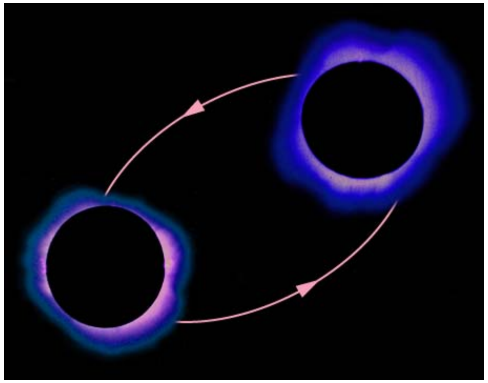
Double NS: Detection Rate and Stochastic Background



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LIGO-G050506-00-Z

The Model

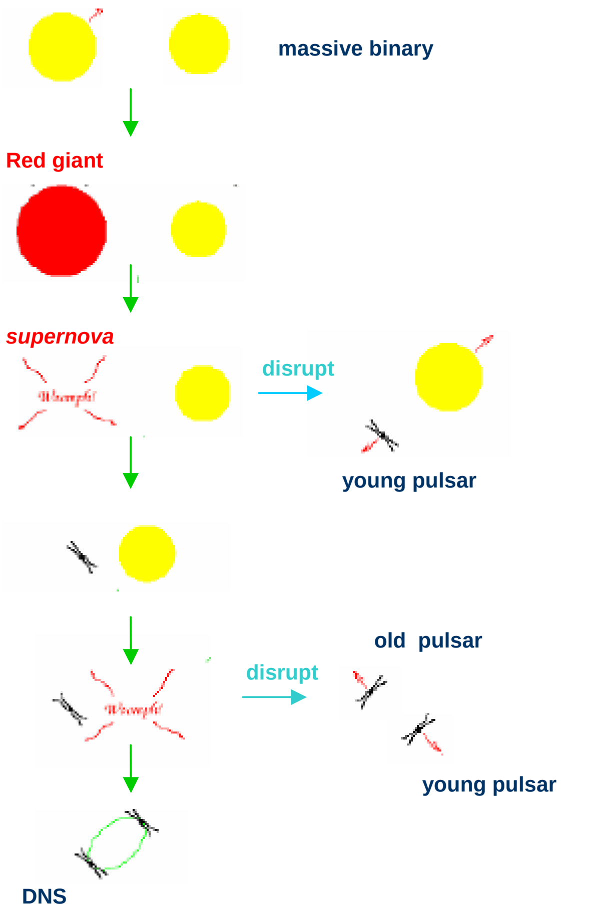
- a very small fraction of massive binaries remains bounded after 2 supernova explosions
- the resulting system consist of a:

  1. partially reaccelerated pulsar

  2. young pulsar with

     - same period evolution (magnetic dipole spin down) as normal radio pulsars

     - same kick velocity as millisecond pulsars (for which the supernova didn't disrupt the system either)



The Galactic Coalescence Rate

$$\nu_c(t) = \lambda \beta_{NS} f_b \int_{\tau_0}^{t-\tau_*-\tau_0} R_*(t-\tau_*-\tau) P(\tau) d\tau$$

$R_*(t)$: star formation rate (Rocha-Pinto et al., 2000)

λ: fraction of formed stars in the range 9-40 $M_{\odot}$ ($\lambda = \int_9^{40} \mathrm{mAm}^{-2.35} \mathrm{dm}$)

f_b : fraction of massive binaries formed among all stars

β_{NS} : fraction of massive binaries that remain bounded after the second supernova

$P(\tau)$: probability for a newly formed NS/NS to coalesce in a timescale τ

τ_0 : minimum coalescence time

τ_* : mean timescale required for the newly formed massive system to evolve into two NSs

The Galactic Star Formation Rate

➢ **previous studies:**

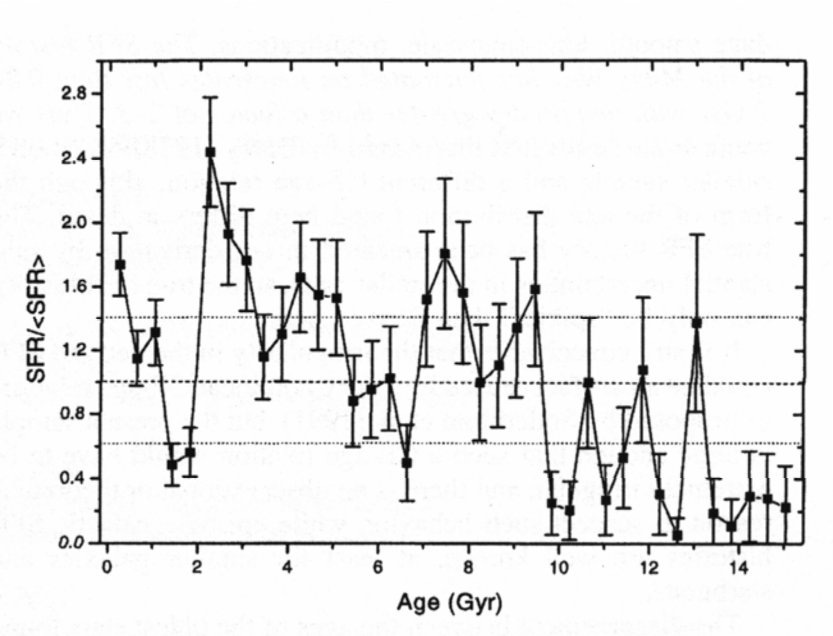
The star formation rate is proportional to the available mass of gas as: $R_*(t) \propto \exp(-\alpha t)$

➢ **present work:**

The star formation history is reconstructed from observations:

▪ ages of 552 stars derived from chromospheric activity index

(Rocha-Tinto et al., 2000)



▪ enhanced periods of star formation at 1 Gyr, 2-5 Gyr and 7-9 Gyr probably associated with accretion and merger episodes from which the disk grows and acquires angular momentum

(Peirani, Mohayaee, de Freitas Pacheco, 2004)

Numerical Simulations ($P(\tau)$, τ_0, β_{NS})

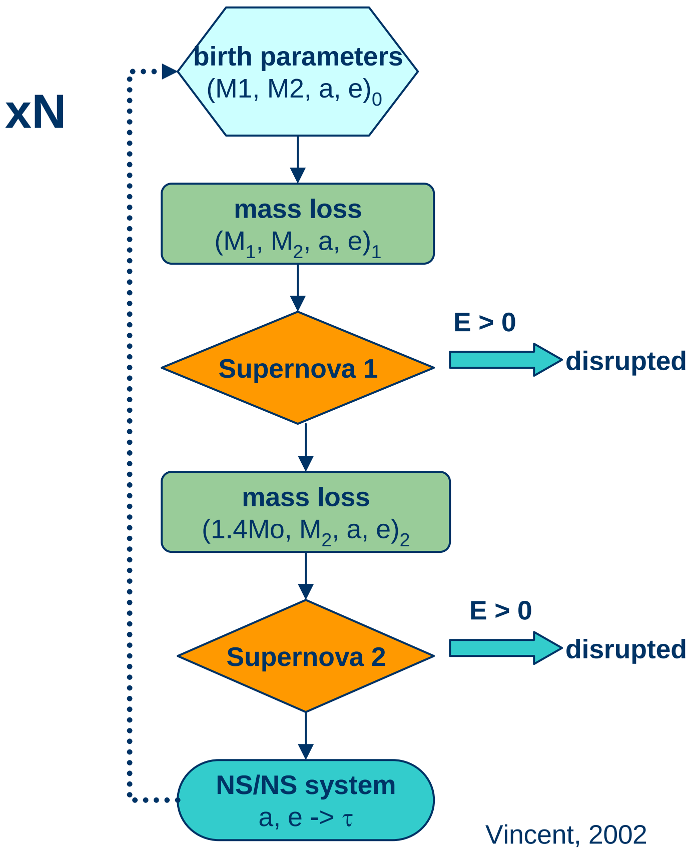
➢ **initial parameters**:

- masses: M_1, Salpeter IMF, M_1/M_2: probability derived from observations
- separation: $P(a)da=da/a$ between 2-200R_{Roche}
- eccentricity: $P(e)de = 2ede$

➢ **evolution of orbital parameters due to mass loss (stellar wind)**

➢ **statistical properties**

- β_{NS}= 2.4% (systems that remain bounded after the second supernova)
- $P(\tau) = 0.087/\tau$ (probability for a newly formed system to coalesce in a timescale τ)
- $\tau_0 = 2\times10^5$ yr (minimum coalescence time)



Vincent, 2002

Population Synthesis (f_b)

➢ **single radio pulsar properties:**

- N_p ~250000 (for 1095 observed)
- **birth properties**

	mean	dispersion
P_0 (ms)	240 ± 20	80± 20
ln τ_0 (s)	11 ± 0.5	3.6 ± 0.2

➢ **second-born pulsar properties:**

- **period evolution**: alike single radio pulsars

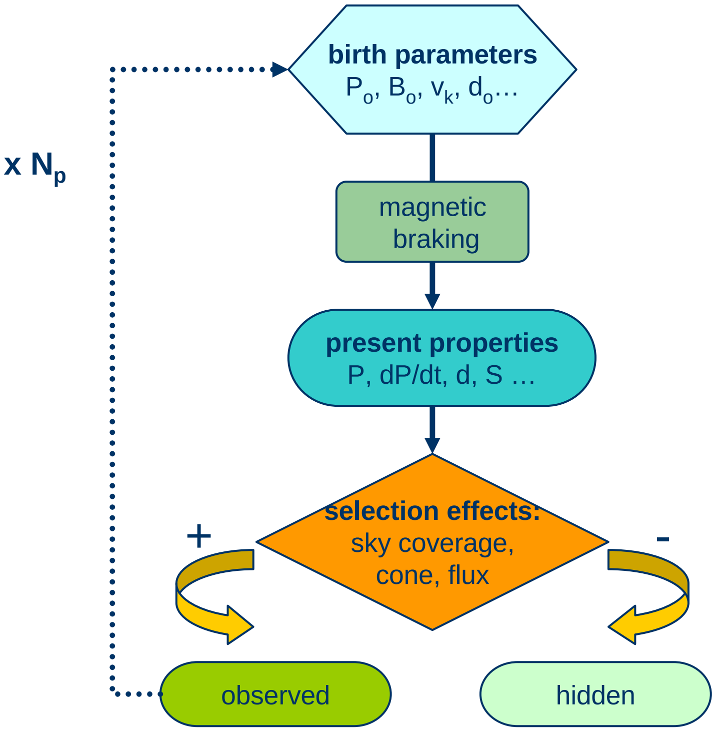
(magnetic dipole spin down)

- **kick velocity**: alike millisecond pulsars

(in the low tail of the distribution because the system survives to the supernova)

- N_b = 730 (for two observed)

➢ $$\frac{N_p}{N_b} = \frac{1}{\beta_{NS}}\frac{1-f_b}{f_b} + 2\frac{1-\beta_{NS}}{\beta_{NS}} \rightarrow f_b = 0.136$$



Regimbau, 2001&2004

The Local Coalescence Rate

Bulk of stars formed in the first 1-2 Gyr. The pairs merging today were formed with long coalescence times

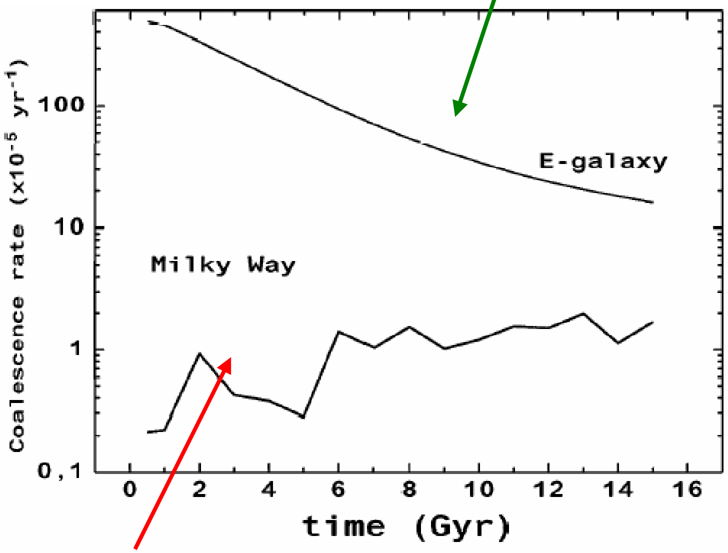
- weighted average over spirals (f_S=65%) and ellipticals (f_E=35%)

$$\nu_c = \nu_S (f_S + f_E \frac{\nu_E}{\nu_S} \frac{L_S}{L_E}) = 3.4 \times 10^{-5} yr^{-1}$$

- same f_b and β_{NS} as for the Milky Way

- spiral galaxy coalescence rate equal to the Milky Way rate:
  $\nu_S = (1.7 \pm 1) \times 10^{-5}\ yr^{-1}$

- elliptical galaxy star formation efficiency estimated from **observations - color & metallicity indices** *(Idiart, Michard & de Freitas Pacheco, 2003)*
  $\nu_E = 8.6 \times 10^{-5}\ yr^{-1}$



Intermitent star formation history: modulation in the coalescence rate

The Detection Rate

➢ **coalescence rate within the volume V=4/3 π D^3**

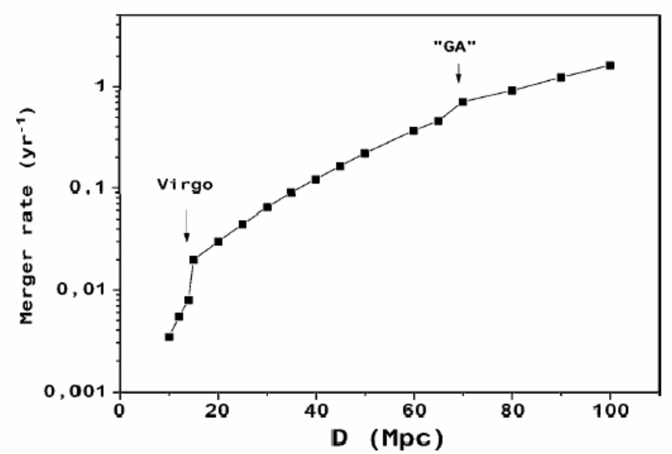
$$\nu(<\mathrm{D}) = \nu_c \frac{L_{\mathrm{V}}}{L_{\mathrm{MW}}} \ \text{with } \mathrm{V} = \frac{4}{3}\pi \mathrm{D}^3$$

counts of galaxies from the LEDA catalog:

▪10^6 galaxies (completness of 84% up to B = 14.5)

▪ inclusion of the **Great Attractor**

intersection of Centaurus Wall and Norma Supercluster corresponding to 4423 galaxies at Vz = 4844 km/s



➢ **maximum probed distance and mean expected rate**
(S/N=7; false alarm rate=1) :

VIRGO	LIGO	LIGO Ad
13 Mpc 1 event/148 yr	14 Mpc 1 event /125 yr	207 Mpc 6 events/yr

Possible Improvements in the Sensitivity…

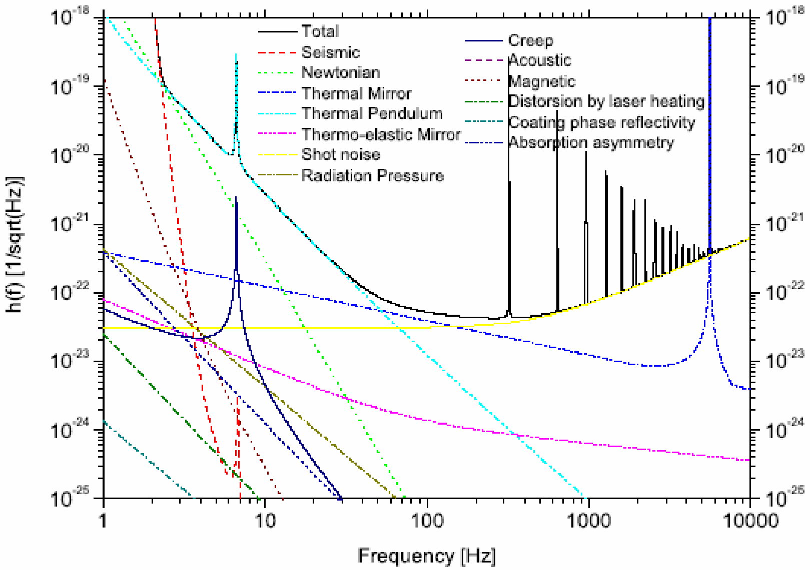
➢ **gain in the VIRGO thermal mirror noise band (52-148 Hz):**
reduction of all noises in the band by a factor 10
(Spallicci, 2003; Spallicci et al., 2005)

➢ **gain throughout VIRGO full bandwidth**
reduction of pendulum noise by a factor 28, thermal mirror 7, shot 4
(Punturo, 2004; Spallicci et al., 2005)

- maximum probed distance = 100 Mpc
- detection rate =1.5 events / yr

➢ **use networks of detectors**:
LIGO-H/LIGO-L/VIRGO
(Pai, Dhurandhar & Bose, 2004)

- false alarm rate = 1, detection probability = 95%
- maximum probed distance: 22 Mpc
- detection rate: 1 events / 26 yrs



The Stochastic Background

➢ **Two contributions:**

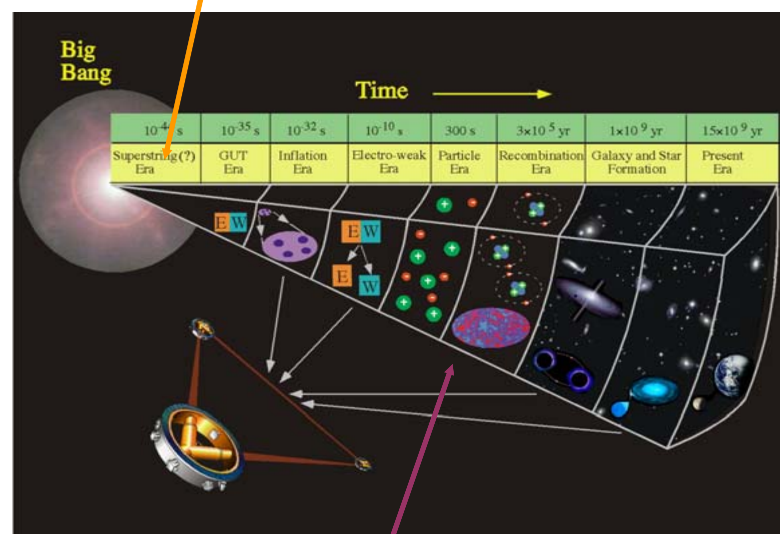
▪ **cosmological:** signature of the early Universe
inflation, cosmic strings, phase transitions…

▪ **astrophysical:** superposition of sources since the beginning of the stellar activity:
systemes binaires denses, supernovae, BH ring down, supermassive BH, binary coalescence …

➢ **characterized by the energy density parameter:**

$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)} = \frac{10\pi^2 f^3}{3H_0^2} S_{gw}(f)$$

10^{-43}s: gravitons decoupled (T = 10^{19} GeV)



300000 yrs: photons decoupled (T = 0.2 eV)

Last thousands seconds before the last stable orbit:

96% of the energy released, in the range [10-1500 Hz]

Population Synthesis

- **redshift of formation of massive binaries (Coward et al. 2002)**

$$P_f(z_f) = \frac{R_f(z_f)}{\int_0^5 R_f(z_f)dz_f} \quad \text{with } R_f(z_f) = \lambda_p \frac{R_f^*}{1+z}\frac{dV}{dz}$$

- **redshift of formation of NS/NS**

$$z_b = z_f - \Delta z(\tau_b) \text{ with } \tau_b = 10^8 \text{ yr}$$

- **coalescence time**

$$P_\tau(\tau) = \frac{0.087}{\tau} \quad \text{with } \tau \in [2\times10^5; 2\times10^{10} \text{yr}]$$

- **redshift of coalescence**

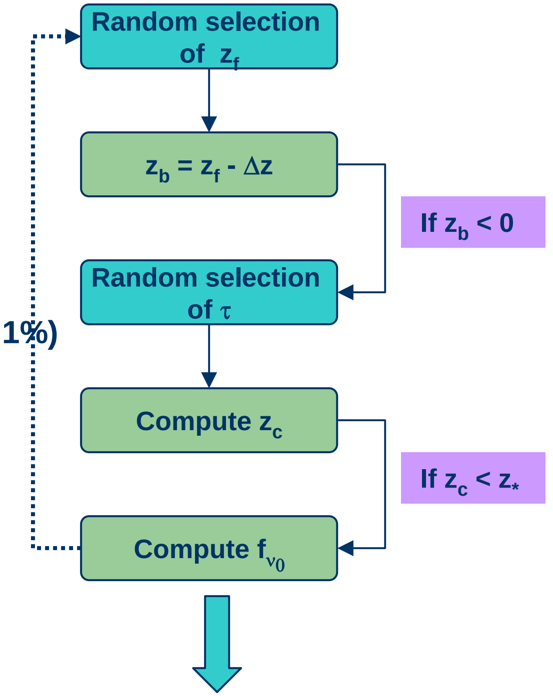
$$\tau = \frac{1}{H_0}\int_{z_c}^{z_b} \frac{dz}{(1+z)E(z)}$$

- **observed fluence**

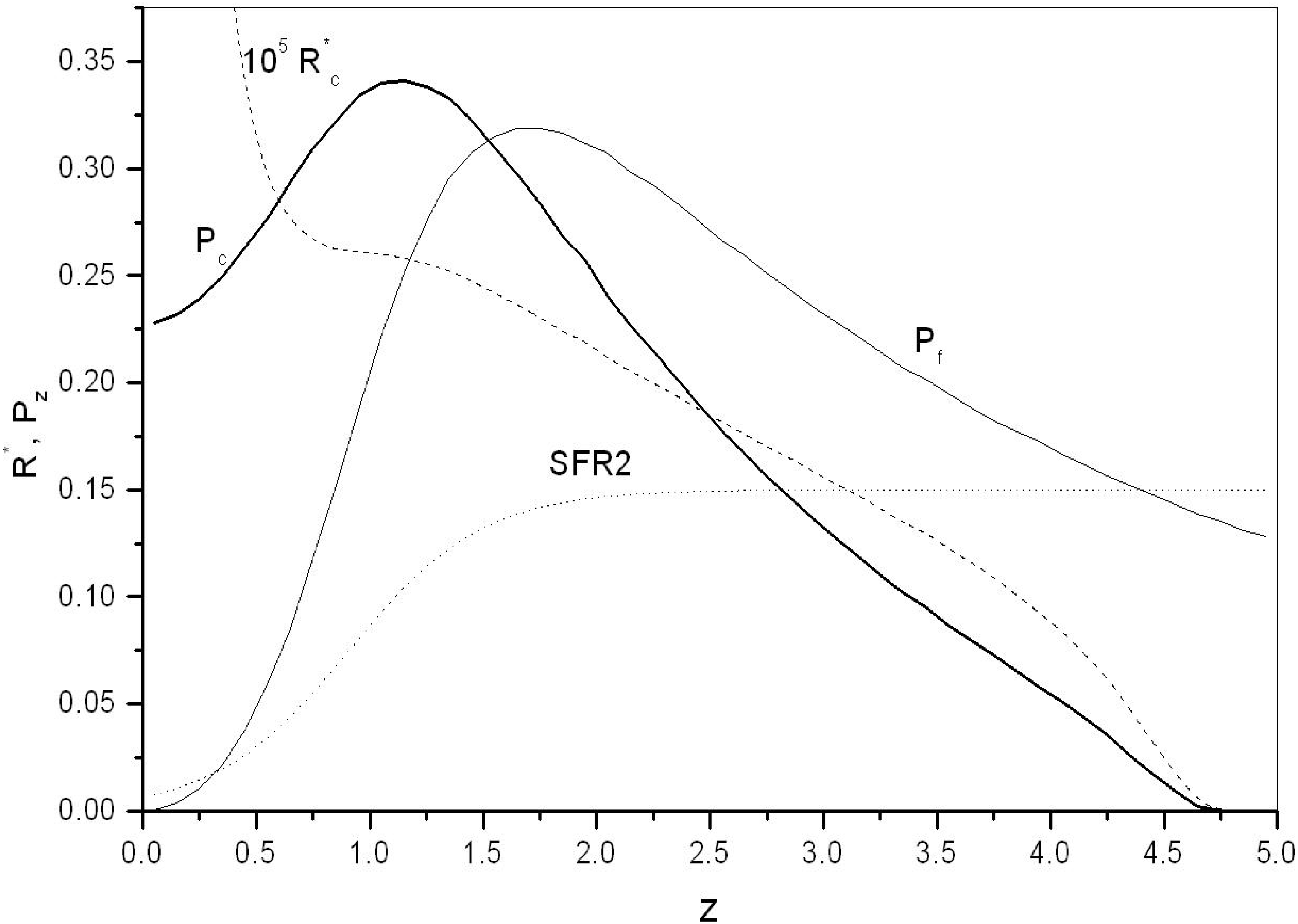
$$f_{\nu_o} = \frac{1}{4\pi d_L^2}\frac{dE_{gw}}{d\nu_0} = \frac{K\nu_o^{-1/3}}{4\pi r^2(z_c)(1+z_c)^{4/3}}$$

x $N=10^6$

(uncertainty on Ω_{gw} <0.1%)



$$\Omega_{gw}(f) = \frac{\nu_0 F_{\nu_0}}{\rho_c c^3} \text{ with } F_{\nu_0} = \frac{N_{DNS}}{N}\sum_{i=1}^{N} f_{\nu_0}^i$$



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
R*, P_z
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
z
10^5 R*_c
P_c
P_f
SFR2

Three Populations

The duty cycle characterizes the nature of the background.

$$D(z) = \int_0^z < \tau > (1+z')R_c(z')dz'$$

$<\tau>$ = 1000 s, which corresponds to 96% of the energy released, in the frequency range [10-1500 Hz]

- **D >1: continuous** (87%)

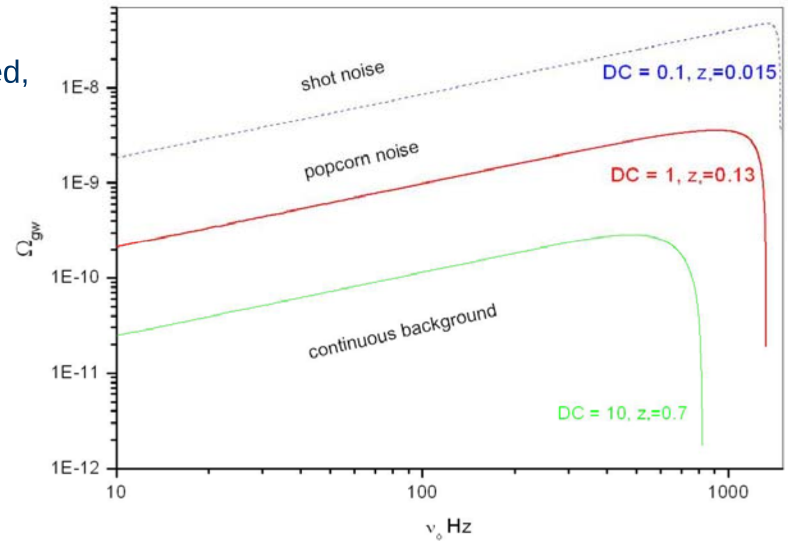
  The time interval between successive events is **short** compared to the duration of a single event.

- **D <1: shot noise**

  The time interval between successive events is **long** compared to the duration of a single event

- **D ~1: popcorn noise**

  The time interval between successive events is **of the same order as** the duration of a single event



Detection of the Continuous background

The stochastic background can't be distinguished from the instrumental noise.

The optimal strategy is to cross correlate the outputs of two (or more) detectors.

➢ **Hypotheses**:

- isotrope, gaussian, stationary
- signal and noise, noises of the two detectors uncorrelated

➢ **Cross correlation statistic**:

- combine the outputs using an optimal filter that maximizes the signal to noise ratio

$$Y = \int \tilde{s}_1(f)\tilde{Q}(f)s_2(f)df \quad \text{with} \quad \tilde{Q}(f) \propto \frac{\gamma(f)S_{gw}(f)}{P_1(f)P_2(f)}$$

➢**Signal to Noise Ratio:**

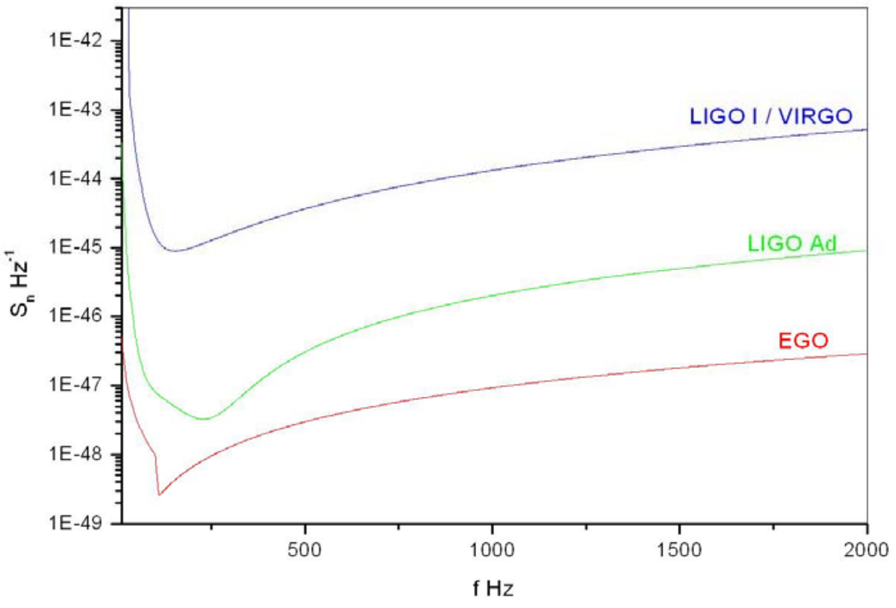
:

$$(S/N)^2 = \frac{9H_0^4}{8\pi^4} T \int_0^\infty \frac{\Gamma^2(f)\Omega_{gw}(f)}{F^2 f^6 P_1(f)P_2(f)}$$

Detection of the Continuous background

S/R for 2 co-located and co-aligned interferometers after 1yr of integration for the first three generations of interferometers:

IFOs	VIRGO LIGO I	LIGO Ad	EGO
S/R	0.006	1.5	25



Conclusions and Future Work

Local Events:

- **Coalescence rate:** 3.4×10^{-5} yr^{-1}
- **detection rate**:
  - first generation: 1 ev/125 yr
  - second generation: 6ev/yr

Cosmological Events:

- **continuous background**
  - critical redshift: z=0.13
  - $\Omega_{max} \sim 3.5 \times 10^{-9}$ at 920 Hz
  - detectable with cross correlation techniques with the second generation of detectors
- **popcorn noise**
  - critical redshift: z=0.015
  - $\Omega_{max} \sim 4.8 \times 10^{-8}$ at 1300 Hz
  - detectable with the PEH algorithm (Coward et al.) ??