Introduction to High-Energy Low-Temperature Physics

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Special thanks to: P. Schiffer, D. D. Osheroff

Basic question: What happens when a very high-energy particle $(\mu^{\pm}, \gamma, (n)...)$ impinges on a very low-temperature liquid (^{3}He...)?

"Cryogenic Track"

Experiments on nucleation of ^{3}He-B (Osheroff '72)

⇓

cosmic-ray hypothesis (AJL '84)

⇓

Stanford experiments ('93), including neutrons

⇓

systematic investigation of nucleation (Stanford '95–)

⇓

alternative theoretical proposals (Bunkov et al. '98)

"Cosmological Track"

Scenario for production of cosmic strings in early Universe (Kibble '76)

⇓

suggestion for simulation in condensed matter systems (Zurek '85)

⇓

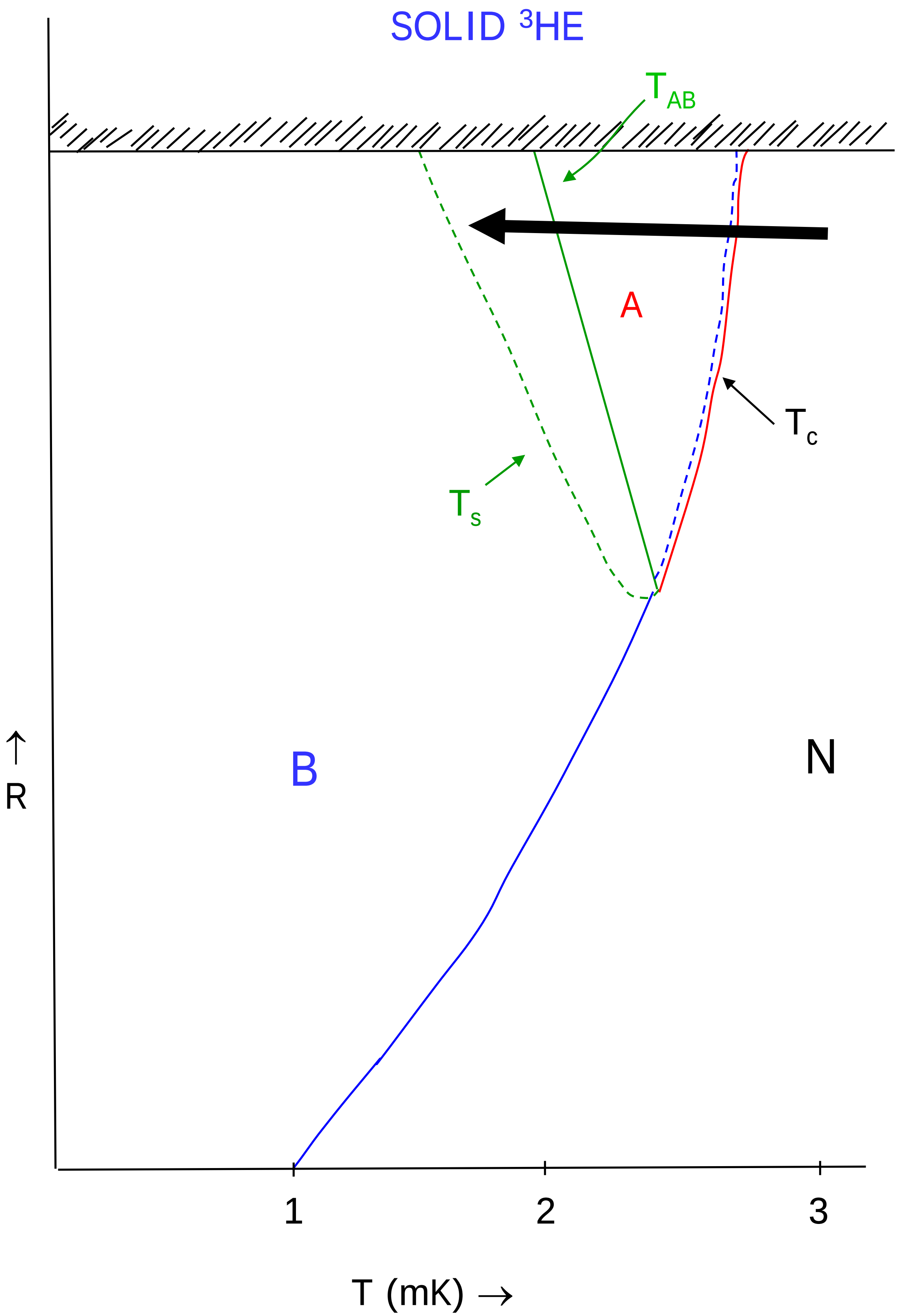
initial tests in sup. ^{4}He (Hendry et al. '94)

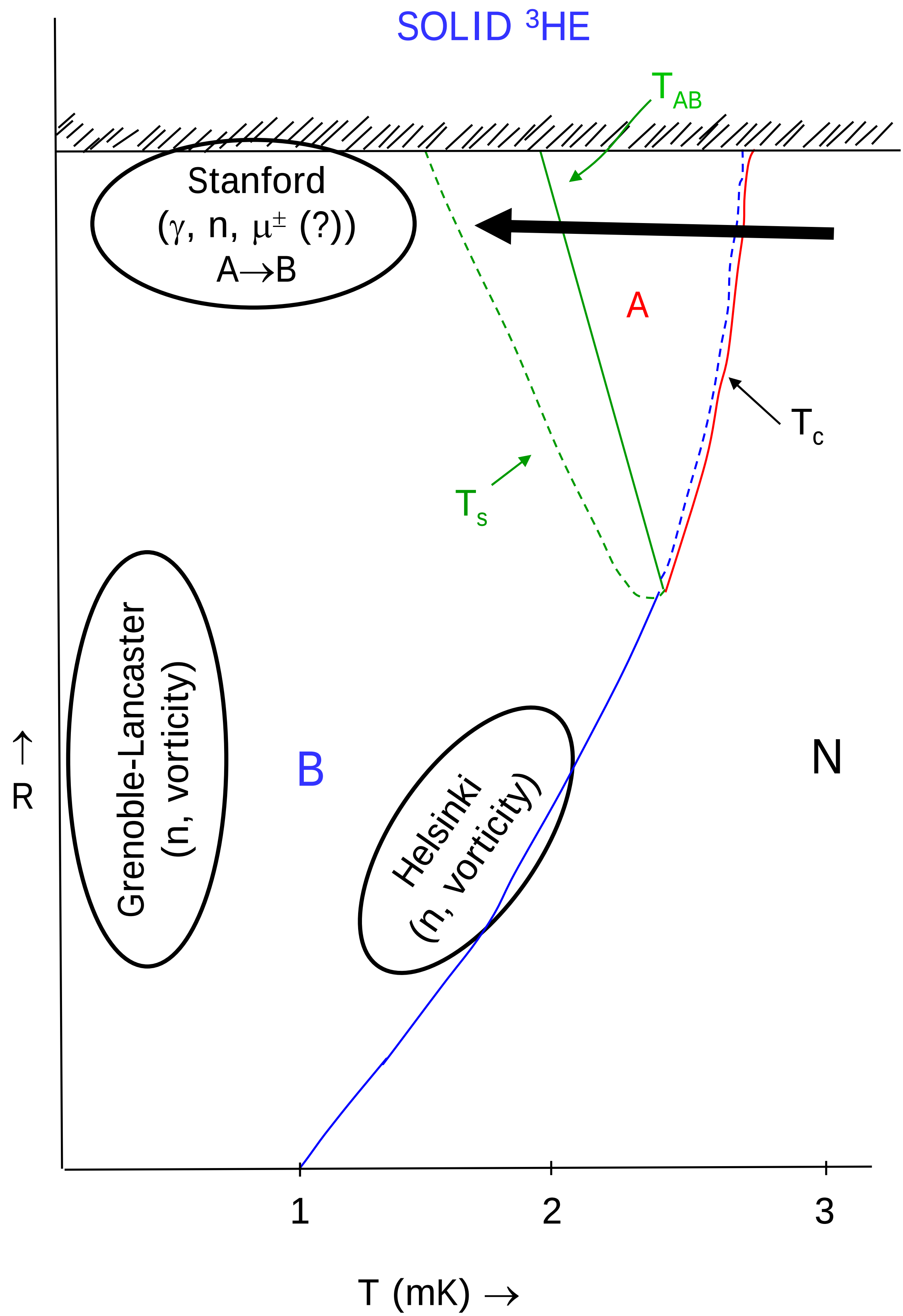
⇓

neutron experiments on ^{3}He (Bäuerle et al. '96, Ruutu et al. '96

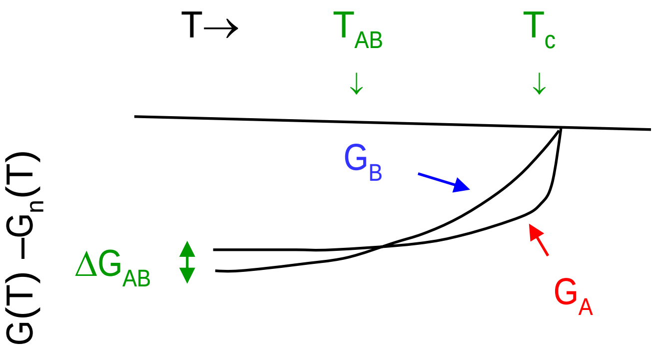
⇓

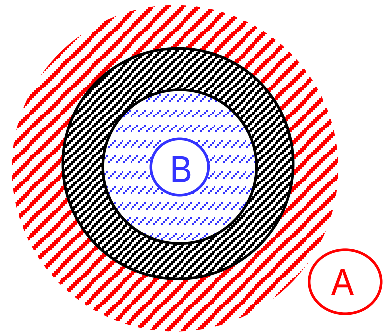
further tests (^{4}He, sup^{rs}...('98–...)


SOLID ³HE
T_AB
A
T_c
T_s
B
N
↑
R
1
2
3
T (mK) →

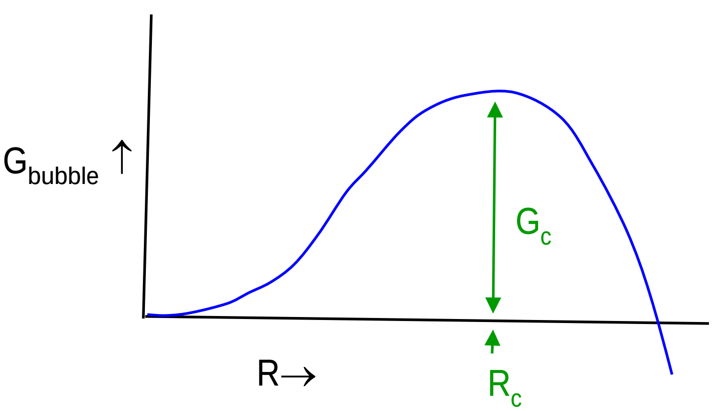

SOLID ³HE
T_AB
Stanford
(γ, n, μ± (?))
A→B
A
T_c
T_s
Grenoble-Lancaster
(n, vorticity)
B
Helsinki
(n, vorticity)
N
↑
R
1
2
3
T (mK) →

Cahn-Hilliard Nucleation





$$G_{bubble} = -\frac{4\pi}{3} R^3 \Delta G_{AB} + 4\pi R^2 \sigma_{AB}$$



$$R_c = 2\sigma_{AB} / \Delta G_{AB}$$

$$G_c = \frac{16\pi}{3} \sigma_{AB}^3 / (\Delta G_{AB})^2$$

Nucleation rate:

$$\omega_0 \exp - G_c / k_B T$$

Problem: We Know Too Much!

$R_c \gtrsim 0 \cdot 5\mu$, $G_c \gtrsim 10^3 K$

Reminders about (our current theoretical understanding of) ^{3}He-A and -B

Both phases are Cooper-paired Fermi superfluids, with
$\ell = S = 1$ (traditional sup^{rs}: $\ell = S = 0,$)
but the nature of the pair ("diatomic-molecule") wave function is different for A and B.

B phase is "BW state", i.e. (spin-orbit-rotated) ^3P_o state. Energy gap Δ isotropic, so few excitations as T $\to$ 0. Susc. $\chi<\chi_n$

A phase is (probably) "ABM state," i.e. only $\uparrow\uparrow$ and $\downarrow\downarrow$ pairs formed, with common "axis of angular momentum" $\hat{\ell}$. Energy gap has nodes, so many excitations as T $\to$ 0. Susc. $\chi=\chi_n$, hence always stable for $H > H_{AB}(T)$ ($H_{AB}(0)$ ~ 5.5 kG)

Possible explanations for B-phase nucleation:

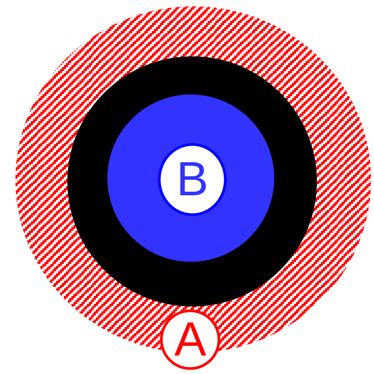
1. Pathological thermodynamics
2. Modification of A phase near surface
3. Corners, cracks, etc.
4. Dirt
5. Quantum tunnelling
6. "Q-balls"
7. Heating followed by re-annealing
8. Pre-existing singularities in A phase.

"CAHN-HILLIARD" MECHANISM FOR ^{3}HE A→B (recap):

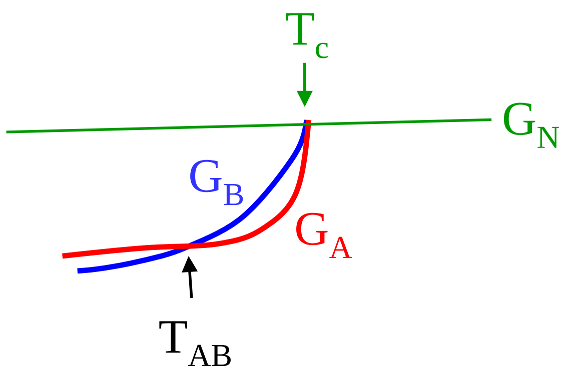
$R_c \gtrsim 0.5\ \mu$

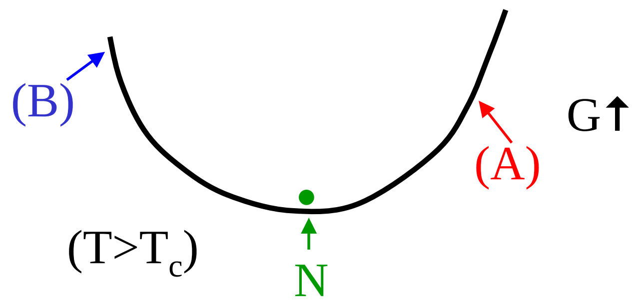
$P \sim \omega_o \exp - \overbrace{G_c/k_B T}^{\sim 10^6}$

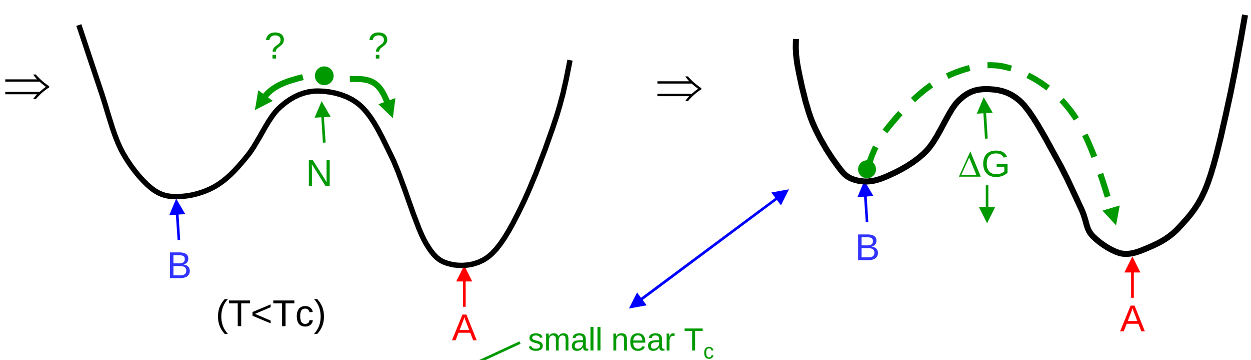
$\ll$ (age of Universe)$^{-1}$!



Passage through 2nd-order Transposition: N → A or N → B ?







$P_{B\to A} \sim \omega_o \exp - \Delta G/kT$

"Figure of merit": $K \equiv P\,\Delta t$

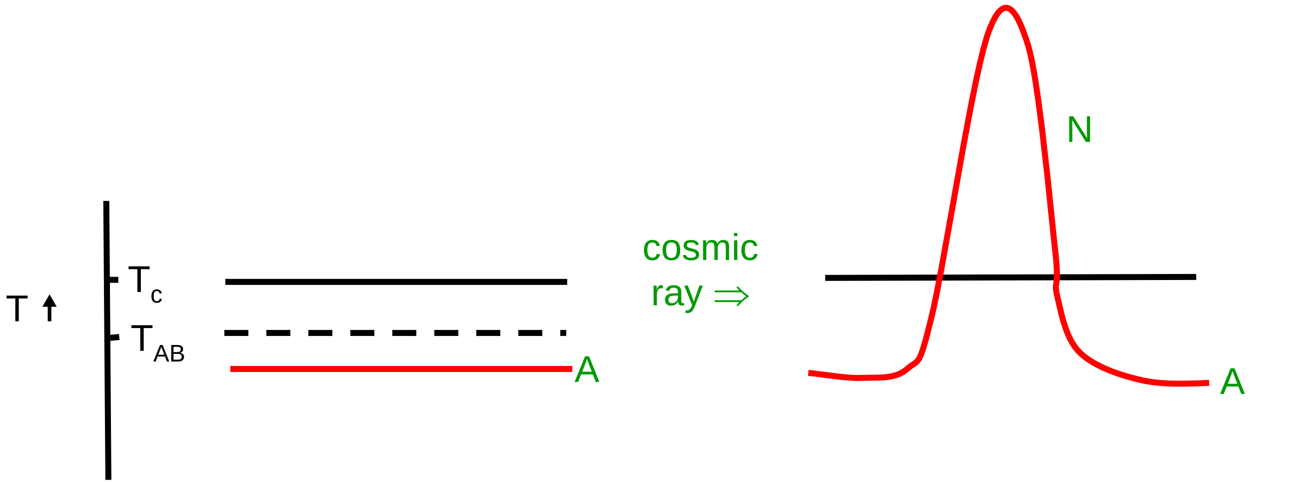
K»1: final state certainly A

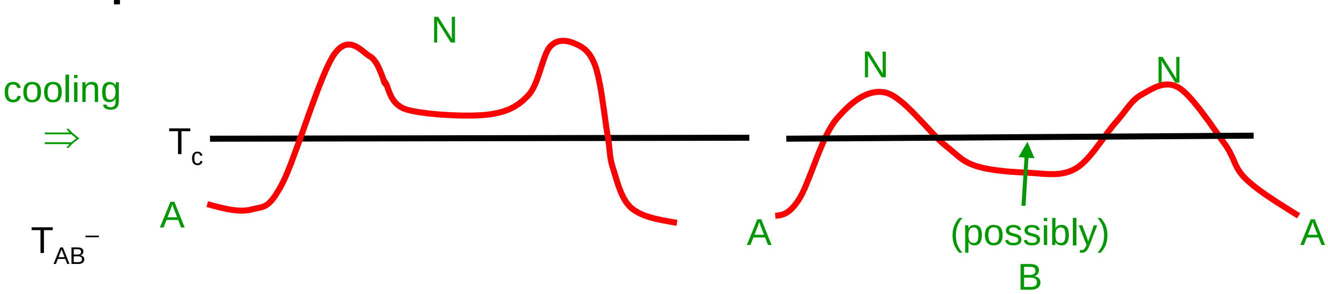
$K \lesssim 1$: final state possibly B

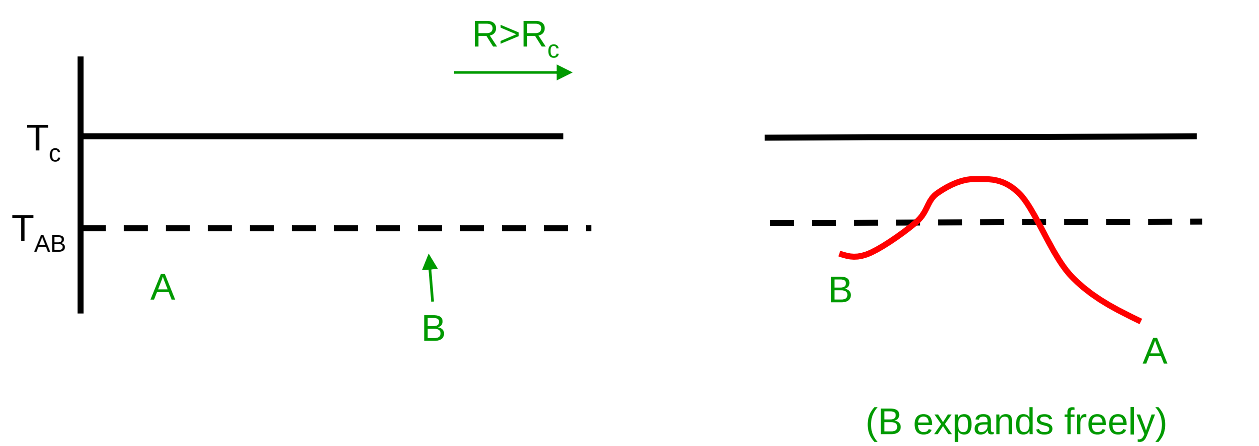
To get $K \lesssim 1$:

- —rapid cooling
- —small volume
- —isolation from outside A phase

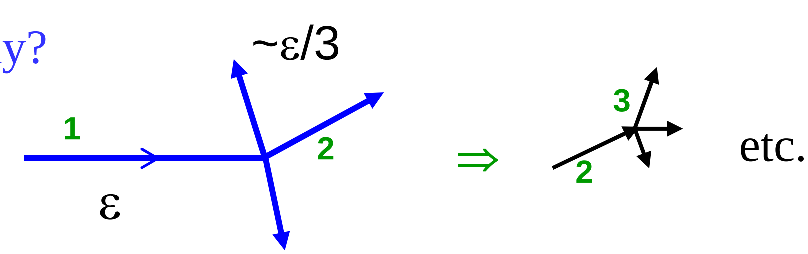
THE "BAKED-ALASKA" SCENARIO





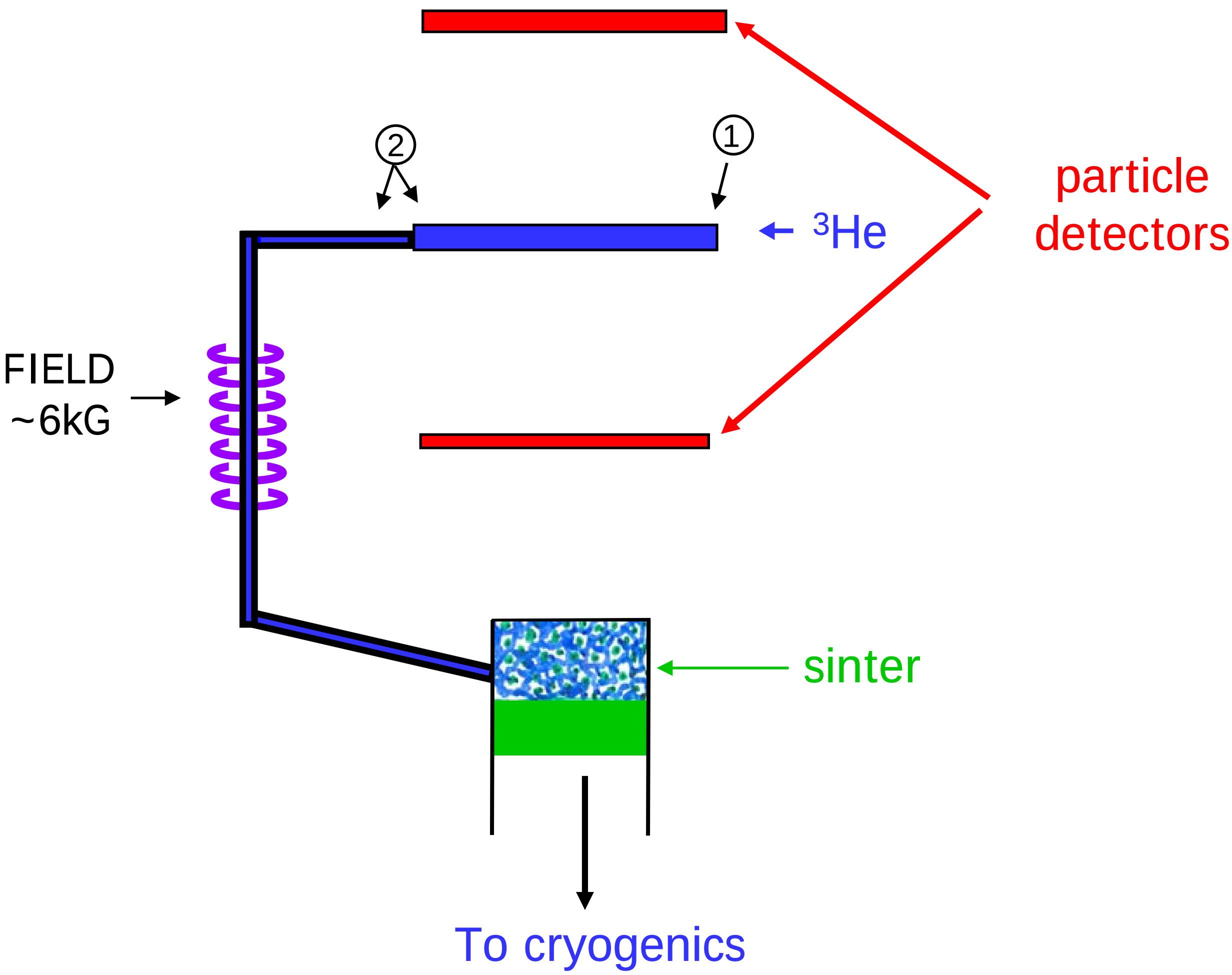


Why?



$$\ell(\varepsilon) \propto \varepsilon^{-2} \Rightarrow \ell_2 \sim 9\ell_1,\ \ell_3 \sim 9\ell_2\ \ldots.$$

LANL EXPERIMENT (SCHEMATIC)

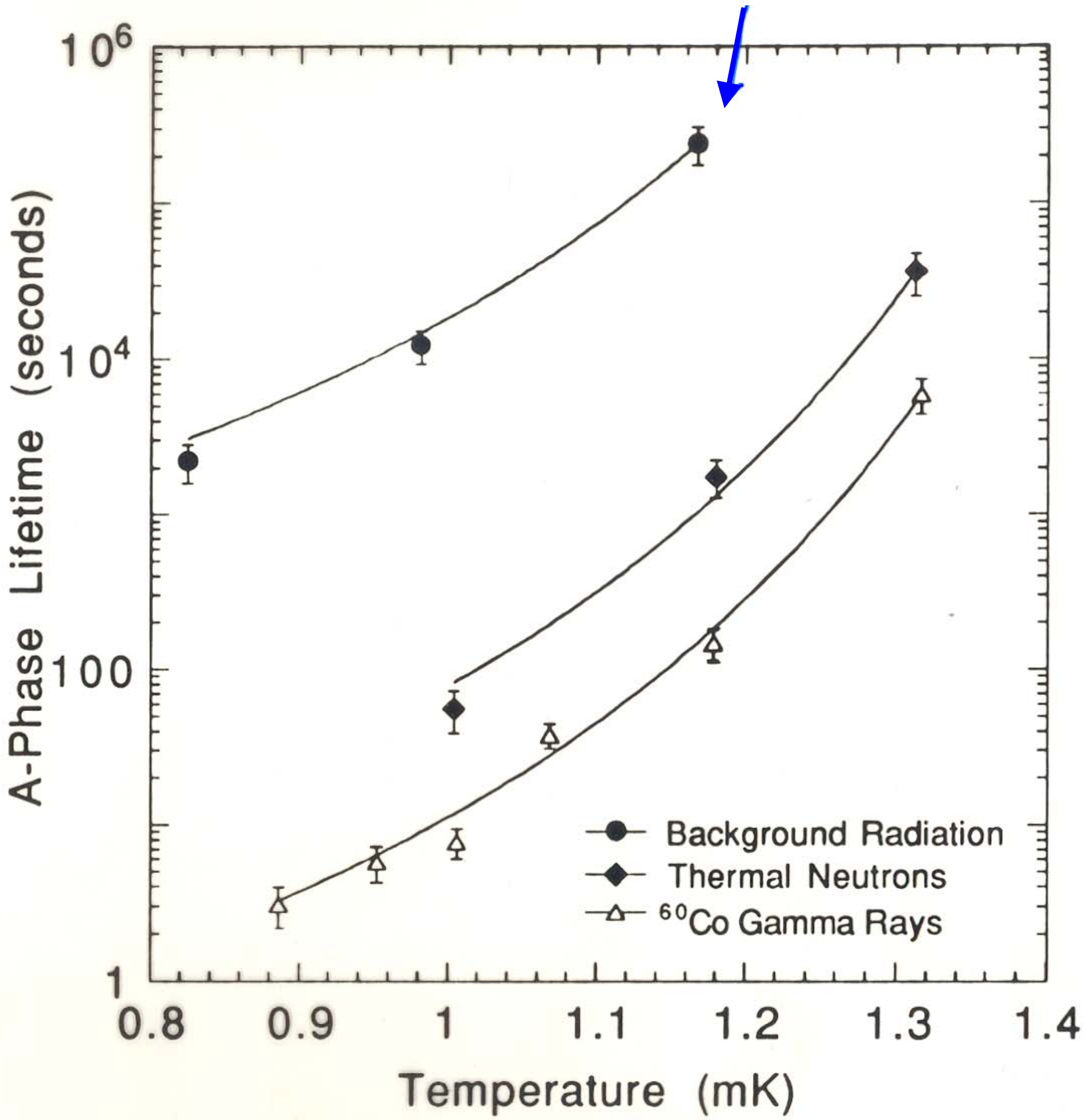


Principal results:

(1) Nucleation primarily in 2 special regions of cell

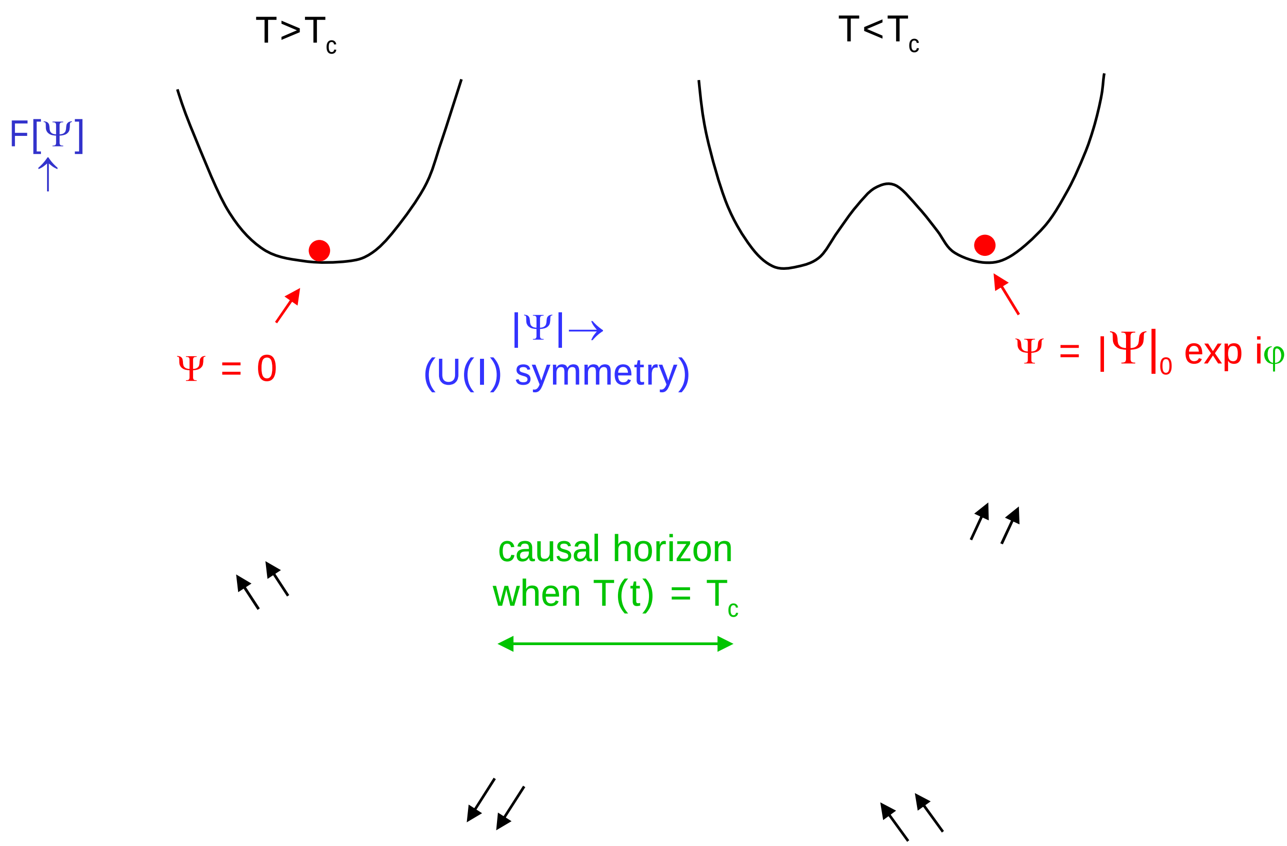
(2) No correlation with cosmic-ray events

Note does not extrapolate to earlier data!



Kibble Mechanism for generation of cosmic strings (etc.) in early Universe

(T. W. Kibble, J. Phys. *A9*, 1387 (1976))



NB: criterion of mutual isolation, similar to $A \rightarrow B$!

Proposal for "simulation" in ^{4}He:
(W. H. Zurek, Nature *317*, 505 (1985))

initial tests (Lancaster): uniform (pressure) quench

1996 experiments: (Helsinki, Lancaster-Grenoble):
strongly nonuniform quench (neutrons)

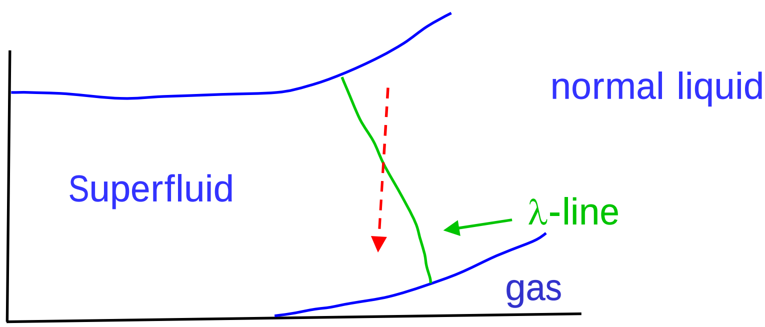
cf. also: tests on superconductors (Haifa)
tests on liquid xtals

Experiments on Nucleation of Vorticity in Superfluid ^{4}He by "Quench"

Proposal: W. H. Zurek, Nature *317*, 505 (1985)

^{4}He:

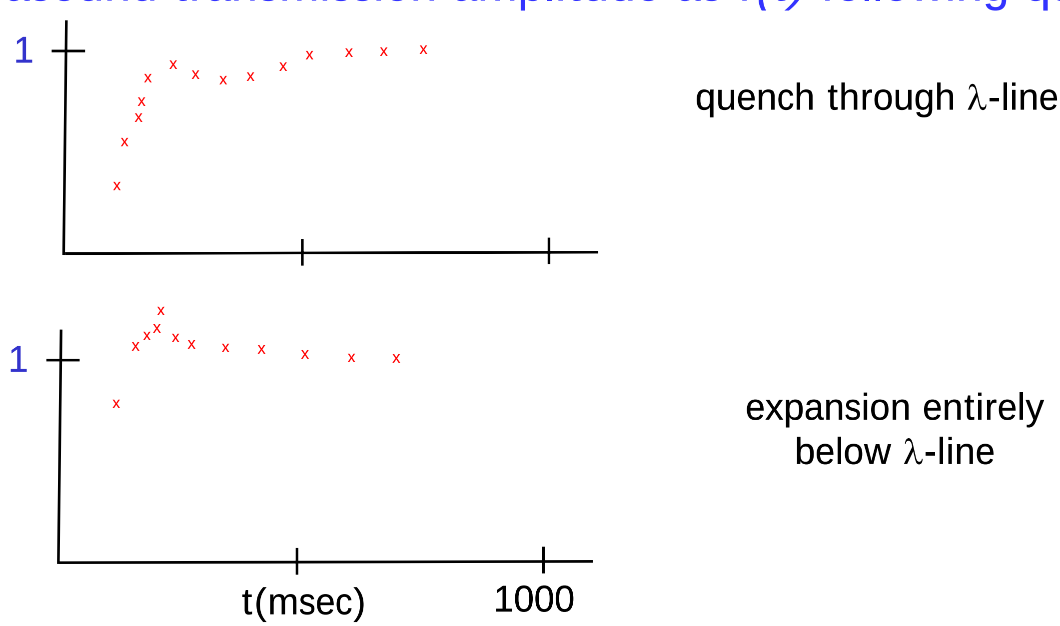
P. C. Hendry et al., Nature *368*, 315 (1994)



pressure quench

raw data:

ultrasound transmission amplitude as *f(t)* following quench.



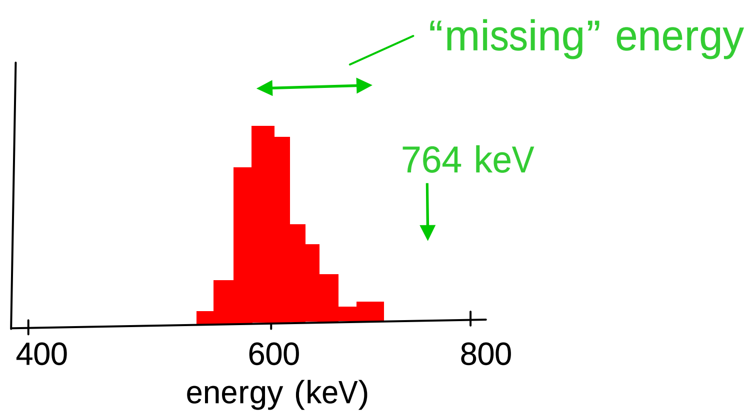
Neutron Experiments on ^{3}He-B

A. C. Bäuerle et al. (Lancaster-Grenoble collaboration)
Nature *382*, 332 (1996)

Cryostat stationary, Cu walls

Initial temperature (down to) ~160 μK, i.e. $\sim 0 \cdot 1\ T_c$ (necessary because of vibrating-wire determination of heat input)

Raw data: energy deposited in form of heating of bulk liquid.



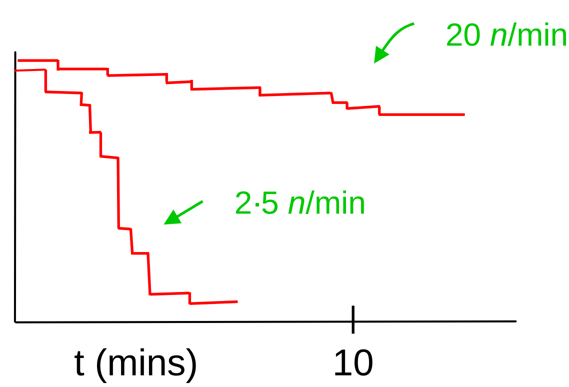
B. V. Ruutu et al., (Helsinki-Moscow . . . collaboration)
Nature *382*, 334 (1996)

Cryostat (or liquid or both) rotating, so at wall $v_{sn} = \omega R$. relative sup. normal velocity

Initial temperature $0{\cdot}9$–$0{\cdot}97\ T_c$

Raw data:

NMR observation as *f(t)*



Interpretation of Bäuerle et al.:

As “fireball” cools through T_c, conditions are similar to those of early Universe, i.e. different regions causally disconnected, and analog of Kibble mechanism occurs, resulting in production of vortex rings, which then expand, absorbing the “missing fraction” of energy. Overall magnitude and P-dependence of estimated vorticity from Zurek calculation agrees qualitatively with experiment. (nb: hydrodynamic scenario).

Interpretation of Ruutu et al.:

Similarly, vortex rings produced. Condition for ring to expand (and eventually fill whole volume) is [Langer and Fisher 1967]

$$r > r_o(\upsilon_s) = \frac{\hbar}{4m_3\upsilon_s}\ln(r_c/\xi_o)$$

(υ_s = relative superfluid – normal velocity)

The number of rings produced with radius $>r_0(\upsilon_s)$ in a fireball of radius R_b should be of general form

$$N(\upsilon_s) = const.\left[\left(\frac{2R_b(P,T)}{\alpha r_0(\upsilon_s)}\right)^3 - 1\right]$$

Hence:

$$N(\upsilon_s) = const.\left[\left(\frac{\upsilon_s}{\upsilon_c(P,T)}\right)^3 - 1\right]$$

Agreement with experiment impressive!

Everything in beautiful agreement with KZ scenario....

↑ : Dodd et al., PRL (*81*, 3703 (Oct. '98):
repeat of original experiment on ^{4}He with added precautions

NO VORTICITY PRODUCED AT ALL!

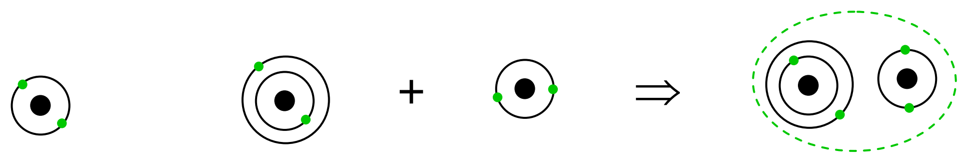
	^{4}He (pressure quench)	^{3}He (neutron irradiation)	Early Universe
speed of quenching through critical region	slow	fast	fast (?)
quenching uniform in space?	yes	no	yes
pre-existing rotation?	no	{ no (L-G) yes (H-M)	no
ions produced by quenching?	no	yes	no
neutral excimers?	no	yes	no

Explanation based on speed of quenching through critical region: Karra and Rivers, PRL *81*, 3707 (1998).

Bäuerle et al. (G-L) experiment:

calorimetric, ~5–10% of neutron energy missing: "where else could it have gone (but into vorticity)?"

Answer: Into production of $A^3\Sigma_u^+$ molecular excimers!



Characteristics of $A^3\Sigma_u^+$ excimer:

Excitation energy ~18eV

Binding energy ~1 eV

Lifetime in bulk $\gtrsim$ 15 secs (!)

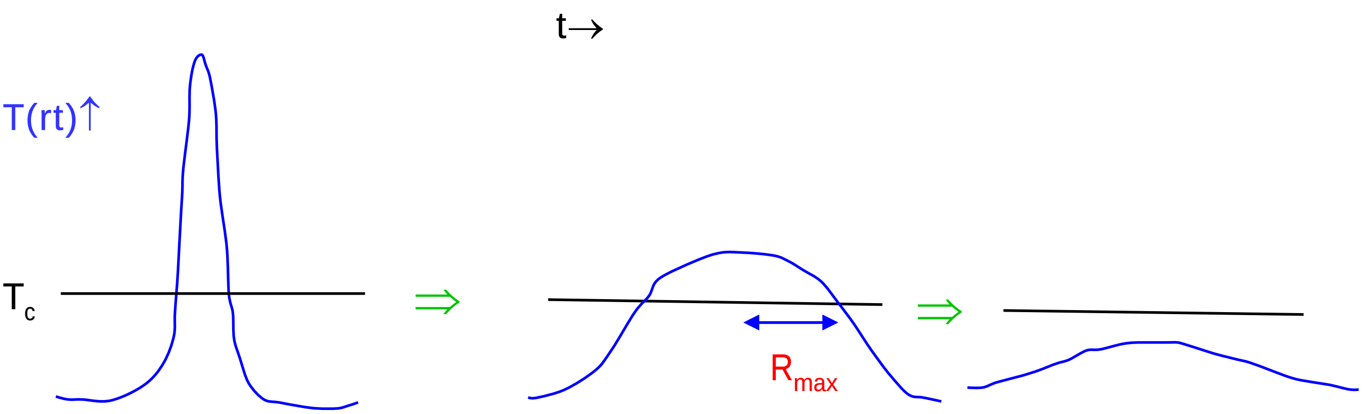
Recombination probably primarily at walls

Production by high-energy charged particles: (^{4}He) extremely copious!

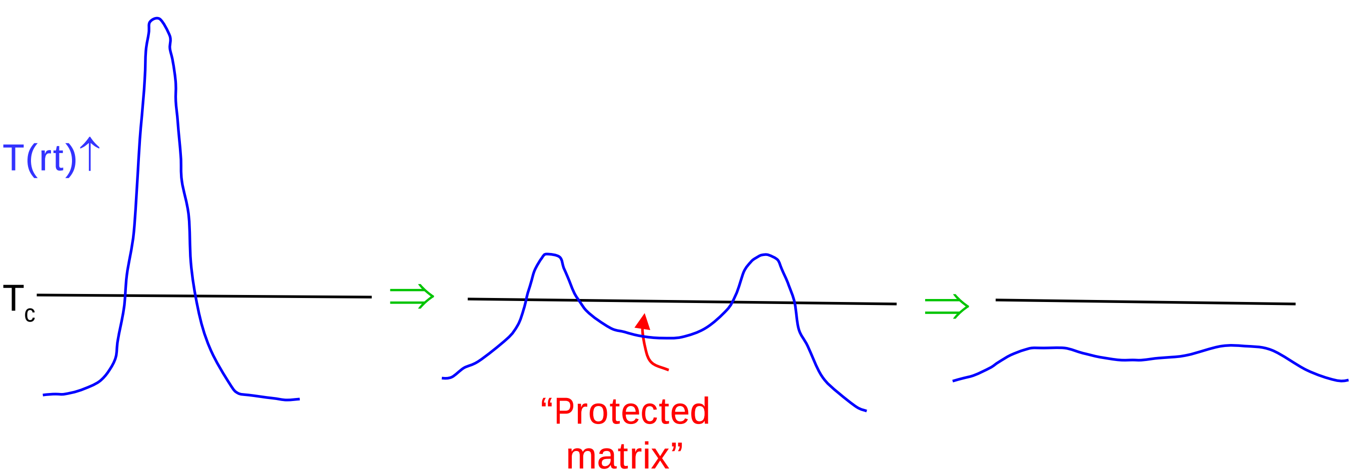
Estimated energy sunk in excimer formation under conditions of G-L experiment: ~45 keV, i.e. ~6–15%!

Two Scenarios for Later Stages of Cooling of “Hot Spot” ($t \gtrsim 10^{-8}$ secs):

A. Hydrodynamic (Zurek, Kibble, Volovik):



B. “Baked-Alaska” (AJL)



How is “protection” achieved in hydrodynamic scenario?

see Volovik and Kibble, JETF

If $R_{max} \gg \ell$, hydrodynamic scenario almost certainly right.

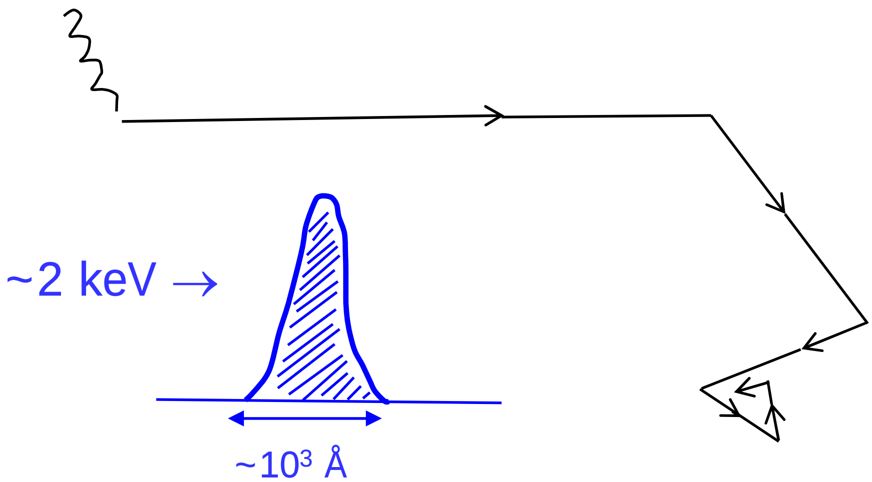
If $R_{max} \ll \ell$, baked-Alaska scenario somewhat plausible.

How Localized is the Energy Deposition?

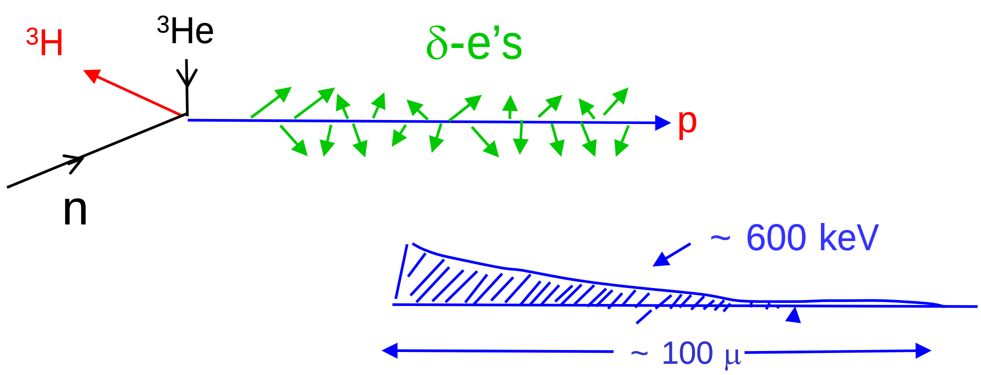
A. γ-rays, cosmic ray $\mu^{\pm}$:

initially, single fast electron (E~1-2 MeV) produced:

$\ell(E) \propto E^{-2}$

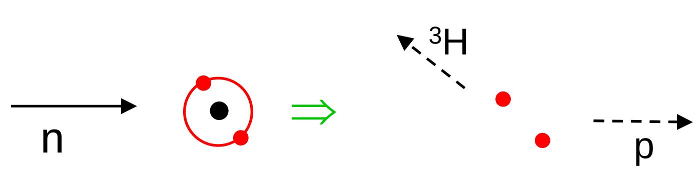


B. Neutrons:



Problem: baked-Alaska requires δ-e- ex. $\gtrsim$ 2 keV, but this is forbidden, in neutron case, by kinematics!

?? "Orphaned" e^-'s?



Conclusions

1. High-energy particles can nucleate, in superfluid ^{3}He, both the A→B transition and the appearance of vorticity.

2. A→B transition: a scenario based on the “baked-Alaska” hypothesis gives semiquantitative agreement with the (low-T) Stanford data, but fails for the higher-T data (for which originally proposed!)

3. Nucleation of vorticity: the KZ scenario gives semiquantitative agreement with the H-M experiments (and possibly with the L-G experiments) in ^{3}He, but apparently fails for ^{4}He (for which originally proposed!)

4. Two crucial questions:

   (a) is strongly local heating necessary for nucleation of vorticity and/or A-B transition?

   (b) (irrespective of (a)): when heating is strongly local, is correct scenario baked-Alaska, hydrodynamic or something in between?