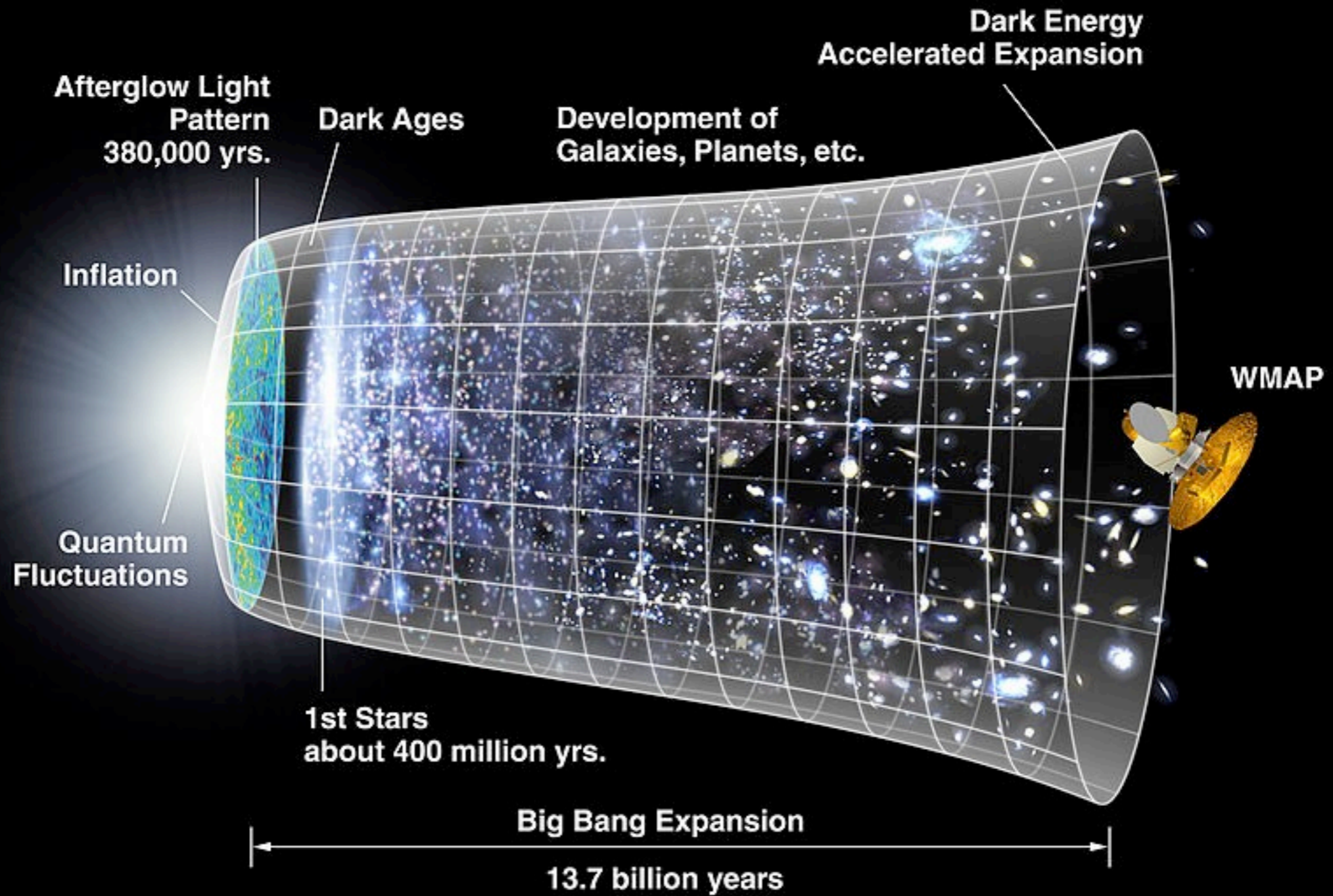


Gases quânticos: a matéria mais fria do Universo

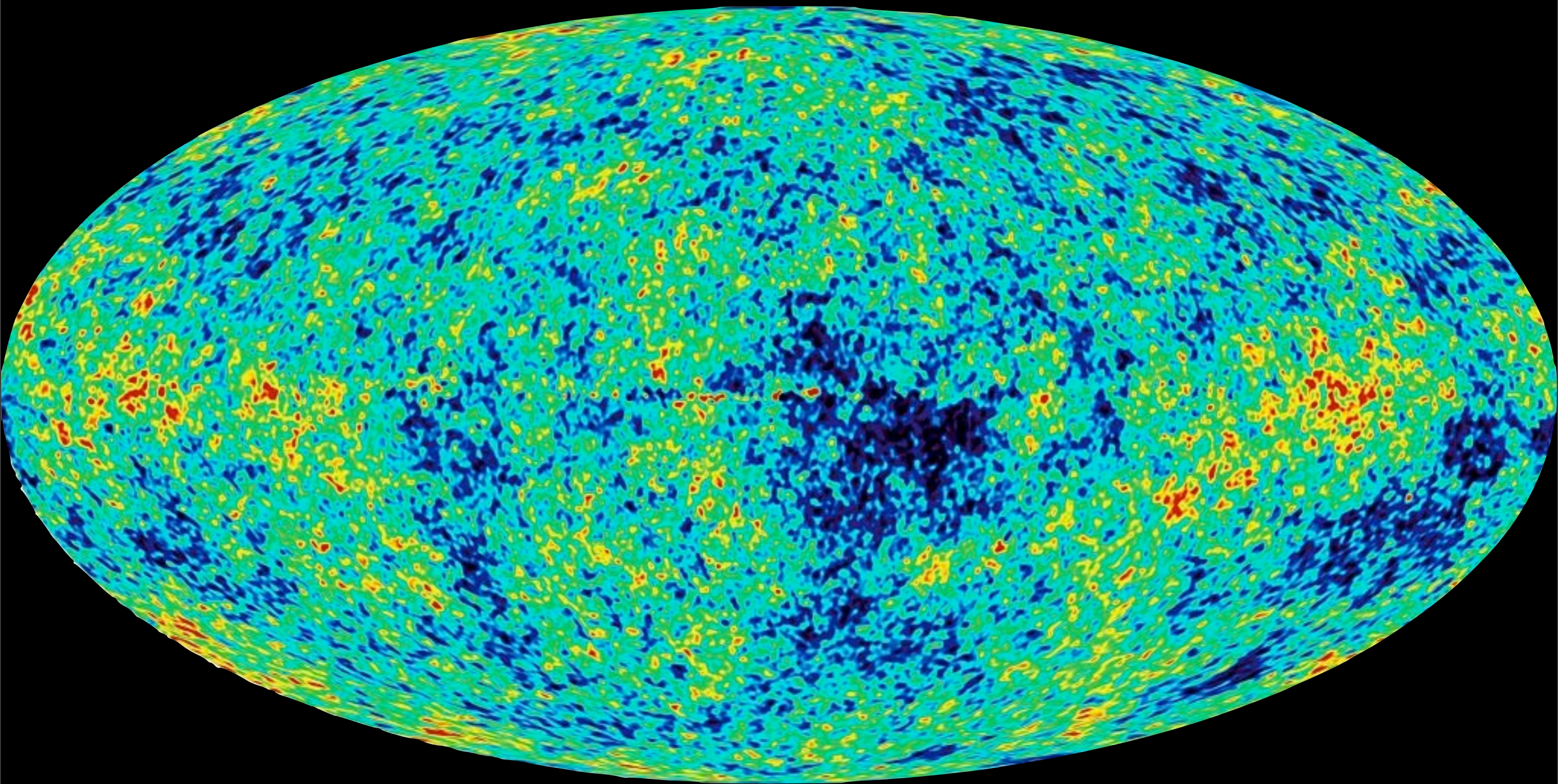
Sérgio R. Muniz
IFSC - USP

Matéria ultrafria?

Por que é a matéria mas fria do Universo?



Temperatura de fundo do Universo



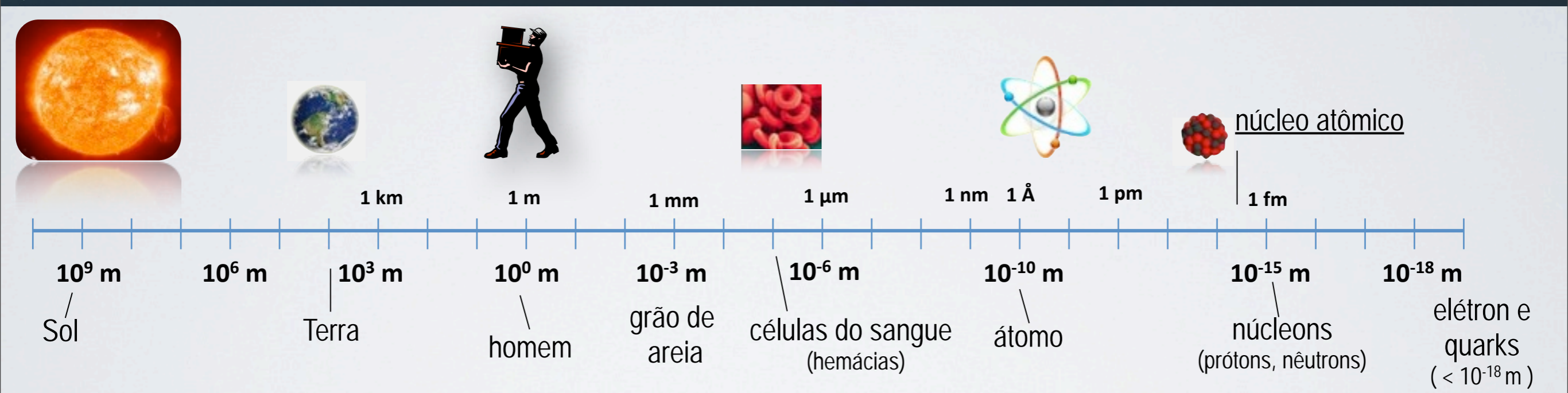
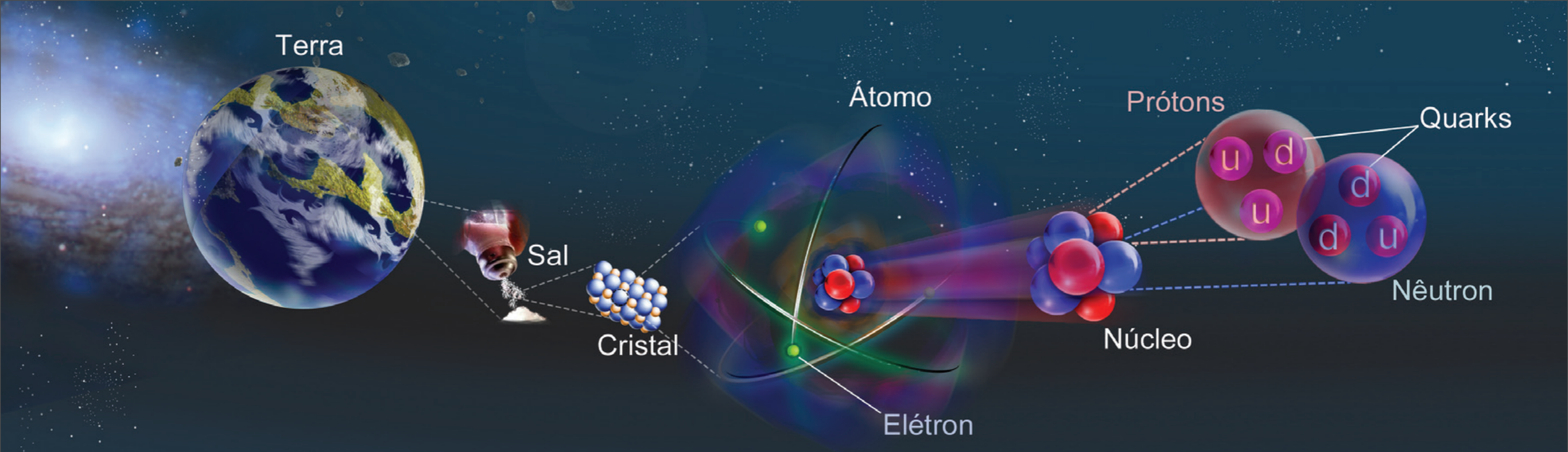
-200 μK

(2,725 K)

200 μK

O que é *Matéria* ?

Do que é feito o Universo?

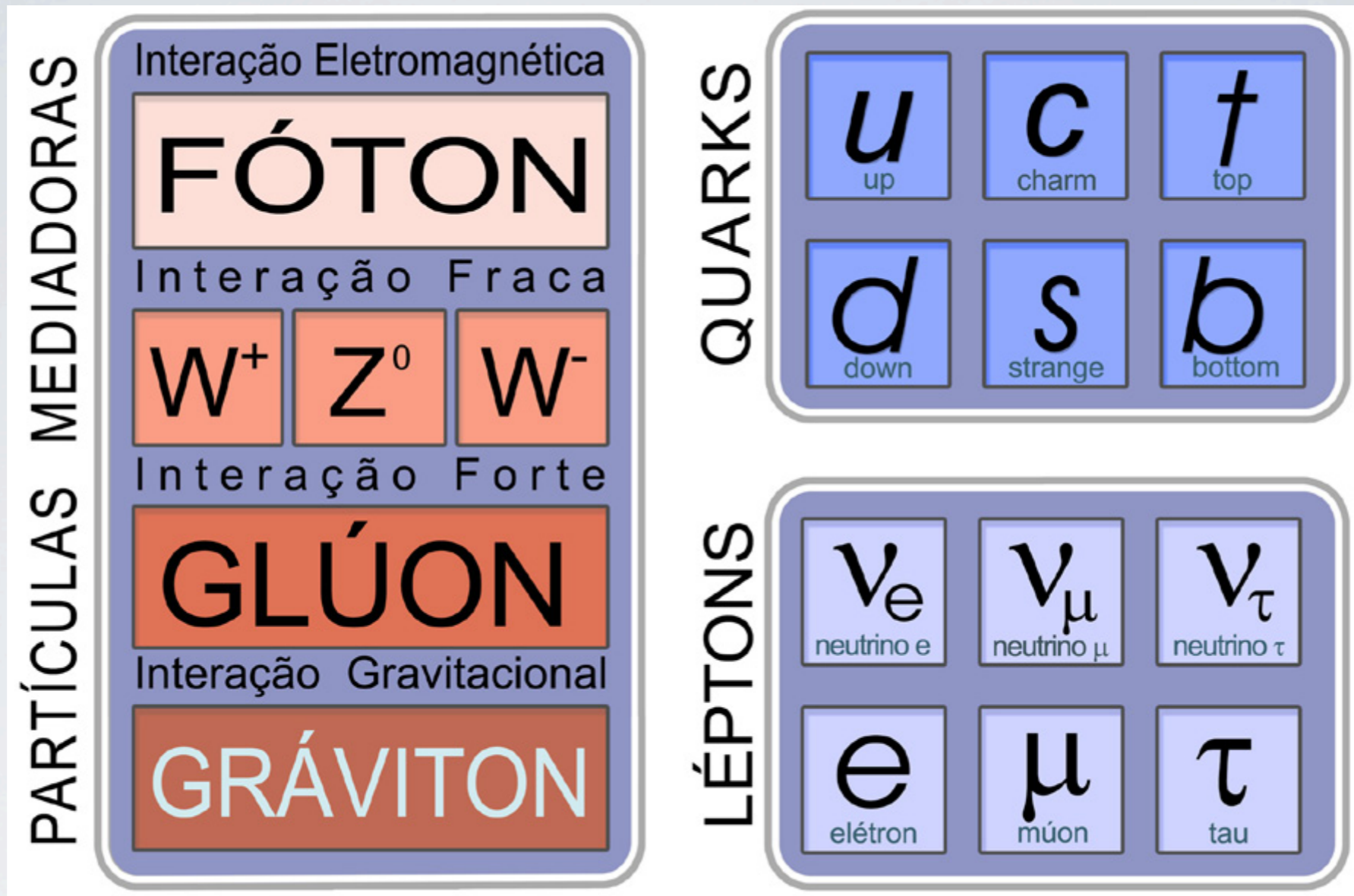


O TAMANHO DAS COISAS

Ganhando intuição sobre as escalas do Universo

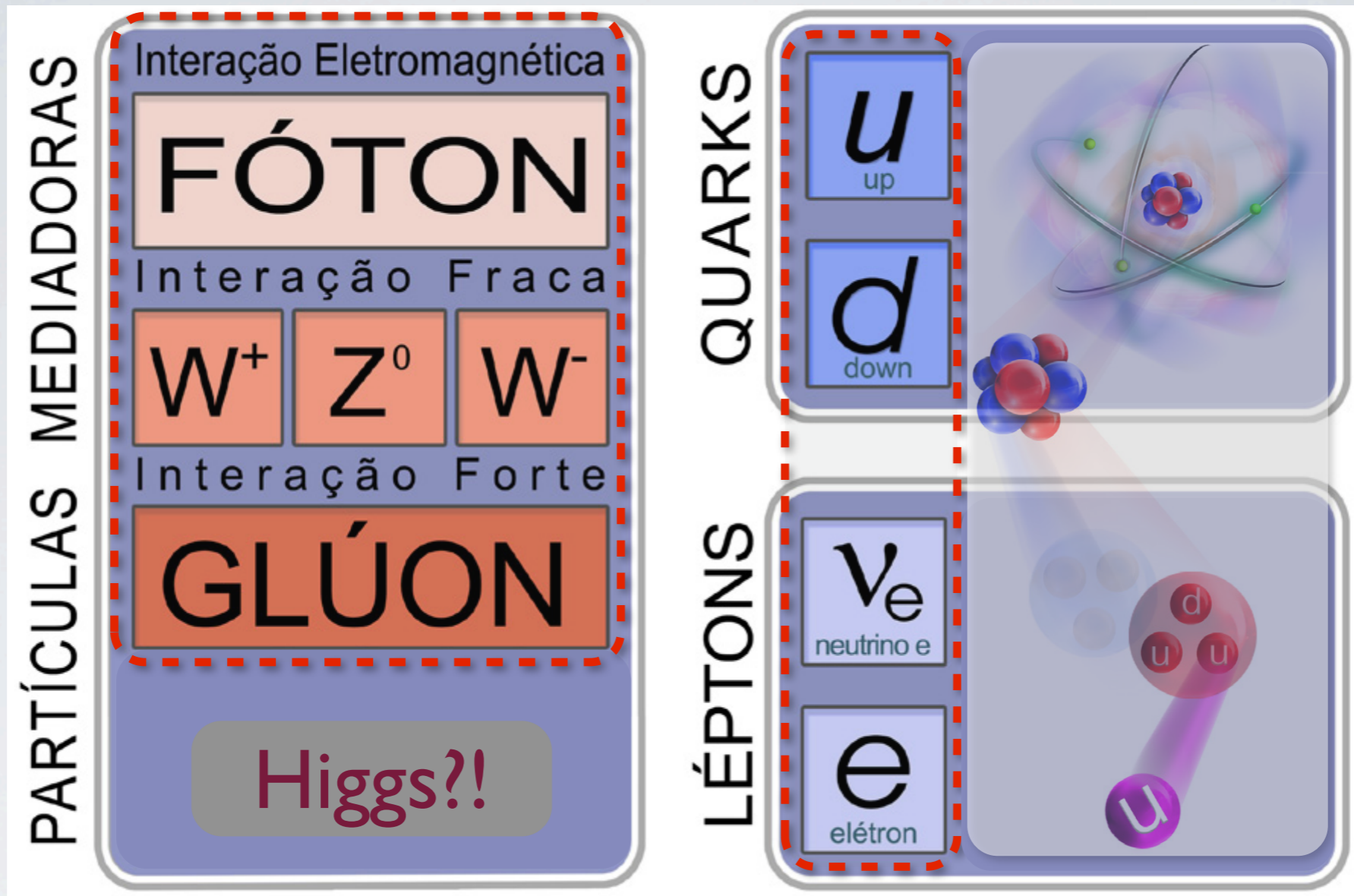
Bósons

Férmions



○ MODELO PADRÃO

das partículas elementares



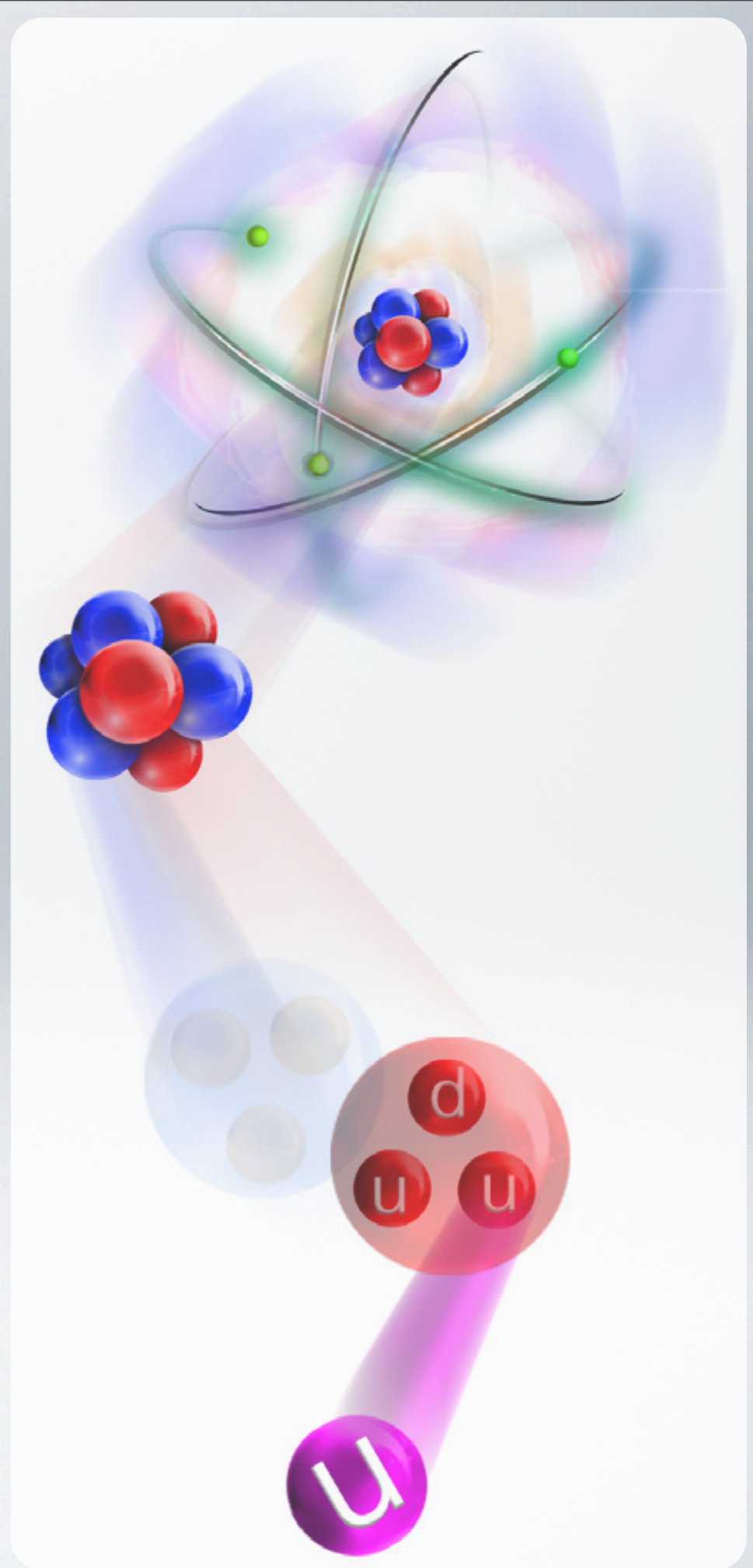
OBSERVADAS NO UNIVERSO ATUAL

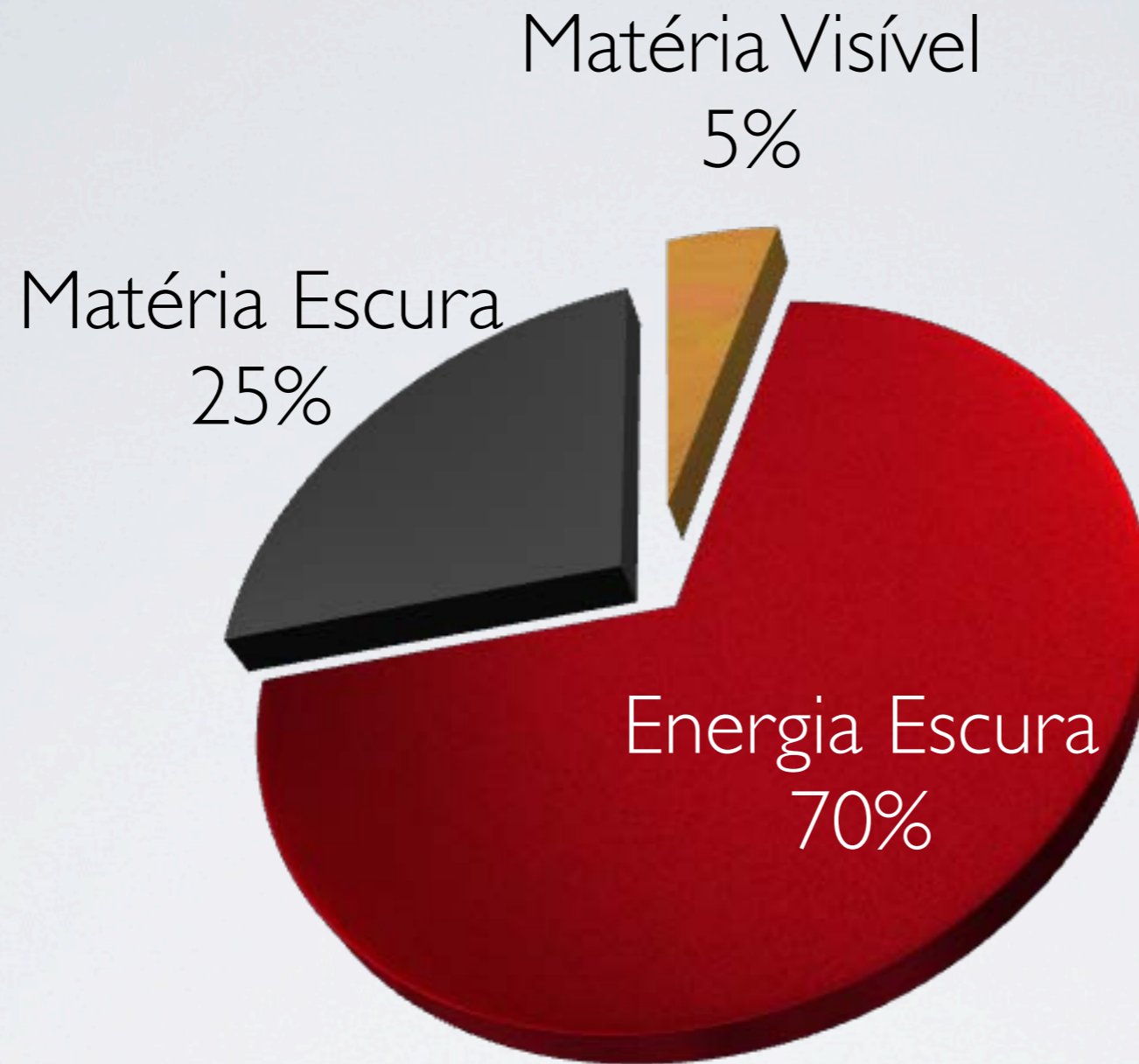
As partículas elementares da matéria a nossa volta

A matéria é feita de...

O ÁTOMO

e partículas subatômicas
(matéria comum ou visível)





MATÉRIA NO UNIVERSO

Distribuição dos tipos de Matéria/Energia conhecidos
(o que sabemos até este momento)

O que é *BEC* ?

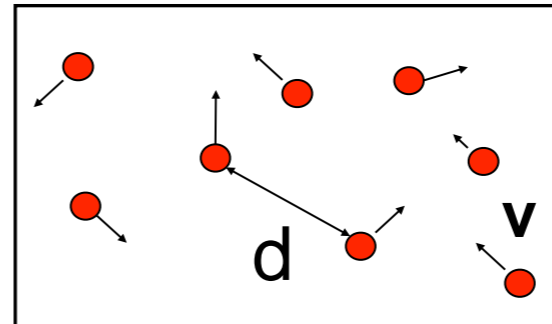
“Bose-Einstein Condensation”

Gases Clássicos & Gases Quânticos

❖ Partículas Distinguíveis

X

Modelo Clássico de um Gás

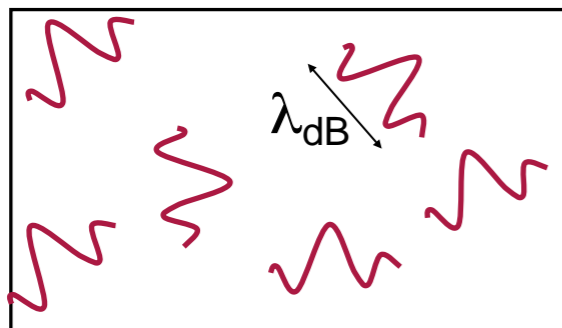


Maxwell-Boltzmann

$$\eta(\epsilon) = \frac{\epsilon}{e^{\epsilon/k_B T}}$$

❖ Partículas Indistinguíveis !??

Pacotes de Onda



Princípio de simetização



Ψ_{total} Simétrica:

Bose-Einstein

$$\eta(\epsilon_i) = \frac{\epsilon_i}{e^{(\epsilon_i - \mu)/k_B T} - 1}$$



Ψ_{total} Anti-Simétrica:

Fermi-Dirac

$$\eta(\epsilon_i) = \frac{\epsilon_i}{e^{(\epsilon_i - \mu)/k_B T} + 1}$$

Spin

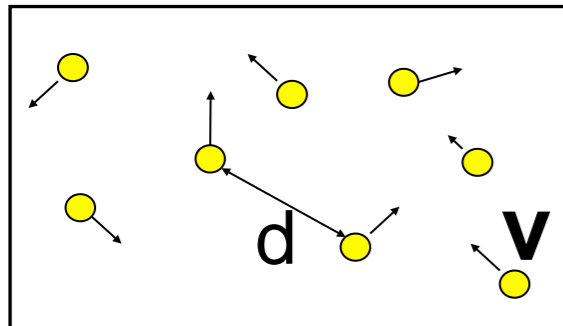
Propriedade que distingue as partículas em dois grandes grupos.



PROPRIEDADES DAS PARTÍCULAS

BEC in a nutshell

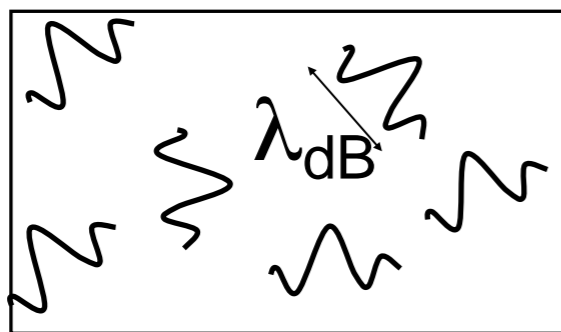
Condensação de Bose-Einstein



Altas Temperaturas

$$\lambda_{dB} / d \ll 1$$

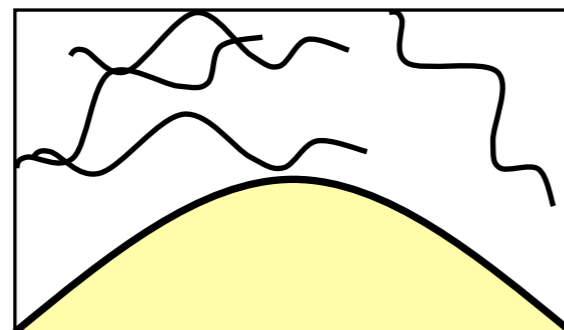
“Corpusculos Massivos”



Baixas Temperaturas

$$\lambda_{dB} \propto T^{-1/2}$$

“Pacotes de Onda”



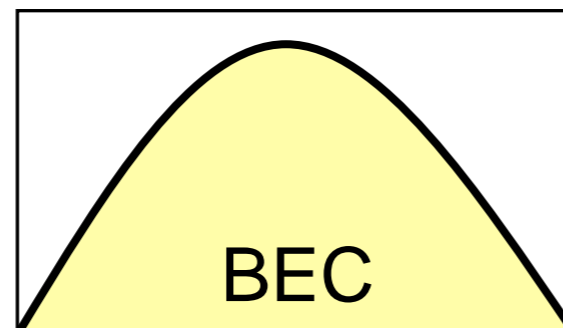
$T = T_c$: BEC

$$\lambda_{dB} \approx d$$

“Overlap de Ondas de Matéria”

Comprimento de onda de de Broglie

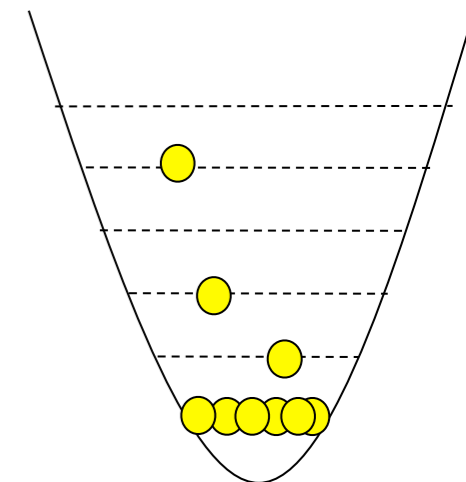
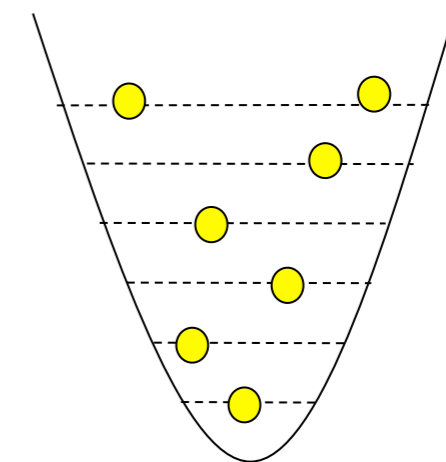
$$\lambda_{dB} \equiv \sqrt{2\pi\hbar^2 / mk_B T}$$



$T = 0$: Condensado Puro

“Onda de Matéria

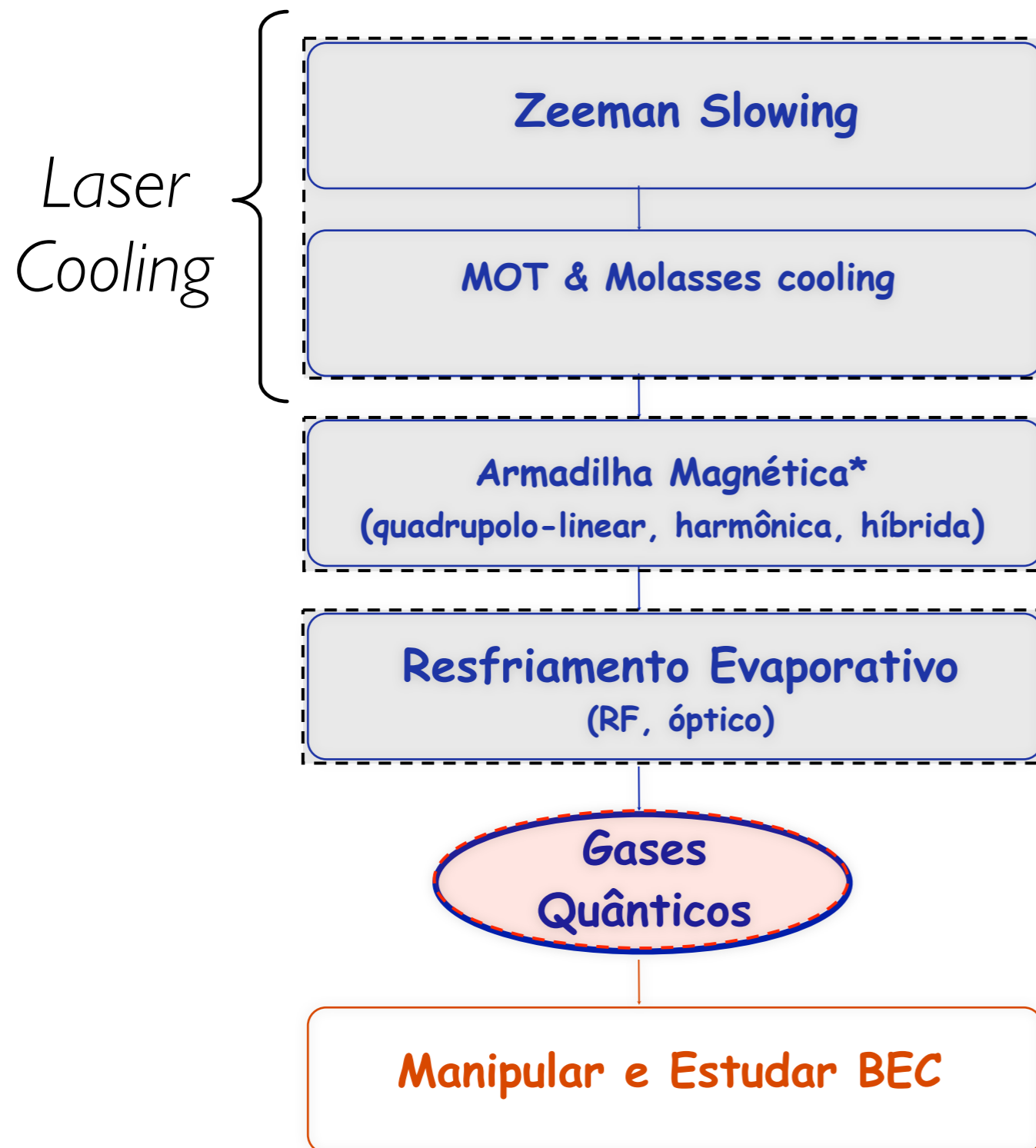
Macroscópica”



$$n_i = \frac{1}{(e^{(\epsilon_i - \mu)/k_B T} - 1)}$$

$\mu \leq 0$ (bósons)

Receita da família para produzir gases quânticos



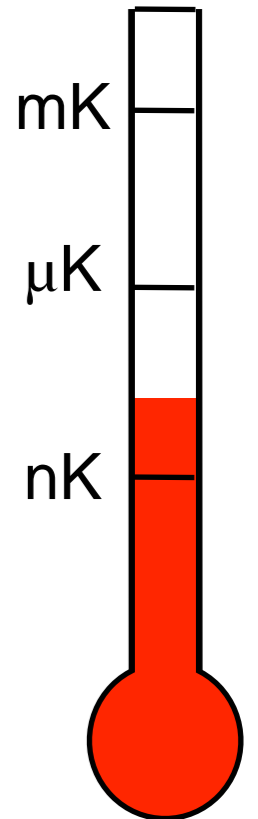
T: 800K → 1mK

T: 1mK → 0.1mK

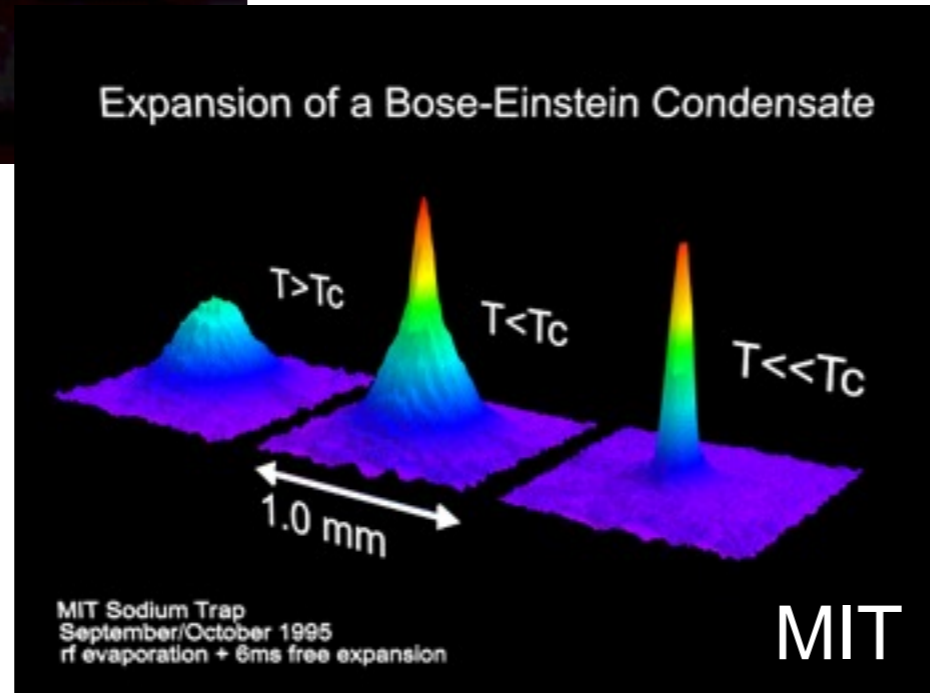
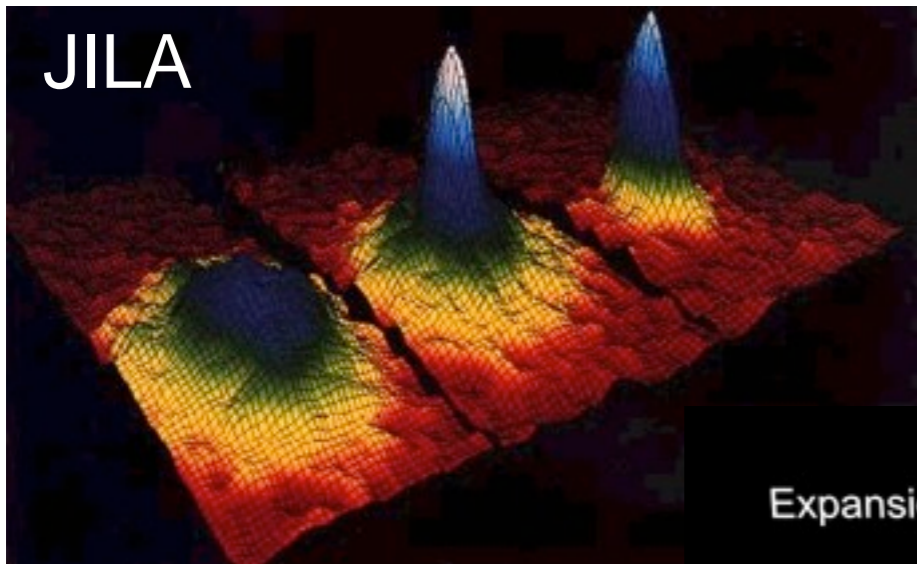
T: 100 → 500μK

T: 500 → 0.1 μK

$T \lesssim 1 \mu\text{K} \therefore D \gg 1$

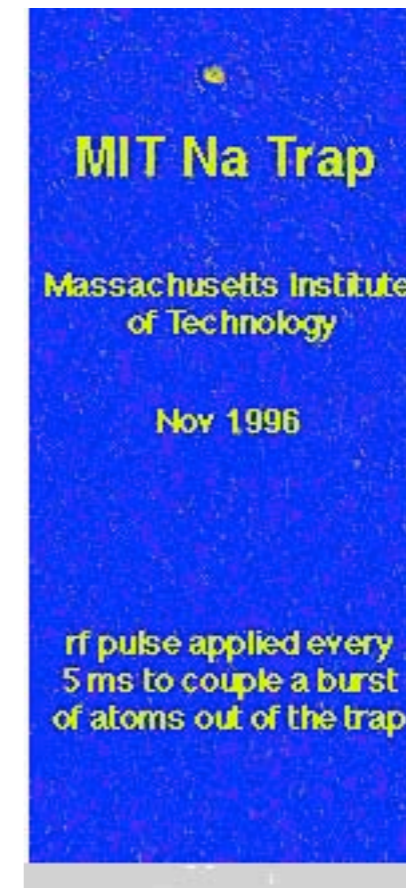
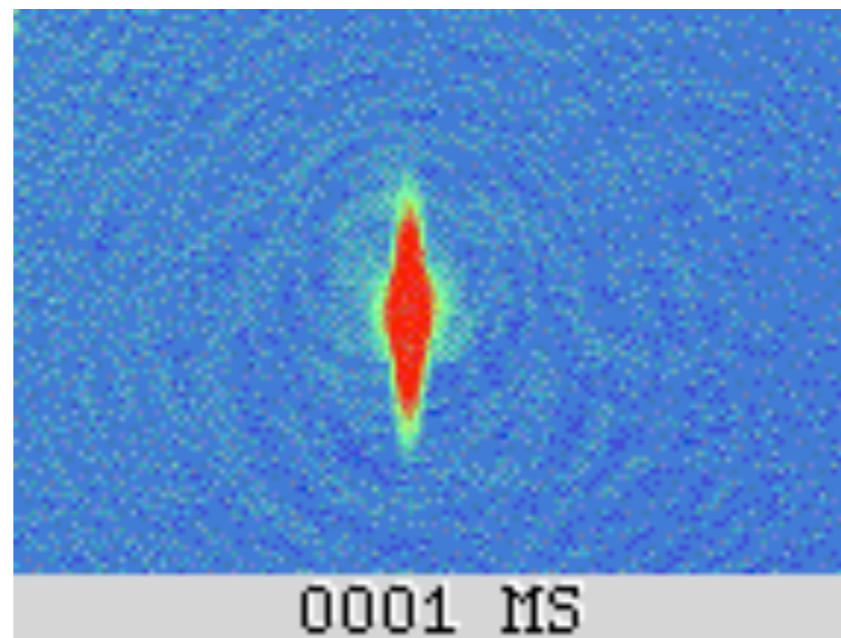
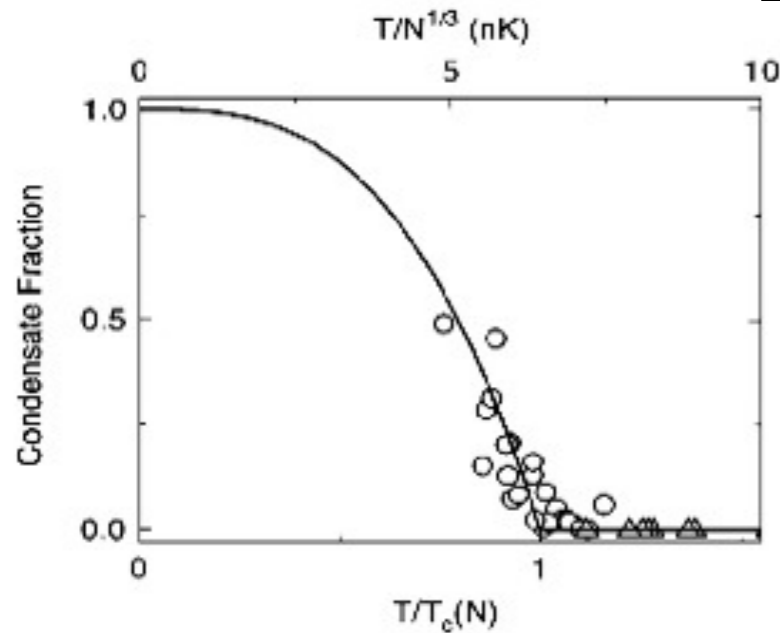


Primeiras observações experimentais de um condensado de Bose-Einstein



Observação de BEC, em átomos de Na. E imagens de expansão livre de um condensado puro.

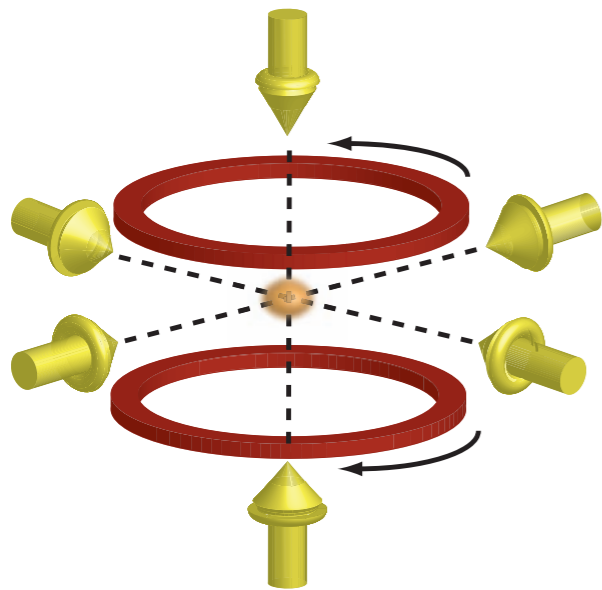
Medida da ocupação macroscópica do estado fundamental!!



Demonstração do princípio de funcionamento de um LASER ATÔMICO

Como se faz matéria ultrafria & BECs ?

Basicamente dois passos:

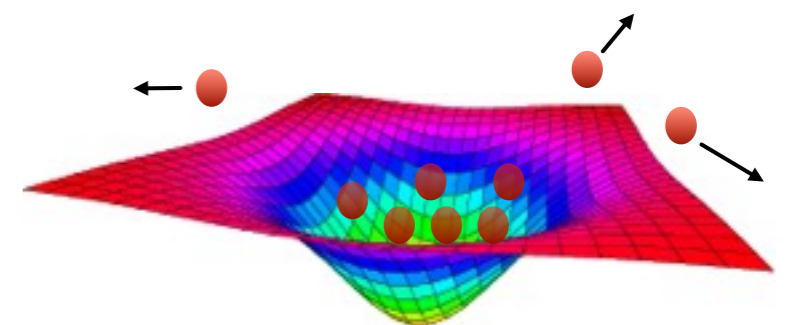


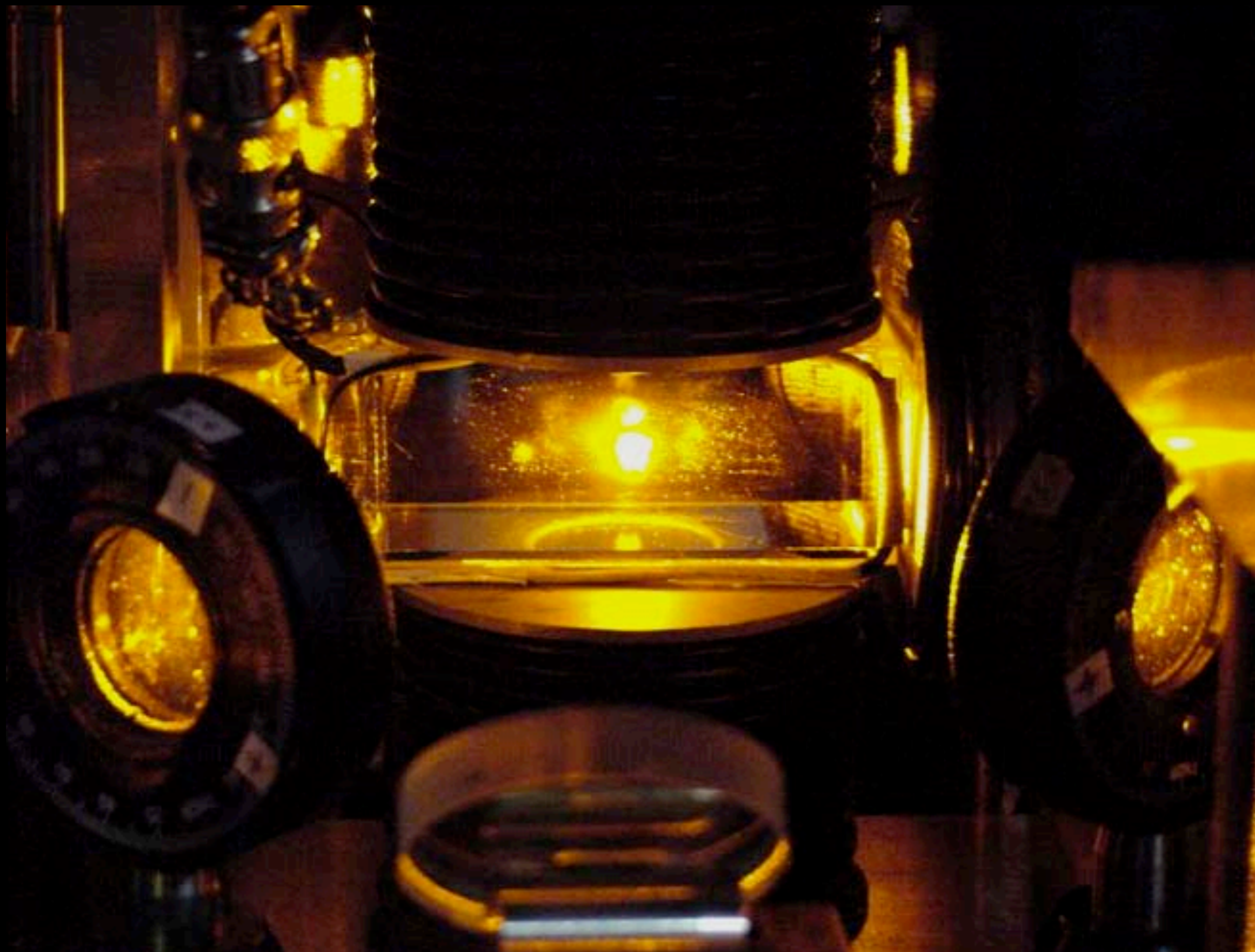
Resfriamento Laser: Resfriamento Doppler

- Magneto-Optical Trap (MOT)

Resfriamento Evaporativo: Evaporação Forçada

- Magnetic traps or Optical traps





MOT sódio — S.R.Muniz (2002)

Como funciona?

“Laser Cooling” = Resfriamento Laser

Dois tipos de interação luz-matéria:

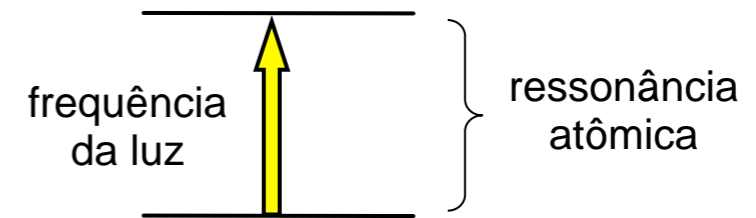
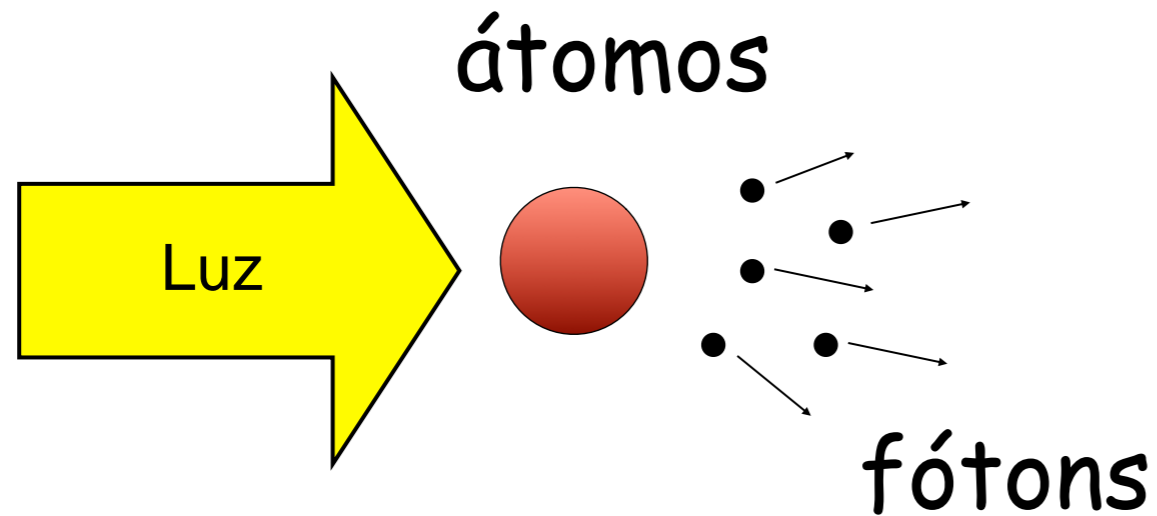
- Força espontânea → Pressão de radiação
- Força de dipolo → Potenciais conservativos

Força da Luz!

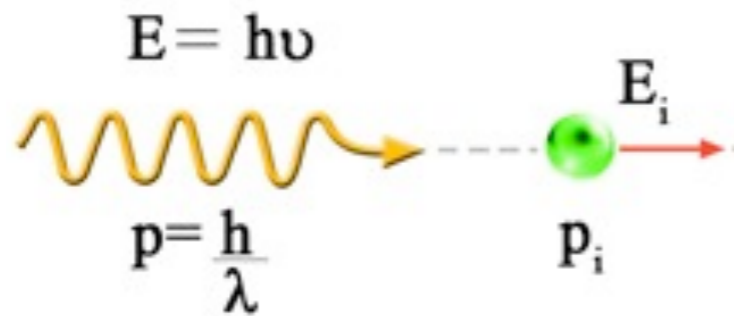
Pressão de radiação



Força da luz sobre os átomos



Luz próxima à ressonância:
aquecimento/resfriamento
(Força Dissipativa)



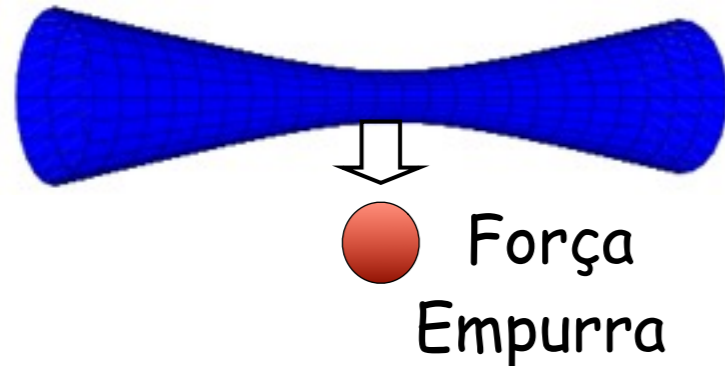
Resfriamento Doppler:

Espalhamento de fótons

$$\vec{F} = \hbar \vec{k} \gamma_s = \hbar \vec{k} \frac{\Gamma \Omega^2}{4\Delta^2}$$

Demo: Laser Cooling

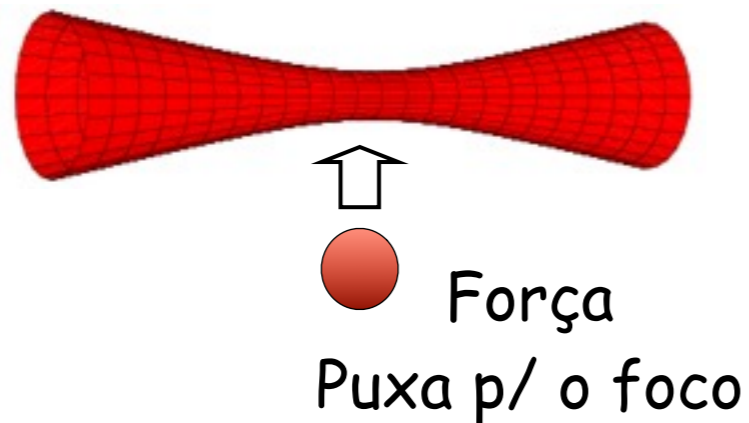
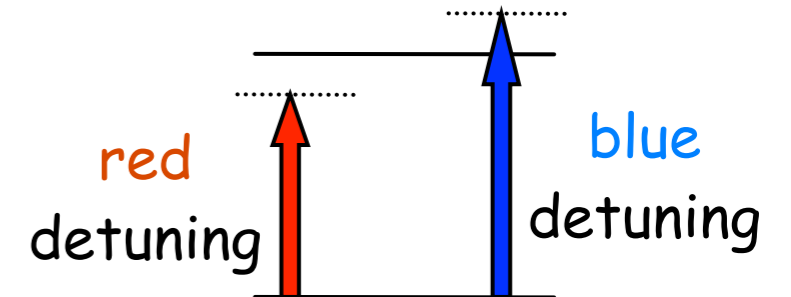
Força da luz sobre os átomos



Luz fora de ressonância:

dependendo do “detuning” pode ser atrativa ou repulsiva

(Força Conservativa)



Força de Dipolo:

Gradiente de intensidade
Depende da frequência

$$\vec{F}(\mathbf{r}) = -\frac{\hbar \vec{\nabla} \Omega^2(\mathbf{r})}{4\Delta^2}$$

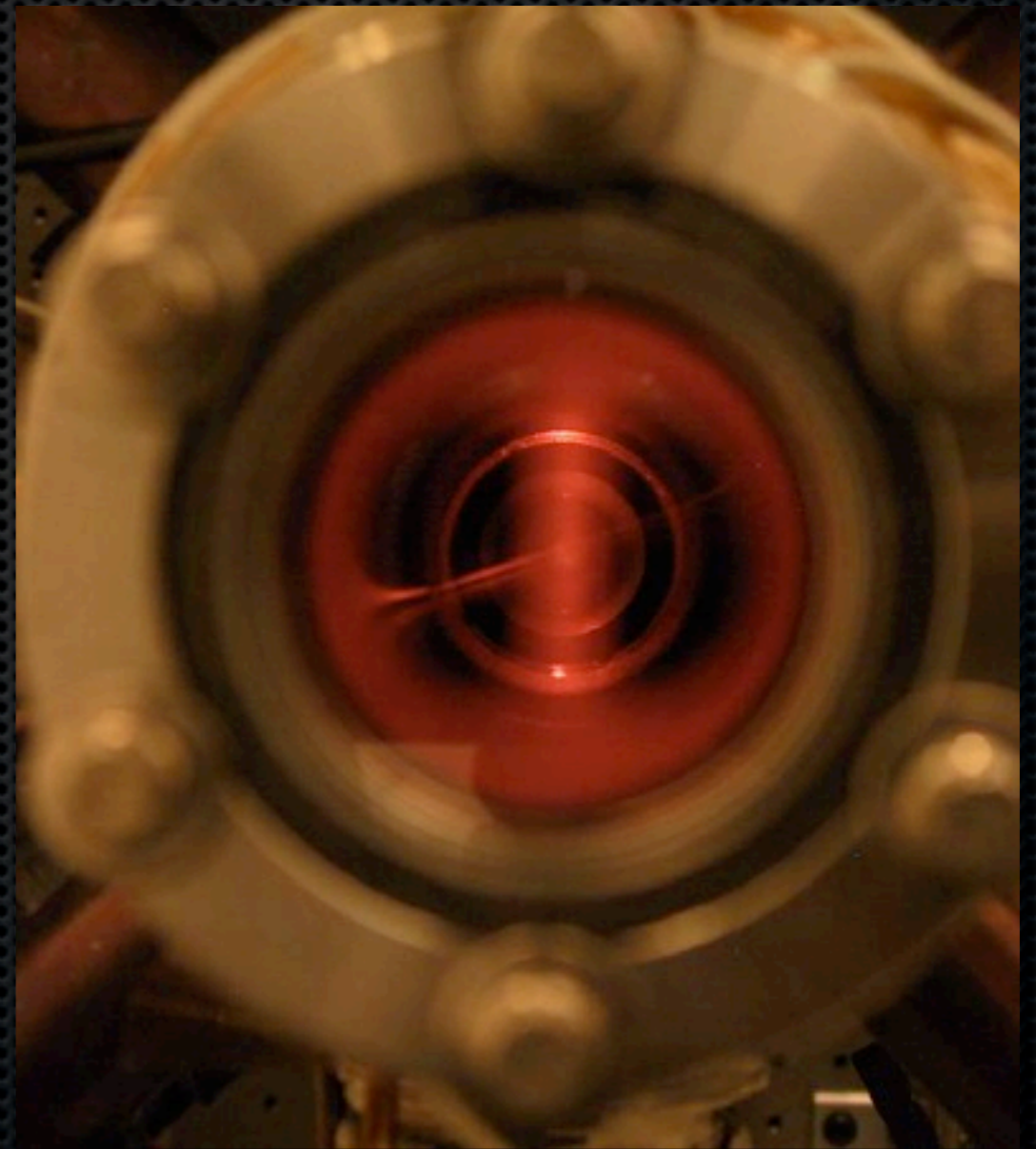
Potencial de dipolo óptico

$$U(\mathbf{r}) = \frac{\hbar \Omega^2(\mathbf{r})}{4\Delta^2}$$

Demo: Pinças ópticas

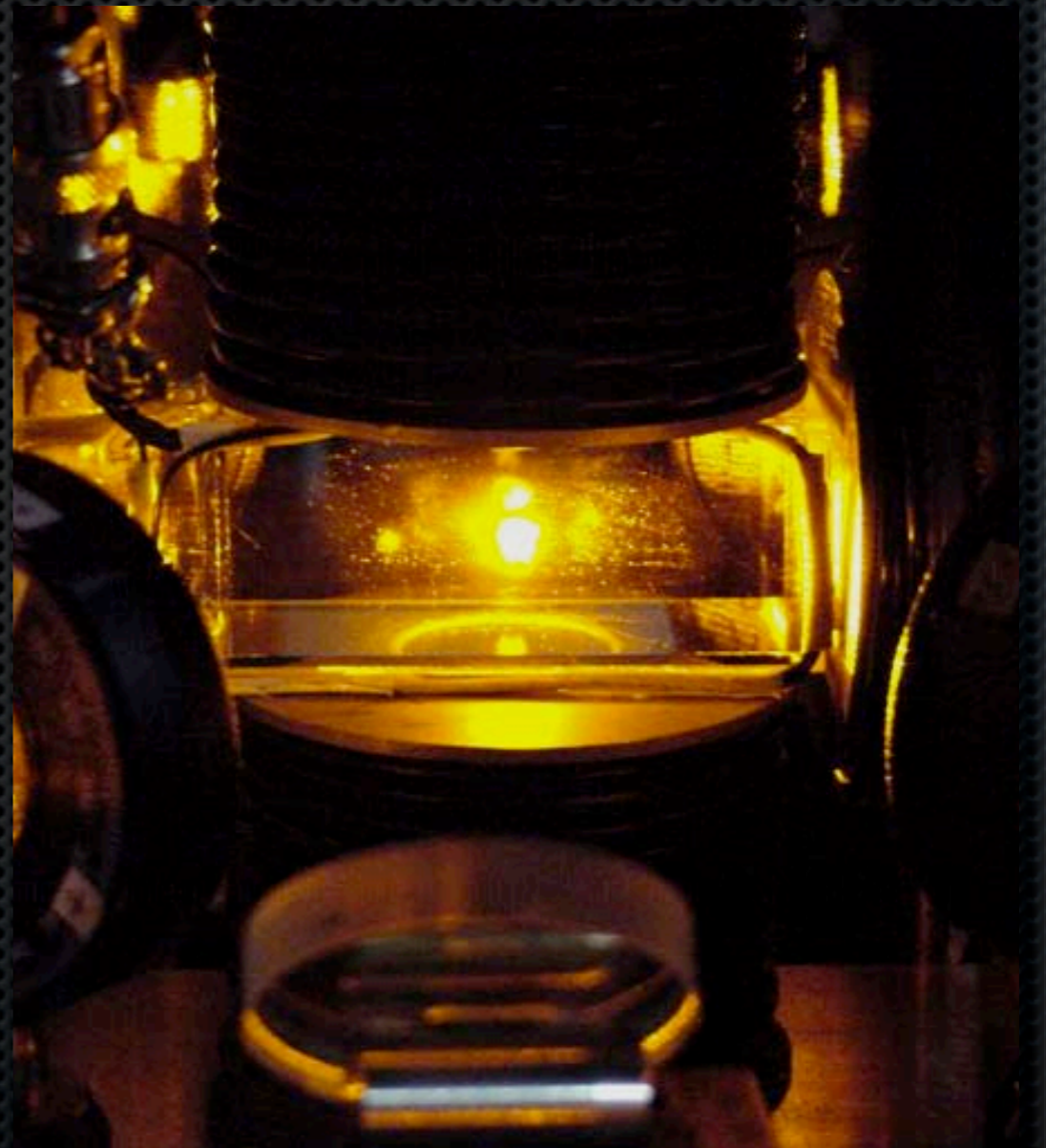
Zeeman Slowing: (“opcional”) Desaceleração de feixes atômicos

- ✦ Laser: “metralhadora” de fótons freia os átomos
- ✦ Campo magnético compensa efeito Doppler
- ✦ Temperaturas ~ 1 K



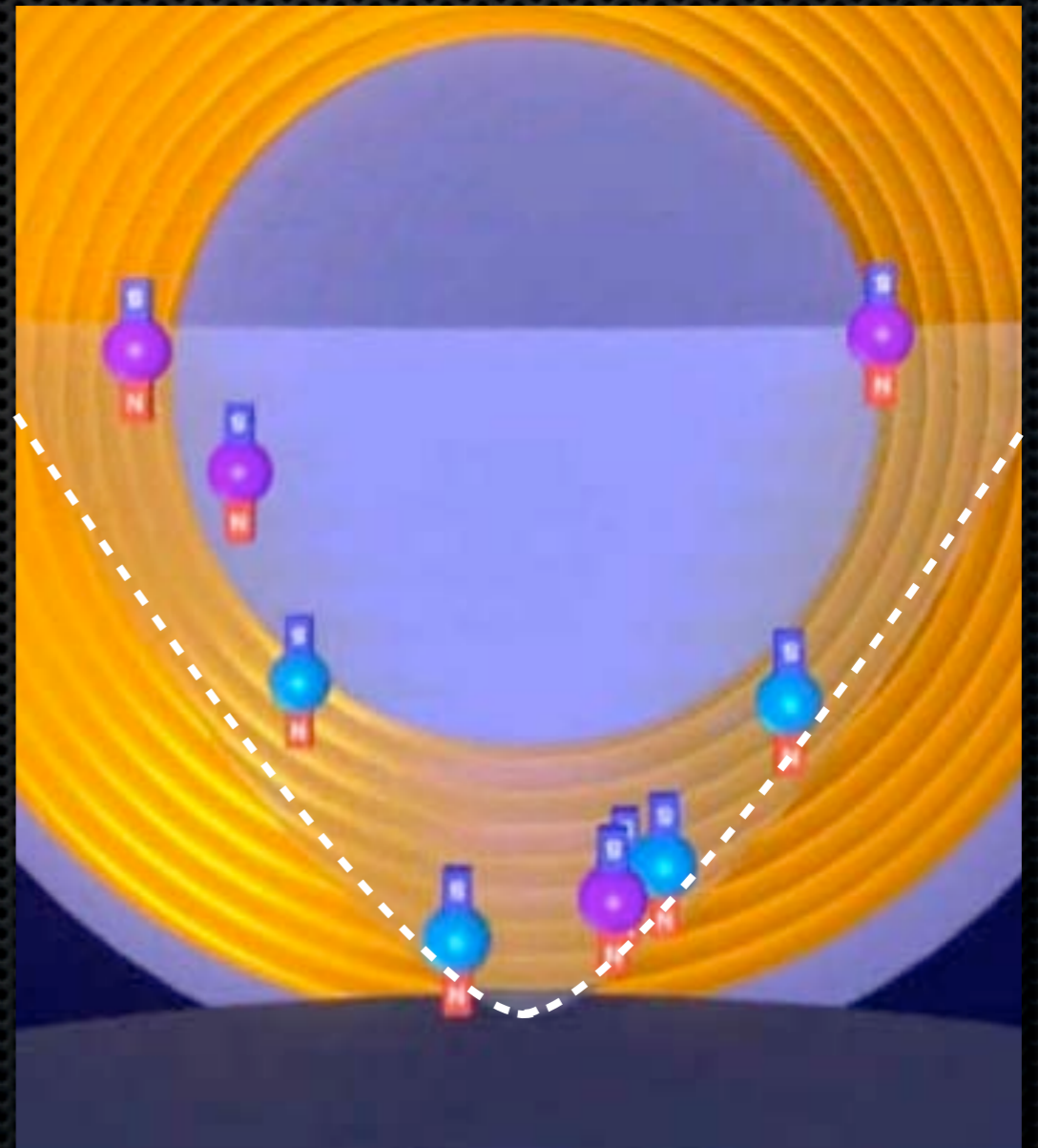
MOT: Armadilha Magneto-Óptica

- Armadilha viscosa (melaço) feita de “luz”
- Campo magnético produz sistema 2-níveis
- Temperaturas $\sim 100 \mu\text{K}$



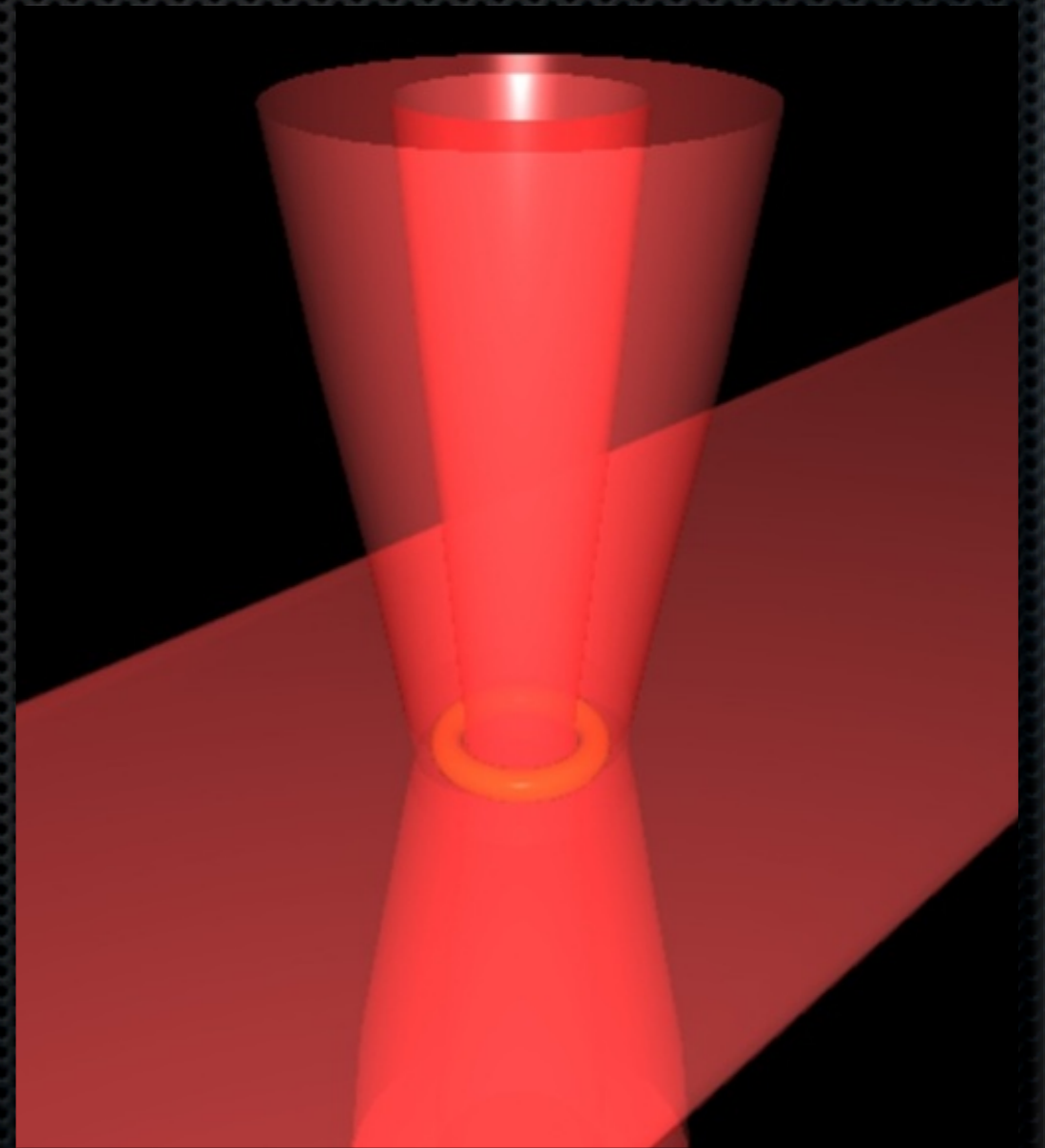
MagTrap: Armadilha puramente Magnética

- ✦ spin dos átomos é como pequenos ímãs
- ✦ Campo magnético produz um “poço” de potencial
- ✦ Temperaturas $\ll 1 \mu\text{K}$



Dipole Trap: Armadilha puramente Óptica

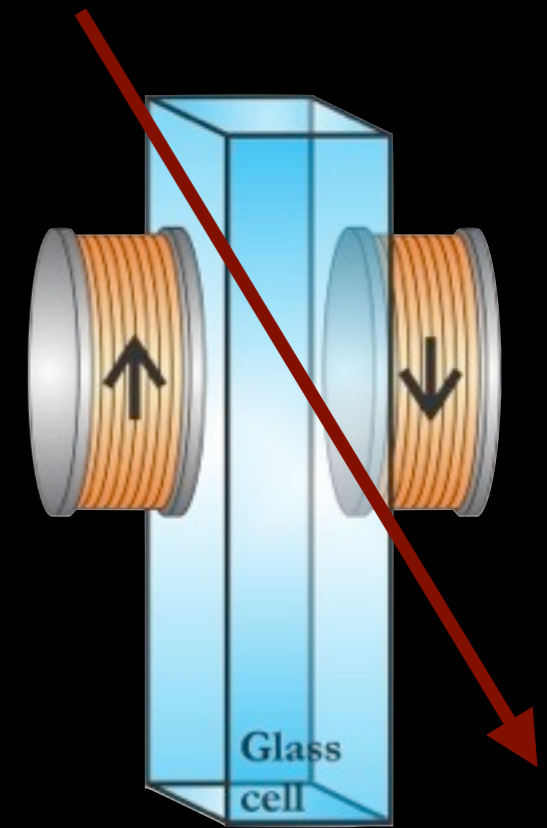
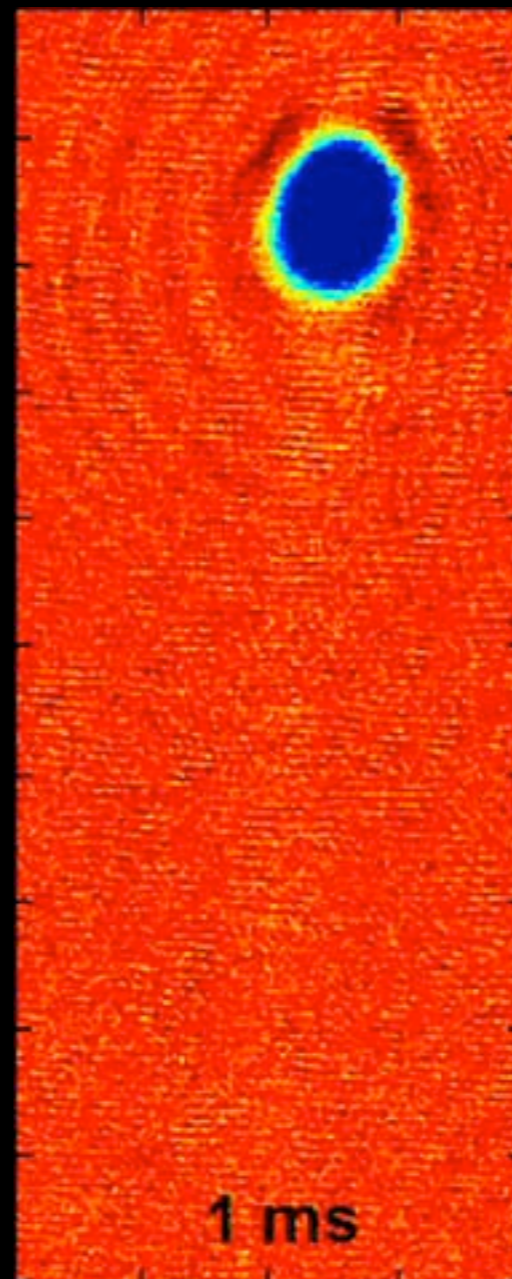
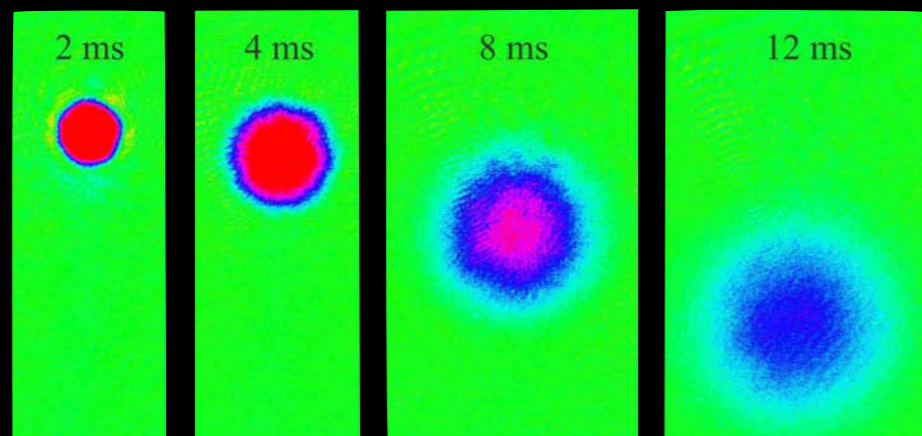
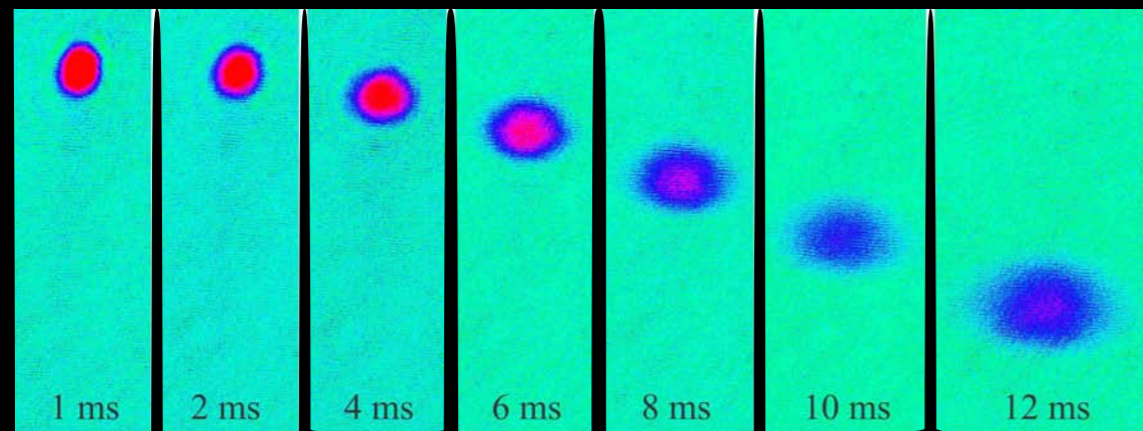
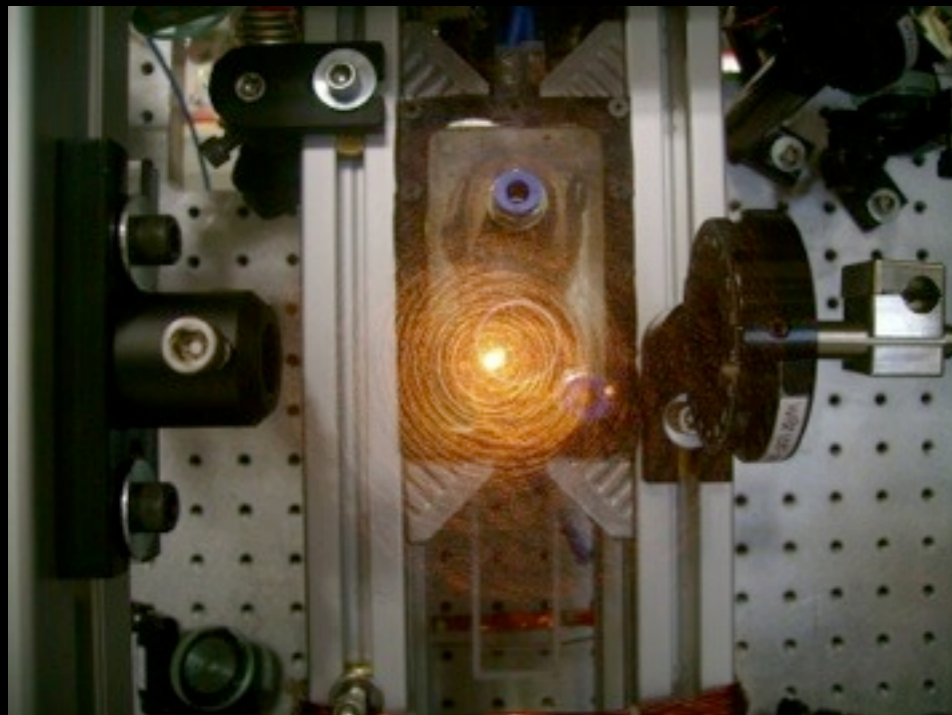
- ✦ Armadilha de “luz”
- ✦ Campo elétrico produz potencial conservativo
- ✦ Temperaturas $\ll 1\mu\text{K}$



BEC no IFSC (Rb-I)



Novo condensado do IFSC (Rb-II)



Magnetismo quântico
Superfluidez &
Supercondutividade
Informação &
Computação quântica

Porque BEC ?

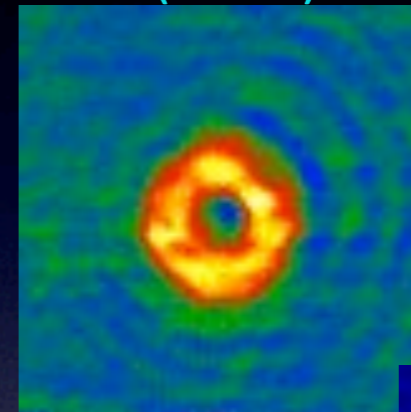
Novas Áreas de Pesquisa

- Simulação quântica de sistemas complexos
- Explorar novos caminhos em QIP: emaranhamento em sistemas de muitos corpos
- Potenciais ópticos dinâmicos de altíssima precisão e novas técnicas de imagem (reconstrução holográfica e NMR)

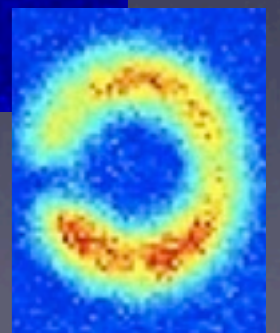
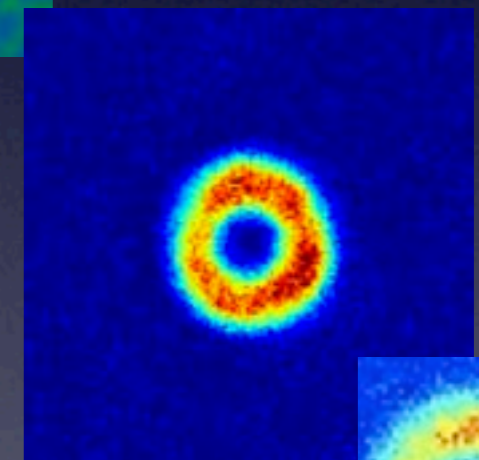
Potenciais ópticos no IFSC

- “Engenharia” de potenciais ópticos arbitrários: SLMs, AODs
 - Holografia (em uso)
 - contraste de fase (demonstrada)
 - Técnicas acusto-ópticas (em uso)

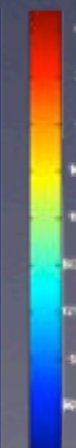
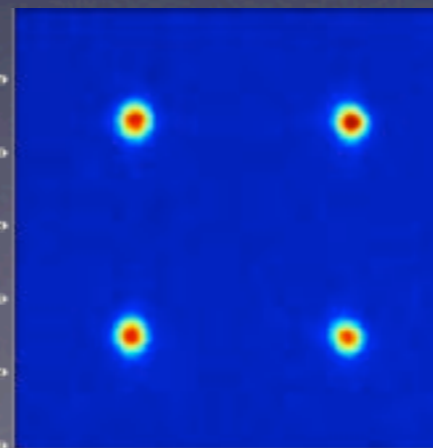
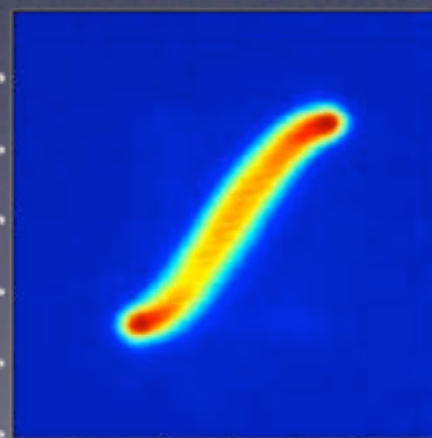
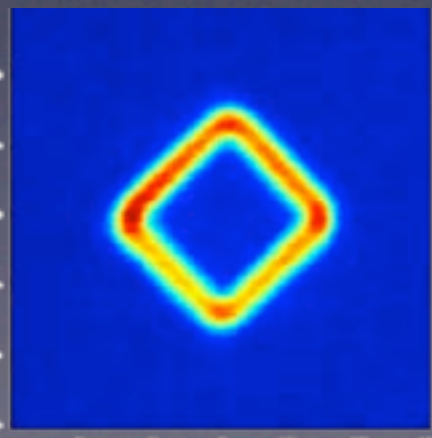
GT (2005)



NIST (2010)



Persistent Currents
Weak links and
Atomic-SQUID



BEC = função de onda macroscópica

$$\Psi = \sqrt{n(x)} e^{i\phi(x)}$$

↑
densidade atômica

↑
fase
macroscópica

Equação de Schrödinger não linear

$$i\frac{\partial}{\partial t}\Psi = \left(\frac{-\hbar^2}{2M}\nabla^2 + V(x) + \frac{4\pi\hbar^2 a}{M}|\Psi|^2 \right) \Psi = \mu\Psi$$

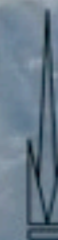
Campo médio de interação atômica

From quantum simulation and quantum twisters to quantum information



NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce



Georgia Institute
of Technology



Katrina/2005



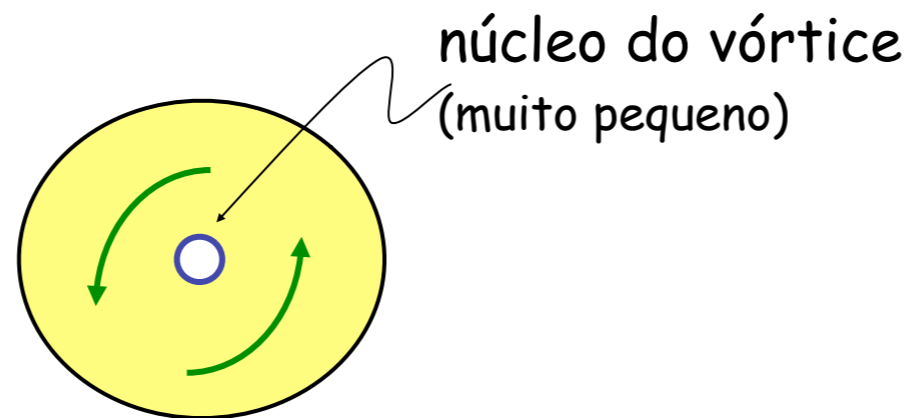
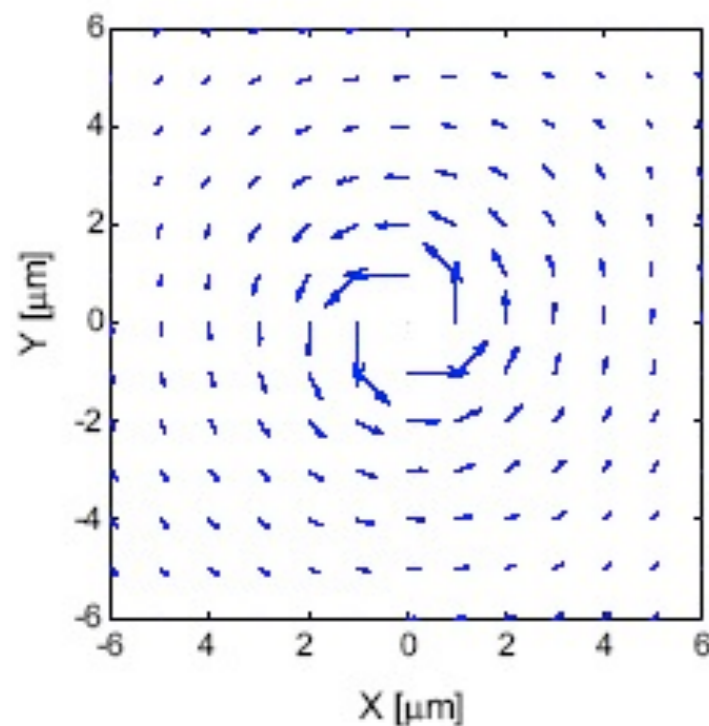
- *Tremendous amount of energy* can cause massive destruction through *friction* and large scale (macroscopic) weather changes...

O mundo quântico é um lugar estranho...

“A hurricane is perhaps Earth's most devastating vortex. But even the deadliest hurricanes die out as they move away from warm waters that power them. Not so in the frictionless world of superfluids.”

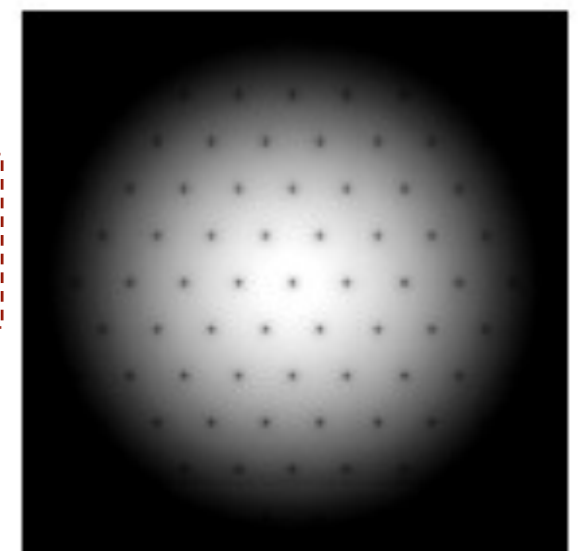


Superfluidos são 'irrotacionais'!!



Momento angular é quantizado

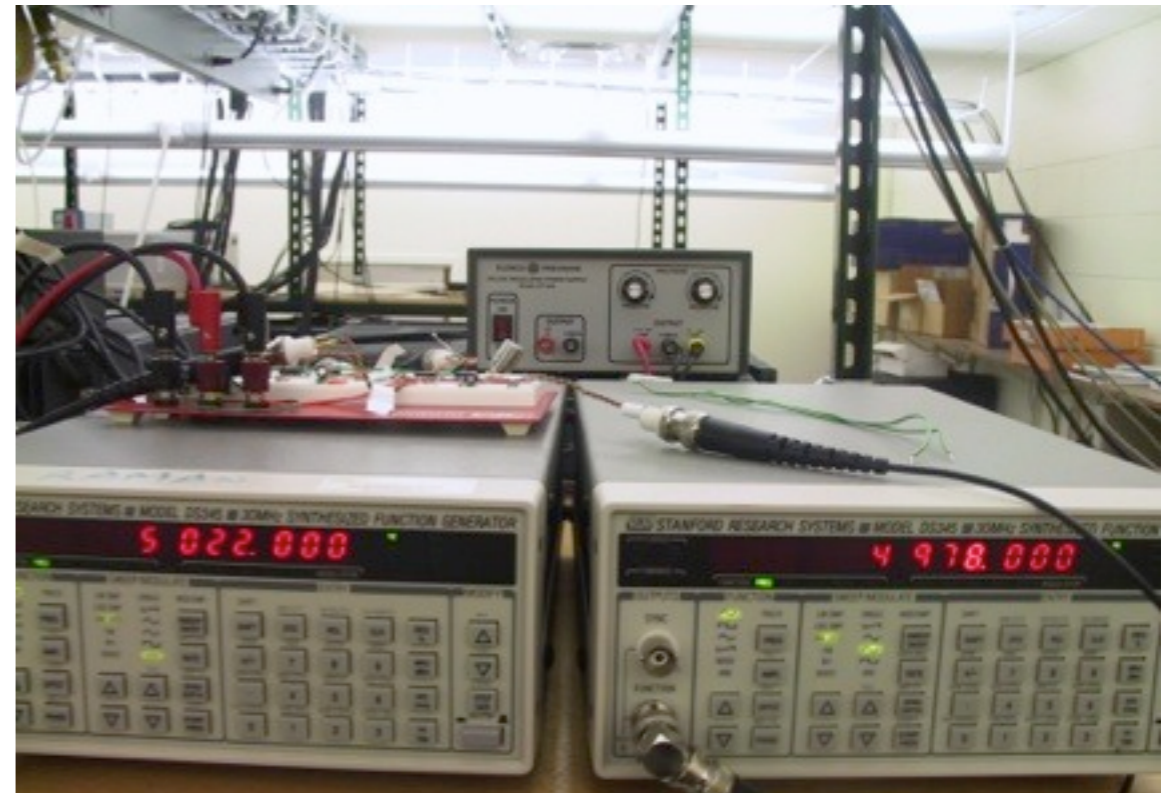
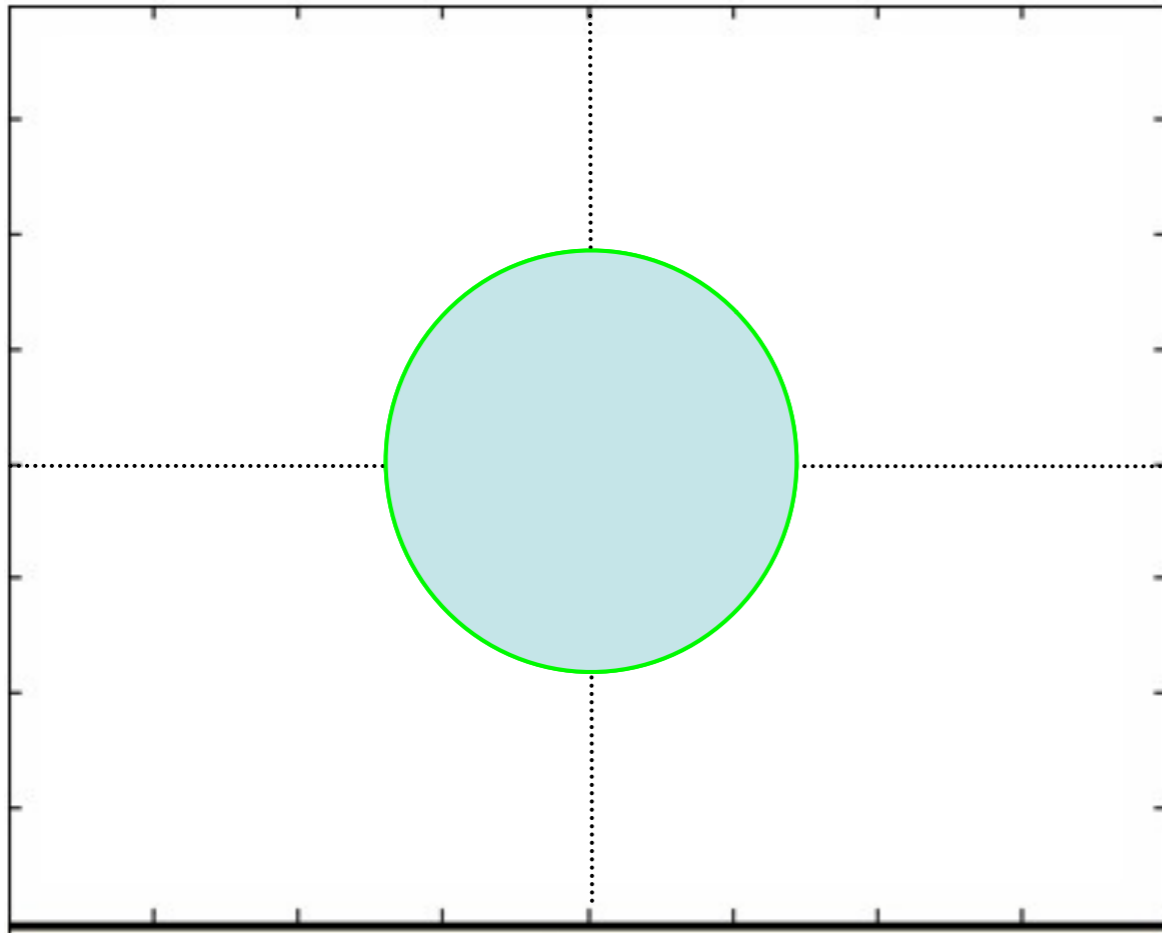
Rodando mais rápido
cria uma rede de vórtices



Vórtice no superfluido

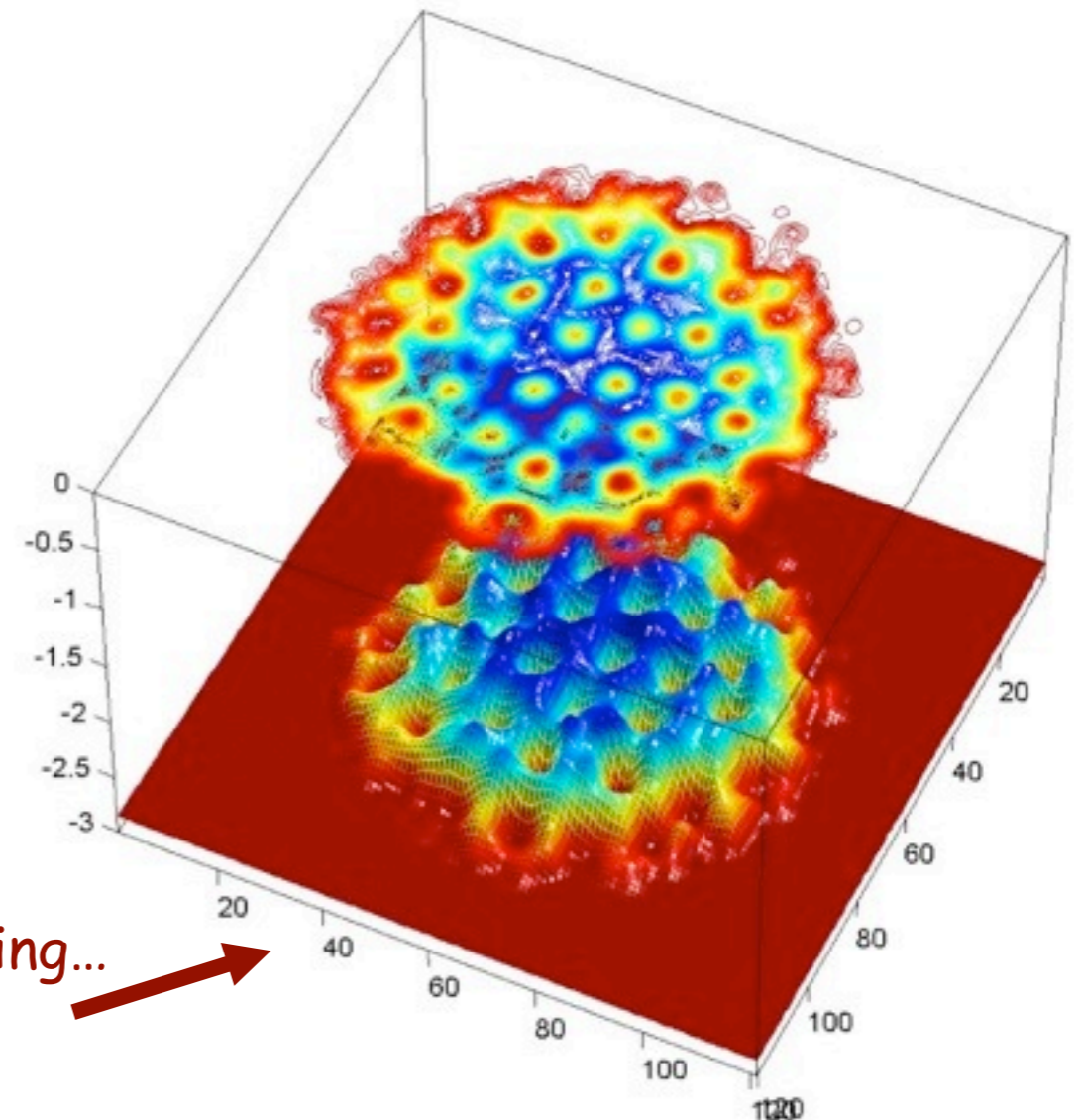
...Muito diferente de um
fluido clássico!!

Creating vortices in a superfluid : (Rotating BECs in the TOP trap)

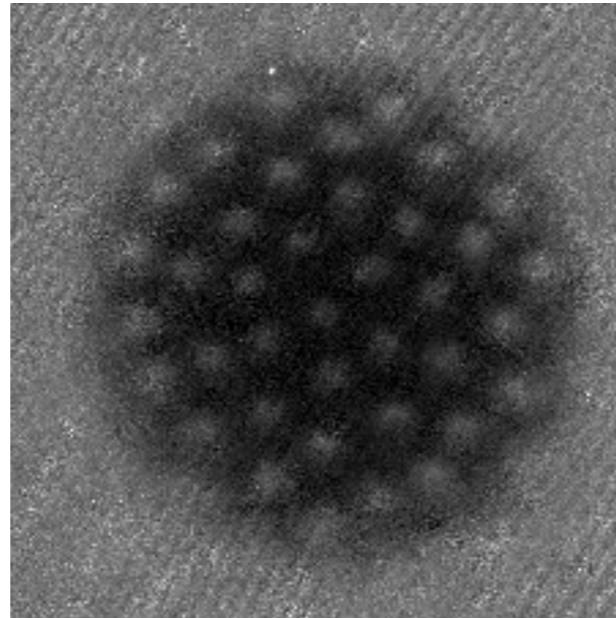
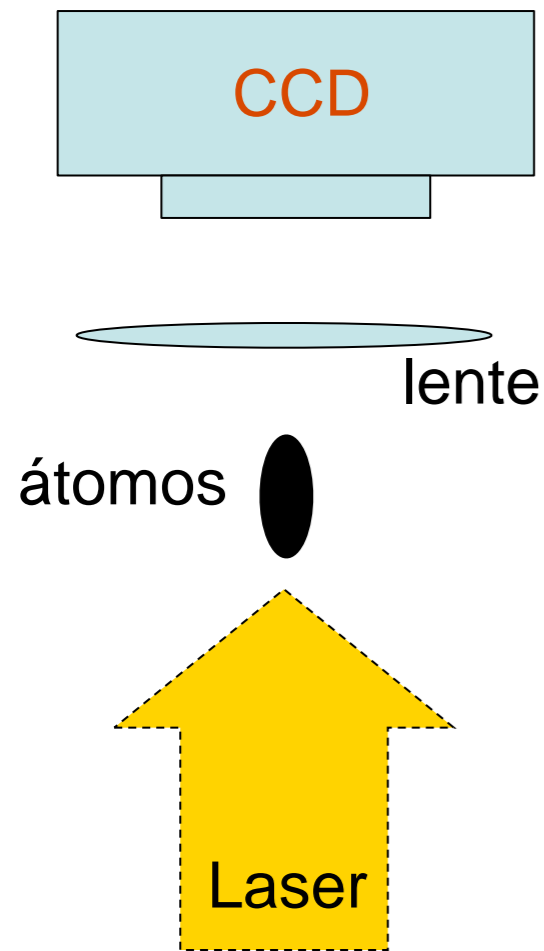


$$B_x(t) = B_0 \cos(\omega_{TOP} + \Omega)t + \varepsilon \cos(\omega_{TOP} - \Omega)t$$
$$B_y(t) = B_0 \sin(\omega_{TOP} + \Omega)t - \varepsilon \sin(\omega_{TOP} - \Omega)t$$

Spatial Density Distribution, as seen by TOF imaging...
'holes' represent the vortex cores!



Vendo redes de vórtices quantizados no laboratório



Dependendo dos parâmetros,
Podemos formar um ou muitos vórtices...

Tempo de Rotação ~ 1 a 1,5 sec
Equilibração 1 a 1,5 sec

TOF = 50 ms

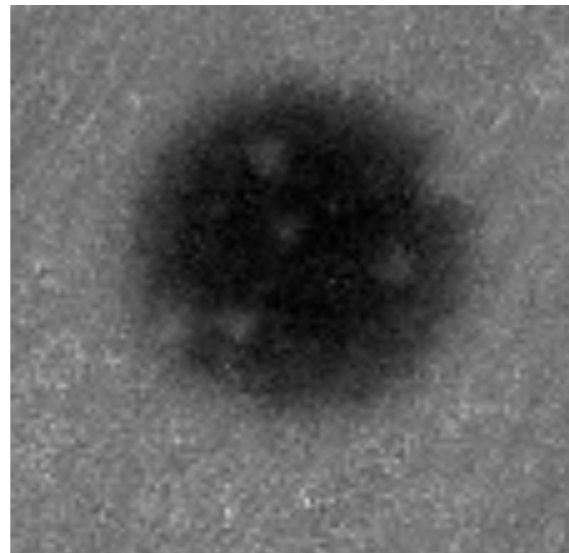
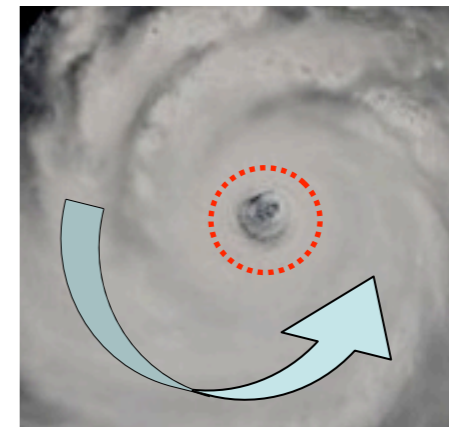


Imagem de absorção é similar
à imagem de satélite do Katrina

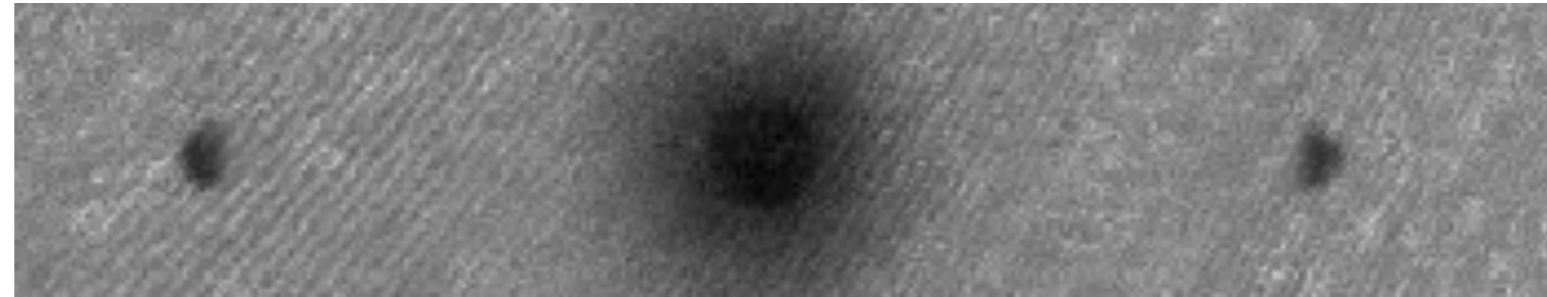


Imagens mostram densidade mas não informação da fase...
i.e.: Qual o sentido de rotação? E o campo de velocidade microscópico?

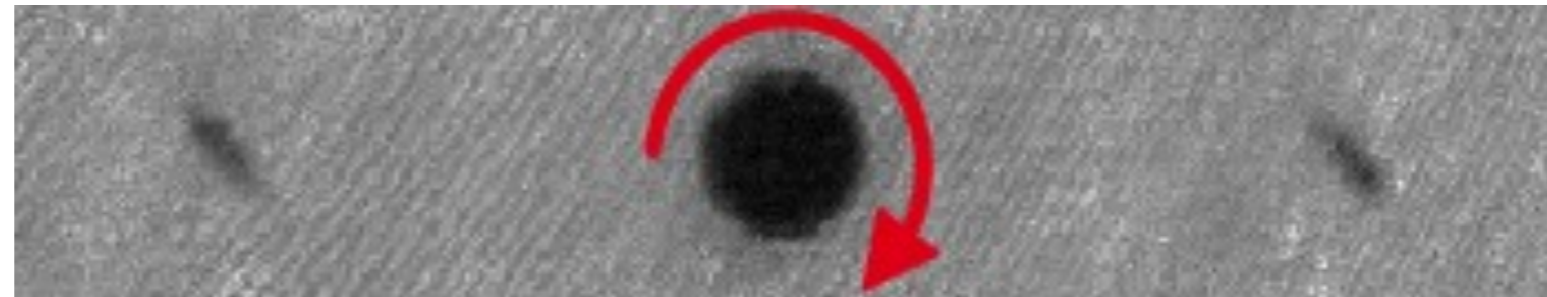
Spatial information in the diffracted cloud

10 ms

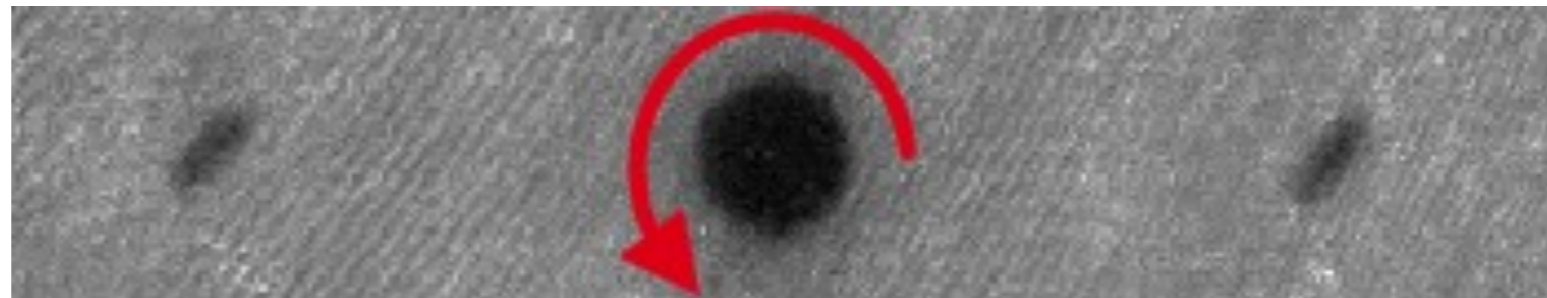
No vortices



Clockwise Rotation



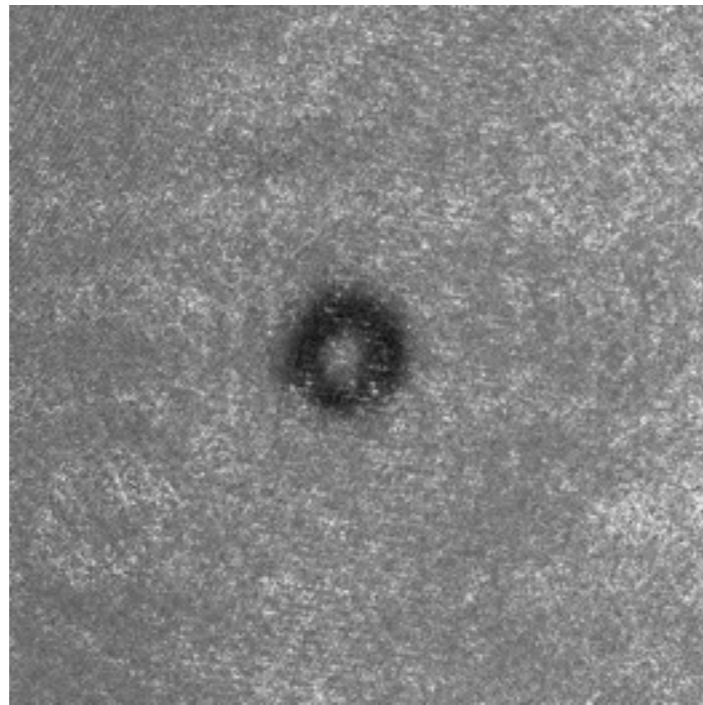
Counter-Clockwise
Rotation



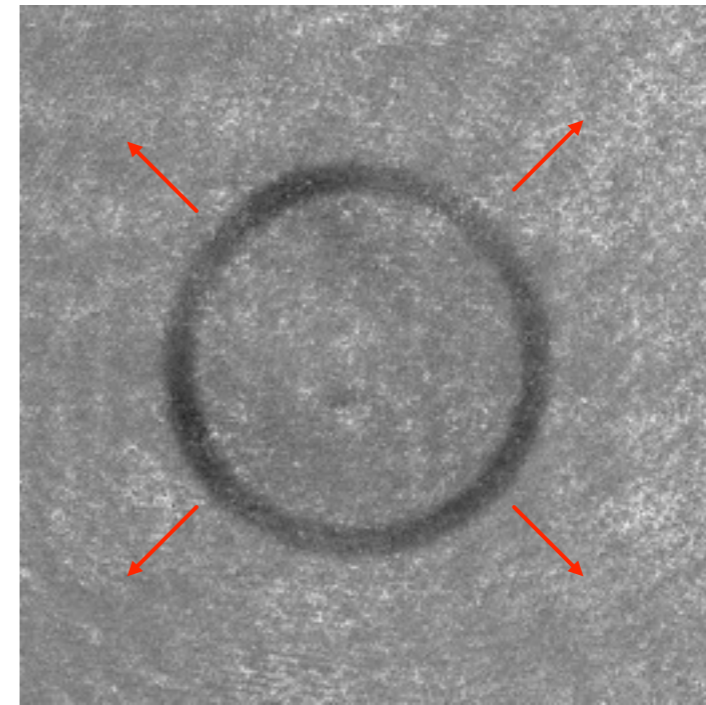
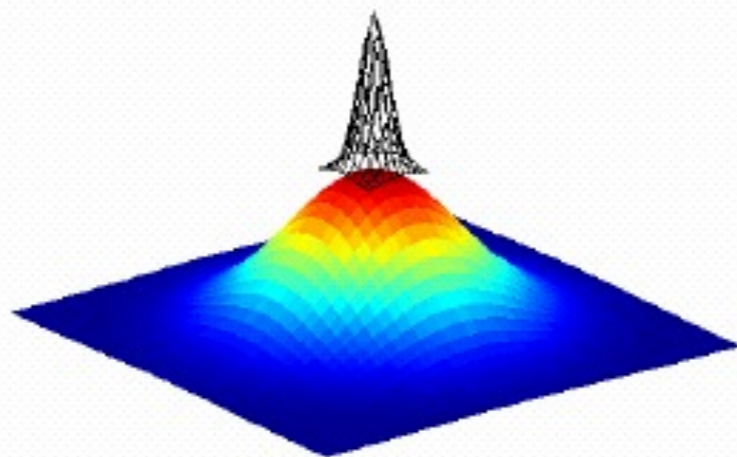
Direct sensing of rotation!

A short digression: Ring-shaped Matter Wave propagation

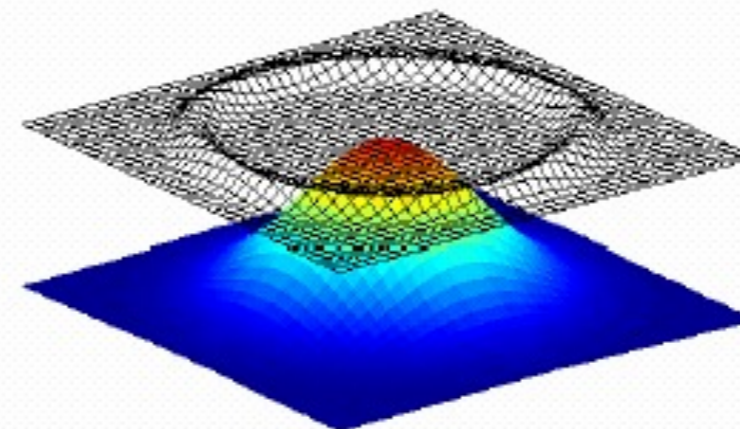
Pulse on a 70 micron plug after
switching off the trap



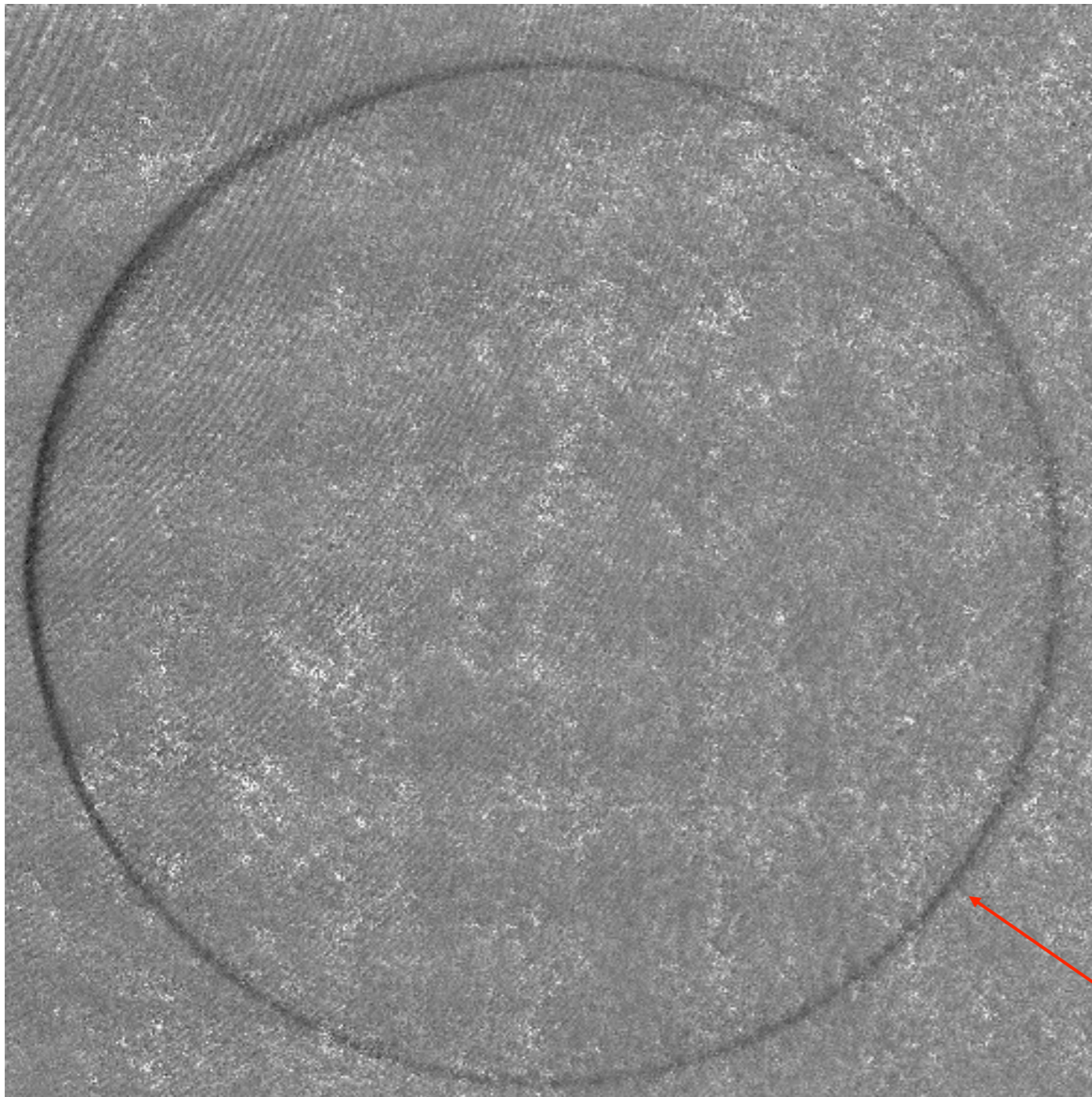
5 ms



10 ms

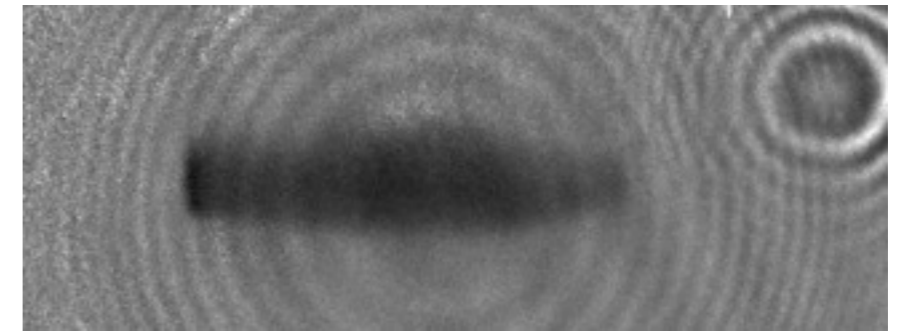


Correctly focused...



2.8 mm

20 ms TOF



View from the side

Ring

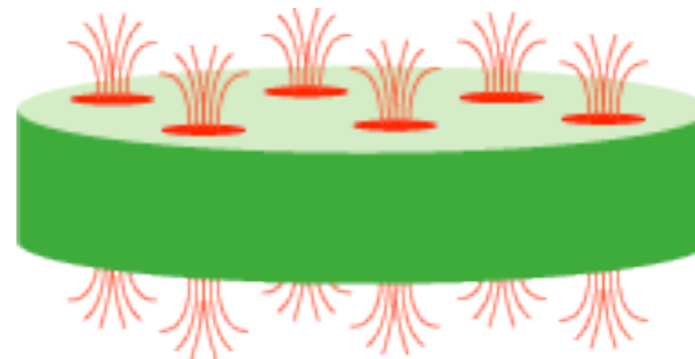
BEC

20 microns
width

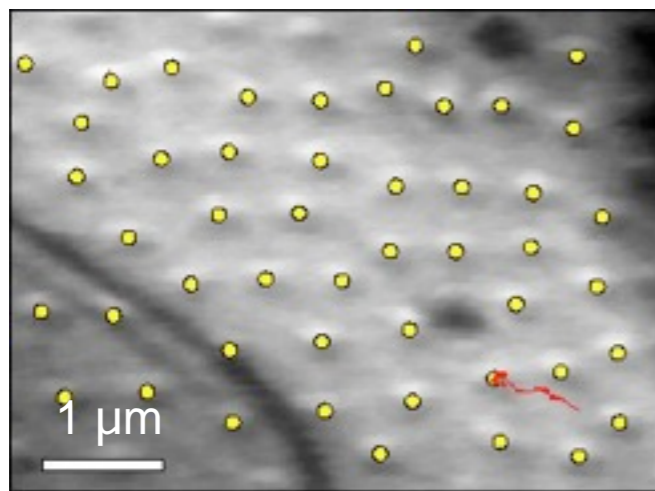
Dinâmica de vórtices em Superfluidos

Vórtices estão âmago da superfluidez, entender sua dinâmica é a chave para entender e controlar a supercondutividade do tipo-II...

Vórtices em Superconductores de alta temperatura



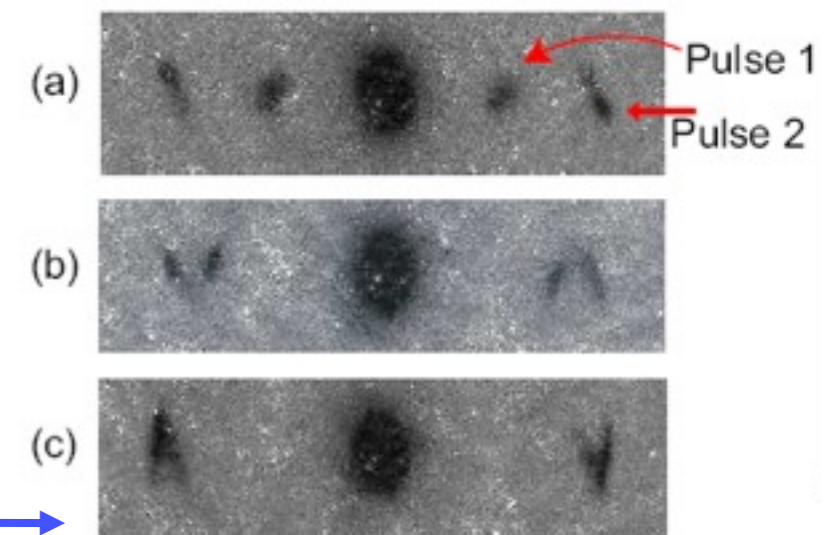
Fluxóides: Campo Magnético penetra nos materiais do do tipo-II na forma de tubos (vórtices) quantizados



Vortex matter, (Nb-film @ 4.5K)
(*Phys. Rev. Lett.* **80**, 2693)

Mapeamento espectroscópico da dinâmica de vórtices via técnica de difração Bragg

Multi-pulse Bragg Scattering



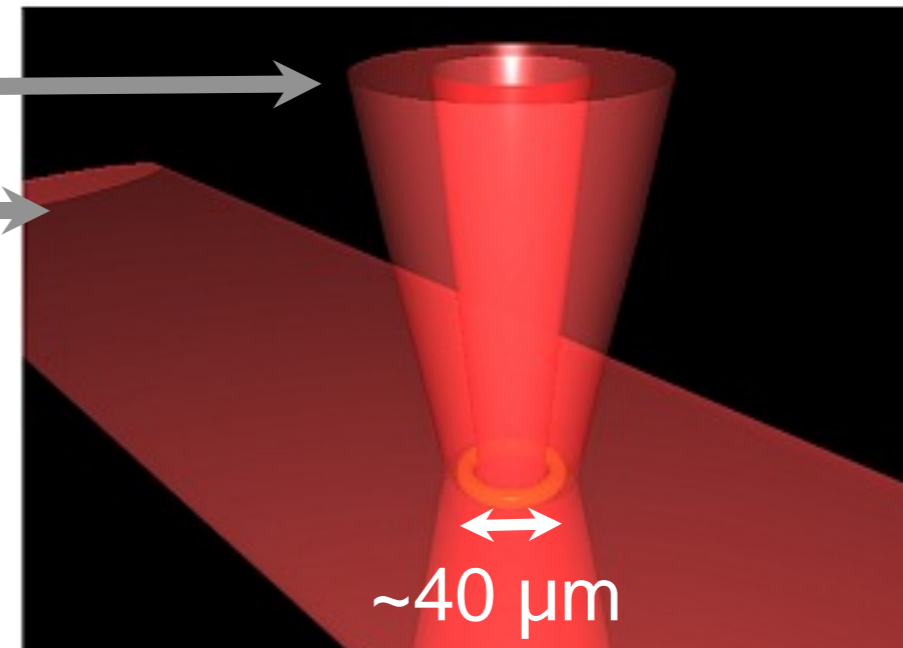
Muniz et al., Math. Comput. Simul., 74, 397 (2007)

NIST all-optical toroidal trap for BEC

LG₀₁ 'Ring' beam

'Sheet' beam

Uniform to:
< 0.5% of typical depth
< 10% of typical μ



ω_z : 500-2000 Hz

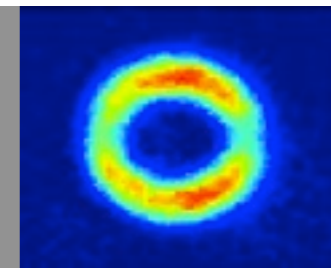
ω_R : 20-160 Hz

$N \sim 1.5 \times 10^5$ atoms

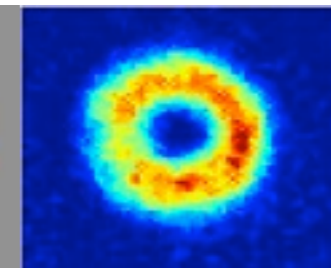
$\mu \sim 50$ nK (1 kHz)

$T < 40$ nK

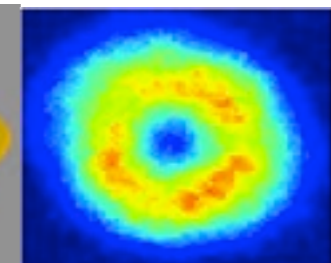
3D

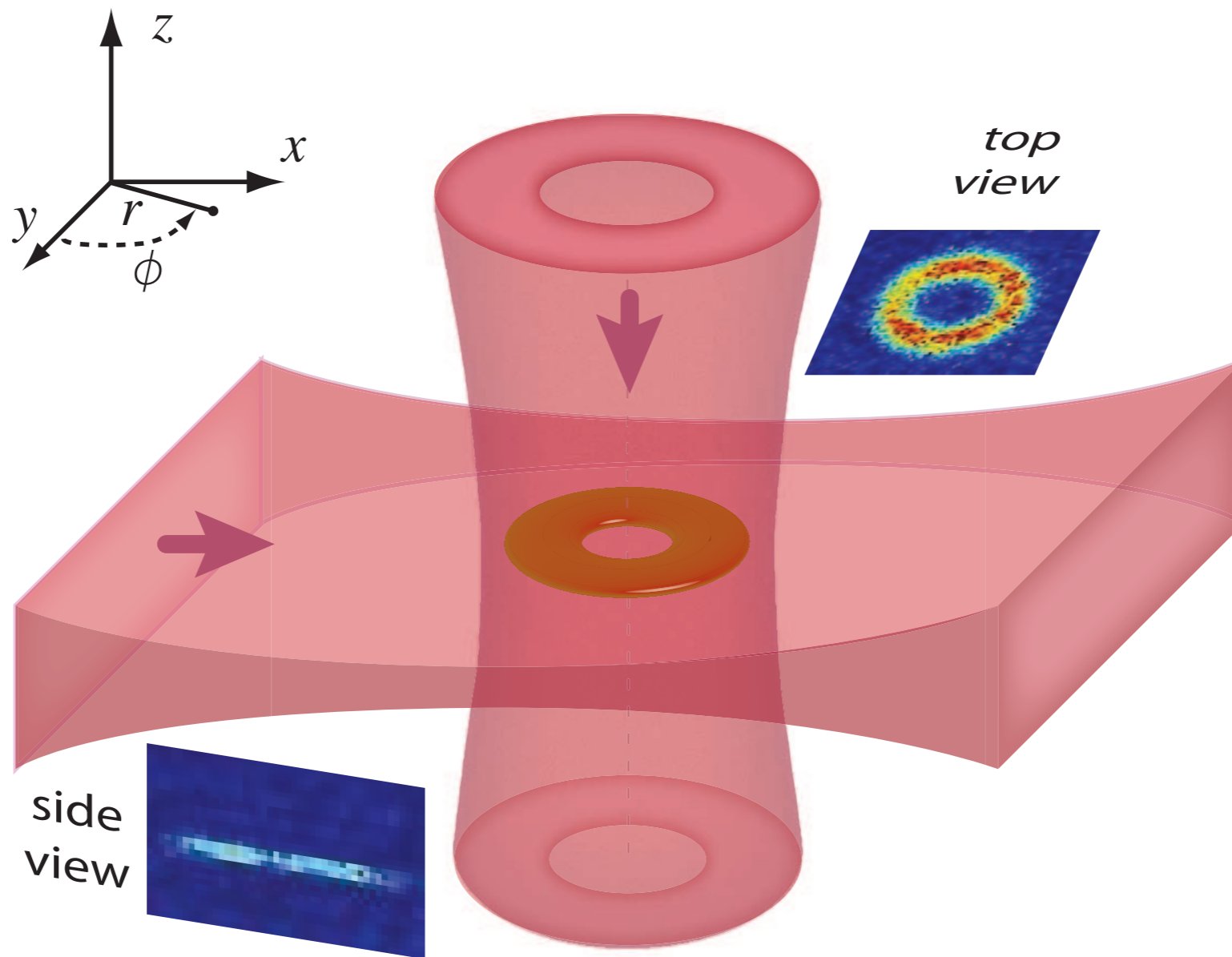


?D

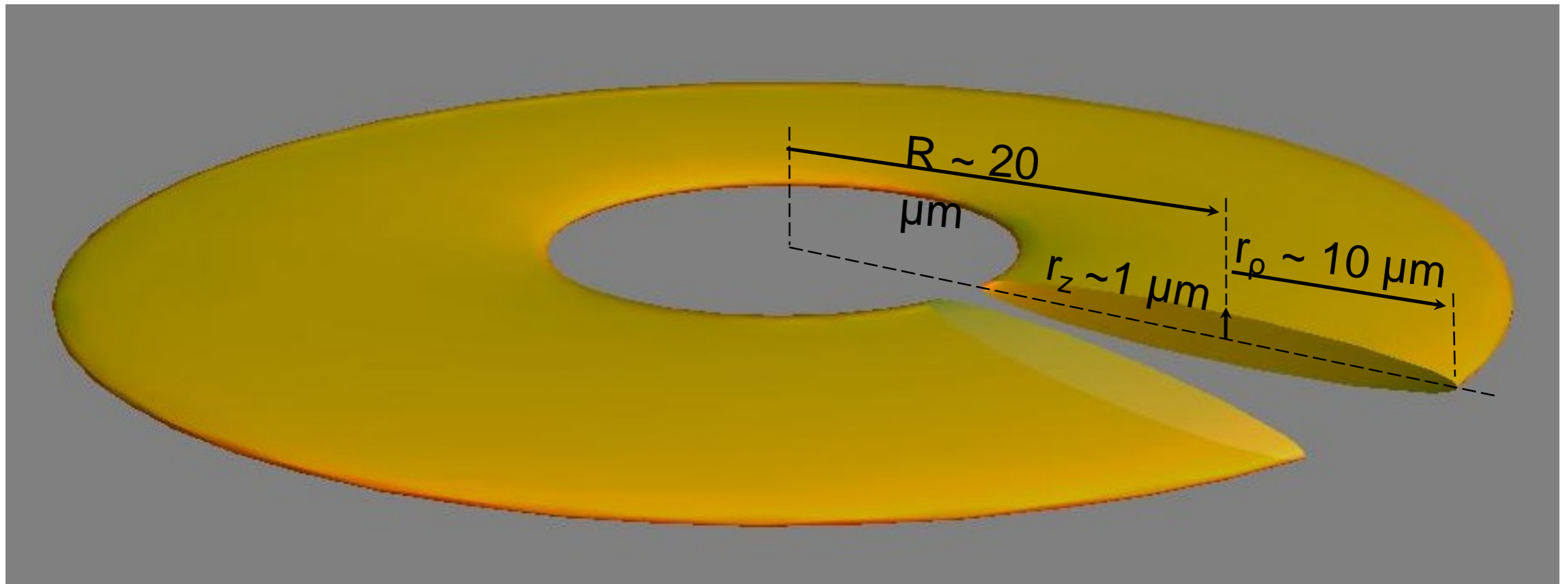


Quasi-2D





Geometria típica da armadilha (BEC)



Frequência vertical $\sim 500 \text{ Hz}$
Frequência 'Radial' $\sim 80 \text{ Hz}$

$N \sim 1.5 \times 10^5$ átomos
 $\rho \sim 5 \times 10^{13}$ átomos/cm³

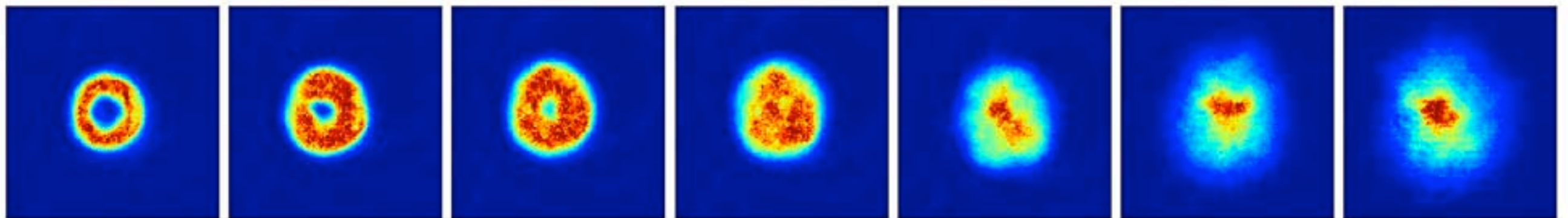
$T < 40\text{nK}$

$\mu \sim 1 \text{ kHz}$

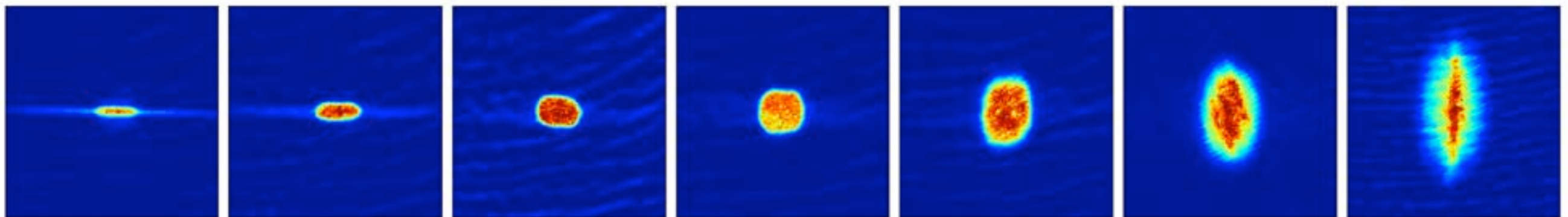
Expansão em tempo de voo (TOF)

(sem circulação)

Top View

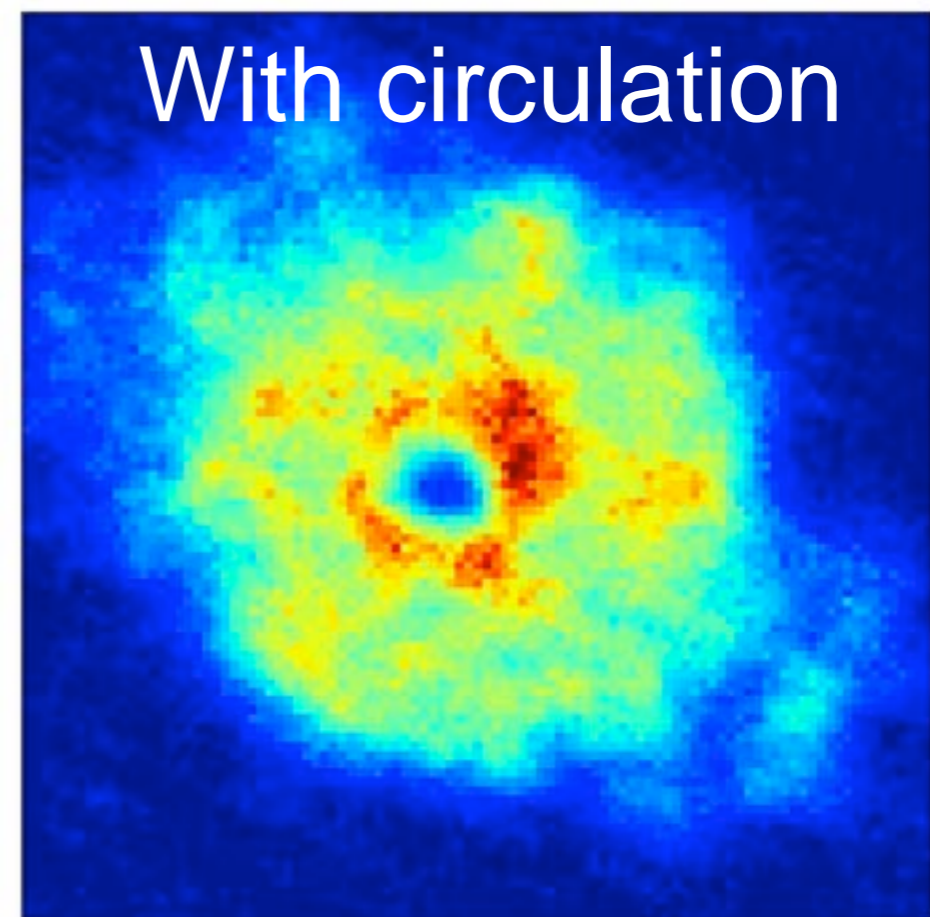
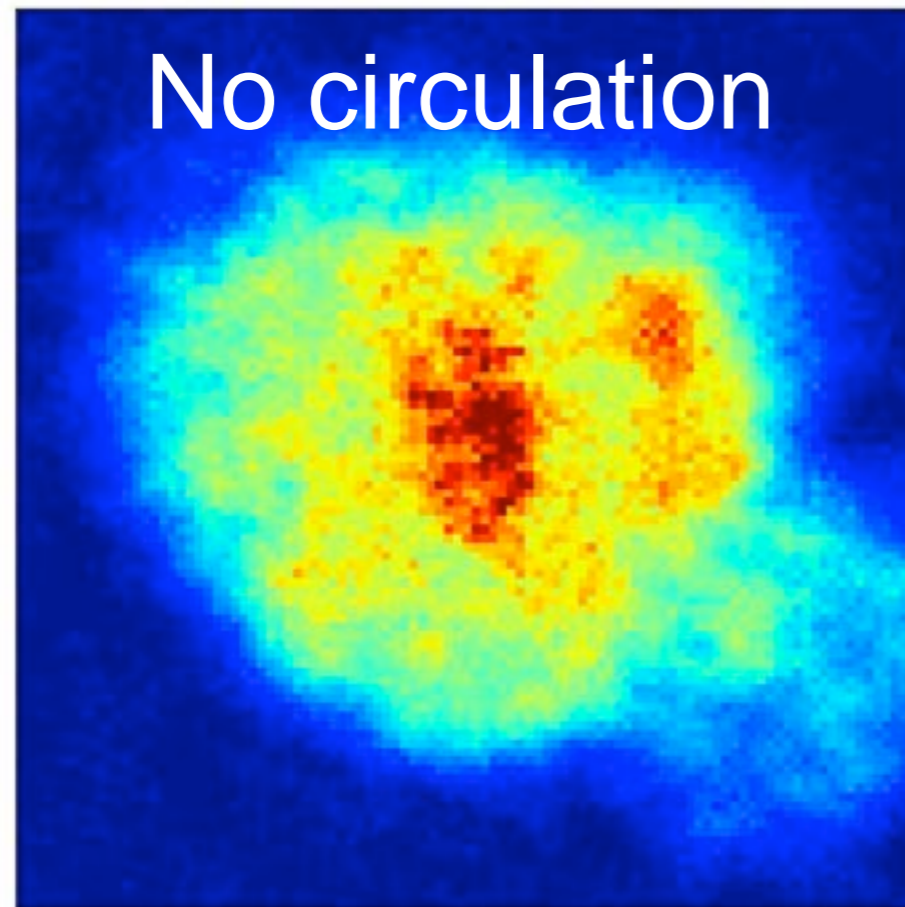


Side View



Detectando Circulação em TOF

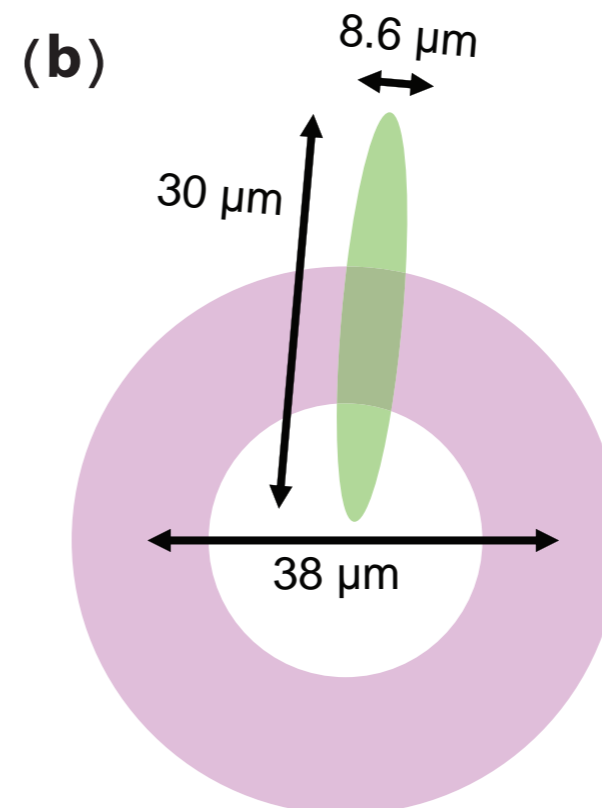
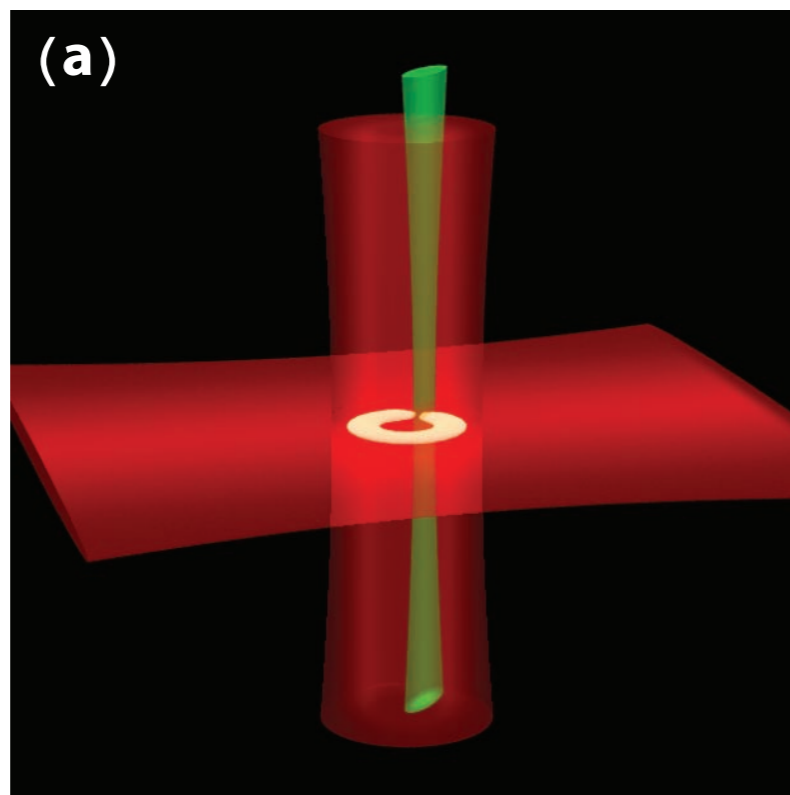
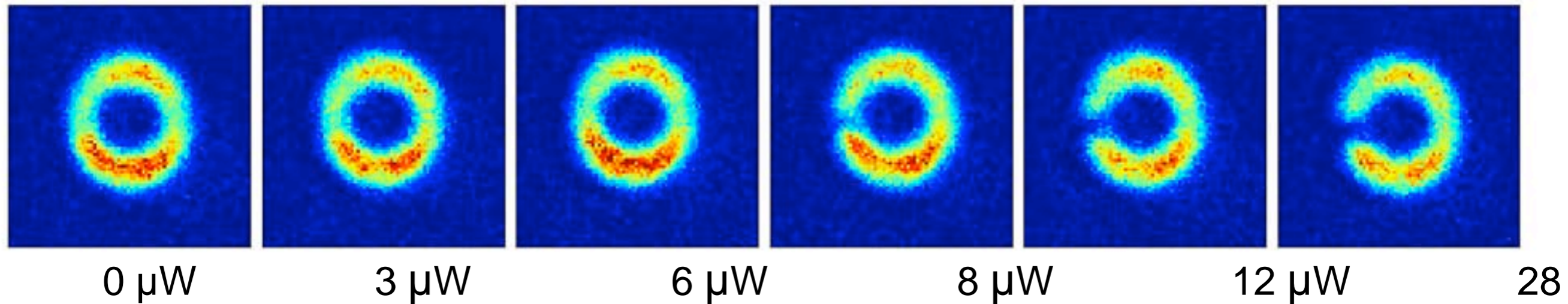
(Images taken after 10 ms expansion)



*Supercorrente persiste por até **40 segundos(!)***

Limitada por Vácuo (~30 sec. BEC tempo de vida)
Não uniformidade da armadilha (<5 nK)

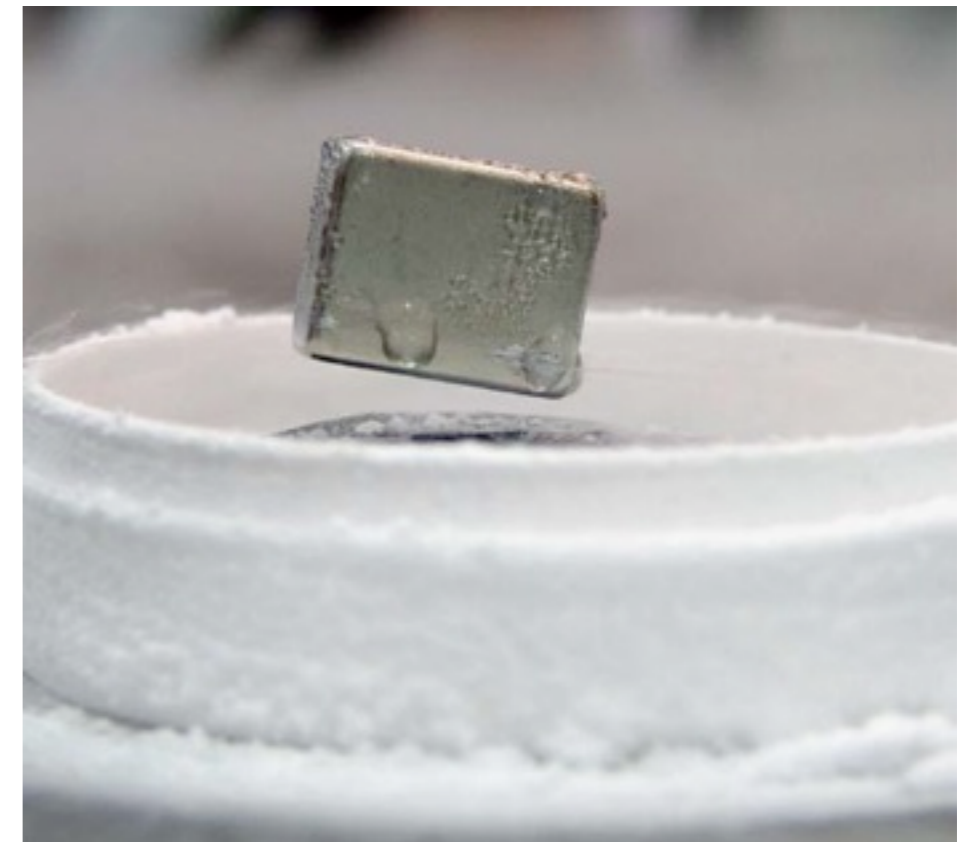
“Quebrando” o superfluxo com uma Barreira



BEC e os super-fenômenos

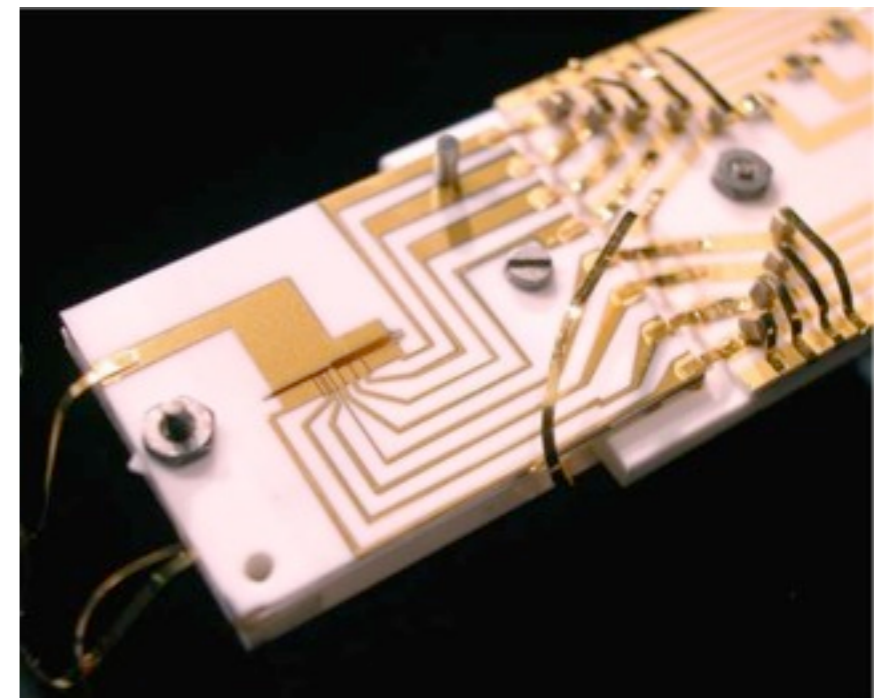


Superfluidez



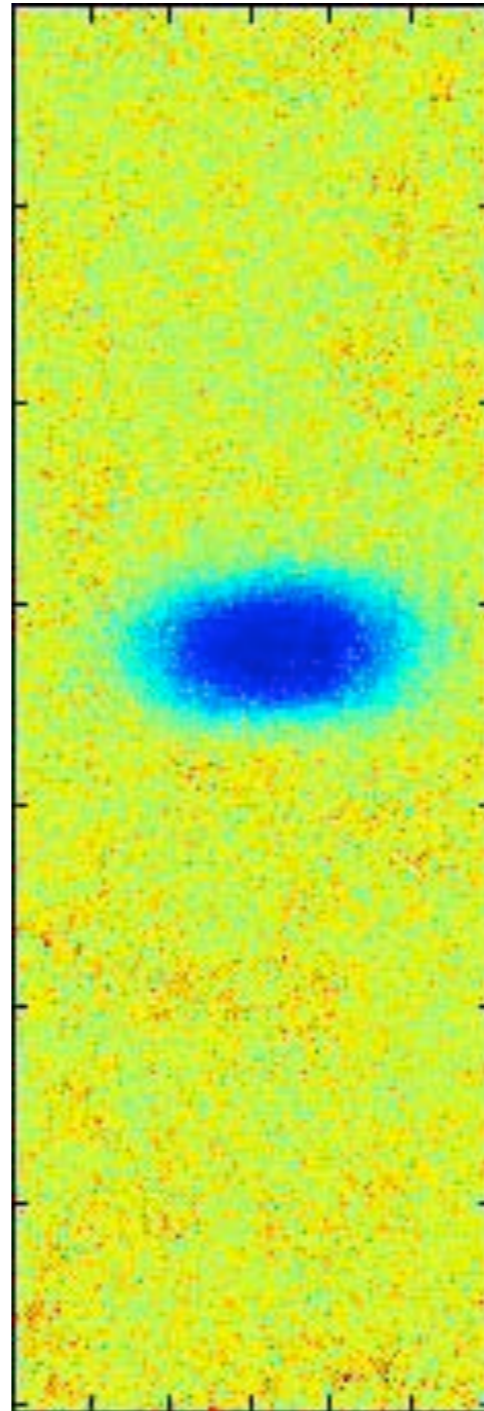
Supercondutividade

Matéria quântica... super computadores(?)!



“Proto-processador” quântico

Demo: BEC e antigravidade...



Levitron...

Obrigado!

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