Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Design Considerations for the Mu2e II Tracker

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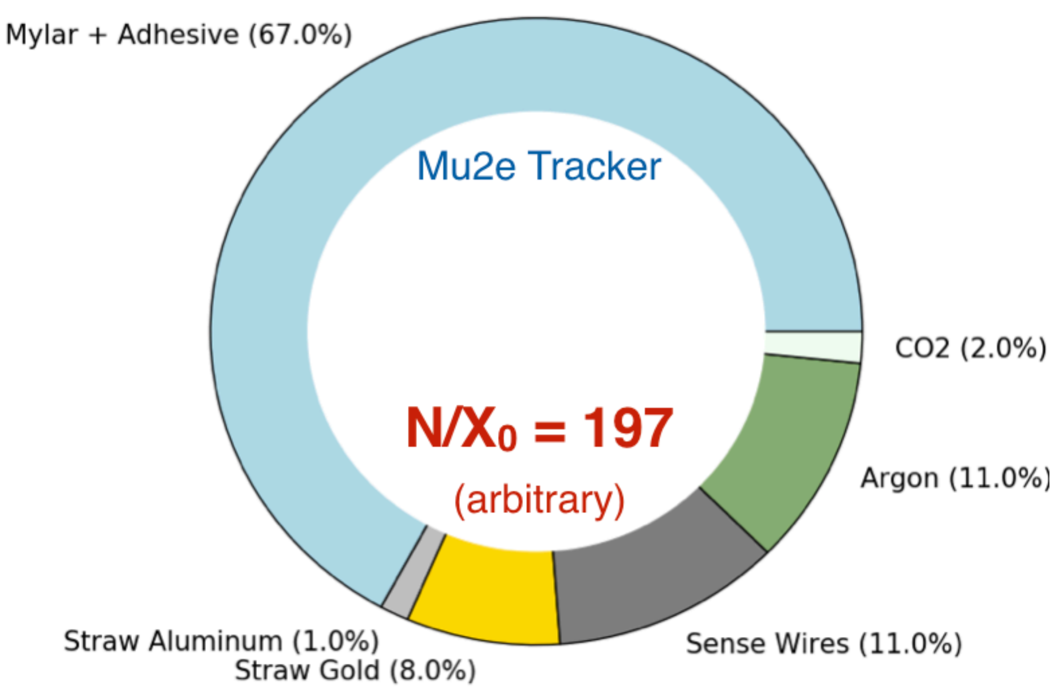
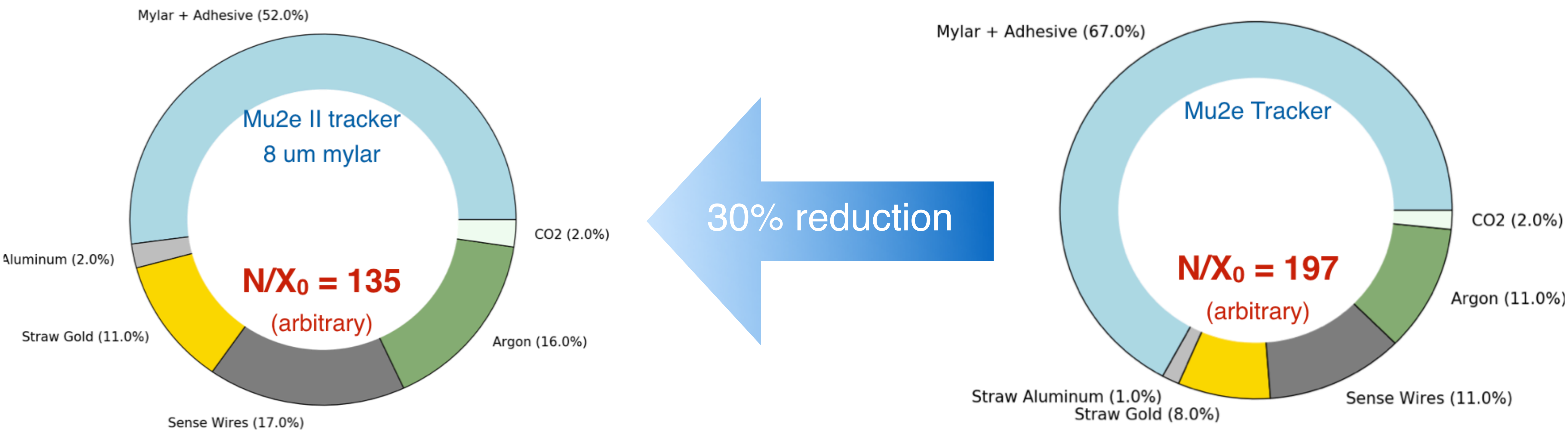
Overview

- The Mu2e tracker will already be the lowest mass per surface-area(2), straw-tube detector ever to be held in vacuum
  - Straws length > 1 m; straw wall thickness = 15 µm; straw surface area > 3×10^6 cm^2
  - Herein lies a major challenge
- The Mu2e II tracker will be in a higher rate environment
  - 3x instantaneous and x10 integrated dose
    - Rad hardness electronics
    - Space charge screening
    - Aging
  - DIO background scales linearly with muon occupancy
    - Need higher precision to mitigate the 10 fold increase
    - Momentum resolution is dominated by material effects
- <u>We require a lower mass tracker</u>



Overview

- The mylar drives the scattering and energy loss in the tracker
- The snowmass report considers a reduction in wall thickness from 15 to 8 um
  - https://arxiv.org/abs/1307.1168



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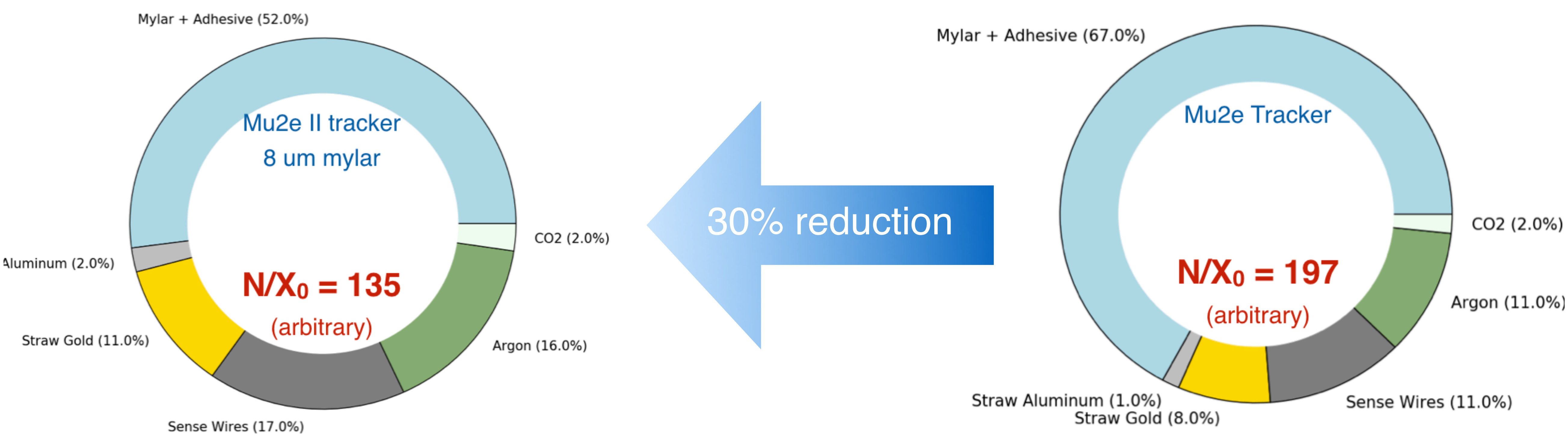
Can 8 um straws be made? Dan will address this!

Can we even use 8 um straws?



8 Micron Mylar in Mu2e II

Will evaluate feasibility of using thinner straws:

- Average longitudinal stress and tension relaxation
- Average hoop stress and circumferential creep (ballooning)
- Peak von Mises stress and straw destruction
- Leak rate

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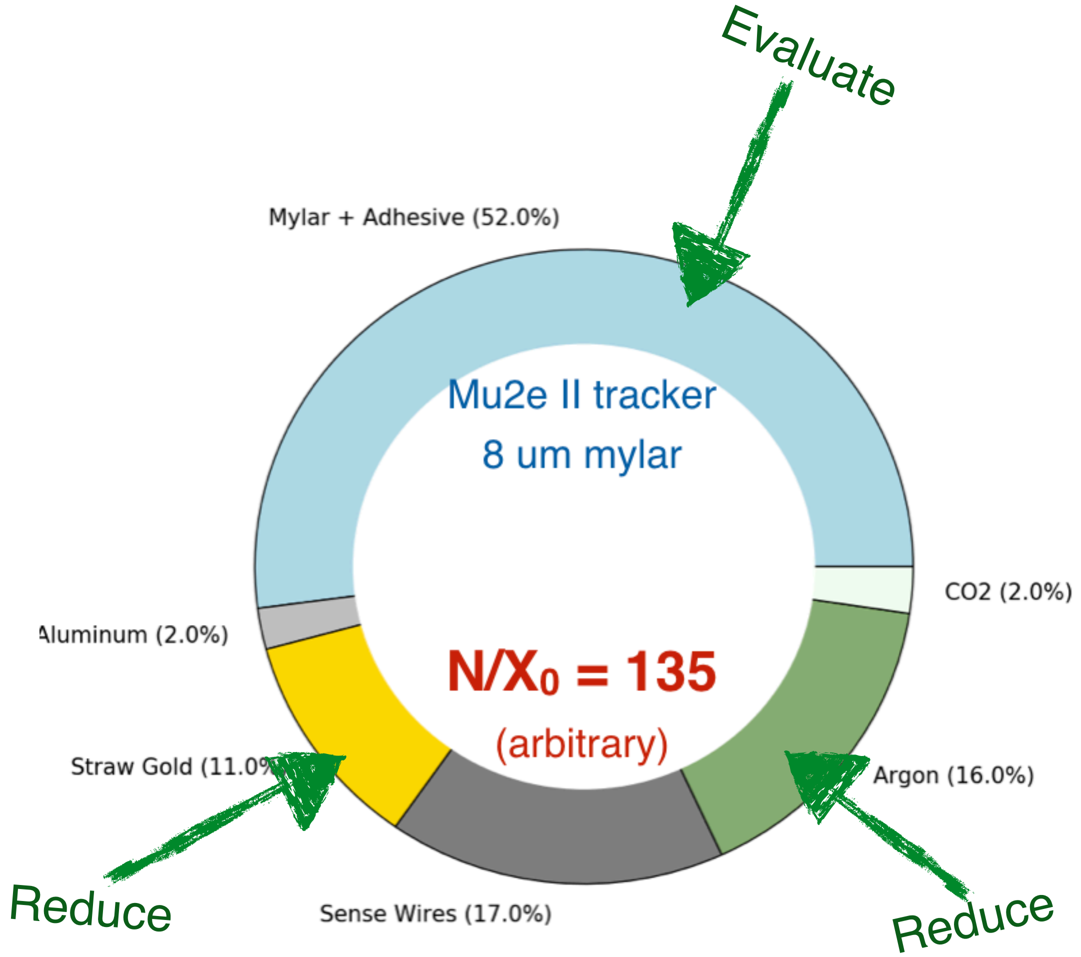
And relatedly:

- Sub atmospheric gas pressures
- Reduction/removal of gold



8 Micron Mylar in Mu2e II

8 um straws will likely need to be wound

- Welding straw seams has only been accomplished for thicker mylar
  - The thinner the sheets, the harder it is to get a continuous seam
- Winding 2.54x2 um mylar with 2.92 um glue is a likely path forward
  - Proceeding calculations assume 2.5 + 2.5 + 3 um with spiral 2.5 um seams

Longitudinal Stress

- For simplicity, normalize to Mu2e conditions
  - tension = 1, wall thickness = 1, wall area = 1, straw weight = 1, etc
- Mu2e II conditions
  - call the above conditions T, t, A, w, etc.

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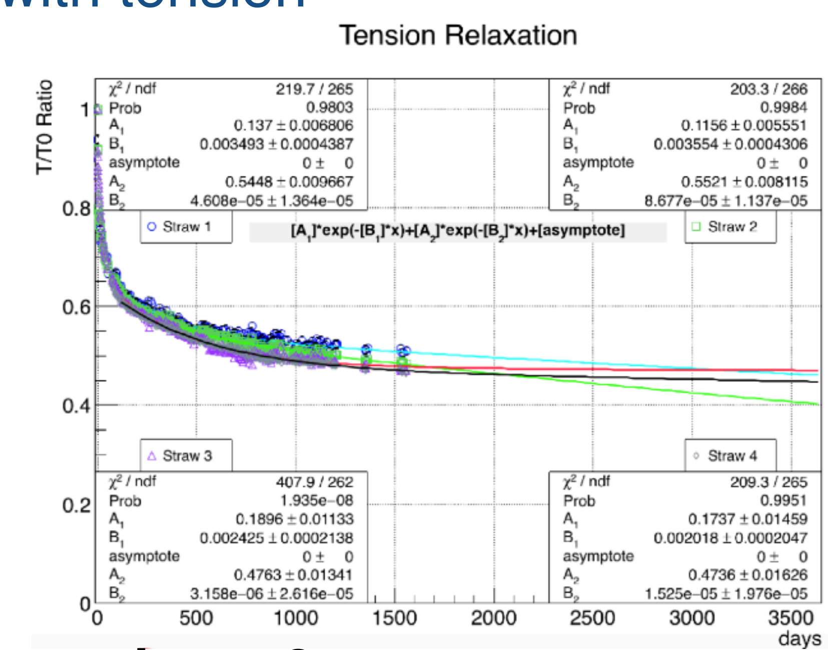
- For now, dial down the gas pressure to match the wall thickness, P=8/15
- t =8/15 → w = 8/15; sag is proportional to w and inversely proportional to tension
  - To achieve the same level of straw straightness, T = 8/15
  - The stress, S = T/A = 1
  - We know from data collected by Duke, that the creep rate scales with tension
    - And almost certainly scales, more generally, with stress
    - <u>The relative tension relaxation rate = 1</u>
  - The stretch coefficient, Cs = 15/8
  - So the initial stretch, ΔX= T*Cs = 1



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Same initial straw stretch

Same longitudinal straw stress

Same relative tension relaxation over time (longitudinal creep)

As a side benefit, better radiation length

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Now turn the gas pressure up to P=1

Longitudinal Stress

- The straw weight goes up
- A force (that I don't know the name for) that exacerbates straw curvature, goes up
  - It arises because cylindrical symmetry is broken, and "top" and "bottom" surface area becomes unequal
- In Mu2e, these two forces together account for (9.5 + 6.6 = 16.1)% of the tension needed to reduce long-term out-of-straightness
- Both terms are linear with pressure
- So if one takes the results from before, and brings the pressure up from 8/15 to 1, one gets closer to a 30% effect, or additional ~14% needed tension
  - $S=1 \rightarrow 8/7$; $\Delta X \rightarrow 8/7$
  - ie higher peak stress, higher absolute stress relaxation over time, and higher initial stretch

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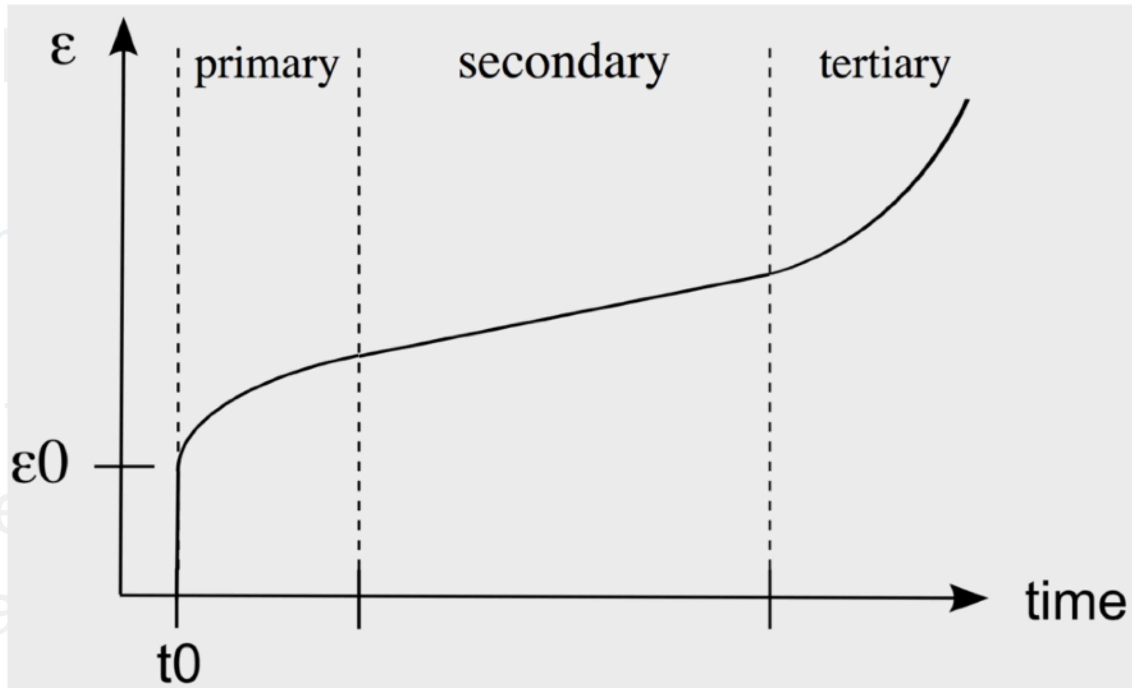
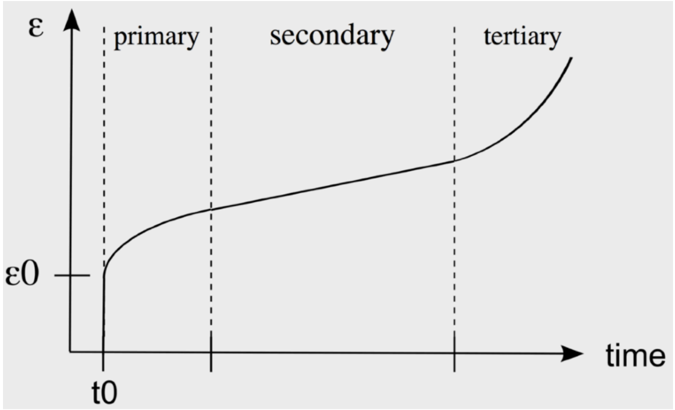


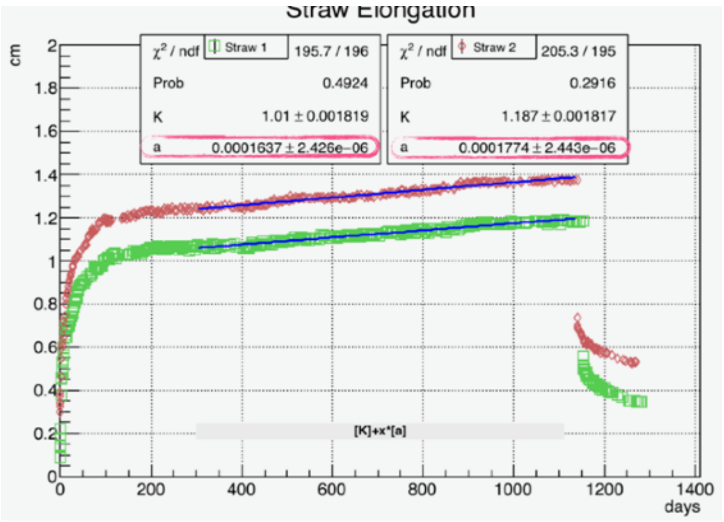
<u>**These could lead to ruptured straws, tertiary creep behavior, and larger leak rates**</u>

<u>**Straw R&D is especially needed if we keep the gas pressure at 1 atm**</u>

Hoop Stress and Creep

- Hoop stress is $S_h = Pr/t$.
- In mu2e straws, S_h = 2500 psi, circumferential
- Duke measured straw creep from 3321 psi of longitudinal stress
  - Longitudinal relative expansion: $7.1\times10^{-3} + 3.9\times10^{-4}$/year
  - Only valid in the secondary region
- Scaling for pressure and diameter, we expect 0.041 mm diametric expansion over 10 years in mu2e
  - We see that the assumption of negligible exponential “ballooning” holds well
- <u>In Mu2e II, the average hoop stress becomes 4,687 psi and the diametric creep becomes 0.077 mm</u>





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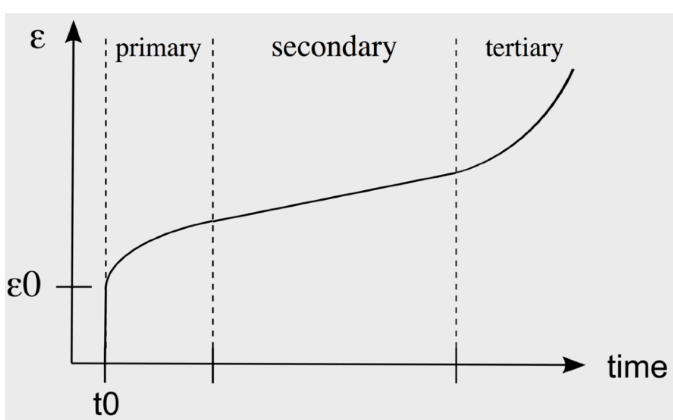

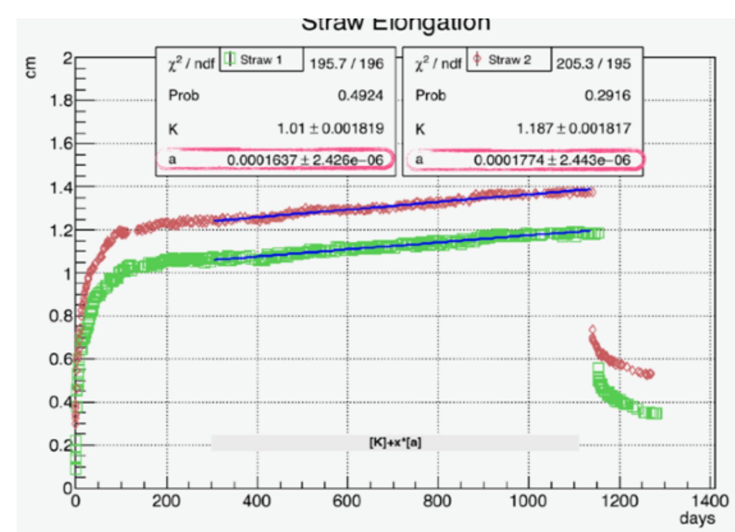

The calculated diametric creep is small, but we have no long term studies at ~4700 psi

Peak Hoop Stress and Rupture

- Duke overpressure Mu2e straws and found that the seams break around 70 psi gas pressure
  - The longest test was only 10 mins!
- The peak stress occurs at the seams (6.25 um)
  - Incidentally, this corresponds to a hoop stress of 27,600 psi
- In (this picture of) Mu2e II straws, the corresponding gas pressure is found by scaling by the single layer thickness ratio
  - equivalent destructive gas pressure = 70*(2.5/6.25) = 28 psi

Mu2e safety factor:	4.6
Mu2e II safety factor:	1.8
If the gas pressure is reduced by 8/15:	3.4

Either way, long term tests are needed

We may have to reduce the gas pressure and/or the straw diameter

The von Mises Stress and Rupture

- If you add the peak longitudinal and hoop stresses in quadrature
  - Assume 0.55 kgf tension → at the 2.5 um seam, you get 10,627 psi
  - The hoop stress at 1 atm is 15,000 psi
  - The von Mesis stress is 18,382 psi

Mu2e safety factor:	4.6
Mu2e II safety factor:	1.8
For von Mesis:	1.5
If the gas pressure is reduced by 8/15:	3.4
For von Mesis:	2.8

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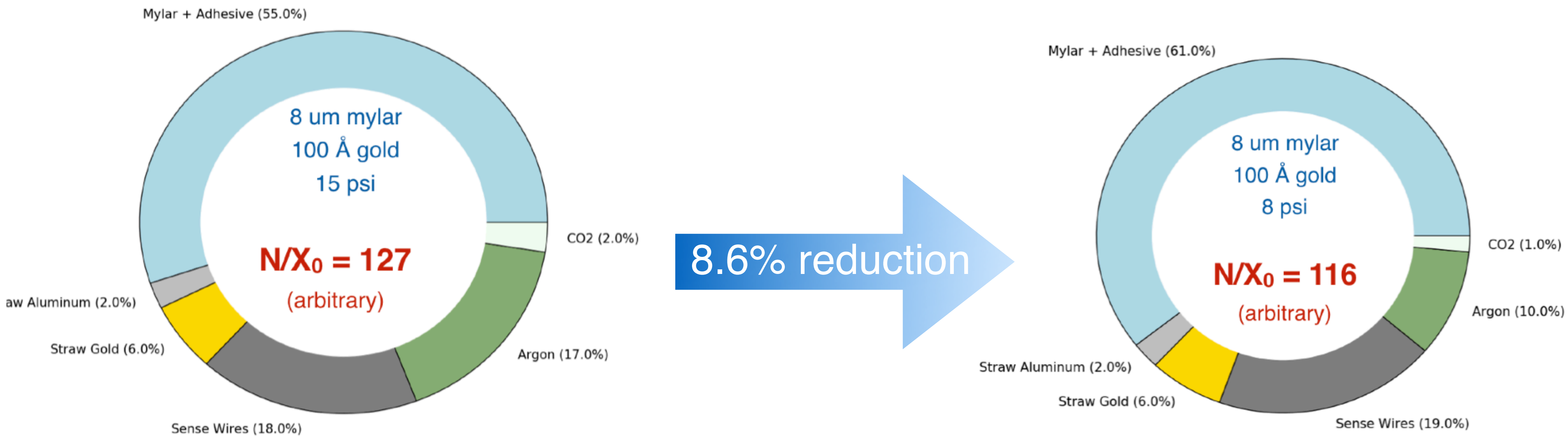
Going Sub-Atmospheric: Cons

- Need active pumping on the drift gas
  - Space could be an issue
- QC must be done in an ambient vacuum
  - HV tests would be challenging, but it could be done
  - Outgassing and leak tests already done in vacuum
- A (re-) characterization of gain, drift speed, resolution etc. must also be done in vacuum
  - A single prototype with a few straws may only be needed
- If the ambient vacuum fails, the tracker could be destroyed
  - A mitigating feedback system would need to be put in place
- Fewer ionization clusters
- Lorentz effect increases
  - As it turns out, mu2e is right at the threshold before large Lorentz angles

Going Sub-Atmospheric: Pros

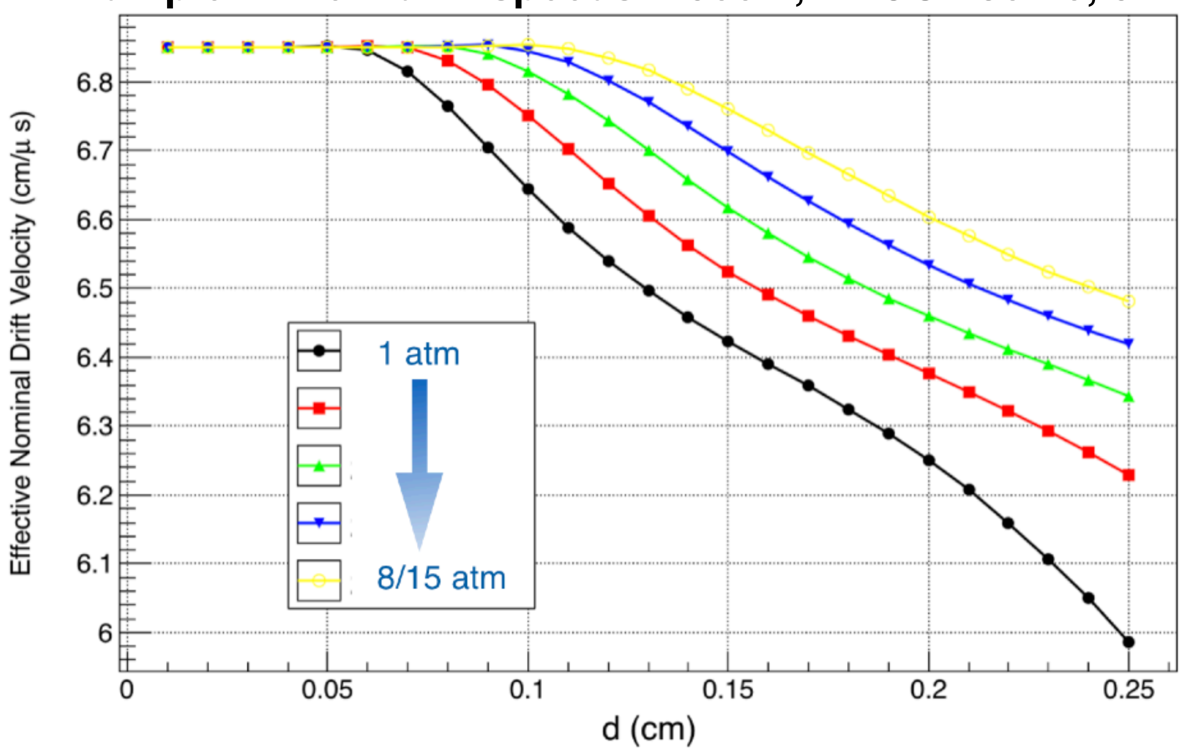
- Many major mechanical conditions can be made nearly identical to Mu2e
  - Longitudinal creep, average hoop stress, average longitudinal stress, straw elongation
- The leak rate goes down
  - Leaks from holes in mylar proportional to gas pressure
  - Leaks from CO2 dissolving are proportional to gas pressure and gas pressure squared
    - For micro-cracks in the metallization that are smaller and bigger than the mean free path, respectively
  - Less straw elongation also means lower leak rate
- The mass of the tracker goes down
  - # of radiation lengths reduces by 8.6%



Going Sub-Atmospheric: Pros (cont)

- The electron drift velocity goes up
- The ion drift velocity goes up
  - Ion drift time at 1 atm is $\mathcal{O}$(75 us)
    - Integrates over several proton pulses $\mathcal{O}$(1 us)
  - So space charge screening, which could be a problem with the high occupancy in Mu2e II, goes down
- The gain goes up
  - May run at lower voltage or with more quencher

Example Mu2e II drift speeds: 1500 V, Ar:CO2 80:20, 5mm



Thin Straws and Leak Rate

- The leak mechanisms are varied, but they all depend on mylar thickness
  - Geometric leaks are proportional to the mylar thickness
  - Leaks involving dissolving of CO_2 have different dependencies, but all go down with thickness
- Thinner mylar is also more delicate
  - More micro-cracks in the metallization from handling
  - More holes in the mylar itself
- <u>Leak rates for straws under a variety of conditions needs to be studied</u>
  - After handling
  - Under tension
  - Under pressure
    - Relating to the von Mises stress, for long term

Gold in Mu2e

- We have 500 angstroms of aluminum on each side
  - For gas seal and electrical conductivity
- One side has an additional 200 angstroms of gold
  - To avoid the interior of the straw becoming an insulator
    - Otherwise an alumina layer develops with higher resistivity by many many orders of magnitude
- As it turns out, all of the Au ends up as a compound
  - Au Al, Au Al_2, Au_2 Al, etc.
  - Compounds are still good conductors!
    - The resistivity of most compounds are around 2-4 times that of pure Au
    - Worst compound's resistivity is ~10 times that of pure Au
    - I.e. many many orders of magnitude better than alumina!
- On the non-gilded side, the alumina is so thin that electrical connection is not a problem
  - Accidental mechanical abrasion is enough to break the oxide layer!

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Gold drives the cost of the straws and reduces the radiation length, so what are we getting out of it?

Gold in Mu2e II

- Ions drift towards the grounded straw wall
- Pure aluminum means an insulating oxide layer
- If charge can't be exchanged, the ions build up near the straw wall
- After sufficient build up, the voltage is enough to punch through the oxide layer
  - You then get a burst of emitted electrons which can cause further ionizations
  - More ions travel back toward the straw wall along their Lorentz angle
  - For a transverse tracker geometry, the Lorentz angle can be zero for (anti-)parallel fields
  - Positive feedback loop

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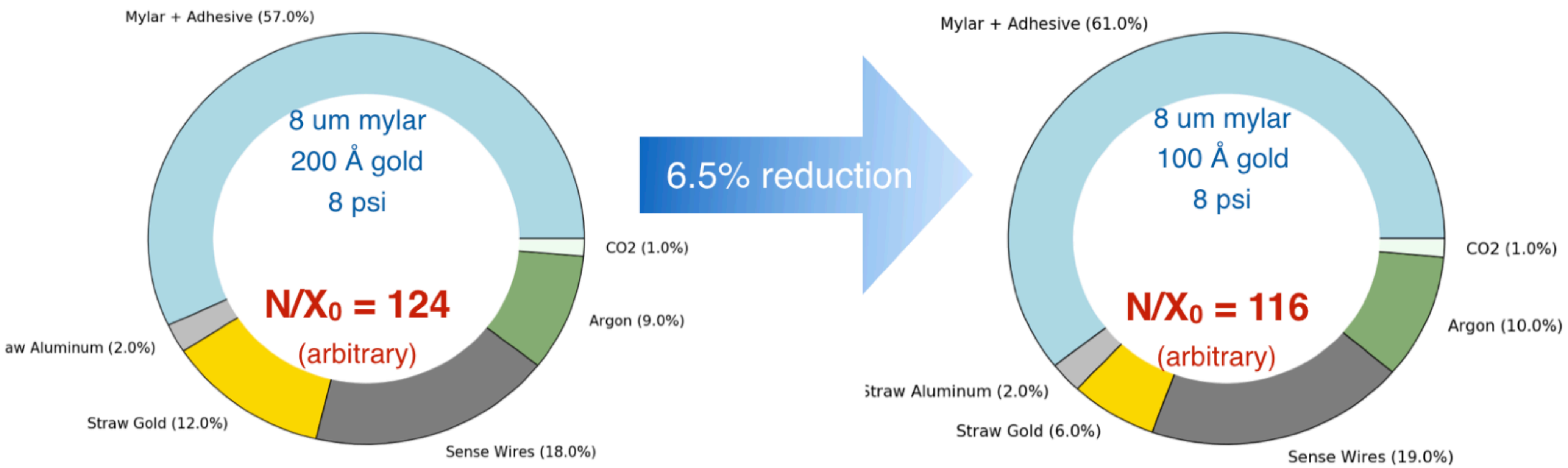
But with R&D, one could test to see if:

1) A fraction of the gold will have the same effect
2) No gold is needed at all

Half Gold in Mu2e II

- Since all of the gold is in compound form anyway, this is likely the case hand has its benefits
  - Reduce high Z material
  - Reduce a driving cost
  - For leak tightness, one could replace the missing Au with Al



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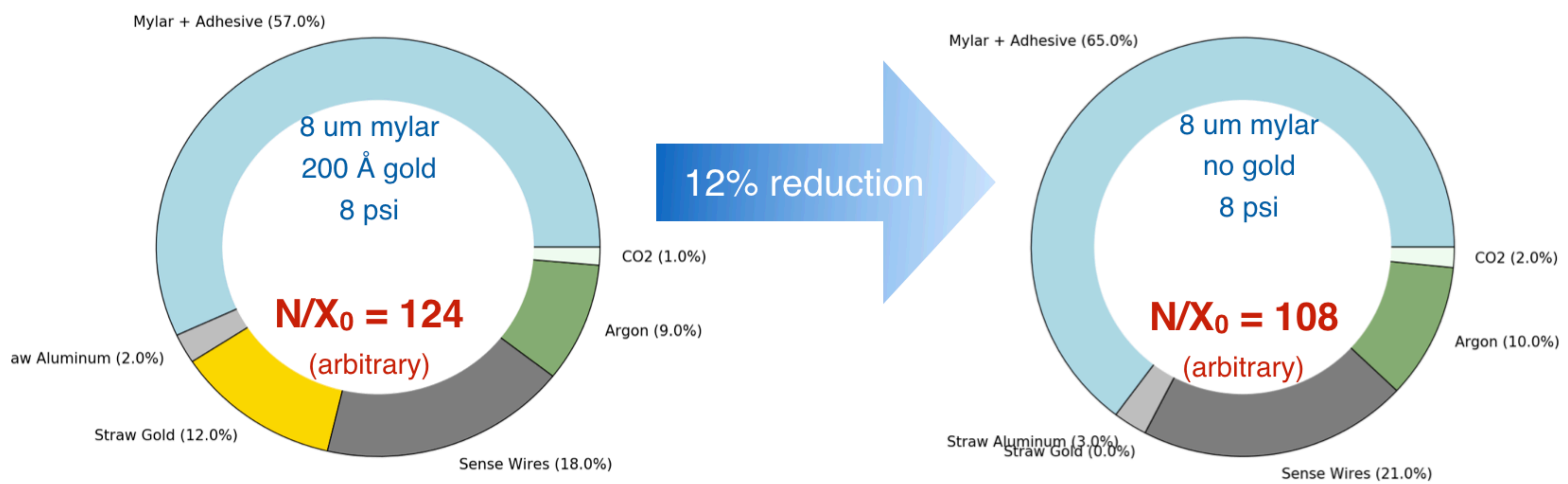
No Gold in Mu2e II

- This would require more thorough testing, but the elimination of gold would, in some ways, be ideal
  - Removal of high Z material
  - Remove a driving cost
  - Reintroduced otherwise excluded manufacturers of metalized material
  - For leak tightness, one could replace the missing Au with Al



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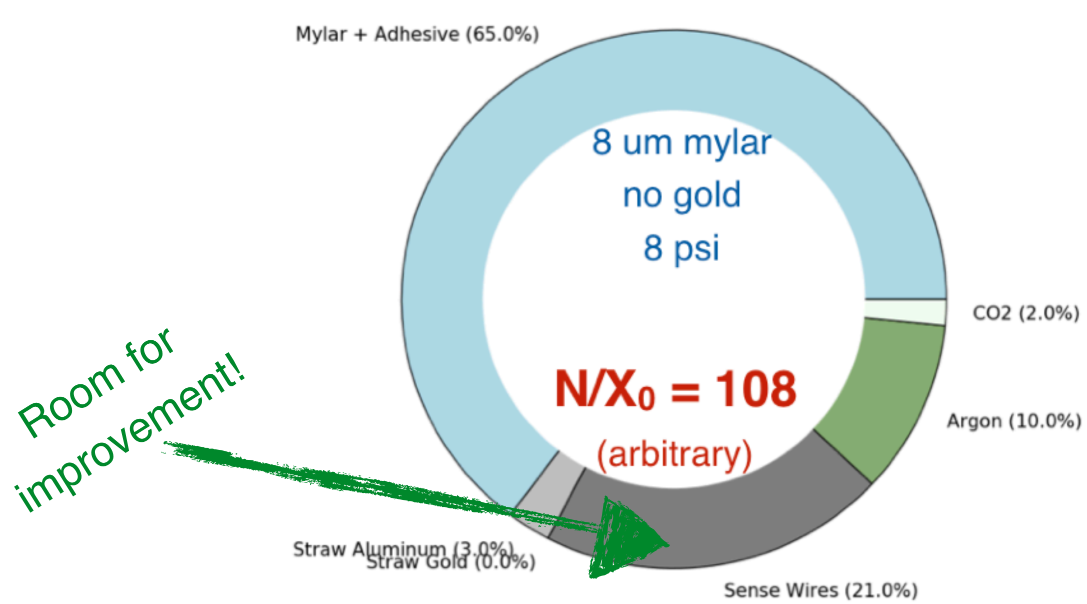
Summary

A few points:

- 5 mm straws with 8 um walls at 1 atm may fail
  - Testing is needed
- Sub atmosphere is about more than scattering
  - At 8 psi, many mechanical Mu2e conditions are replicated
  - Above 8 psi, the straws may break down
- <u>While the thin straws bring down the inverse rad length by ~**30%**, its possible to drop another ~**20%** with sub-atmospheric pressure and reduction/removal of gold</u>
  - <u>At that point, the wires account for ~**20%** inverse rad lenth, which **JF** will address!</u>



A few R&D projects:

- Tension relaxation
  - As well as the related longitudinal creep
- Responce to hoop stress
  - Diametric creep from over pressure is a possibility
    - few micron level measurements needed
  - Destructive tests
    - von Mises
- Systematic exploration into sub atmospheric
  - Depending on the mechanical tests, it could be avoided
    - but that's unclear for now; we are pushing the straws to their limit
  - The benefits may still outweigh the costs
  - Many implications for performance and operations need to be examined
- Performance with low/no gold straws
- Leak studies
  - After handling
  - Under tension
  - Under pressure
- Reintroduce the idea time varying gain?
  - Requires ultrafast switching

Backup: Copper in Mu2e II

- Replacement of all metallization with copper is a possibility
  - The oxide is conducting
  - But the radiation length wouldn't be dramatically different for the same thickness
- We have straws with a copper layer made by Lamina
  - The manufacturer had a difficult time winding because of the metallization's stiffness
  - With ~2.5 micron mylar, the problem could be worse

Copper likely wouldn't be much of an improvement