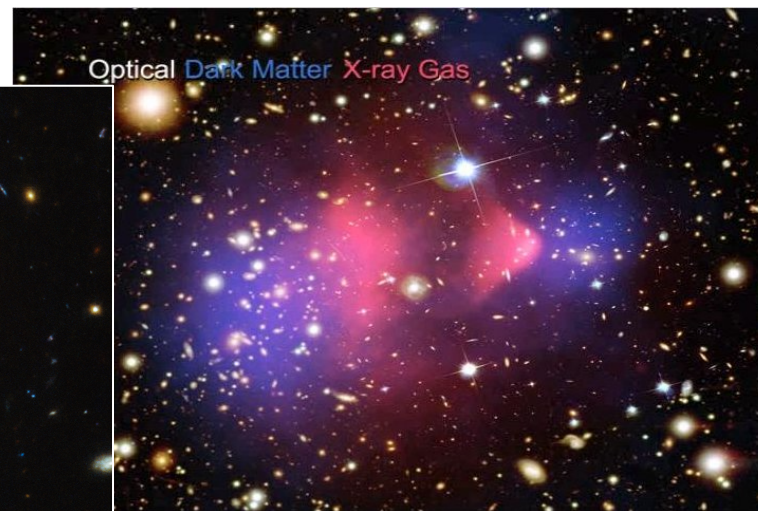
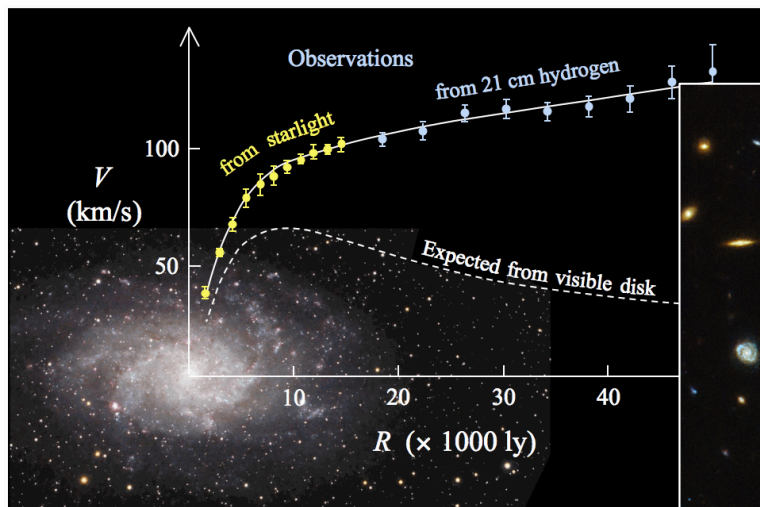


Overview of dark matter candidates

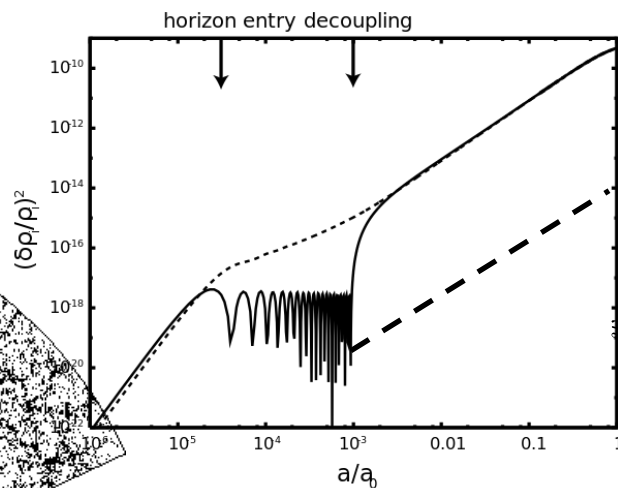
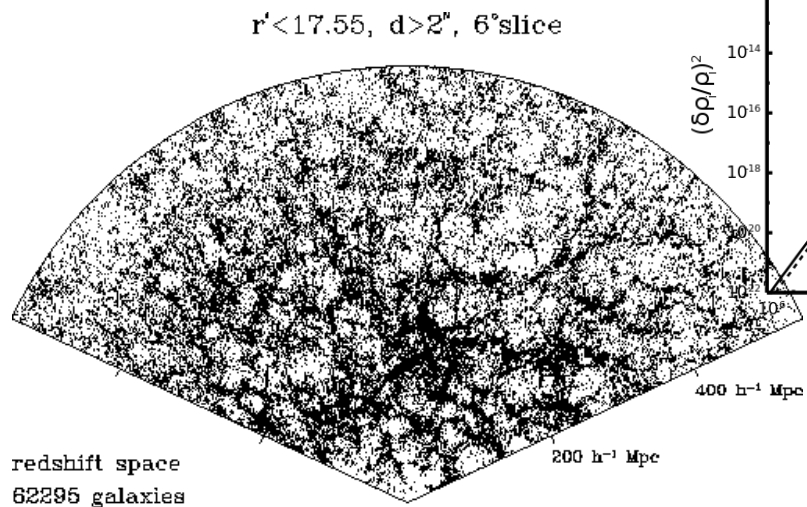
Chang Sub Shin (APCTP)

*2nd KR-LHC TH-EXP Cross Seminar
At SNU, May. 26, 2017*

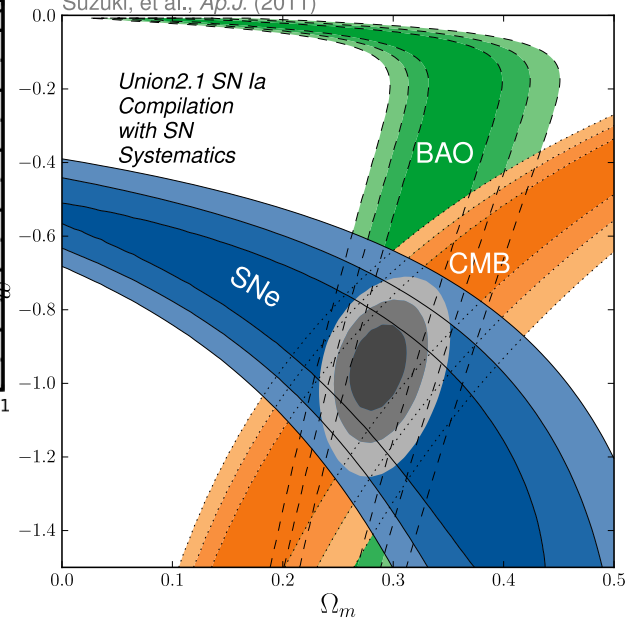
Dark matter paradigm



Dark matter paradigm



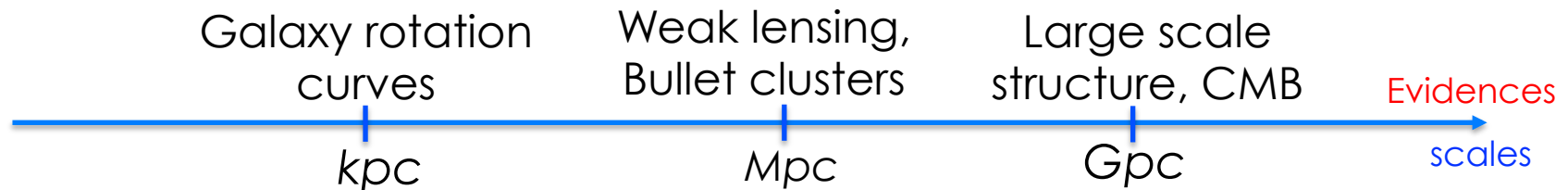
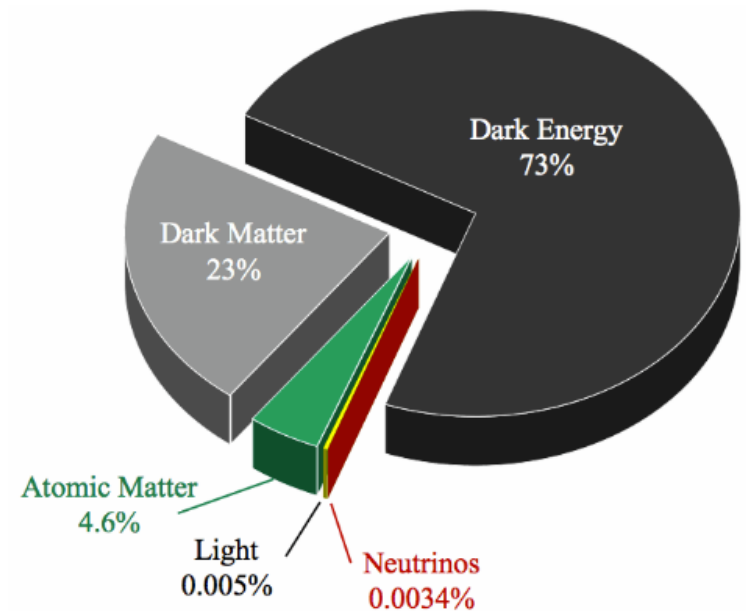
Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



Existence of dark matter

New Physics beyond the Standard Model

Gravitational interacting,
Stable,
Charge neutral,
Non-baryonic,
23-25% of total energy,
Non dissipative,
Cold $p_{DM} = w\rho_{DM}, \quad w \simeq 0$



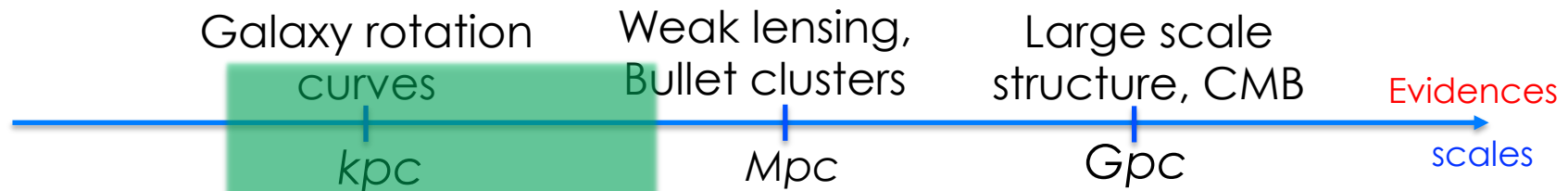
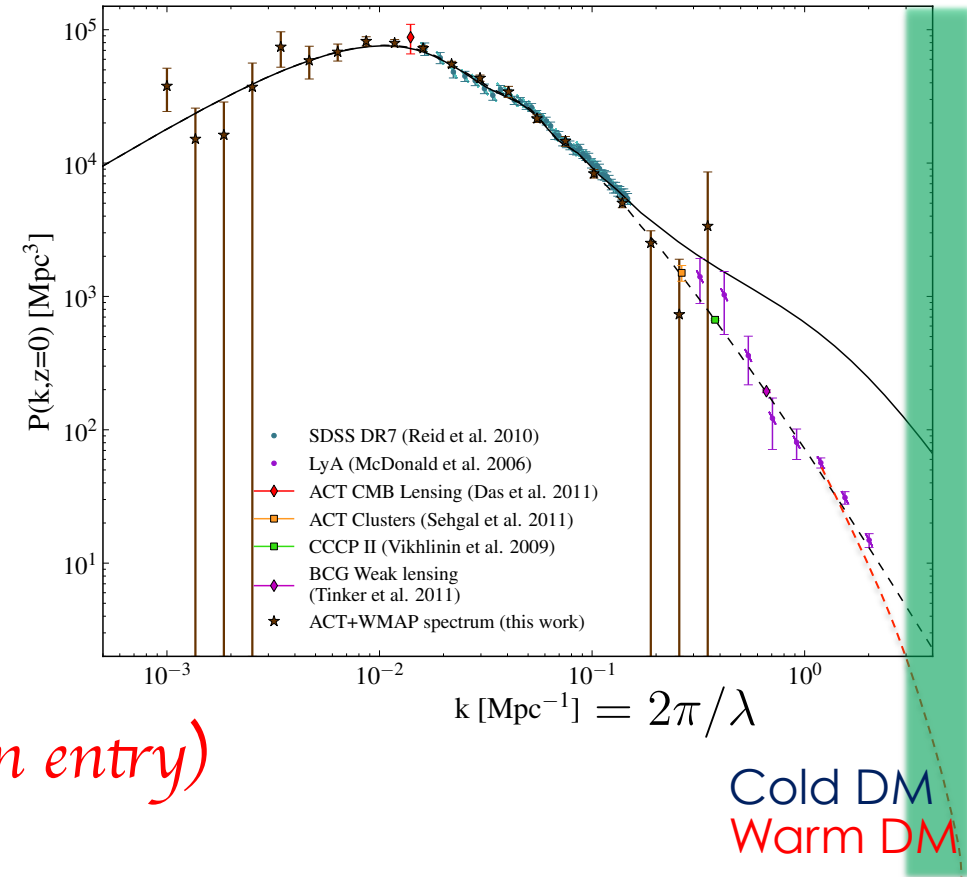
Existence of cold dark matter ?

Gravitational interacting,
Stable,
Charge neutral,
Non-baryonic,
23-25% of total energy,
Non dissipative,

Cold $p_{DM} = w\rho_{DM}, \quad w \simeq 0$

(depending on the time of Horizon entry)

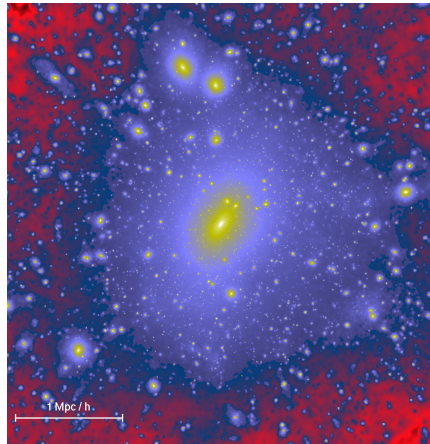
$\lambda = 1/H(t_{\text{entry}})$



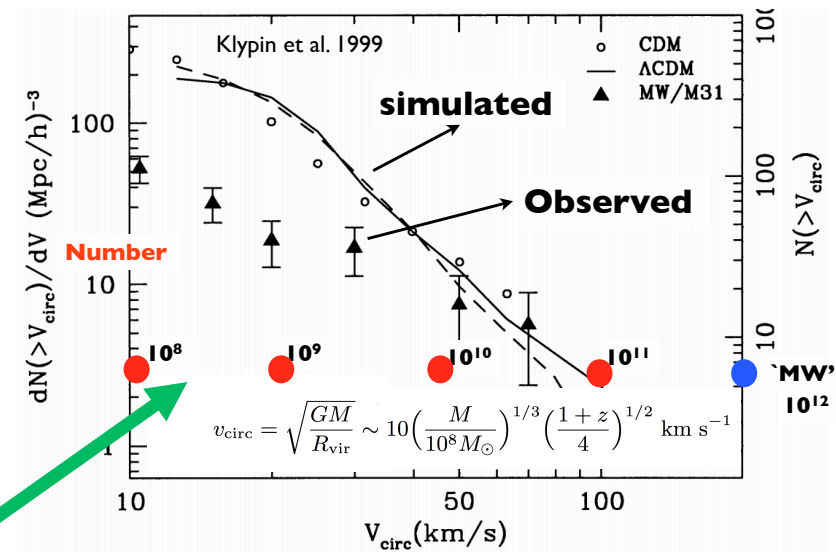
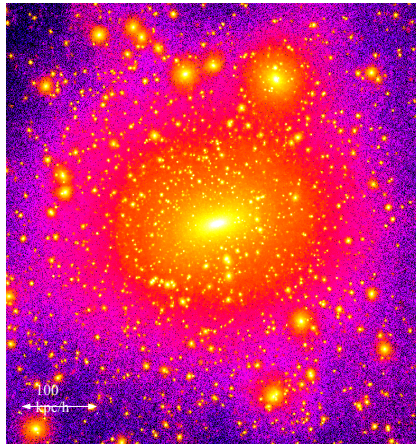
missing satellite, too big to fail, cusp-core problems

Missing satellite, too big to fail problems

A rich galaxy cluster halo
Springel et al 2001

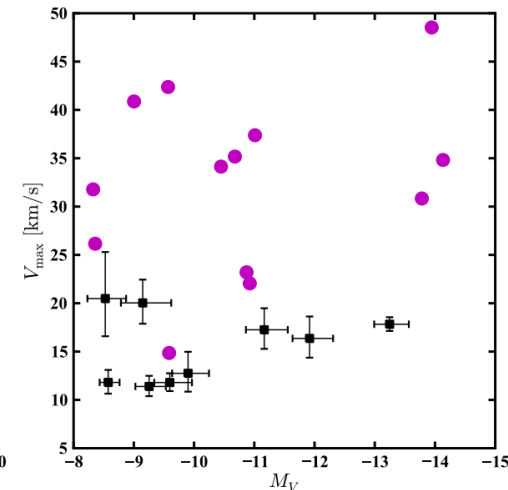
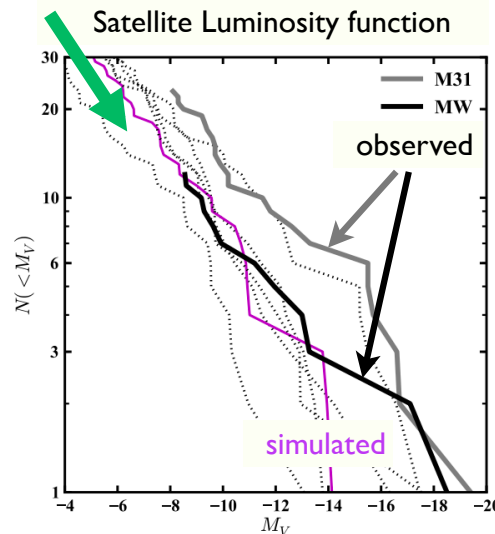
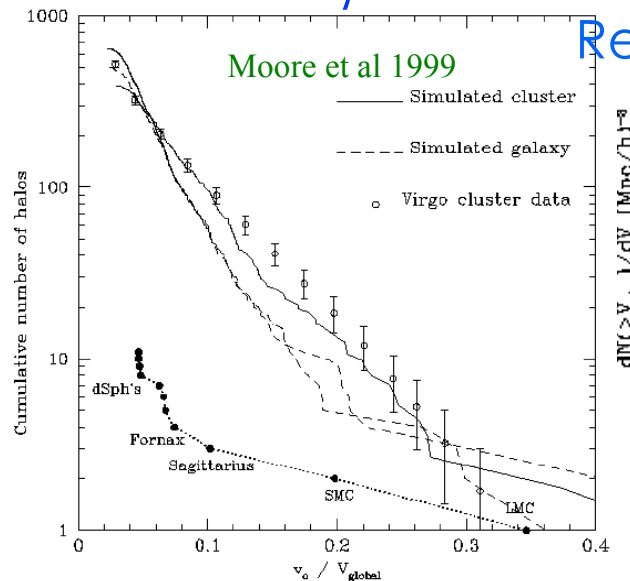


A 'Milky Way' halo
Power et al 2002



Resolution: baryonic feedback processes (which suppress the star formation) is most efficient in low mass (luminosity) satellites.

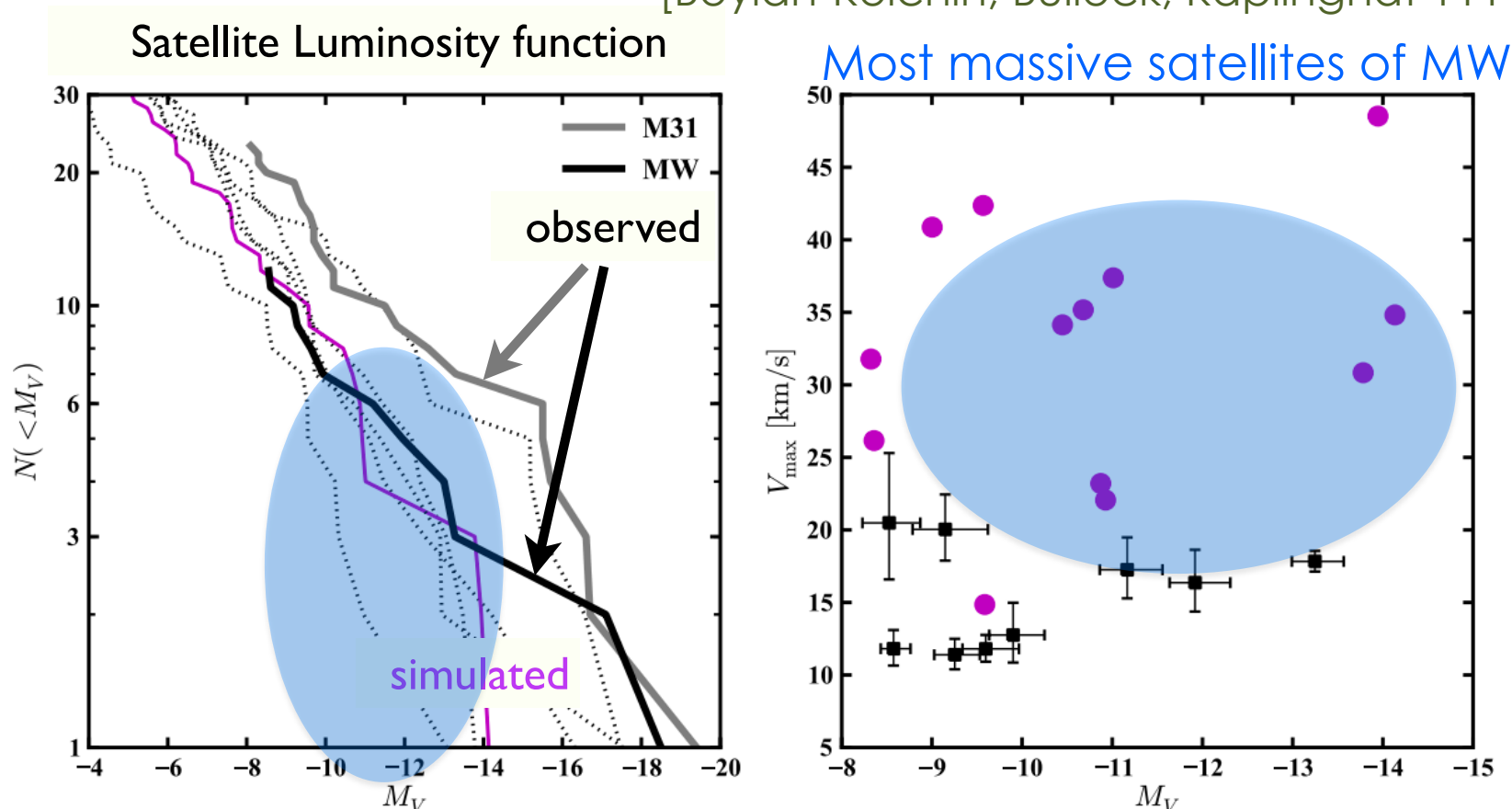
Reflected, and select most massive satellites of MW



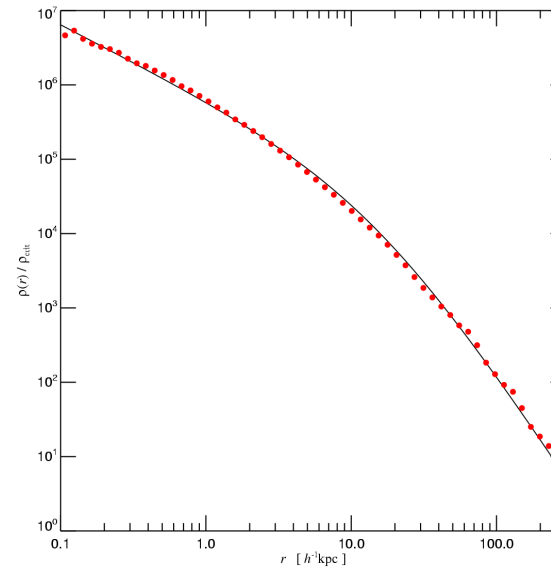
Missing satellite, **too big to fail** problems

Predicted most luminous satellite galaxies are **too massive** (not observed) **to fail** star formations

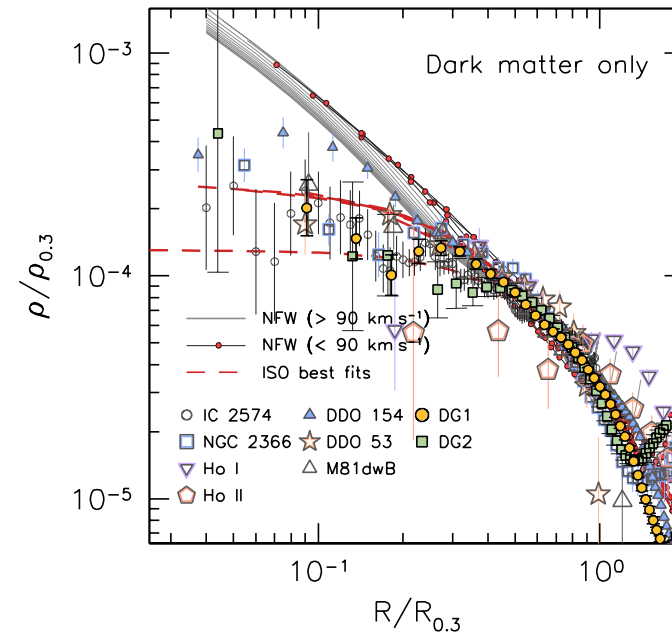
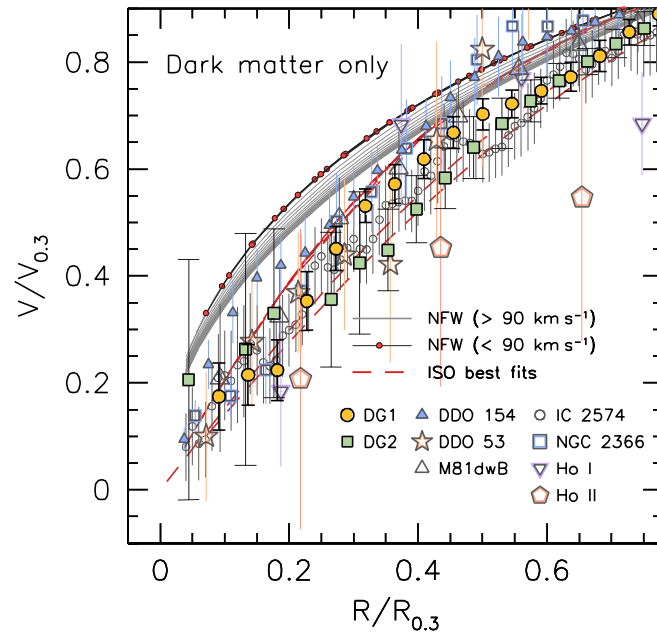
[Boylan-Kolchin, Bullock, Kaplinghat 1111.2048]



Cusp-core problem

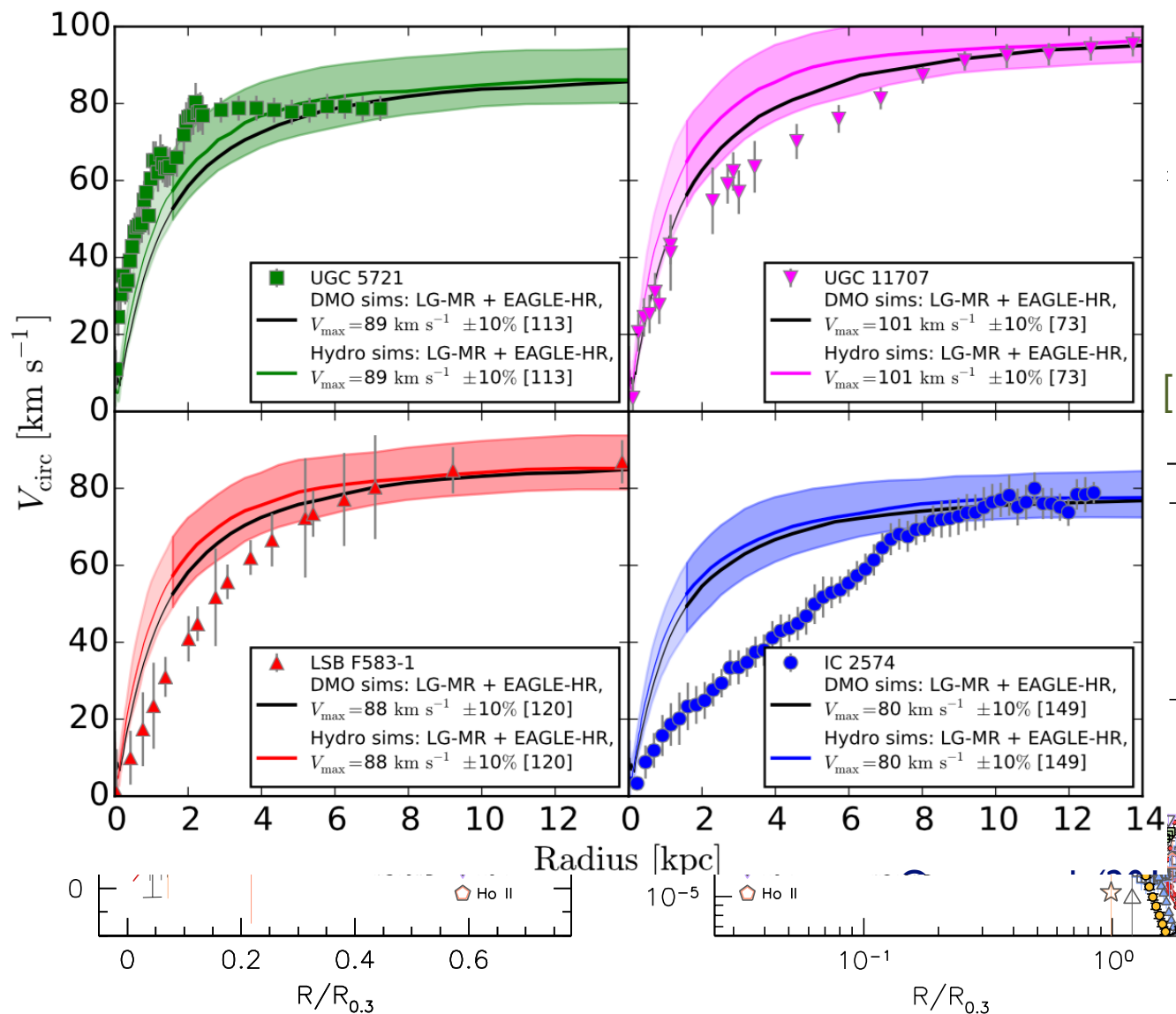
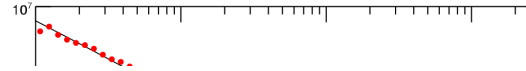
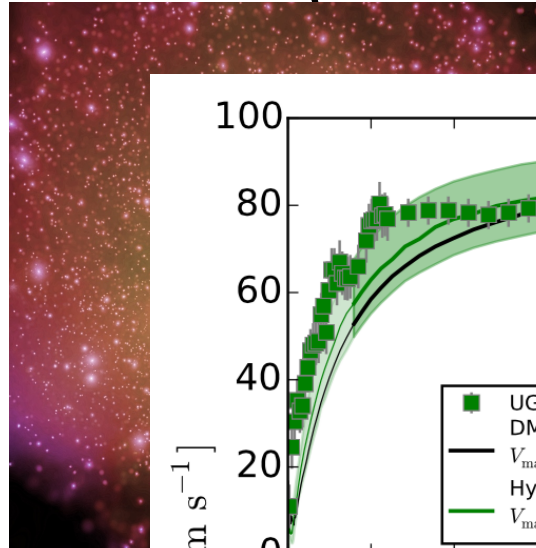


$$\rho_{NFW}(r) = \frac{\rho_0}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$$



[1011.2777]

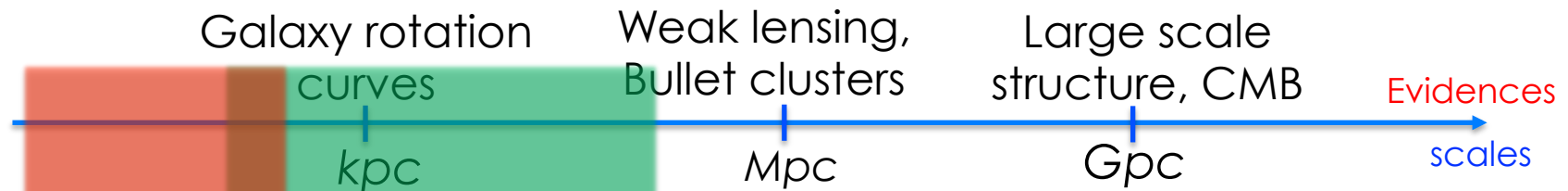
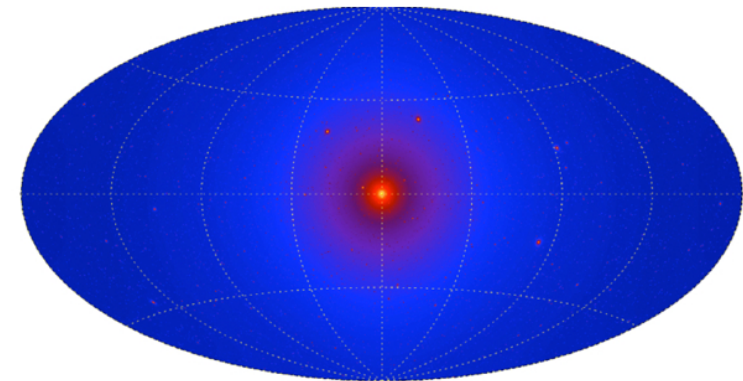
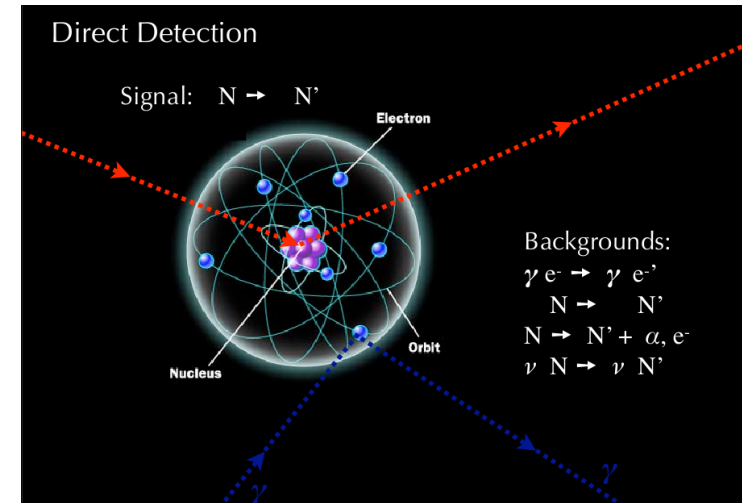
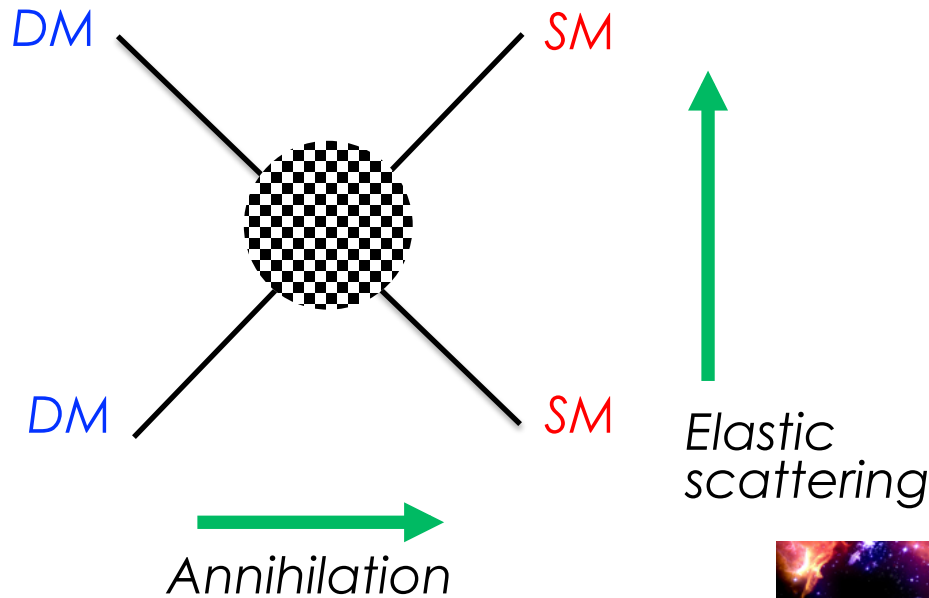
Cusp-core problem (diversity of rotation curves)



$$\frac{\rho_0}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$$

[1504.01437]

Existence of **WIMP** dark matter ?



No clear evidence yet

Nature of the dark matter ?

Is DM a particle? *spin, mass, compositions ?*

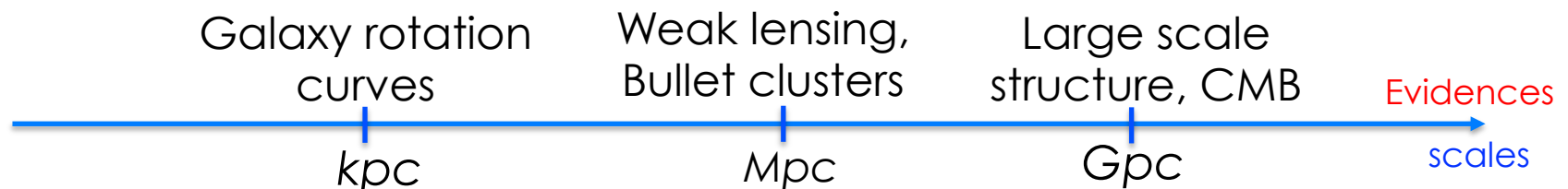
Why is it stable? *gauge/global, continuous/discrete symmetries ?*

What are the interactions between DM and the SM particles besides gravity *(like strong/weak interactions) ?*

What is the production mechanism of DMs at the early Universe ?
Why 25% of total mass of the present Universe ?

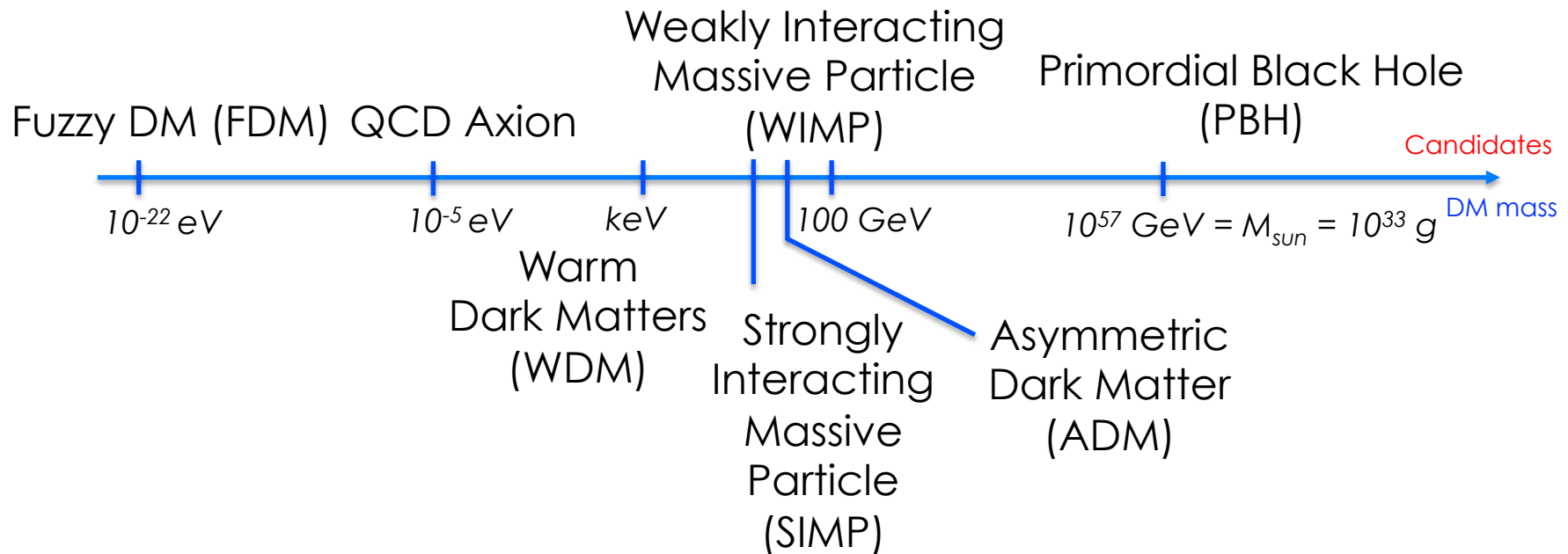
How can we detect it at sub *kpc* scales *(at the earth) ?*

What are the additional predictions ? *solving several small scale problems*

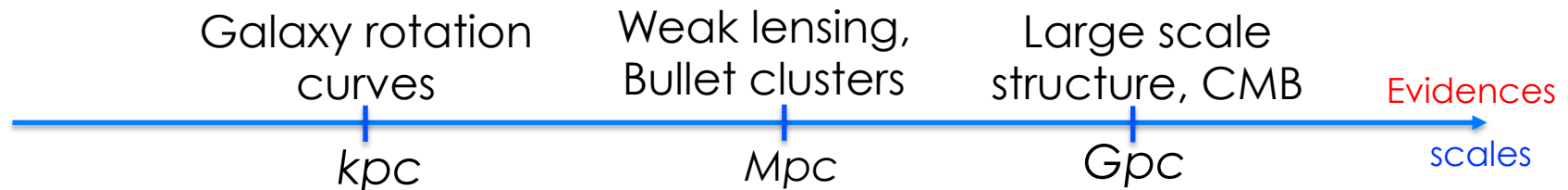


Nature of the dark matter ?

$$\bar{\rho}_{\text{DM}} = m_{\text{DM}} \bar{n}_{\text{DM}} \simeq 0.25 \bar{\rho}_{\text{tot}} = 1.2 \times 10^{-6} \text{ GeV}/\text{cm}^3 \text{ (observation)}$$



Evolutions of each DMs are different,
and give (possibly) different predictions for small scales



Coincidence ?

$$\Omega_{DM} \simeq 0.25$$

- WIMP

$$\Omega_{DM} = 0.25 \left(\frac{3 \times 10^{-26} \text{cm}^3/\text{sec}}{\langle \sigma_{\text{ann}} v \rangle_{fr}} \right)$$

$$\langle \sigma_{\text{ann}} v \rangle_{fr} \simeq \frac{1}{8\pi} \frac{g^4}{m_{\text{weak}}^2} \quad (g \sim 0.1)$$

- QCD Axion

$$\Omega_{DM} = 0.25 \alpha_a \left(\frac{f_a}{10^{10} \text{GeV}} \right)^{7/6}$$

$$f_a \sim \sqrt{m_{\text{weak}} M_{Pl}} \quad \alpha_a = 0.01 - 1$$

- SIMP

$$\Omega_{DM} = 0.25 \left(\frac{50 \text{MeV}}{m_{DM}} \right) \left(\frac{3 \times 10^{-52} \text{cm}^6/\text{sec}}{\langle \sigma_{3 \rightarrow 2} v^2 \rangle_{fr}} \right)^{1/2}$$

$$\langle \sigma_{3 \rightarrow 2} v^2 \rangle_{fr} \simeq \frac{1}{m_{DM}^5} \quad m_{DM} \sim m_{\pi}$$

- Asymmetric DM $\Omega_{DM} = (4 - 5) \Omega_{\text{baryon}}$

$$\Omega_{DM} = \mathcal{O}(\Omega_{\text{baryon}})$$

- Relativistic freeze-out DM

$$\Omega_{DM} = \frac{230}{g_*(T_{\text{dec}})} \left(\frac{m_{DM}}{2 \text{keV}} \right)$$

$$m_{\text{WDM}} \sim \mathcal{O}(\text{keV})$$

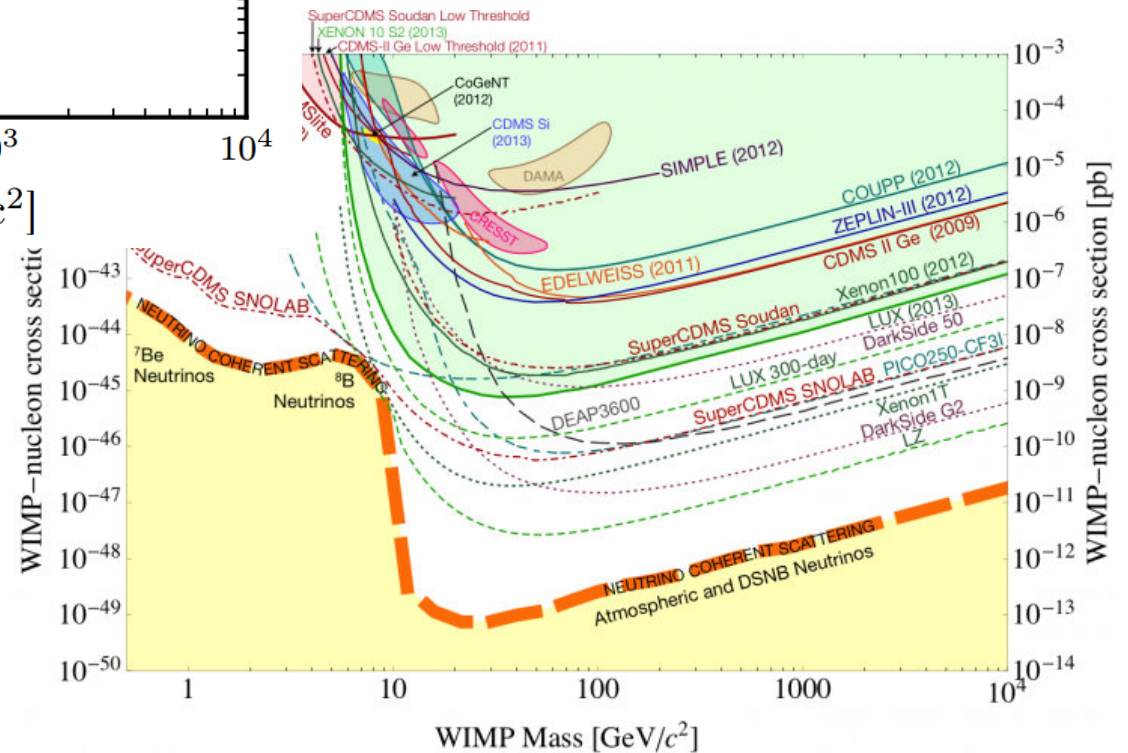
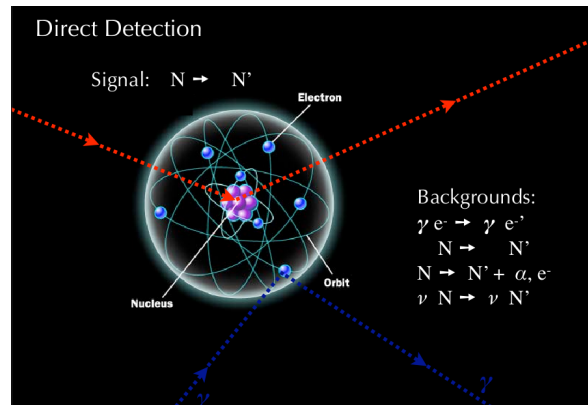
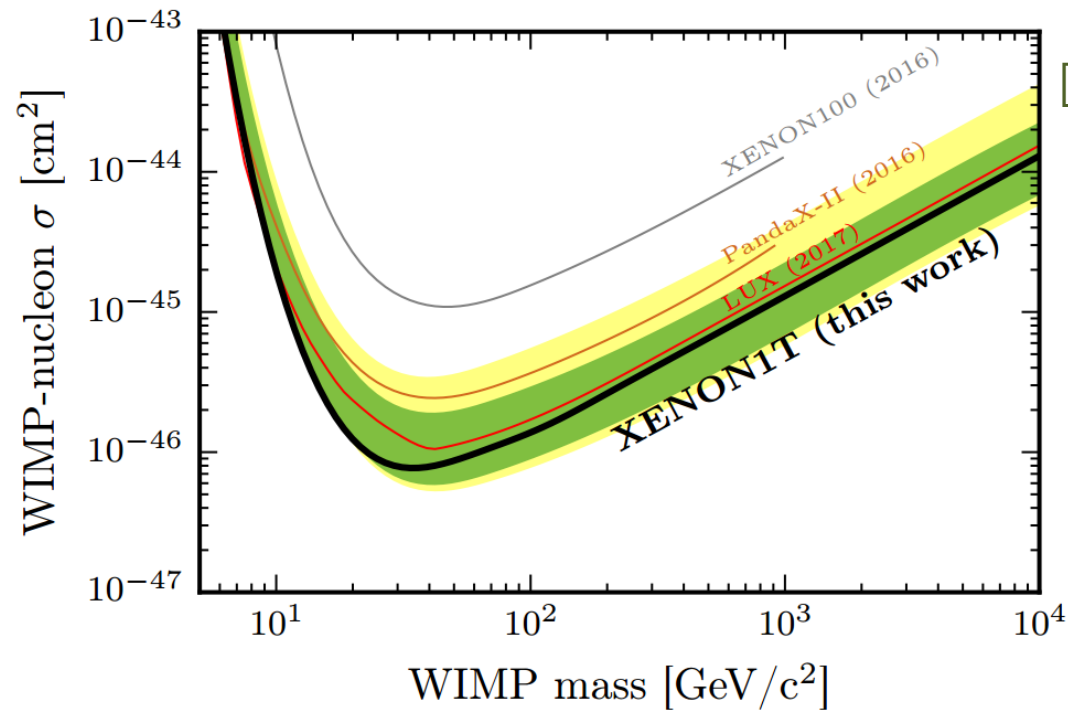
- Fuzzy DM

$$\Omega_{DM} = 0.25 \left(\frac{F}{10^{17} \text{GeV}} \right)^2 \left(\frac{m_{DM}}{10^{-22} \text{eV}} \right)^{1/2}$$

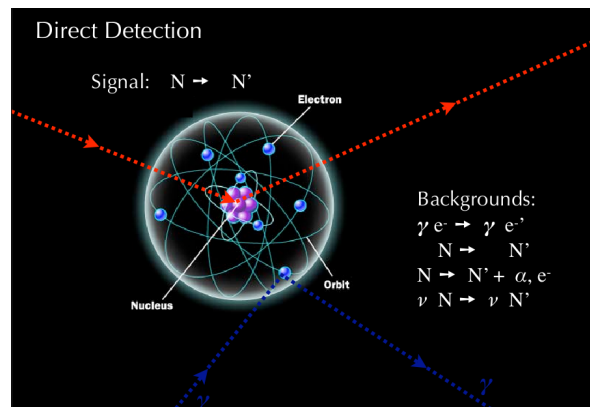
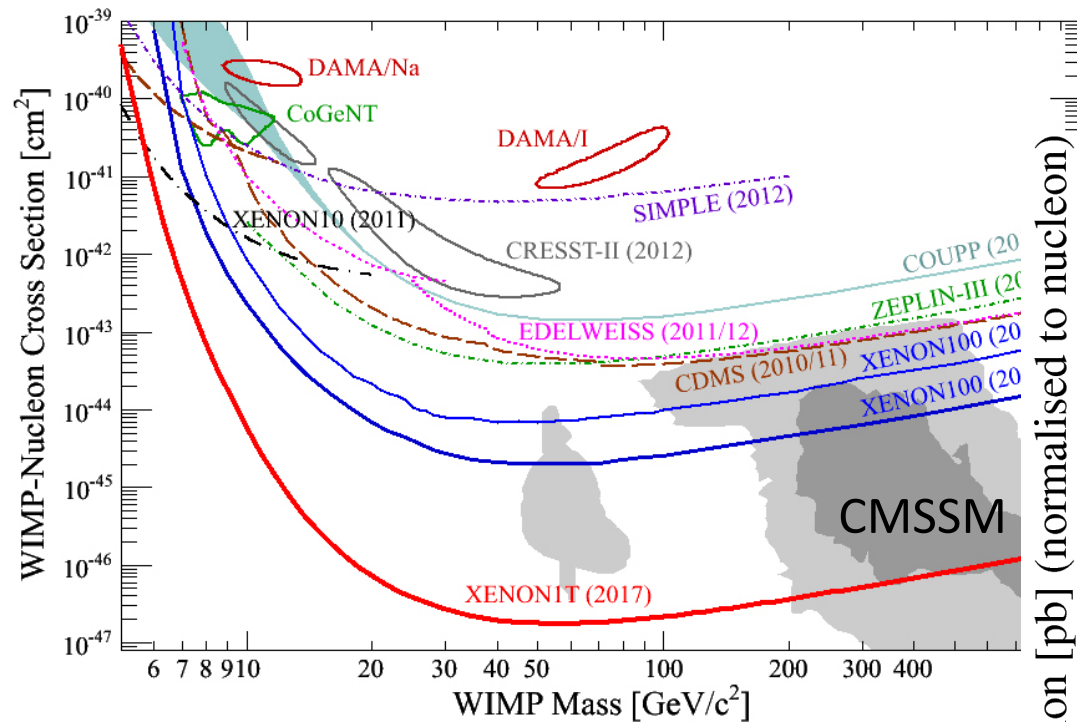
$$F \sim M_{\text{GUT}} - M_{Pl}$$

WIMP

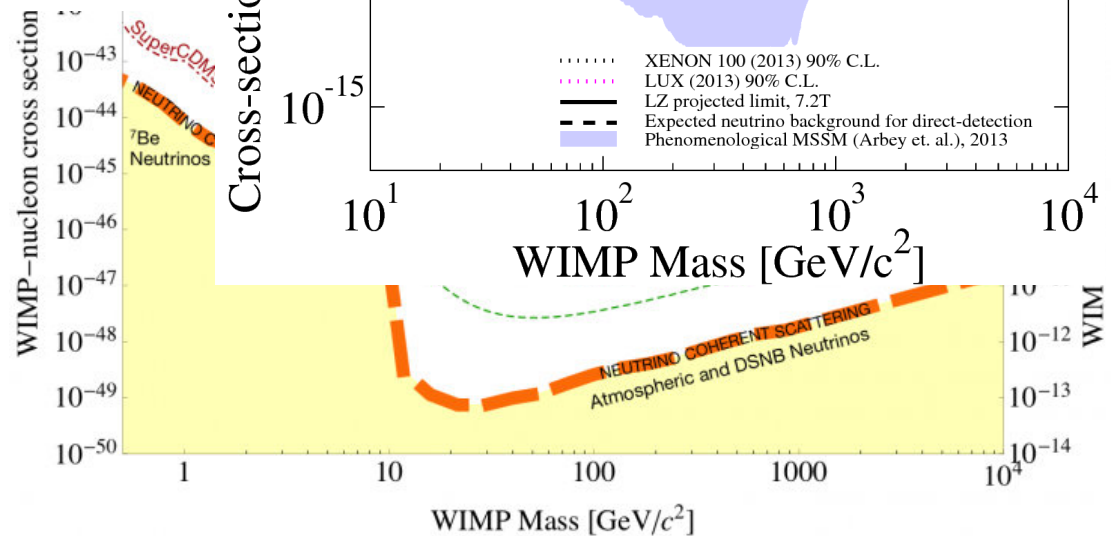
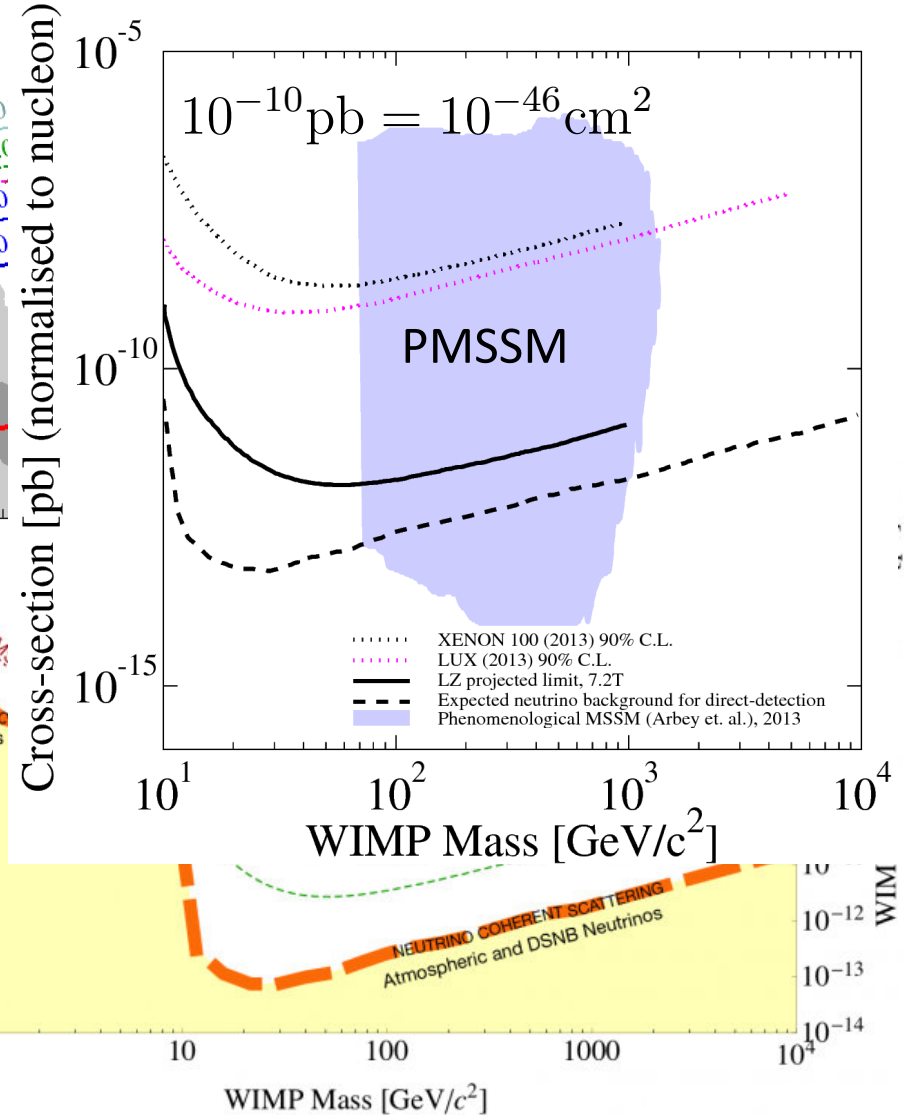
WIMP direct detection



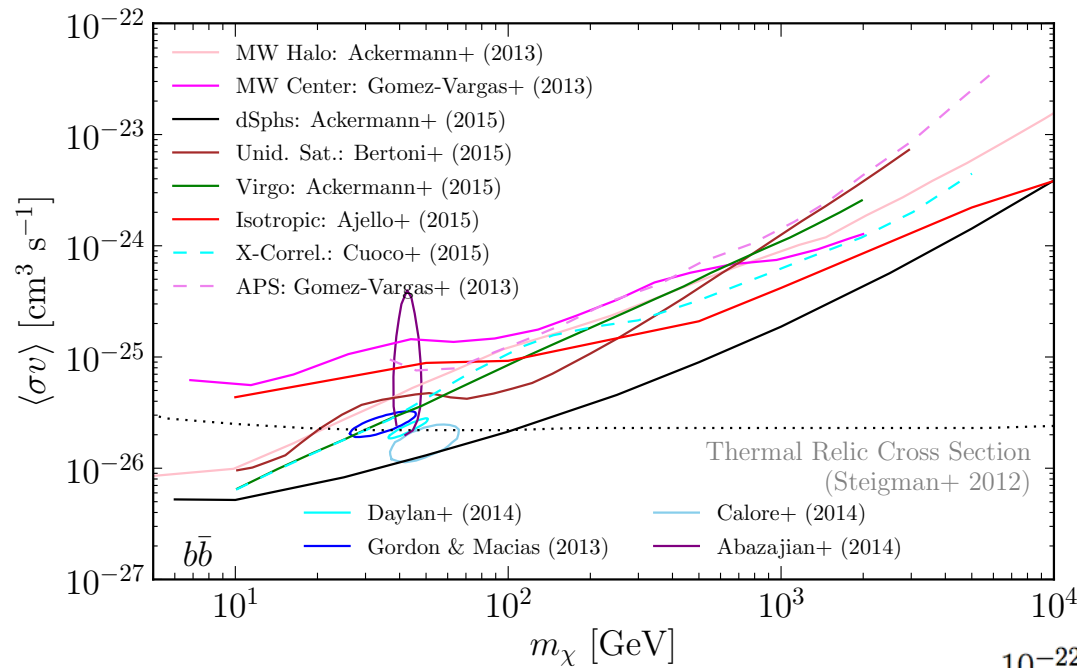
WIMP direct detection



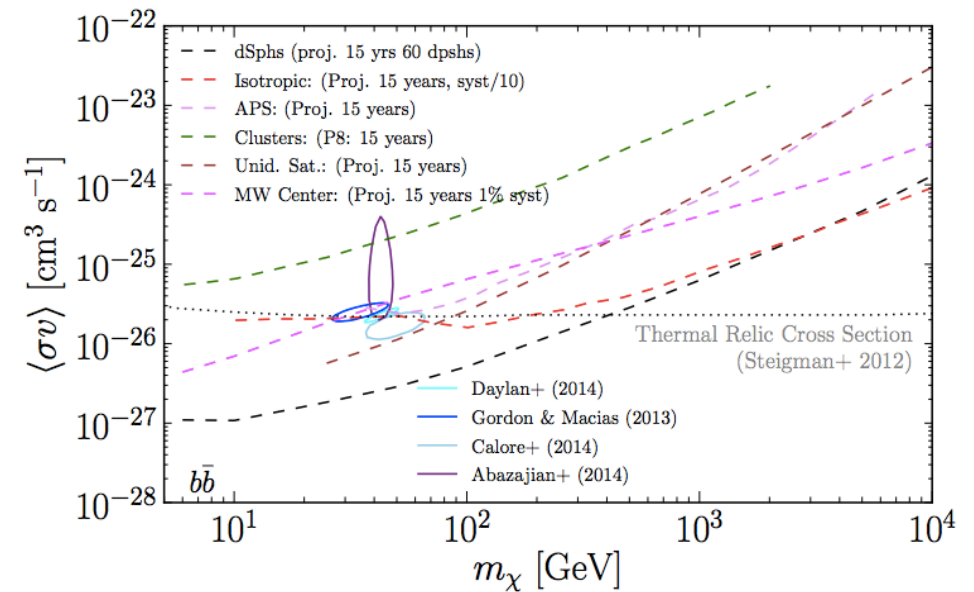
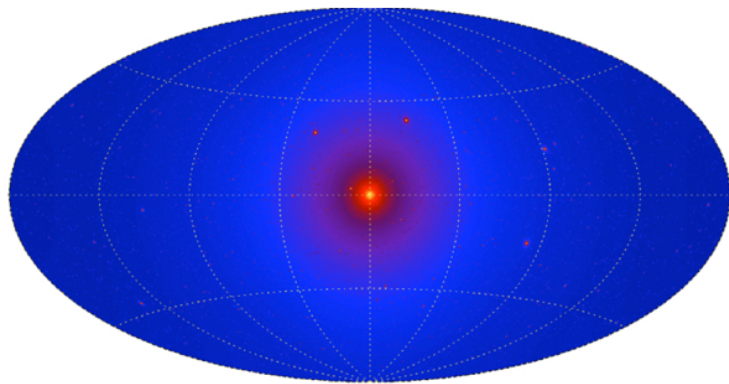
[Mahmoudi, Arbey 1411.2128]



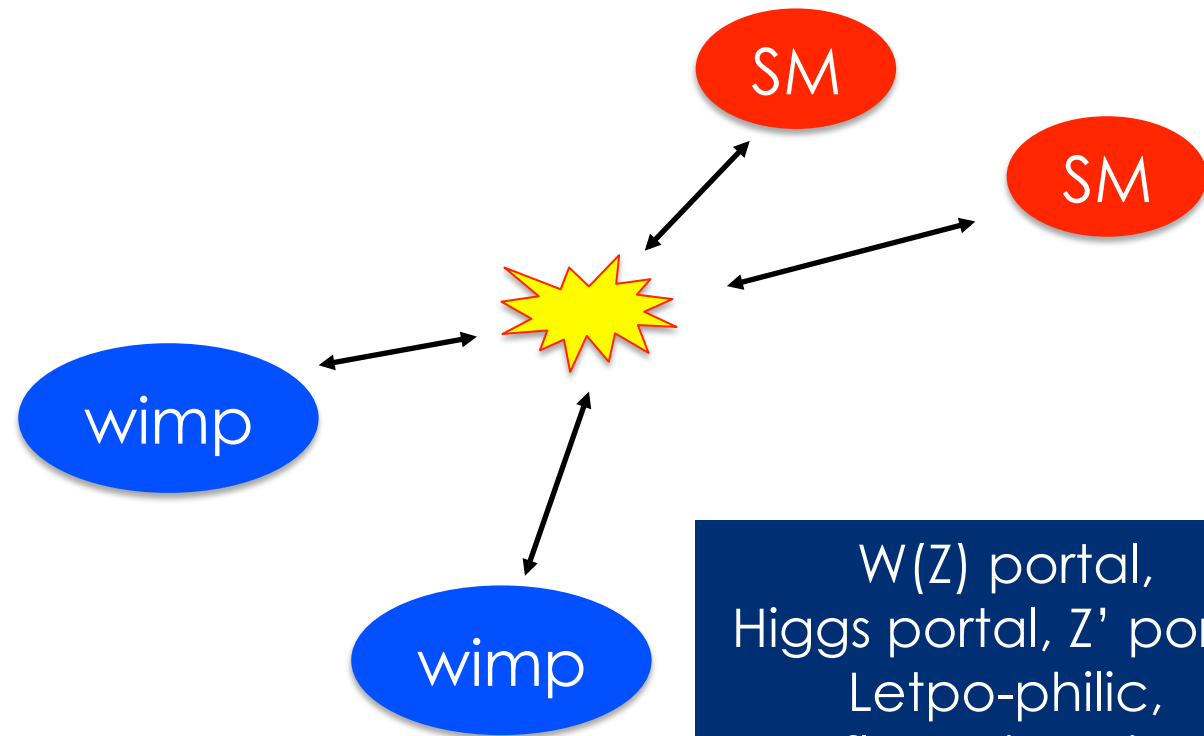
WIMP indirect detection



[Fermi-LAT 1605.02016]



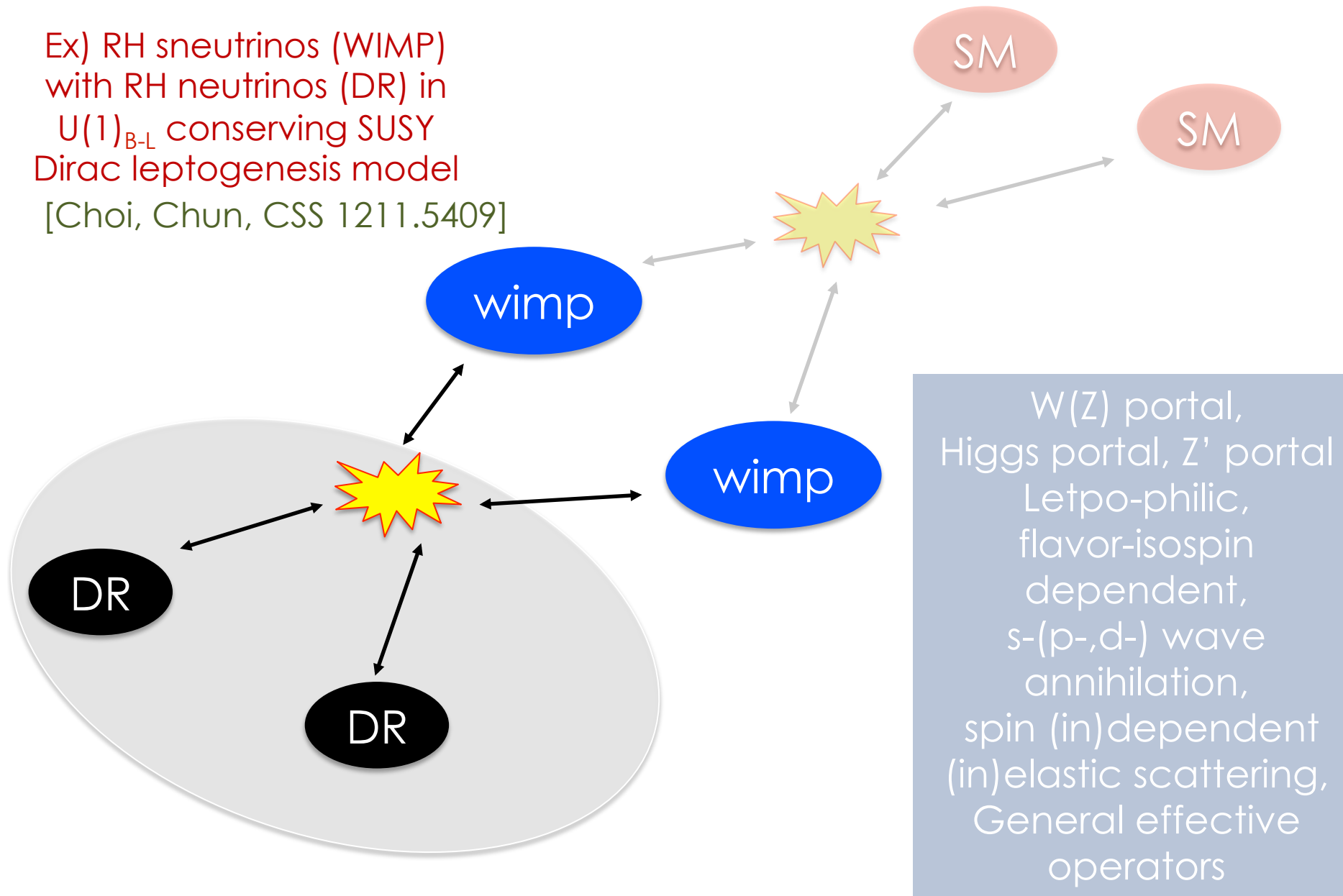
WIMP paradigm



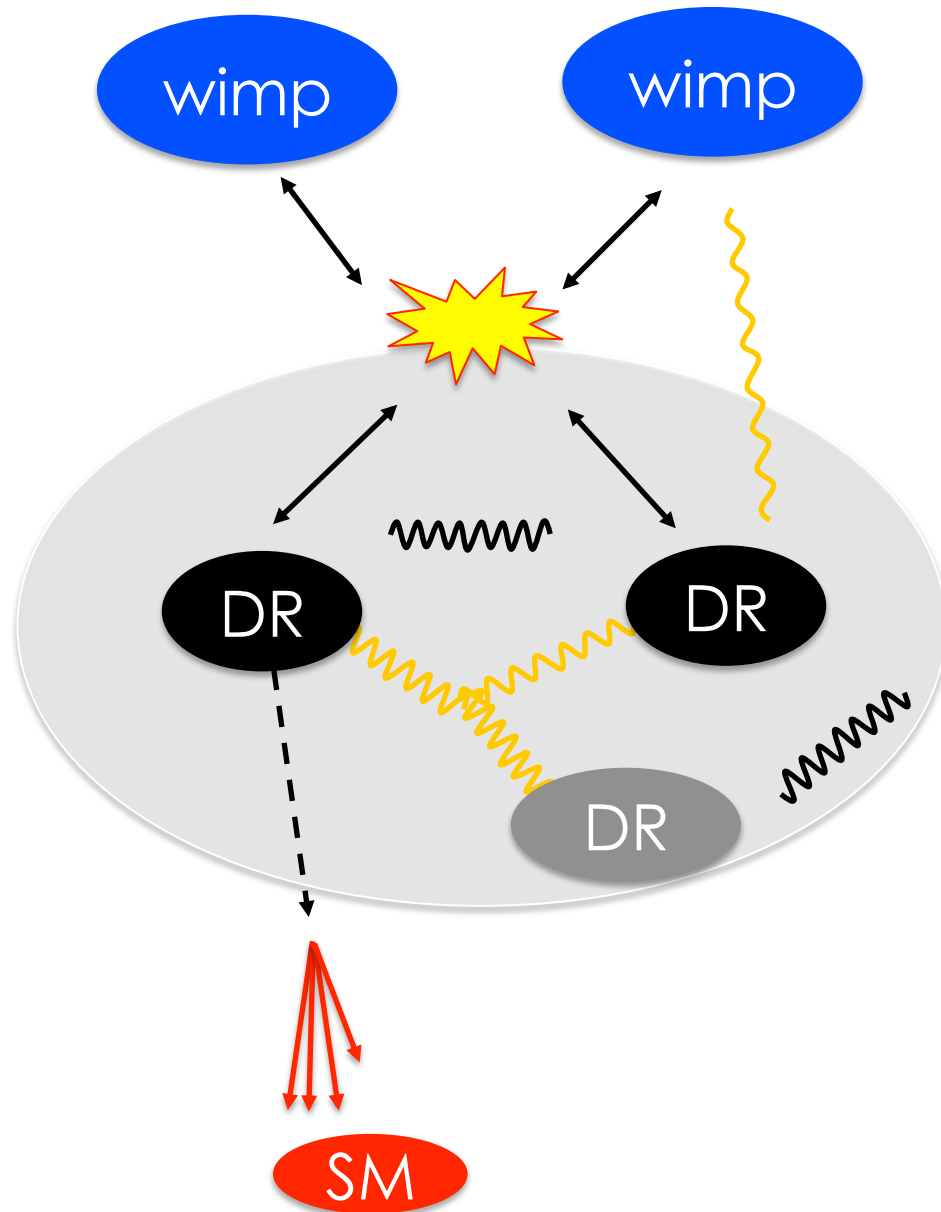
W(Z) portal,
Higgs portal, Z' portal
Lepto-philic,
flavor-isospin
dependent,
s-(p-,d-) wave
annihilation,
spin (in)dependent
(in)elastic scattering,
General effective
operators

Still WIMP paradigm

Ex) RH sneutrinos (WIMP)
with RH neutrinos (DR) in
 $U(1)_{B-L}$ conserving SUSY
Dirac leptogenesis model
[Choi, Chun, CSS 1211.5409]



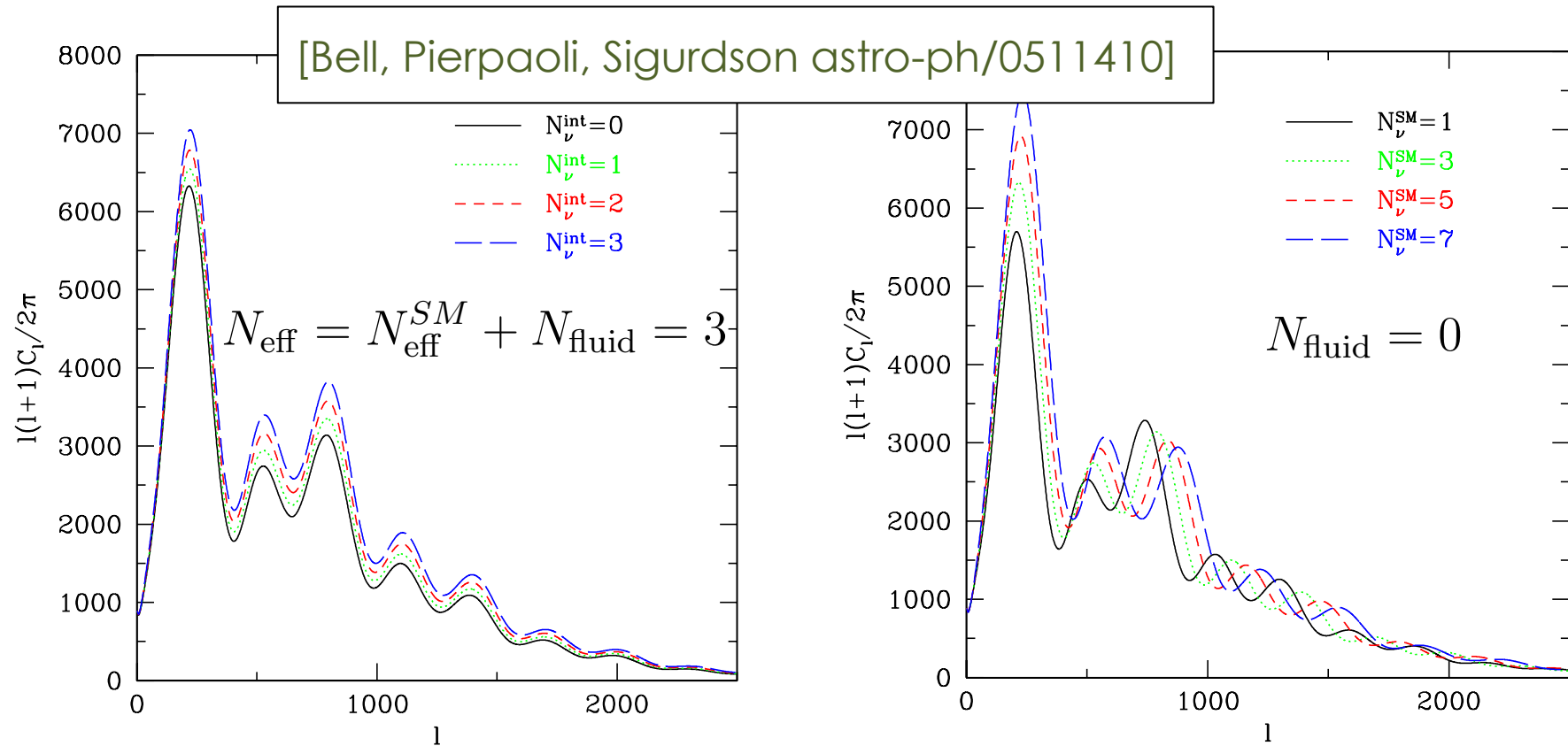
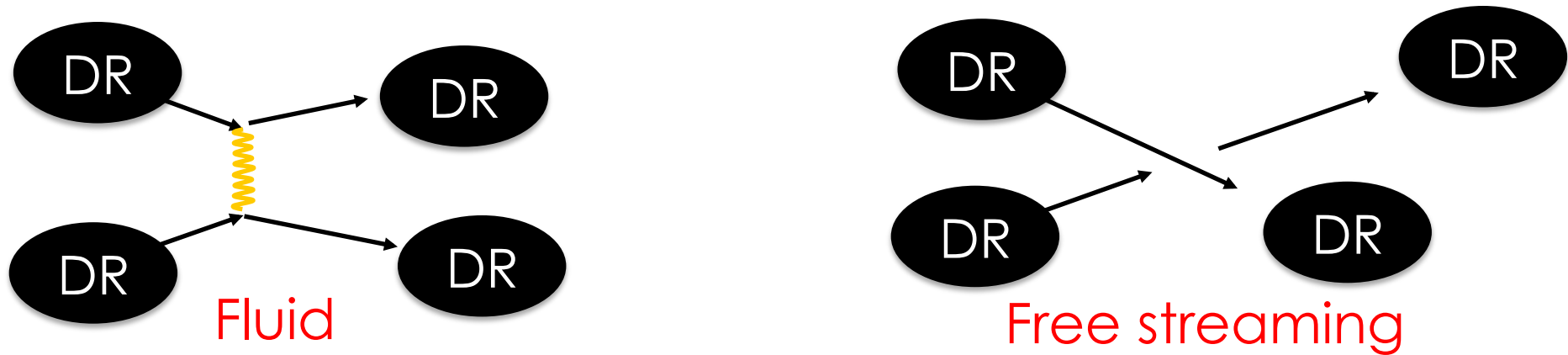
Still WIMP paradigm



New constraints/predictions
from cosmology

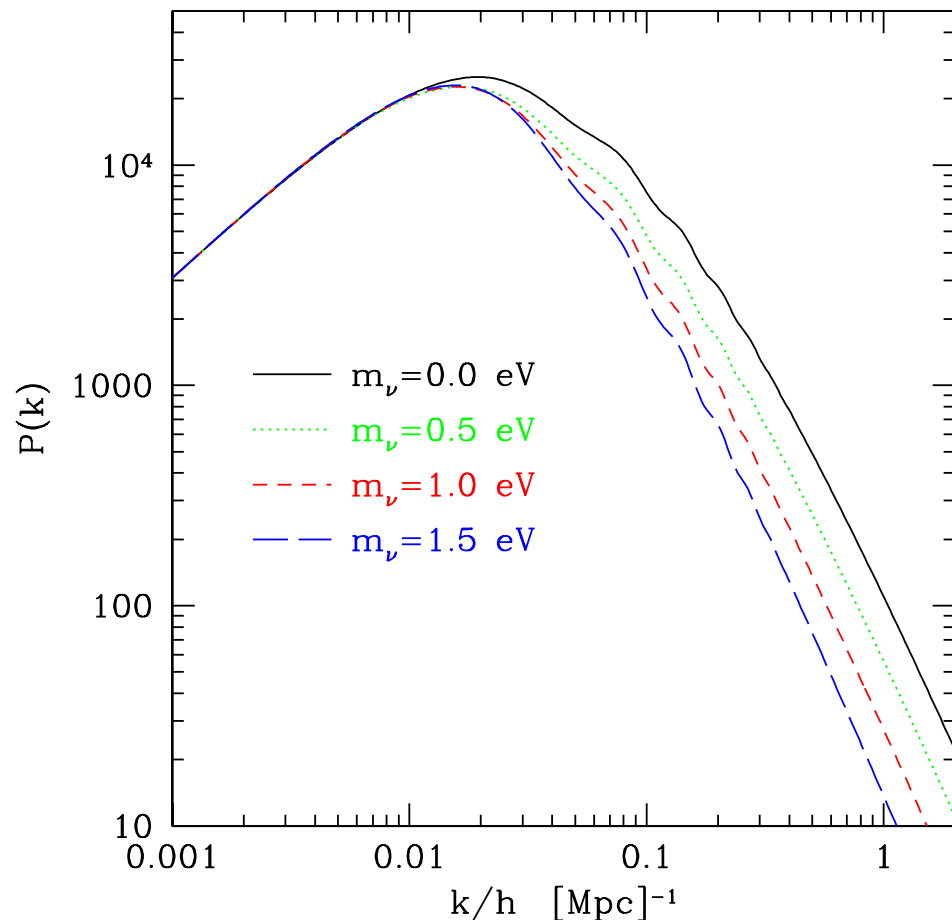
New signatures for the
indirect detection of DM

DR contributes to N_{eff}

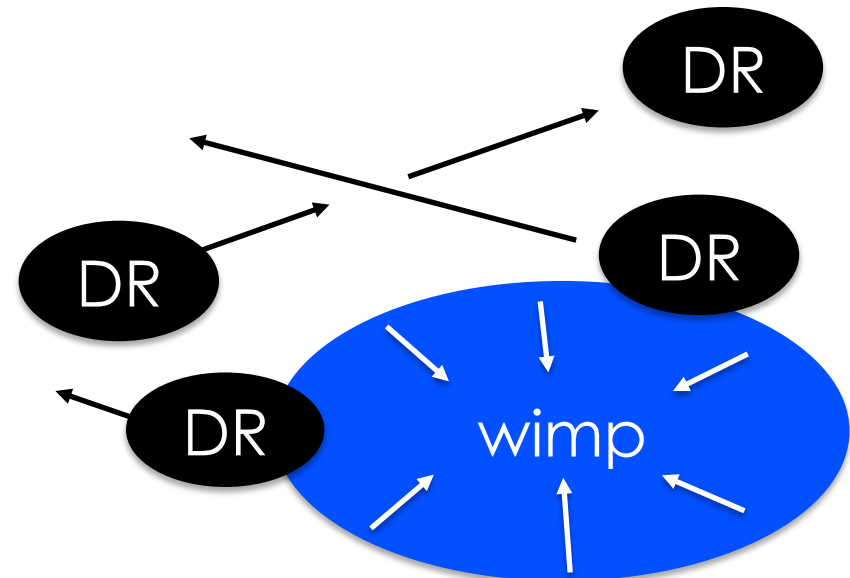


Finite **DR** mass ($\sim \text{eV}$) : Hot DM

DRs : relativistic during RD ($T > \text{eV}$), non-relativistic after matter-radiation equality ($T < \text{eV}$), and they contribute to the total dark matter density at present. For scales that enter the horizon before matter-radiation eq, HDM perturbations are suppressed $\rightarrow$ suppression of matter power spectrum



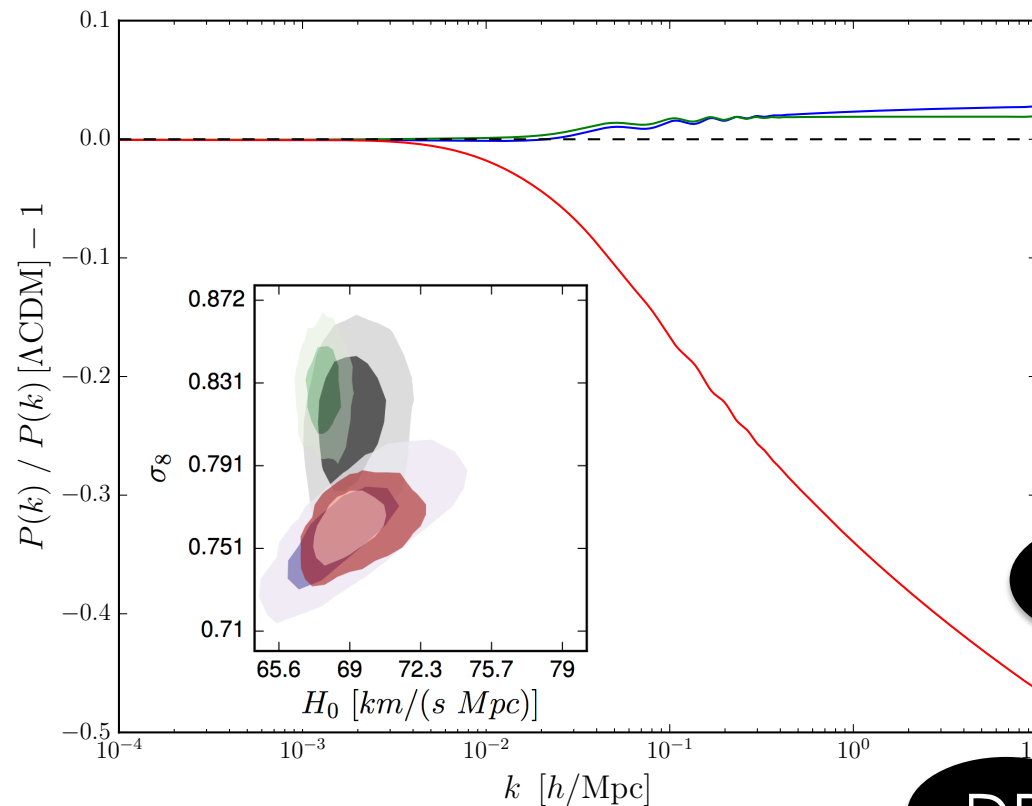
$$\frac{\delta\rho_{DM}}{\rho_{DM}} \simeq \frac{\delta\rho_{\text{wimp}}}{\rho_{\text{wimp}} + \rho_{\text{HDM}}} < \frac{\delta\rho_{\text{wimp}}}{\rho_{\text{wimp}}}$$



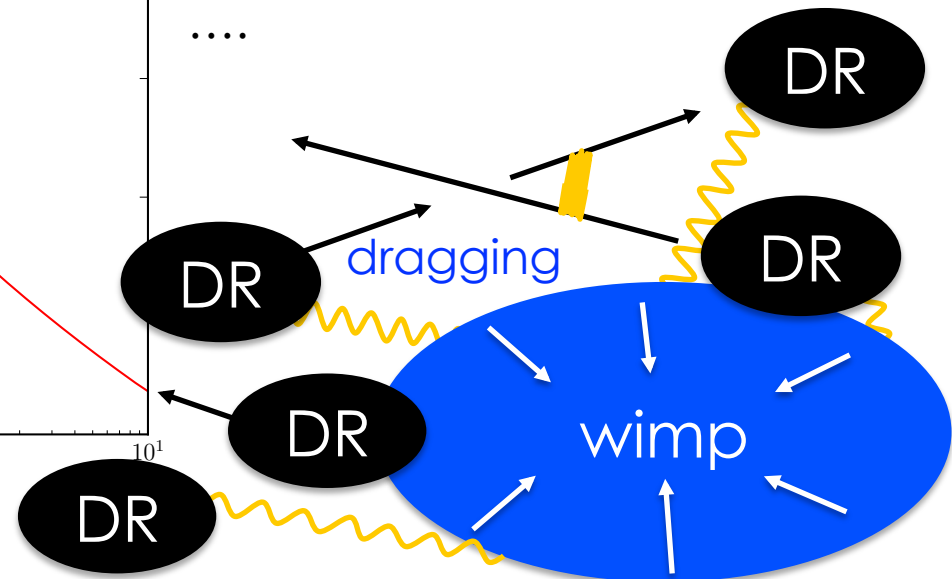
Growing perturbation by self gravity

DR-WIMP interactions

Sizable interactions between **DR** and **DM** give dark acoustic oscillation (DAO) ($\Gamma \gg H \rightarrow \Gamma < H$) or the drag effect ($\Gamma \sim H$) for the evolution of matter perturbations



Unbroken hidden SU(N)
[Lesgourgues, Marques-Tavares,
Schmaltz 1507.04351]
Unbroken hidden U(1)
[Ko, Tang 1608.01083]
....



tuning $\Gamma(T) \simeq H(T)$ for $T \gtrsim T_{\text{eq}}$

Growing perturbation by self gravity

Metastable DR ($m > \text{MeV}$): messenger

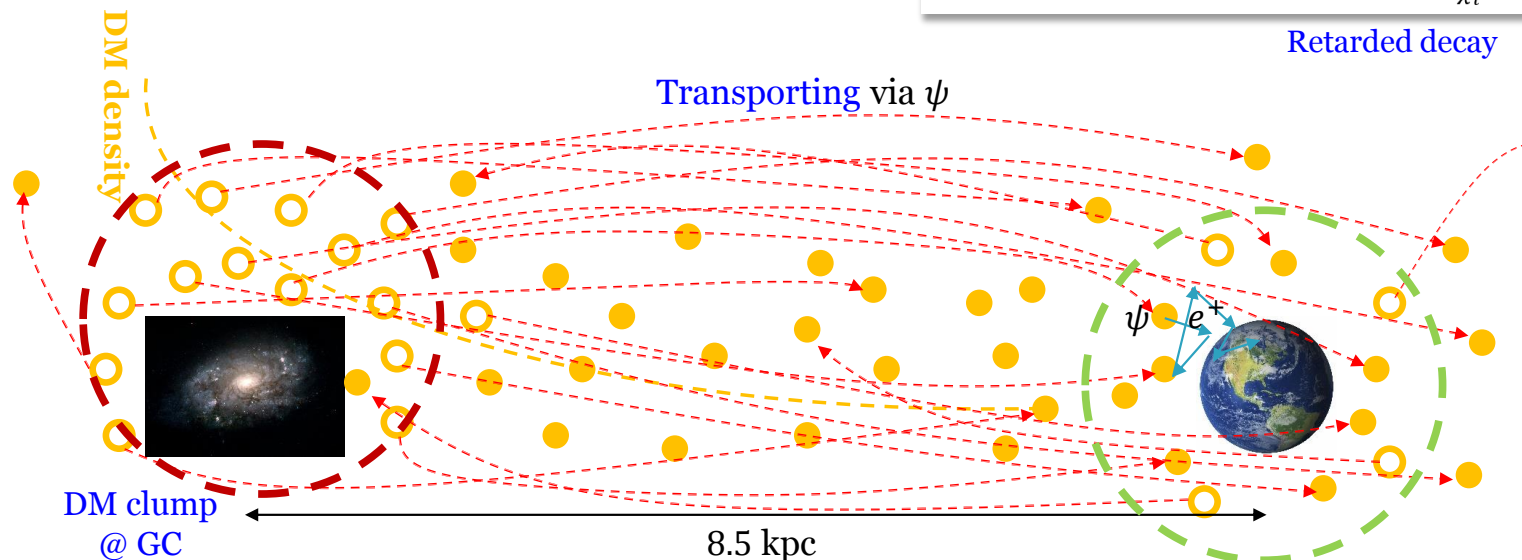
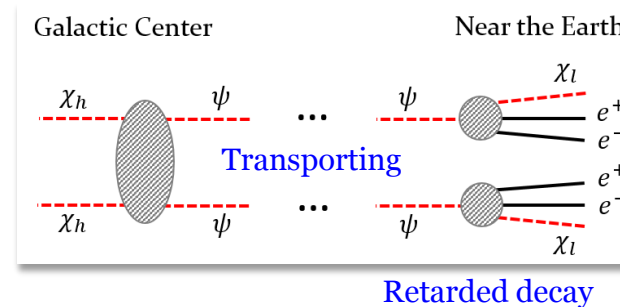
WIMP DM Annihilation at the galaxy center can generate (partial) directional cosmic ray signals.

D. Kim, JCP & S. Shin [1702.02944]

❖ “**Transporting**” (effectively) DM at the GC to the vicinity of the Earth via a “proxy” ψ

❖ $2\chi_h \rightarrow 2\psi$ & $\psi \rightarrow e^+e^-\chi_l + \dots$

- χ_h : heavier DM, dominant relic, no direct coupling to SM
- ψ : heavy “meta”-stable dark sector state
- χ_l : lighter DM, subdominant relic, direct coupling to SM



[JC Park's slide at Pheno 17]

Axion-like DM
(*QCD axion, Fuzzy DM*)

(ultra) light pseudo scalar fields

- Very light compared to the background temperature $m_a \ll \text{eV}$
- Still can be cold dark matter by “coherent oscillation”

$$m_a = \frac{\Lambda^2}{F}$$

$$\mathcal{L} = \frac{1}{2} F^2 (\partial_\mu \theta)^2 - \Lambda^4 (1 - \cos \theta)$$

$$a(x) \equiv F\theta(x)$$

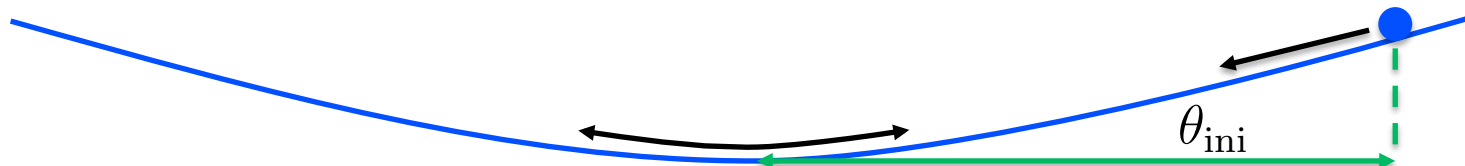
$$\theta(t, x) \simeq \theta_{\text{ini}} \cos(m_a t) R(t)^{-3/2} \text{ for } m_a \gtrsim H(t)$$

$$p_{DM} = w \rho_{DM}, \quad w \simeq \cos 2m_a t$$

$$\langle w \rangle_t = 0 \text{ for } m_a \gg H(t)$$

- Cosmologically stable $(\partial_\mu \theta) J_5^\mu, \theta F \tilde{F}, \dots$

$$\tau_a \simeq (m_a^3 / F^2)^{-1} = (F / 10^{10} \text{ GeV})^2 (10^{-4} \text{ eV} / m_a)^3 10^{27} \text{ years}$$



QCD axion

- Solution to the strong CP problem *(it is also the origin of the axion mass)*

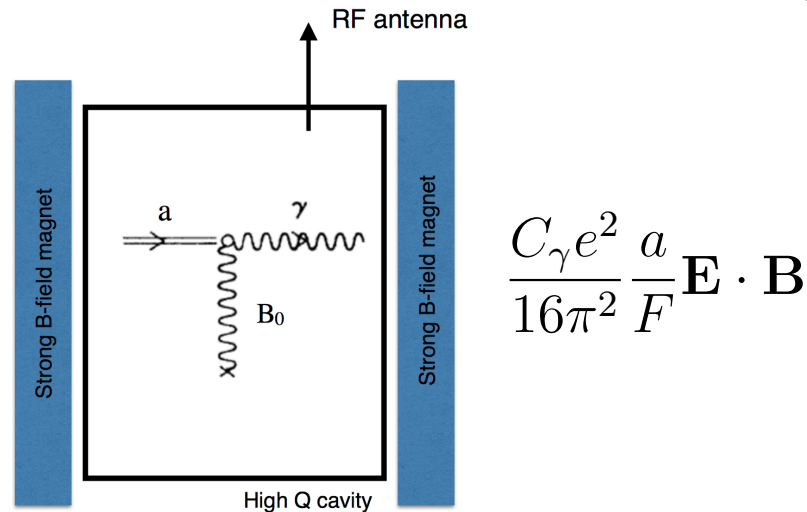
$$\boxed{|\theta_{\text{obs}}| < 10^{-10}} \quad \frac{g_s^2}{32\pi^2} \theta G^a \tilde{G}^a \text{ with } \langle \theta \rangle = 0 \Rightarrow \Lambda \sim \Lambda_{QCD} \sim 100 \text{ MeV}$$

$$m_a \simeq 10^{-5} \text{ eV} \left(\frac{10^{11} \text{ GeV}}{F} \right) \simeq (2\text{cm})^{-1} \left(\frac{10^{11} \text{ GeV}}{F} \right)$$

microwave

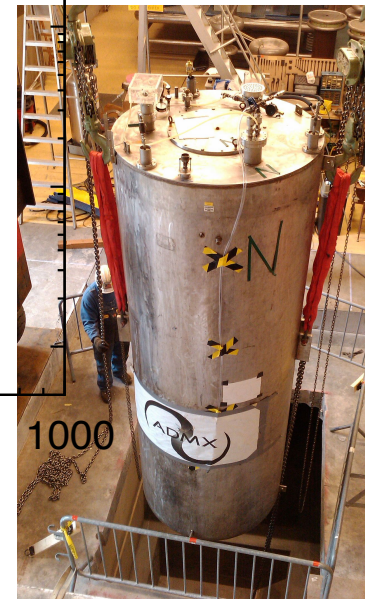
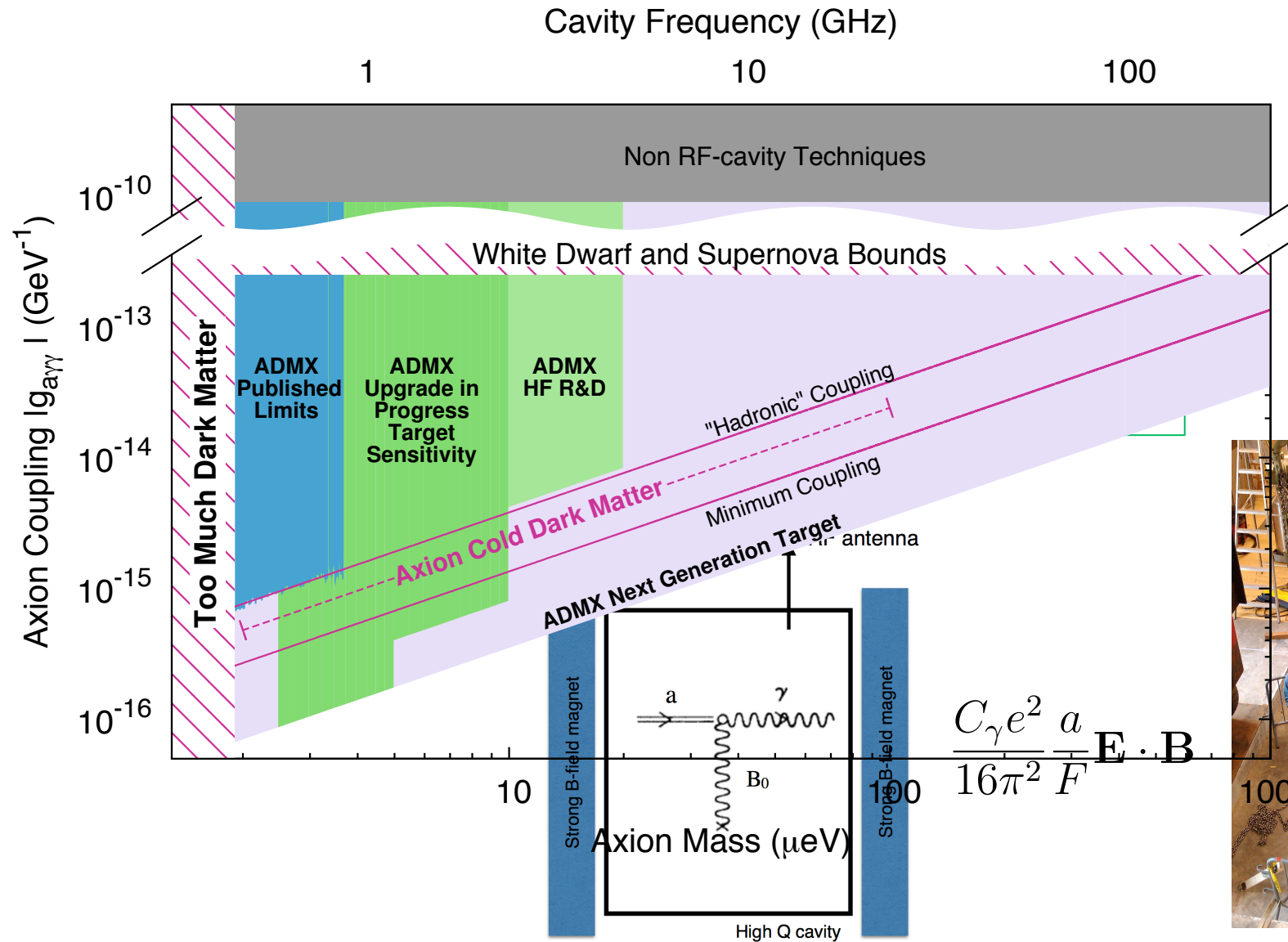
$$\Omega_{DM} \simeq 0.25 \left(\langle \theta_{\text{ini}}^2 \rangle_{\text{osc.}} + \alpha_{\text{dec.}} \right) \left(\frac{F}{10^{12} \text{ GeV}} \right)^{7/6}$$

- The axion DMs (around the earth) can be converted to photons in strong magnetic fields



QCD axion

ADMX Achieved and Projected Sensitivity



QCD axion

- For the axion DM, the energy density is related with a oscillating $\theta(t)$

$$\rho_{DM}|_0 = m_a n_a|_0 = \frac{1}{2} m_a^2 F^2 \theta_0^2 \sim \Lambda_{QCD}^4 \theta_0^2$$

$$= \theta_0 \cos m_a t$$

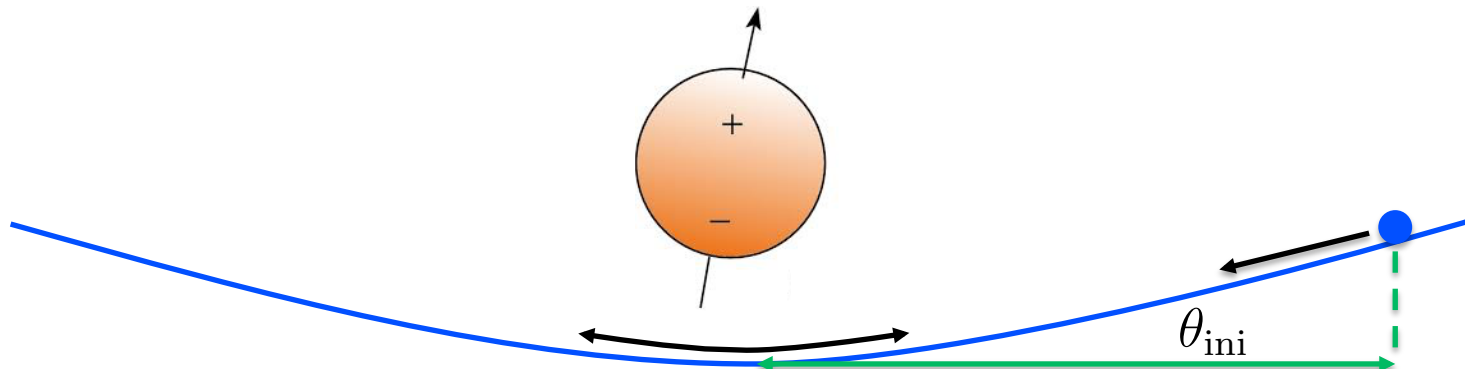
- The amplitude θ_0 at present time is independent of F : $\theta_0|_{\text{Earth}} \sim 10^{-38}$

$$\frac{g_s^2}{32\pi^2} \theta G^a \tilde{G}^a \text{ with } \langle \theta \rangle = 10^{-38} \cos m_a t$$

- For a larger F (a lower mass) the oscillation period becomes longer :

$$F = M_{Pl} \quad (m_a = 10^{-12} \text{ eV} = (10^{-3} \text{ sec})^{-1})$$

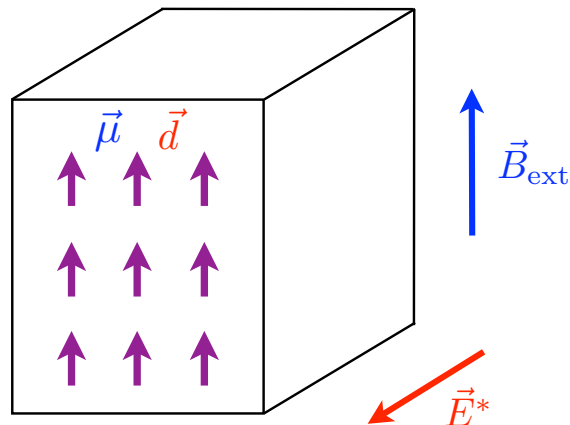
- oscillating CP violating effects (*oscillating EDM of nucleus*):



QCD axion

Cosmic Axion Spin Precession Experiment (CASPER) related with a oscillating $\theta(t)$

NMR techniques + high precision magnetometry



Larmor frequency = axion mass $\rightarrow$ resonant enhancement

$$= \theta_0 \cos m_a t$$

$$\sim \Lambda_{QCD}^4 \theta_0^2$$

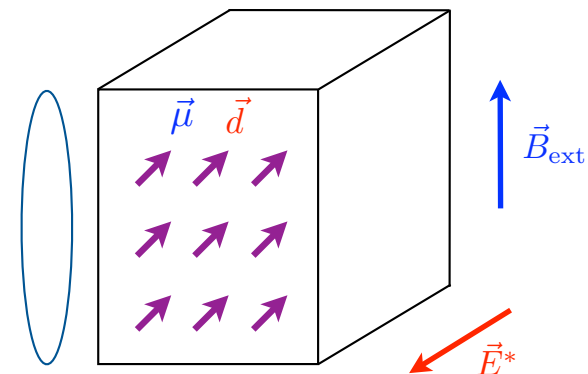
$$\text{of } F: \theta_0|_{\text{Earth}} \sim 10^{-38}$$

$$-38 \cos m_a t$$

period is long :

- oscillating CP violating effects (

SQUID
pickup
loop



Larmor frequency = axion mass $\rightarrow$ resonant enhancement

SQUID measures resulting transverse magnetization

[P. Graham's slide at Pheno 17]

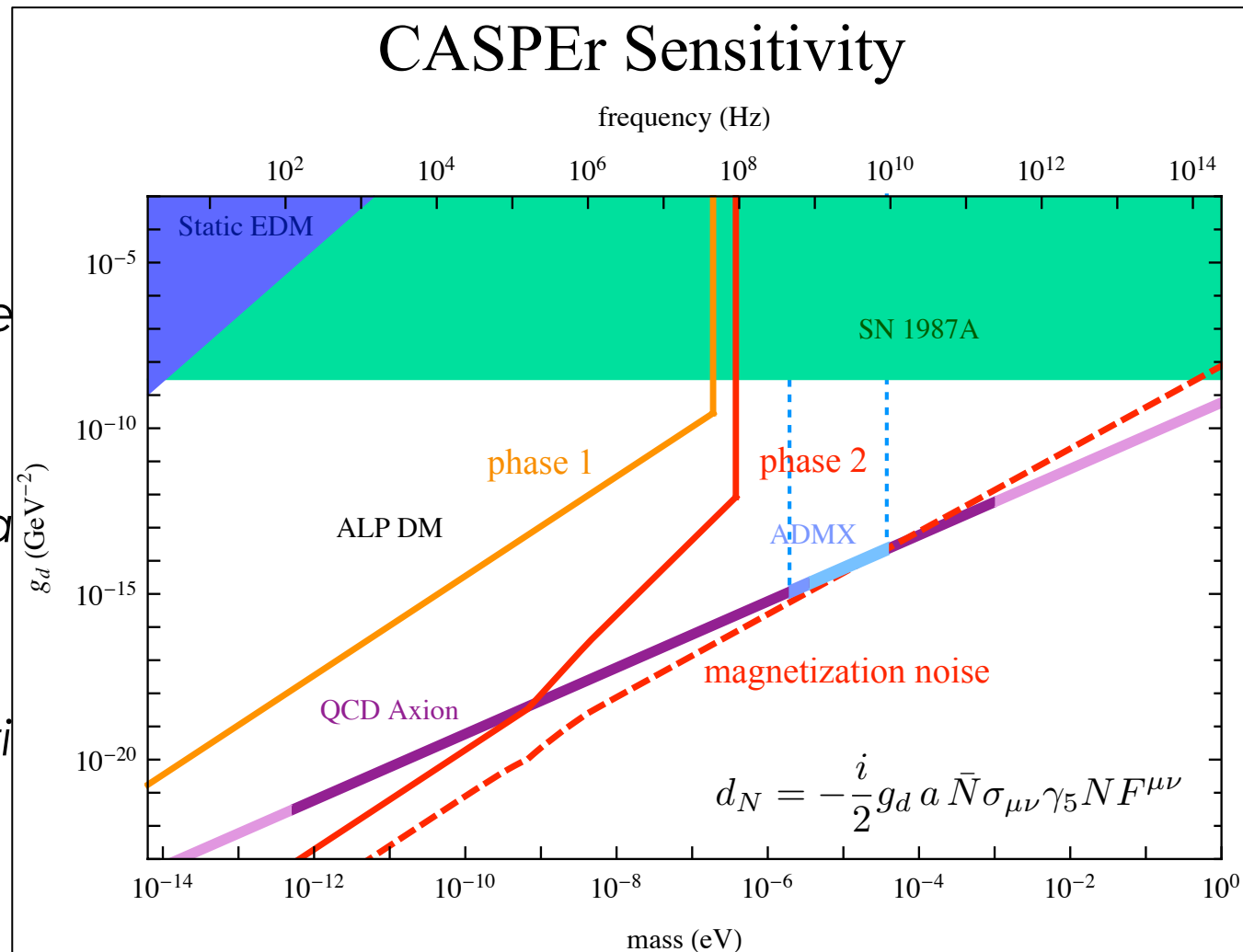
QCD axion

• For the

• The pre

• For a la

• oscillati



ating $\theta(t)$

$$\theta(t) = \theta_0 \cos m_a t$$

38

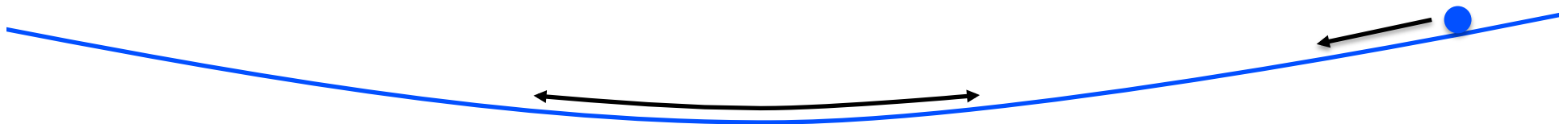
[P. Graham's slide at Pheno 17]

Fuzzy DM (ultra-light pseudoscalar DM)

- No contribution from the SM sector

$$\mathcal{L} = \frac{1}{2}F^2(\partial_\mu\theta)^2 - \Lambda^4(1 - \cos\theta)$$

- Non-perturbative corrections, $\Lambda^4 = M_{\text{Pl}}^2 m^2 e^{-S_{\text{inst.}}}$ can give various ranges of mass (e.g. $\Lambda \ll \Lambda_{\text{QCD}}$ or $\Lambda \gg \Lambda_{\text{QCD}}$)



- For the ultra-light coherent oscillating DM with $\rho, \mathbf{V}$

$$\dot{\rho} + 3H\rho + \frac{1}{R}\nabla \cdot (\rho\mathbf{v}) = 0 \quad [\text{Hui, Ostriker, Tremaine, Witten 1610.0829}]$$

$$\dot{\mathbf{v}} + H\mathbf{v} + \frac{1}{R}(\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{R}\nabla\Phi + \frac{\hbar^2}{2R^3m_a^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Quantum pressure

- For lower masses, DM is more wave-like :

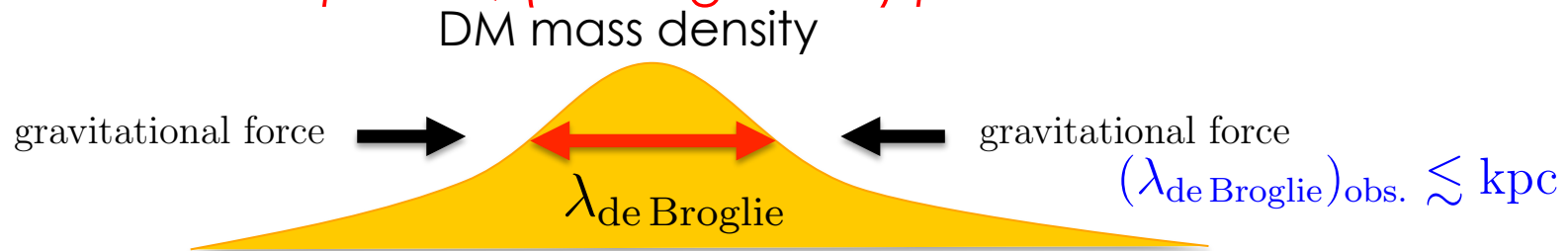
$$\lambda_{\text{de Broglie}} = \frac{h}{m_a v_0} \sim \left(\frac{10^{-22} \text{ eV}}{m_a}\right) \left(\frac{10^{-3} c}{v_0}\right) = 0.4 \text{ kpc}$$

[Hu, Barkana, Cruzinov astro-ph/0003365]

Fuzzy DM (ultra-light pseudoscalar DM)

- The quantum pressure prevents to make a cusp in the DM halo below the de Broglie length scale of the FDM, $\lambda_{\text{de Broglie}}$

→ Resolve the cusp-core, (too big to fail) problem



- This also address the “missing satellite problem”

$$\dot{\rho} + 3H\rho + \frac{1}{R}\nabla \cdot (\rho\mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + H\mathbf{v} + \frac{1}{R}(\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{R}\nabla\Phi + \frac{\hbar^2}{2R^3m_a^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Suppress the growth of sub Mpc
scales density perturbation like
WDM

Quantum pressure

$$\lambda_{\text{de Broglie}} = \frac{h}{m_a v_0} \sim \left(\frac{10^{-22} \text{ eV}}{m_a}\right) \left(\frac{10^{-3} c}{v_0}\right) = 0.4 \text{ kpc}$$

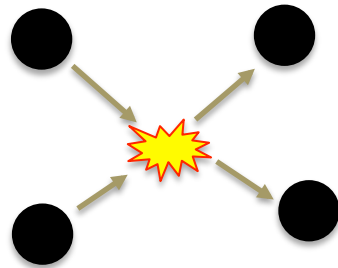
$k_{\text{cut}} = 4.5 \text{ Mpc}^{-1} (m_a / 10^{-22} \text{ eV})^{4/9}$

Self Interacting DM (SIDM)

Self interactions ($\Gamma \gtrsim H_0$)

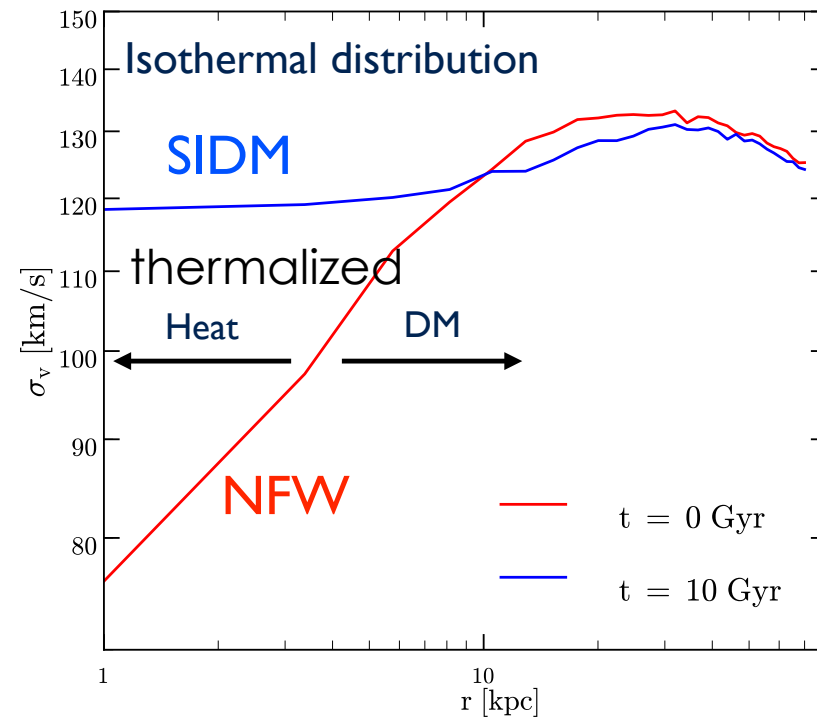
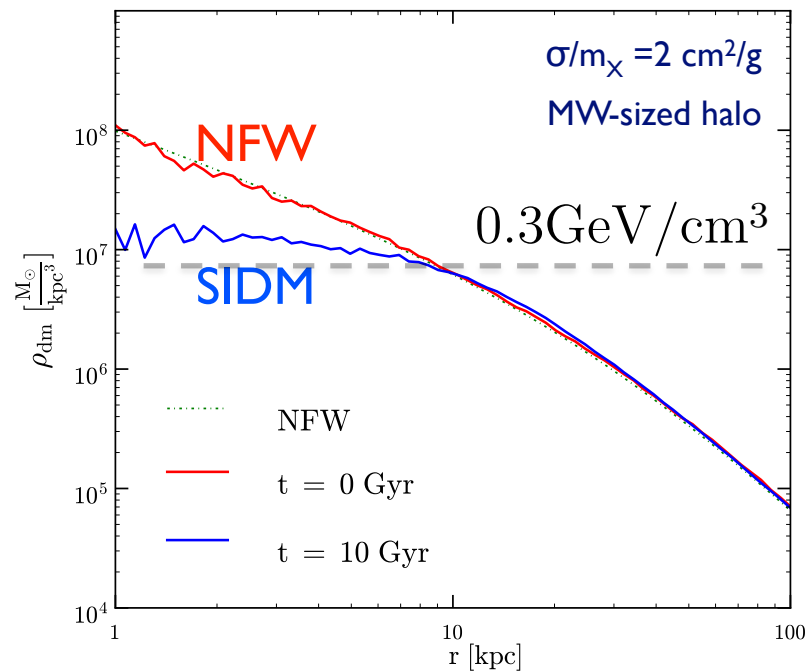
Dark matter self interactions could be in thermal equilibrium around the center of the galaxies : *Solving Cusp-core, too big to fail problem*

[Spergel, Steinhardt astro-ph/9909386]



$$\Gamma = \sigma n_{DM} v = (0.1 \tau_{\text{Univ.}})^{-1} \left(\frac{\sigma / m_{DM}}{1 \text{ cm}^2 / \text{gram}} \right) \left(\frac{\rho_{DM}}{0.3 \text{ GeV} / \text{cm}^3} \right) \left(\frac{v}{10^{-3} c} \right)$$

age of the Universe



$$\sigma / m_{\chi} \sim 1 \text{ cm}^2 / \text{g} \simeq (50 \text{ MeV})^{-3}$$

$$\simeq (0.5 \text{ MeV})^{-2} (\text{TeV})^{-1}$$

SIMP DM with m=50 MeV

WIMP DM with MeV mediator

Velocity dependence

Hints and constraints on the self interactions

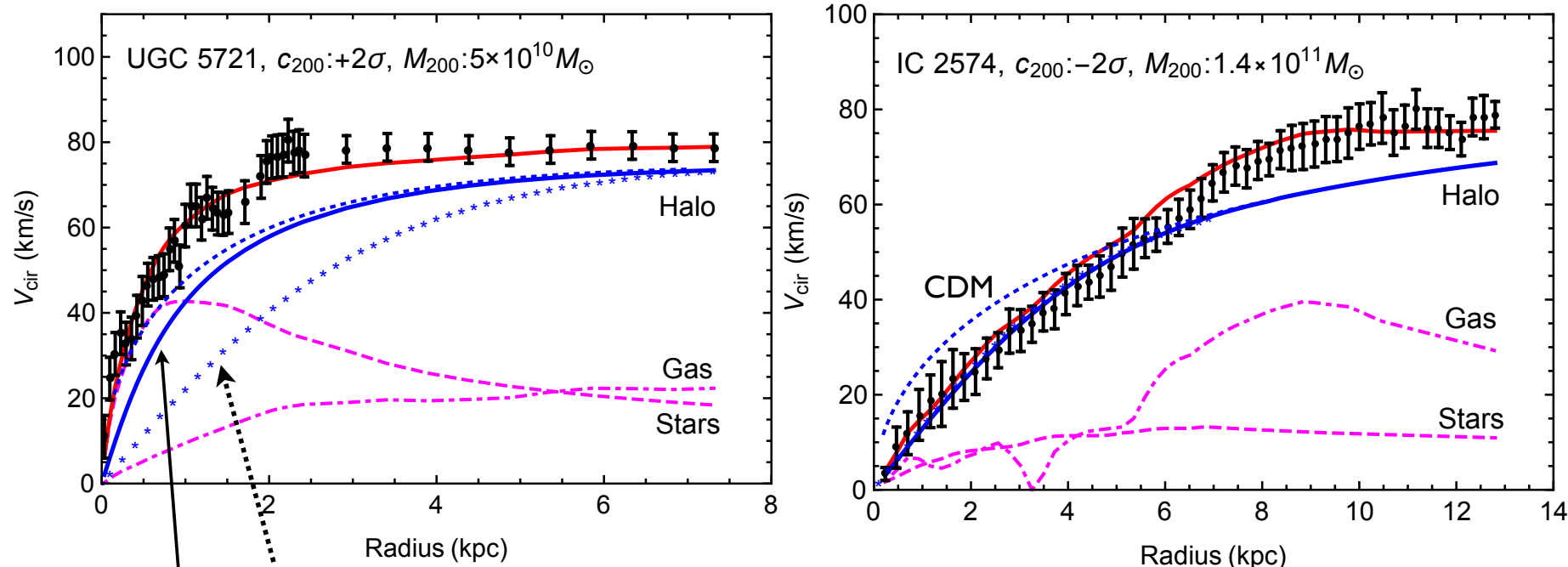
Positive observations	σ/m	v_{rel}	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1 \text{ cm}^2/\text{g}$	30 – 200 km/s	Rotation curves	[64, 80]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6 \text{ cm}^2/\text{g}$	50 km/s	Stellar dispersion	[74]
Local Group	$\gtrsim 0.5 \text{ cm}^2/\text{g}$	50 km/s	Stellar dispersion	[75]
Cores in clusters	$\sim 0.1 \text{ cm}^2/\text{g}$	1500 km/s	Stellar dispersion, lensing	[80, 90]
<i>Abell 3827 subhalo merger</i>	$\sim 1.5 \text{ cm}^2/\text{g}$	1500 km/s	DM-galaxy offset	[91]
<i>Abell 520 cluster merger</i>	$\sim 1 \text{ cm}^2/\text{g}$	2000 – 3000 km/s	DM-galaxy offset	[92, 93, 94]
Constraints				
Halo shapes/ellipticity	$\lesssim 1 \text{ cm}^2/\text{g}$	1300 km/s	Cluster lensing surveys	[73]
Substructure mergers	$\lesssim 2 \text{ cm}^2/\text{g}$	$\sim 500 - 4000 \text{ km/s}$	DM-galaxy offset	[79, 95]
Merging clusters	$\lesssim \text{few cm}^2/\text{g}$	2000 – 4000 km/s	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
<i>Bullet Cluster</i>	$\lesssim 0.7 \text{ cm}^2/\text{g}$	4000 km/s	Mass-to-light ratio	[68]

[Tulin, Yu 1705.02358]

Diversity of rotation curves

Since the dark matter *only* density profile has a smooth core, its shape is more sensitive to the additional baryonic gravitational potential compared to the CDM case in which its own gravitational potential is more important.

[Kamada, Kaplinghat, Pace, Yu 1611.02716]



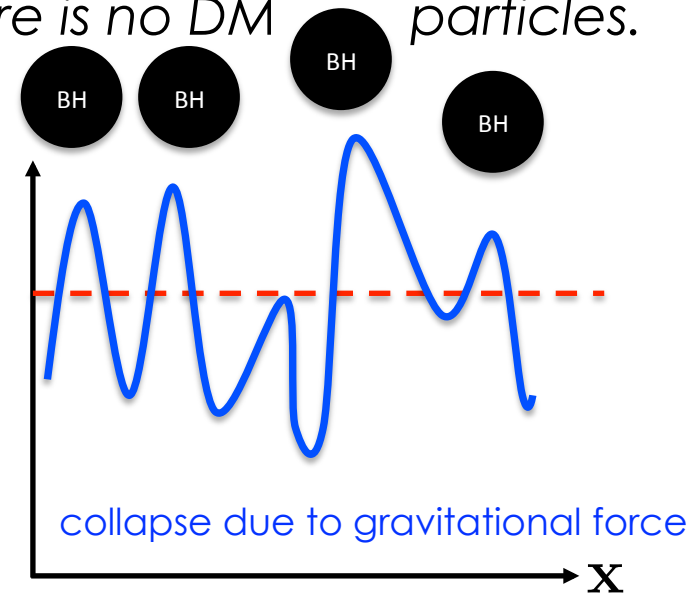
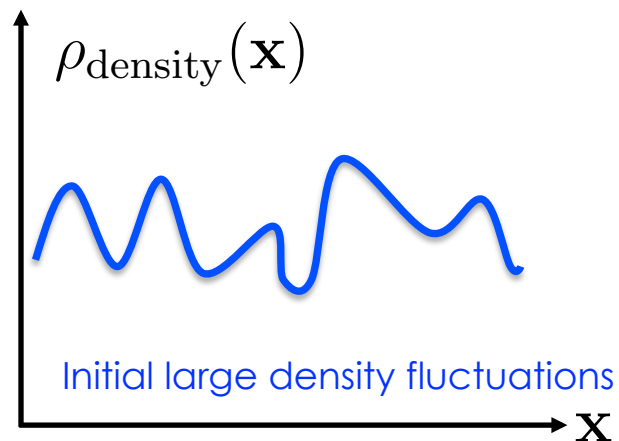
Isothermal profile without the baryonic influence
True SIDM profile with the baryonic influence

30 galaxies
 $V_{\text{max}} \sim 25\text{--}300 \text{ km/s}$

Primordial Black Hole (PBH)

Formation of PBH

- The black holes could be generated at the early Universe, (*not from stellar evolutions at the late time Universe*), if the initial density fluctuations are large enough, even if there is no DM particles.



- Formation time determines the mass of the PBH.

$$\rho_{\text{PBH}} = \frac{M_{\text{PBH}}}{\frac{4\pi}{3}R_S^3} = \frac{3}{32\pi G^3 M_{\text{PBH}}^2} = \rho_{\text{univ.}}(t_{\text{form}})$$

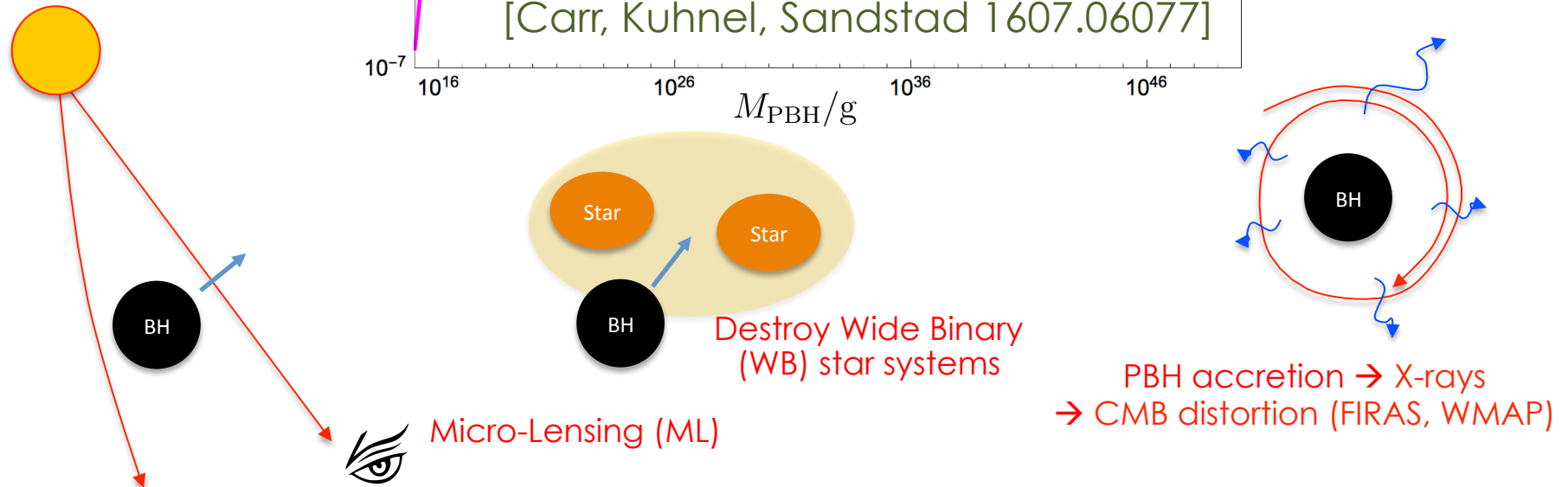
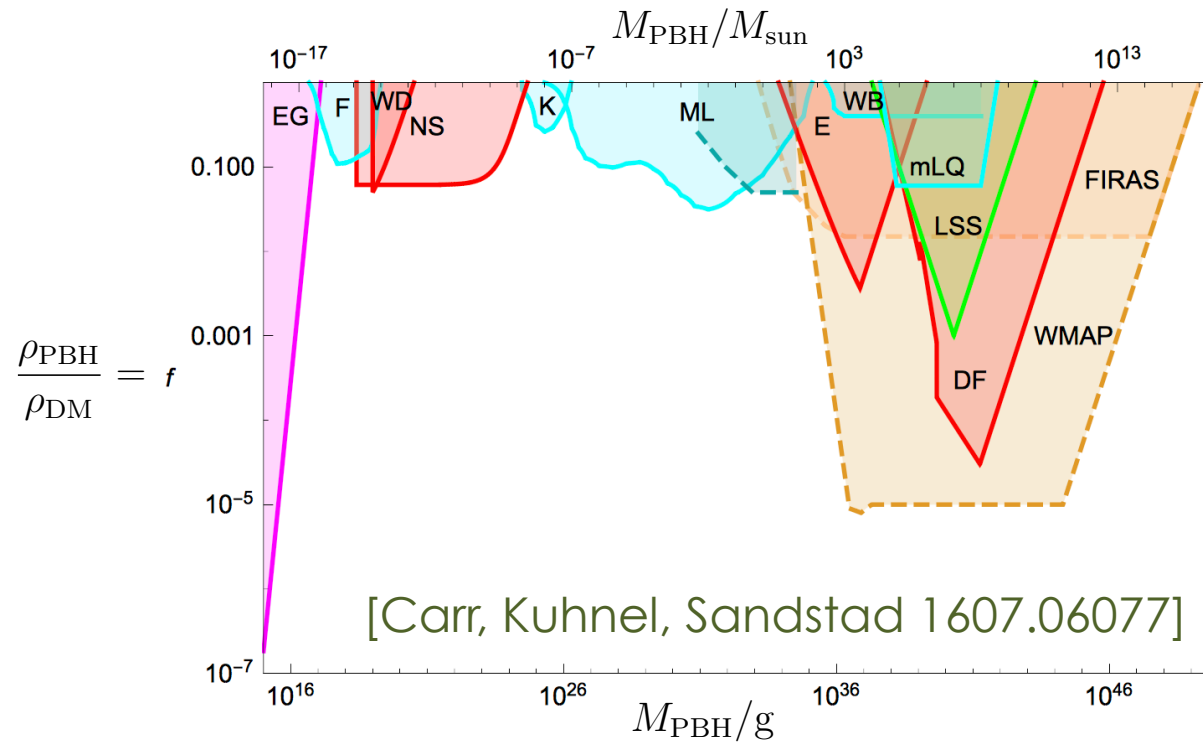
$$R_S = 2GM_{\text{PBH}}$$

$$\begin{aligned} M_{\text{PBH}} &= 5 \times 10^{-19} M_{\text{sun}} & \text{at } t_{\text{form}} &= 10^{-23} \text{ sec} \\ &= M_{\text{sun}} & \text{at } t_{\text{form}} &= 10^{-5} \text{ sec.} \end{aligned}$$

- Life-time (due to Hawking radiation) $\tau_{\text{PBH}} = 10^{64} \text{ year} \left(\frac{M_{\text{PBH}}}{M_{\text{sun}}} \right)^3$

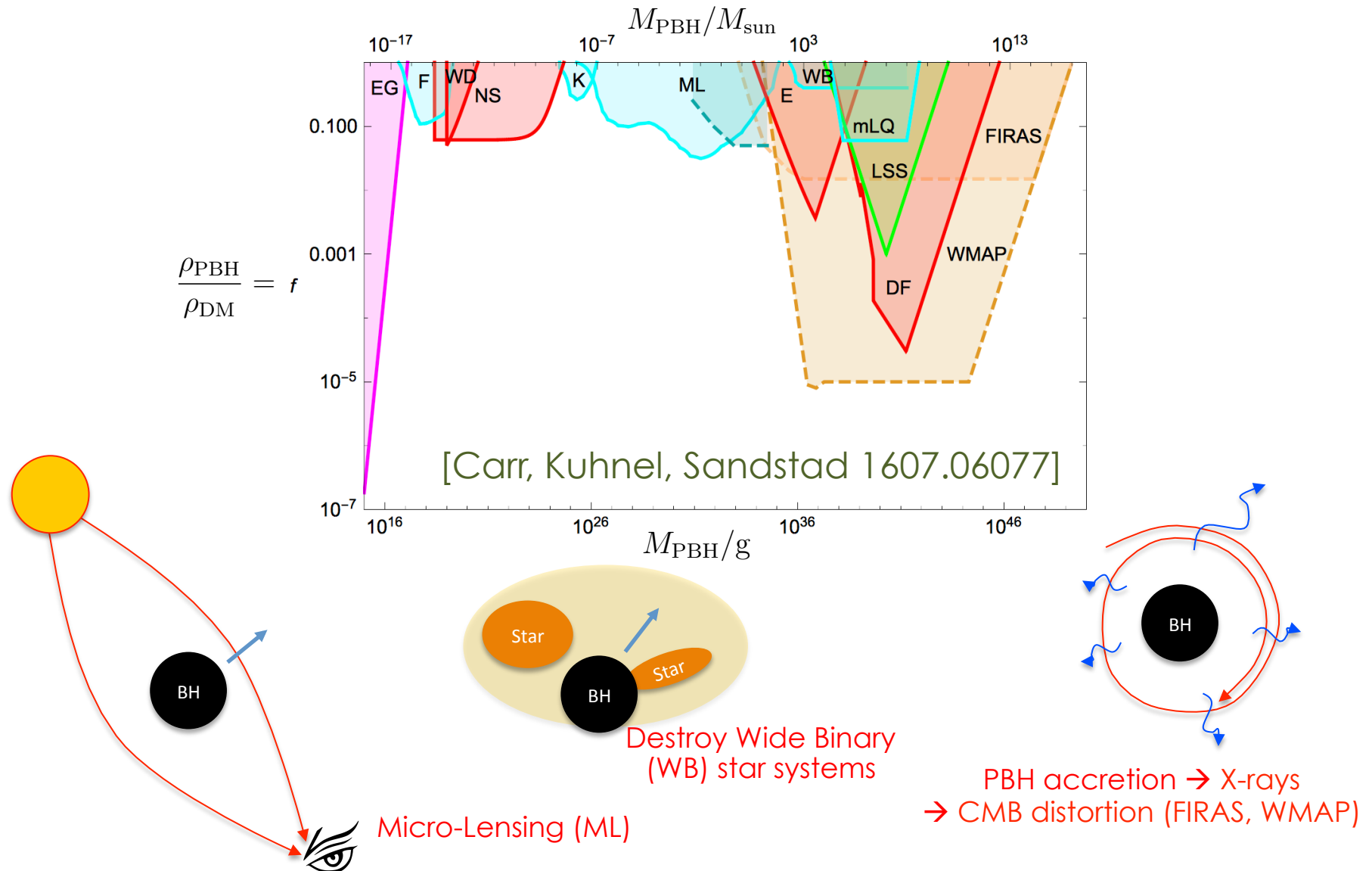
PBH constraints

- Various constraints on the fraction of PBH DM for different PBH masses



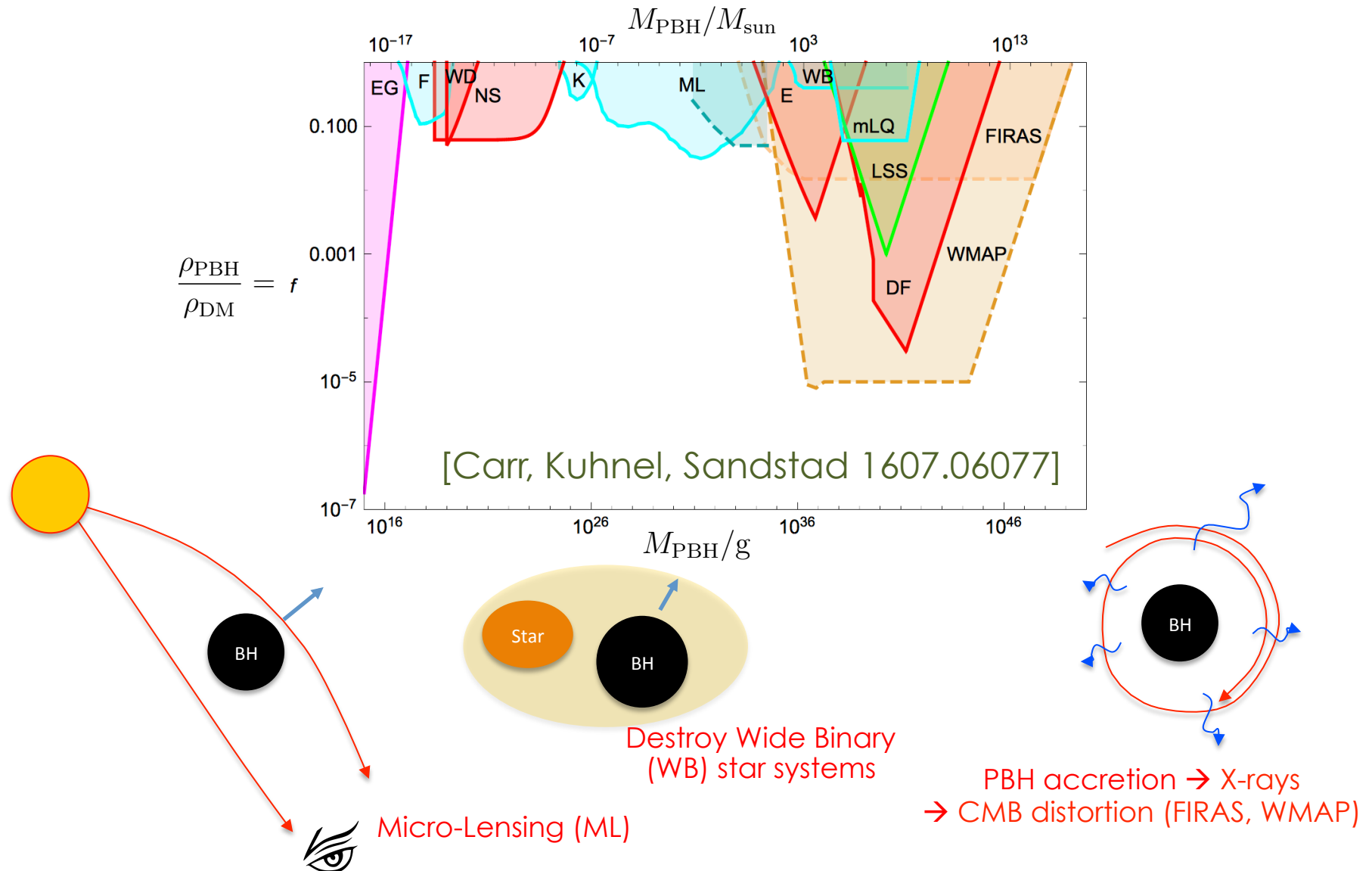
PBH constraints

- Various constraints on the fraction of PBH DM for different PBH masses



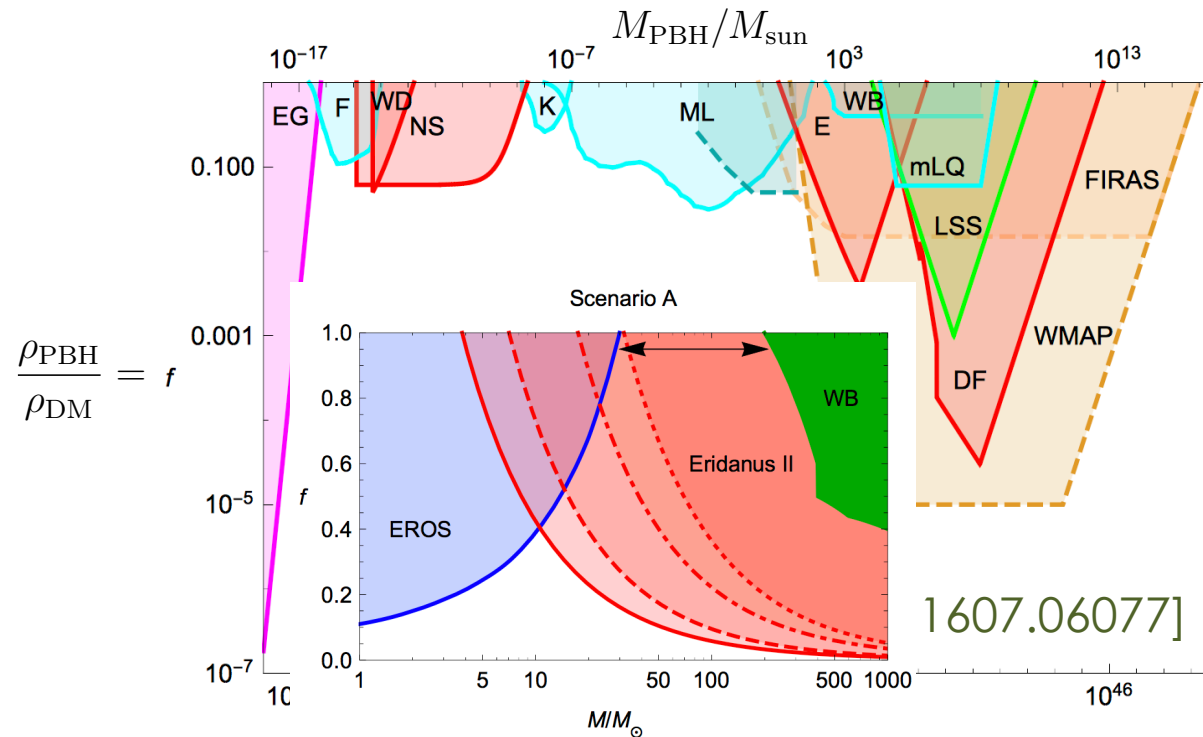
PBH constraints

- Various constraints on the fraction of PBH DM for different PBH masses



PBH constraints

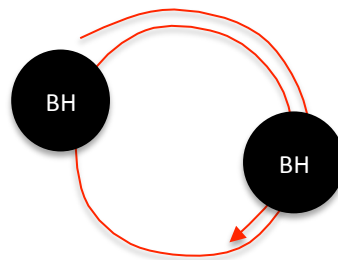
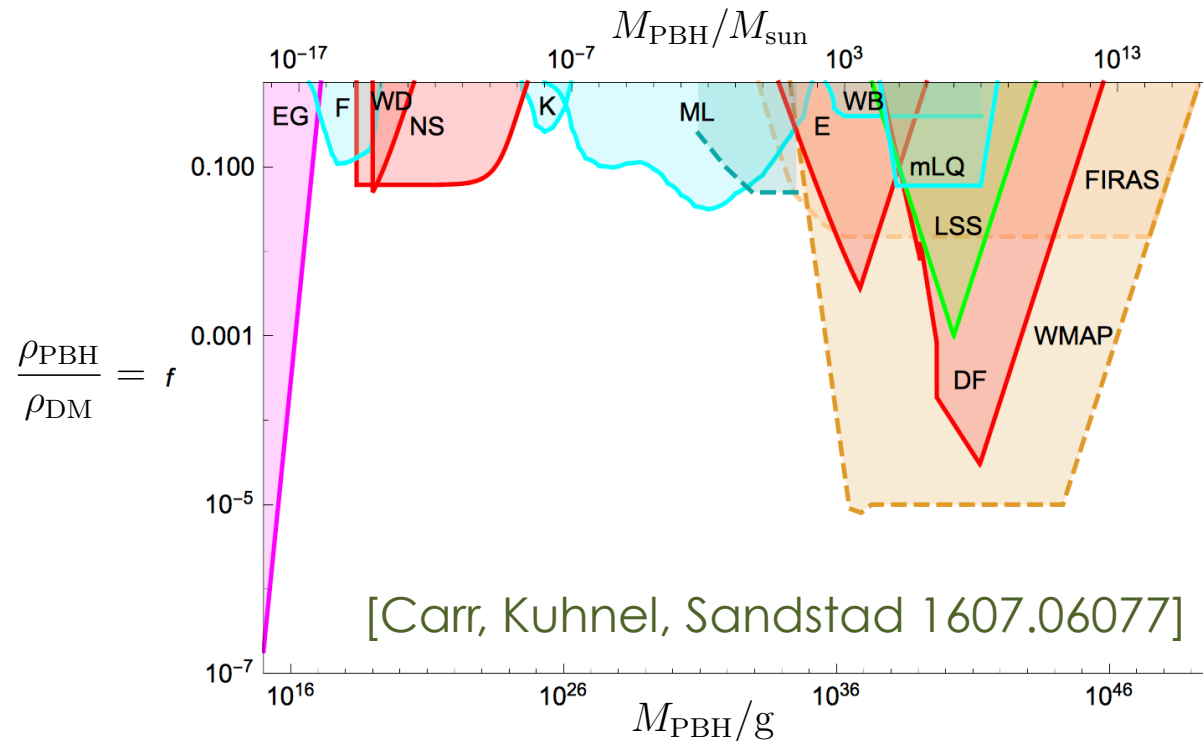
- Various constraints on the fraction of PBH DM for different PBH masses



Star cluster in dwarf galaxy could be destroyed
 : depending on the DM density, velocity dispersion,
 expected age of the cluster

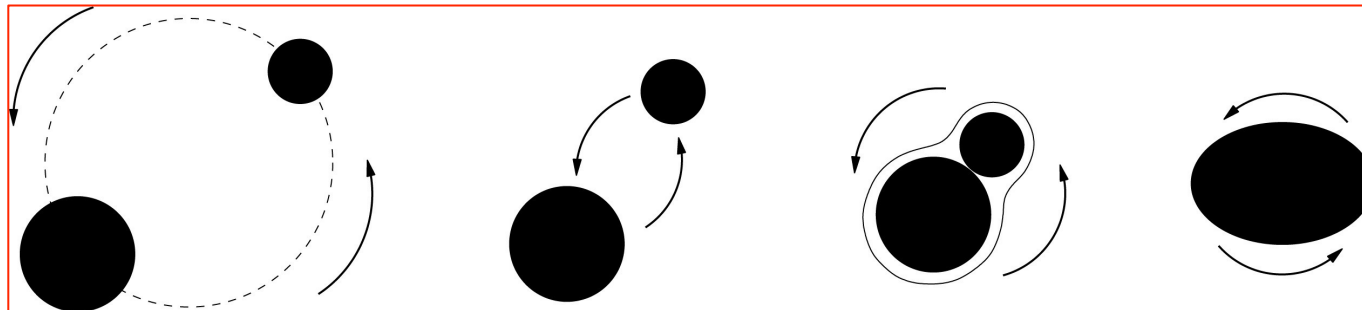
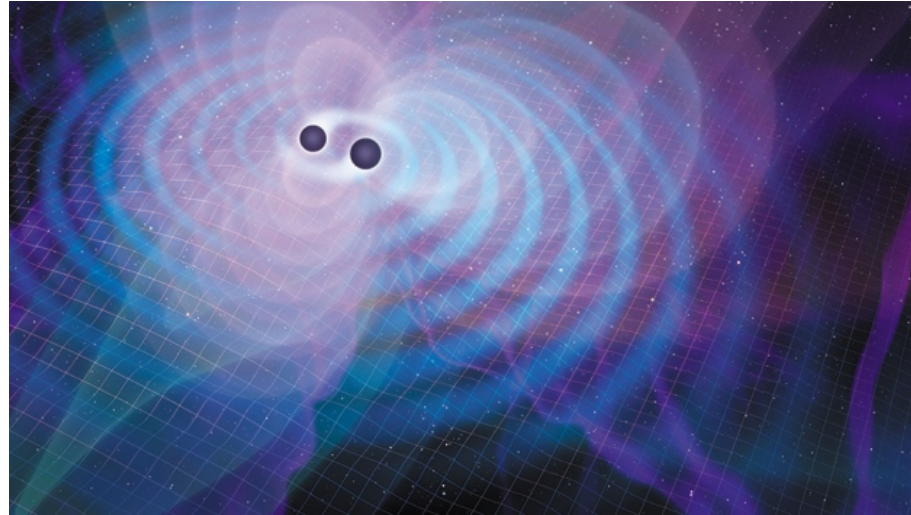
PBH constraints

- Various constraints on the fraction of PBH DM for different PBH masses*

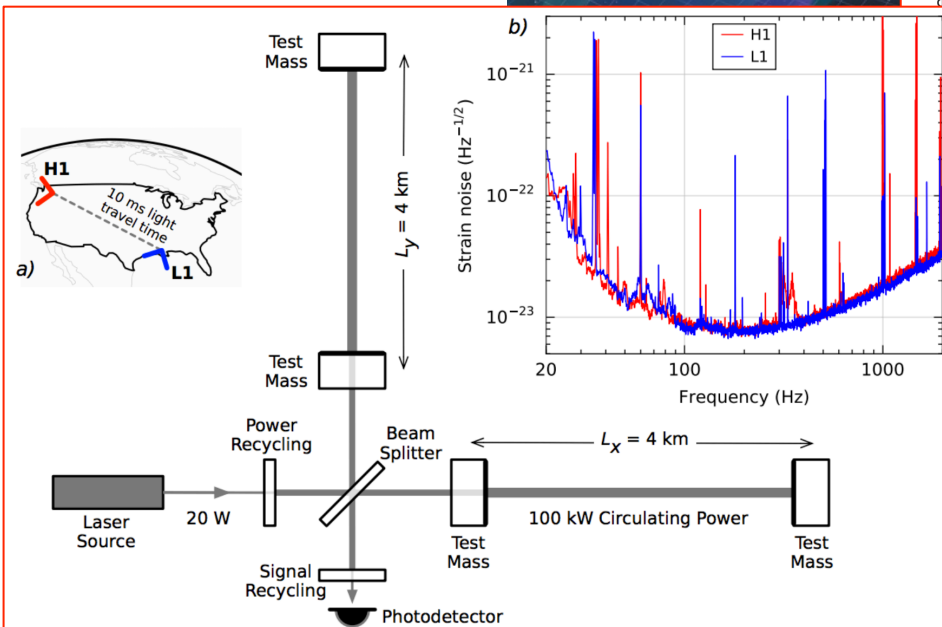
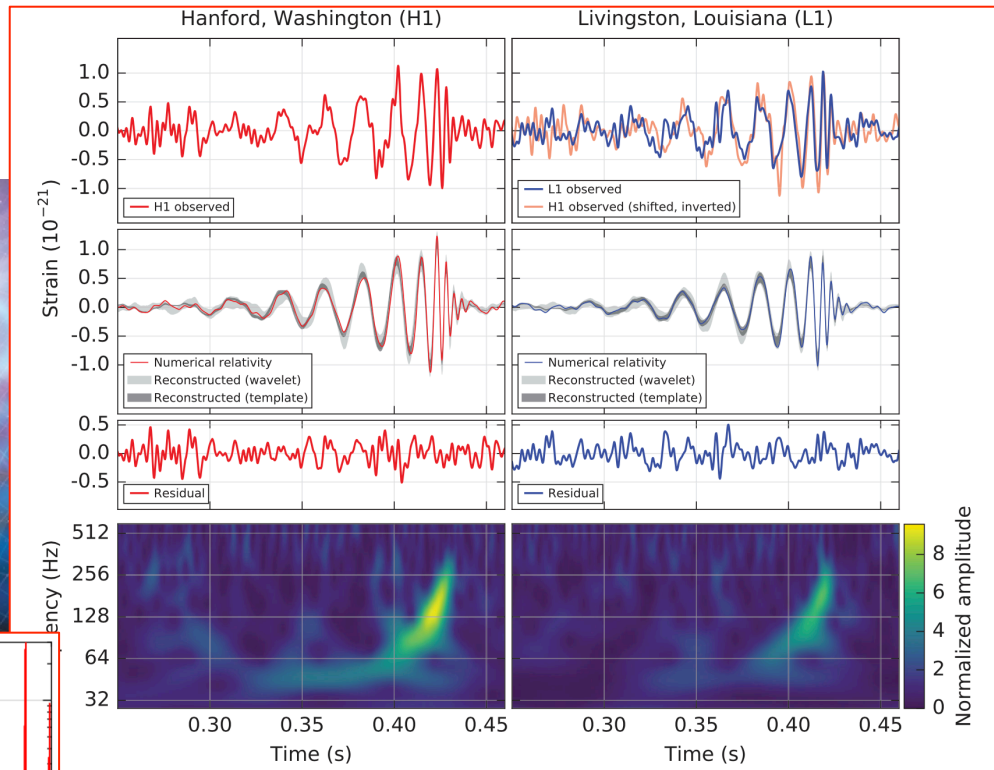
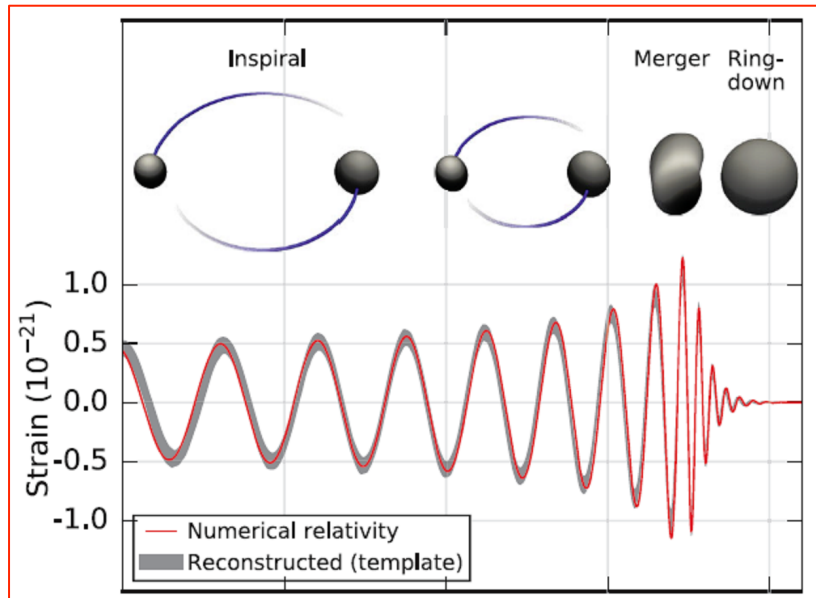


Binary PBHs (and merging) can be the source of strong gravitational waves

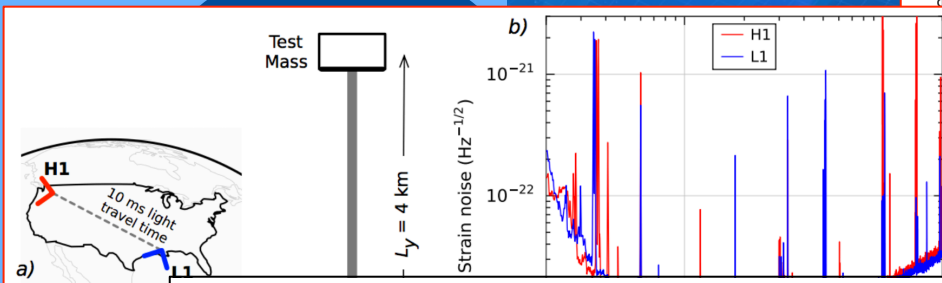
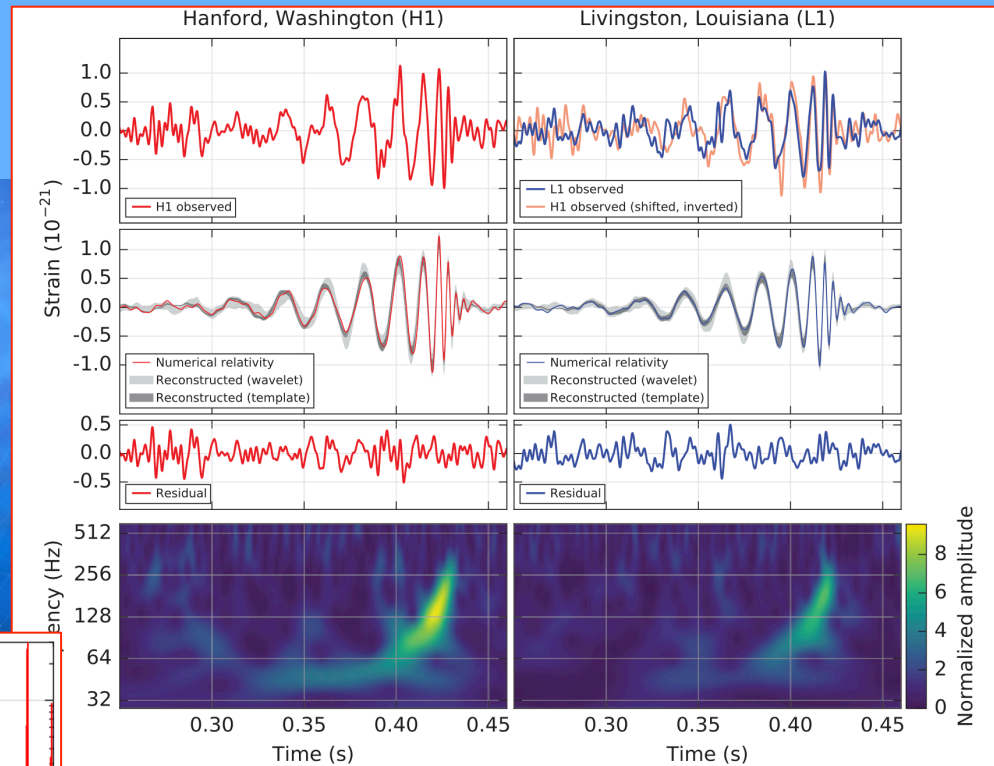
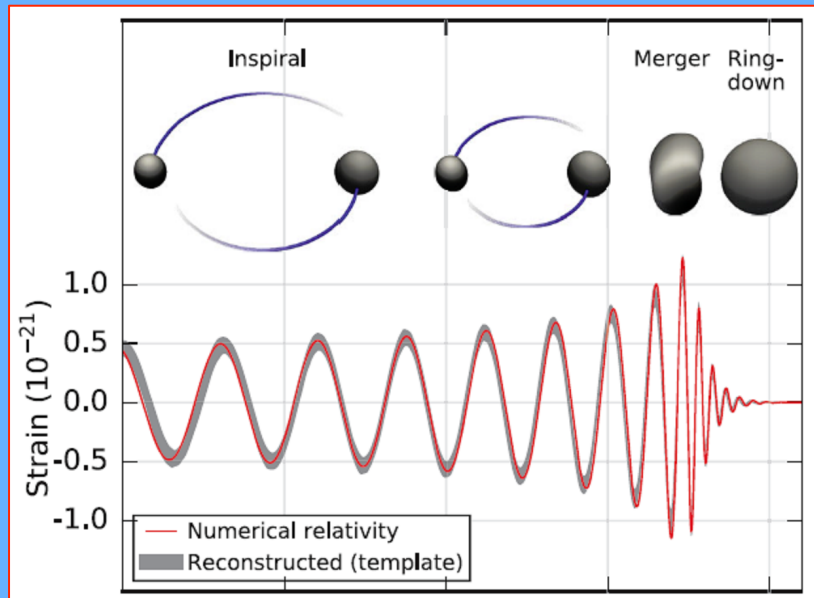
Forming binary black holes and coalescing → Gravitational waves



Strong gravitational waves are produced



Strong gravitational waves are produced

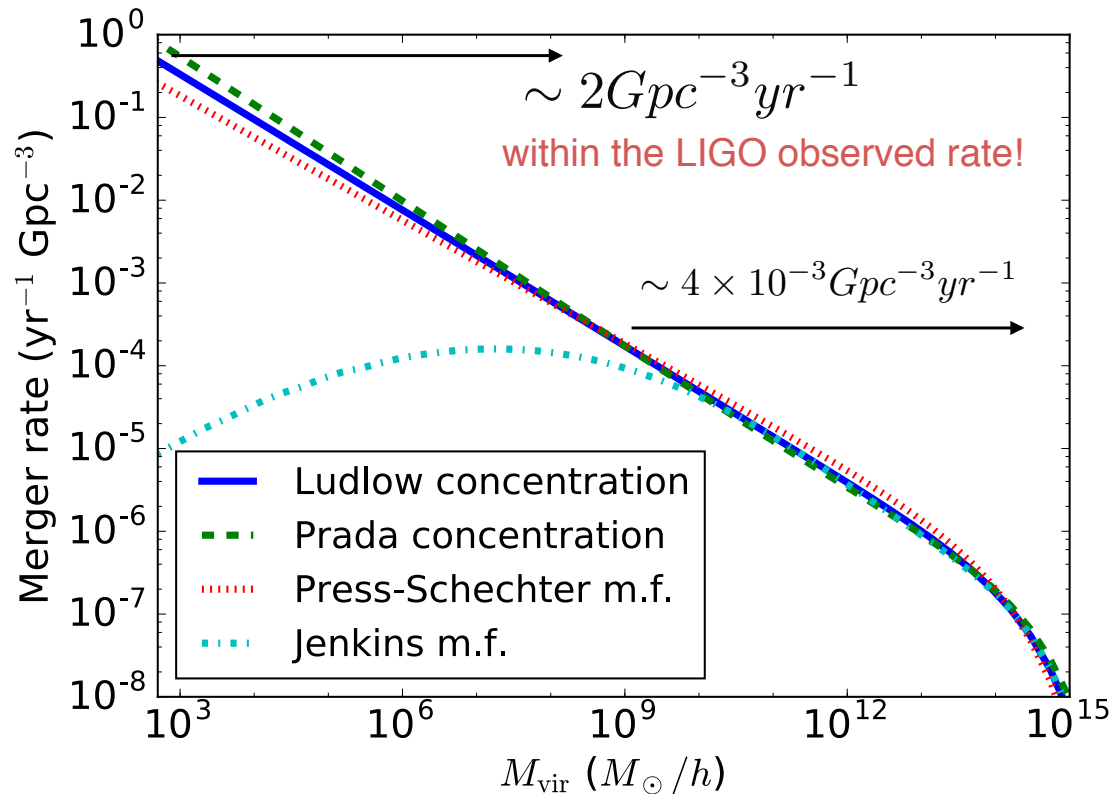
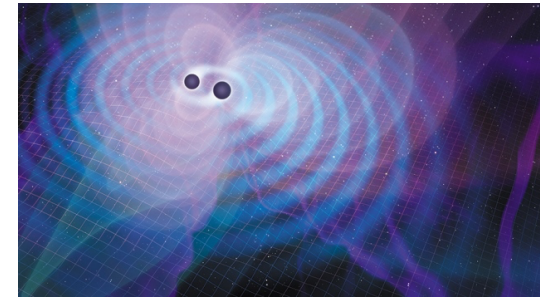


$$36M_{\text{sun}}(\text{BH}) + 29M_{\text{sun}}(\text{BH}) \rightarrow 62M_{\text{sun}}(\text{BH}) + 3M_{\text{sun}}(\text{GW})$$

First direct detection of gravitational waves,
GW150914 (2015)

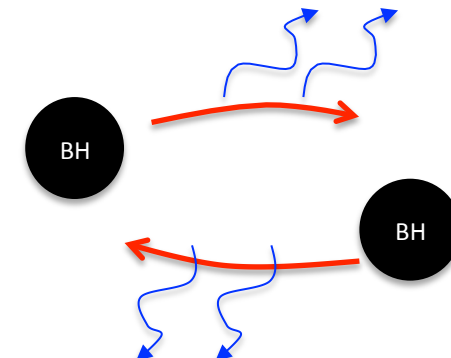
Merger of a PBH binary

- Based on GW150914, GW151226, LVT151012, event rate is estimated as $2 - 50 \text{ Gpc}^{-3} \text{ year}^{-1}$
- Estimating the PBH binary merger rate



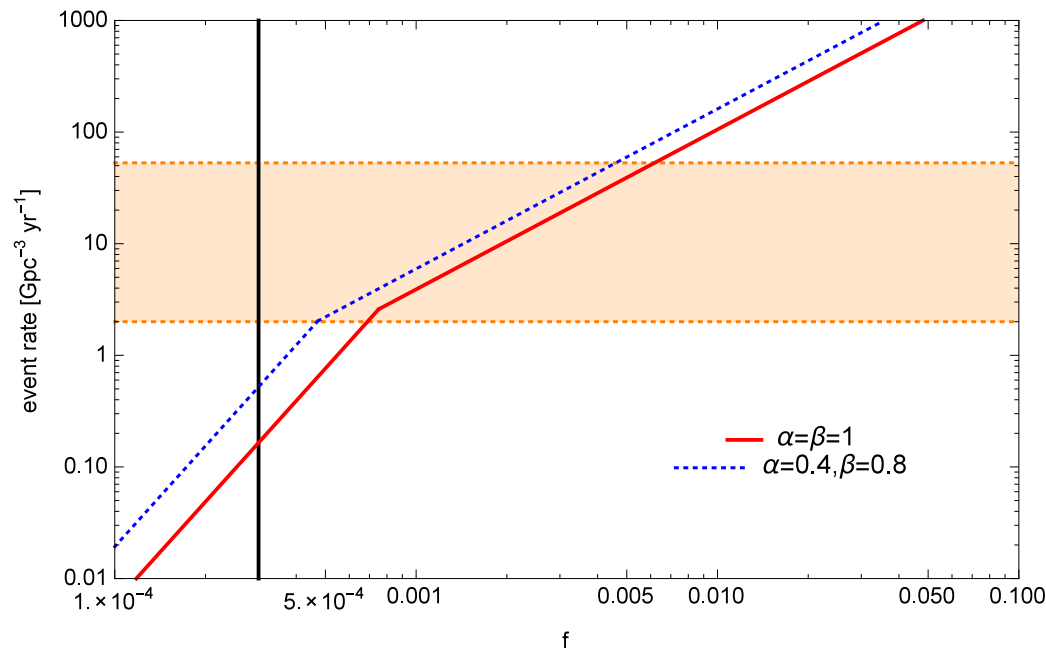
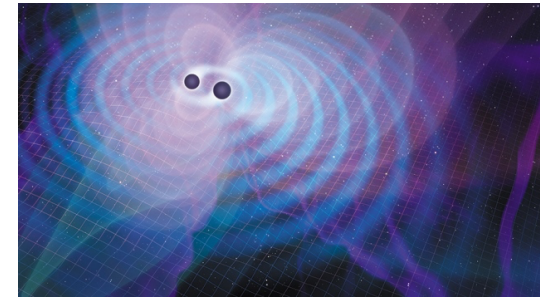
[Bird et. al. 1603.00464]

Formation inside the dark matter halo in the late Universe with NFW profiles assuming that PBHs are most of dark matter



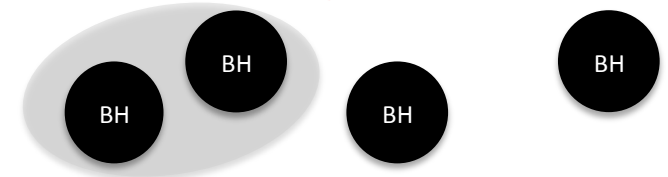
Merger of a PBH binary

- Based on GW150914, GW151226, LVT151012, event rate is estimated as $2 - 50 \text{ Gpc}^{-3} \text{ year}^{-1}$
- Estimating the PBH binary merger rate



[Sasaki et. al. 1603.08338]

Formation in the early Universe after matter-radiation equality (before virialization) assuming a certain probability distribution for the distances among PBHs. Only fractional DM PBHs are enough.



Outlook

- We have sketched “a few types” of dark matter candidates. I didn’t discuss the detailed constraints on the class of warm dark matter, asymmetric dark matter, and mixed (multi-component) dark matter, Lightest fermion dark matter, etc.
- Also different thermal histories for the same dark matter candidate are possible to give also interesting signatures that give the hint for the early Universe.
- The future astro-cosmological experiments will reveal the detailed structure of dark sectors.