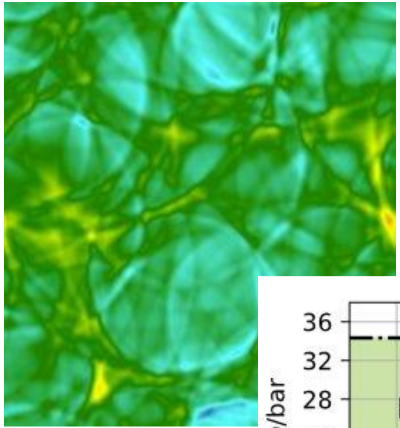
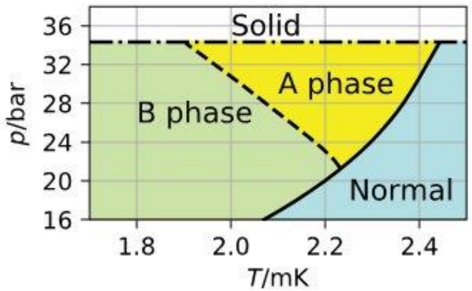
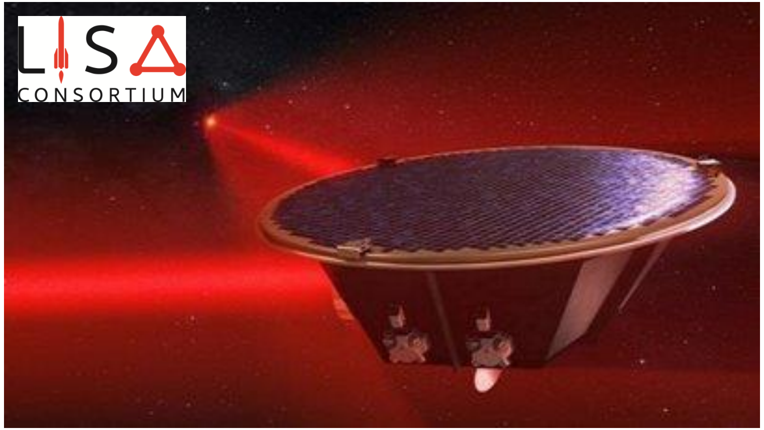




Cosmology and the AB phase transition in superfluid ^{3}He

QUEST DMC

Samuli Autti



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EMP European Microkelvin Platform

Lancaster University

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

- WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter
- **WP2: Phase transitions in extreme matter**

QUEST DMC

Core Team

EXPERIMENTAL	
Dr. Samuli Autti	Robert Smith
Dr. Andrew Casey	Dr. Michael Thompson
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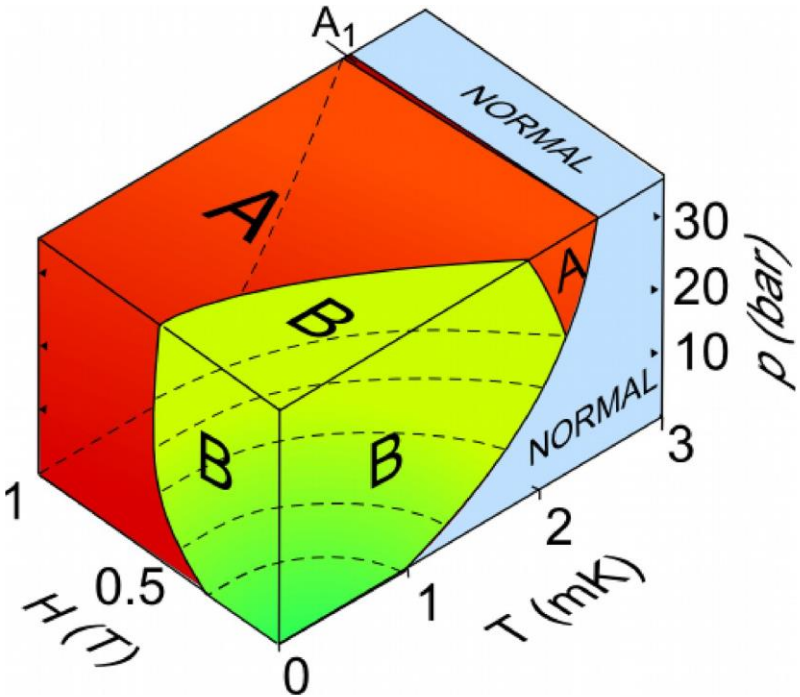
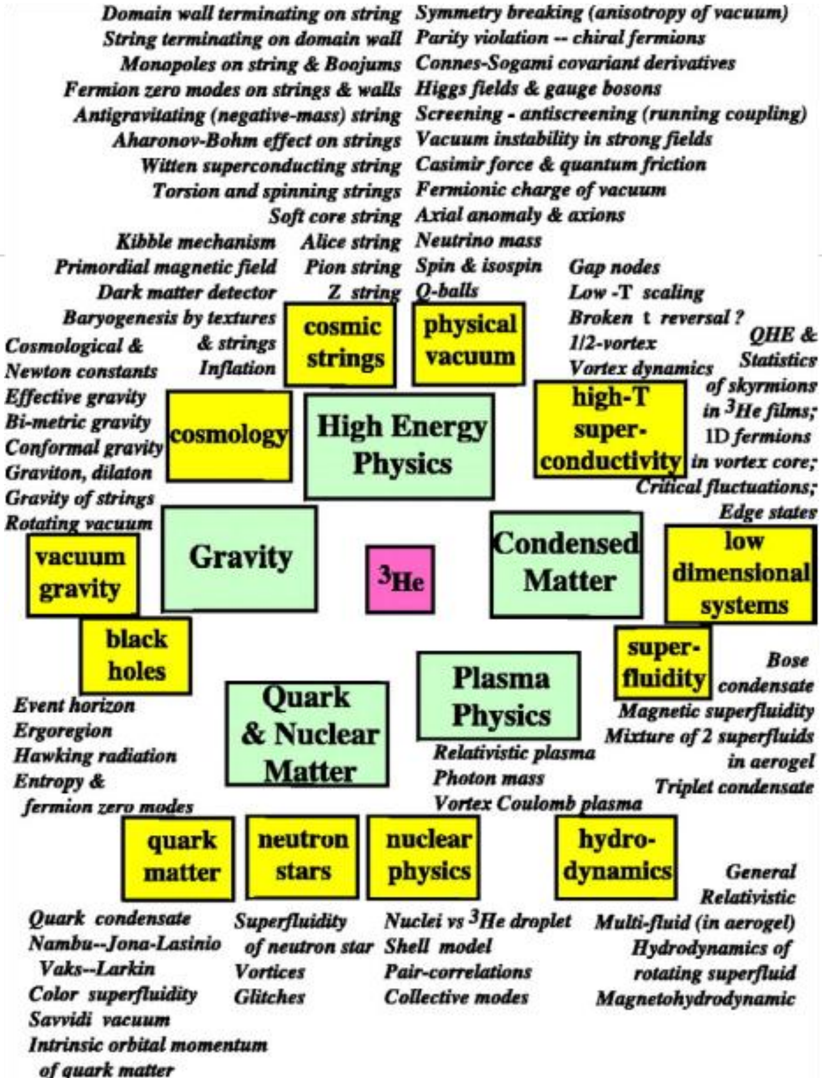
Prof. Richard Haley	Dr. Dmitry Zmeev
Dr. Petri Heikkinen	Dr. Vladislav Zavyalov
Dr. Sergey Kafanov	Tineke Salmon
	Luke Whitehead
Dr. Elizabeth Leason	**THEORY**
Dr. Lev Levitin	Prof. Mark Hindmarsh (Leading WP2)
Prof. Jocelyn Monroe (Leading WP1)	Prof. Stephan Huber
Dr. Jonathan Prance	Prof. John March-Russell
Dr. Xavier Rojas	Dr. Stephen West
Prof. John Saunders	Dr. Quang Zhang

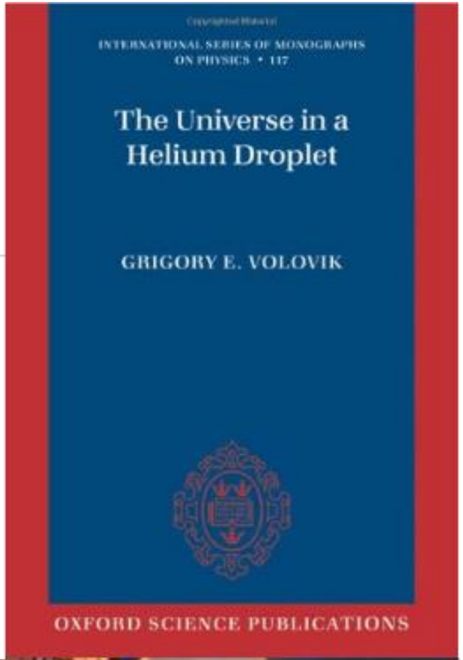
Superfluid ^3He

1. Fermions, so no BEC
   --> Cooper pairs as in superconductors?
1. Hard core repulsion
2. P-wave pairing, S=1 and L=1
3. Order parameter describing S, L, Δ, φ

--> First-order phase transition




Domain wall terminating on string
String terminating on domain wall
Monopoles on string & Boojums
Fermion zero modes on strings & walls
Antigravitating (negative-mass) string
Aharonov-Bohm effect on strings
Witten superconducting string
Torsion and spinning strings
Soft core string
Alice string
Pion string
Z string
Symmetry breaking (anisotropy of vacuum)
Parity violation -- chiral fermions
Connes-Sogami covariant derivatives
Higgs fields & gauge bosons
Screening - antiscreening (running coupling)
Vacuum instability in strong fields
Casimir force & quantum friction
Fermionic charge of vacuum
Axial anomaly & axions
Neutrino mass
Spin & isospin
Q-balls
Kibble mechanism
Primordial magnetic field
Dark matter detector
Baryogenesis by textures
& strings
Inflation
Cosmological &
Newton constants
Effective gravity
Bi-metric gravity
Conformal gravity
Graviton, dilaton
Gravity of strings
Rotating vacuum
Gap nodes
Low -T scaling
Broken t reversal ?
1/2-vortex
Vortex dynamics
QHE &
Statistics
of skyrmions
in 3He films;
1D fermions
in vortex core;
Critical fluctuations;
Edge states
cosmic strings
physical vacuum
cosmology
High Energy Physics
high-T super-conductivity
Gravity
3He
Condensed Matter
low dimensional systems
vacuum gravity
black holes
super-fluidity
Plasma Physics
Quark & Nuclear Matter
Bose
condensate
Magnetic superfluidity
Mixture of 2 superfluids
in aerogel
Triplet condensate
Event horizon
Ergoregion
Hawking radiation
Entropy &
fermion zero modes
Relativistic plasma
Photon mass
Vortex Coulomb plasma
quark matter
neutron stars
nuclear physics
hydro-dynamics
General
Relativistic
Multi-fluid (in aerogel)
Hydrodynamics of
rotating superfluid
Magnetohydrodynamic
Quark condensate
Nambu--Jona-Lasinio
Vaks--Larkin
Color superfluidity
Savvidi vacuum
Intrinsic orbital momentum
of quark matter
Superfluidity
of neutron star
Vortices
Glitches
Nuclei vs 3He droplet
Shell model
Pair-correlations
Collective modes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The Universe in a Helium Droplet
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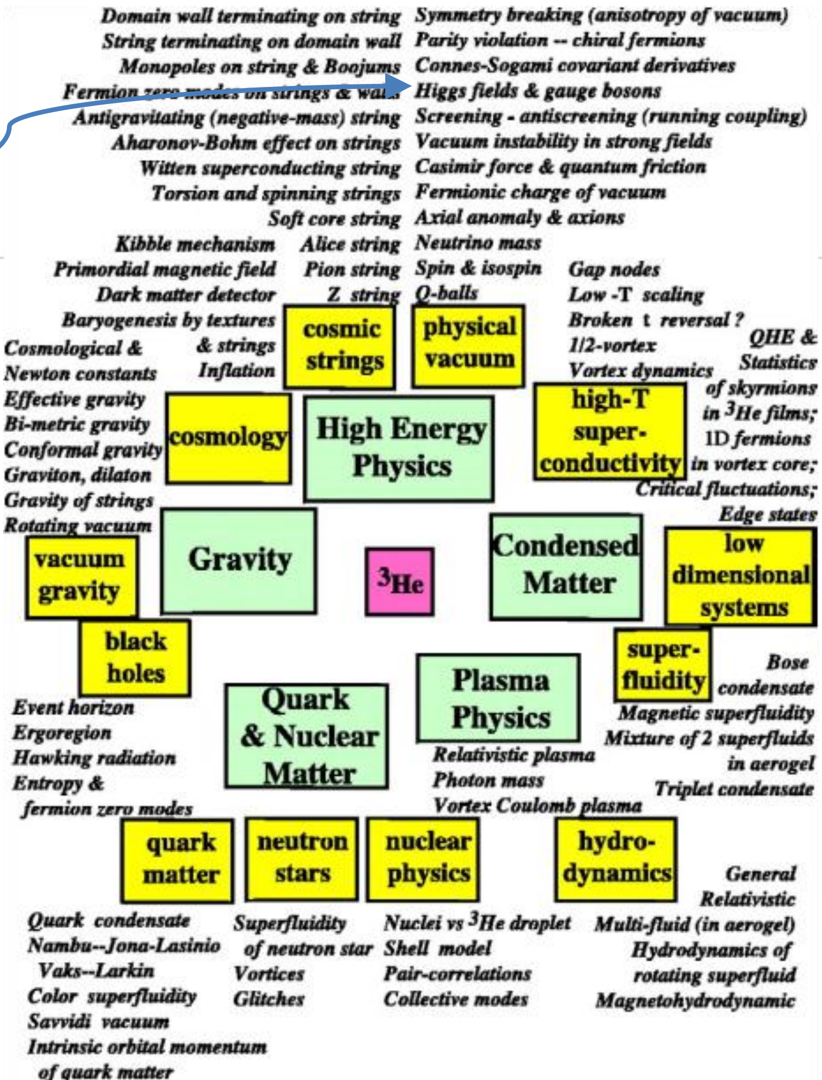
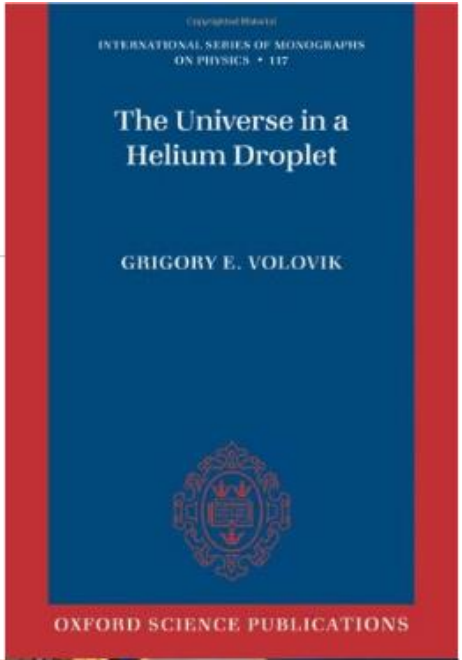
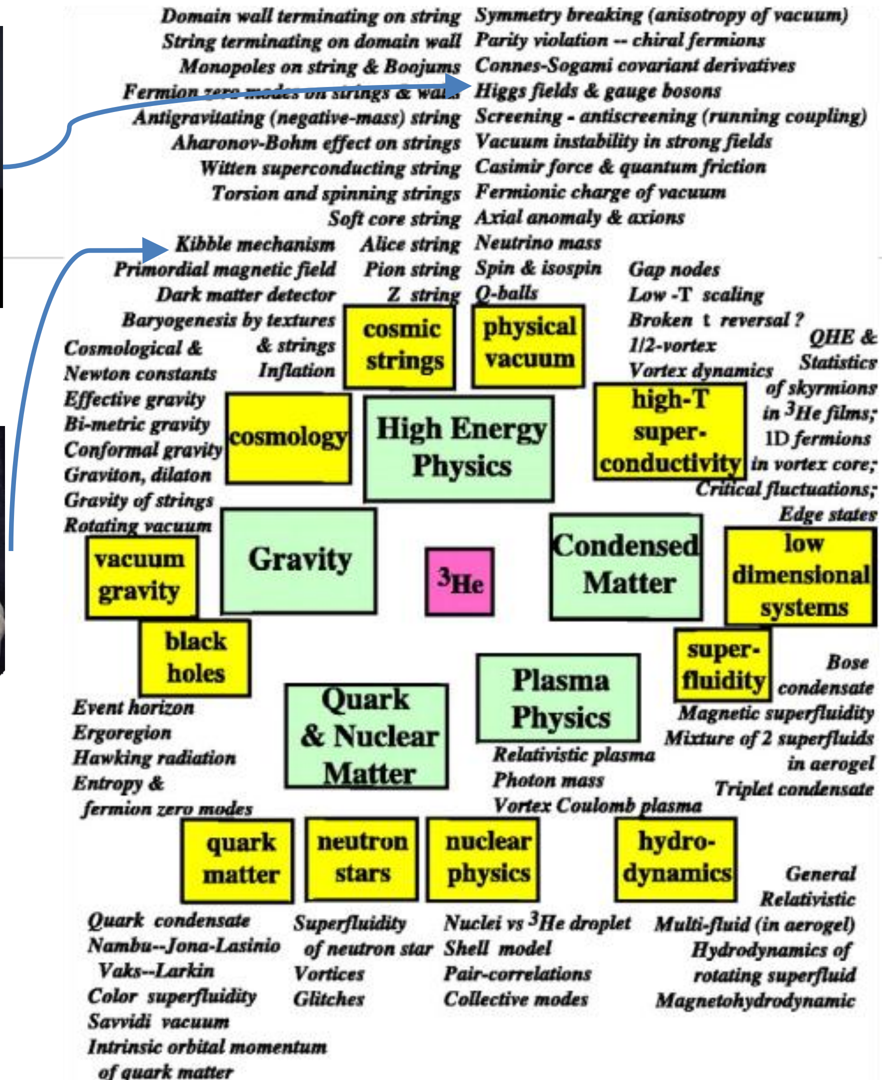
2013 Nobel:
Higgs & Englert

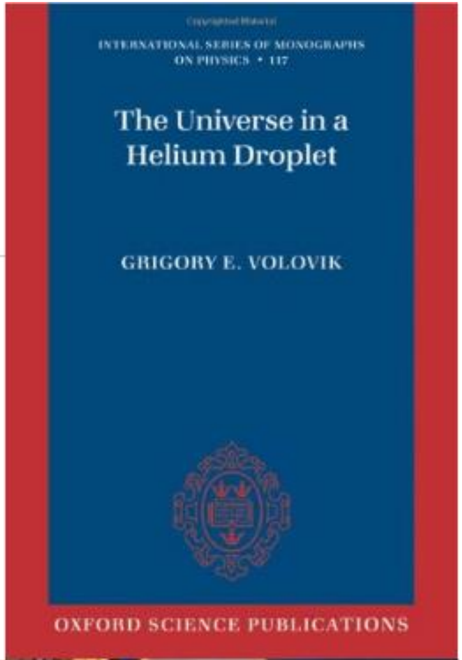




2013 Nobel:
Higgs & Englert

Kibble-Zurek
mechanism





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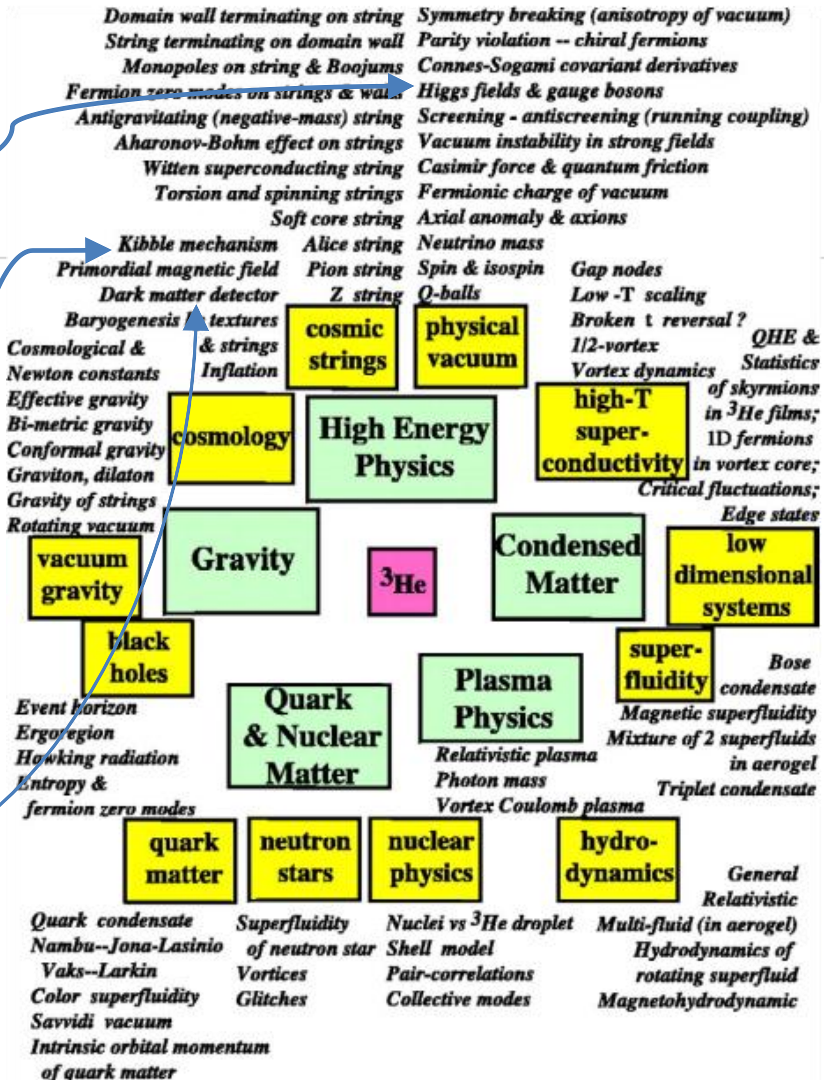
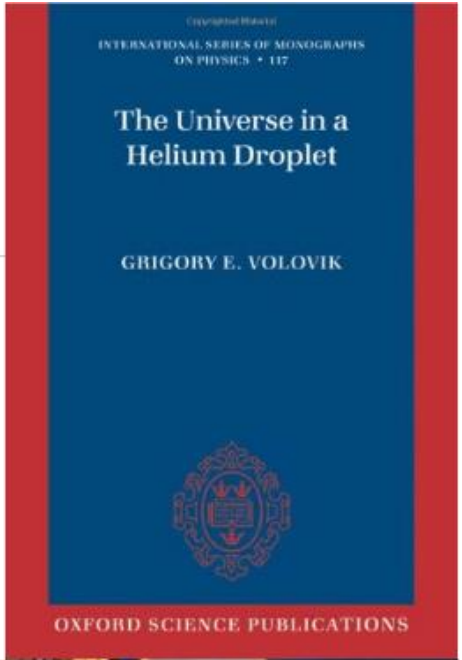
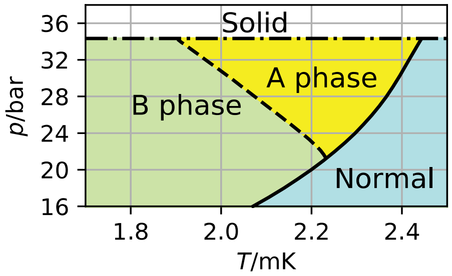
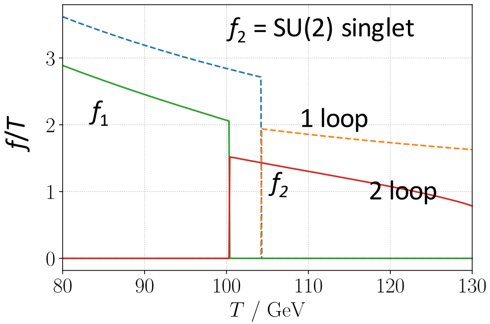
WP1: Dark matter detector







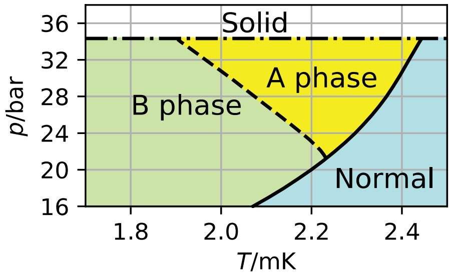
^{3}He & Cosmology



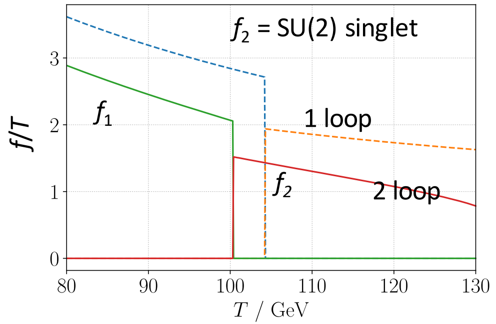
Niemi, Schicho, Tenkanen 21

^{3}He

Standard Model (& beyond)



^{3}He & Cosmology



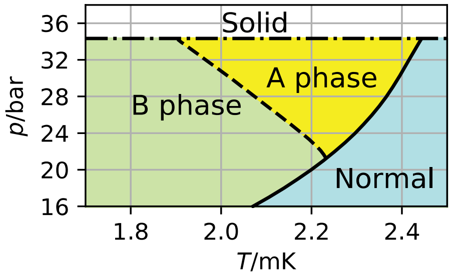
Niemi, Schicho, Tenkanen 21

^{3}He

- Fermionic quasiparticles
- Triplet pairing interaction
- Order parameter *A*
  - 3x3 complex, spin x ang. mom.
- Ginzburg-Landau theory
  - Bulk free energy density $f_b(A)$

Standard Model (& beyond)

- Quarks & leptons
- --- (technicolour etc.)
- Fundamental (?) Higgs field(s) f (f_2, …)
  - Irreps of $SU(2)_w \times U(1)_Y$ (G_{GUT})
- High *T* effective action
  - Effective potential $V_T(f)$



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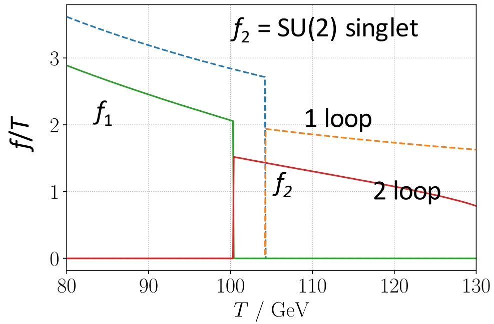


Niemi, Schicho, Tenkanen 21

^{3}He

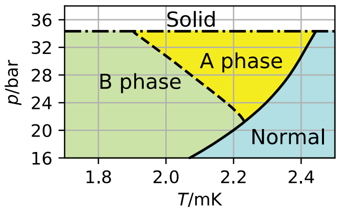
- Fermionic quasiparticles
- Triplet pairing interaction
- Order parameter A
  - 3x3 complex, spin x ang. mom.
- Ginzburg-Landau theory
  - Bulk free energy density $f_b(A)$
- Vortices and other topological defects
- Multiple superfluid phases $T <$ O(mK)
- 1st order phase transition A/B

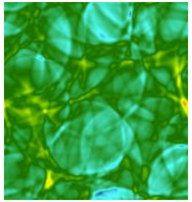
Standard Model (& beyond)

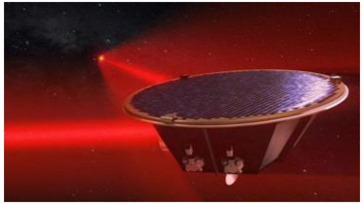
- Quarks & leptons
- --- (technicolour etc.)
- Fundamental (?) Higgs field(s) f (f_2, …)
  - Irreps of $SU(2)_W \times U(1)_Y$ (G_{GUT})
- High T effective action
  - Effective potential $V_T(f)$
- (cosmic strings and other defects)
- 1 (multiple) Higgs phase(s) T < O(10^{16} K)
- (1st order PTs normal-SF & between Higgs phases)

Outline

- Future space-based gravitational wave detectors (e.g. LISA) will probe the early Universe at $T \sim 100$ GeV and $t \sim 10$ ps.
- Theories extending the Standard Model to account for dark matter and the baryon asymmetry often have 1st order phase transitions, leading to GW production.
- Calculations of the GW power spectrum depend on homogeneous nucleation theory
- Superfluid ^{3}He A/B transition is the only homogeneous 1st order transition in the laboratory, but it does not follow the homogeneous theory
- QUEST-DMC is addressing the nucleation puzzle with confinement, magnetic fields, & HPC tools from cosmology

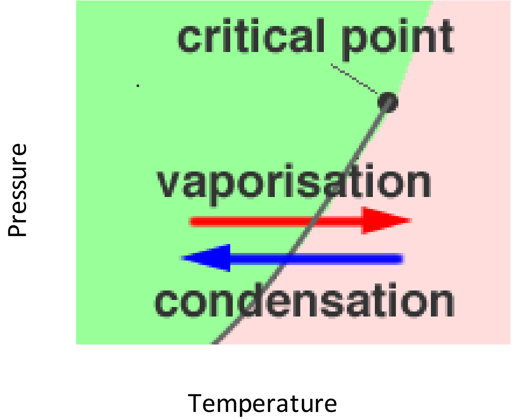






Phase transitions in the early Universe

- At very high temperatures and pressures, the state of matter in the Universe changes
  - T_c ~ 100 MeV (1 ms) QCD (quark-hadron)
  - T_c ~ 100 GeV (10 ps) Electroweak (mass generation)
  - T_c >> 100 GeV new symmetries, interactions?



Phase transitions in the early Universe

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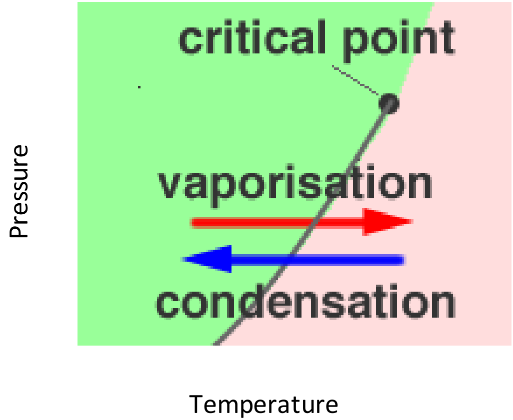
  - T_c >> 100 GeV new symmetries, interactions?
- First order phase transition? Kirzhnits, Linde (1972) Steinhardt (1982)
  - Departures from equilibrium and homogeneity:
  - -> Baryon asymmetry of the Universe

    Sakharov 68; Kuzmin, Rubakov, Shaposhnikov (1985)
  - -> Gravitational wave production

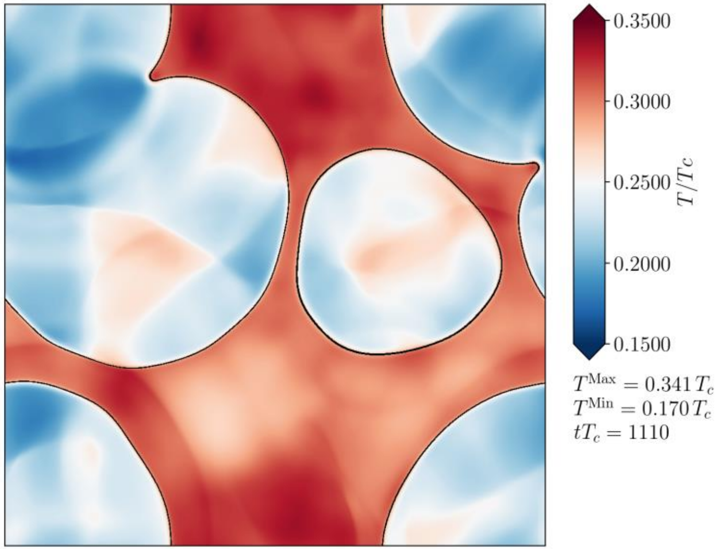
    Witten (1984), Hogan (1986)



First order phase transition?

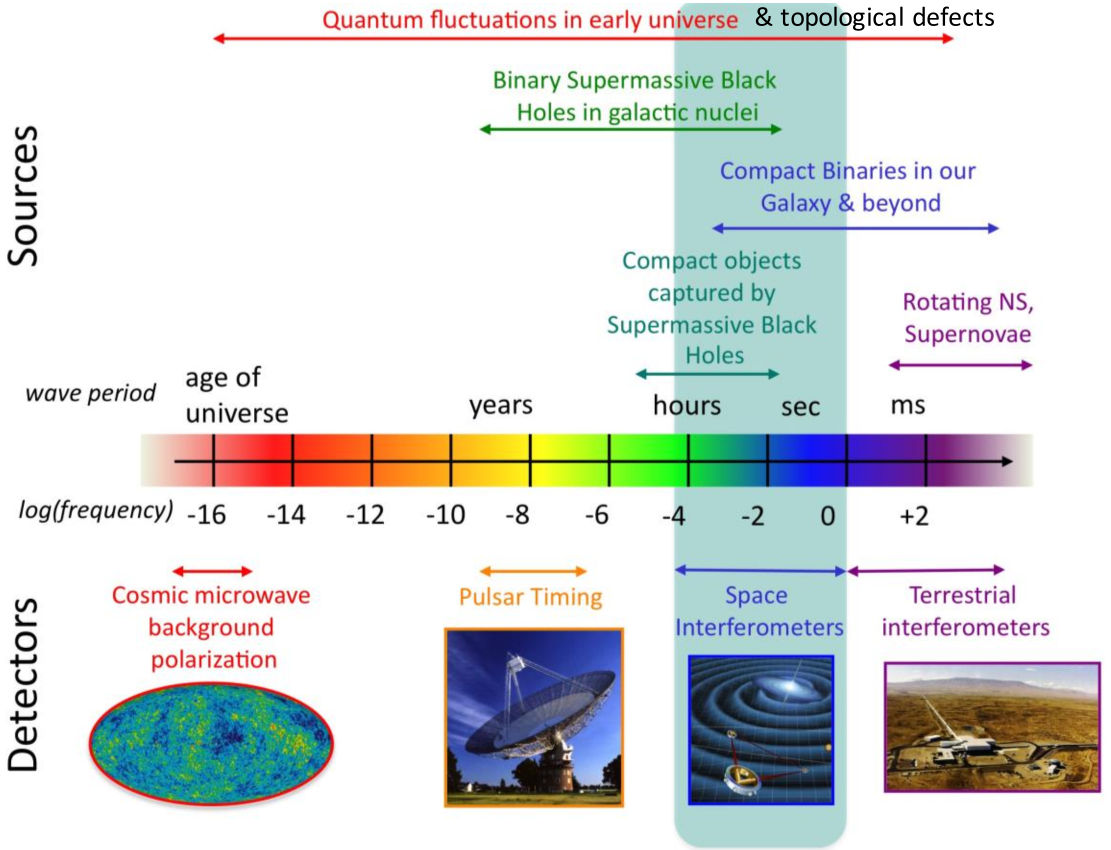
- Transition by nucleation of bubbles of low-*T* phase
  Langer 1969, Coleman 1974, Linde 1983
- Nucleation rate/volume rapidly increases below T_c
- Relativistic condensation/combustion: "fizz"
- Expanding bubbles generate pressure waves
  Steinhardt (1982); Hogan (1983); Gyulassy et al (1984)
- Gravitational wave production
  Witten (1984); Hogan (1986)
- GWs have information about the phase transition
  MH, Huber, Rummukainen, Weir (2013,5,7); Hindmarsh(2017); Hidnmarsh & Hijazi (2019); Cutting, MH, Weir (2019)

Fluid temperature



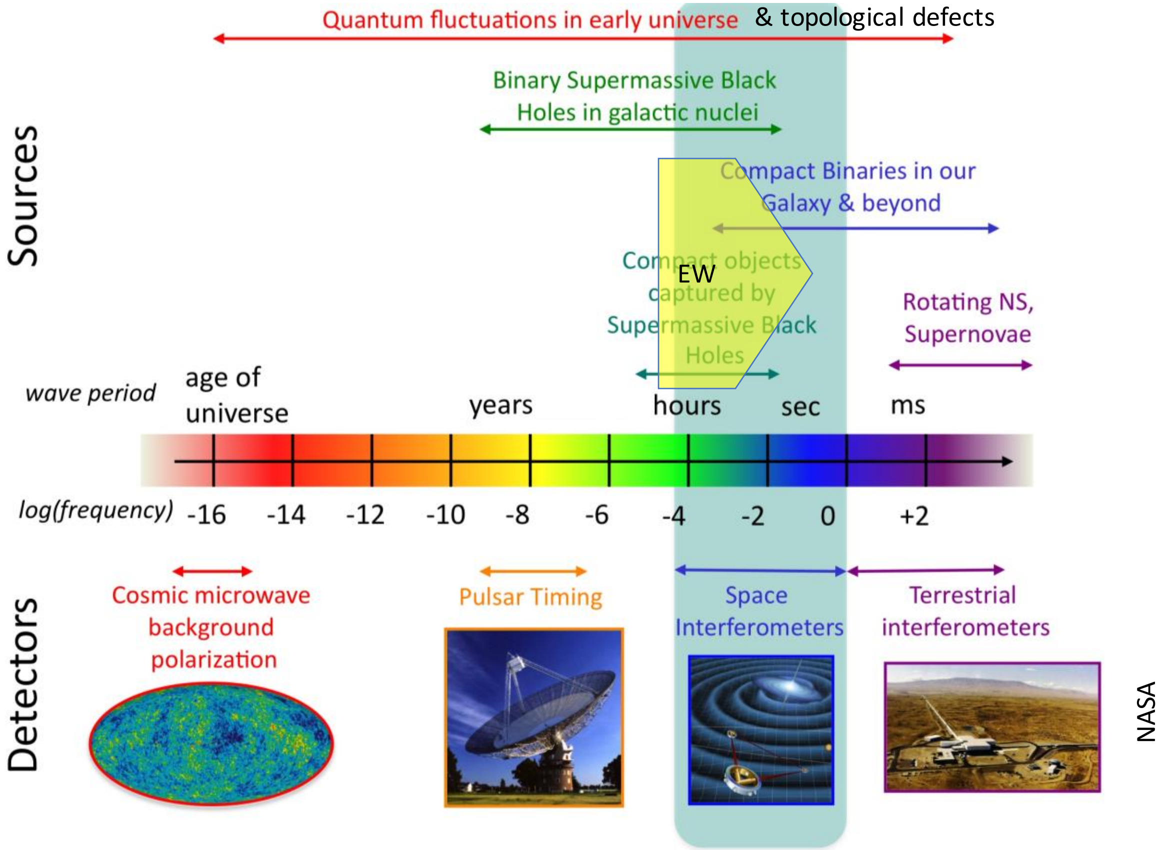
Hindmarsh, Huber, Rummukainen, Weir (2013,5,7)
Cutting, Hindmarsh, Weir (2019)

Gravitational wave spectrum



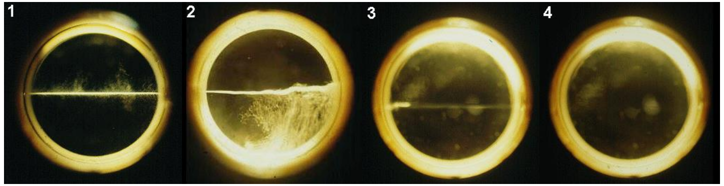
NASA

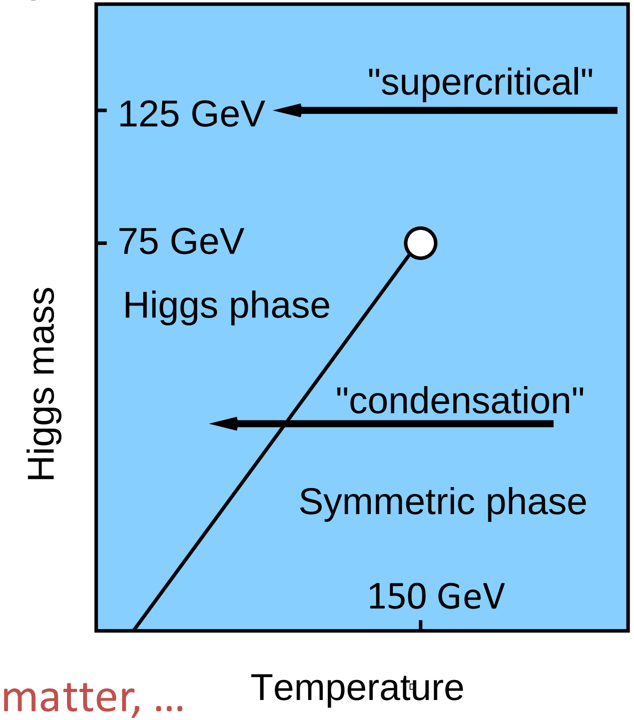
Gravitational wave spectrum



Electroweak transition: 100 GeV, 10 ps

- But: in the Standard Model, transition is a cross-over
  Kajantie, Laine, Rummukainen, Shaposhnikov (1995,6)
  - Susceptibility peak at *T* ~ 160 GeV
    D'Onofrio, Rummukainen (2015)
- Same universality class as liquid-vapour in water
  Rummukainen et al (1995)
  - SM transition like a supercritical fluid





- SM stays close to equilibrium, no GWs
- New physics required for baryon asymmetry, dark matter, …

1^{st} order phase transitions
Beyond the Standard Model 1: extra Higgs

Departure from equilibrium

Kuzmin, Rubakov, Shaposhnikov (2009)

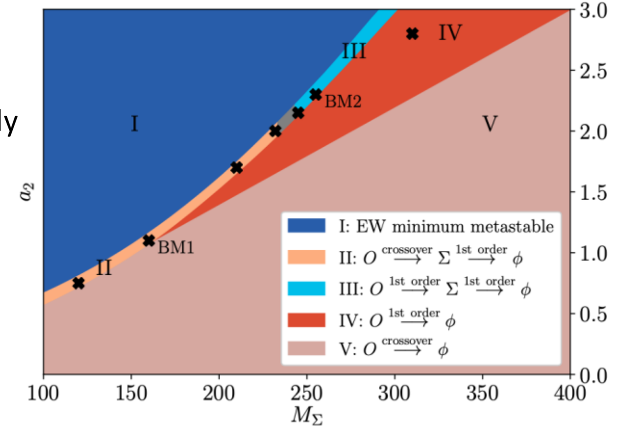
Baryogenesis

- SM + singlet
  - Strong 1^{st} order phase transitions possible
    Espinosa, Konstandin, Riva (2012)
    Cline, Kainulainen (2013)
    Kozaczuk (2015)
    Kotwal et al (2016)
  - Even without LHC traces
    Ashoorioon and Konstandin (2009)
    Curtin, Meade, Yu (2011)
  - *Zh* signal at future e^+e^-
    Curtin, Meade, Yu (2011)
    Cao, Huang, Xie, Zhang (2017)

- SM + doublet ("2HDM")
  - Baryogenesis and B physics
    Cline, Kainulainen (2011)
  - Heavy A^0 ← strong 1^{st} order phase transition ($v(T_c)/T_c > 1$)
    Dorsch, Huber, No (2014)
  - Signal: $A^0 \to H^0 Z$
    Dorsch, Huber, Mimasu, No (2016); Andersen et al (2017)

- SM + triplet
  - +2 parameters only

  Niemi et al (2020)



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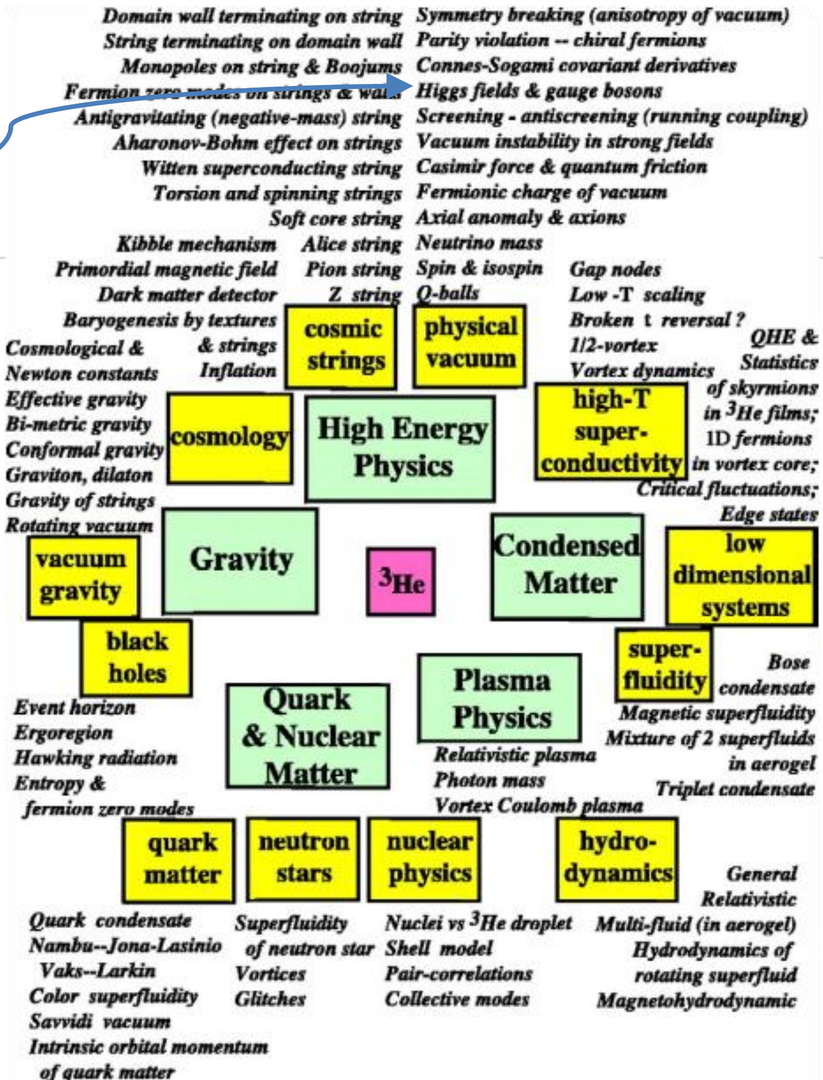
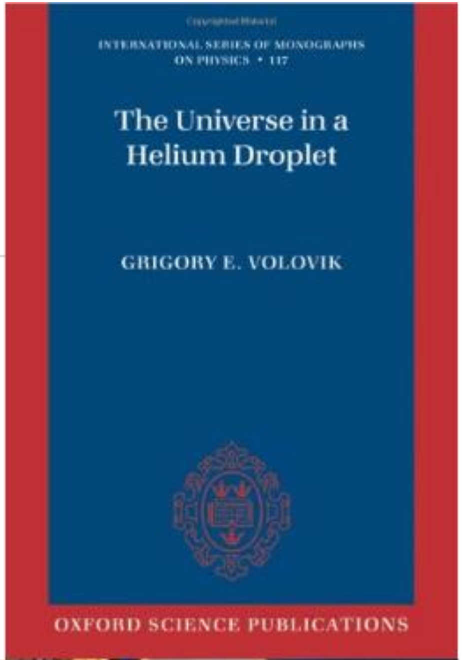
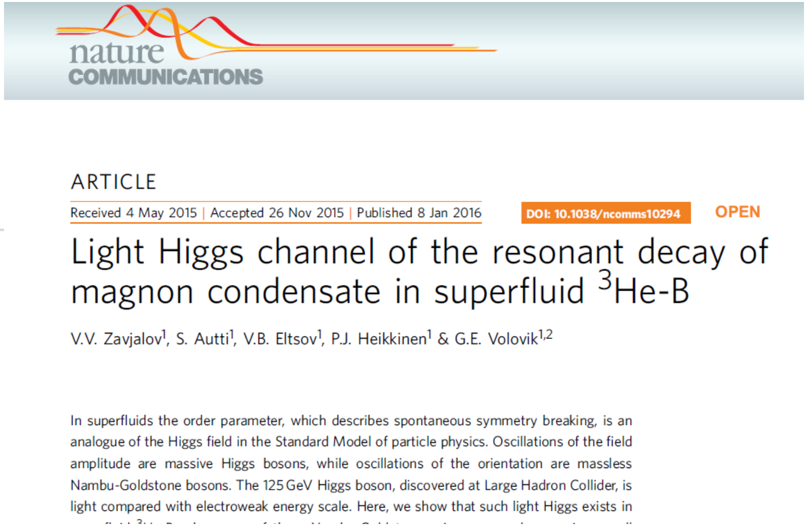
Higgs & Englert







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ARTICLE

Received 4 May 2015 | Accepted 26 Nov 2015 | Published 8 Jan 2016 DOI: 10.1038/ncomms10294 OPEN

Light Higgs channel of the resonant decay of magnon condensate in superfluid ^{3}He-B

V.V. Zavjalov[1], S. Autti[1], V.B. Eltsov[1], P.J. Heikkinen[1] & G.E. Volovik[1,2]

In superfluids the order parameter, which describes spontaneous symmetry breaking, is an analogue of the Higgs field in the Standard Model of particle physics. Oscillations of the field amplitude are massive Higgs bosons, while oscillations of the orientation are massless Nambu-Goldstone bosons. The 125 GeV Higgs boson, discovered at Large Hadron Collider, is light compared with electroweak energy scale. Here, we show that such light Higgs exists in

"..the light Higgs mode has parallel with the 125-GeV Higgs boson. However, in addition, the 3He-B has the high-energy sector with 14 heavy Higgs modes. This suggests that in the same manner, **the 125-GeV Higgs boson belongs to the low-energy sector** of particle physics, and if so, one may expect the existence of the **heavy Higgs bosons at TeV scale**."

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<u>arXiv:2209.10910:</u>

"The largest excess in the resonant search is observed at a **resonance mass of 1 TeV**, with a local (global) significance of 3.□σ (2□0σ)."

"..the light Higgs mode has parallel with the 125-GeV Higgs boson. However, in addition, the 3He-B has the high-energy sector with 14 heavy Higgs modes. This suggests that in the same manner, **the 125-GeV Higgs boson belongs to the low-energy sector** of particle physics, and if so, one may expect the existence of the **heavy Higgs bosons at TeV scale**."

1^{st} order phase transitions Beyond the Standard Model 2

- SUSY with 1^{st} order PT
  - NMSSM
  - nMSSM
  - GNMSSM ~

  Pietroni (1993)
  Davis, Froggatt, Moorhouse (1996)
  Cline, Kainulainen (1996)
  Huber, Schmidt (1999,2001)
  Panagiotakopoulos, Tamvakis (1999)
  Menon, Morrissey, Wagner (2004)
  Huang et al (2014)
  Kozaczuk et al (2015)

- TeV-scale strong dynamics
  - Minimal walking technicolor

    Järvinen, Kouvaris, Sannino (2010)

  - Holographic models

    Bea et al 2019
    Ares, Henrikson, MH, Hoyos, Jokela 2022

- SM + dilaton (nearly-conformal models)

  Creminelli, Nicolis, Rattazzi 2001
  Nardini, Quiros, Wultzer 2007
  Konstandin, Servant 2011

- SM + dim 6

$$V_{\text{eff}}(H) = -\frac{\mu^2}{2}H^2 + \frac{\lambda}{4}H^4 + \frac{1}{8M^2}H^6$$

  - Tree level 1^{st} order phase transition for $\lambda < 0$

  Zhang (1993)
  Grojean, Servant, Wells (2004)
  Ham, Oh (2004)
  Bodeker et al (2004)
  Cao, Huang, Xie, Zhang (2017)

- String landscape

  Garcia, Krippendorf, March-Russell 2015

Bulk phases of superfluid ^{3}He

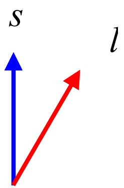
- Superfluid below T_c ~ 2 mK

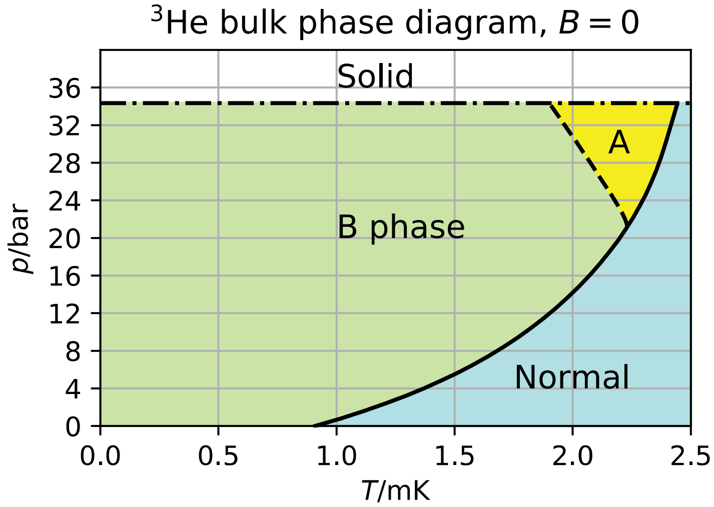
- Symmetry group of free energy:
  - $SO(3)_S \times SO(3)_L \times U(1)_N$
- B phase: $SO(3)_J$ Balian, Werthamer (1964)

$$A_B = \frac{\Delta_B}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$ isotropic

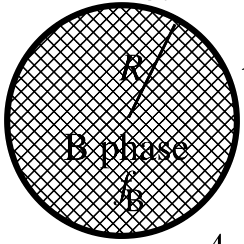
- A phase: $U(1)_{Sz} \times U(1)_{Lz+N}$ Anderson, Morel (1961) Anderson, Brinkman (1973)

$$A_A = \frac{\Delta_A}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & i & 0 \end{pmatrix}$$ anisotropic





Why do we ever get the B phase?



- ^{3}He AB transition rate puzzle   Kaul, Kleinert 1980; Bailin, Love 1980
- Homogeneous nucleation theory
  - nucleation rate per unit volume   Langer 1969, Linde 1983

$$p(T) \sim \omega \xi_{\mathrm{GL}}^{-3} \exp\left(-E_{\mathrm{c}}/T\right)$$

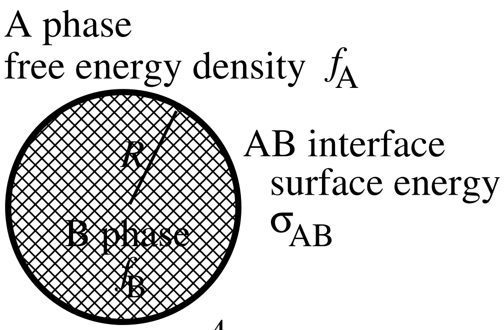
  - $E_c\,(T)$ – energy of critical droplet/bubble
  - $E_c/T \sim 10^6$ in ^{3}He A/B GL theory

$$E(R) = 4\pi R^2 \sigma_{\mathrm{AB}} - \frac{4\pi}{3} R^3 (f_A - f_B)$$

Critical bubble:

$$\left.\frac{dE}{dR}\right|_{R_c} = 0, \quad E_c = \frac{16\pi}{3} \frac{\sigma_{AB}^3}{|f_A - f_B|^2}$$

Why do we ever get the B phase?



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- Homogeneous nucleation theory
  - nucleation rate per unit volume   Langer 1969, Linde 1983

$$p(T) \sim \omega \xi_{\mathrm{GL}}^{-3} \exp\left(-E_{\mathrm{c}}/T\right)$$

$$E(R) = 4\pi R^2 \sigma_{\mathrm{AB}} - \frac{4\pi}{3} R^3 (f_A - f_B)$$

Critical bubble:

$$\left.\frac{dE}{dR}\right|_{R_c} = 0, \quad E_c = \frac{16\pi}{3} \frac{\sigma_{AB}^3}{|f_A - f_B|^2}$$

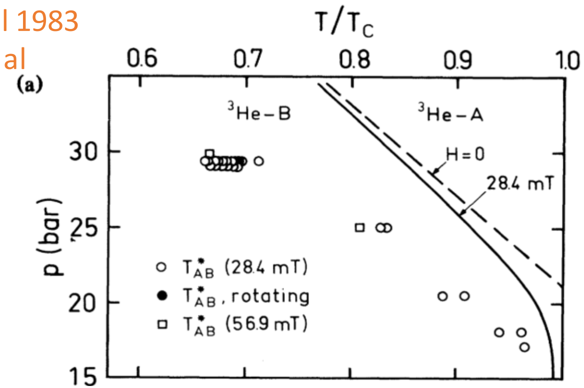
  - E_c (T) – energy of critical droplet/bubble
  - $E_c/T \sim 10^6$ in ^{3}He A/B GL theory
- Prediction: supercooled A lasts a *long* time
- But AB transition is observed   Kleinberg et al 1974; Hakonen et al 1985; Fukuyama et al 1987; Swift, Buchanan 1987; Schiffer et al 1992; O’Keefe, Barker, Osheroff 1996 …
  - Ionising radiation? (“baked Alaska”, Kibble-Zurek)   Leggett 1984, Bunkov, Timofeevskaya 1998
  - Boundary effects? (e.g. “lobster pots”)   Leggett & Yip 1990
  - Non-topological solitons?   Hong 1988
  - Resonant tunnelling?   Tye Wohns 2011

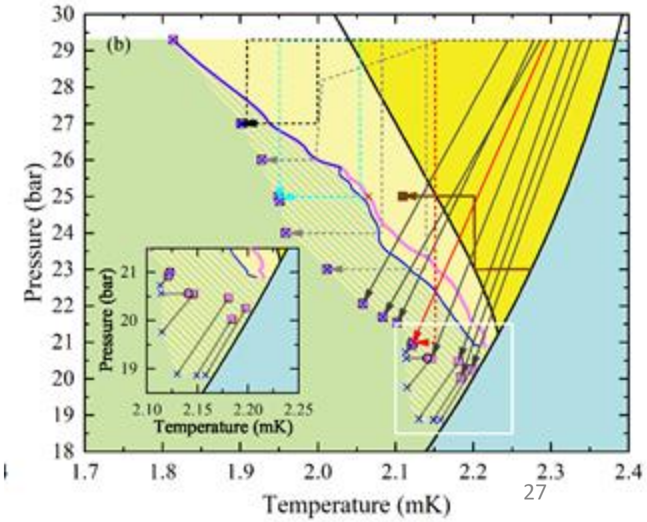
Boundary effects in AB transition

- Nucleation with rough surfaces
  - Spontaneous, AB “catastrophe line”
  - Can be induced by mechanical shock

O’Keefe, Barker, Osheroff 1996; Bartkowiak et al 2000

Hakonen et al 1983
Fukuyama et al 1987





Boundary effects in AB transition

Hakonen et al 1983
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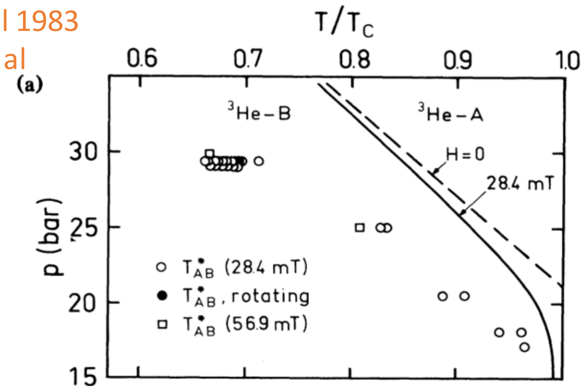

- Nucleation with rough surfaces
  - Spontaneous, AB "catastrophe line"
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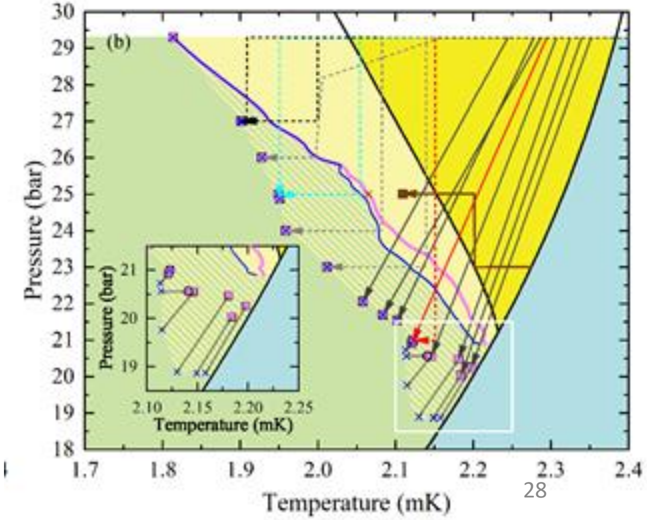
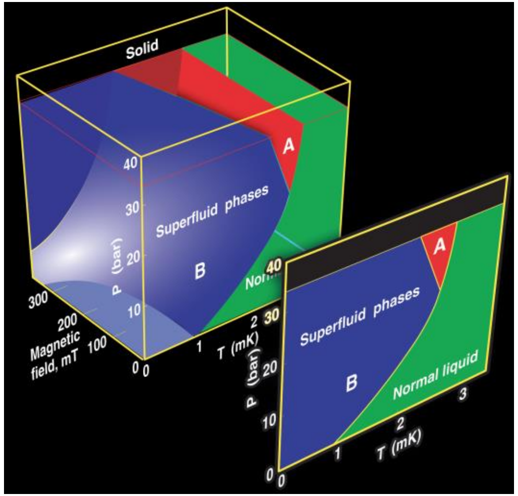
  O'Keefe, Barker, Osheroff 1996; Bartkowiak et al 2000

- Path-dependent nucleation, rough surfaces
  - "Catastrophe line" depends on P_{max} in A phase
  - Model: B-phase "seeds" in O(μm) cavities
    - Heat exchanger?
  - Seeds are complex order parameter configurations at curved boundaries?
  - Stable or metastable?

Tian et al 2022



Eliminating boundaries with magnetic fields?



- Magnetic field favours A phase
  - A has spins aligned
  - No B-phase for H > 0.3 T

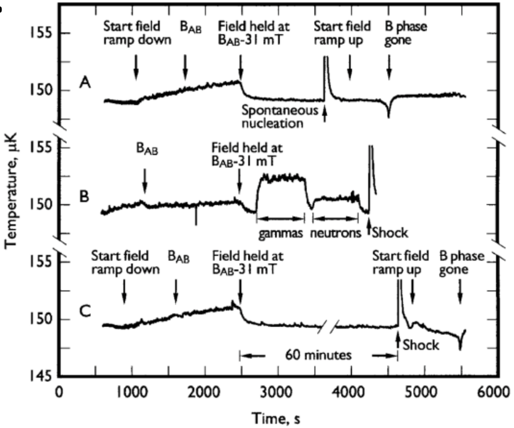
$$f_H = g_H H_\alpha (AA^\dagger)_{\alpha\beta} H_\beta$$

$$(AA^\dagger)^B \propto 1,$$

$$(AA^\dagger)^A \propto \mathrm{diag}(0,0,1)$$

- Create a region of low field, phase boundary stabilised by the field gradient
- Observations from rudimentary attempts:
  - Changing H can induce transition
  - Undermagnetisation of A phase, not just overmagnetisation of B phase
  - Mechanical shock can induce transition

--> Full isolation from walls etc is essential!



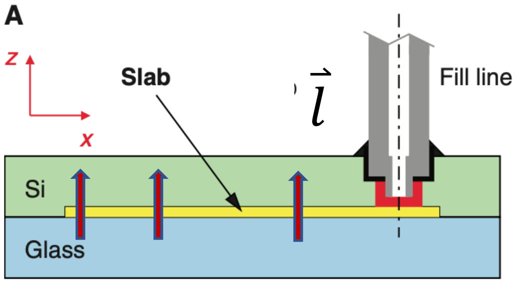
Controlling boundaries with confinement?

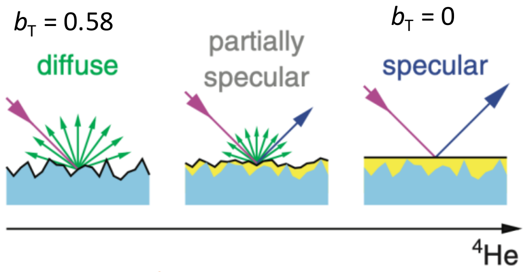
Ambegaokar, de Gennes, Rainer 1973

- Boundaries break Cooper pairs & suppress order parameter

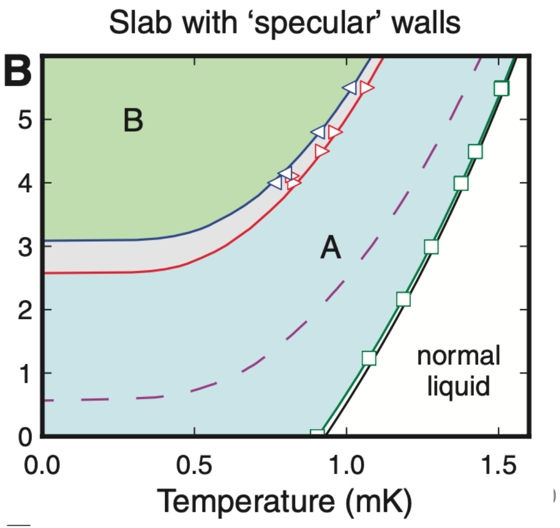
$$A_{\alpha i} n_i = 0, \quad (b_T + \mathbf{n}\cdot\nabla) A^{\parallel}_{\alpha i} = 0$$

  - Control b_T with 4He coating
- Angular momentum of Cooper pairs normal to boundaries
- Thin slab favours A phase





Levitin et al 2013



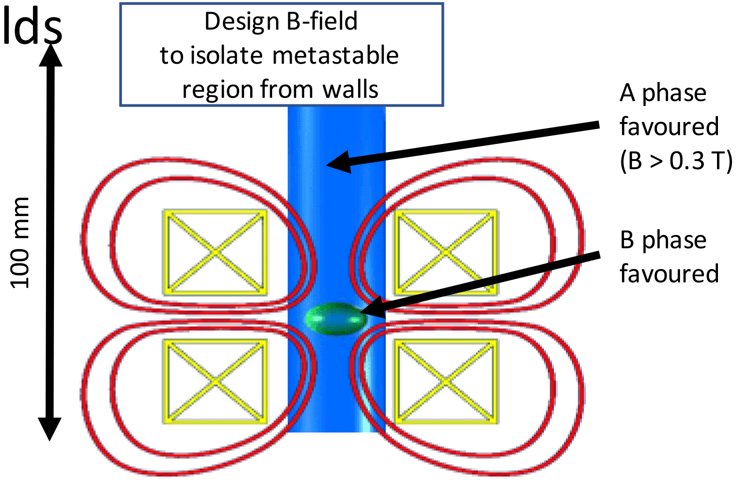
QUEST-DMC: solving the nucleation puzzle

Quantum-Enhanced Superfluid Technologies for Dark Matter and Cosmology

PTs with magnetic fields

In Lancaster

- Eliminate boundary effects
- Transition in shaped magnetic fields



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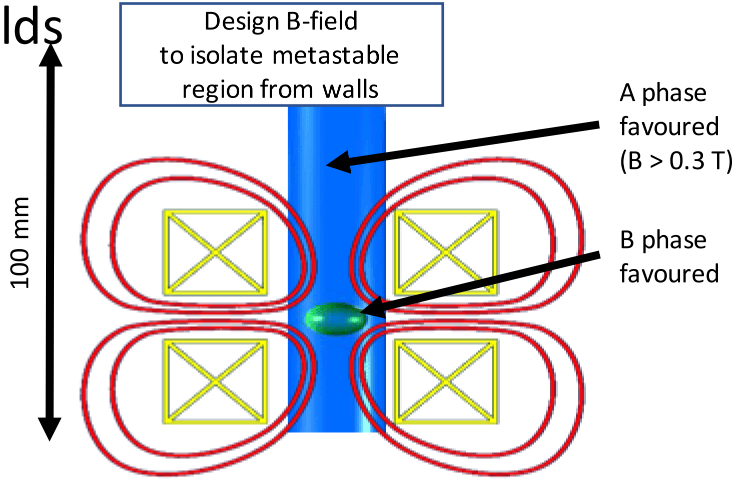
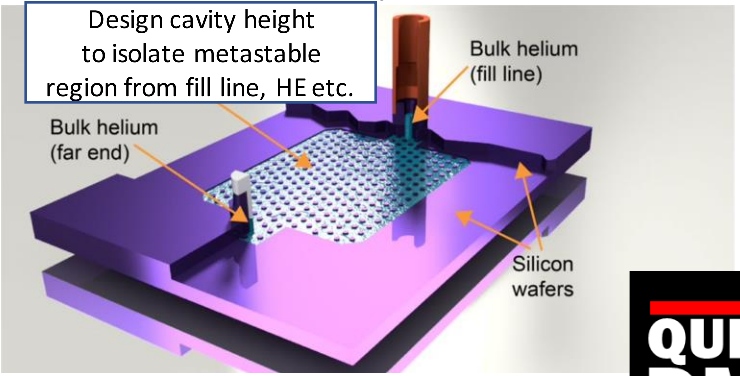


PTs under confinement

At Royal Holloway

- Control boundary effects
- Transition under confinement with atomically smooth walls



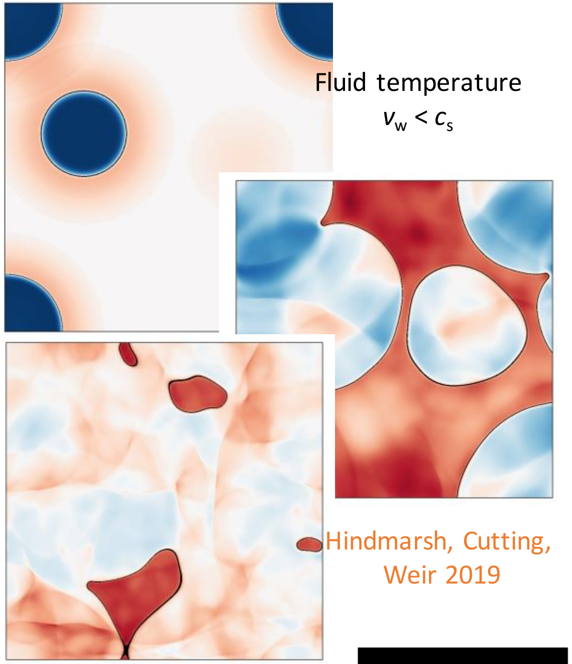
QUEST-DMC: solving the nucleation puzzle

Quantum-Enhanced Superfluid Technologies for Dark Matter and Cosmology

Applying computation methods from cosmology

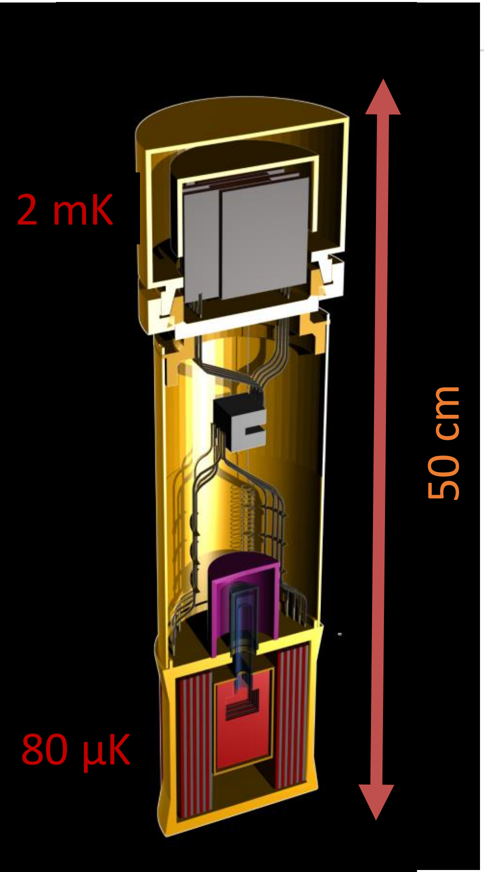
University of Sussex, University of Helsinki

- Cosmological simulations of phase transitions use [TD]GL analogue on large grids (up to 10000^3)
  - Compute critical bubbles, static & dynamic
  - Compute phase transition dynamics
- Aim: compute equilibrium order parameter configurations in experimental geometries
  - Metastability & barriers
- Future: compute AB boundary dynamics
  - Quasiparticle distribution functions?

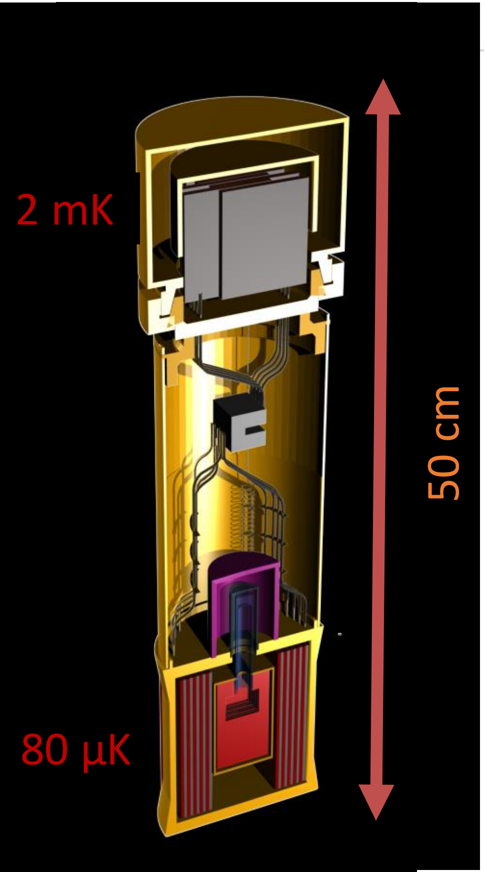


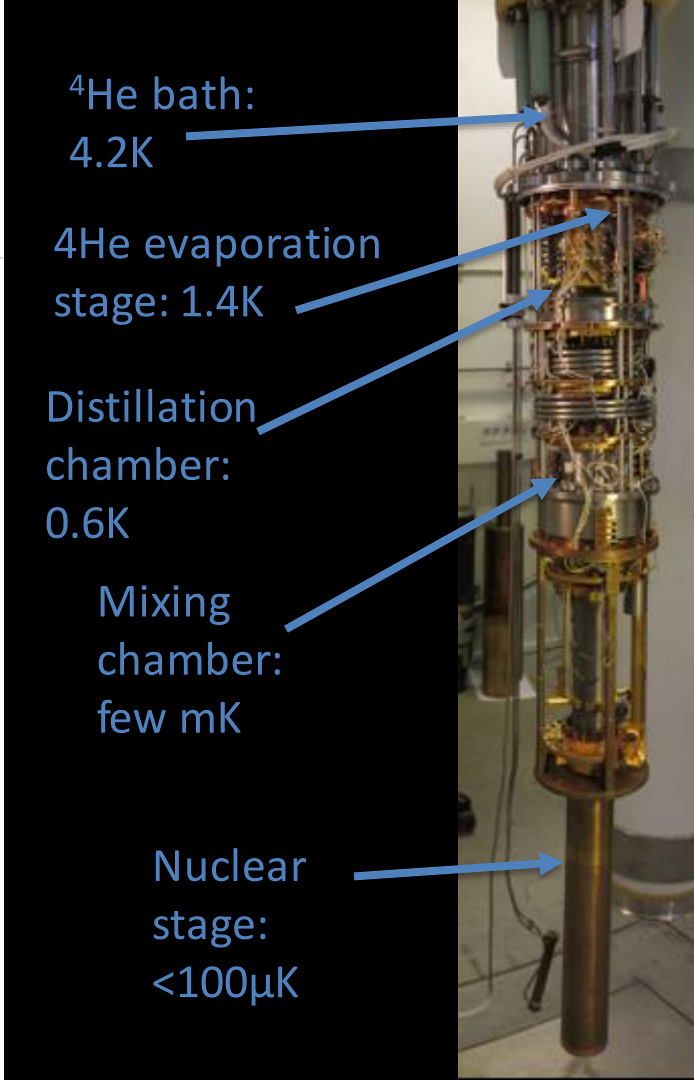
Hindmarsh, Cutting, Weir 2019

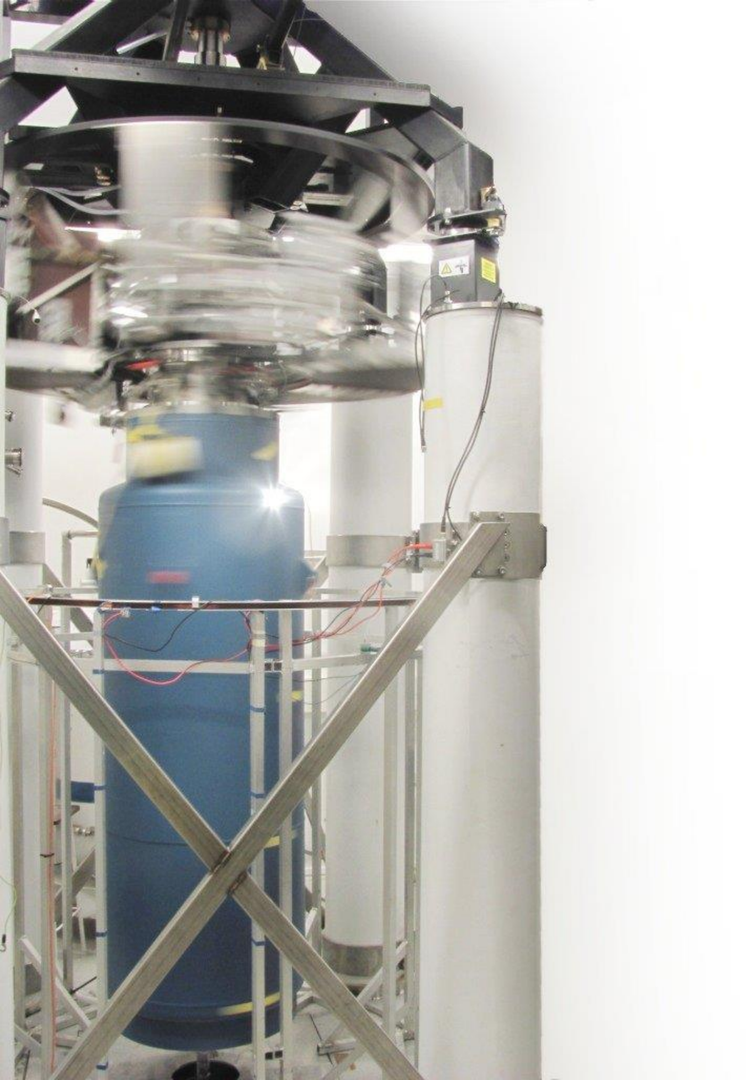
^{3}He experiments

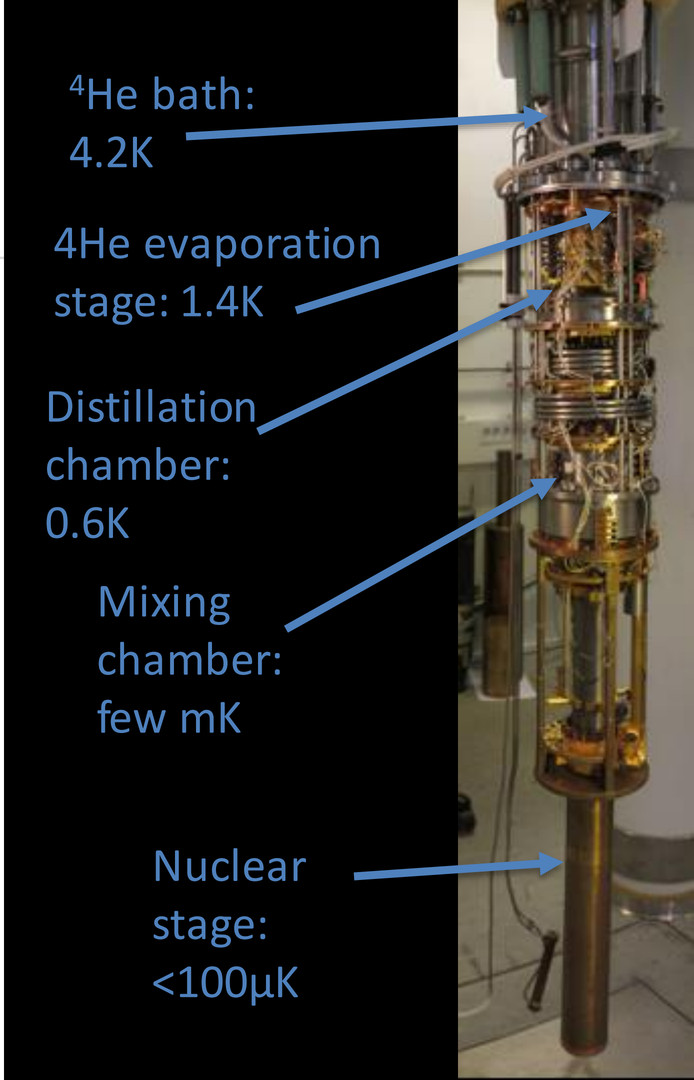


^{3}He experiments

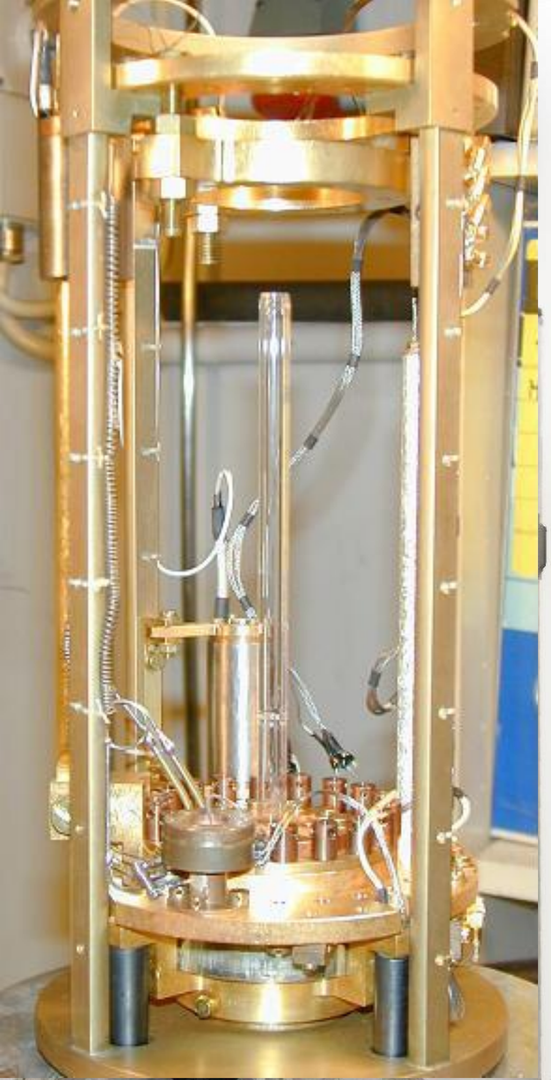


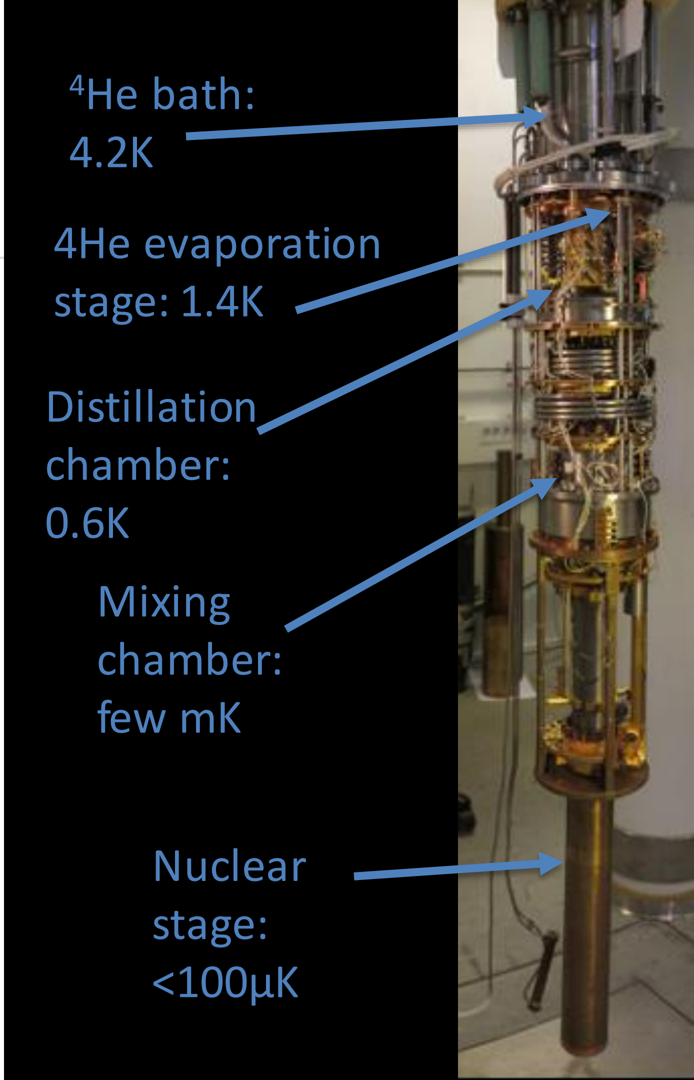


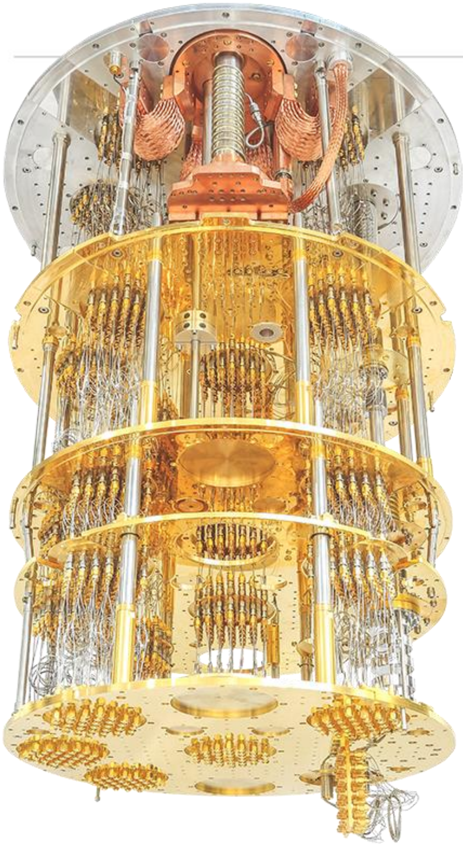




⁴He bath:
4.2K
4He evaporation
stage: 1.4K
Distillation
chamber:
0.6K
Mixing
chamber:
few mK
Nuclear
stage:
<100µK




4He bath: 4.2K
4He evaporation stage: 1.4K
Distillation chamber: 0.6K
Mixing chamber: few mK
Nuclear stage: <100μK



^{4}He bath:
4.2K

4He evaporation
stage: 1.4K

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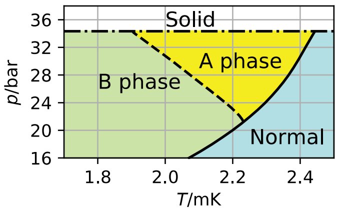
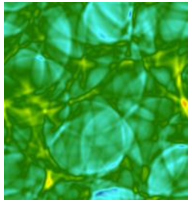
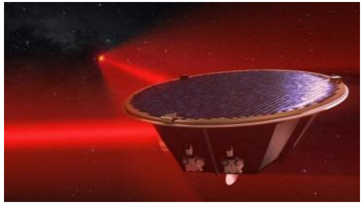
ge:
<100µK

Summary

- Future space-based gravitational wave detectors (e.g. LISA) will probe the early Universe at $T \sim 100$ GeV and $t \sim 10$ ps.
- Theories extending the Standard Model to account for dark matter and the baryon asymmetry often have 1st order phase transitions, leading to GW production.
- Calculations of the GW power spectrum depend on homogeneous nucleation theory
- Superfluid ^{3}He A/B transition is the only homogeneous 1st order transition in the laboratory, but it does not follow the homogeneous theory
- QUEST-DMC is addressing the nucleation puzzle with confinement, magnetic fields, & HPC tools from cosmology

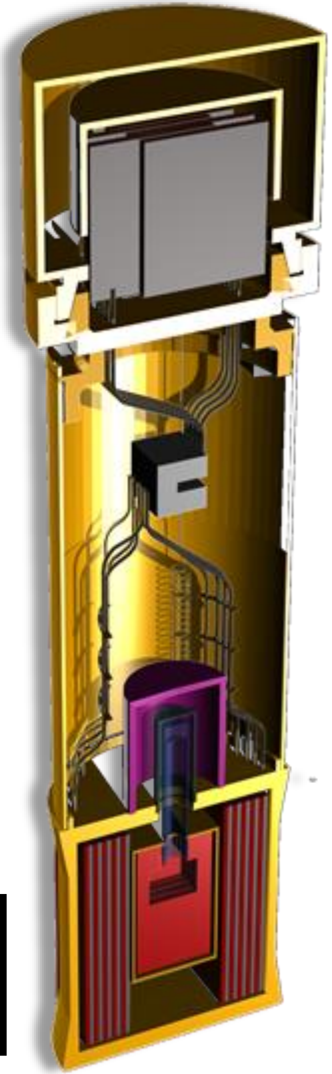






LISA CONSORTIUM

QUEST DMC



Thank you

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UKRI
Science and Technology Facilities Council

QUEST DMC

EMP European Microkelvin Platform

Lancaster University