Adiabatic cooling of antiproton plasmas

Giovanni Manfredi

Centre National de la Recherche Scientifique

Institut de Physique et Chimie des Matériaux de Strasbourg

`E-mail: manfredi@unistra.fr`

`Web page: http://dyno.u-strasbg.fr/`

Outline

- Motivations: Antimatter and gravity
  - GBAR experiment (Gravitational Behavior of Antihydrogen at Rest)
- Adiabatic cooling of antiprotons
  - Experiments
  - Simulations
- Conclusions

Antimatter physics — open questions

- **Why matter−antimatter imbalance?**
  - Standard model predicts same amount in the early universe
  - Fundamental asymmetry or accident?

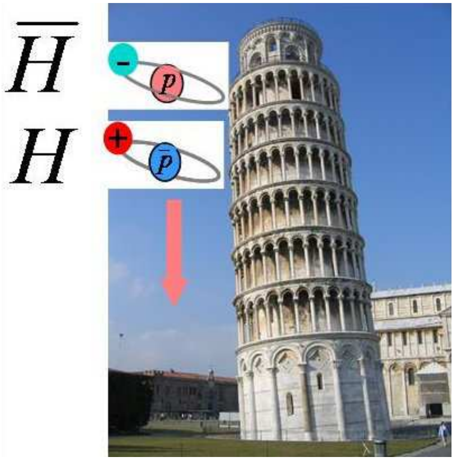
- **Gravitational behavior of antimatter**
  - Equivalence principle never tested directly for antimatter
    - ➢ Same as matter (attraction)
    - ➢ Slightly different (attraction, but different coupling)
    - ➢ Matter-antimatter repulsion (anti-gravity)

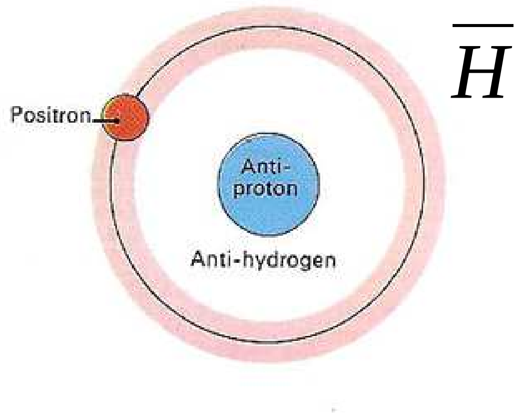
      “Dirac-Milne Universe”, A. Benoit-Levy and G. Chardin, *Astron. Astroph.* (2012)

Antimatter and gravity – The GBAR collaboration

- **GBAR** (Gravitational Behaviour of Anti-hydrogen at Rest)
  - Free-fall acceleration of antihydrogen atoms in the gravitational field of the Earth
  - International collaboration involving several countries (France, UK, Japan, Switzerland, Russia)

- Other collaborations: ATRAP, ALPHA, AEGIS, ...

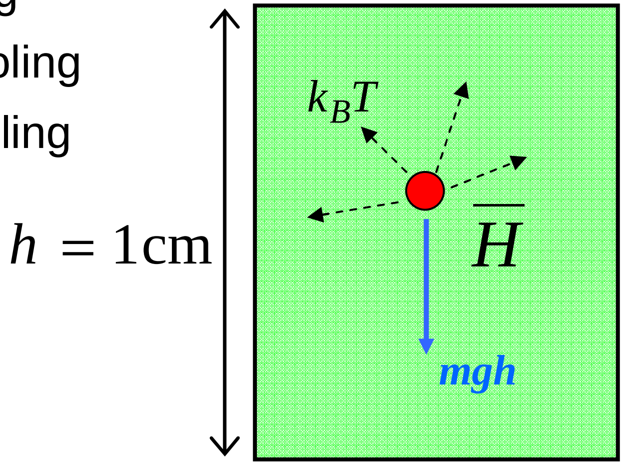




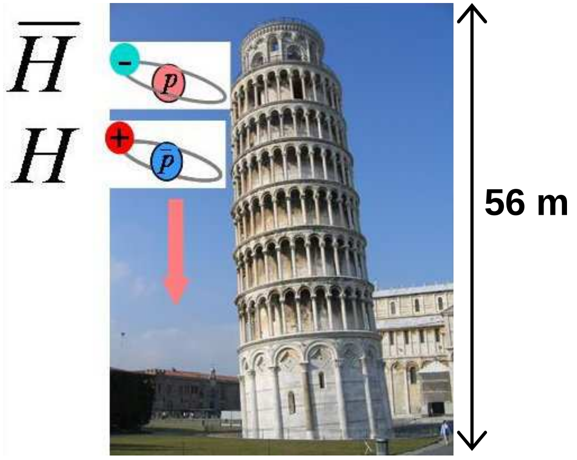
Cold antimatter

- Gravitational experiments on antihydrogen ($\overline{H}$) require low temperatures
- Difficult to obtain − positrons and anti-protons are usually produced at high energies
- Various cooling procedures
  - Adiabatic cooling
  - Sympathetic cooling
  - Evaporative cooling

$$\boxed{\begin{array}{l} mgh = k_B T \\ T \approx 10\,\mu\text{K} \end{array}}$$

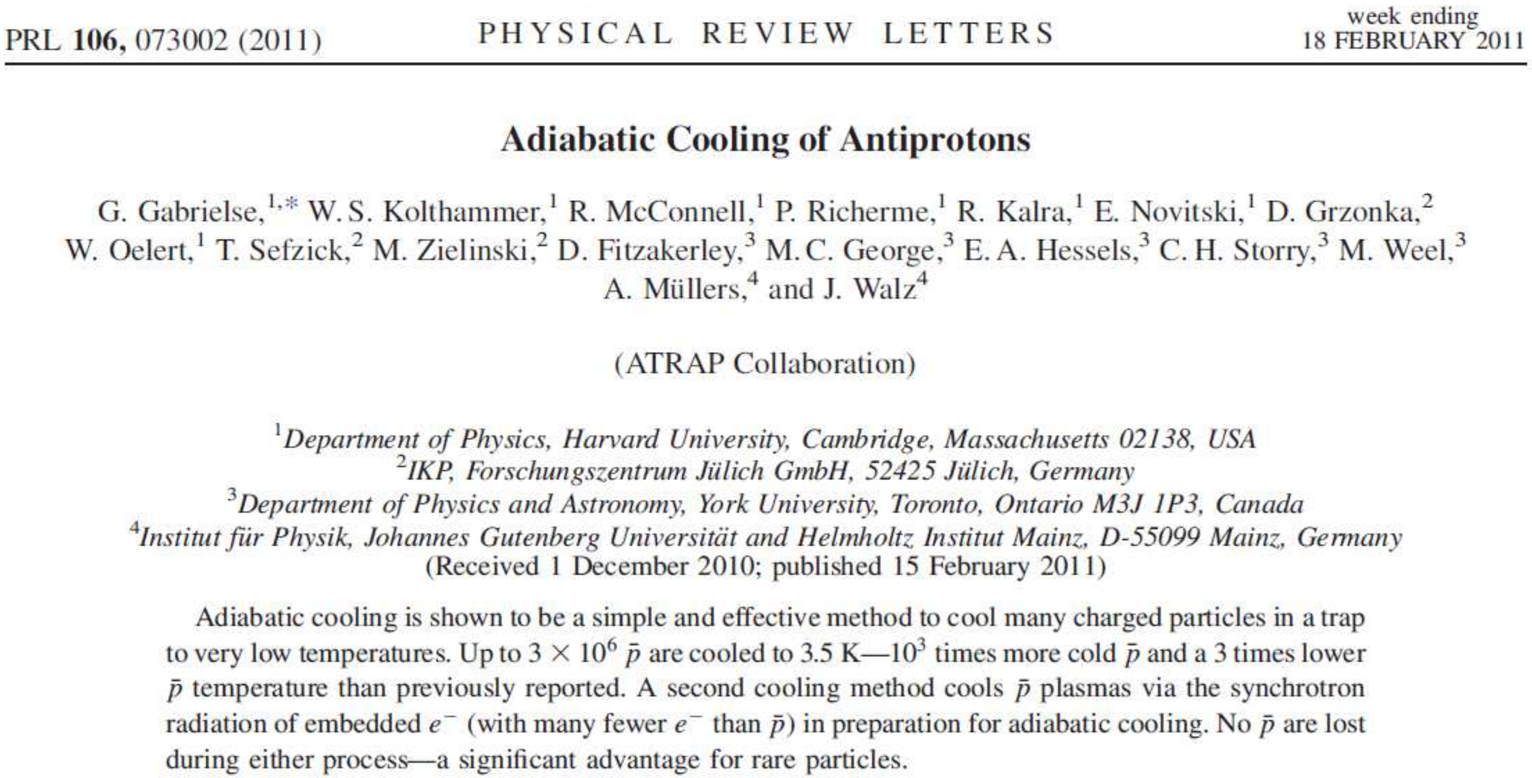


$m = m_p$



$m = 1\,\text{kg}$

Adiabatic cooling experiments



PRL **106,** 073002 (2011) PHYSICAL REVIEW LETTERS week ending 18 FEBRUARY 2011

Adiabatic Cooling of Antiprotons

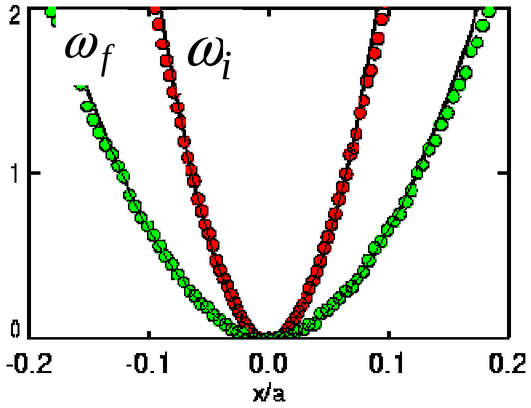
G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2]
W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3]
A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*
(Received 1 December 2010; published 15 February 2011)

Adiabatic cooling is shown to be a simple and effective method to cool many charged particles in a trap to very low temperatures. Up to 3×10^6 $\bar{p}$ are cooled to 3.5 K—10^3 times more cold $\bar{p}$ and a 3 times lower $\bar{p}$ temperature than previously reported. A second cooling method cools $\bar{p}$ plasmas via the synchrotron radiation of embedded e^- (with many fewer e^- than $\bar{p}$) in preparation for adiabatic cooling. No $\bar{p}$ are lost during either process—a significant advantage for rare particles.

Principles of adiabatic cooling



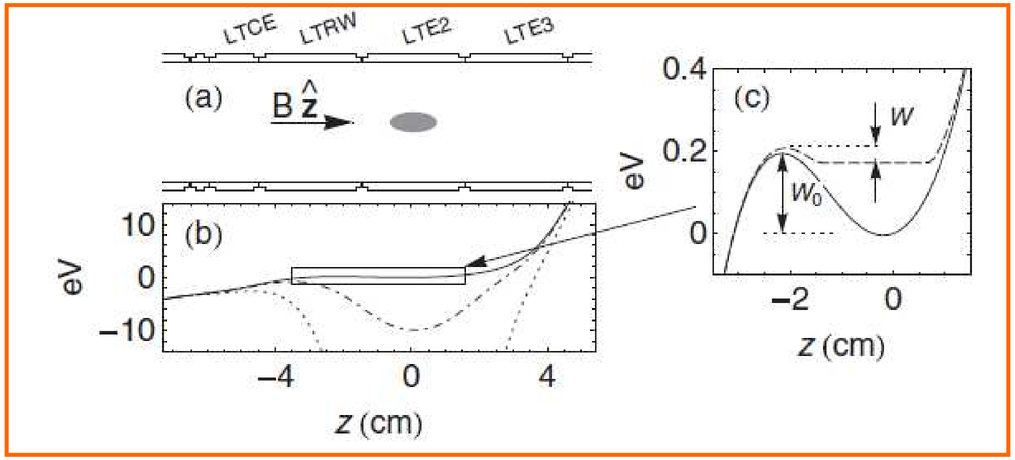
Harmonic confining potential

$$U = m\omega^2 z^2/2$$

- Slowly reduce ω(t) from ω_i to $\omega_f < \omega_i$
- For independent particles: adiabatic invariant: E / ω = const.
- But T ~ E
- Therefore: T ~ ω, or $\boxed{T_f = T_i \dfrac{\omega_f}{\omega_i}}$
- **Things are very different for many interacting particles (plasma)**

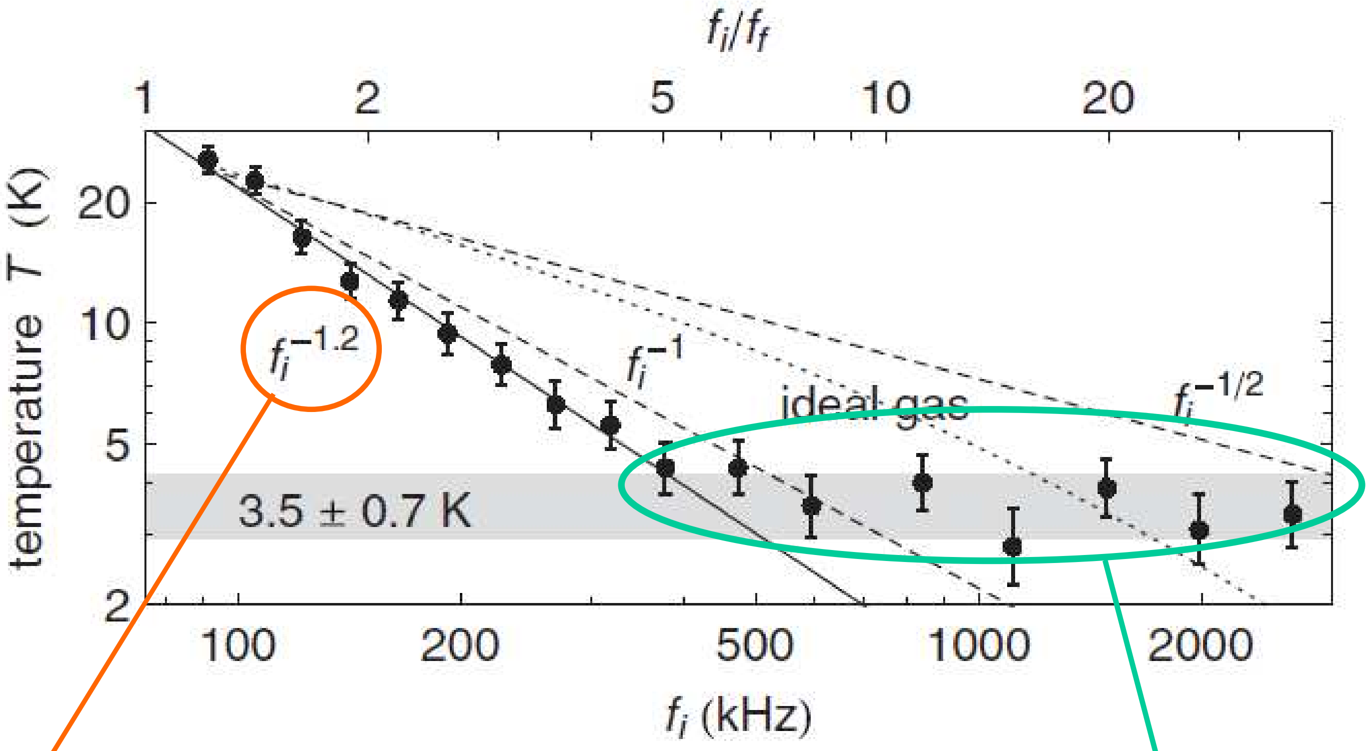
Experiments

- Antiprotons pre-cooled to **T_i = 31K** via collisions with electrons
- Subsequently, adiabatic cooling starts
- **N ≈ 500 000 antiprotons** are confined in a cylindrical trap, with
  - R ≈ 2 mm
  - L_z ≈ 10 mm
  - B = 3.7 T



- Final confining frequency:
  - **$\omega_f / 2\pi$ = 75 kHz**
- Initial frequency in the range:
  - **90 kHz < $\omega_i / 2\pi$ < 3000 kHz**

Main experimental result



Slope = –1.2

Saturation

Theoretical model

- Kinetic simulations: Vlasov-Poisson equations
- 1D geometry
- But the “thermodynamic” dimensionality is given by the collision rate
  - *If collisions are negligible: 1D regime*
  - *If (isotropic) collisions are dominant: 3D regime*

Vlasov-Poisson equations in the collisionless regime

$$\frac{\partial f}{\partial t} + v_z \frac{\partial f}{\partial z} - \left(\omega^2(t) z + \frac{eE_z}{m} \right) \frac{\partial f}{\partial v_z} = 0,$$

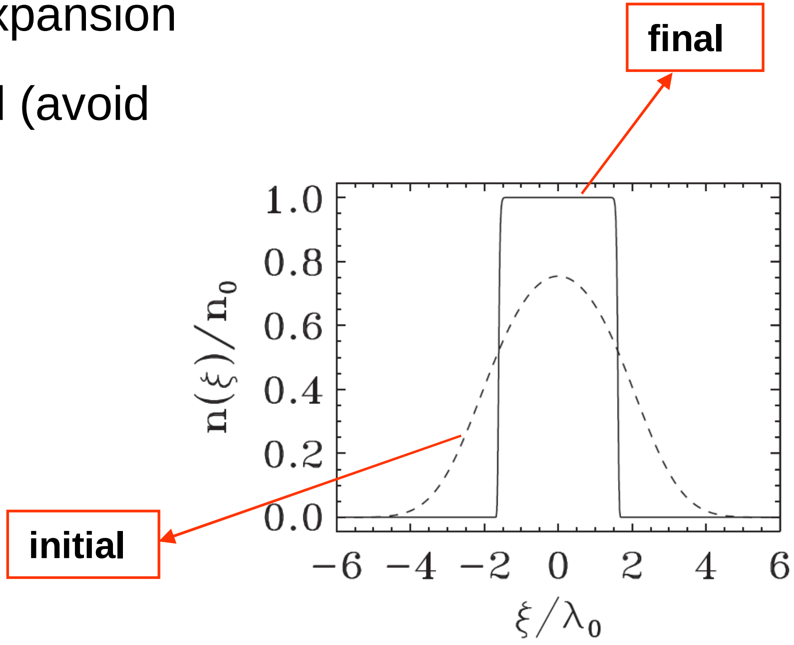
$$\frac{\partial E_z}{\partial z} = -\frac{e\sigma_\perp}{\varepsilon_0} \int f(z, v_z, t)\, dv_z,$$

Phase-space rescaling methods

- Transform space, time and velocity: $(z, v_z, t) \to (\xi, \eta, \vartheta)$

$$\boxed{z = C(t)\xi; \quad dt = A^2(t)d\theta; \quad v_z = (C/A^2)\eta + \dot{C}\xi.}$$

- $C(t)$ allows to absorb the spatial expansion
- $A(t)$ keeps velocity space bounded (avoid "heating" in the rescaled space)

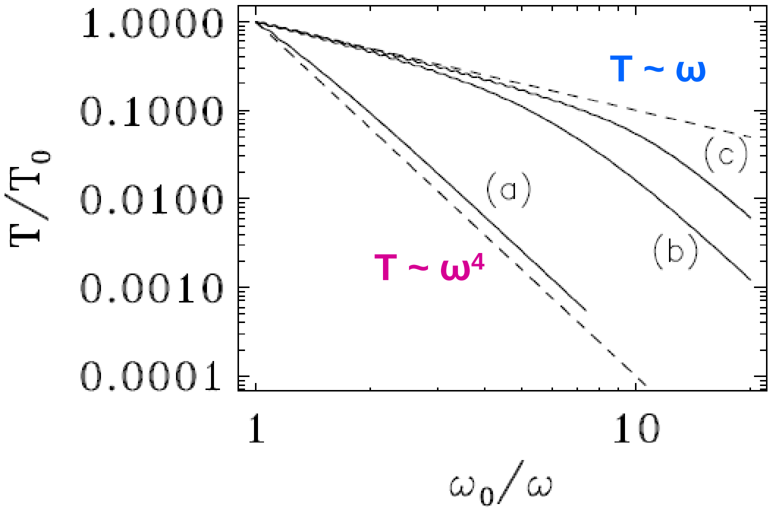


Results in the 1D (collisionless) case

- Two regimes
  - Low plasma density, N < 1
  - High plasma density, N > 1

$$\boxed{N \sim \frac{\omega_p}{\omega_0}}$$

- For N < 1: single-particle régime: **T ~ ω**
- For N > 1: self-consistent many-body regime: **$T \sim \omega^4$**



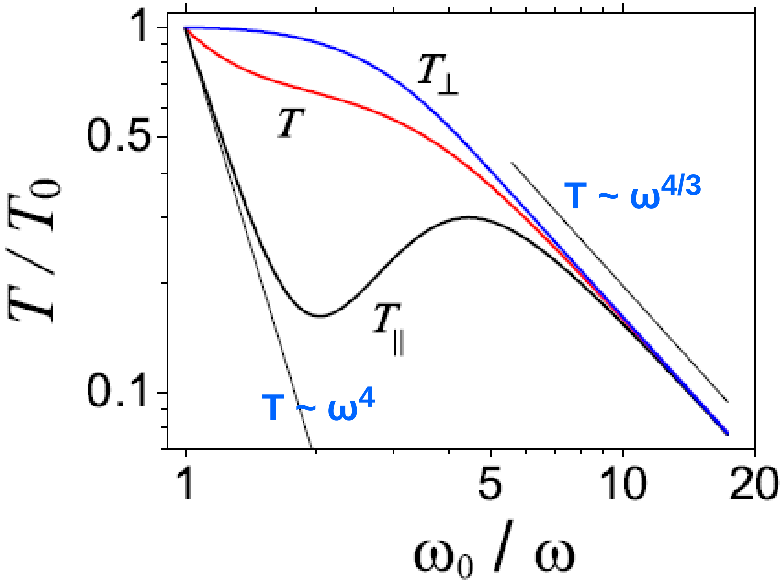
- N = 10 (a)
- N = 0.3 (b)
- N = 0.1 (c)

Results in the 3D (collisional) case

Collisions couple the parallel (along *z*) and perpendicular dynamics

$$\begin{cases} \dfrac{\partial f}{\partial t} + v_z \dfrac{\partial f}{\partial z} - \left[\omega^2(t) z + \dfrac{eE_z}{m}\right] \dfrac{\partial f}{\partial v_z} = \boxed{\left(\dfrac{\partial f}{\partial t}\right)_{\mathrm{coll}} = -\nu_{\mathrm{coll}} \left(f - \dfrac{n e^{-m(v_z - u)^2/2k_B T_\perp}}{(2\pi k_B T_\perp/m)^{1/2}} \right)} \\ \dfrac{dT_\perp}{dt} = -\dfrac{\nu_{\mathrm{coll}}}{2}(T_\perp - T_\parallel) \end{cases}$$

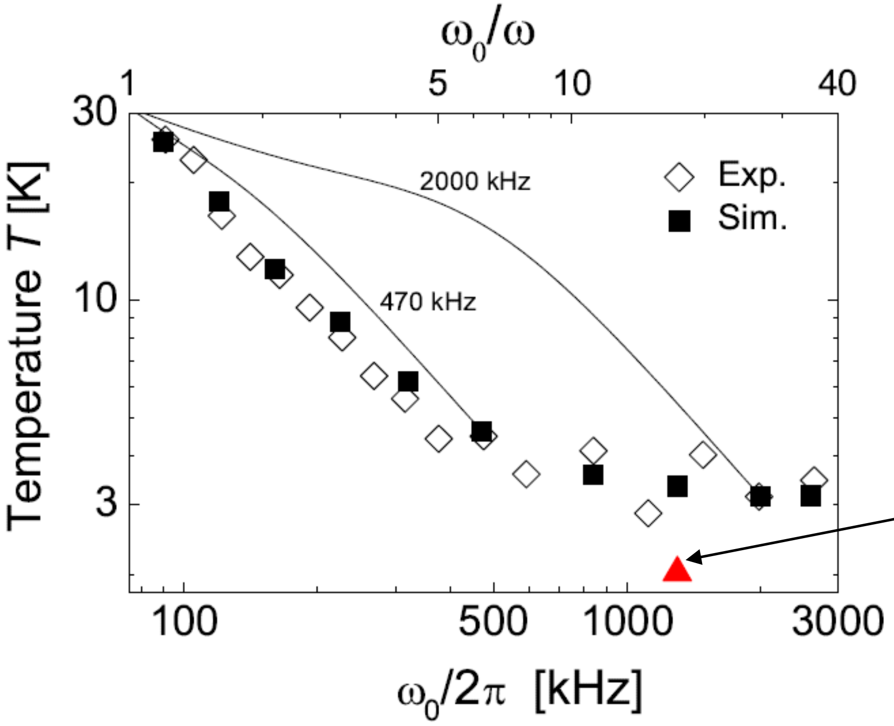
- In 3D, the relation between temperature and frequency becomes: **$T \sim \omega^{4/3}$**



Comparison to experiments

- All data taken from experiment
- Collision rate, taken from fist-principles theory
- **No free adjusting parameters**

M. E. Glinsky, T. M. O'Neil, M. N. Rosenbluth, K. Tsuruta, and S. Ichimaru, Phys. Fluids B **4**, 1156 (1992).



Lower B field
Higher collision rate

Conclusions

- Antimatter gravitation experiments available in the near future
  - GBAR project: Free-fall of antihydrogen atoms
- Necessary to produce cold antihydrogen
- Pre-cooling of antiprotons:
  - Sympathetic cooling
  - Adiabatic cooling
  - ...
- **Adiabatic cooling** is effective to bring antiprotons to T ~ 1K
- Results of experiments explained by self-consistent Vlasov-Poisson model including collisions

Bibliography

- G. Manfredi and P.-A. Hervieux, *Adiabatic Cooling of Trapped Non-Neutral Plasmas*, Phys. Rev. Lett. **109**, 255005 (2012).