Particle cosmologically probing light species

Kenji Kadota (Nagoya Univ)

- **'Probing Neutrinos from Planck and Forthcoming Galaxy Redshift Surveys'**
  [arXiv:1310.0673] with Yoshitaka Takeuchi (Nagoya)

- '***Cosmologically probing ultra-light particle dark matter using 21 cm signals***'
  [arXiv:1312.1898] with
  Yi Mao (IAP), Kiyomoto Ichiki (Nagoya), Joe Silk (IAP, Johns Hopkins,Oxford)

'free streaming'

- **'Constraining the smallest DM halo from LHC and DM direct detection experiments'**
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- ➢ Model

- ➢ The neutrino effects on the cosmological observables

- Cosmological Observables
- ✓ CMB
- ✓ Large scale structure (galaxies from Photo-z survey, Spec-z survey)

- The neutrino effects on:

CMB & large scale structure

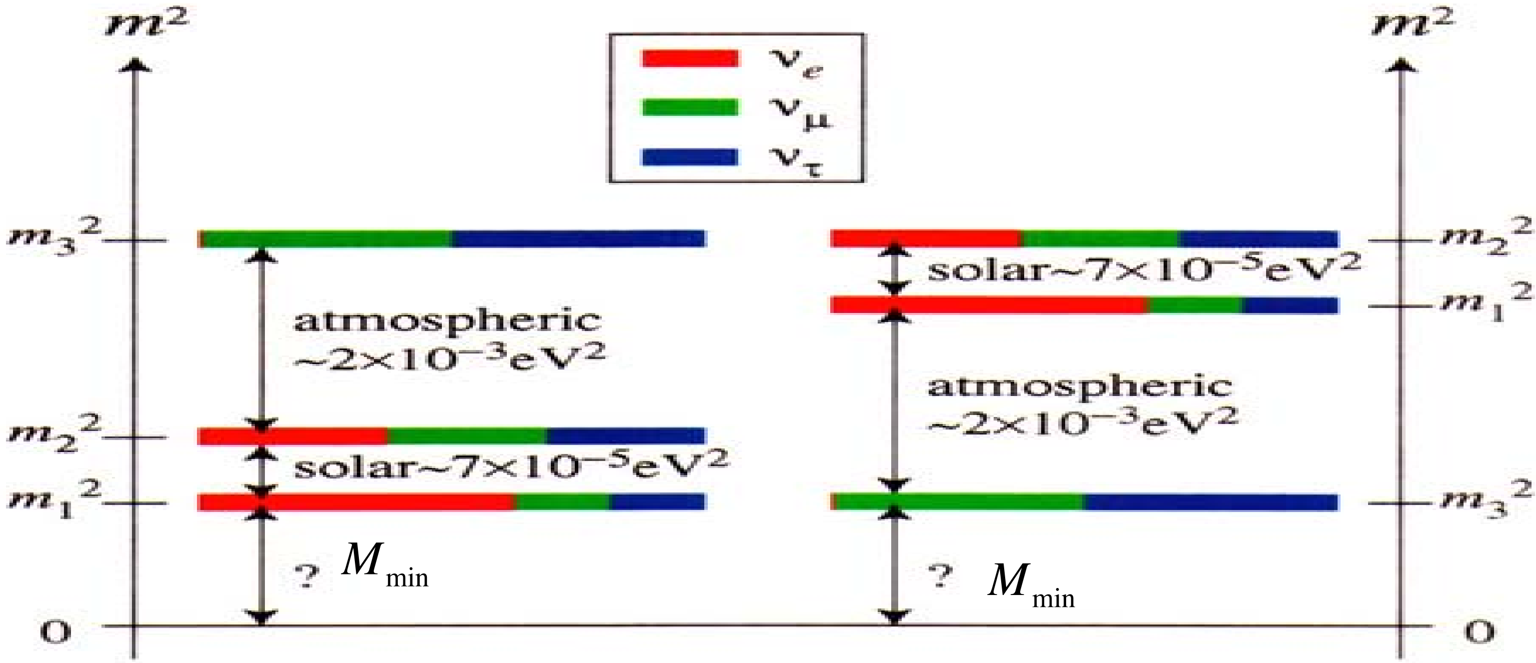
- ➢ Forecast results

- $\sigma(\Sigma m_\nu) \sim 0.02 eV$

Neutrino mass splitting

Neutrino oscillation data (e.g. Daya Bay, RENO, KamLAND, CHOOZ,T2K, MINOS,KamLAND etc)

$$\Delta m_{21}^2 = (7.54)\times 10^{-5}\, eV^2, \left|\Delta m_{31}^2\right| = (2.47)\times 10^{-3}\, eV^2 \text{ (Fogli et al (2012))}$$



Normal Hierarchy Inverted Hierarchy

Can cosmology distinguish normal and inverted hierarchy scenarios?

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Massive neutrino effects on cosmological observables

Cosmological Observables

- CMB :

Planck
completed the observation in Oct , 2013. (5x all sky survey)

Temperature, CMB lensing

- Photometric galaxy redshift survey:

LSST(Large Synoptic Survey Telescope)
8.4 m mirror in Chile, operation in 2022

Galaxy weak lensing tomography, galaxy distribution C(l)

- Spectroscopic galaxy redshift survey:

Euclid, launch in 2020

P(k) (including redshift space distortion)

(Our work differs from the others in that we combine all of them together with cross correlations)

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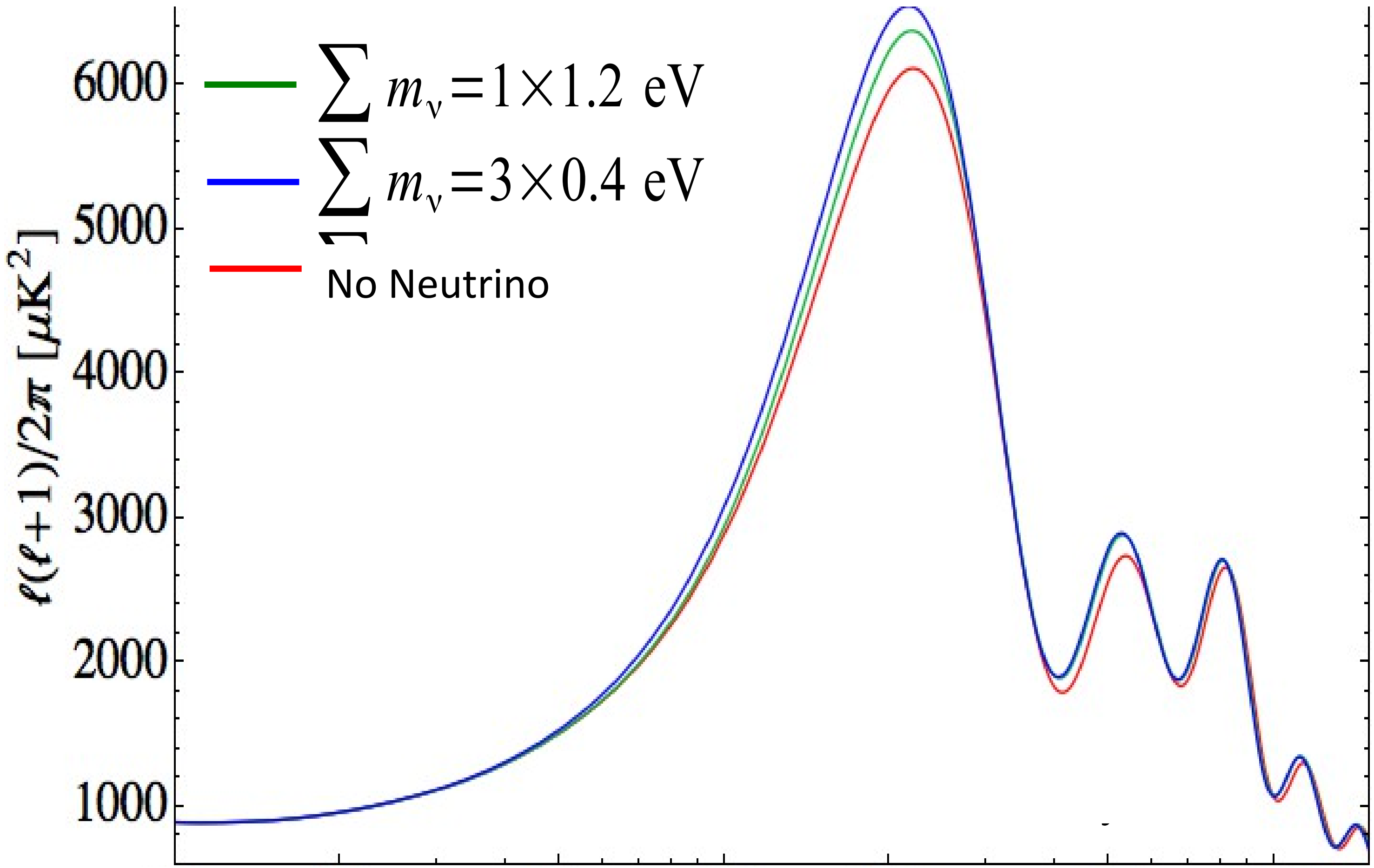
The effects of massive neutrinos on primary CMB

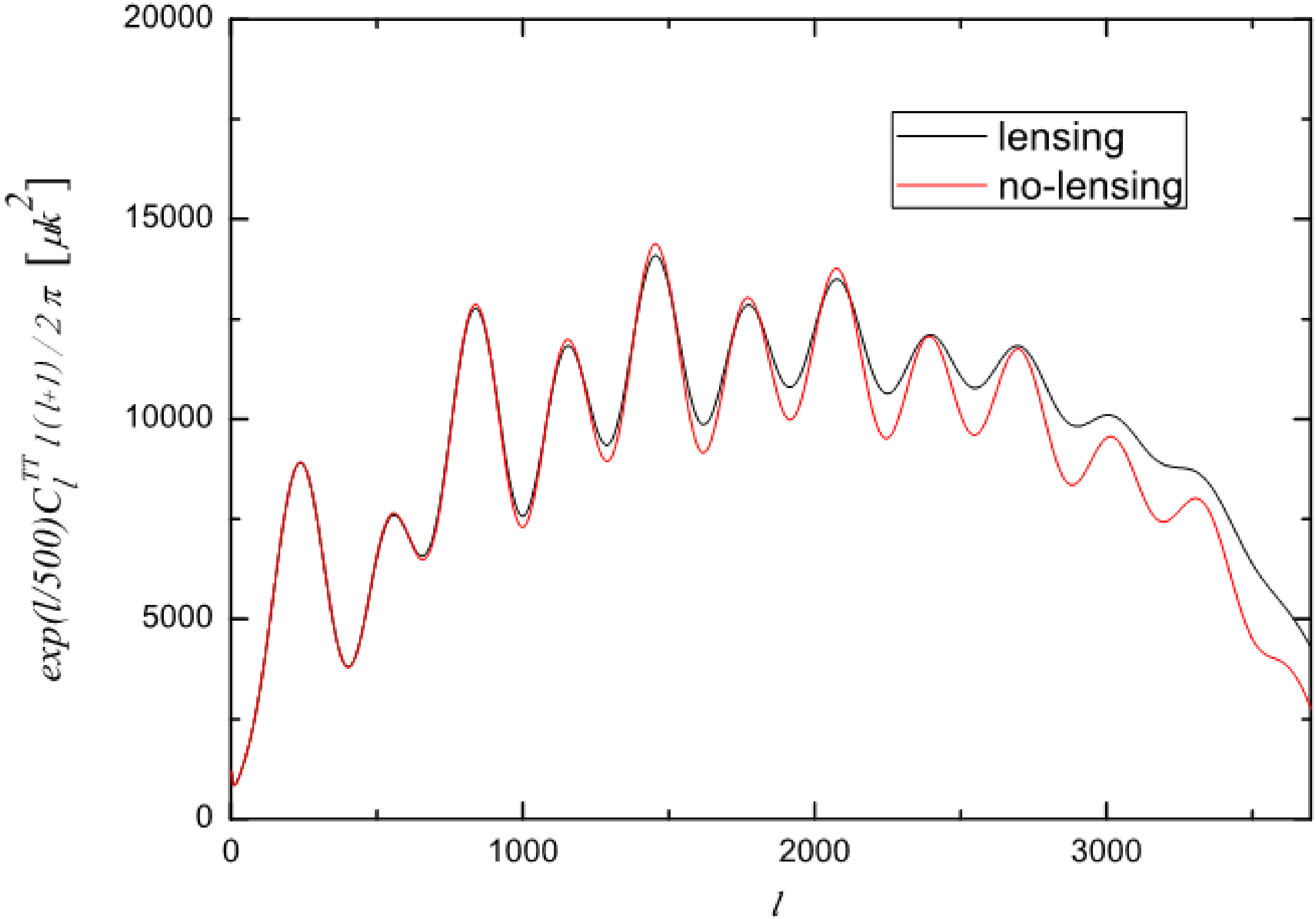
eV-mass neutrinos become nonrelativistic close to the last scattering epoch

ISW effects



CMB lensing (c.f. Lewis & Challinor 2006)

CMB lensing cares about the structure growth as well as geometry



$T(x) \rightarrow T(x+\alpha)$

α : deflection field

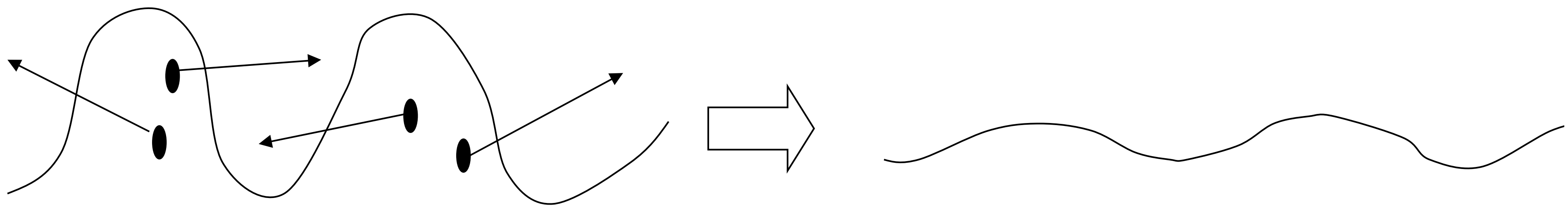
$\alpha = \nabla\psi$

About 3% broadening of acoustic peaks

Planck detected at 25 sigma

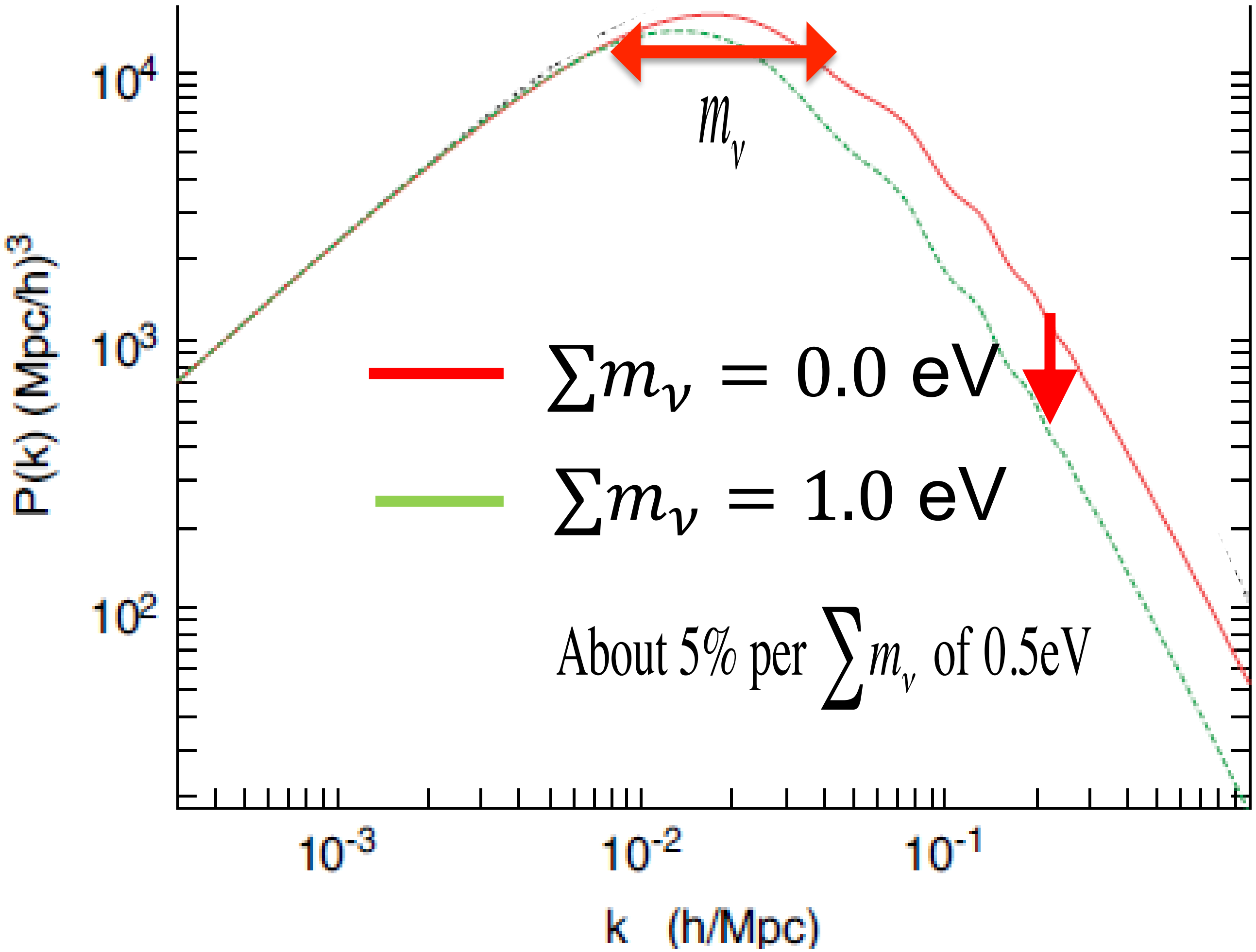
- Free streaming scale:

Characteristic scale within which perturbation cannot grow.



Free-streaming erases the inhomogeneities

Massive Neutrino effects on Large Scale Structure (c.f. Lesgourgues&Pastor 06)



$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

$$P \sim \langle \delta\delta \rangle$$

$$k_{fs} \sim 0.015 / Mpc \left(\frac{m_\nu}{0.05eV} \right) \sqrt{\frac{1}{1+z}}$$

$$\delta \propto a^{1-3f_\nu/5} (f_\nu \equiv \Omega_\nu / \Omega_m)$$

$$\frac{\Delta P}{P} \sim -8 \frac{\Omega_\nu}{\Omega_m} \quad \text{(Hu et al 1998)}$$

Photometric redshift survey

- Galaxy weak lensing tomography

The distortion (shear) depends on the projected mass density along the line of sight

Tomography: Binning in redshifts for the source galaxies (probe on the redshift evolution of the mass density)

- Galaxy power spectrum C(l)

$$bias \equiv \frac{\text{clustering of galaxies}}{\text{clustering of dark matter}} = \frac{measurements}{theory}$$

$$P(k) = b^2(k) P_{DM}(k), \delta_{gal} = b\delta_{DM}$$

Spectroscopic redshift survey: 3D P(k) (3D in redshift space)

Redshift space distortion (Kaiser (1987))

Real Space Redshift space

Coherent infall bulk motion of galaxies towards the halo center (overdense region).
(the bias parameter comes into the galaxy distribution but not in this galaxy velocity)

$$\delta_{gal} = \left(b + f\mu^2\right)\delta_{DM}$$

μ: angle between and k and the line of sight, $\mu^2 = \cos^2\theta = k_{\parallel}^2 / (k_{\parallel}^2 + k_{\perp}^2)$,

$f = \text{growth rate} = d\ln D / d\ln a$

growth factor: $D(z) = \sqrt{\dfrac{P(k,z)}{P(k,z=0)}}$

Redshift space distortion from longitudinal modes separates out the bias and the growth

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Forecast

- Fisher analysis

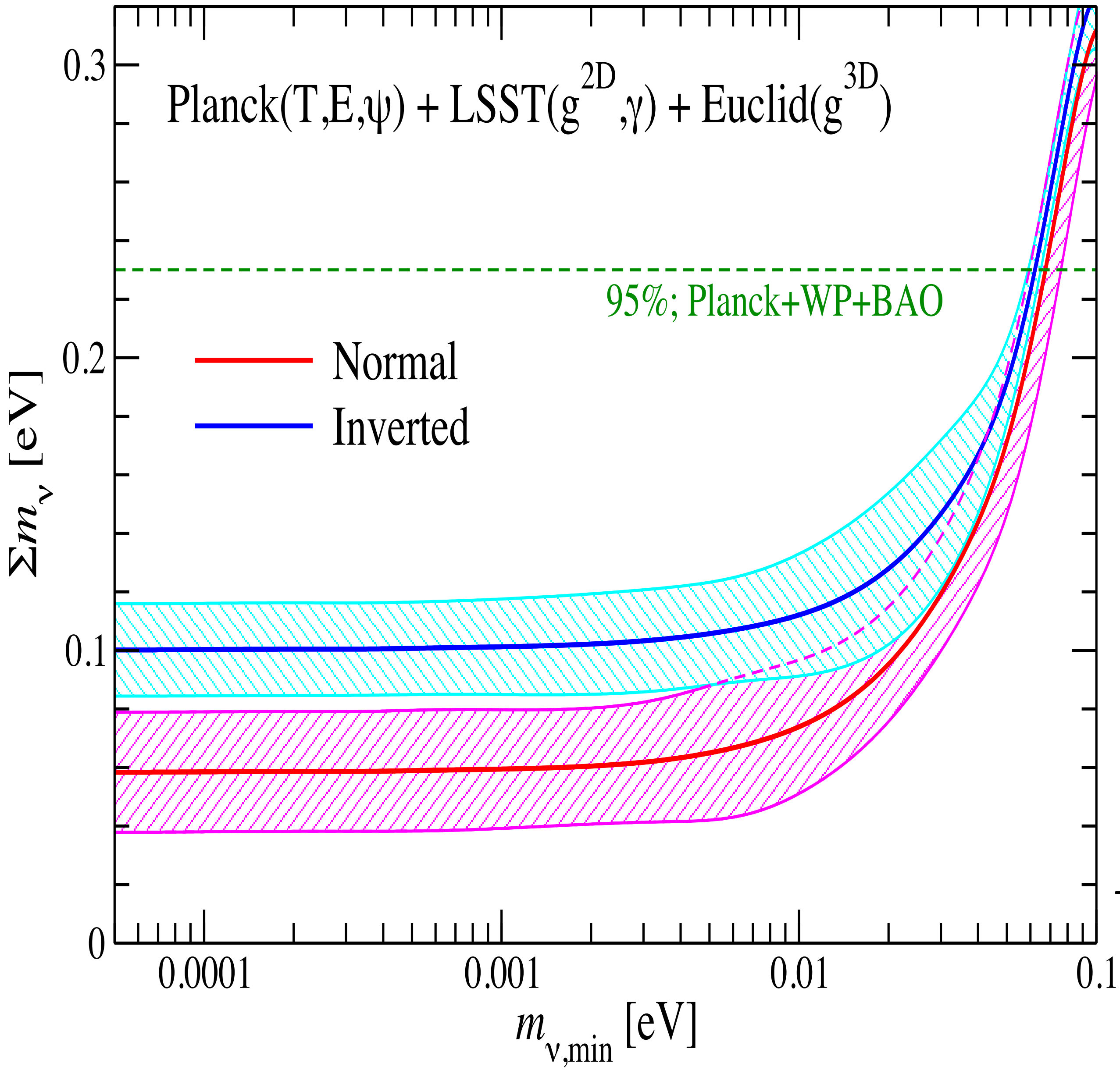
Cosmological parameters: $f_\nu (\equiv \Omega_\nu / \Omega_m), N_{eff}, M_{\min}, w,$

and the standard cosmological parameters such as $\Omega_c h^2, \Omega_\Lambda)$

Observables: (all the auto and cross correlations into account)

- Planck CMB
- LSST-like photo-z surveys (2D galaxy distribution, galaxy weak lensing (tomography))
- Euclid-like surveys with spectroscopic data (3D galaxy distribution)

Survey	Observables	$f_{\rm sky}$	$\ell_{\rm min}$ or $k_{\rm min}$	$\ell_{\rm max}$ or $k_{\rm max}$	redshift bin
Planck	CMB (T, E, ψ)	0.65	2	3000	—
LSST	photo-z (g, γ)	0.5	2	500	5
Euclid	spec-z ($\mathrm{g}^{\rm 3D}$)	0.2	10^{-4} h/Mpc	$k_{\rm nl}$	10



$$\sigma(\Sigma m_\nu) \sim 0.02eV$$

Takeuchi and K.K. (2014)

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- Model

ALPs (Axion-like particles)

- ALP fluctuations

- Cosmological observables

CMB and 21cm

- Forecast Results

Uncertainties in f_a, m_a: 10~20 %

Model: Ultra-light scalars (ALPs (axion-like particles))

- Ultra-light mass :

$m_a \sim H_0 \sim 10^{-33} eV$ DE (Barbieri et al (2005),…)

$m_a \sim 10^{-22} eV$ DM (Hu (2000),…)

$m_a \sim 10^{-22} eV - 10^{-10} eV$ String axiverse (Arvanitaki et al (2009),...)

(Likelihood analysis: Amendola et al (2005), Marsh et al (2013)…)

$$m_a, f_a = \Omega_a / \Omega_m \sim O(0.01)$$
$$m_a \leq H(t) : \rho_a = const$$
$$m_a > H(t) : \rho_a \propto 1/a^3$$

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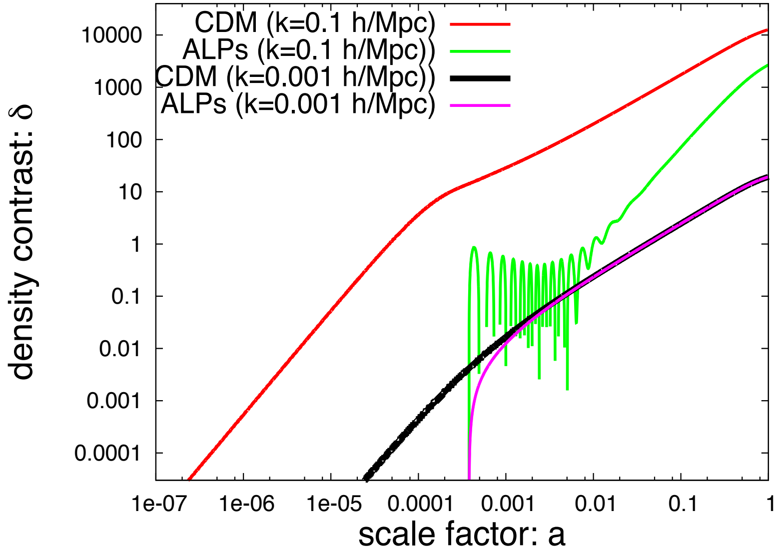
Fluctuations of ALPs



The perturbation evolutions for ALPs ($m_a = 10^5 H_0$, $f_a = 0.05$) and CDM

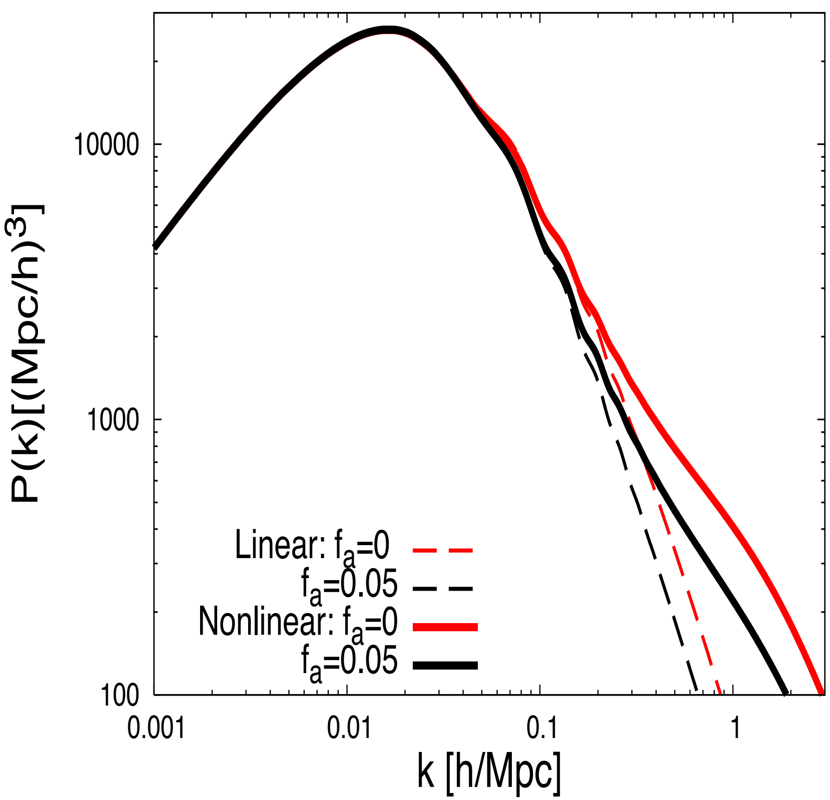
KK, Mao, Ichiki, Silk (1312.1898[hep-ph])

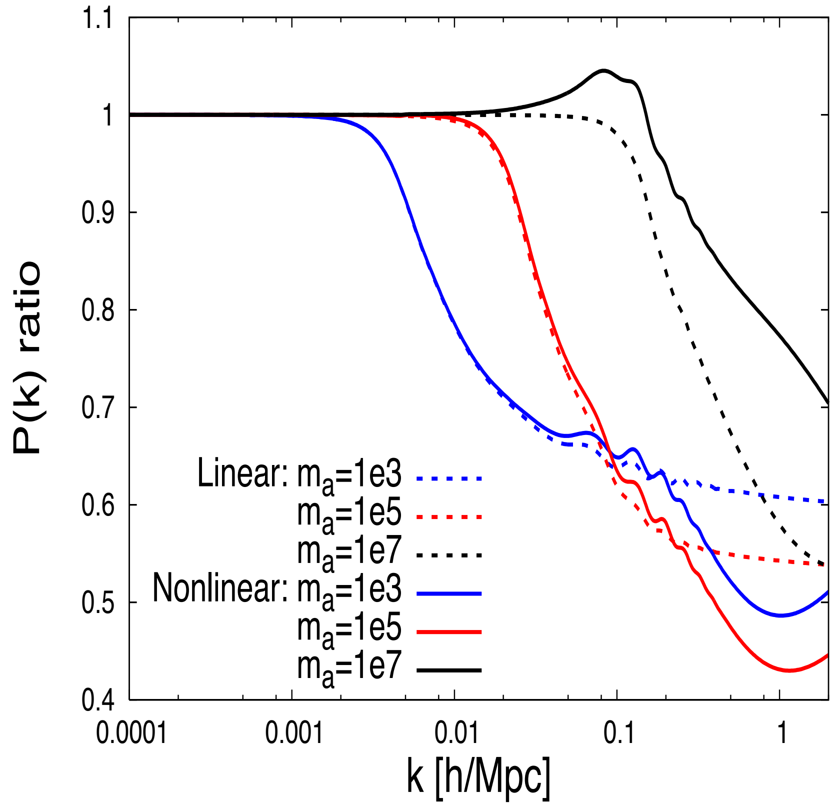
Cannot grow inside the free streaming scale Pressure term: $(k^2 / a^2) c_s^2 \delta_k$

Power spectrum P(k)

If oscillation starts during matter domination : $z_{osc} \sim m^{2/3}, k_* \sim m^{1/3}$

If oscillation starts during radiation domination : $z_{osc} \sim m^{1/2}, k_* \sim m^{1/2}$





$k^3 P(k) / 2\pi^2 \sim 1$

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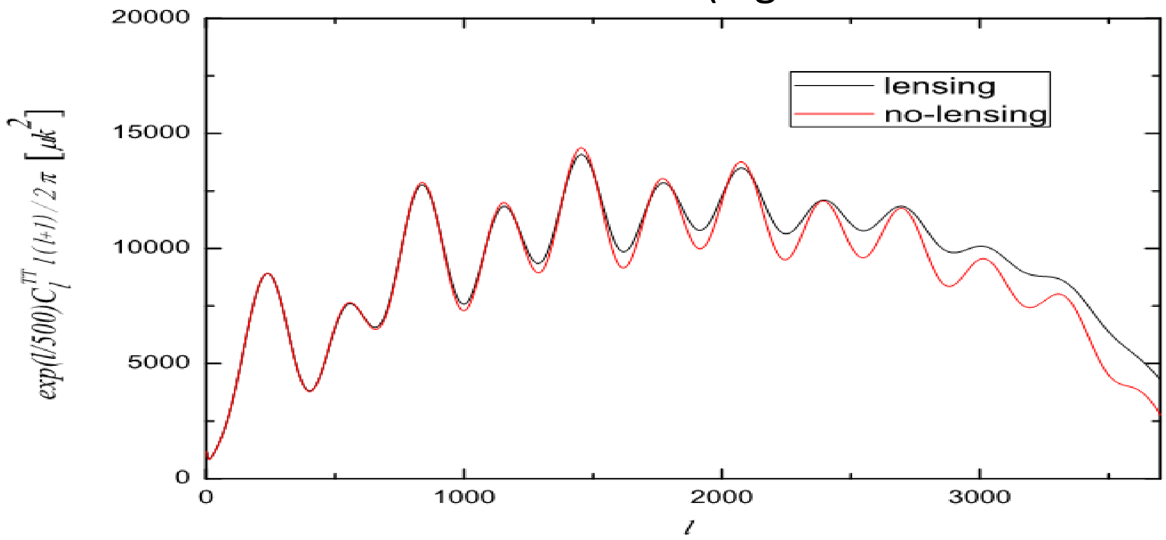
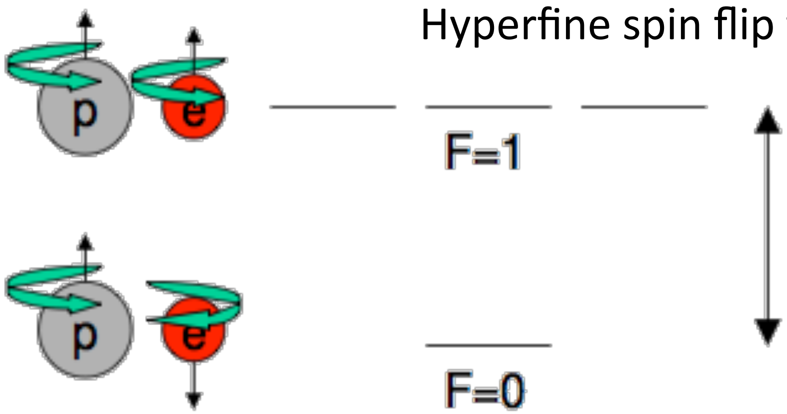
Cosmological observables: CMB (including lensing) + 21cm

(e.g. Lewis & Challinor 2006)



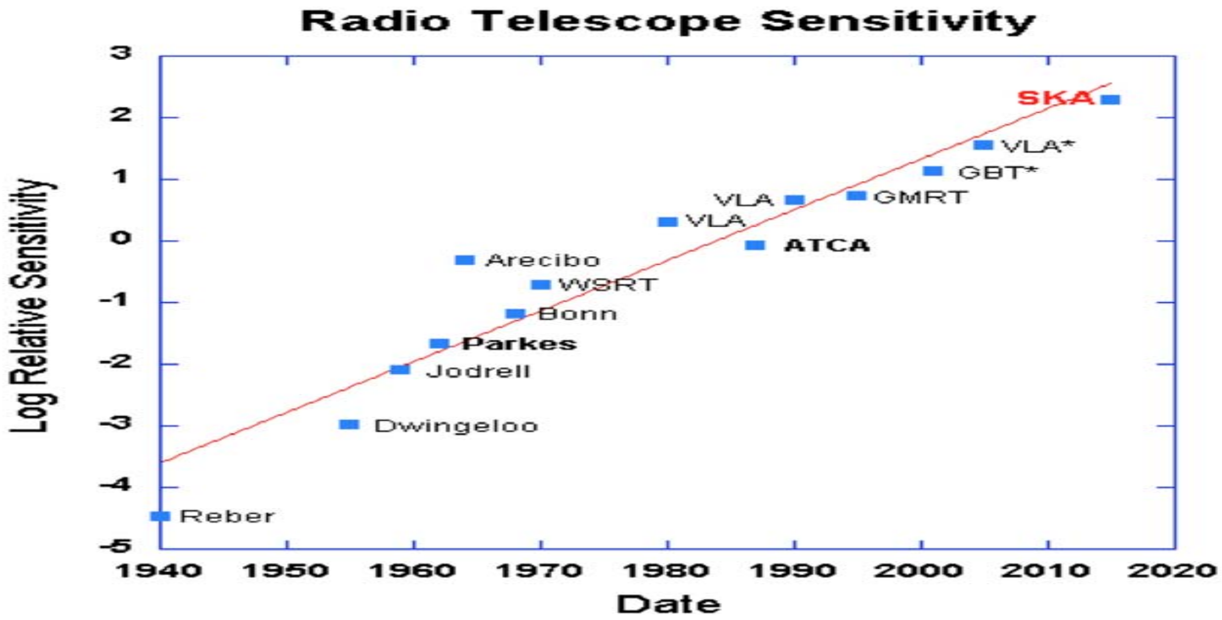
Hyperfine spin flip transition



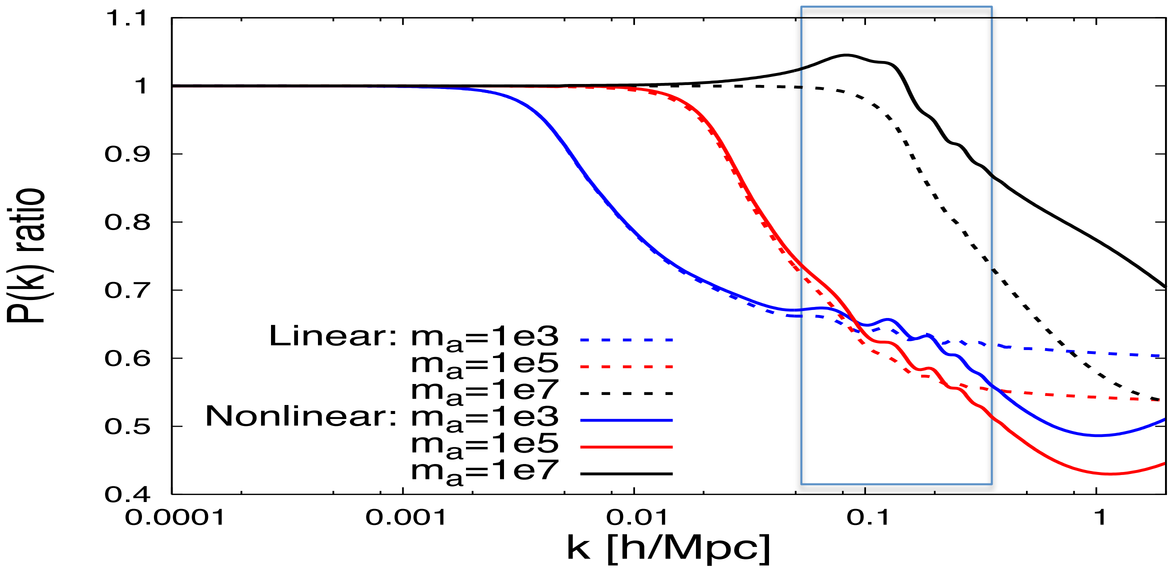
21 cm signals

$\lambda = 21\,\mathrm{cm}$

$$\Delta P / P \sim 1/\sqrt{N}$$



Square Kilometer Array
(S. Africa/Australia)
Data taking around 2020.



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Likelihood analysis

- Fisher forecasts: CMB + 21cm.

$$\Omega_\Lambda, \Omega_m h^2, \Omega_b h^2, n_s, A_s, \tau, N_{eff}, m_a, f_a, f_\nu, x_{HI}, b_{HII}(z)$$

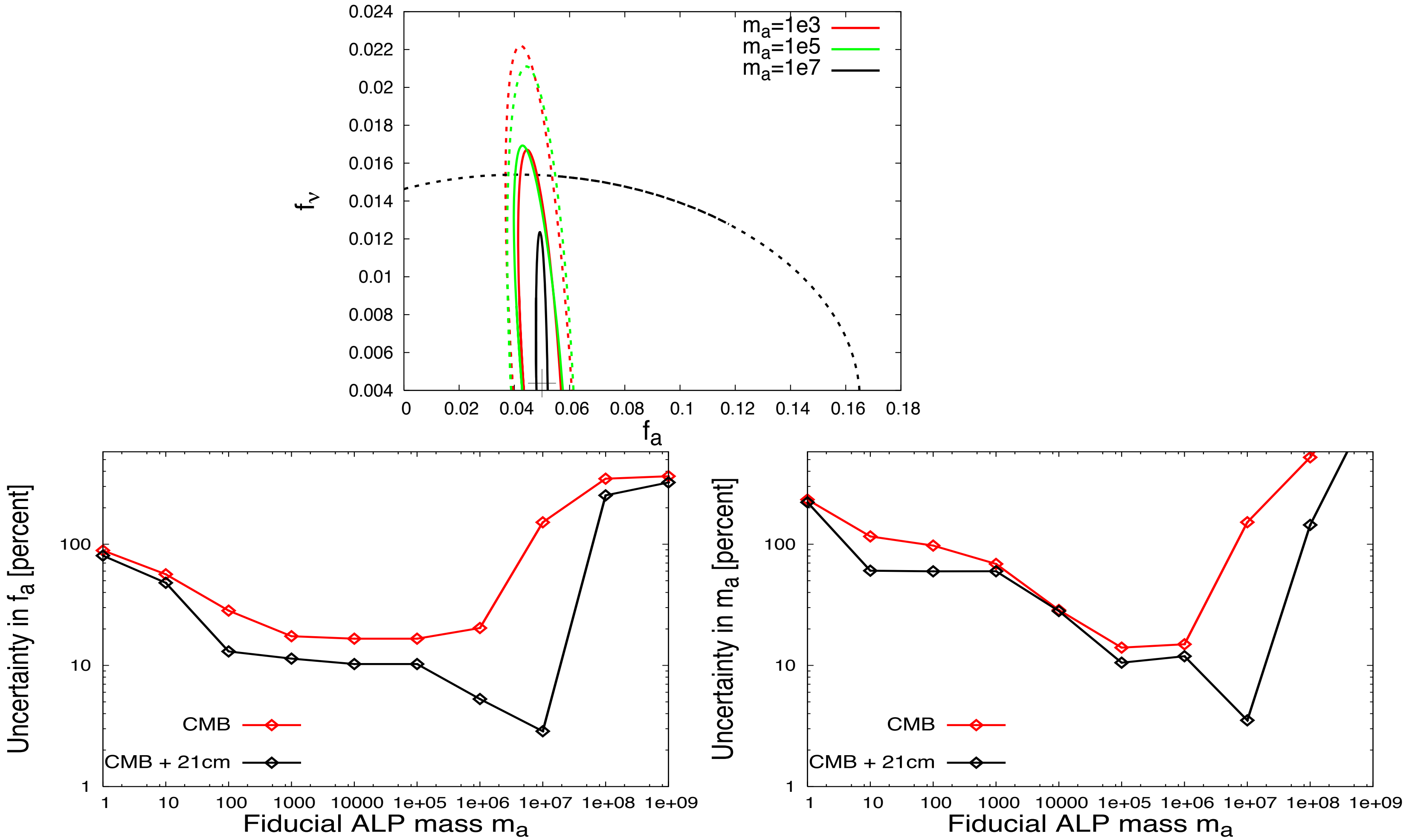

Figure 4: 1σ errors in f_a and m_a (the fiducial value $f_a = 0.05$) for several fiducial values of m_a in terms of $H_0 (\approx 2 \times 10^{-33}$ eV).

KK, Mao, Ichiki, Silk (1312.1898[hep-ph])

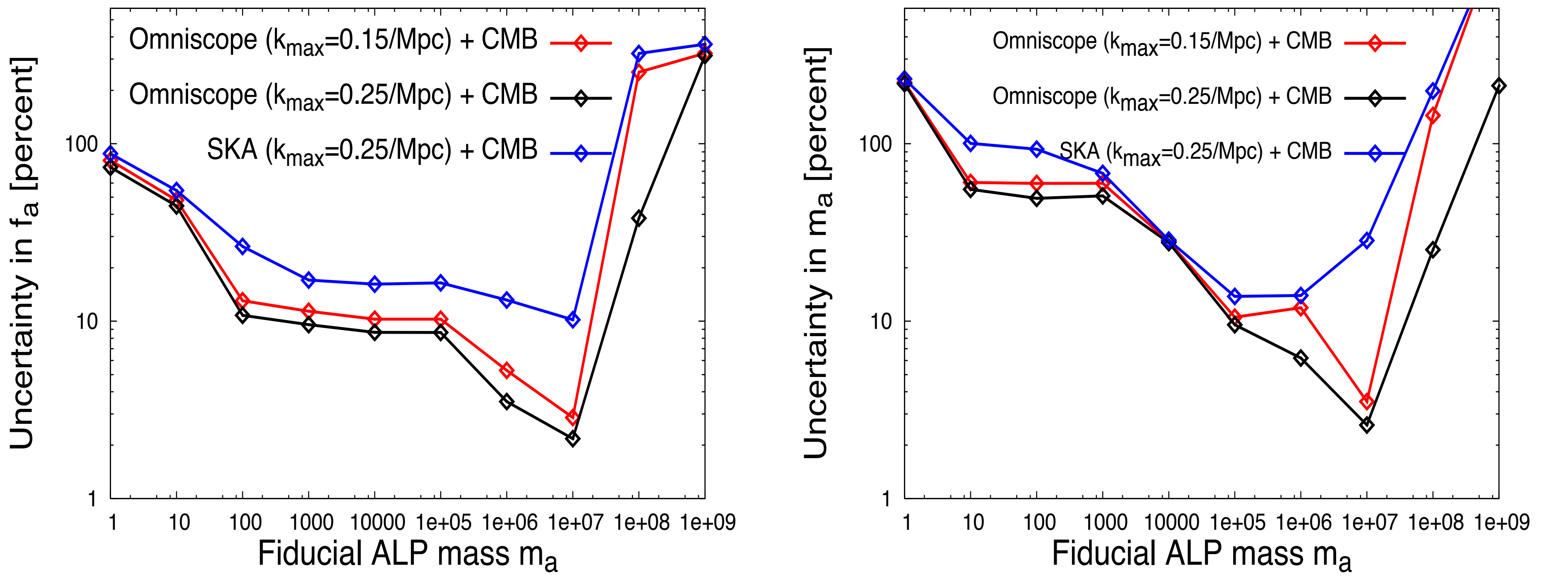

Figure 6: 1σ error in f_a and m_a for different experiment specifications. The fiducial values of m_a are in terms of $H_0 (\approx 2 \times 10^{-33}$ eV).

TABLE IV: Specifications for 21cm interferometers

Experiment	N_{ant}	Min. baseline (m)	f.o.v. (deg^2)	A_e (m^2) at z=6/8/12[a]
MWA	500	4	$\pi\, 16^2$	9/14/18
SKA	7000	10	$\pi\, 8.6^2$	30/50/104
LOFAR	77	100	$2 \times \pi\, 2.4^2$	397/656/1369
FFTT	10^6	1	2π	1/1/1

[a] We assume that the effective collecting area is proportional to λ^2 such that the sensitivity (A_e/T_{sys} in m^{2}K^{-1}) meets the design specification

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Most sensitive m_a:

$$CMB : m_a \sim 10^{4-6} H_0 (10^{-29\sim-27} eV)$$
$$21cm : m_a \sim 10^{7} H_0 (10^{-26} eV)$$

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- Dark matter free streaming length
  size of the smallest dark matter halo

- Observables
  LHC and Direct DM search experiments

- Results
  The smallest dark matter halo mass: Earth size ($10^{-6}\,M_{sun}$)

Free streaming length of Dark Matter (DM)

Free streaming length (c.f. Kolb and Turner)

$$\lambda \equiv a(t_0)\int_{t_{dec}}^{t_0} dt v(t)/a(t) = a(t_0)a(t_{dec})v(t_{dec})\int_{t_{dec}}^{t_0} dt 1/a^2(t)$$

$$a \sim t^{1/2}, a \sim t^{2/3}$$

$$v(t_{dec}) \sim \sqrt{T(t_{dec})/m}$$

- Chemical decoupling (Temperature ~ 10 GeV)

DM annihilation rate < expansion rate of the Universe

(DM abundance freezes out)

- Kinetic decoupling (Temperature ~ 10 MeV)

DM scattering rate < expansion rate of the Universe

(Structures start forming)

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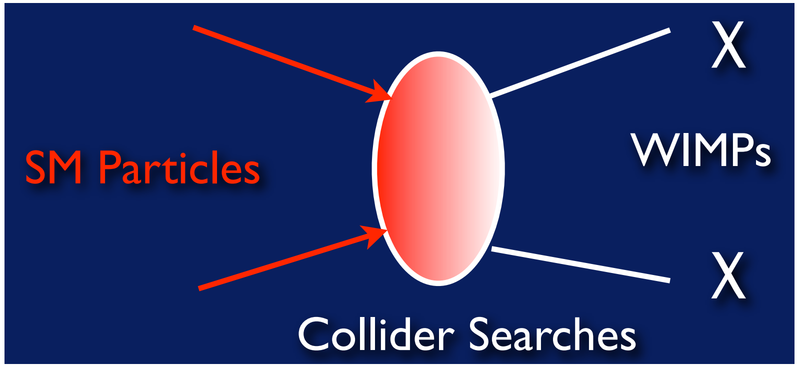
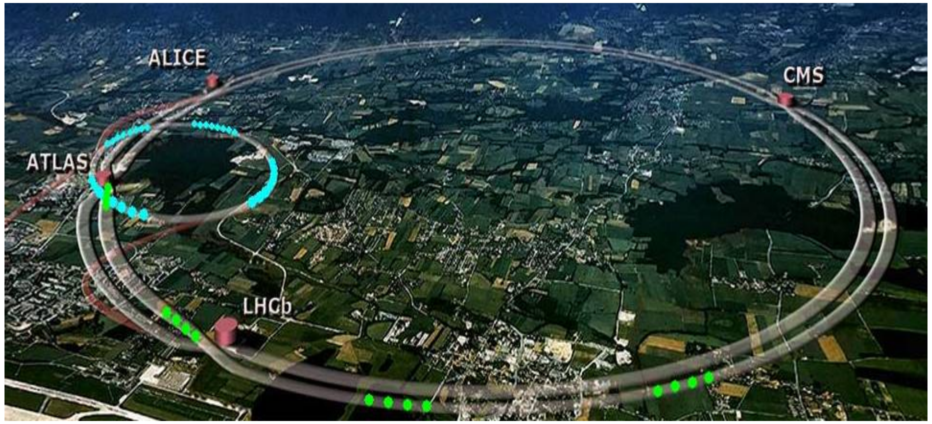
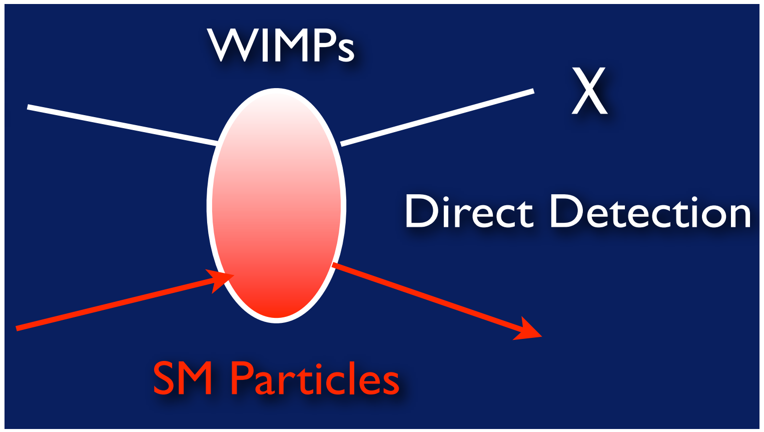
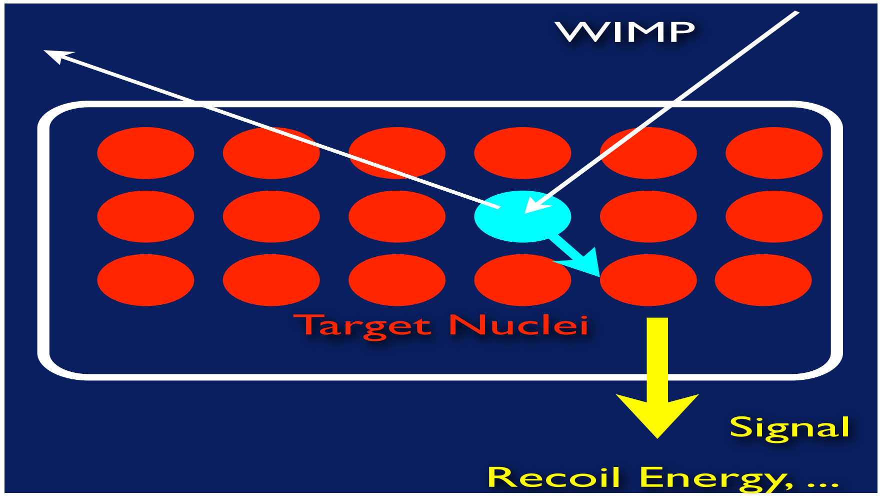
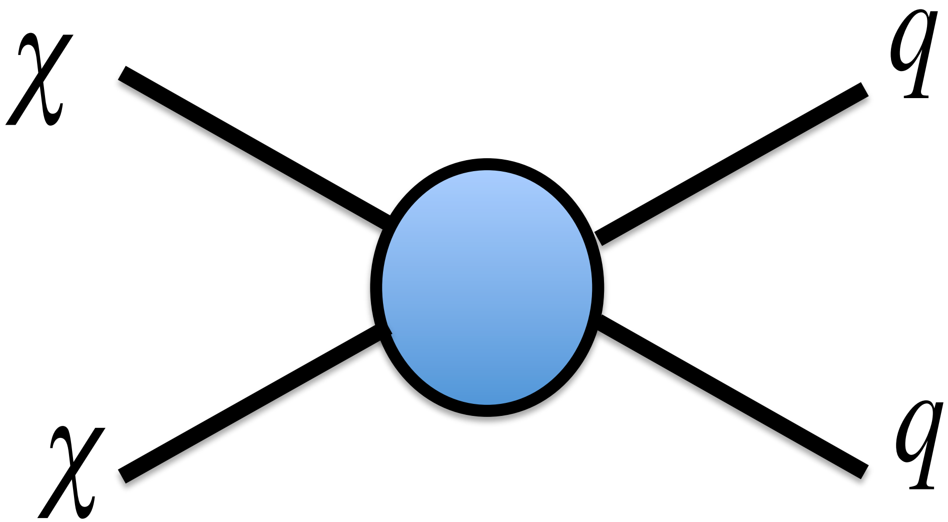

X
WIMPs
X
SM Particles
Collider Searches


ALICE
CMS
ATLAS
LHCb


WIMPs
X
Direct Detection
SM Particles

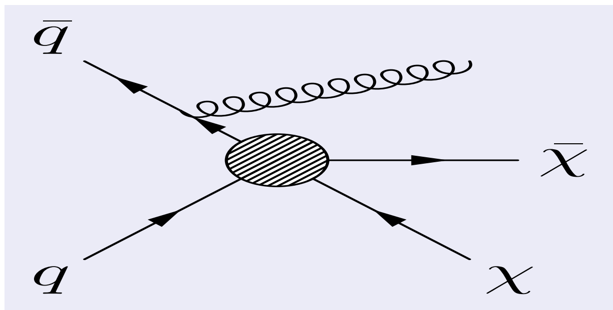

WIMP
Target Nuclei
Signal
Recoil Energy, ...

DM-quark interactions: Effective operators



$$O_s = \sum_q \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

Mono-jet events by the CMS 4.7/fb @7TeV
Pt>110GeV,|η|<2.4
Missing transverse energy >350GeV
(Madgraph/Madevent, pythia)



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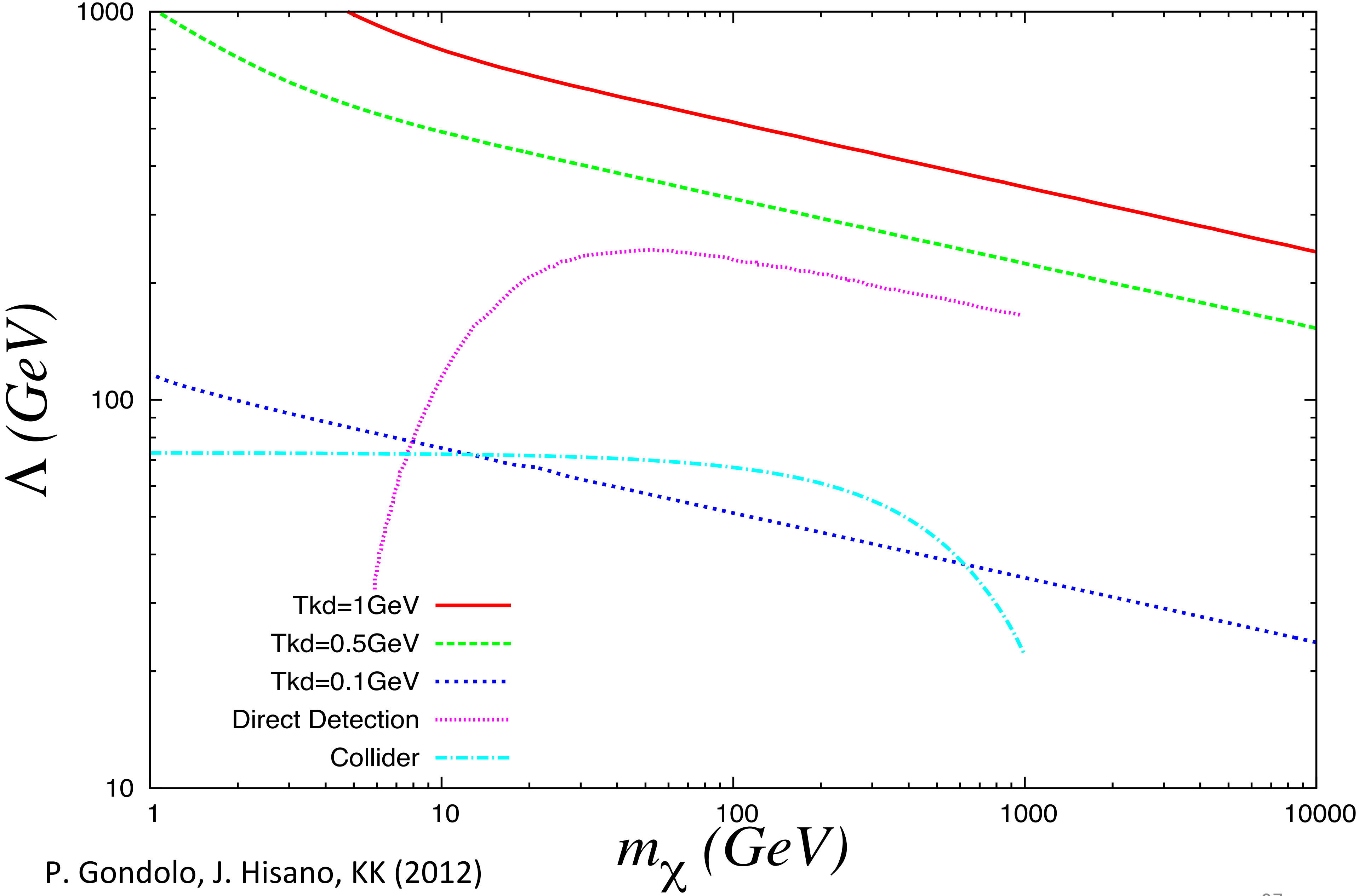

P. Gondolo, J. Hisano, KK (2012)

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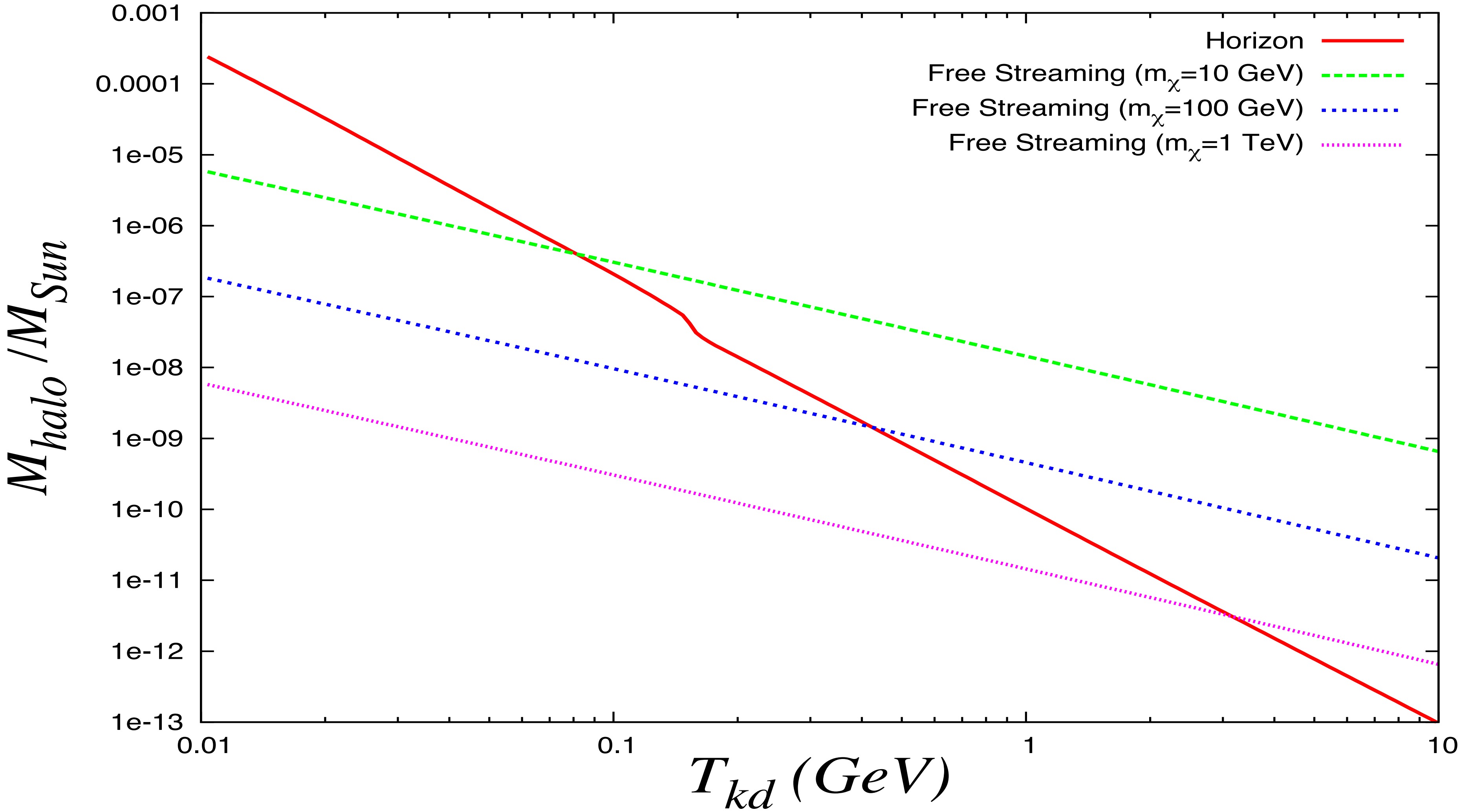

P. Gondolo, J. Hisano, KK (2012)

$$M_{kd} \sim (\tau_{kd})^3 \sim (T_{kd})^{-3}$$

$$M_{fs} \sim \left(\sqrt{T_{kd}/m_\chi}\,\tau_{kd}\right)^3$$

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Dipole DM

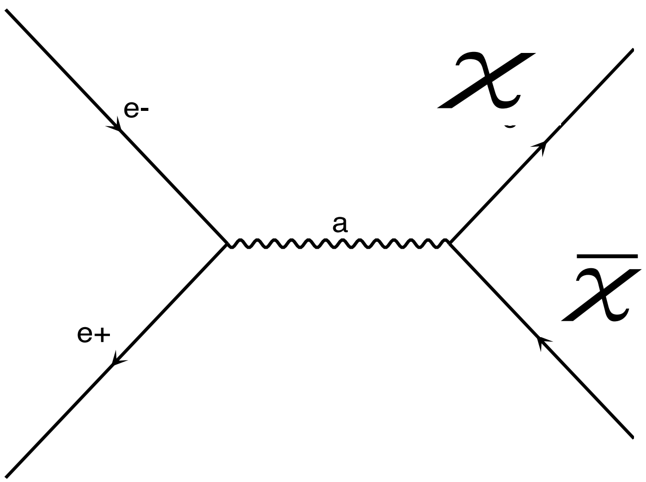
➢ Observables
ILC and SN 1987A

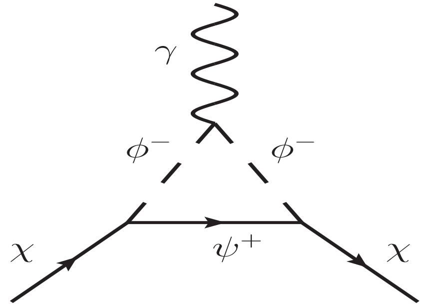
➢ Results:
The particle physics and astrophysics can compliment each other.

Dipole DM

- DM with a dipole moment: Coupling of DM to photon.

$$L_{MDM} \sim -\frac{i}{2}\mu\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \qquad \mu \equiv \frac{1}{\Lambda}$$





$$\mu \sim \frac{eg^2}{M}$$

Pospelov and Veldhuis (2000), Sigurson et al(2004), Barger et al (2012), Heo and Kim (2012),Graham (2012) Nobile et al (2014),

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  ILC and SN 1987A

- Results:

  The particle physics and astrophysics can compliment each other.

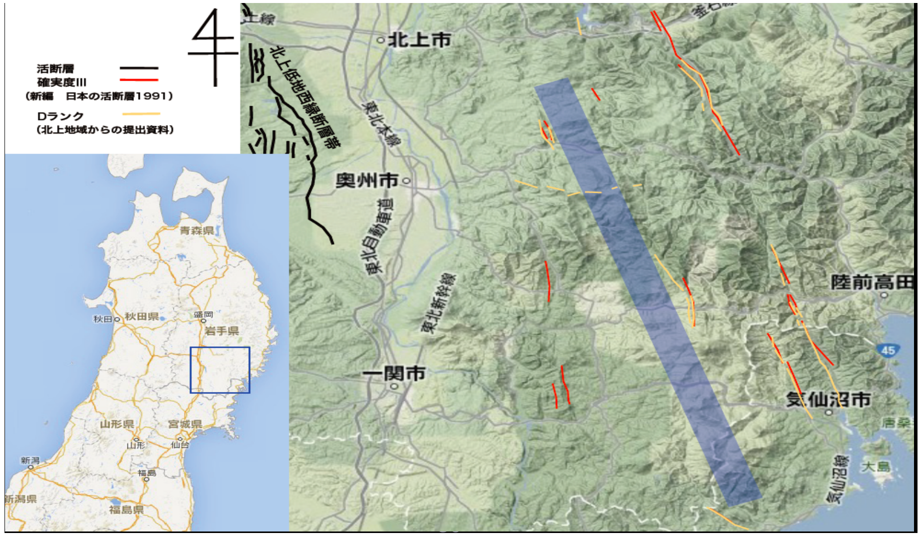
ILC

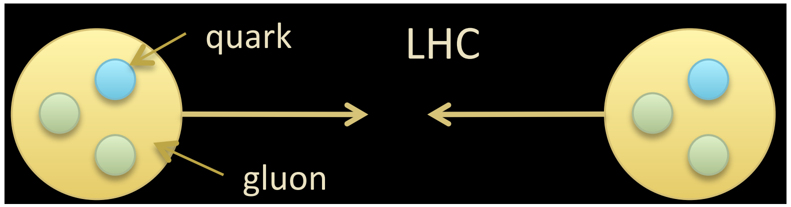
2018 Construction starts

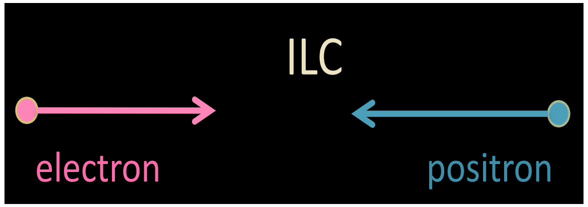
2028 Run starts

- 500GeV CM with 31km (First stage 250 GeV Higgs Factory)

-> upgrade later to 1TeV CM with 50 km

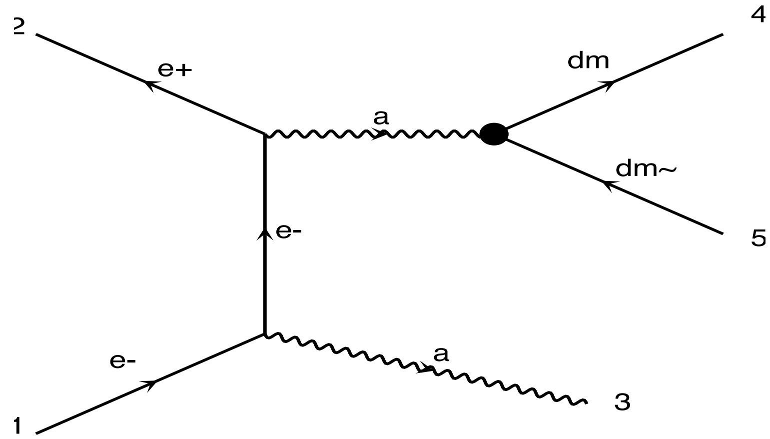




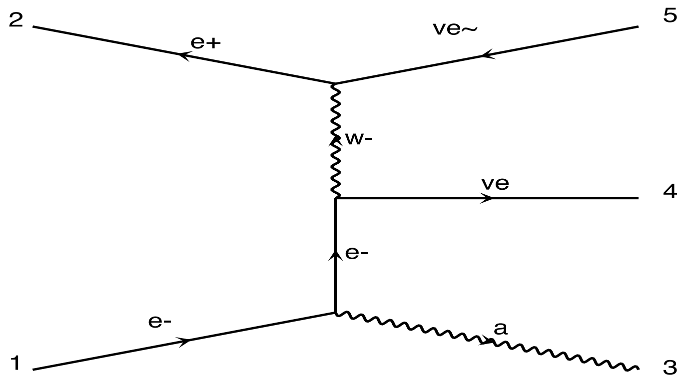


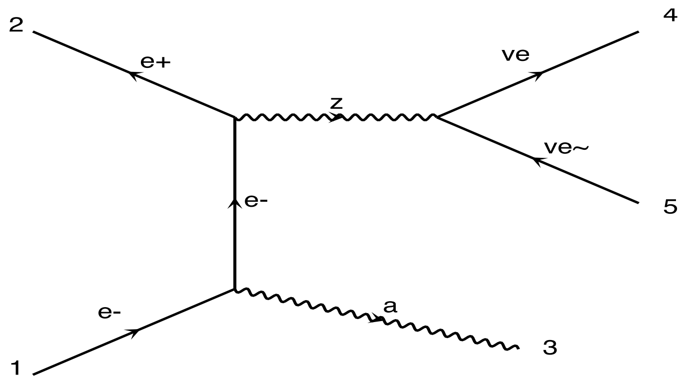
Mono-photon search at ILC

$$e^+e^- \longrightarrow \chi\bar{\chi}\gamma$$



Main SM Background $e^+e^- \longrightarrow \nu\bar{\nu}\gamma$





$$|\cos\theta_\gamma| < 0.995, E_\gamma > 8GeV$$

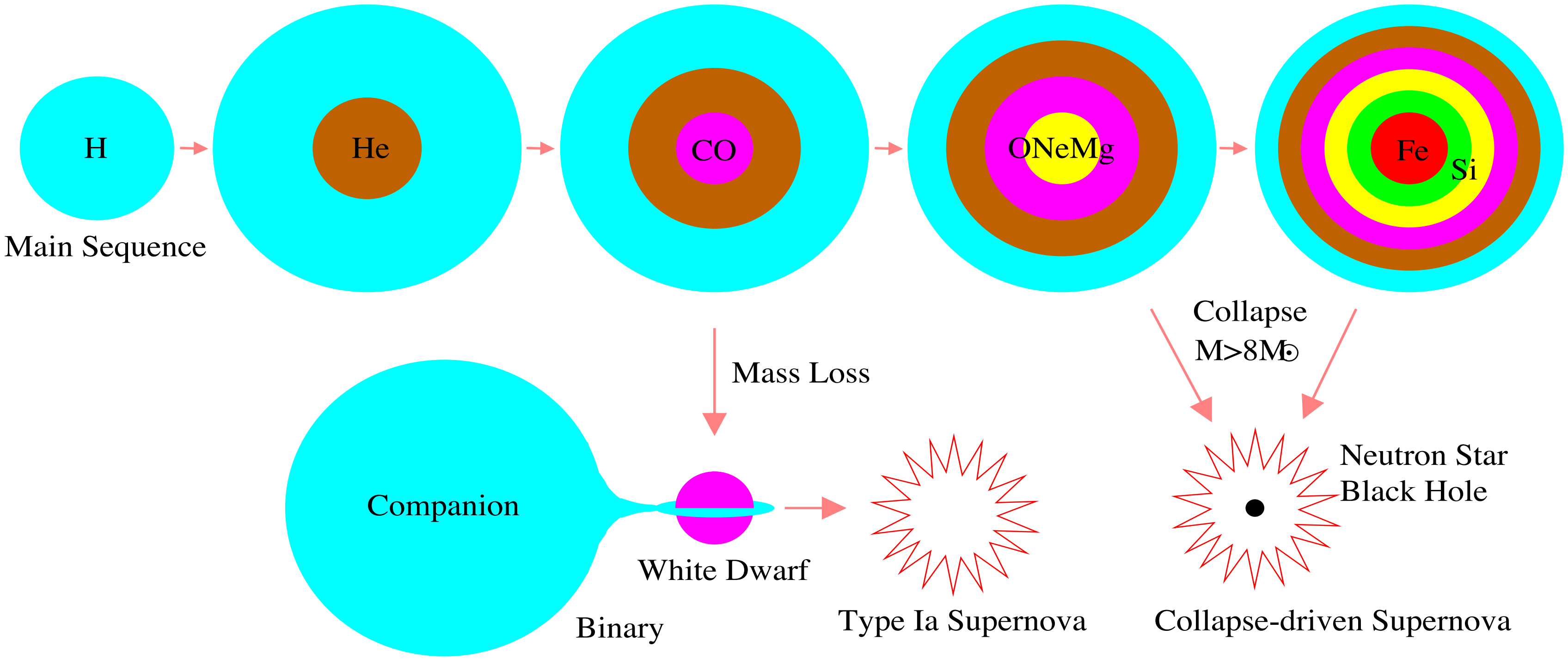
E_γ peaks @$242GeV, 496GeV$ for $\sqrt{s} = 500GeV, 1TeV$

$P(e^+, e^-) = (-30\%, +80\%)$

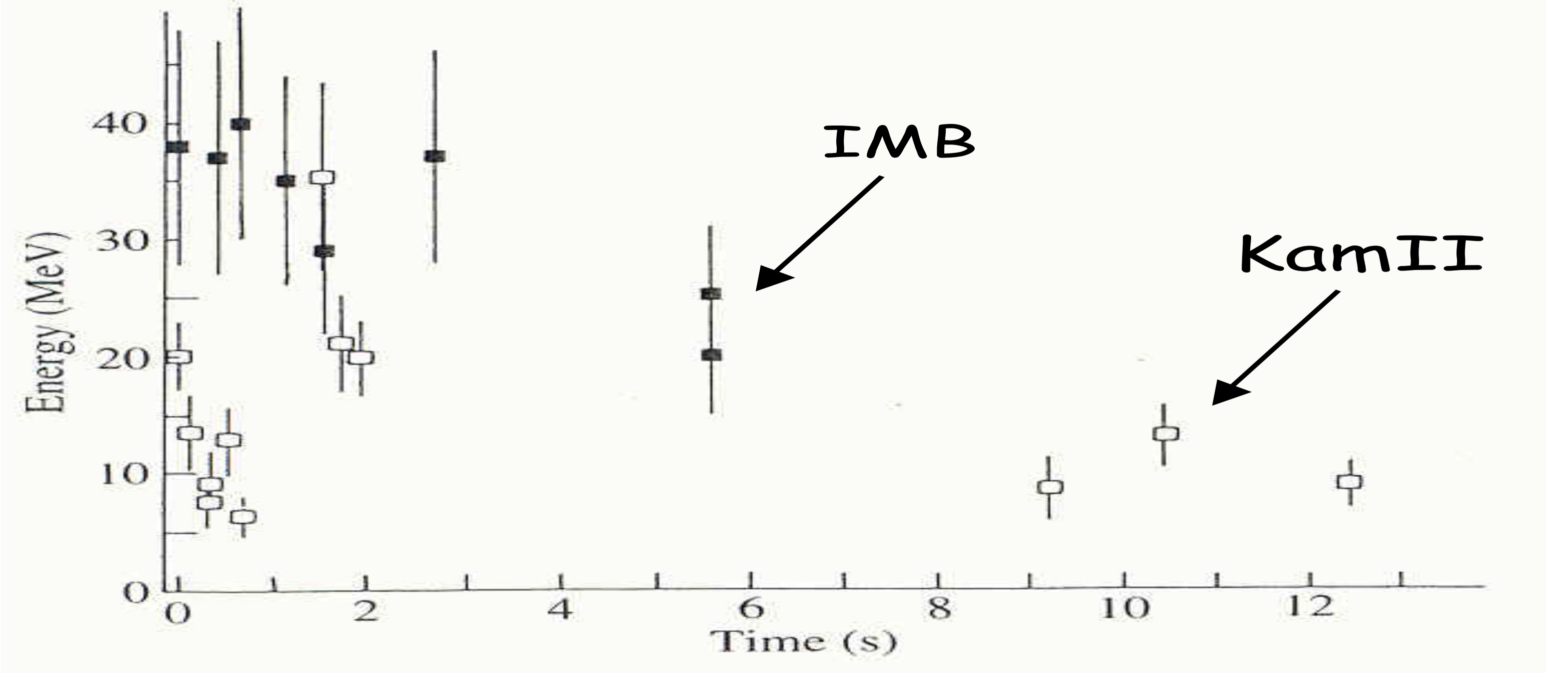
$E_\gamma < 220GeV, E_\gamma < 450GeV$

$$N_{sig} + N_{bag} - 1.64\sqrt{N_{sig} + N_{bag}} > N_{bag} + 1.64\sqrt{N_{bag}}$$ (Madgraph/Madevent)

Supernova



SN 1987A



Turner(1988), Ellis et al(1988), Barbieri and Mohapatra (1989), Lau(1993), Dreiner et al (2003),Keung et al (2013),…

$$e^-(p_1)e^+(p_2) \longrightarrow \chi(p_3)\bar{\chi}(p_4)$$

Raffelt criteria: $\text{Energy loss rate} < 10^{19}\ \text{erg/g/s}$

DM trapping: $\lambda \sim 1/n\sigma \sim 10km$

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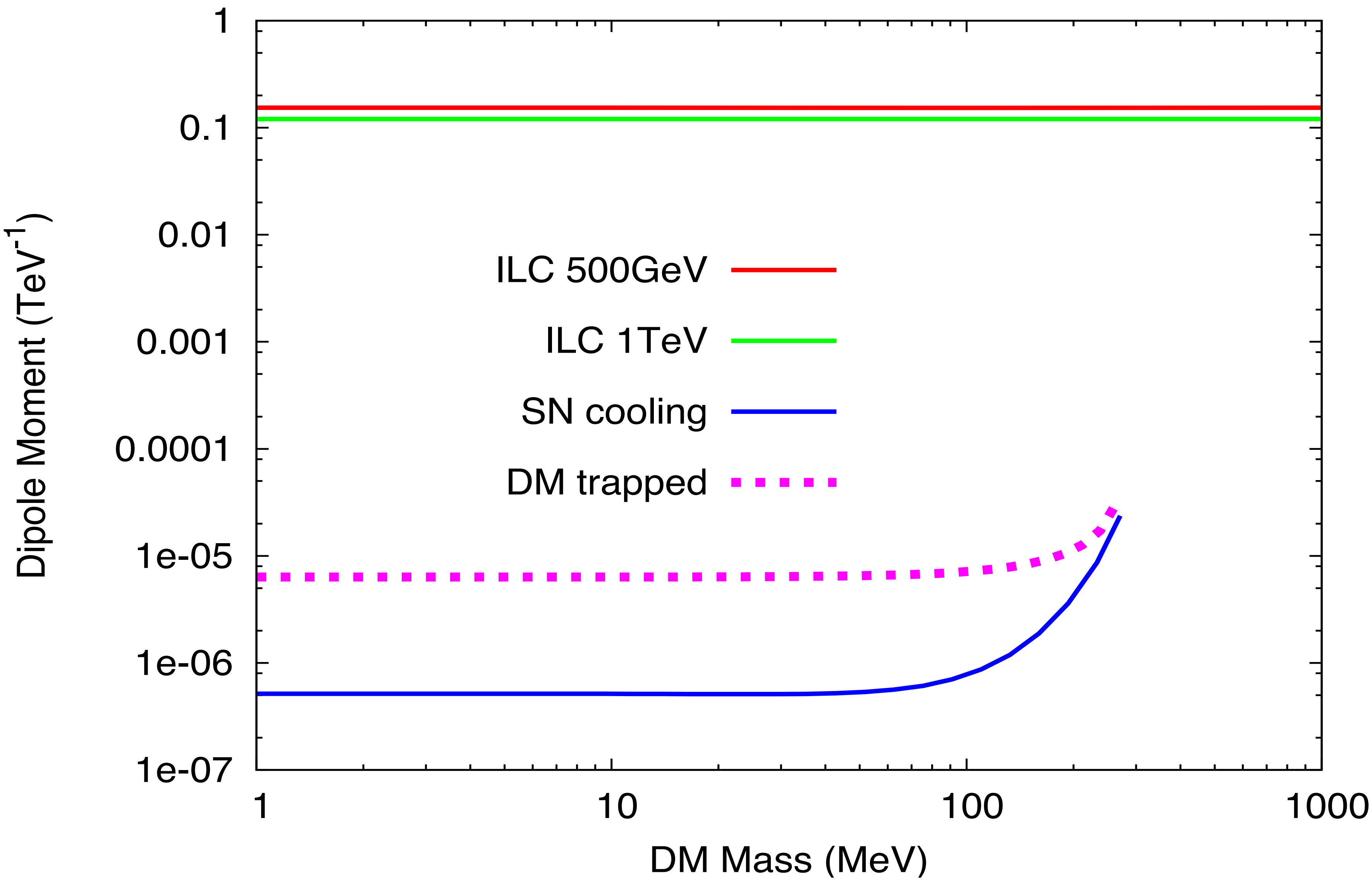

KK and J. Silk (2014)

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Particle cosmologically probing light species

Kenji Kadota (Nagoya Univ)

- **‘Probing Neutrinos from Planck and Forthcoming Galaxy Redshift Surveys’**
  [arXiv:1310.0673] with Yoshitaka Takeuchi (Nagoya)

- ‘***Cosmologically probing ultra-light particle dark matter using 21 cm signals***’
  [arXiv:1312.1898] with
  Yi Mao (IAP), Kiyomoto Ichiki (Nagoya), Joe Silk (IAP, Johns Hopkins,Oxford)

‘free streaming’

- **‘Constraining the smallest DM halo from LHC and DM direct detection experiments’**
  [arXiv: 1205.1914] with Paolo Gondolo (Utah) and Junji Hisano (Nagoya)

- ***‘Constraints on Light (MeV) Dipole Dark Matter from ILC and Supernova***’
  [arXiv:1402.7295] with Joe Silk (IAP, Johns Hopkins,Oxford)

➢ Future:

Data driven research: So much data expected in particle cosmology.

e.g. CMB, galaxy clusters, dark matter, collider

Combining these data together (particle physics and cosmology) to probe the properties of our Universe.