Modeling the Dynamics of Plastic Flow Serrations in Bulk Metallic Glasses

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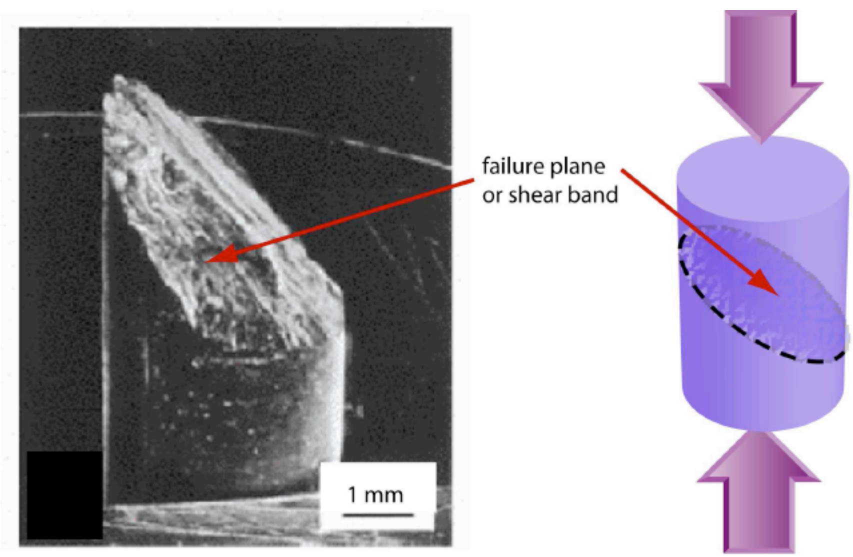
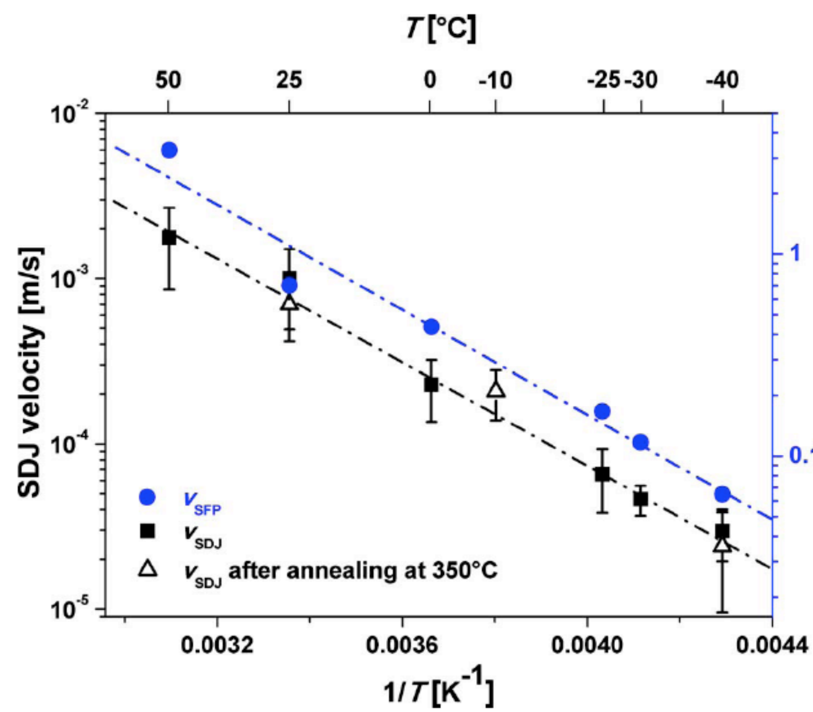
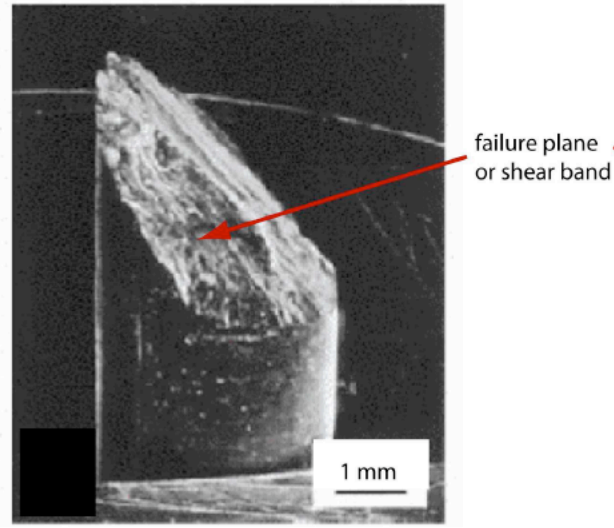


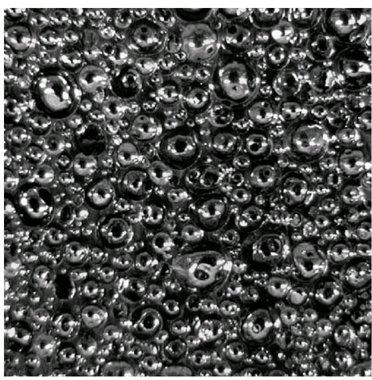


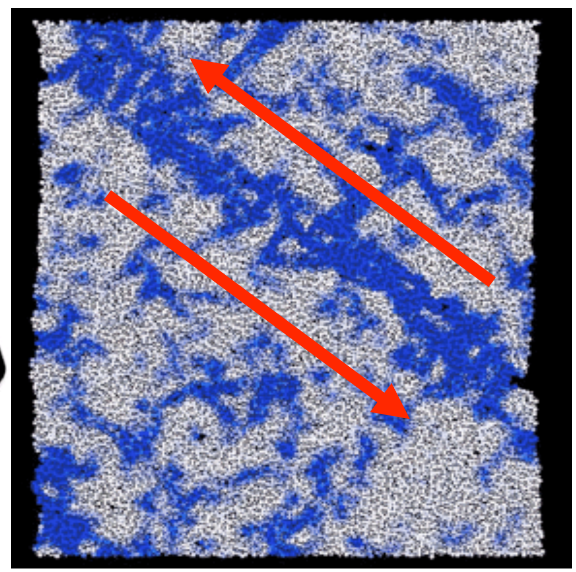
Bulk Metallic Glasses

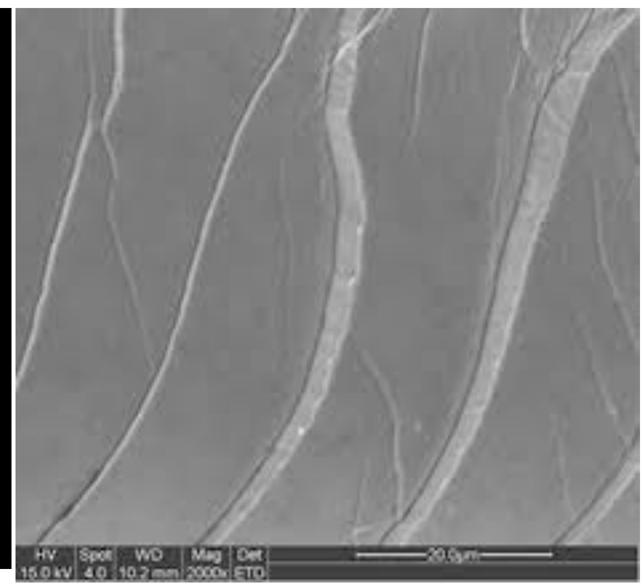
Some metal alloys can form glasses rather than crystalline solids when cooled rapidly.

The mechanical properties of these materials are not well understood.





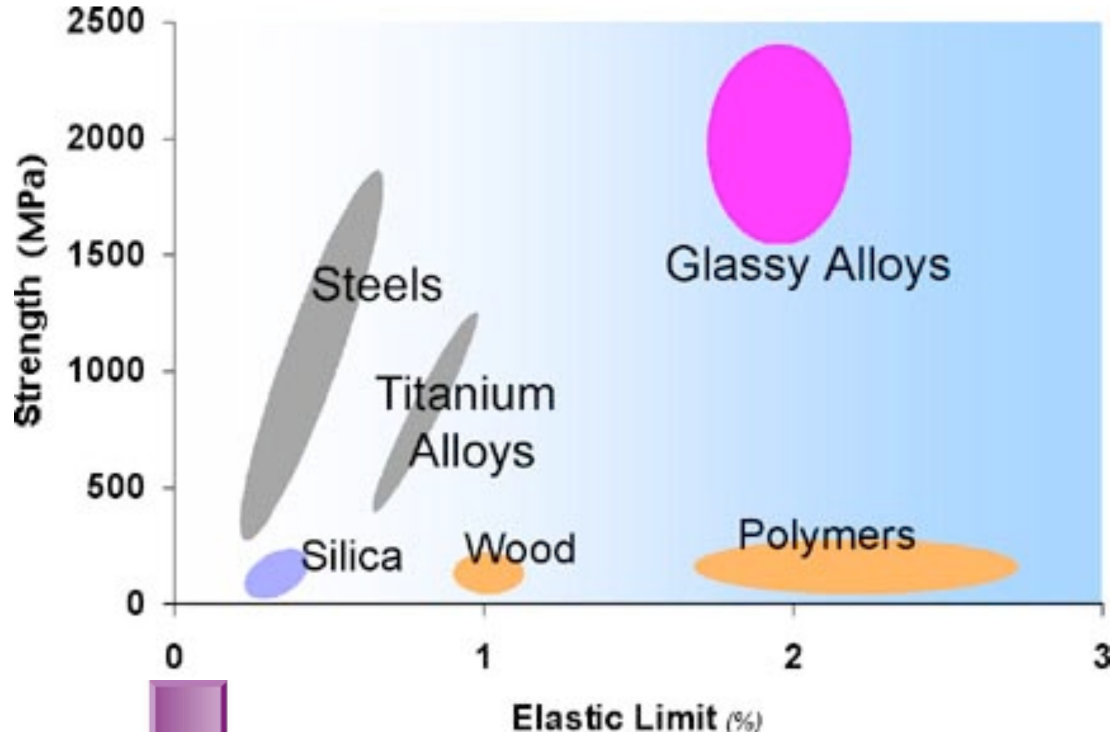


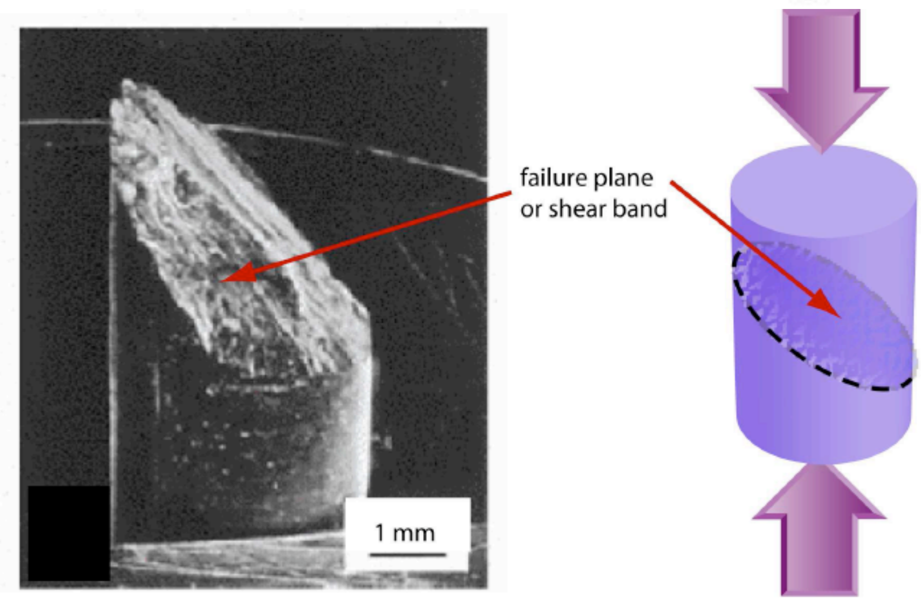


Bulk Metallic Glasses

Metallic glasses have high yield strengths (vertical axis) and remain elastic for large strains (horizontal axis).

However, beyond the elastic limit, they tend to fail catastrophically.





This talk will focus on understanding how glasses deform beyond the elastic limit.

Bulk Metallic Glasses

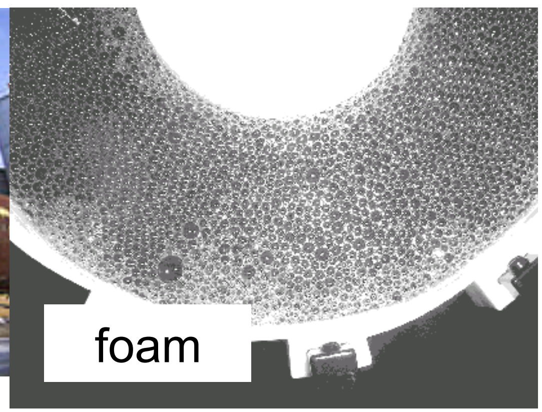
How do glasses (and other non-crystalline materials) deform and fail?

Idea: come up with continuum model (like Navier-Stokes for fluids)

Challenging problem: needs to capture both solid-like and fluid-like behavior.

University of Queensland Pitch Drop Experiment:

- Began in 1930
- To date, 8 drops
- Glassy materials can both flow and fracture!

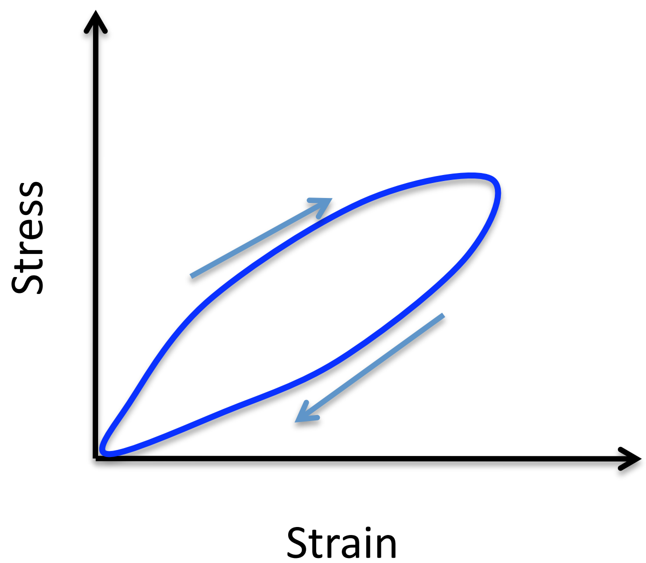


dense colloids/ emulsions

Plastic Deformation in Glasses

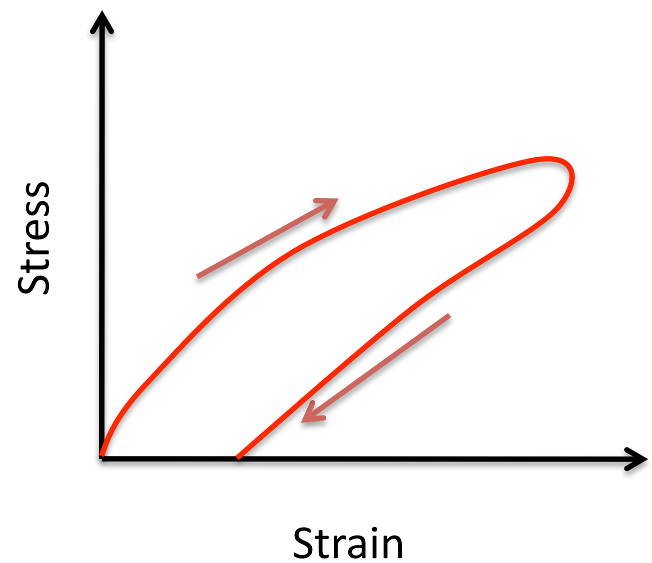
Focus on plasticity in metallic glasses in this talk. Ask similar questions to the ones we have about nonlinear elasticity:

Nonlinear Elasticity



Nonlinear relationship between stress and strain.
System returns to (0,0) = no permanent deformation (elastic)

Plasticity

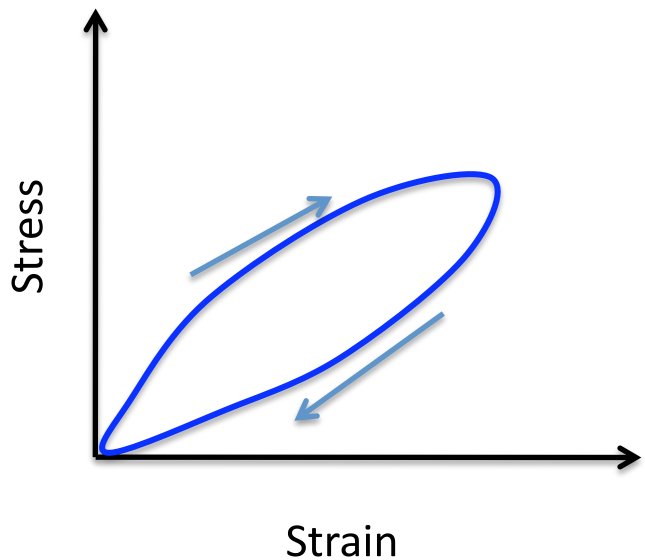


Nonlinear relationship between stress and strain.
System has permanent (plastic) deformation when stress removed

Plastic Deformation in Glasses

Focus on plasticity in metallic glasses in this talk. Ask similar questions to the ones we have about nonlinear elasticity:

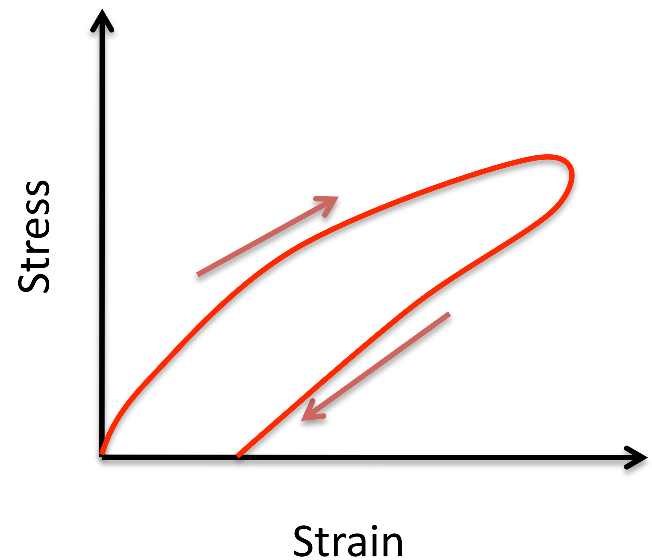
Nonlinear Elasticity



$$\tau = \mu \times \epsilon = \underline{\mu(\epsilon)} \times \epsilon$$

Capture nonlinearity by expressing modulus as a function of strain (and possibly other quantities)

Plasticity



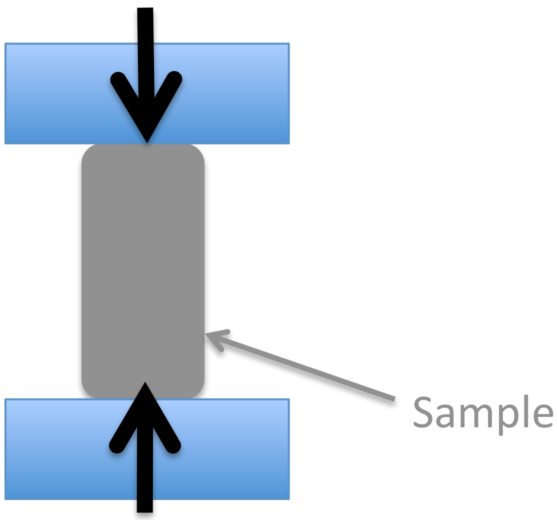
$$\epsilon_{tot} = \epsilon_{el} + \epsilon_{pl}$$

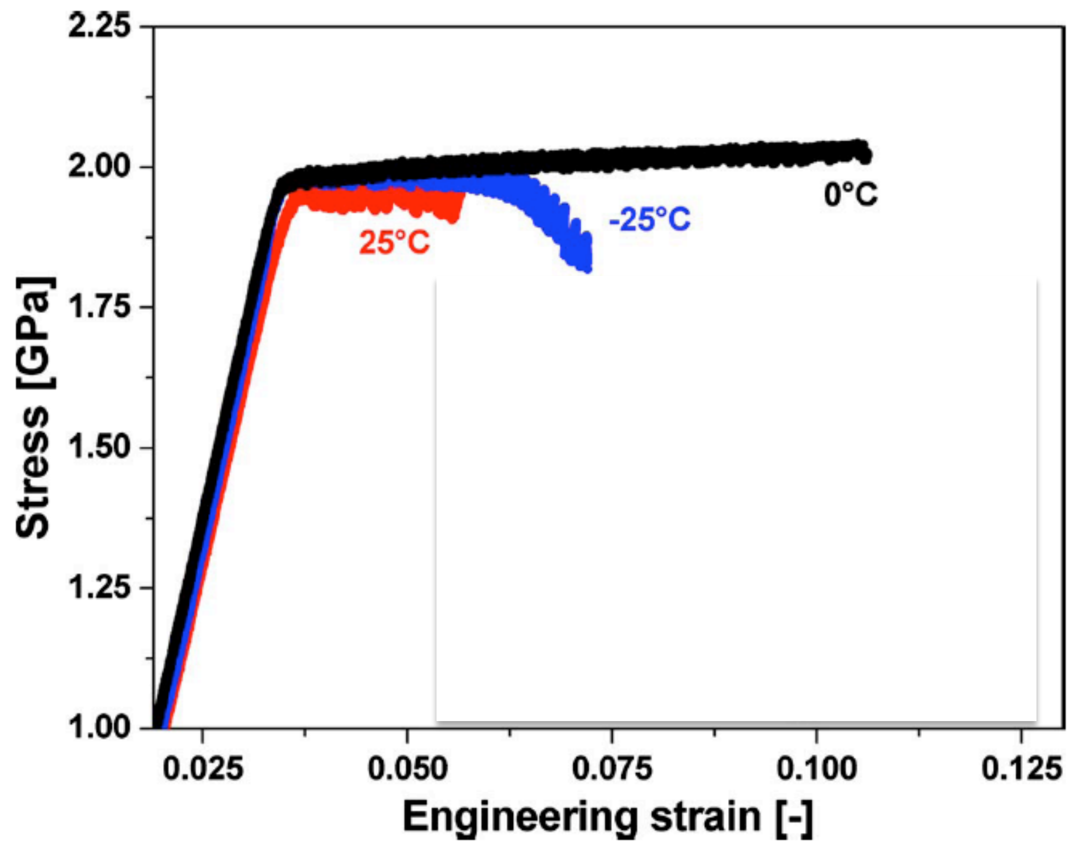
$$\Rightarrow \tau = \mu \times (\epsilon_{tot} - \underline{\epsilon_{pl}})$$

Instead, need to write strain as sum of elastic and plastic parts. Understand how plastic strain evolves instead of modulus

Experiments on Plasticity of Metallic Glasses

Experiments on plastic deformation of metallic glasses (Klaumuenzer et al., 2010)



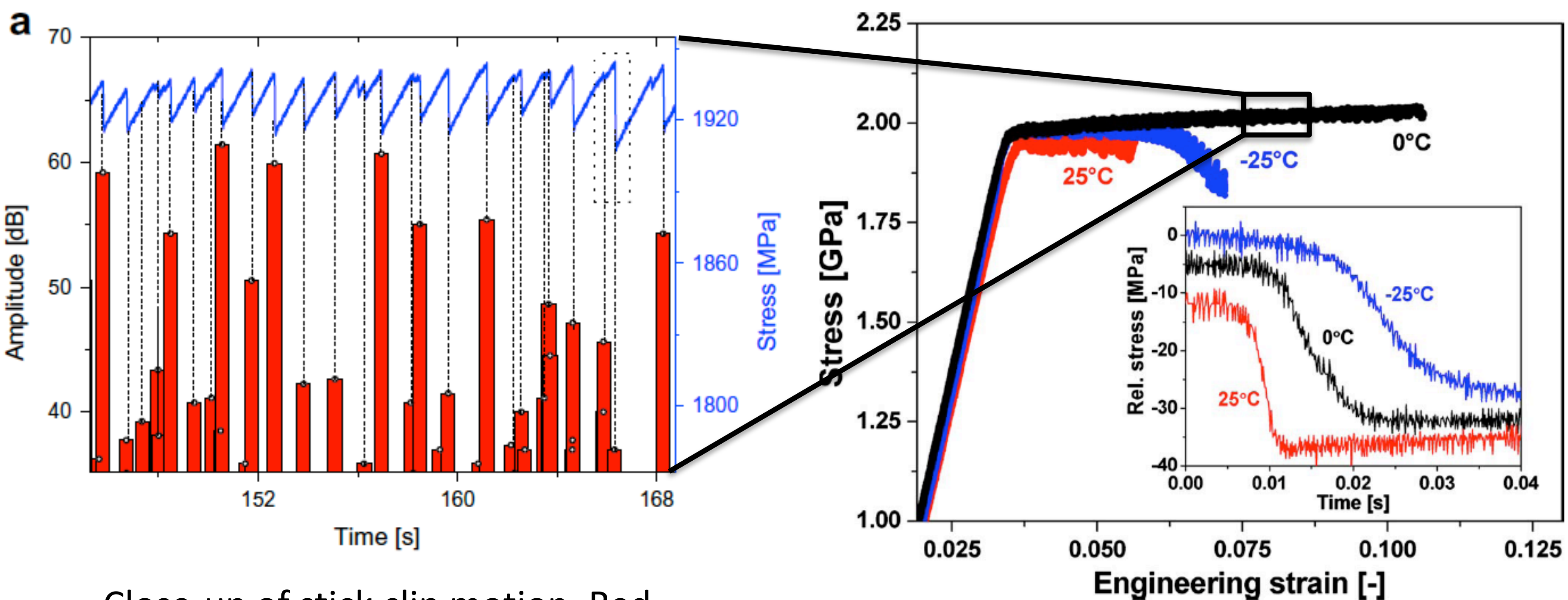


Test under uniaxial compression

Experiments done at constant strain rate (10^{-3} s^{-1}), measure stress

Note: as pointed out before, (1) high yield strength, (2) remains linear elastic at several % strain, (3) plastic deformation occurs beyond linear elastic limit

Stick-Slip Behavior During Plastic Flow



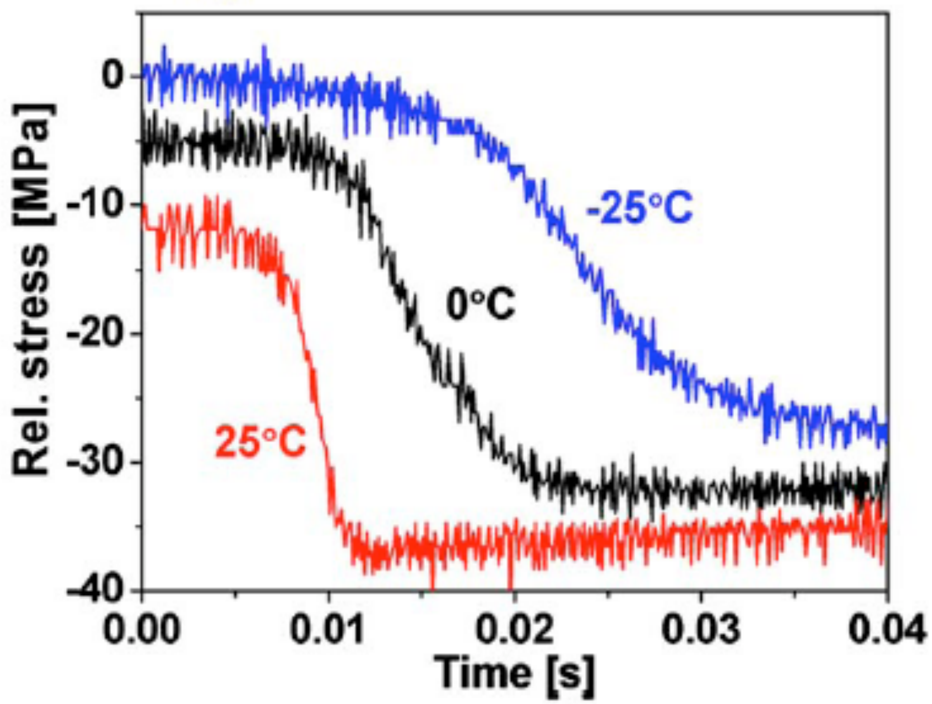
Close-up of stick-slip motion. Red bars are acoustic emission measurements.

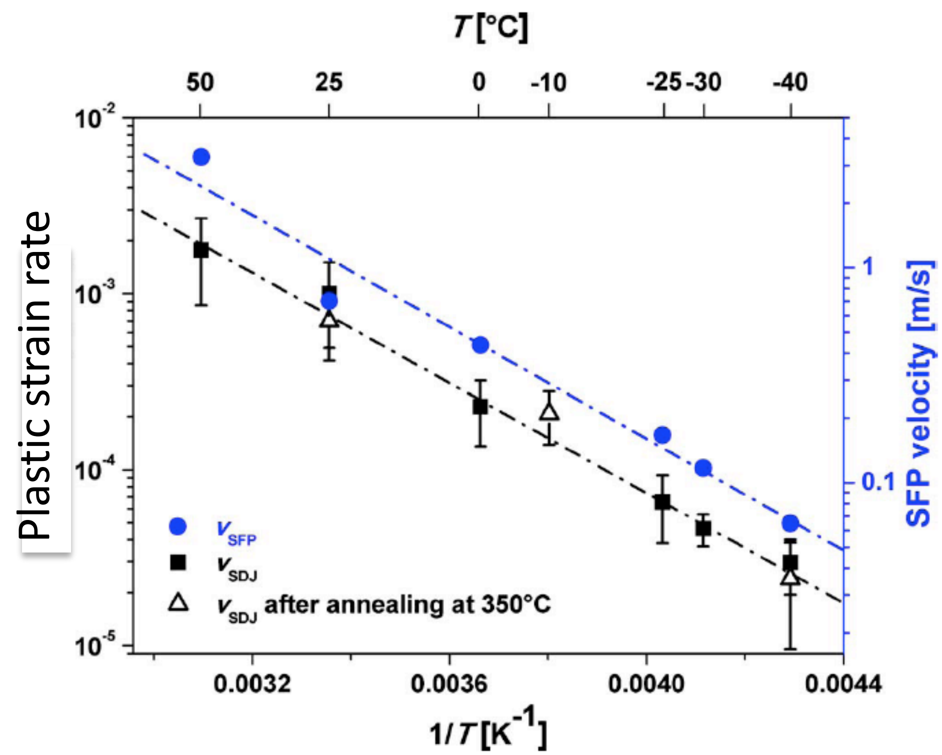
Note that between slip events, stress-strain is linear elastic (tells us this is plastic and not nonlinear elastic behavior)

Inset shows stress vs. time during slip for various temperatures.

Note temperature dependence in how plastic deformation occurs.

Stick-Slip Behavior During Plastic Flow





$$\tau = \mu \times (\epsilon_{tot} - \epsilon_{pl})$$

$$\Rightarrow \frac{d\tau}{dt} = \mu\,(\dot{\epsilon}_{tot} - \dot{\epsilon}_{pl})$$

Slope during slip proportional to plastic strain rate

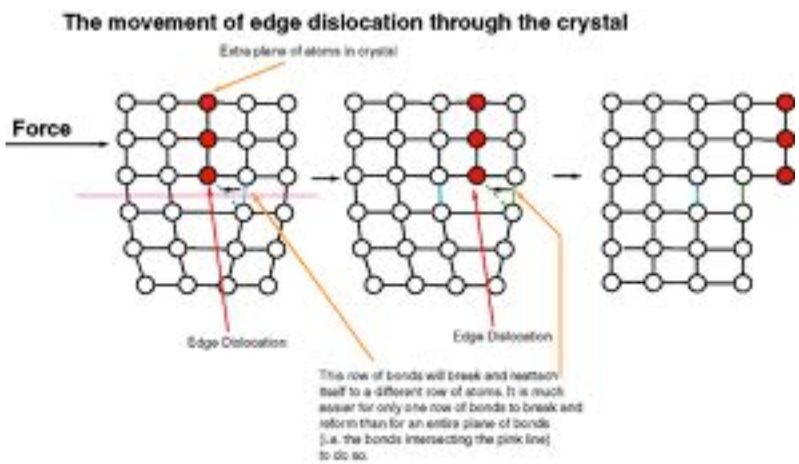
log(slope) is linear in 1/T

Can we use this information to constrain plastic strain rate?

How Does Plastic Deformation Occur?

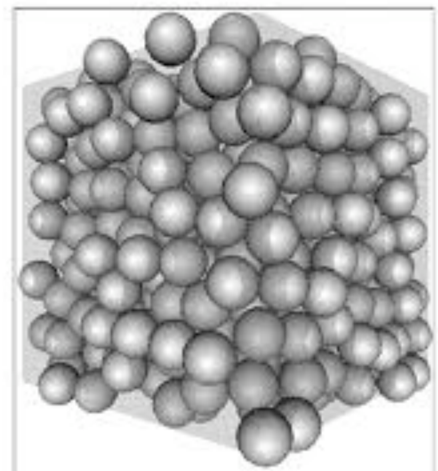
Plasticity is not well understood in amorphous materials like glasses.

Crystalline Material



Plastic deformation occurs in crystals through dislocations: irregularities in the crystal structure

Glassy Material

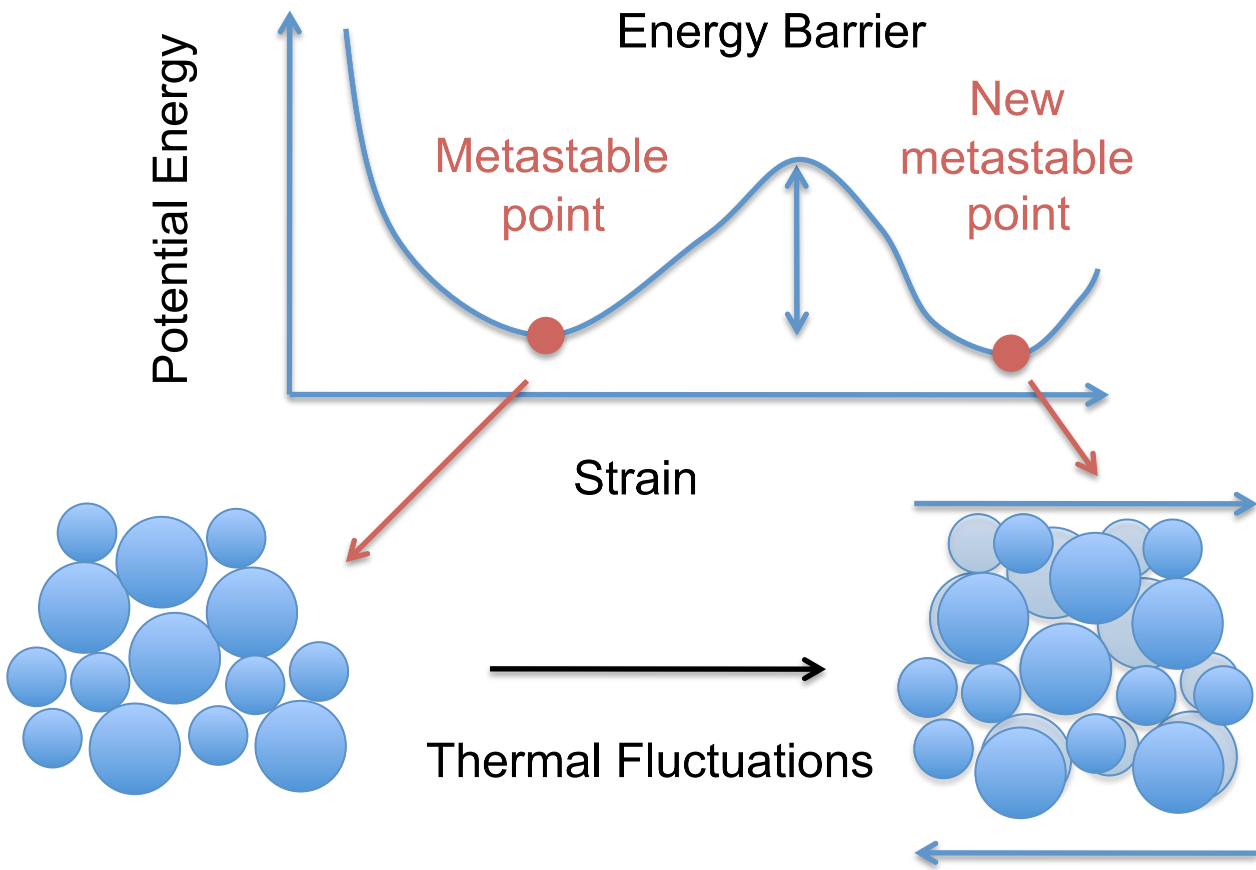


No crystal structure, no easily identifiable dislocations.

However, idea is that there are still “soft spots” in packing where plastic deformation occurs (a current area of active research).

Relating "Soft Spots" to Strain Rate

Idea: amorphous material has "soft spots" where plastic deformation occurs. Like dislocations, these are regions have relatively high potential energy and are easier to deform

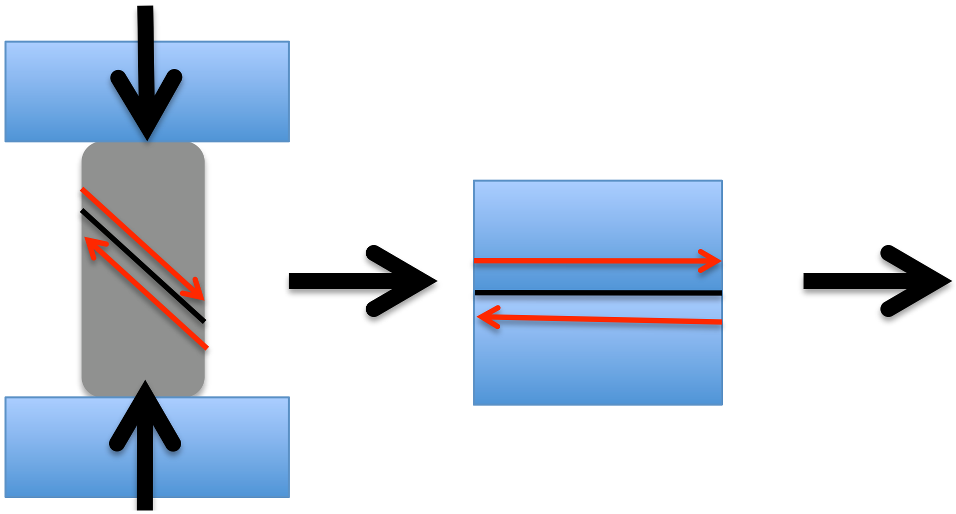


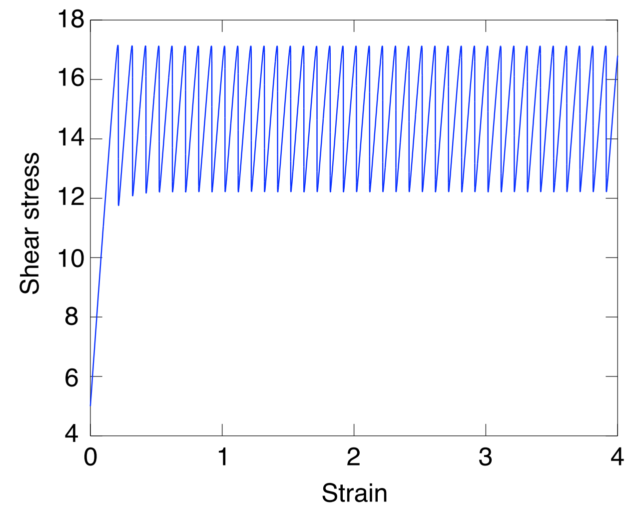
At higher temperatures, plastic strain rate larger because thermal fluctuations are larger?

$$\dot{\epsilon}_{pl} \propto \exp\left(-\frac{E}{kT}\right)$$

Modeling Plasticity of Metallic Glasses

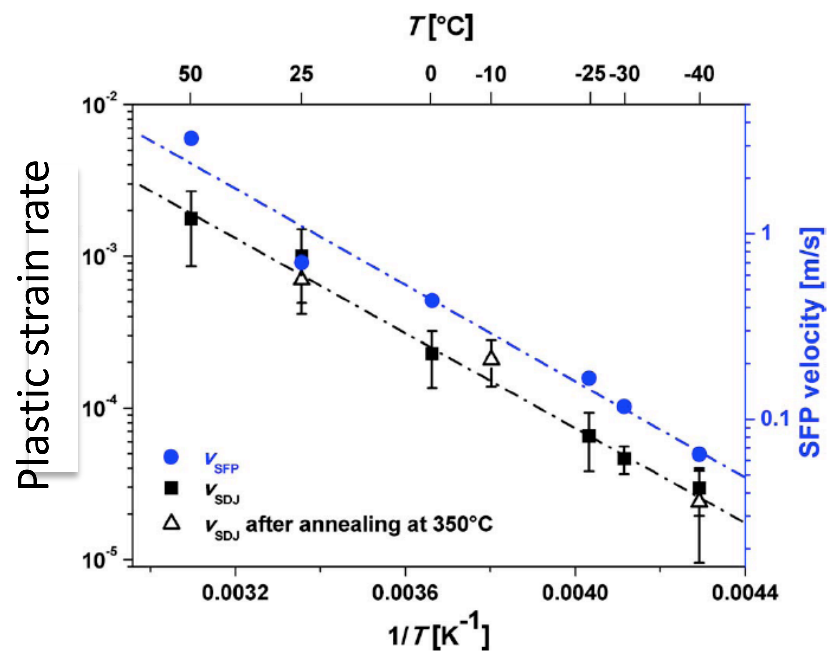
Simple modeling to study plasticity and stick-slip in metallic glasses:





$$\frac{d\tau}{dt} = \mu\left(\dot{\epsilon}_{tot} - \dot{\epsilon}_{pl}\right)$$

$$\dot{\epsilon}_{pl} \propto \exp\left(-\frac{E}{kT}\right)$$

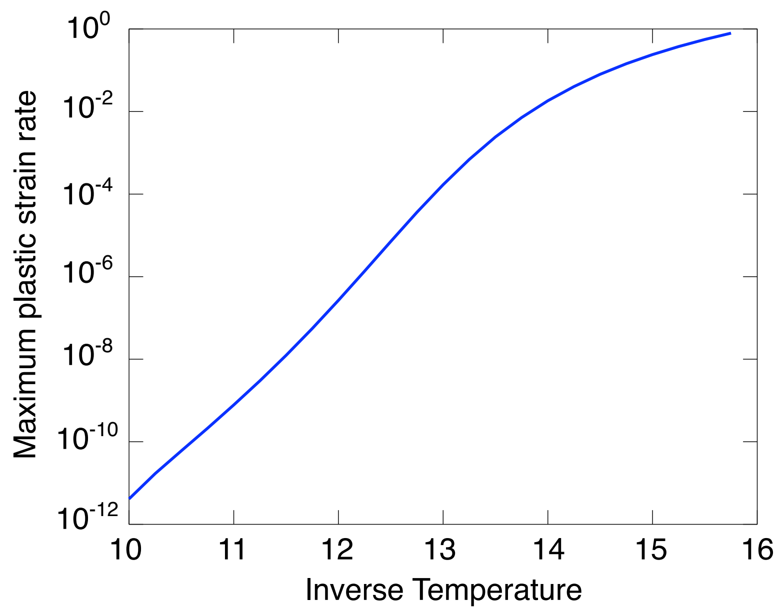


Using model, vary thermal temperature, determine how maximum plastic strain rate scales with T.

Modeling Plasticity of Metallic Glasses

Simple modeling to study plasticity and stick-slip in metallic glasses:

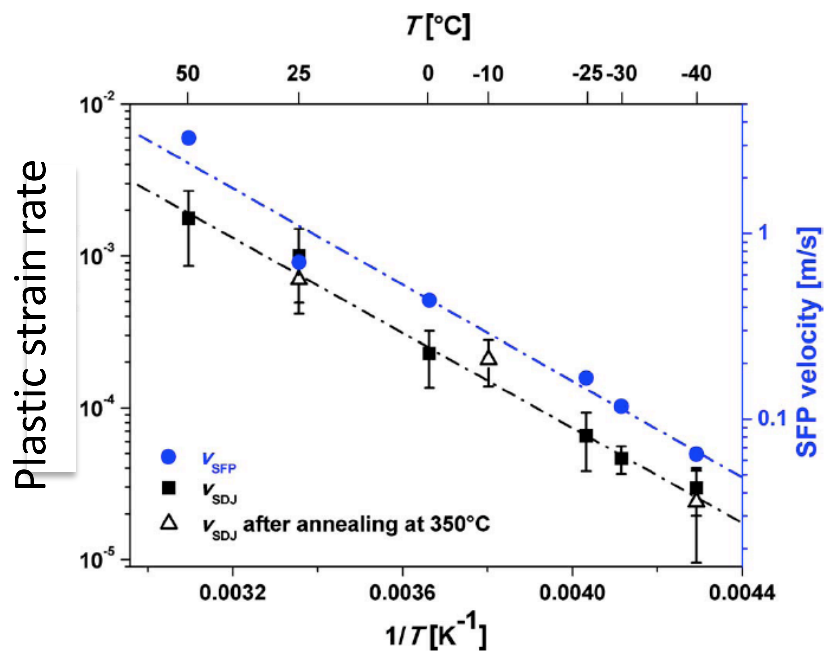
Model



$$\dot{\epsilon}_{pl} \propto \exp\left(-\frac{E}{kT}\right)$$

This gives wrong scaling!

Experiments



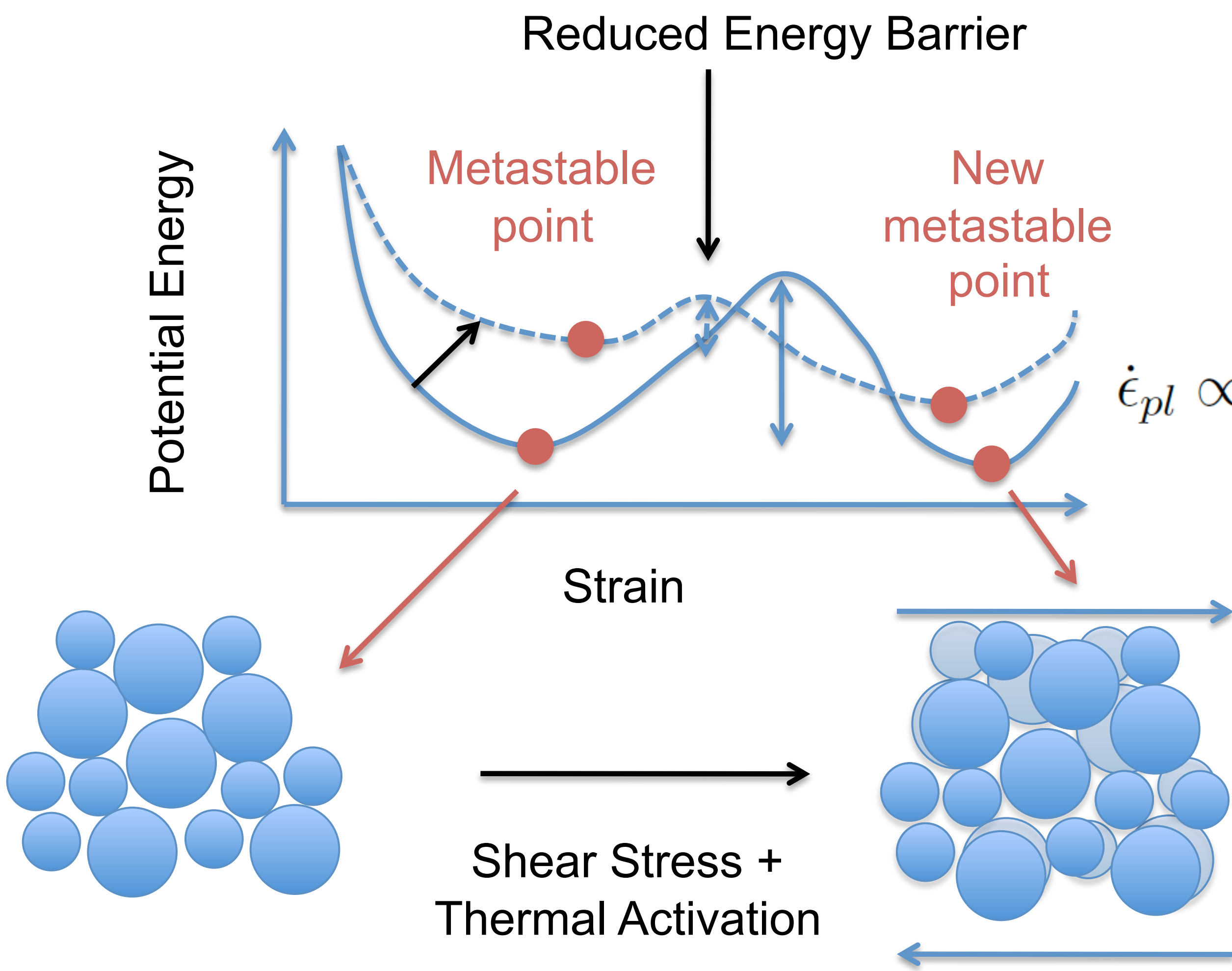
Why?

Complicated nonlinear system (ask me later if you want to know)

But thermal fluctuations aren't only source of rearrangements.

Temperature and Stress are Both Important

But thermal fluctuations aren't the only way to get the system to deform. Apply a stress, material deforms, particles move, and barrier is reduced.



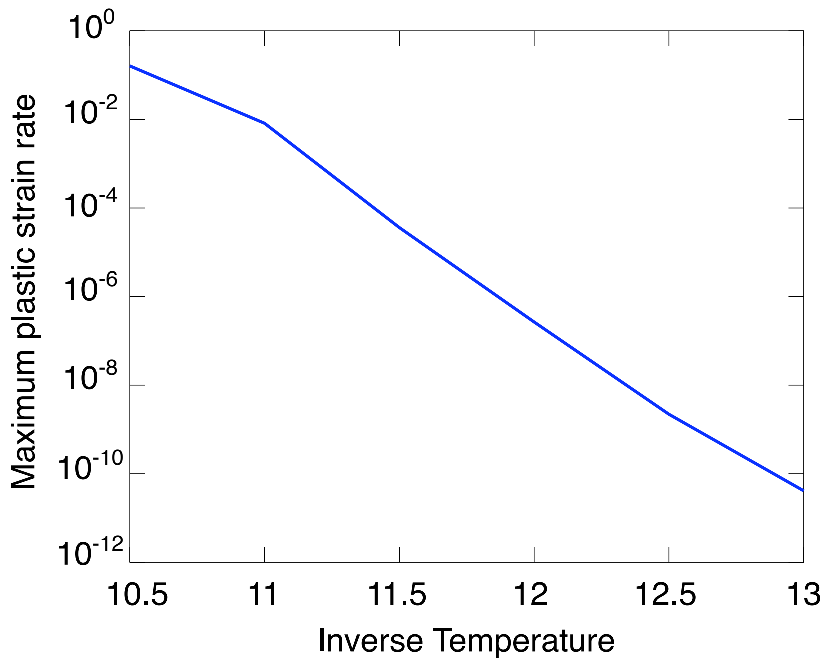
So both thermal and stress effects are important:

$$\dot{\epsilon}_{pl} \propto \exp\left(-\frac{(E-\tau V^*)}{kT}\right)$$

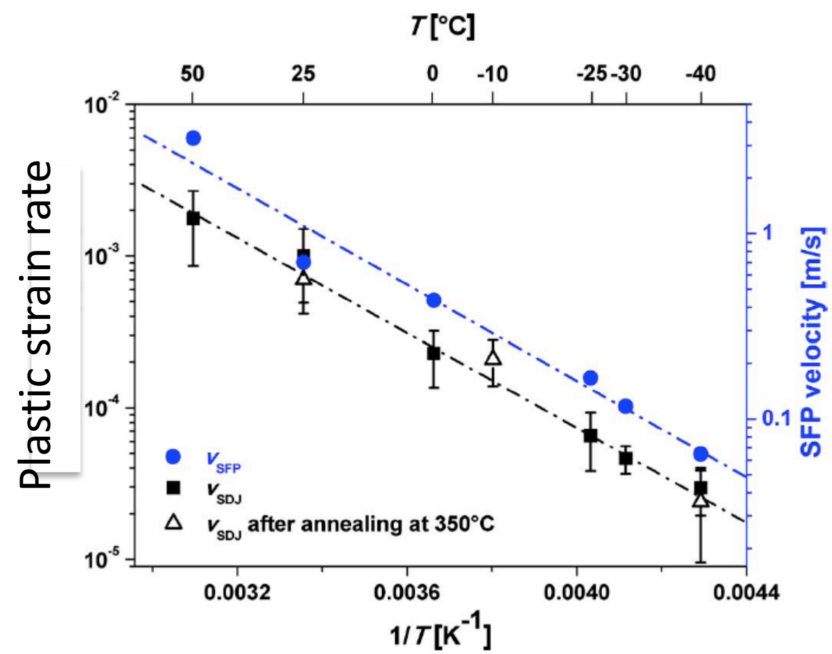
Modeling Plasticity of Metallic Glasses

Simple modeling to study plasticity and stick-slip in metallic glasses:

Model



Experiments



$$\dot{\epsilon}_{pl} \propto \exp\left(-\frac{(E - \tau V^*)}{kT}\right)$$

Now scaling is correct.

Thermal and stress effects both important.

Modeling Plasticity of Metallic Glasses

- Metallic glasses deform plastically in compression tests, exhibit stick-slip
- Experiments at different temperatures constrain how plastic strain depends on temperature and stress
- Further work: explore scaling for other parameters: stress drop, variation with applied strain rate, etc.