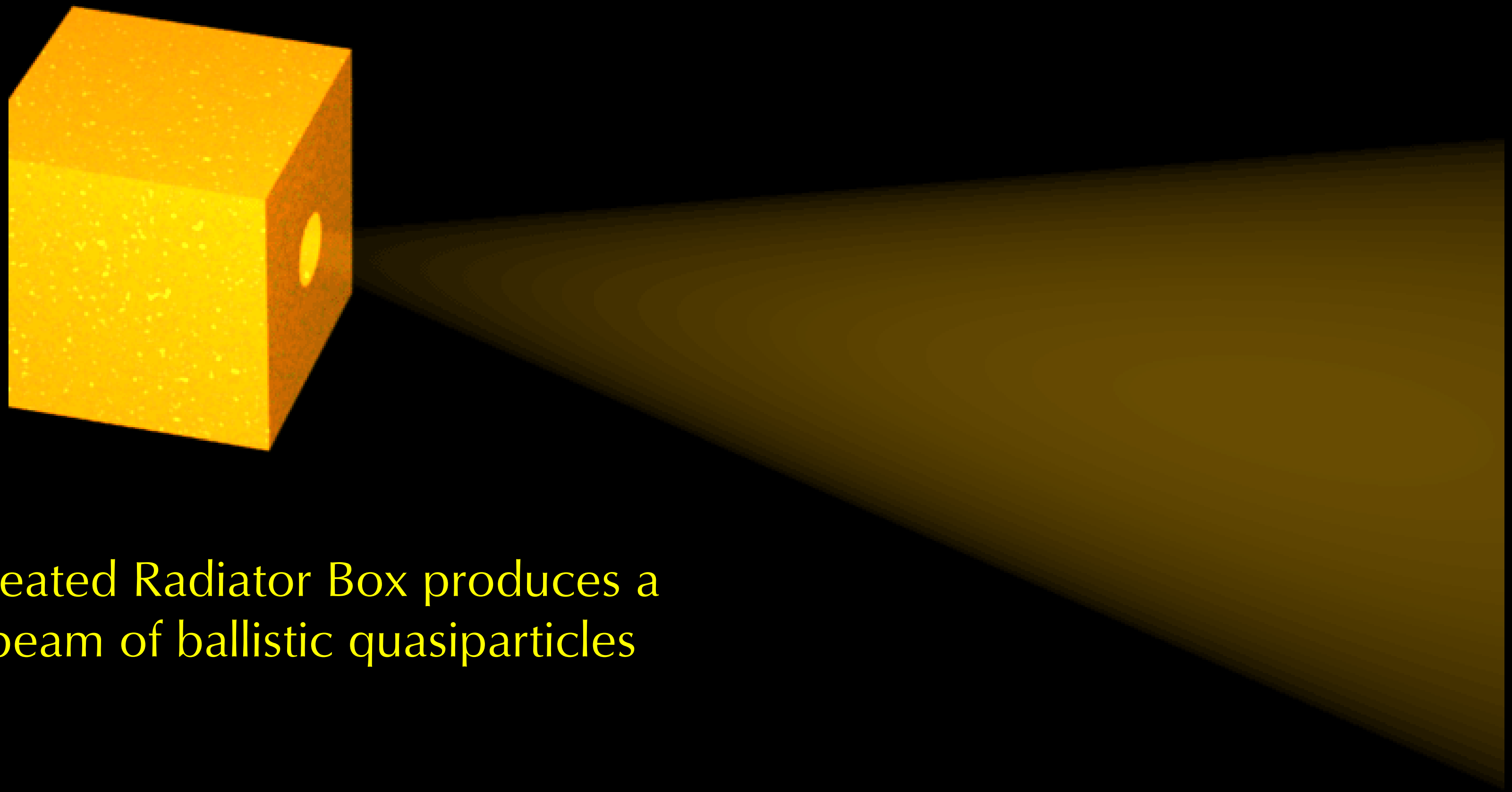
Cross-correlation of vortex signal (grid v=3.3mm/s)



Cross-correlation of vortex tangle signal (grid v=5.7mm/s)

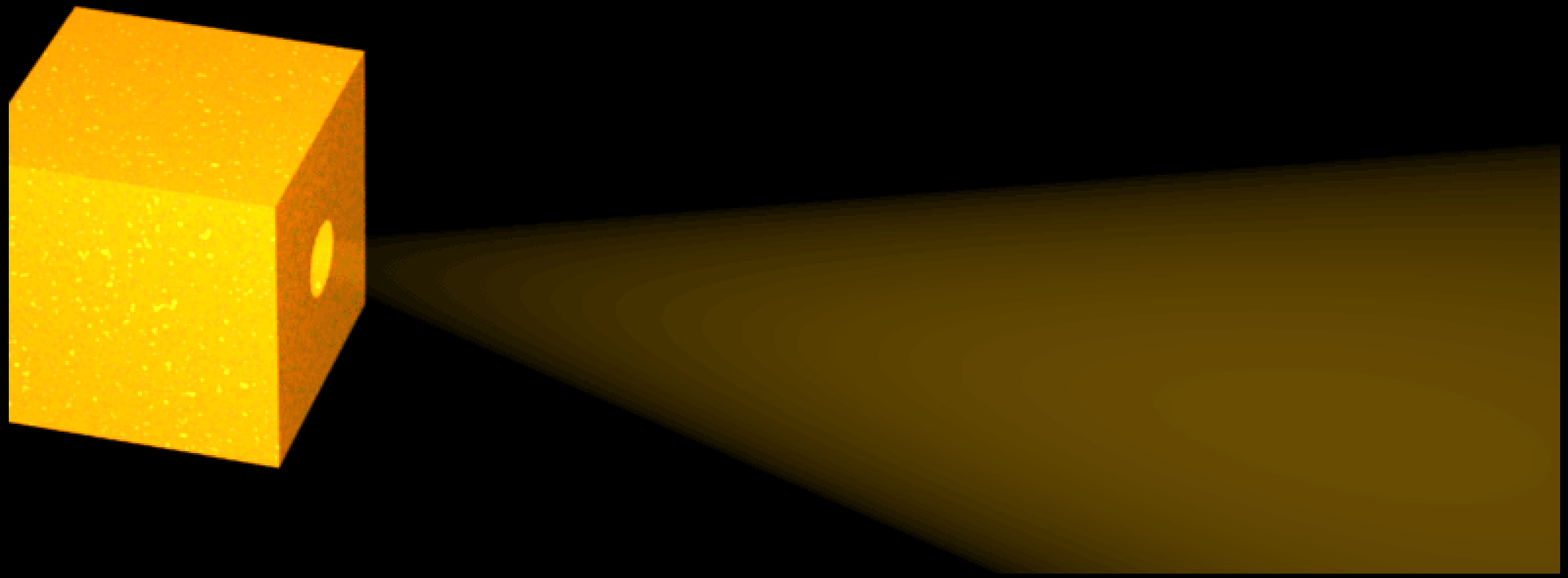


Quasiparticle Imaging



Heated Radiator Box produces a beam of ballistic quasiparticles

Quasiparticle Imaging



Array of detectors (e.g. tuning forks) produce an image of the excitation beam flux.

Quasiparticle Imaging

We can then image the quasiparticle shadows cast by vortices or other superfluid structures.

Can anything like this be done in superconductors ?