Supermassive Stars and Black Hole Seeds

- a narrow mass range with triple trouble

-dark sector production of SMBH seeds

Focus Week on Primordial Black Holes

Kavli IPMU, Kashiwa, Japan, December 3, 2019

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First, let’s consider possible dark sector physics, including that involving *neutrinos* . . .

There has long been speculation about low energy scale vacuum phase transitions as a way to generate neutrino masses – which are small!

Neutrino anomalies . . . *are there any*?

If so, or if there are outstanding cosmological issues
Involving the neutrino sector, then new physics is at play.

Some of these ideas involve cosmic vacuum phase transitions.

EXAMPLE:

miniBooNE: near maximal vacuum active-sterile neutrino mixing at mass-squared difference $\delta m^2 \sim 1\ \mathrm{eV}^2$??

The Sterile Neutrino from **HELL**

The possible ways out of this dilemma are intriguing!

A net lepton number $L_{\nu_\alpha} \geq 10^{-4}$ residing in any of the active neutrino species (Abazajian, Bell, Fuller, Wong 2006; Chu & Cirelli 2006)

— interestingly in the range of what we would need to drive resonant sterile neutrino dark matter production for a sterile neutrino with rest mass $m_s \sim 10\,\mathrm{keV}$.

But possible troubles with BBN, N_{eff}, $\sum m_\nu$ for $m_s > 0.6\,\mathrm{eV}^2$ – see N. Saviano et al. 2017 – but need full 4X4 analysis

Low inflation re-heat temperature (e.g., Gabriel, Palmerez-Reiz, Pascoli 2004)

Non-standard ("secret") sterile neutrino interactions
Hannestad et al. 2013; Mirizzi et al. 2013; others

see especially B. Dasgupta & J. Kopp "Cosmologically safe eV-scale sterile neutrinos and improved dark matter structures" Phys. Rev. Lett. **112**, 031803 (2014).

A whole new sterile neutrino self-interacting sector? Other steriles? Interaction with dark matter, whatever that is?

see also L. Johns & G. M. Fuller PRD **100**, 023533 (2019)

See J. Cherry, A. Friedland, I. Shoemaker arXiv:1411.1071 – opacity for PeV/ICECUBE neutrinos, engineers dark matter self-interaction;

Low energy-scale cosmic vacuum phase transitions can:

(1) Create non-gaussian density fluctuations post recombination

(2) Convert early-dark-energy (EDE) into radiation

Here we consider a late phase transition, perhaps associated with a symmetry breaking event associated with neutrino mass or other neutrino properties

E. W. Kolb & Y. Wang PRD **45**, 4421 (1992)
J. A. Frieman, C. T. Hill, R. Watkins, PRD **46**, 1226 (1992)
C. T. Hill, D. N. Schramm, J. N. Fry Comments Nucl. Part. Sci. **19**, 25 (1990)
G. M. Fuller, D. N. Schramm, PRD **45**, 2595 (1992)

Nucleation of phase, bubble dynamics:
S. Coleman PRD **15**, 2929 (1977)
C. J. Hogan, Phys. Lett. **133B**, 172 (1983)

Binding, *The Wasserman Mechanism*:
I. Wasserman Phys. Rev. Lett. **57**, 2234 (1986)
A. Patwardhan & GMF PRD **90**, 063009 (2014)

Nucleation scale for first order vacuum phase transitions. Typical bubble size at bubble percolation: $\delta\, H^{-1}$, where δ is a fraction of the Hubble length H^{-1}

$$\delta \approx \left[4B_1\, \ln\frac{m_{\rm pl}}{T_{\rm c}}\right]^{-1}$$

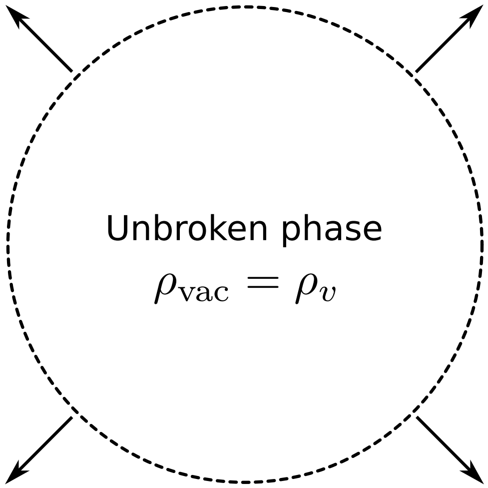
where $T_{\rm c}$ is the critical temperature and B_1 is the logarithmic derivative of the nucleating action in units of the cosmological time t. We use $B_1 = 1$ here.

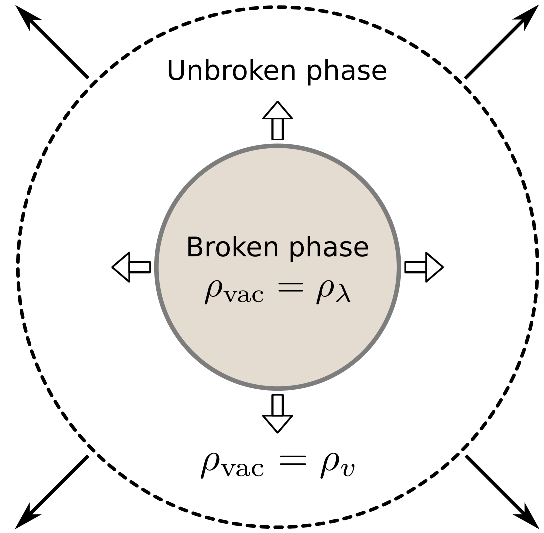
We consider a range $T_{\rm c} \sim 0.01 - 0.1\,{\rm eV}$.

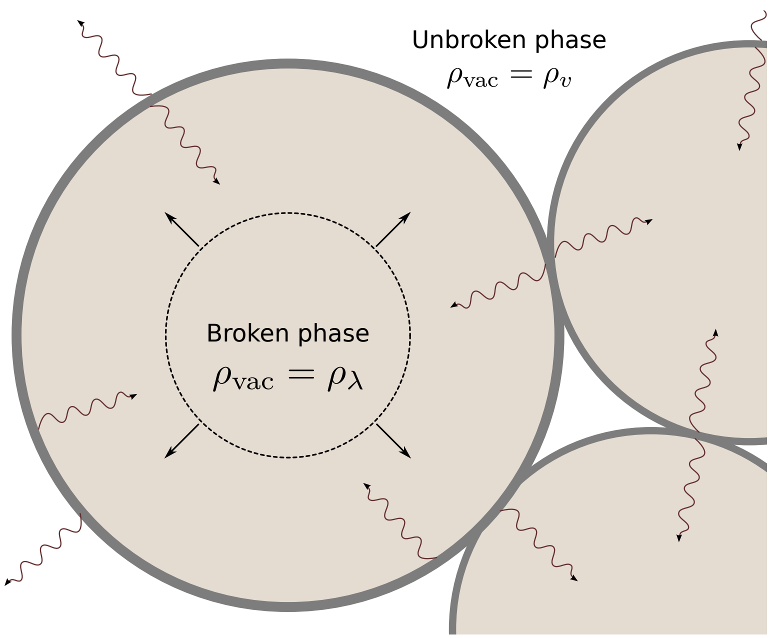
This implies $\delta \sim 1/300B_1 \sim 10^{-3}$, or about $\sim 10^8$ or 10^9 bubbles per horizon, with a spatial extent of each bubble $R_f \equiv \delta H_{\rm c}^{-1} \sim \left[4B_1\, \ln\frac{m_{\rm pl}}{T_{\rm c}}\right]^{-1}\left[\frac{8\pi}{3m_{\rm pl}^2}\,\rho_{\rm c}\right]^{-1/2}$

This implies a total mass enclosed within the bubble $M_f \approx (4/3)\pi R_f^3\, \rho_{\rm NR,onset}$, so the upper limit to the total mass in these bubbles is $M_f \sim 5\times 10^8\,{\rm M}_\odot$ to $\sim 3\times 10^{11}\,{\rm M}_\odot$

In practice, only a fraction of this mass may become gravitationally bound.





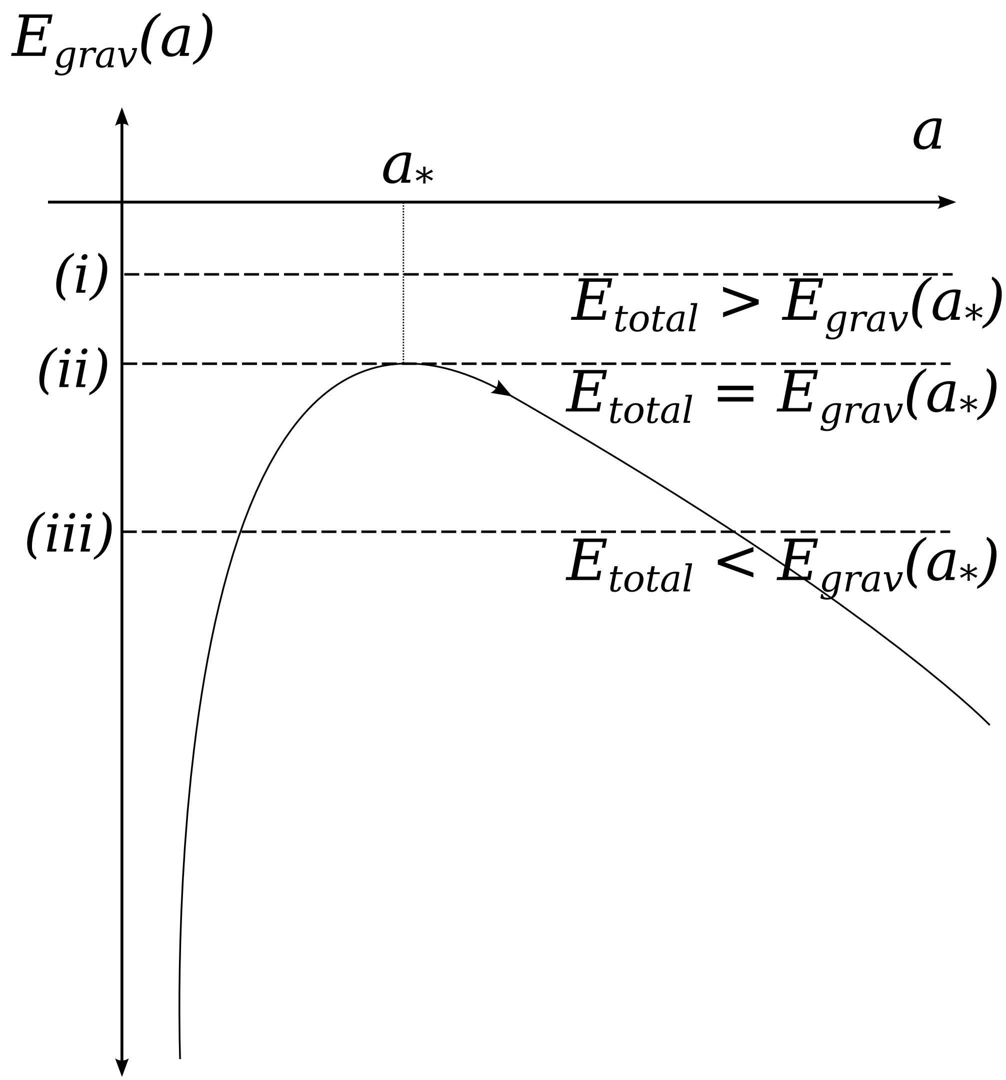


bubbles of the broken phase nucleate, detonate into the unbroken phase, sweeping up the vacuum energy onto the bubble walls. When the walls collide this swept up energy is radiated as relativistic “radiation”, effecting binding of the bubble region

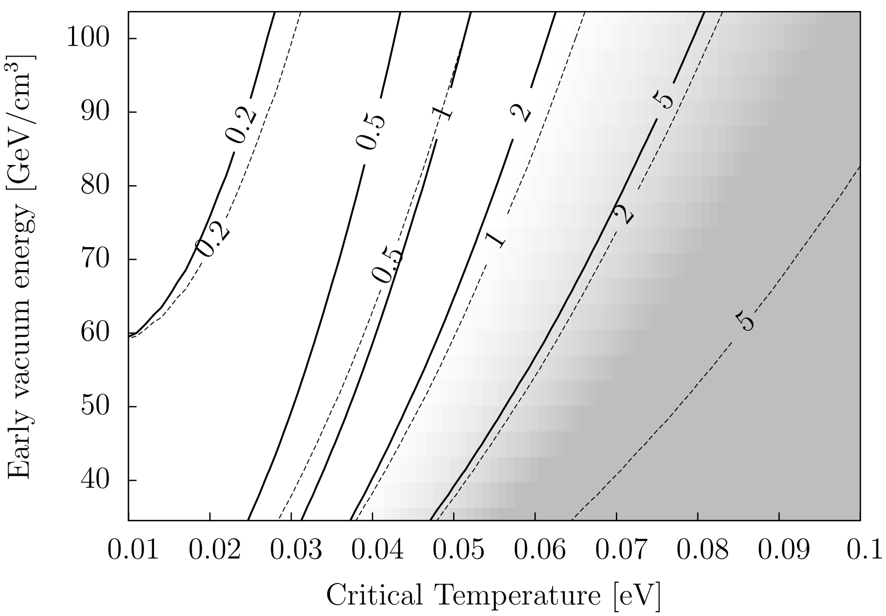
A. Patwardhan & GMF PRD **90**, 063009 (2014)

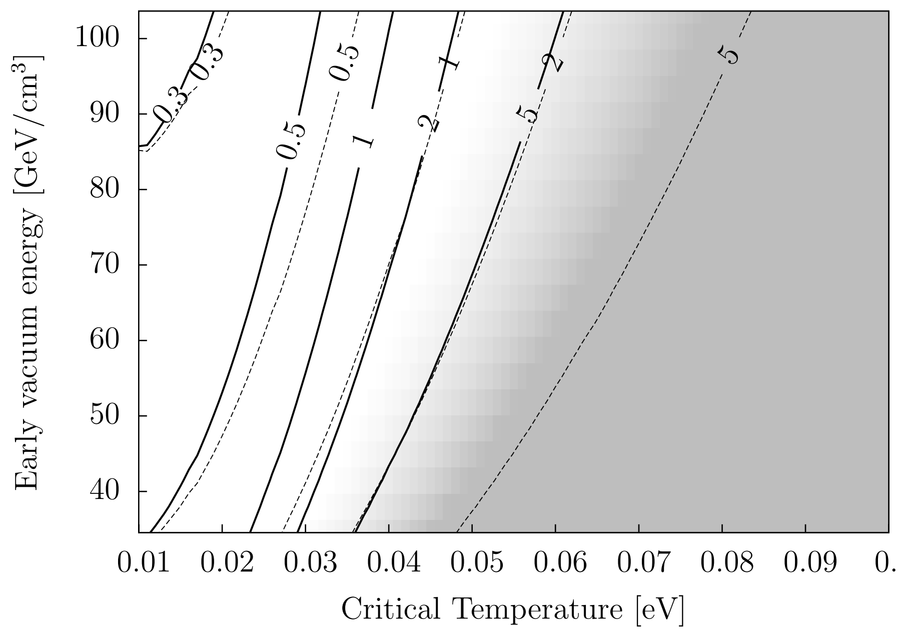
Energetics of fluctuation binding

kinetic energy must go to zero
to attain binding , and this happens
only if the total energy intersects
the potential energy E_{grav} curve
(solid line)



A. Patwardhan & GMF PRD **90**, 063009 (2014)

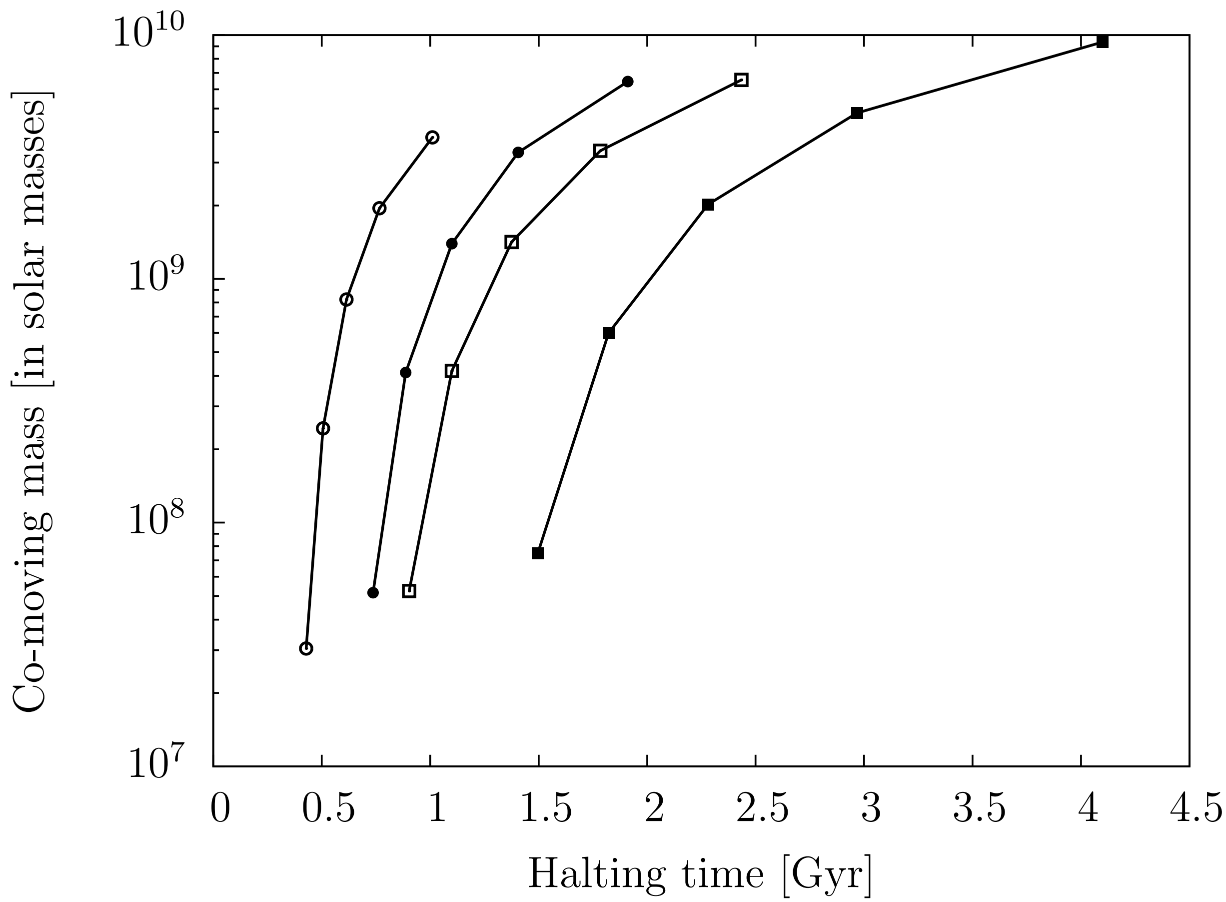




Contours of fluctuation “Halting Times” (labeled in GYR) for ranges of EDE and T_c

Left and right plots correspond to comoving shells with 0.1 and 0.5 times the nucleation scale, respectively.

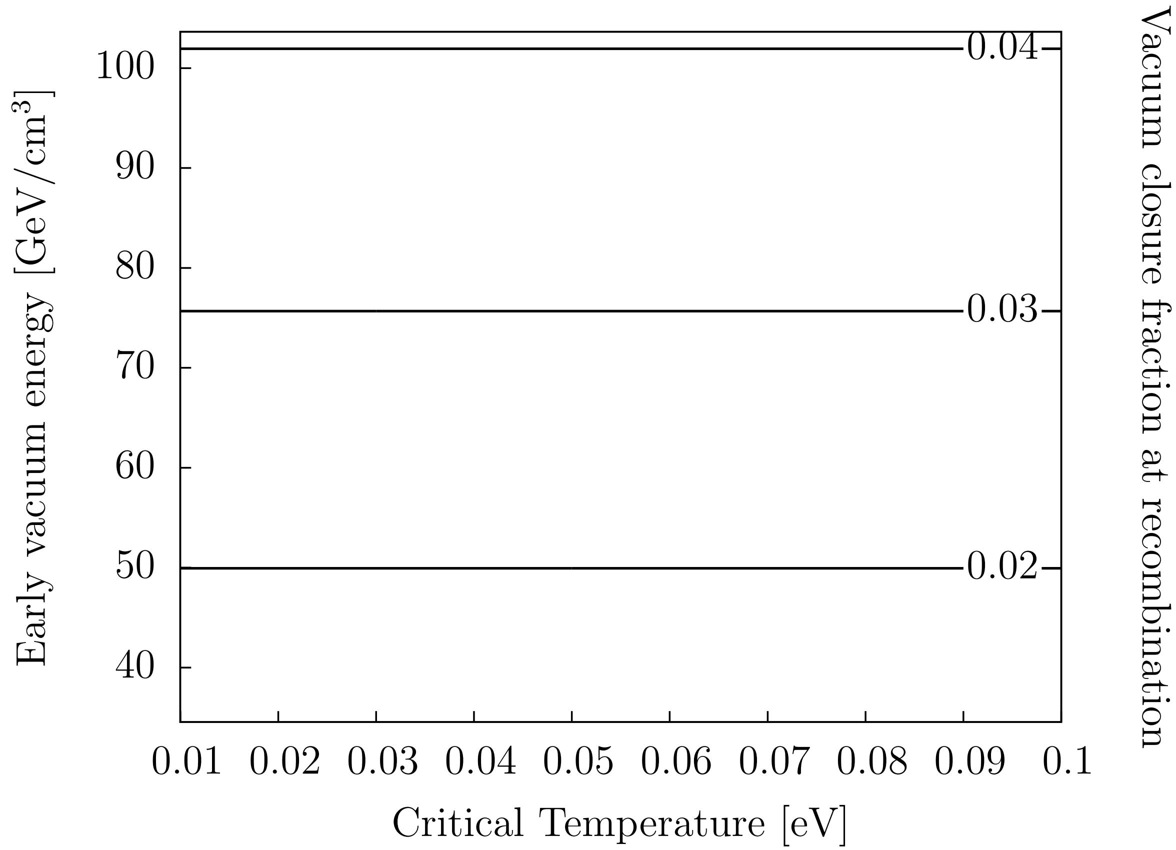
A. Patwardhan & GMF PRD **90**, 063009 (2014)



Halting times for different mass scales, with various parameters

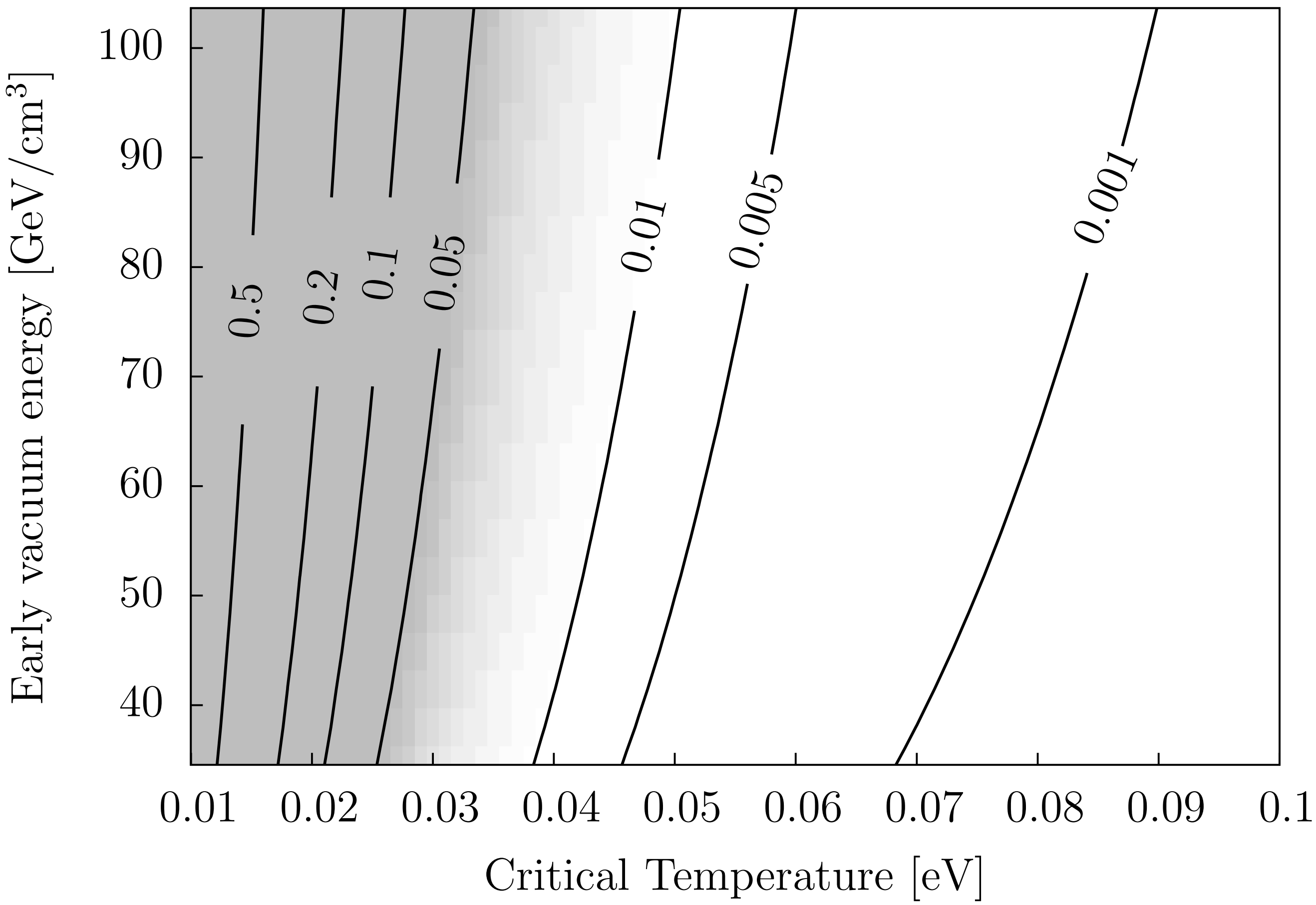
- Lower critical temperatures and higher vacuum energy densities favor imply stronger binding

A. Patwardhan & GMF PRD **90**, 063009 (2014)



Contours of early vacuum energy closure fraction at photon decoupling

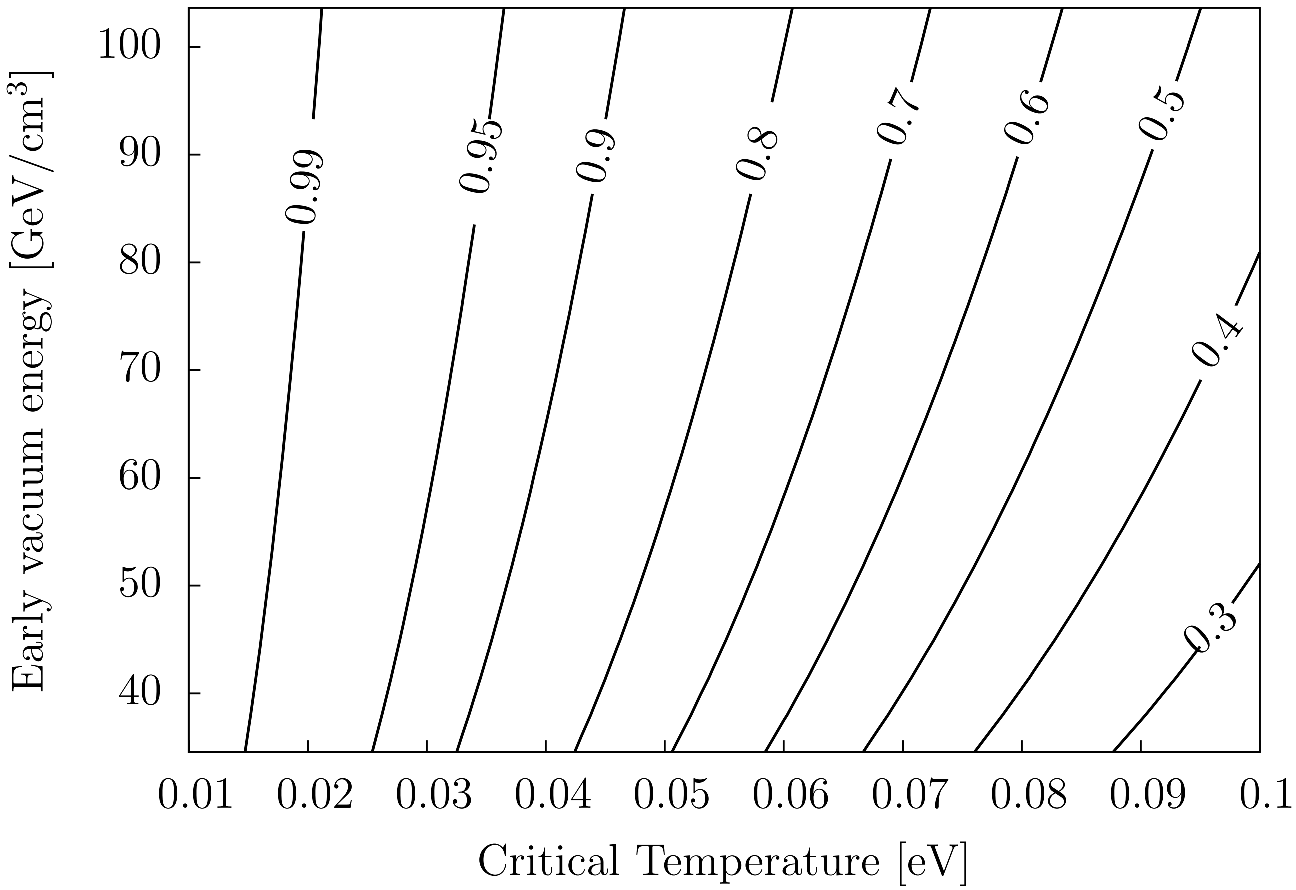
A. Patwardhan & GMF PRD **90**, 063009 (2014)



Contours of closure fraction at the current epoch of the “leftover” radiation from bubble collisions

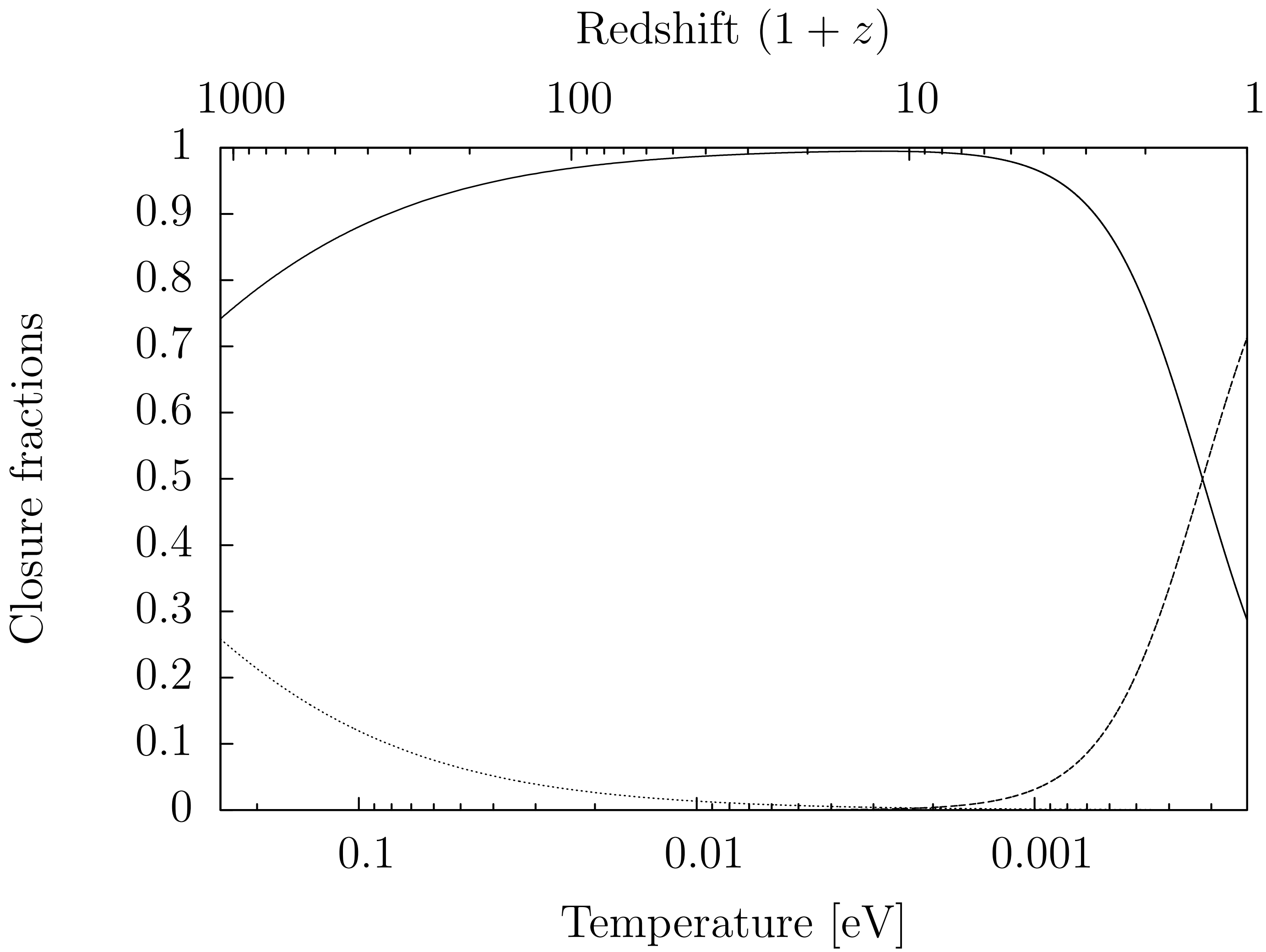
Shaded region disfavored by current observational data

A. Patwardhan & GMF PRD **90**, 063009 (2014)



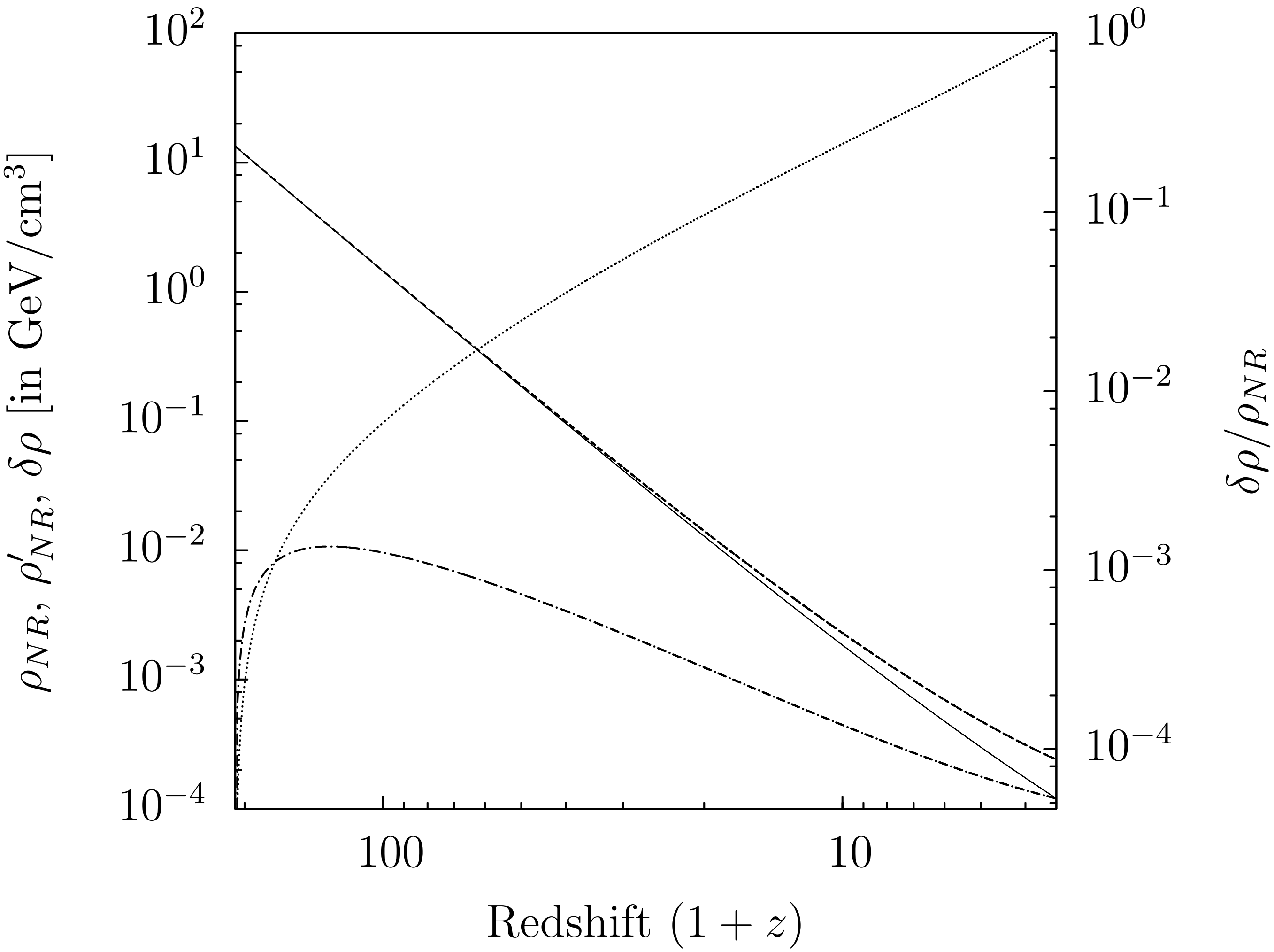
Contours of early vacuum energy closure fraction at the onset of the phase transition, i.e., at $T=T_c$

A. Patwardhan & GMF PRD **90**, 063009 (2014)



Evolution of the closure fraction contributions in standard LCDM cosmology:
Solid, dashed, dotted lines are for nonrelativistic, relativistic, and vacuum energy densities, respectively.
(Neutrinos taken as massless here.)

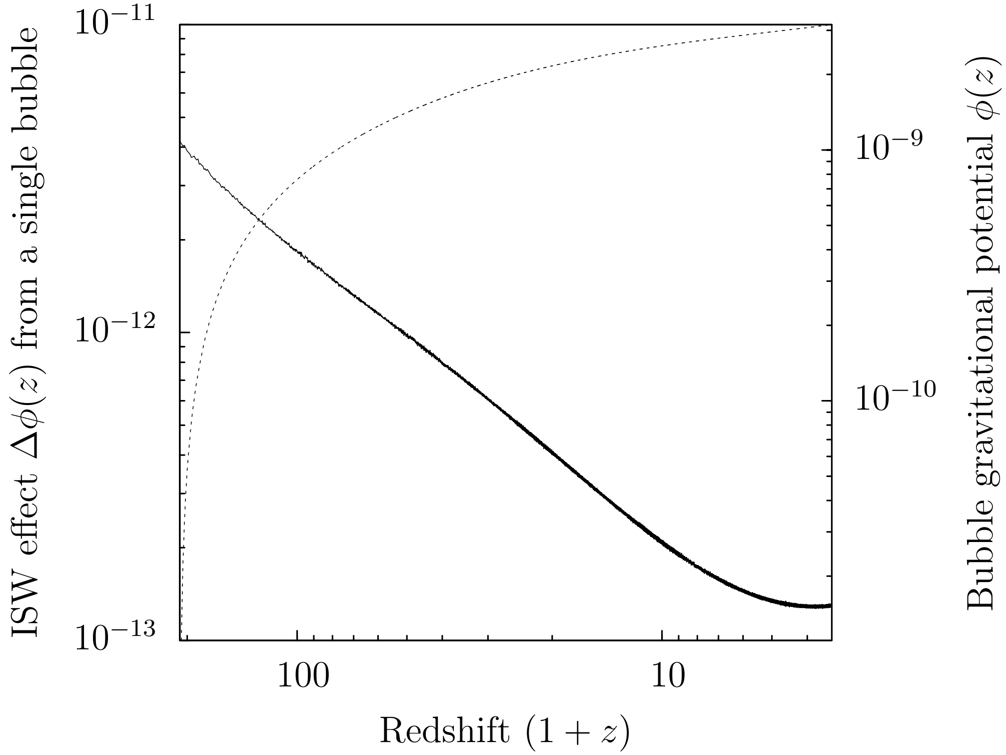
A. Patwardhan & GMF PRD **90**, 063009 (2014)



Evolution of energy densities (as labeled) as a function of redshift (1+z)

Calculated with T_c=0.05 eV and ρ_{vac} = 76 GeV cm^{-3}

A. Patwardhan & GMF PRD **90**, 063009 (2014)

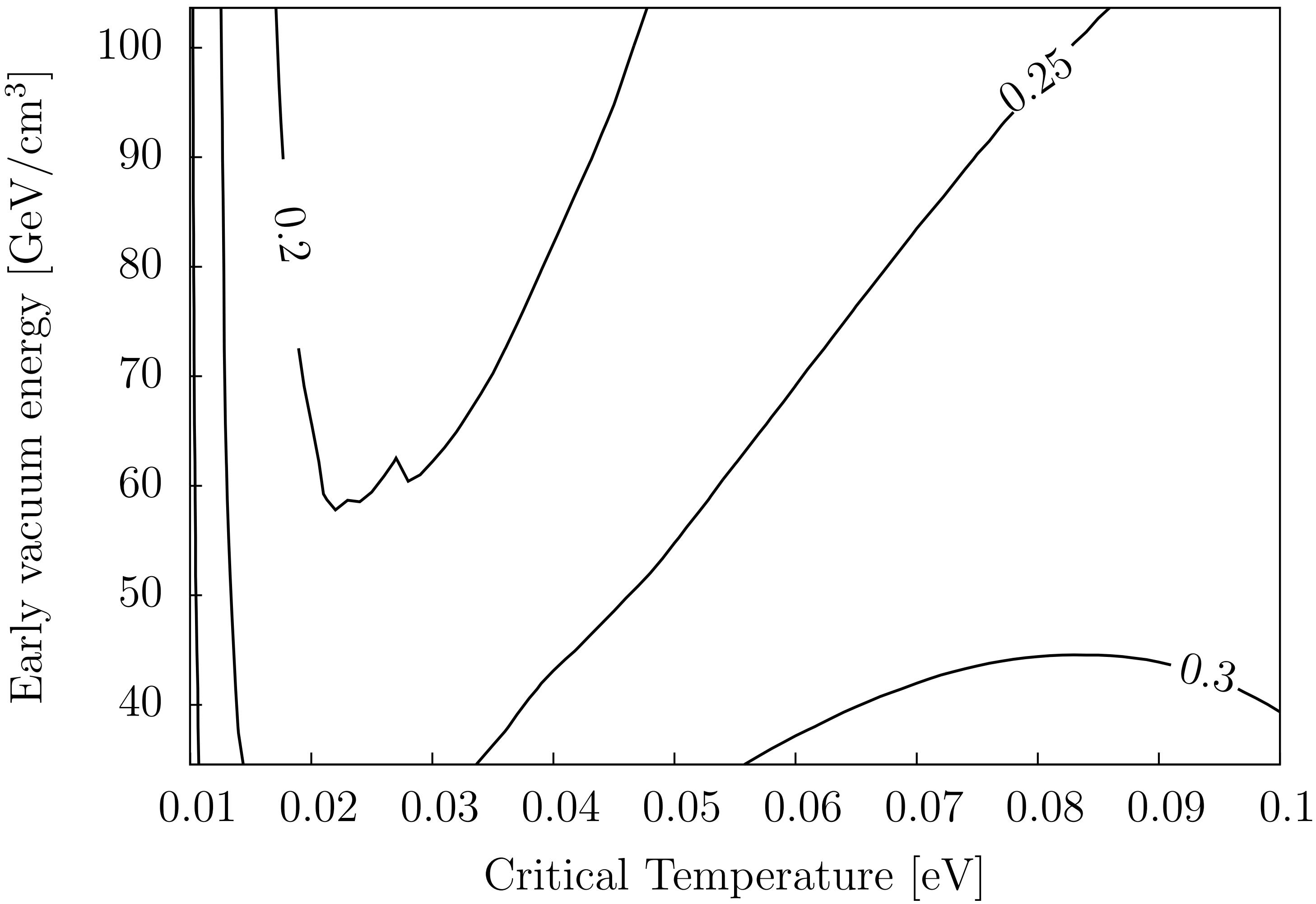


Gravitational potential $\phi(z)$ (dotted line) of individual fluctuations generated in our model at different redshifts along theline of sight , along with integrated Sachs-Wolfe effect $\Delta\phi(z)$ (solid curve) that a photon passing through these fluctuations would experience.
Here we take T_c=0.05 eV and ρ_{vac} = 76 GeV cm^{-3}

Knowing the fluctuation size R_f we can estimate the number of fluctuations along the photon trajectory as $N \sim d_{\mathrm{A}}(z)/R_f$. This is $N \sim 10^4$ for $z_{\mathrm{c}} \sim 100$. Then the net ISW effect experienced by a photon can be bounded using

$$\frac{\Delta T}{T} = \sum_{i=1}^{N} \frac{\Delta T}{T}(z_i) < N \times \max\left\{\Delta\phi(z)\right\}$$

A. Patwardhan & GMF PRD **90**, 063009 (2014)



contours of angular scale in today's sky (in arcminutes) corresponding to nucleation scale

A. Patwardhan & GMF PRD **90**, 063009 (2014)

Reconciling different Hubble parameters at CMB decoupling and later
with a little extra radiation energy density

- sterile neutrino decay, see G. Gelmini, A. Kusenko, V. Takhistov, arXiv:1906.10136

- EDE from massive neutrinos becoming nonrelativistic
  J. Sakstein & M. Trodden arXiv:1911.1176

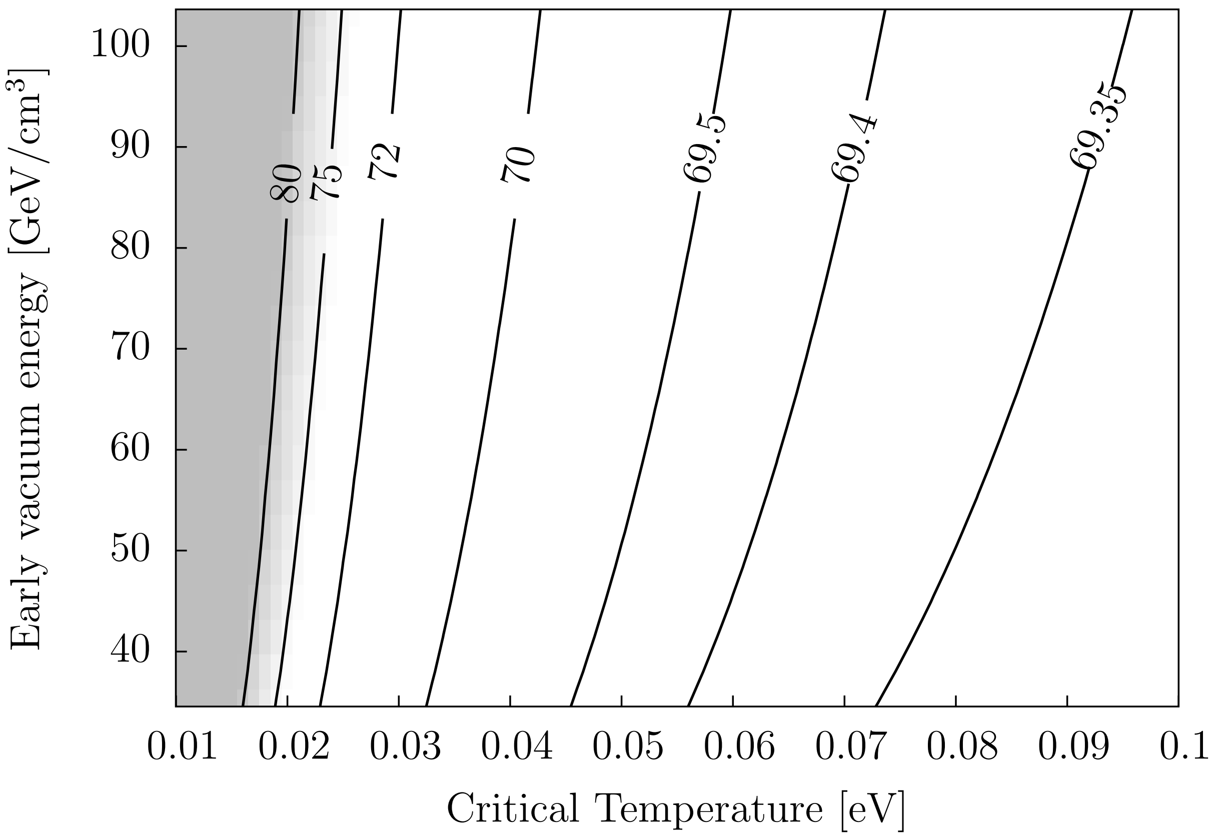
- Strong neutrino self-interactions C. D. Kreisch, Cyr-Racine, O. Dor arXiv:1902.08261

Etc.

Here we consider late phase transition conversion
of EDE (early vacuum energy) to radiation as a solution

A. Patwardhan & G. M. Fuller, *Physical Review* D **90**, 063009 (2014).

Contours of Hubble parameter, H_0, in km s^{-1} Mpc^{-1}, for Early-Dark-Energy and Vacuum Phase Transition critical temperature



shaded region is excluded by observations

H_0 discrepancy?

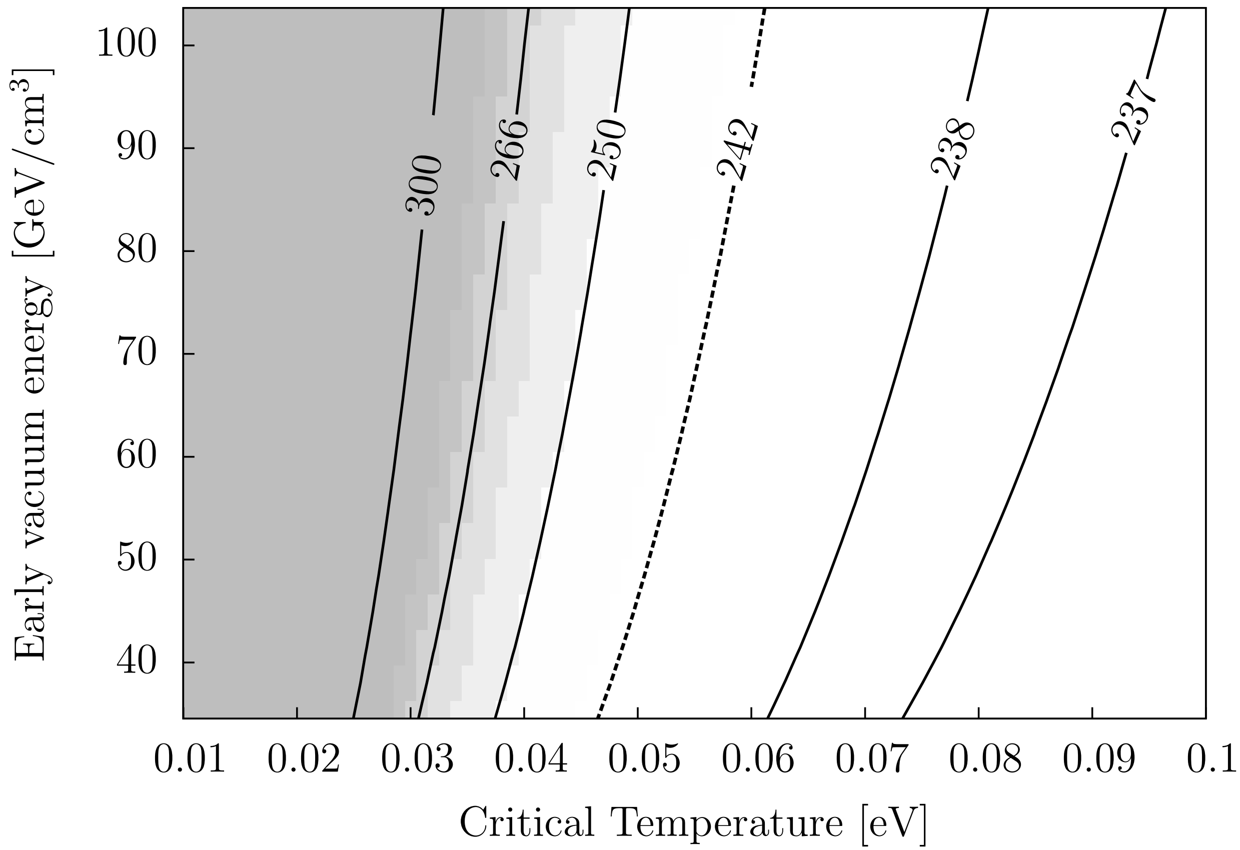
Cepheids, SNIa, etc.,
see A. G. Riess et al., Astrophys. J. **876**, 85 (2019)
$\Rightarrow \; H_0 = 74.03 \pm 1.42 \, \mathrm{km\,s^{-1}\,Mpc^{-1}}$

CMB determination/fit for ΛCDM
see N. Aghanim et al. (Planck) arXiv:1807.06209
$\Rightarrow \; H_0 = 67.66 \pm 0.42 \, \mathrm{km\,s^{-1}\,Mpc^{-1}}$

better than a 4σ disagreement

A. Patwardhan & G. M. Fuller, *Physical Review* D **90**, 063009 (2014).

Contours of Hubble parameter, $H_{2.36}$, in km s^{-1} Mpc^{-1} ,
for Early-Dark-Energy and Vacuum Phase Transition critical temperature



Calculated in our late phase transition models for redshift z = 2.36

The Hubble parameter can be measured at higher redshift:

-shaded region is significantly at odds (> 3σ) with result in A. Font-Ribera et al. JCAP **05**, 027 (2014)
(dashed line at 242 km s^{-1} Mpc^{-1} is the 95% confidence limit in that work)

Along the way, these vacuum phase transitions generate
nonlinear regime density fluctuations that may produce primordial metallicity
supermassive stars – these quickly collapse to supermassive black holes.

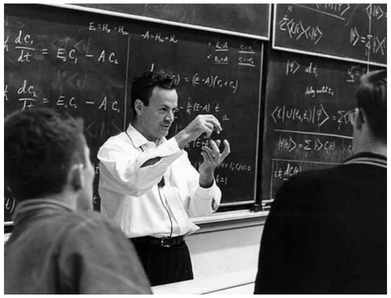
Or do they?

Primordial Supermassive Stars

They collapse to supermassive black holes . . . . Are there signatures?

whenever the pressure support for the star is from particles moving near the speed of light the star is "**trembling on the verge of instability**"

MASS in $M_\odot$	Main Seq. Entropy per baryon s/k_B	Collapse Entropy per baryon s/k_B	Iron core mass in $M_\odot$	Instability Mechanism	Fraction of rest mass radiated as neutrinos	Neutrino Trapping / Thermal equilibrium
10 to ~ 100	**~ 10**	**~ 1**	**~ 1.4**	**Electron capture / Feynman-Chandrasekhar G.R. instab.**	**~ 10%** Iron core mass	**Yes**
~ 100 to ~ 10^4	**~ 100**	**~ 100**	**NONE**	$e^\pm$ **pair instability**	**~ 10%** C/O burning core	**Yes**
~ 10^4 to ~ 10^8	**~ 1000** no main seq.	**~ 1000**	**NONE**	**Feynman-Chandrasekhar G.R. Instability**	**~ 1%**	**No**



These stars go unstable as a result of the Feynman-Chandrasekhar General Relativistic instability and (for zero initial metals) collapse to a black hole.

This collapse is non-homologous on account of prodigious neutrino-pair production/loss.
Fuller, Woosley, Weaver Ap. J., 307, 675 (1986)

The star largely is transparent to neutrinos until a trapped surface forms.

Nuclear Evolution

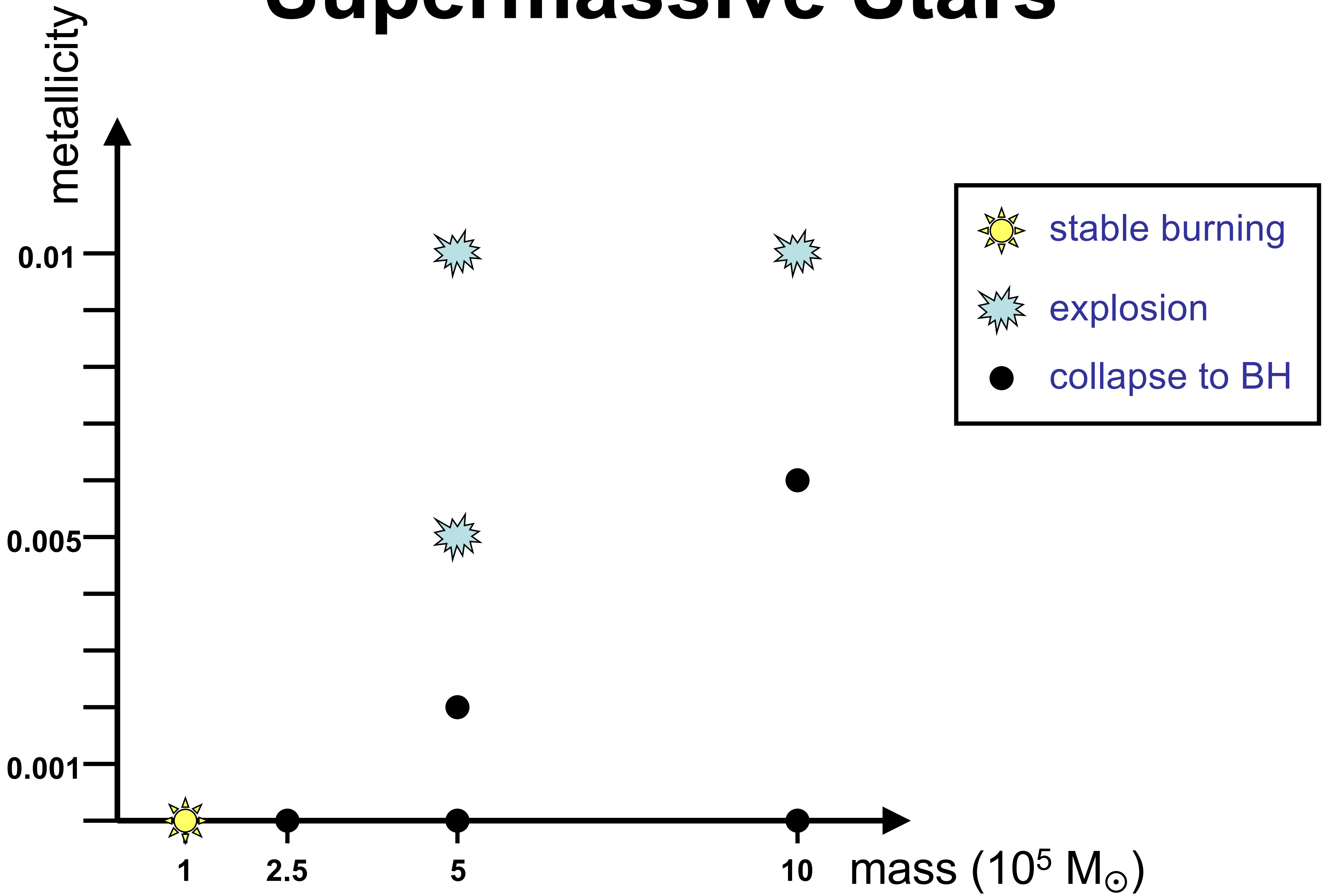
Primordial metallicity SMS initially will burn hydrogen via the pp-chain. The big ones will suffer the GR instability at or near the onset of collapse.

During the collapse there is a race on: Will the collapsing core get to high enough density so that the triple alpha process can generate enough carbon to enable hydrogen burning on the CNO cycle, and break-out into the *rp*-process, before the core builds up a huge in-fall kinetic energy debt and neutrino losses become prodigious?

Fraction of rest mass released in hydrogen burning: **roughly 1%**

Fraction of rest mass released in helium burning and subsequent burning with heavier ions: **more like 0.1%**

Supermassive Stars



(after Fuller, Woosley, & Weaver 1986)

$*$ High entropy means that these objects are radiation/$e^{\pm}$-pair dominated

$*$ Neutrino pairs produced copiously via $e^- + e^+ \rightarrow \nu + \bar{\nu}$

$*$ Neutrino energy emission rate scales as **nine** power of temperature, $\sim T^9$, meaning that most of the neutrino radiation comes out just before black hole formation.

$*$ Stars with homologous core masses $M_{\rm HC} < 5 \times 10^4\,{\rm M}_{\odot}$ will have neutrino mean free paths smaller than the core size and therefor trap neutrinos via scattering – lower neutrino emission over a longer time scale.

$*$ Stars with homologous core masses $M_{\rm HC} > 5 \times 10^5\,{\rm M}_{\odot}$ will not get hot enough to radiate a significant fraction of the star's rest mass before they become black holes.

But . . . k-J. Chen, A. Heger, S. E. Woosley, A. Almgren, D. Whalen, J. Johnson, *Astrophys. J.* **790**:162 (6pp) (2014)

Suggest that primordial metallicity stars with masses 55,000 solar masses will explode via "explosive" helium burning

Seb Tawa & GMF cannot reproduce this, but stars in a narrow range of mass around this value ***are*** in triple trouble! (M4 = M/10,000 solar masses)

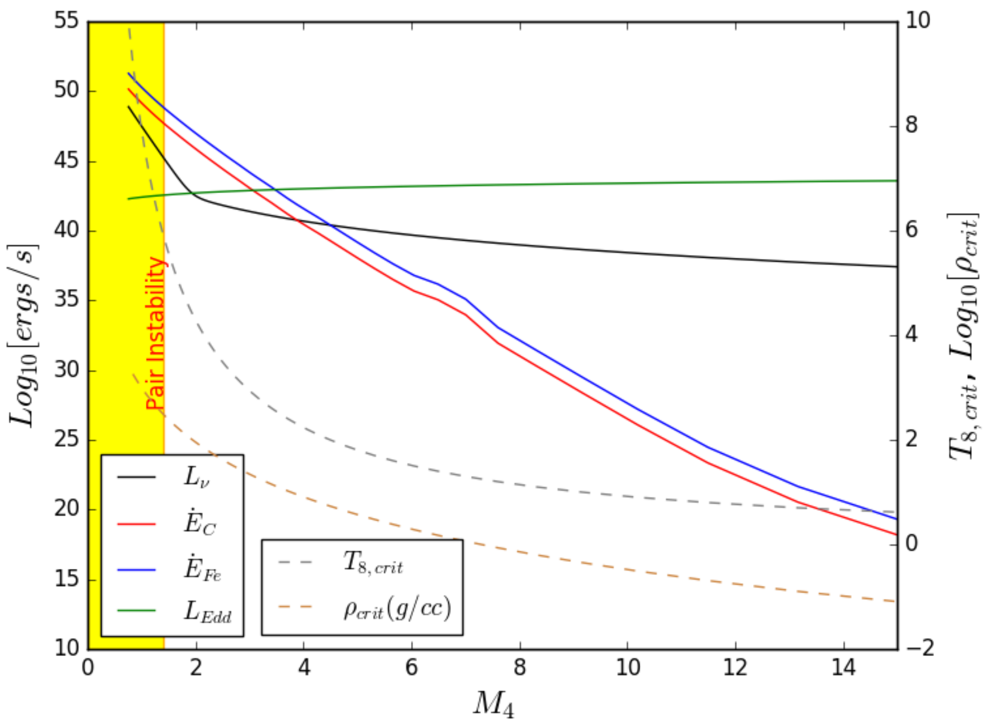
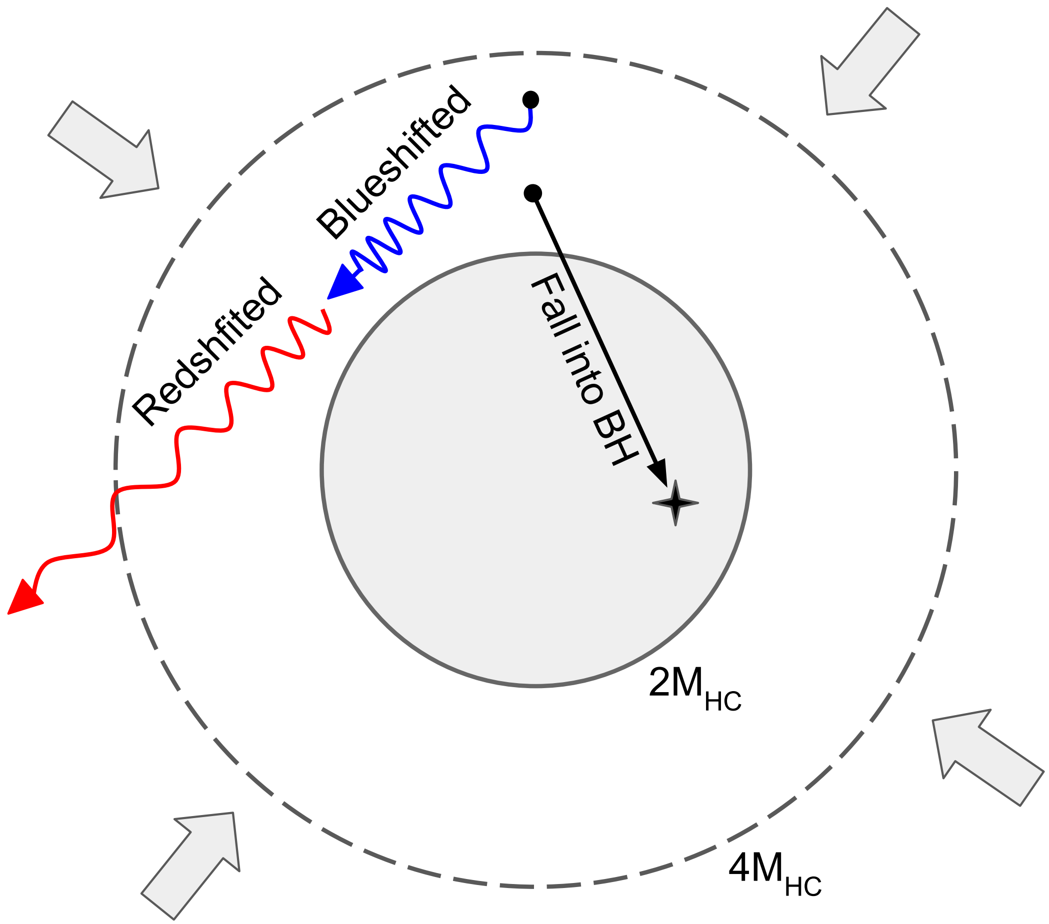


Figure 6.9: Nuclear Energy Generation and Neutrino Luminosity at the GRI. Various energy generation/loss rates at the GRI (left vertical axis) as a function of stellar mass. $\dot{E}_C$ is the energy generation rate of a star only fusing $3\alpha \longrightarrow {}^{12}C$. $\dot{E}_{Fe}$ is the energy generation rate of a star fusing ${}^4He$ straight to ${}^{56}Fe$. The bump around $M_4 = 7$ is a numerical artifact of the interpolation scheme. Both assume $\mu = \frac{4}{3}$ (mass fraction of ${}^4He = 1$). Neutrino luminosities are calculated using the fits in [60]. The energy generation rate required to support the star against gravity is $L_{Edd} + L\nu$ (green + black) . A SMS with mass $\tilde{<} 4M_4$, will produce enough energy through triple-α fusion to support the star against gravity. If the star is to explode, it must reach instability before this point, while still being hot enough to fuse ${}^4He$ ($T_8 \tilde{>} 1 \longrightarrow M_4 \tilde{<} 9$, see fig. 8.11), and while still containing enough ${}^1H$ for the star to be primarily supported by the CNO process. Note that EPPI boundary is a 'soft' boundary, and that the $L\nu$, $pair \approx L_{Edd}$ is a very good proxy for the location of the EPPI. If temperatures exceed $T_8 \approx 5$, the star won't be able to explode, as most of the energy generated will be lost in neutrinos.



another handle on collapse of SMS to Black Holes:
Gravitational wave "memory signal" from accompanying neutrino burst

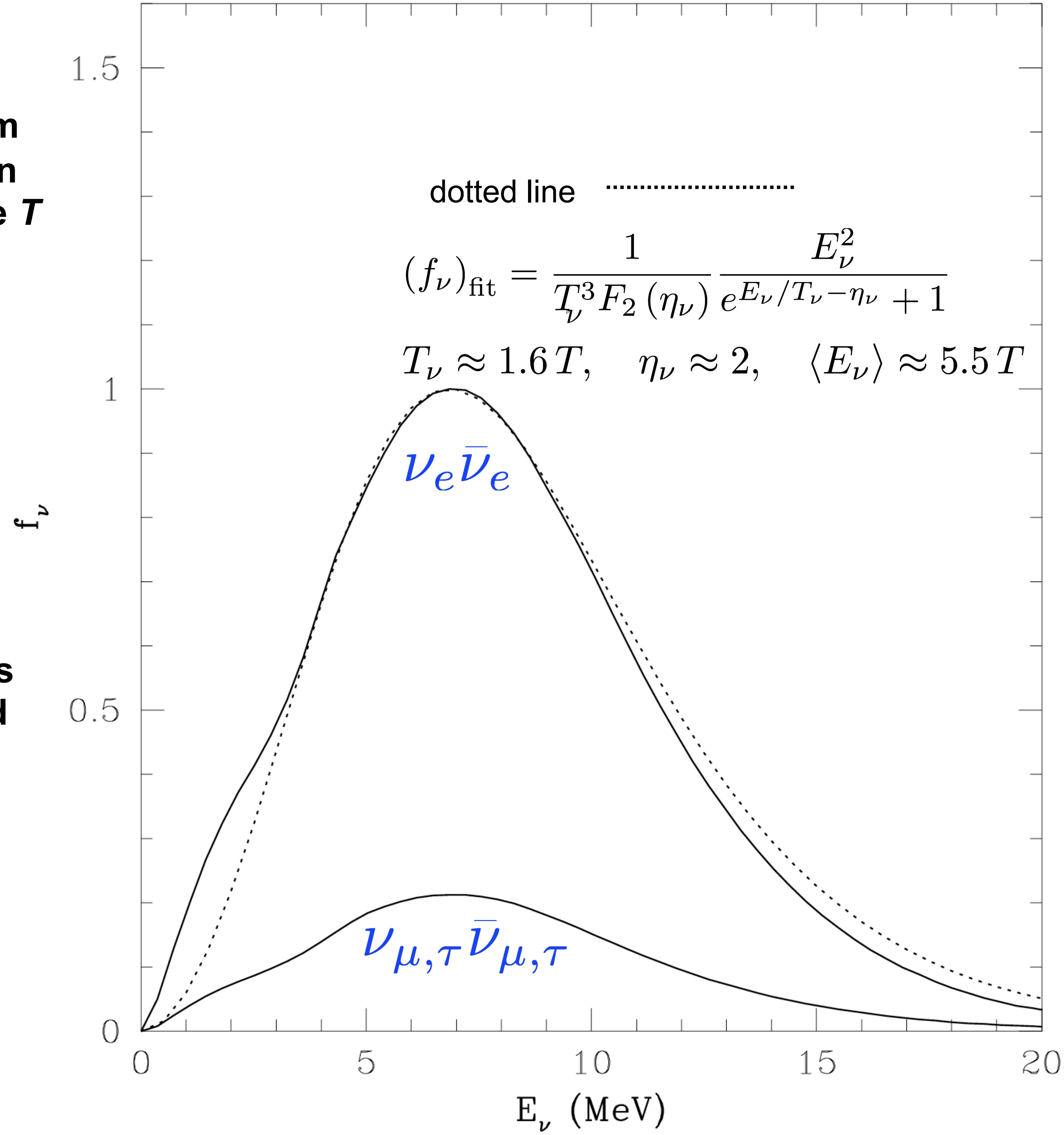
Jung-Tsung Li, GMF, C. T. Kishimoto , PRD **98**, 023002 (2018)

Neutrino/antineutrino energy spectra resulting from electron/positron annihilation in a plasma with temperature *T*

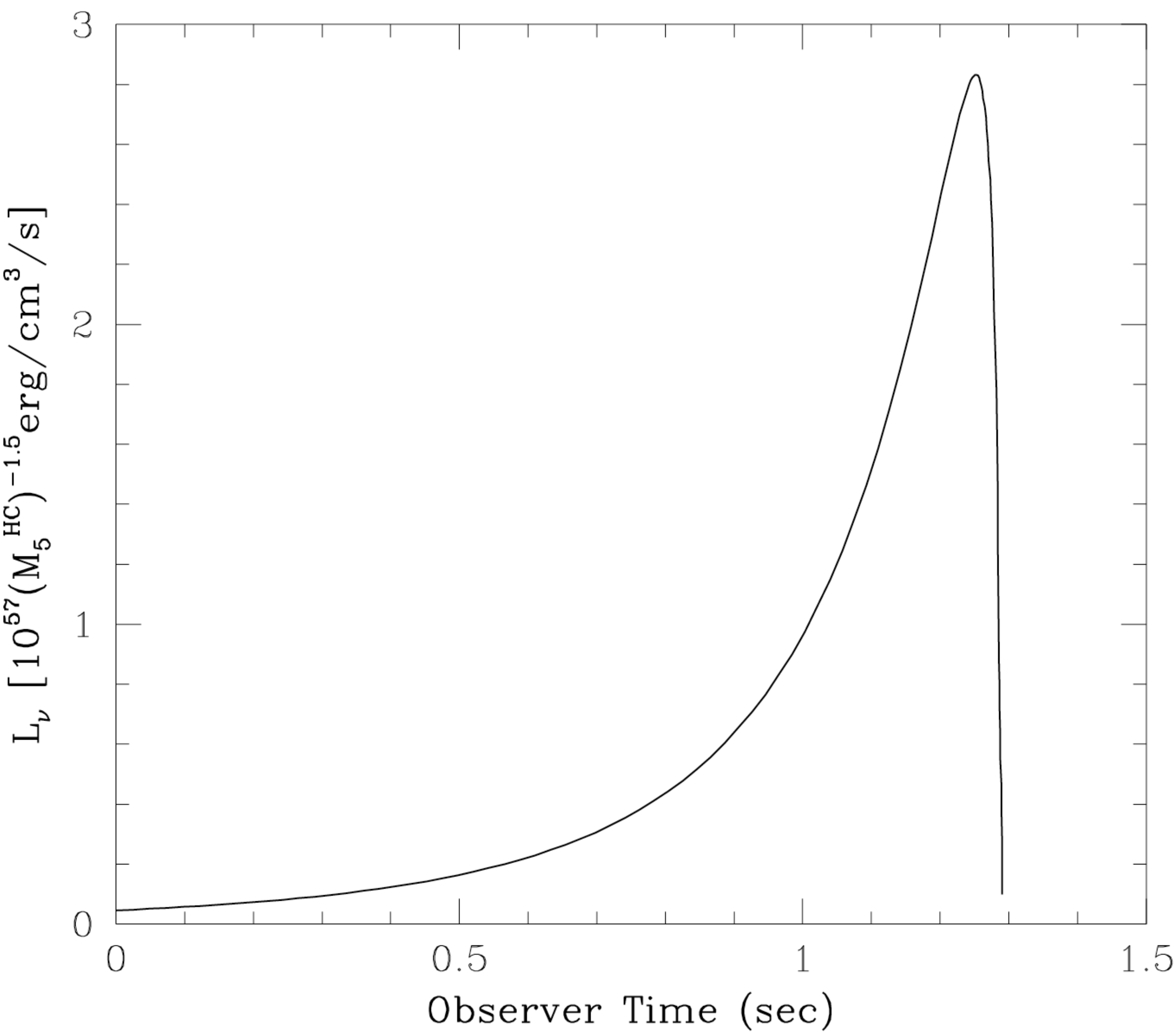
Ratio of fluxes:

$$\frac{\varphi_{\nu_e \bar{\nu}_e}}{\varphi_{\nu_\mu \bar{\nu}_\mu}} \approx \frac{5}{1}$$

Why? electron flavor neutrinos have both neutral and charged current production channels; mu and tau flavor neutrinos produced only in the neutral current channel



X. Shi & G. M. Fuller, Astrophys. J. 503, 307 (1998).



$$M_5^{\rm HC} \equiv \frac{M_{\rm homol.\ core}}{10^5\,{\rm M}_\odot}$$

X. Shi & G. M. Fuller, Astrophys. J. 503, 307 (1998).

Linear memory

- The non-oscillatory piece in the waveform.
- The source consists of several freely moving objects -- gravitationally unbound to each other.
- A few examples of linear memory
  1. Hyperbolic binary stars (bremsstrahlung) [Turner 1977; Kovacs & Thorne 1978]
  2. Matter or neutrinos ejected from supernova [Epstein 1978; Muller & Jenka 1997]
  3. Gamma ray bursts [Sago et al. 2014]

Matter ejected to infinity

Linearized field Eq: $\Box h_{\mu\nu}^{\mathrm{TT}} = -16\pi T_{\mu\nu}^{\mathrm{TT}}$

$$\Delta h_{ij}{}^{\mathrm{TT}} = \Delta\Sigma \frac{4M_a}{r(1-v_a^2)^{1/2}} \left[\frac{v_a^i v_a^j}{1-\vec{N}\cdot\vec{v}_a} \right]$$

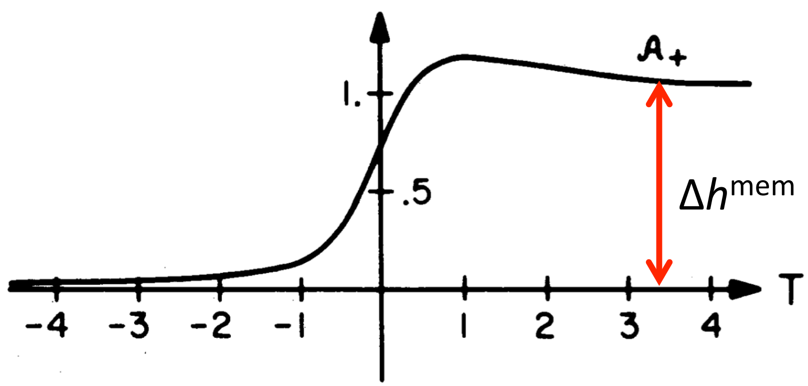
The gravitational-wave with "*memory*"

- Non-oscillating part in the waveform
- Produce **permanent** changes in the separation of free-fall test masses.
- Initial strain $h^{TT}_{ij}=0$ before the signal arrives; and non-zero strain $h^{TT}_{ij}\neq 0$ after the signal has passed:

$$\Delta h^{\mathrm{mem}} = h(t \to \infty) - h(t \to -\infty)$$

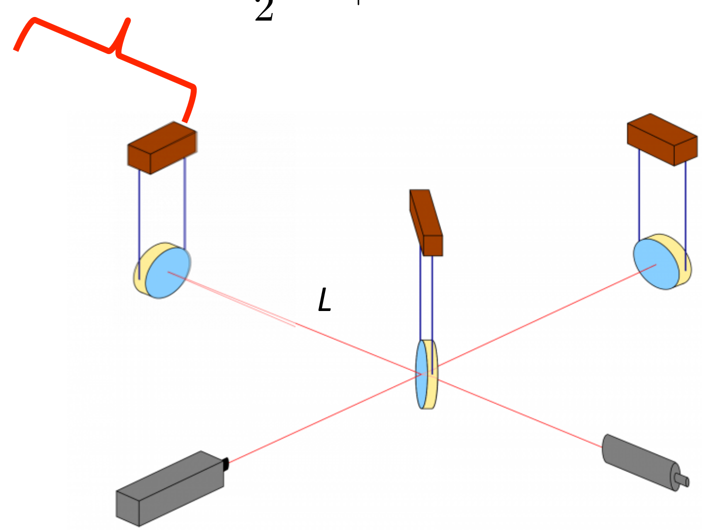
- Leave a DC (constant) offset on the strain after the burst has passed by.

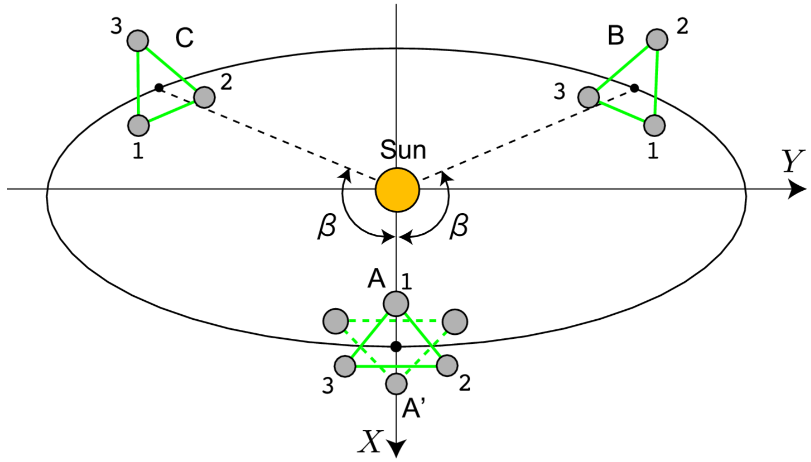
(Two stars in a hyperbolic orbit)



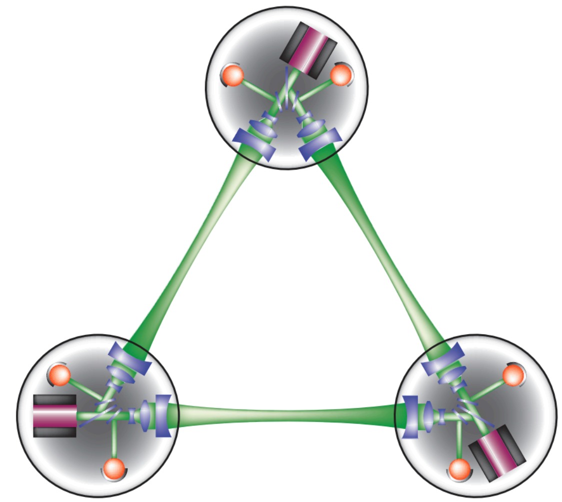
Kovacs & Thorne, *ApJ,224.,62* (1978)

$$\delta x^{\mathrm{mem}} = \frac{L}{2}\Delta h_{+}^{\mathrm{mem}}$$

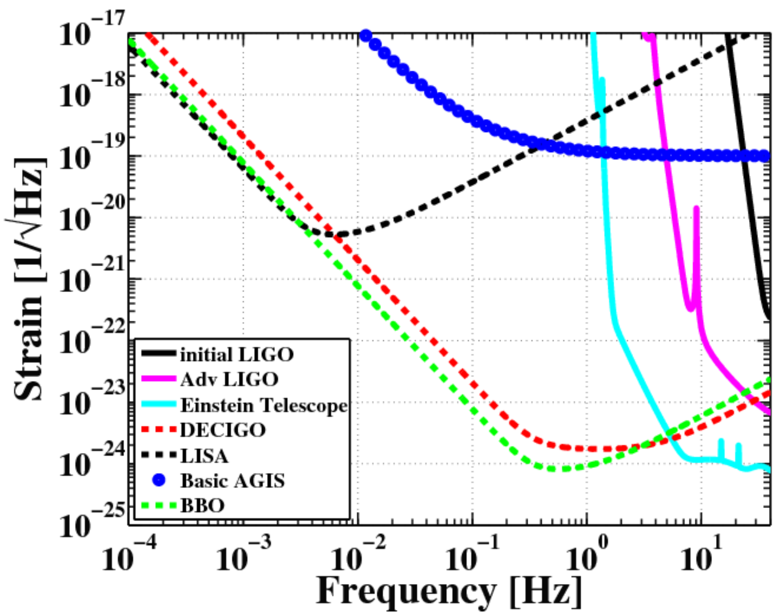


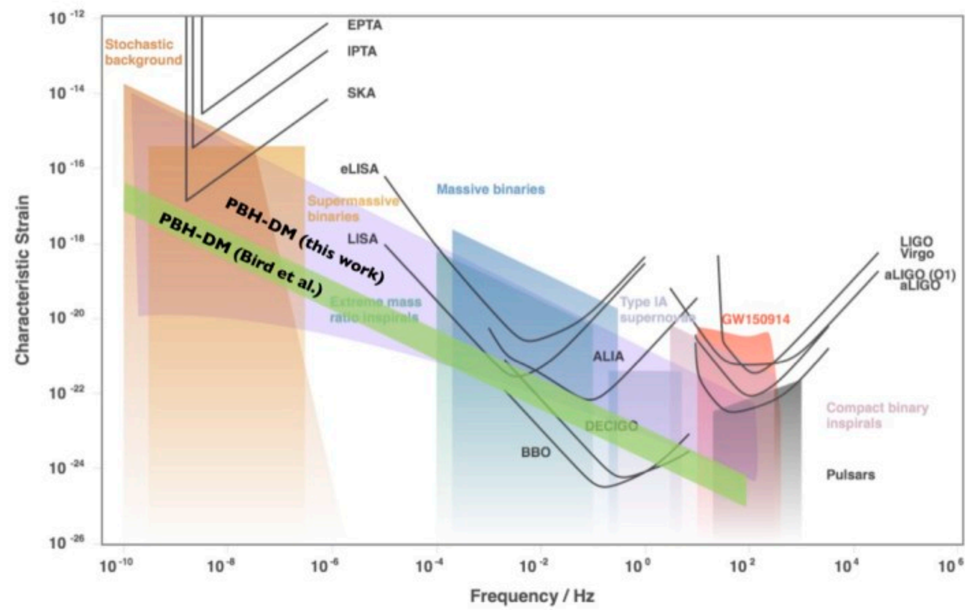


Cosmological test of gravity with polarizations of stochastic gravitational waves around 0.1-1 Hz - Nishizawa, Atsushi *et al.*
Phys.Rev. D81 (2010) 104043 arXiv:0911.0525 [gr-qc]



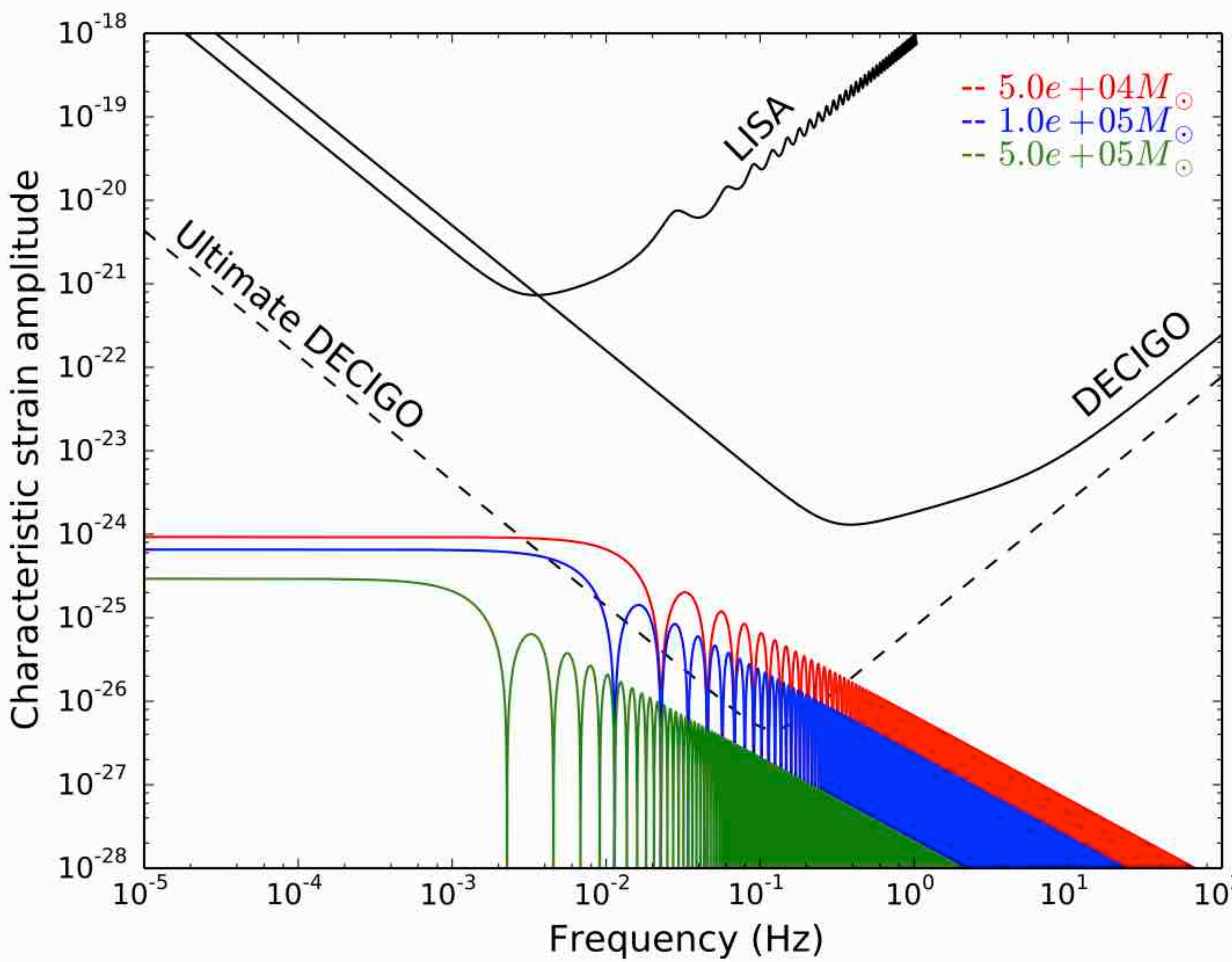
DECIGO constellation concept~\cite{Sato:DECIGO2009}



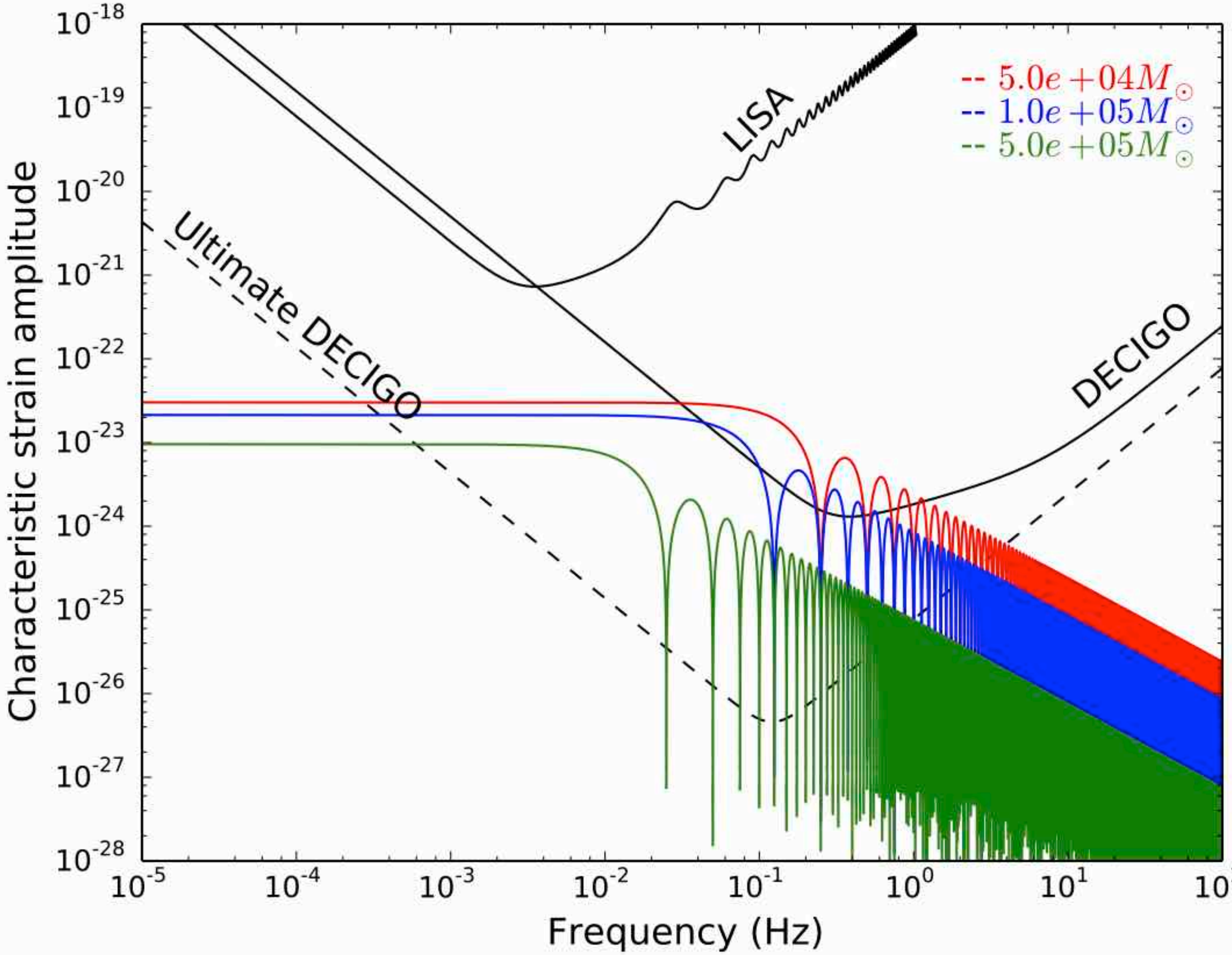


Left:
Adhikari, Rana X Rev.Mod.Phys. 86 (2014) 121 arXiv:1305.5188 [gr-qc] LIGO-P1200121

Right:
https://arxiver.wordpress.com/2016/10/27/detecting-the-gravitational-wave-background-from-primordial-black-hole-dark-matter-cea/#jp-carousel-203276



LISA
Ultimate DECIGO
DECIGO
-- $5.0e+04M_\odot$
-- $1.0e+05M_\odot$
-- $5.0e+05M_\odot$
Characteristic strain amplitude
Frequency (Hz)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}



Characteristic strain amplitude
Frequency (Hz)
LISA
DECIGO
Ultimate DECIGO
-- $5.0e+04 M_\odot$
-- $1.0e+05 M_\odot$
-- $5.0e+05 M_\odot$
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
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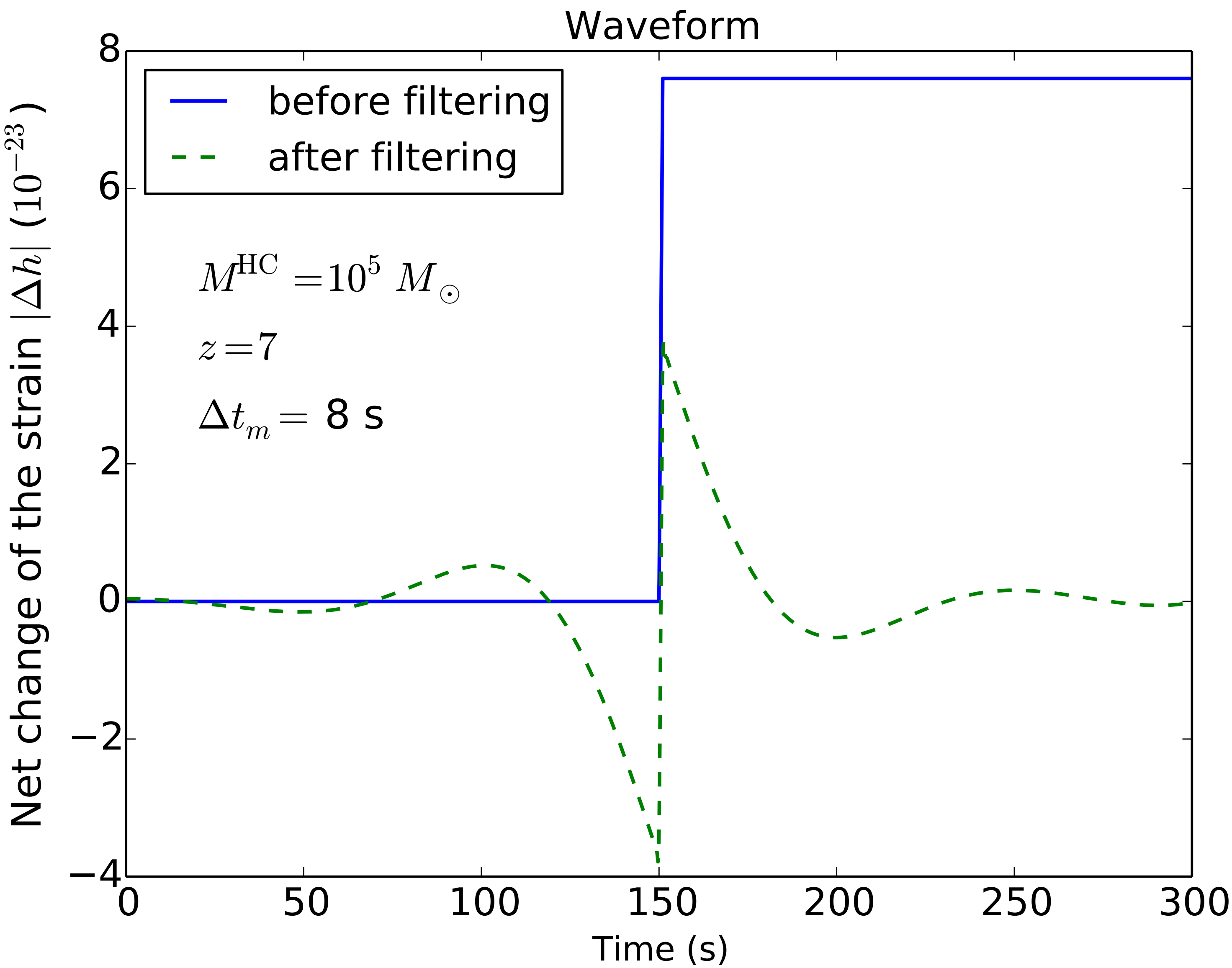
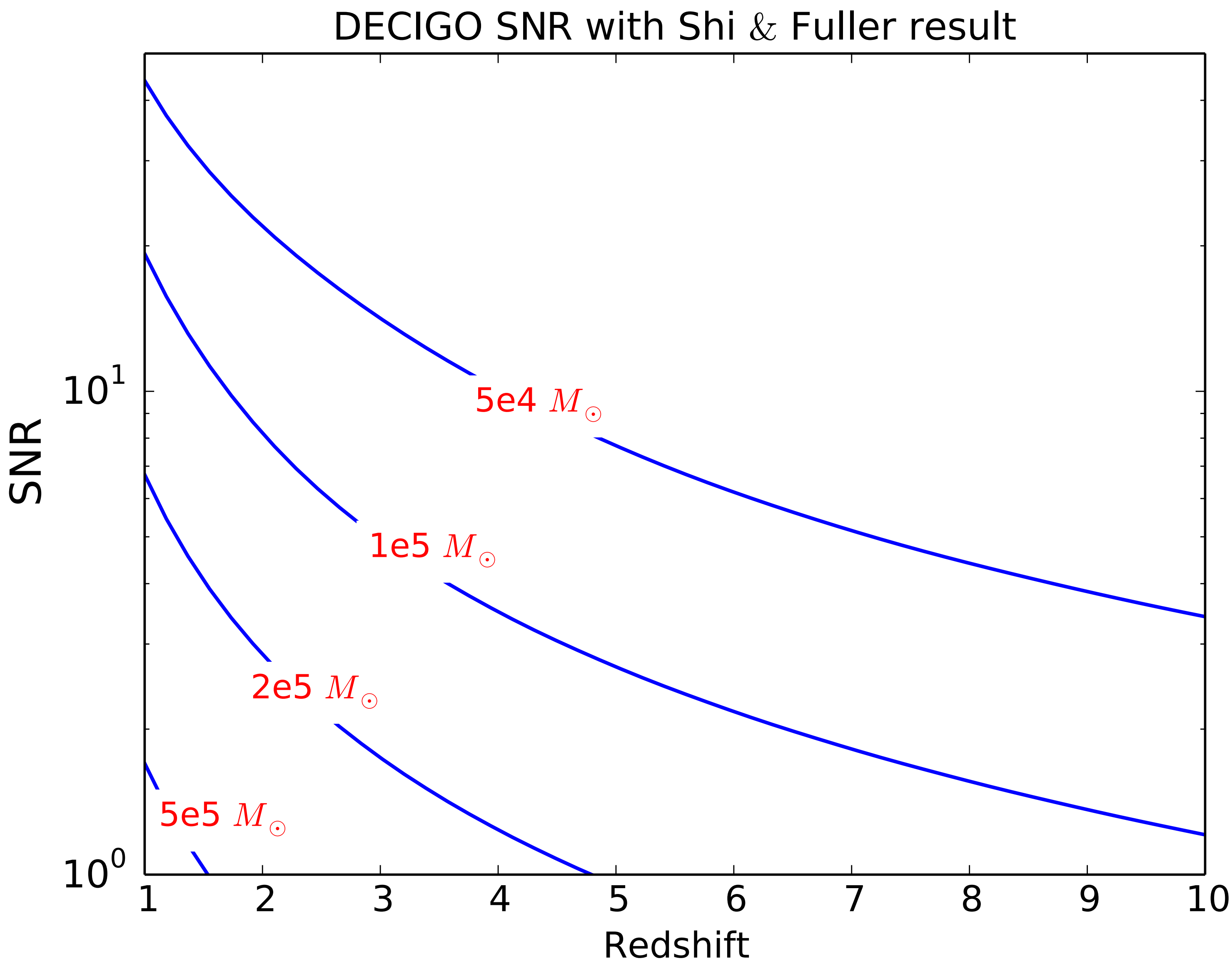
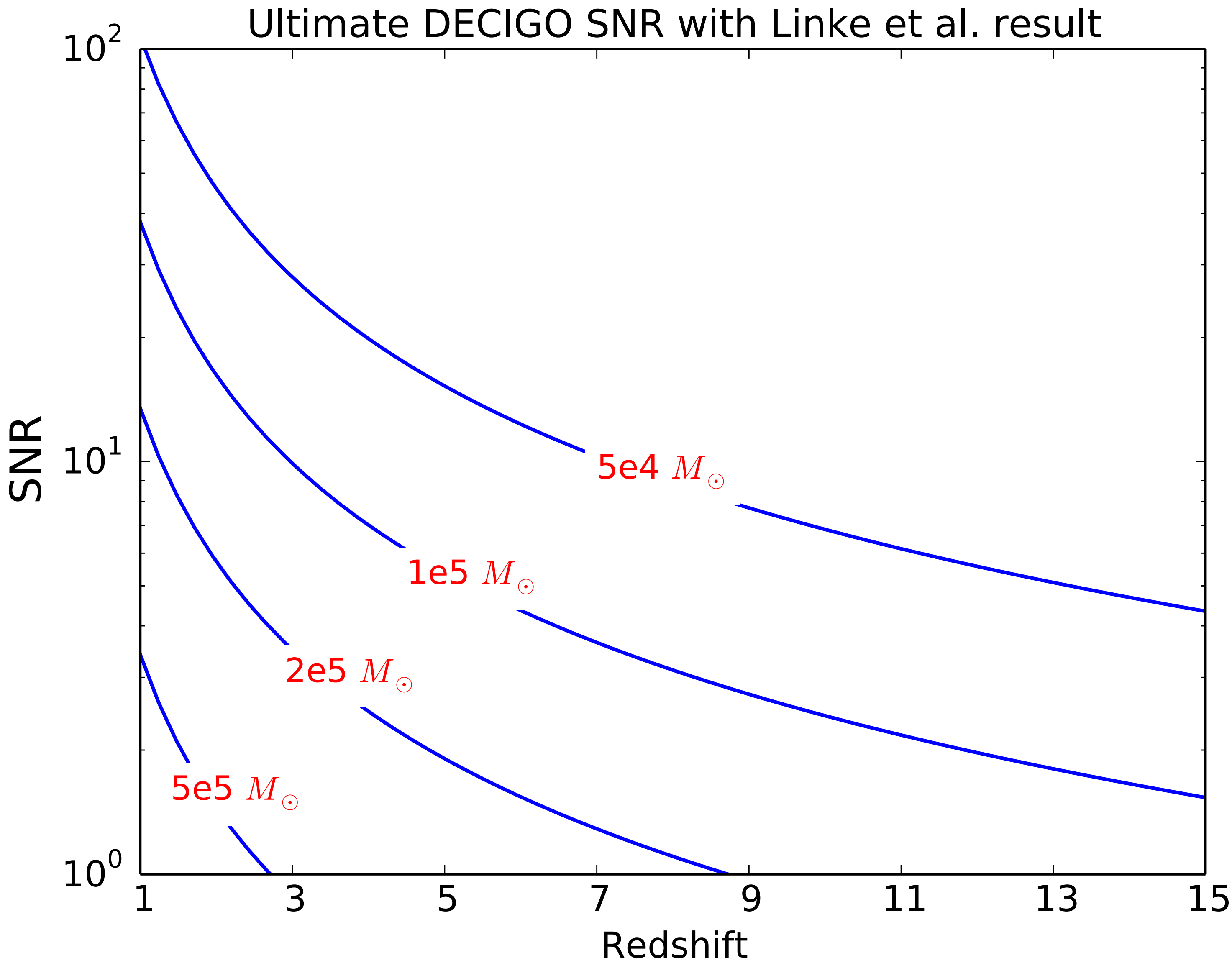
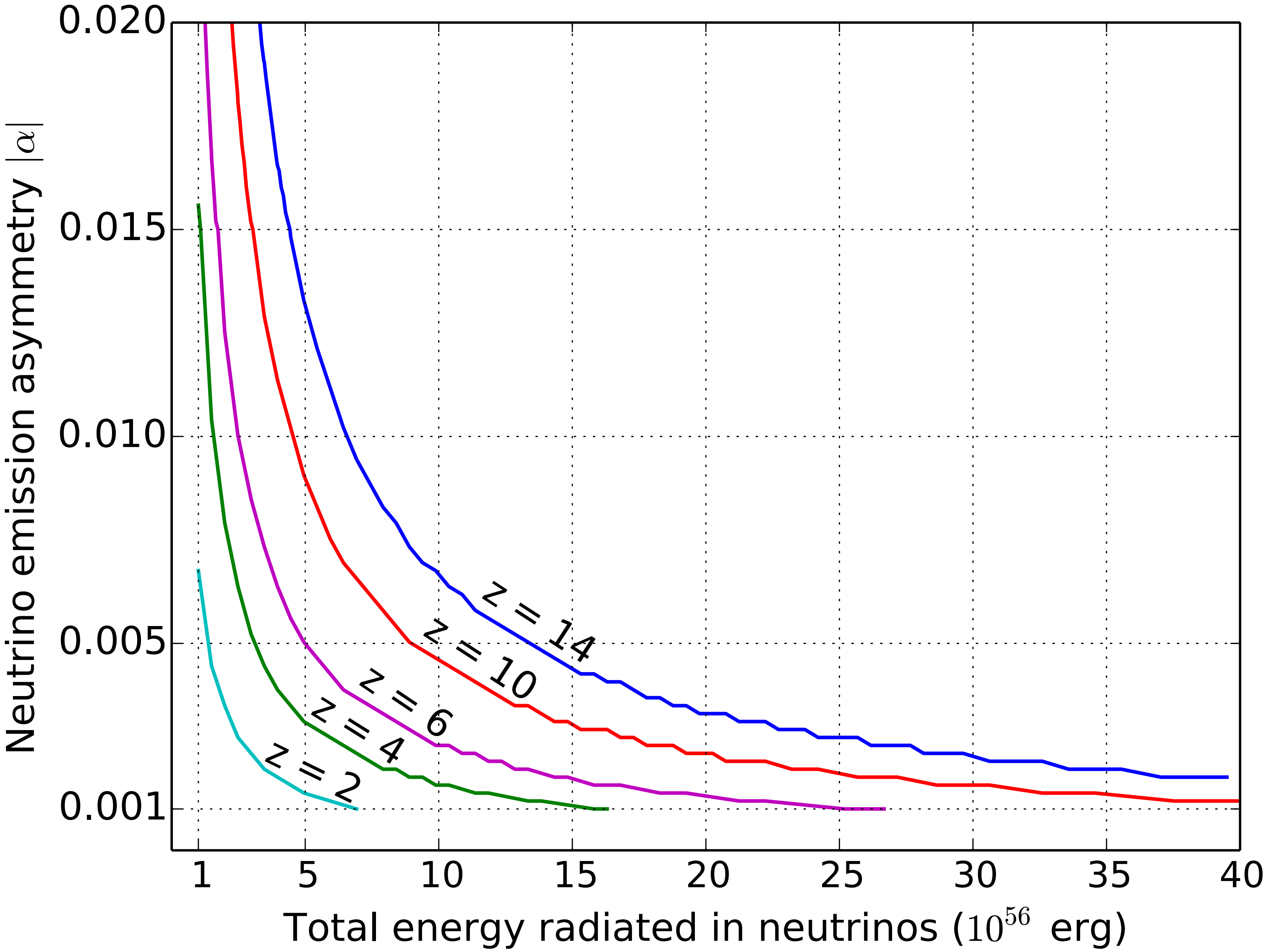
10^{0}
10^{1}
10^{2}



Waveform
before filtering
after filtering
$M^{\mathrm{HC}} = 10^5\ M_\odot$
$z = 7$
$\Delta t_m =$ 8 s
Net change of the strain $|\Delta h|$ (10^{-23})
Time (s)
8
6
4
2
0
−2
−4
0
50
100
150
200
250
300


DECIGO SNR with Shi & Fuller result
SNR
Redshift
10^1
10^0
1
2
3
4
5
6
7
8
9
10
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$


Ultimate DECIGO SNR with Linke et al. result
SNR
Redshift
10^2
10^1
10^0
1
3
5
7
9
11
13
15
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$



Neutrino emission asymmetry $|\alpha|$
Total energy radiated in neutrinos (10^{56} erg)
0.020
0.015
0.010
0.005
0.001
1
5
10
15
20
25
30
35
40
z = 14
z = 10
z = 6
z = 4
z = 2