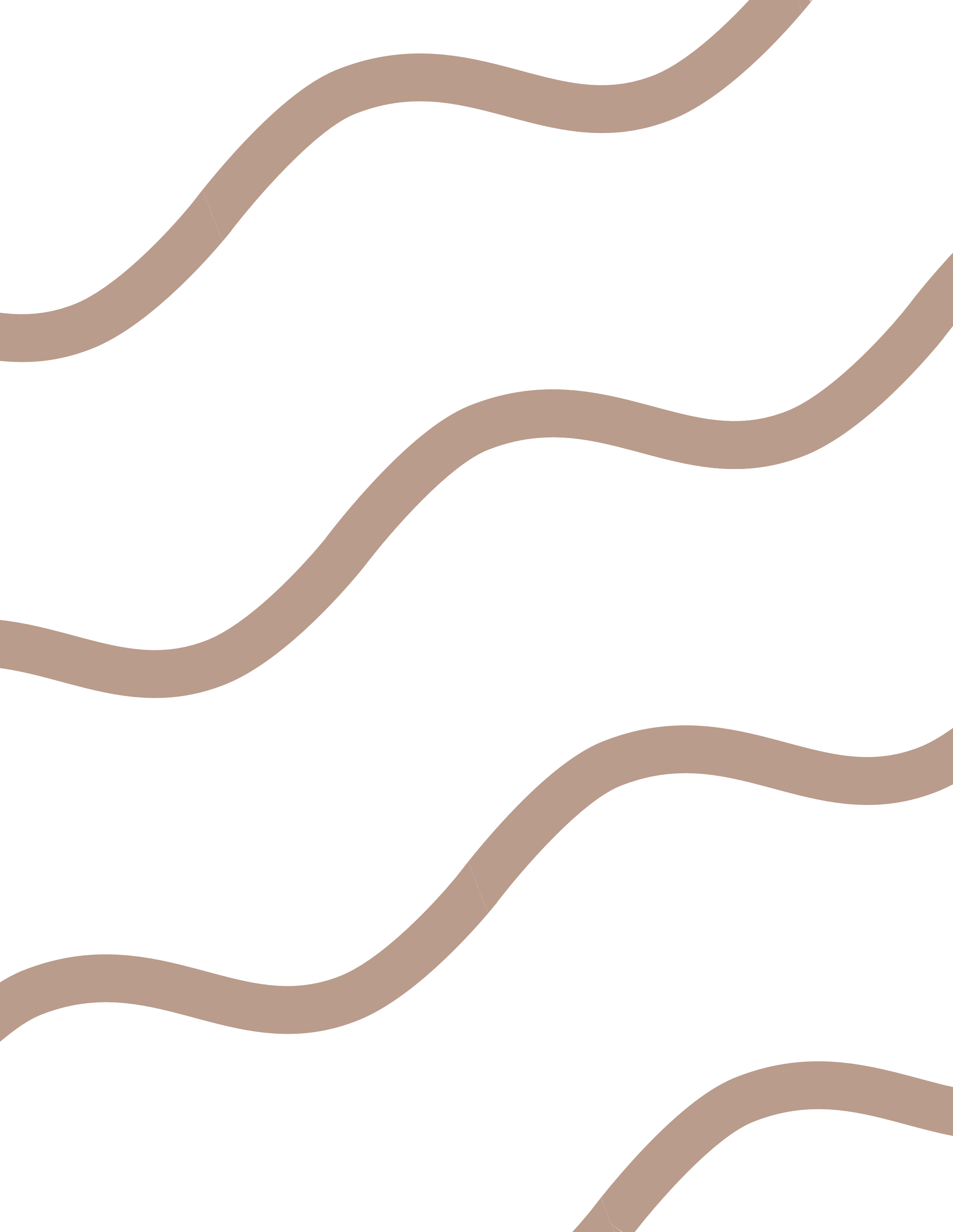


Taweewat Somboonpongkul: taweewat.s@chula.ac.th

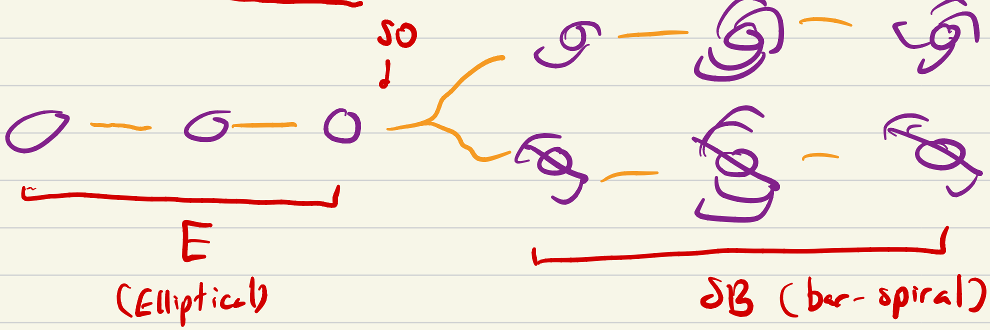
## Galaxy Cluster

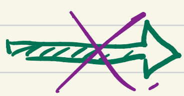
- Messier → 18th century (1700s) → Virgo Cluster
- Abell, Zwicky – catalogs – list of all detectable clusters

Ex Abell 1835, Abell 2027,

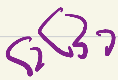
### Hubble Tuning Fork

S (spiral)



wrong idea!



IR
(irregular)

| morphology | 3 objects |
| --- | --- |
| E/S0 | 2, 6, 9 |
| S | 12, 1, 8 |
| SB | 4, 3, 10 |
| IR | 5, 7, 11 |

4, 12, 6, 9, 8, 13, 3,

10, 1, 5, 7, 2

Until 1: 40 PM !

I (E/S0)  II (S/SB)  III IR  IV uncertain

A

B

C

D

| | I | II | III | IV | |
|---|---|---|---|---|---|
| | E/SO | S/SB | IR | uncertain | total |
| A | 9 | 10 | 11 | 12 | |
| | + | + | + | + | |
| C | 5 | 4 | 14 | 14 | |
| total | 14 | 14 | 25 | 26 | 79 |

| | |
|---|---|
| B | |
| D | |
| total | |

A+C

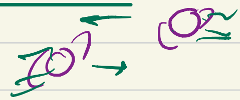
% of Elliptical $= \frac{e}{n} = \frac{14}{79} = \ldots\%$

B+D

$= \ldots\%$

| | Cluster (ในกระจุก) | | Field (นอกกระจุก) | |
|---|---|---|---|---|
| | Elliptical ✓ | Spiral | Elliptical | Spiral ✓ |
| 1 | 86 | 14 | 44 | 56 |
| 2 | 79/58 | 21/20 | 8/43 | 92/23 |
| 3 | 51 | 49 | 62 | 45 |
| 4 | 60 | 33 | 29 | 63 |
| 5 | 86 | 14 | 40 | 60 |
| 6 | 63 | 37 | 47 | 53 |
| 7 | 50 | 50 | 39 | 61 |
| 8 | 83 | 17 | 69 | 31 |
| 9 | 72 | 28 | 18 | 82 |
| 10 | 62 | 38 | 40 | 60 |
| 11 | 64 | 36 | 48 | 52 |
| 12 | 72 | 28 | 47 | 53 |
| 13 | 55 | 45 | 47 | 53 |
| | 80 | 20 | 30 | 70 |

## Why galaxies in clusters have more elliptical than spiral?

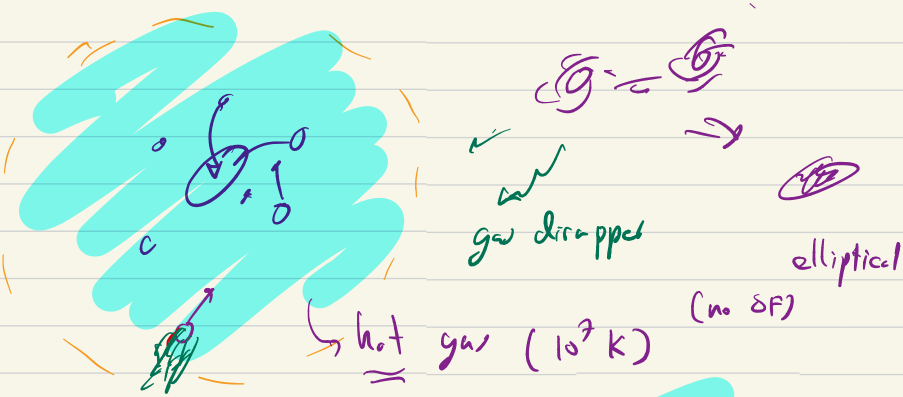


1. E older → form clusters

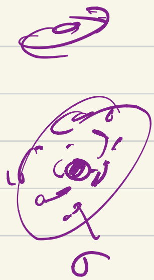
2. Clusters have more collision (closer together) → spiral pattern disappear
   interaction

   high redshift galaxies!

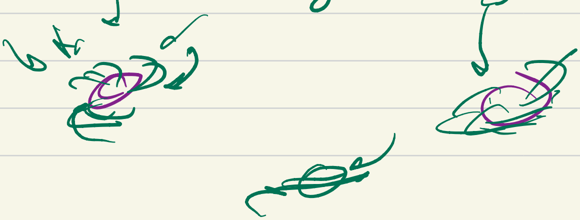
3. Observation bias: easier to observe spirals in fields




4. ram pressure stripping


spiral → ellipticals
↓
no gas

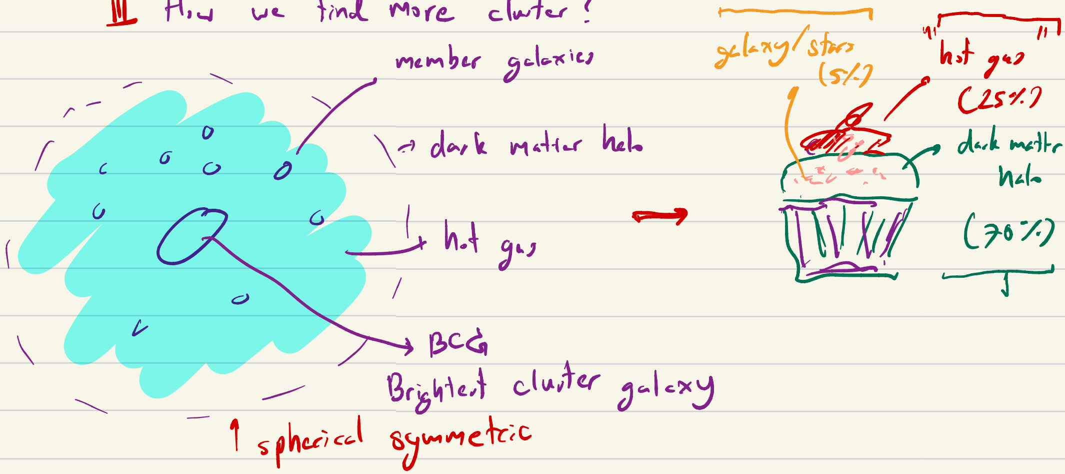


# Outline

I Gas Properties of clusters

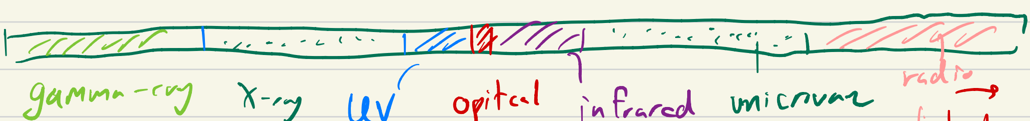
II Why do we care about cluster?

III How we find more cluster?




hot gas → How do we see hot gas?

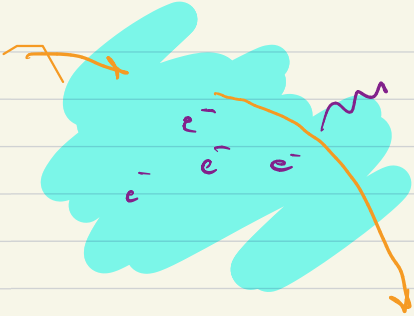
EM wave




high ↗

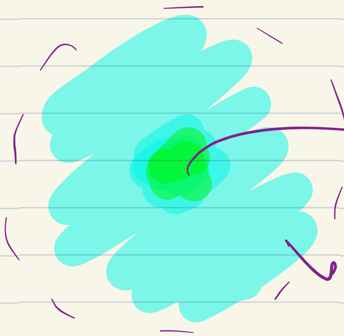
← $10^6 - 10^{7.5}$ K   $10^5 - 10^6$ K   6000 K   300 K   ~10 K   1 K →

hot gas $10^7$ K ⇒ bright in X-ray!




X-ray = Thermal Bremsstrahlung

$$E \propto n^2 \cdot T$$



brightest in X-ray

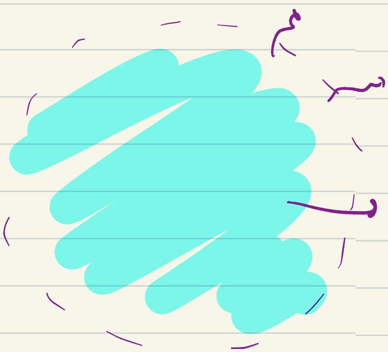
fainter in outskirts

Extended objects

## What can we learn from X-ray radiation in cluster?

- Bullet, Bubble, Sloshing $\Rightarrow$ different aspects of cluster.

See figure at the end.



X-ray radiation continously.

Why hot gas stay gas?

T ⇓ ⇒ Move inward


X-ray ⇒

Cooling flow

filamentary structure ⇒ cooling flow

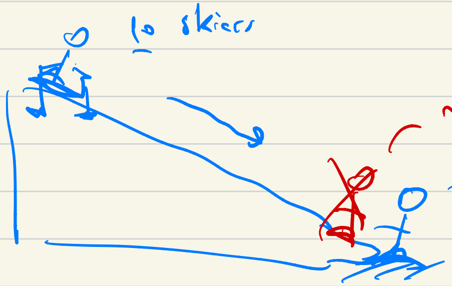
calculation / simulation

observation

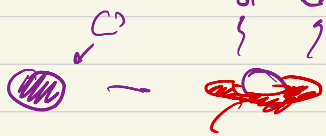
We do not see cooling flow in normal cluster

↳ "Cooling flow" Problem

⇑

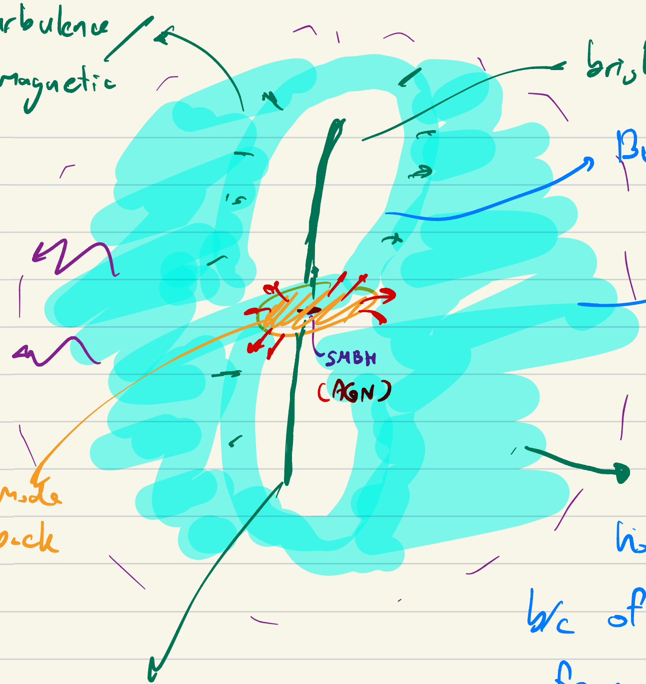



release a lot of energy




Soln   AGN feedback

(Active Galactic Nuclei) = active black hole.

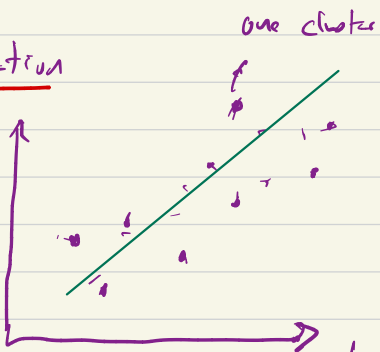



($10^7$ K)
temperature of hot gas remain high b/c of input energy from central AGN.

- radiative mode feedback

- kinetic mode feedback

Observation




Cavity power / jet power (radio)

⇓

Heating

→ $\boxed{\text{Cooling} = \text{Heating}}$

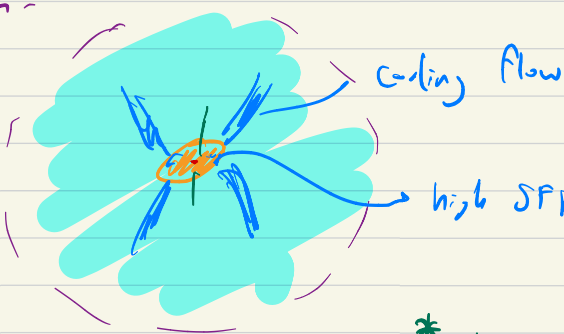
Energy released X-ray

$L_{\text{x-ray}}$

⇓

cooling

But we discovered clusters w/ cooling flow!




ex. Phoenix cluster (2012)

⇓

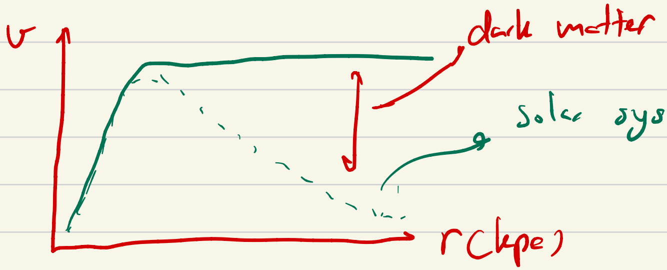
* Why do we find cooling flow?

---

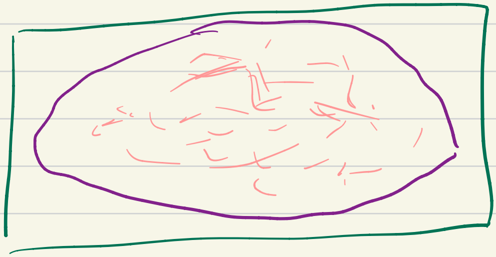
Why do we care about clusters?

Dark Matter:

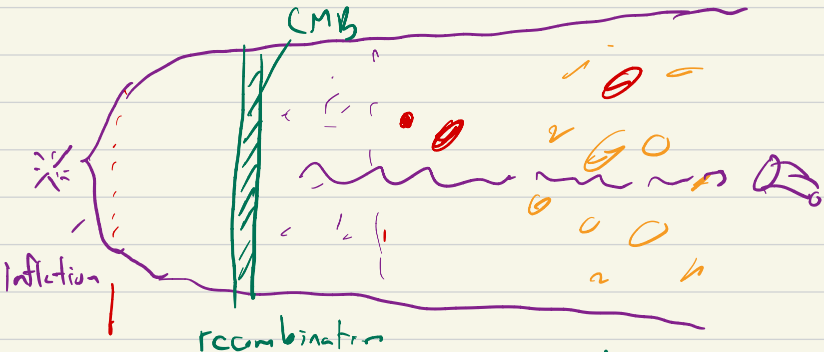
- flat rotation curve from spiral galaxies (Vera Rubin)




- CMB



# CMB: Cosmic Microwave Background (first light)




high temperature

$p^+$ $p^+$ $e^-$ $e^-$ $e^-$ (scatter)

$\gamma$ free electrons

As time passes

lower temp.

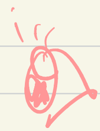
$p^+ e^-$

H

recombination
($z = 1{,}100$)

CMB

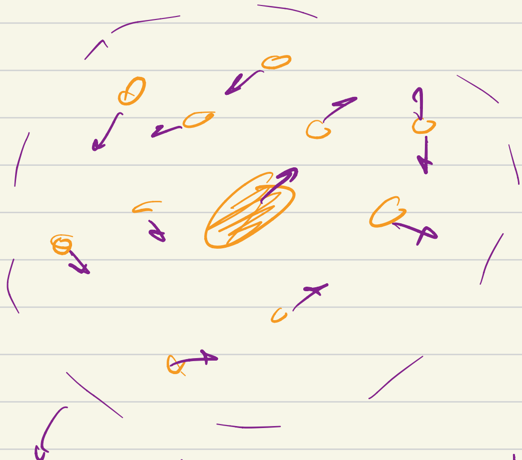
$p^+ e^-$



CMB → properties of young universe

→ $\Omega_M$ ⇒ Dark matter exist

3. Galaxy Cluster → first method (Zwicky)



Coma Cluster

velocity dispersion of member galaxies is too high.

⇓

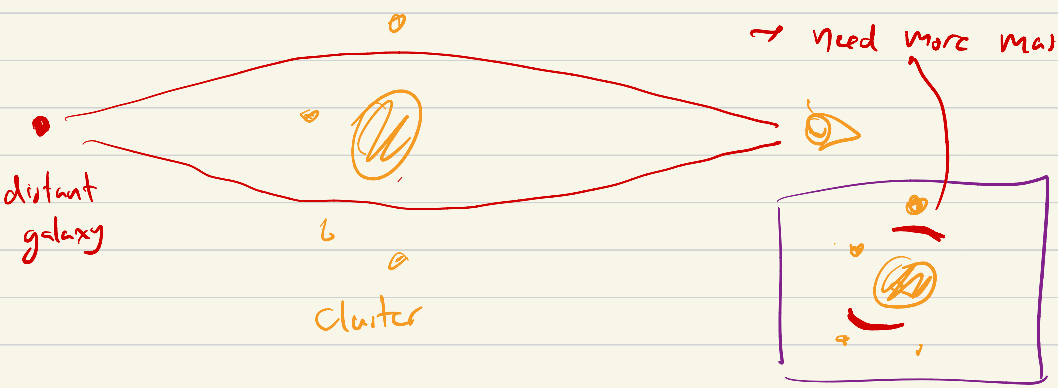
additional matter that is invisible ⇒ "Dark Matter"

$$\frac{\cancel{m} v^2}{r} = \frac{G M \cancel{m}}{r^2}$$

if $v^2$ very high → M must be very high

4. Gravitational Lensing

Calculate for mass required → need more mass.



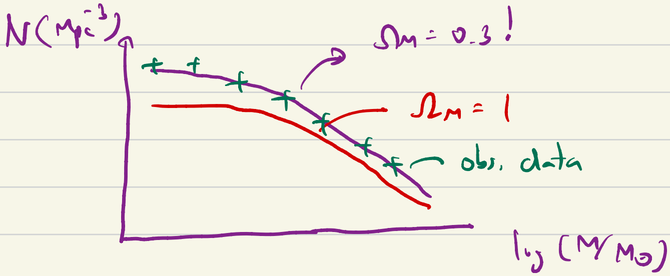
# Additional Benefit of Cluster

- Probe for cosmology

"Crisis of Cosmology" → different $H_0$ between CMB and SN

Using galaxy cluster to study cosmology

1. Cluster Abundance → number density




2. Gas mass fraction

| Cluster | ~ | Universe |
|---|---|---|
| $f_{DM} \sim 30\%$ | | $\Omega_M \sim 30\%$ |
| $f_{\text{hot gas + galaxy}} \sim 5\%$ | | $\Omega_b \sim 5\%$ (gas + star) |

$$f_{gas} = \frac{\text{hot gas}^{①}}{\text{hot gas + DM}^{②}} \approx f_b = \frac{\Omega_b}{\Omega_M}^{③} \Bigg\} \; \Omega_M \, ?$$

# Galaxy Cluster as tool to understand DM

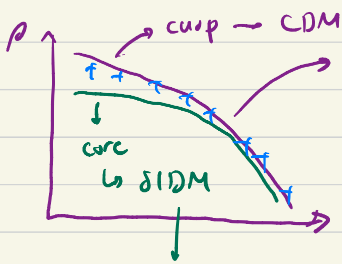
DM = - what particle? What mass per particle?
- DM cross section (unit in area)
  prob. of DM interacting with itself and other matter.

## 1. Bullet Cluster


if hot gas and DM are very different, DM cross section is low

(e.g. < 1.25 $cm^2/g$)

## 2. Cluster Density Profile



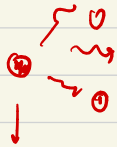

CDM or SIDM or WDM!

(e.g. < 0.19 $cm^2/g$)

self interacting → lower density in the core

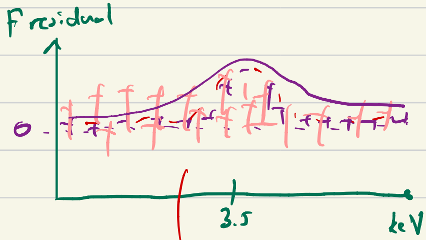
$E = \frac{hc}{\lambda}$

3. 3.5 keV line of DM decay

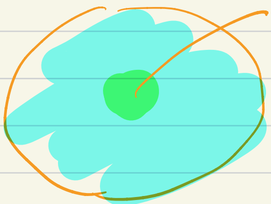


3.5 keV photon $\Rightarrow$ X-ray

sterile neutrino (very low cross section)

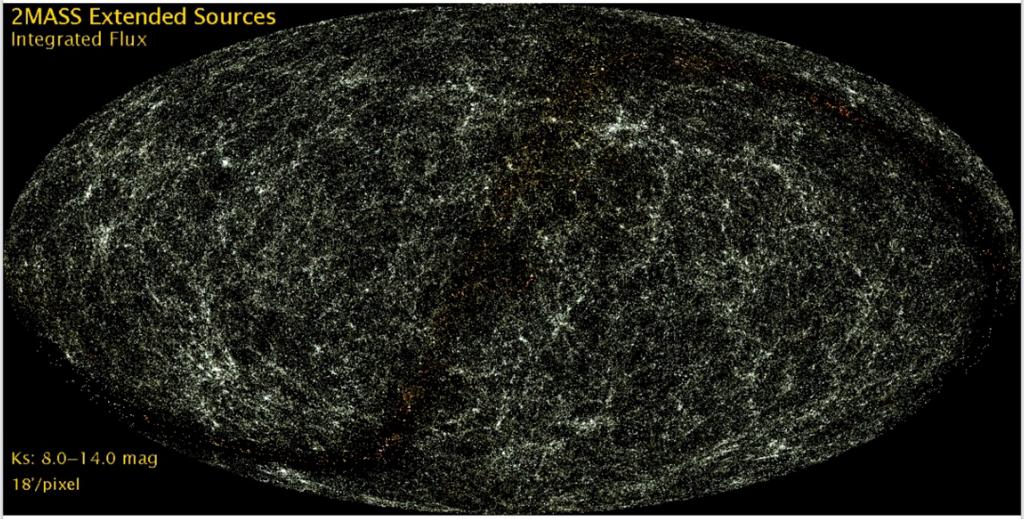


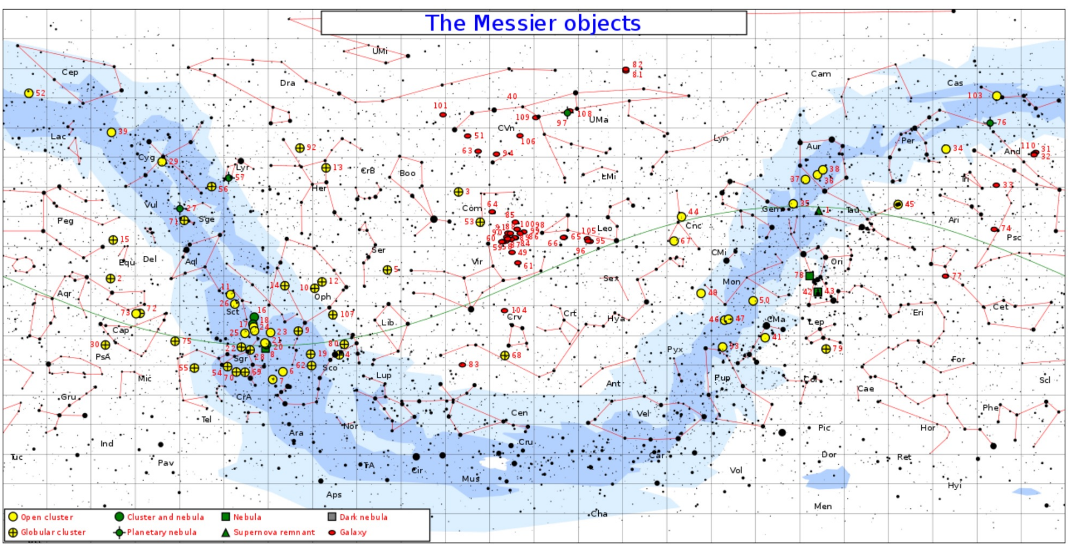

evidence for sterile neutrino (IF)

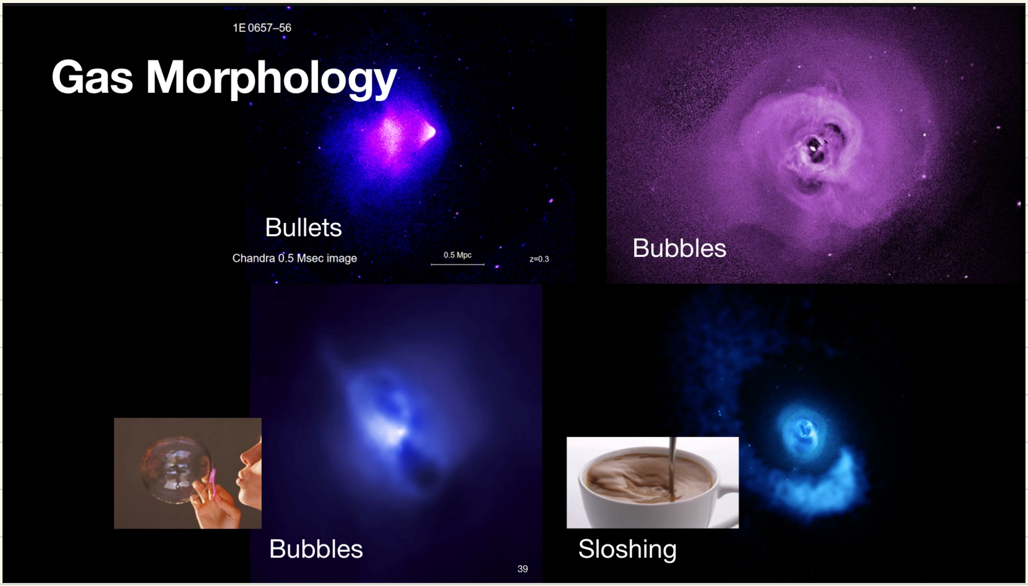


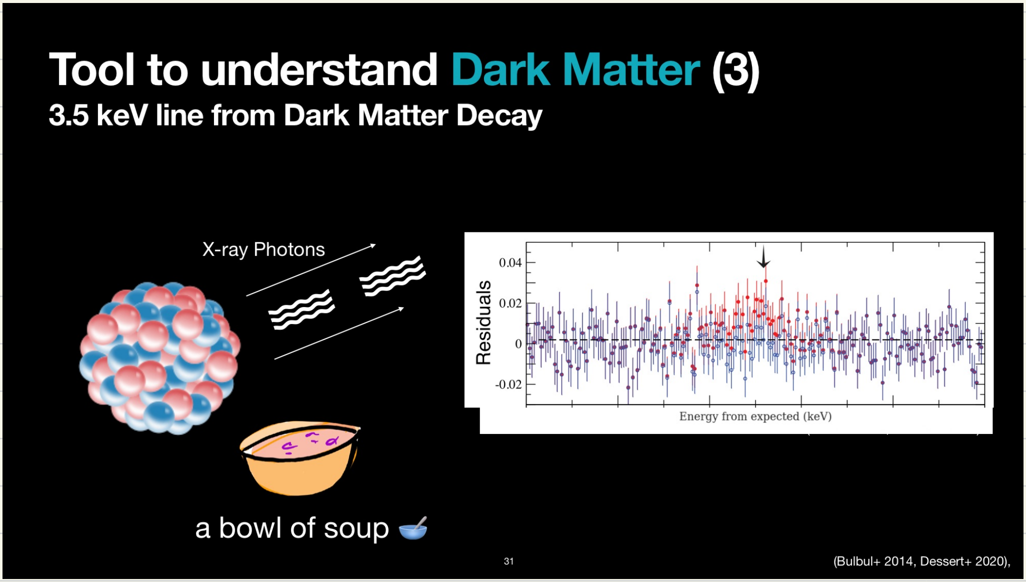
highest DM density

↳ more prob. for DM decay


2MASS Extended Sources
Integrated Flux
Ks: 8.0–14.0 mag
18'/pixel


The Messier objects
Open cluster
Globular cluster
Cluster and nebula
Planetary nebula
Nebula
Supernova remnant
Dark nebula
Galaxy

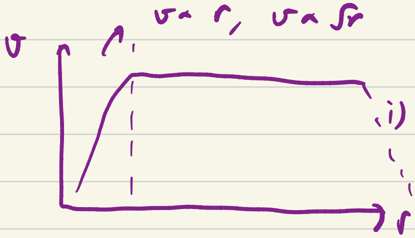

1E 0657–56
Gas Morphology
Bullets
Chandra 0.5 Msec image
0.5 Mpc
z=0.3
Bubbles
Bubbles
Sloshing
39


Tool to understand Dark Matter (3)
3.5 keV line from Dark Matter Decay
X-ray Photons
a bowl of soup
0.04
0.02
0
-0.02
Residuals
Energy from expected (keV)
31
(Bulbul+ 2014, Dessert+ 2020),

## กระดาษทด

$\rho(r) \propto \frac{1}{r}$ ; $r < r_0$

$\rho(r) \propto \frac{1}{r^3}$ ; $r > r_0$




$\frac{\cancel{m}v^2}{r} = \frac{GM\cancel{m}}{r^2}$

i) if $v$ const ; $M \propto r$

$\rho(r) \propto \frac{1}{r^3}$

$M = \rho \cdot V$

$\propto \frac{1}{\cancel{r^3}} \frac{4}{3}\pi \cancel{r^3}$

$M = \text{const.}$

ii) if $v \propto r$

if $\rho \propto \frac{1}{r}$ → $M = \frac{1}{r}\frac{4}{3}\pi r^{3} \propto r^2$

$\frac{mv^2}{r^2}$

$\frac{GM}{r} = \frac{v^2}{r} \propto \frac{r^2}{r} = r$

if $\rho \propto \frac{1}{r^2} \Rightarrow v^2 = \frac{1}{r^2} G \frac{4}{3}\pi r^2$

$v = \text{const}$

$\frac{v^2}{r} = \frac{G}{r^2}\left(\rho \frac{4\pi}{3} r^3\right)$

$v^2 = \rho G \frac{4}{3}\pi r^2$ → if $\rho \propto \frac{1}{r^3} \Rightarrow v^2 = \frac{1}{r^3} G \frac{4}{3}\pi r^2 \propto \frac{1}{r}$

$v = \frac{1}{\sqrt{r}}$

if $\rho \propto \frac{1}{r} \Rightarrow v^2 = \frac{1}{r} G \frac{4}{3}\pi r^2 \propto r$

$v \propto \sqrt{r}$