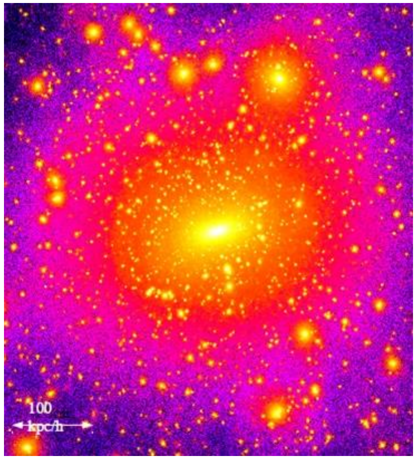
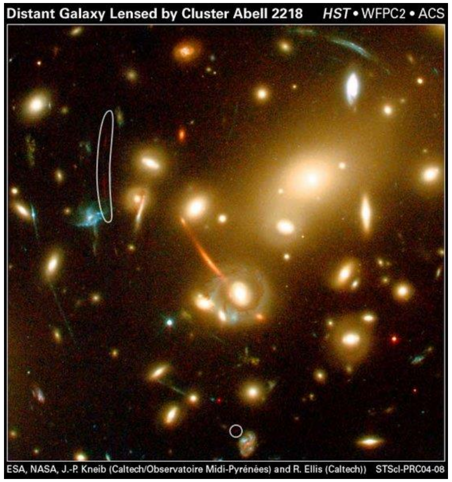
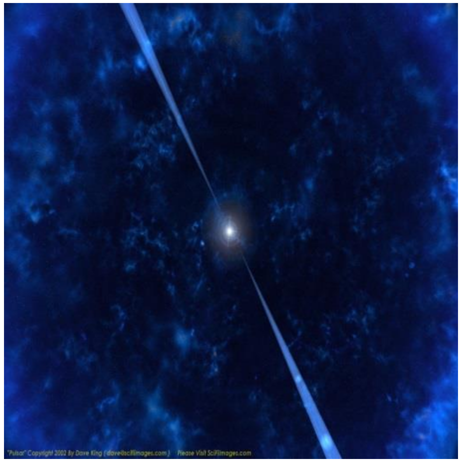
New Astrophysical Probes of Dark Matter Substructures: Pulsar Timing & Weak Transient Lensing







Shant Baghram

IPM-School of Astronomy

4May 2013

IPM international school and workshop on Particle Physics (IPP13): Flavor physics and dark matter

Acknowledgment

- **On behalf of:**

Sohrab Rahvar (SUT/PI), Niayesh Afshordi (PI/UW), Kathryn Zureck (Michigan)

- **Astrophysical probes of DM team and non linear SF:**

Niayesh Afshordi (PI/UW), Sohrab Rahvar(SUT/PI), Royaa Mohayaa(IAP),

Ed. Bertschinger (MIT), Jesus Zavala (PI/UW), S.B.

- **Based on:**

1)Small Scale Power Spectrum of Matter via Transient Weak Lensing of Dark Microhalos

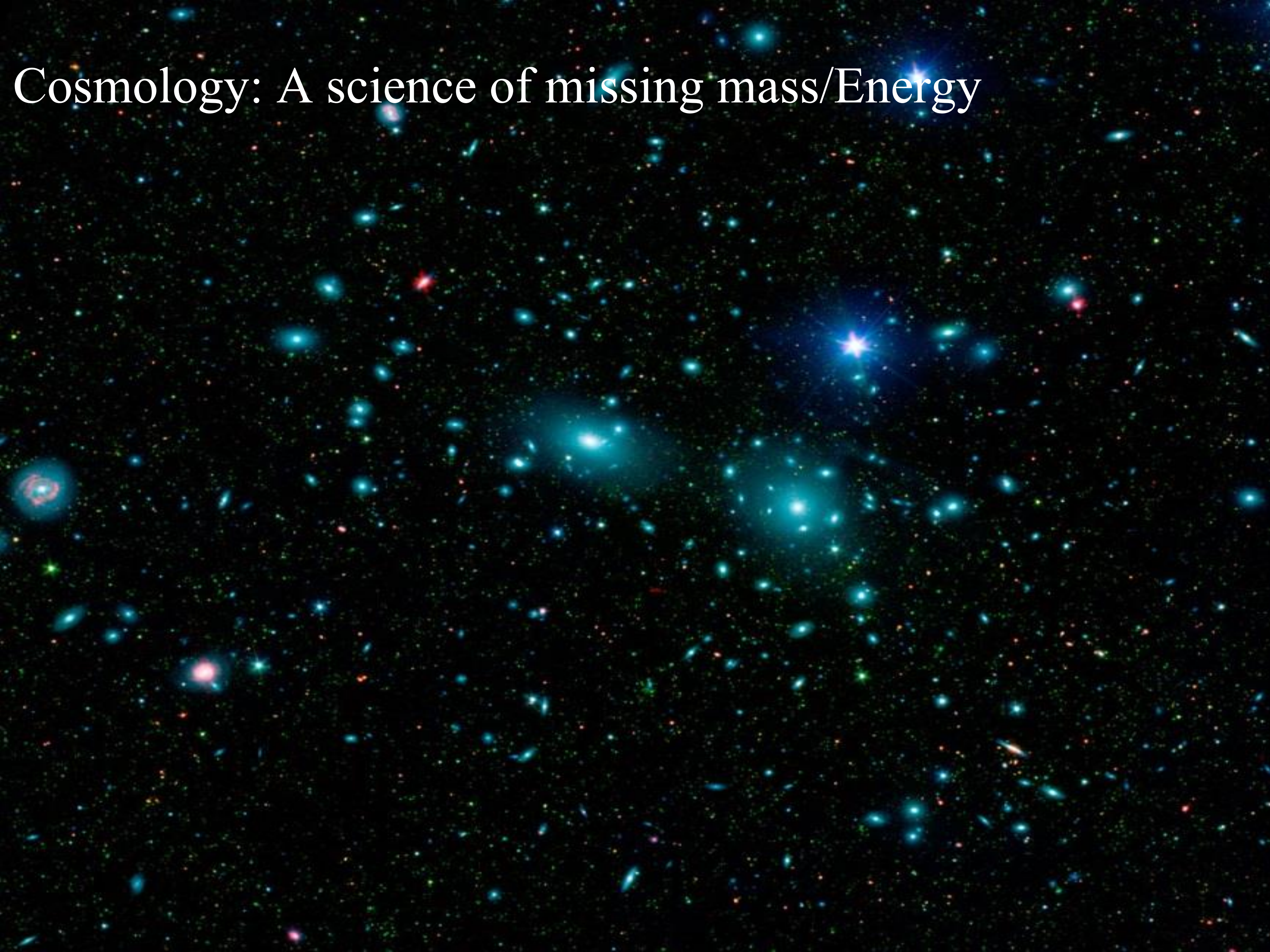
Sohrab Rahvar, SB, Niayesh Afshordi : final stage appeared 1305….

2)Transient Weak-Lensing by Cosmological Dark Microhalos

Sohrab Rahvar, SB, Niayesh Afshordi : final stage appeared 1305…..

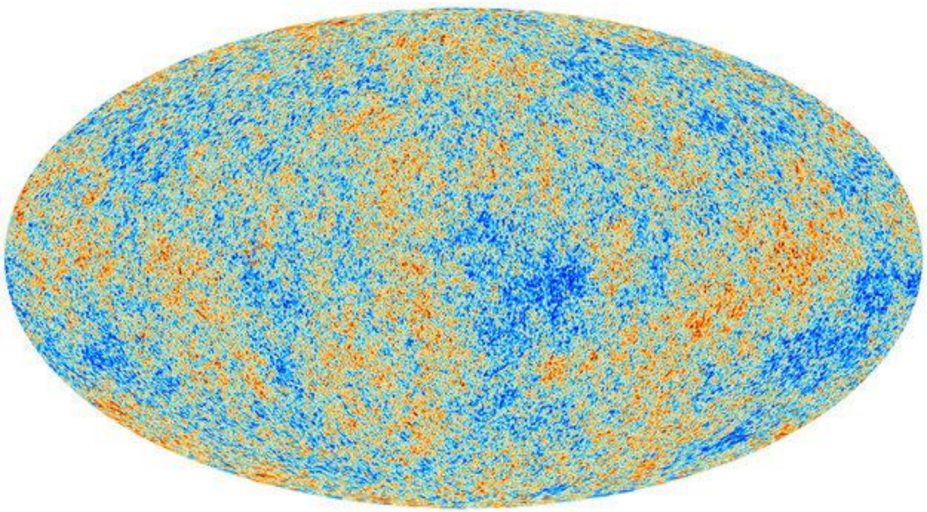
3)Shant Baghram, Niayesh Afshordi and kathryn Zure k, Phys.Rev.D84:043511,2011

Cosmology: A science of missing mass/Energy

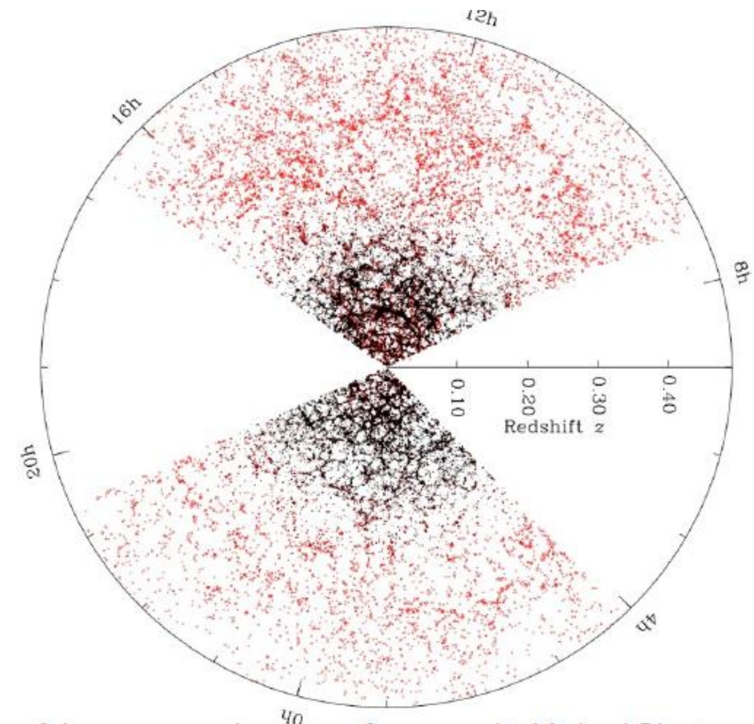


Why we need DM in cosmology?

- Two matter power spectrums



$$\frac{\delta T}{T}(\hat{n}; z_d)$$



3degree around equator. figure credit: Michael Blanton

$$n_g(\hat{n}, z_d)$$

Why we need DM in cosmology?

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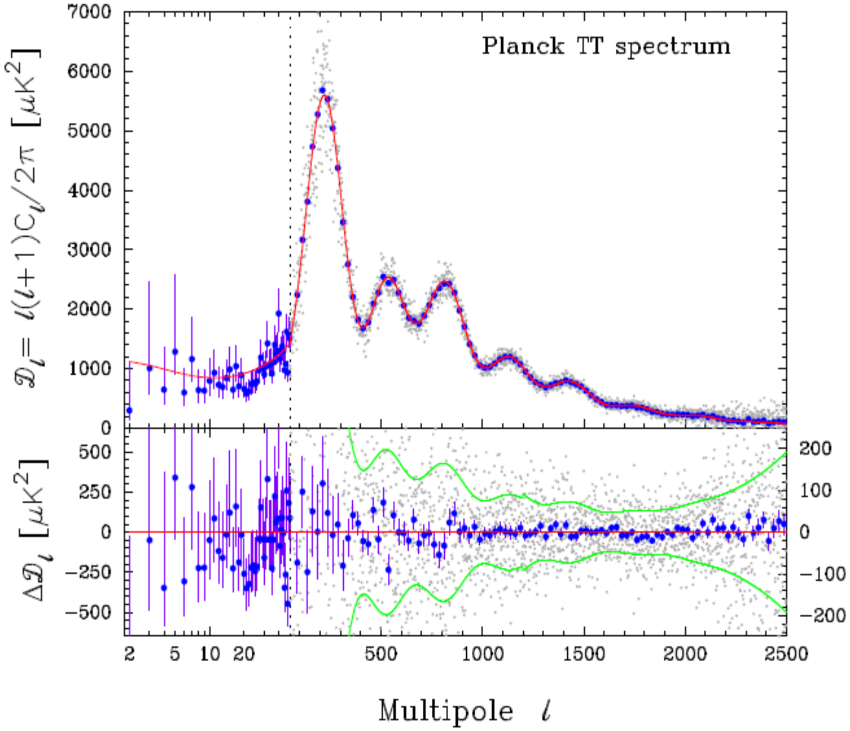
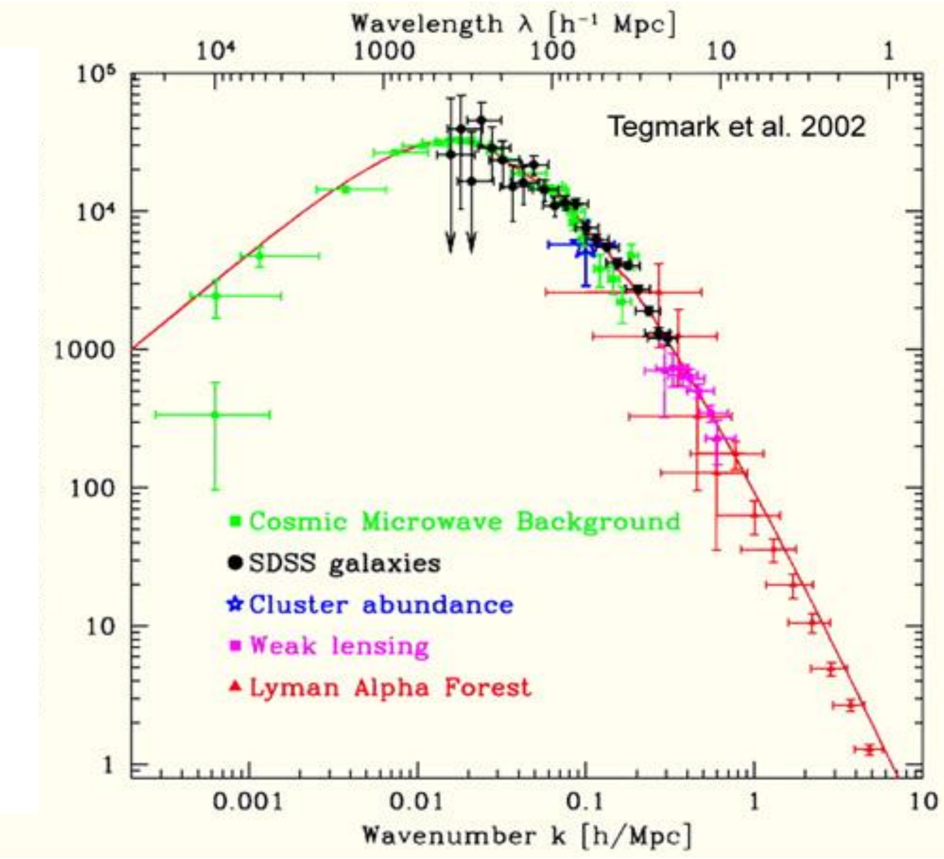
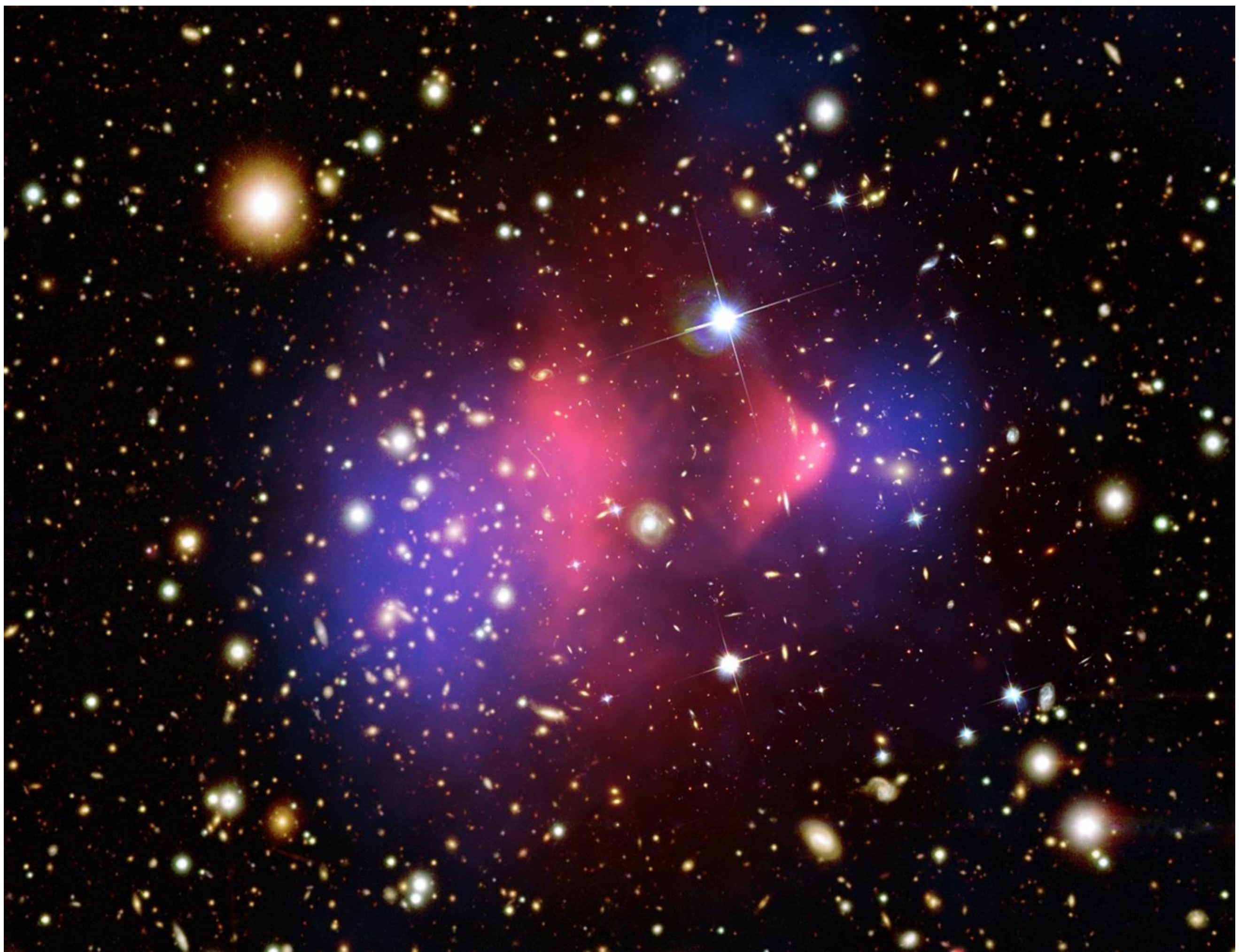




Non Baryonic Dark Matter

- What are the strongest evidence for Non baryonic dark matter

Bullet cluster: Clowe et al. ApJ 2004



Non Baryonic Dark Matter

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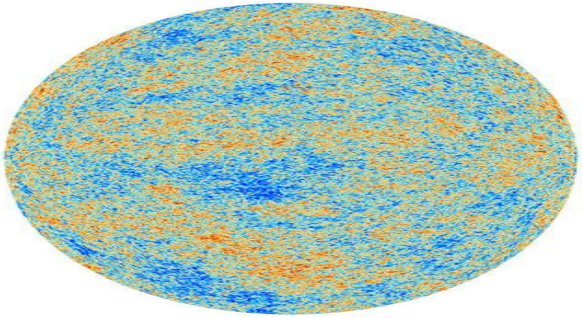
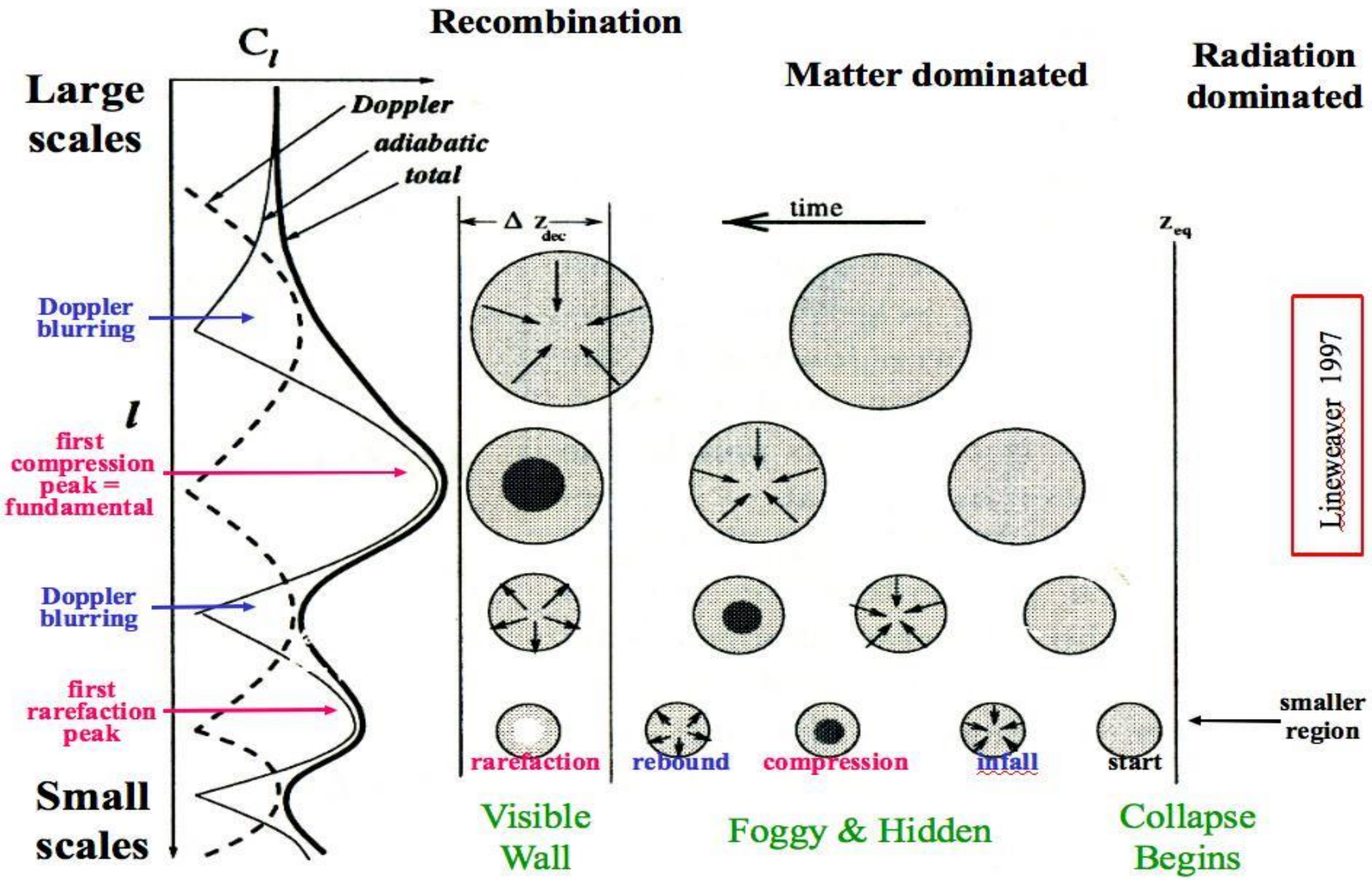


Planck 2013



Paradigm of CDM structure Formation

Cold : Small free streaming

Dark : Small self interaction

Halos: Bound systems of halos

Hierarchical: merger of smaller halos to form bigger ones.

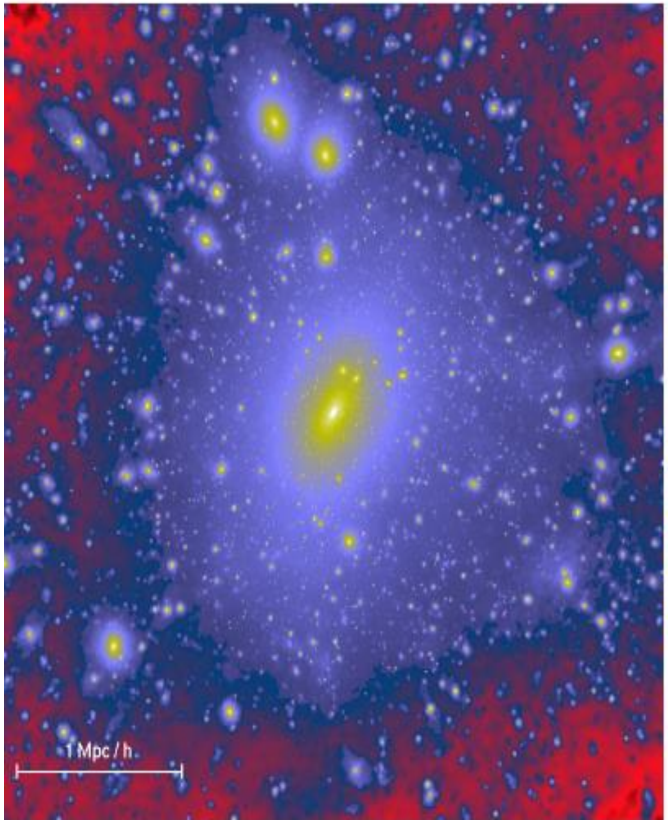
Thermal relics: Relate the DM particle properties to density parameter in Universe

$$\Omega_{DM} \sim \frac{10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

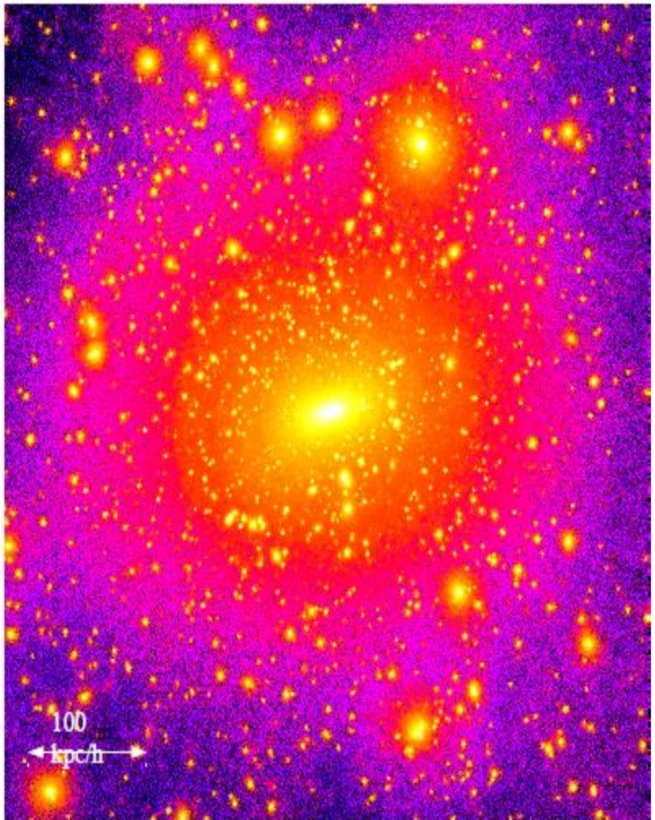
Dark Matter Substructures

- CDM matter paradigm that predict a hierarchical Structure formation predicts a wealth of subs structures

A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002

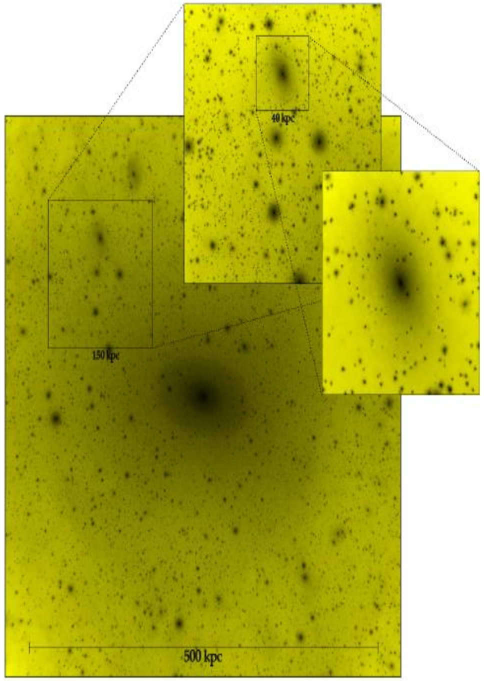


Phase Space of Dark Matter

- The phase space of Dark Matter is so EMPTY!!!

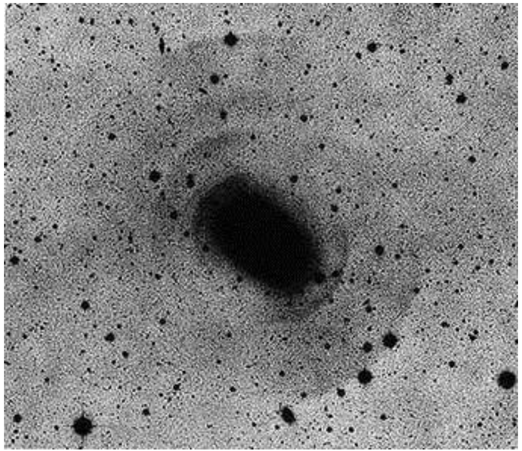
$$f_{CDM} \sim \frac{(\bar{\rho}_{CDM} / m_\chi)}{\delta v_{CDM}^3} \sim 10^{-2} m_\chi^2 (GeV)(cm/s)^{-3}(cm)^{-3}$$

$$\langle f_{CDM} \rangle \sim \frac{M_{gal} / m_\chi}{(10kpc)^3 (200km/s)^3} \sim 10^{-22} m_\chi^{-1} (GeV)(cm/s)^{-3}(cm)^{-3}$$



Kuhlen, Diemand, et al.

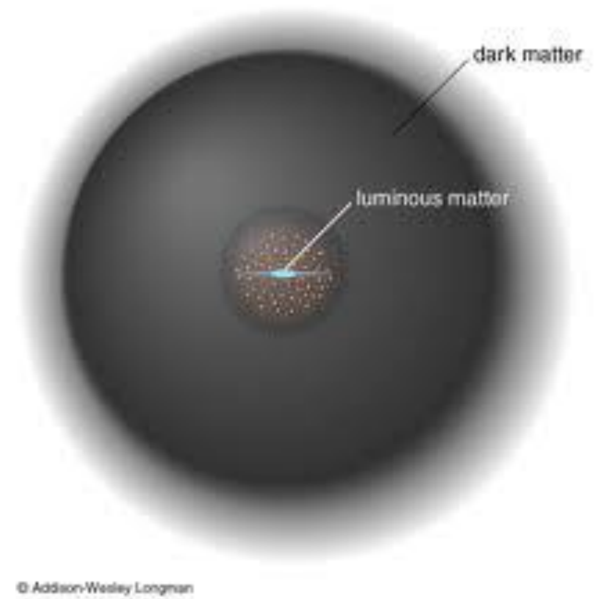
- Fundamental discreetness



NGC
3923

What are the questions astrophysicist are interested in DM?

- What is the distribution of DM in Universe (Cosmology)
- Alternative theories of Gravity
- What is the distribution of DM in halo structures
- Are there any intrinsic small scale for DM structures
- What is the relation of galaxies and clusters of gala:
  DM
- **Dark Matter substructures**



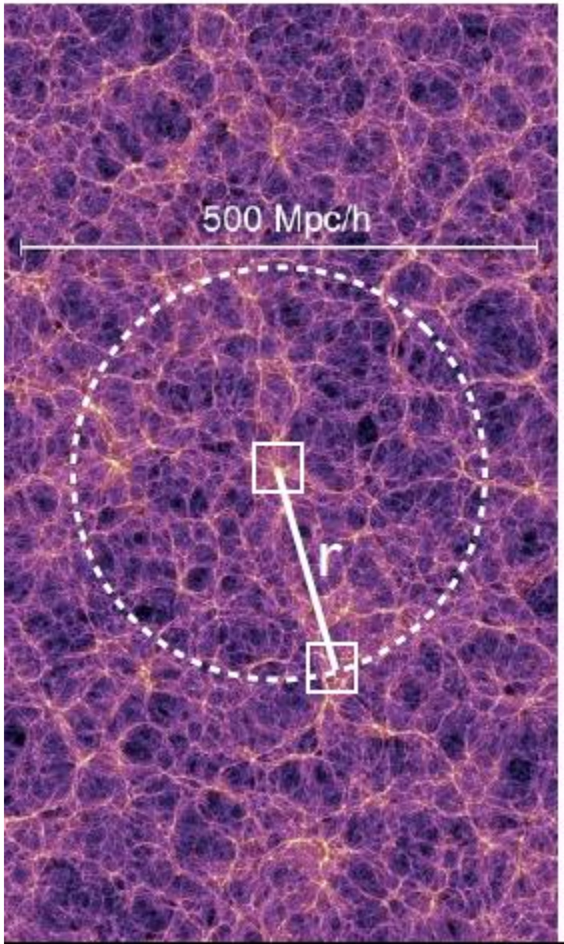
Statistical Properties of our Universe

- We need to define the two point correlation function as:

$$\xi(\vec{r}) = \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \right\rangle$$

where the correlation function is the excess of particles from randomness.

$$\delta(x) = \frac{\rho(x) - \rho_b}{\rho_b}$$



Where power-spectrum is the Fourier transform of correlation function as:

$$\left\langle \delta(\vec{k})\delta(\vec{k}') \right\rangle = (2\pi)^3 P(k)\delta^D(\vec{k}+\vec{k}')$$

What we observe?

Observations

✓ Gravitational effect of DM on Photons

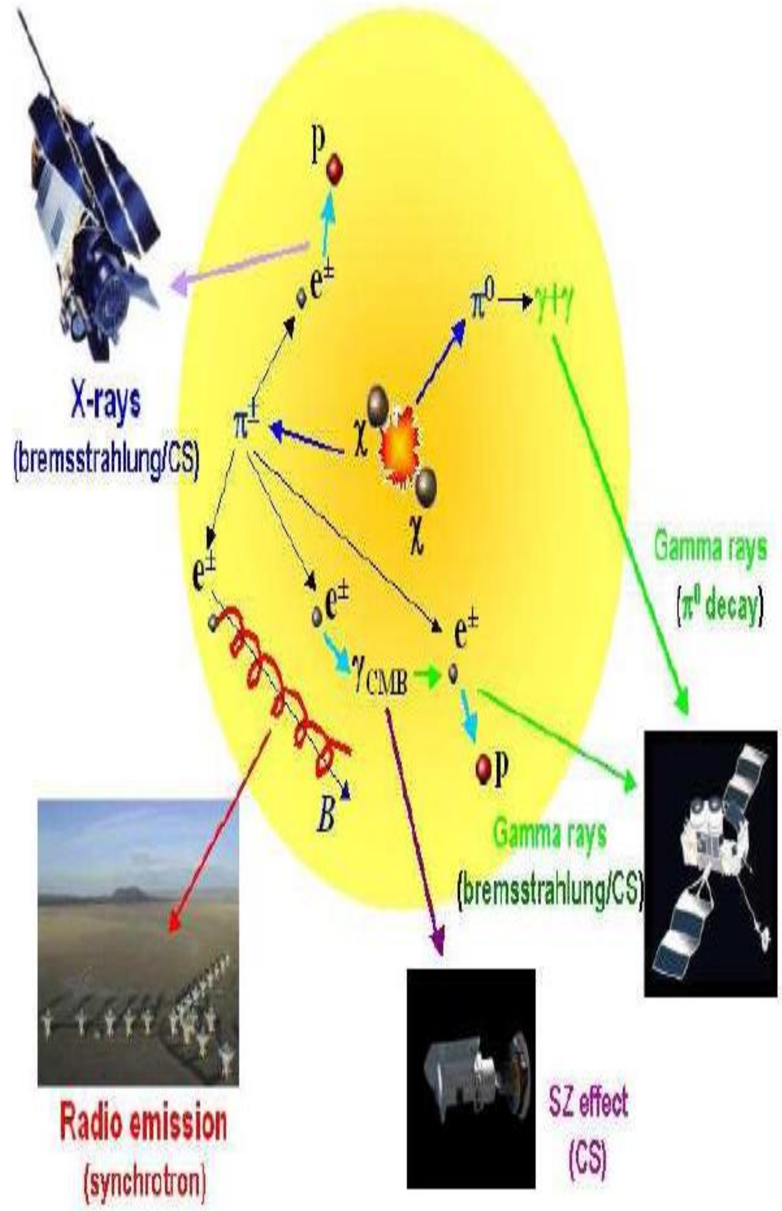
Gravitational Lensing, …   + I will add two more

✓ Gravitational effect of DM on baryons

Kinematic of the stars and galaxies

Astrophysics and Indirect searches of DM

$$\frac{dL_i}{dE_i} = \frac{\langle \sigma_{\rm ann} v \rangle E_i}{2m_\chi^2} \frac{dB_i}{dE_i} \Phi \ ; \qquad \Phi \equiv \int \rho^2(\mathrm{x}) d^3\mathrm{x}$$



S.Colafrancesco arXiv:1004.3869

N. Afshordi, R. Mohayaie, E. Bertschinger, arXiv:0911.0414

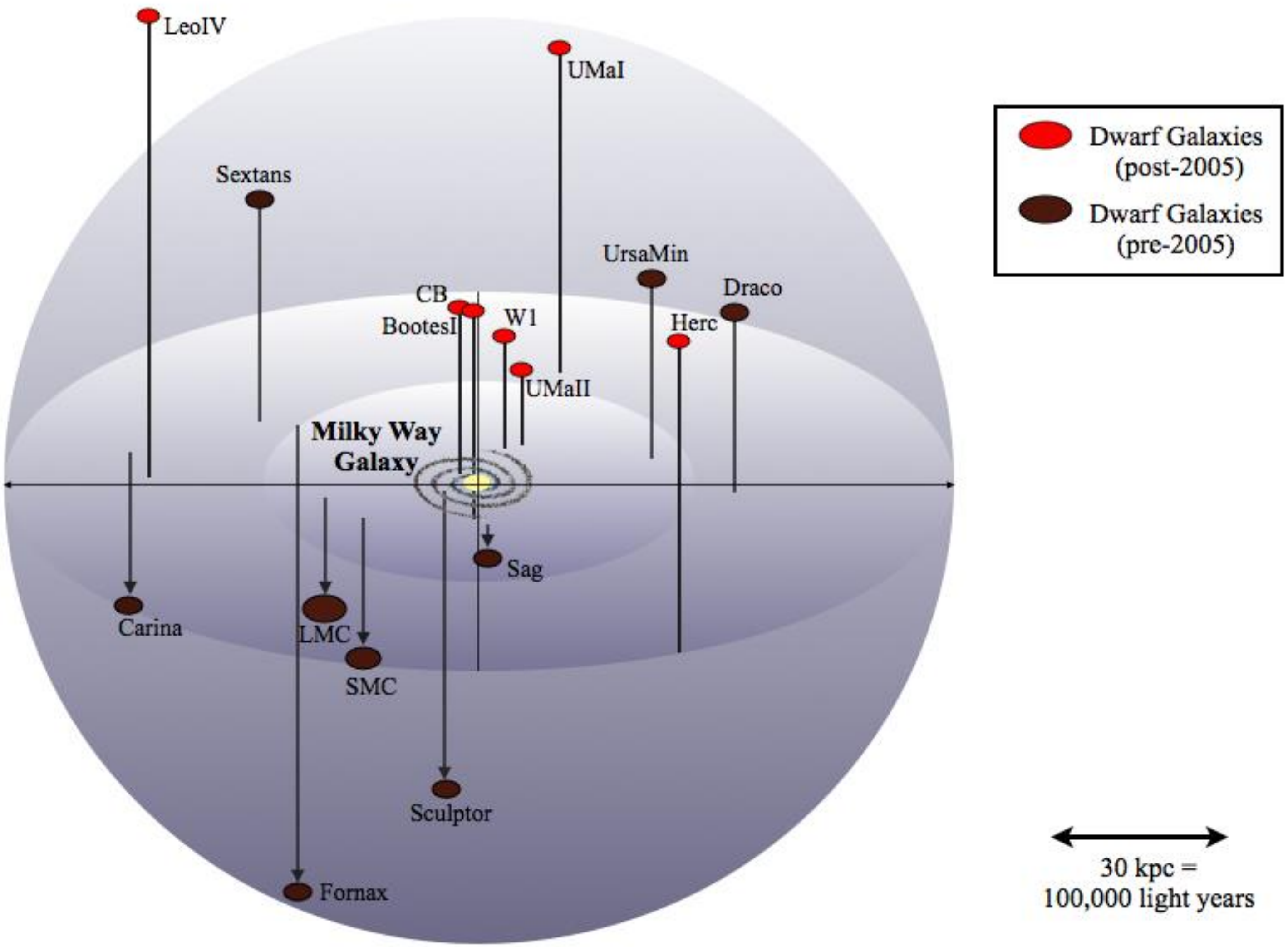
V

DM substructures

- Prediction of LCDM ; How we can detect them?
- Related to the particle physics properties of DM
- We see anomalies !!!
- Small Scale power spectrum of matter (curvature in EU)

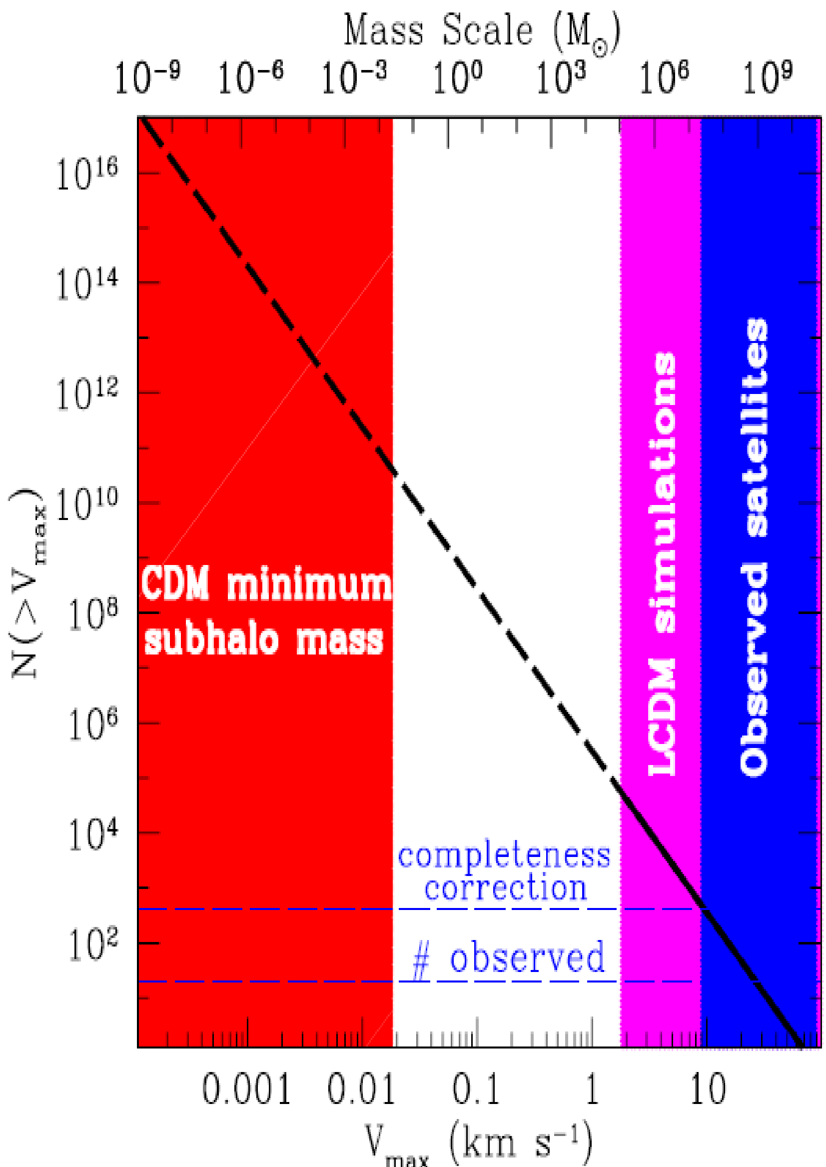
…

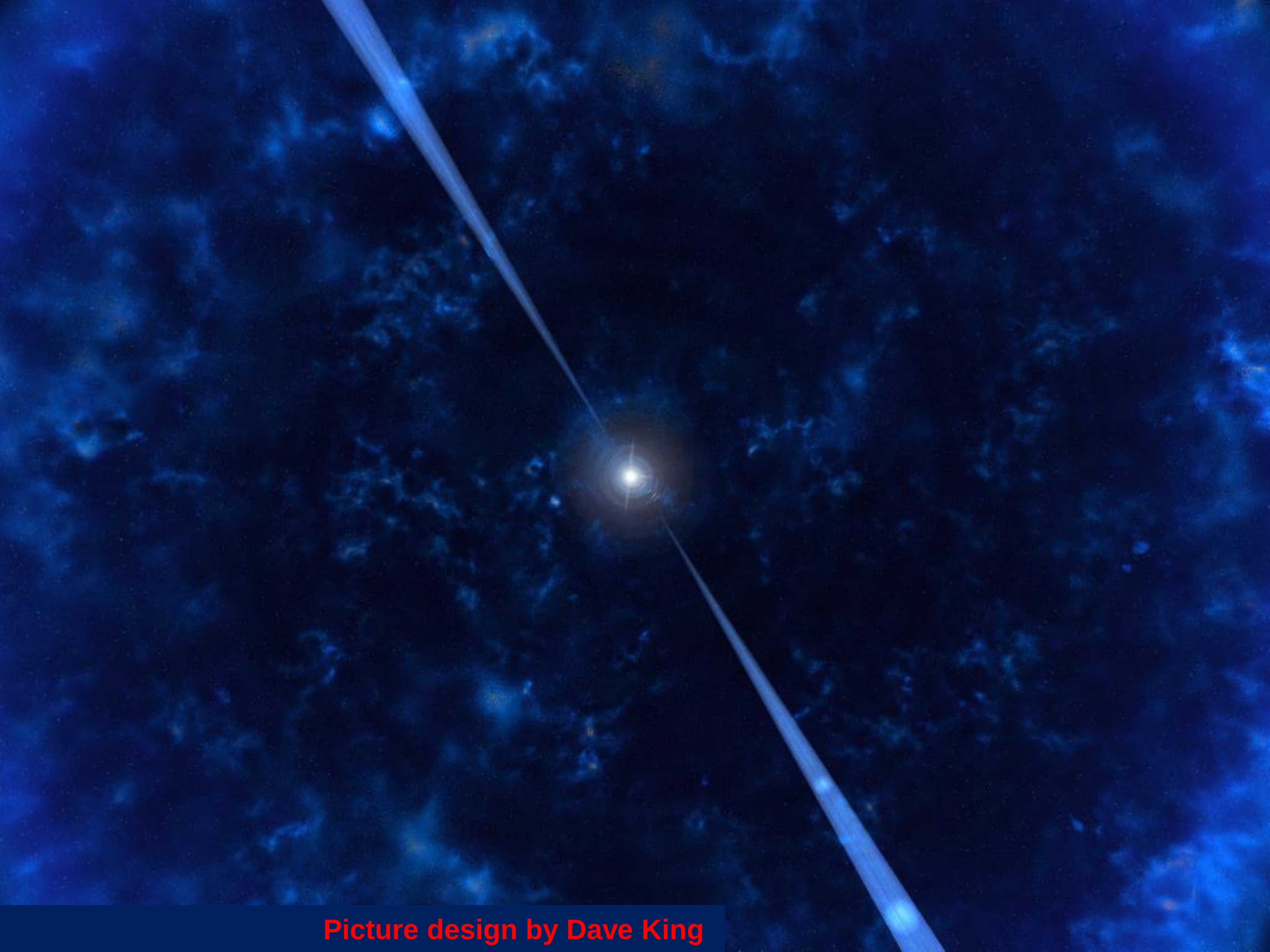
DM substructures in our neighborhood



Missing Satellite Problem

- ✓ Special scale in DM
- ✓ Special Scale in Galaxy formation





Picture design by Dave King

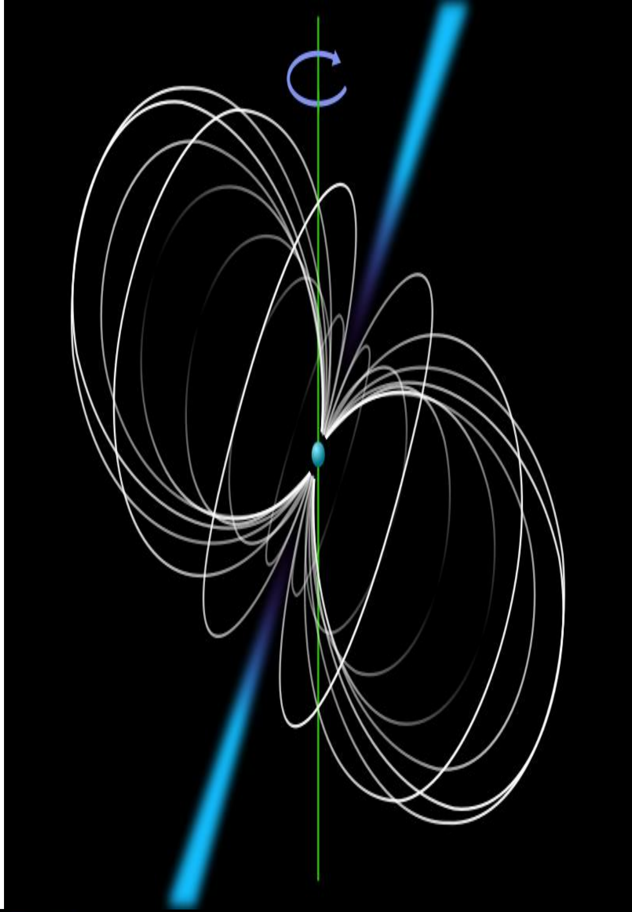
Pulsars

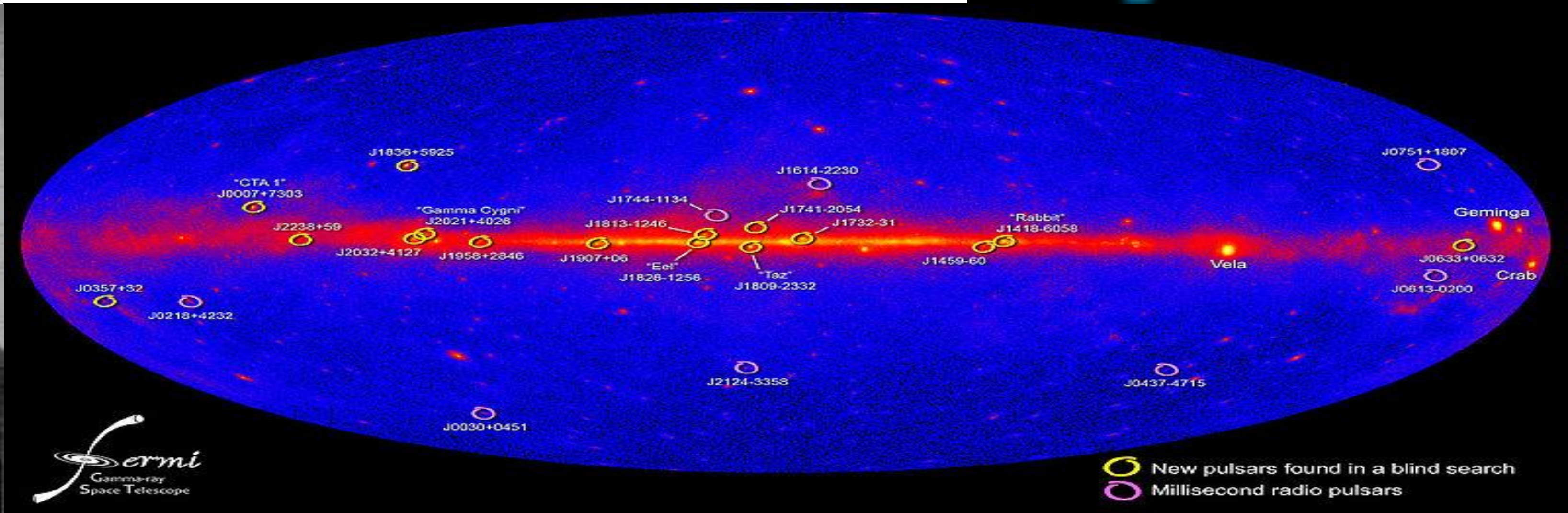
- Magnetized neutron stars
- Non alignment of magnetic field and rotation axis
- Two Nobel prizes :

Jocelyn Bell Burnell & Antony Hewish (1967)

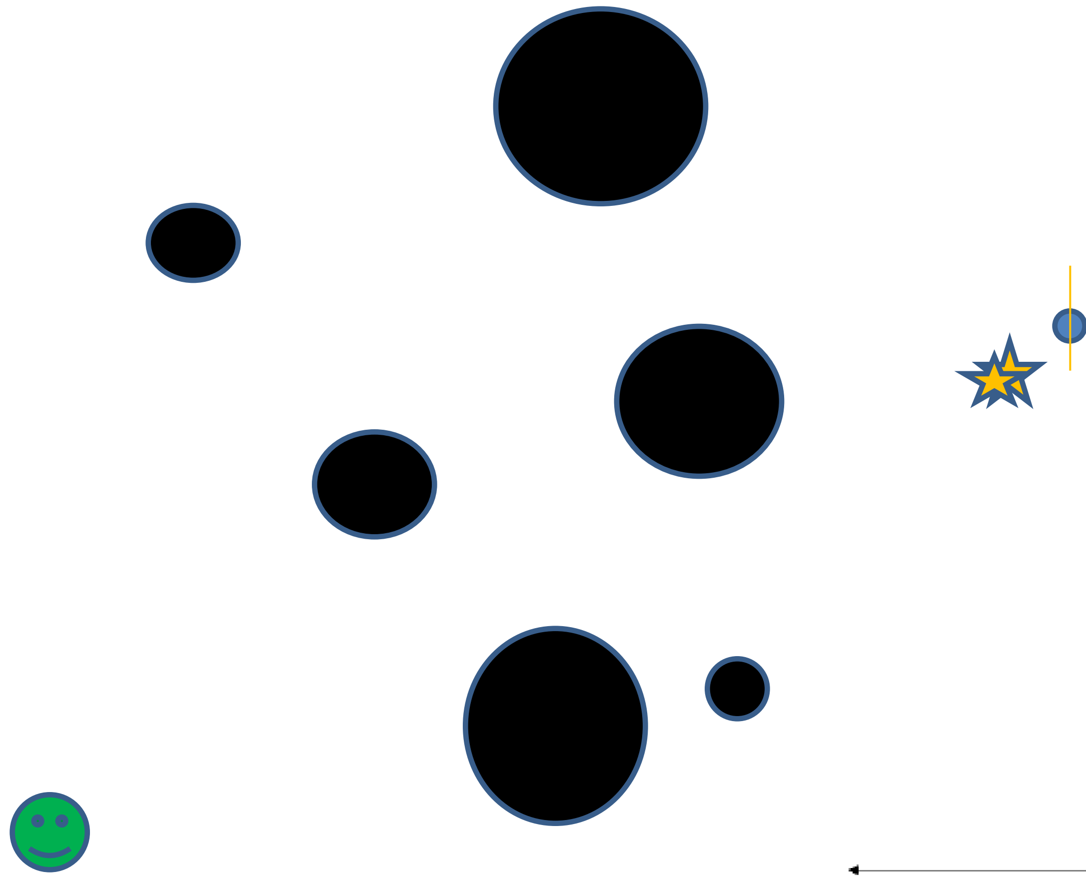
Taylor (1993)

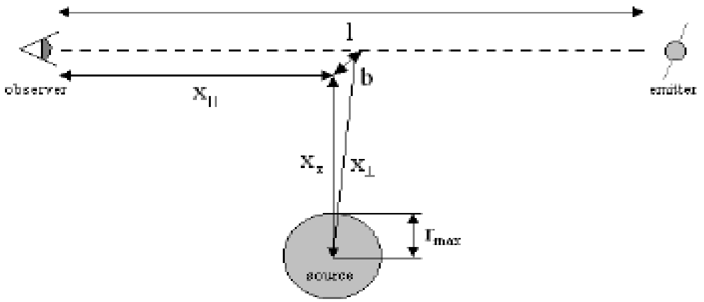
- A very precise clock with millisecond to second period





Pulsar timing : A new horizon to see DM





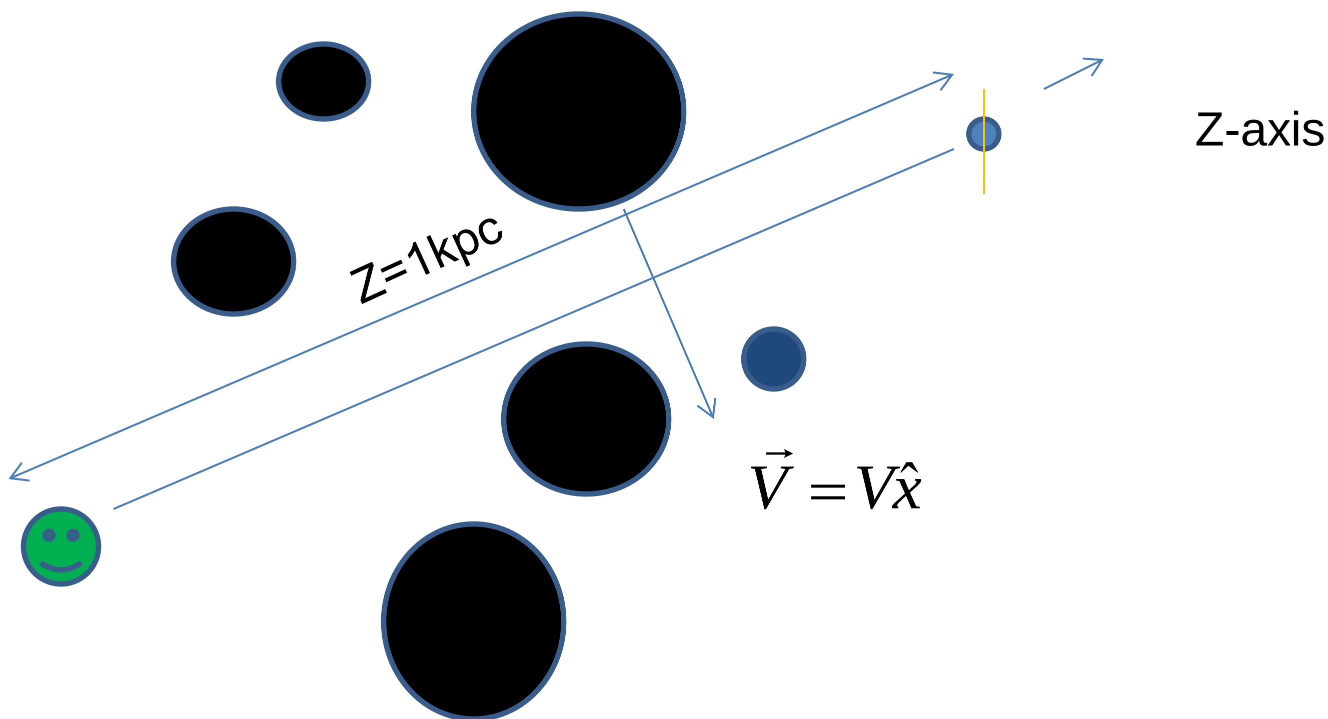
E. R. Siegel, M. P. Hertzberg, J. N. Fry
arXiv:astro-ph/0702546v2

Shapiro and Doppler Effect

$$ds^2 = -(1+2\Phi)dt^2 + (1-2\Phi)d\vec{x}^2,$$

$$t = t_0 + \delta t = \int_{x_{em}}^{x_{obs}} (1-2\Phi)d\vec{x},$$

$$\dot{\delta t} = \frac{\delta\nu}{\nu} = 2\int \dot{\Phi} d\vec{x},$$



How to detect this effects? (Shapiro)

- Statistical Point of view

$$\langle (\frac{\delta\nu}{\nu})_{\text{I}} (\frac{\delta\nu}{\nu})_{\text{II}} \rangle = \frac{1}{2\pi} \int P_{\frac{\delta\nu}{\nu}}(\omega) e^{-i\omega\Delta t} d\omega.$$

- Shapiro effect is applied

$$\langle (\frac{\delta\nu}{\nu})_{\text{I}} (\frac{\delta\nu}{\nu})_{\text{II}} \rangle = 4 \int_0^{z_0} \int_0^{z_0} dz_{\text{I}} dz_{\text{II}} v^2 \langle \frac{\partial}{\partial x} \Phi_{\text{I}} \frac{\partial}{\partial_x} \Phi_{\text{II}} \rangle,$$

- Final we get:

$$\boxed{\omega P_{\frac{\delta\nu}{\nu}}(\omega) = \frac{4z_0}{v} \int \frac{dk^y}{2\pi} \omega^3 P_\phi \left(\sqrt{\frac{\omega^2}{v^2} + k_y^2} \right)}$$

Potential power spectrum

How to detect this effects? (Doppler effect)

- Statistical Point of view

$$\langle(\frac{\delta\nu}{\nu})_{\text{I}}(\frac{\delta\nu}{\nu})_{\text{II}}\rangle = \frac{1}{2\pi}\int P_{\frac{\delta\nu}{\nu}}(\omega)e^{-i\omega\Delta t}d\omega.$$

- Doppler effect is applied

$$\langle(\frac{\delta\nu}{\nu})_{\text{I}}(\frac{\delta\nu}{\nu})_{\text{II}}\rangle = \int_{-\infty}^{t_1} dt \int_{-\infty}^{t_2} dt' \langle\nabla_z\Phi_{\text{I}}\nabla_z\Phi_{\text{II}}\rangle$$
$$\times \; e^{\varepsilon(t-t_1)}e^{\varepsilon(t'-t_2)},$$

Potential power spectrum

- Final we get:

$$\boxed{P_{\frac{\delta\nu}{\nu}}(\omega) = \frac{1}{4\pi}\int dk_* \frac{k_*^3}{v\omega^2}P_\phi\left(\sqrt{\frac{\omega^2}{v^2}+k_*^2}\right),}$$

From Gravitational potential to matter power spectrum

- Poisson Equation is applied:

$$P_\Phi(\vec{k}) = \left(\frac{4\pi G}{k^2}\right)^2 P_\rho(\vec{k}).$$

Questions:

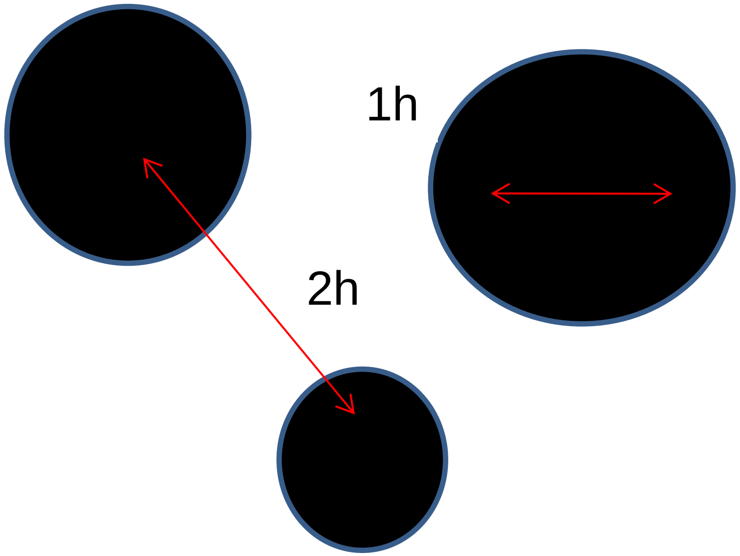
1)What scales we are looking at?

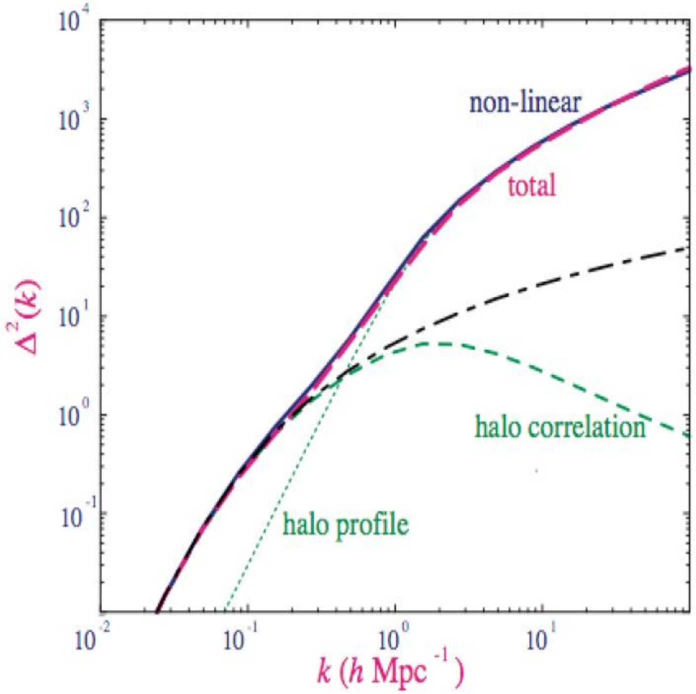
2)How we are going to compute the matter power spectrum in those scales?

Matter Power Spectrum in NL regimes

- Halo Model

$$dn(M,z) = -\sqrt{\frac{2}{\pi}}\frac{\rho_b}{M^2}\frac{\delta_c R}{3\sigma^2(R,z)}\frac{d\sigma(R,z)}{dR}\exp\left[-\frac{\delta_c^2}{2\sigma^2(R,z)}\right]dM$$

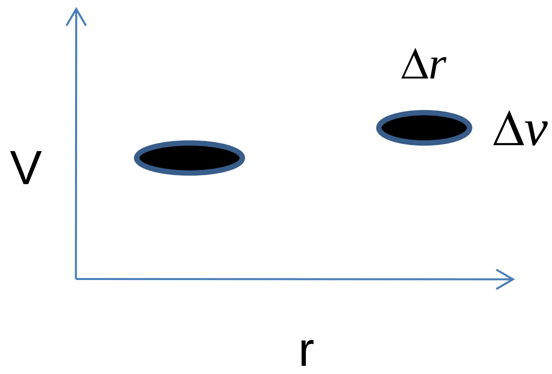




$$\frac{\rho}{\rho_{cr}} = \frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

Matter Power Spectrum in NL regimes

- Stable Clustering in Phase Space



$$\frac{df}{dt} = \frac{\partial \tilde{f}_i}{\partial t}|_{\Delta r, \Delta v} + \frac{\partial \tilde{f}_i}{\partial \Delta r}.\Delta v - \frac{\partial \tilde{f}_i}{\partial \Delta v}.(\nabla\nabla\Phi.\Delta r) = 0,$$

Edmund Bertschinger, Phys.Rev.D81:101301,2010. Roya Mohayaee, Niayesh Afshordi,

Matter Power Spectrum in NL regimes

- We find a solution for the phase space density

1) It depends on the mass of DM Structure (Local)

2) The time of DM subS. formation (Cosmological background)

3) The Survival of DM substructures

$$\langle \tilde{f} \rangle_p = \mu \xi_s = F\left[(\Delta \mathrm{v})^2 + 100H(\xi_s)^2(\Delta \mathrm{r})^2\right] ,$$

$$\xi_s \sim \frac{10H(\xi_s)}{G^2 M(\xi_s)}, \qquad \sigma_{vir} \sim 10 H r_{vir},$$

Stable Clustering in Phase Space

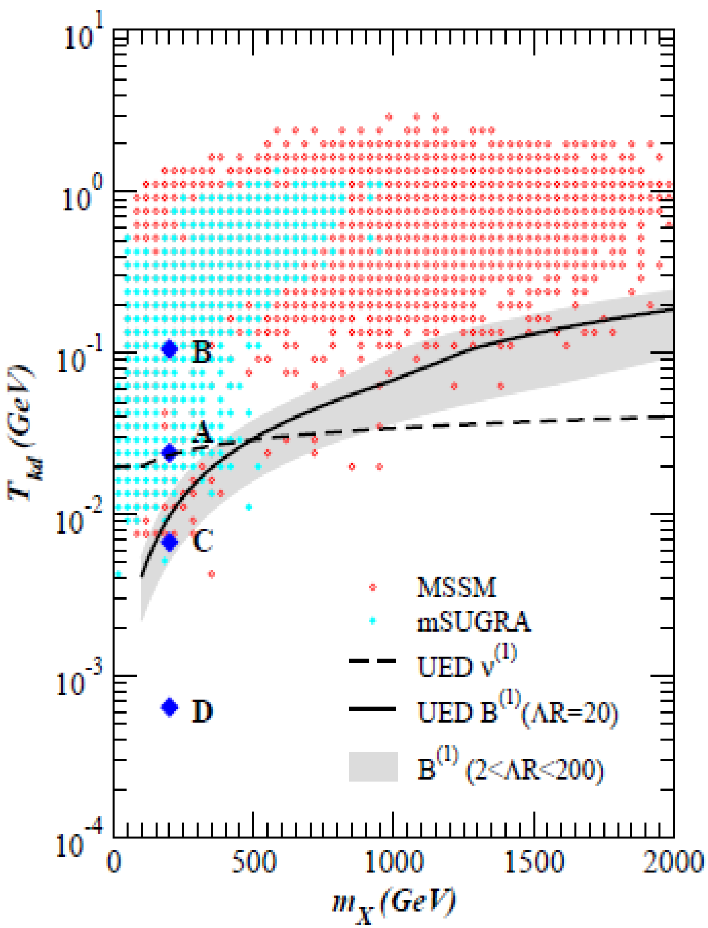
- It depends on the mass of DM Structure (Local)

- DM fluctuations are suppresses on the scale of the comoving horizon at the time of kinetic decoupling of DM.

Loeb & Zaldarriaga 2005, Bertschinger 2006

Stefano Profumo, Kris Sigurdson, Marc Kamionkowski;Phys.Rev.Lett. 97 (2006) 031301

$$M_{\min} = 10^{-4} \left(\frac{T_d}{10MeV}\right)^{-3} M_{sun}$$



Stable Clustering in Phase Space

- The time formation (Cosmological background)

$$\boxed{\left[\frac{H(\xi_s)}{H_0}\right]^{-2/3} \sigma[M(\xi_s)] \sim \delta_c \simeq 1.7,}$$

- Spherical Collapse + Knowledge on linear scale matter power spectrum

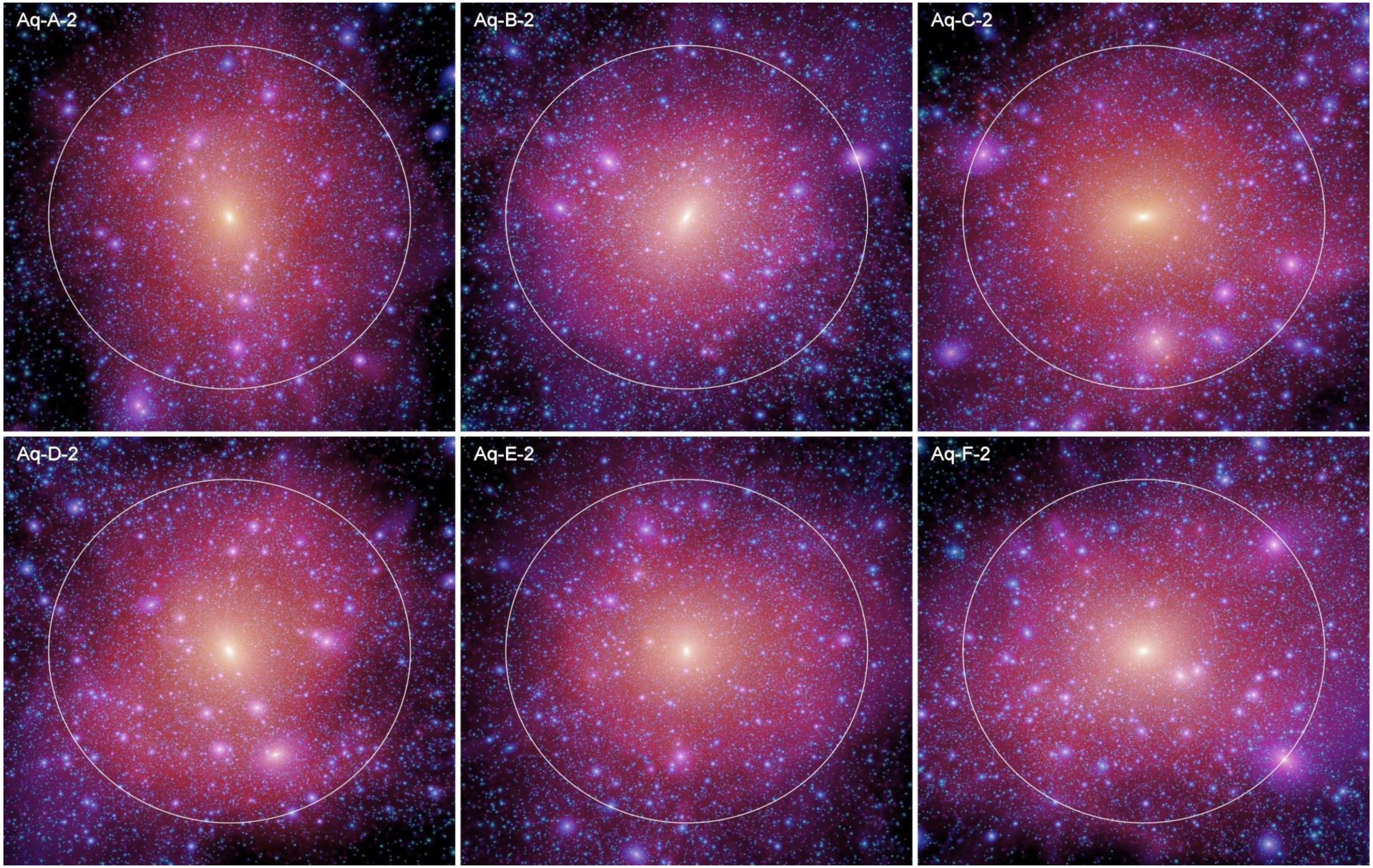
$$\sigma^2(M) = \int \frac{d^3k}{(2\pi)^3} P_L(k) W^2(kR),$$

$$R = \left[\frac{m}{1.162 \times 10^{12} h^2 M_\odot \Omega_m^0}\right]^{1/3} Mpc$$

Stable Clustering in Phase Space

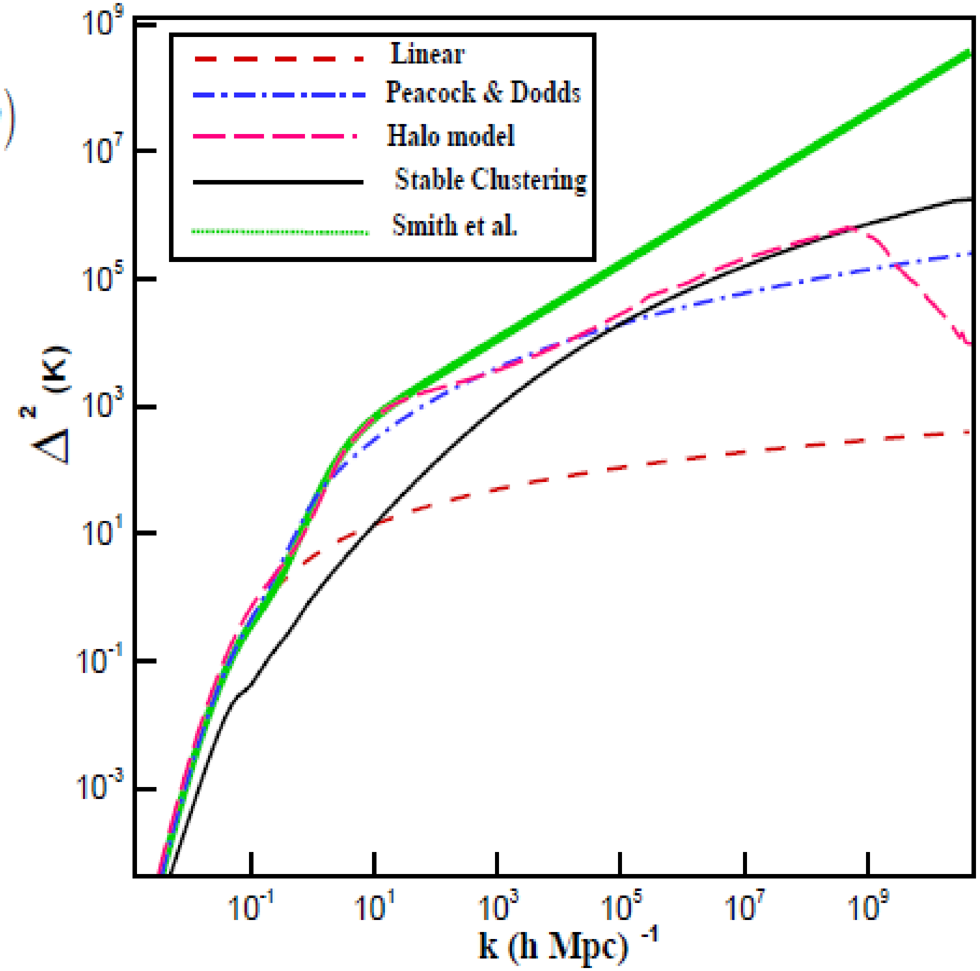
- The Survival of DM substructures

Jesus Zavala (UW/PI): Work in progress



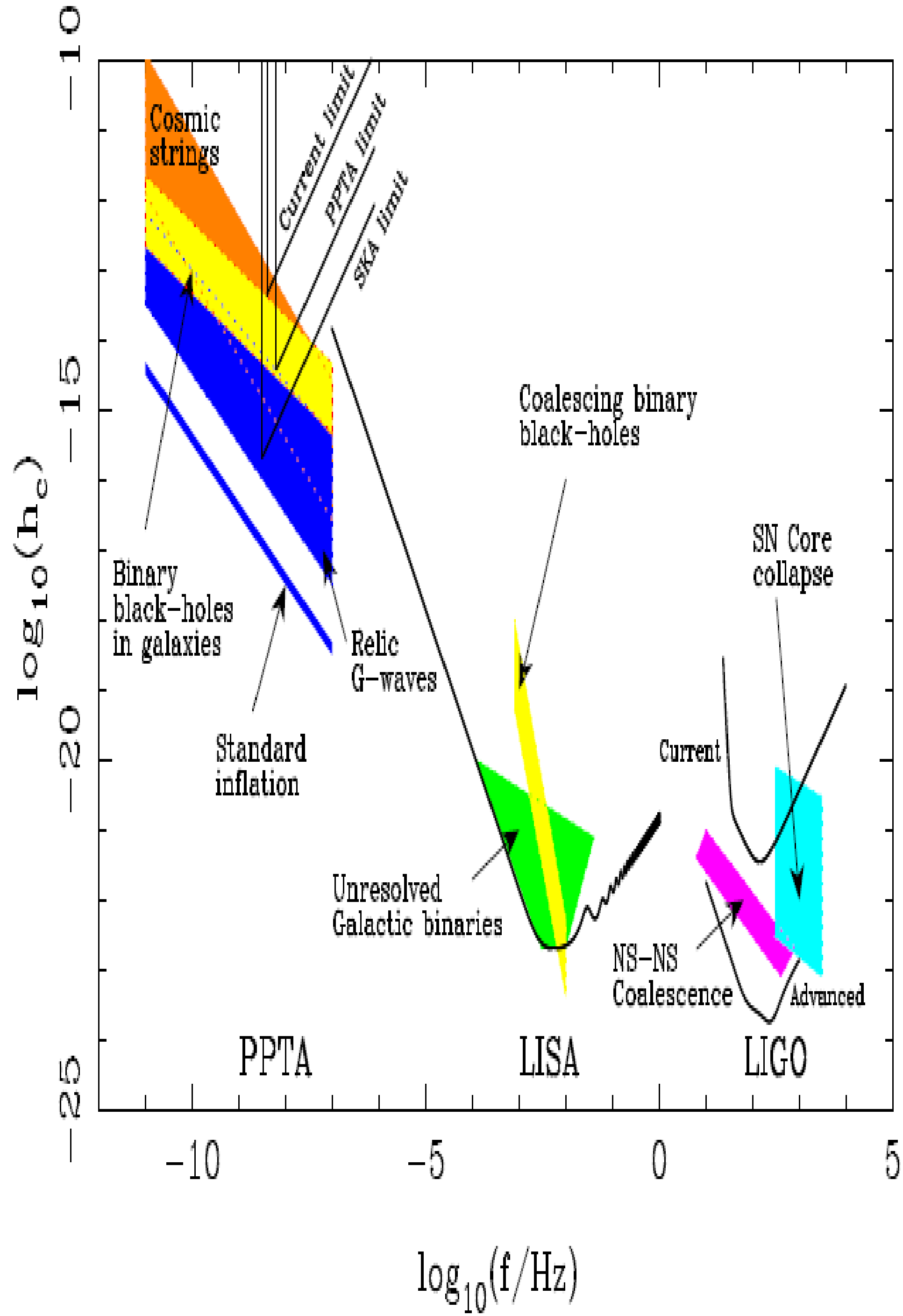
Stable Clustering non linear power spectrum

$$\begin{aligned}
\langle \rho(\vec{r}_1)\rho(\vec{r}_{11})\rangle &= \int d^3\vec{v}_1 d^3\vec{v}_{11}\langle f(\vec{r}_1,\vec{v}_1)f(\vec{r}_{11},\vec{v}_{11})\rangle \\
&\simeq \int d^3\bar{\vec{v}} d^3\Delta\vec{v}\mu\langle f(\bar{\vec{r}},\bar{\vec{v}})\rangle\xi_s(\Delta r,\Delta v) \\
&= \mu\bar{\rho}_{avg}\int d^3\Delta\vec{v}\xi_s(\Delta r,\Delta v).
\end{aligned}$$



Detection

- Dimensionless power spectrum of pulsar timing change is the same quantity as strain of GW



Results：How we can use this!!

- Detection
- Small scale PS

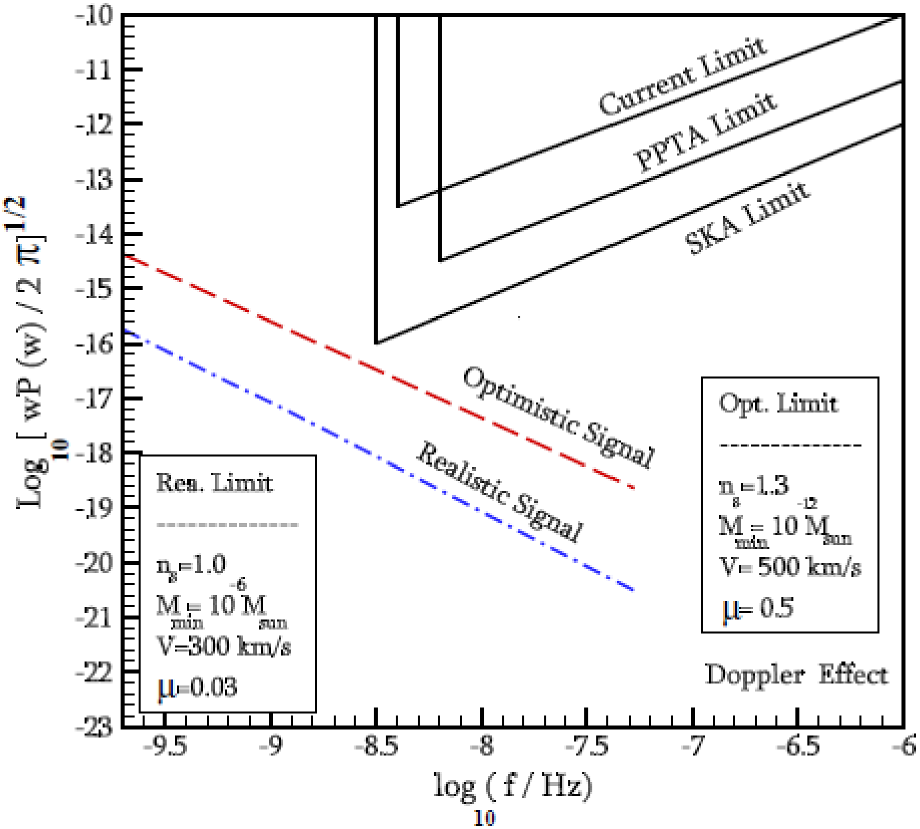
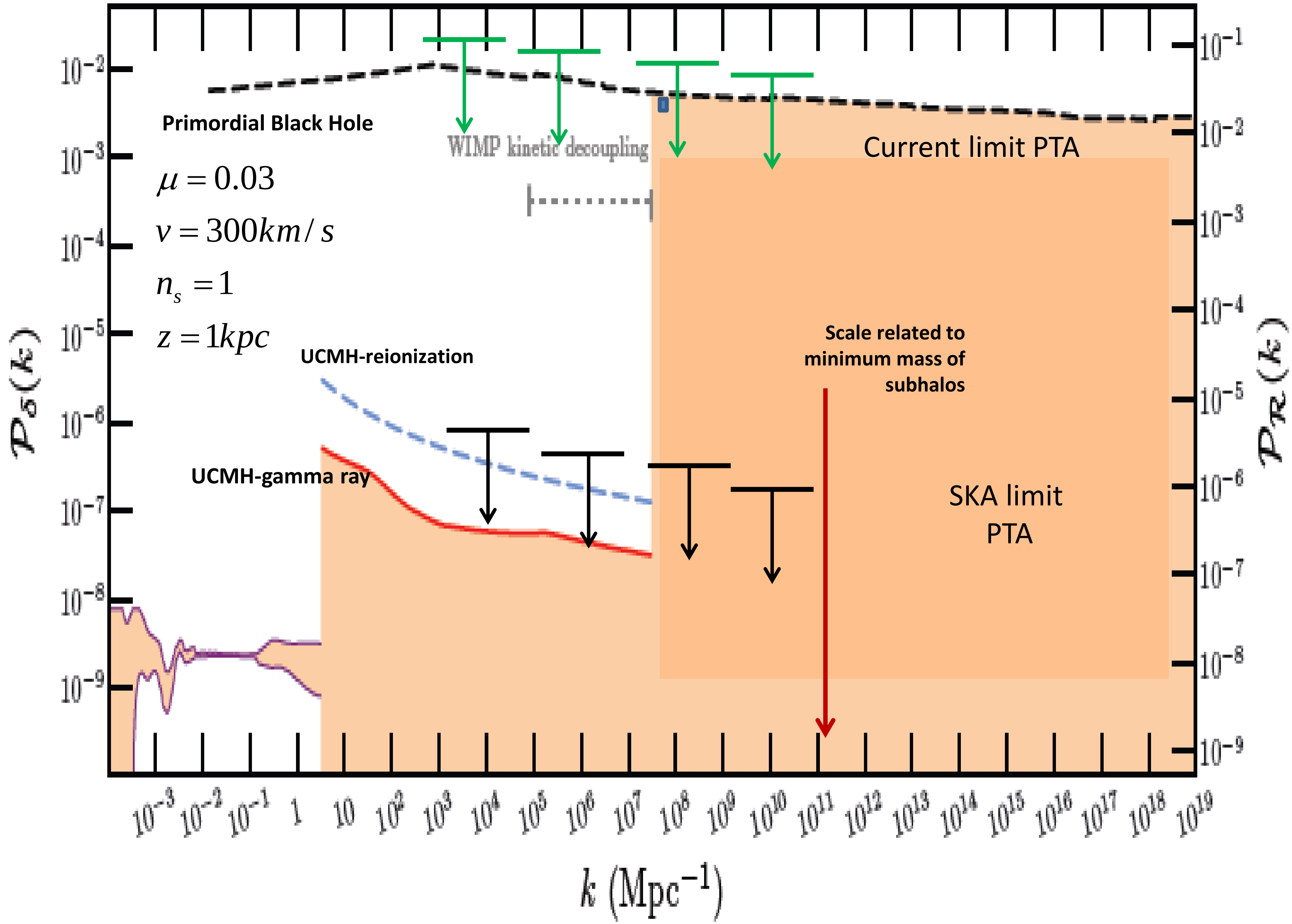
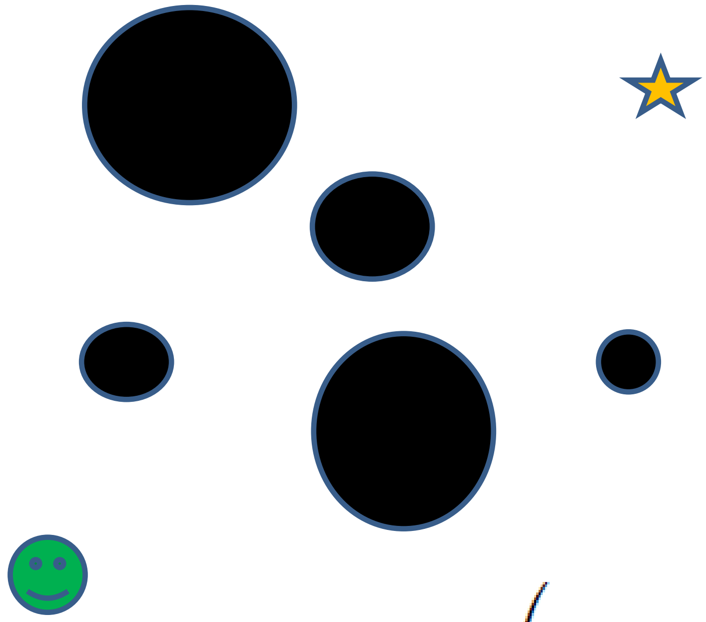
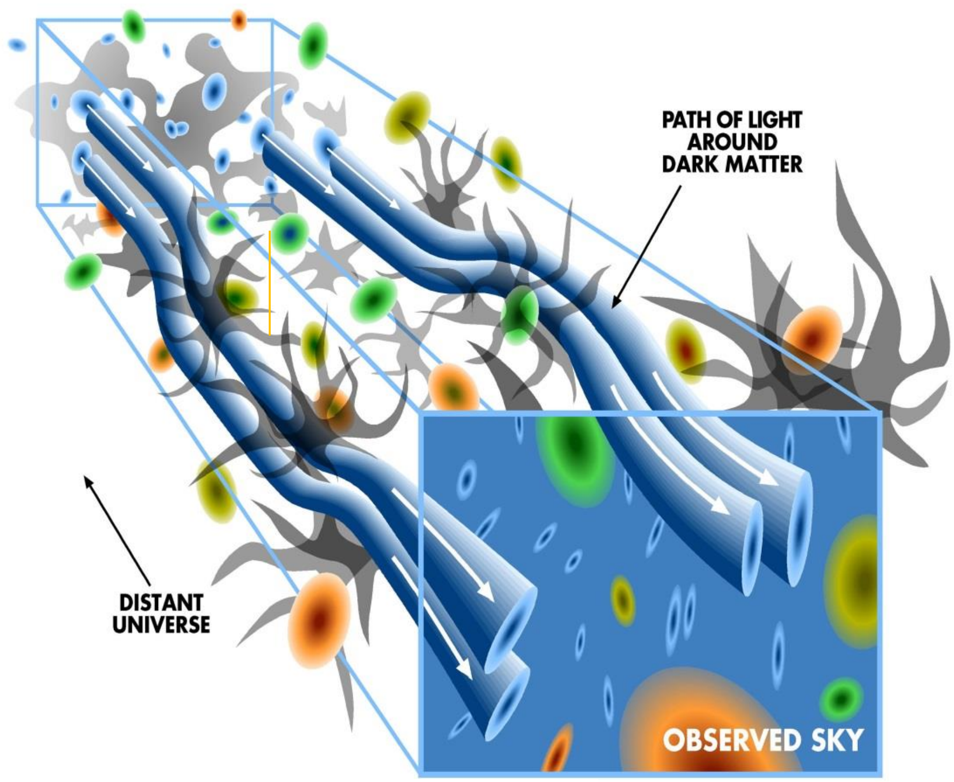


FIG. 9: Pulsar residual power spectrum as a function of the frequency for Doppler effect for realistic and optimistic signals (see text for definition of realistic and optimistic parameters). The limits from current and future experiments are also shown.


Primordial Black Hole
WIMP kinetic decoupling
Current limit PTA
$\mu = 0.03$
$v = 300 km/s$
$n_s = 1$
$z = 1kpc$
UCMH-reionization
Scale related to minimum mass of subhalos
UCMH-gamma ray
SKA limit PTA
$\mathcal{P}_\delta(k)$
$\mathcal{P}_\mathcal{R}(k)$
$k\ (\mathrm{Mpc}^{-1})$

Weak gravitational lensing





$$\psi_{ij} = \begin{pmatrix} \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & \kappa + \gamma_1 \end{pmatrix}$$

where $\nabla_{\hat{\mathrm{n}}} = D\nabla$ and

$$\psi_{ij} = 2\int dD \frac{D(D_s - D)}{D_s} \nabla_i \nabla_j \Phi(D\hat{\mathbf{n}}, \eta(D))$$

Even Newer Proposal for detecting the Gravitational Effect of Dark Matter: Transient Weak Lensing

- The magnification is defined as

$$A_{ij} = \frac{\partial \beta^i}{\partial \theta^j} = \delta_{ij} + 2\int \Phi_{,ij}(\chi')(1 - \frac{\chi'}{\chi})\chi' d\chi'.$$

The magnification change is obtained as:

$$\delta A(t) = 2\int_0^{\chi_s} \int \frac{dk^3}{(2\pi)^3} k_\perp^2 \Phi(k) e^{-ik_\perp(t)\chi_\perp} e^{-ik_{||}\chi'} (1 - \frac{\chi'}{\chi})\chi' d\chi', \quad (5)$$

SB, Sohrab Rahvar, Niayesh Afshordi

The Power Spectrum of magnification change

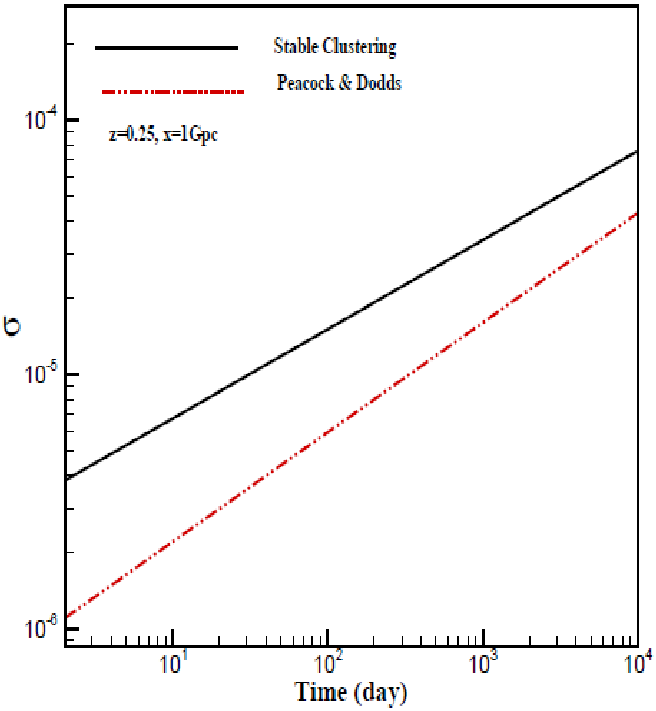
- The statistical description for the magnification change:

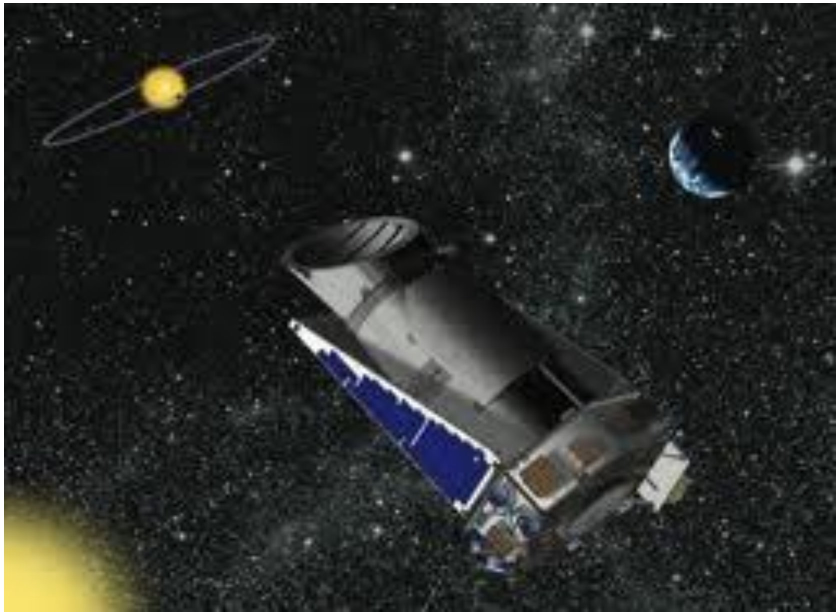
$$\boxed{\begin{aligned} \omega P(\omega) &= 18\pi^2 H_0^4 \Omega_m^{(0)^2} \int_0^{\chi_s} d\chi' \int_0^{\infty} dv\, e^{-v^2/2\sigma^2} \qquad (7) \\ & \left(\frac{v}{\sigma(\frac{\omega}{v}, z_{\chi'})}\right)^2 \frac{\Delta^2(\frac{\omega}{v}, z_{\chi'})}{\omega} (1+z_{\chi'})^3 (1-\frac{\chi'}{\chi_s})^2 \chi'^2, \end{aligned}}$$

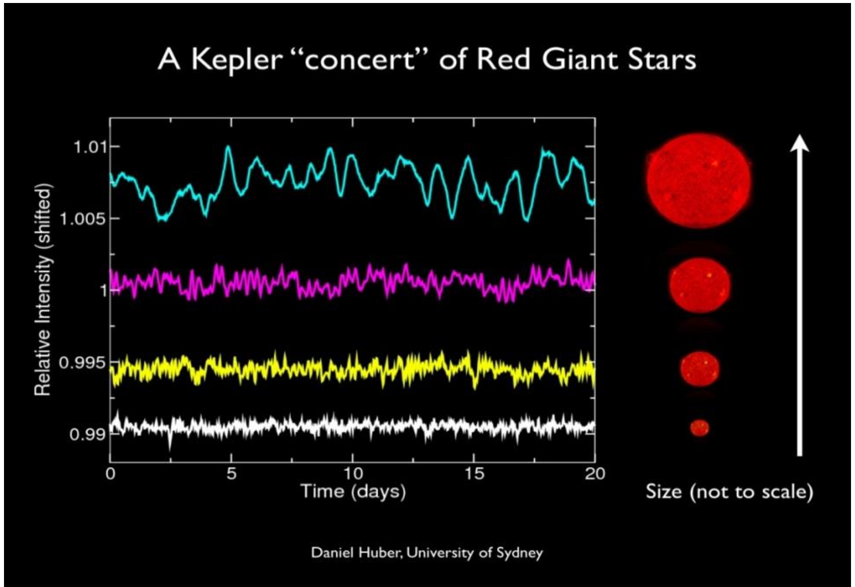
Where :

$$\boxed{P(\omega) = \int \langle \delta A(t_i) \delta A(t_{ii}) \rangle e^{i\omega\tau} d\tau,}$$

A micro-magnitude Signal in Cosmological Scales!







Conclusion

- Although there is more than 80 years than we new there is something missing, but the unknowns are still there.

✓ Phase Space of DM

✓ DM substructures

✓ New Ways to detect and know about DM

✓ Small Scale power spectrum

Thanks