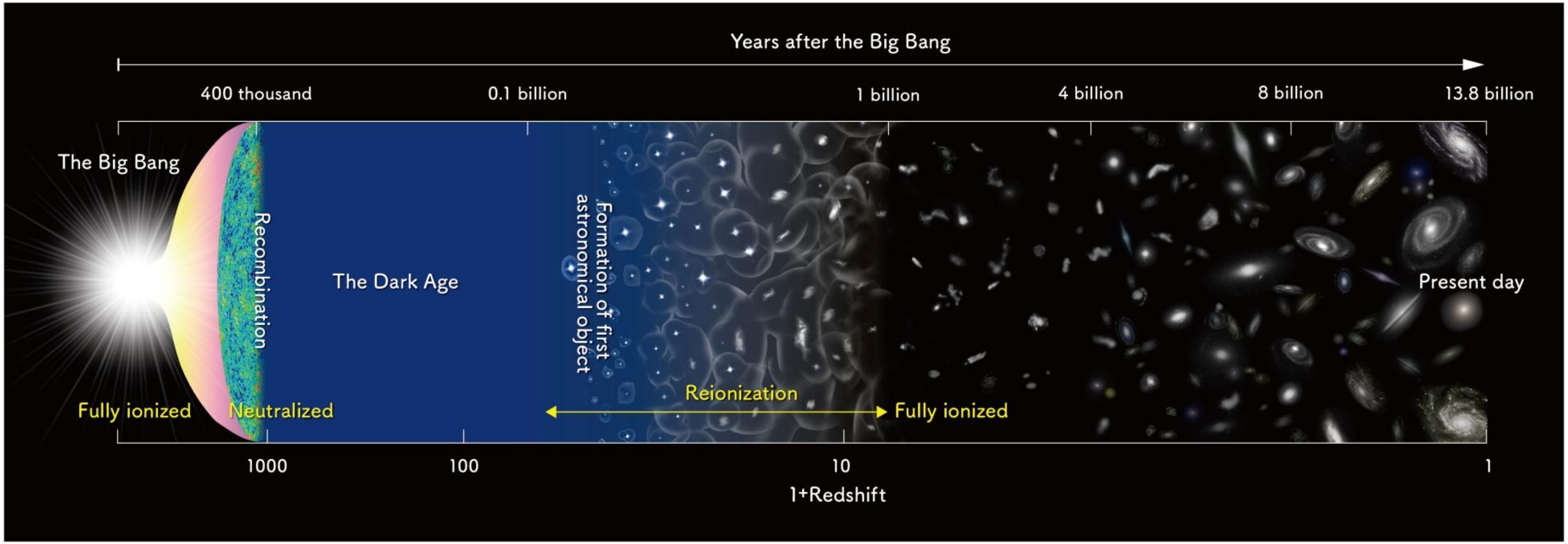
NEUTRINOS FROM THE COSMIC NOON

a probe of the cosmic star formation history



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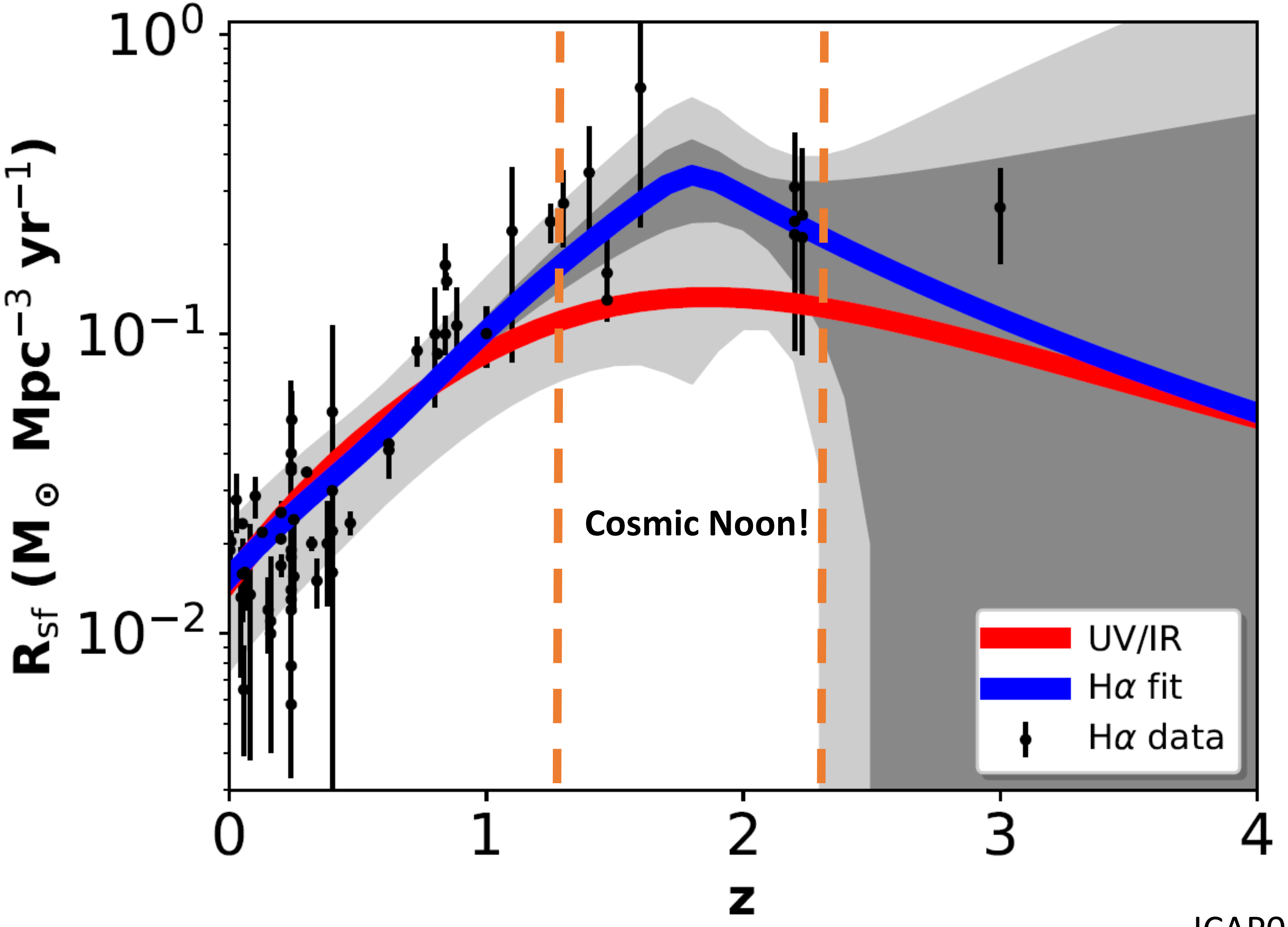
JCAP08(2021)019 astro-ph/2007.03976 (Riya Singh, VR)

Inferences of CSFH from observations are in conflict

$R_{\rm SF}(z)$

Star formation rate density at redshift z



Madau and Dickinson 2014

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Is there another independent observational probe of the CSFH that can resolve the discrepancy?

Diffuse supernova neutrino background

Key results of our work

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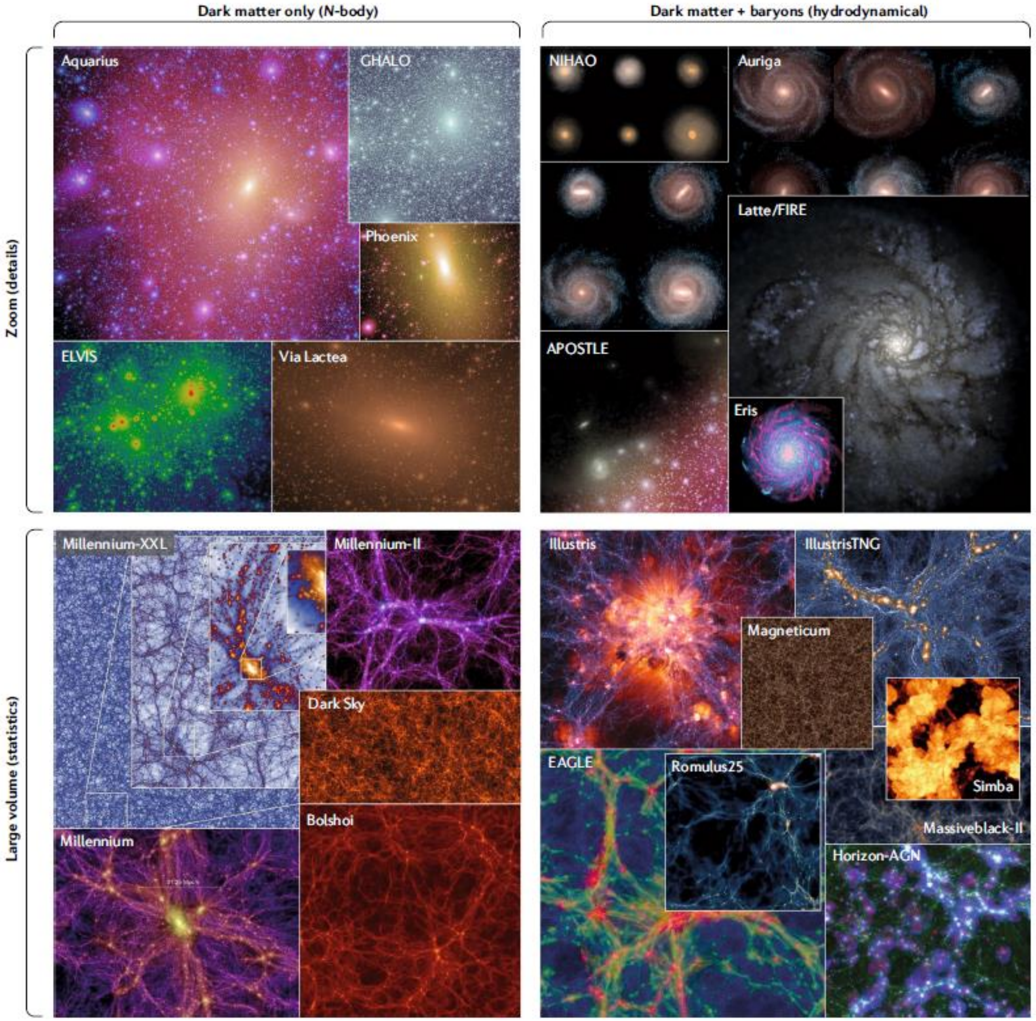
- Pointed out a mild discrepancy in the inferred SFRD at cosmic noon
- Showed that detection and characterization of the DSNB spectrum at Hyper-Kamiokande can cast a deciding vote on the true CSFH
- Milestone for neutrino astrophysics!

Outline

- Motivation
- Diffuse supernova neutrino background
- DSNB detection at Hyper-Kamiokande and backgrounds
- Discrimination of CSFH hypothesis
- Summary and Conclusions

Motivation: Why study the CSFH?

Galaxy formation simulations



Mark Vogelsberger, Federico Marinacci, Paul Torrey & Ewald Puchwein - *Nature Reviews Physics* **volume 2**, (2020)

Confront Observations

Small scales
Missing satellite problem (Klypin et al, Moore et al, 1999)
Too big to fail problem (Boylan-Kolchin et al, 2011)
Core cusp problem (Oh et al, 2010)

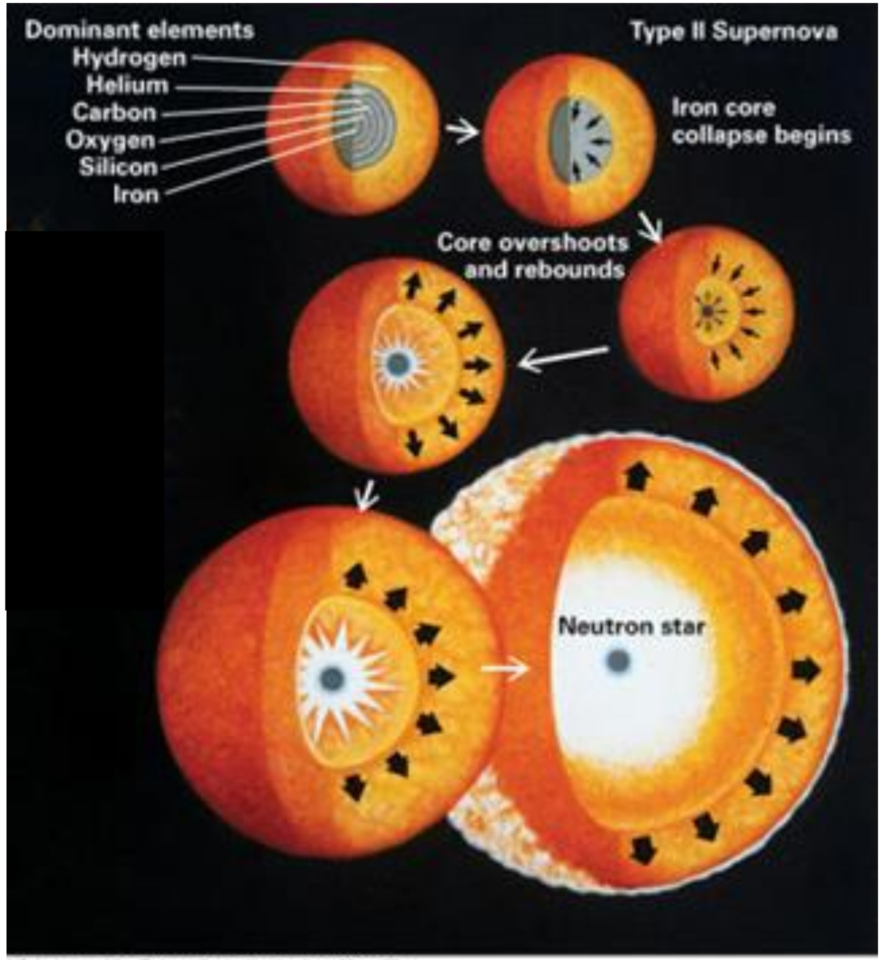
Baryonic feedback or dark matter self interactions?
(Bullock et al 2000, Benson et al 2002, Governato et al 2010)

Star Formation Rate – critical calibration tool

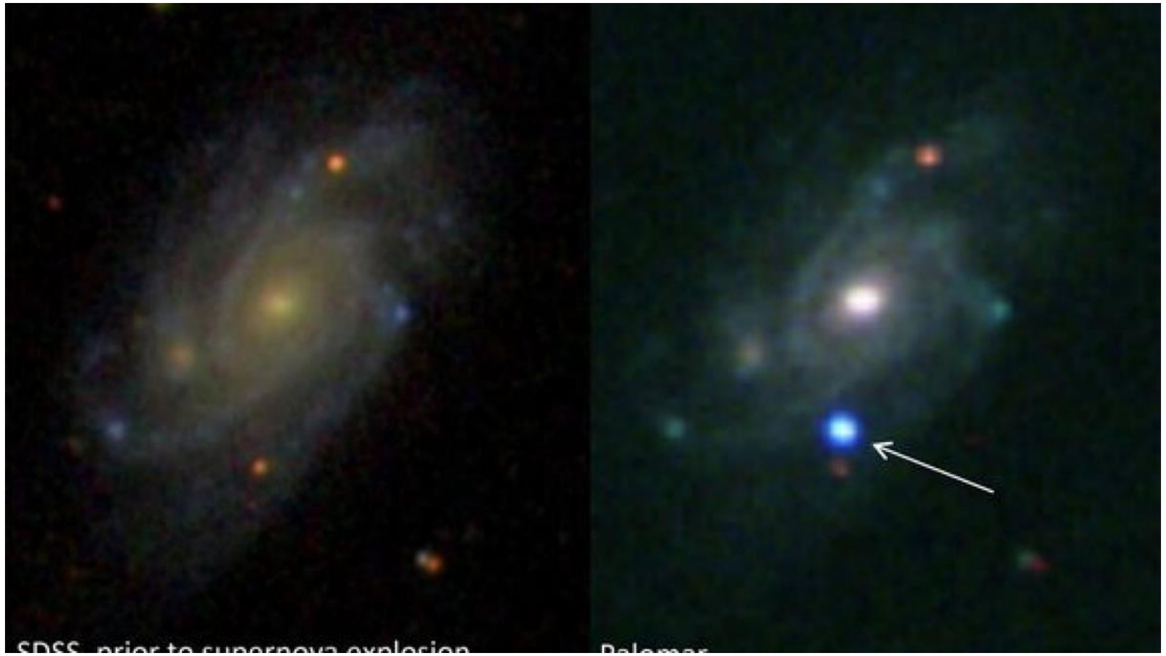
Multi-scale problem, treated with sub-resolution parameters in large scale simulations

Dynamics of core-collapse SN

Dynamics of core collapse SN

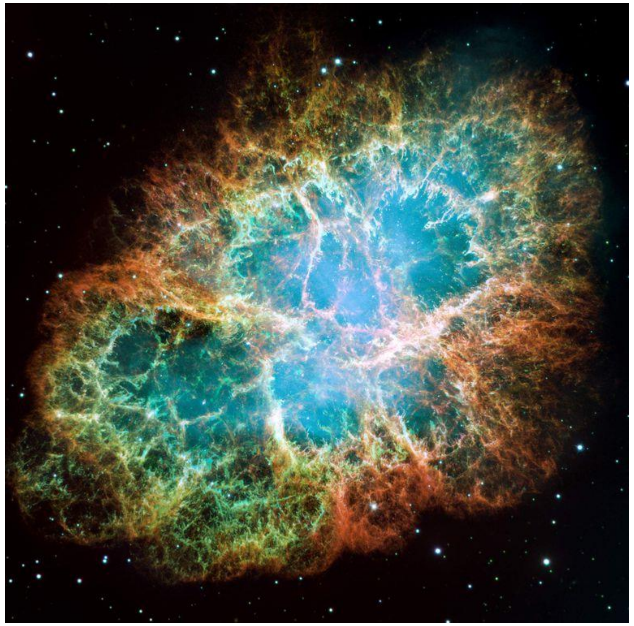


Science and the Future; illustration by Jane Meredith



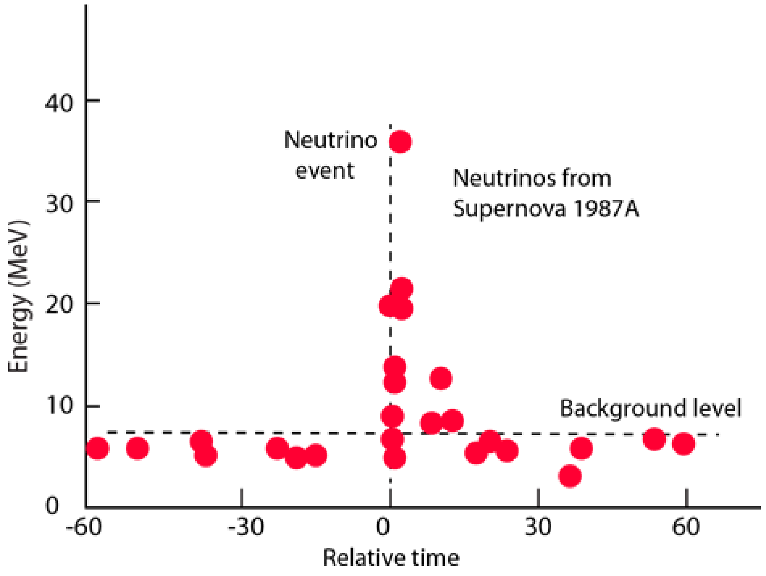
Core-collapse supernovae

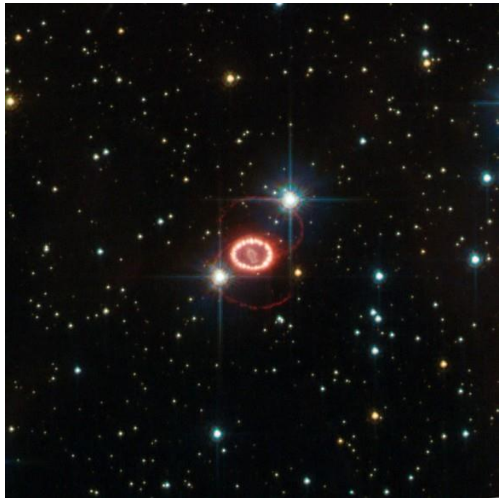
- Massive stars (> 8 $M_{\odot}$) undergo core collapse
- Huge energy release – 3 x 10^{53} erg – 100 times more than the sun will release in its entire lifetime - in just a few seconds
- 99% of the energy released in the form on neutrinos- 10^{59} neutrinos per supernova with 10 MeV energies
- These massive stars are cosmologically short lived with a lifetime ~ 10 Myr
- Birth rate and death rate of massive stars are essentially the same
- Good tracer of massive star formation!



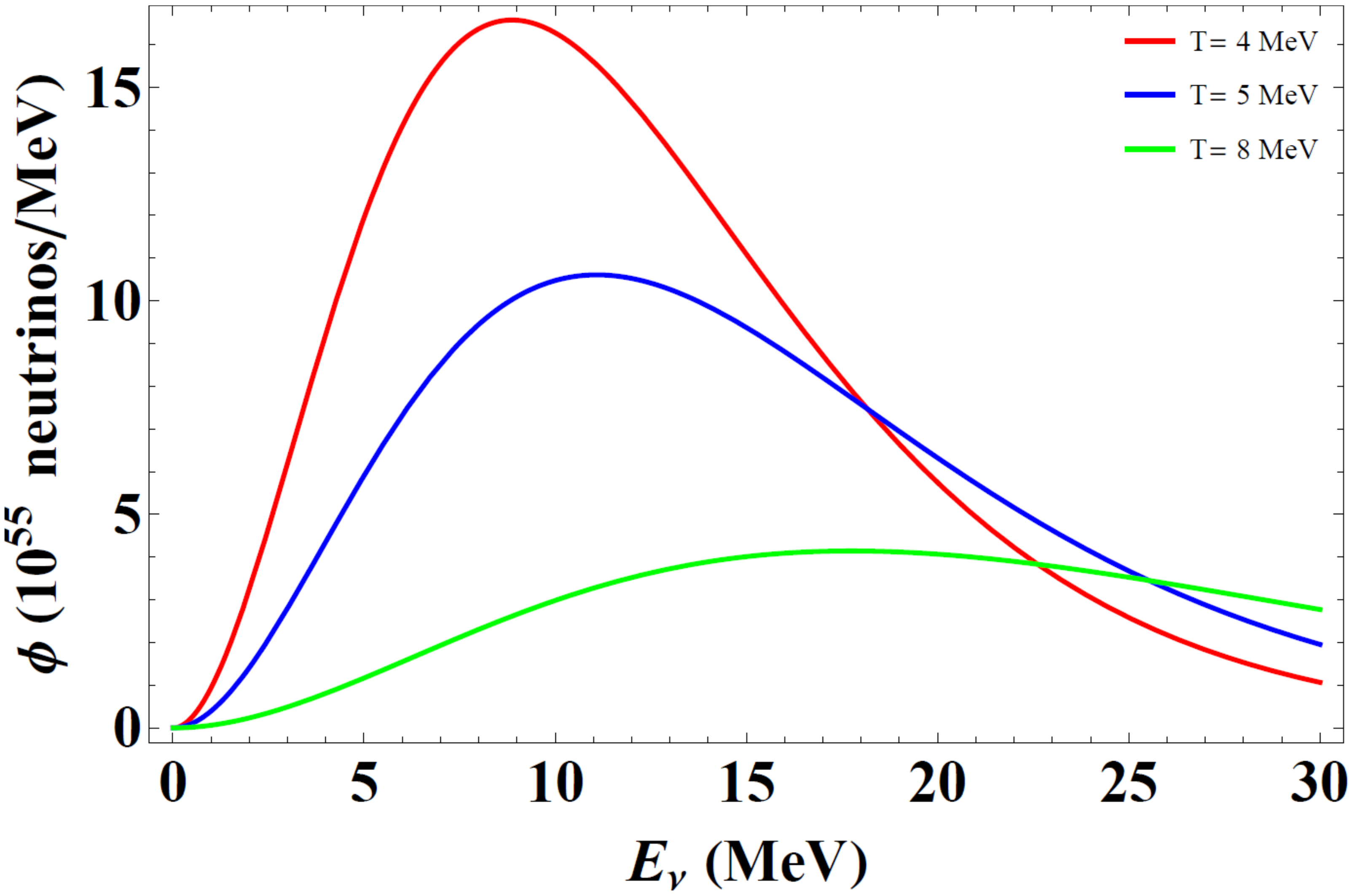
Rate for CC SN are low

- In our galaxy ~ 2.5 per century
- Only neutrino detection from SN1987A – LMC
- Neutrinos seen 3-4 hours before telescopes
- Burst of O(10) neutrinos seen at three different detectors
- 100s-1000s of neutrinos in a modern detector





Neutrino spectrum



$$\phi_{\rm SN}(E_\nu) = \frac{E_{\rm tot}}{6}\frac{120}{7\pi^4}\frac{E_\nu^2}{T^4}\frac{1}{e^{E_\nu/T}+1}$$

SN1987A

$$E_{\rm tot} = 3\times 10^{53}\ {\rm erg}$$

$$T = 5\ {\rm MeV}$$

SN spectrum benchmark scenarios

Spectrum will need to be calibrated by matching observations of nearby SN neutrinos to simulations

$$\phi_{\rm SN}(E_\nu) = \frac{1}{6}\frac{E_{\rm tot}}{\bar{E}}\left(\frac{E_\nu}{\bar{E}}\right)^{\alpha}\frac{e^{-(1+\alpha)E_\nu/\bar{E}}}{\Gamma(1+\alpha)\bar{E}/(1+\alpha)^{\alpha}}$$

$\alpha \simeq 2.3 \qquad T \simeq \bar{E}/3.15 \qquad =>$ FD spectrum

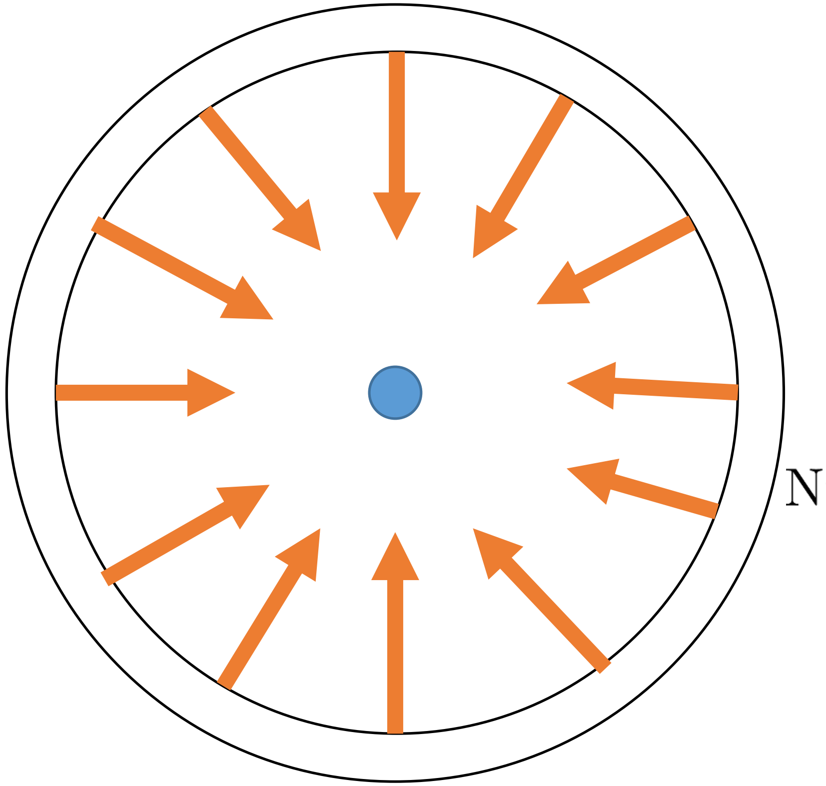
$$\alpha = 3 \qquad \bar{E} = 3.15T$$

$$E_{\rm tot} = 3\times 10^{53}\ \text{erg} \qquad T = 4, 5, 6, 8\ \text{MeV}$$

$$T = 6\ \text{MeV and 10-30\%}\ T = 8\ \text{MeV}$$

Diffuse Supernova Neutrino Background

Diffuse Supernova Neutrino Background



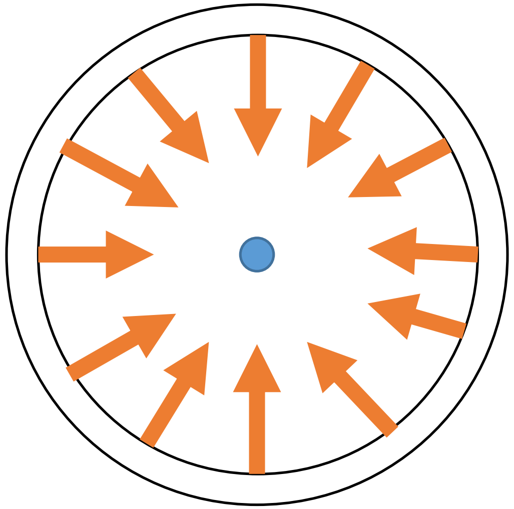
$$\frac{d\Phi}{dE_\nu} = \int_0^\infty \phi_{\rm SN}[E_\nu(1+z)]R_{\rm SN}(z)(1+z)\left|c\frac{dt}{dz}\right|dz$$

Number/Area/Time/Energy

Number/Volume/Time

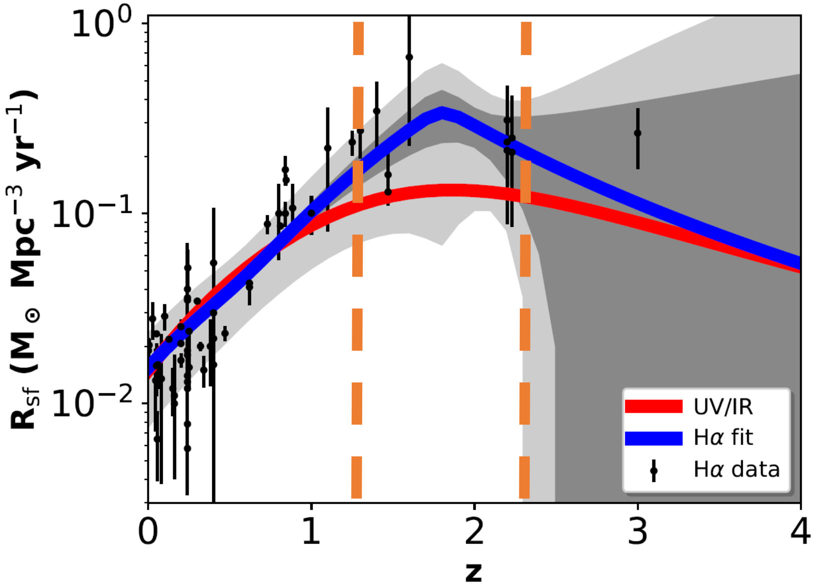
$$\left|\frac{dt}{dz}\right| = \frac{1}{H_0(1+z)}\frac{1}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

SN rate related to the SFRD



Massive stars are cosmologically short lived with a lifetime ~ 10 Myr

Birth rate and death rate of massive stars are essentially the same



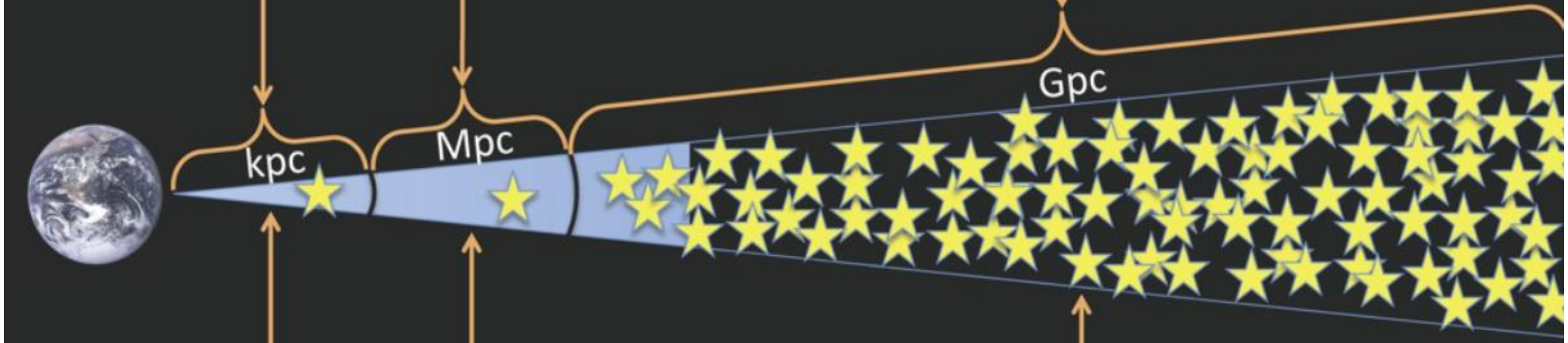
$$\frac{d\Phi}{dE_\nu} = \int_0^\infty \phi_{\rm SN}[E_\nu(1+z)] R_{\rm SN}(z)(1+z)\left|c\frac{dt}{dz}\right| dz$$

$$R_{\rm SN}(z) = \frac{\int_8^{100} dM\left(\frac{dN}{dM}\right)}{\int_{0.08}^{100} dM\left(M\frac{dN}{dM}\right)} R_{\rm SF}(z) = \frac{R_{\rm SF}(z)}{135M_\odot}$$

$$\frac{dN}{dM} \propto M^{-2.35}$$

Salpeter IMF

Distance, Strategy, Science!



N >> 1 : Burst

Rate ~ 0.01/yr

high statistics,
all flavors

N ~ 1 : Mini-Burst

Rate ~ 1/yr

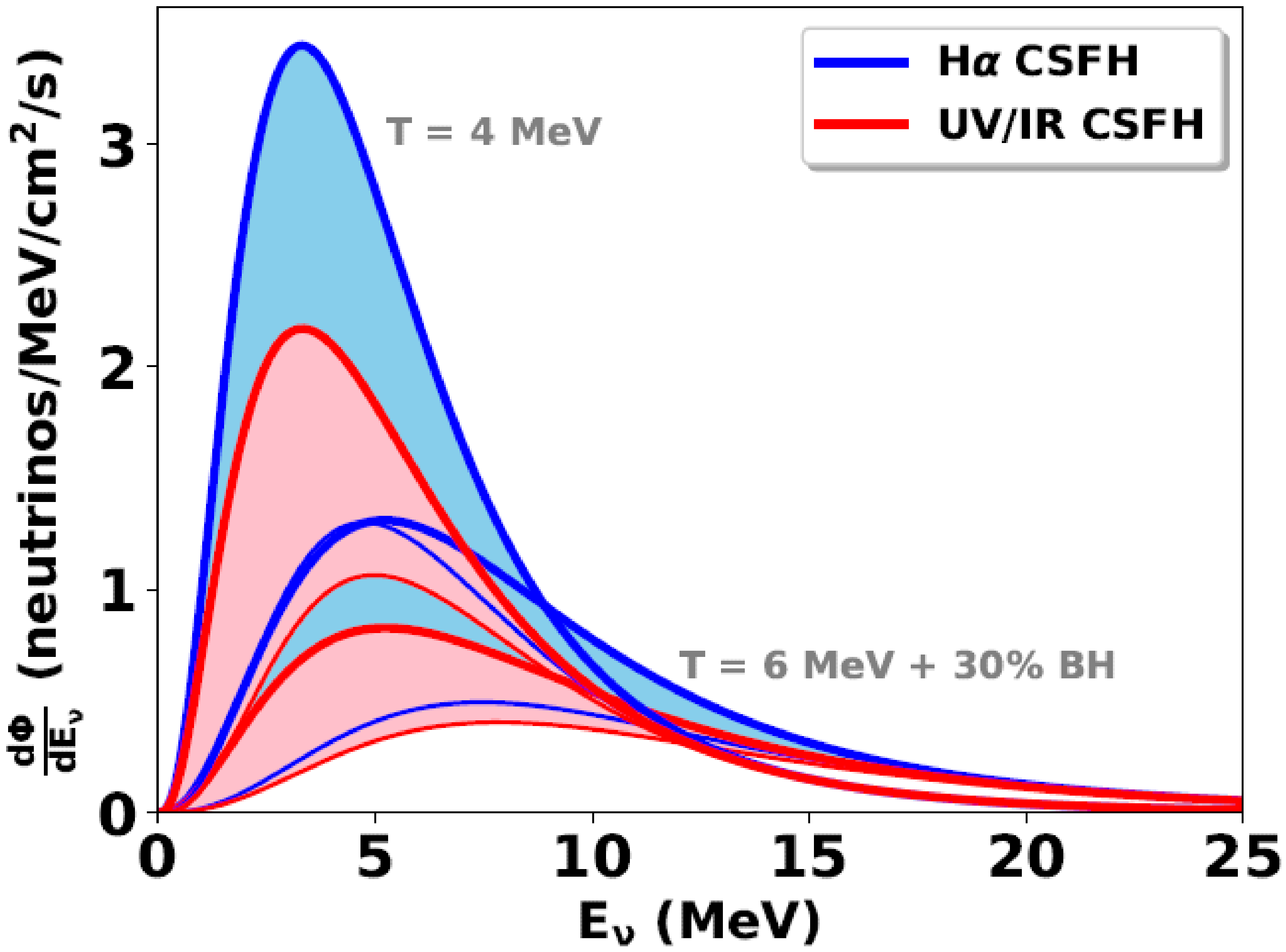
object identity,
burst variety

N << 1 : DSNB

Rate ~ 10^8/yr

cosmic rate,
average emission

Expected DSNB flux spectrum at earth



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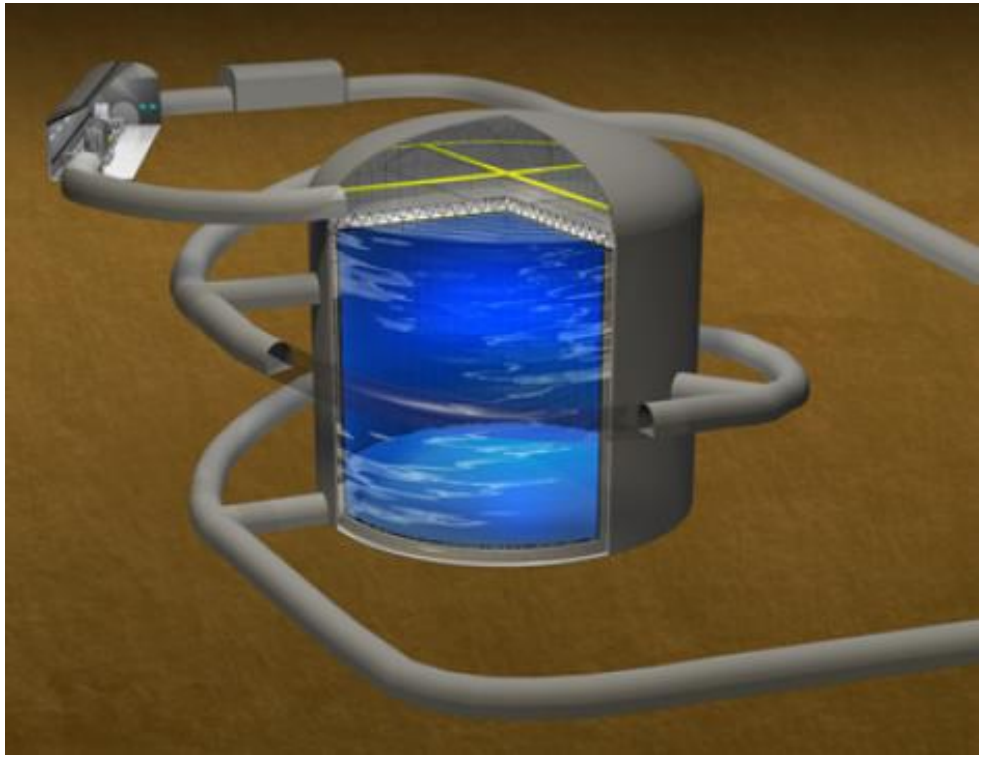
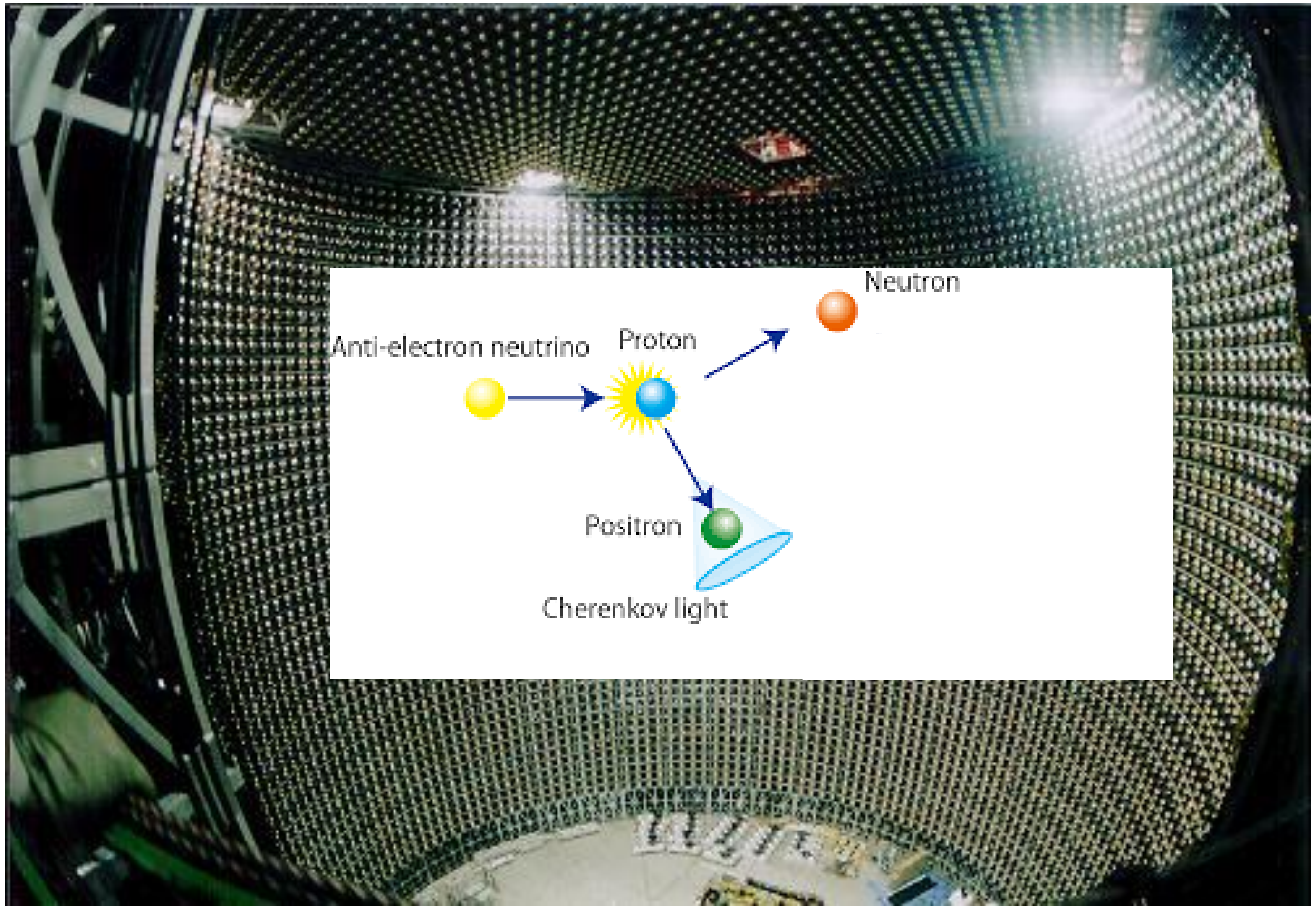
Measuring the DSNB at Hyper-Kamiokande

Neutrino detection at water Cerenkov experiments



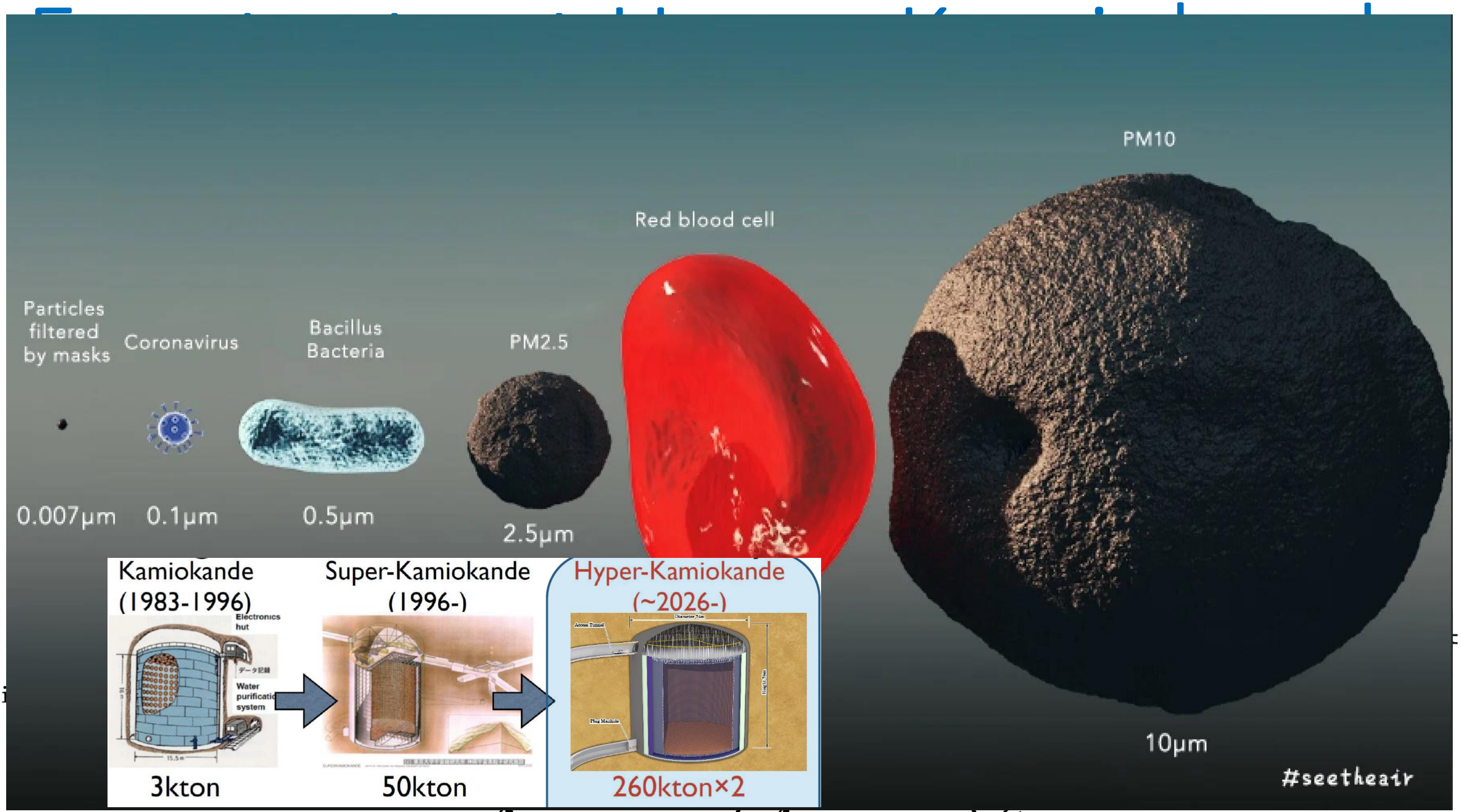
Hyper-Kamiokande Experiment



Timeline and exposures of various detectors

- Kamiokande –1983-1996 – 3 kton - Nobel prize 2002 (SN 1987A)
- Super Kamiokande (1996-current) – 50 kton - Nobel prize 2015 (Neutrino oscillations)
  - Currently SK-Gd
- Hyper Kamiokande (2025? -) – 260 x 2 kton - **? (DSNB?)**

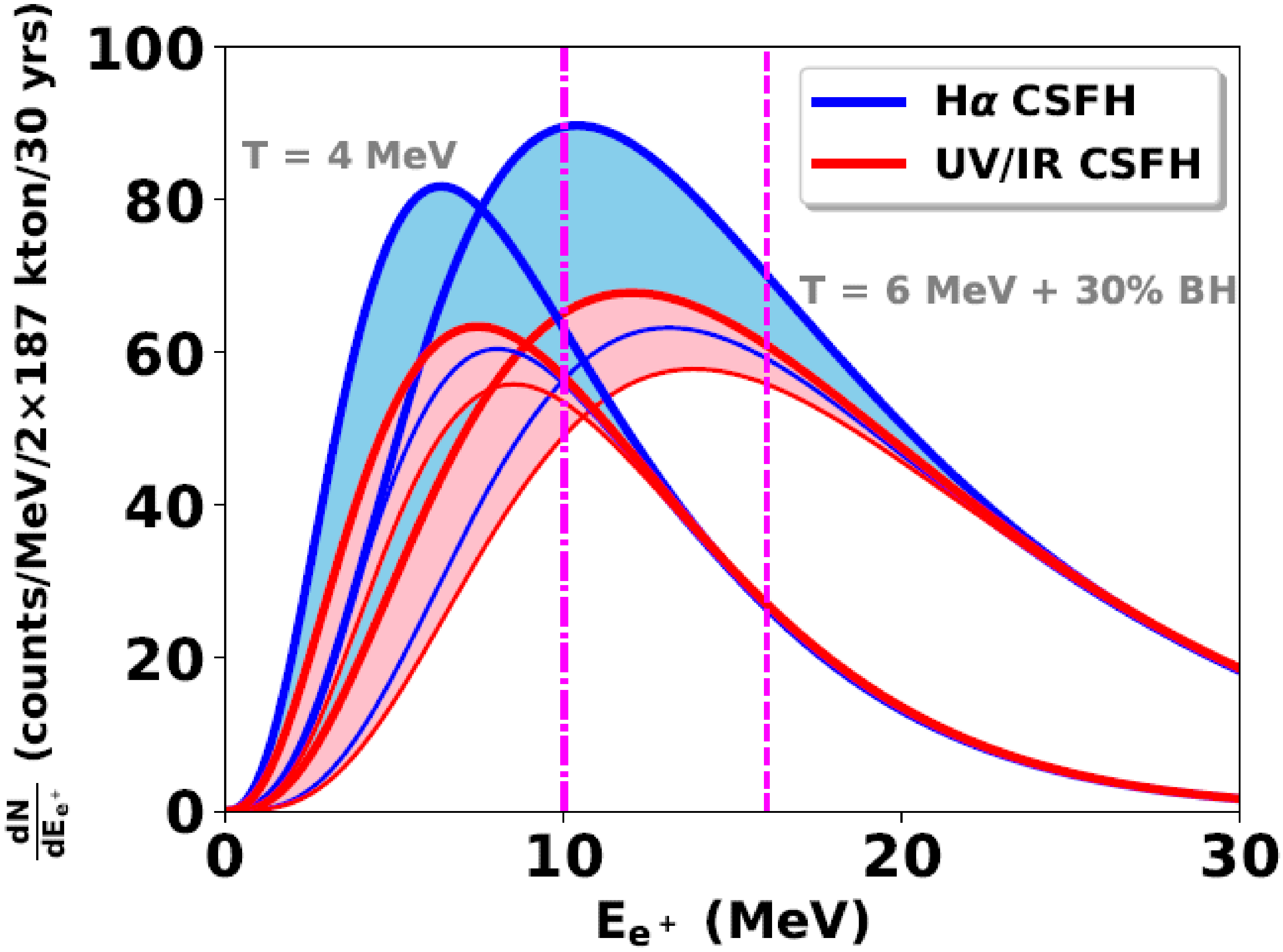
- **Each time a factor ~ 17 increase in fiducial mass**



σ_i

$$A_{\rm eff} \simeq (4\ \mu{\rm m})^2$$

Expected Positron spectrum at HyperKamiokande



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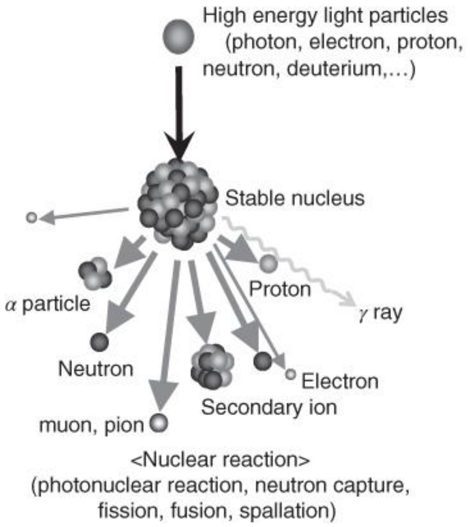
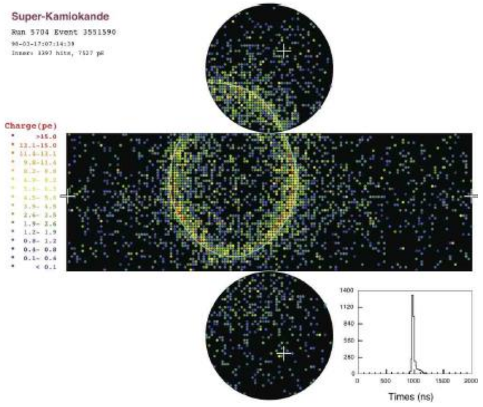
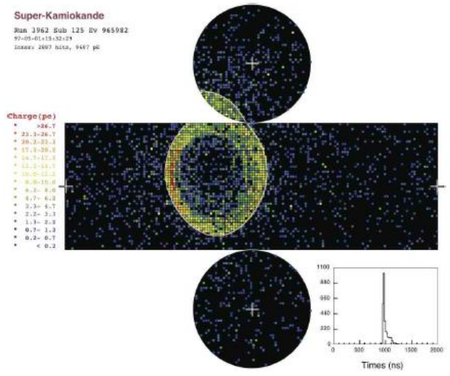
Backgrounds at Hyper Kamiokande

- Cosmic muon spallation
- Invisible muon
- Reactor neutrinos
- Atmospheric neutrinos Neutral Current
- Atmospheric neutrinos Charged Current

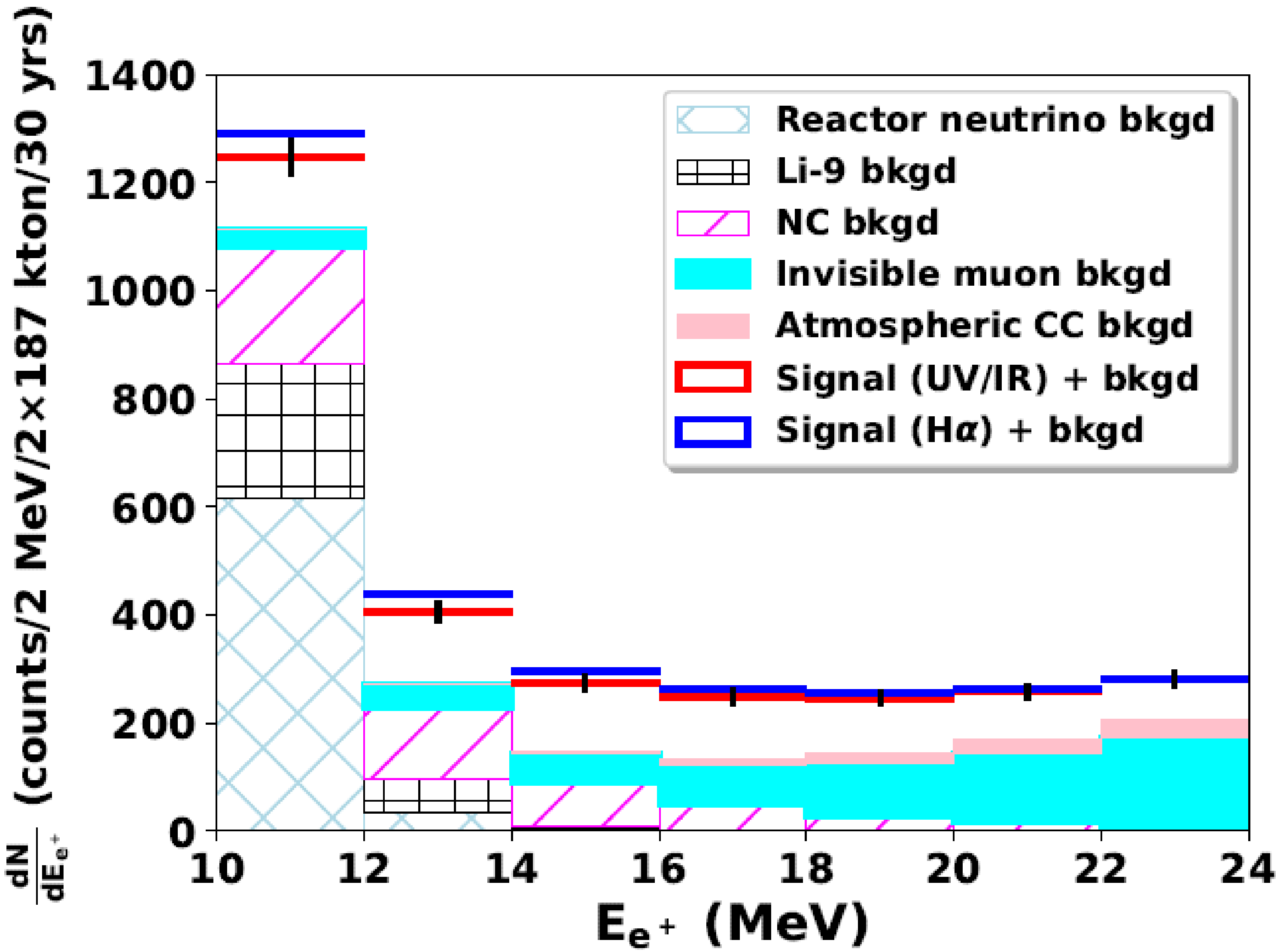
Others: Solar neutrinos, pion fakes







Expected observations at HK-Gd over 30 years



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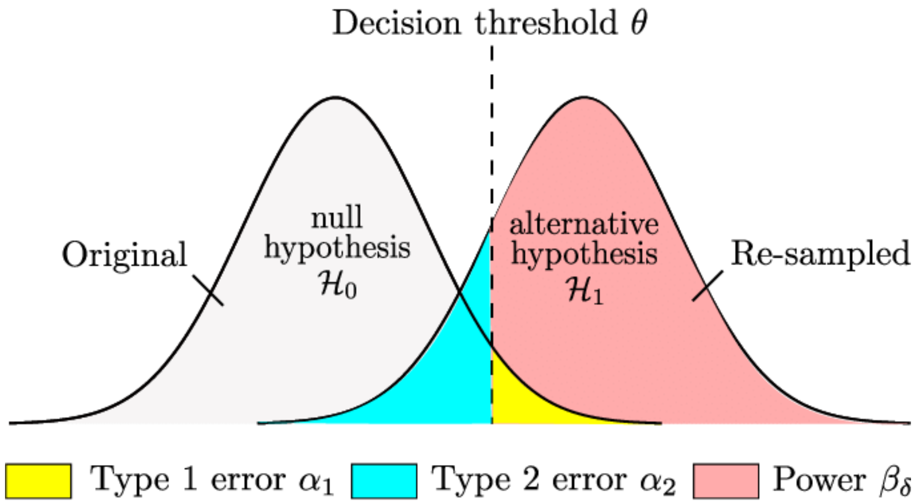
Discriminating between CSFHs with neutrinos

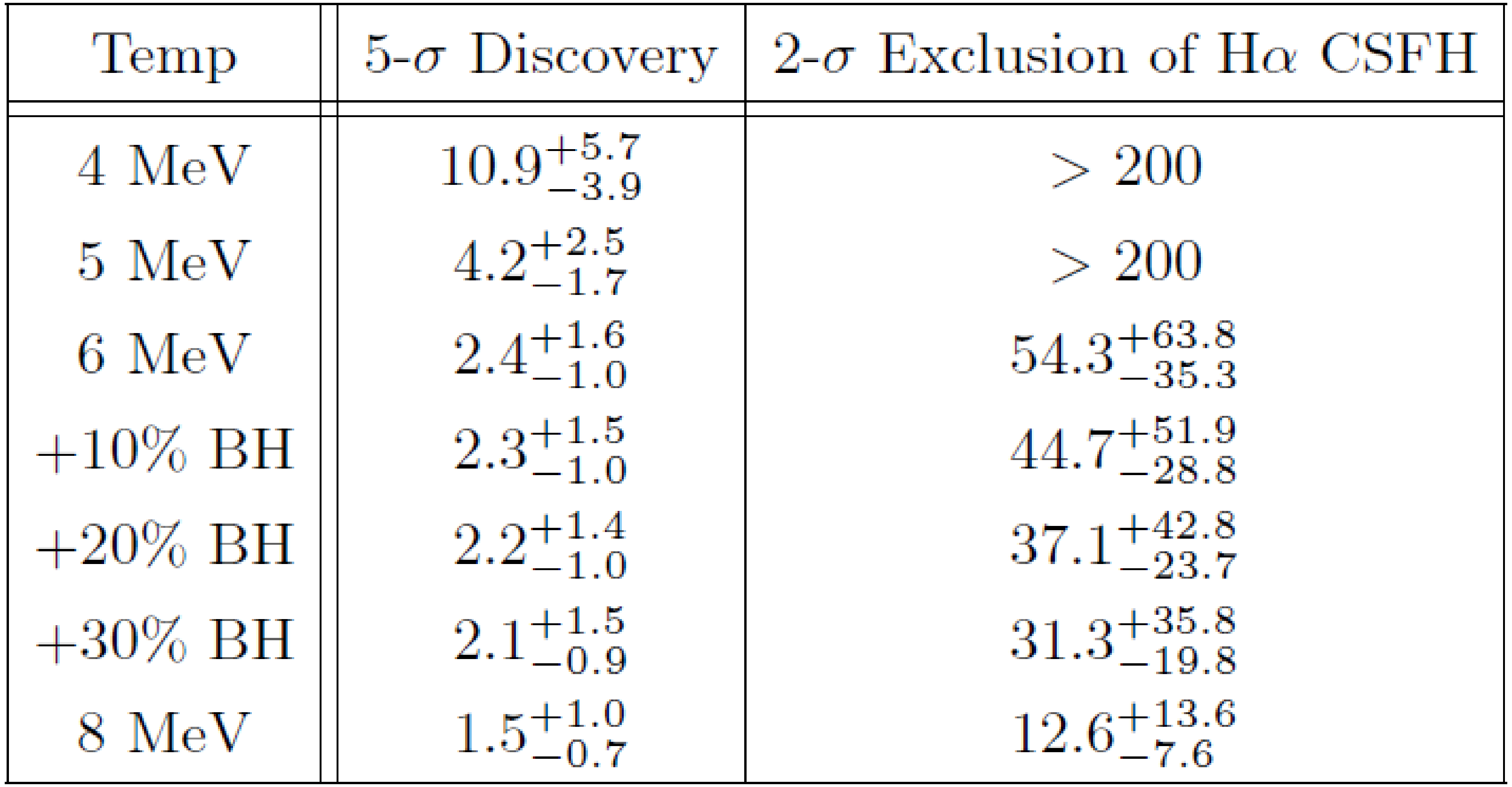
Chi-squared analysis for discovery/exclusion

- Let us assume that the UV/IR CSFH of Madau et al is the correct one
- For discovery –
  - take null hypothesis to be background only – this specifies predictions
  - Now generate pseudo-data assuming background + DSNB signal corresponding to UV/IR CSFH
- For exclusion of alternative Halpha CSFH-
  - Take null hypothesis to be background + DSNB signal corresponding to Halpha CSFH
  - Now generate data assuming background + DSNB signal corresponding to UV/IR CSFH

$$\chi^2 \equiv \sum_i \left(\frac{\mathrm{obs}_i - \mathrm{pred}_i}{\sigma_i} \right)^2$$



Discovery and exclusion potential of HK-Gd



Temp	5-σ Discovery	2-σ Exclusion of Hα CSFH
4 MeV	$10.9^{+5.7}_{-3.9}$	> 200
5 MeV	$4.2^{+2.5}_{-1.7}$	> 200
6 MeV	$2.4^{+1.6}_{-1.0}$	$54.3^{+63.8}_{-35.3}$
+10% BH	$2.3^{+1.5}_{-1.0}$	$44.7^{+51.9}_{-28.8}$
+20% BH	$2.2^{+1.4}_{-1.0}$	$37.1^{+42.8}_{-23.7}$
+30% BH	$2.1^{+1.5}_{-0.9}$	$31.3^{+35.8}_{-19.8}$
8 MeV	$1.5^{+1.0}_{-0.7}$	$12.6^{+13.6}_{-7.6}$

Time in years, assuming UV/IR CSFH is the correct one

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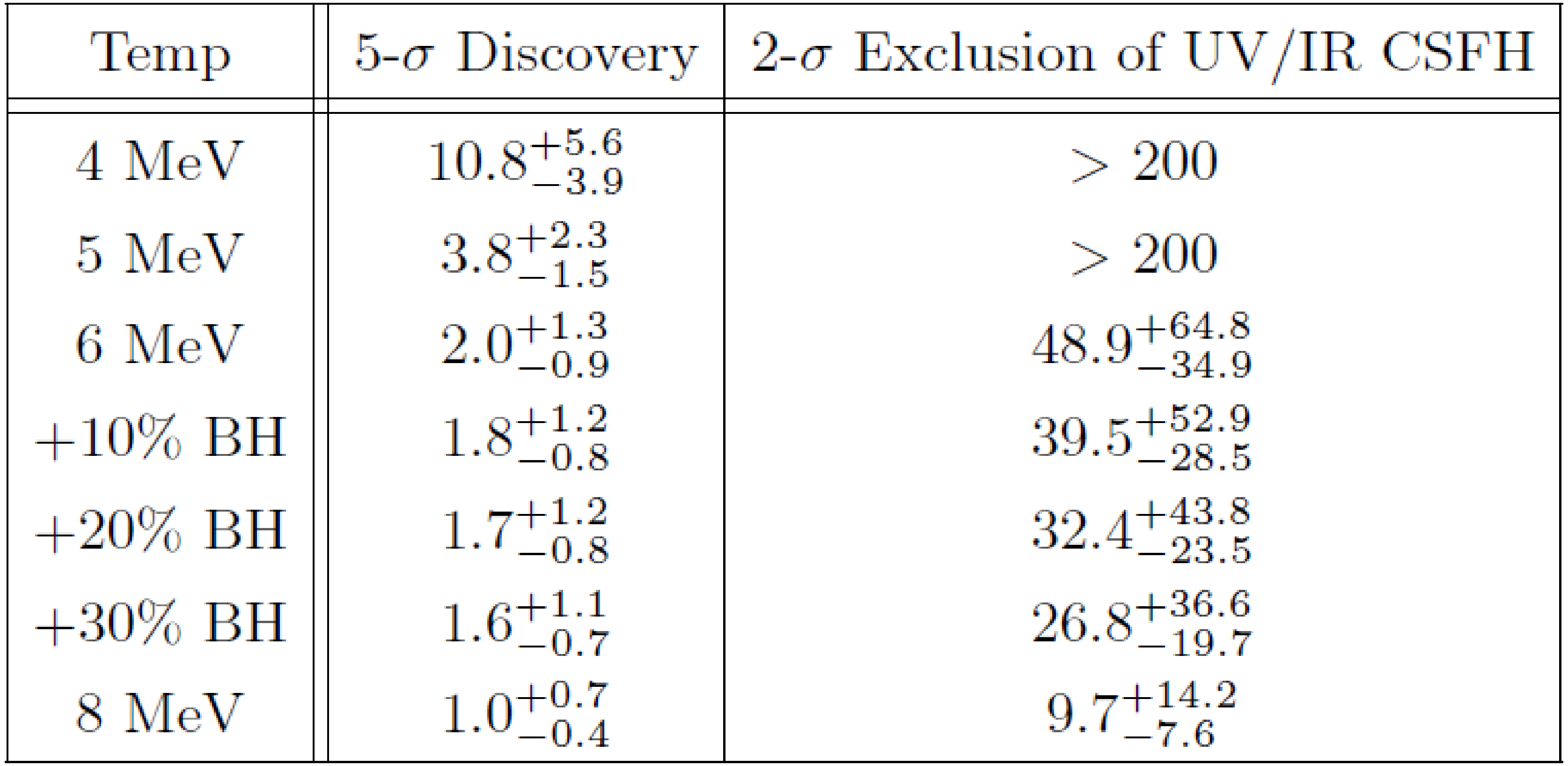
Discovery and exclusion potential of HK-Gd



Temp	5-σ Discovery	2-σ Exclusion of UV/IR CSFH
4 MeV	$10.8^{+5.6}_{-3.9}$	> 200
5 MeV	$3.8^{+2.3}_{-1.5}$	> 200
6 MeV	$2.0^{+1.3}_{-0.9}$	$48.9^{+64.8}_{-34.9}$
+10% BH	$1.8^{+1.2}_{-0.8}$	$39.5^{+52.9}_{-28.5}$
+20% BH	$1.7^{+1.2}_{-0.8}$	$32.4^{+43.8}_{-23.5}$
+30% BH	$1.6^{+1.1}_{-0.7}$	$26.8^{+36.6}_{-19.7}$
8 MeV	$1.0^{+0.7}_{-0.4}$	$9.7^{+14.2}_{-7.6}$

Time in years, assuming Hα CSFH is the correct one

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Expectation from SK-Gd, and HK without Gd

SK-Gd:

- Discovery possible at 22.5 kton SK-Gd only if T = 6, 8 MeV CSFH with 20-30 year exposure
- Alternative CSFH cannot be ruled out

HK without Gd:

- Discovery possible at HK without Gd (16 MeV threshold) for T = 5, 6, 8 MeV with 8-30 years of exposure
- Alternative CSFH cannot be ruled out

Need both the large volume of HK as well as low threshold sensitivity with Gd loading!

Factors limiting detection threshold of cosmic noon neutrinos

- Energy dependence of neutrino cross-section
- Detector backgrounds – limited by reactor neutrinos with Gd, spallation without Gd

Need a favorable neutrino spectrum with high T for detection

Summary and Conclusions

- Mild discrepancy in the inferred SFRD at cosmic noon z ~ 2
- Diffuse Supernova Neutrino Background (DSNB) detection has the potential to resolve this discrepancy
- Requires a large volume, low threshold detector like HK-Gd
- Discovery of DSNB within 10 years, exclusion of alternative CSFH within 10-30 years for high CC SN temperatures
- Need to calibrate the CC SN spectrum to observations of local SNe

Questions? Comments? Suggestions?

Why look for neutrino signals and not light signals from CC SN?

- Light signals – unreliable measure of SFRD
  - Poor statistics
  - Dust obscuration
  - Possible dark collapses

- Neutrino signals
  - 99% energy release to neutrinos
  - Full sky coverage
  - No dust obscuration
  - Low detection efficiency

Outline

- Motivation
- Diffuse supernova neutrino background
- DSNB detection at Hyper-Kamiokande and backgrounds
- Discrimination of CSFH hypothesis
- Summary and Conclusions

Astrophysical background

- How star formation works and why we expect a peak in the CSFH
- Observational probes of the CSFH and discrepancy

Conditions for Star formation

- Neutral Hydrogen - HI regions (molecular H_2)
- High density, low temperature
- Scale of gas clouds
- Scatters UV/visible light, transmits IR
- Reemits IR
- Emission is complex and depends on dust composition

Cosmic star formation rate

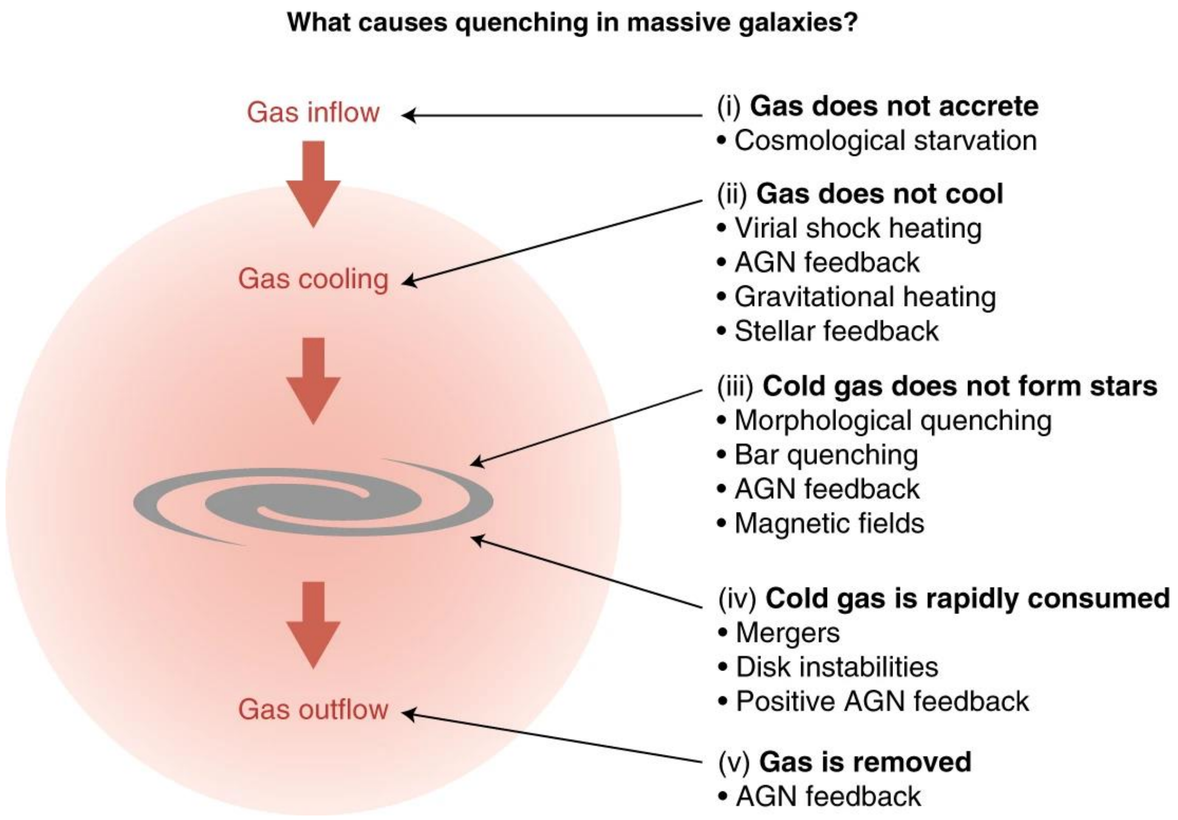
CSFR = star formation efficiency X mass density of galaxy halos

Involves complex baryonic physics

Feedback, AGNs, SN winds, cosmological starvation, mergers

Well understood growth of structure

Star formation in galaxies has turned off. Why?



What causes quenching in massive galaxies?

(i) **Gas does not accrete**
- Cosmological starvation

(ii) **Gas does not cool**
- Virial shock heating
- AGN feedback
- Gravitational heating
- Stellar feedback

(iii) **Cold gas does not form stars**
- Morphological quenching
- Bar quenching
- AGN feedback
- Magnetic fields

(iv) **Cold gas is rapidly consumed**
- Mergers
- Disk instabilities
- Positive AGN feedback

(v) **Gas is removed**
- AGN feedback

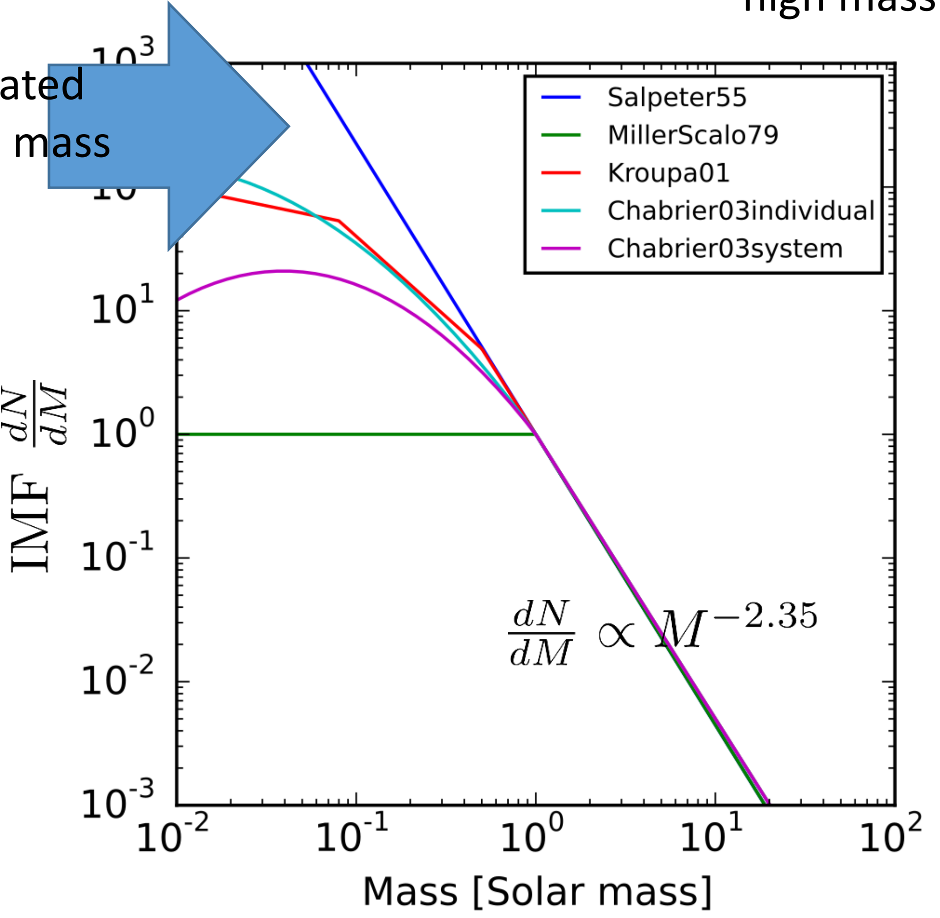
Star formation quenching in massive galaxies

Allison Man & Sirio Belli, *Nature Astronomy* **volume 2**, pages 695–697 (2018)

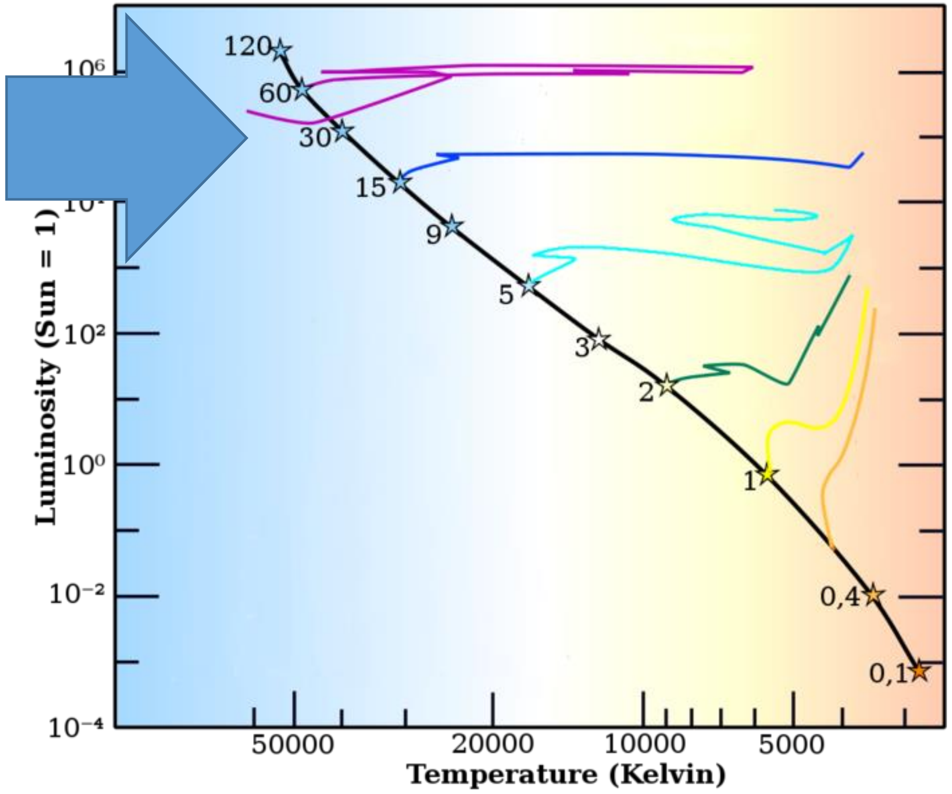
Observational probes of the cosmic star formation rate

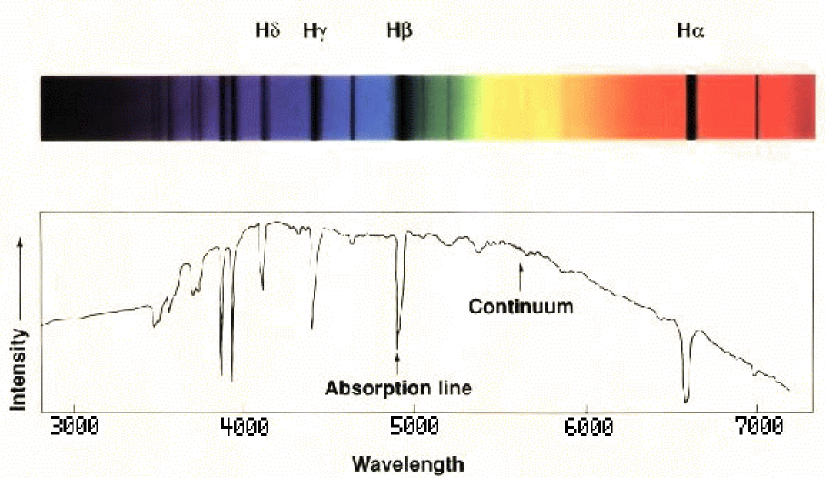
Mapping light to SFRD

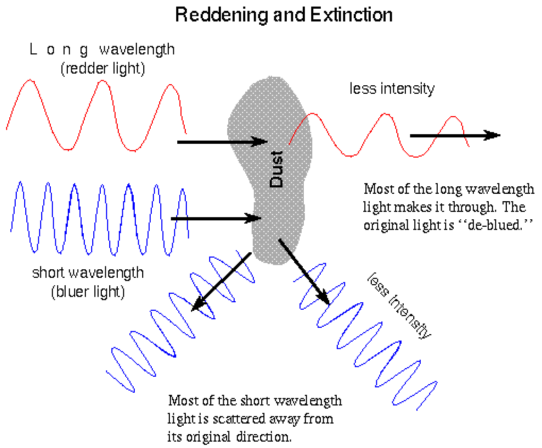
Mass dominated by low mass stars



UV emission dominated by high mass stars

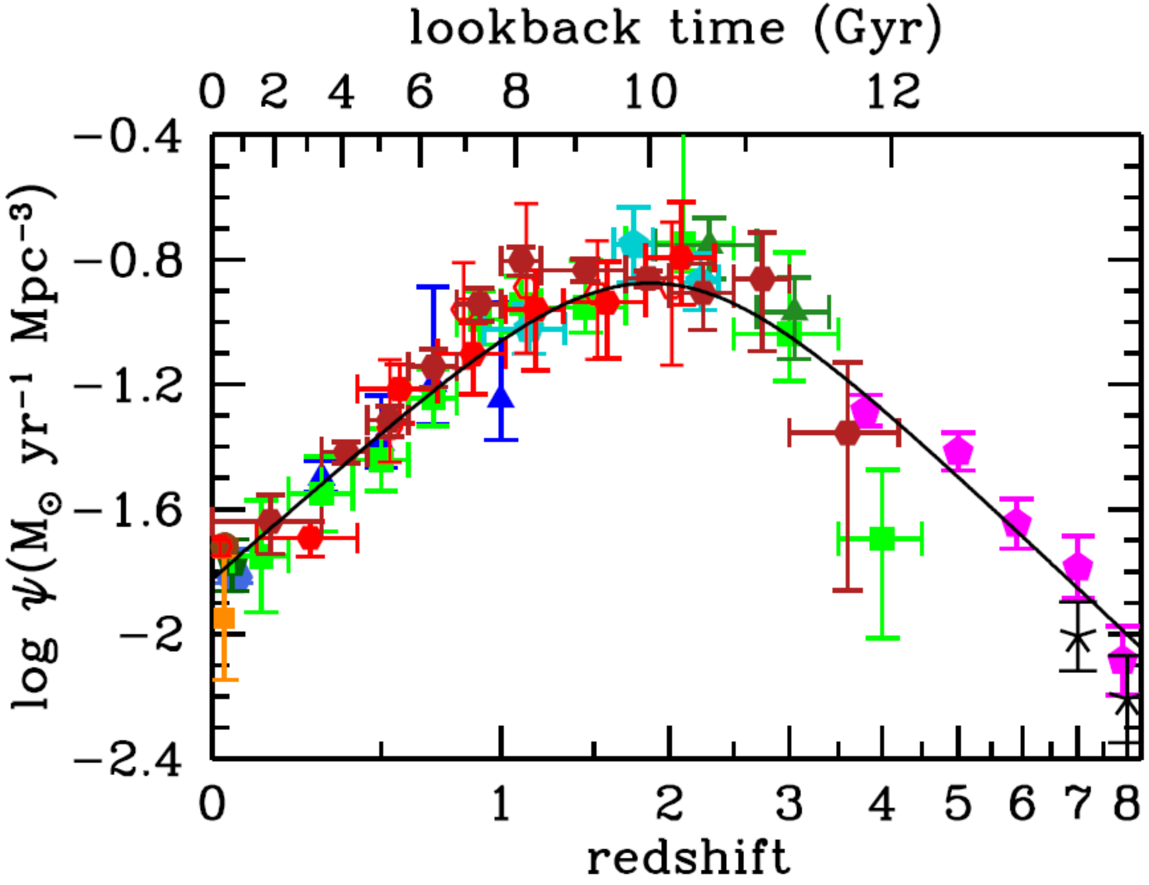






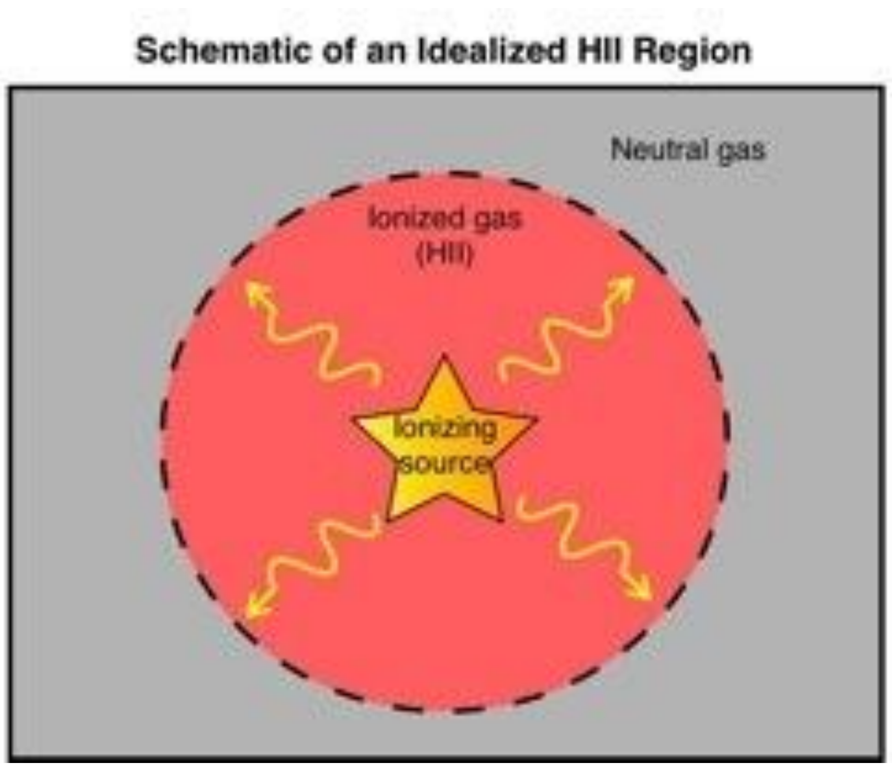
UV/IR inferred cosmic star formation history

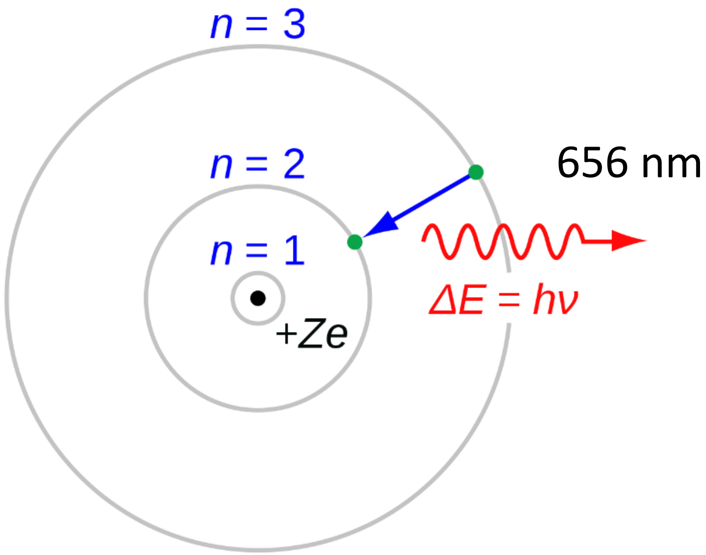
- Expected UV spectrum depends on IMF, extinction, metallicity, galaxy age
- Expected IR spectrum related to UV emission + ISM composition and dust emission



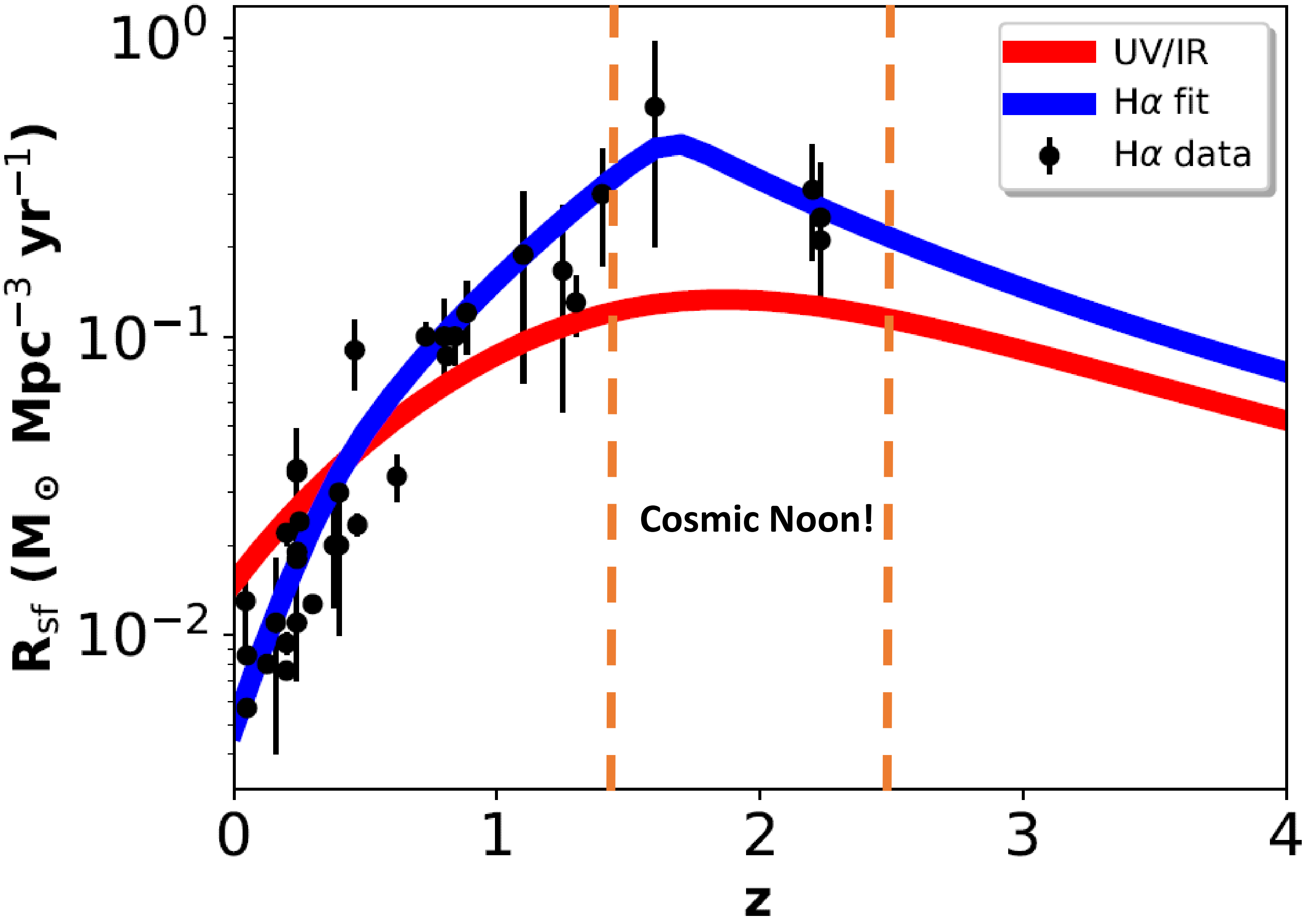
Madau and Dickinson 2014

Hα emission as a probe of the CSFH





Inferences of CSFH from observations are in conflict



astro-ph/2007.03976 (Riya and VR)