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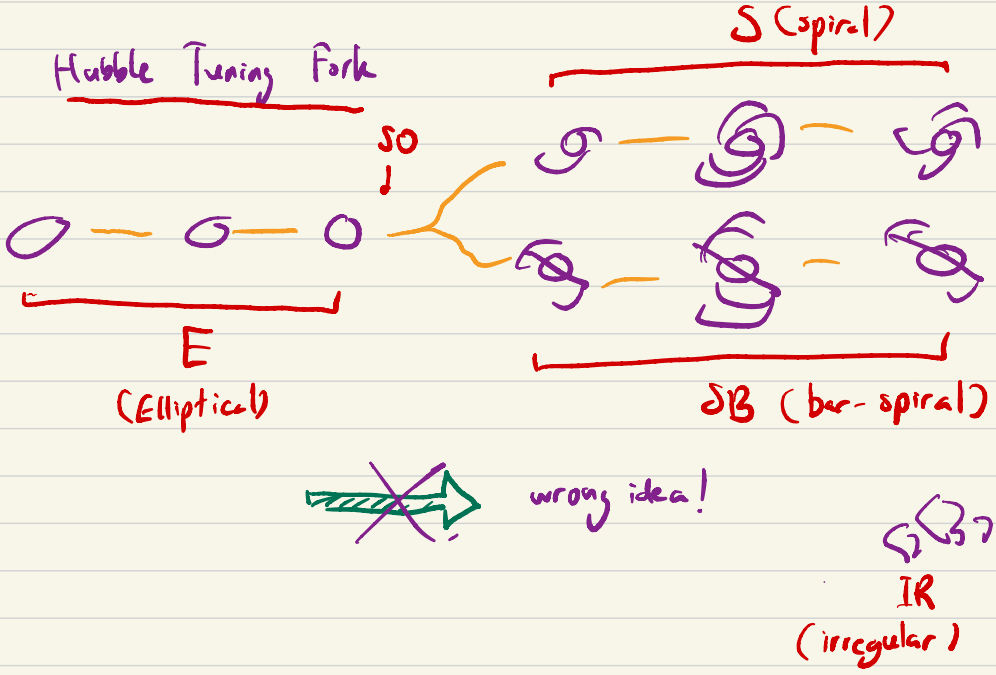
Galaxy Cluster

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

Ex Abell 1835, Abell 2027,



morphology	3 objects
E/SO	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/SO) II (S/SB) III IR IV Uncertain

A

B

C

D

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

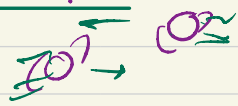
A+C | B+D

% of Elliptical = $\frac{e}{h} = \frac{14}{79} = \ldots\%$ | = .. %

	Cluster (Tunnicliffe)		Field (Tunnicliffe)	
	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?

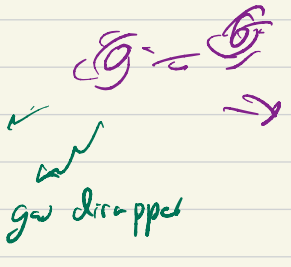
1. E older → form clusters



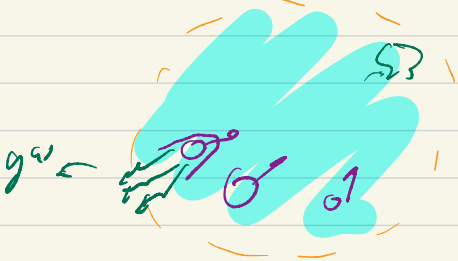
2. Clusters have more collision (closer together) → interaction

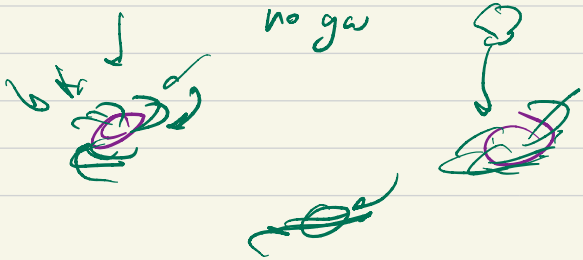
spiral pattern disappear

3. Observation bias: easier to observe spirals in fields → high redshift galaxies!



4. ram pressure stripping



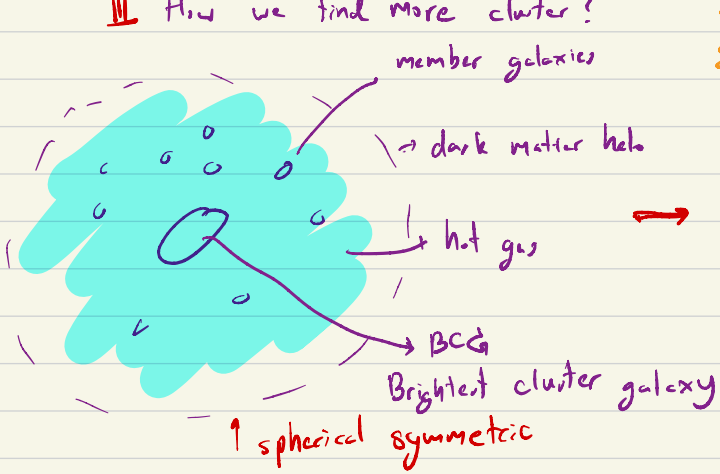


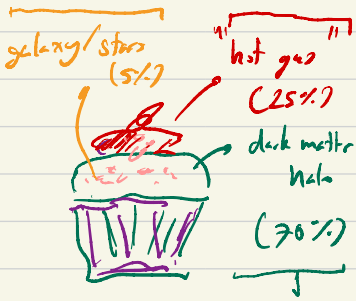
Outline

I Gas Properties of clusters

II Why do we care about cluster?

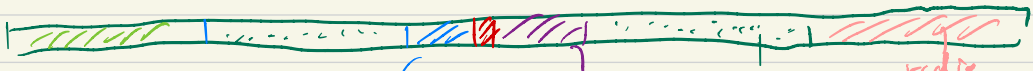
III How we find more cluster?





hot gas → How do we see hot gas?

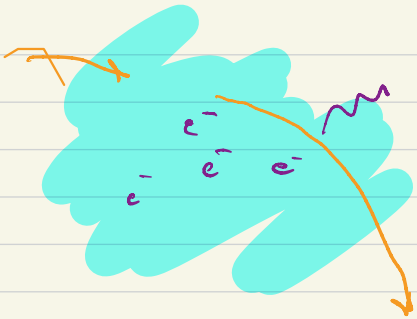
EM wave



gamma-ray | X-ray | UV | optical | infrared | microwave | radio

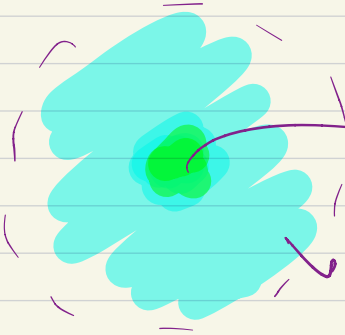
$10^6 - 10^{7.5}$ K | $10^5 - 10^6$ K | 6000 K | 300 K | ~10 K | 1 K →

hot gas 10^7 K ⇒ bright in X-ray!



X-ray = Thermal Bremsstrahlung

$E \propto n^2 \cdot T$



brightest in X-ray

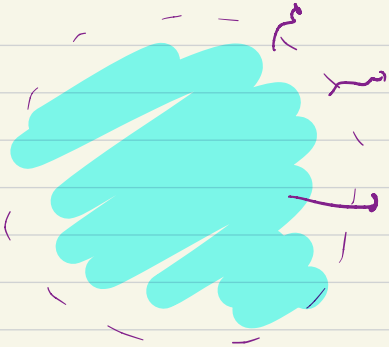
fainter in outskirts

} Extended objects

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

- Bullet, Bubble, Sloshing ⇒ different aspects of cluster.

↓ See figure at the end.



X-ray radiation continously.

Why hot gas stay gas?

T ↓ ⇒ Move inward

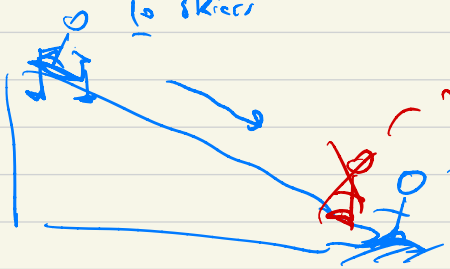
X-ray ⇒

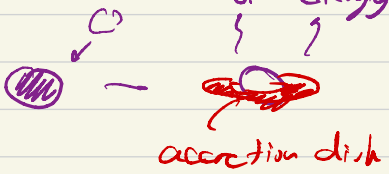
Cooling flow

filamentary structure ⇒ cooling flow ← calculation / simulation

We do not see cooling flow in normal cluster ← observation

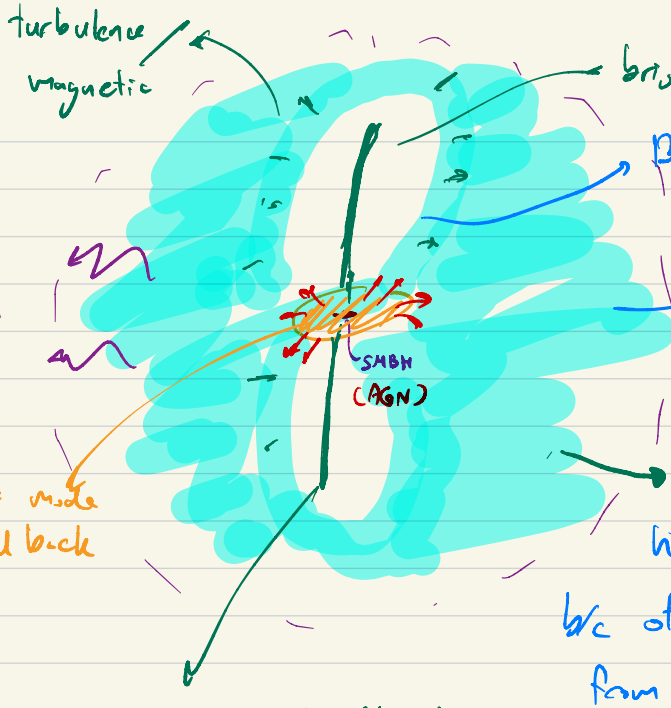
↳ "Cooling flow" Problem





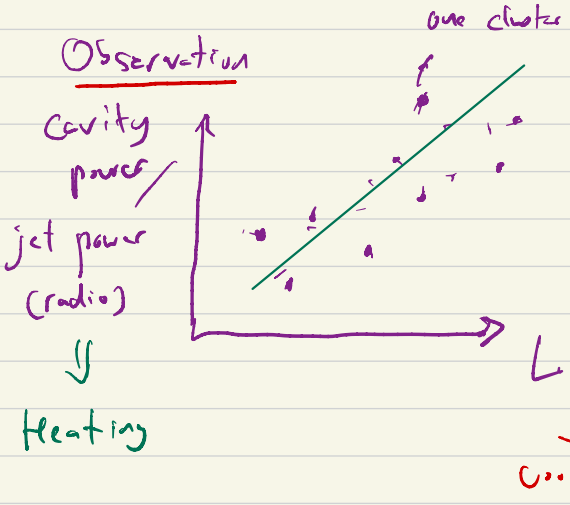
Soln AGN feedback

(Active Galactic Nuclei) = active black hole.



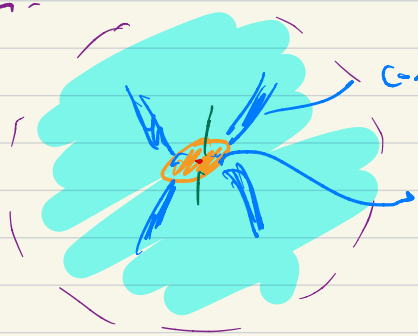
- radiative mode feedback
- kinetic mode feedback

Observation



Cooling = Heating

But we discovered clusters w/ cooling flow!



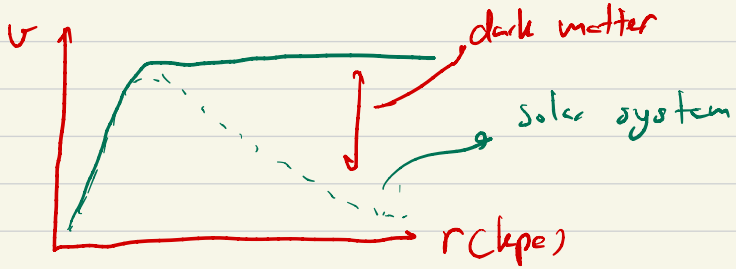
ex. Phoenix cluster (2012)

* Why do we find cooling flow?

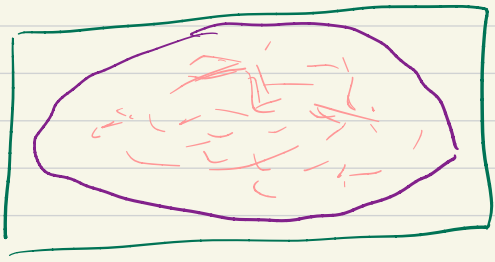
Why do we care about clusters?

Dark Matter:

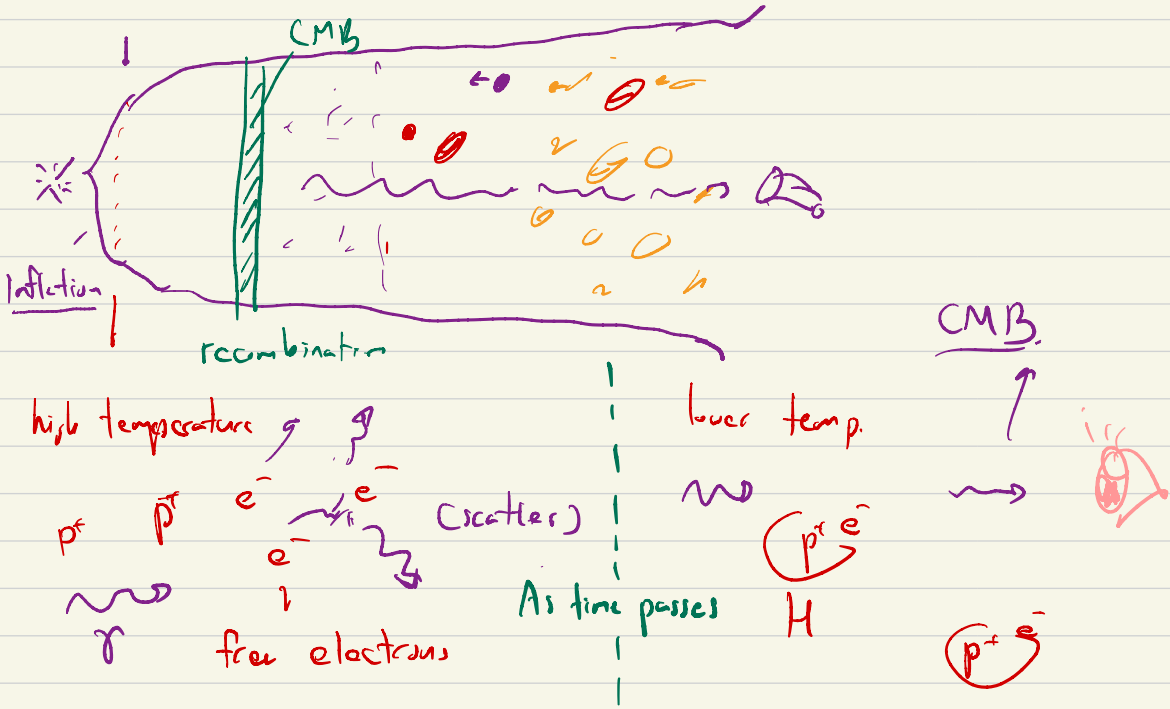
- flat rotation curve from spiral galaxies (Vera Rubin)



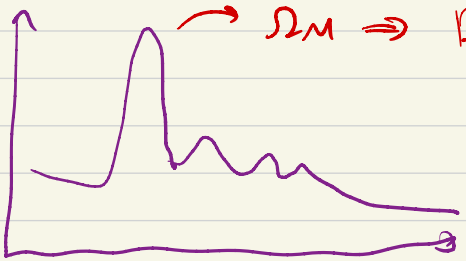
- CMB



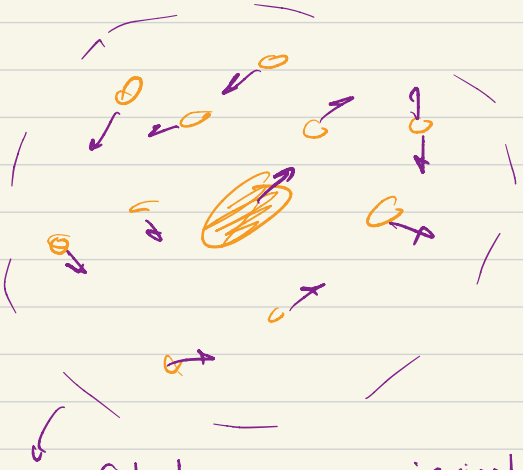
CMB: Cosmic Microwave Background (first light)



CMB → properties of young universe



3. Galaxy Cluster → first method. (Zwicky)



velocity dispersion of member galaxies is too high.

⇓

additional matter that is invisible ⇒ "Dark Matter"

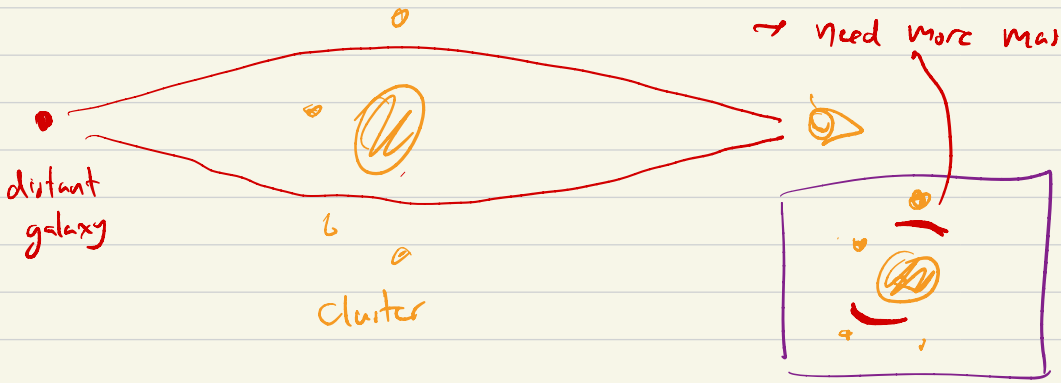
Coma Cluster

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

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

4. Gravitational Lensing

Calculate for mass required → need more mass.



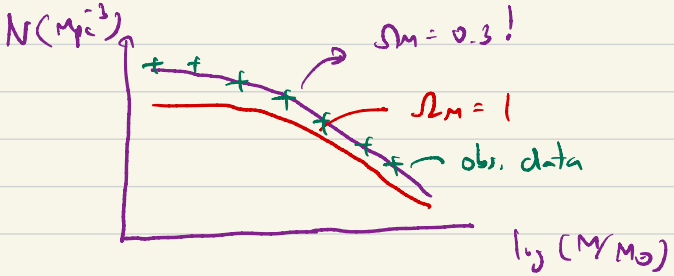
Additional Benefit of Cluster

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

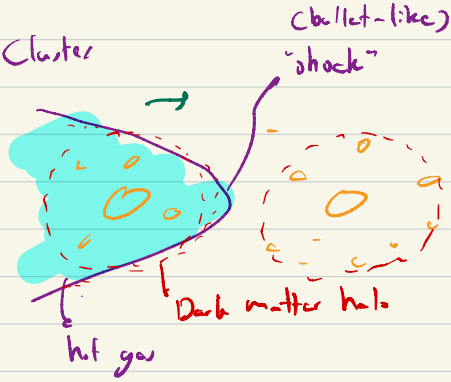
$$f_{gas} = \frac{\text{hot gas}}{\text{hot gas + DM}} \quad (1)\ (2) \qquad \approx \qquad f_b = \frac{\Omega_b}{\Omega_M} \quad (3)$$

$\int \Omega_M$?

Galaxy Cluster as tool to understand DM

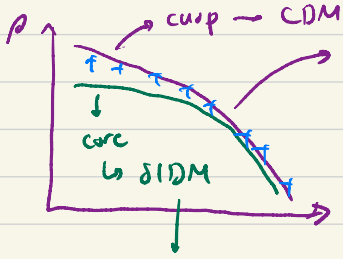
DM = - what particle? What mass per particle?
- DM cross section (unit in area)
prob. of DM interacting with itself and other matter.

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



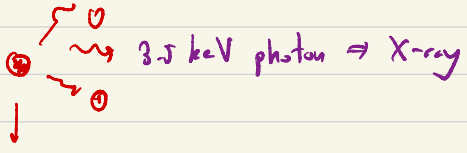
CDM or SIDM or WDM !

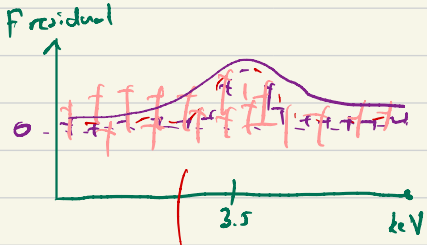
(e.g. $< 0.19\ cm^2/g$)

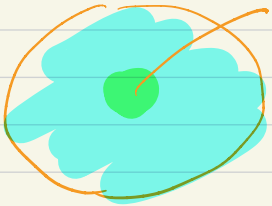
self interacting → lower density in the core

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

3. 3.5 keV line of DM decay

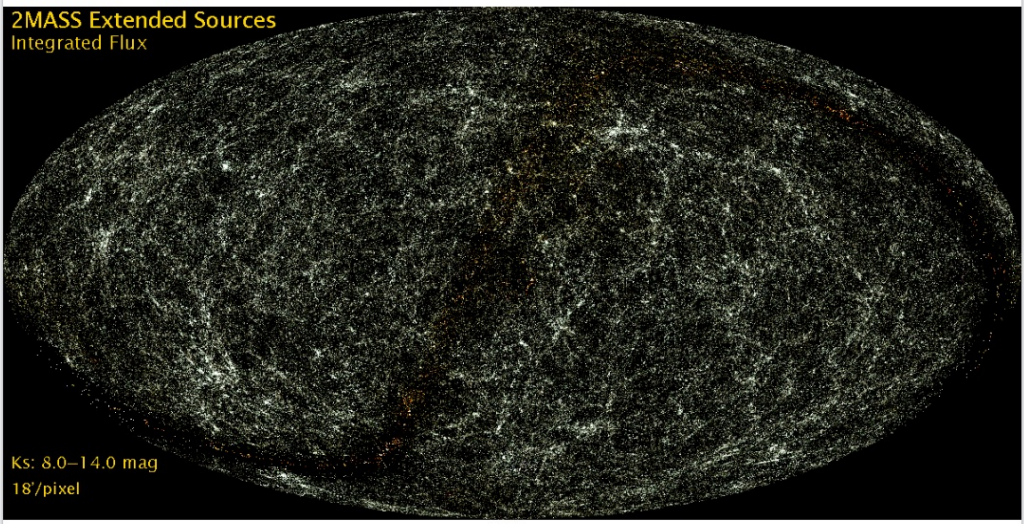


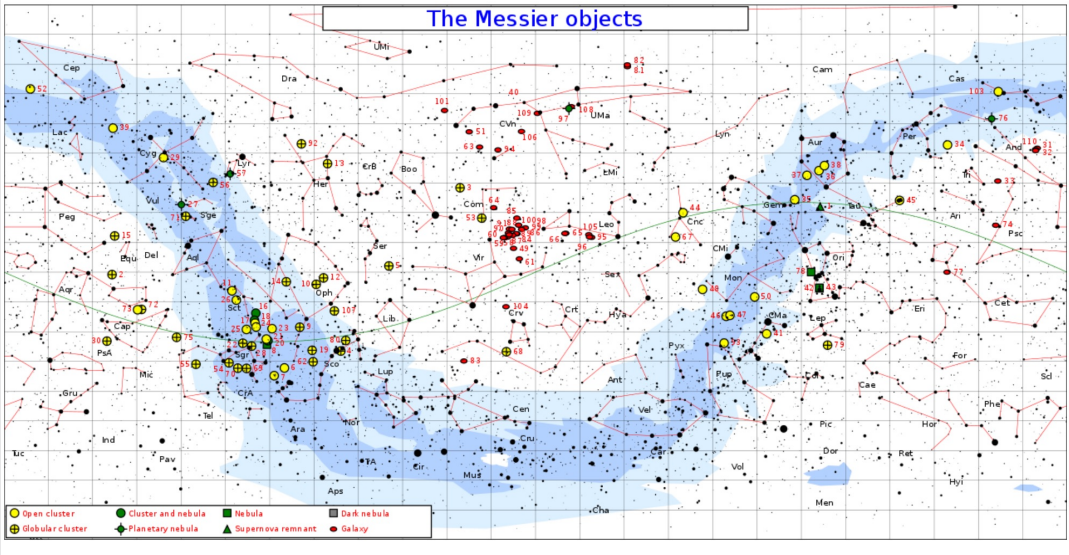




highest DM density
⇒ more prob. for DM decay

evidence for sterile neutrino (IF)

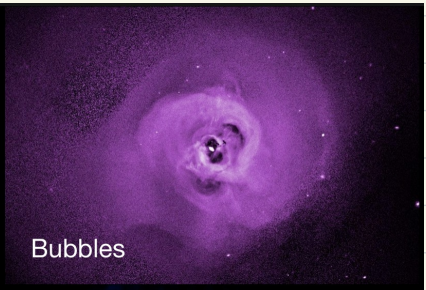

2MASS Extended Sources
Integrated Flux
Ks: 8.0–14.0 mag
18"/pixel


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

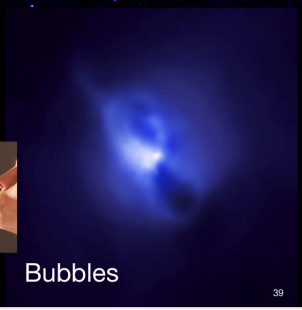
Gas Morphology

Bullets

Chandra 0.5 Msec image



Bubbles



Bubbles

Sloshing

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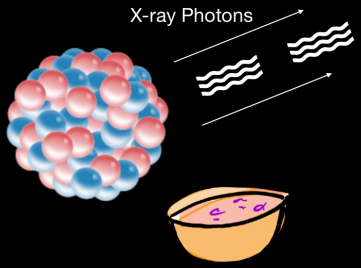
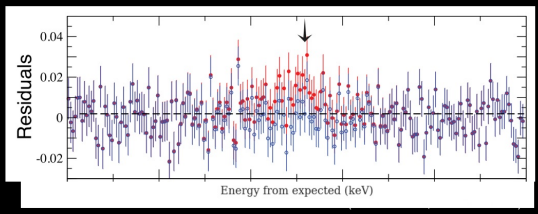
Tool to understand Dark Matter (3)

3.5 keV line from Dark Matter Decay



a bowl of soup



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(Bulbul+ 2014, Dessert+ 2020),