“Hunting for Dark Matter”

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The Adventures of the Princess and Mr. Whiffle

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Lake Louise Winter Institute 2019

Roadmap

- Part I: Observational Evidence for Dark Matter
  - Origins to modern era
  - Past, current, and future hints from structure formation

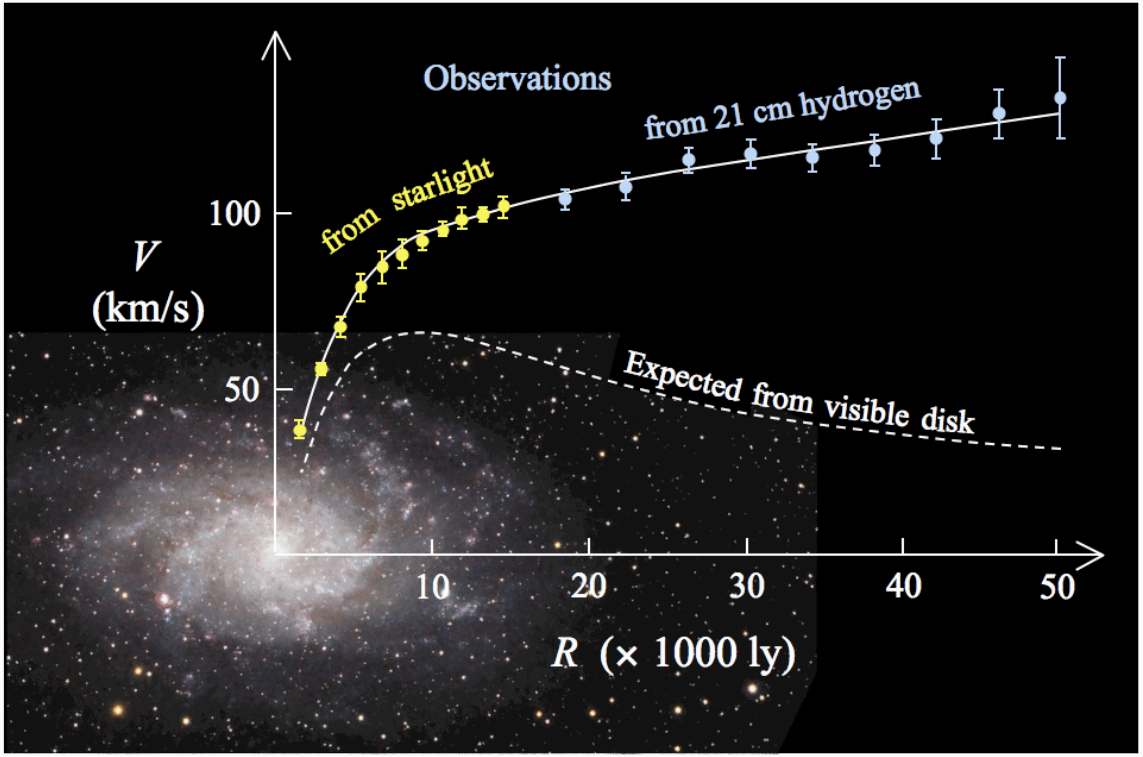
- Part II: Surveying the Dark Matter Field
  - zeV to PeV and everything in between
  - “How does *X* become dark matter, and how can we find it?”

Disclaimers

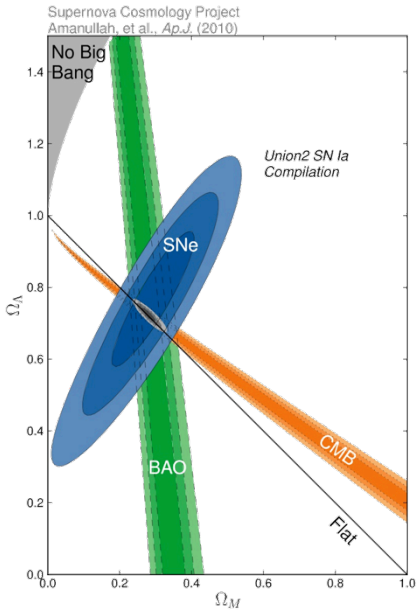
- This survey:
  - is *NOT* exhaustive
  - *is* direct-detection centric
  - probably *won't* mention your experiment (trying to choose examples not otherwise represented at this conference)

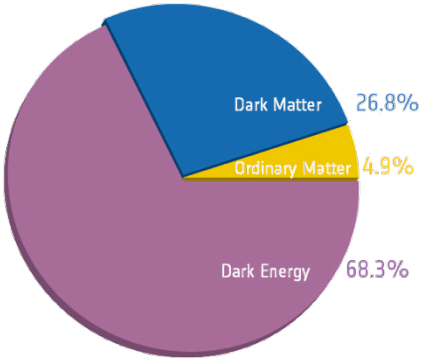
Observational Evidence – Origins (dynamics)

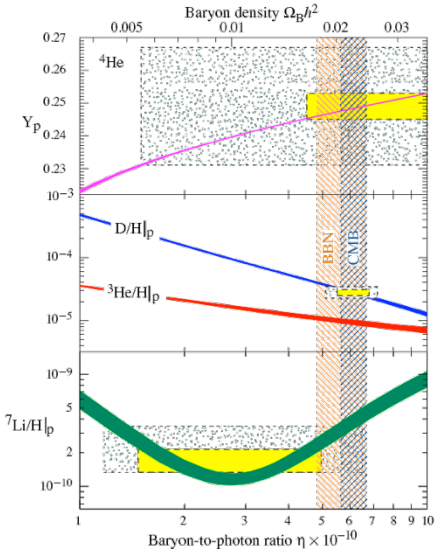
- Fritz Zwicky, 1933
  - Motion of galaxies in Coma Cluster
- Vera Rubin et. al., 1960's
  - Motion of stars, satellites around galaxies

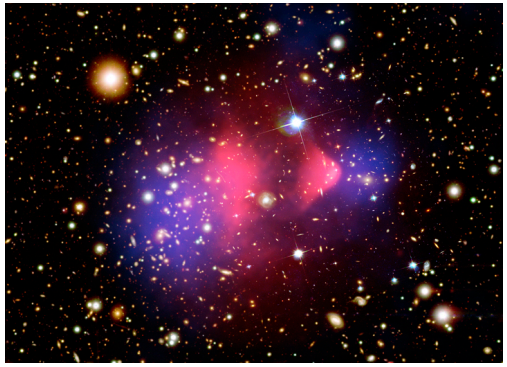


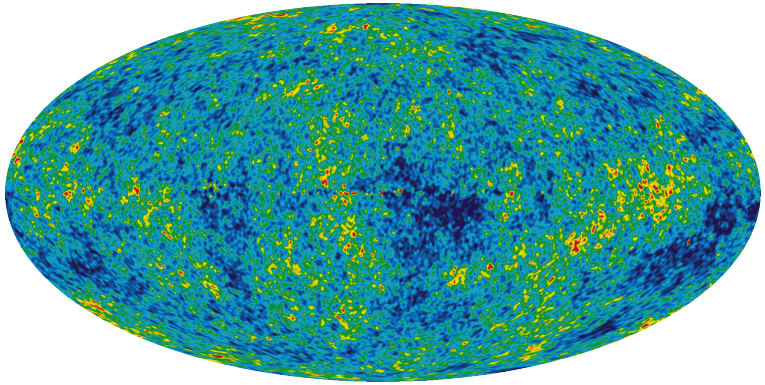
Modern Evidence for Dark Matter

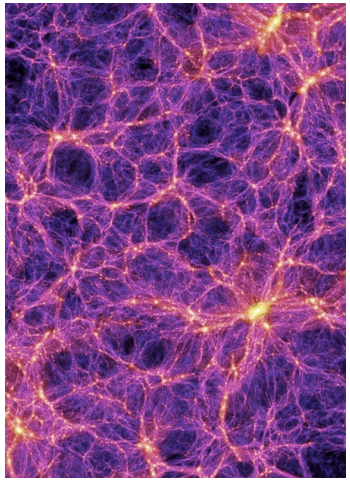




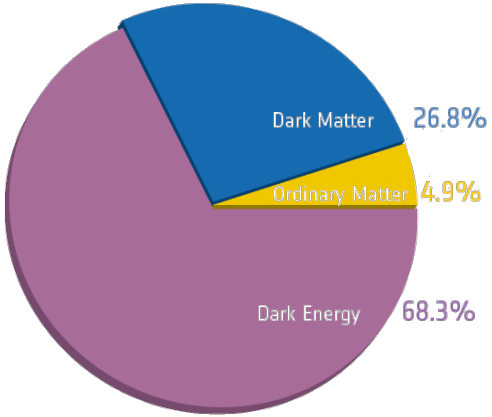


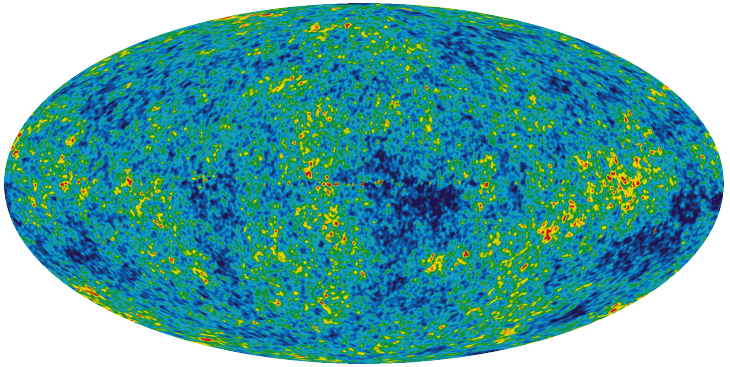


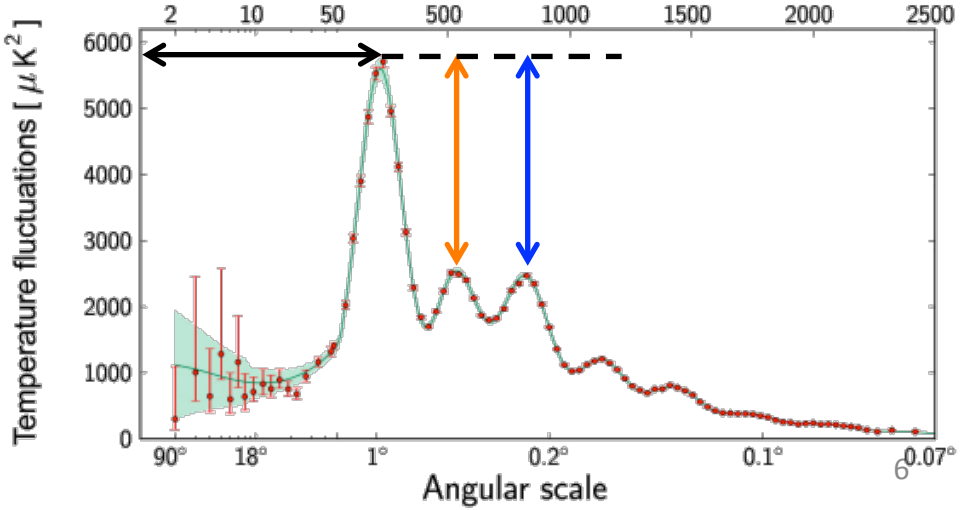




Observational Evidence – CMB

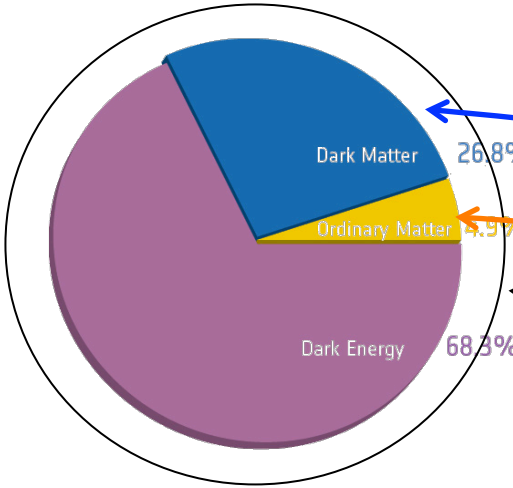


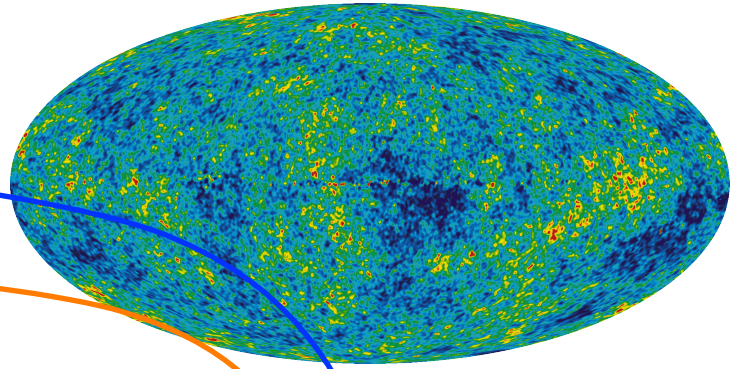


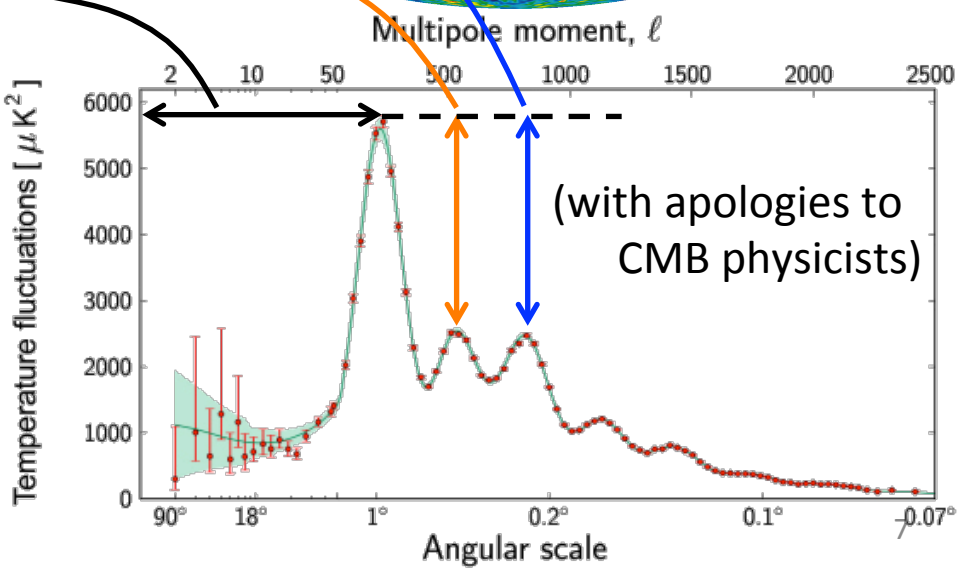


- TT Power Spectrum
  - Snapshot of density variation at surface of last scattering
  - Acoustic oscillations driven by gravity and radiation pressure

Observational Evidence – CMB



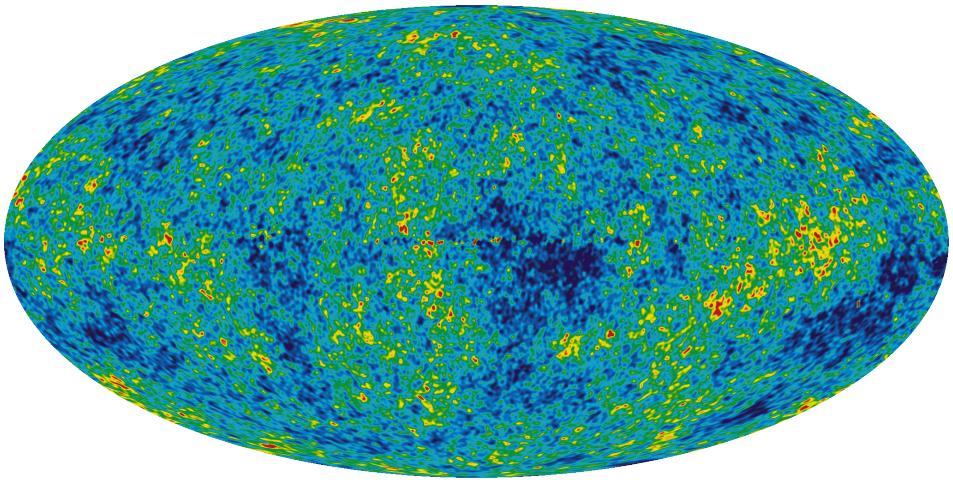


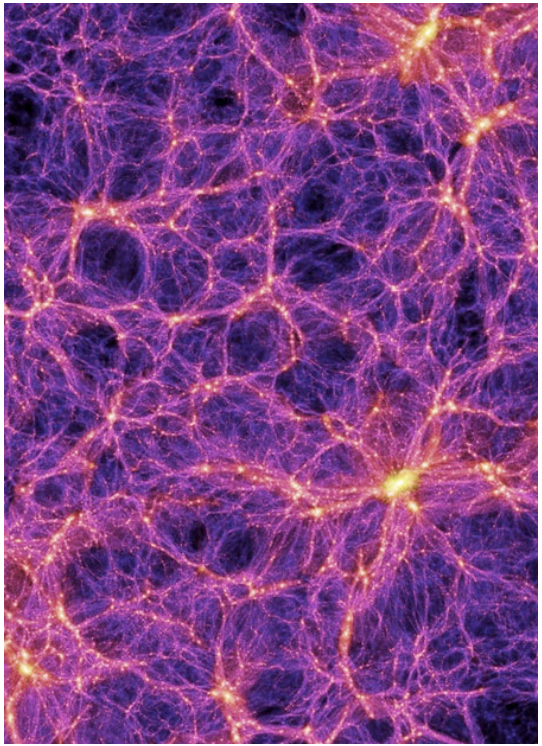


(with apologies to CMB physicists)

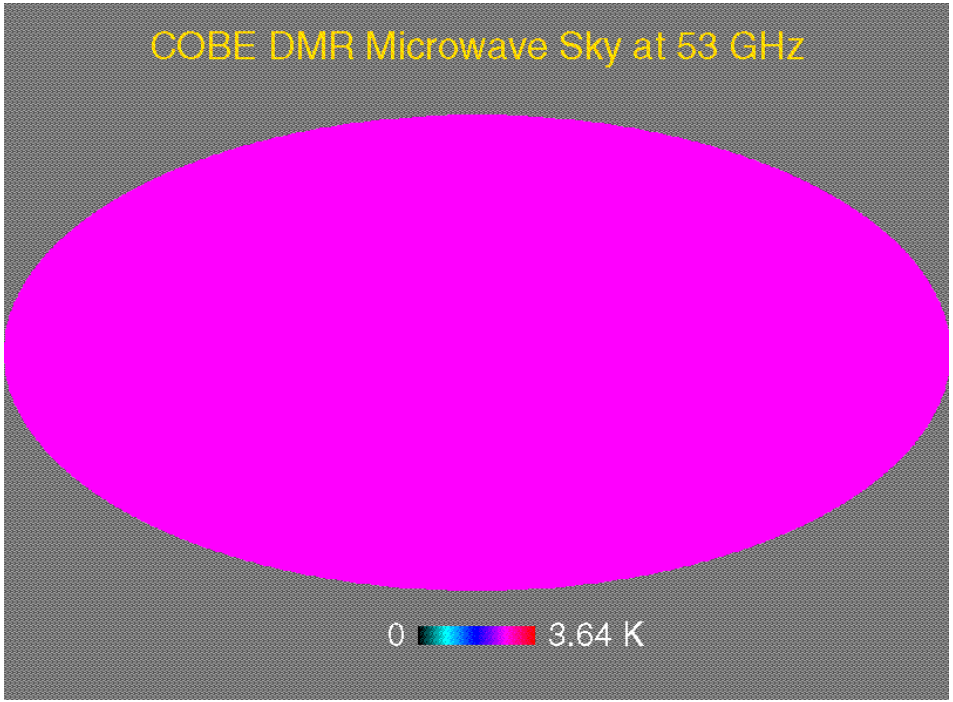
- TT Power Spectrum
  - Acoustic waves driven by gravity (all matter) + radiation pressure (baryonic matter)
  - More info: http://background.uchicago.edu/~whu/

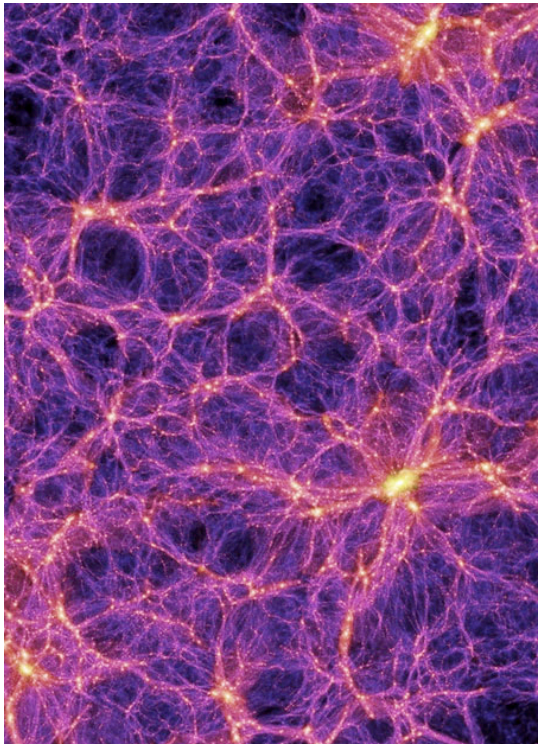
Observational hints: Structure formation





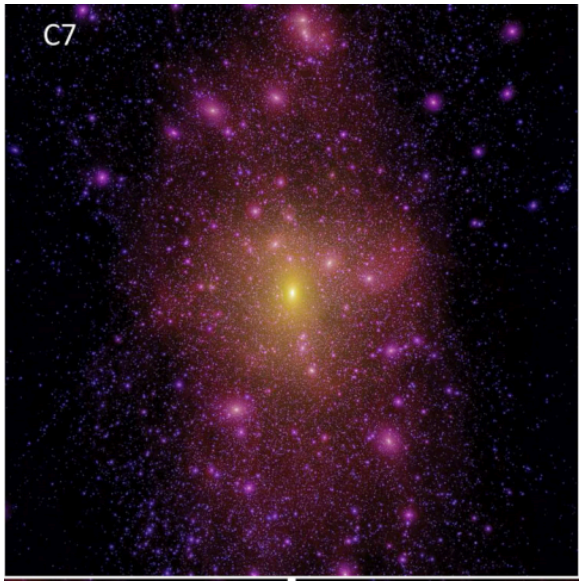
Observational hints: Structure formation





Requires cold dark matter

More hints from structure formation?



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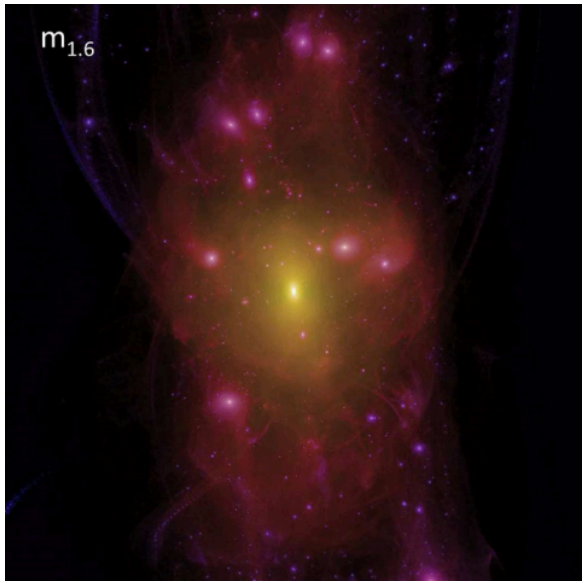
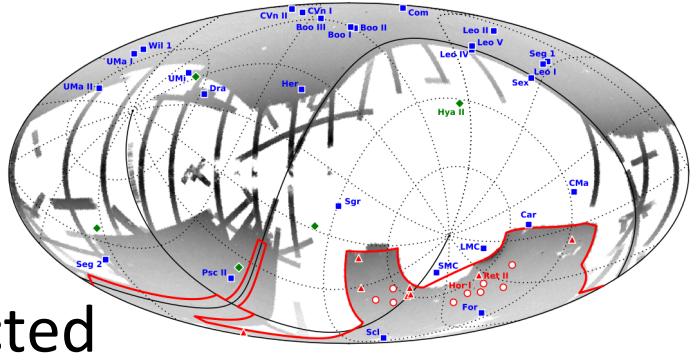


Lovell+ 2014

- Missing Satellites ⟶ Warm Dark matter?

More hints from structure formation?

- Current status:
  - More Milky Way dwarfs found
  - Fewer Milky Way dwarfs predicted
    - Simulations with baryons show “The Milky Way is a lot like the Cookie Monster” −A. Peter https://www.quantamagazine.org/the-problem-of-the-missing-satellite-galaxies-gives-way-now-theres-too-many-20190109/



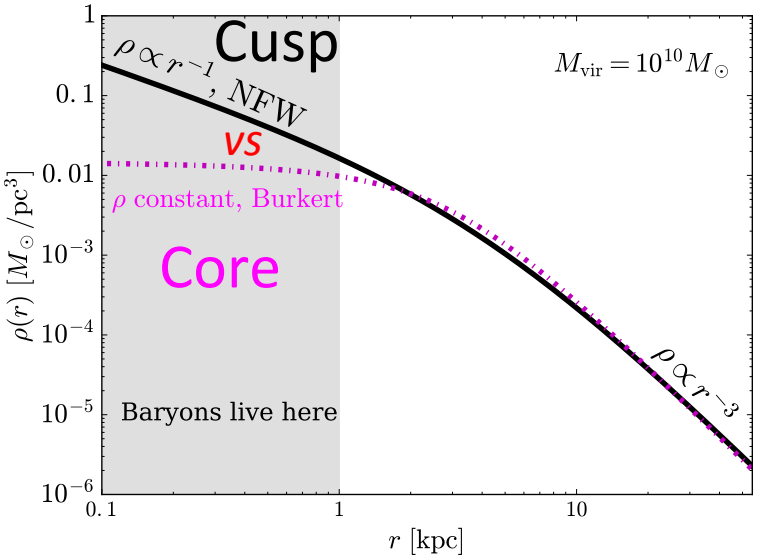
Drlica-Wagner+ 2015 DES

- ~~Missing~~ Satellites ⟶ ~~Warm~~ Dark matter

Too Many

Cold

Future hints from structure formation?



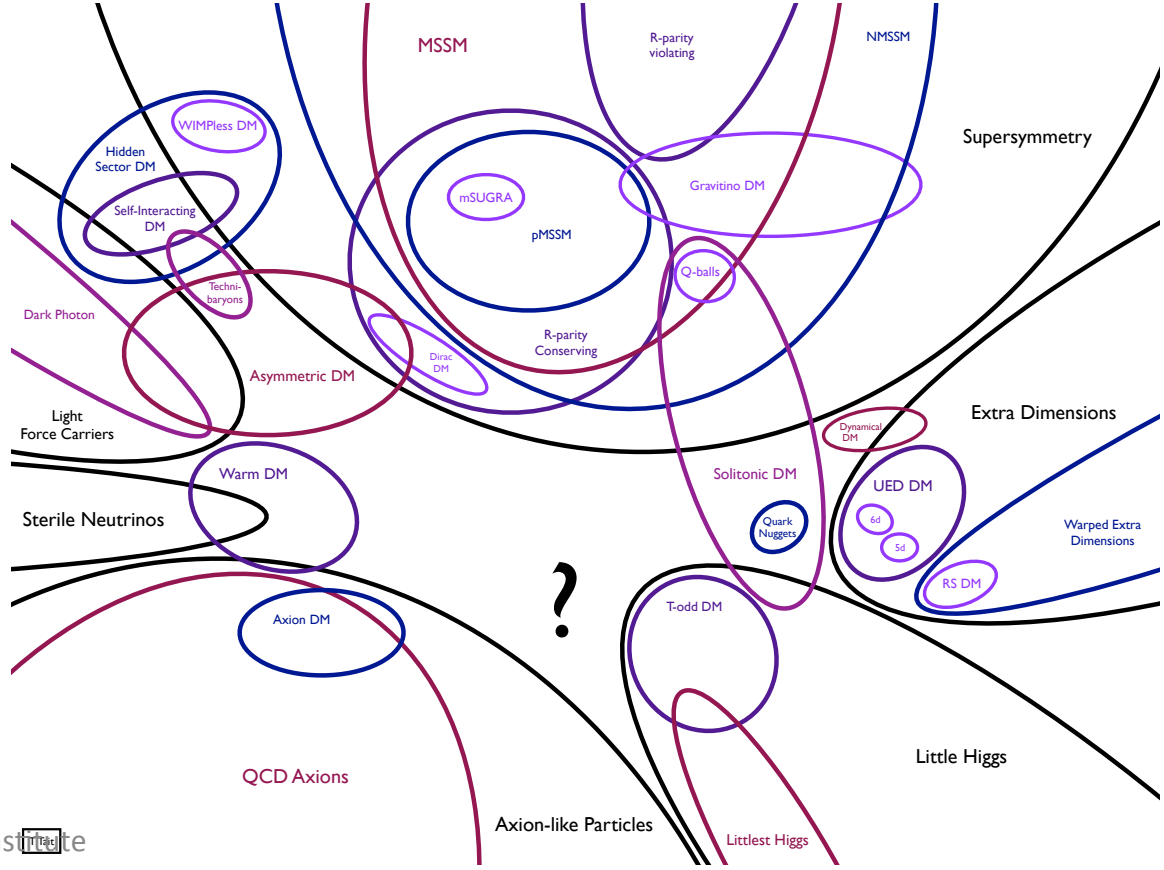
Buckley, Peter 1712.06615

- Observations favor cored halo profiles, DM-only sims produce cusps
- Baryonic or dark matter physics at play?
  - Simulations indicate halo history matters…
- We will learn more from LSST / JWST / WFIRST …

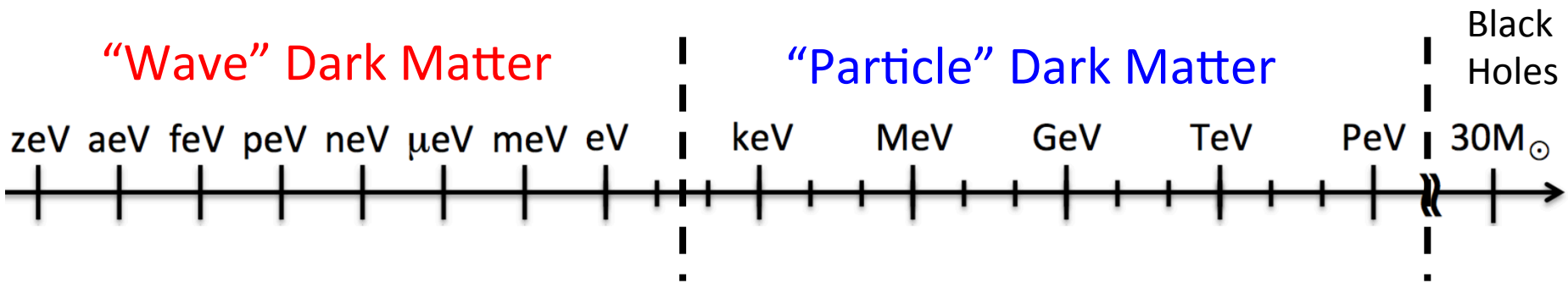
see Drlica-Wagner et al, arXiv:1902.01055

Cold Dark Matter Candidates

Cold Dark Matter Candidates

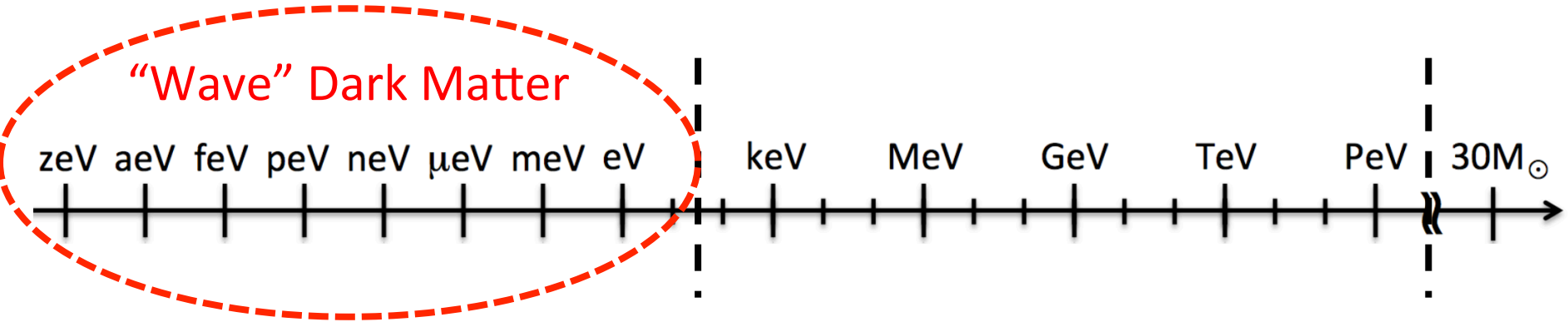


Cold Dark Matter Candidates



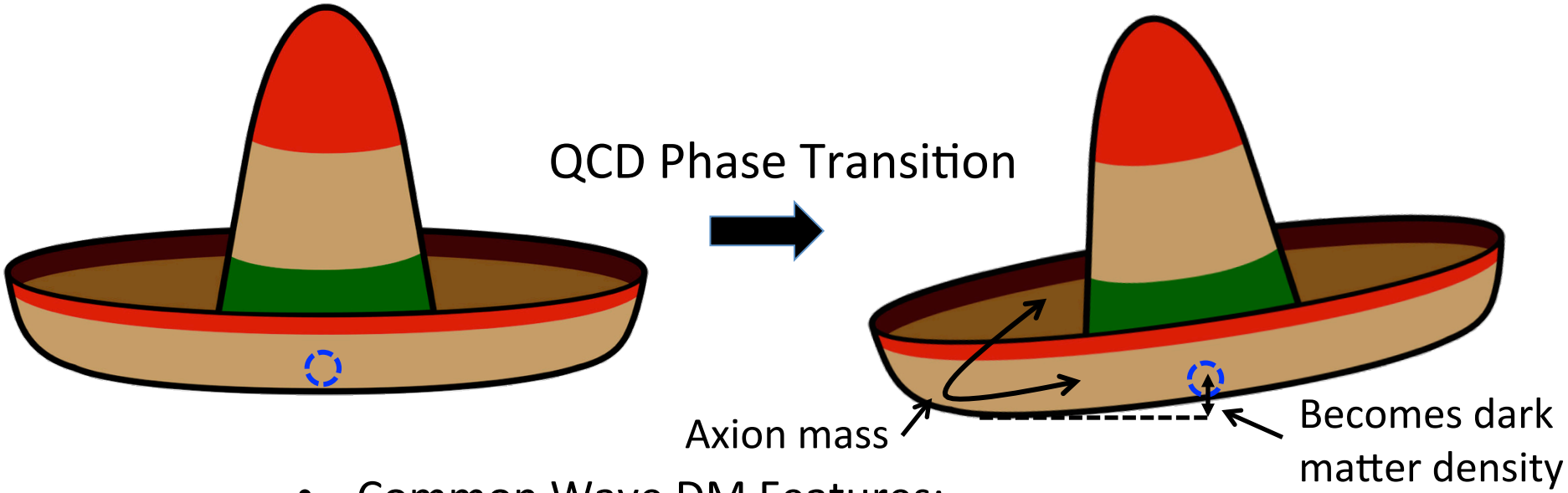
- 3 Questions for each candidate:
  - How does this give the right amount of dark matter?
  - How do we look for this?
  - How do we *discover* this?

Ultralight Dark Matter



- Must be bosonic
  - Can't fit enough fermions in dwarf halos
- Minimum mass of $\sim 10^{-21}$ eV
  - Compton wavelength = halo size
- Must be athermal / weakly coupled
  - Non-relativistic -> colder than SM stuff

Example: QCD Axion



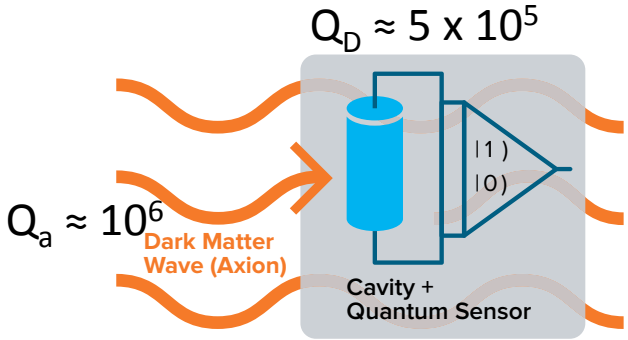
- Common Wave DM Features:
  - Product of some new symmetry
  - Gets mass from phase transition, $O(\mu eV)$ in this case
  - Born cold

“Wave” Dark Matter Detection

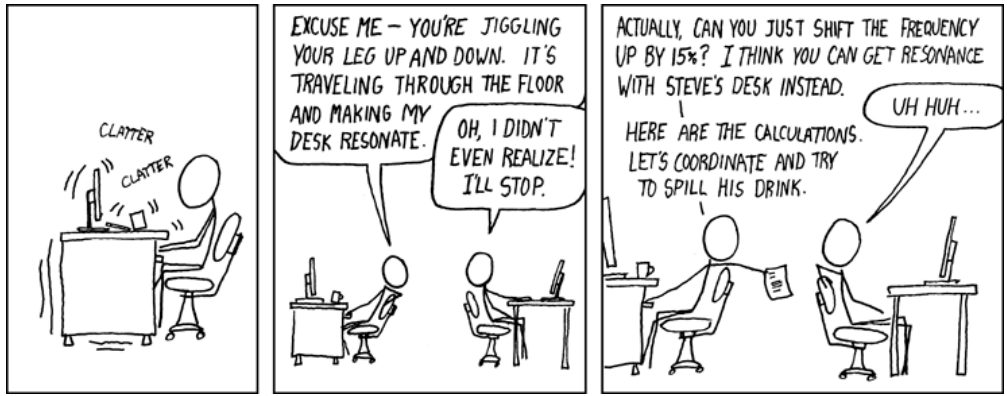
- Occupancy #’s for ultralight DM are high
  - DM behaves like a classical field, oscillating at

$$\omega = \frac{m_a}{\hbar}\left(1 + \frac{v^2}{2}\right)$$

- Resonant detection possible (haloscope)

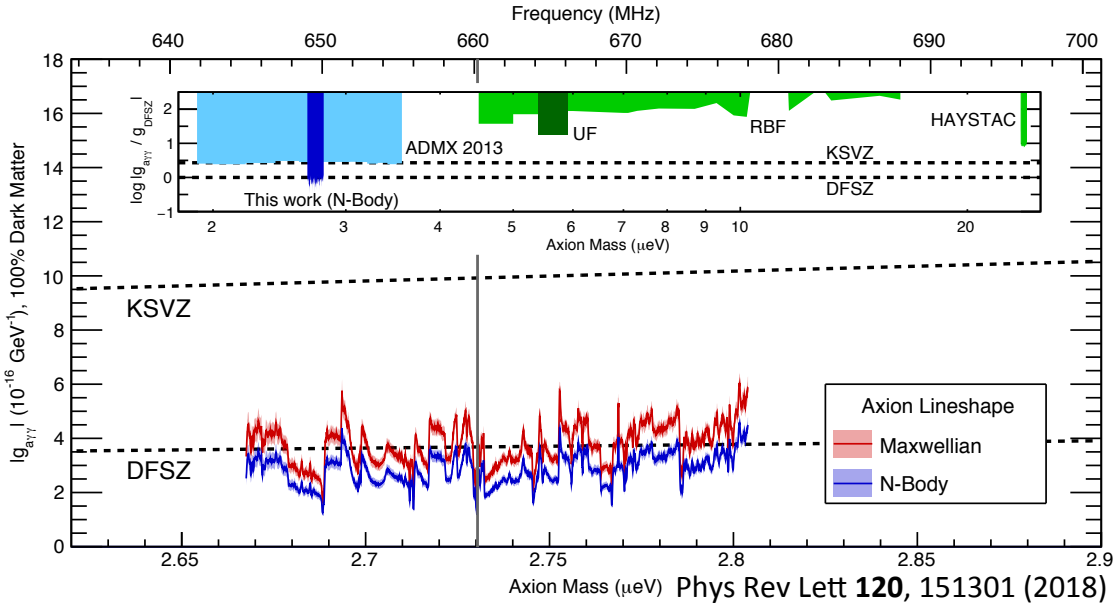


https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_Brochure.pdf



https://xkcd.com/228/, copyright Randall Monroe

ADMX (RF Cavity Search)



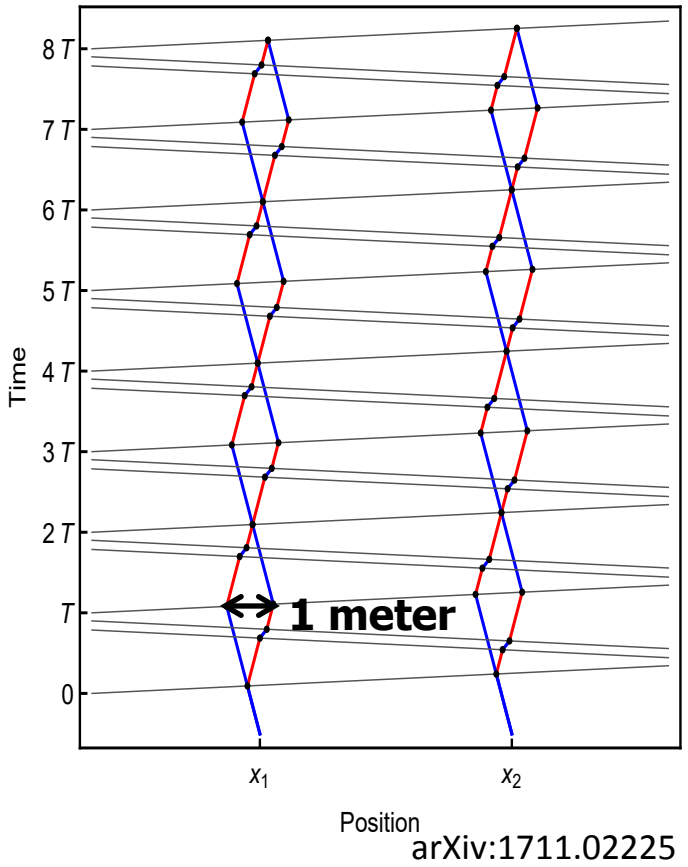
Phys Rev Lett **120**, 151301 (2018)

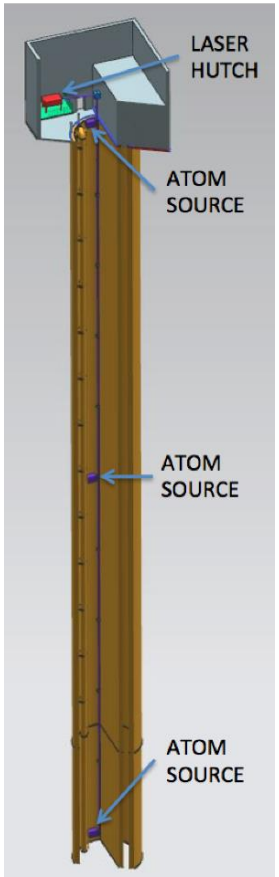
- Similar techniques with LC circuits, NMR, *etc*
- Could discover tomorrow!

  If only we knew the right frequency…

Other searches for ultralight DM…

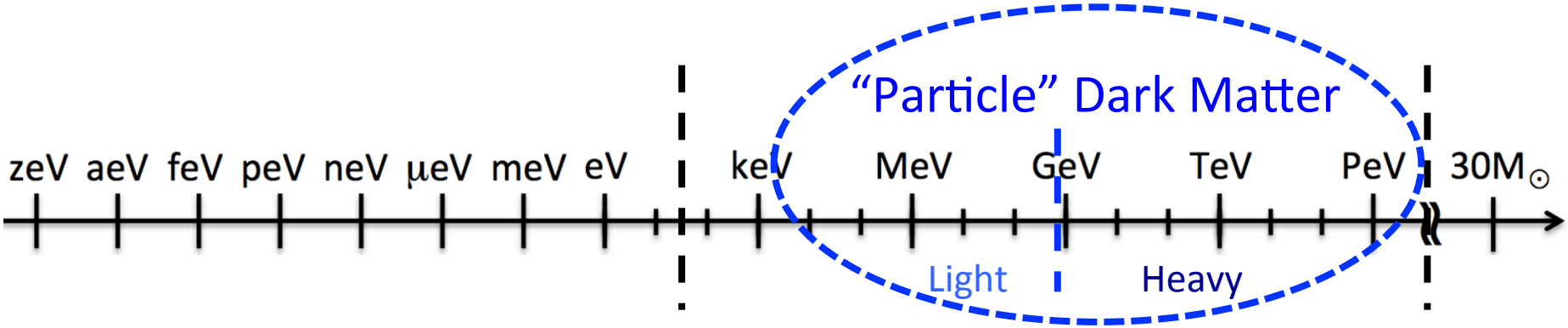
- Precision instruments looking for time-varying signals
  - MAGIS-100: atom interferometer sensitive to ~Hz oscillations (10^{-15} eV dark matter)



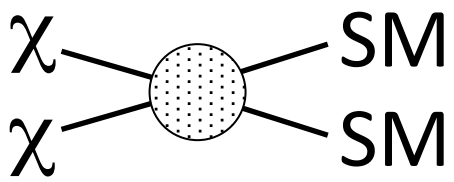


arXiv:1711.02225

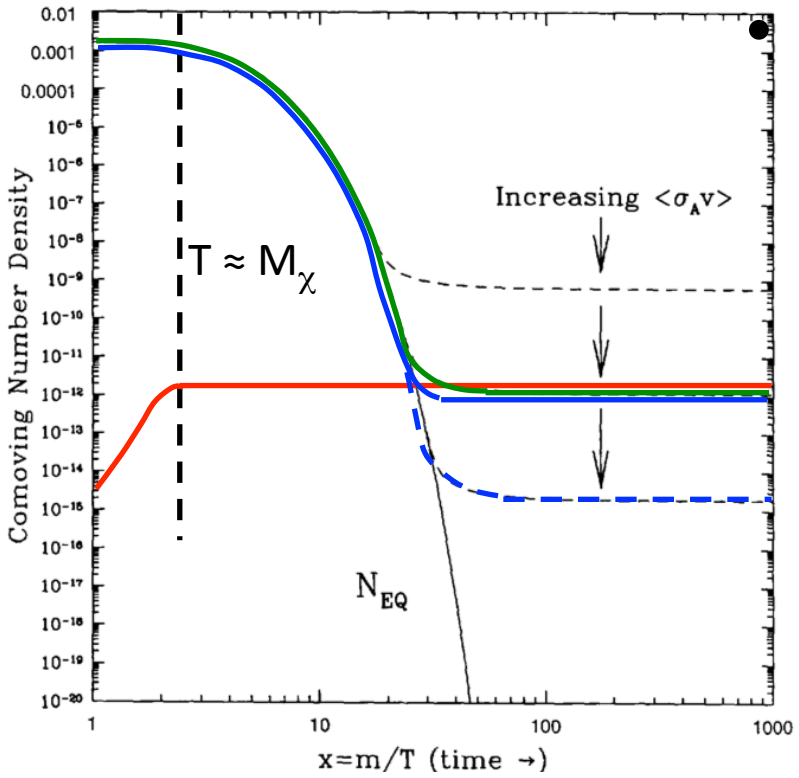
“Particle” Dark Matter



- “Thermal” dark matter candidates
  - Production tied to interactions with SM particles



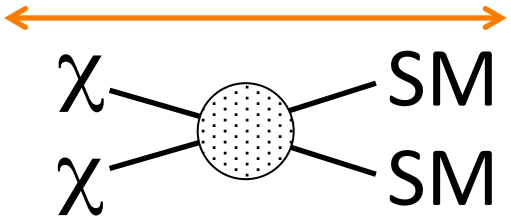
Thermal production of dark matter



Thermal history, three options (there are more):

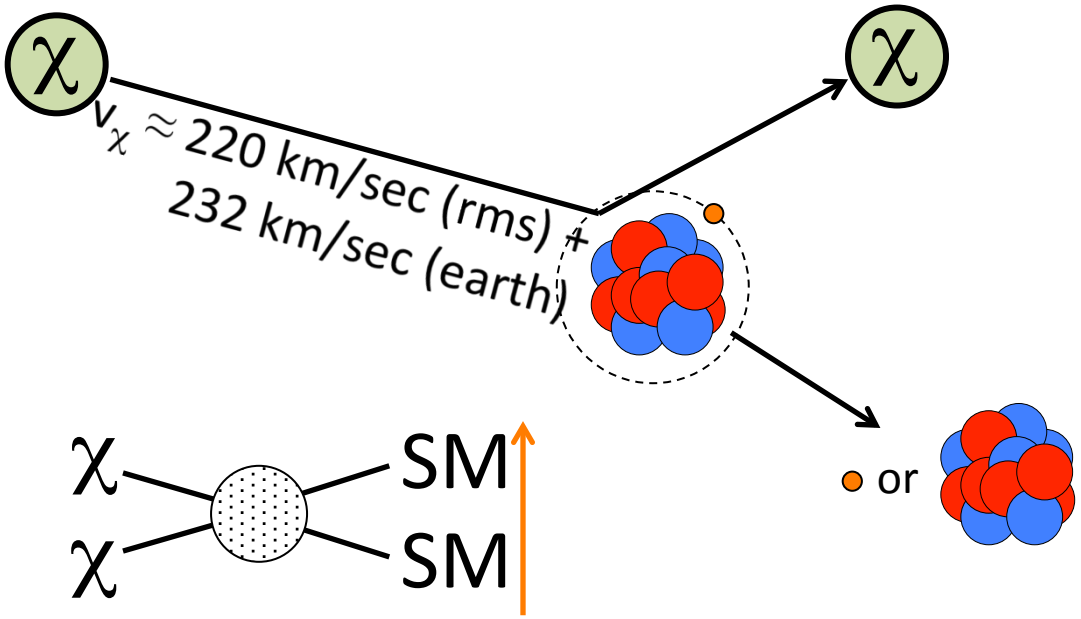
- Freeze-out ($\sigma_{ann} = \sigma_0$)
- Asymmetric ($\sigma_{ann} \geq \sigma_0$)
- Freeze-in ($\sigma_{ann} << \sigma_0$)

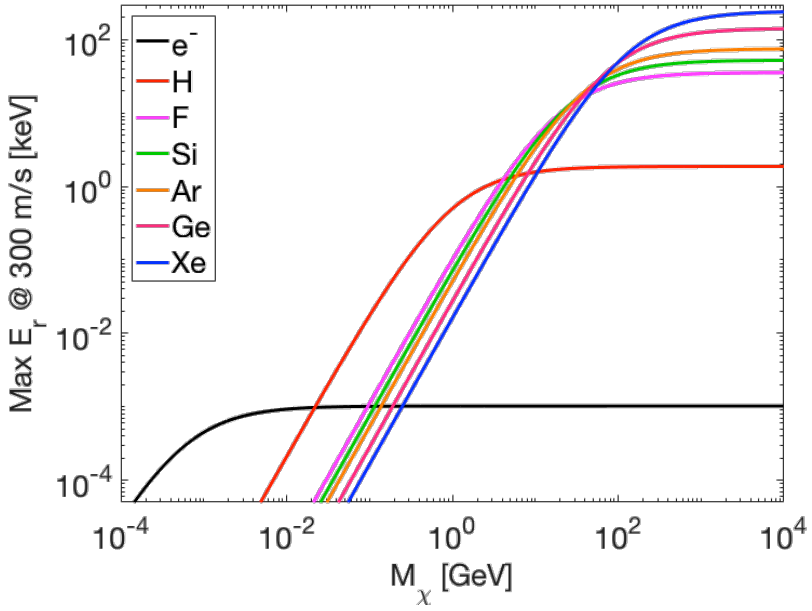
- Common element: some interaction with SM required



Direct Detection of particle DM

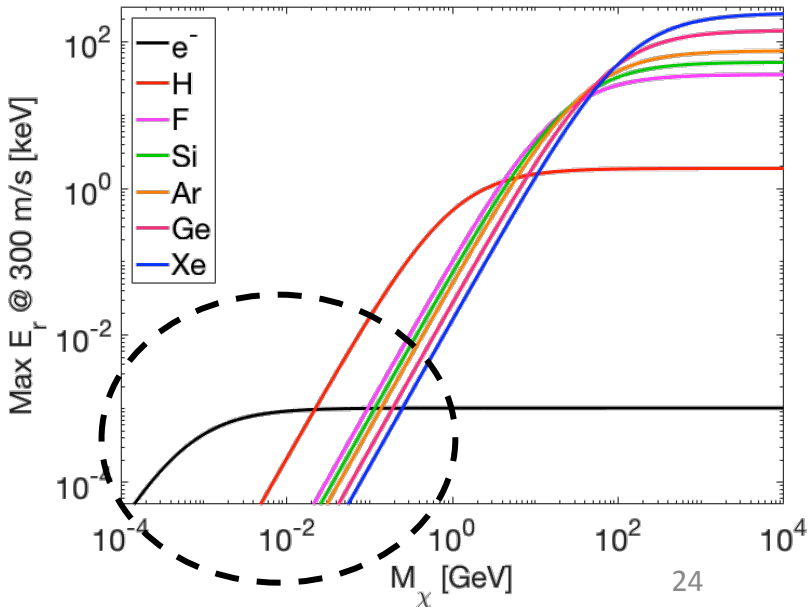
- Elastic Recoils (electron or nuclear)





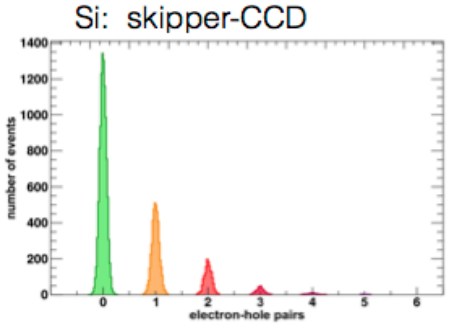
Direct Detection of Light DM

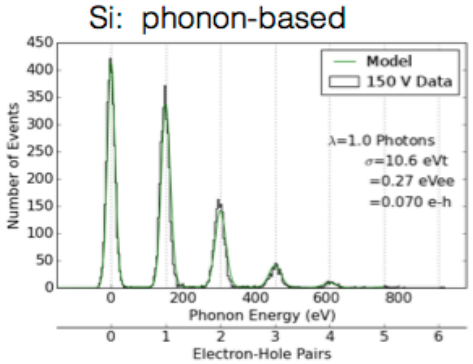
- Challenges:
  - Threshold! (~eV energy depositions, single- or few-quanta measurement)
  - Dark count rate
- Less of a challenge
  - Exposure (g to kg enough)
  - Radioactive backgrounds



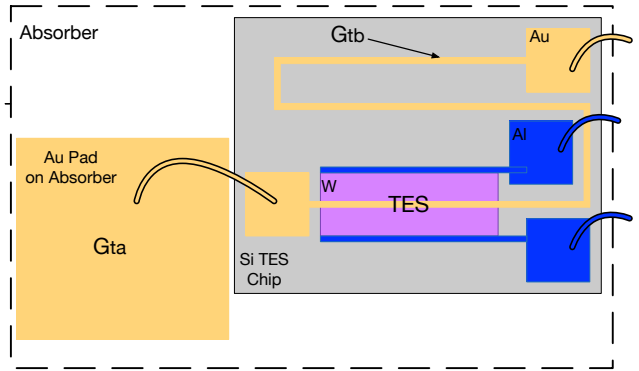
Advancing Technologies for light DM

- eV Thresholds:
  - Silicon ionization:





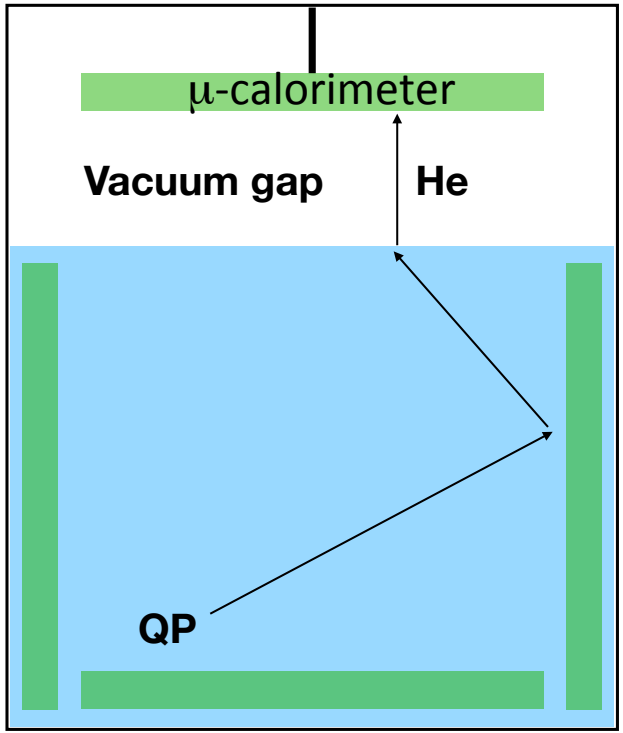
  - TES-based micro-calorimeters:



arXiv:1503.01200

Advancing Technologies for light DM

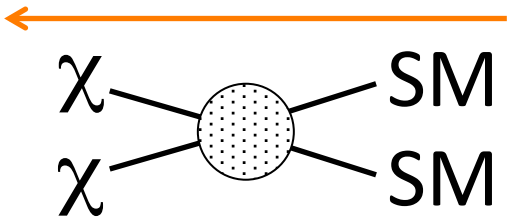
- meV Thresholds:
  - DM scatter produces quasi-particles (rotons) in superfluid ^{4}He
    - QP -> Quantum evaporation at liquid surface
    - He adheres to micro-calorimeter

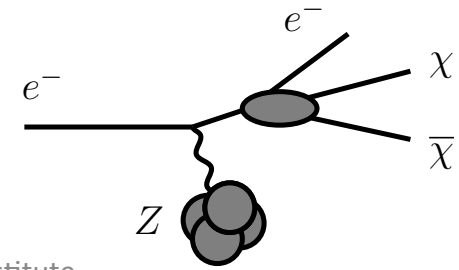


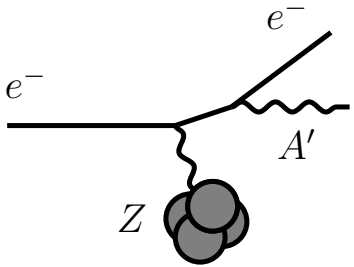
Hertel, McKinsey, Pinckney

Light DM at Accelerators

- Sub-GeV DM accessible in fixed-target missing-momentum experiments
  - Advantage: directly sensitive to creation/annihilation cross section, Can reach freeze-out goalpost







LDMX: arXiv:1808.05219

Heavy DM Motivation

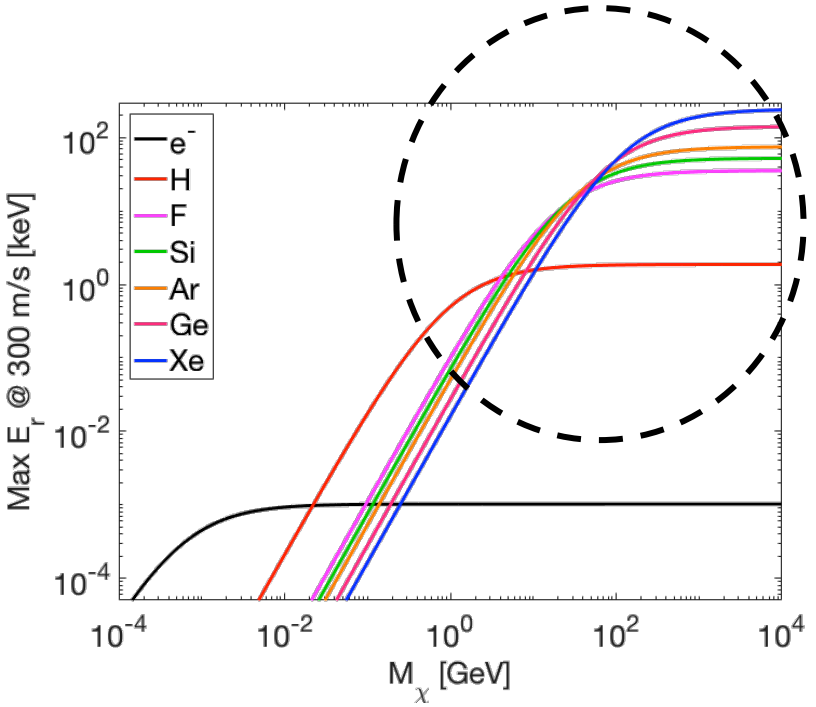
- Still considered (by me) the best-motivated candidates
  - Asymmetric DM: If same asymmetry as in light-sector, expect similar number density

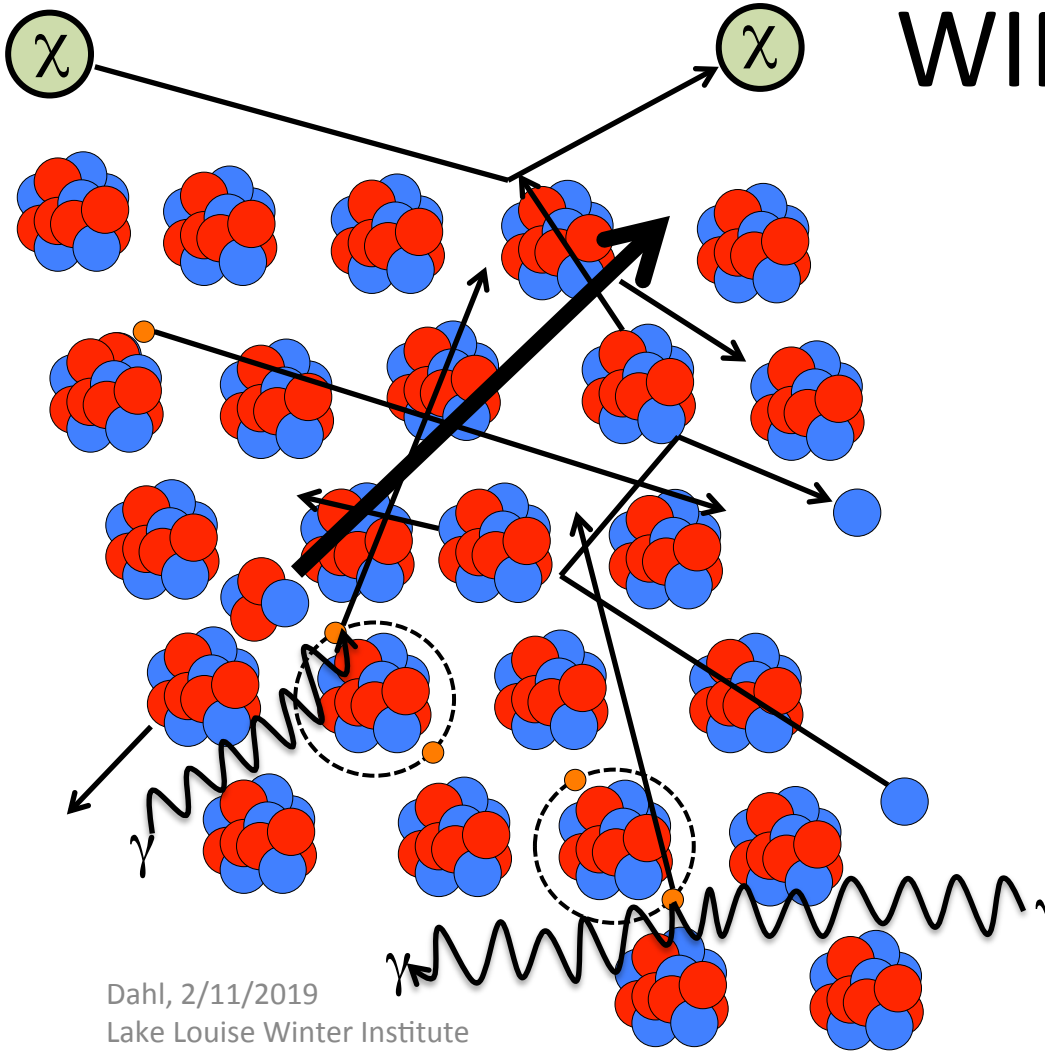
    $M_\chi \approx 5$ GeV
  - Freeze-out DM: A new stable particle in electroweak physics can't *not* be dark matter (WIMP Miracle)

    $M_\chi \approx 10$ GeV − 100 TeV

Direct Detection of Heavy DM

- Challenges:
  - Exposure: ton-years+
    - Because we've made progress over the last 30 years
  - Thresholds: 0.1 – 10 keV
  - Backgrounds:
    - Typical goal for WIMP search < 1 background event per year



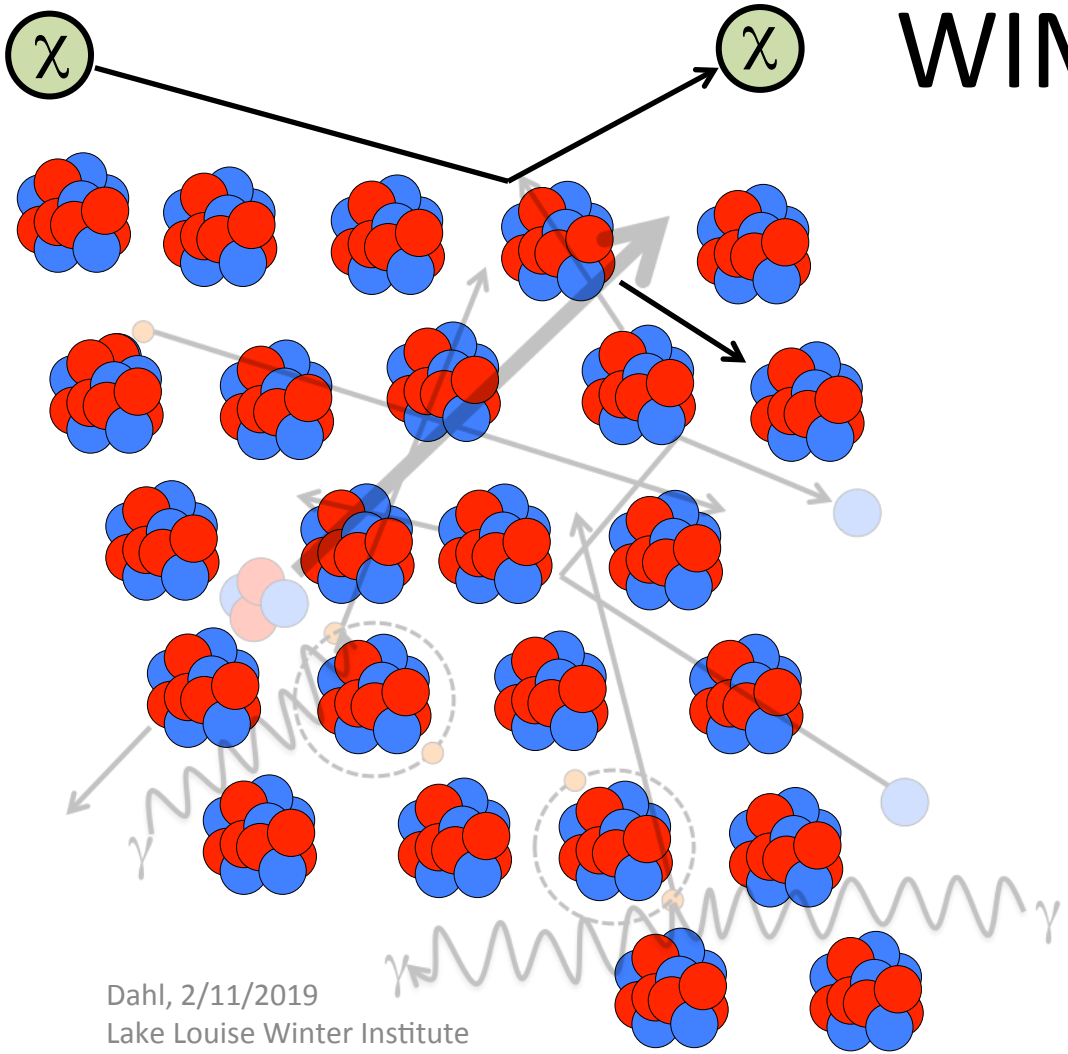


WIMP Backgrounds

Basic low-background practices are *necessary* …

- Go underground
- Shield external gammas and neutrons
- Screen and purify detector elements

… but not *sufficient*



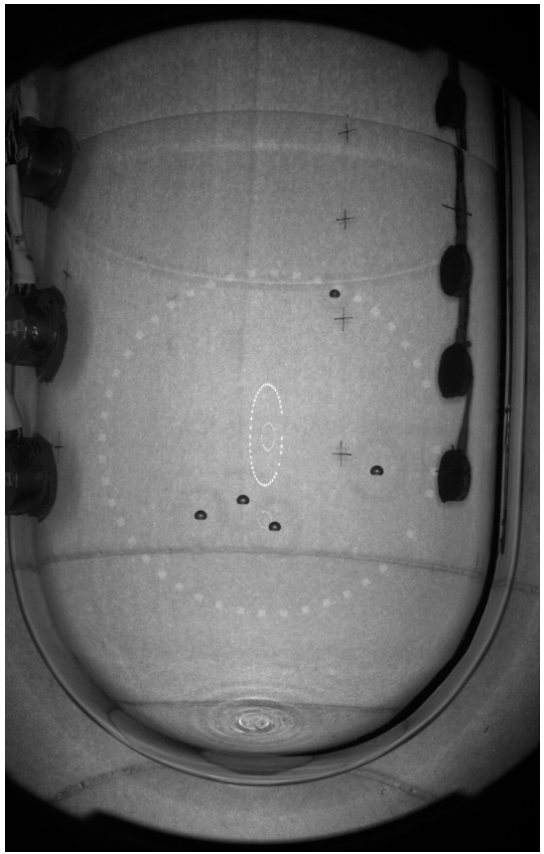
WIMP Backgrounds

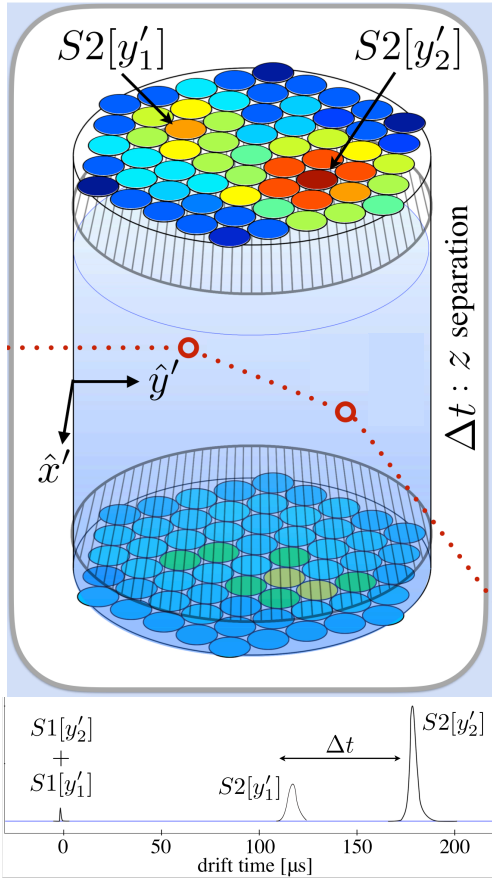
Must be able to *discriminate* against all of these backgrounds…

…as well as against backgrounds we haven't run into yet…

Background Rejection Technique #1: Multiple Scattering

- Mean free paths
  - neutrons: *O*(10)cm
  - gammas: *O*(10)cm
  - WIMPS: ≥*O*(10^{16})cm
- Not limited to XYZ recon
  - segmented detectors
  - external vetoes
- *Only way* to discriminate against neutron backgrounds





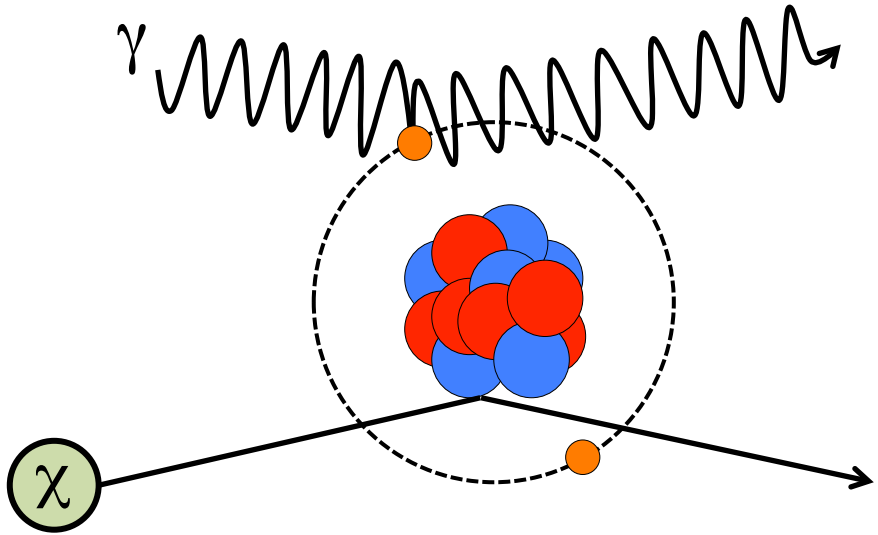
Background Rejection Technique #2 Energy Reconstruction

WIMP recoil	0 – *O*(0.1 – 10) keV, falling
Beta-decay	0 – *O*(100) keV, approx flat
Compton scatters	0 – *O*(100) keV, approx flat
Neutron scatters	0 – *O*(10) keV (depending on target nucleus), falling
Alpha-decay	**4 – 8 MeV, mono-energetic lines**

- Not particularly useful for most WIMP backgrounds…
- But *only way* to identify alpha-decays

Background Rejection Technique #3
Electrons vs nuclei

- Electron recoils:
  - Compton Scatters
  - Beta-decays
  - $\nu e \rightarrow \nu e$ (solar ν's)
- Nuclear recoils:
  - WIMPs
  - Neutrons
  - Alpha-decays
  - $\nu N \rightarrow \nu N$ (solar and atmospheric ν's)



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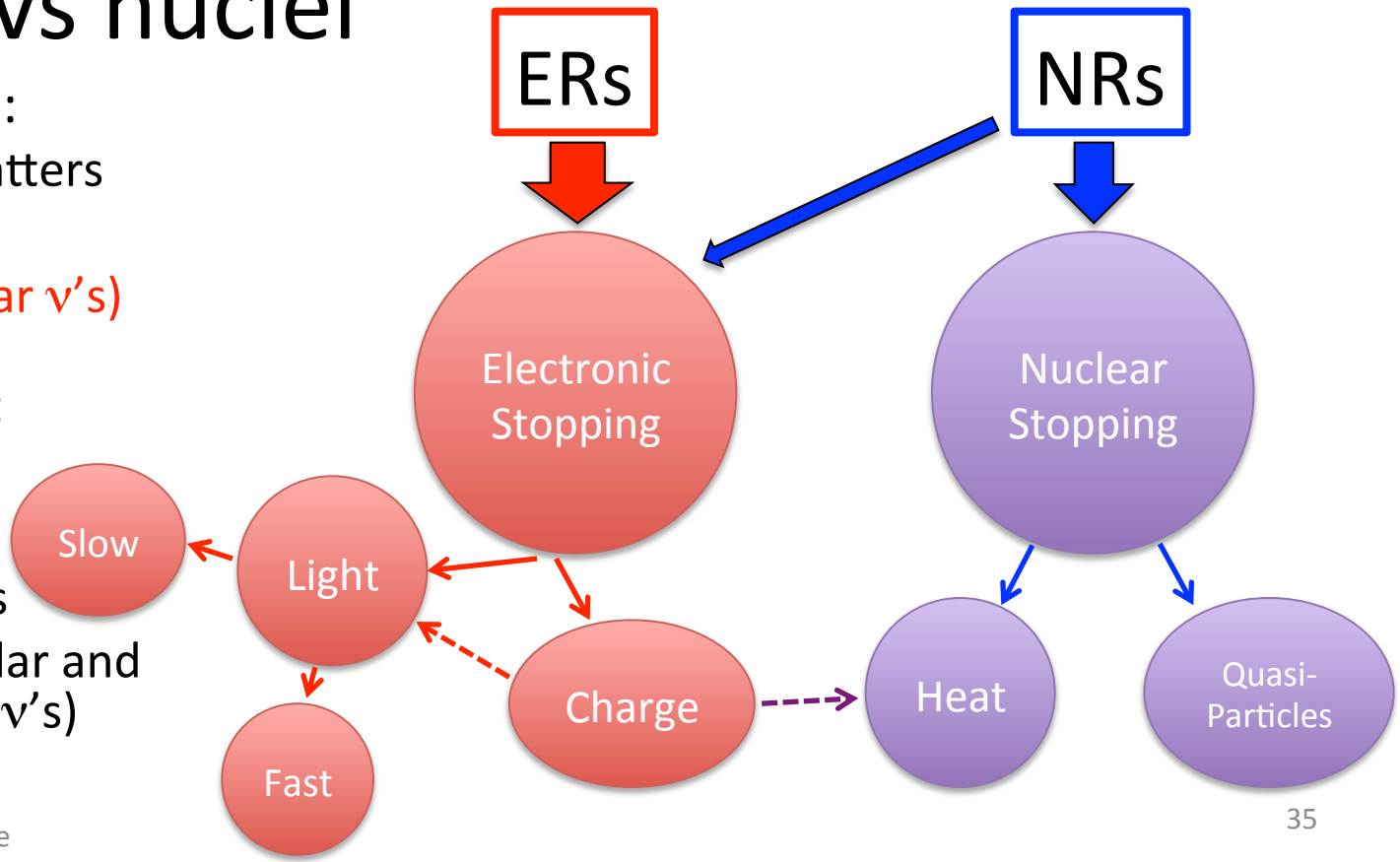
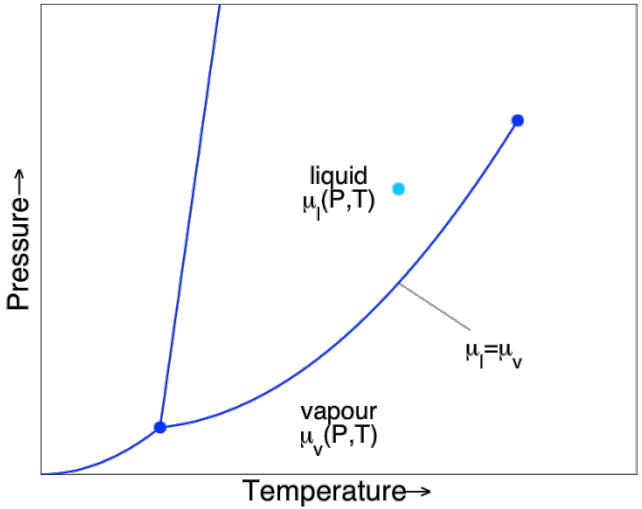
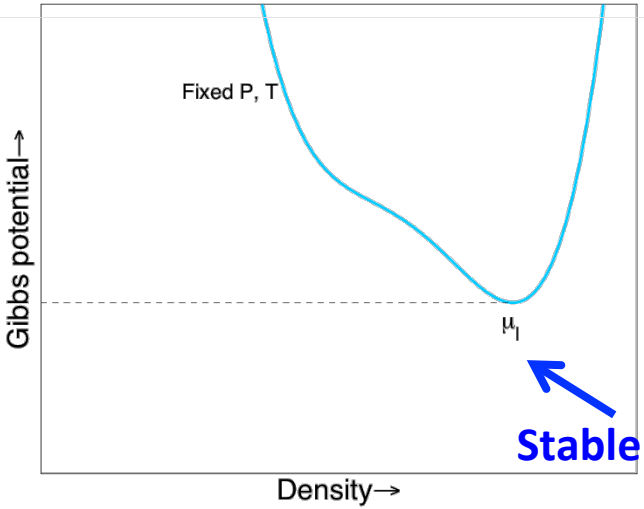
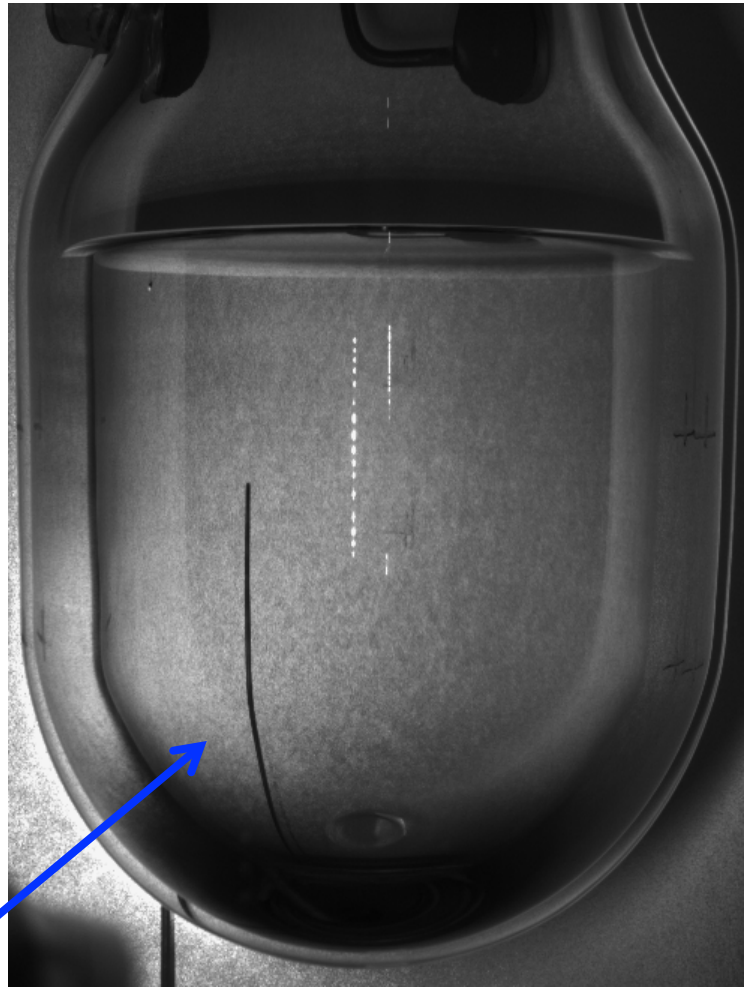


Scintillating Bubble Chamber







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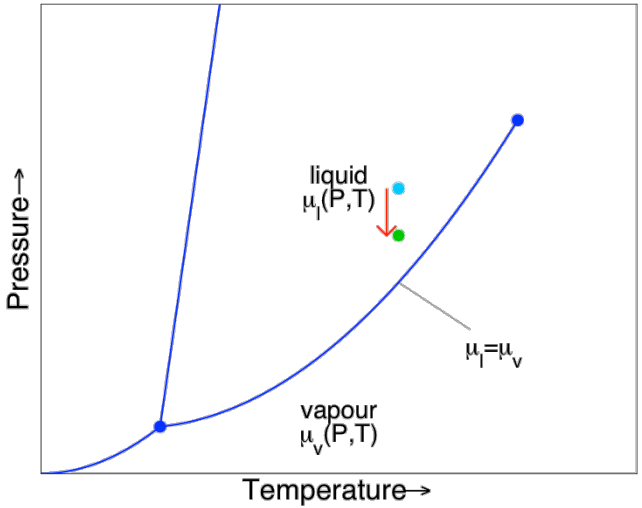

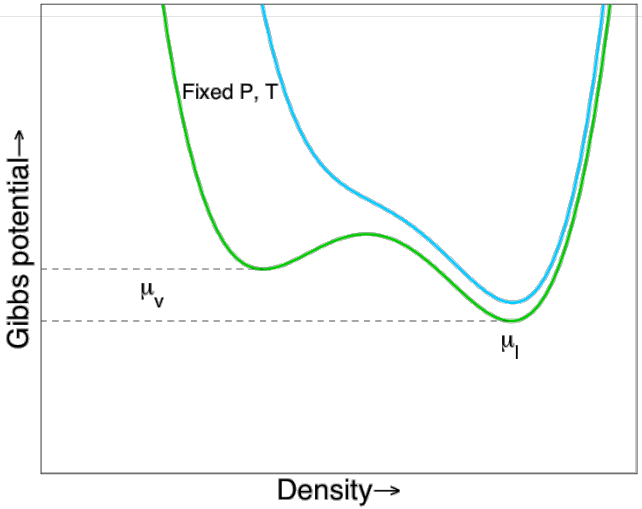

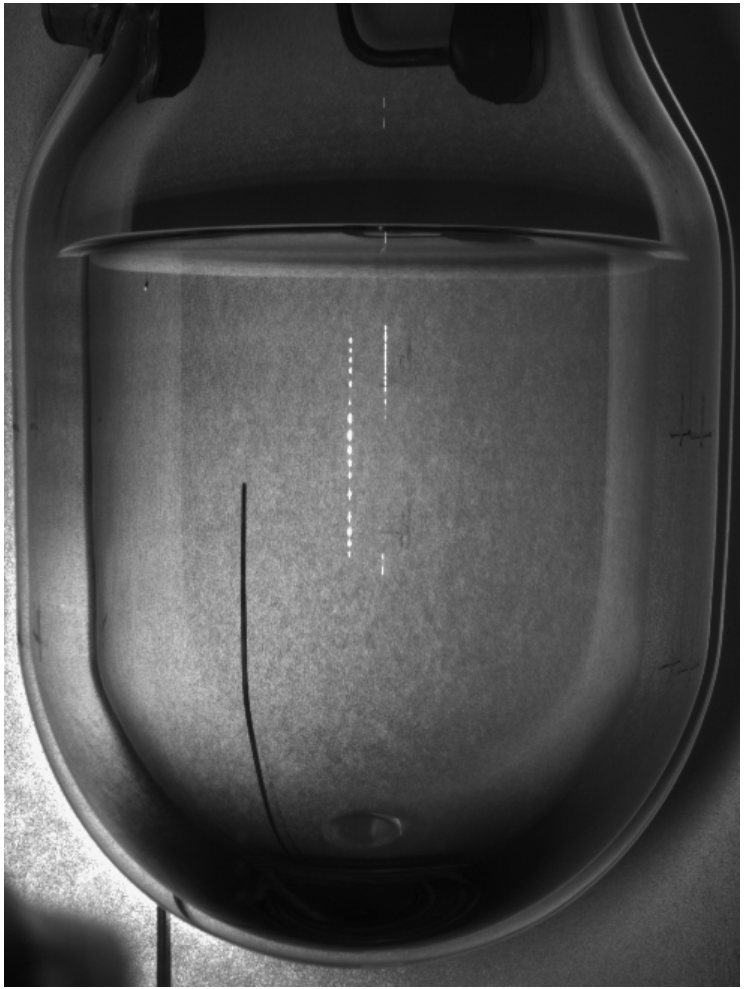

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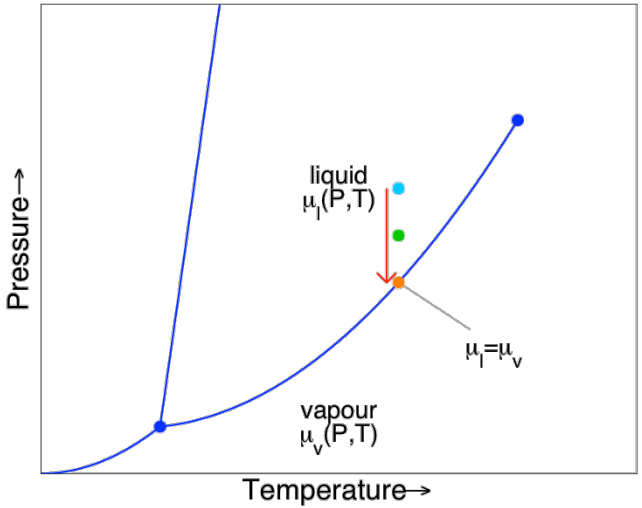

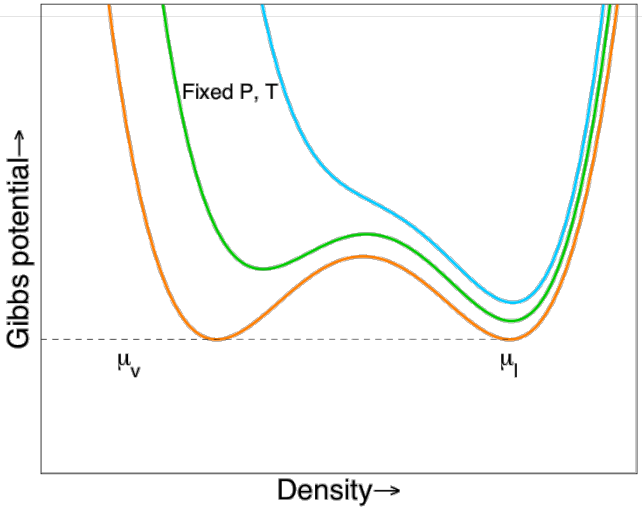

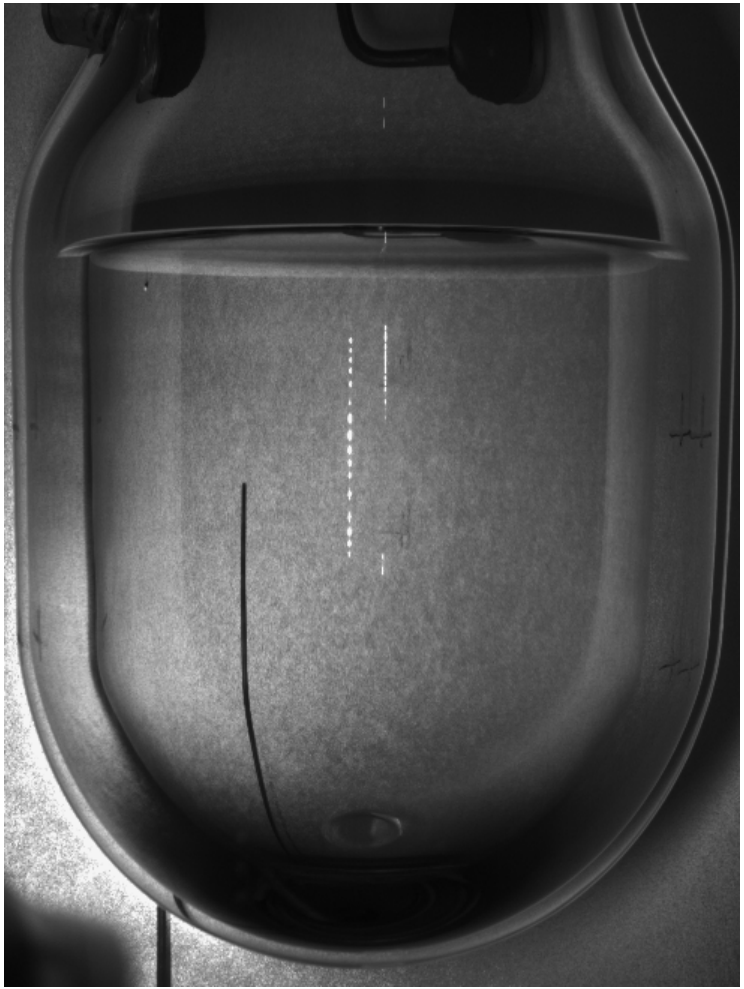

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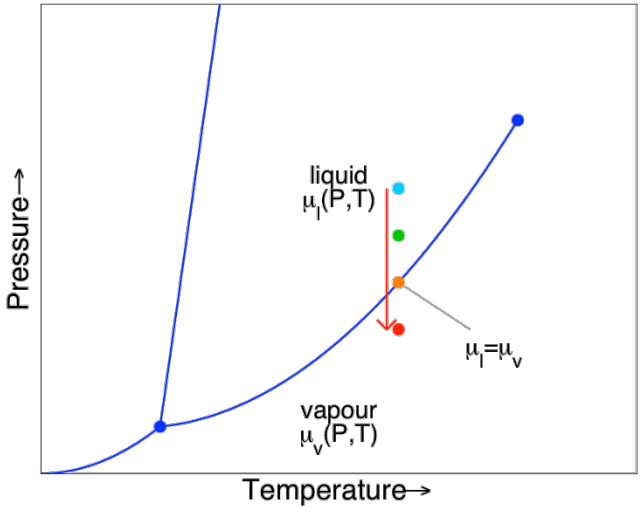

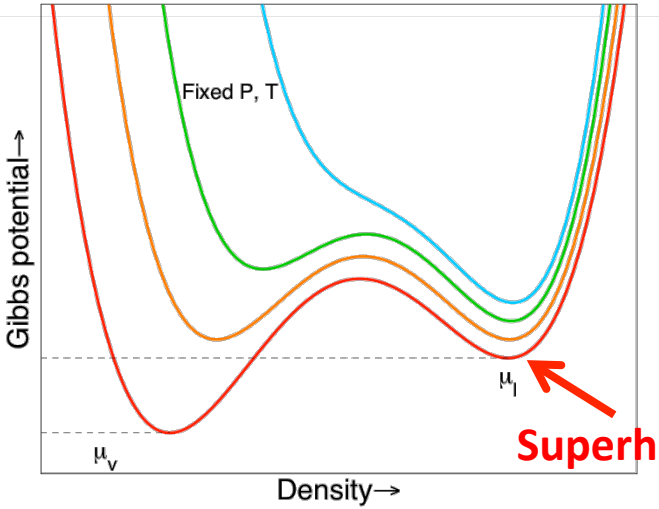

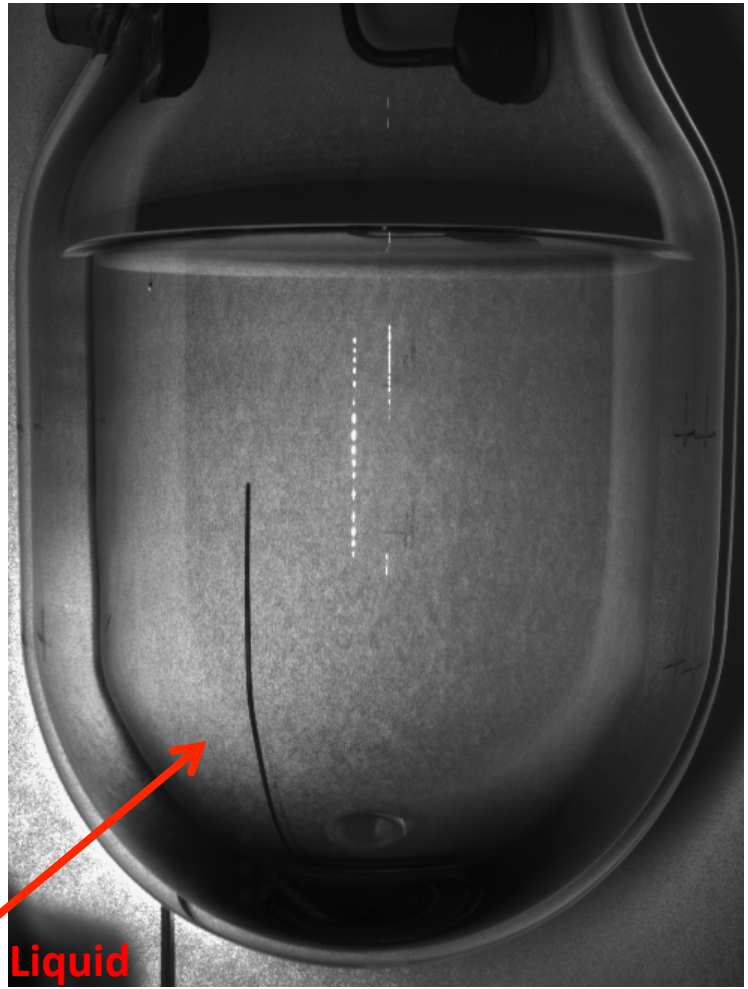

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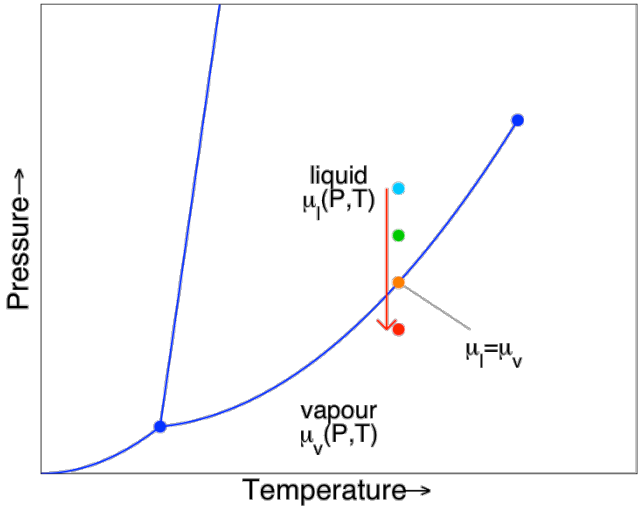

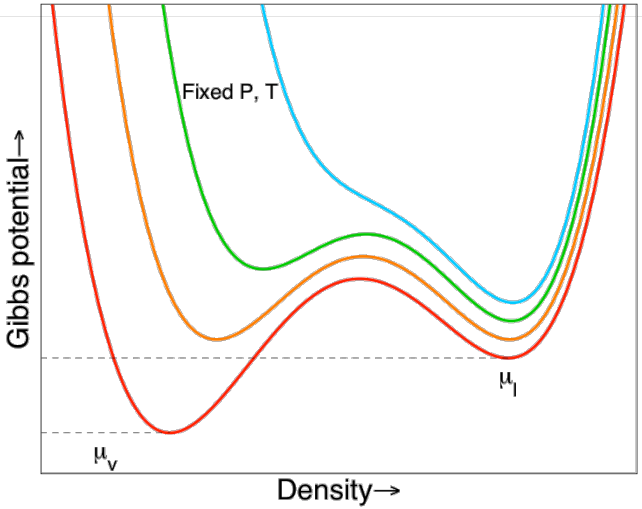

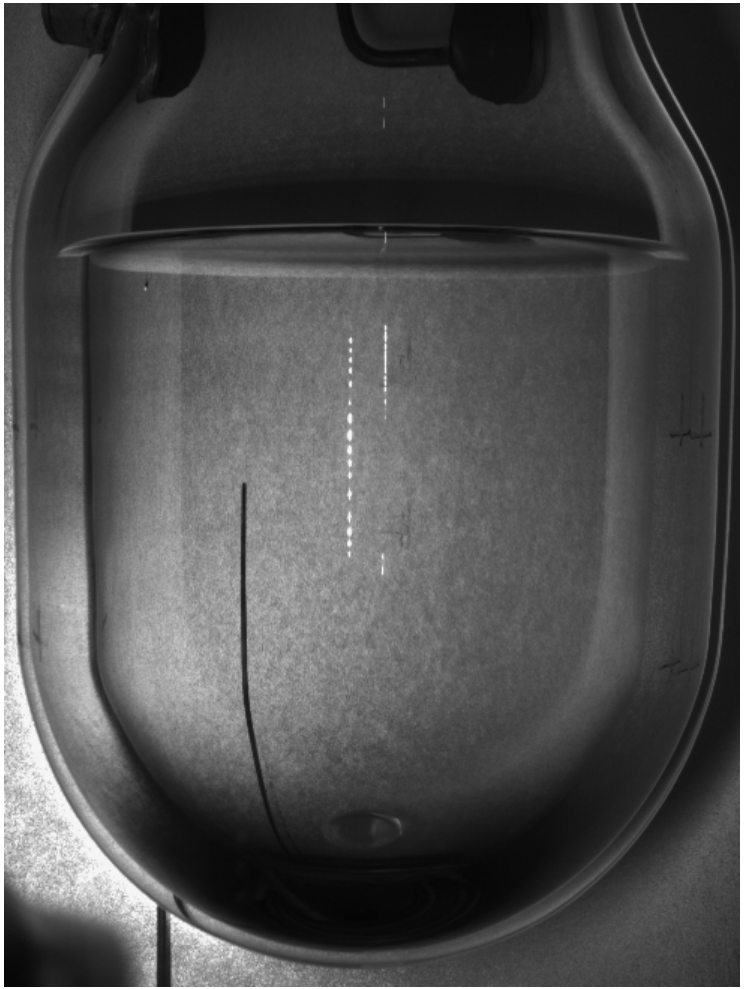

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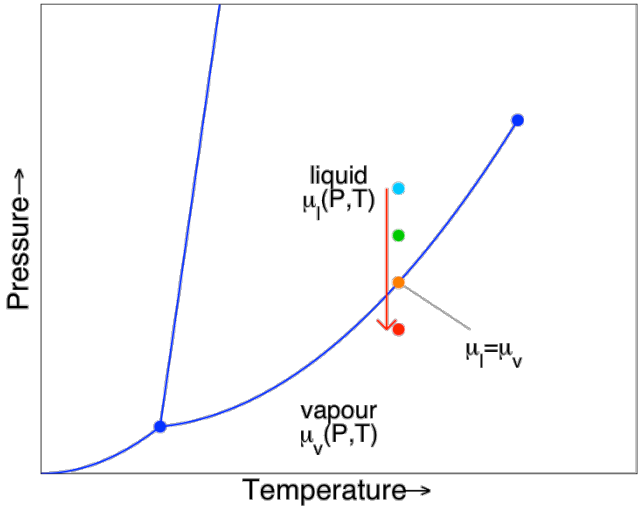

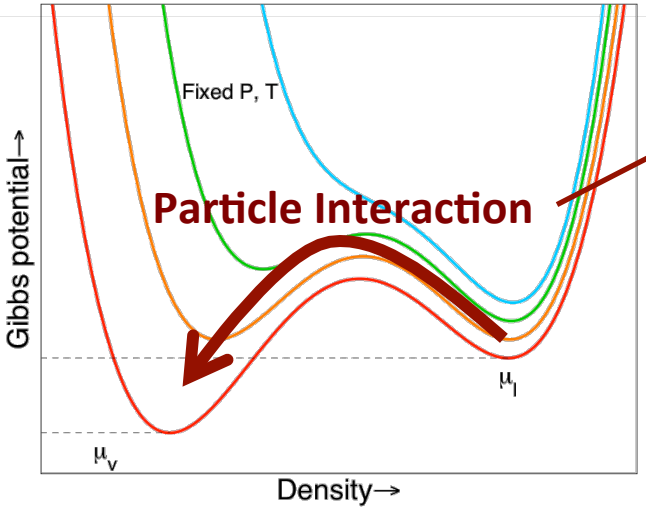

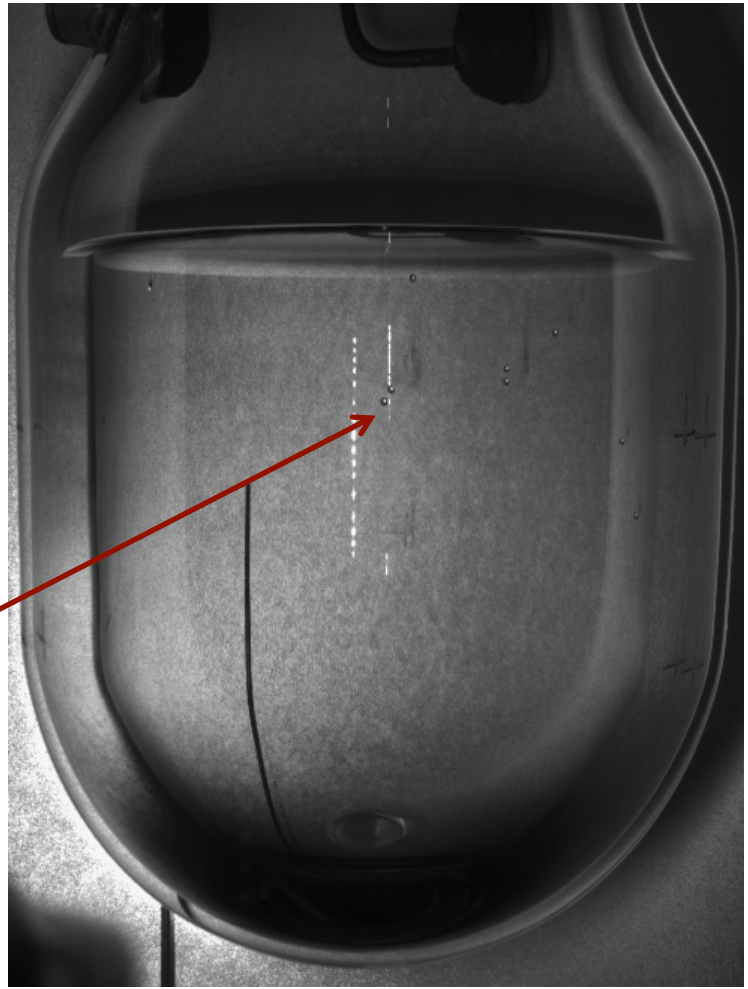

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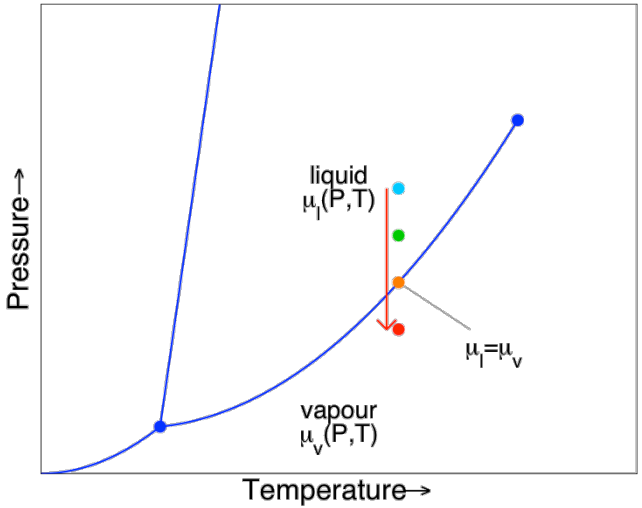

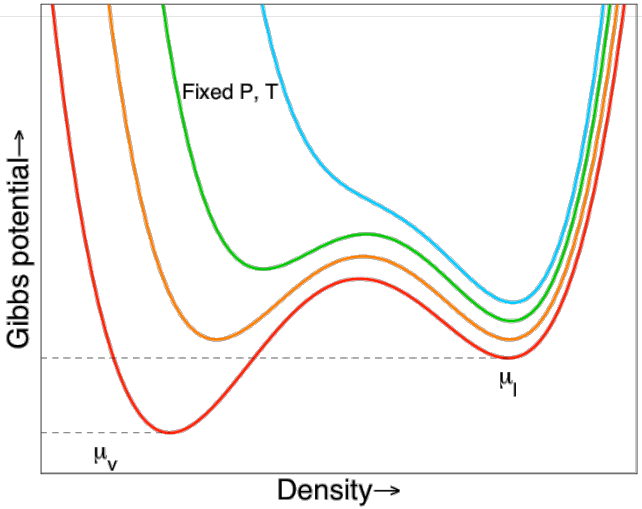

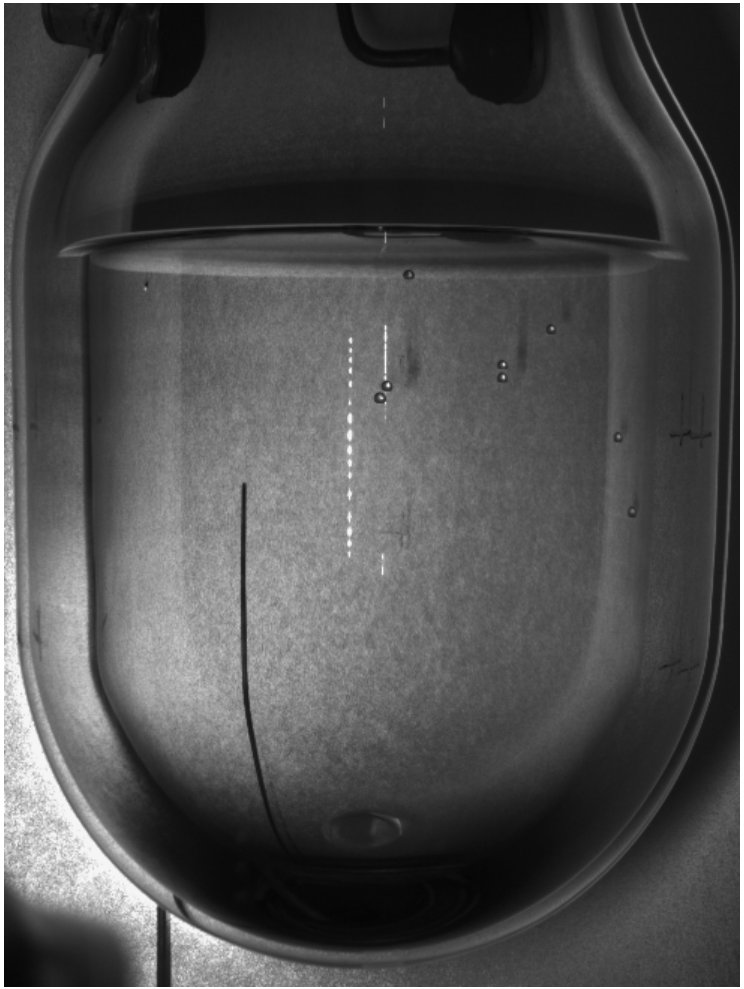

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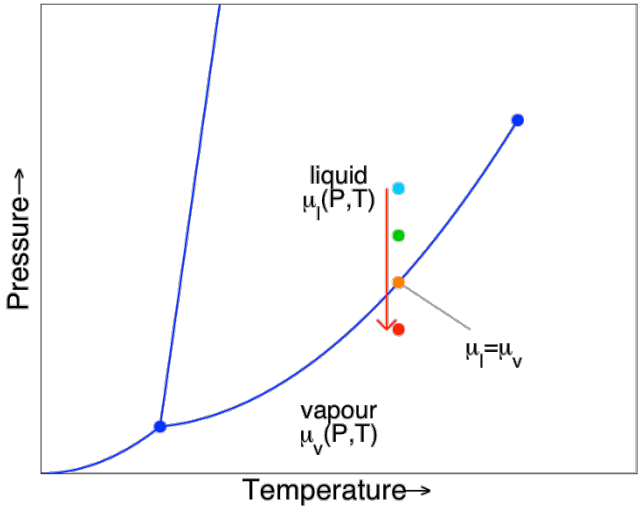

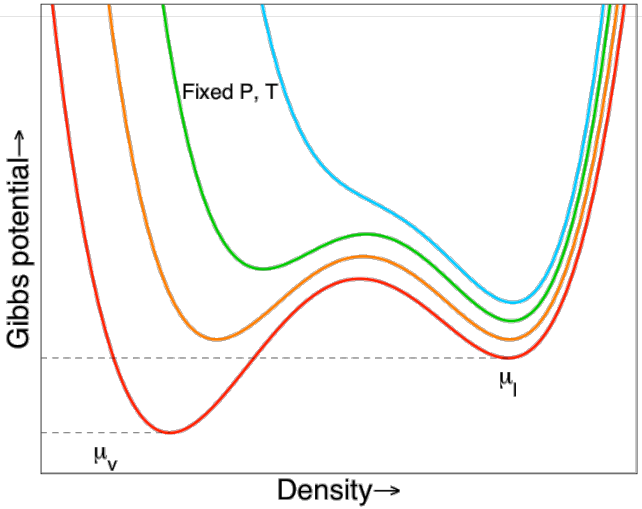

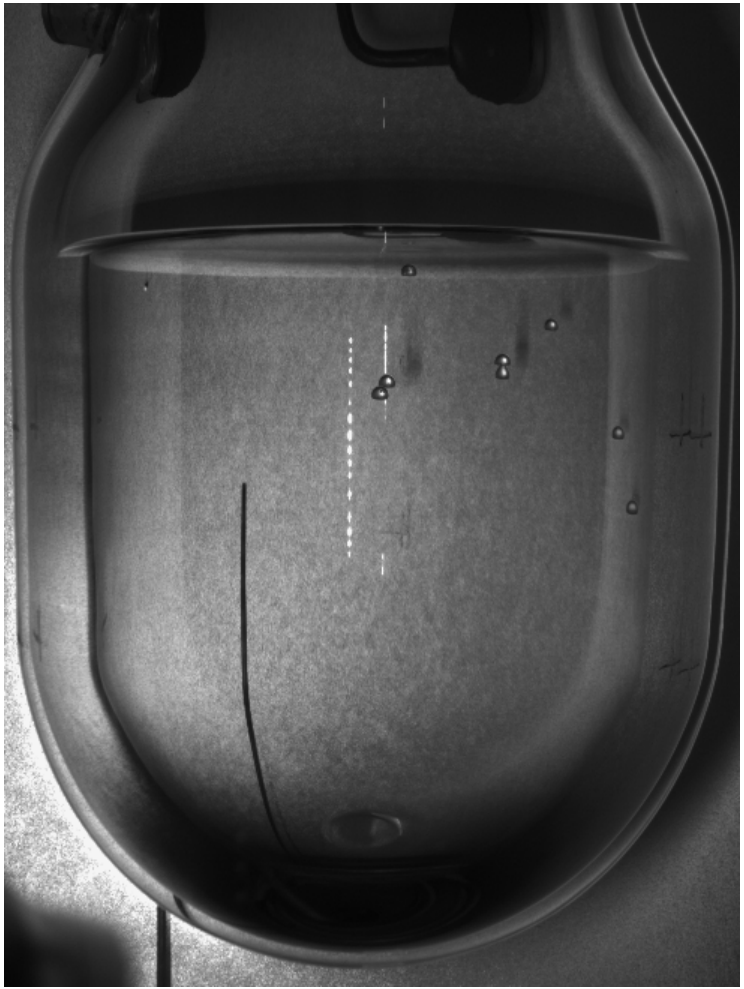

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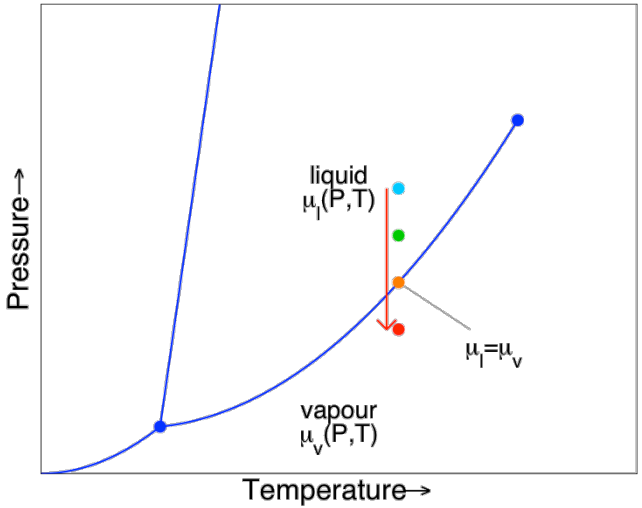

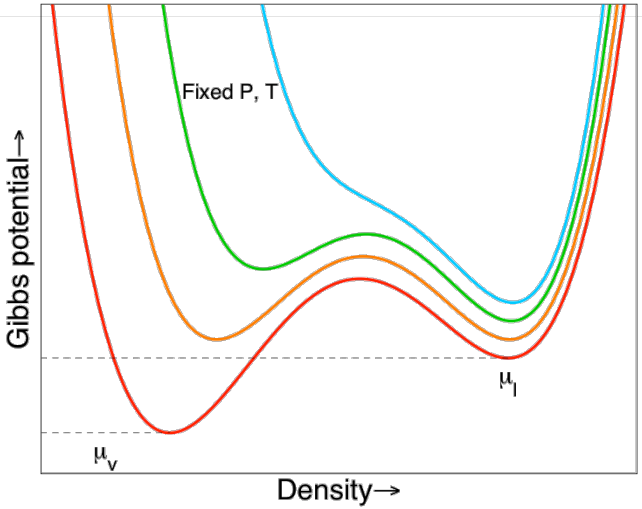

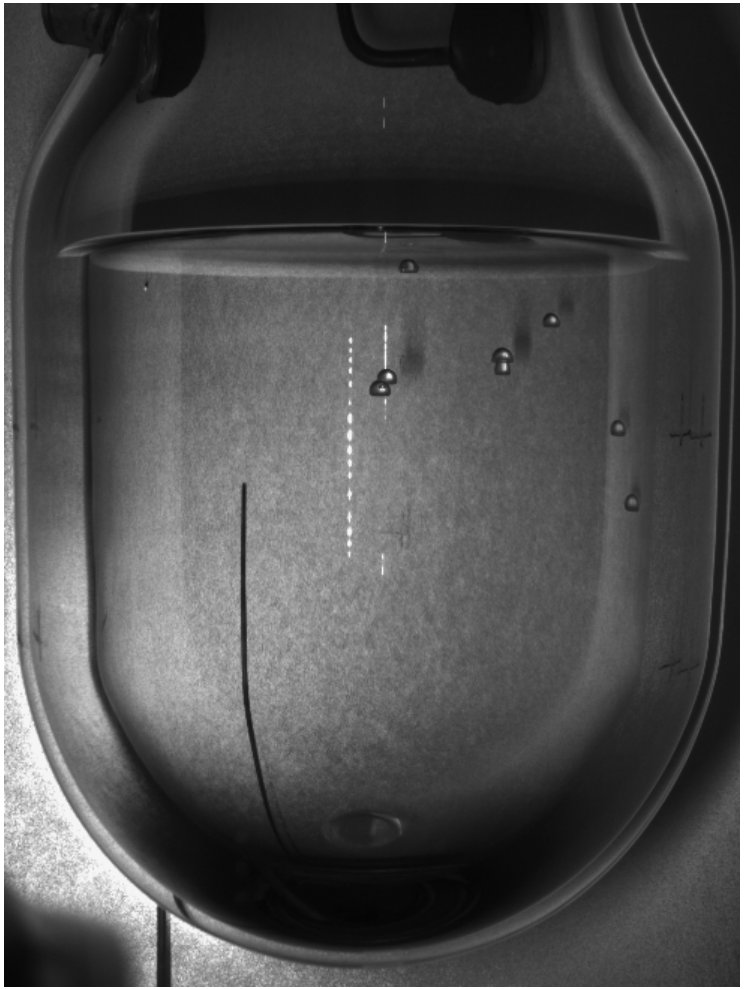

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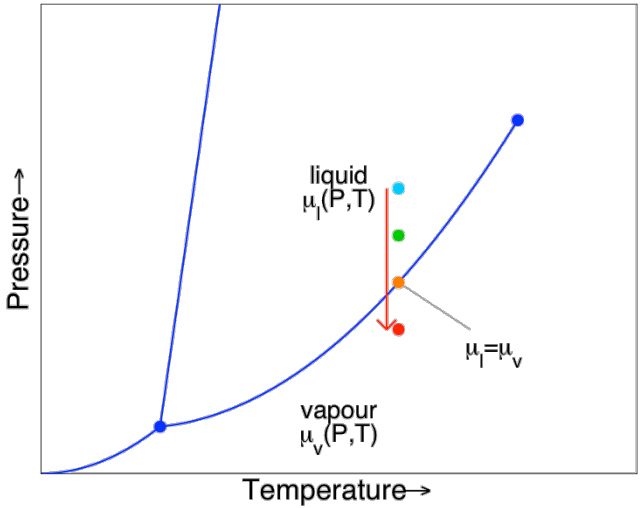

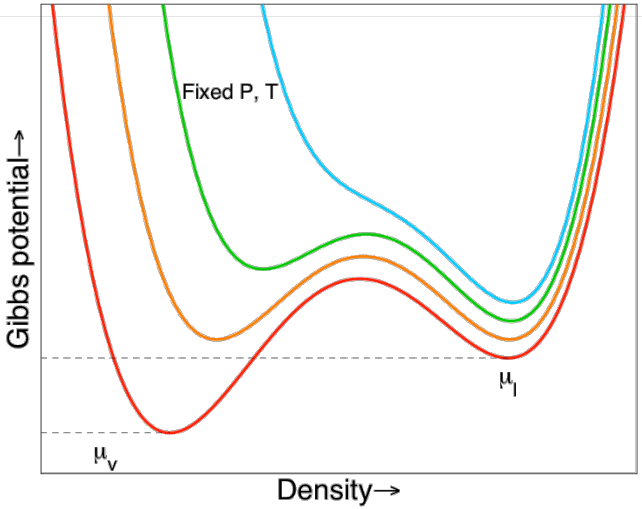

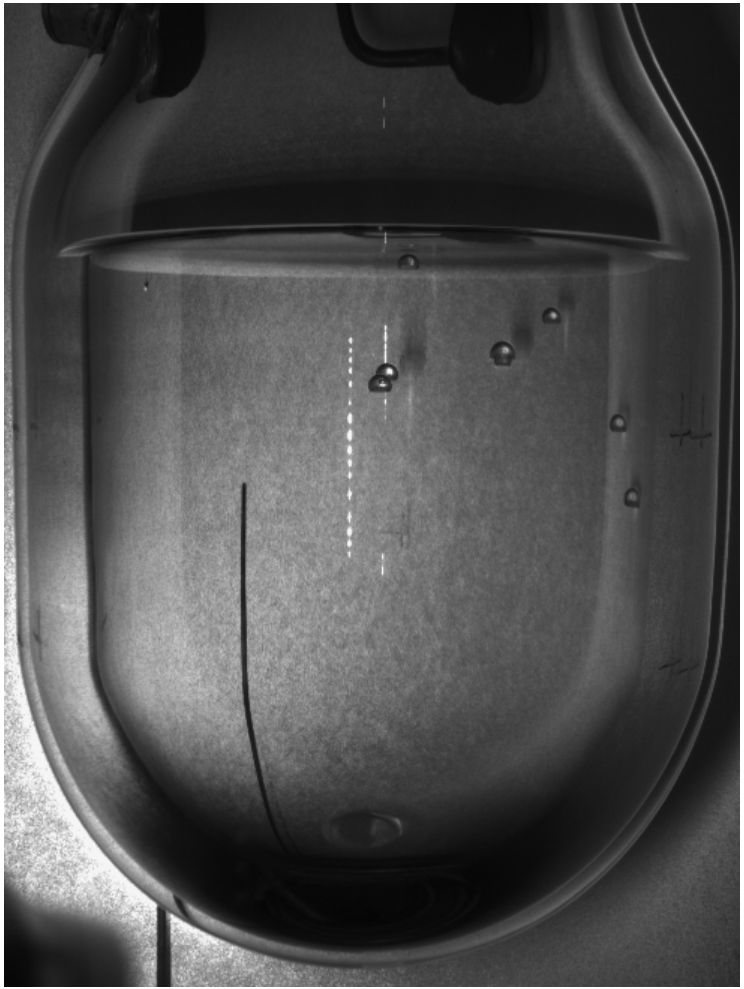

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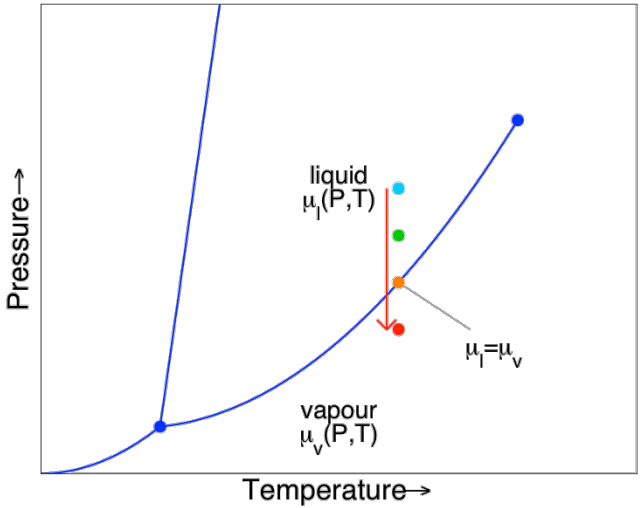

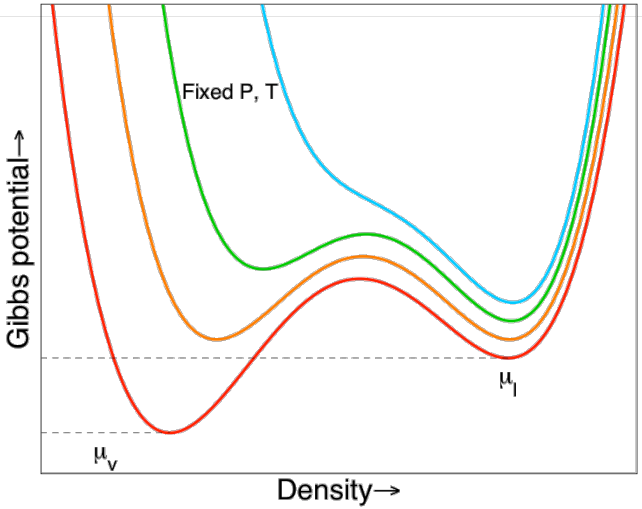

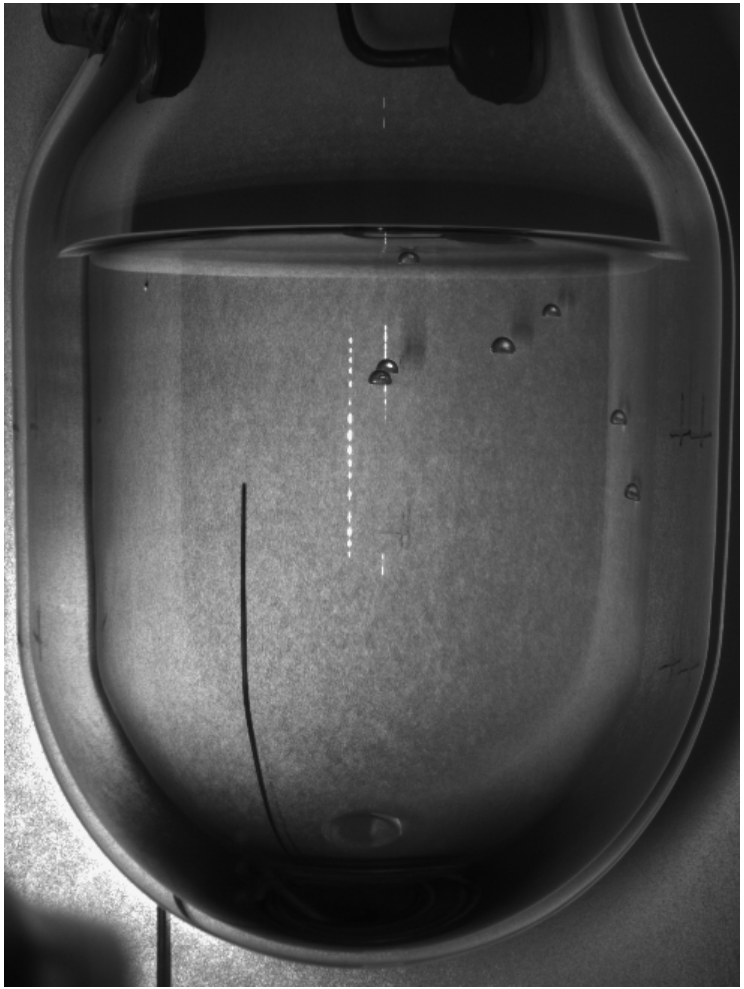

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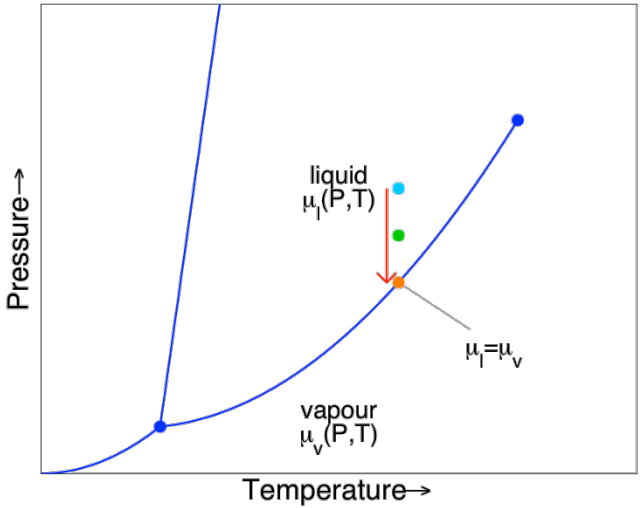

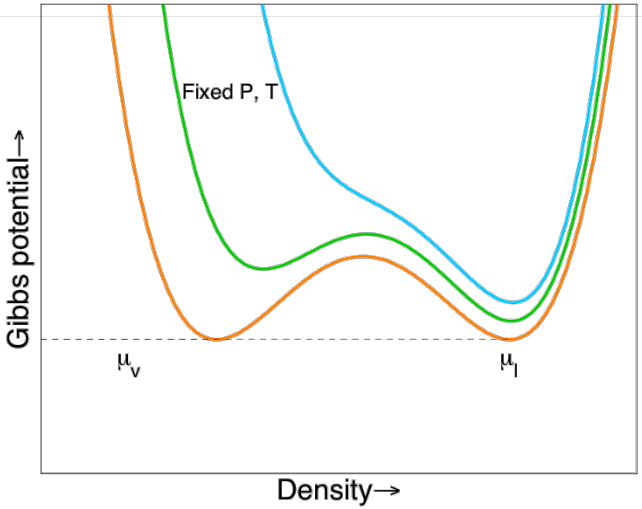

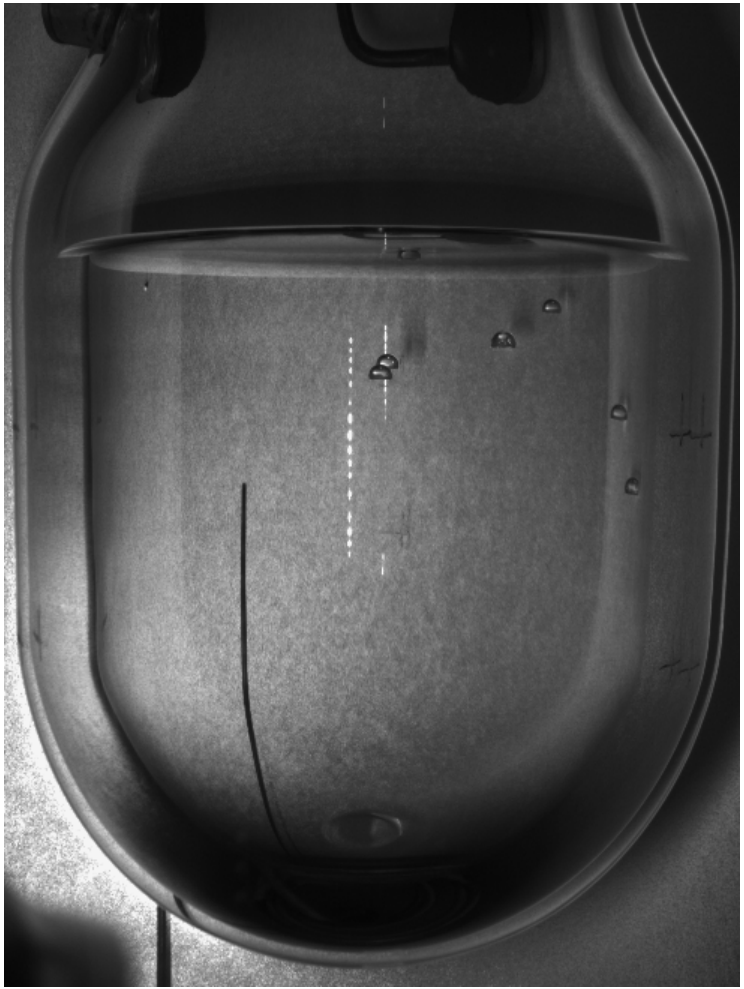

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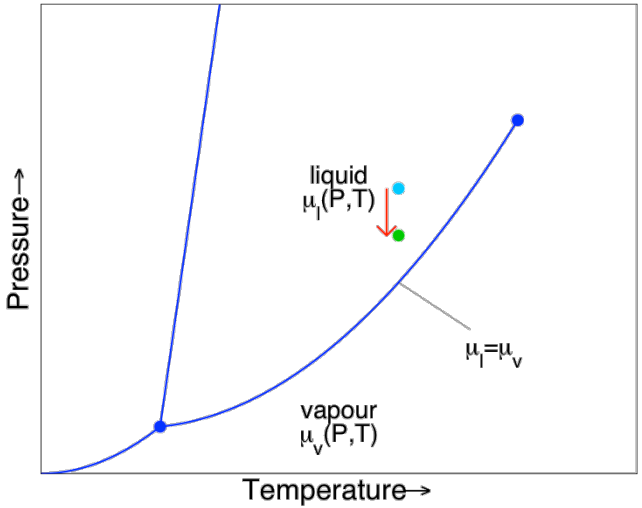

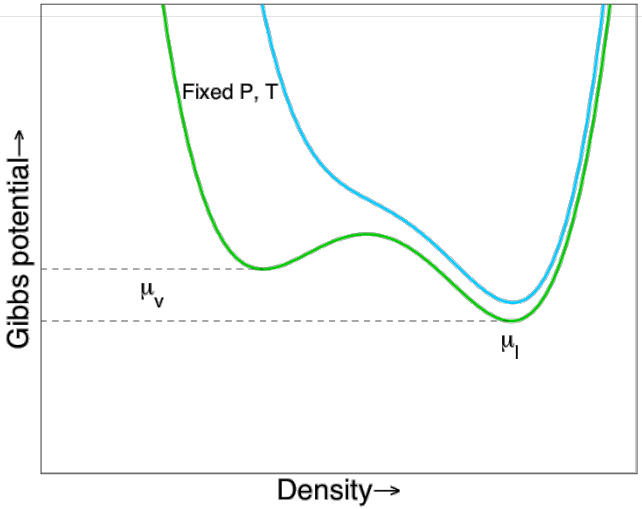

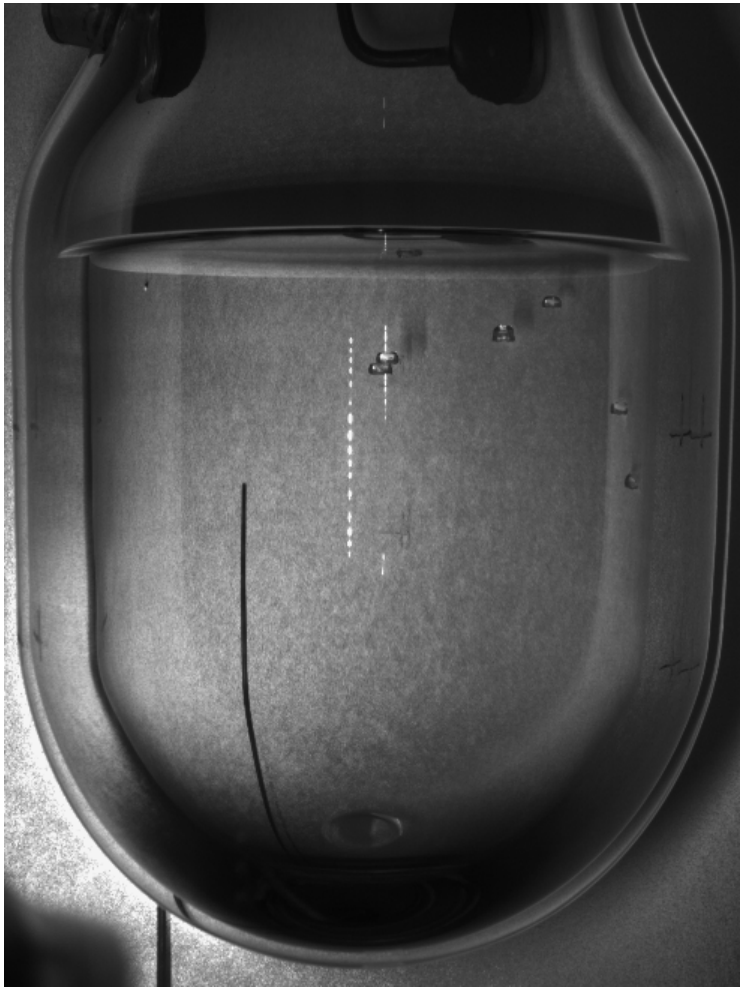

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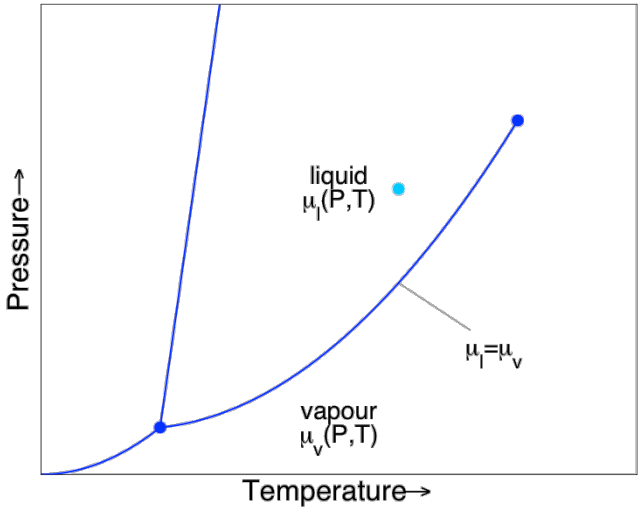

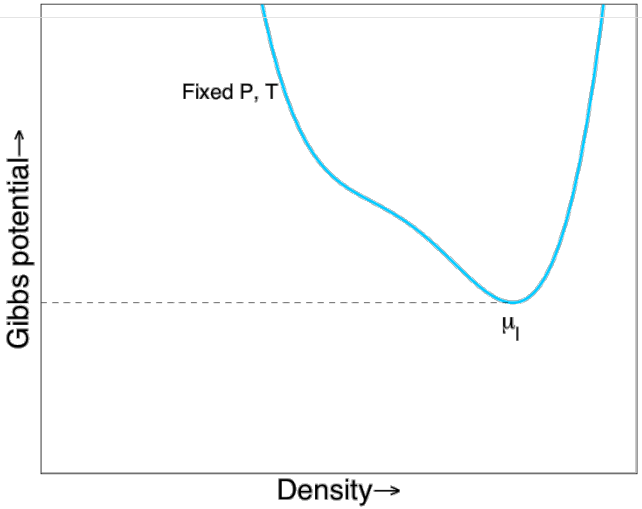

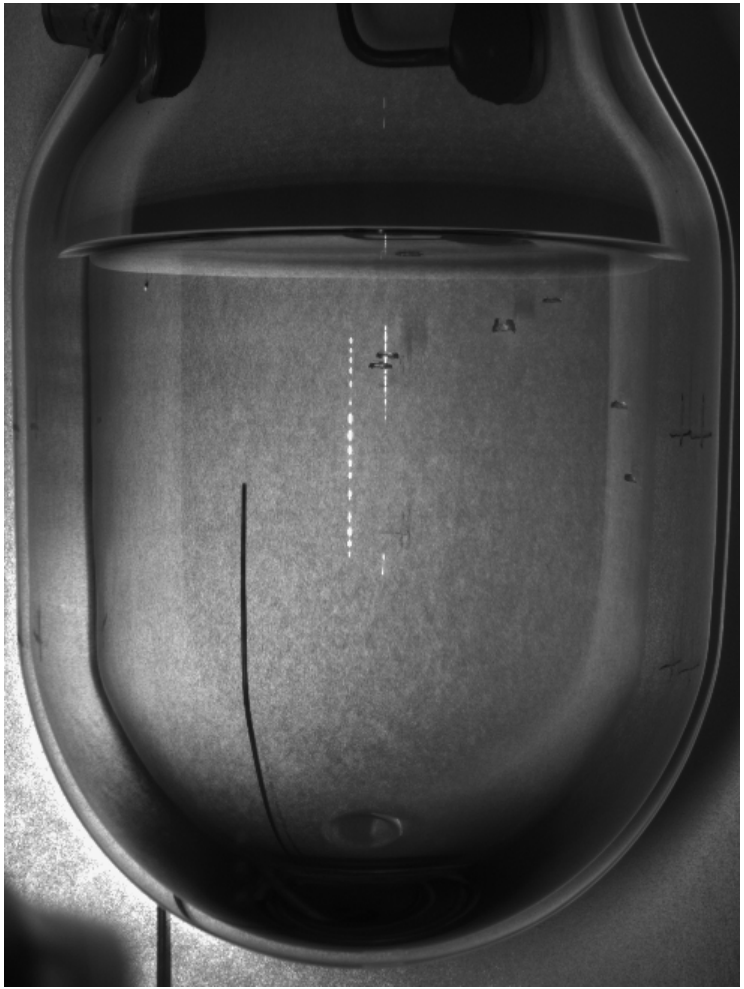

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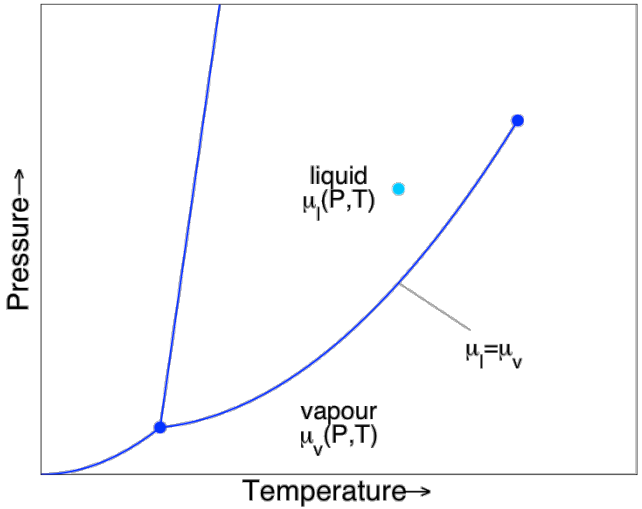

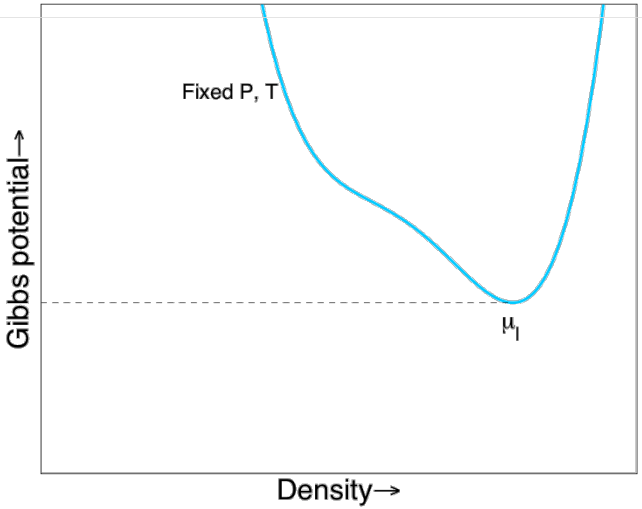

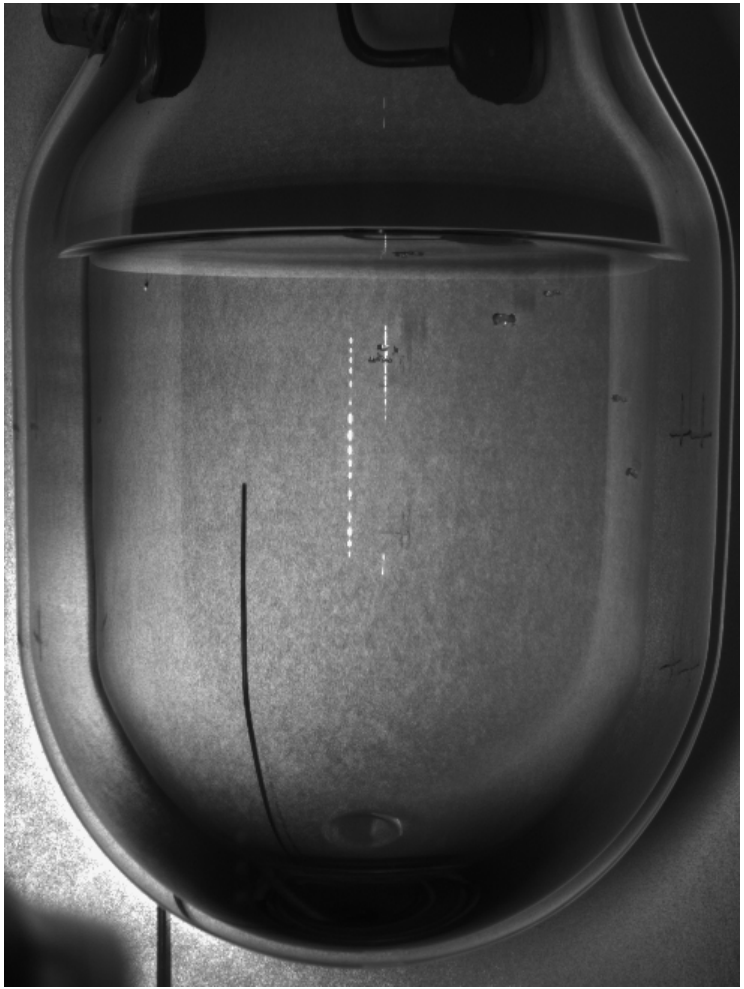

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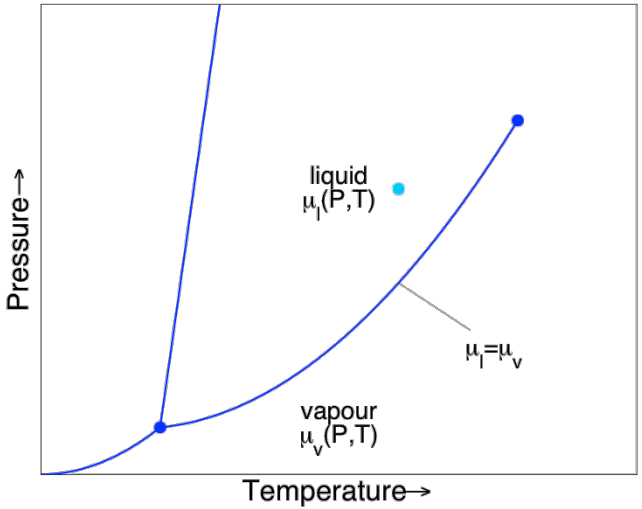

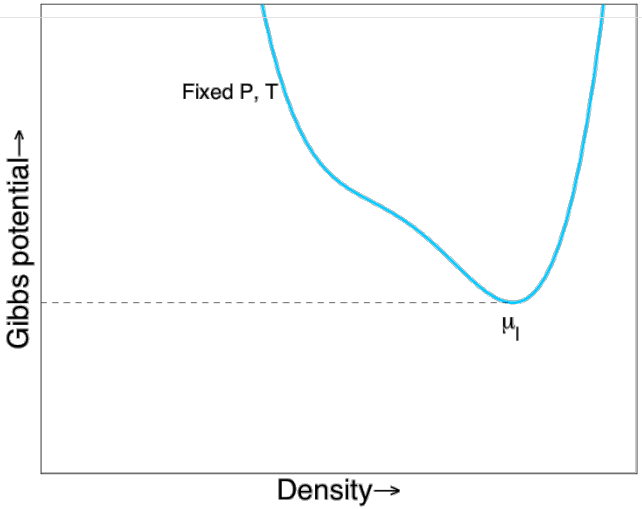

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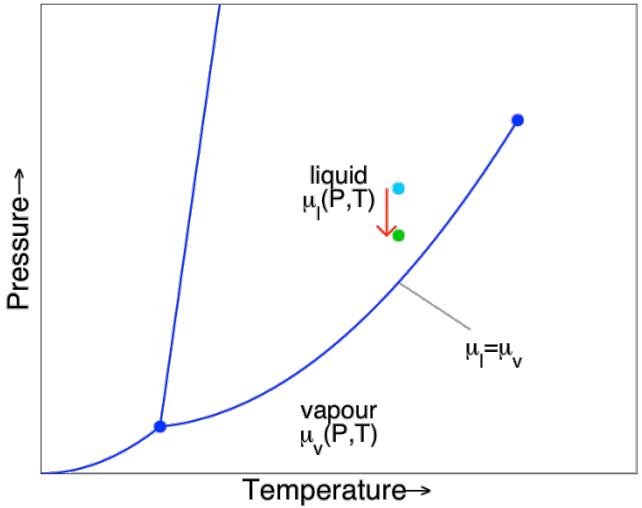

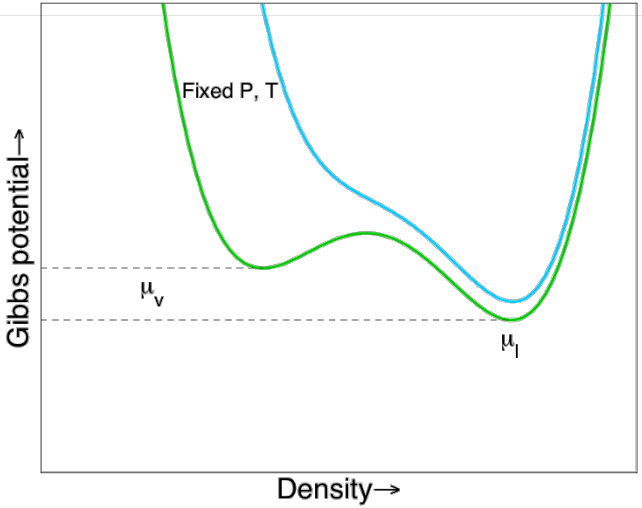

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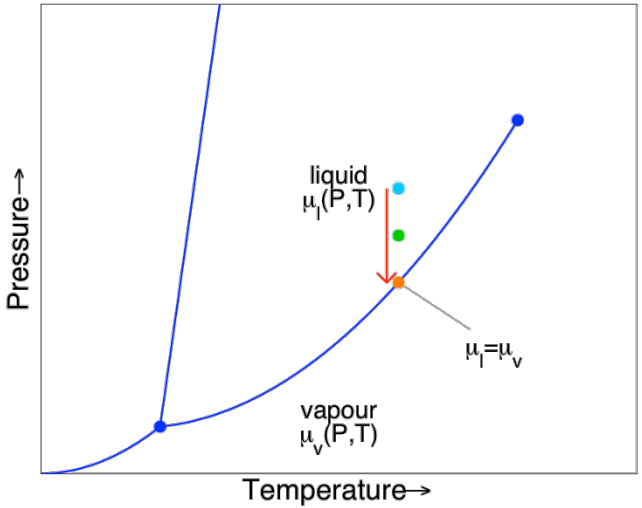

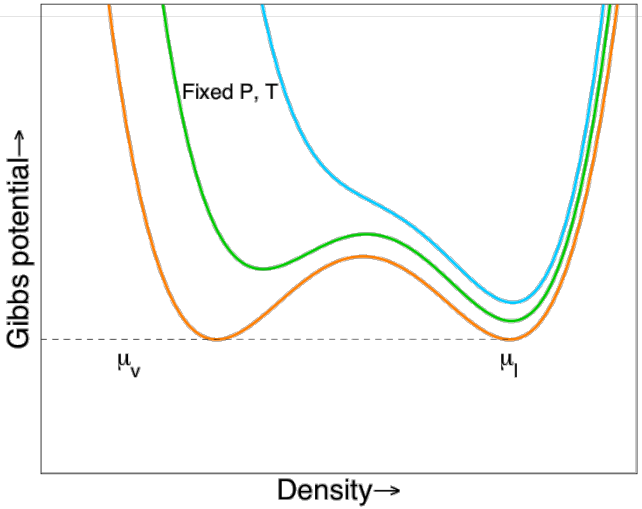

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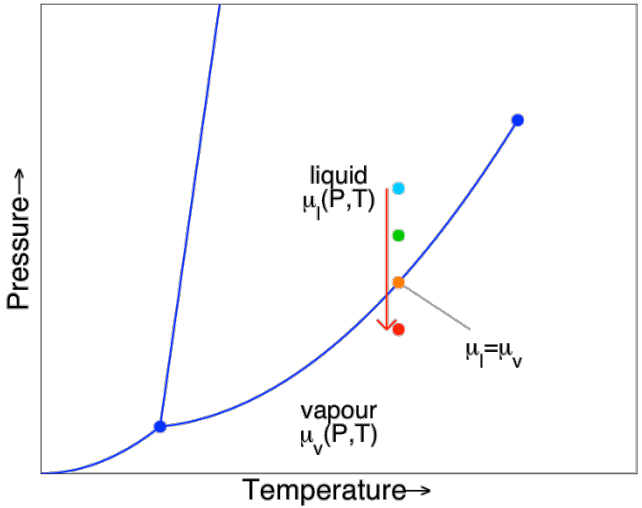

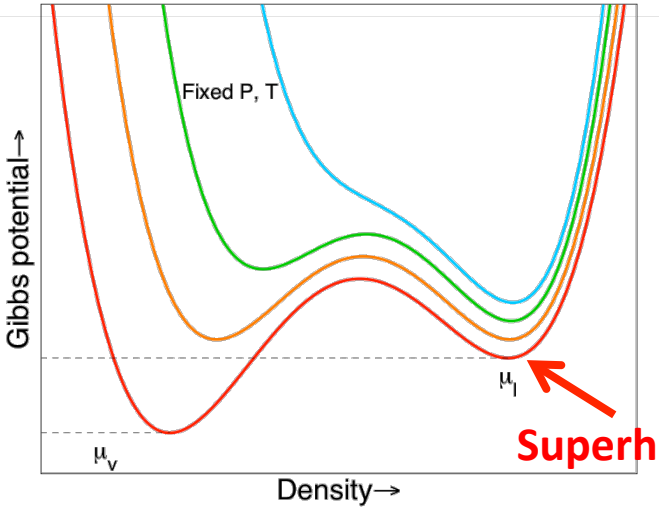

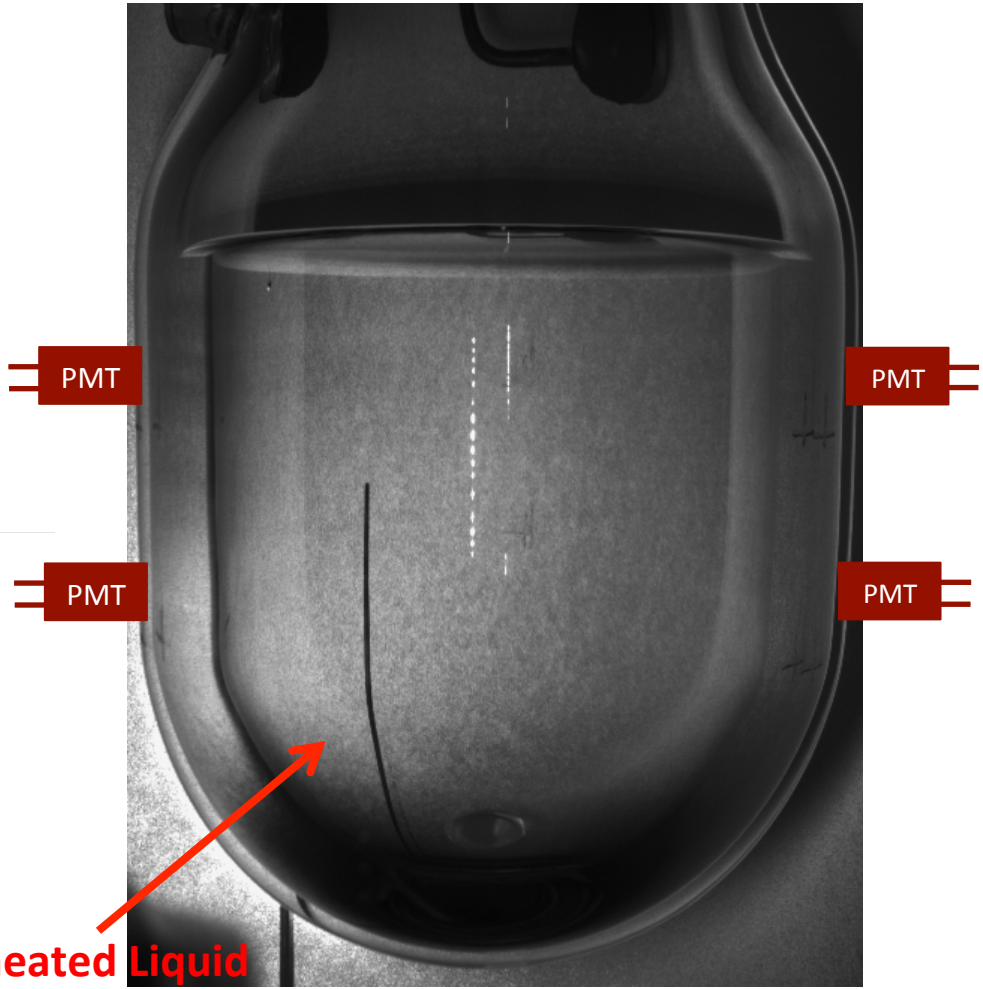

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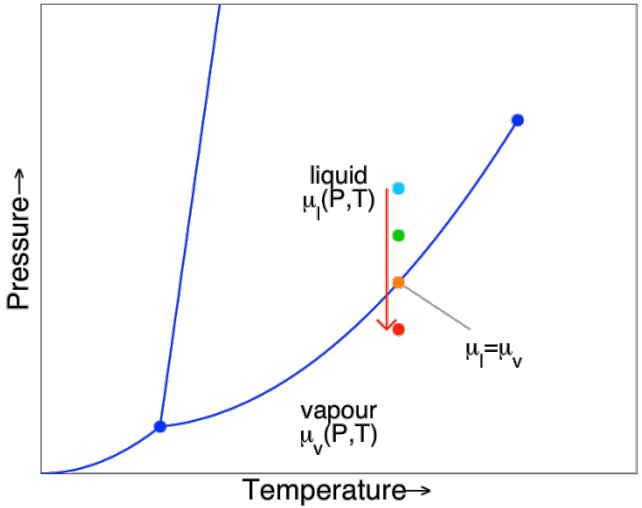

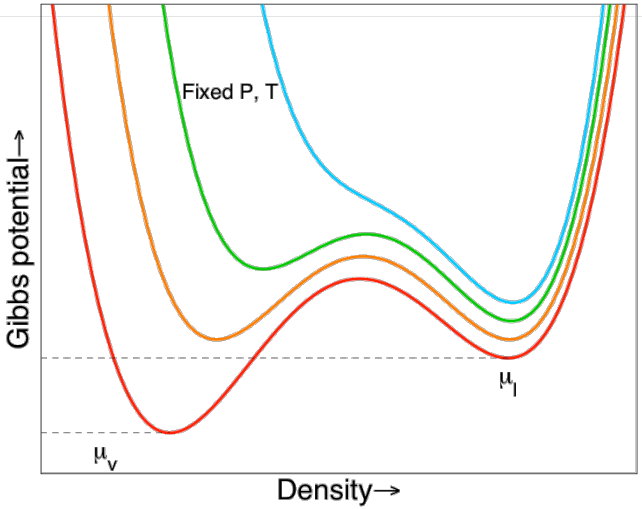

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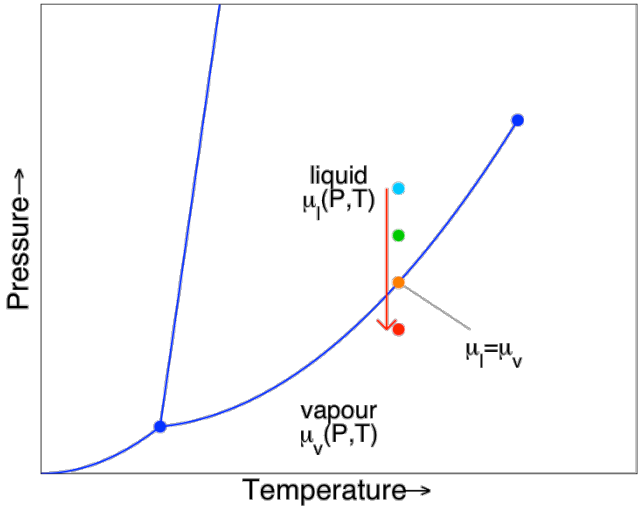

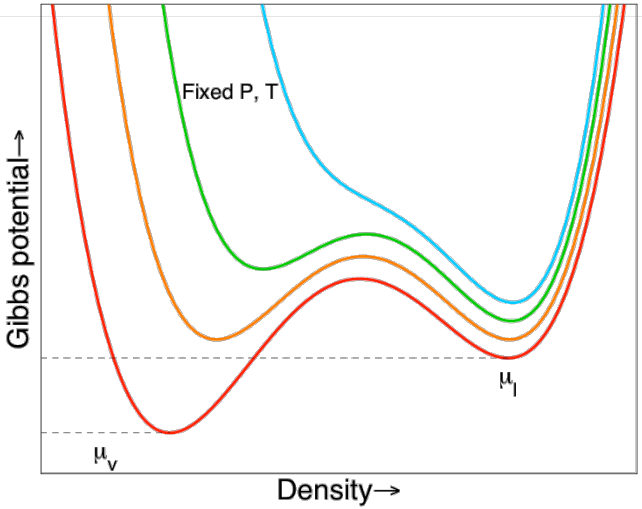

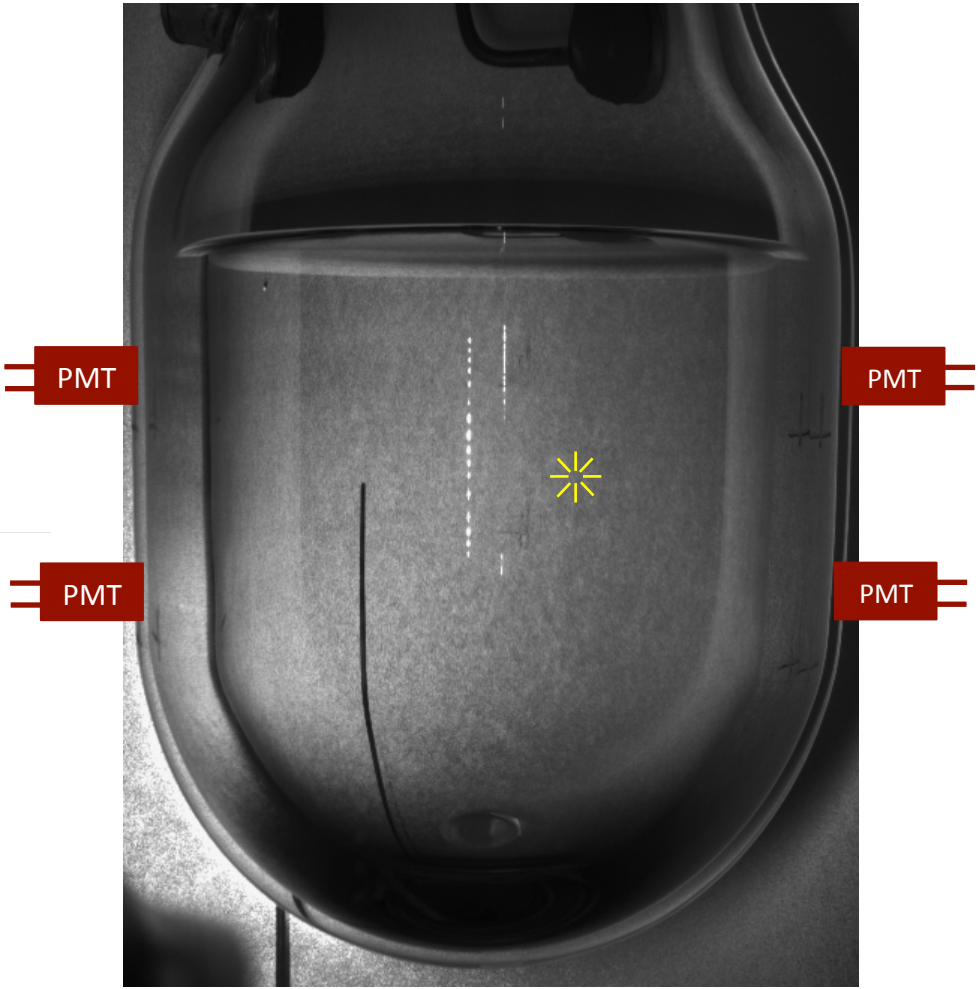

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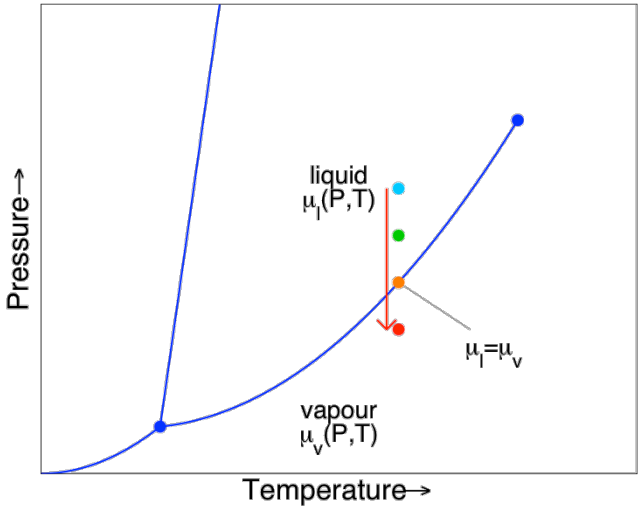

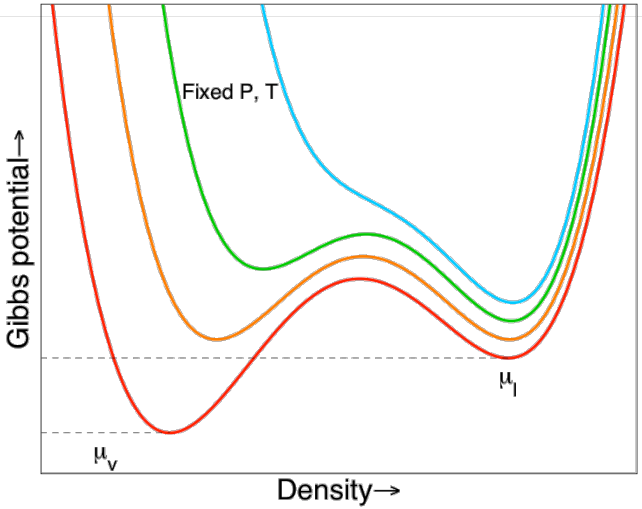

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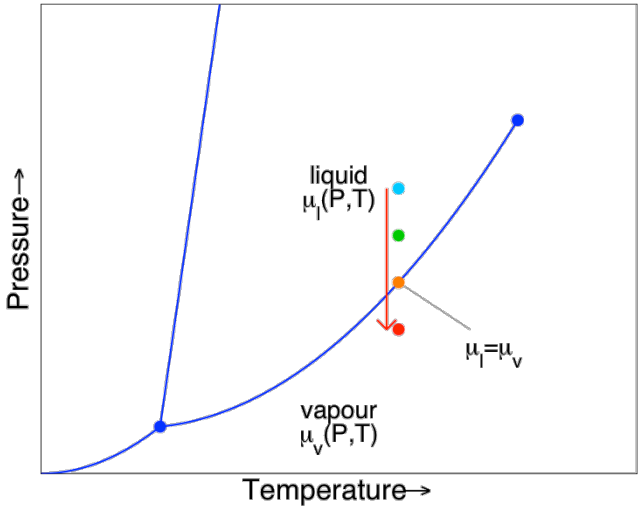

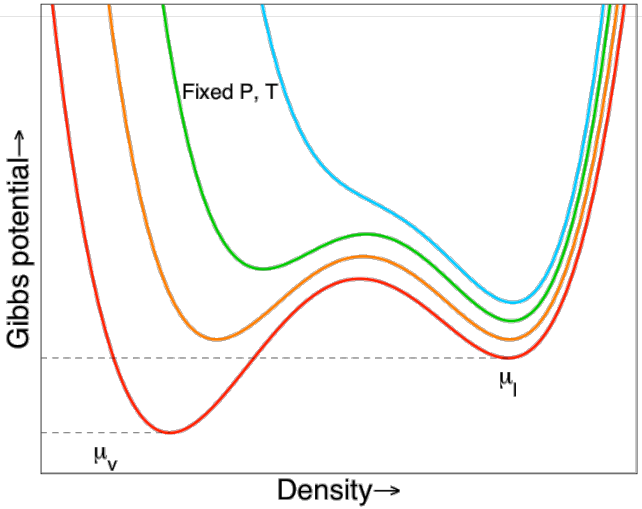

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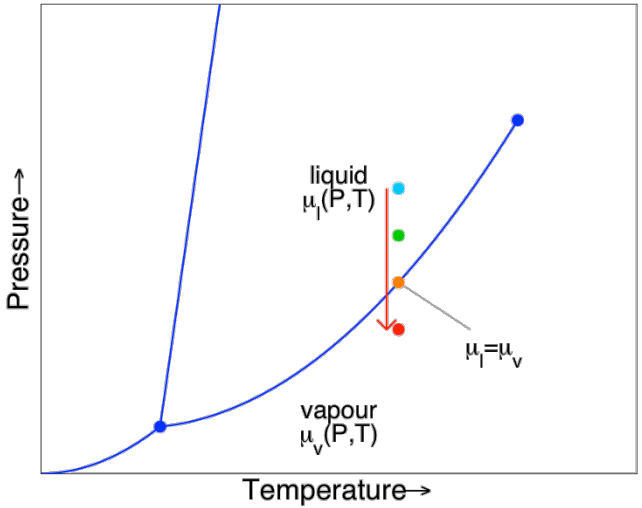

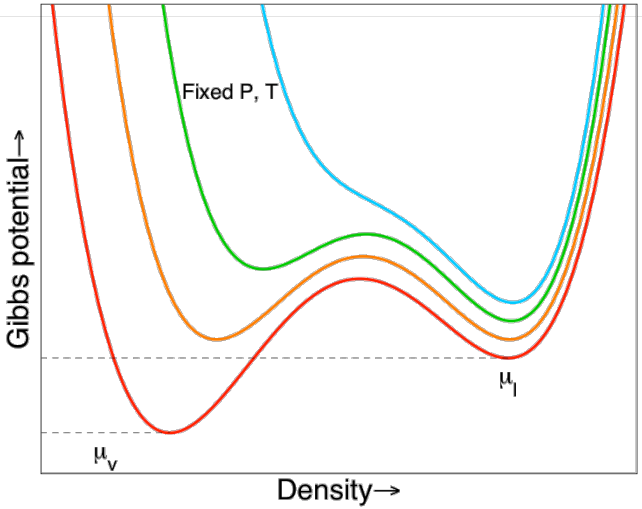

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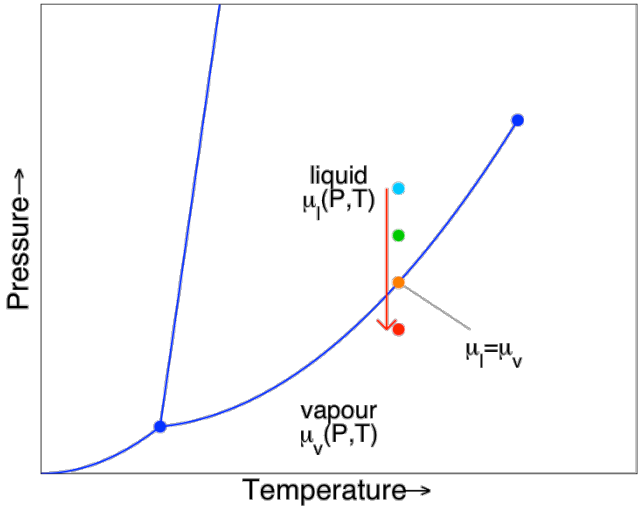

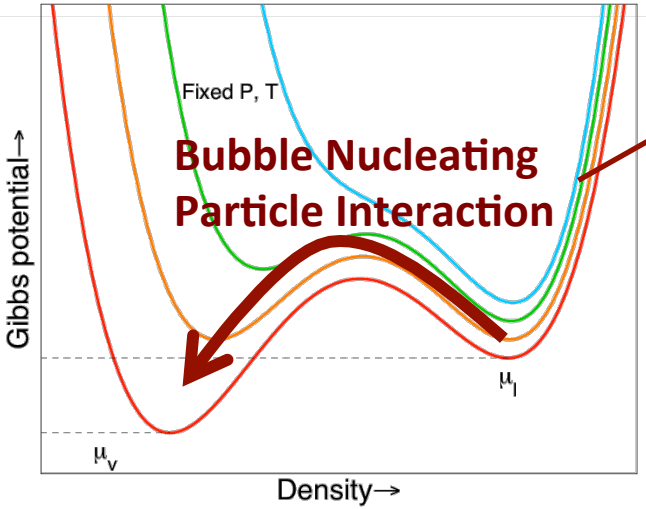

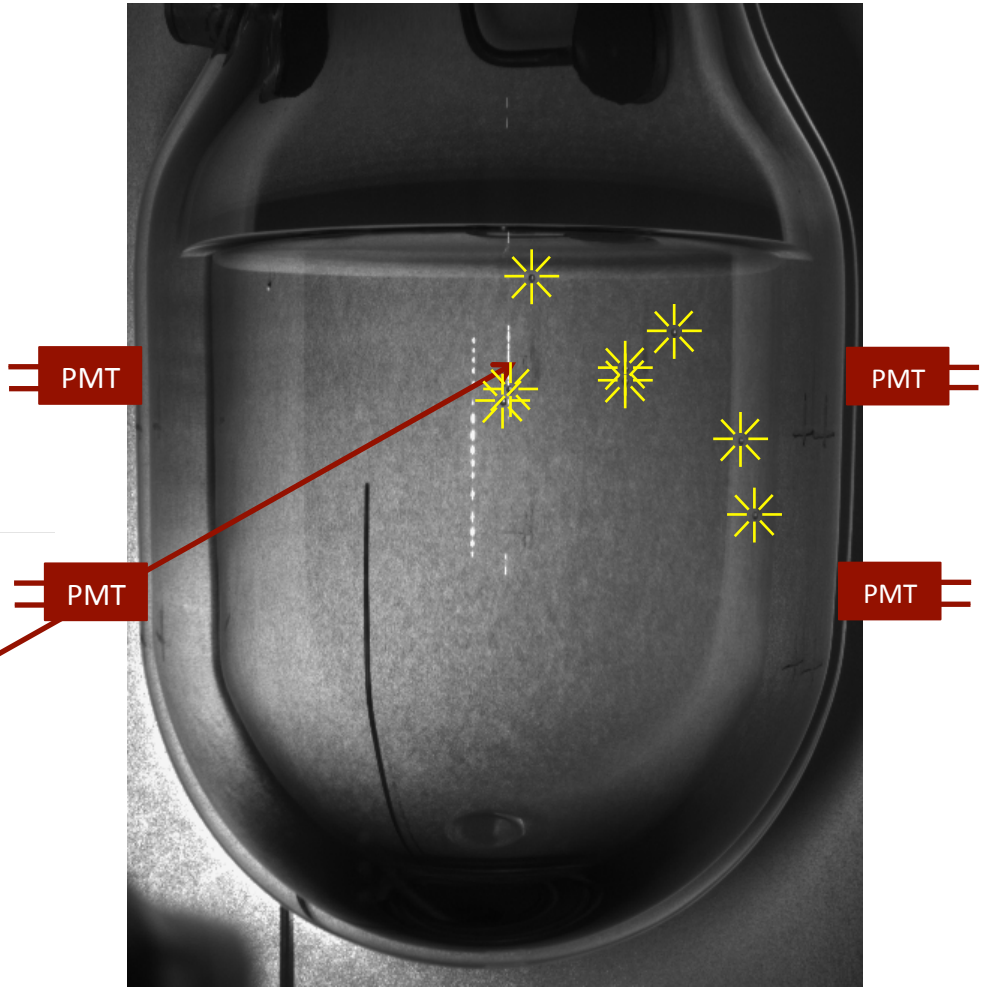

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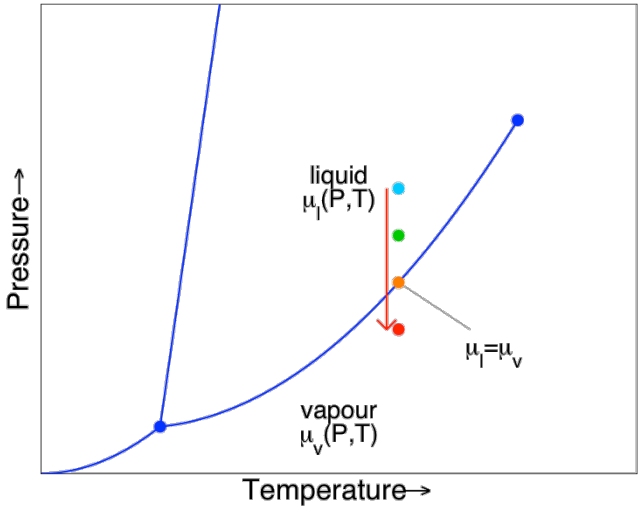

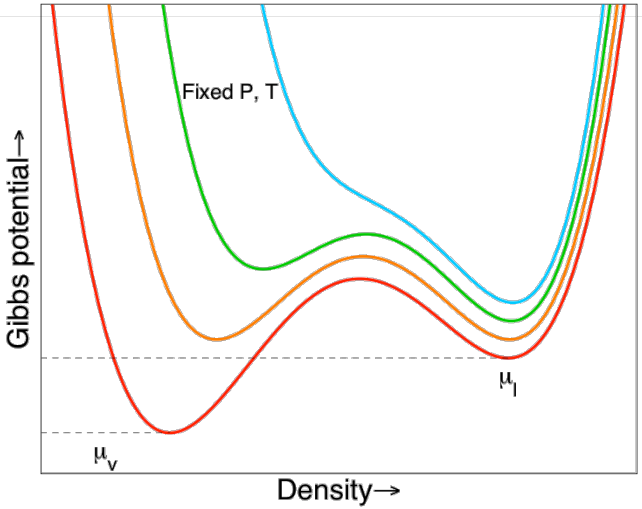

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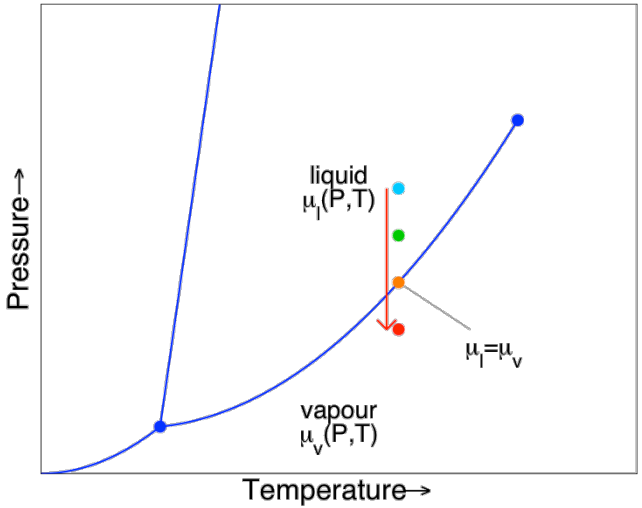

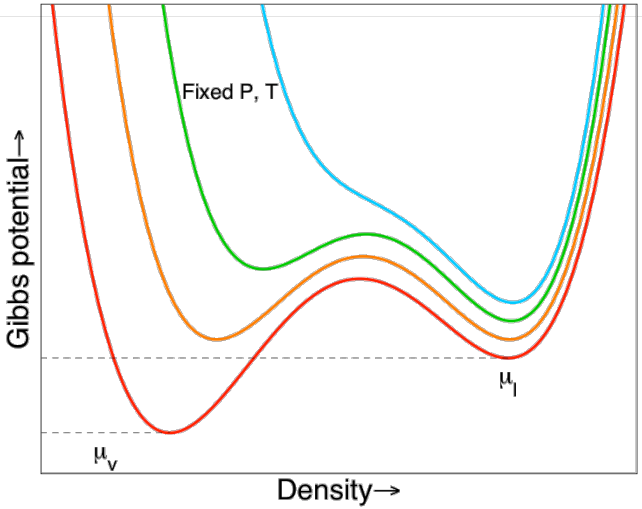

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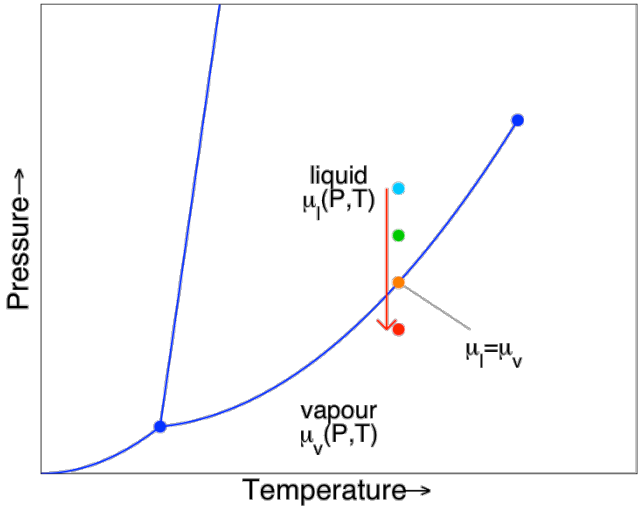

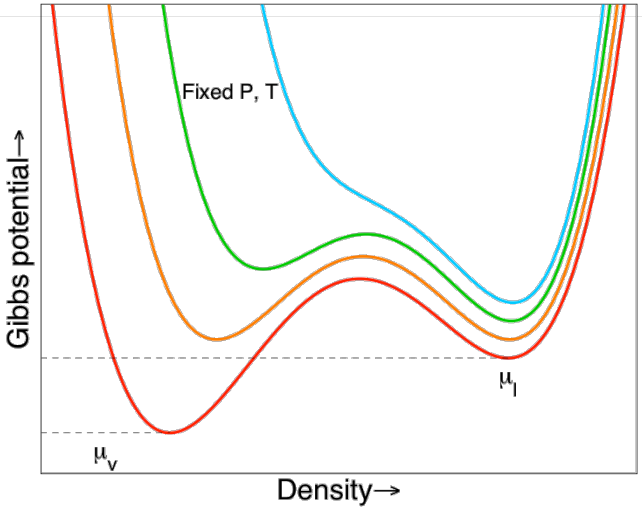

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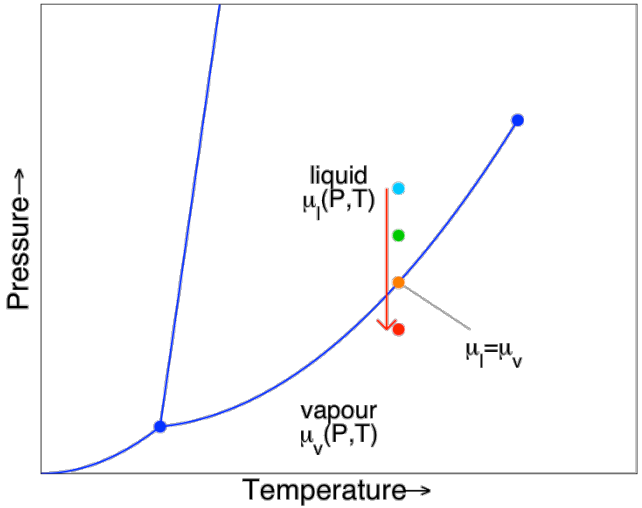

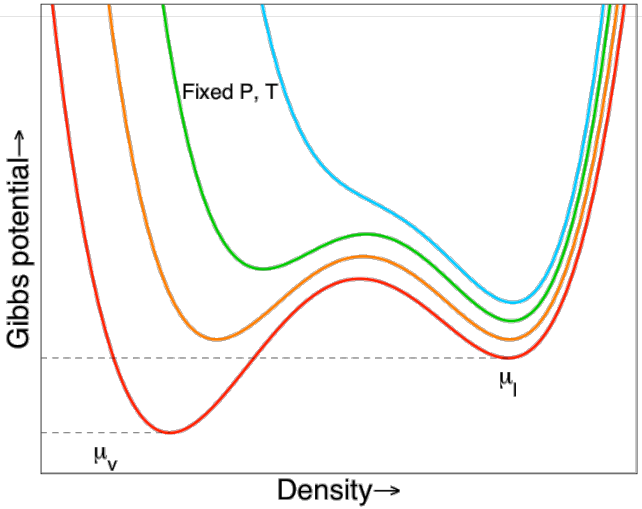

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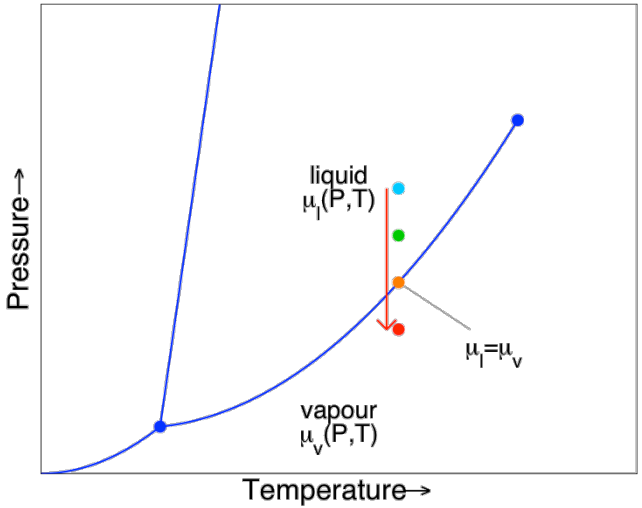

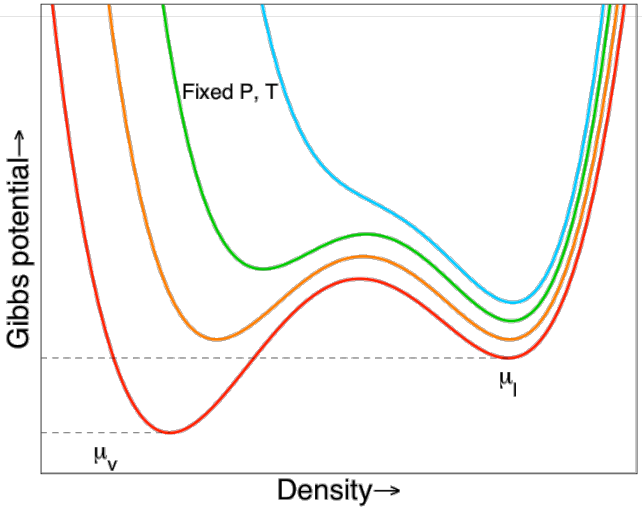

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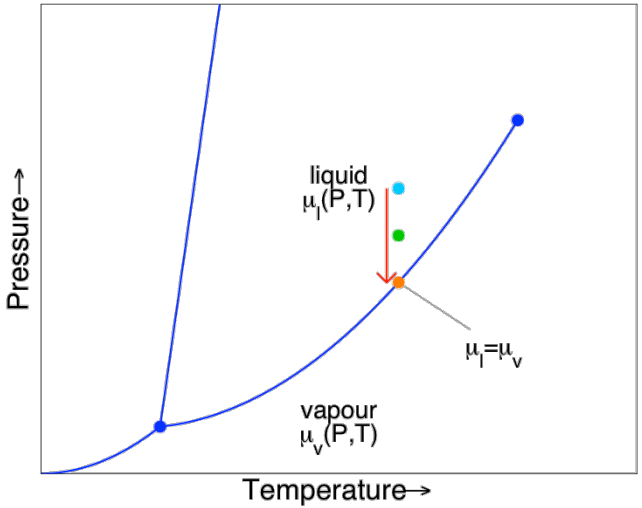

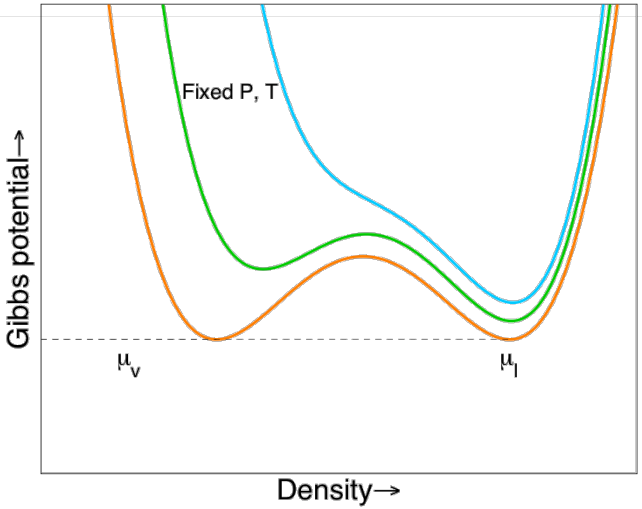

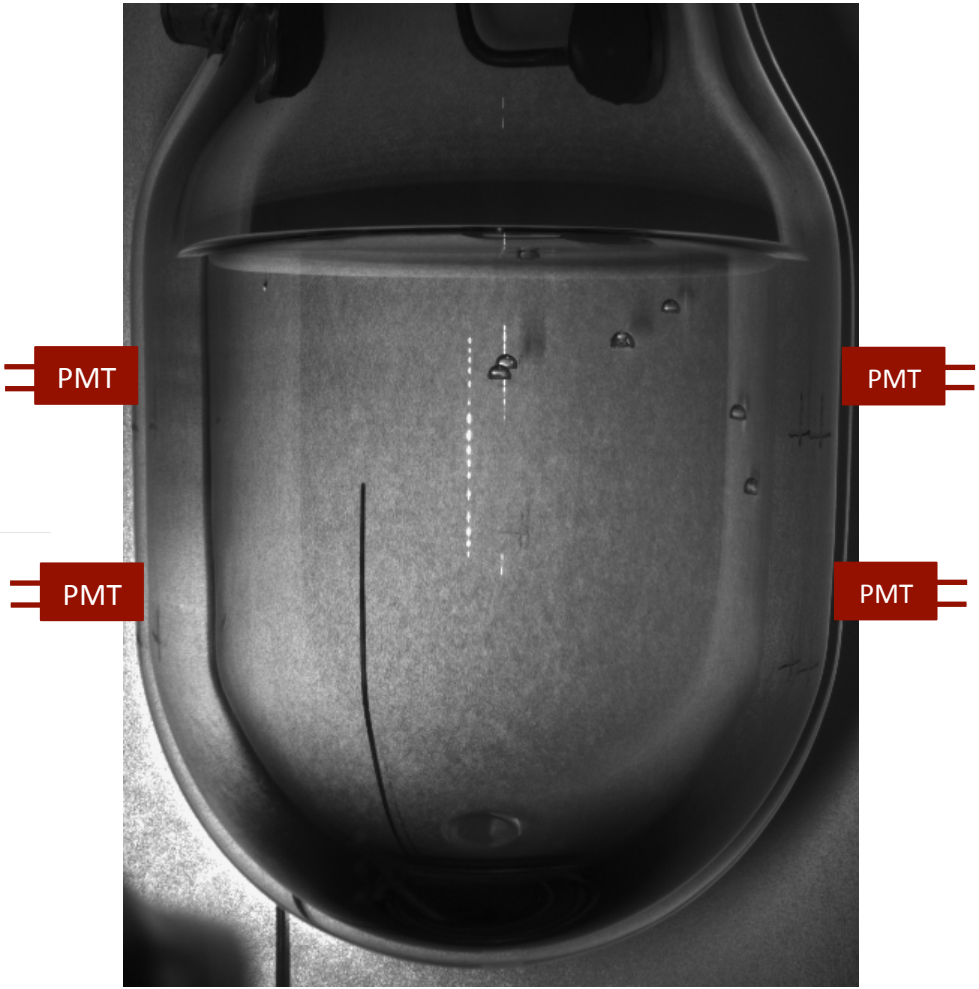

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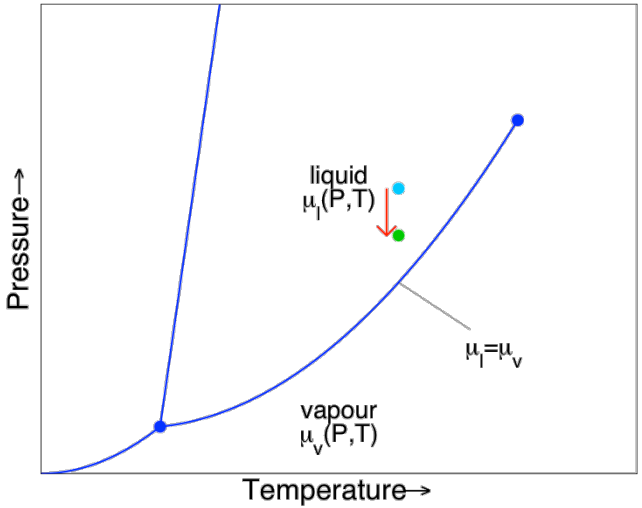

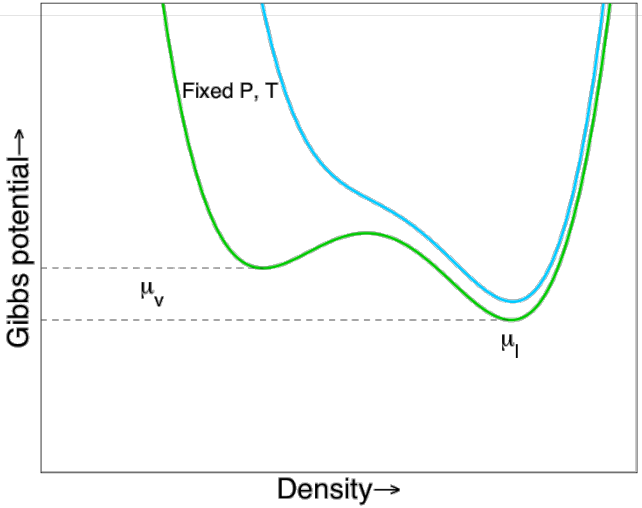

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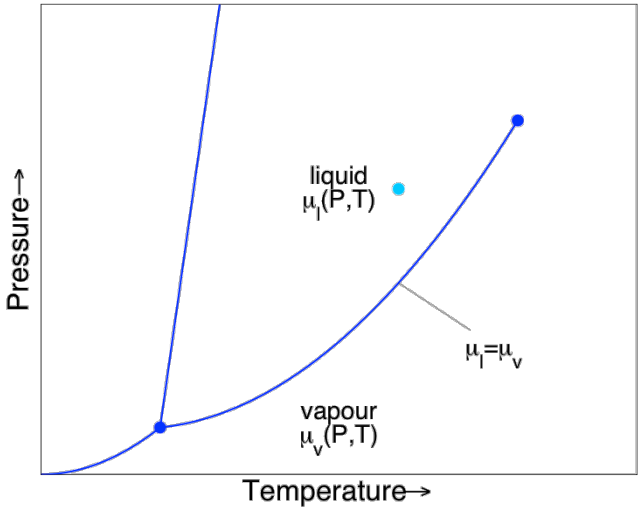

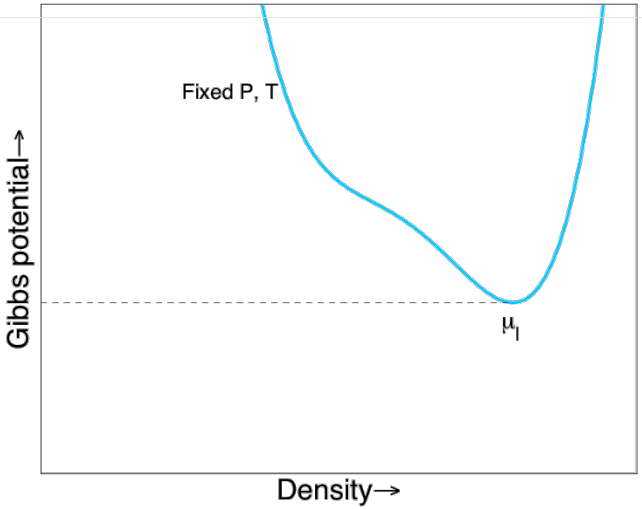

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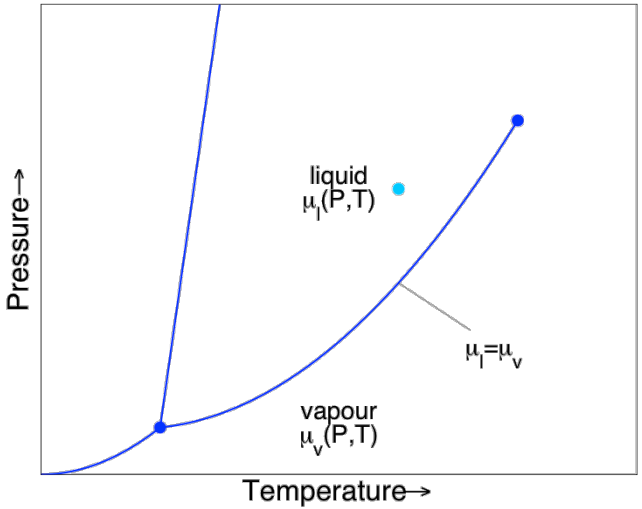
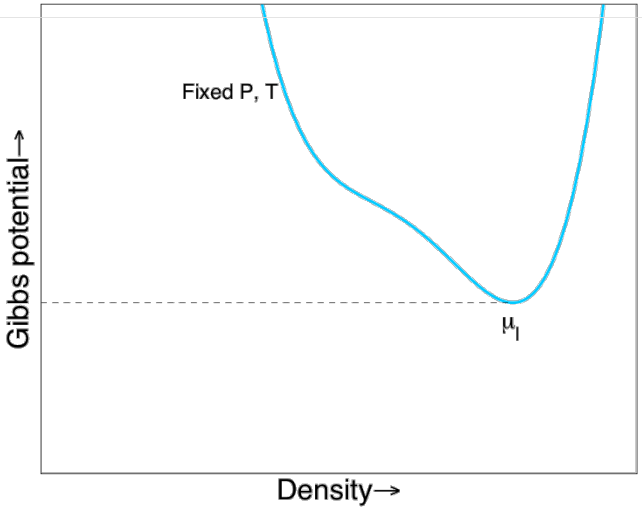
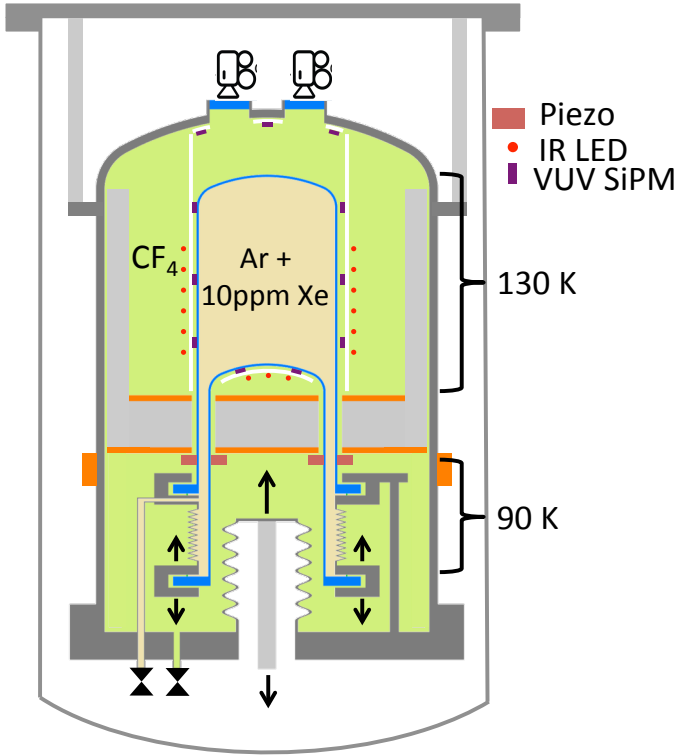
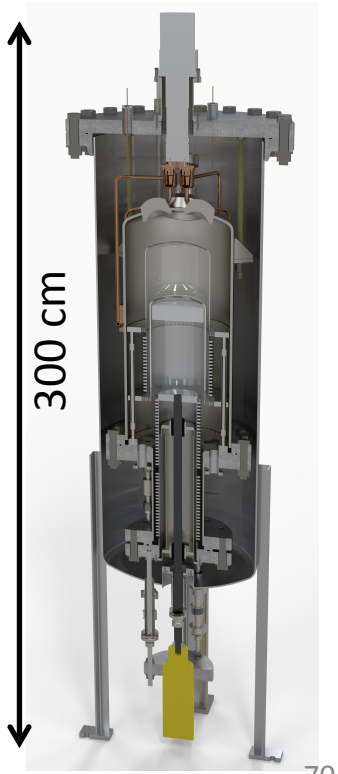




Fermilab LDRD 2018-003 (Supported also by CFI, NSERC, COFI)

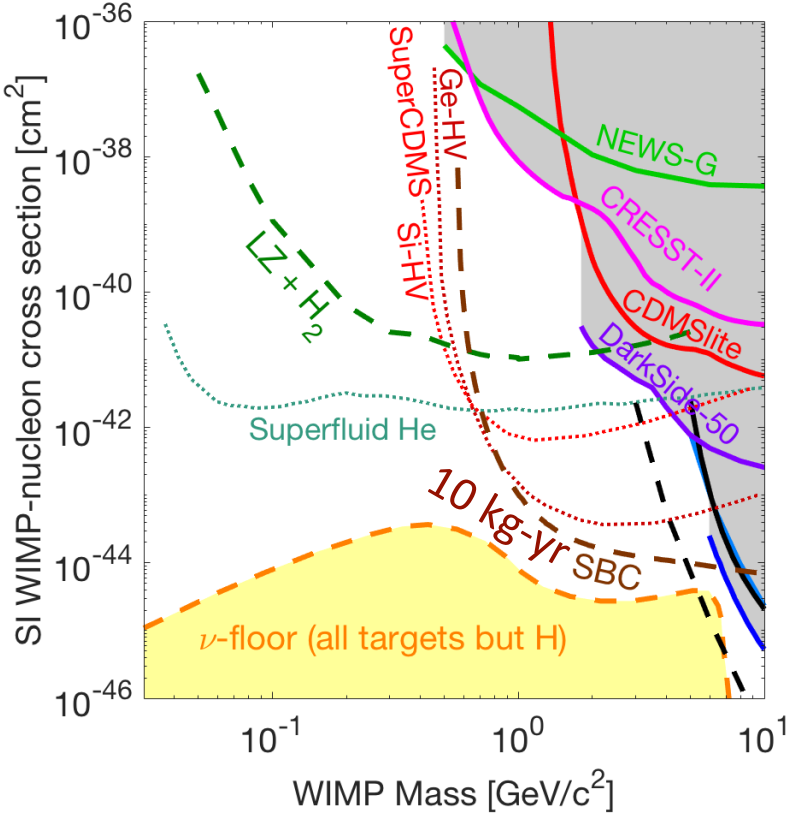
- Target: 10 kg superheated Ar
- Goal: 100 eV threshold with 10^9 ER discrimination





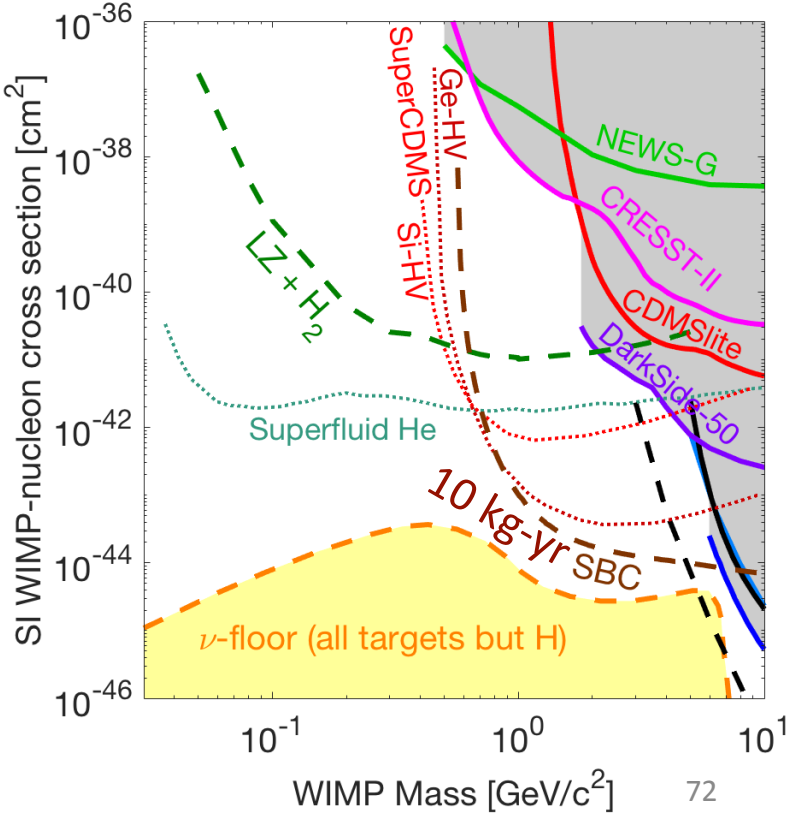
State of the Field: 30 MeV – 30 GeV

- Prime space for asymmetric dark matter
  - Full exploration requires trifecta of
    - sub-keV threshold
    - strong discrimination
    - large (100 kg-yr) exposure



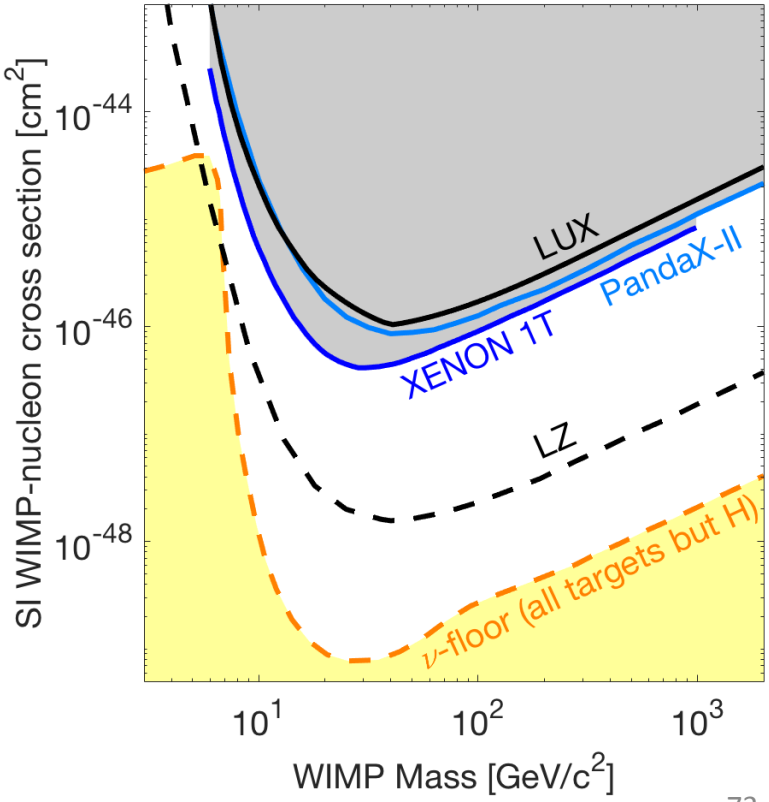
State of the Field: 30 MeV – 30 GeV

- Nearing the solar Coherent Elastic neutrino-Nucleus Scattering (CEvNS) floor
  - Indistinguishable from DM on event-by-event basis
  - Unless you have a directional detector (see CYGNO)

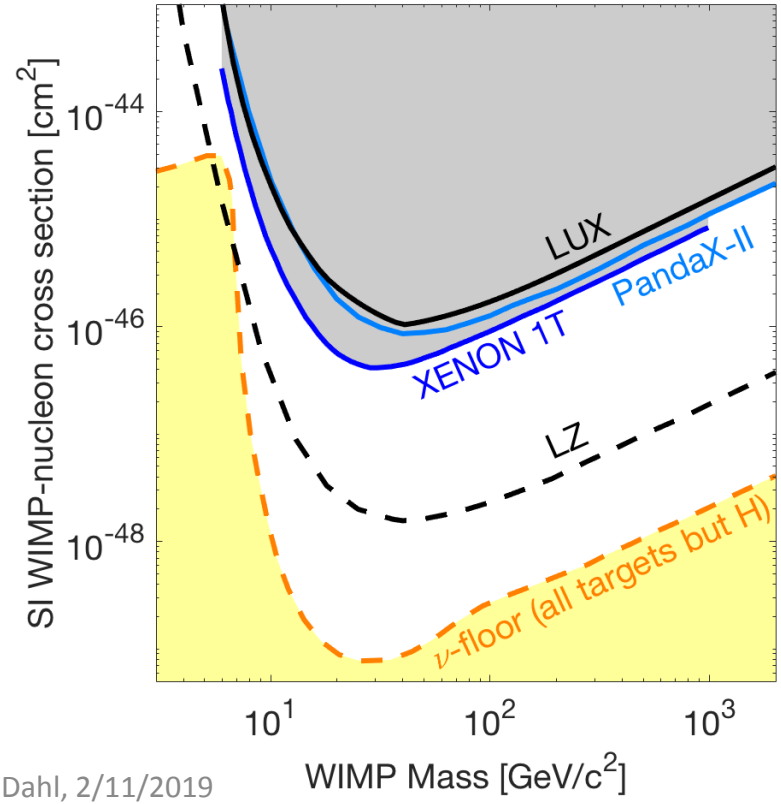


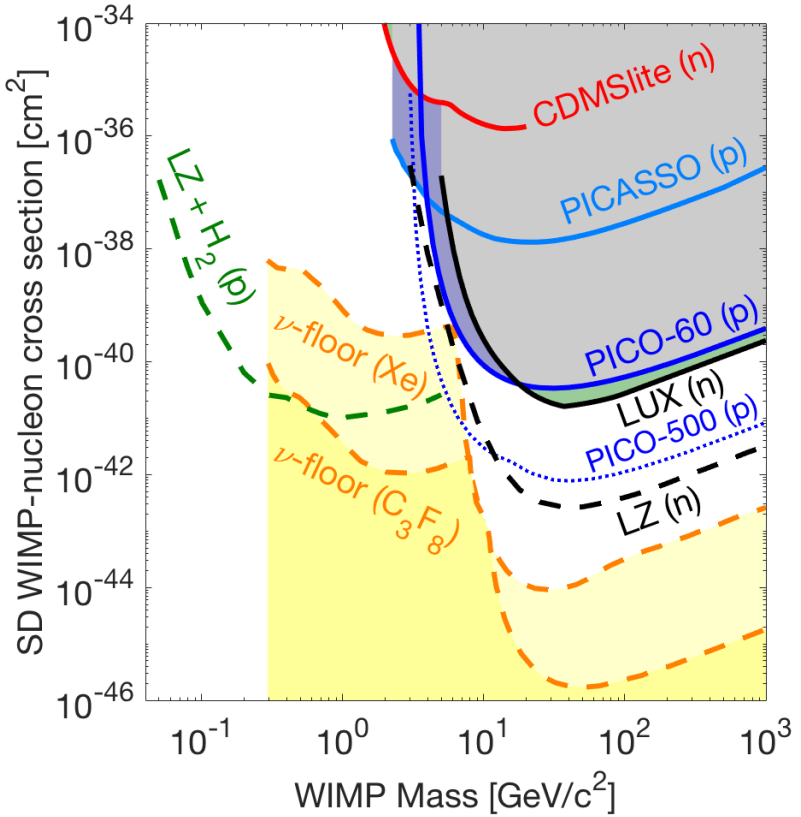
State of the Field: 10 GeV – 10 TeV

- Canonical WIMP space currently ruled by XeTPCs
  - XeTPCs might not reach CEvNS floor due to $\nu e \rightarrow \nu e$ background, but coming generation gets close
  - Directional detection can't help with this one…



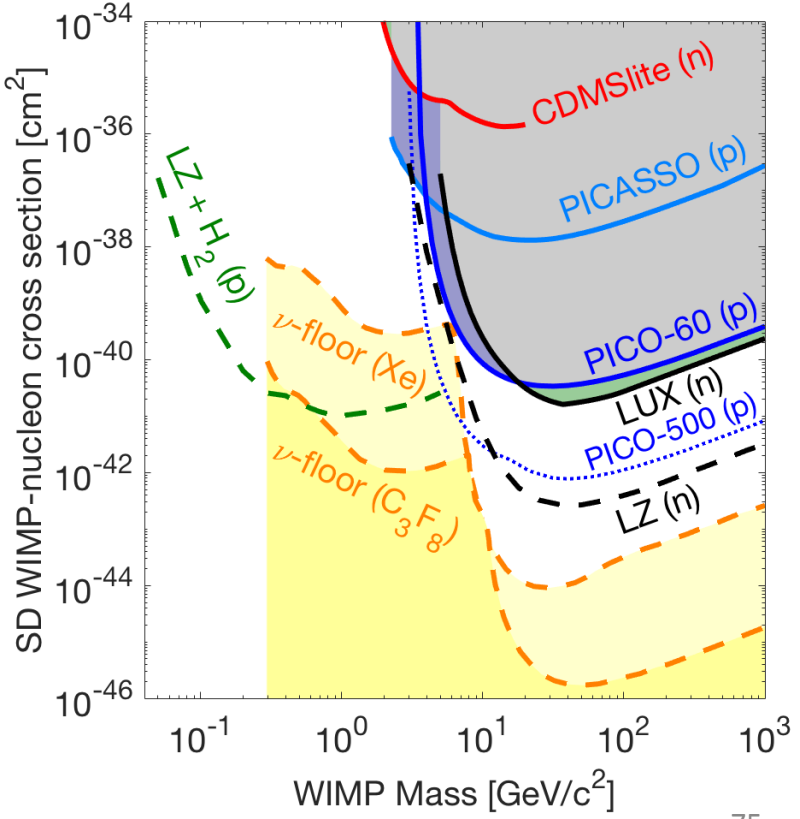
State of the Field: Spin-Dependent





State of the Field: Spin-Dependent

- Spin-Independent searches have same(-ish) CEvNS floor for all targets
- Spin-Dependent searches do not!
  - SD parameter space inaccessible to xenon may be reached with fluorine
  - Effective no CEvNS floor for hydrogen: $\sin^2\theta_W \approx \frac{1}{4}$



Preparing for a WIMP Discovery

- The field has a history of surprise "pathological" backgrounds:
  - Surface betas (CDMS Run 1)
  - Gamma-X (Xenon10)
  - Suspended particulate (COUPP, PICO)

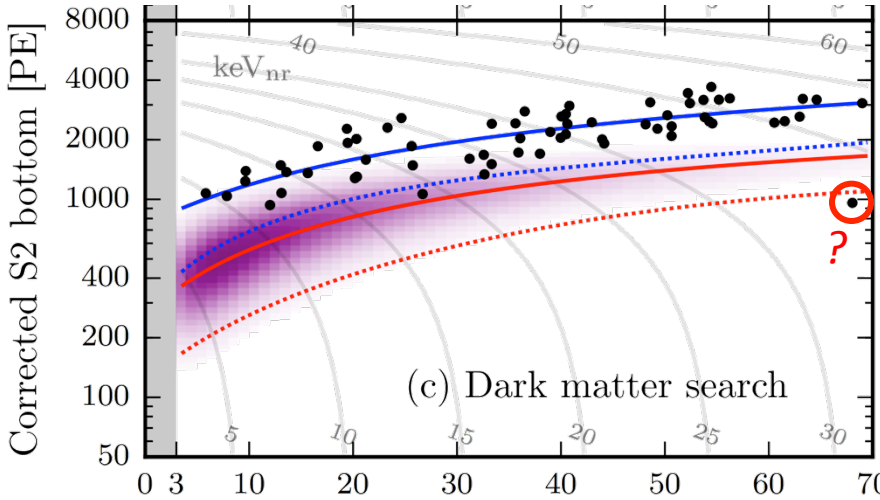
None of these were *predicted*

All were recognized after the fact as new, detector-specific backgrounds

All are now resolved

Preparing for a WIMP Discovery

- Setting WIMP limits is easy. Discovery will be hard.
- Multiple technologies with different pathological backgrounds will be key



XENON1T

*Phys Rev Lett **119**, 181301 (2017)*

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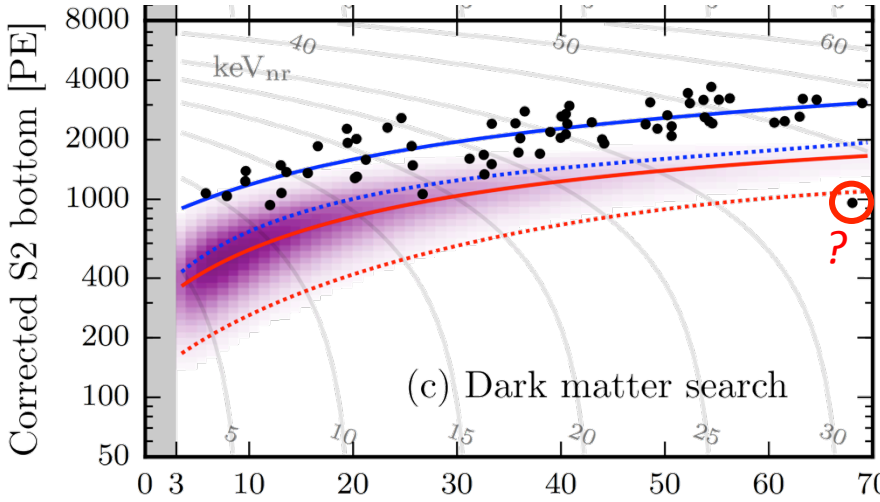


XENON1T

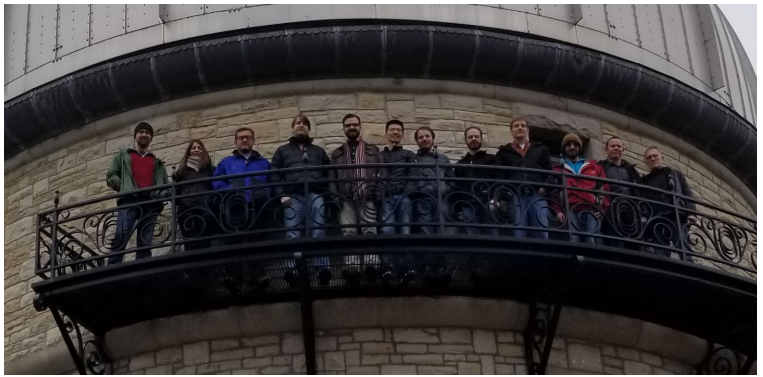
*Phys Rev Lett **119**, 181301 (2017)*

(Resolved in 2018 result)

SBC, Dec 2018

Parting Thoughts

- Dark Matter will be the discovery of the century.
  - Individually, we must be optimists.
    Prepare for discovery in YOUR experiment!
  - As a field, we have be smart – use all the tools we have, and leave no stone unturned.



Funding:
Department of Energy Award DE-SC0012161, FNAL LDRD 2018-0003, Postdoctoral support from COFI