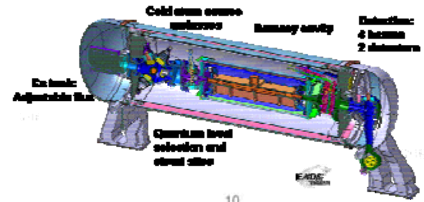
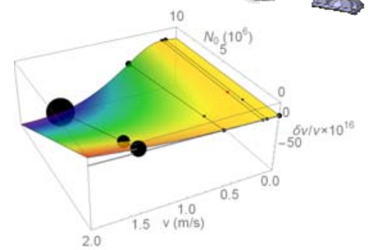
The on-Orbit Accuracy Evaluation of PHARAO and its Implications for Clock Comparisons

- Most systematics will be evaluated during the commissioning of PHARAO, just as for ground clocks.
- 1st order Doppler shifts (DCP) & cold collision shift will take more than 1 year to realize its ultimate accuracy
  - BBR may also improve dramatically years from now.
  - BBR coefficient drops out of Cs-Cs comparisons
- Make & report measurements knowing that the uncertainties will likely improve significantly without any further frequency comparisons.
  - Frequency correction and the overall uncertainty are likely to change (not exactly blind measurements)
- Frequency instabilities of 2D extrapolations, versus launch velocity and density





PHARAO (10^{-16})	Shift	Uncertainty
Quadratic Zeeman	900	0.1
Blackbody radiation	-171.7	0.7
Microwave Lensing	1.14	0.4
Ultracold collisions & Cavity Phase	+1	$3.8\times10^{-13}\tau^{-1/2}$
Total		**1.1**

Laboratoire Kastler Brossel — Physique quantique et applications
l'Observatoire de Paris — SYRTE — Systèmes de Référence Temps-Espace

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Support from CNES, CNRS, ENS, ESA, First TF, NASA, LNE, SYRTE, Penn State, & UPMC

Expectations & Possibilities, with a Caveat

"It's tough to make predictions, especially about the future."
-Danish Proverb (Karl Kristian Steincke & later Yogi Berra)

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Total		**1.1**

after 2 months of live time:

PHARAO (10^{-16})	Shift	Uncertainty
Quadratic Zeeman	900	0.1
Blackbody radiation	-171.7	0.7
Microwave Lensing	1.14	0.4
Ultracold collisions & Cavity Phase	+1	1.66
Total		**1.86**

after 11 months of live time:

PHARAO (10^{-16})	Shift	Uncertainty
Quadratic Zeeman	900	0.1
Blackbody radiation	-171.7	0.7
Microwave Lensing	1.14	0.4
Ultracold collisions & Cavity Phase	+1	0.7
Total		**1.1**

Cs-Cs comparison, 22 months??

PHARAO (10^{-16})	Shift	Uncertainty
Quadratic Zeeman	900	0.1
Blackbody radiation	-171.7	0.1
Microwave Lensing	1.14	0.05
Ultracold collisions & Cavity Phase	+1	0.5
Total		**0.58**

Make & report measurements knowing that uncertainties will improve, even with no further comparisons.

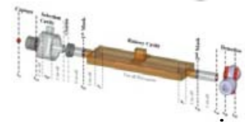
(Also for future fountain measurements.)

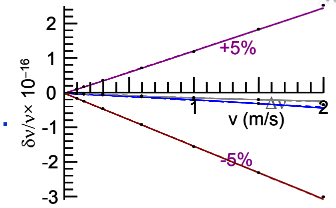
Laurent, Esnaut, KG, Peterman, Lévèque, Delaroche, Grosjean, Moric … Salomon (in prep.)

Combined Cold Collision & Cavity Phase Shifts Extrapolations & their Uncertainties

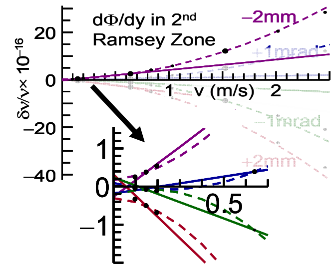
- 1st order Doppler (Cavity Phase) depends on launch velocity
  - Unknown dependence: fit to linear and quadratic in v & extrapolate $\delta\nu$ to v=0.
  - Error is less than the difference for sample cavity defects.

$$\delta\nu = \tfrac{1}{\pi}\left(\Phi_1 - \Phi_2\right)\Delta\nu$$



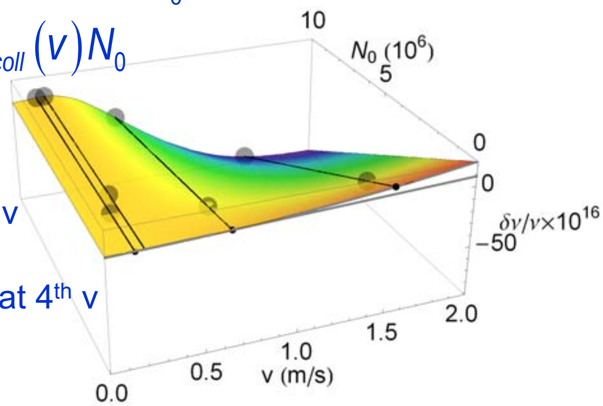


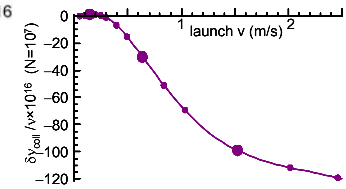
- Cold collision shift is proportional to number of atoms N_0, and coefficient depends on launch v.
  - Extrapolate to N_0=0.
- No detected atoms at v=0 or N_0=0.



$$\delta\nu = \delta\nu_{CP}\left(v\right) + \delta\nu_{coll}\left(v\right)N_0$$

3 launch velocities v × 2 N_0's + max N_0 at 4th v





- Operate at a 4th velocity (measure its collision shift during the evaluation)

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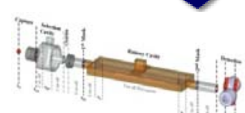
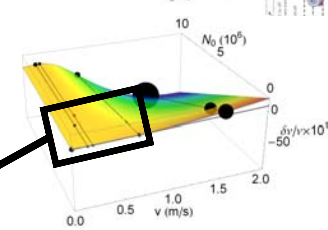
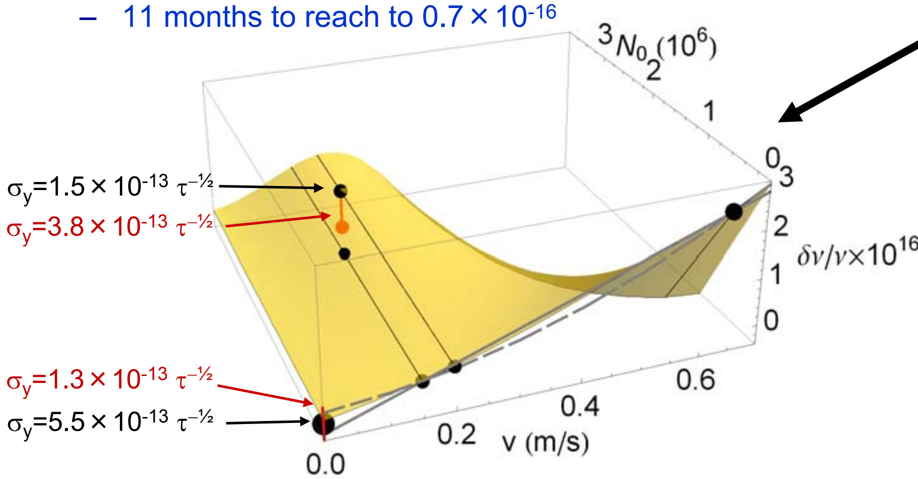
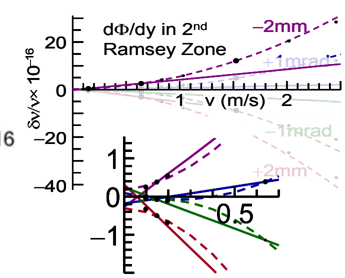
Combined Cold Collision & Cavity Phase Shifts Extrapolations & their Uncertainties

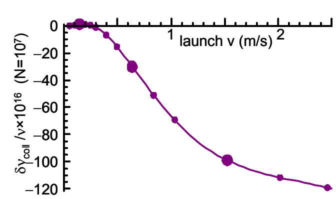
- Instability of extrapolation is insufficient to reach time transfer approaching 10^{-16} during 20 day quiet windows.
- **High Stability:** operate only at 0.2m/s - $1.5\times10^{-13}\ \tau^{-1/2}$
- Separately evaluate the frequency offset of this point.
  - 11 months to reach to 0.7×10^{-16}











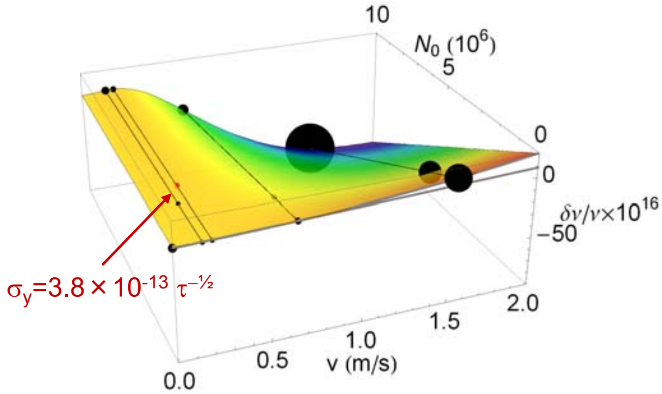
- **Initial Evaluation** (3 months): operate at 7 (v, N_0) points
- **Normal Operation** (11+ months): 7 (v, N_0) points plus ~20% of time at High Stability point (0.2 m/s,0.3 N_0)
- Instability of systematic error is small – independent frequency over 3 yrs.

Laurent, Esnaut, KG, Peterman, Lévèque, Delaroche, Grosjean, Moric … Salomon (in prep.)

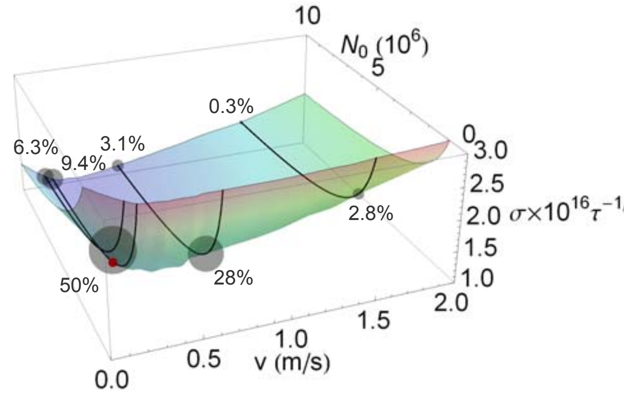
Optimization of Instabilities

- Time spent at each (N_0 ,v) is optimized.

Doppler + Collision Shift



Instability



- >90% of the operating time is at low v and/or low N_0.
- An initial solution: re-optimize after commissioning, during Initial Evaluation, …

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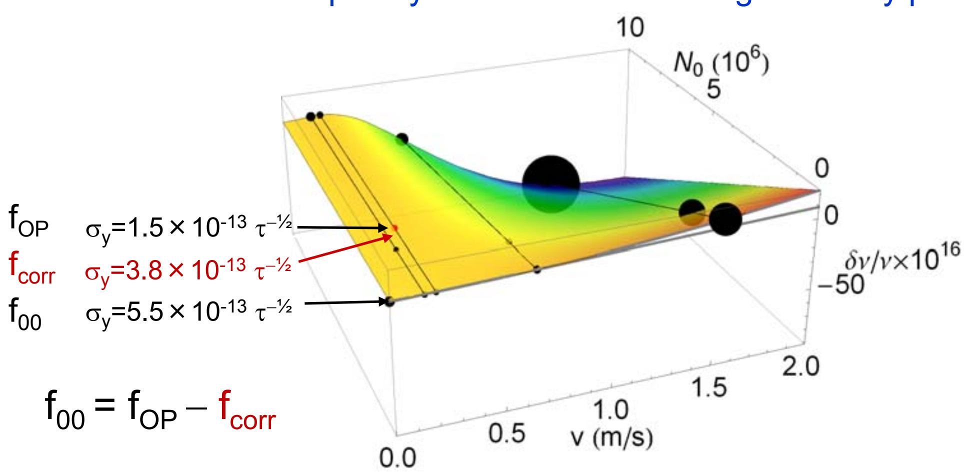
Uncertainties of Cold Collision & Cavity Phase Shifts

- **Normal Operation** (11+ months): 7 (v, N_0) points plus ~20% of time at High Stability point (0.2 m/s,0.3 N_0) to evaluate f_{corr}, the correction for the High Stability operation.
- Use additional frequency measurements at High Stability point to improve f_{corr}?



- Normal Operation: 8 uncorrelated frequency measurements → f_{corr} & f_{00} have correlations.
- Using any measurement of f_{Op} to determine f_{corr} degrades the correlations that give f_{corr} its smaller instability. f_{Op} doesn't improve f_{00} → uncertainty of f_{corr} must increase as f_{Op} uncertainty decreases.

Summary

- Most systematics will be evaluated during the commissioning of PHARAO, just as for ground clocks.
- 1st order Doppler shifts (DCP) & cold collision shift will take more than 1 year to reach ultimate accuracy
  - BBR may also improve dramatically years from now.
- Make & report measurements knowing that the uncertainties will likely improve significantly without any further frequency comparisons.
- Linear and quadratic DCP extrapolations vs. launch v.
- Combined collision shift & cavity phase extrapolation is a statistical error, with negligible systematic.
- Normal Operation will evaluate correction (and give a degraded clock stability)
- High Stability operation designed to meet 10^{-16} time transfer goals for 20 day quiet periods
- Reoptimize operation using first on-orbit data

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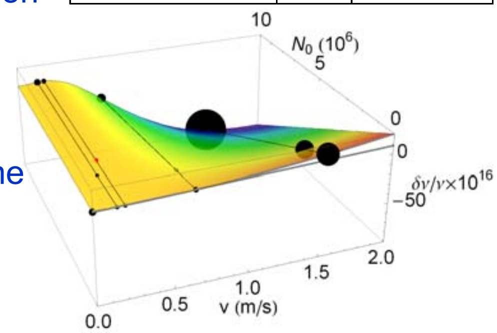

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Penn State, Obs. de Paris, CNES, & Ecole Normale Supérieure

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