# Basics of Dark Matter & Stars

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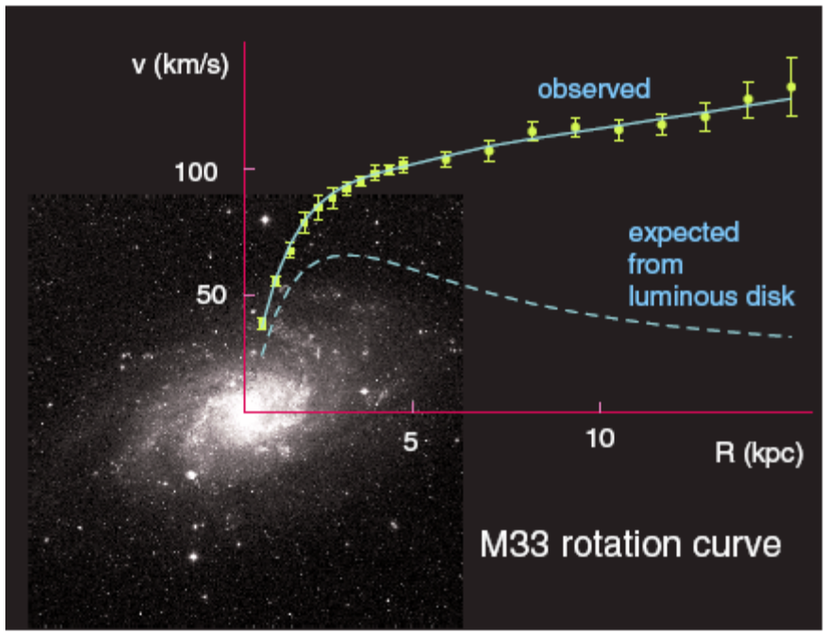
# The Missing Mass of the Universe

## A Mystery for 80 years!

Virial Theorem on Coma cluster

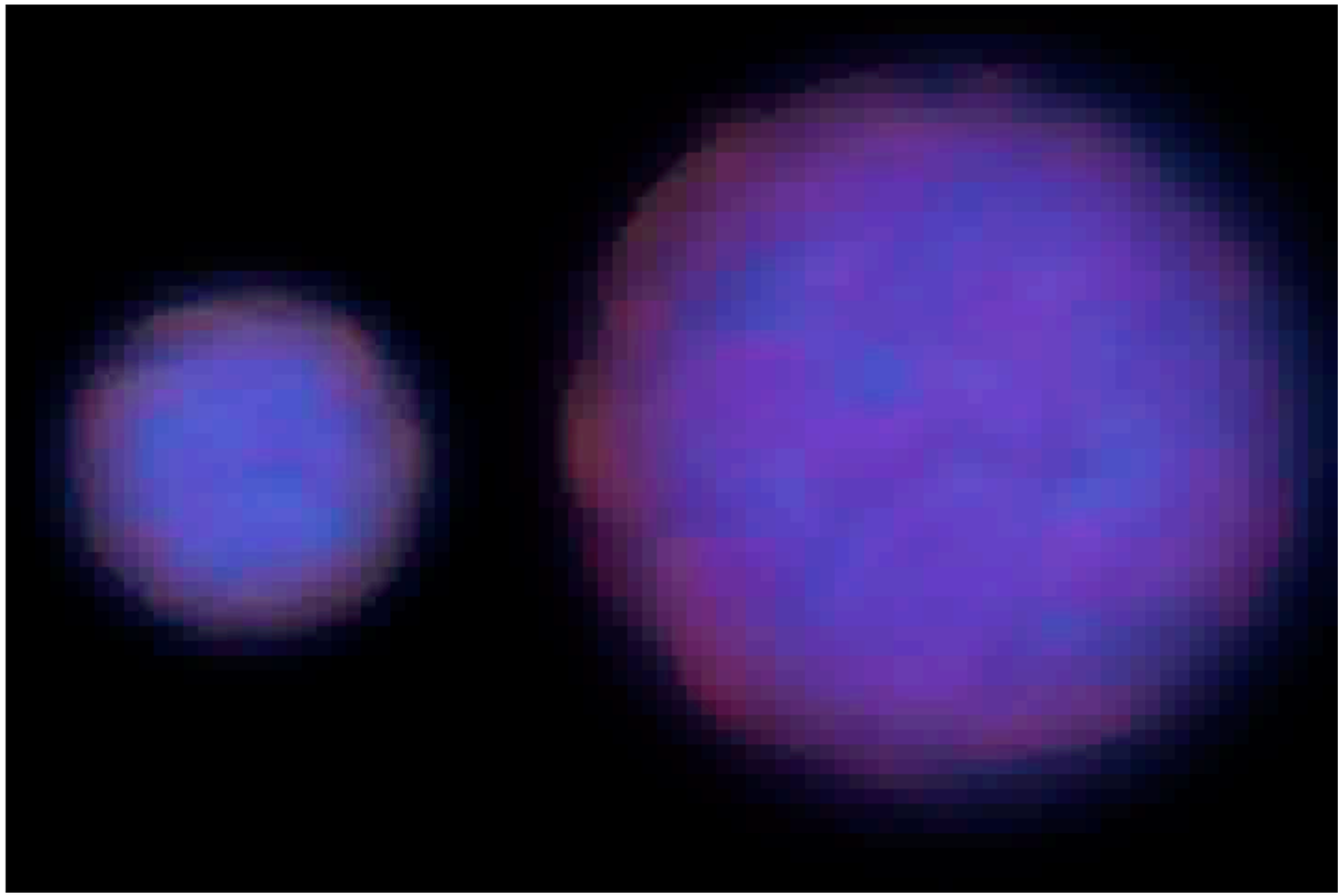
# The Missing Mass of the Universe

## A Mystery for 80 years!



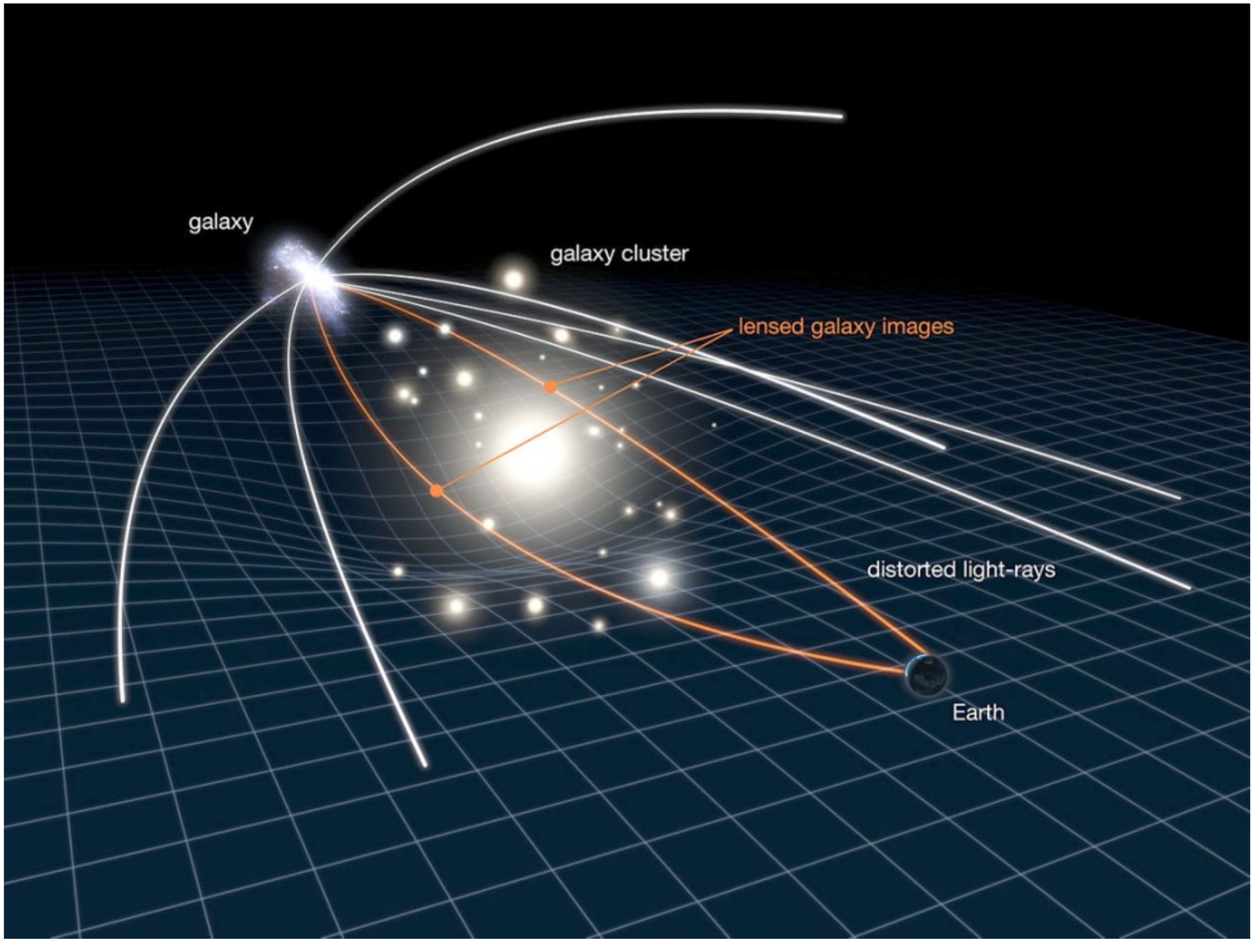

Rotation curves of Andromeda are not
falling according to Newton's law!

# Bullet Cluster



# Bullet Cluster

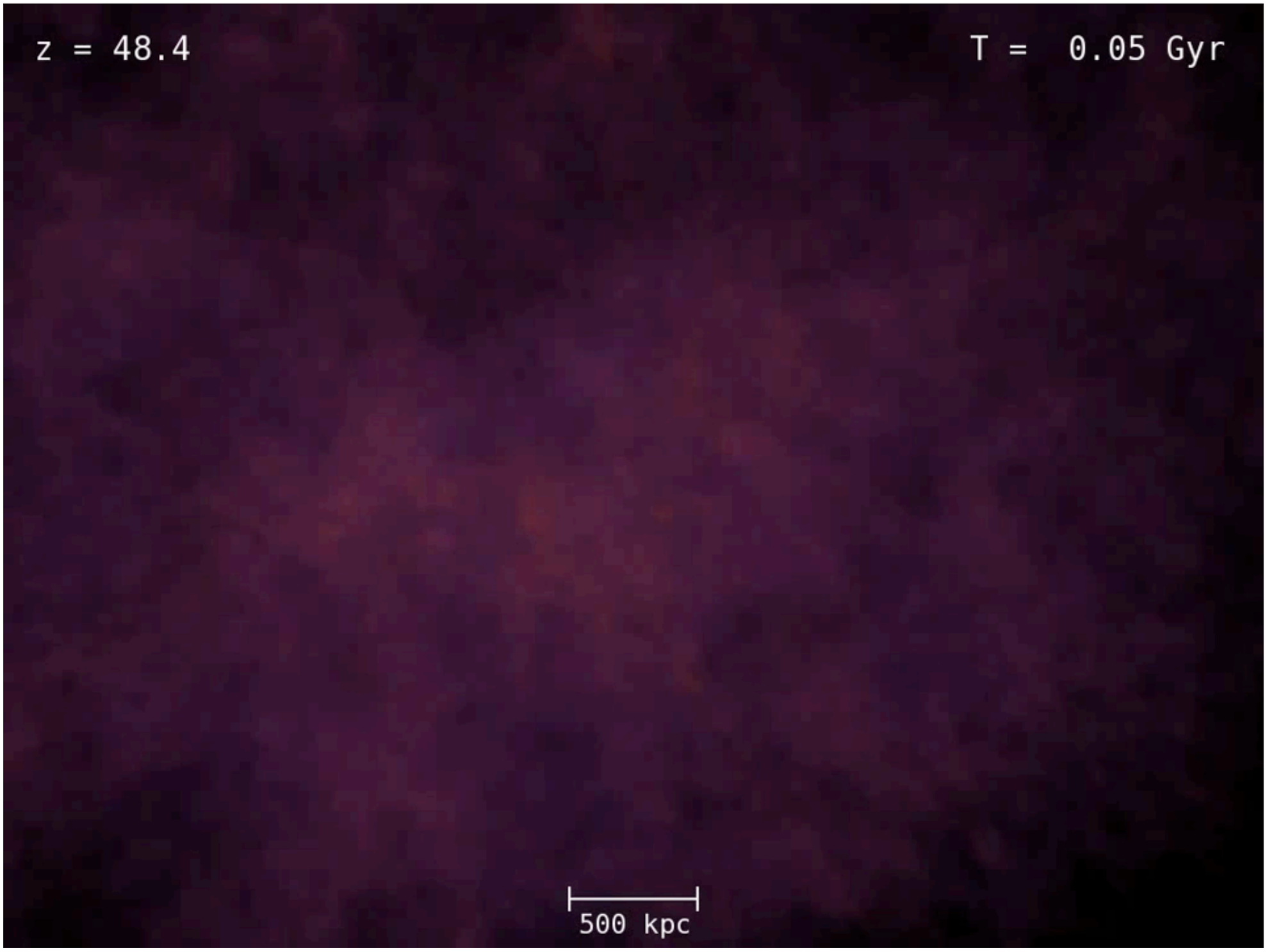
# Gravitational Lensing



# Galaxies without Dark Matter!

Galaxy NGC 1052-DF2, no dark matter!!!

# Simulating the Universe



# Dark Matter is <u>NOT</u>

- Baryons!!!
- MACHOs ruled out by microlensing observations $10^{-7}$–$30\,M_\odot$
- Neutrinos

Light neutrinos: are problematic in small scale structure
m>500 eV (Tremaine-Gunn) otherwise neutrinos violate Pauli blocking in dwarf galaxies. But for m>500 eV gives too much dark matter
Heavy Neutrinos: m> 2 GeV (Lee-Weinberg)
excluded by direct dark matter search experiments unless the mass is huge

- ChaMPs (Charged Massive Particles)
- SIMPs (Strongly Interacting Massive Particles)

ruled out by anomalous hydrogen isotope searches in ocean water*

# Dark Matter could be

- Primordial Black Holes ~$10^{59}$ GeV
- WIMPzillas ~$10^{16}$ GeV
- WIMPs ~100 GeV
- Sterile Neutrinos ~keV
- Axions <$10^{-5}$ eV

???

Technicolor

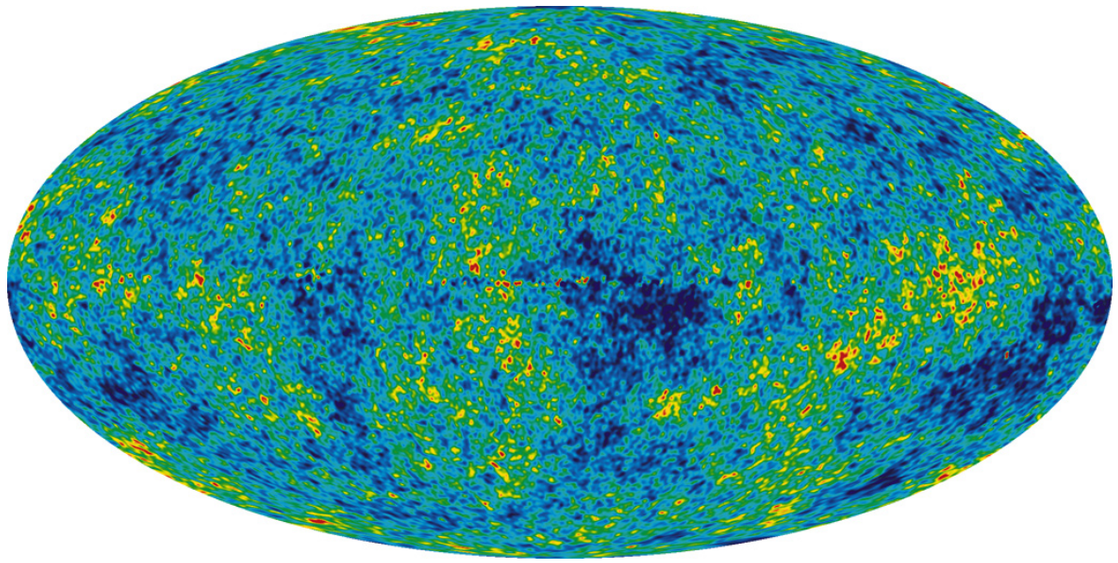
Supersymmetry

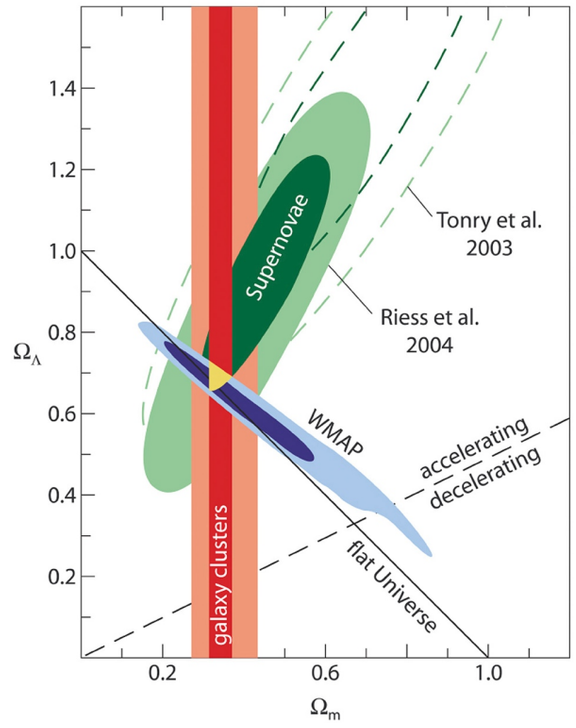
Axion

Hidden Sector

Kaluza-Klein

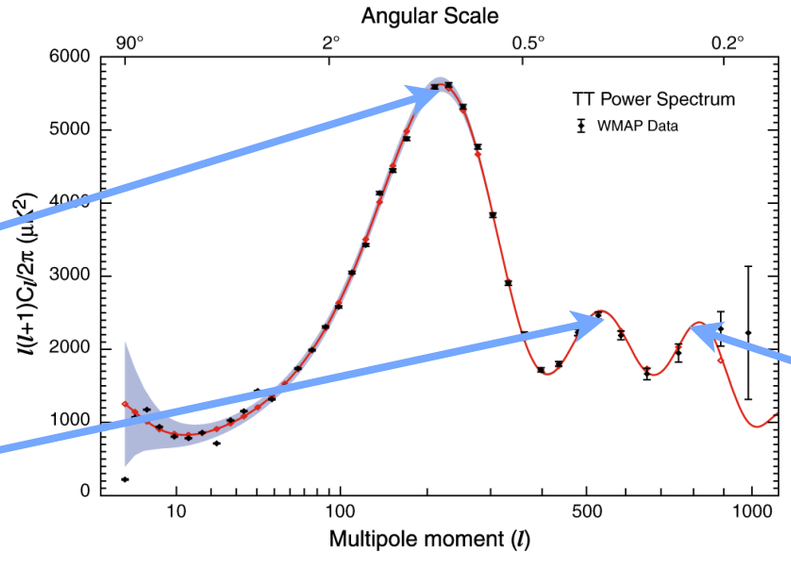
# Microwave Background Radiation






flatness of Universe

Baryonic matter

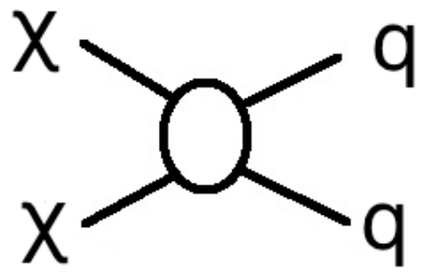



Dark Matter

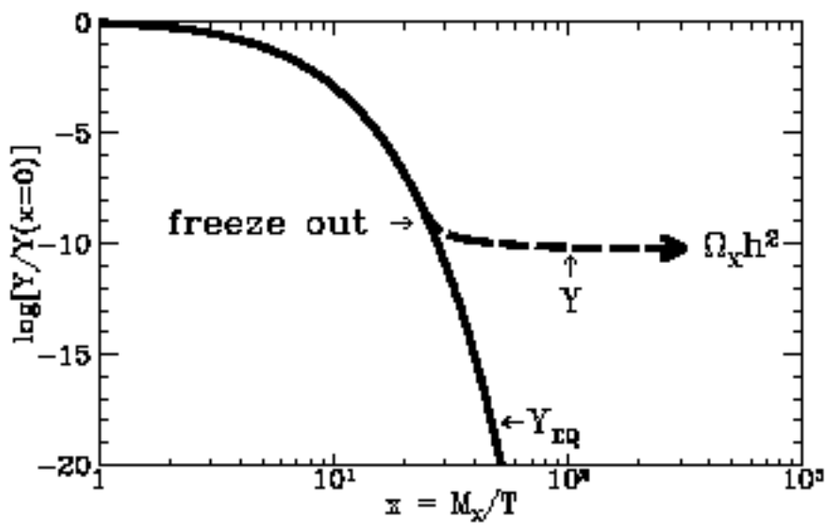
# Dark Matter Production in the Universe I

WIMP Miracle

WIMP Annihilations



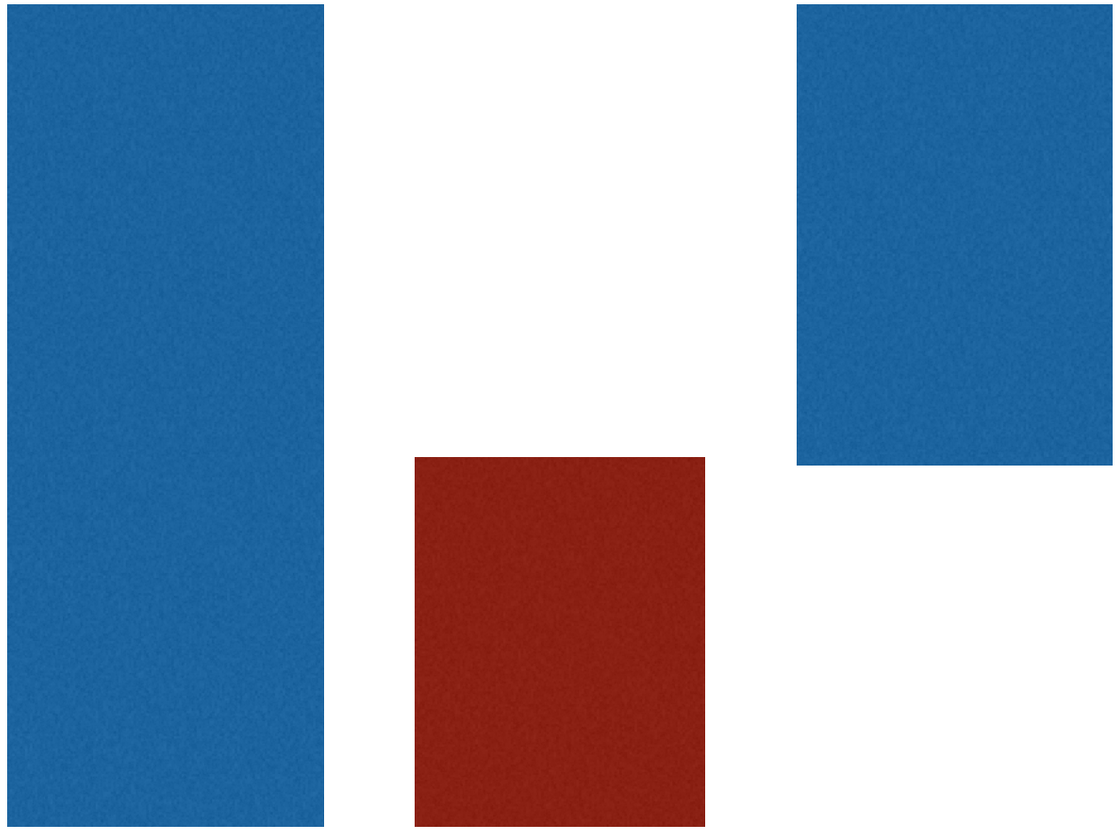

Freese-out: Expansion of the Universe becomes faster than annihilation rate



# Dark Matter Production in the Universe II

Asymmetric Dark Matter

Asymmetry mechanism similar to baryon asymmetry



DM anti-DM left over DM

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{n_{TB}}{n_B}\frac{M_{TB}}{M_p}$$

if for every baryon we create a DM particle, ~5 GeV DM accounts for the DM relic density

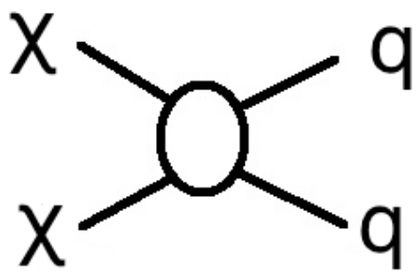
# Discovery of Dark Matter

## Dark Matter Searches

- **Underground**: DAMA, Xenon, CDMS, CoGeNT, CRESST, PICASSO, SIMPLE...
- **Balloon/Satellite Experiments**: ATIC, HEAT, PAMELA, FERMI, XQC, WMAP, PLANCK, EGRET, CHANDRA ...
- **Neutrino Detectors**: IceCube, Super-Kamiokande...
- **Accelerators**: Tevatron, LHC
- **Telescopes**: Hubble
- **Anomalous Isotope searches, Axion dark matter searches**

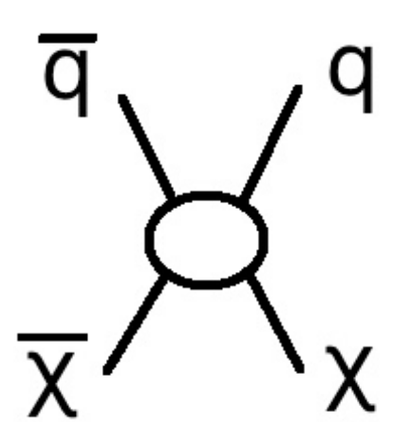
# Detection of Dark Matter

## Direct detection



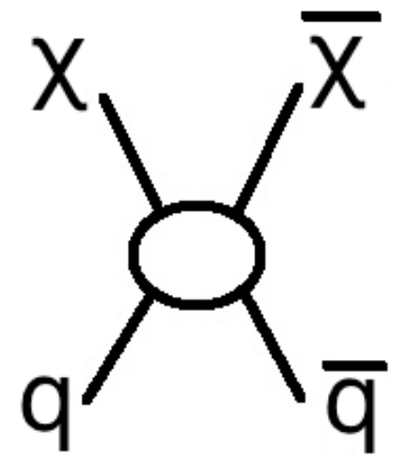

Inconclusive!
DAMA has signals compatible with dark matter. Xenon, Picasso, LUX null results.

## Indirect detection




Inconclusive!
PAMELA and AMS-02 positron excess

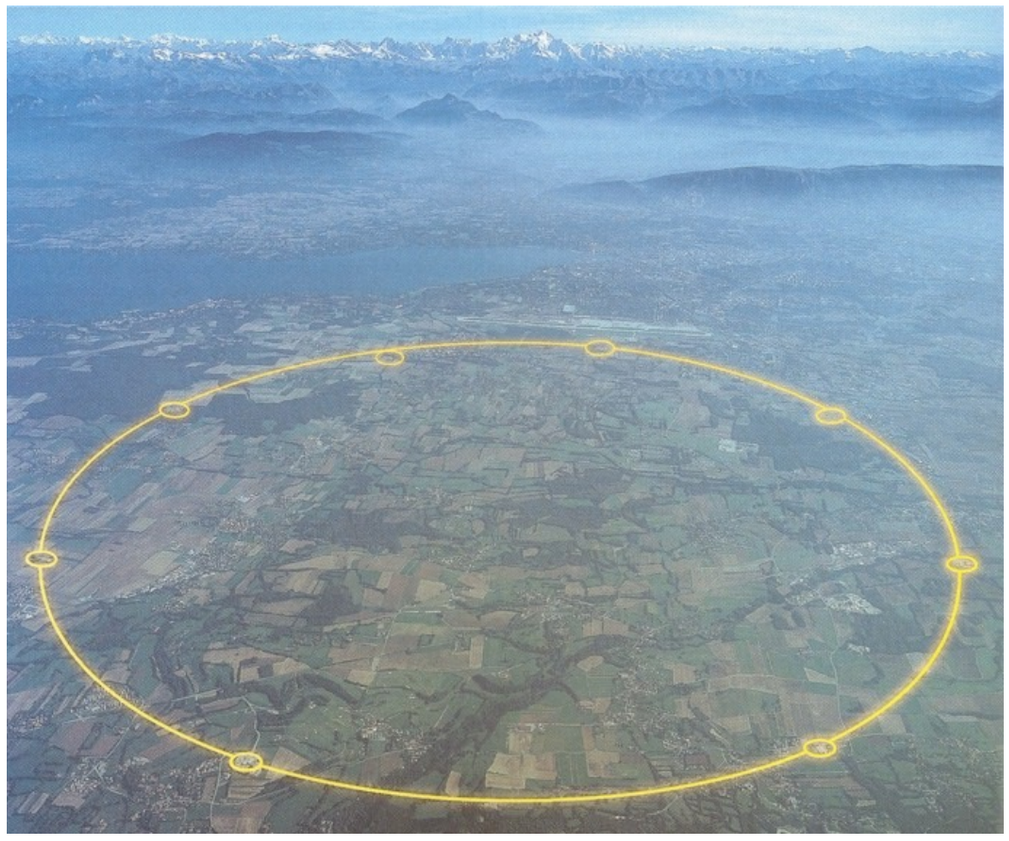
## Production



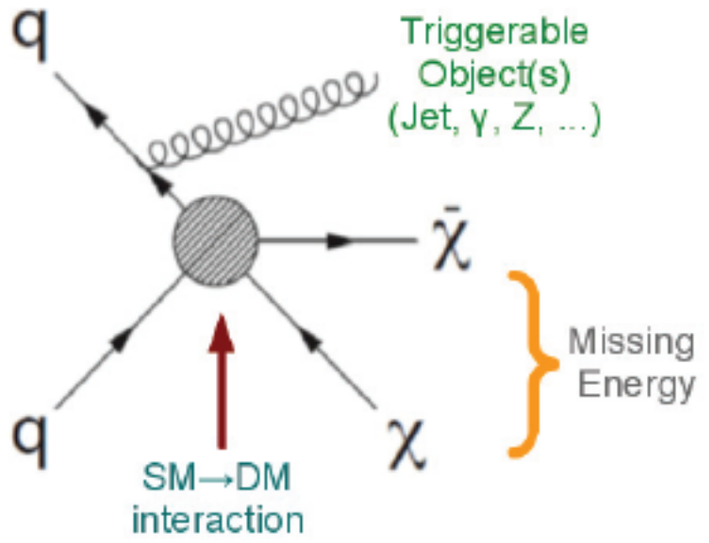

Inconclusive!
LHC monophoton, monojet production and missing energy signal... nothing yet

# Production of Dark Matter

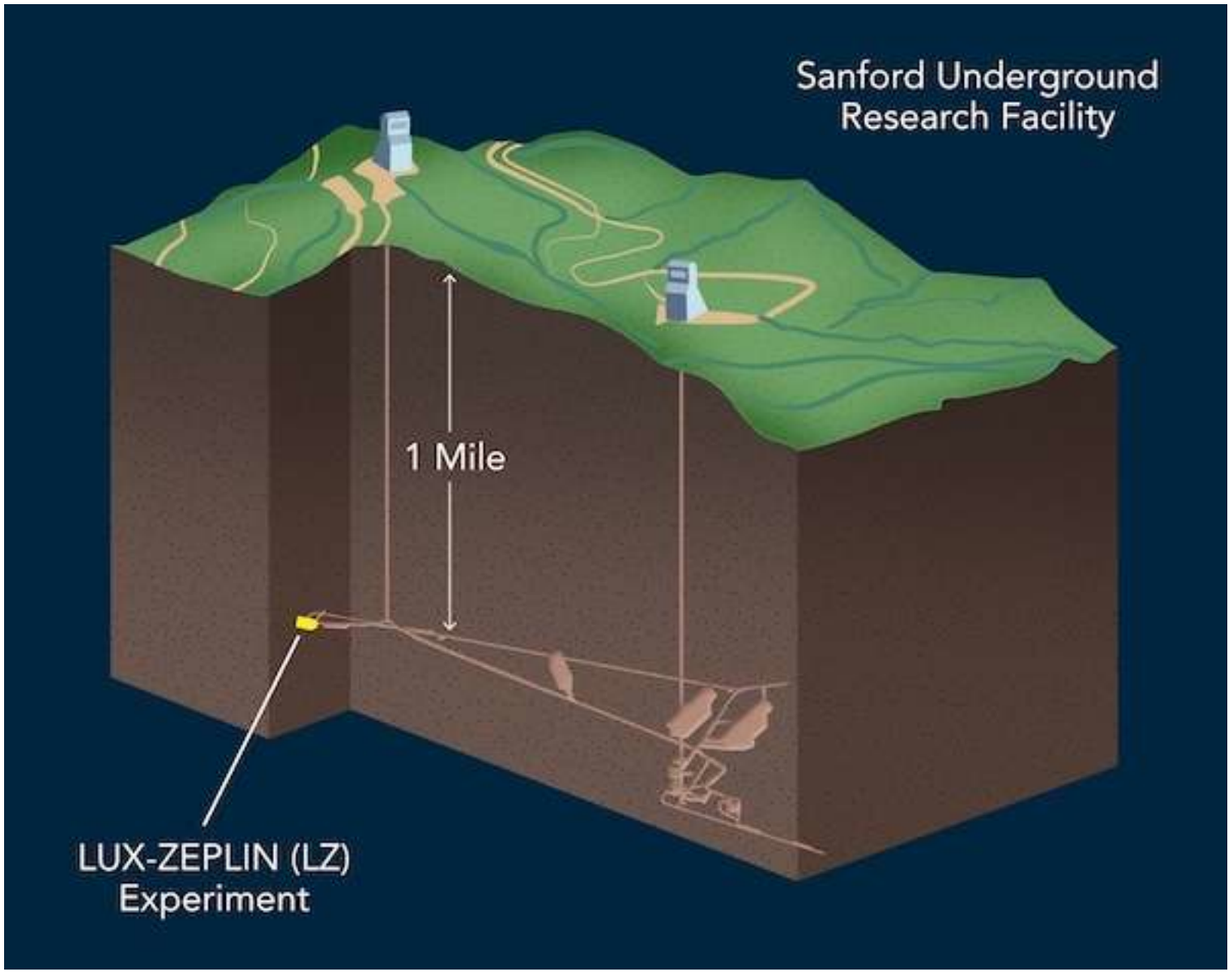
## Large Hadron Collider



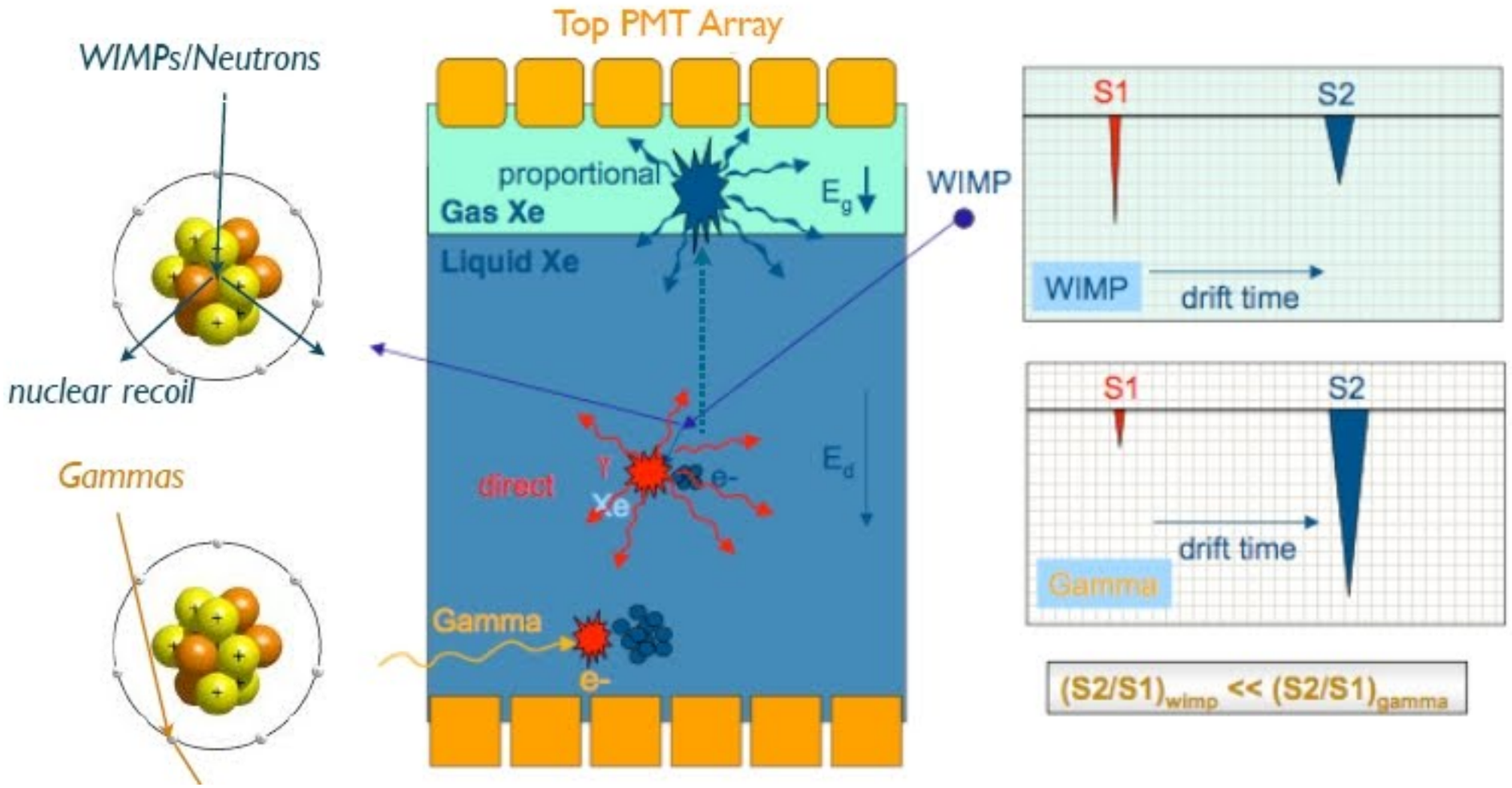
## Monophoton-Monojet



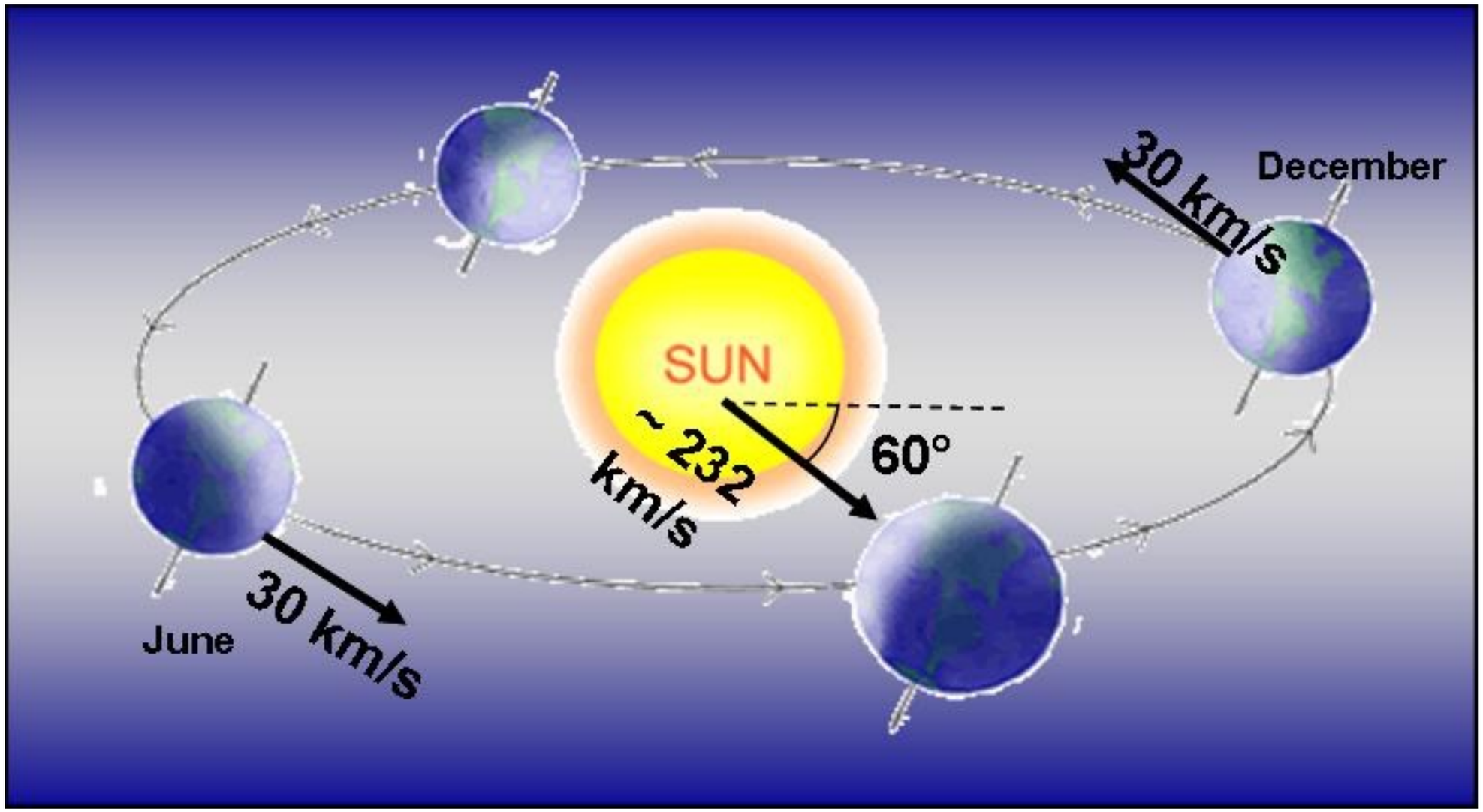
# Direct Detection

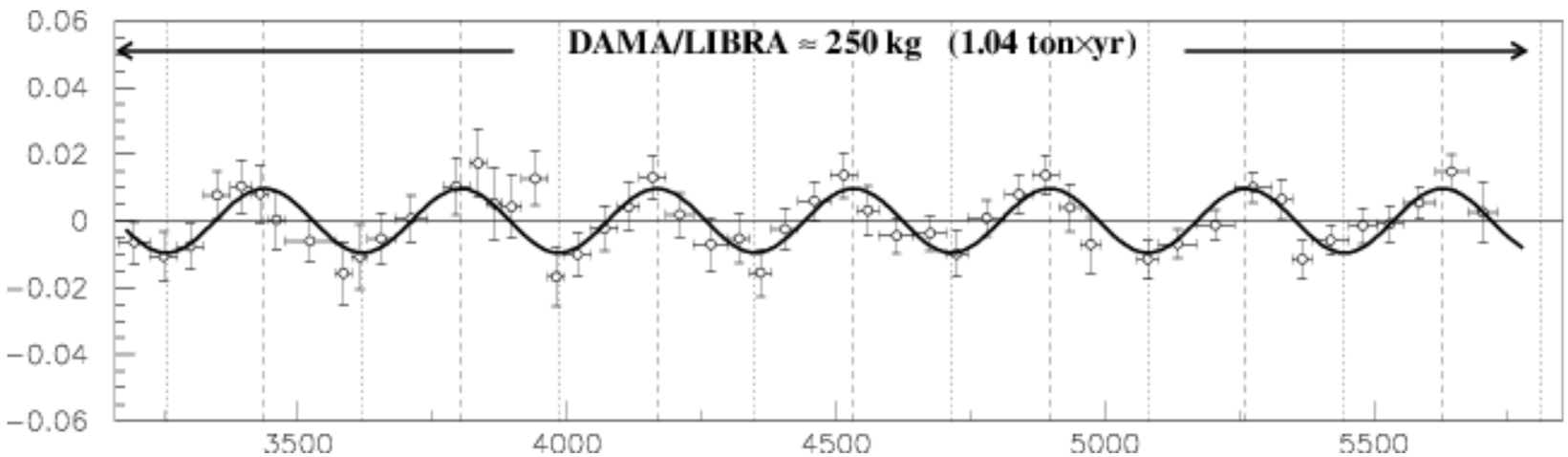


# Direct Detection



# Annual Modulation in Direct Detection

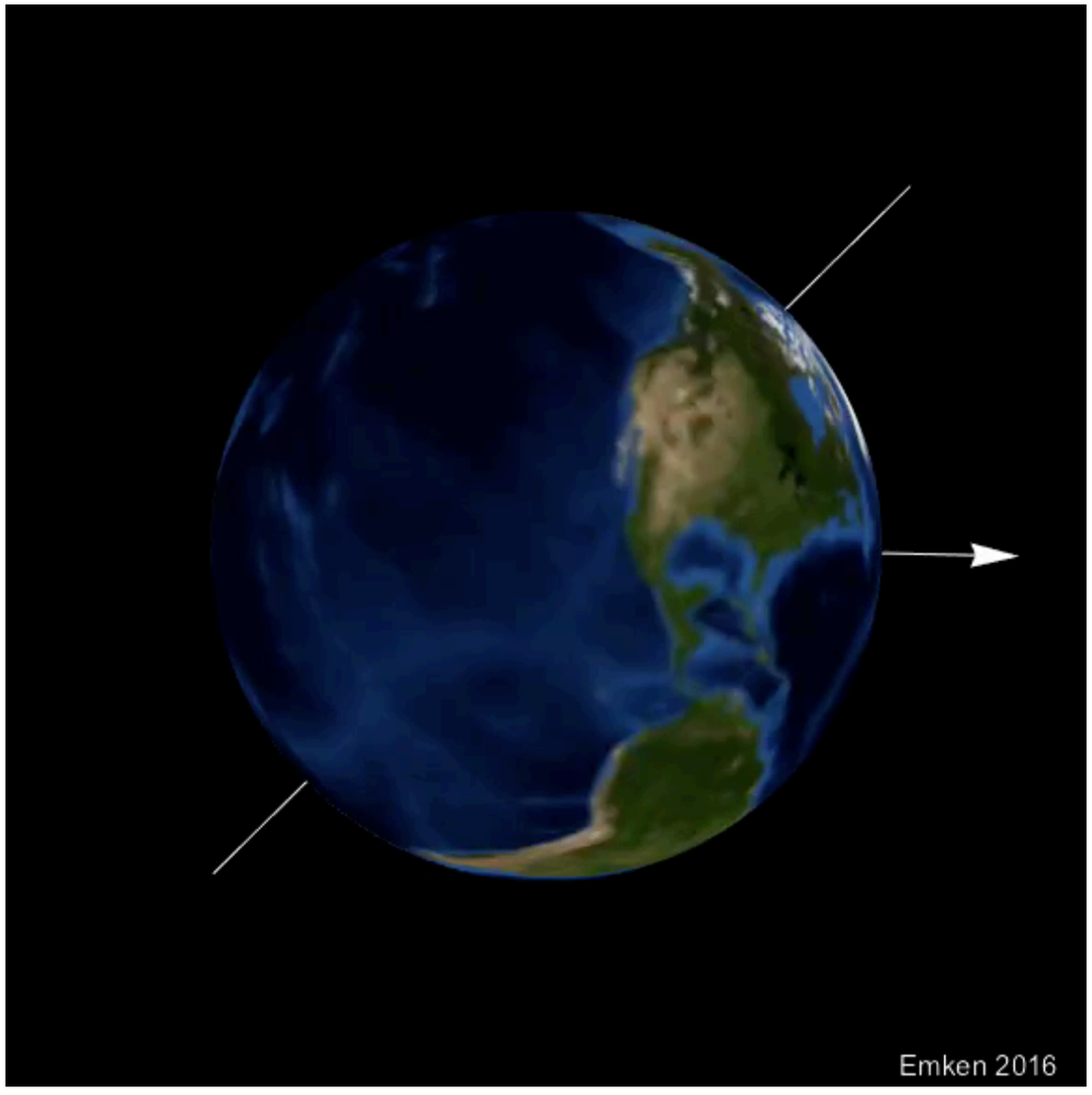


# Daily Modulation in the Dark Matter Signal

The dark matter signal in underground detectors has three types of diurnal modulation:

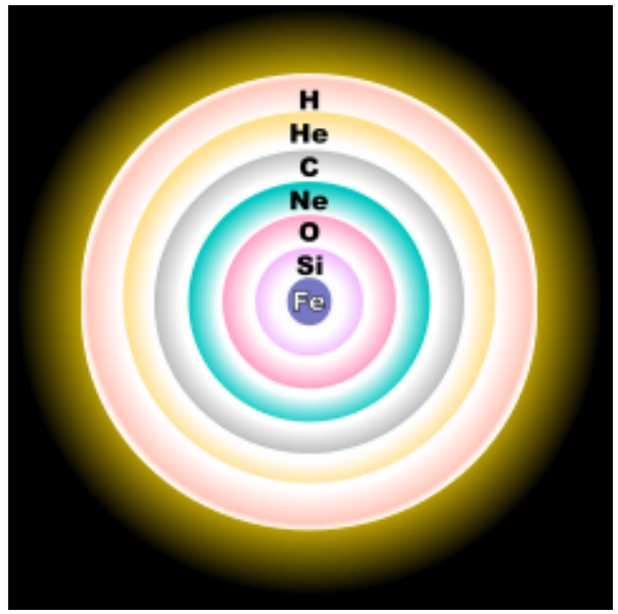
- Gravitational focusing
- Rotational velocity of the Earth
- Shadowing effect



# Neutron Stars

Result of Supernova II explosion of supermassive stars ~9-20 $M_\odot$

No fusion and energy production




Very compact objects:
Mass: $M \approx 1\text{-}2\ M_\odot$
Radius: $R \approx 10\text{-}12$ Km
density: $5\text{-}10\ \rho_0$

$n_0 = 0.16\ \text{fm}^{-3} \Rightarrow \rho_0 = 3 \cdot 10^{14}\ \text{g/cm}^3$

Extreme Magnetic Fields: up to $B \sim 10^{16}$ G

Fast Spinning: Periods msec to sec (pulsars)

# The Interior of the Neutron Stars

- **Atmosphere**

  thickness: ~1 m,
  density: $\rho \leq 10^4$ g/cm$^3$
  composition: atoms, Fe…

- **Outer Crust/Envelope**

  thickness: ~hundreds of m
  density: $\rho = 10^4\text{-}4 \cdot 10^{11}$ g/cm$^3$ (neutron drip point)
  composition: Fermi gas of electrons and lattice of neutron rich nuclei

- **Inner Crust**

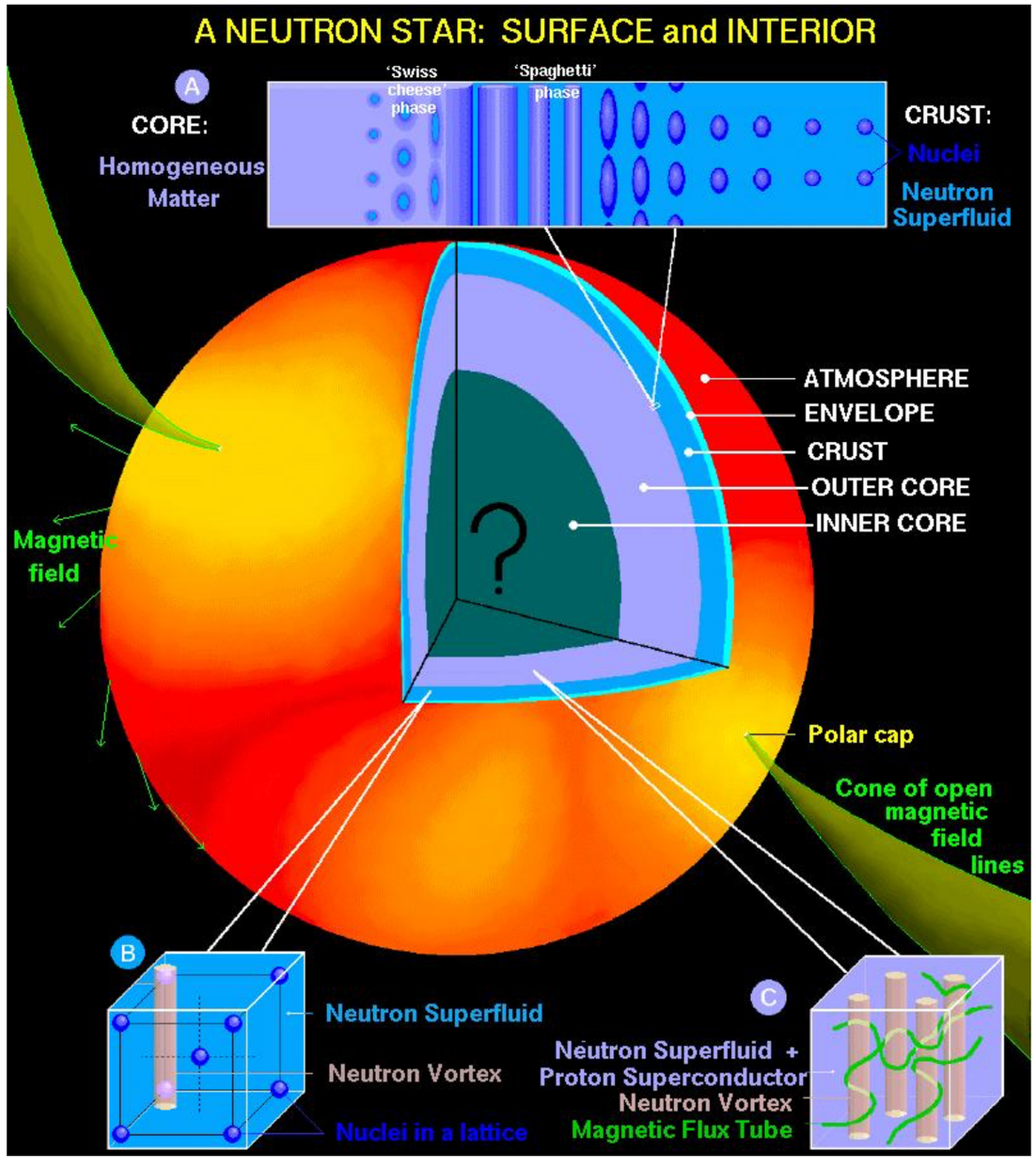
  thickness: ~1-2 km
  density: $\rho = 4 \cdot 10^{11}\text{-}10^{14}$ g/cm$^3$
  composition: electron gas, neutron rich atomic nuclei and clusters and free neutrons

- **Outer Core**

  thickness: ??
  density: $\rho_0/2\text{-}2\rho_0$
  composition: free electrons, (superconducting) protons, (supefluid) neutron

- **Inner Core**

  thickness: the rest
  density: 2-10 $\rho_0$ ??
  composition: exotic phases, quark core, color superconductive phases, meson condensation, other hadronic phases




credit: http://www.astro.umd.edu/~miller/Images/NStarInt.jpeg

# The Neutron Star EoS

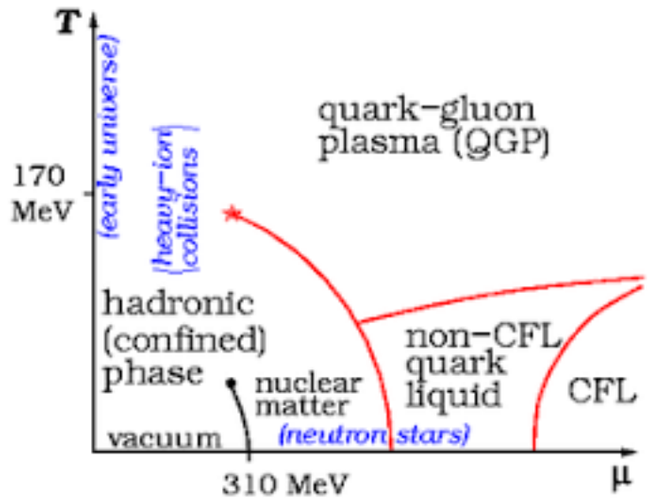
Outer Core: weak equilibration

$$n + n \to p + e^- + \bar{\nu}_e + n \qquad \text{direct Urca process}$$

$$n + p + e^- \to n + \nu_e + n \qquad \text{modified Urca process}$$

$$\mu_n = \mu_p + \mu_e \qquad p_{\mathrm{F}e} = \hbar(3\pi^2 n_e)^{1/3}$$

Inner Core: potential exotic quark phases



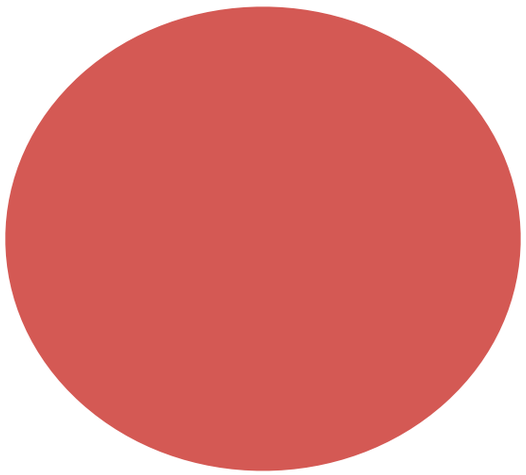

EoS are constrained by mass-radius relations, GW EoS+ Tolman Oppenheimer Volkoff

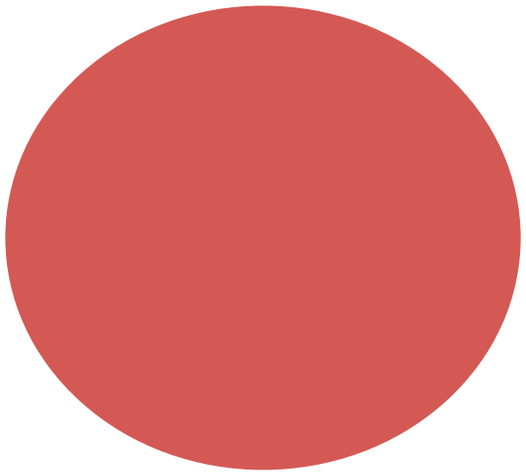
$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}\frac{\left[1+\frac{P}{\rho}\right]\left[1+\frac{4\pi r^3 P}{M}\right]}{\left[1-\frac{2GM}{r}\right]}$$

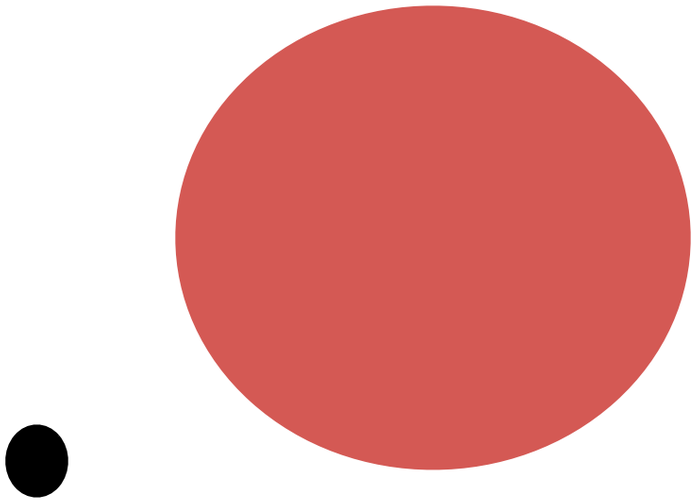
Maximum mass without strong interactions ~0.7 $M_\odot$

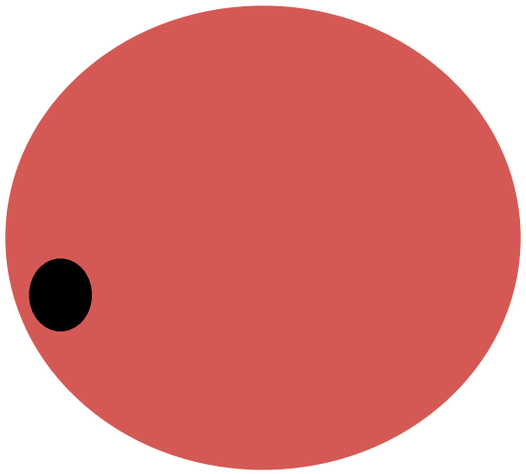
PSR J1614−2230 1.97 $M_\odot$ Black Widow, ~2.4 $M_\odot$

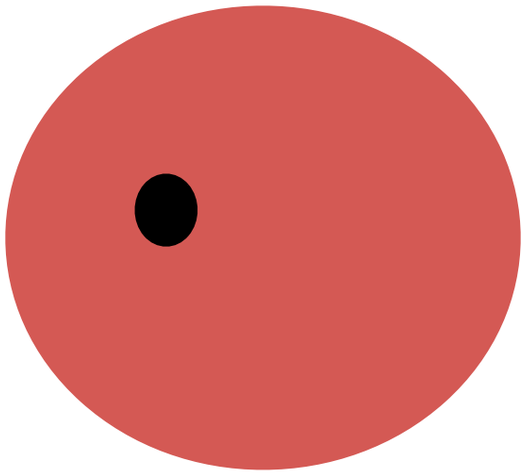
# Heating up Compact Stars

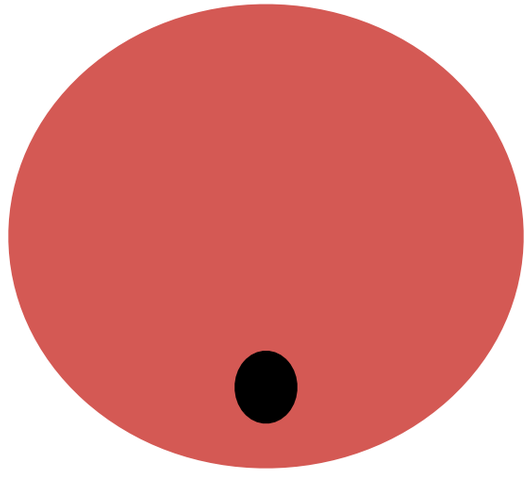


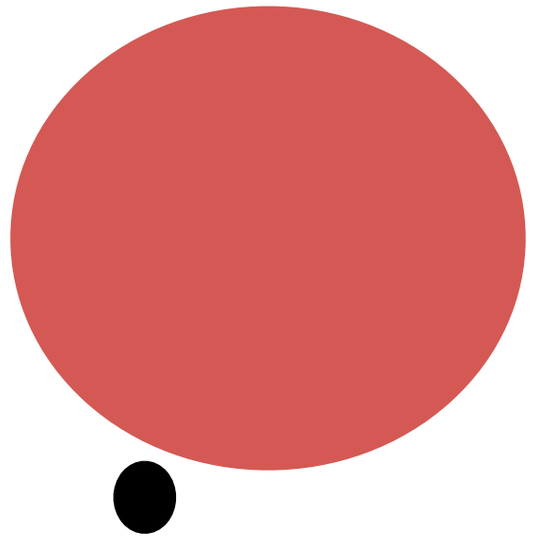


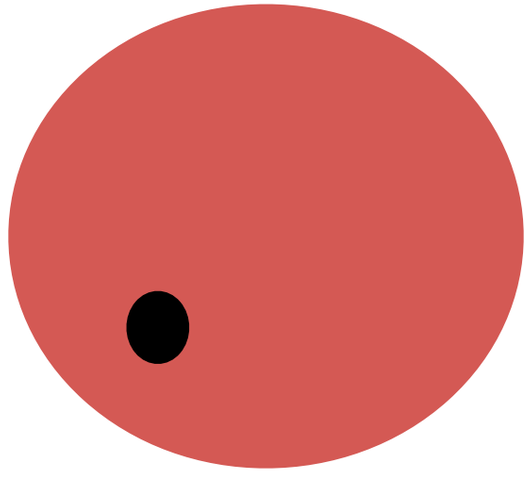


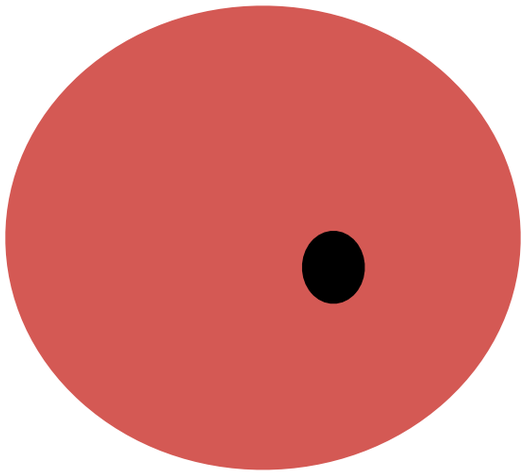


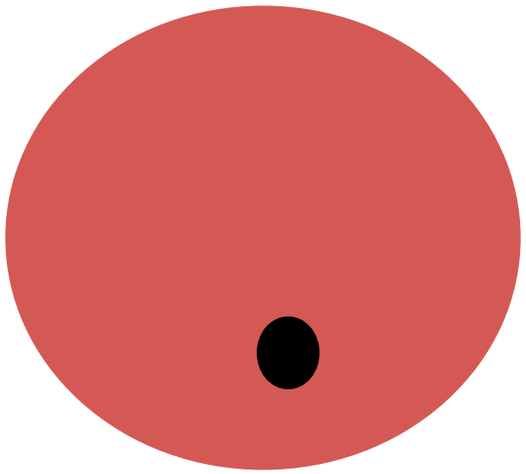


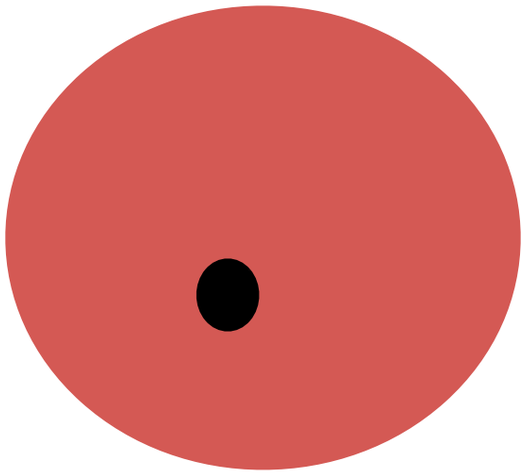


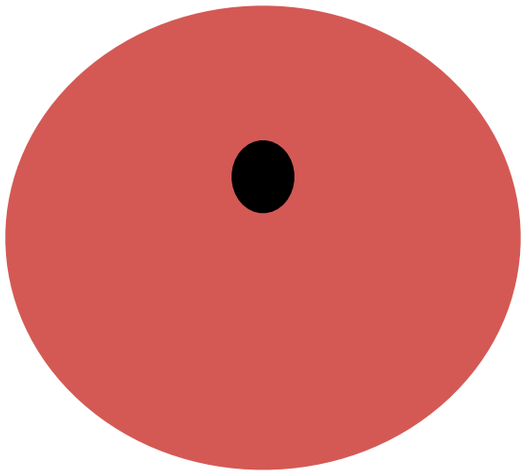


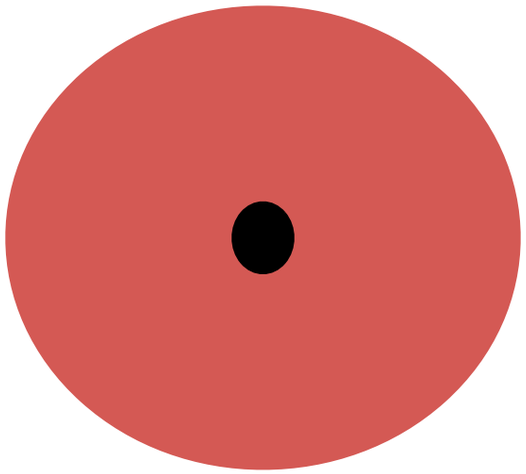


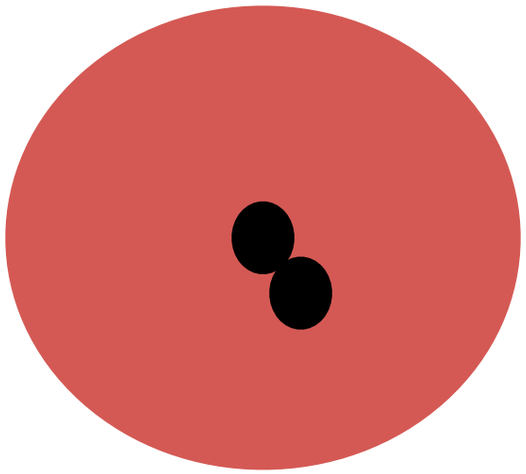


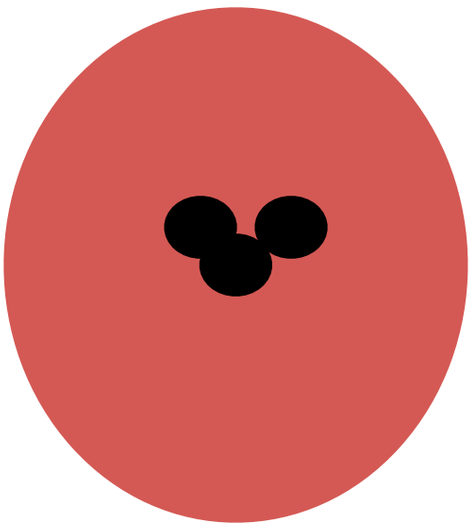


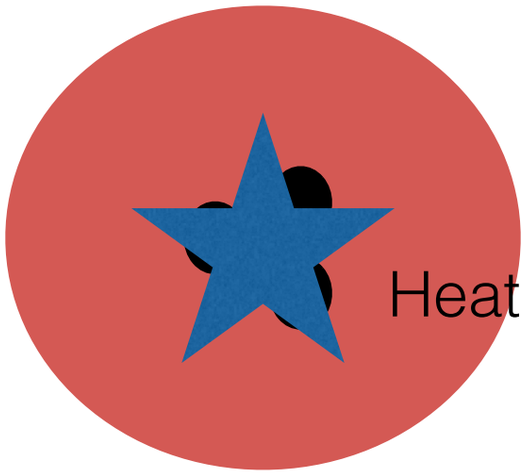











Heat

# Destroying Neutron Stars