Sterilisation limits for sample return planetary protection measures "SterLim"

Presentation to the Committee on the Review of Planetary Protection Requirements for Sample Return from Phobos and Deimos

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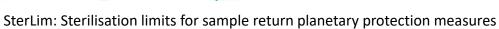


## **INTRODUCTION AND WELCOME**











#### Study objectives

- To produce test and simulation data to allow sterilisation limits to be derived (to support):
  - backward planetary protection measures essential to support MSR mission studies (e.g., MSR-O and ERC)
  - related technology developments (e.g., containment system)
  - confirm the Phobos Sample Retrun planetary protection category in light of studies indicating substantial material transfer from Mars to Phobos.



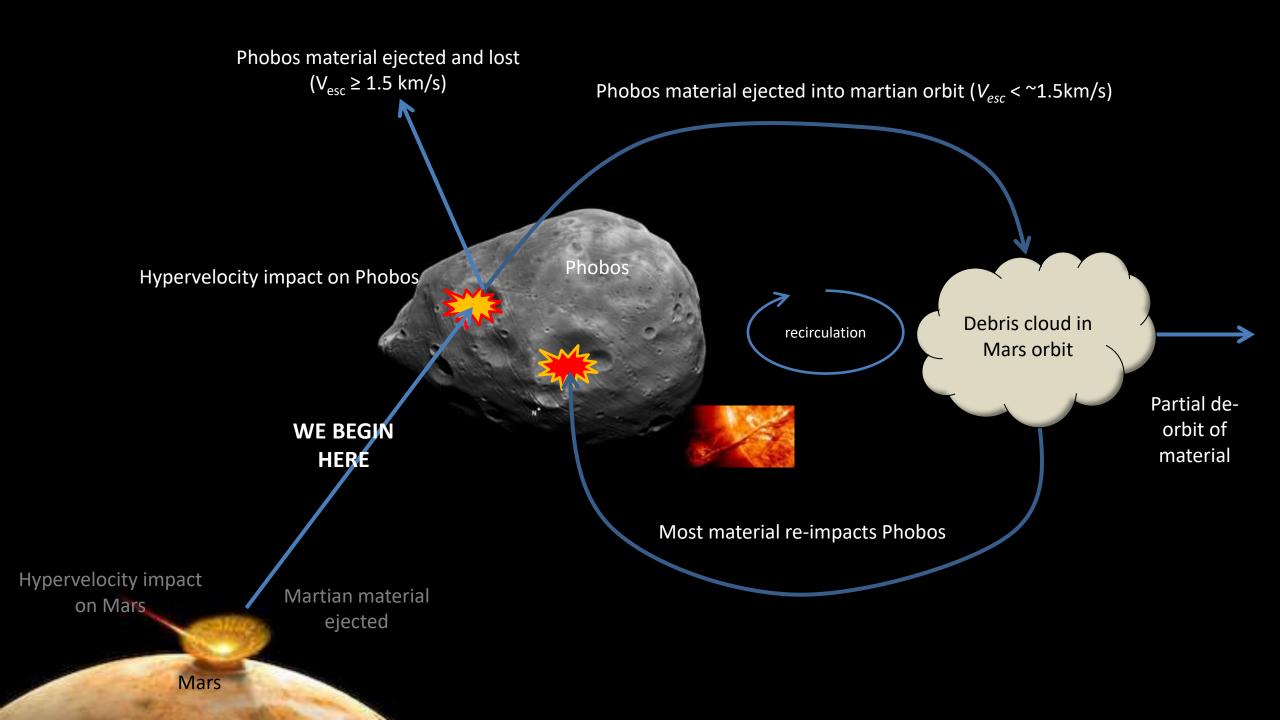






#### Study objectives

- Achieving the overall objective is based on a phased approach:
  - Phase 1 to identify the necessary tests and simulations to achieve the overall objective and to demonstrate the feasibility of the described tests and simulations.
  - Phase 2 to conduct the majority of the tests and simulations.
- Phase 1 completed
- Phase 2 almost complete

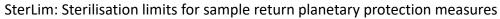






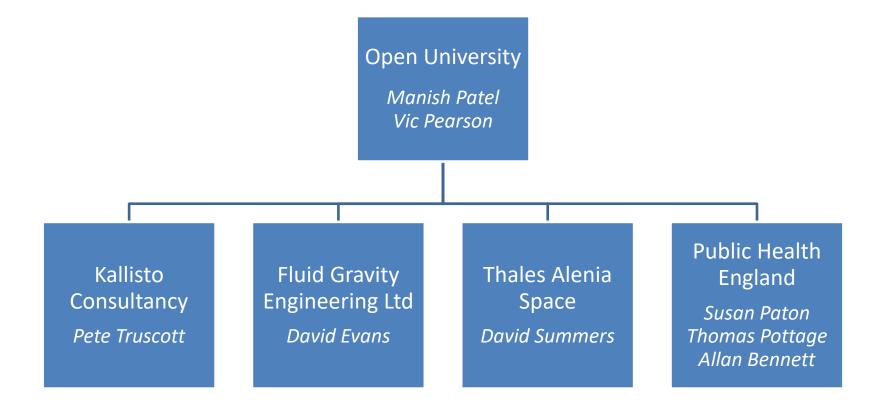








#### Study consortium





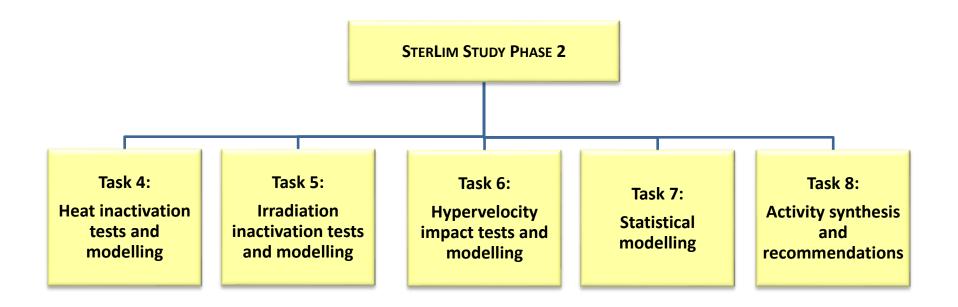








#### Work breakdown structure















#### Requirements

- 48 explicitly stated study requirements defined in the ESA Statement of Work
  - Statistical (4)
  - Biological (12)
  - Impact test and modelling (17)
  - Heat test (6)
  - Radiation test and modelling (9)









#### Requirement-10:

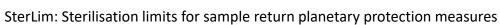
The probability that a single unsterilized particle from Mars ≥10 nm in diameter is in a sample returned from Phobos shall be  $\leq 1 \times 10^{-6}$ 













#### The task...

# How do we establish Req-10 against the process of transfer of material from Mars to Phobos and Deimos?







#### Primary sterilisation factors

- Two processes were specified as the driving sterilising factors
  - Radiation
  - Impact process
- Study aimed at generating lab data supported by context modelling

Impact response of organisms Heat pulse response of organisms Radiation response of organisms Modelling impact process and radiation on Phobos/Deimos Combine in a statistical model













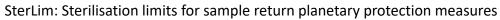
# **BIOLOGICAL MODELS**













#### Selection of Biological Models

#### Req-80: The biological model systems shall include at least:

- Bacterial spores
- Simple organisms (Coxiella)
- Capnophiles
- D. radiodurans
- Resistant small viruses (bovine virus diarrhoea)

Biological model group	Biological model identified	Short name	Why chosen		
Bacterial spores	Bacillus atrophaeus BG		Most hardy, resistant to dry heat/desiccation		
Simple organisms	Brevundimonas diminuta	B. dim	Simple growth requirements (RG1), resistance to desiccation		
Capnophiles	Clostridium difficile	C. difficile	Requires CO <sub>2</sub> to grow, hardy spores		
Deinococcus radiodurans	Deinococcus radiodurans	D. rad	Resistant to irradiation and desiccation		
Resistant small viruses	MS-2 coli phage	MS2	No cell culture (reduced processing time), some resistance to desiccation, can be grown to 10 <sup>12</sup> per ml		









#### Validation of Biological Models

- Biological models were procured and resuscitated by PHE
- Grown to working concentration suspensions
- Assay and recovery from different substrates used in the study:
  - Platinum
  - Aluminium
  - Basalt projectile/simulant regolith target
- Initial studies indicate that the addition of BSA helped to protect the biological models from desiccation during the drying process









#### Issues and Replacement Capnophile

- C. difficile could not be used during the hypervelocity phase of the study
- An alternative ACDP hazard group 1 capnophile was selected after consultation with ESA
- Clostridium bowmanii
- Required something that would grow within the timescales of the project
- Has strict growth requirements, is not very well characterised and were unable to make it produce spores within project.
- Following discussions, capnophile abandoned















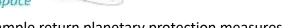
## **HEAT TEST SETUP AND TEST PLAN**







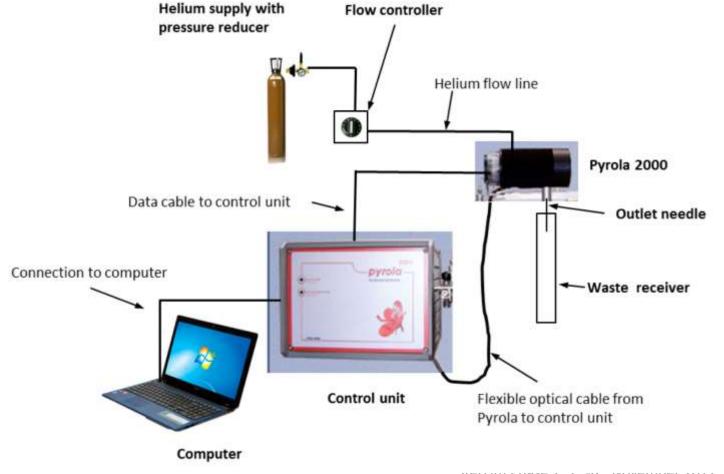






#### Heat test set up

To mimic the temperatures and timescales invoke during the HVI experiments





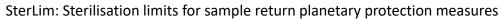














# Pyrola system







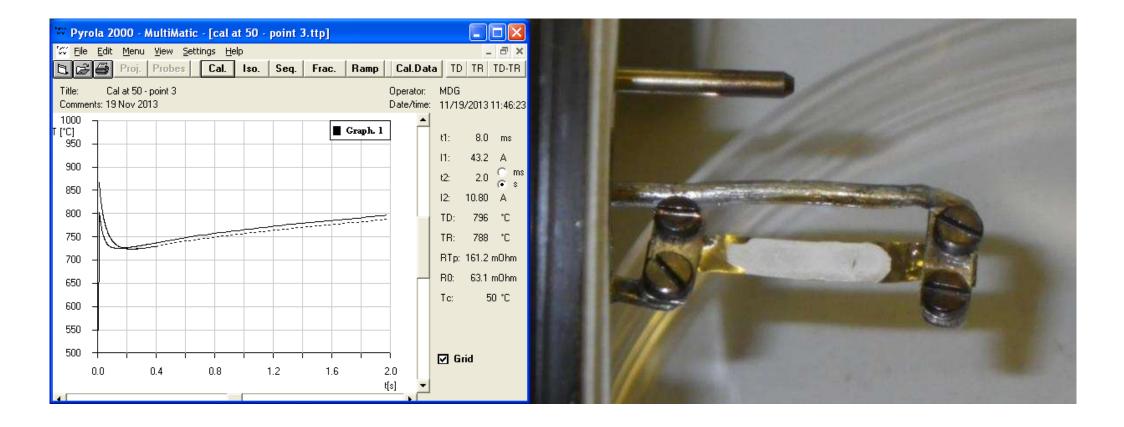








# Methodology















Priority	1		2		3		4		5
Time /s	Temperature / °C								
	200	300	400	500	600	700	800	900	1000
0.125									
0.25									
0.5									
1					Not/Unlikely to be needed				





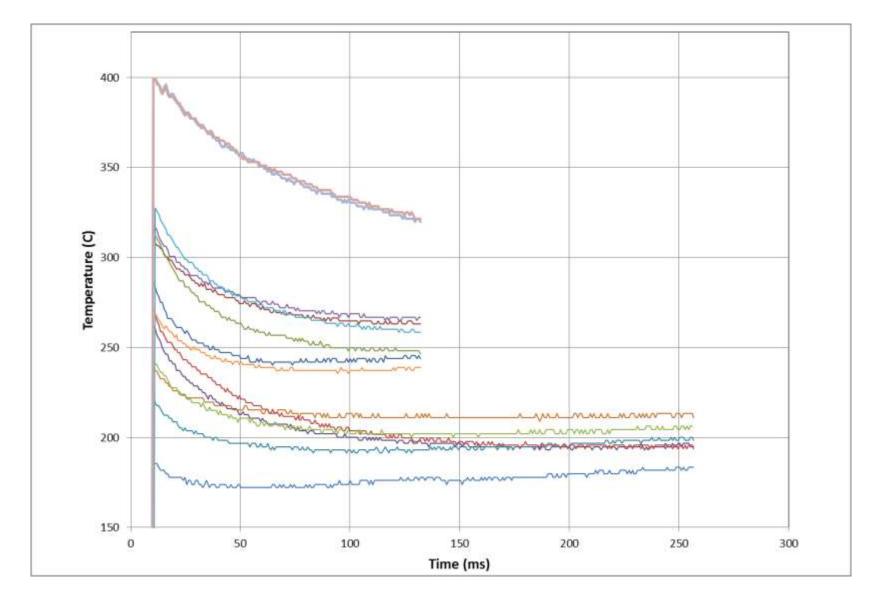






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# HEAT TEST RESULTS AND STERILISATION MODELLING









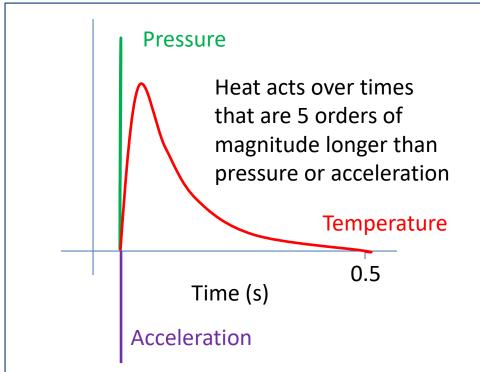




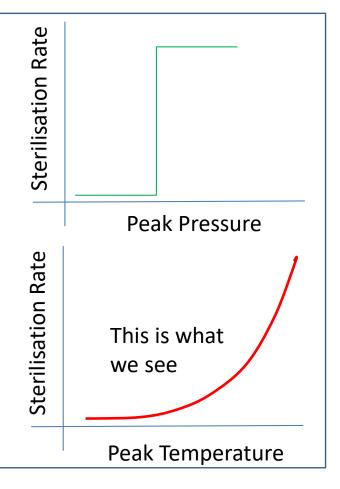
#### Heat Tests & Sterilisation Model - Assumptions

- The primary sterilisation mechanism is thermal
  - Other potential mechanisms: pressure and acceleration

The effects of heat are localised at the molecular bonds that need to be broken



- The organisms will experience more or less the same peak pressure and acceleration so we would expect an almost binary sterilisation.
- Molecular vibrations will follow a Maxwellian distribution so there will be an extended increase in sterilisation rate with temperature



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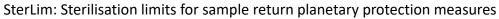








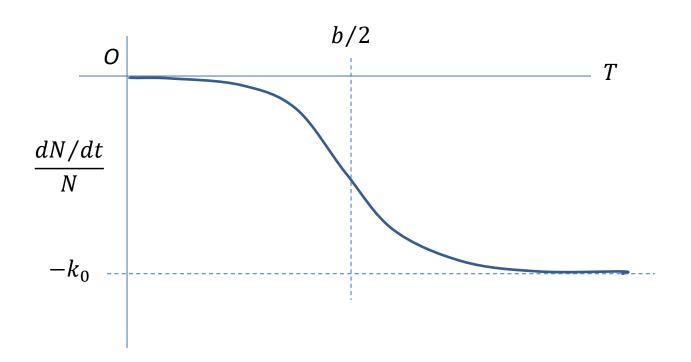






#### Heat Tests & Sterilisation Model - Assumptions

- The sterilisation rate is similar to chemical reaction rates
  - Damage to DNA, membranes etc. requires breaking of key molecular bonds
  - Adopt Arrhenius Rate equation for sterilisation rate:



$$\frac{dN}{dt} = -k_0 N exp\left(-\frac{b}{T}\right)$$

N – Number of organisms

t – time

T – Absolute temperature

 $k_0$ , b – model parameters











#### Heat Tests & Sterilisation Model – Data Fitting

Given a history of temperature the total sterilisation can be calculated using

$$S = ln\left(\frac{N_e}{N_0}\right) = -\int_{\tau=0}^{t_e} k_0 \exp\left[-\frac{b}{T(\tau)}\right] d\tau$$

O subscripts denote starting conditions e subscripts denote the end state

or equivalently,

$$S = \frac{k_0}{\beta} \int_{T=T_0}^{T_e} \frac{\exp(-b/T)}{T - T_e} dT$$

where the cooling takes the form

$$T = T_e + (T_0 - T_e)e^{-\beta t}$$

For the experiments  $T_e$  is 323K (50°C) and the cooling rate  $\beta$  was inferred from previous tests with more detailed data.











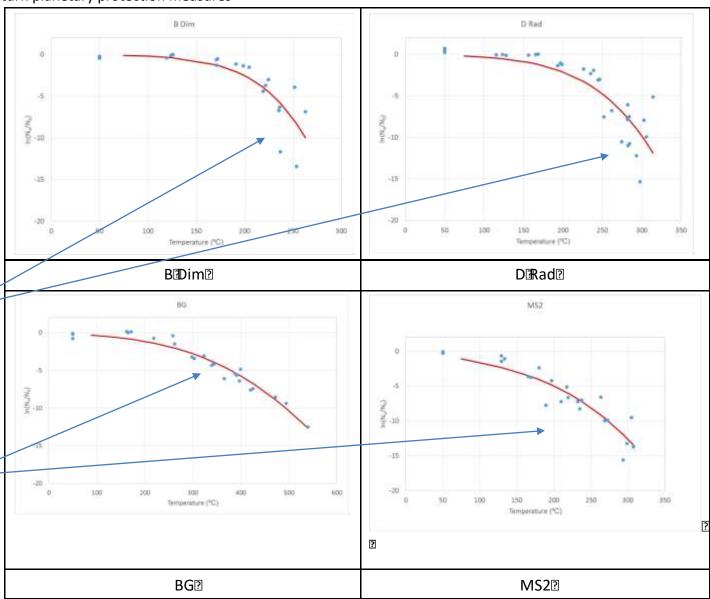


# Heat Tests & Sterilisation Model – Data Fitting - 2

 Least squares fit of Model to the data

Spread of data tends to increase with temperature for *B. dim* and *D. rad* 

For BG and MS2 the data spread is more uniform across all temperatures



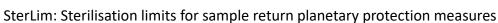








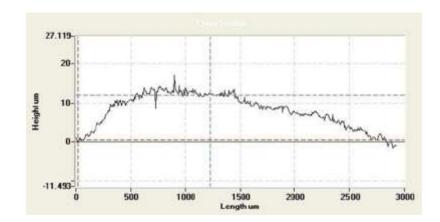


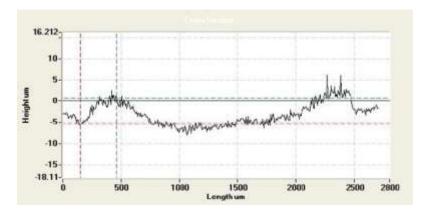




#### Heat Tests & Sterilisation Model – Error Characterisation

- *D. rad* and *B. dim* are vegetative bacteria whereas the BG organisms were spores and MS2 is a phage
- D. rad and B. dim will be large compared to BG and MS2
- Thickness variation in the samples is apparent from scans
- This will affect the rates of cooling and other thermal properties
- This can lead to variation in the measured sterilisation that is proportional to *S*.













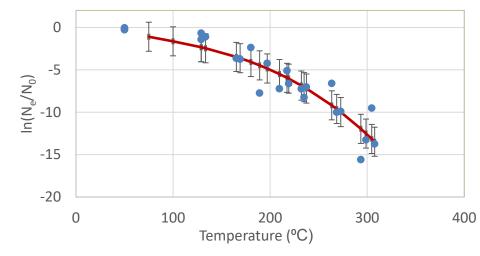




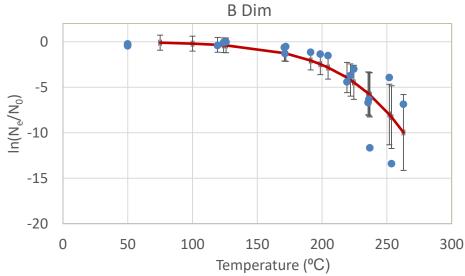
#### Heat Tests & Sterilisation Model – Error Characterisation - 2

#### Source of data spread:

- Experimental
  - Applies to all species
  - Expected to be uniform
- Sample thickness
  - Applies predominantly to the large species (D. rad & B. dim)
  - Proportional to sterilisation
- Characterisation of spread allows  $\chi^2$  fitting which can also provide confidence limits



MS2







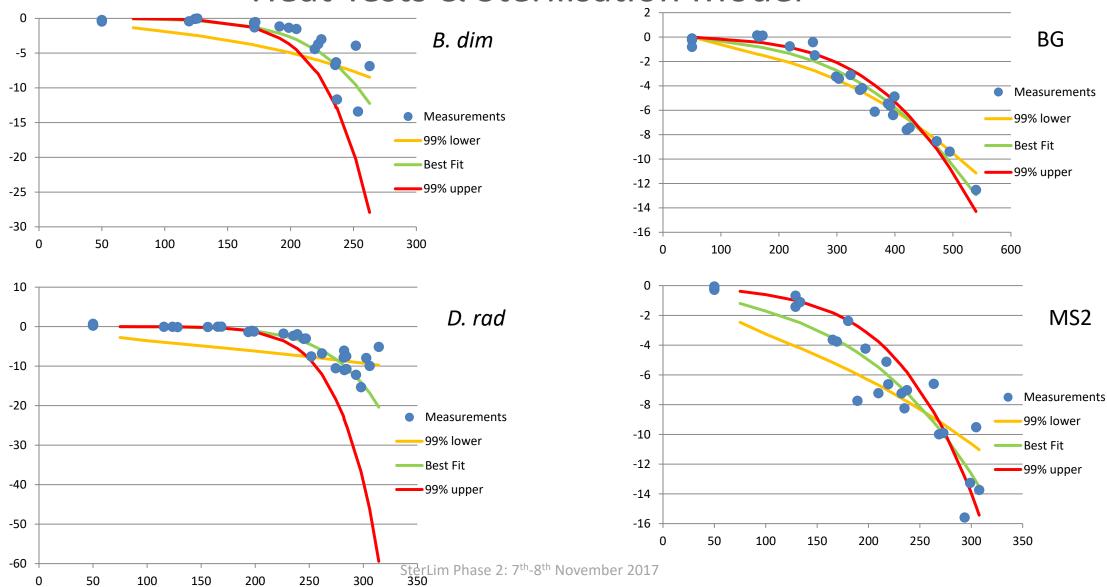






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#### **Heat Tests & Sterilisation Model**















# **IMPACT TEST SETUP AND TEST PLAN**











#### Impact test setup (OU)

- Two-stage light gas gun (impacts up to 7 km/s)
- Projectiles: 3 mm dia. Basalt cylinders with 0.7 mm hole drilled along axis (organism internal deposition)
- Low (0.5 km/s) to high (1.8 km/s) velocities



































# Test plan

	Velocity range /km s-1					
	Range 1	Range 2	Range 3 (TBD)			
	0.5 to 0.75 km/s	1 to 1.99 km/s	0.75-0.99 or			
			>2 km/s as needed			
Impact angle 0° (vertical shot)	✓	✓	✓			
Impact angle ~30-40° (AOR, horizontal shot)	✓	✓	✓			













# IMPACT TEST RESULTS AND STERILISATION MODELLING



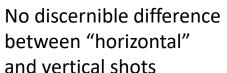






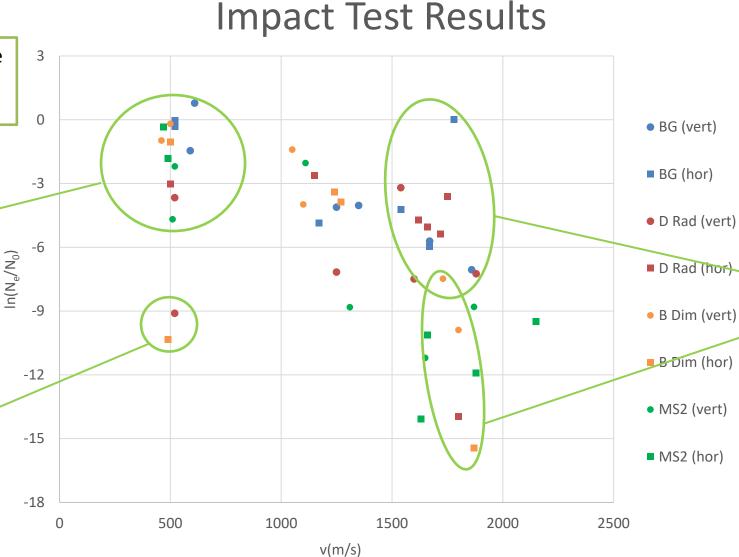






Cluster of points which are expected to produce 0 sterilisation gives an indication of the experimental variation.

Assumed to be outliers probably due to loss of a significant projectile fragment.



"Horizontal" shots are those with the gun horizontal and the target tilted so actually about 40° to the vertical.

Large variation in sterilisation for nominally similar conditions.

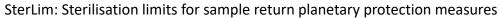






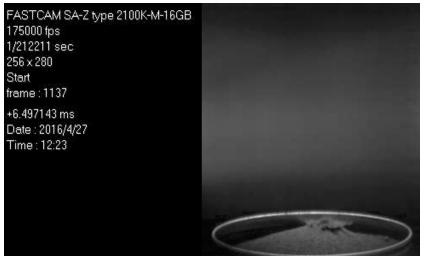


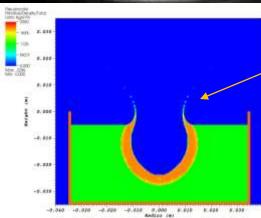






#### Impact Test Results – Modelling the Impact Tests

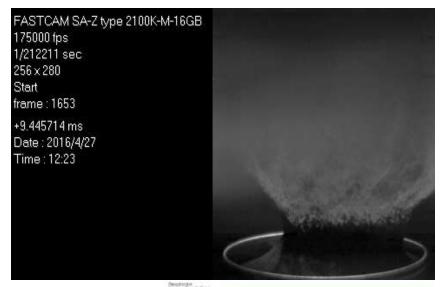


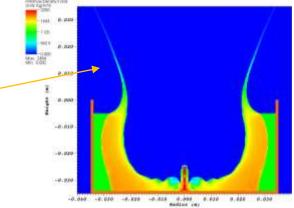


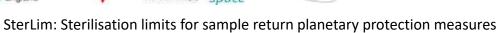
The material properties in the hydrodynamic simulations have been adjusted to match the impact dynamics of the experiments.

The propagation speed of the expanding opening has been matched.

The pattern of the ejecta cone has been matched.



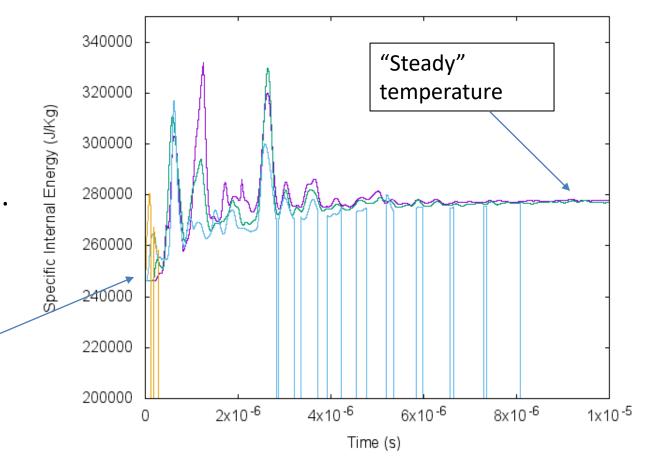






# Impact Test Results – Temperature of the organisms

- The hydrodynamic model allows the heat energy transferred to the organisms to be computed.
- After transient effects the specific energy settles down after about 5µs.

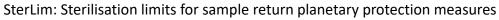














Upper and lower

limits estimated

for the transfer

Simulations

Model

Lower

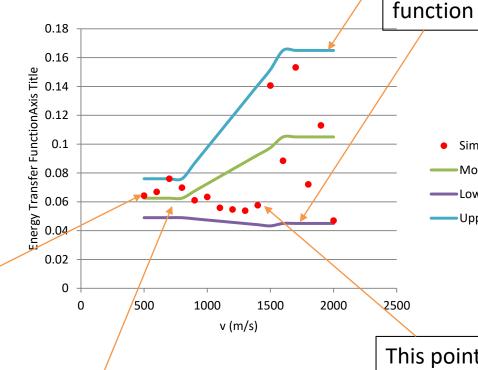
Upper

# Impact Test Results – Energy Transfer

Heating is characterised using the Energy Transfer Function = Specific Energy Added after Transients / Incident Specific Kinetic Energy

Fraction of kinetic energy in projectile converted to heat.

Initially fairly constant but then becomes highly variable



The transfer function is modelled assuming that a real projectile will break up over a range of velocities – its strength will be variable whereas the hydrodynamic model is uniform

This point corresponds to the projectile disintegrating so that it follows the chaotic flow.

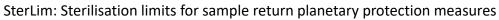






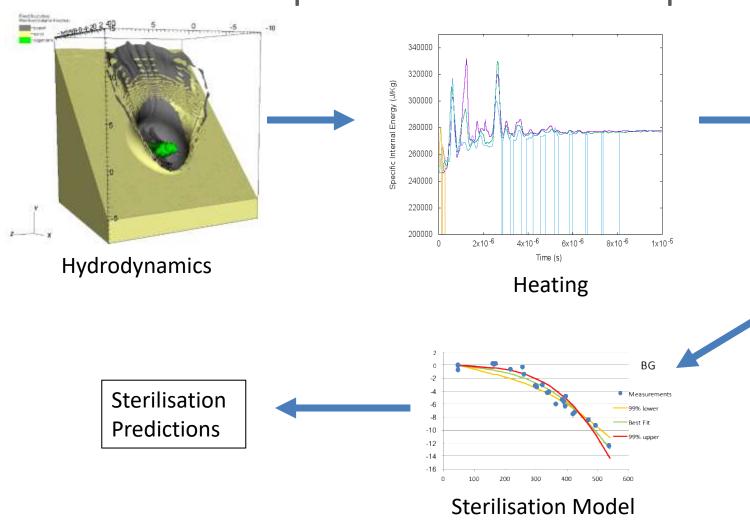








### Impact Test Results – Impact Model



**Energy Transfer Function** 

#### Cooling rate?

This last remaining parameter is

- Difficult to measure
- Not the same as in the heat tests

It is determined for each species by fitting the impact model to the impact test data

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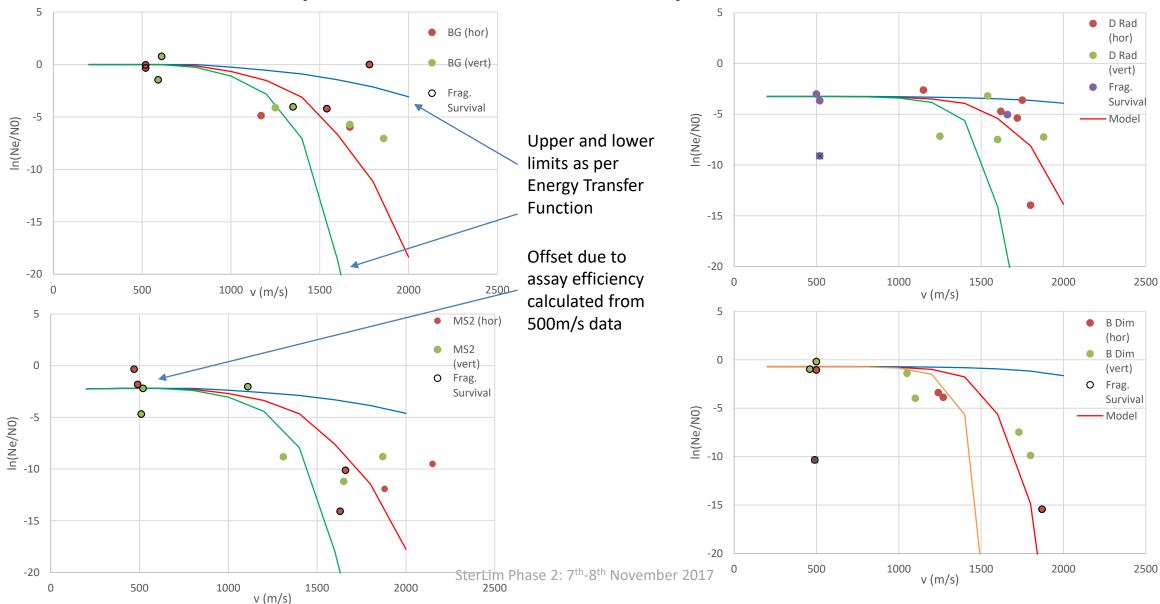








# Impact Test Results – Impact Model - 2















# **IMPACT MODELLING RESULTS**





# Phobos Impact Modelling

- The necessary components are now in place to allow application to Phobos impacts
- Objective: Produce a model for impact sterilisation that can be used by the statistical analysis
  - Hydrodynamic simulation can be used to develop this but the model will need to be simpler
  - A level of abstraction to an "engineering model" is required
  - Most of this is in place with the sterilisation model etc.
  - How can we construct a suitable energy transfer function or similar?



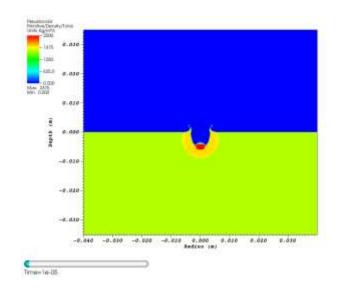


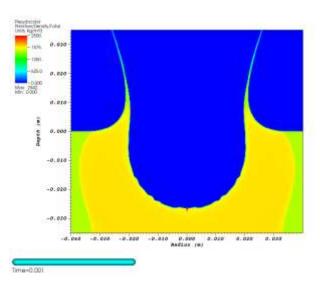




# Phobos Impact Modelling – Spherical Projectiles

- The impact modelling will employ spherical projectiles
  - Given that significant impacts will result in disintegration of the projectile and subsequent behaviour is fluid-like, shape is unlikely to be important
- The heat transfer will be studied across the entire projectile
  - The Energy Transfer function is now dependent of spatial variables as well as impact velocity



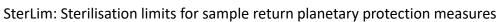








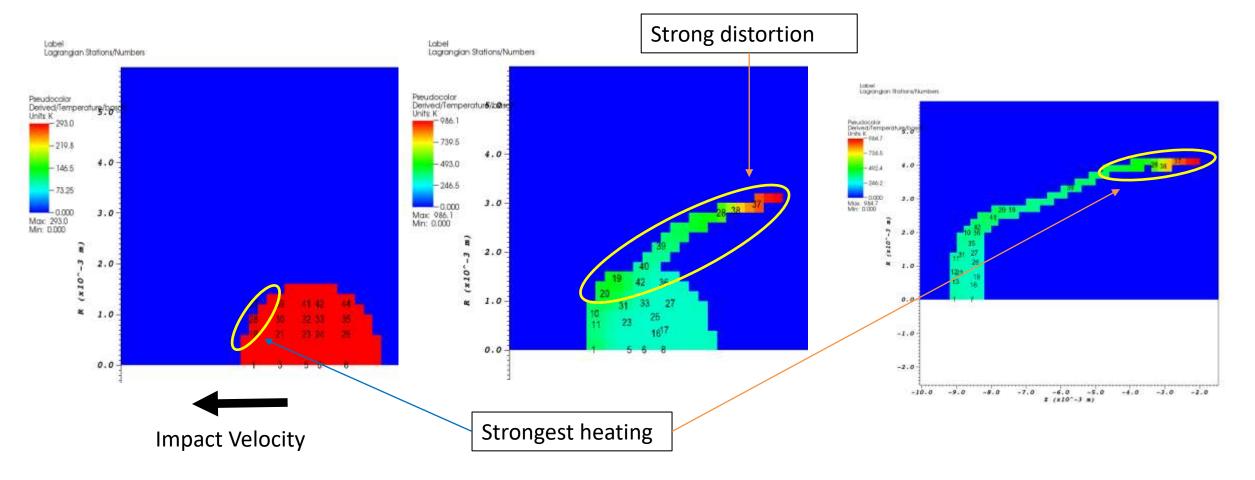






# Phobos Impact Modelling – Projectile Distortion

As the impact proceeds the projectile material is strongly distorted and heated









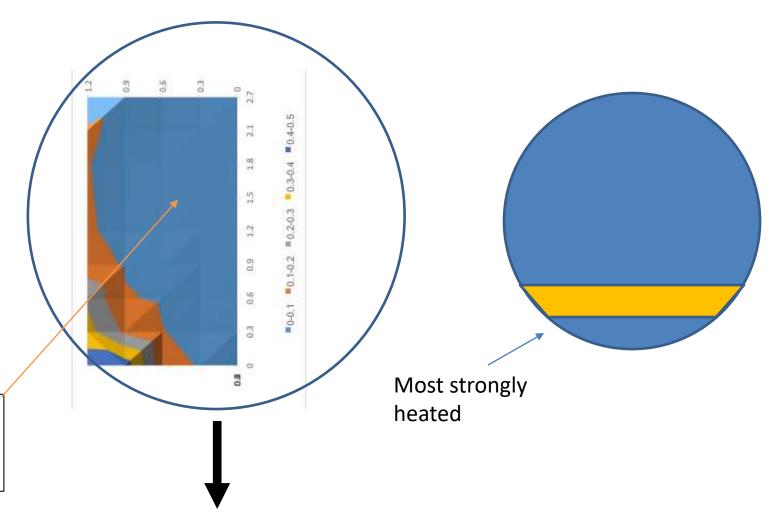




# Phobos Impact Modelling – Energy Transfer

 Energy Transfer function shows peak heating around leading "shoulder". This is an average over many impact speeds from 500 m/s to 2000 m/s.

A large volume of the projectile is barely heated at all









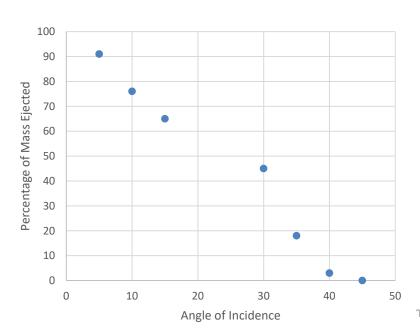


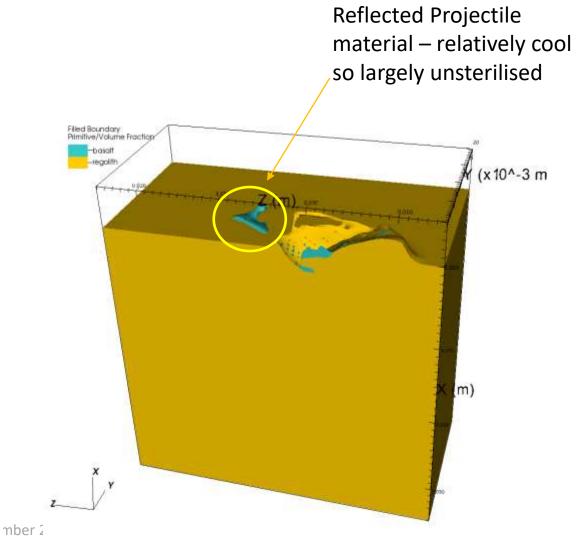




# Phobos Impact Modelling – Other Factors

- Scaling the Phobos impact model has no intrinsic length-scale so it should scale hydrodynamically – doubling the size also doubles the time-scale.
- Modelling shows that **angle of incidence** has little effect up to 45° as has also been seen in the experiments. Beyond this the there is an increasing amount of projectile mass that is reflected off.

















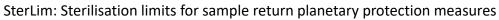
# **RADIATION TEST SETUP AND TEST PLAN**







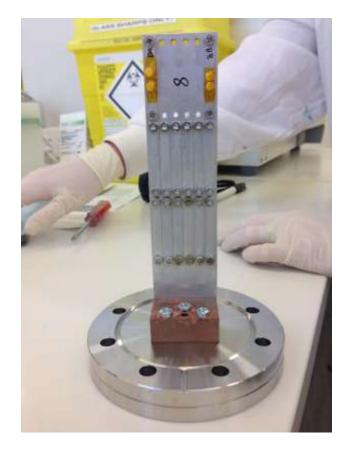






### Radiation test setup - gamma

- Organisms dried onto Al strips
- Strips sealed inside vacuum chamber
- Inert atmosphere (pure N<sub>2</sub>)
- Kept at -80°C during irradiations
- 1, 3, 10, 25, 50, 75 and 100 kGy doses



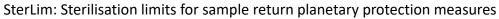








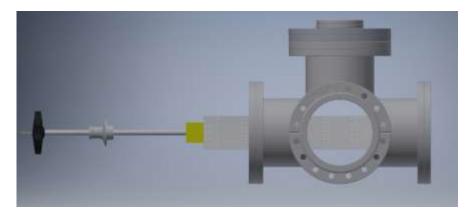




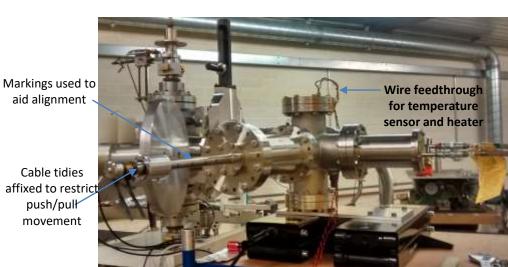


# Radiation test setup – proton/alpha

- Organisms dried onto Al strips
- Cryogenic vacuum chamber with (cooled) sliding sample mount behind a beam mask
- Multiple irradiations without breaching vacuum seal







SterLim Phase 2: 7<sup>th</sup>-8<sup>th</sup> November 2017











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# Test plan

#### Proton

Irradiation	Energy (MeV)	TID (krad)	TID (kGy)	Fluence (protons.cm <sup>-2</sup> )	Flux (protons.cm <sup>-2</sup> .s <sup>-1</sup> )	Time to irradiate all samples (hrs)
Part 1	7.5	75	0.75	8.2E+10	6.0E+08	0.1
	7.5	300	3	3.3E+11	6.0E+08	0.3
	7.5	1000	10	1.1E+12	6.0E+08	1.0
Part 2	7.5	2500	25	2.7E+12	6.0E+08	1.3
	7.5	5000	50	5.4E+12	6.0E+08	2.5
	7.5	7500	75	8.2E+12	6.0E+08	3.8
	7.5	10000	100	1.1E+13	6.0E+08	5.0

### Alpha

Irradiation	Energy (MeV)	TID (krad)	TID (kGy)	Fluence (helium.cm <sup>-2</sup> )	Flux (helium.cm <sup>-2</sup> .s <sup>-1</sup> )	Time to irradiate all samples (hrs)
	10.0	75	0.75	8.77E+09	8.00E+07	0.1
Part 1	10.0	300	3	3.51E+10	8.00E+07	0.2
	10.0	1000	10	1.17E+11	8.00E+07	0.8
Part 2	10.0	2500	25	2.92E+11	8.00E+07	1.0
	10.0	5000	50	5.85E+11	8.00E+07	2.0
	10.0	7500	75	8.77E+11	8.00E+07	3.0
	10.0	10000	100	1.17E+12	8.00E+07	4.1

SterLim Phase 2: 7<sup>th</sup>-8<sup>th</sup> November 2017

#### Gamma

TID	TID	Synergy Health		
TID (krad)	TID (kGy)	Dose rate (kGy.hr <sup>-1</sup> )	Time (hrs)	
100	1	2	0.5	
300	3	2	1.5	
1000	10	2	5.0	
3000	25	2	15.0	
5000	50	2	25.0	
7500	75	2	37.5	
10000	100	2	50.0	













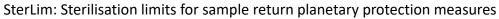
# RADIATION TEST RESULTS, RE-TEST AND STERILISATION MODELLING







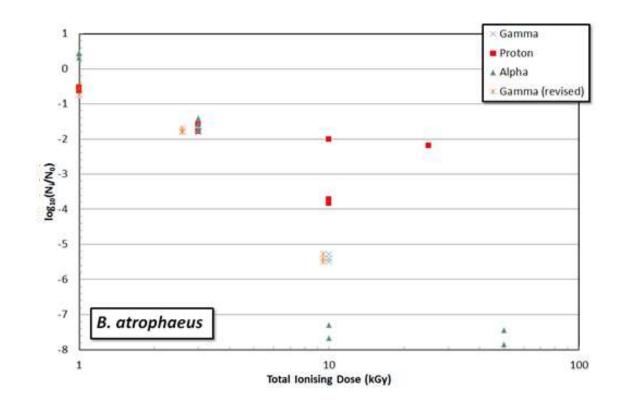






#### Phase 1 Irradiation Results

- γ-ray results showed general consistency for D. radiodurans and B. atrophaeus; B. diminuta showed no survival at any γ-ray dose
- Proton and  $\alpha$ -particle results showed significant anomalies, e.g.:
  - No clear trend in proton dose (*D. rad*) or anticorrelation (*B. dim*)
  - Inconsistent trend with increasing LET, e.g.  $\alpha$  vs.  $\gamma$  (D. rad, MS2 & possibly B. dim)
  - Very high survival, and similar trends for p and  $\alpha$  for MS2
  - Non-monotonic trend in  $\gamma$  for MS2

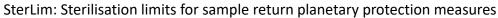










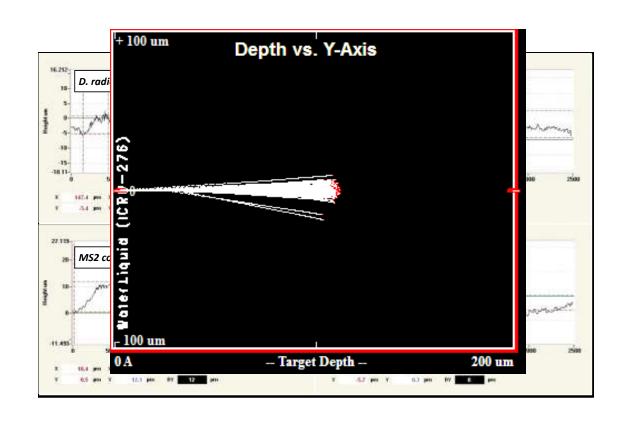




### Potential Causes of Anomalies (1)

# A range of possible causes has been considered, including:

- Thickness of sample affecting ions?
  - Problems greater for longer-range protons
  - Thickness of samples measured as 20μm max
- Effects of straggling?
  - SRIM simulations indicate good  $\alpha$ -penetration
- Contamination of edges?
  - Significant care taken during slide handling
- Cross-contamination of slides?
  - "Blank" slides showed no contamination
- Energies of p/ $\alpha$  lower than expected and stopped early
  - Beamline monitor slightly upstream and close to outlet pipe: showed particles being detected







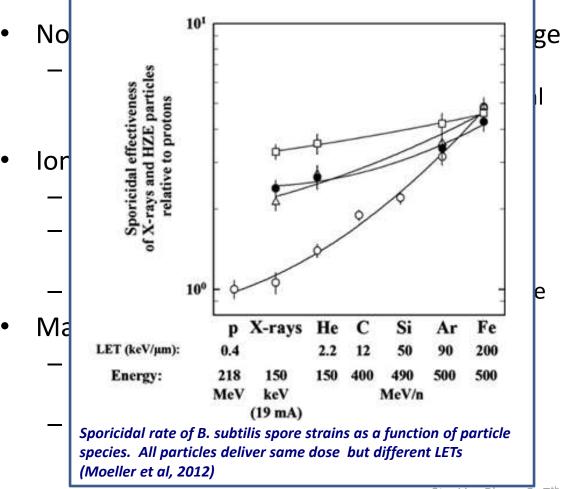








# Potential Causes of Anomalies (2)



#### Temperature effects

- Greater loss of micro-organisms at RT, particularly MS2 and B. diminuta
- Positive samples (controls) did not follow the same temperature cycle
- "Cold positives" intended to correct for different temperature cycle, but sensitivity of corrections to assumed environment?

#### Non-standard LET response

Such response not expected <100 keV/μm unless dealing with special cases, e.g. partial penetration of cells (Moeller)</li>









### Strategy

- Sensitivity of temperature dependence on survival appears to be important for irradiations: p,  $\alpha$  and  $\gamma$
- Repeat  $\gamma$ -irradiations for MS2 and B. diminuta easier to conduct and more **generally controllable** compared to  $p/\alpha$
- Also included *D. radiodurans* since uncertainty about 3 kGy results
- Apply tight controls on temperature throughout for samples and positives
- Generate models based on  $\gamma$  only
  - Ignoring higher-LET intended to represent worst-case
  - Consider returning to p/ $\alpha$  irradiations in possible future activity

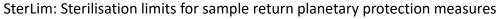






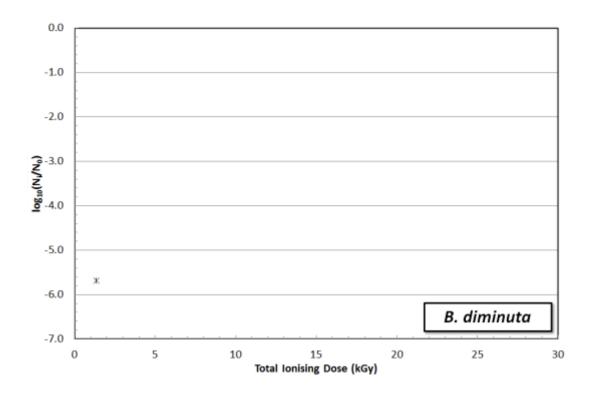








#### Phase 2 Irradiations and Basis of Model



 Model follows variation of Moeller et al (2012):

$$\frac{N_i}{N_0} = \exp(\lambda D): \ \lambda < 0$$

$$\ln\left(\frac{N_i}{N_0}\right) = -\ln(10)\frac{D}{D_{10}}$$

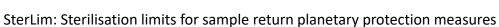
- D = absorbed dose;  $N_i/N_0$  = fraction surviving
- From outset of SterLim, assumed no repair mechanisms active
- Exp-dependence originally preferred as simplified calculation for doses from different LETs





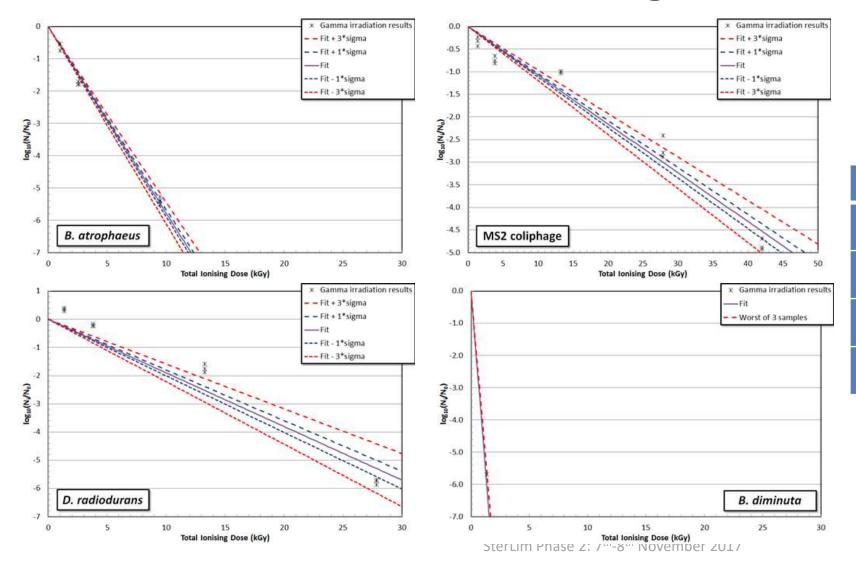








# Final Model Parameters Using Phase 1 & 2 Irradiations



Micro-organism	D <sub>10</sub> [kGy]
B. atrophaeus	1.73 ± 0.03 R = 0.997
D. radiodurans	5.26 ± 0.33 R = 0.959
MS2 coliphage	$9.27 \pm 0.33$ R = 0.982
B. diminuta	0.24 R = (N/A)













# **RADIATION MODELLING RESULTS**



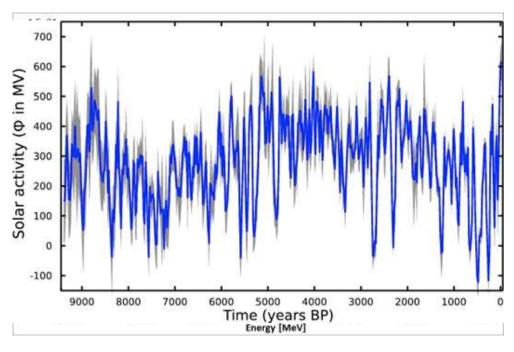




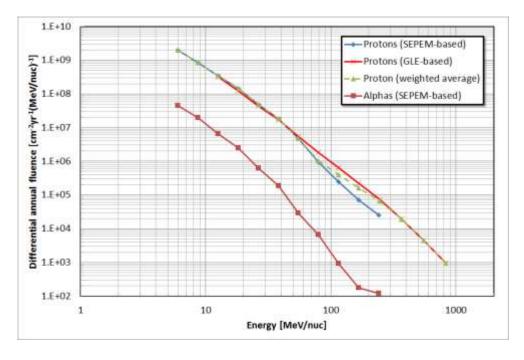




### Source Particle Conditions (GCR & SEP)



- ISO-15390 cosmic ray model for H to Ni and different helio-potentials ( $\Phi$ )
- Steinhilber *et al* for  $\Phi$  results from 9000 yrs BP to present



- Solar H & He GOES+SMS data 1974-2015 from ESA SEPEM reference dataset
- Augmented with GLE data for 43 events (1956-2006) analysed by Tylka et al







# Irradiated Geometry / Primordial Radioactivity

#### Phobos surface represented as:

- Semi-infinite planar surface, 10 m deep
- Homogeneous composition and density  $(2.1 \text{ g/cm}^3)$
- Composition based on Tagish Lake meteorite (carbonaceous chondrite)
- Isotropic irradiation for planar surface
- Dose and flux determined as function of depth:
  - 1 mm layers to 3 cm;
  - 1 cm layers from 3 cm to 5 cm;
  - 2.5 cm layers from 5 cm to 50 cm;
  - 10 cm layers from 50 cm to 1 m.

#### Primordial radioactivity adds third source of ionisation

<sup>232</sup>Th, <sup>238</sup>U and <sup>40</sup>K based on Brown *et* al analysis for Tagish Lake meteorite

Isotope	Half-life	Estimated concentration in soil [PPB]
<sup>232</sup> Th	$1.41\times10^{10}$	40 ± 8
<sup>238</sup> U	$4.49\times10^{9}$	$8\pm4$
<sup>40</sup> K	$1.25 \times 10^{9}$	$78 \pm 6$









#### **Geant4 Simulations**

- Geant4 Monte Carlo simulations performed for each ion and intervals in  $\Phi$  (for GCR)
- Simulations covered spectra decades separately and results recombined  $\Rightarrow$ Improved statistics for high energy
- Geant4 v10.1 patch 2 with GRAS v3.4
- Physics used:
  - Standard EM physics with Option 3
  - ParticleHP for low energies
  - Liege intranuclear cascade (INCL++) for intermediate energies
  - Fritof (FTF) for high-energy ions $Z \ge 2$ ; QGS for high-energy protons/neutrons
- TID, particle fluxes and LET spectra recorded at boundaries





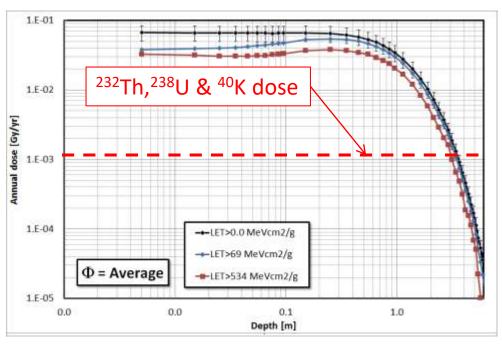


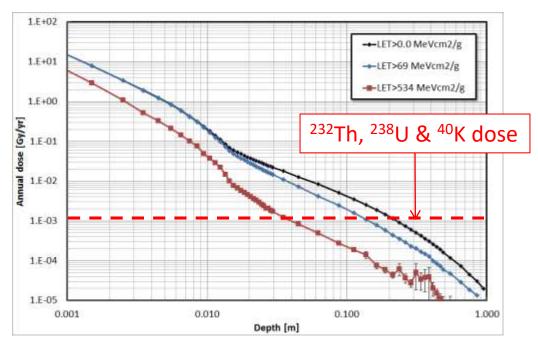






### Dose Versus Depth (GCR & SEP)





#### **GCR**

- Approximate exponential decrease in dose versus depth
- Harder spectrum ⇒
  - affects greater depths
  - Doses may initially increase for larger  $\Phi$

#### **SEP**

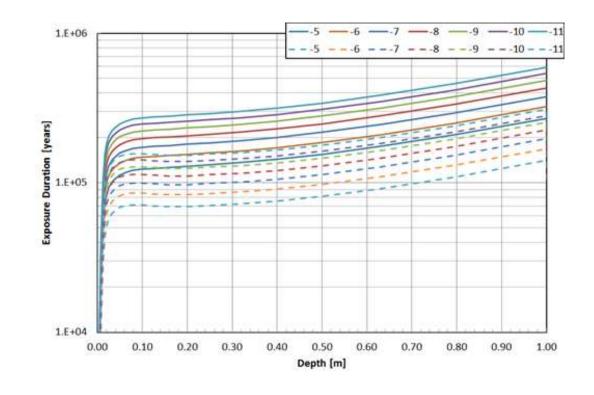
Softer spectrum ⇒ steep dose vs depth





# First-order influence of higher LET

- Moeller et al work for wild-strain type B. subtilis:
  - ×1.4, ×1.9 and ×2.2 increased sporicidal for LETs 2.2, 12 and 50 keV/ $\mu m$
- Assume similar trend in biological effectiveness of low- and higher-LET particles for *B. atrophaeus*
- Graph shows exposure required for different log<sub>10</sub> reductions assuming:
  - All absorbed dose is from low-LET (γ-ray based) model (solid lines)
  - 6.9≤LET<53 and 53≤LET<100 keV/μm have RBE 1.7 and 2.2 (dashed lines)















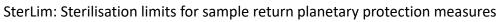
# STATISTICAL ANALYSIS





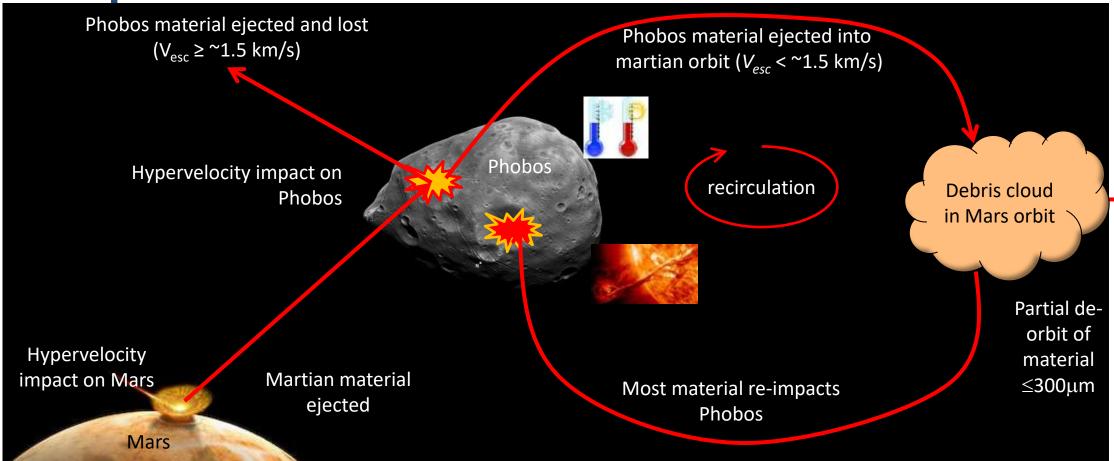








# The process simulated



**Req-10**: The probability that a single unsterilized particle from Mars  $\geq$  10 nm in diameter is in a sample returned from Phobos shall be  $< 1 \times 10^{-6}$ .













# Simulation

Monte Carlo simulation – the Monte Carlo probes the parameter space in a rigorous way

- Mars Ejecta
  - Defined by AD4, Material Transfer from the Surface of Mars to Phobos and Deimos, Final Report: NNX10AU88G, H. J. Melosh
- Cloud about Mars
  - Defined by AD5, Mars impact ejecta in the regolith of Phobos: Bulk composition and distribution, Ramsley, K. R., et al.
- Hyper Velocity Collision with Phobos (Deimos)
  - · Modelled in this study by FGE, model covers both the dynamics and the sterilization
- Radiation on the surface of the Phobos (Deimos)
- Modelled in this study by Kallisto, model covers both the radiation environment, and the sterilization So sterilization only considered on the moon (HV & radiation) and not on the Mars Ejecta or Cloud.

Note simulation probes parameter space to give understanding, but it is the understanding that is used to reach conclusion.

Here we present the understanding, detailed results are in the documentation.













# Distilling the conclusion to a single equation

Or a simple formula for the life that ends up on moons

$$\Delta M \times \frac{\text{cfu per mass}}{\text{Surface Area}} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$









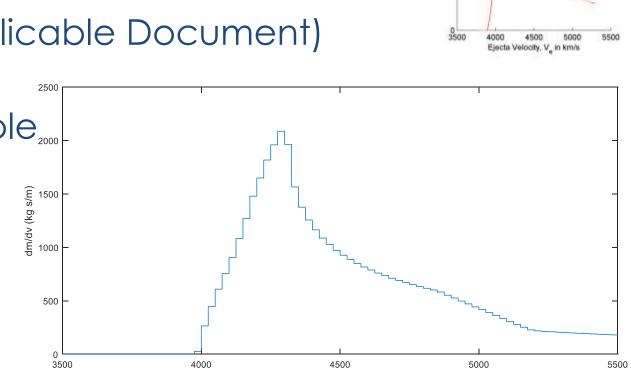


# Mass Transferred (Phobos)

Or a simple formula for the life that ends up on moons

$$\Delta M \times \frac{\text{cfu per mass}}{\text{Surface Area}} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$

- $\Delta M = 1.12E6$  kg (Melosh Applicable Document)
- $\Delta M = 1.63E6$  kg (This work actually compatible with Melosh)
- Note different method for assessing collision with the moon



Ejection Velocity (m/s)

Total Mass impacting phobos over 10 Myrs = 1.1217 10











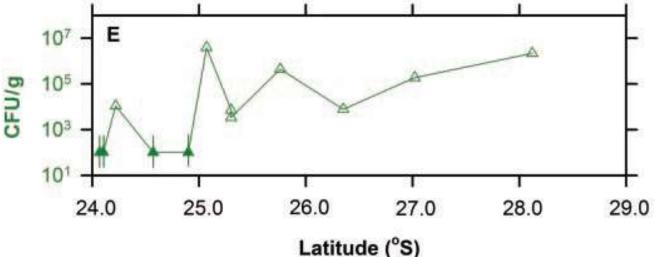


# **Amount of life**

Life in the desert – do the deserts miss the rain?

$$1e6 \text{ kg} \times \frac{\text{cfu per mass}}{\text{Surface Area}} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$

- Life per mass is taken from Atacama Desert
- Driest place on Earth, most like Mars (this is an assumption!)
- 1e5-1e10 cfu/kg range



Mars-Like Soils in the Atacama Desert, Chile, and the Dry Limit of Microbial Life, Rafael Navarro-González etal., 7 NOVEMBER 2003 VOL 302 SCIENCE

Yungay typical < 1e7 cfu/kg













# **Area of Phobos**

Or a simple formula for the life that ends up on moons

$$\frac{1e6 \text{ kg} \times \frac{1e5 - 1e10 \text{ cfu/kg}}{\text{Surface Area}} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$

- Hopefully the thing we are sure of
- Phobos 1548.3 km2













# Before Sterilisation – how much life?

Or a simple formula for the life that ends up on moons

$$1e6 \text{ kg} \times \frac{1\text{e}5-1\text{e}10 \text{ cfu/kg}}{1\text{e}9 \ m^2} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$

- Before any sterilization
- 1e2-1e7 cfu/m2
- This is a significant level of life











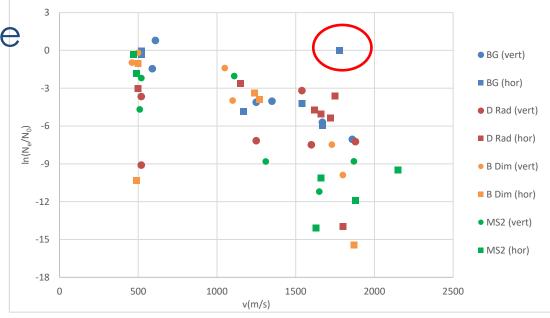


# **Hypervelocity Impact**

The effect of chaos

$$1e6 \text{ kg} \times \frac{1\text{e}5-1\text{e}10 \text{ cfu/kg}}{1\text{e}9 \ m^2} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC \text{(Radiation)}$$

- The HV Impact is chaotic
- Something like 10% does not have much heating
- Seen in modelling & testing
- That 10% dominates life that survives, other 90% is irrelevant
- Not very dependent on velocity















# When material arrives

On average – which is what statistics needs ...

$$1e6 \text{ kg} \times \frac{1\text{e}5-1\text{e}10 \text{ cfu/kg}}{1\text{e}9 \ m^2} \times 0.1 \times \frac{1}{\text{Total Time}} \times \textit{TC} \text{ (Radiation)}$$

- Material arrives over a 10MY period
- Material is mainly very small
- So 1e6kg in 10MY = 100g per year
- This is an \*average\* rate ...
- ... but that is what statistics needs













# Rate of life arriving on the surface

Or a simple formula for the life that ends up on moons

$$1e6 \text{ kg} \times \frac{1\text{e}5-1\text{e}10 \text{ cfu/kg}}{1\text{e}9 \ m^2} \times 0.1 \times \frac{1}{10\text{MY}} \times \textit{TC} \text{(Radiation)}$$

- So rate of life arriving 10<sup>-6</sup>-10<sup>-1</sup> cfu / year / m<sup>2</sup>
- So each year each m<sup>2</sup> will receive comparable or more than Req-10 limit
- Note we give numbers per unit area of the moon, as most material is on (or close) to the surface









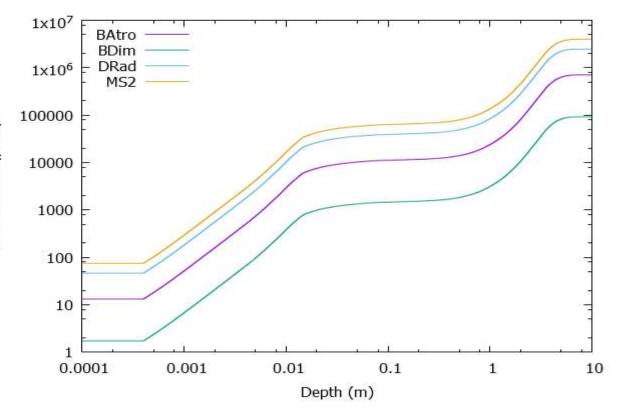


# Radiation

$$1e6 \text{ kg} \times \frac{1\text{e}5-1\text{e}10 \text{ cfu/kg}}{1\text{e}9 \ m^2} \times 0.1 \times \frac{1}{10\text{MY}} \times \textit{TC} \text{(Radiation)}$$

- Radiation time constant is ~halflife
- Time constant depends on (solution) to depth

  Even on surface can have
- Even on surface can have TC=100 years
- 63% of all life arrives in last time constant















# Rate of Life left

Or a simple formula for the life that ends up on moons

$$1e6 \text{ kg} \times \frac{1e5-1e10\text{cfu/kg}}{1e9 m^2} \times 0.1 \times \frac{1}{10\text{MY}} \times 100Y = 10^{-4} - 10 \text{ cfu/m}^2$$

- So putting all this together
- Radiation on the surface where radiation is largest
- 10<sup>-4</sup>-10 cfu/m<sup>2</sup> of Phobos
- This is just in the uncomfortable range
  - 10<sup>-4</sup> cfu/m<sup>2</sup> a 10 cm square consistent with Req-10
  - 10 cfu/m<sup>2</sup> 0.3 mm square consistent with Req-10













# **On Deimos**

A simple formula for the life that ends up on moons

4.61e4 kg × 
$$\frac{1e5 - 1e10 \text{ cfu/kg}}{495.1548e6 m^2}$$
 × 0.1 ×  $\frac{1}{10\text{MY}}$  × 100*Y* ~ 10<sup>-5</sup> – 1 cfu/m<sup>2</sup>

- So 1 order less life on Deimos
- If life at the 1 cfu/ $m^2$  rate, 1 mm square for Req-10













# Reflections on Depth distribution

If material is buried in the HV collision

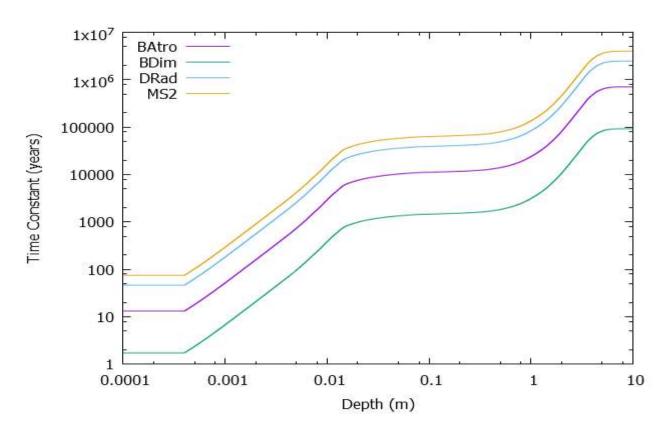
Material is expected to be at the surface

- Regolith bounce back expected
- Impactors are typically very small However if material is deposited 1cm down, there is 10<sup>3</sup> less sterilization.

Can we be sure that material isn't deposited 1 cm down?

But if we do go down to that depth – its constant out to 1m (due GCR)

This gives one area of sensitivity. How is this best dealt with?









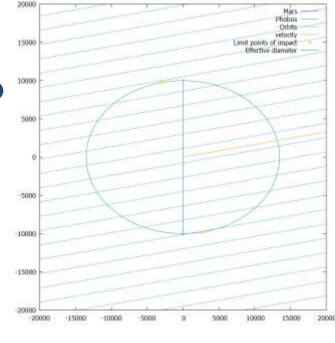


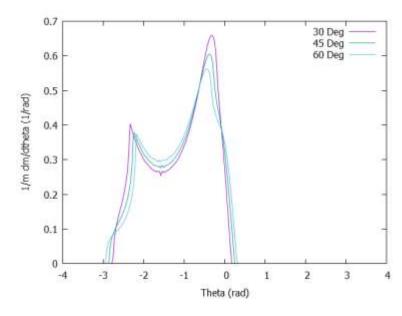


# Reflections – is distribution isotropic?

Time to the final presentation, so have space to reflect

- We assumed material isotropic on the moon
- However look at distribution of arrival angles
- Any one angle will cover half the moon
- However arrival angles slightly less than  $\pi$
- This suggests that there is a small area, to the tail of Phobos, where material isn't directly transferred
- What about material from the cloud?

















# Life in the cloud

Does life survive in the cloud about Mars?

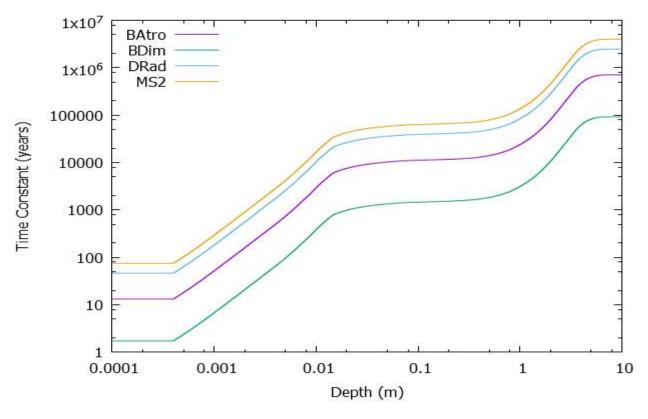
[AD5] Mars impact ejecta in the regolith of Phobos: Bulk composition and distribution, Ramsley, K. R., et al.

"Impact ejecta fragments from Phobos may orbit around Mars for months, years or centuries before re- impacting onto Phobos."

So time in the cloud is comparable to the time constant.

Material in the cloud will typically be dust

So exposed to the full radiation So chance it is sterilized



Burried 4 radii









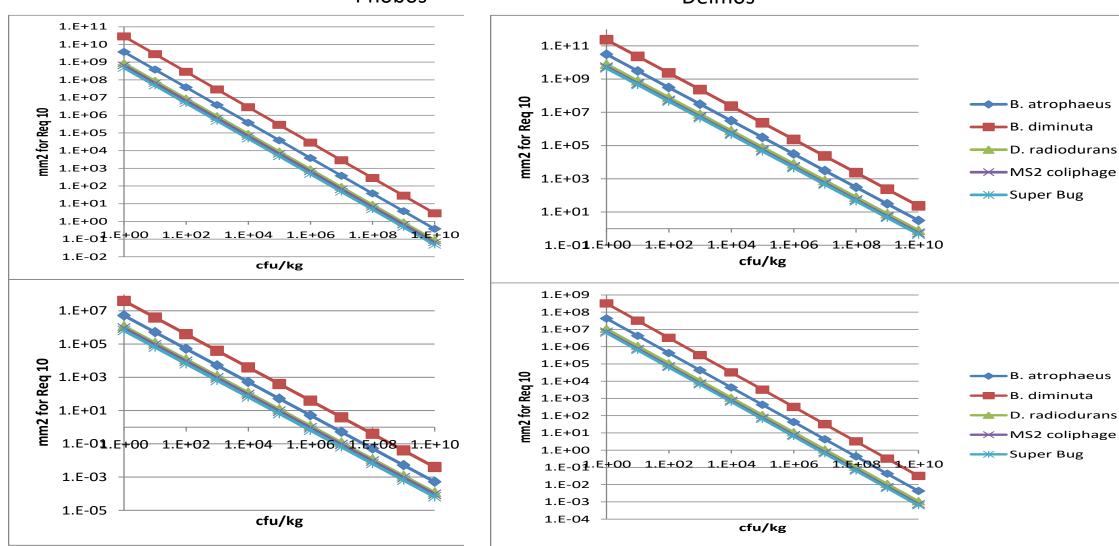


SterLim: Sterilisation limits for sample return planetary protection measures

# Conclusions

#### **Phobos**

#### Deimos



SterLim Phase 2: 7<sup>th</sup>-8<sup>th</sup> November 2017





#### **Overall Conclusions**

- Compliance with Req-10 is highly variable
- Critical dependence of study outcome on assumed initial bioburden
- Mars ejecta was out of scope of the study
- Assumed martian bioburden could form a study within itself
- When considering martian subsurface material, this theoretical range extends from 1 cfu/kg upwards.
- Application of SterLim study results to Phobos Sample Return will necessitate an ESA-approved definition of assumed initial bioburden for Mars ejecta.