# Section 15:
# Predicting residual acceleration effects on space experiments

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## GOAL:

**Predict sensitivity of the experiment to the acceleration environment**

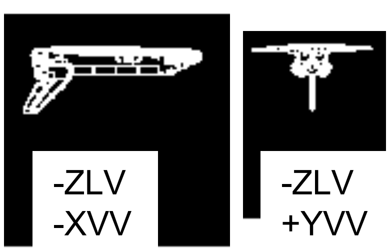
- PI must justify ***need for microgravity***
- PI must be able to predict ***tolerable*** (and intolerable) ***environments***

# PI’s choices (and assignments) affect the quality of the µg environment

- ***flight mode*** ***( attitude of the carrier with respect to the earth)***
- ***deadband*** ***(allowable angular displacement from the desired mode)***
- ***location*** of experiment relative to CG
- ***orientation*** of the experiment w.r.t. Shuttle (or ISS) body axes
- scheduling of ***crew activities***
- operation of ***other apparatus*** or experiments

# Recommendations to minimize g-jitter effects based on flights of MEPHISTO (directional solidification)

- Use flight modes which do not require ***Shuttle maneuvers*** for water dumps, etc. (e.g., -ZLV,+YVV) for long-duration microgravity (>3 days)
- To minimize large accelerations, ***specify a flight mode*** requiring fewer thruster firings to maintain attitude; ***2° deadband*** required fewer thruster firings than 1° -- better µg
- Experiments should be ***aligned with Shuttle's z body axis*** for these flight modes to minimize transient acceleration effects (least transmission of disturbances along this axis)




**MEPHISTO I: STS-52 10/92**

$x_{CG}$ = (27.7, 0, 9.3) m

$x_{MI}$ = (25.5, 1.05, 10.8) m

(a) −ZLV,−XVV at 300 km

← velocity

Earth ↓

**MEPHISTO II: STS-62 3/94**

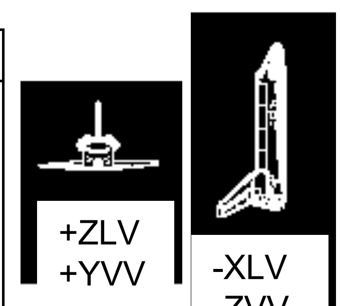
$x_{CG}$ = (27.8, 0, 9.5) m

$x_{MII}$ = (25.5, 1.05, 10.8) m

(b) −ZLV,+YVV at 300 km

(c) +ZLV,+YVV at 260 km

(d) −XLV,−ZVV at 300 km




**– de Groh and Nelson, 1994**

# Strategy for assessing experiment sensitivity to the μg environment

(1) Identify the ***tolerance criterion***

(2) ***Correlate acceleration*** to the tolerance criterion

(3) Perform “simple” analyses to determine ***range of sensitivity***

(4) As necessary, perform a ***detailed analysis*** in the range of sensitivity

(5) Develop ***detailed μg tolerance specifications***

# 1. Identify tolerance criterion

**Tolerance criteria are**:

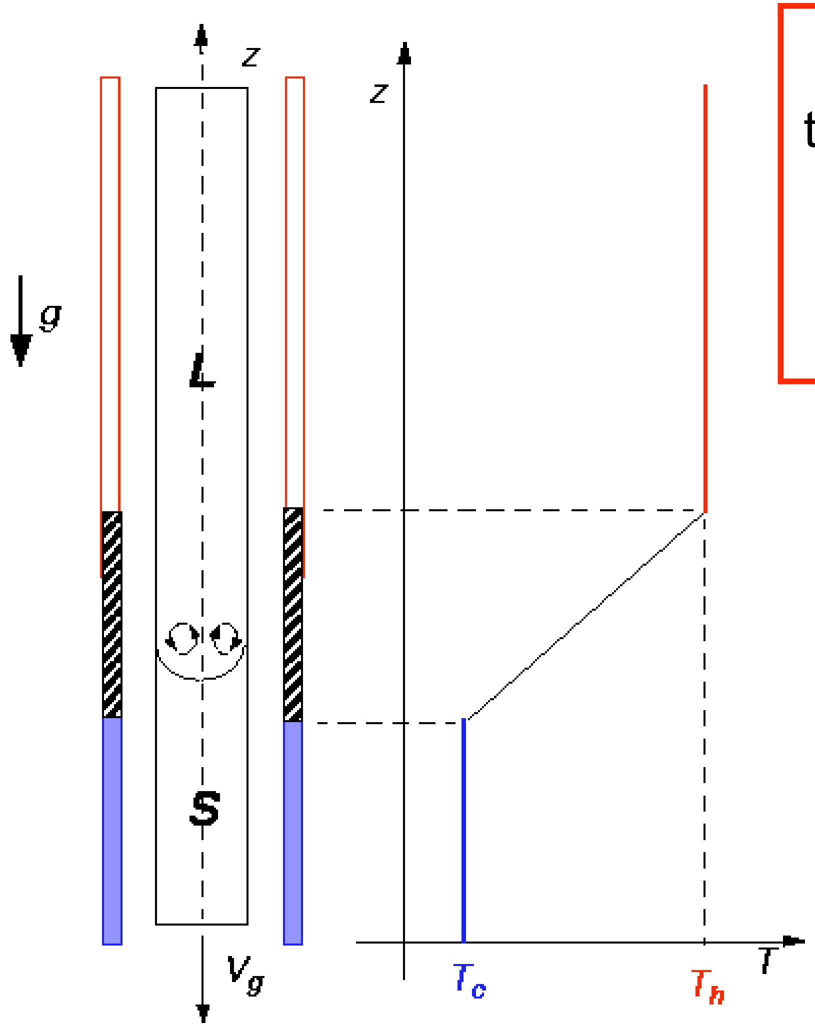
- ***subjective***
- ***arbitrary (to some extent)***
- functions of ***many parameters***
  - physics
  - experiment goal
  - composition of system (thermophysical properties, etc.)
  - geometry of system (aspect ratio, length of test section, etc.)
  - applied boundary conditions (applied thermal or pressure field, velocity of boundaries, etc.)

A good tolerance criterion is a function both of the ***specific experiment design*** and the ***specific environment*** in which it is placed

# Two examples

- ***directional solidification:*** buoyancy-driven flow of a passive scalar field (natural convection)
  - goal is to *suppress convection* to maximize homogeneity of the crystal (diffusion-controlled growth)
  - *highly sensitive* to residual acceleration (orientation, magnitude, frequency)
  - requires very *long duration* microgravity (hours to days)
  - *lots of previous studies*, including space experiments
- ***granular flow:*** segregation of a binary mixture of particles in a collision-dominated flow
  - uses kinetic theory of gases as analog to grain fluctuation energy, T
  - *relatively insensitive* to residual acceleration
  - *relatively short-duration* microgravity (minutes)
  - *no similar previous investigations*

# Bridgman growth of semiconductor crystals



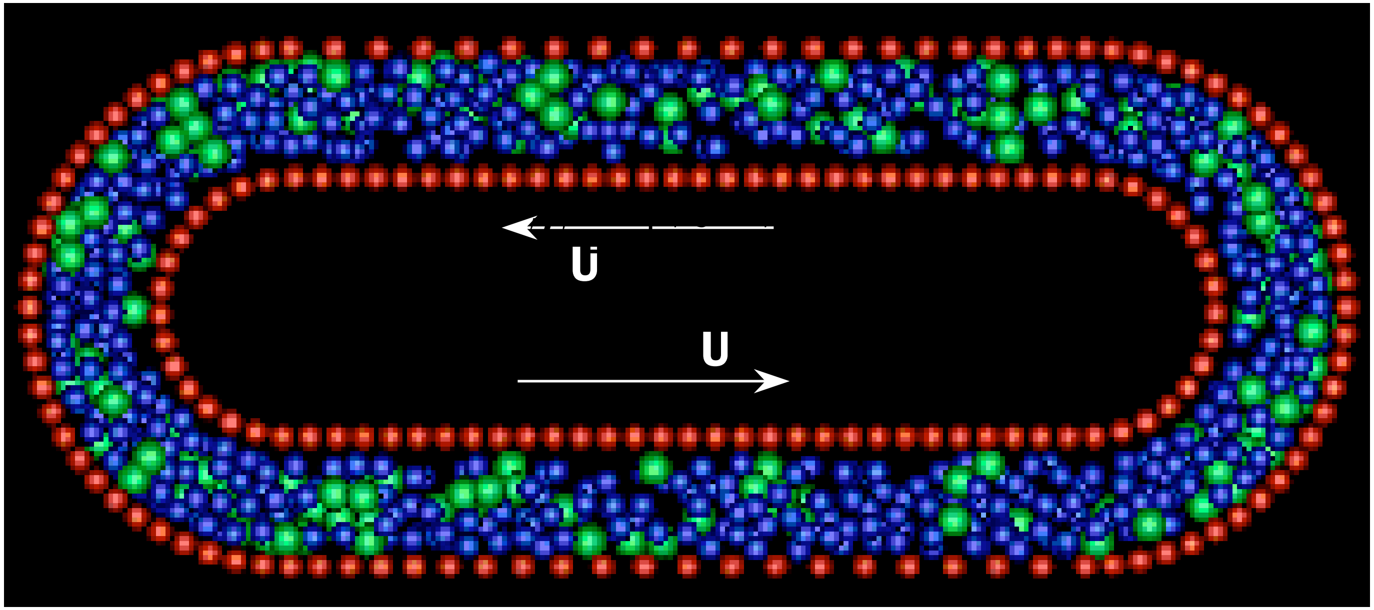

First, develop the tolerance criterion in terms that are ***physically meaningful w.r.t. the experiment***

Tolerance criterion:
**1% variation in solute concentration** at solid/liquid interface (for example)

$$\xi = \frac{c_{max_{interface}} - c_{min_{interface}}}{c_{bulk}}$$

# Microgravity segregation of energetic grains ($\mu$gseg)

Test section




Test section

<u>Tolerance criterion</u>: g-jitter can contribute up to **5% variation in mean granular temperature, T,** across test section

$$T = \frac{1}{3}\tilde{u}_i' \cdot \tilde{u}_i'$$

– Jenkins and Louge, 1998

# 2. Correlate acceleration to tolerance criterion

- All experiments will have some dependence on acceleration ***magnitude***, ***frequency***, ***orientation***, and ***duration***
- Experimental system ***response varies enormously***, e.g.,:
  - may be very sensitive to *specific* frequencies, orientations, etc. esp. for interfaces, critical point experiments
  - require examination of *overall* momentum input, esp. for bulk flows
  - may need *long recovery times* for short disturbances, esp. for flows with large Schmidt or Prandtl number

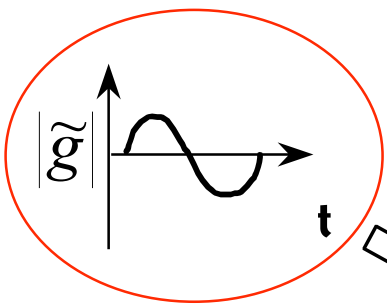
Key: what drives the sensitivity?

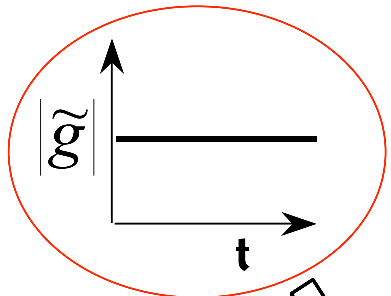
# Analysis tools include:

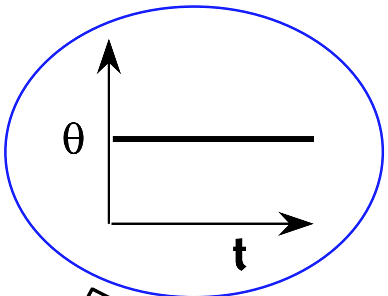
- ***theoretical*** analysis
  - order-of-magnitude analysis
  - exact solution of a simplified problem
- ***numerical*** simulation
  - traditional FD/FE/FV approach
  - direct numerical simulation
  - stochastic approach
- ***experimental*** testing (ground-based)
  - ground-based facilities, e.g., KC-135, drop tower
  - vibrating platforms
  - centrifuge

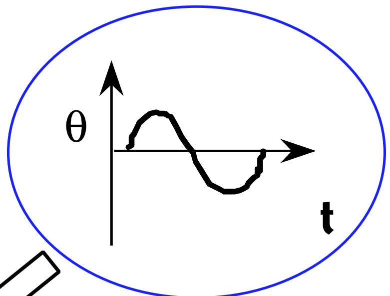
**FD: Finite Difference**
**FE: Finite Element**
**FV: Finite Volume**

# Develop a model of experiment response to acceleration input

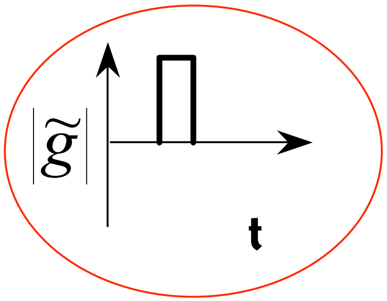


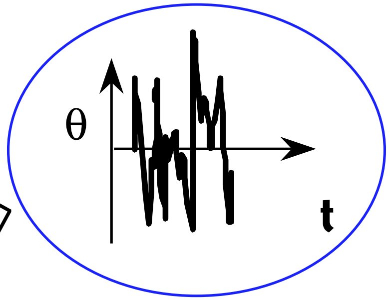



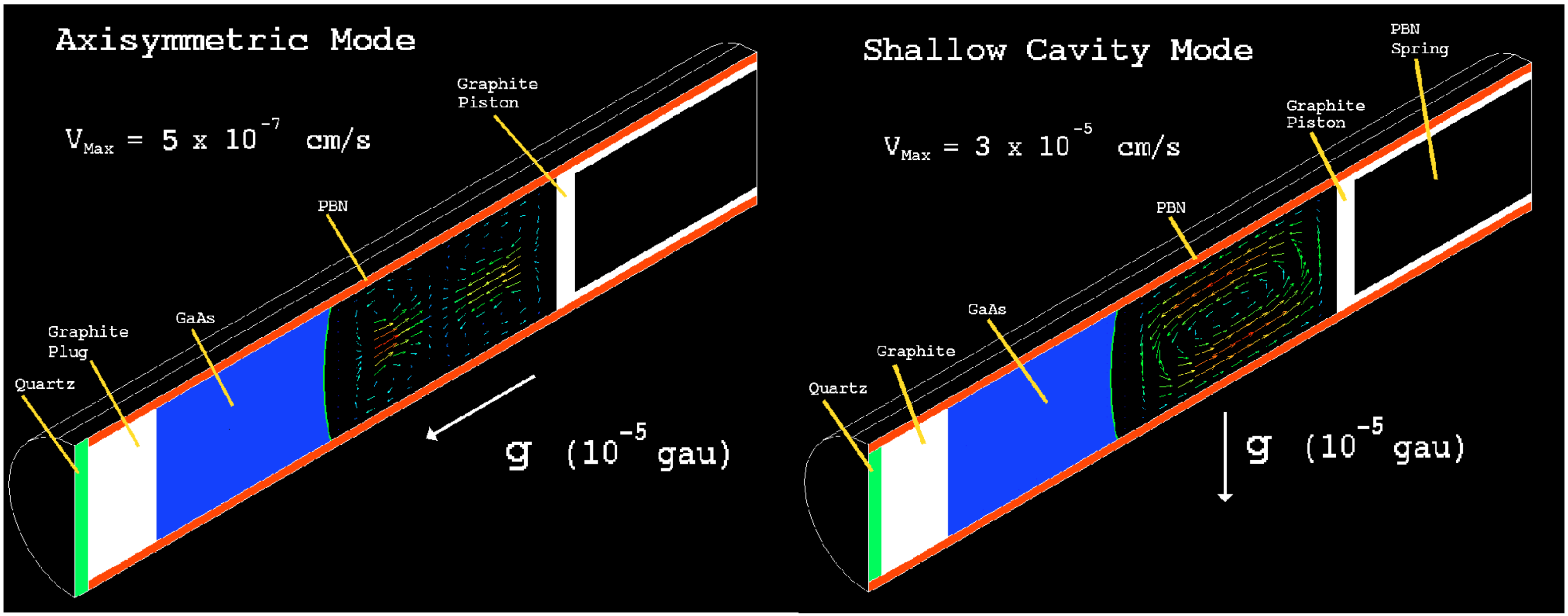

For convenience (or by necessity), we may study components of **g** separately



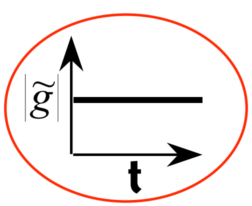



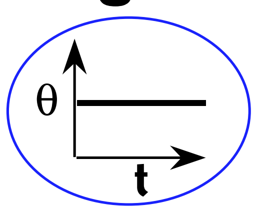

Q: Does the system exhibit linear response to acceleration input?

## Develop a model of experiment response to acceleration input (cont'd)



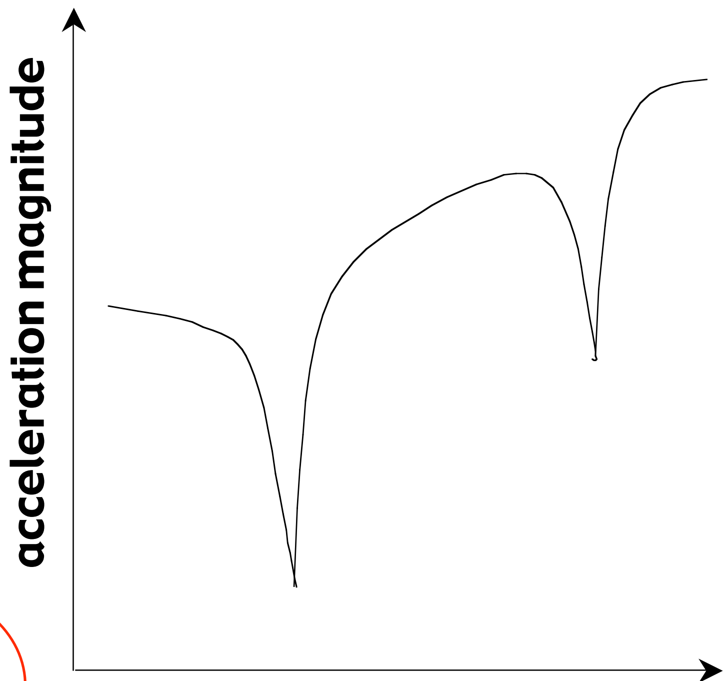

# Effect of g orientation on directional solidification

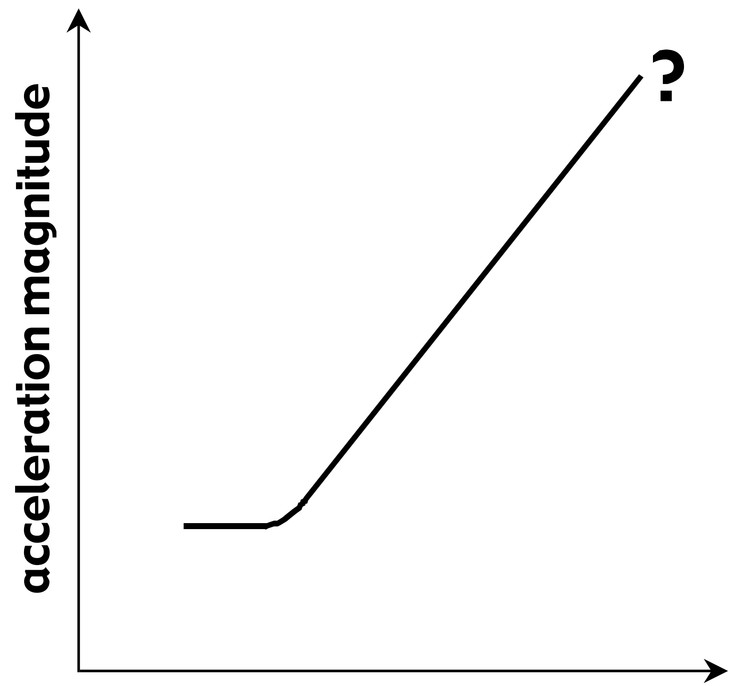


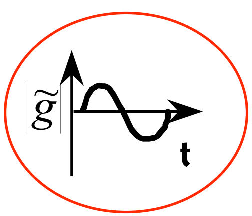



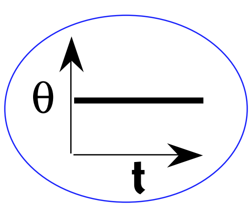

– Arnold et al., 1991

## Develop a model of experiment response to acceleration input (cont'd)



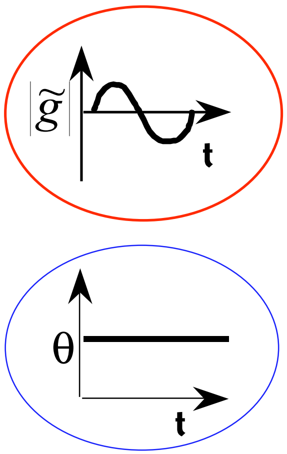



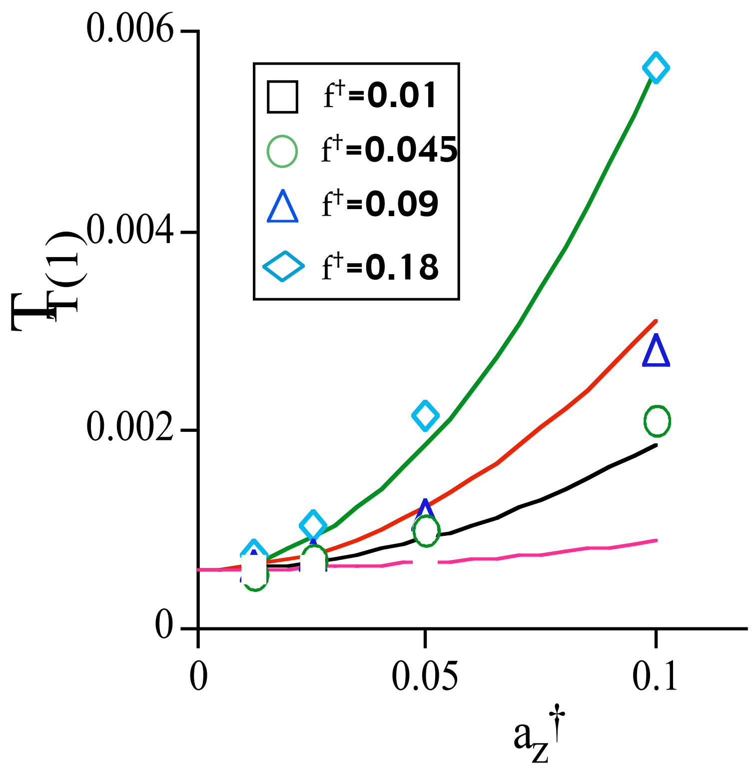




**liquid bridges**

**natural convection**

## Develop a model of experiment response to acceleration input (cont'd)



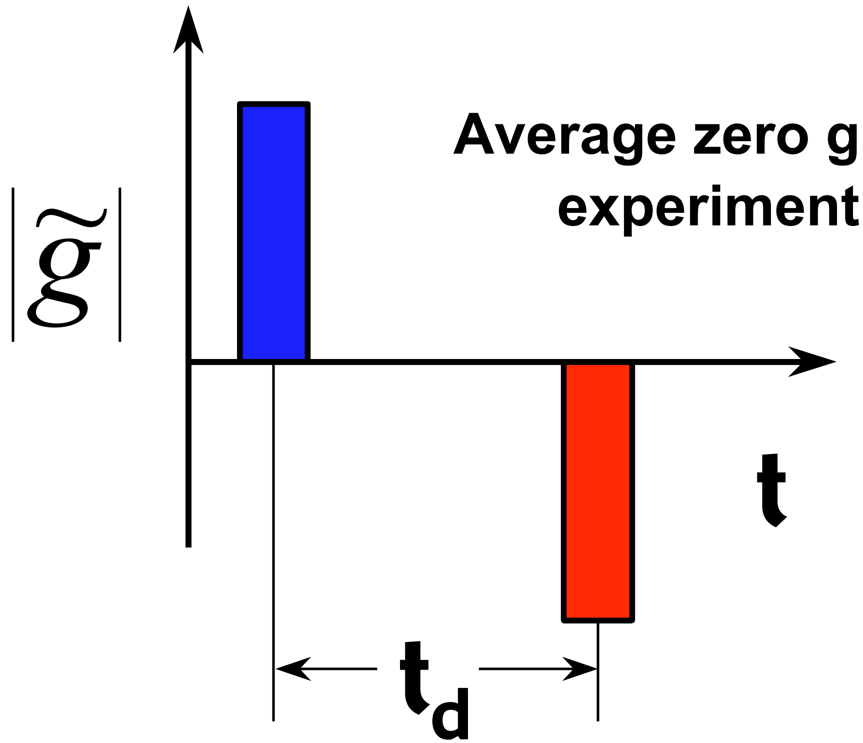

Mean granular temperature as a function of acceleration frequency and amplitude

$$\boxed{T = T_0 + c_i\, f^{\dagger} a^{\dagger 2}}$$

**granular shear flows**

– Jenkins and Louge, 1998

## Develop a model of experiment response to acceleration input (cont'd)

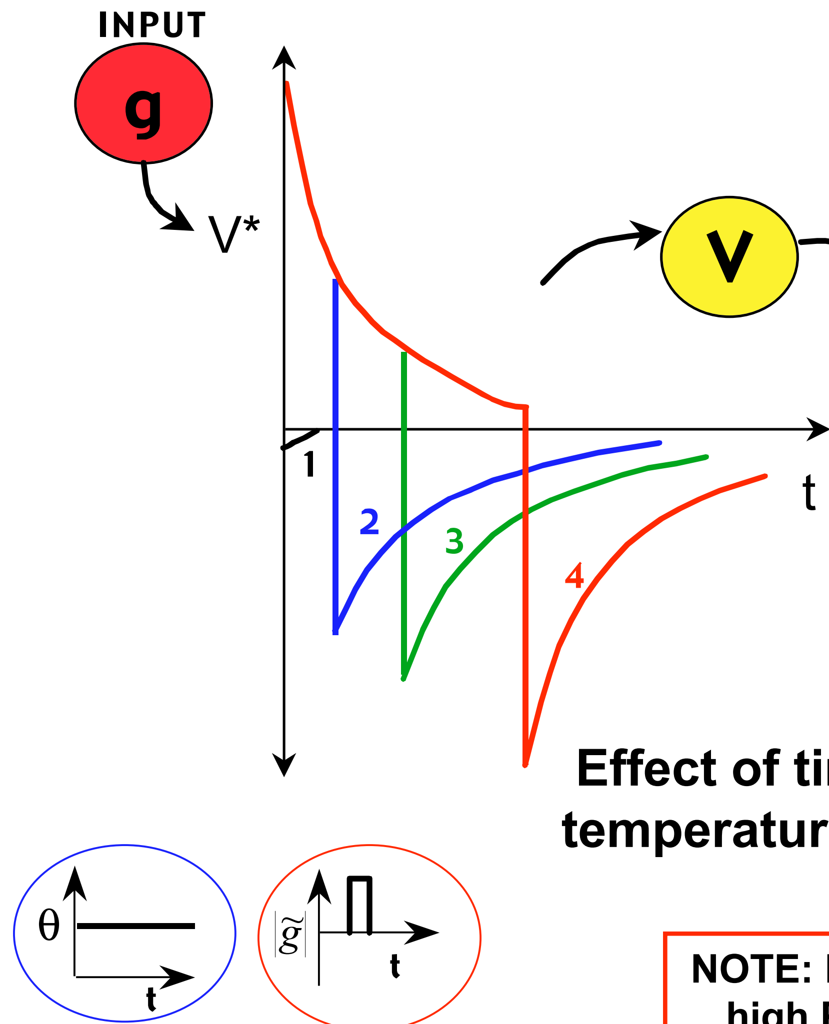


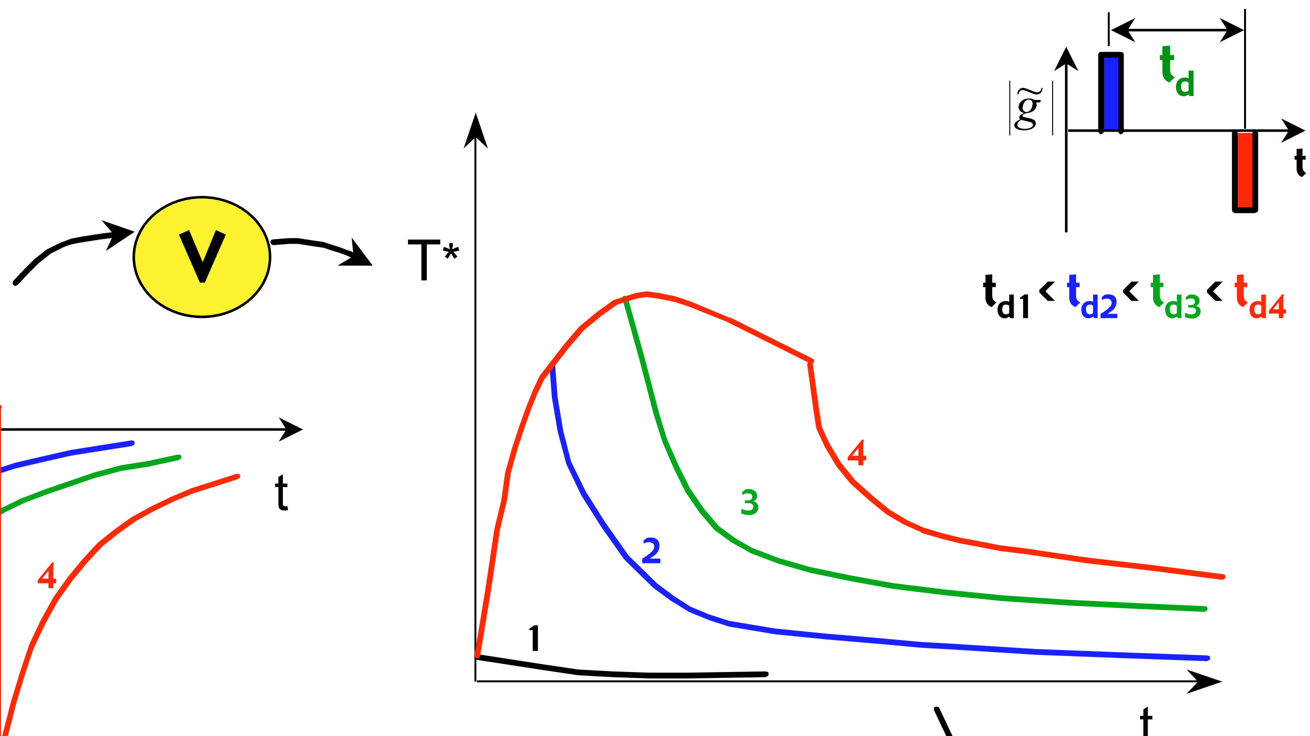

**Average zero g ≠ zero effect on experiment necessarily**

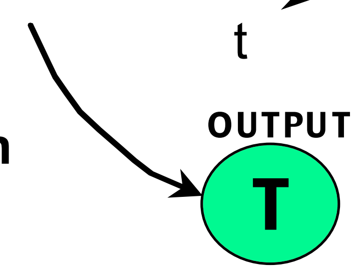
Net acceleration=0, *but* system reacts in a *transient* manner with finite response time

$\Rightarrow$ Net system response may be nonzero

## Develop a model of experiment response to acceleration input (cont'd)




**Effect of time delay on velocity and temperature in natural convection in enclosures**

**NOTE: Especially important for high Pr or Sc number flows**

- Monti et al., 1990

## Develop a model of experiment response to acceleration input (cont'd)

**But eventually, we must consider the actual acceleration environment for the carrier of interest, e.g.:**

- International Space Station
- sounding rocket
- Space Shuttle
- free flyer
- low-g aircraft, e.g., KC-135
- Mir

## Develop a model of experiment response to acceleration input (cont'd)

**To describe the actual environment for numerical or theoretical analysis:**

- use ***actual acceleration data*** at or near location of experiment

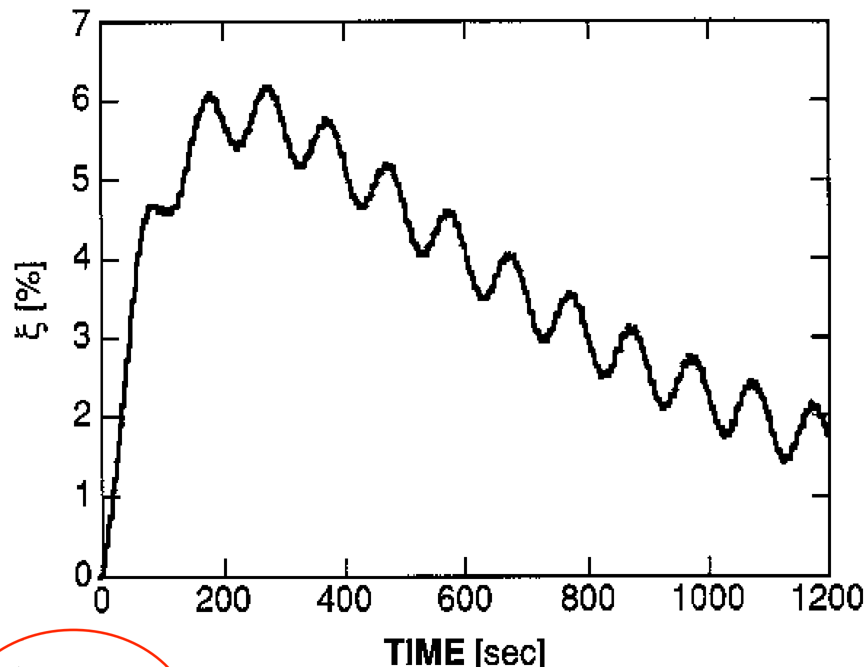
$$g_i(t), \quad i = x, y, z$$

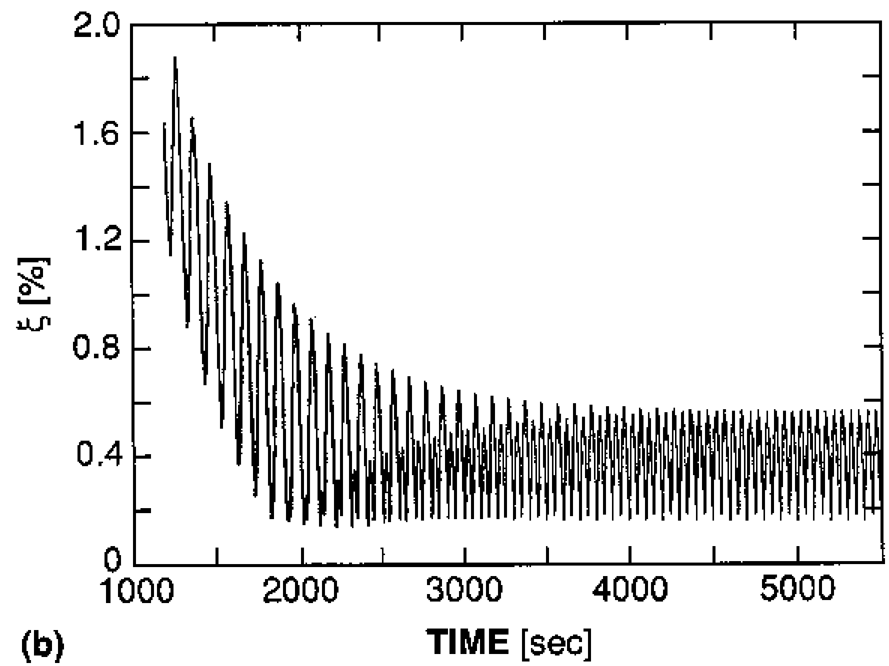
- construct g in the ***time*** domain using ***predicted spectral data***, e.g., from ISS predictions, simplified data spectrum

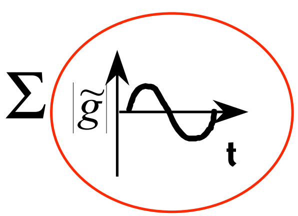
$$g_i(t) = g_{qs,_i} + \sum_n g_{o,i} \sin(2\pi f_n t) + g_{t,_i}(t)$$

- examine predicted or actual data in ***spectral*** domain

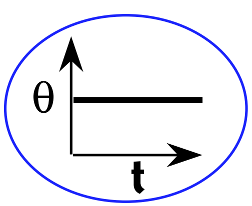
## Develop a model of experiment response to acceleration input (cont'd)



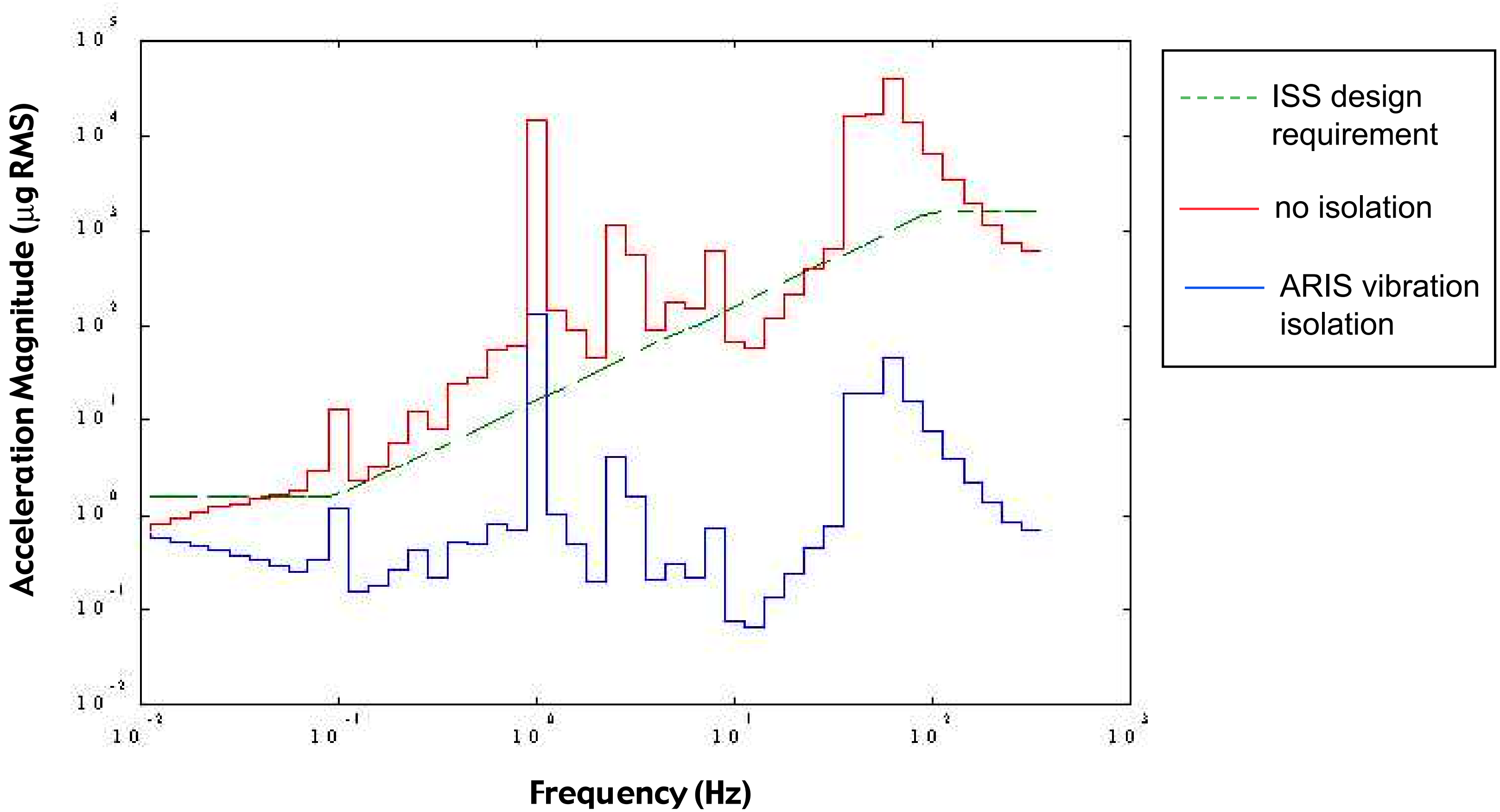

(Concentration variation at solid/liquid interface as a function of time using a simplified spectrum of the Shuttle acceleration environment)



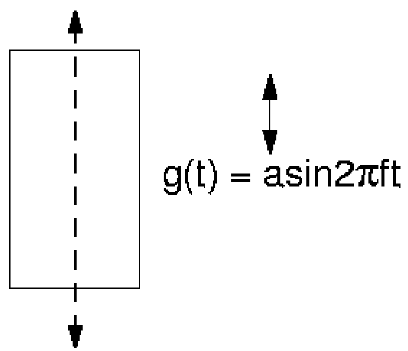

**Initial transient in natural convection in enclosures: Startup of multifrequency sinusoidal disturbance**

- Alexander et al., 1991

# 3. Identify range of sensitivity

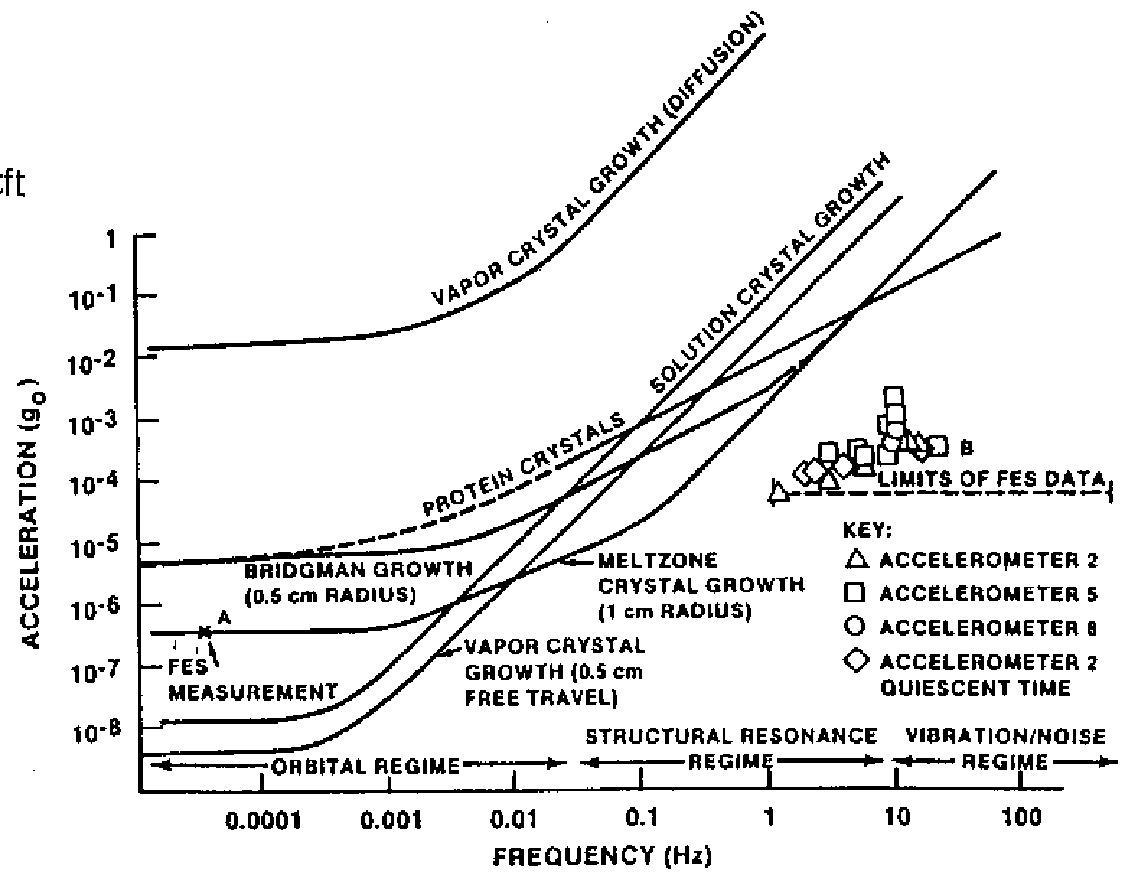


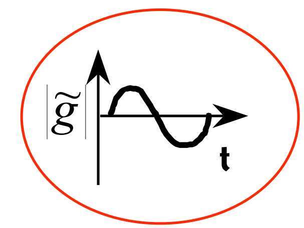
# Tolerability limits for buoyancy-driven flows in enclosures

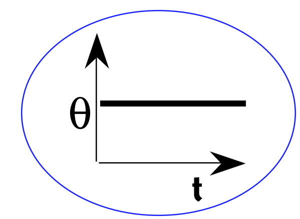



FREQUENCY VS ACCELERATION

G-LEVEL TOLERANCE FOR MONOCHROMATIC OSCILLATING DISTURBANCES POINTS AT A & B ARE SPACE LAB 3 ACCELERATION MEASUREMENTS

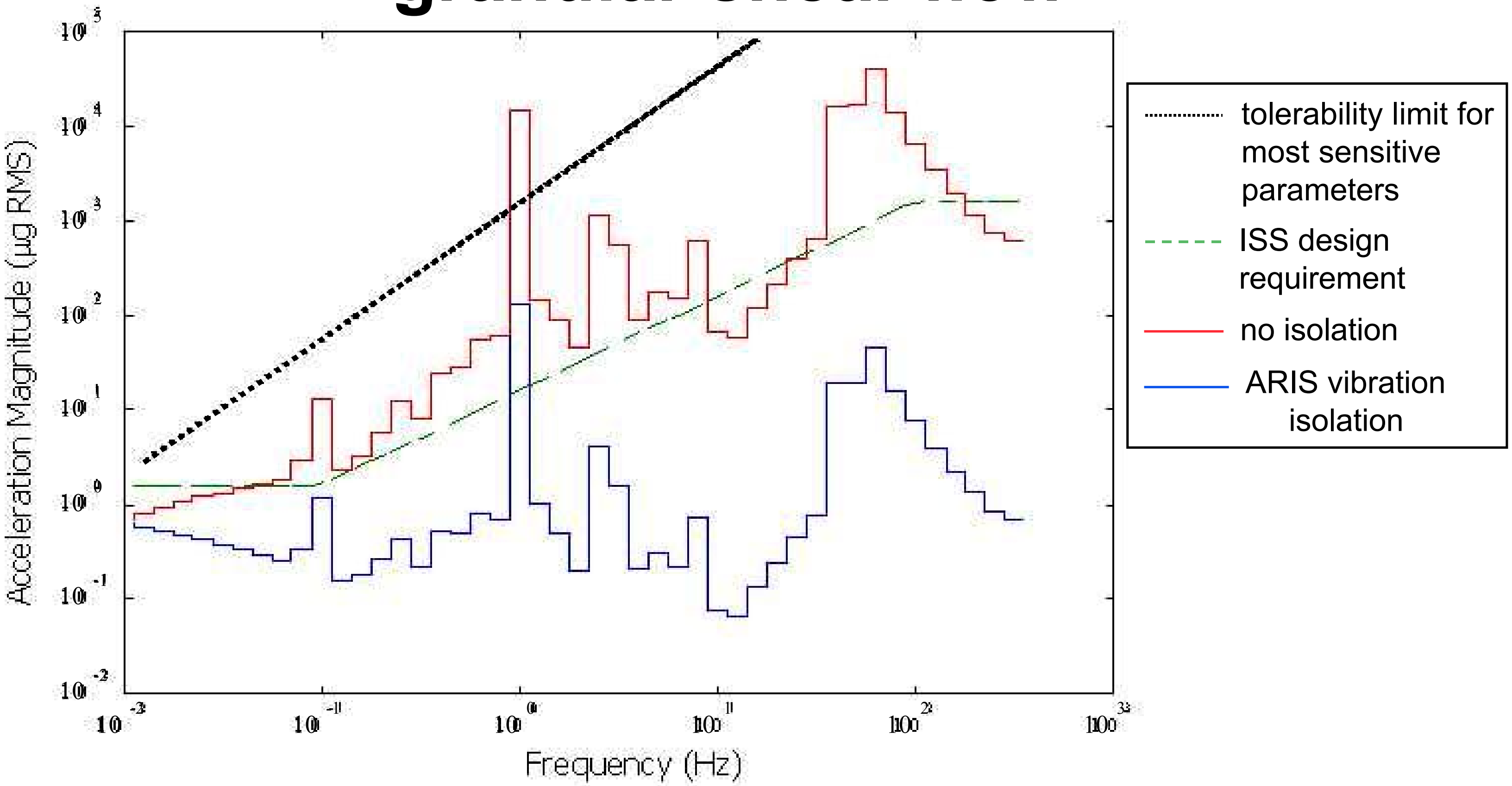



– Demel, 1986

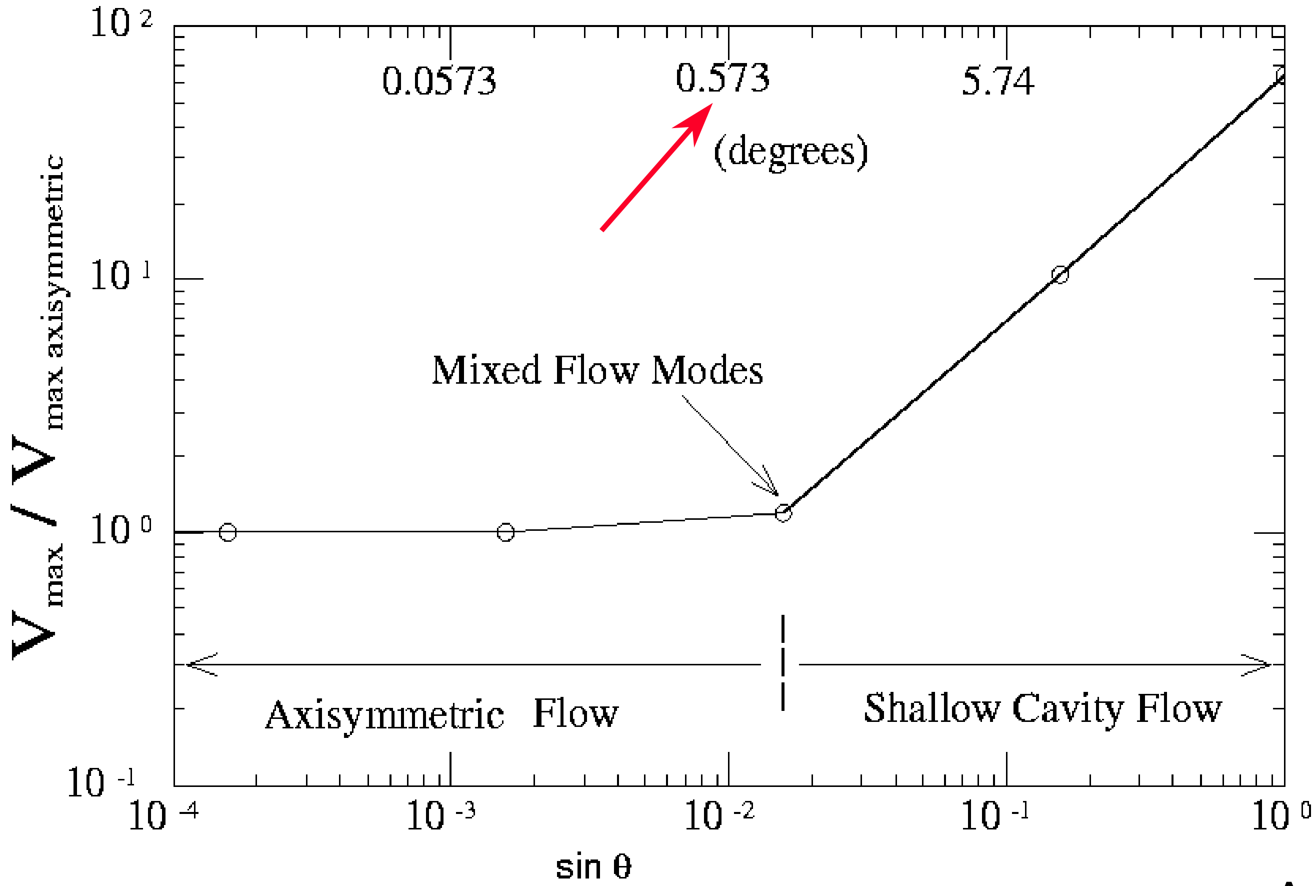
# Effect of single-frequency g-jitter on T in granular shear flow




<u>CONCLUSION</u>: suitable environment can be found on ISS

– Jenkins and Louge, 1998

# Sensitivity of directional solidification to quasisteady g orientation

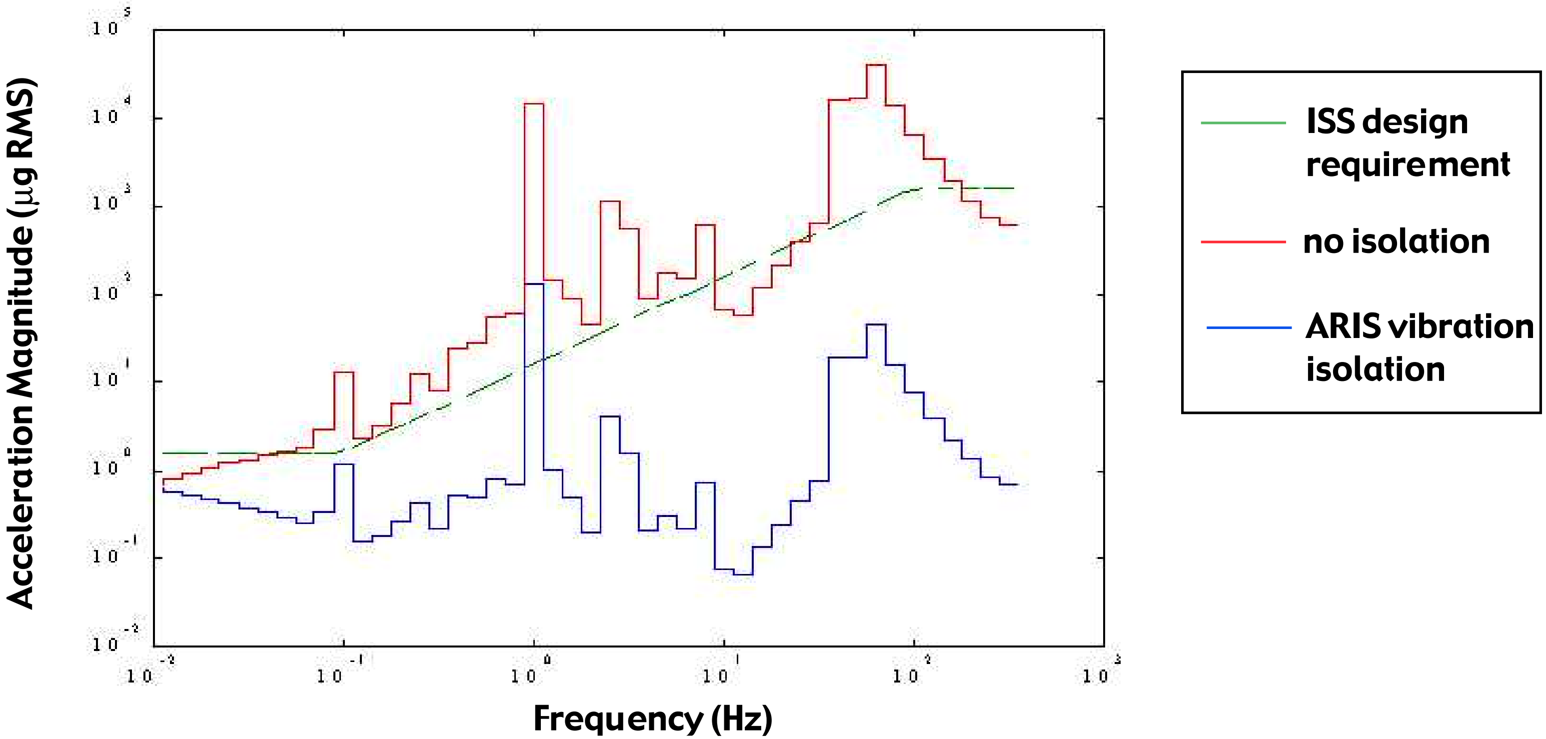



Be aware that any inhabited spacelab is likely to be ***extremely*** variable in θ due to the rich variety of acceleration sources!

NOTE: For other experiments, this tendency towards improved mixing may actually be beneficial!

Arnold et al., 1991

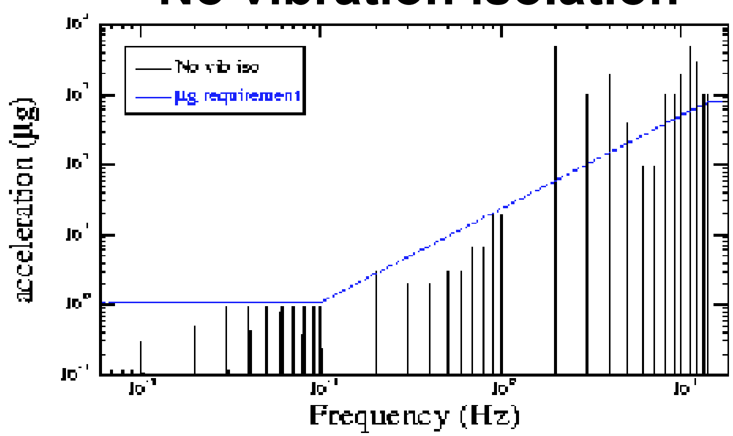
# 4. Perform detailed analysis



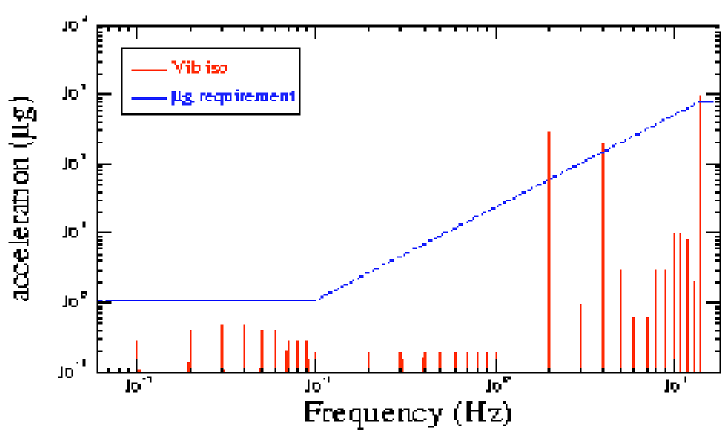

**Q**: Is vibration isolation necessary?

# Effect of vibration isolation on directional solidification

### No vibration isolation




### ARIS vibration isolation




## Idealized ISS environment:

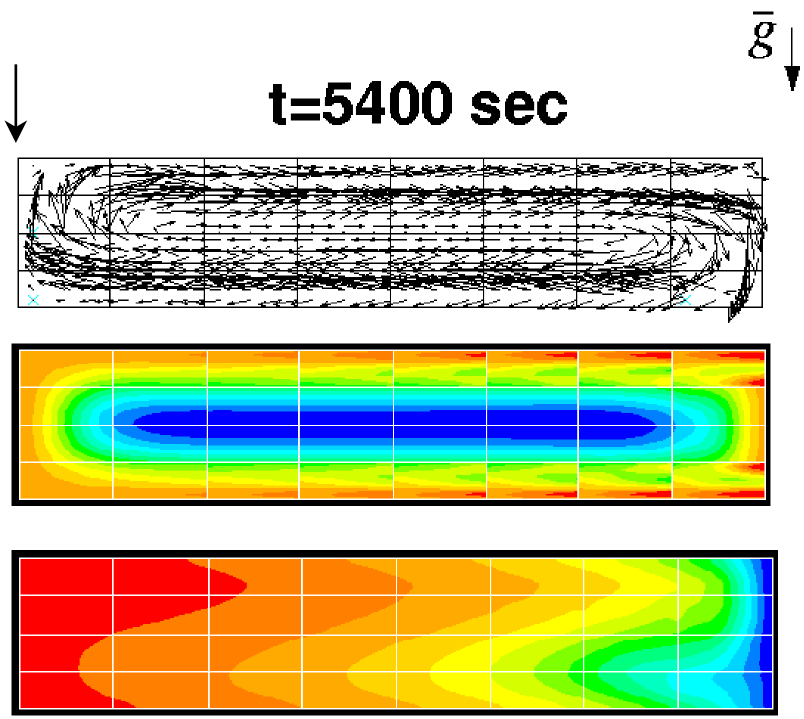
- constructed from DAC-3 (Design Analysis Cycle #3)
- used a frequency range from 0.01 to 14 Hz for several hours of simulated μg
- neglected effects of robot arm (big peak at 0.1 Hz), but included treadmill and other facility operations

Use this data to create g(t):

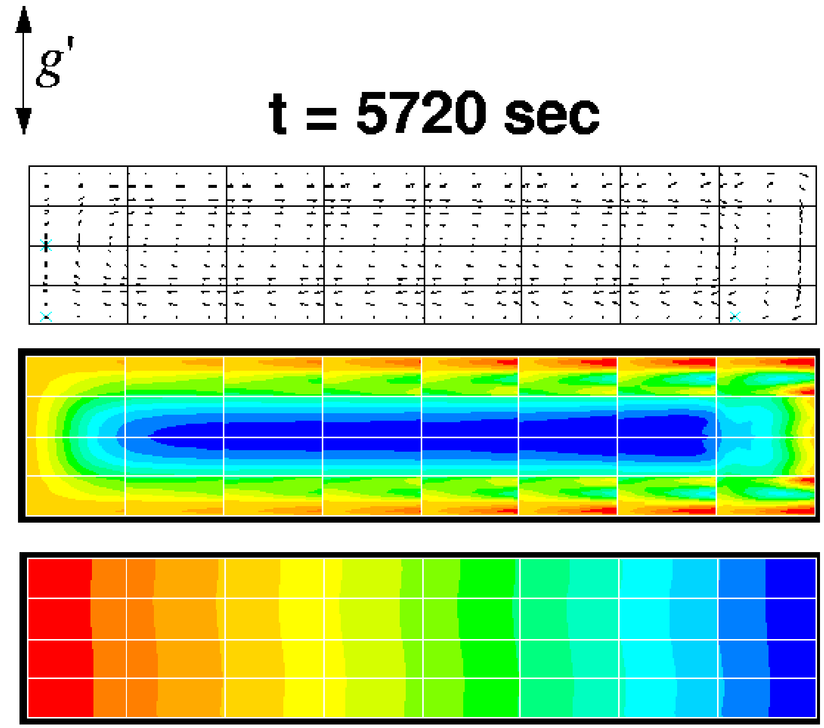
$$g_i(t) = g_{qs,_i} + \sum_n g_{o,_i} \sin(2\pi f_n t)$$

– Nelson and Kassemi, 1997

## Effect of vibration isolation on directional solidification (cont'd)



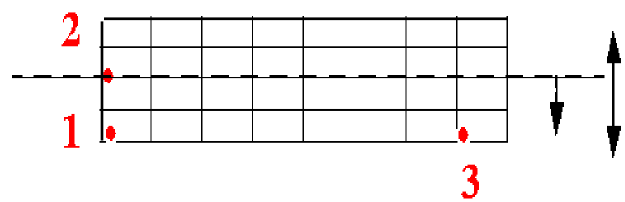

No vibration isolation

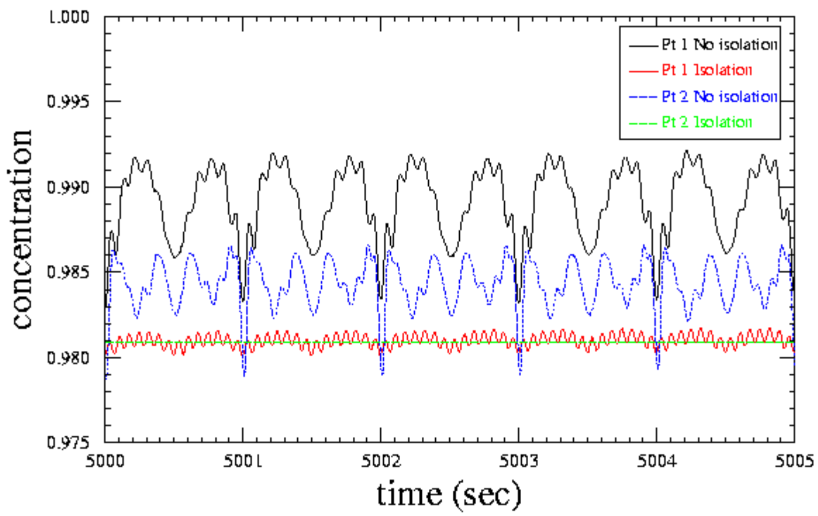


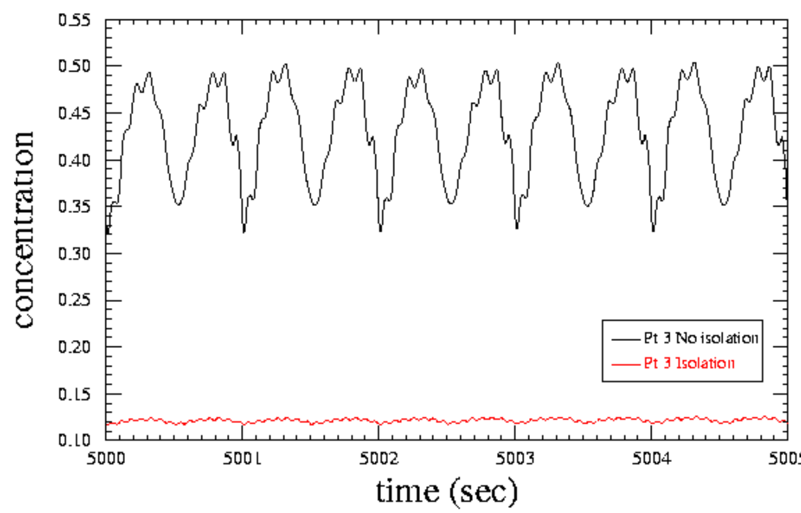

Vibration isolation

Nelson and Kassemi, 1997

## Effect of vibration isolation on directional solidification (cont'd)




Nelson and Kassemi, 1997

## Effect of vibration isolation on directional solidification (cont'd)

**Q**: Is vibration isolation necessary for this case?

**A**: Yer darn tootin'!

# 5. Develop detailed microgravity tolerance specs

- **Specify *duration* of experimental runs**
  - *typical* length
  - anticipated *maximum/minimum* length
  - expected *number of runs* per 30-day microgravity period
- **Describe the *quasisteady* acceleration limits**
  - upper bound of QS *magnitude* (expect several µg on ISS)
  - desired *orientation* (if choices are available); angular *tolerance* about that orientation (e.g., align experiment with torque equilibrium attitude (TEA) of ISS with a tolerance of $\pm 0.05$ . Maintain QS **g** orientation to within TEA $\pm 10$

- **Identify *oscillatory* acceleration limits**
  - *specific frequencies at particular magnitudes* of concern
  - frequency *cutoff* (frequencies above or below the cutoff are of no concern)
  - *thumbs up/down for specific environments*, e.g.,
    - acceleration data from Shuttle, sounding rocket, KC-135, ISS...
    - predicted ISS environment, e.g., from DAC-xx for a specific configuration and disturbance environment:
      - unisolated rack
      - ARIS vibration isolation
      - passive vibration isolation
      - MIM, g-LIMIT, or other active sub-rack isolation unit
- **Describe *transient* acceleration limits**
  - *thumbs up/down for identified transients* (based on thruster firings, impulsive crew activity, etc., e.g., 100 μg for up to 2 sec);
  - specify *integrated acceleration input* subject to limits (e.g., 300 μg sec with magnitude ≤ 150 μ

# Recap:

## Prediction of experiment sensitivity to the μg environment through modeling

- Identify the ***tolerance criterion***
- ***Correlate acceleration*** to the tolerance criterion
- Perform “simple” analyses to determine ***range of sensitivity***
- As necessary, perform ***detailed analysis*** in the range of sensitivity
- Develop detailed ***μg tolerance specs***

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