LHC and Tevatron physics

Hitoshi Murayama (IPMU Tokyo, Berkeley)

Planck 2010, CERN, June 1, 2010

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dark matter and dark energy from topology

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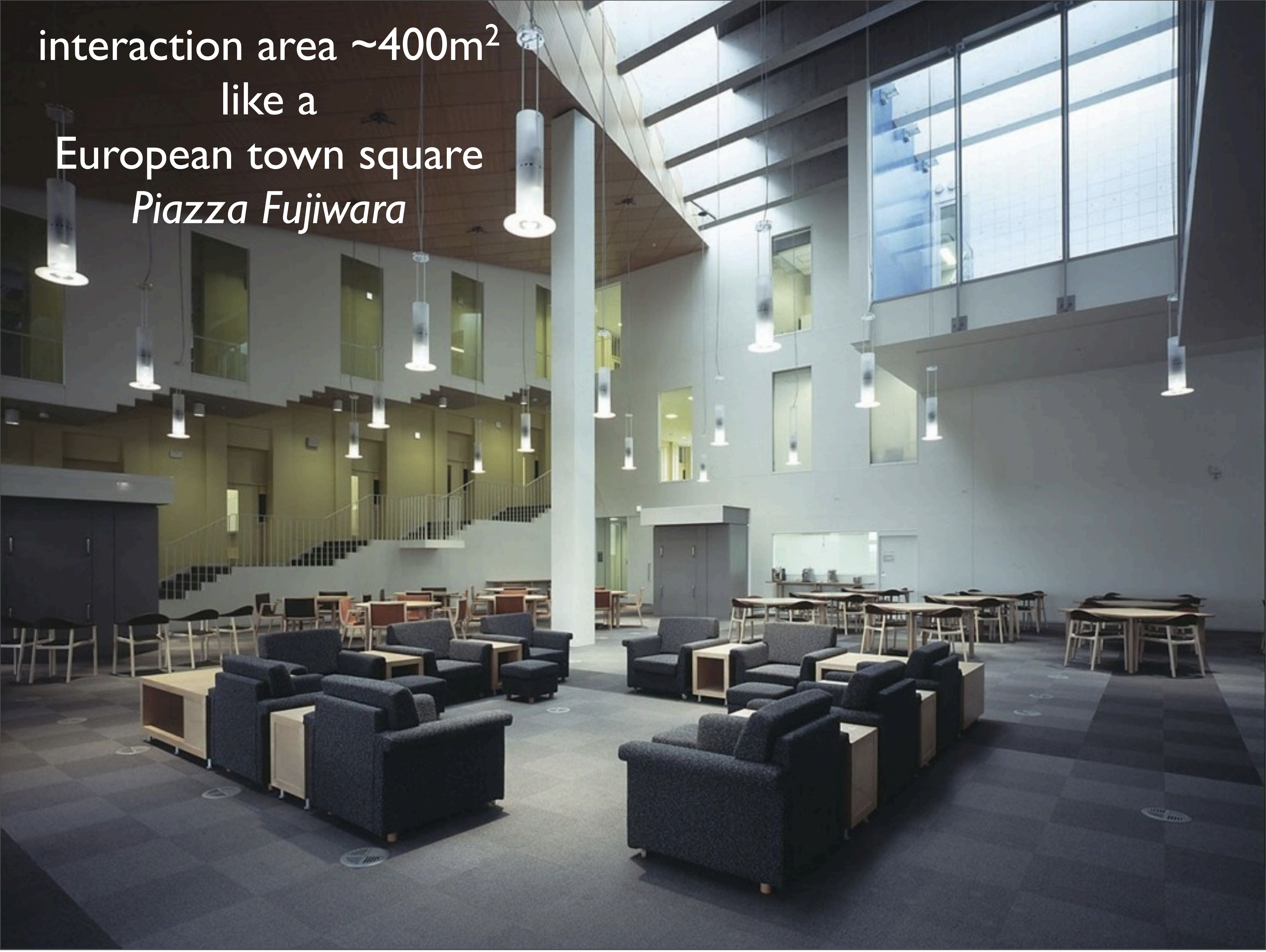
HM & Jing Shu, PLB 686, 162 (2010)

Second Birthday

~60% non-Japanese


occupancy since Jan 18, 2010
~5900 m2


interaction area ~400m2
like a
European town square
Piazza Fujiwara

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dark matter and dark energy from topology

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Conclusion

- so-called Kibble mechanism grossly underestimates the initial density of topological defects
- Pati-Salam below inflation excluded by monopole constraints
- hidden monopoles can be dark matter
- frustrated domain walls may be dark energy, easily evading the CMB constraint

Generality

Topological defects

- common interest among AMO, condensed matter, particle physics, algebraic geometry
- symmetry breaking $G \to H$
- coset space G/H describes vacua
- can the space be mapped non-trivially into the coset space?
- $\pi_0(G/H) \neq 0$: domain walls
- $\pi_1(G/H) \neq 0$: string (vortex)
- $\pi_2(G/H) \neq 0$: monopole
- $\pi_3(G/H) \neq 0$: skyrmion

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Topological DM

- little Higgs theories rely on coset spaces
- e.g. G/H=SU(5)/SO(5)
- non-trivial topology $\pi_3(G/H)=Z_2$
- Z_2 skyrmion ~10 TeV, a kind of "baryon"
- *thermal* relic gives good abundance
- decays like *proton decay in GUT*
- skyrmion → mesons → $(\mu^+\mu^-)^n$

HM and Jing Shu

Little Higgs models

Models	G	H	$\pi_3(G/H)$
Minimal Moose	$SU(3)^2$	SU(3)	Z
Littlest Higgs	SU(5)	SO(5)	Z_2
SO(5) Moose	$SO(5)^2$	SO(5)	Z

skyrmions

- skyrmion is topological soliton in G/H
- In QCD, G/H=SU(3), $\pi_3(G/H)$=Z
- skymion is baryon in QCD (Witten)
- It will likely thermalize
- therefore subject to the unitarity limit m<110 TeV (J=0)
- a very heavy dark matter candidate consistent with "natural" EWSB

other defects?

- Other defects are formed by the mismatch in order parameters beyond correlation length
- monopoles, strings, walls

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Kibble mechanism

- Kibble (1976) argued that phase transitions in expanding universe produce defects
- second-order phase transitions have infinite correlation length $\xi \propto |T-T_c|^{-\nu}$
- Therefore, all regions of causally connected space choose the same vacuum on G/H
- However, there is a finite horizon size $H^{-1} \approx M_{Pl}/T^2$
- Kibble: about one defect per horizon

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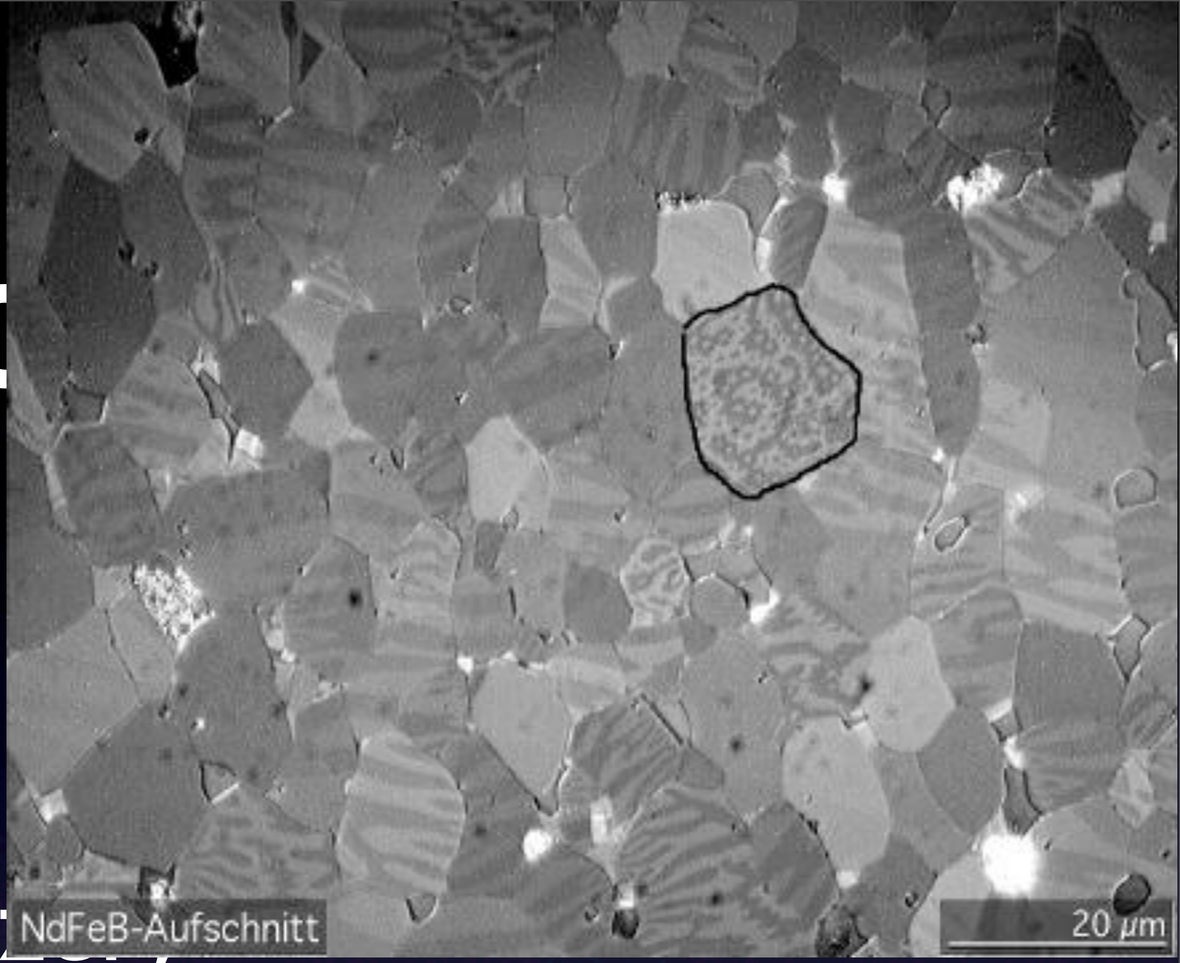
Time scale

- We know that we need to cool the material slowly to grow a bigger crystal (e.g. clear ice in the freezer)
- How does time scale come into the discussion?
- It takes time for things to line up!
  relaxation
- *quench*ed phase transition
- general discussion by Zurek (1985)

Time sc



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  relaxation
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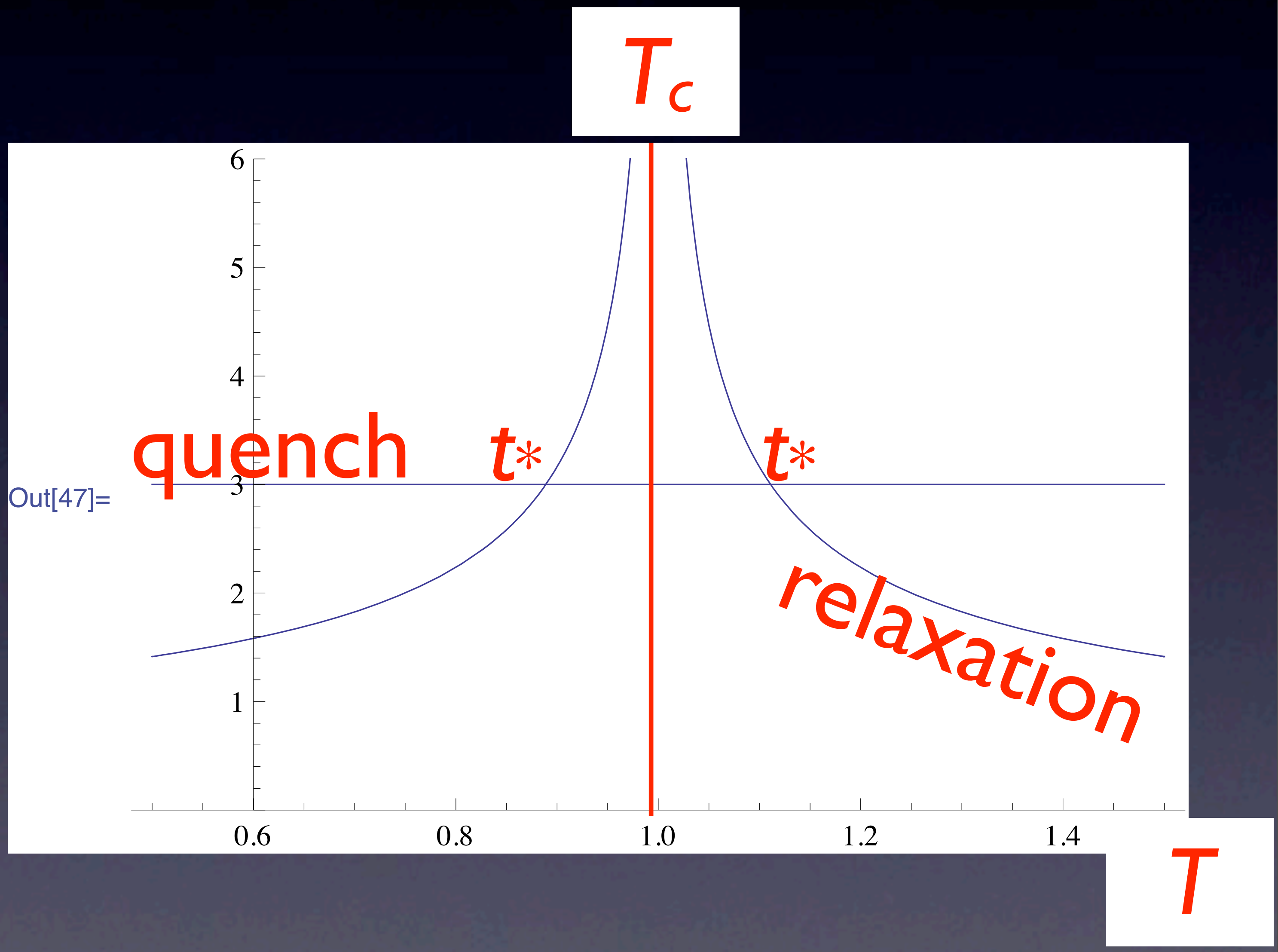
"Cosmological Experiments in Superfluid Helium?"

Phase transition revisited

- correlation length: $\xi \propto |T - T_c|^{-\nu}$
- relaxation time: $\tau \propto |T - T_c|^{-\mu}$
- It takes an infinite amount of time for the system to "line up" at T_c
- If the system cools too quickly, it won't line up even within a causally connected region

time scale

- proximity to T_c: $\varepsilon = |T_c - T|/T_c$
- relaxation time: $\tau = \tau_0\ \varepsilon^{-\mu}$
- quenching rate: $\tau_Q = (t - t_c)/\varepsilon$
- available time for relaxation: $\tau(t_*) = |t_* - t_c|$
- $\tau_0\ \varepsilon(t_*)^{-\mu} = \varepsilon(t_*)\ \tau_Q$
- $\varepsilon(t_*) = |\tau_Q/\tau_0|^{-1/(1+\mu)}$



time scale

- $\xi = \xi_0\ \varepsilon^{-\nu}$
- with the available time given by $\varepsilon(t_*) = |\tau_Q/\tau_0|^{-1/(1+\mu)}$
- the maximum correlation $\xi = \xi_0\ \varepsilon(t_*)^{-\nu} = \xi_0\ |\tau_Q/\tau_0|^{\nu/(1+\mu)}$
- the order parameter cannot "line up" beyond this length scale

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relativistic

- correlation length: $\xi \propto |T - T_c|^{-\nu}$
- relaxation time: $\tau \propto |T - T_c|^{-\mu}$
- classically, $\mu = \nu$
- dimensional analysis: $\xi_0 \approx \tau_0 \approx T_c^{-1}$
- $\tau_Q = (t - t_c)/\varepsilon = 2H(T_c)^{-1}$
- $\xi = \xi_0\ \varepsilon(t_*)^{-\nu} = \xi_0\ |\tau_Q/\tau_0|^{\nu/(1+\mu)}$
  $\approx T_c^{-1}\ |M_{Pl}/T_c|^{\nu/(1+\nu)}$

defect formation

- Kibble estimate: one per $H^{-1} \approx T_c^{-1}|M_{Pl}/T_c|$
- Zurek estimate: one per $\xi \approx T_c^{-1}|M_{Pl}/T_c|^{\nu/(1+\nu)}$
- Landau theory: $L = \kappa(T - T_c)T_c\,\phi^2 + \lambda\phi^2$
- $\xi = \tau = |\kappa(T - T_c)T_c|^{-1/2}$, $\mu = \nu = 1/2$
- Zurek estimate: one per $\xi \approx T_c^{-1}|M_{Pl}/T_c|^{1/3}$
- enormous enhancement by $|M_{Pl}/T_c|^{2/3}$!

Experimental tests

- D. Stamper-Kurn group (Berkeley)
- spinor BEC with ^{87}Rb in *F*=1 states

$$H = -\mu \vec{F}^2 + \lambda F_z^2$$

- O(2) symmetry
- when λ>>μ, O(2) unbroken
- quickly reduce λ (*quantum quench*)
- many domains with different O(2) breaking

Experimental tests

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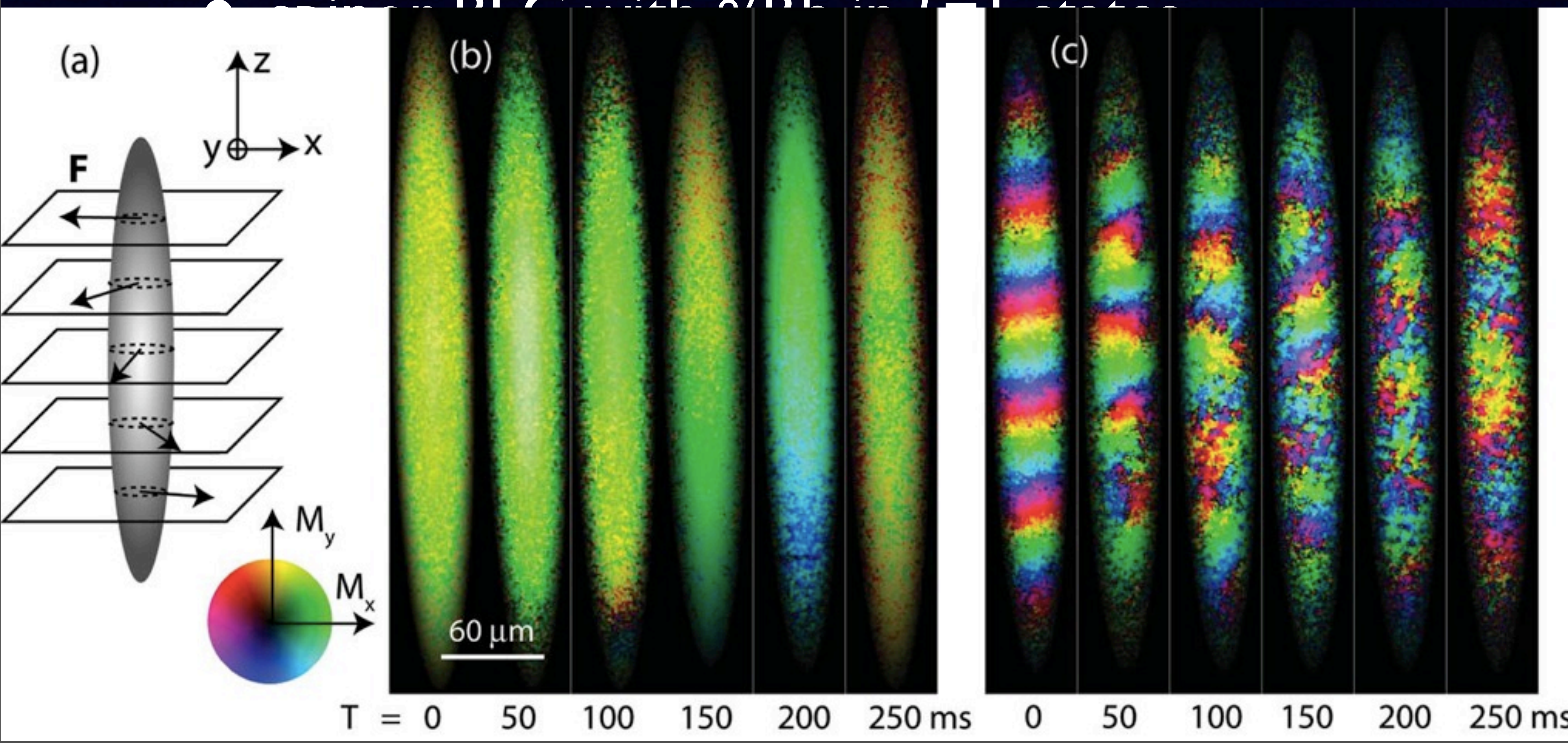
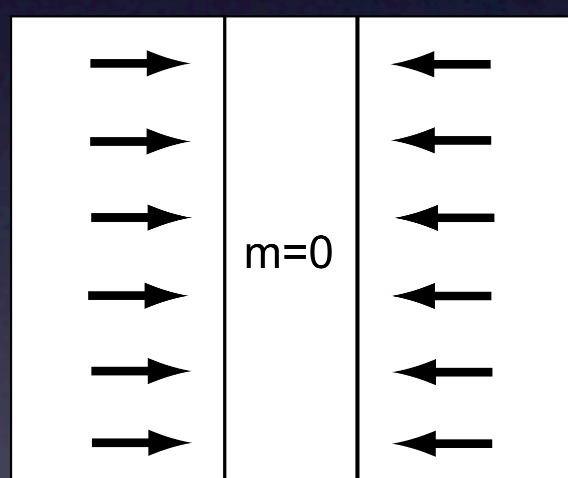
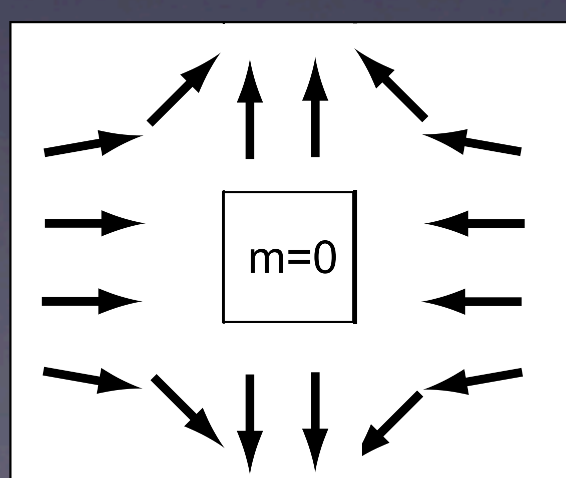


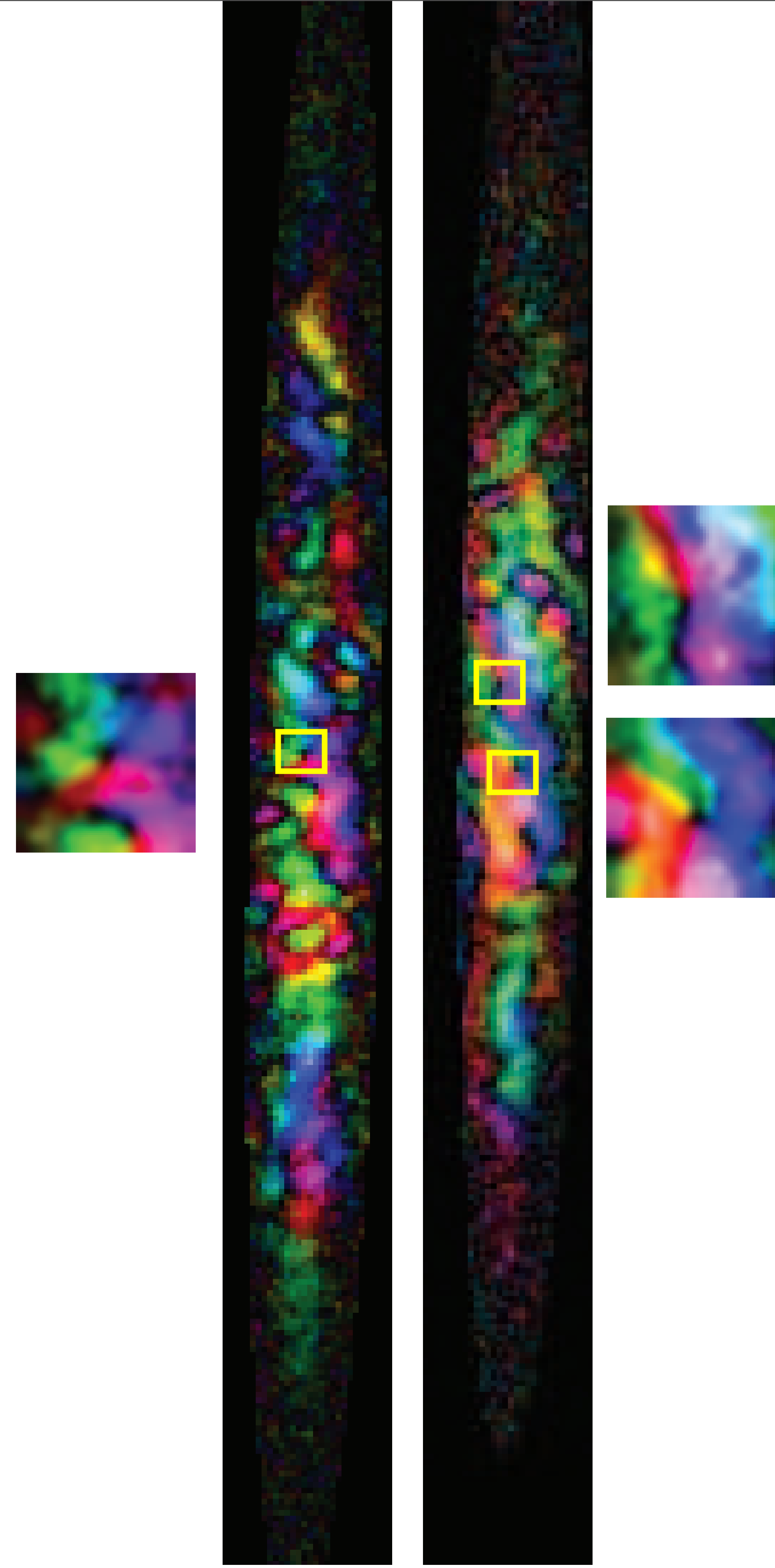
Vortex formation

a



b





Monopoles

Magnetic monopoles

- Standard Model G_{SM}=SU(3)$_C$×SU(2)$_L$×U(1)$_Y$
- It has U(1)$_Y$
- Georgi-Glashow SU(5) Grand Unification
- π_3(SU(5)/G_{SM})=Z
- Pati-Salam G_{PS}=SU(4)$_C$×SU(2)$_L$×SU(2)$_R$
- π_3(G_{PS}/G_{SM})=Z

monopoles

- Kibble mechanism:

$$\left.\frac{n_{PD}}{s}\right|_{T=T_c} \approx \left(\frac{T_c}{M_{pl}}\right)^3 .$$

- Landau theory:

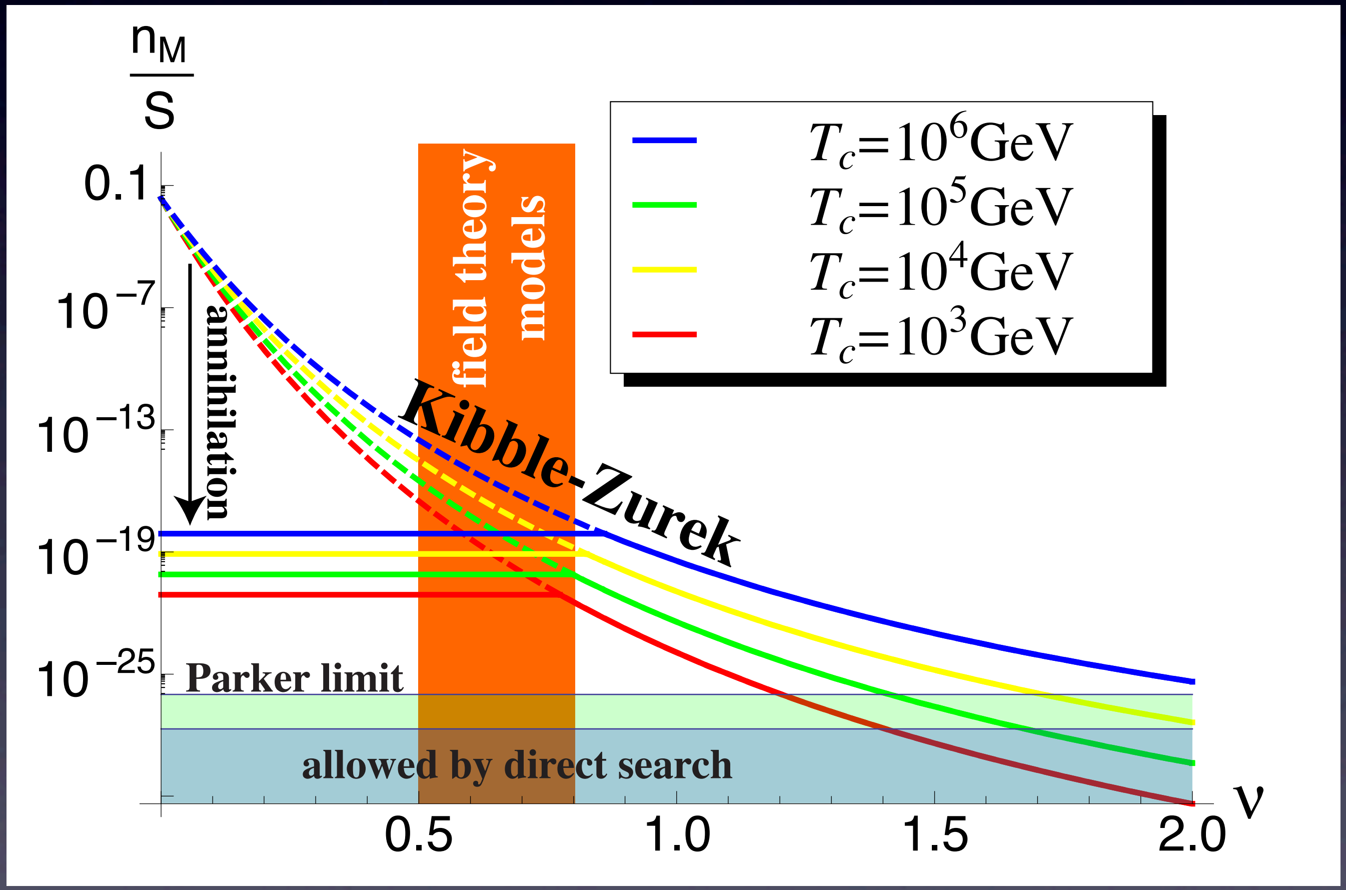
$$\left.\frac{n_{PD}}{s}\right|_{T=T_c} \approx 0.1\,\frac{T_c}{M_{pl}} .$$

- more generally:

$$\left.\frac{n_{PD}}{s}\right|_{T=T_c} \approx 0.006\left(\frac{30T_c}{M_{pl}}\right)^{\frac{3\nu}{1+\nu}} .$$

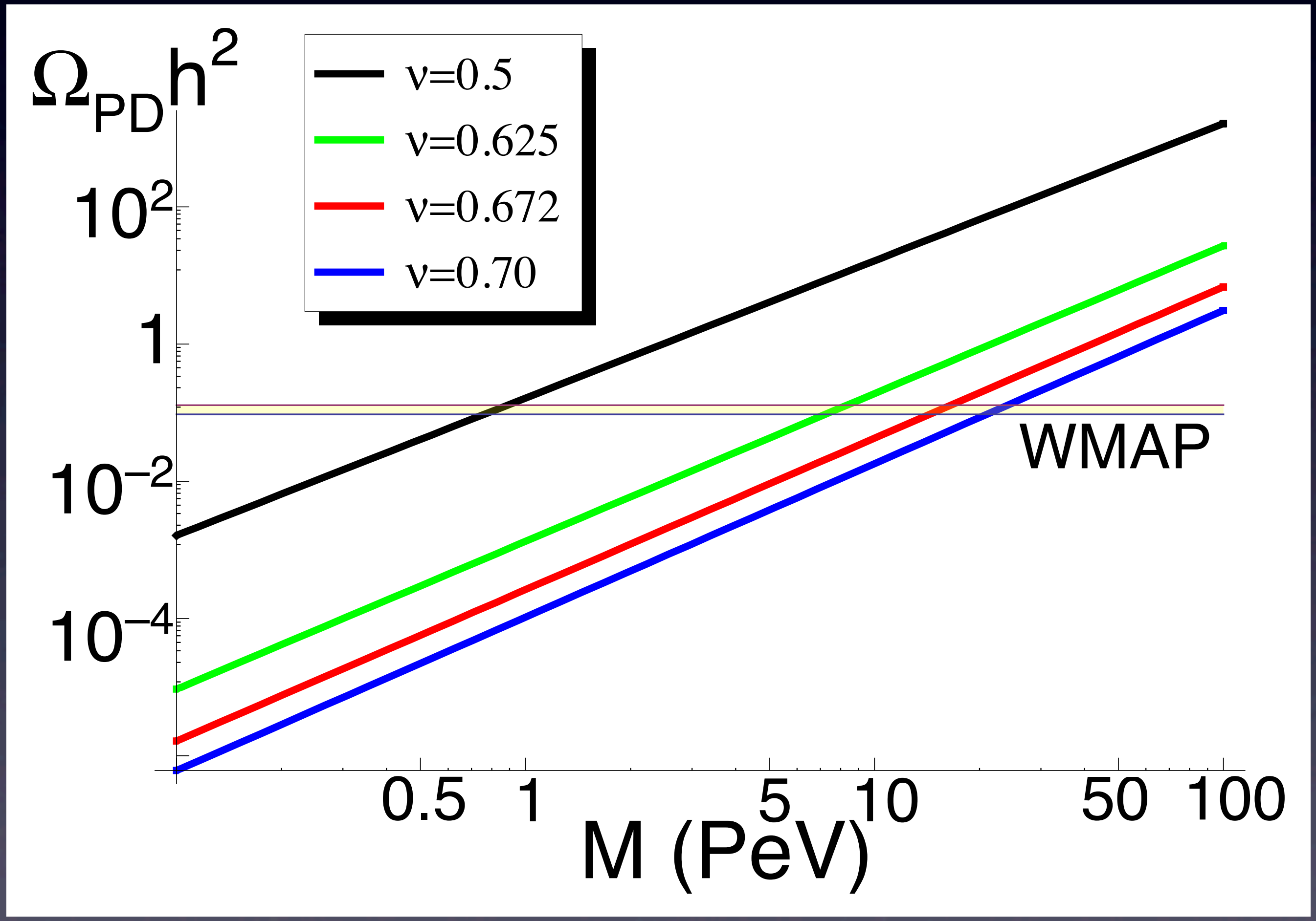
magnetic monopoles

- monopoles annihilate if slowed down by plasma (Preskill)
- we used to think only GUT-scale monopoles are important
- now with enhancement by $(M_{Pl}/T_c)^2$, much lower T_c would be relevant
- Pati-Salam below inflation is all dead!



hidden monopole dark matter

- But monopole may not couple to QED
- "hidden monopole"
- Then it could well be dark matter!



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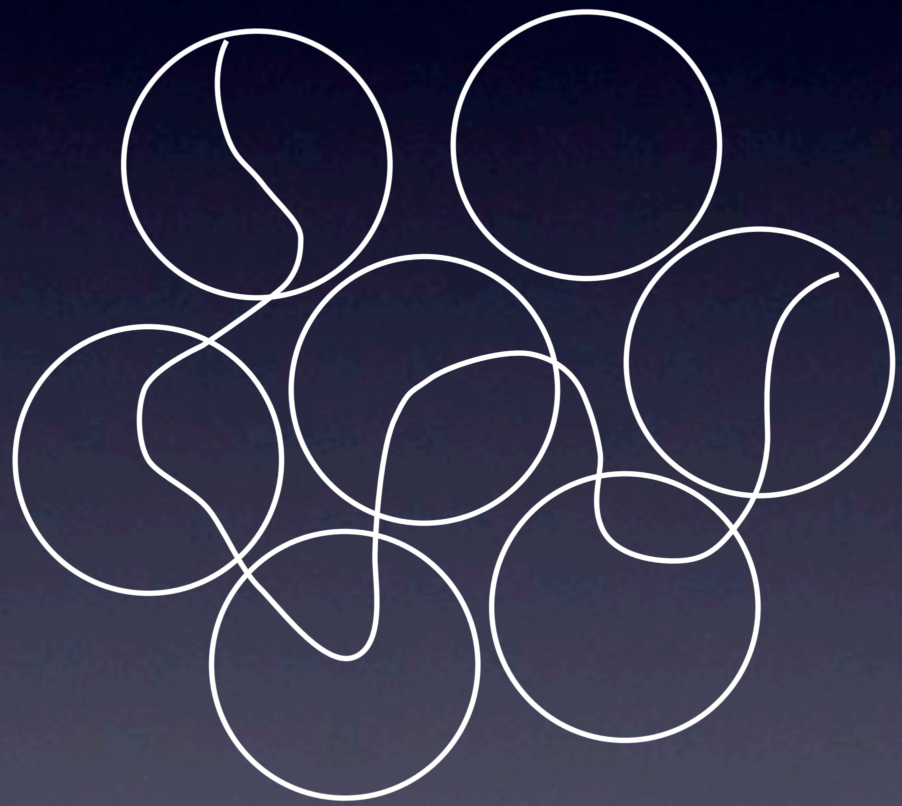
Domain Walls

Alexander Friedland, HM, Maxim Perelstein

PRD 67, 043519 (2003) with updates

Domain Walls

- When a discrete symmetry breaks, domain walls form
- it is usually assumed that the network of domain walls (or strings) *scale*, namely they keep simplifying so that there is practically only one defect per horizon
- initial condition doesn't matter



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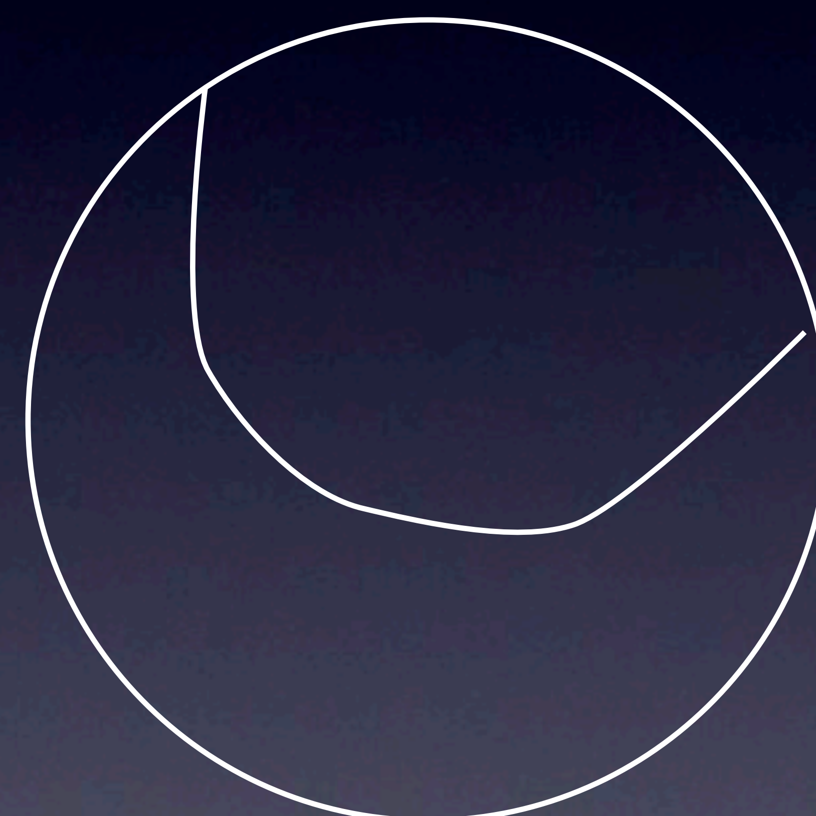

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Frustration

- If the discrete symmetry group is complicated (e.g., large Z_N, non-abelian), network may not find a way of simplifying
- *frustrated* network only gets stretched by the expansion of the Universe
- compare to 1st law of thermo: $\rho \propto R^{-3(1+w)}$
- pointlike defects: $w=0$, $\rho \propto R^{-3}$
- string network: $w=-1/3$, $\rho \propto R^{-2}$
- wall network: $w=-2/3$, $\rho \propto R^{-1}$

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Previous study

- With Friedland and Perelstein, we studied the possibility of domain-wall dark energy
- Used Kibble mechanism
- CMB anisotropy constraint severe
- needed $T_c \approx 100$ keV
- walls *well-behaved*, prob to miss one $p<10^{-3}$
- shouldn't *break* for more than $T_c/T_0=10^8$

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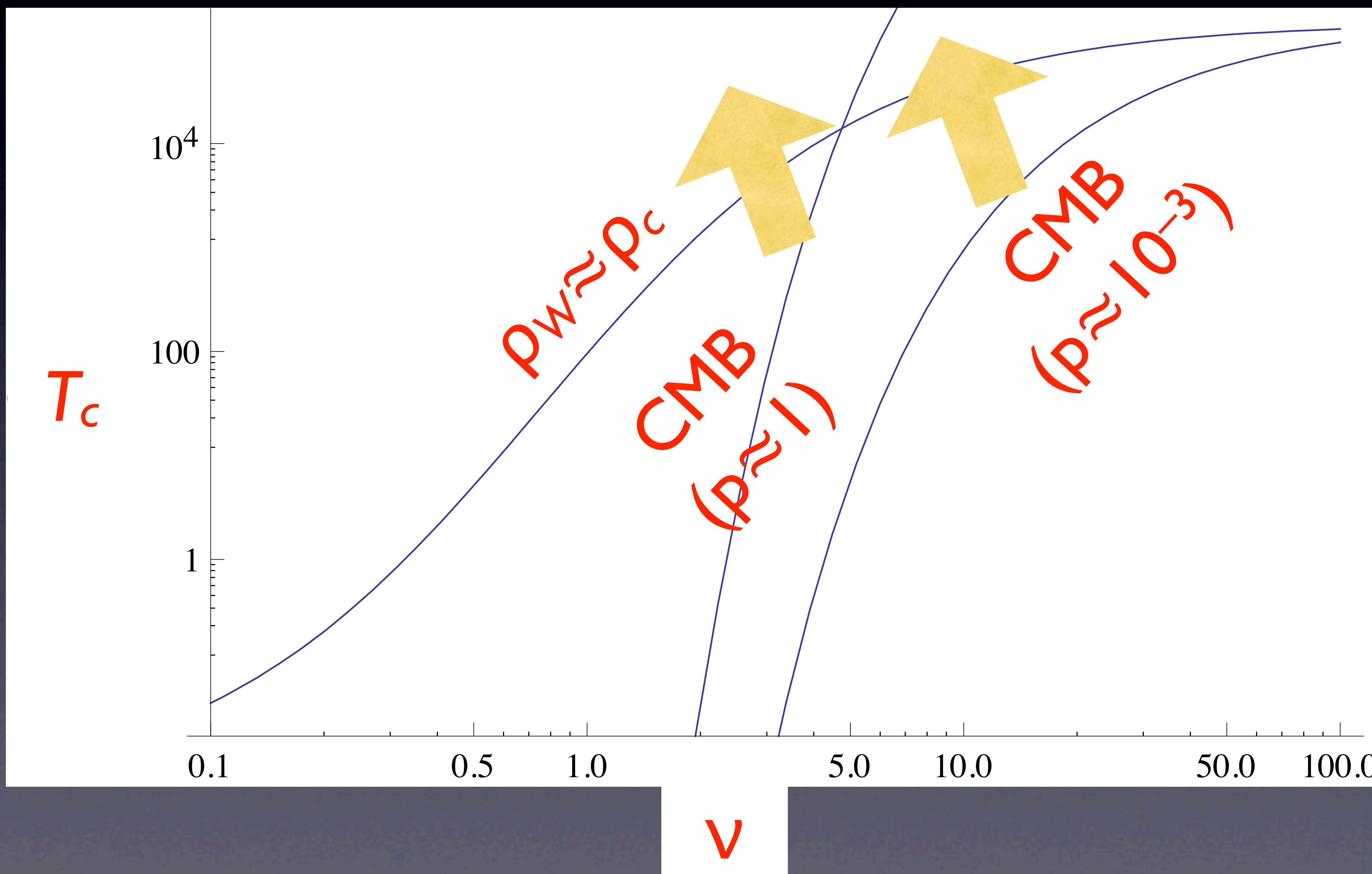
Revised study

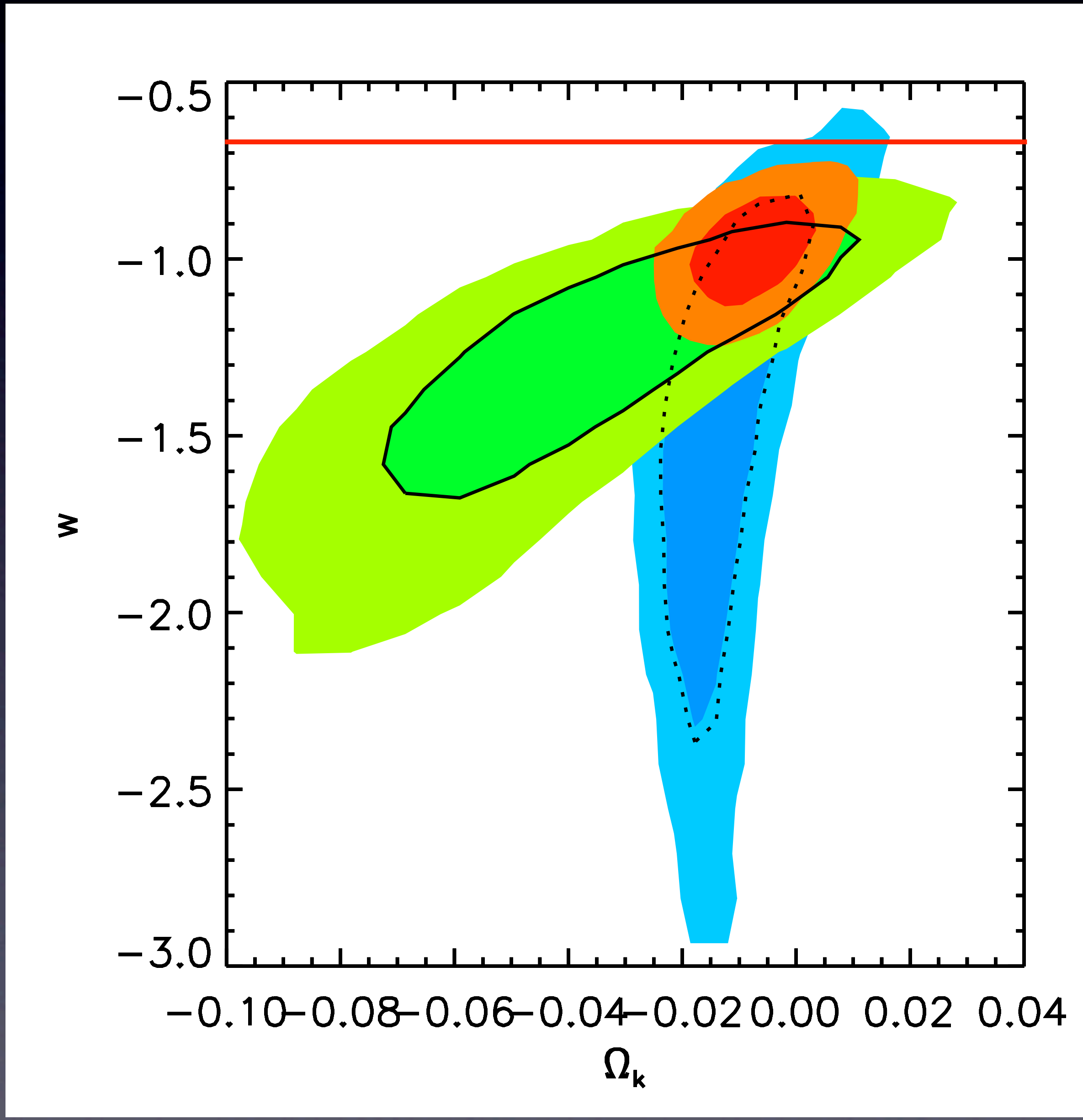
- Used Kibble-Zurek mechanism
- CMB anisotropy constraint trivial
- need $T_c \approx 10$ eV
- walls don't need to be *well-behaved*, prob to miss one $p \approx 1$ OK
- shouldn't *break* for more than $T_c/T_0 = 10^4$

T_c constraints



3 sigma away

- Admittedly, the current constraints from WMAP +BAO+SNe do not prefer w=–2/3
- w=–0.99±0.11
- systematics?
- subdominant contribution?



Percival et al arXiv:0907.1660v3

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