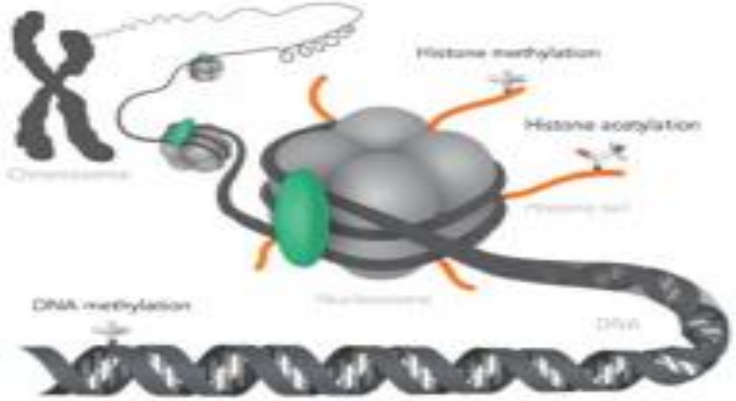
Epigenetics and cancer

National Cancer Institute

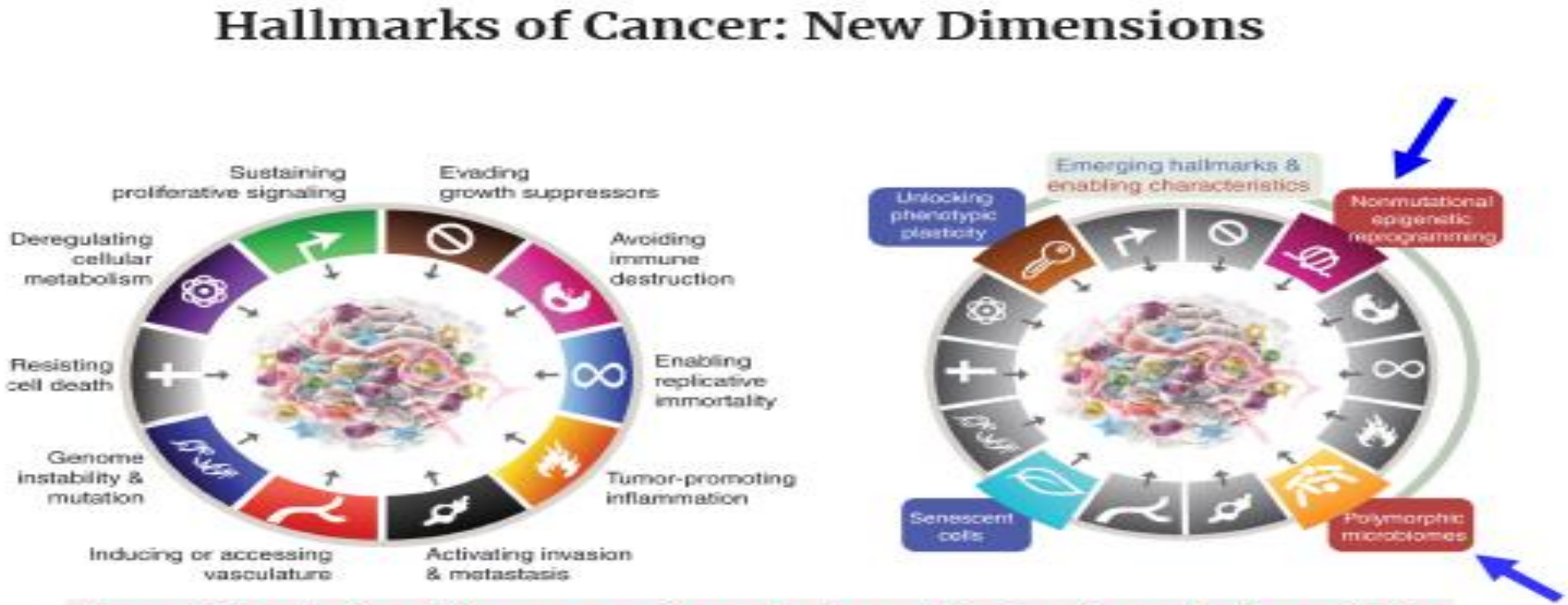
Epigenetics and Cancer



Mukesh Verma, Ph.D.
Chief, Methods and Technologies Branch
Program Director,
Epidemiology and Genomics Research Program
DCCPS, NCI, NIH

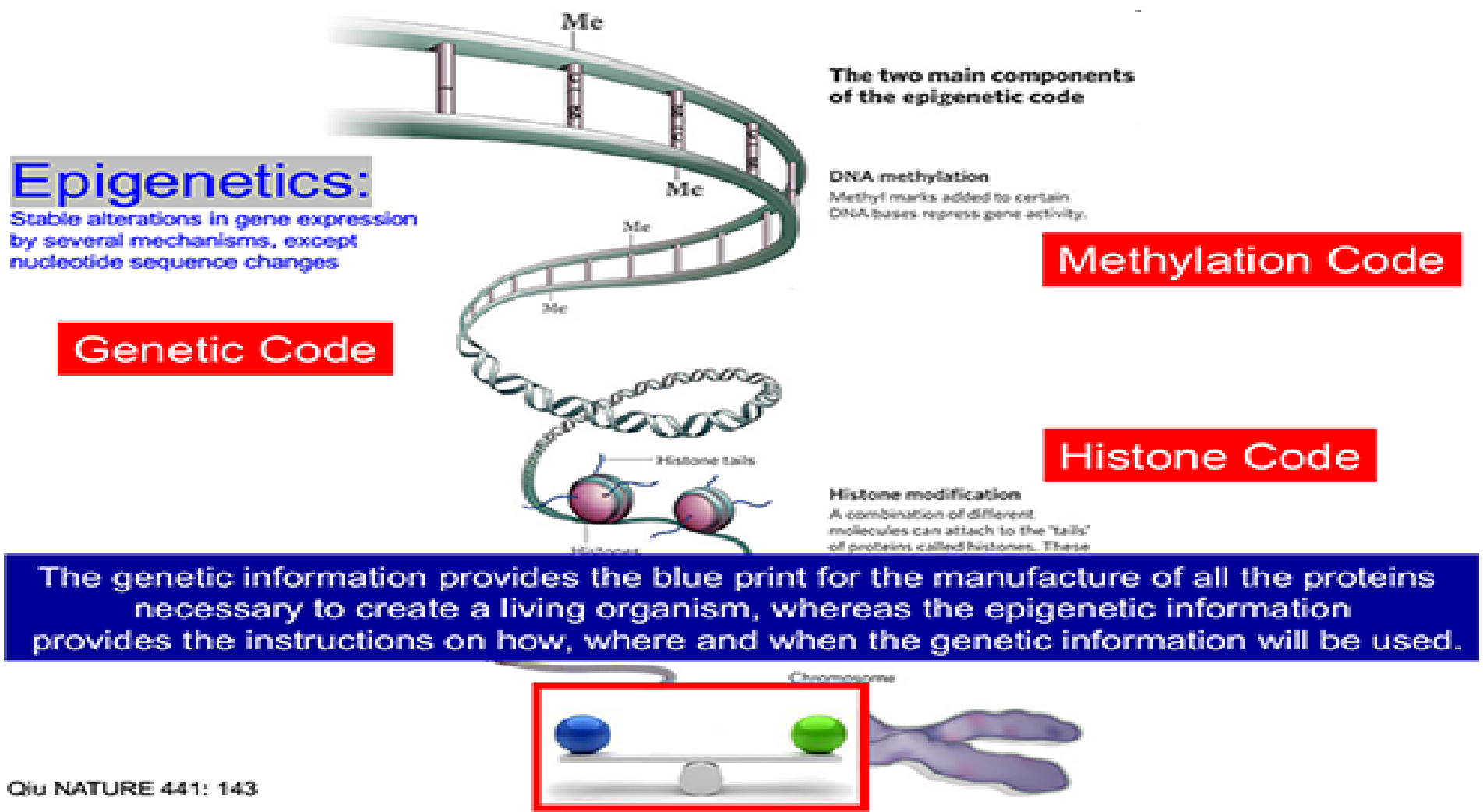
Fig. Credit: https://horizondiscovery.com/en/applications/cell-line/epigenetics

Hallmarks of cancer



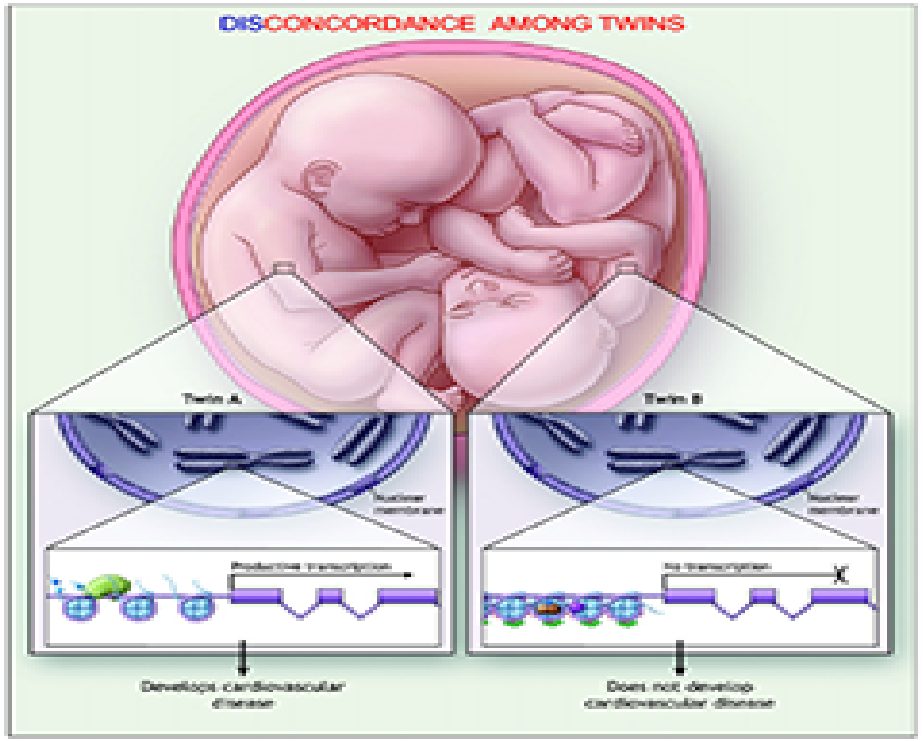
Epigenetics

Epigenetics



DNA and destiny

The choices you make
can change your genes
-- and those of your kids.



Epigenetic predisposition to angiogenesesis? Individual? Populations?

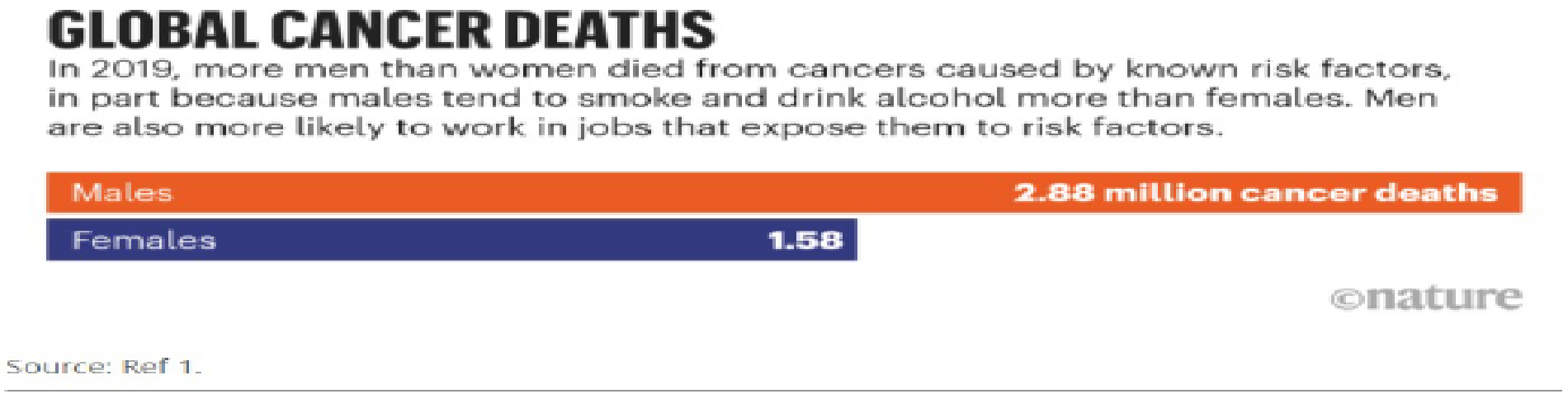
Pharmacogenomics and pharmacoepigenomics (personalized medicine)

Microenvironment, microbiome, and gene expression

GWAS and EWAS

Adapted from Matouk and Marsden Circ Res 102:873

Global cancer deaths

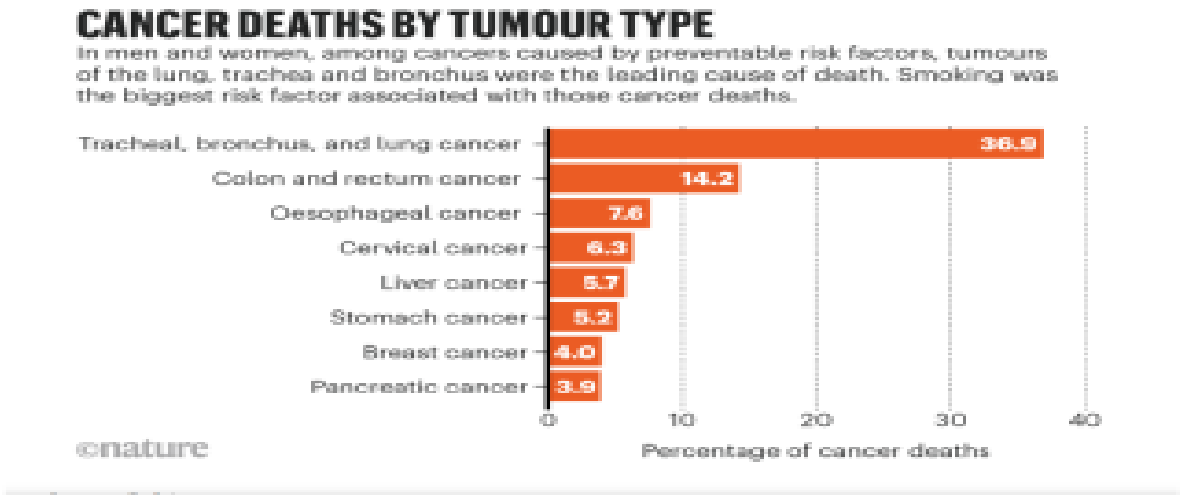


Source: Ref 1.

https://www.nature.com/articles/d41586-022-02355-x

GBD 2019 Cancer Risk Factors Collaborators *Lancet* **400**, 563–591 (2022).

Cancer tumor deaths



doi: https://doi.org/10.1038/d41586-022-02355-

Cancer continuum

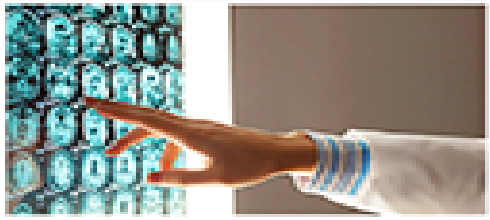
DCCPS covers cancer continuum

Prevention

Tobacco, physical activity, diet, sun, environment, HPV immunization

Early Detection

Breast, cervical, colorectal cancer screening



Diagnosis

Incidence, Stage at diagnosis

Treatment

Trends in cancer treatment

Life After Cancer

Financial burden of cancer care, Cancer survivorship

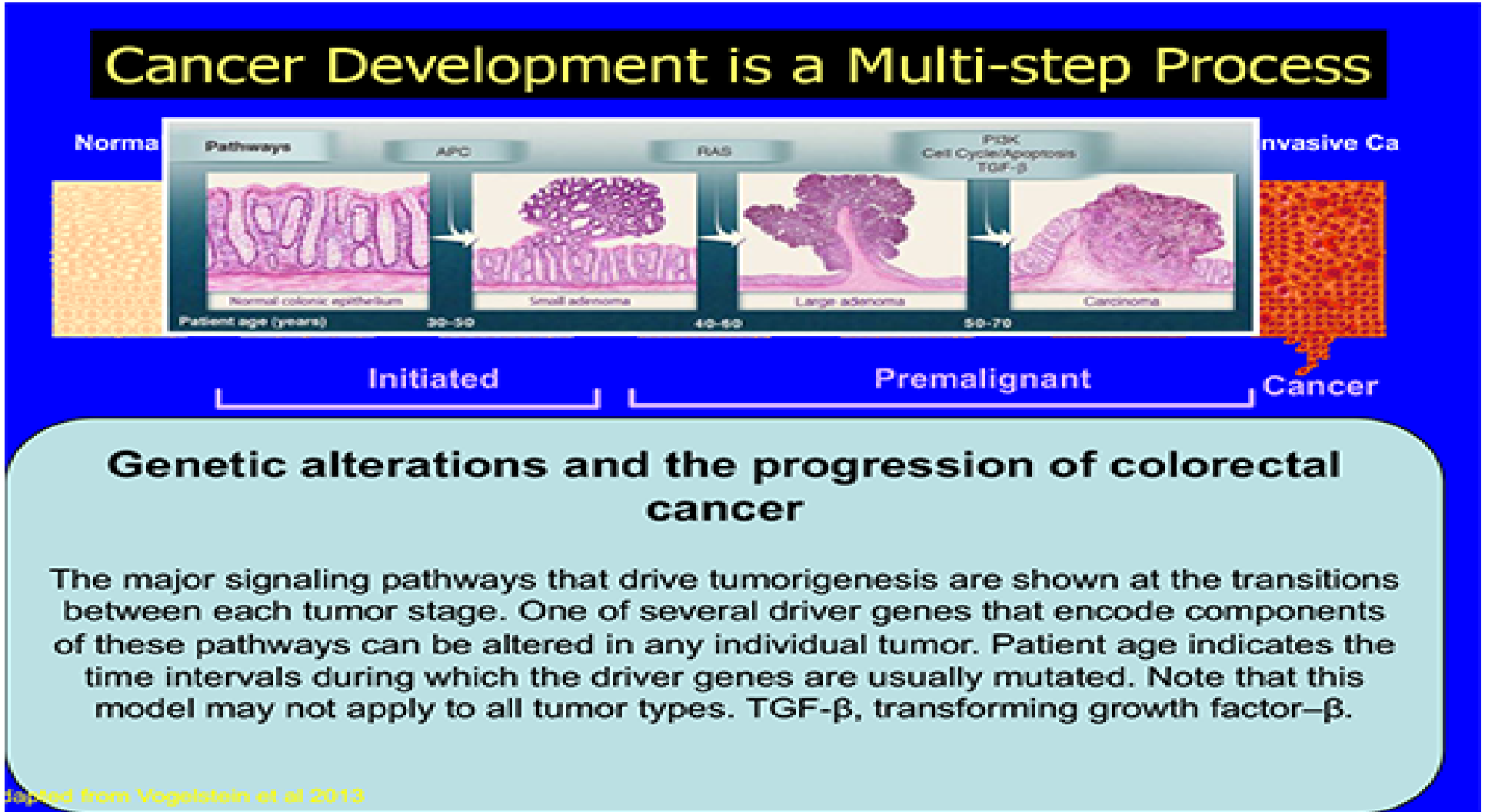
End of Life

Mortality, Person – years of life lost

Prevention → Cancer recurrence, Secondary cancer

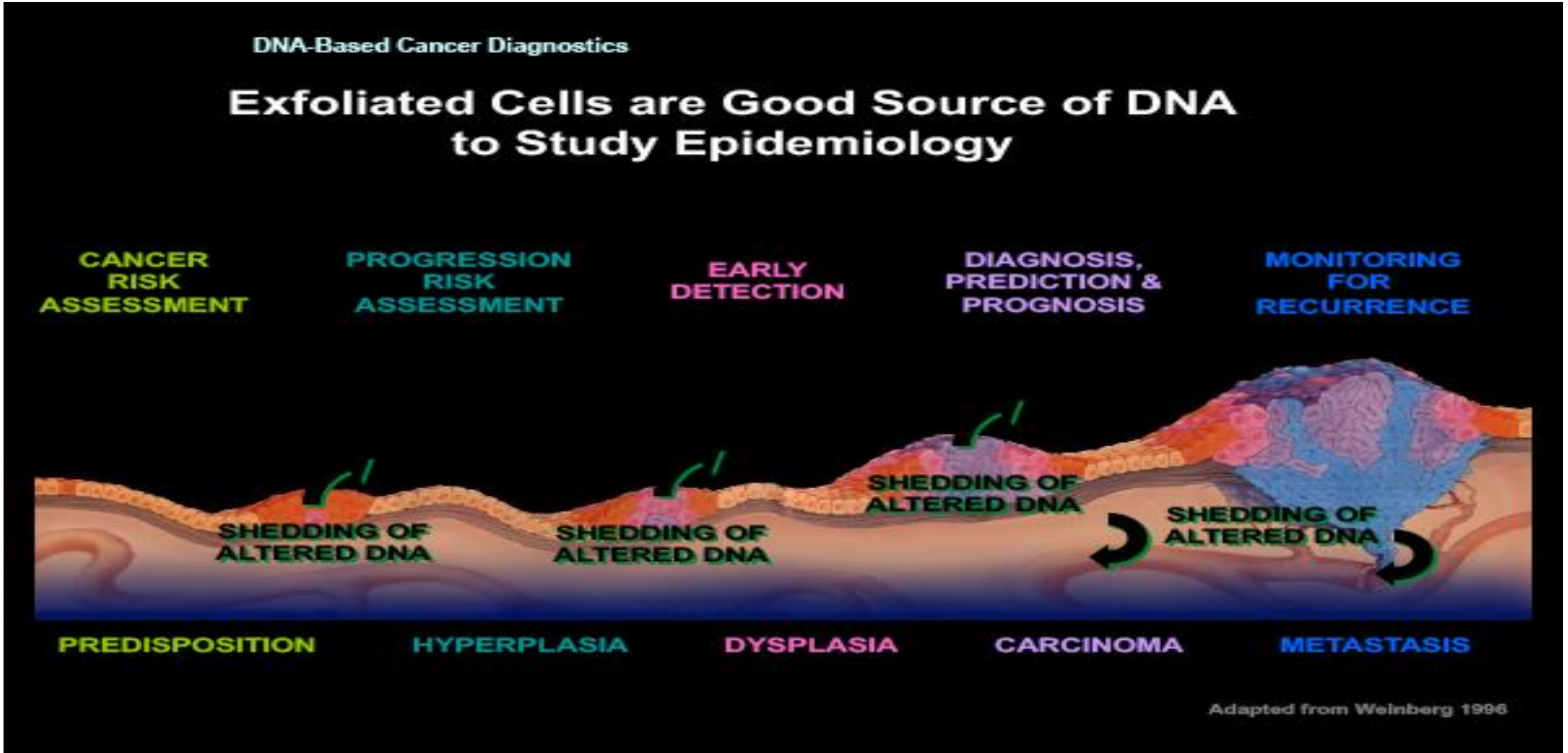
Prevention: restoring transcription, halting progression, or stopping metastasis

Cancer development

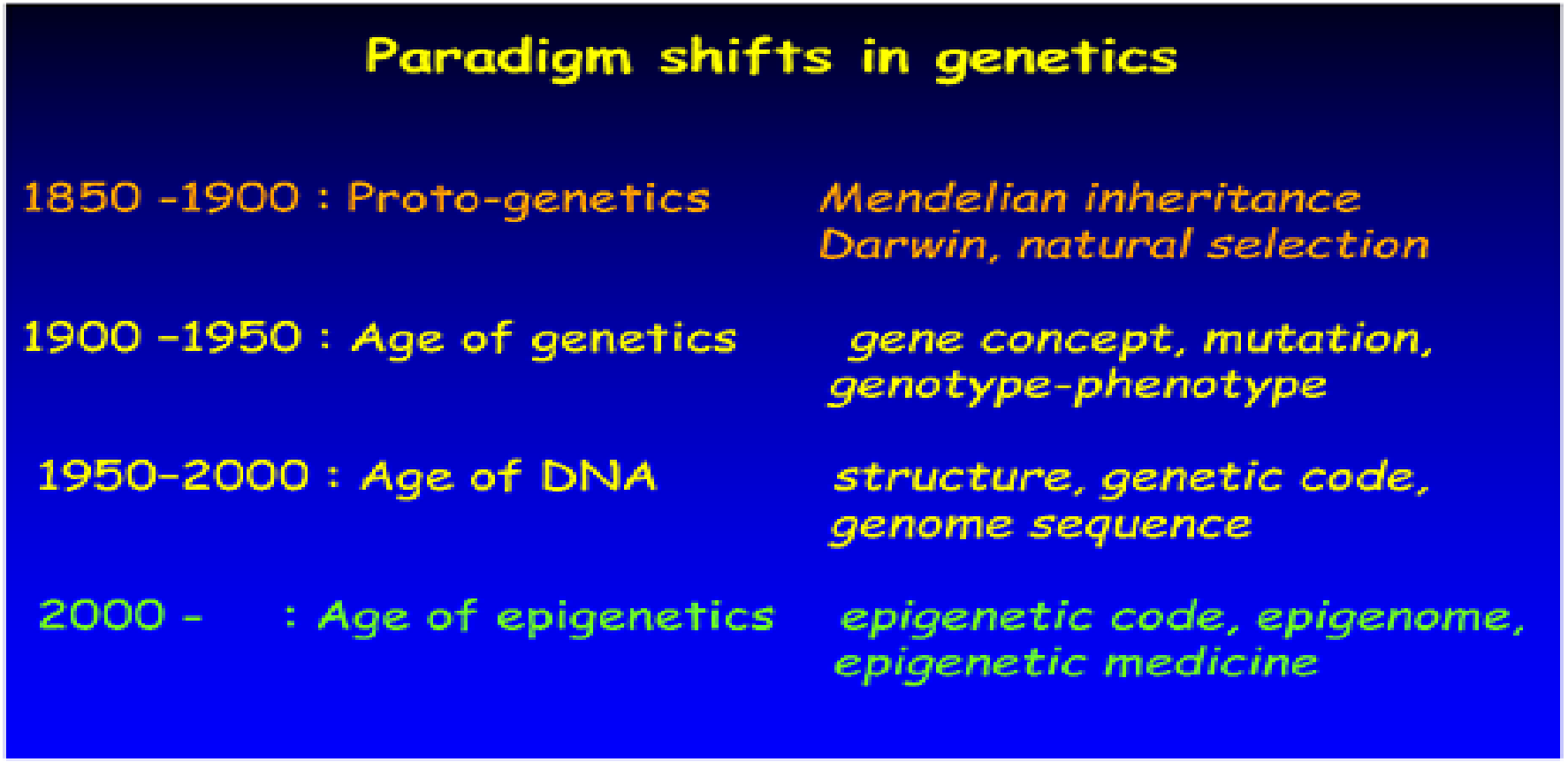


Adapted from Vogelstein et al 2013

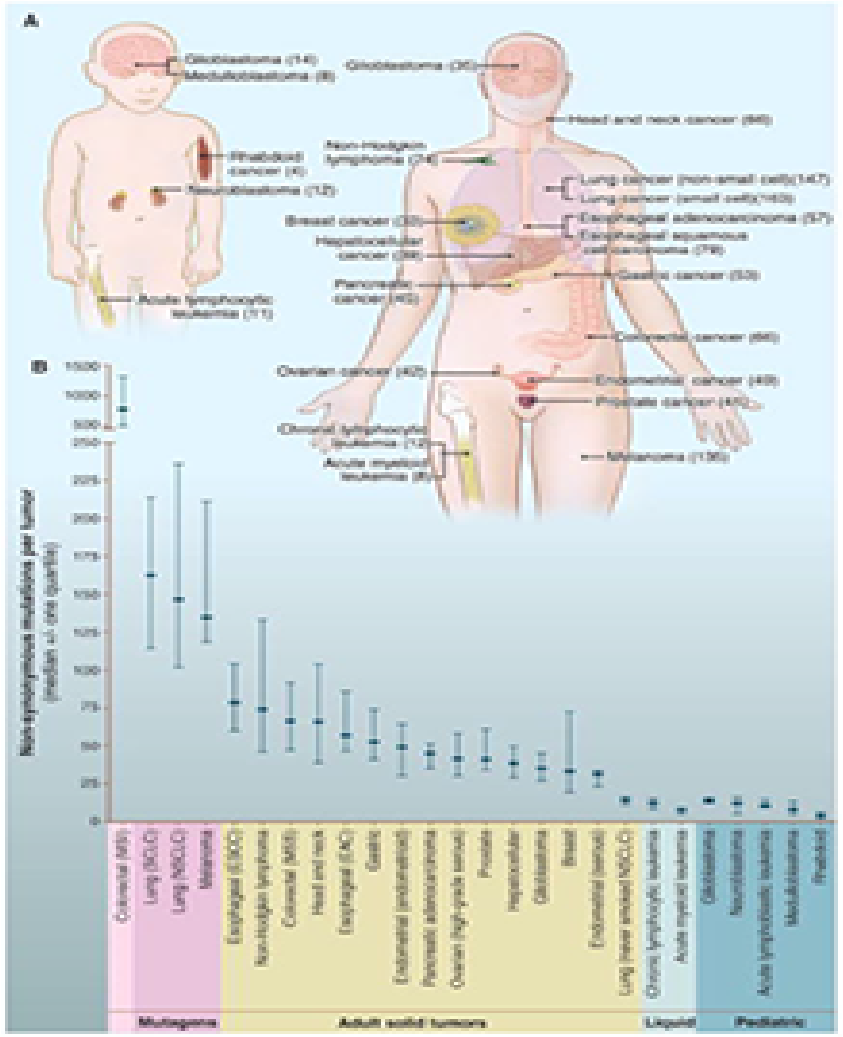
DNA sources


DNA-Based Cancer Diagnostics
Exfoliated Cells are Good Source of DNA to Study Epidemiology
CANCER RISK ASSESSMENT
PROGRESSION RISK ASSESSMENT
EARLY DETECTION
DIAGNOSIS, PREDICTION & PROGNOSIS
MONITORING FOR RECURRENCE
SHEDDING OF ALTERED DNA
SHEDDING OF ALTERED DNA
SHEDDING OF ALTERED DNA
SHEDDING OF ALTERED DNA
PREDISPOSITION
HYPERPLASIA
DYSPLASIA
CARCINOMA
METASTASIS
Adapted from Weinberg 1996

Paradigm shift



Genome landscape

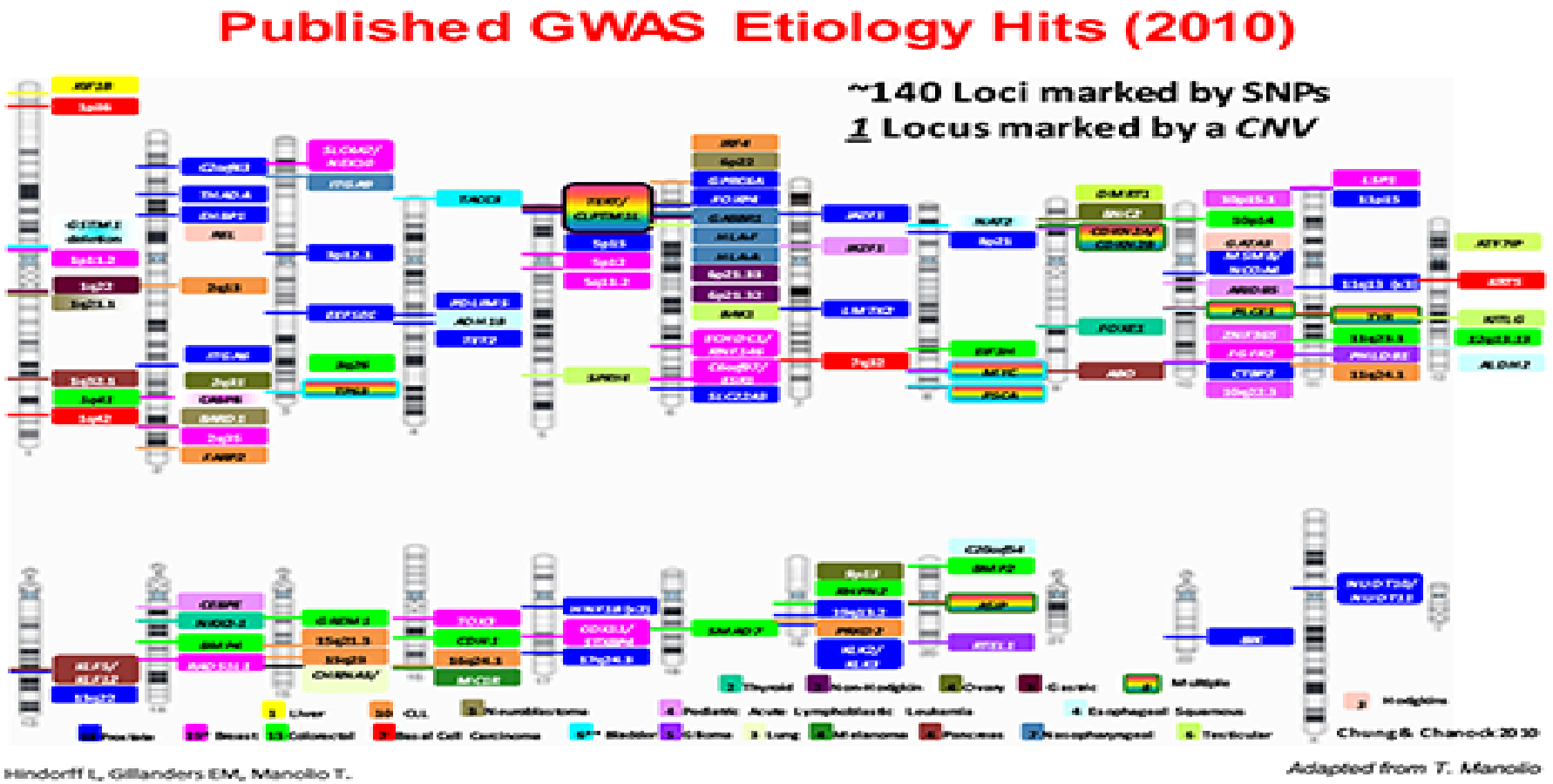


CANCER GENOME LANDSCAPE

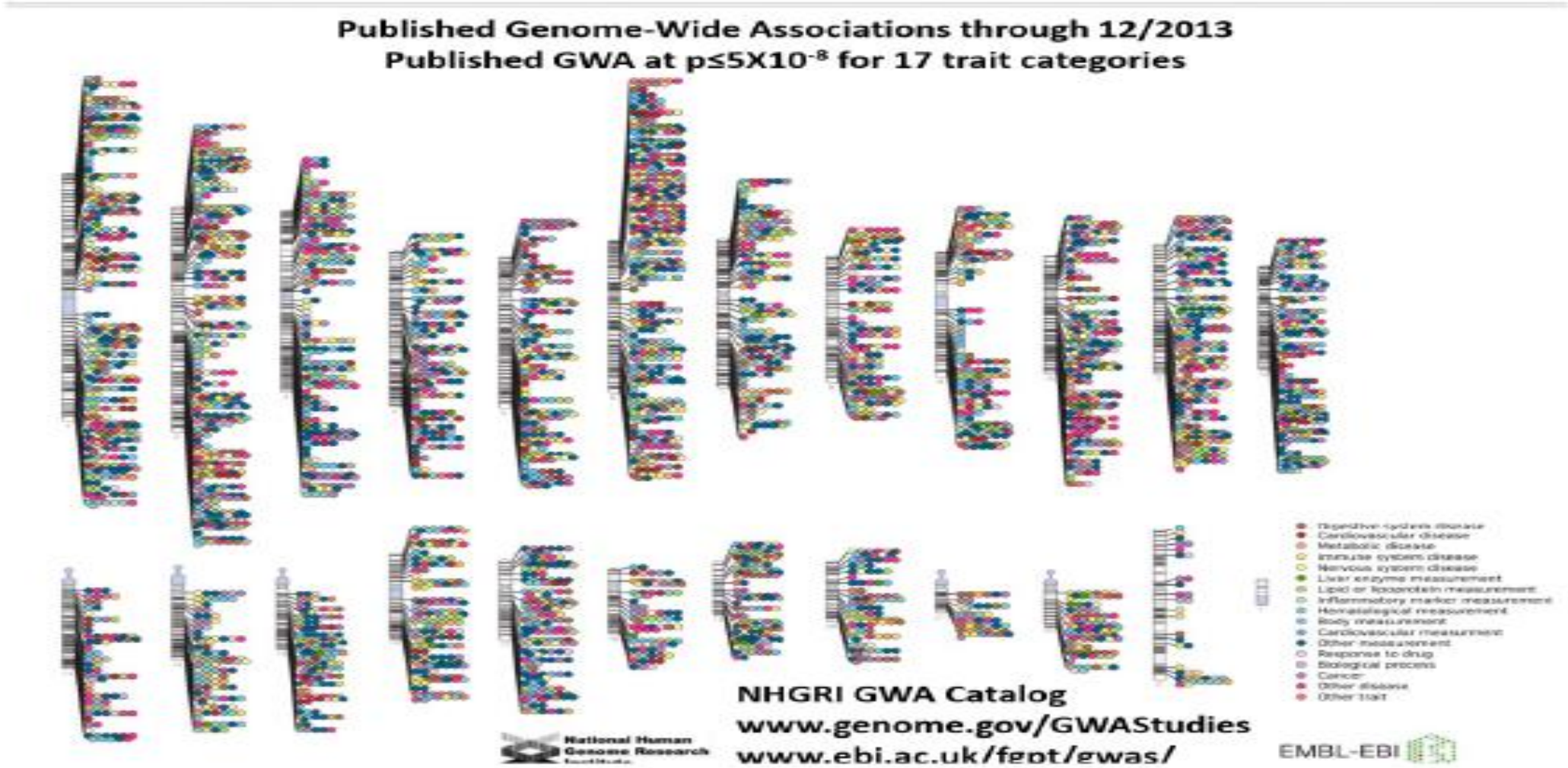
Number of somatic mutations in representative human cancers, detected by genome-wide sequencing studies

Adapted from Vogelstein and Kinzler (Science 2013)

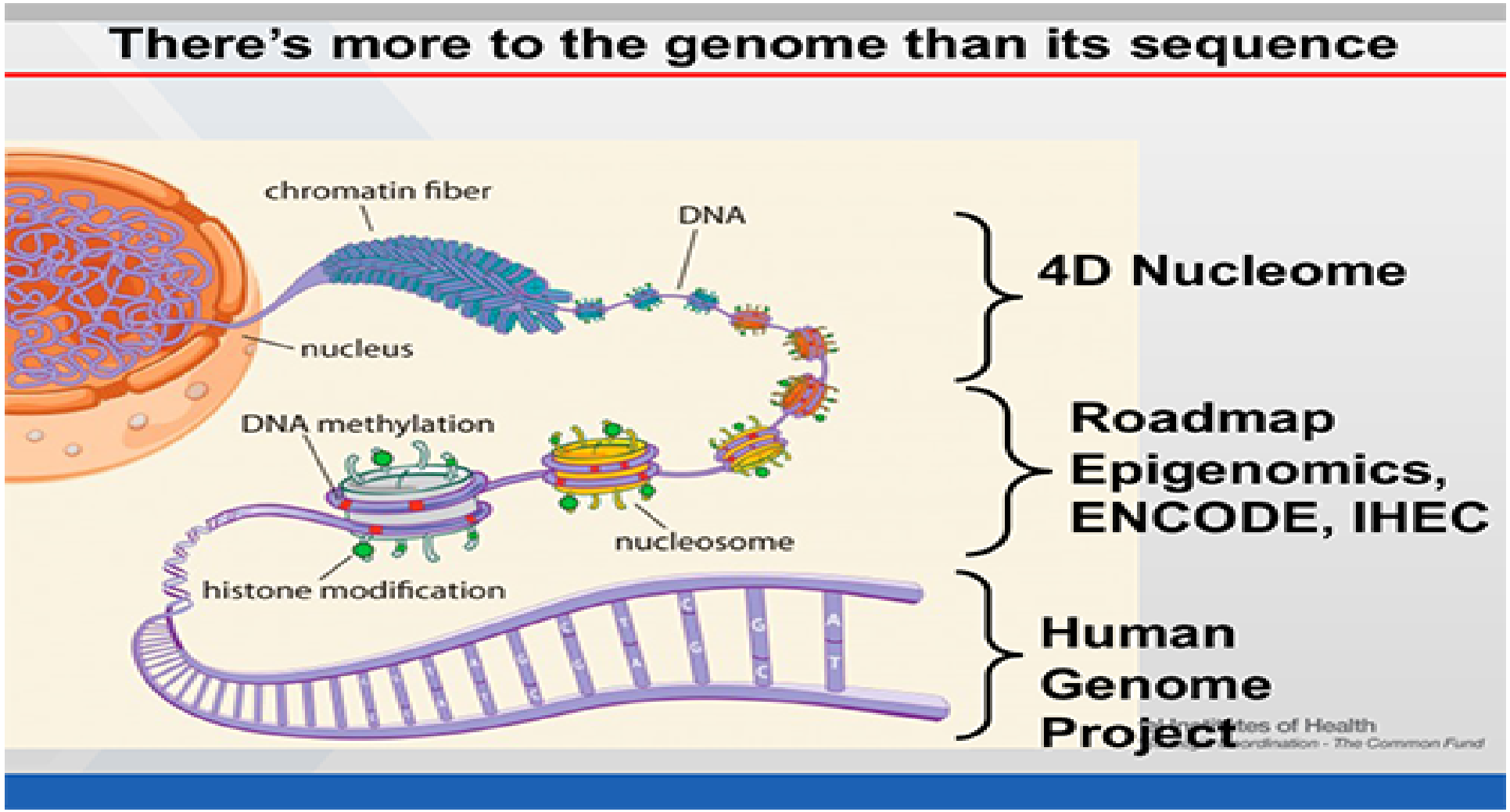
GWAS hits


Published GWAS Etiology Hits (2010)
~140 Loci marked by SNPs
1 Locus marked by a CNV
Hindorff L, Gillanders EM, Manolio T.
Adapted from T. Manolio

Genome associations



Genome sequence



Kornberg and nucleosome

Nucleosomes (Units of Chromatin)

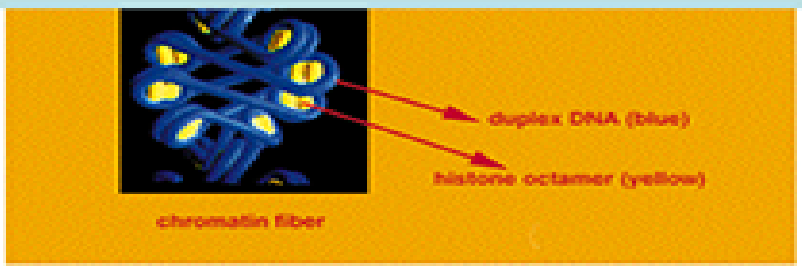
DNA
Histones H2a, H2b, H3, H4

} To neutralize charge and provide stability

H1 is a linker histone which binds to the DNA linking two adjacent nucleosomal cores

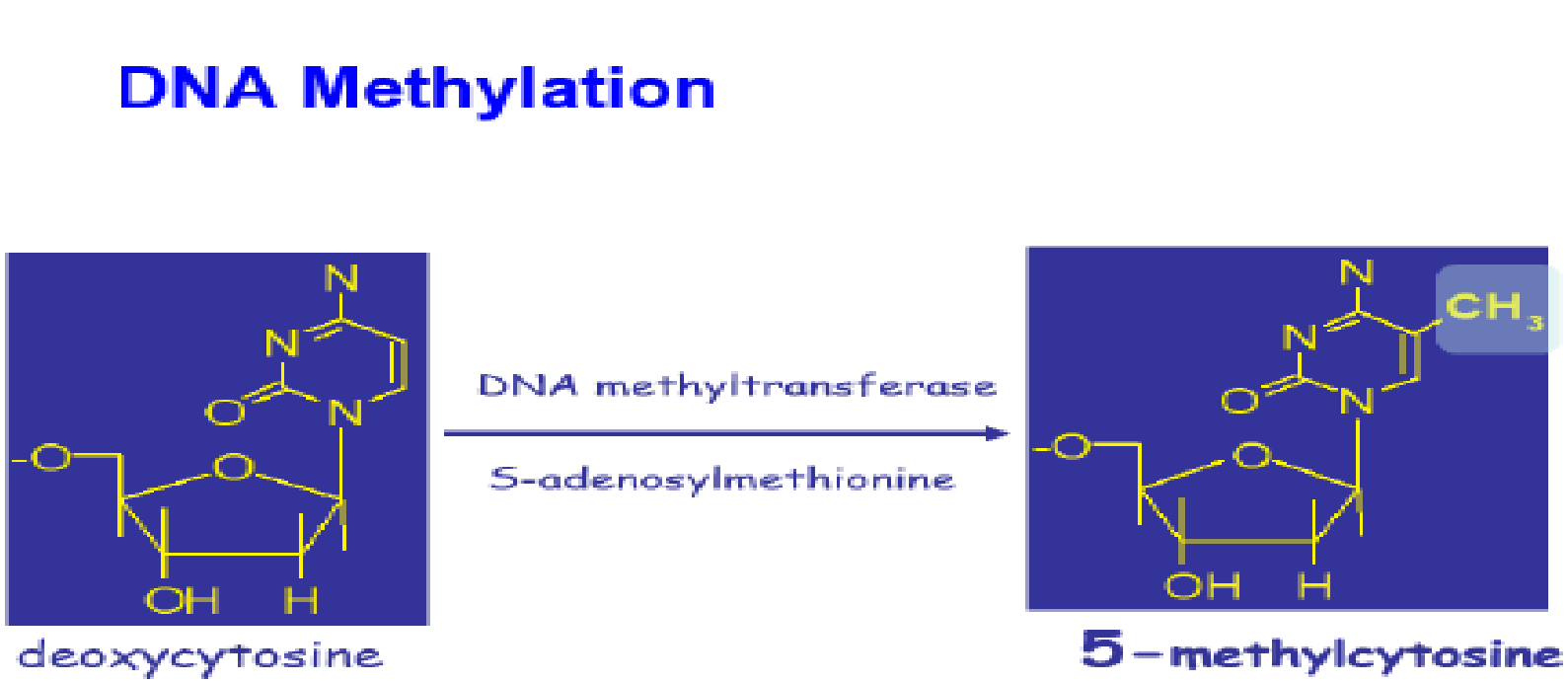
Nucleosome: two turns of DNA (146 base pairs) wrapped around an octomeric complex of two of each of histone types

1974: Roger Kornberg discovers nucleosome who won Nobel Prize in 2006.

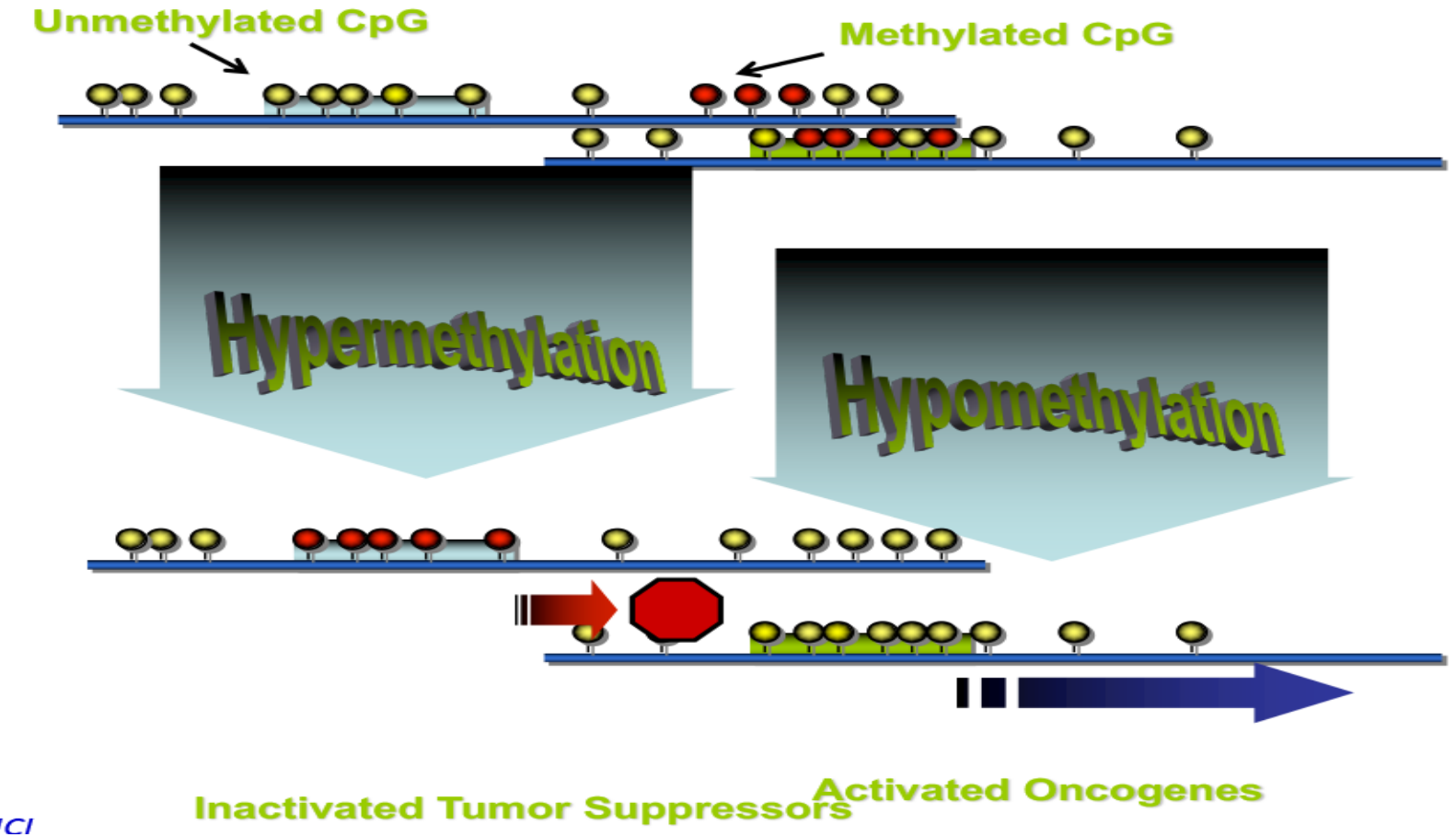


Shores are 0-2kb from islands
Shelves are 2-4 kb and enhancers are beyond shelves

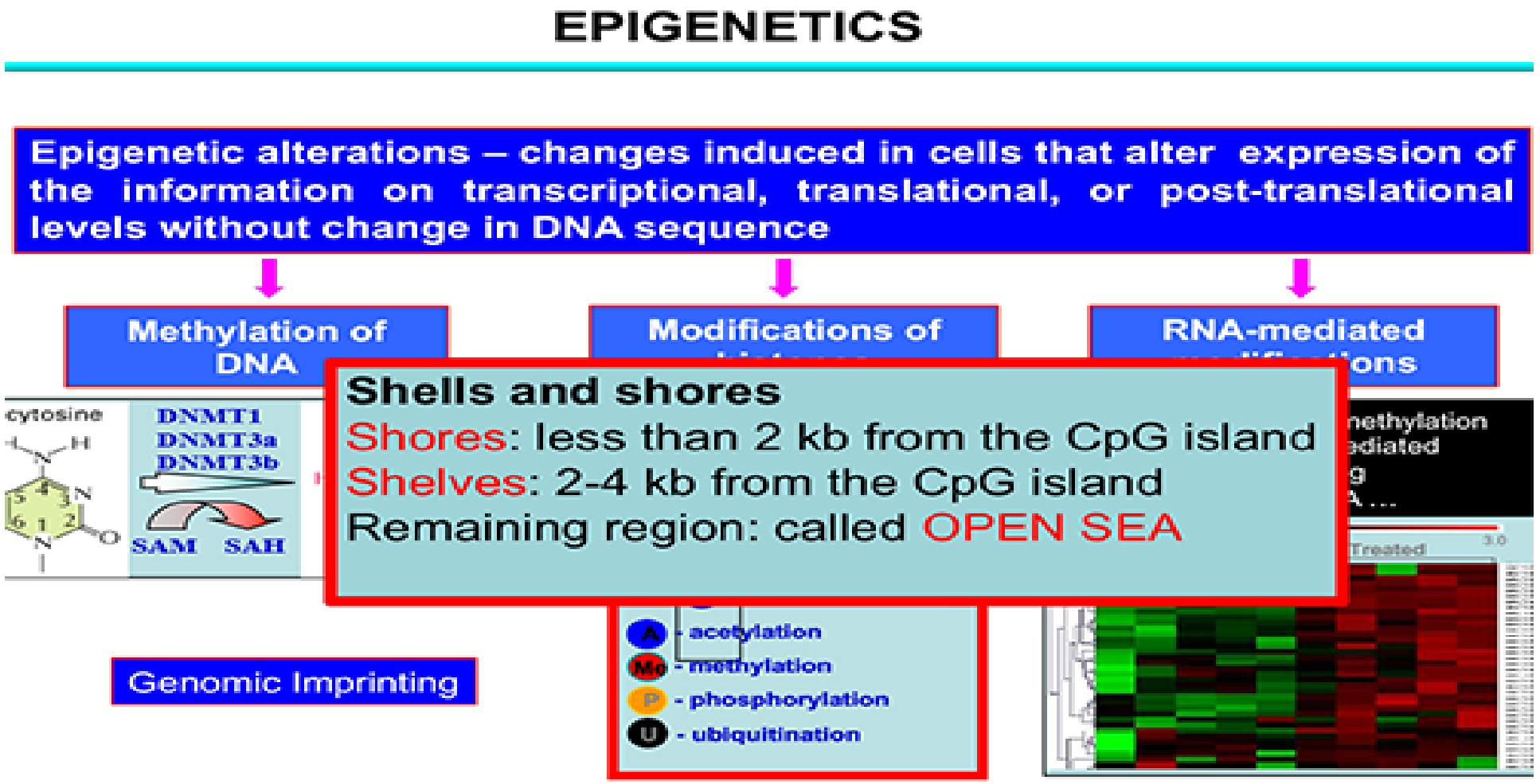
DNA methylation



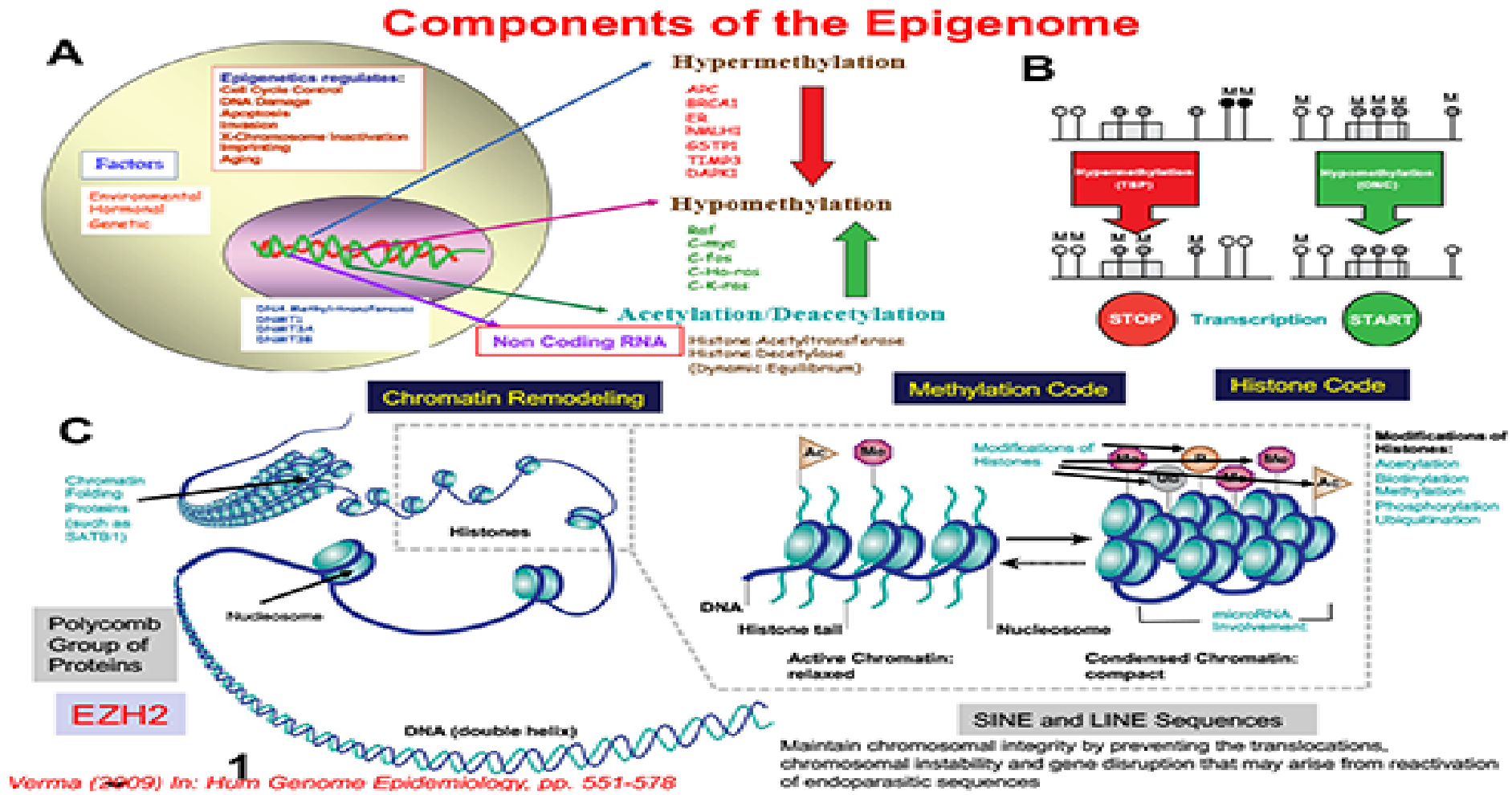
DNA methylation



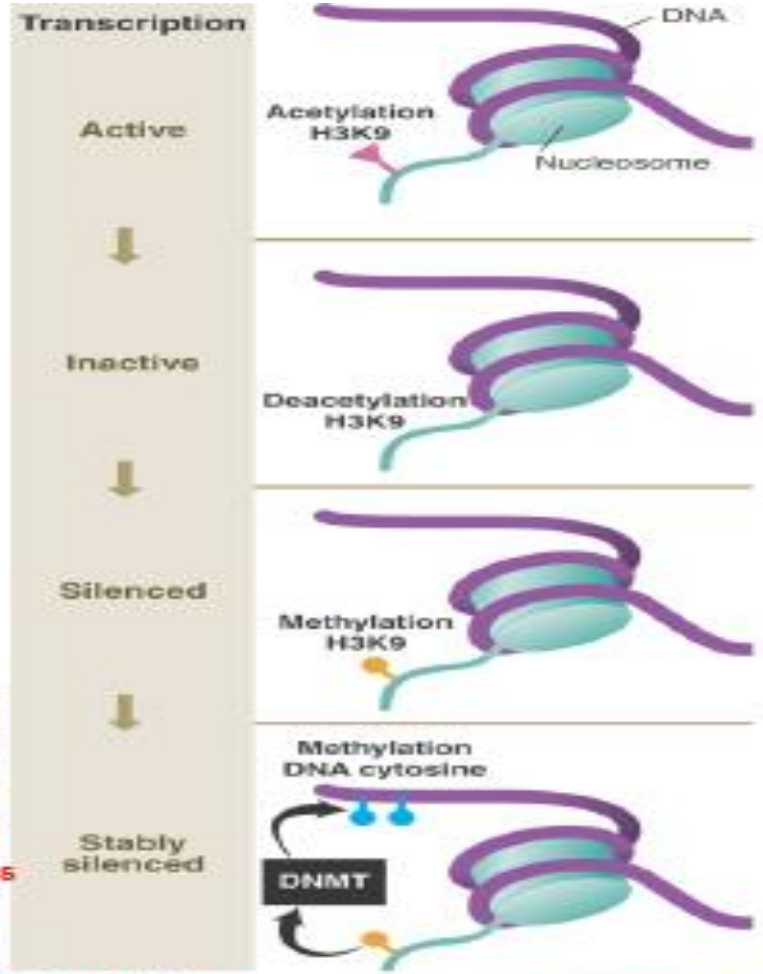
Epigenetics



Epigenome components

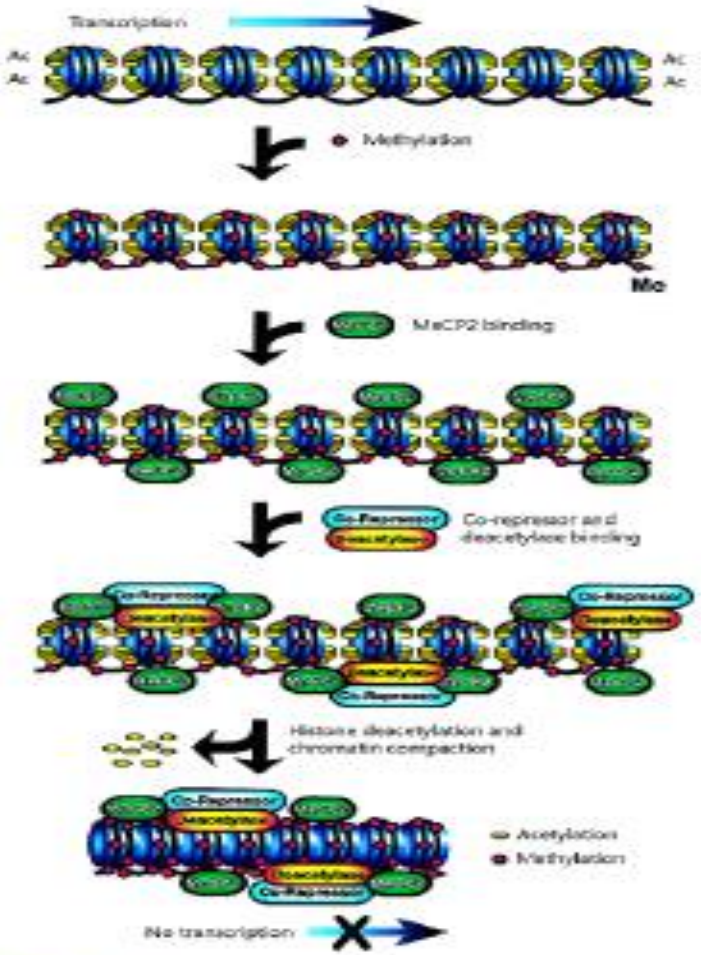


Methylation




Peter Jones


Andrew Feinberg

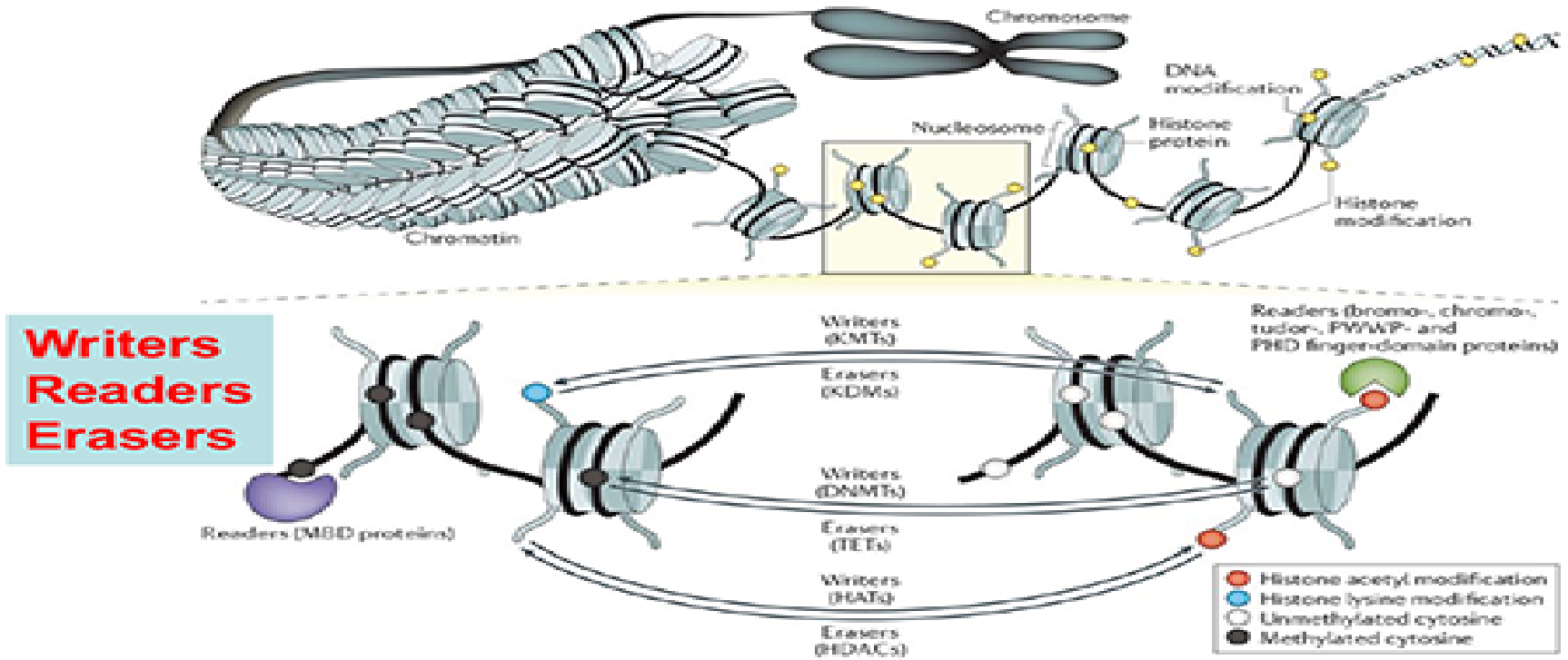


Jones and Laird. *Nat Rev Gen* 21: 163

Chromatin modifications

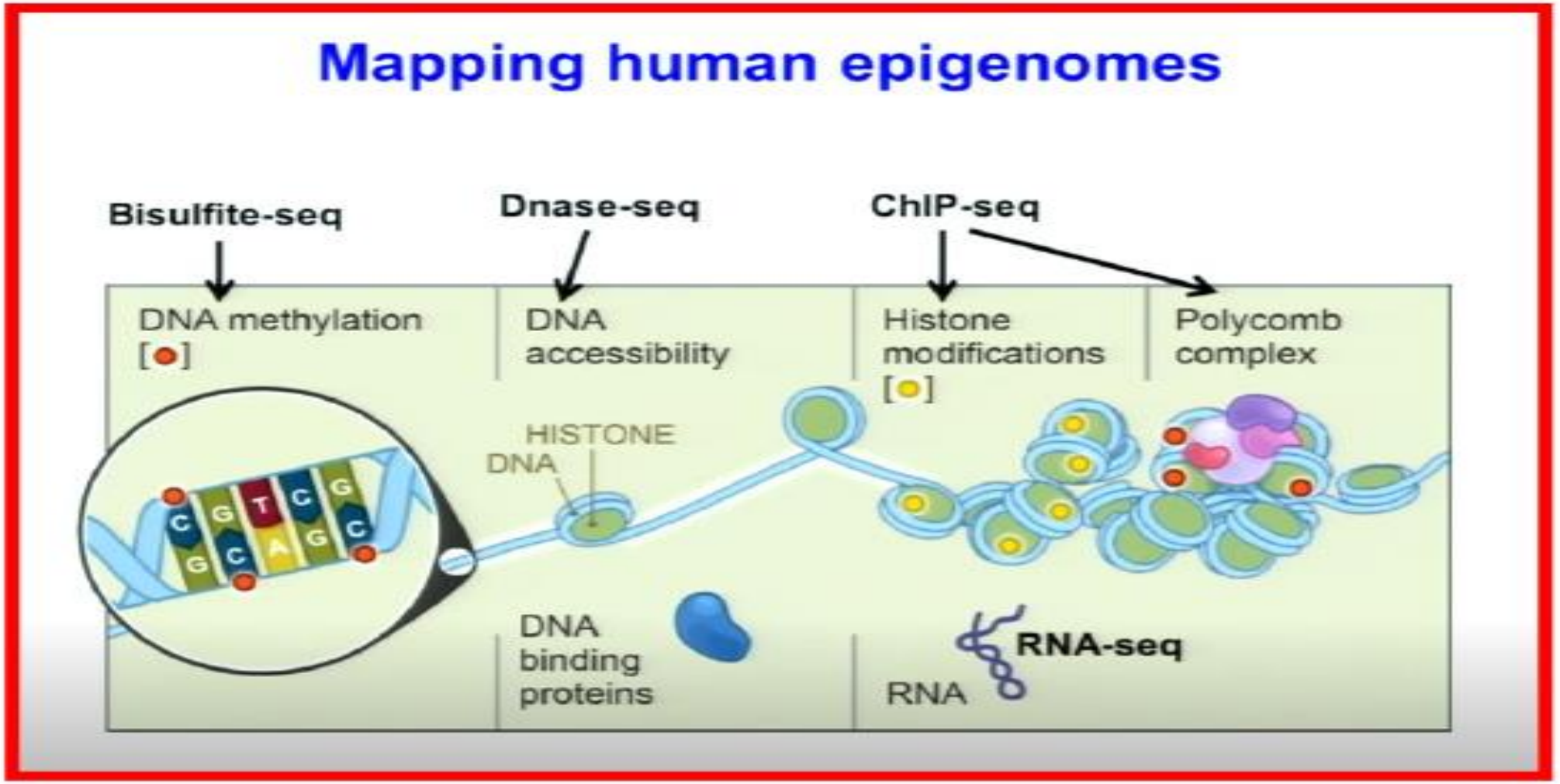
Figure 1 : Modulation of covalent modifications on chromatin.

From: Targeting the cancer epigenome for therapy

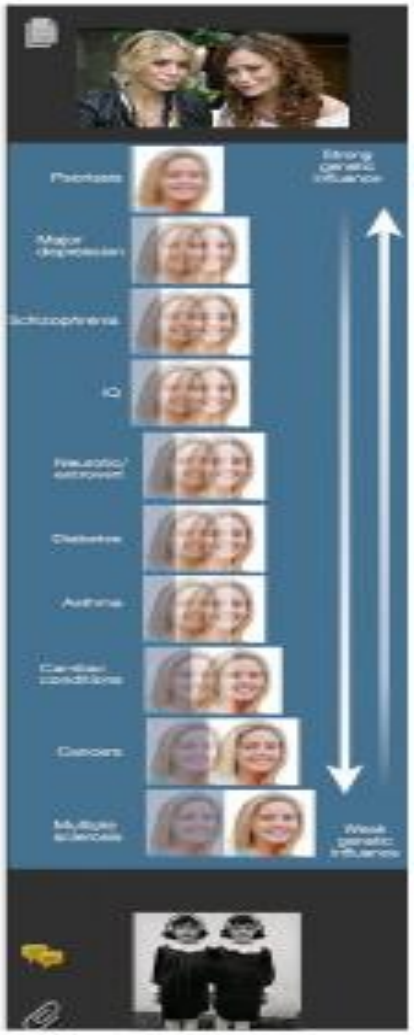


Ten-eleven translocation (TET) family of 5-methylcytosine oxidases.

Epigenomes


Mapping human epigenomes
Bisulfite-seq
Dnase-seq
ChIP-seq
DNA methylation
[●]
DNA
accessibility
Histone
modifications
[●]
Polycomb
complex
HISTONE
DNA
C G T C G
G C A G C
DNA
binding
proteins
RNA-seq
RNA

Genome versus epigenome



Genome vs. epigenome – why is it important?

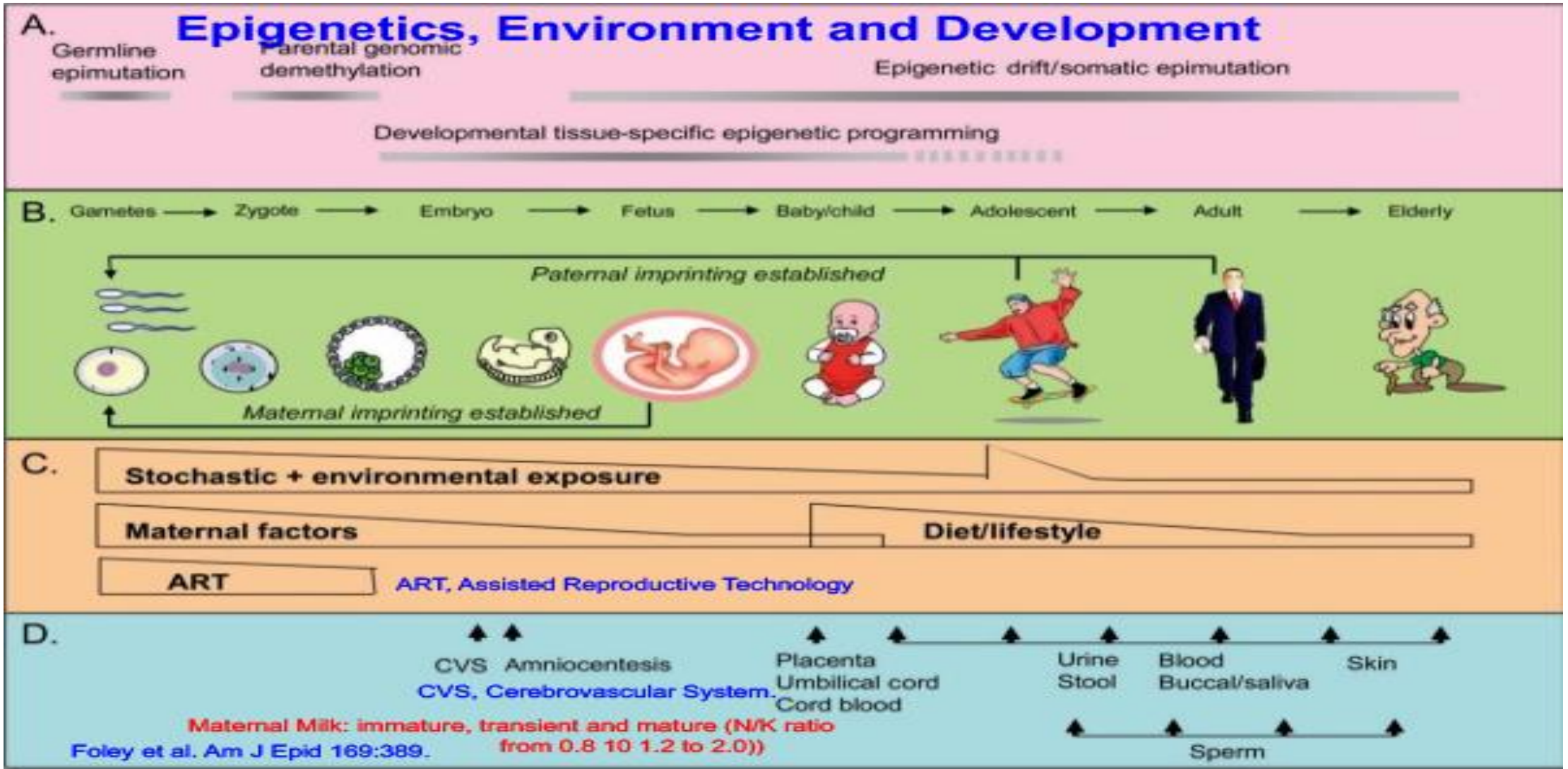
- **Genome is generally constant; epigenome changes**
  - Age
  - Diet
  - Disease
  - Lifestyle
  - Environment

- **Areas of interest:**
  - Molecular basis of disease
  - Biomarker identification
  - Diagnostics development
  - Drug targeting

You only need to sequence your genome once, but you need to determine your epigenome multiple times…

https://www.youtube.com/watch?v=JMT6oRYgkTk

Epigenetics, environment and development



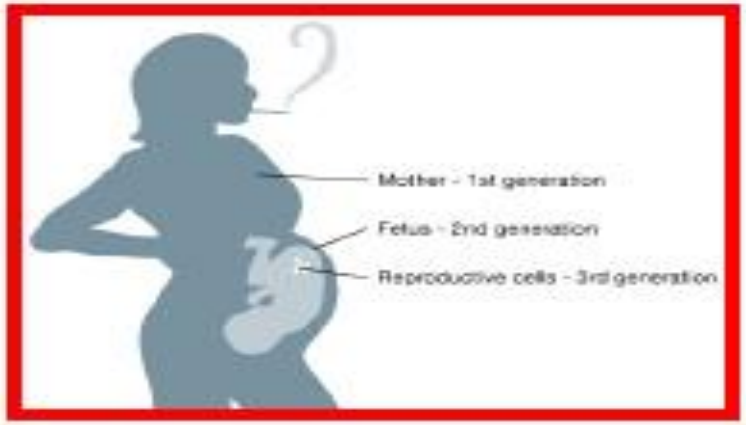
Toxic substances

Key toxic substances affecting the epigenome

Arsenic	Induces genetic and epigenetic changes
Benzene	Benzene and its metabolic product hydroquinone alter methylation profiles and contribute to leukemia
Cadmium	Induces hypermethylation of selected genes in lung cancer
Chromium	Induces hypermethylation in lung cancer
Nickel	Alters chromatin structure and induces histone acetylation
PFOS	Affects prenatal methylation and regulation of *GSTP1* and LINE/SINE sequences
PAHC	Alters histone H3 acetylation in breast cancer model
Uranium	Contributes to leukemia

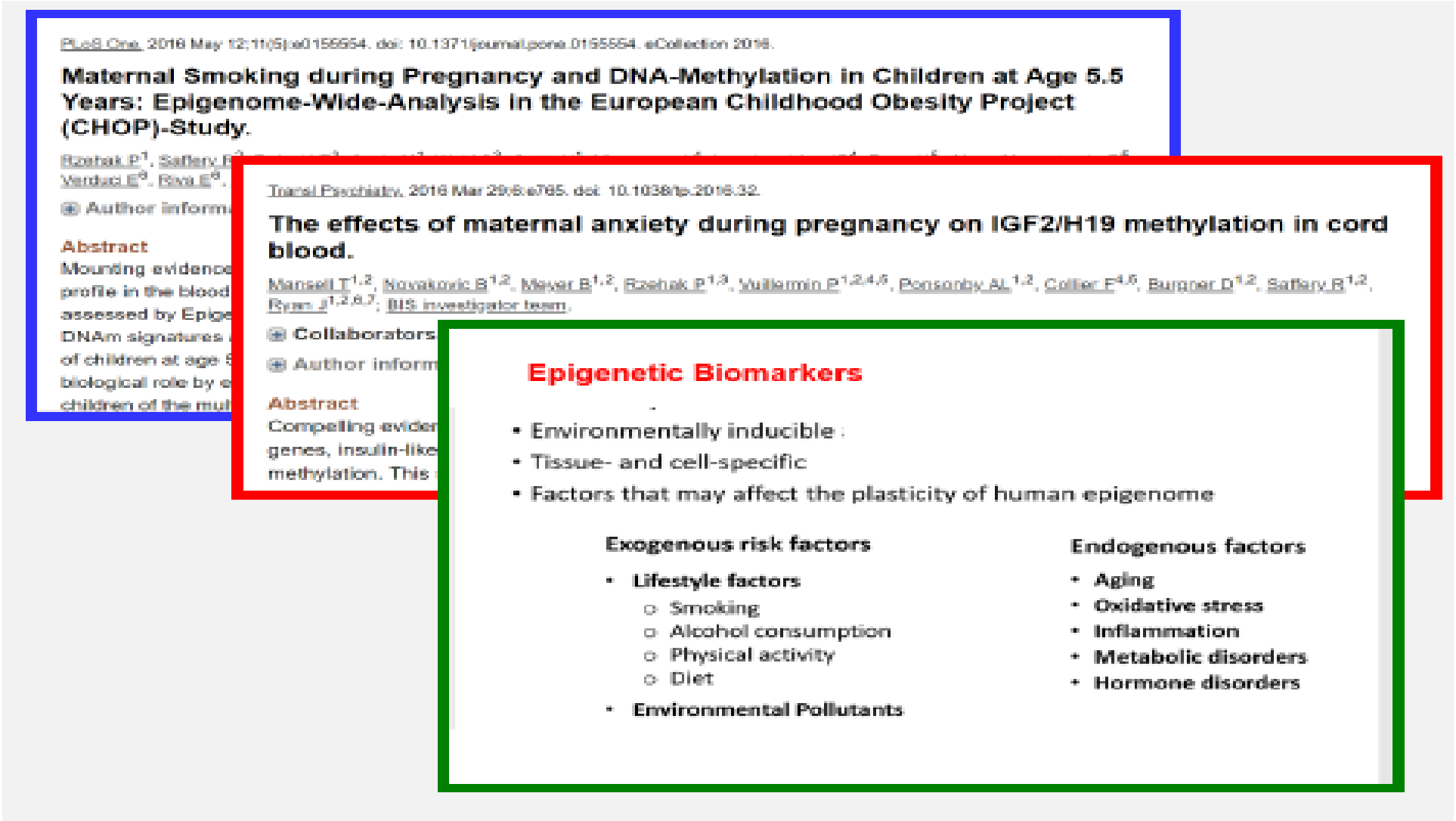
PFOS, Perfluorooctane sulfonate
PAHC, Polycyclic aromatic and halogenated compounds

Histone phosphorylation



Aldehyde and nitric oxide, present in cigarette smoke induce phosphorylation of histones resulting in decreased histone deacetylase 2 activity

Endogenous factors



Behavior

Epigenetics and behavior (including emotions)

Happiness Genes: Unlock the Positive Potential Hidden in Your DNA by James D. Baird and Laurie Nadel, in which we are told, **"Happiness is at your fingertips, or rather sitting in your DNA, right now! The new science of epigenetics reveals there are reserves of natural happiness within your DNA that can be controlled by you, by your emotions, beliefs and behavioral choices."**

Epigenetics and behavior

Epigenome-Wide Association Study of Aggressive Behavior

Translational Psychiatry, 2016 Mar 29;6:e765. doi: 10.1038/tp.2016.32.

The effects of maternal anxiety during pregnancy on IGF2/H19 methylation in cord blood.

Mansell T[1,2], Novakovic B[1,2], Meyer B[1,2], Rzehak P[1,2], Vuillermin P[1,2,4,5], Ponsonby AL[1,2], Collier F[4,5], Burgner D[1,2], Saffery R[1,2], Ryan J[1,2,6,7]; BIS investigator team.

Collaborators (11)

Author information

Abstract

Compelling evidence suggests that maternal mental hea
genes, insulin-like growth factor 2 (IGF2) and H19, are i
methylation. This study aimed to determine the associat
differentially methylated regions (DMRs) of IGF2 (DMR0
offspring. Maternal depression, anxiety and perceived st
Infant Study (n=576). DNA methylation was measured in

Chapter 29

Epigenetic Regulation in Biopsychosocial Pathways

Kristin Litzelman and Mukesh Verma

Cancer Prevention Fellow

Abstract

Theory and empirical evidence suggest that psychological stress and other adverse psychosocial experiences can contribute to cancer progression. Research has begun to explore the potential role of epigenetic changes in these pathways. In basic, animal and human models, exposure to stressors or to the products of

Cross-generational effects

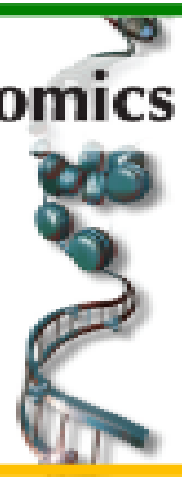
Research Article

For reprint orders, please contact: reprints@futuremedicine.com

CROSS-GENERATIONAL EFFECTS

Cross-generational effects of alcohol dependence in humans on *HRAS* and *TP53* methylation in offspring

Shirley Y Hill*,[1], Gre
[1]Department of Psychiatry, U
[2]Center for Neuroscience, U
[3]Departments of Anesthesio
15213, USA
* Author for correspondenc



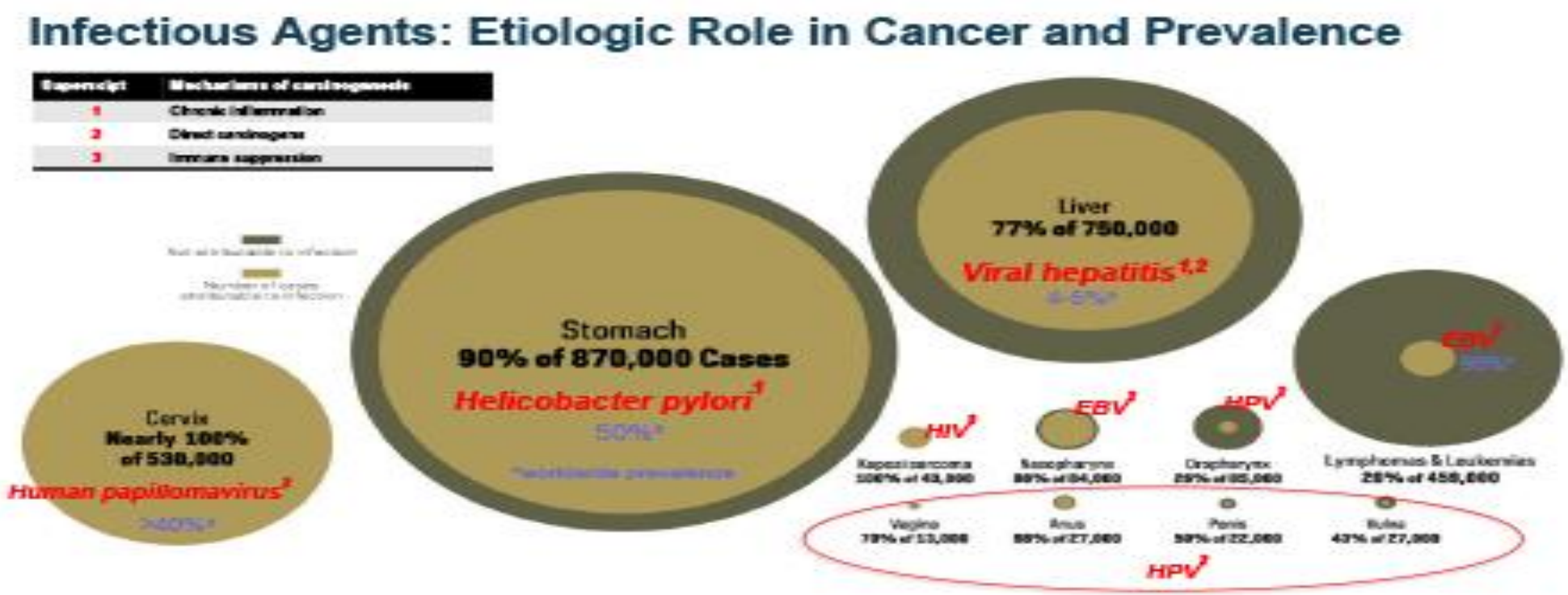
Toxicoepigenomics and Cancer: Implications for Screening

Mukesh Verma

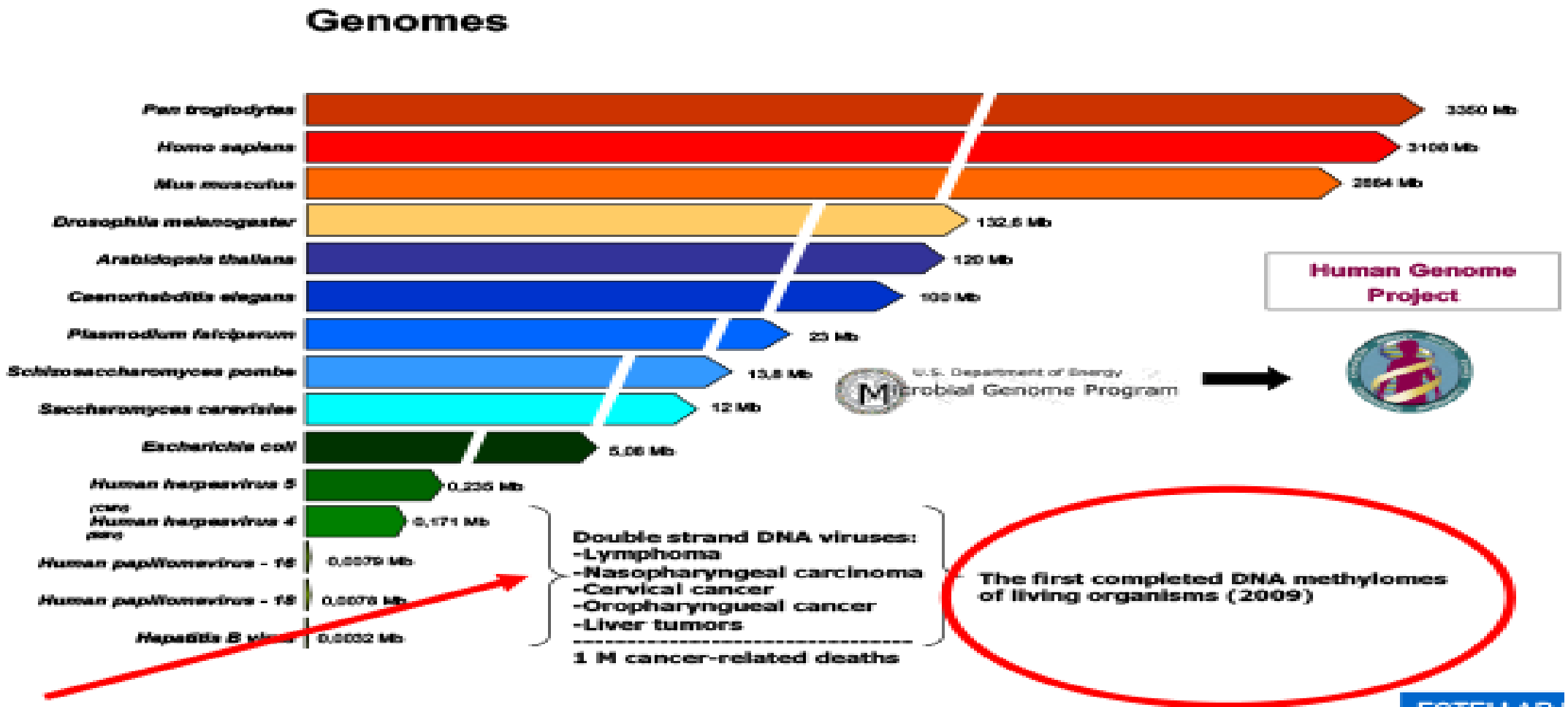
Abstract

Scientists have long considered genetics to be the key mechanism that alters gene expression because of exposure to the environment and toxic substances (toxicants). Recently, epigenetic mechanisms have emerged as an alternative explanation for alterations in gene expression resulting from such exposure. The fact that certain toxic substances that contribute to tumor development do not induce mutations probably results from underlying epigenetic mechanisms. The field of toxicoepigenomics emerged from the combination of epigenetics and classical toxicology. High-throughput technologies now enable evaluation of altered epigenomic profiling in response to toxins and environmental pollutants. Furthermore, differences in the epigenomic backgrounds of individuals may explain why, although whole populations are exposed to toxicants, only a few people in a population develop cancer. Metals in the environment and toxic substances not only alter DNA methylation patterns and histone modifications but also affect enzymes involved in posttranslational modifications of proteins and epigenetic regulation, and thereby contribute to carcinogenesis. This article describes different toxic substances and environmental pollutants that alter

Infectious agents



Genomes



Oncogenic viruses and bacteria

Oncogenic viruses, bacteria and epigenetics

Viruses:	p16 in HPV16/18 (Cervical Cancer)
	RASSF1a in SV40 (Mesothelioma)
	HBV and HCV genes (Liver Cancer)
	LANA in EBV (Nasopharyngeal Carcinoma)
Bacteria:	COX2 in H.pylori Infected Cells (Gastric Cancer)

Int. J. Cancer: **113**, 440–445 (2005)

Frequent p16INK4a Promoter Hypermethylation in Human Papillomavirus-Infected Female Lung Cancer in Taiwan

LANA, Latency Associated Nuclear Antigen
EBNA, Epstein-Barr Virus Nuclear Antigen

Ming-Fang Wu[1,2], Ya-Wen Cheng[2,3], Ji-Ching Lai[4], Min-Chih Hsu[4], Jung-Ta Chen[5], Wen-Shan Liu[6], Ming-Chih Chiou[2,3], Chih-Yi Chen[7] and Huei Lee[3,4]*

[1]*Dep... Internal Medicine, Chung Shan Medical University Hospital, Taichung, Taiwan*

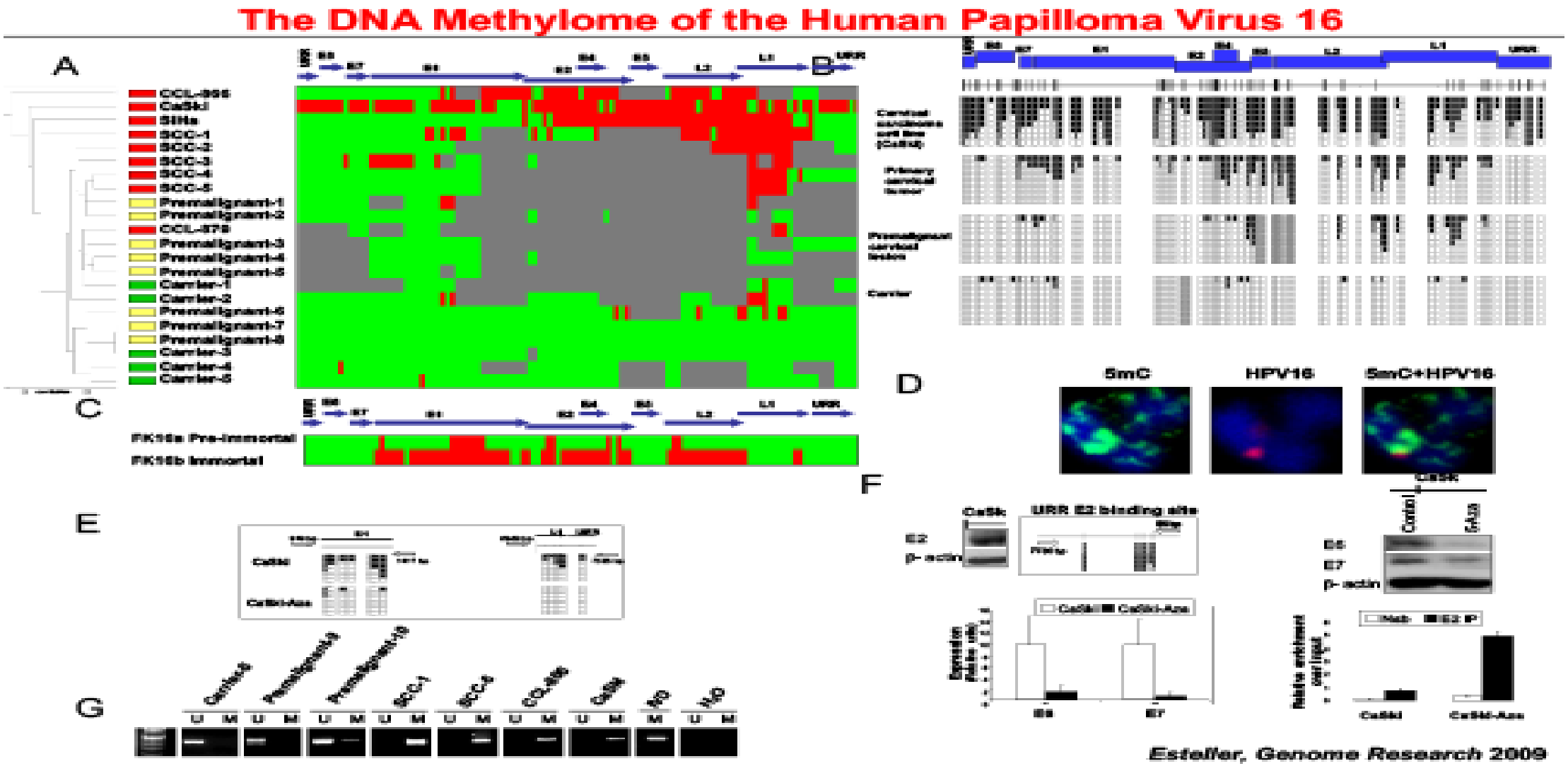
LANA

Complete methylome of HPV, EBV, and HBV.

Esteller M. Genome Research. 2009. 19: 438

EBNA

DNA methylome



Infection and cancer

Infection and Cancer: New and Emerging Associations

Infectious Agent	Cancer
Merkel cell polyomavirus (MCV)	Merkel cell carcinoma
Plasmodium falciparum	Endemic Burkitt's lymphoma
Cytomegalovirus	Brain
Salmonella typhi	Gallbladder
Streptococcus bovis	Colorectal
Chlamydia pneumoniae	Lung
Others?	???

Risk Assessment

Understanding Cancer Etiology and Risk Assessment

Need healthy population (pathologically disease free) (cohort) with information about

- Exposure (Chemicals, Radiations, Infectious Agents, Toxic substance)
- Family History
- Diet and Life Style
- Medication

Need easily collected biospecimens (non-invasive technologies) and analytic tools

Need follow up (for longitudinal studies) for several years

Challenge: Expensive, data sharing

Advantage: Essential to identify risk factors for cancer

Special populations

93

Special Populations in EGRP

African-American men & women

South American women

Asian-American & Asian men & women

Latin-American/Hispanics

African men & women

Alaskan & Hawaiian Natives

Middle-Eastern populations

American-Indian, incl. Navajo

Rural South

Chinese

EGRP Studies Are Everywhere

- Senegal
- Malawi
- The Zambia
- China
- Japan
- Egypt
- Israel
- Brazil
- Colombia
- England
- Canada
- Sweden
- Denmark
- France
- Costa Rica
- Singapore
- Poland
- Australia
- U.S., including Alaska & Hawaii

2.3 Million Subjects
Cohorts, CGN and Family Registries

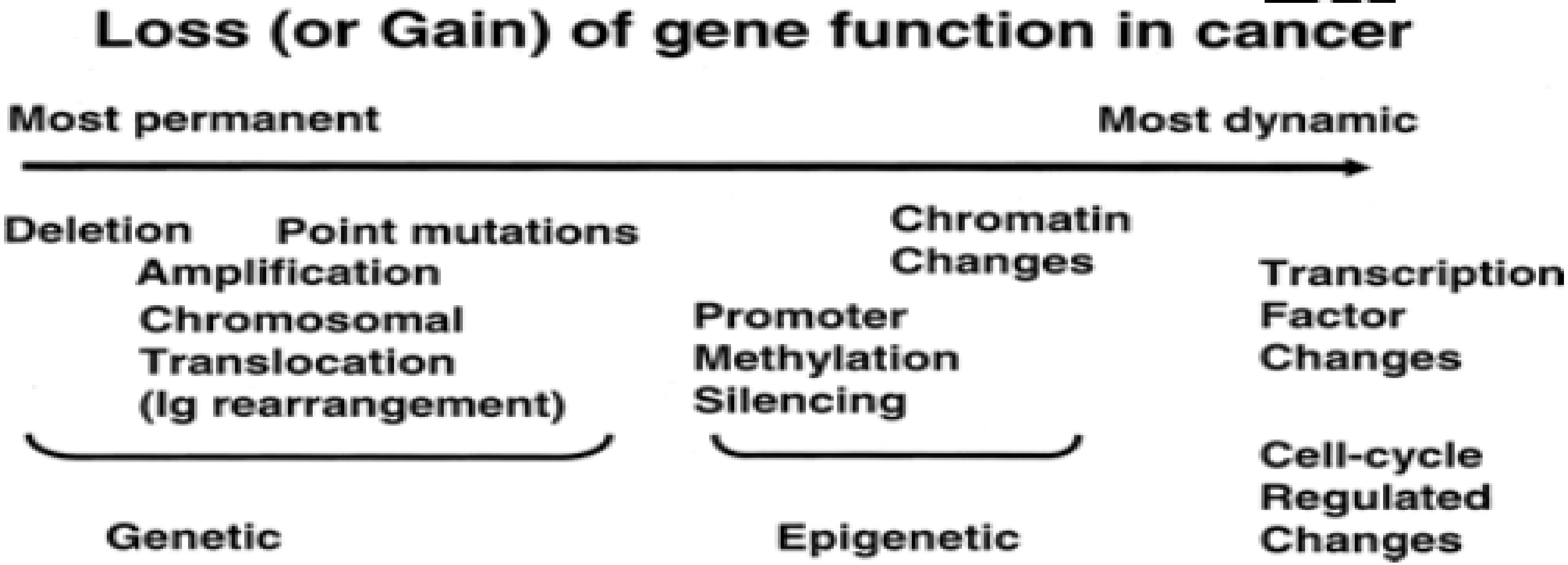
Cohort consortium

The Cohort Consortium (CoCo)

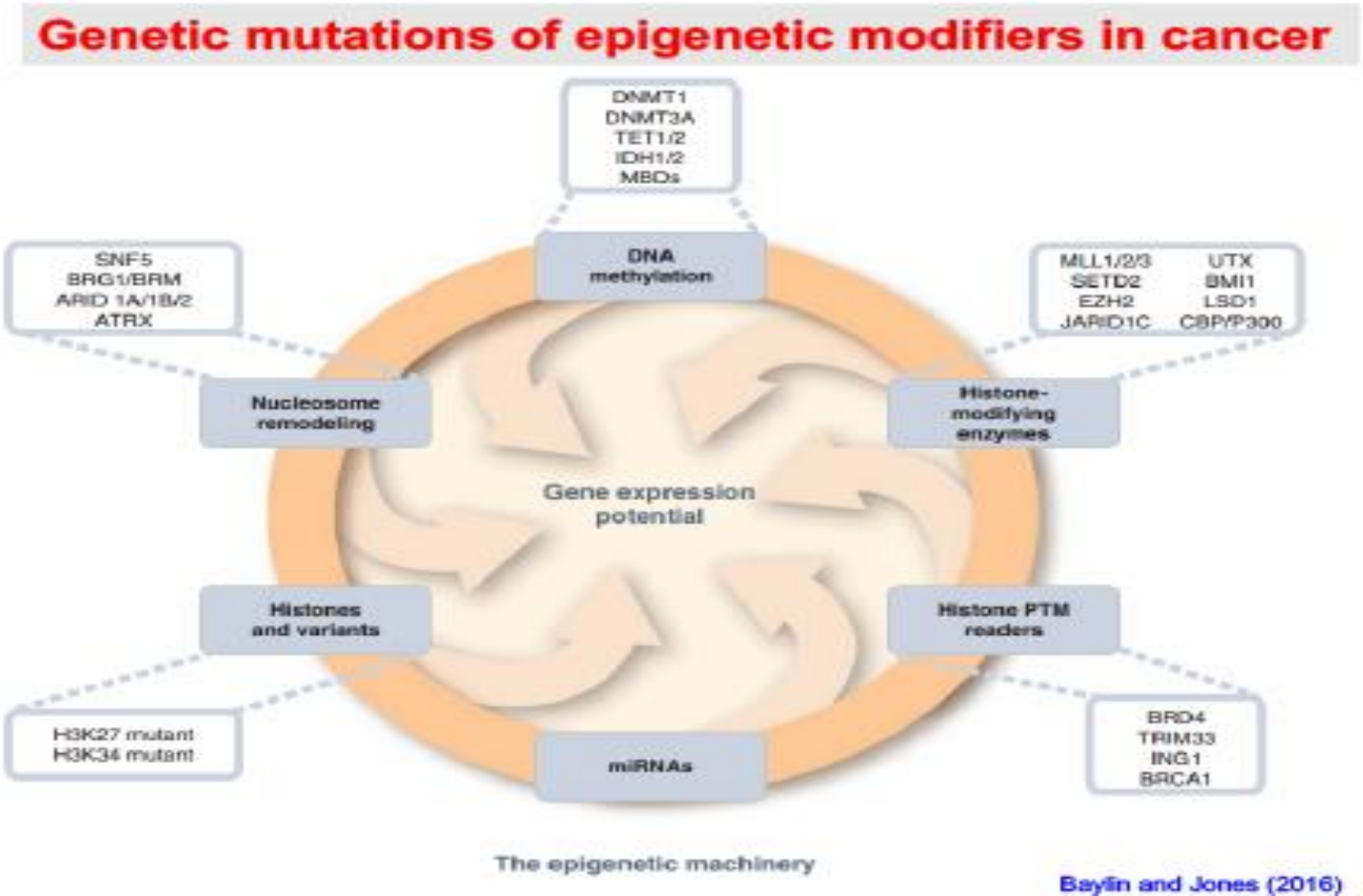
- 73 cohorts, over 4 million individuals
- Membership: cohort studies worldwide with >10,000 subjects, blood samples and questionnaire data on important cancer risk factors
- The Cohort Consortium was formed by NCI to address the need for large-scale collaborations for
  - Rapid identification and confirmation of common polymorphisms and cancer susceptibility (GWAS)
  - Studies of GxG and GxE interactions in the etiology of cancer.

https://epi.grants.cancer.gov/cohort-consortium/members/#members

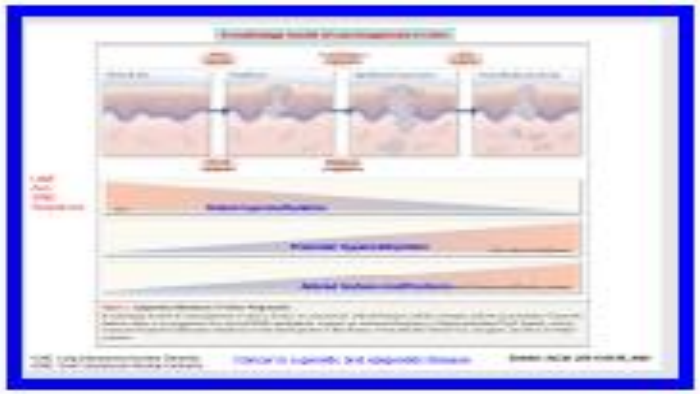
Loss (or gain) of gene function in cancer



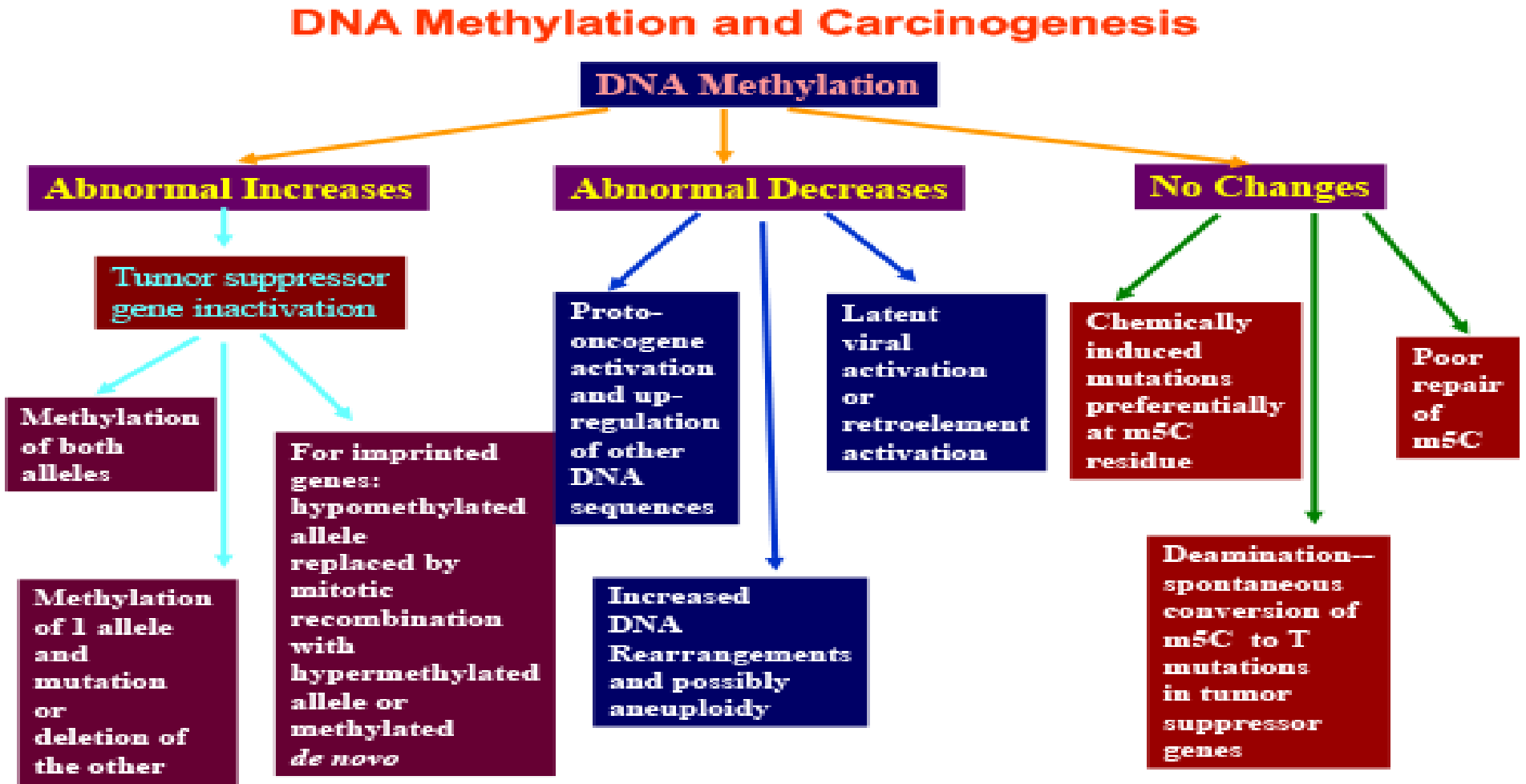
Genetic mutations



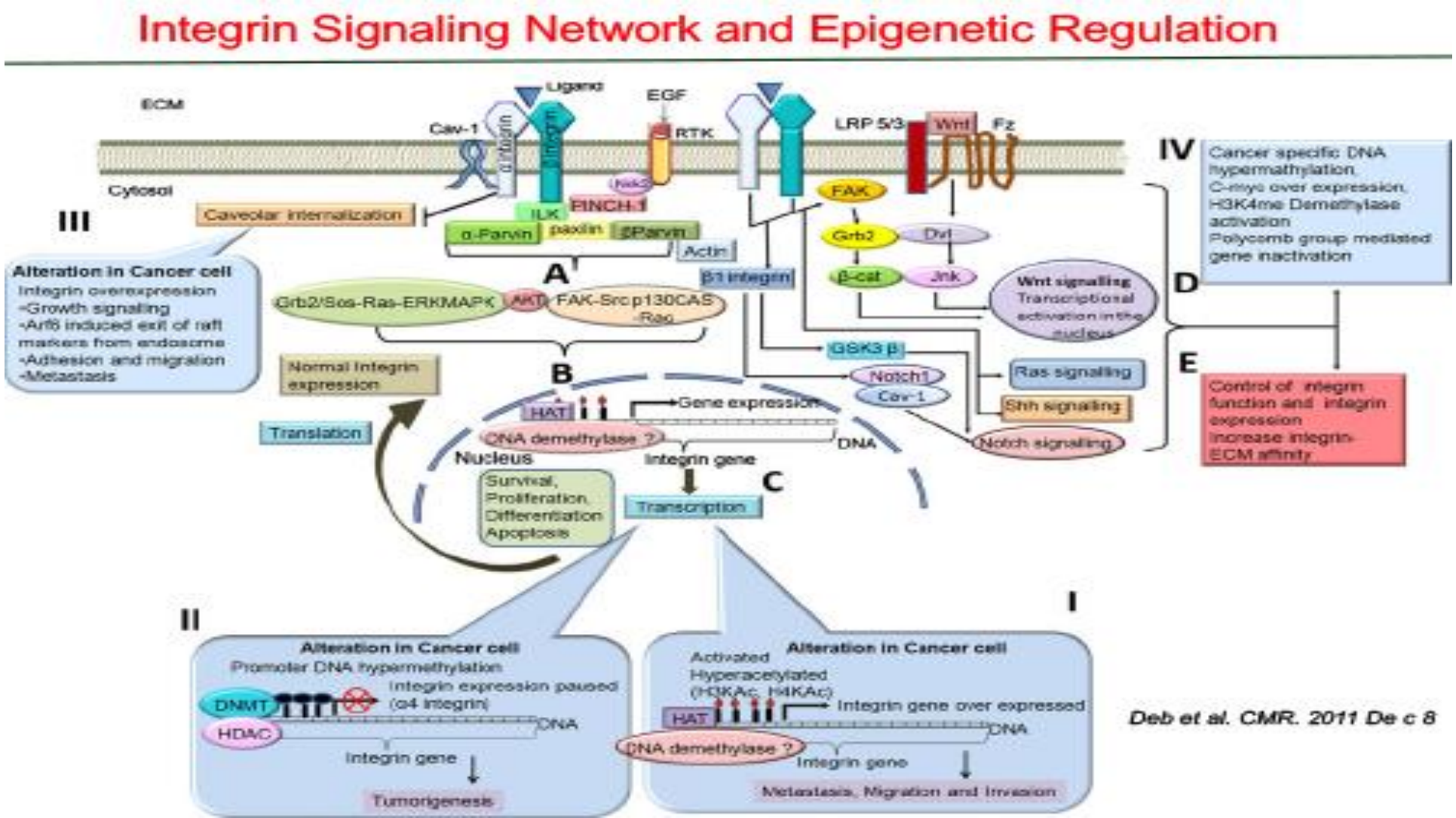
Hypomethylation



DNA methylation and carcinogenesis

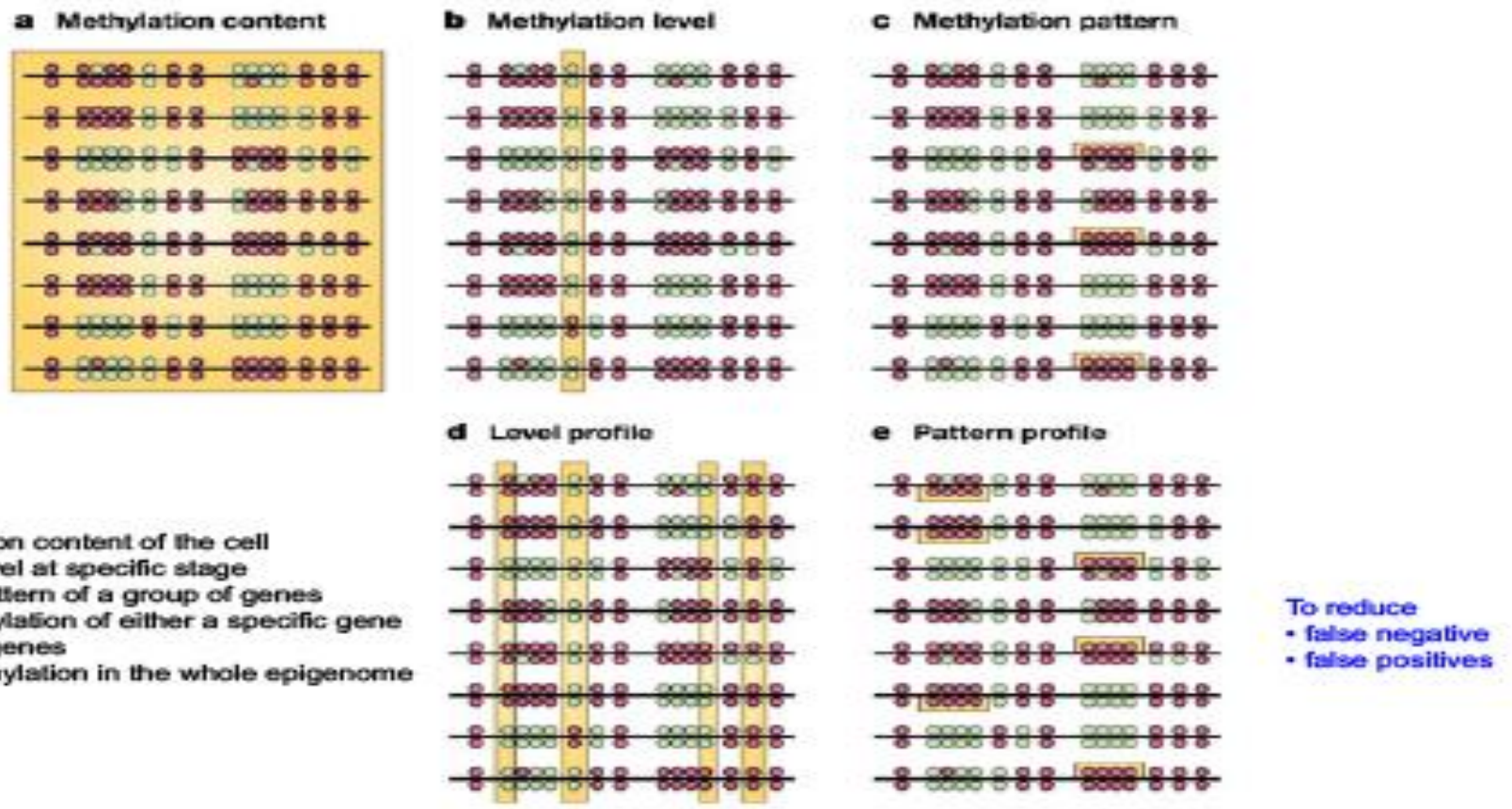


Integrin signaling

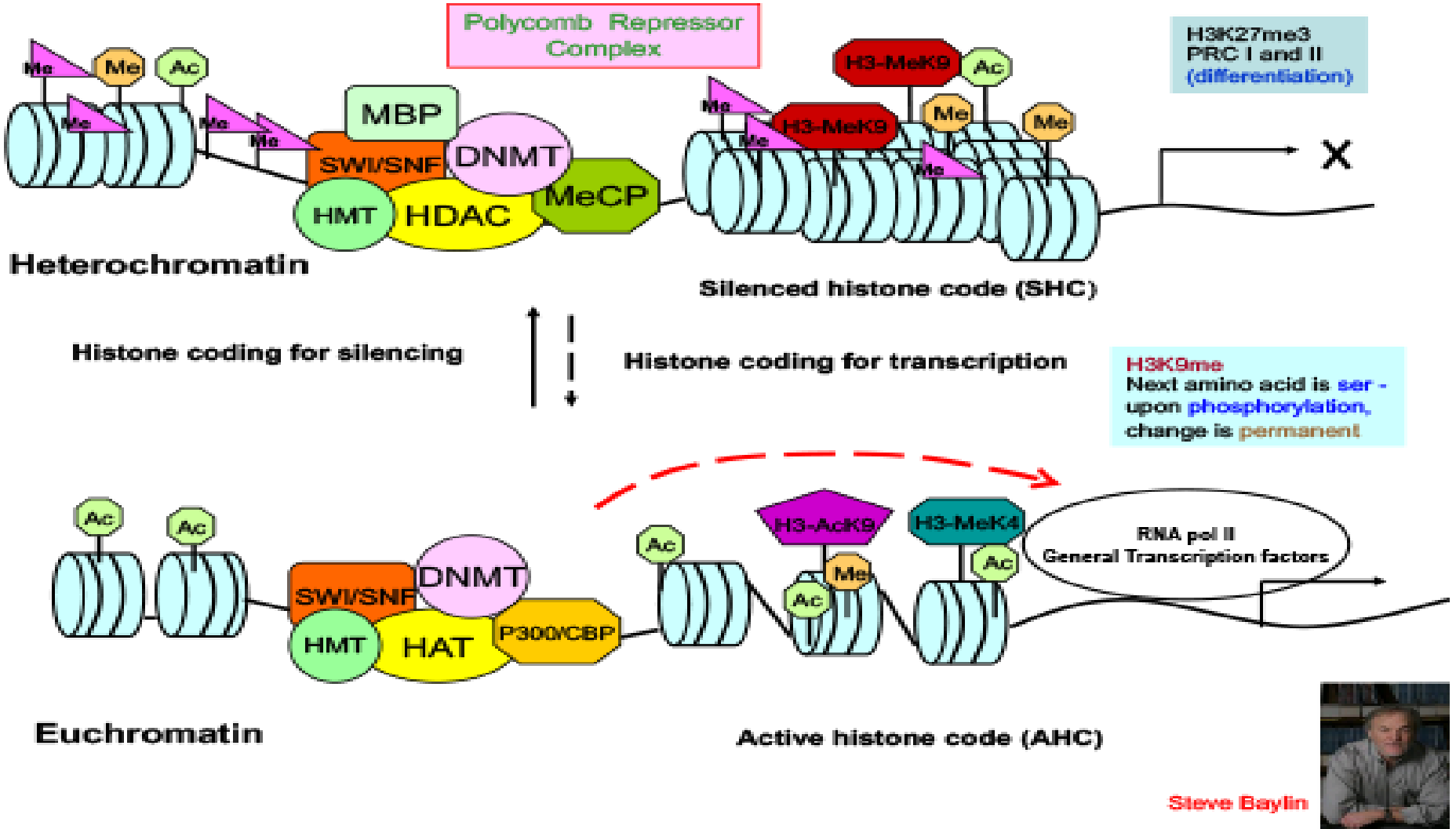


Deb et al. CMR. 2011 De c 8

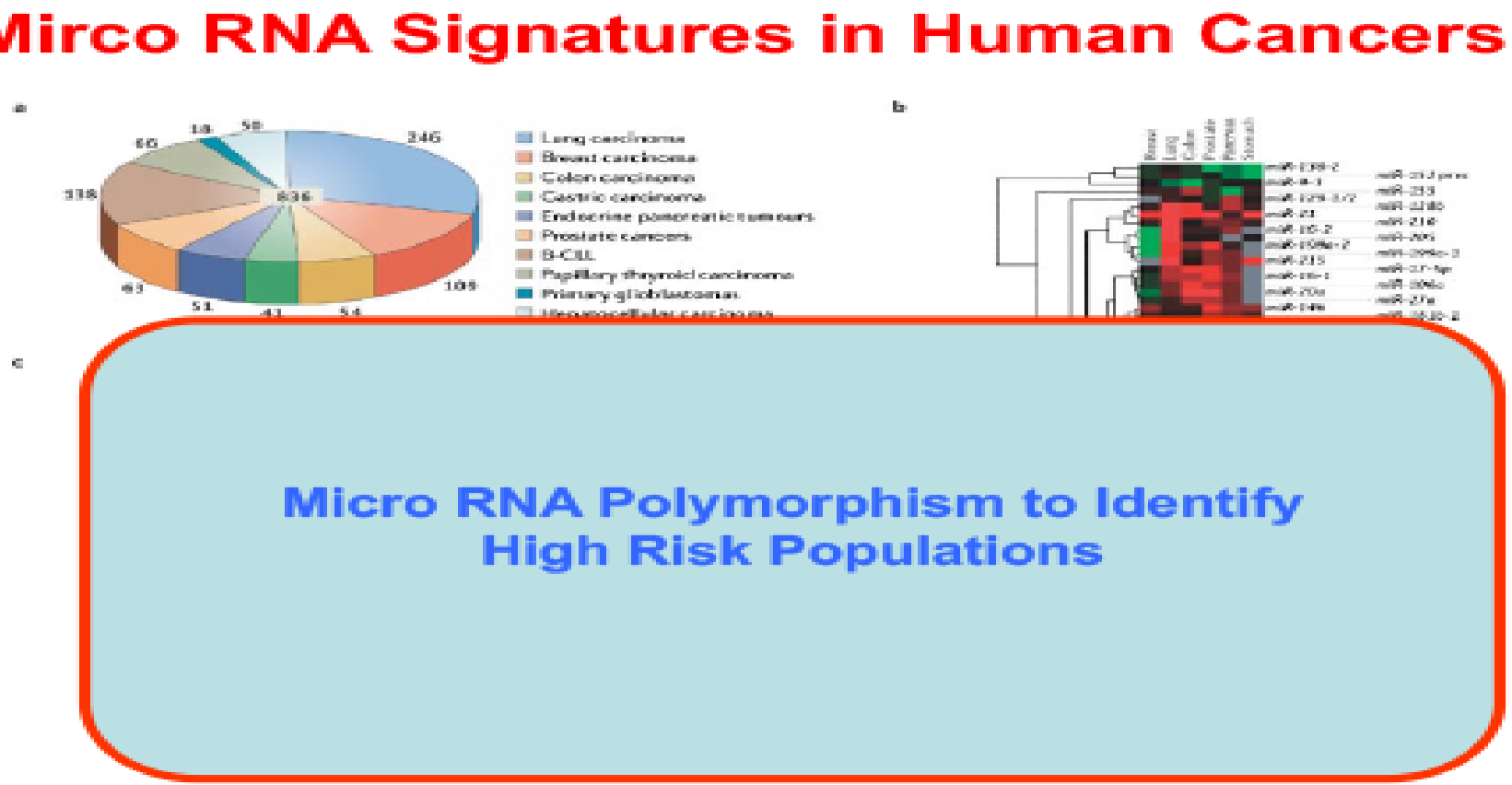
Methylation



Histone acetylation



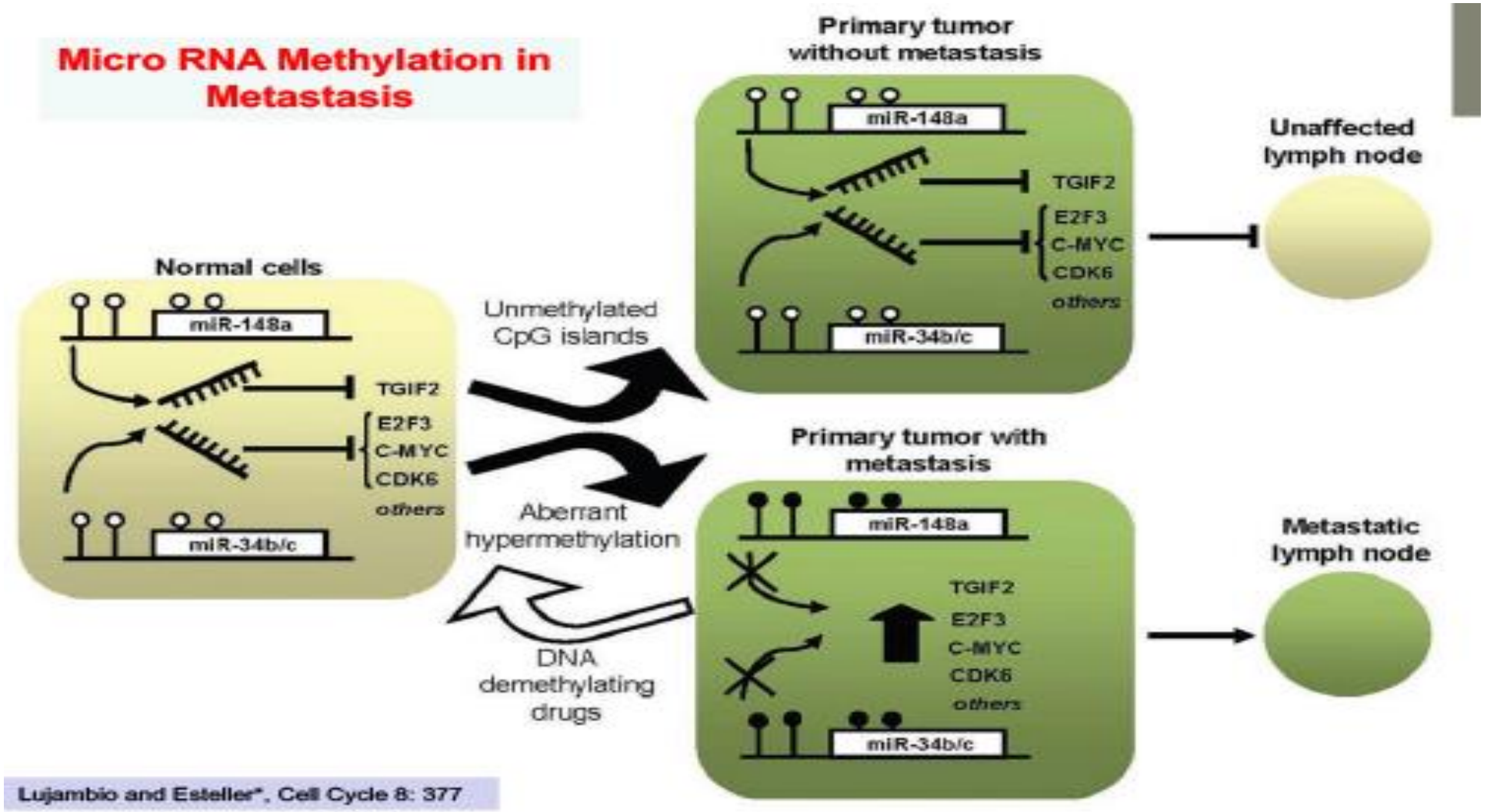
Micro RNA signatures



Mir-31 inhibits metastasis in breast cancer

nature REVIEWS CANCER

Micro RNA methylation



Methylation of microRNAs

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-11826-1 OPEN

Distinct methylation levels of mature microRNAs in gastrointestinal cancers

Masamitsu Konno[1,10], Jun Koseki[2,10], Ayumu Asai[1,2,10], Akira Yamagata[3,10], Teppei Shimamura[4], Daisuke Motooka[5], Daisuke Okuzaki[5], Koichi Kawamoto[6], Tsunekazu Mizushima[6], Hidetoshi Eguchi[6], Shuji Takiguchi[6,7], Taroh Satoh[1], Koshi Mimori[8], Takahiro Ochiya[9], Yuichiro Doki[6], Ken Ofusa[3], Masaki Mori[6] & Hideshi Ishii[2]

The biological significance of micro (mi)RNAs has traditionally been evaluated according to their RNA expression levels based on the assumption that miRNAs recognize and regulate their targets in an unvarying fashion. Here we show that a fraction of mature miRNAs including miR-17-5p, -21-5p, and -200c-3p and let-7a-5p harbor methyl marks that potentially alter their stability and target recognition. Importantly, methylation of these miRNAs was significantly increased in cancer tissues as compared to paired normal tissues. Furthermore, miR-17-5p methylation level in serum samples distinguished early pancreatic cancer patients from healthy controls with extremely high sensitivity and specificity. These findings provide a

Extracellular vesicles

Verma et al. BMC Clinical Pathology (2015) 15:6
DOI 10.1186/s12907-015-0005-5

BMC
Clinical Pathology

REVIEW Open Access

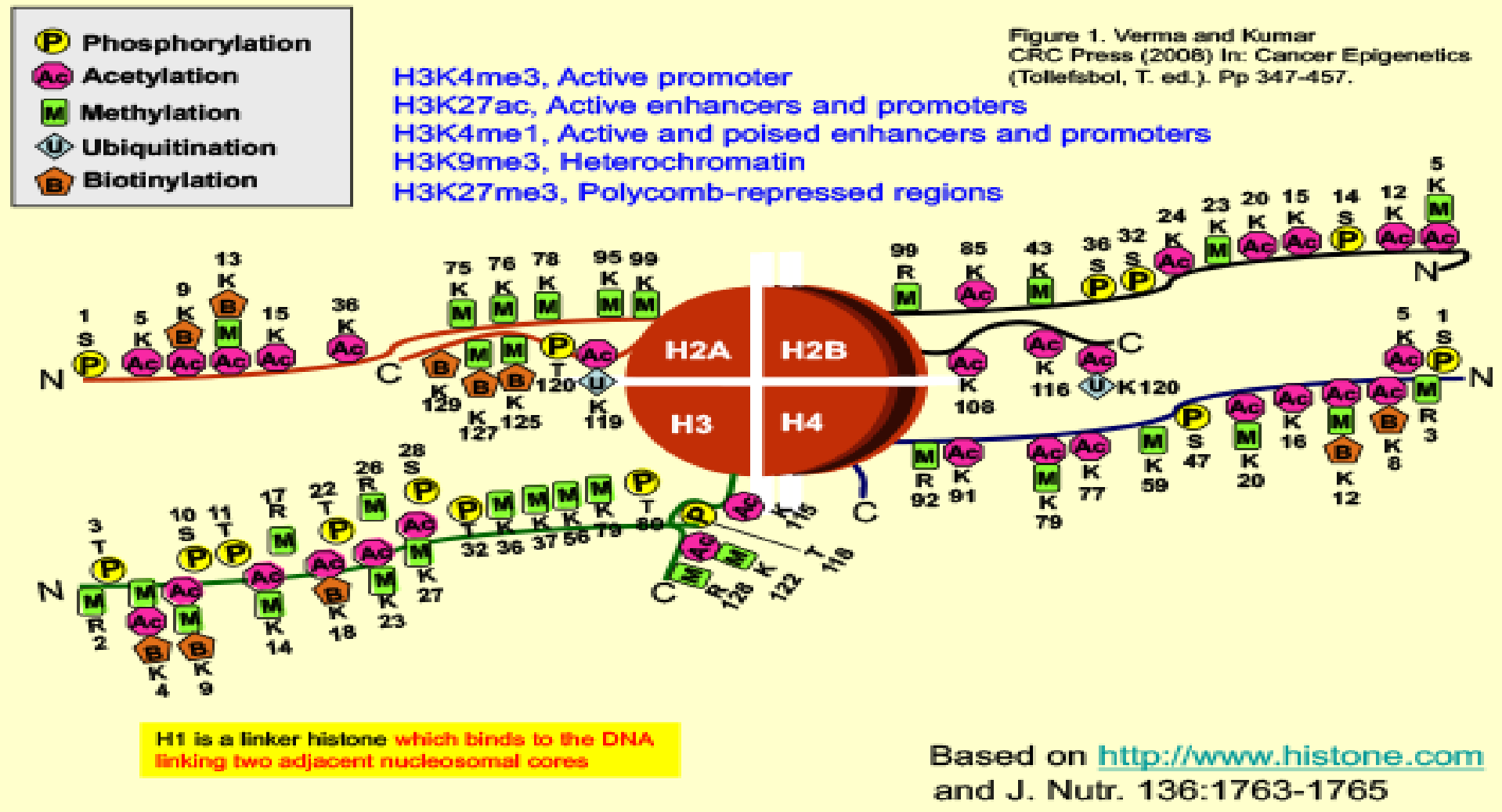
Extracellular vesicles: potential applications in cancer diagnosis, prognosis, and epidemiology

Mukesh Verma*, Tram Kim Lam, Elizabeth Hebert and Rao L Divi

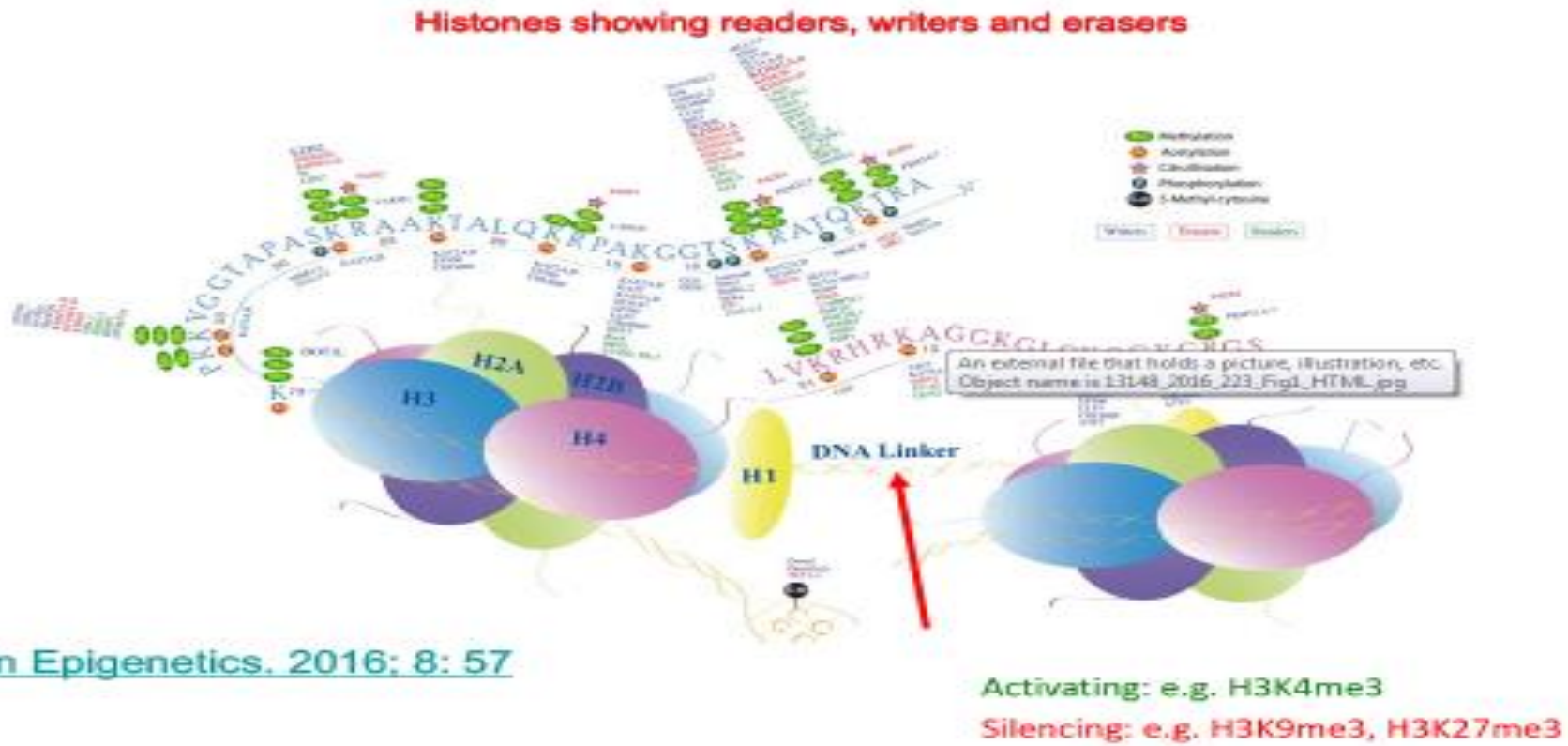
Abstract

Both normal and diseased cells continuously shed extracellular vesicles (EVs) into extracellular space, and the EVs carry molecular signatures and effectors of both health and disease. EVs reflect dynamic changes that are occurring in cells and tissue microenvironment in health and at a different stage of a disease. EVs are capable of altering the function of the recipient cells. Trafficking and reciprocal exchange of molecular information by EVs among different organs and cell types have been shown to contribute to horizontal cellular transformation, cellular reprogramming, functional alterations, and metastasis. EV contents may include tumor suppressors, phosphoproteins, proteases,

Histone modifications



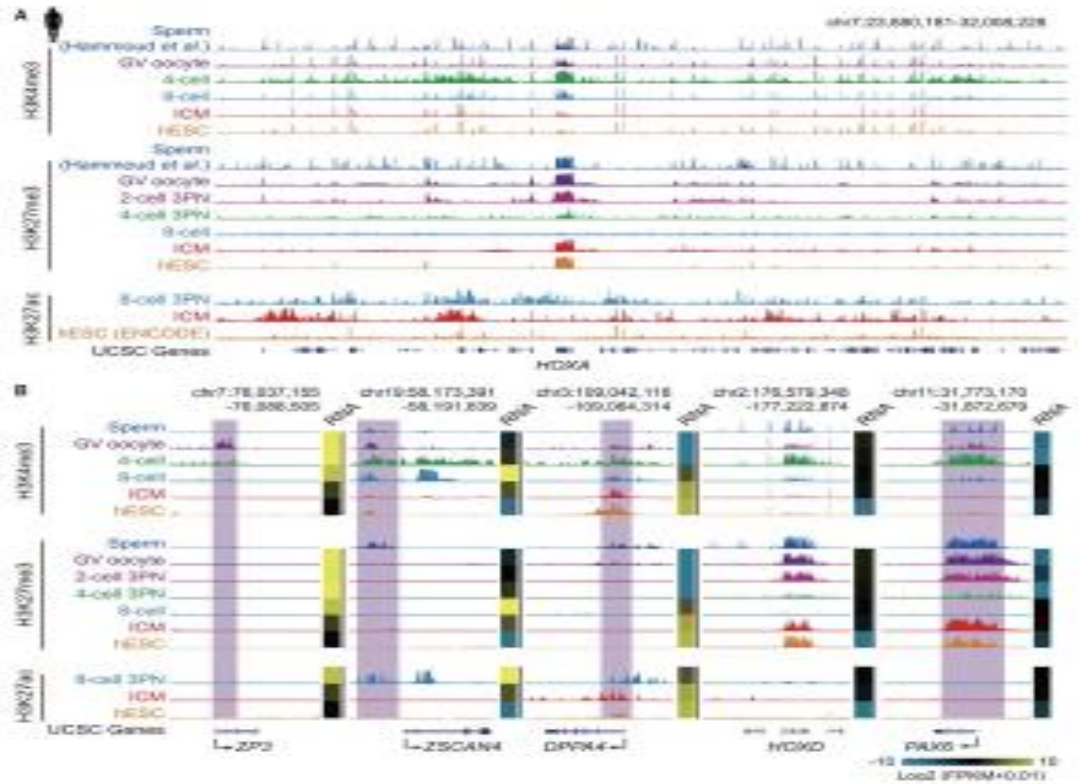
Histones


Histones showing readers, writers and erasers
H2A
H2B
H3
H4
H1
DNA Linker
An external file that holds a picture, illustration, etc.
Object name is 13148_2016_223_Fig1_HTML.jpg
Clin Epigenetics. 2016; 8: 57
Activating: e.g. H3K4me3
Silencing: e.g. H3K9me3, H3K27me3

Histone modifications

Fig. 1 Mapping histone modifications in human gametes and preimplantation embryos.

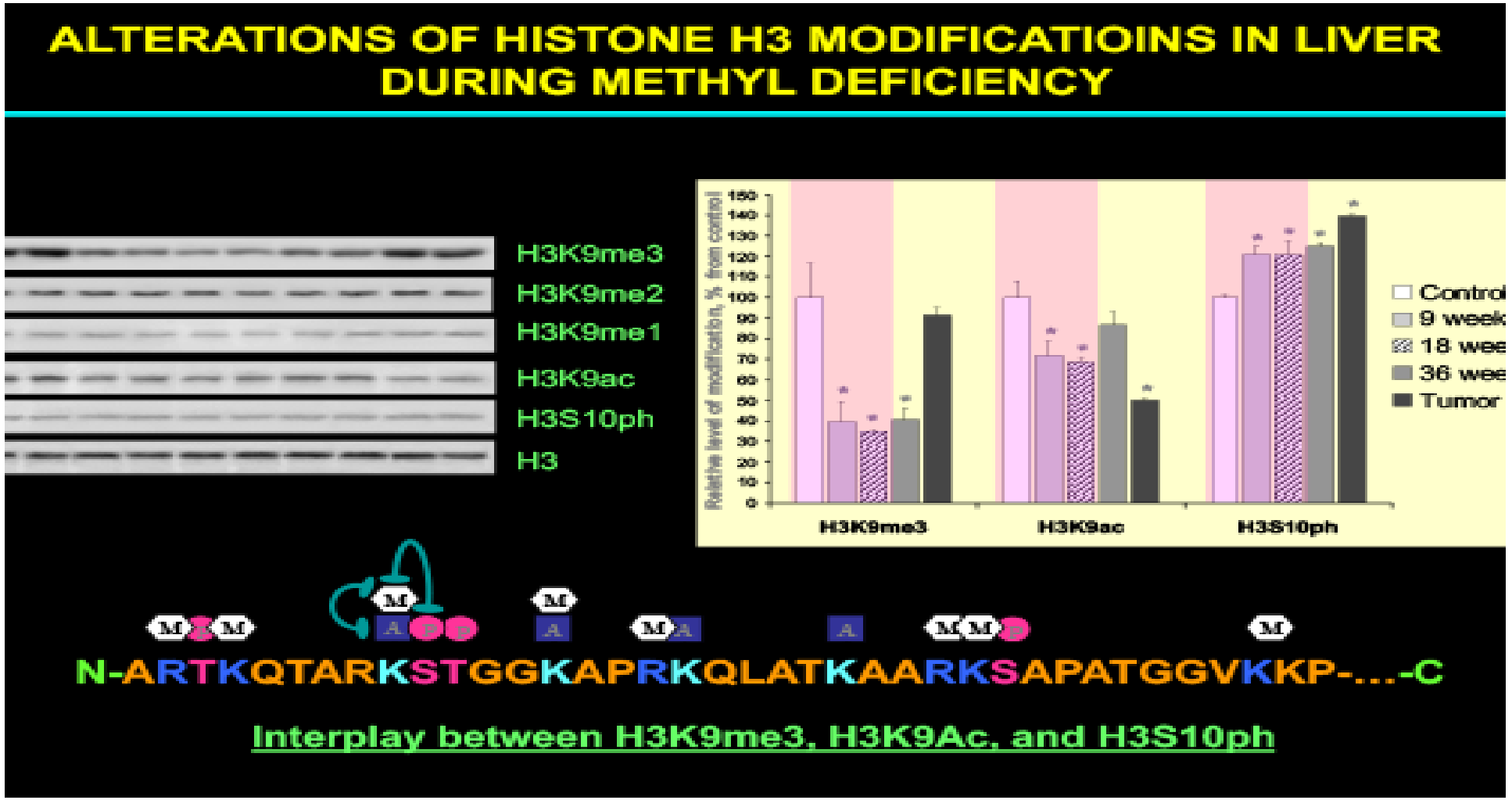
Histone mapping



Weikun Xia et al. Science 2019;365:353-360

Science AAAS

Histone H3 modifications



Epigenetic regulation

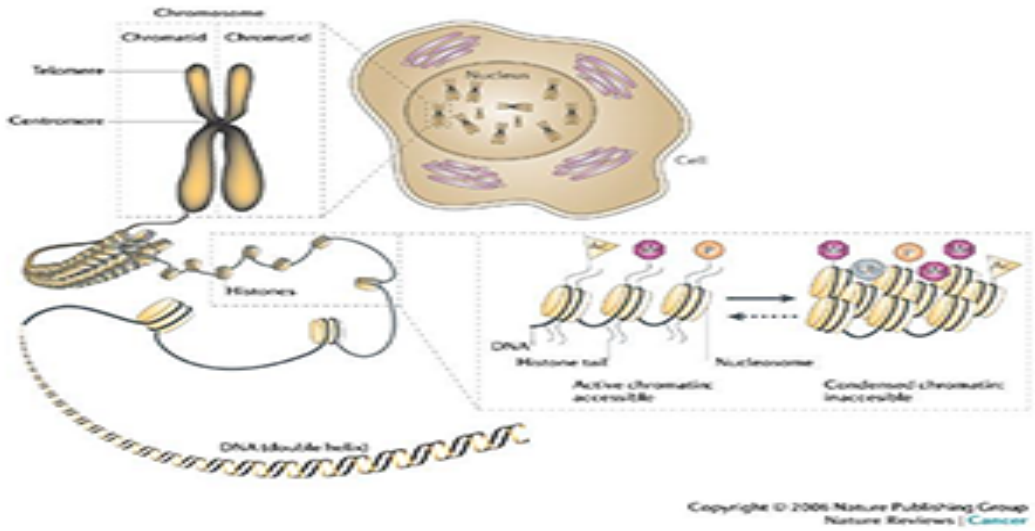
Epigenetic Gene Regulation:

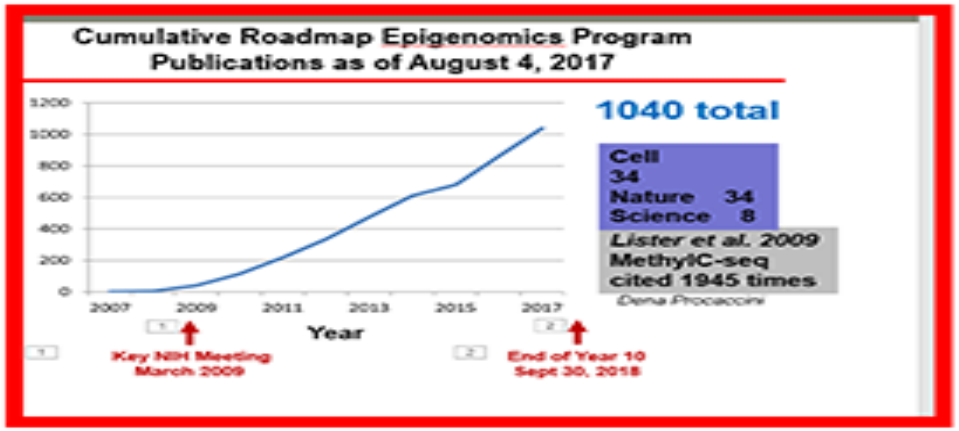
Modification		Methylation			Acetylation
		Mono-methylation	Di-methylation	Tri-methylation	
DNA		Repression	--	--	--
Histone	H3K4	Activation	Activation	Activation	--
	H3K9	Activation	Repression	Repression	Activation
	H3K27	Activation	Repression	Repression	--
	H3K36	--	Repair	Activation	Activation
	H3K79	Activation	Activation	Activation Repression	--
	H3R17	--	Activation	--	--
	H4K5	--	--	--	Activation
	H4K8	--	--	--	Activation
	H4K12	--	--	--	Activation
	H4K16	--	--	--	Activation
	H4K20	Activation	Activation	Repression	--
	H4K16	--	--	--	Activation

Abnova

Epigenetics roadmap

Epigenetics Roadmap





Epigenetically Regulated Diseases:
Several cancers, autoimmune disorders, reproductive disorders, and neurobehavioral and cognitive dysfunctions

The NIH Roadmap Epigenomics Mapping Consortium was launched with the goal of producing a public resource of human epigenomic data to catalyze basic biology and disease-oriented research.

http://nihroadmap.nih.gov/epigenomics/

Epigenetics roadmap

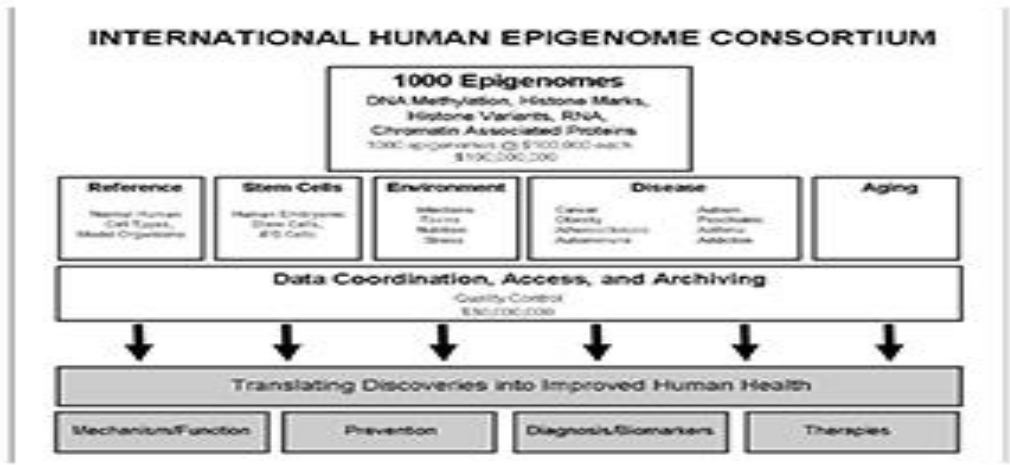
Epigenomics Program Budget

Component	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	Total
RFA 1: Mapping Centers	10	10	10	10	10				50
RFA 2: RM/IC Projects		4	8	12	16	20	16	12	88
RFA 3: Data Analysis/Coord	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	12
RFA 4: Tech Development	3.5	3.5	7	7	7	7	7		42
RFA 5: Discovery of Novel Marks	3.5	3.5	4	2	2				15
NCBI: Public access	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	12

= RFA released

8-Year Total $219 M
(plus $3M JUMPSTART)

Epigenome consortium



Participants in IHEC Meeting: Paris, Jan. 25-26, 2010

Australia
Austria
Canada
China
Euro. Comm. (EU)
France
Germany
Israel
Italy
Japan
Korea
Netherlands
Norway
Poland
Singapore
Spain
Sweden
Switzerland
UK
USA

Funding Agencies
Consiglio Nazionale delle Ricerche, Italy
European Science Foundation
Genome British Columbia, Canada
German Research Foundation, Germany
National Natural Science Foundation, China
Netherlands Genomic Initiative, Netherlands
NIH, USA
Wellcome Trust, UK

Industrial Participants
Affymetrix
Genoscope
Novartis

Other
AACR

Publishers
Nature
Science

Histone modifications

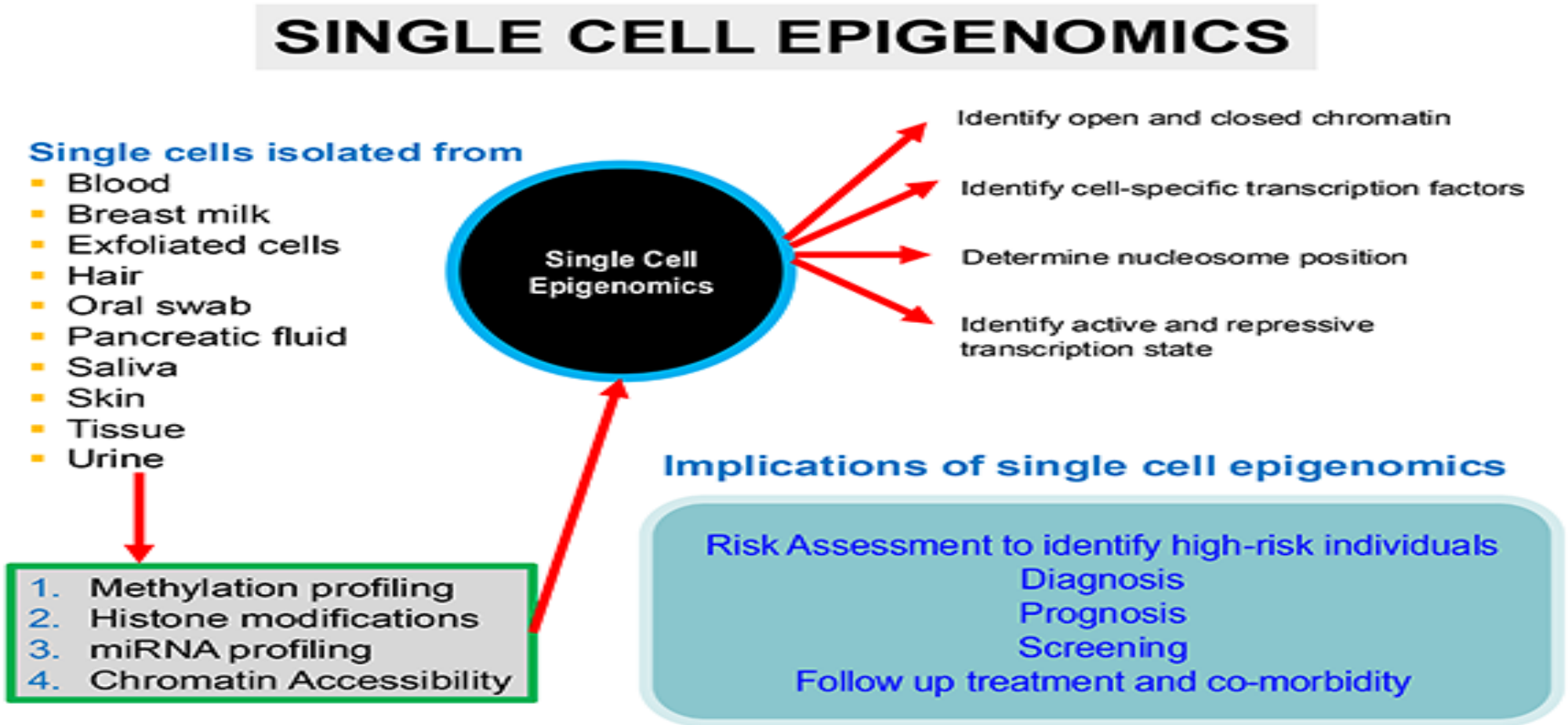
20 Diagnosing Cancer Using Histone Modification Analysis

Mukesh Verma and Deepak Kumar

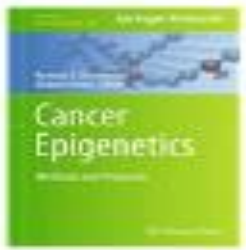
CONTENTS

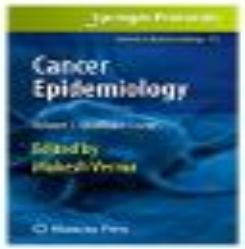
ISBN 9781420045796 - CAT# 45792

Single cell epigenomics



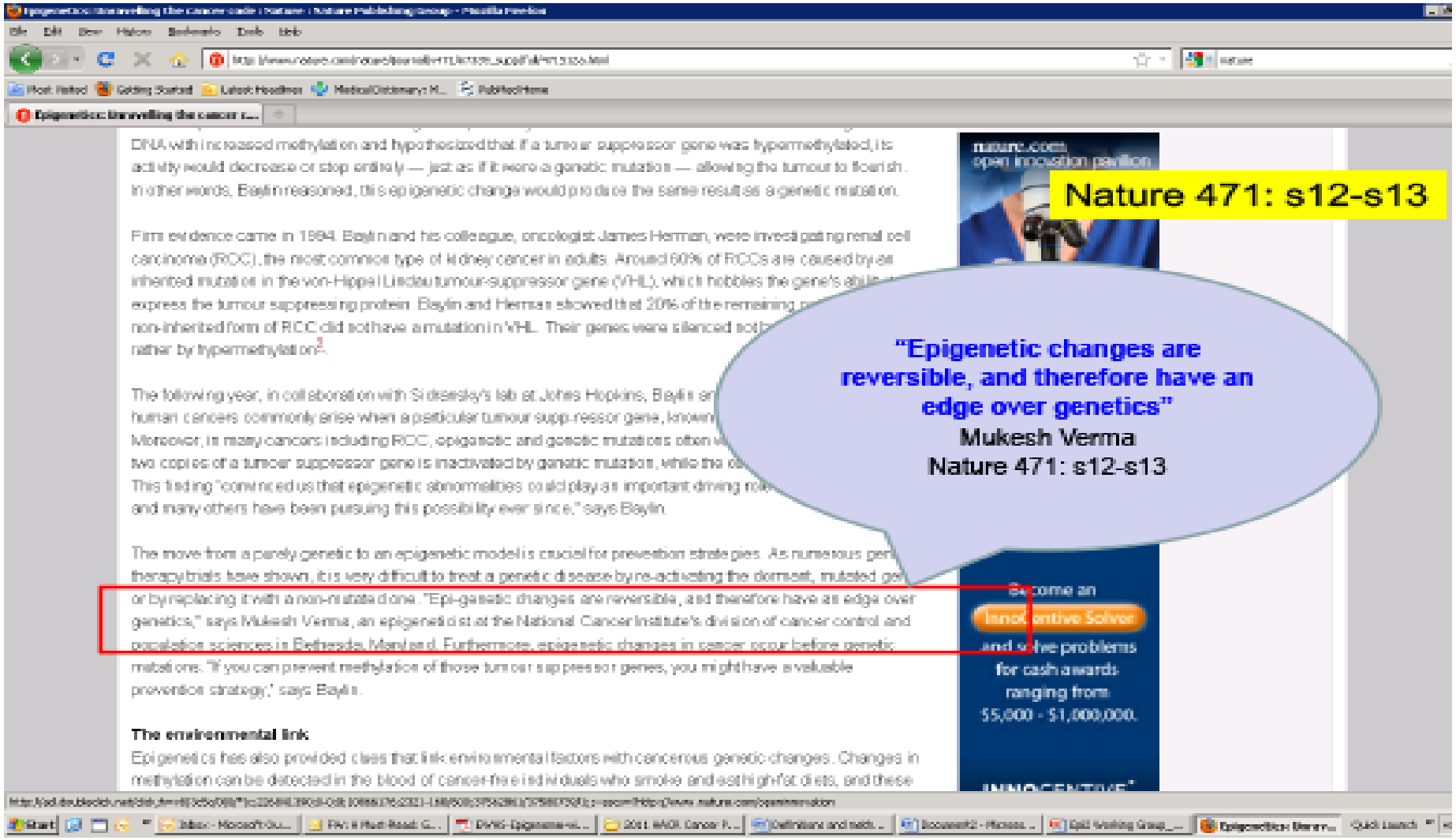
Books



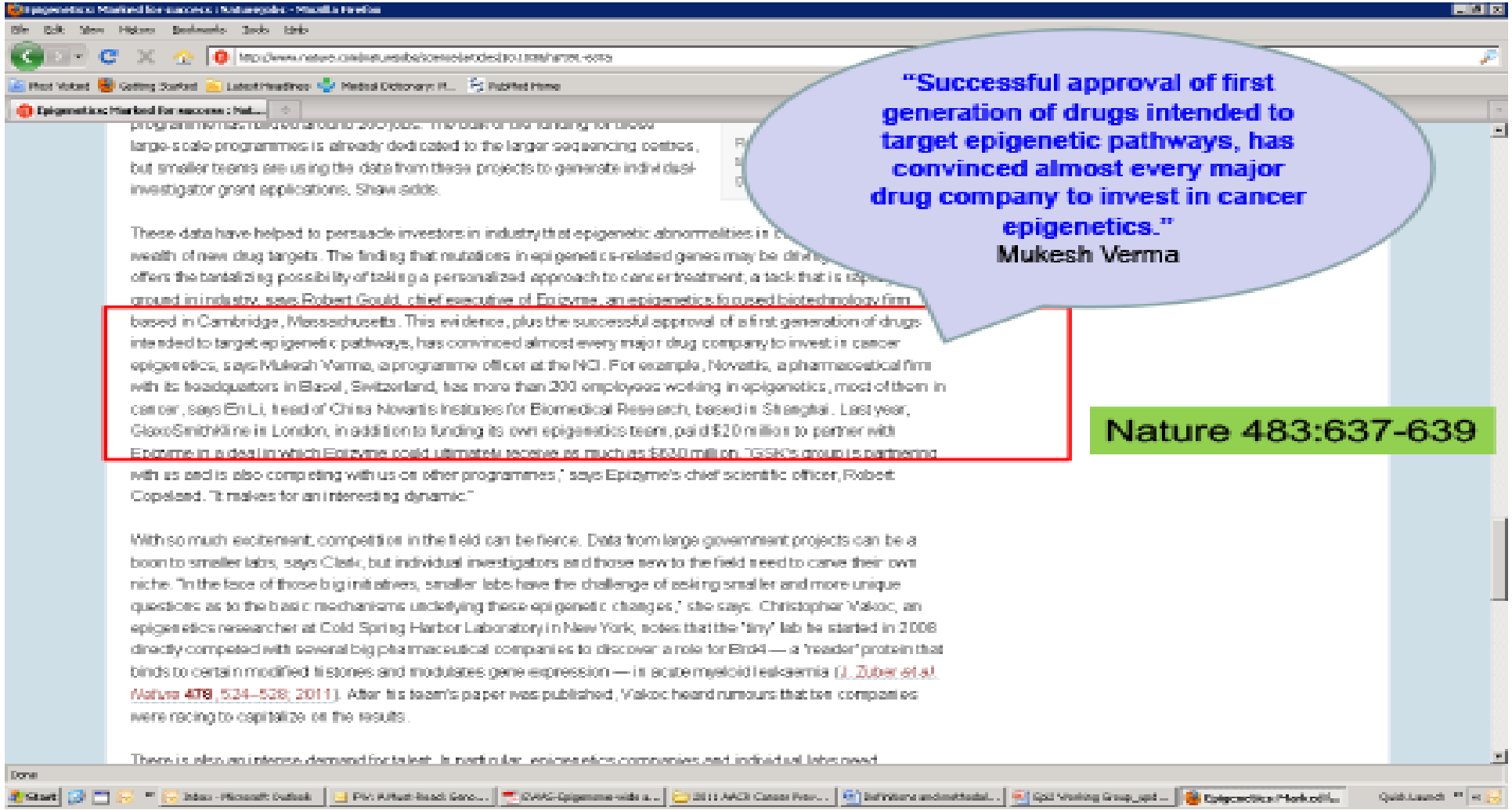


Books edited by Mukesh Verma

Epigenetic changes



Epigenetic drugs



Tumors and epigenetics

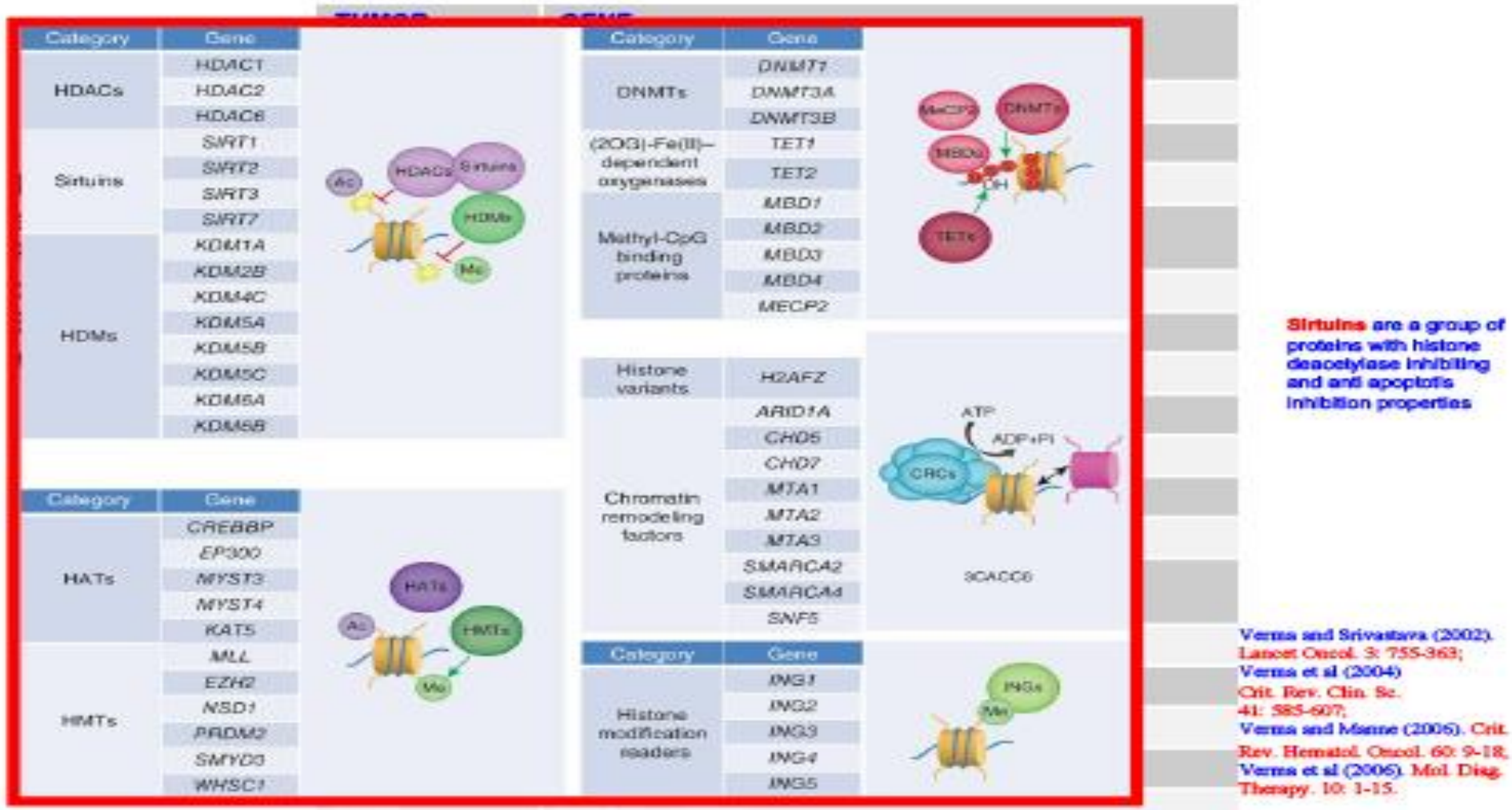
Tumor Types and Genes Regulated by Epigenetic Mechanism

TUMOR LOCATION	*GENE*
Breast	p16, BRCA1, GSTP1, DAPK, CDH1, TIMP-3
Brain	p16, p14^{ARF}, MGMT, TIMP-3
Bladder	p16, DAPK, APC
Colon	p16, p14^{ARF}, CRBP1, MGMT, hMLH1, DAPK, TIMP-3, APC
Endometrium	hMLH1
Esophagus	p16, p14^{ARF}, GSTP1, CDH1, APC
Head and Neck	p16, MGMT, DAPK
Kidney	p16, p14^{ARF}, MGMT, GSTP1, TIMP-3, APC
Leukemia	p15, MGMT, DAPK1, CDH1, p73
Liver	p16, CRBP1, GSTP1, APC
Lymphoma	p16, p15, CRBP1, MGMT, DAPK, p73
Lung	p16, p14^{ARF}, CRBP1, MGMT, GSTP1, DAPK, FHIT, TIMP-3, RARbeta, RASSF1A
Ovary	p16, BRCA1, DAPK
Pancreas	p16, MGMT, APC
Prostate	GSTP1, p27(kip1)
Stomach	p14^{ARF}, P16, APC, hMLH1, MGMT
Uterus	p16, p14^{ARF}, hMLH1

Silencing of a group of promoters with histone deacetylase inhibitors and cytidine analog inhibitor properties

Verma and Srivastava (2002) Lancet Oncol 3: 755-763
Verma et al (2004) Curr Rev Clin Sci 41: 585-607
Verma and Manne (2006) Curr Rev Hematol Oncol 60:9-18
Verma et al (2006) Mol Diag Therapy 10:1-15

Histone enzymes



Epigenetic drugs

Target	Drug	Clinical Trial
DNA Methylation	5-Azacytidine	Phase I/II/III
	5-Aza-2'deoxycytidine	Phase I/II/III
	FCDR	
	Zebularine	
	Procainamide	
	EGCG	Phase I
	Psamaplin A	
	Antisense Oligomers	Phase I
Histone deacetylase	Phenylbutyric acid	Phase I/II
	SAHA (Suberoylanilide hydroxamic acid) or Vorinostat	Phase I/II
	Depsipeptide	Phase I/II
	Valproic Acid	Phase I/II

Sirtuins are a group of proteins with histone deacetylase inhibiting and anti-apoptosis inhibitor properties

[illegible] Nature 420 407

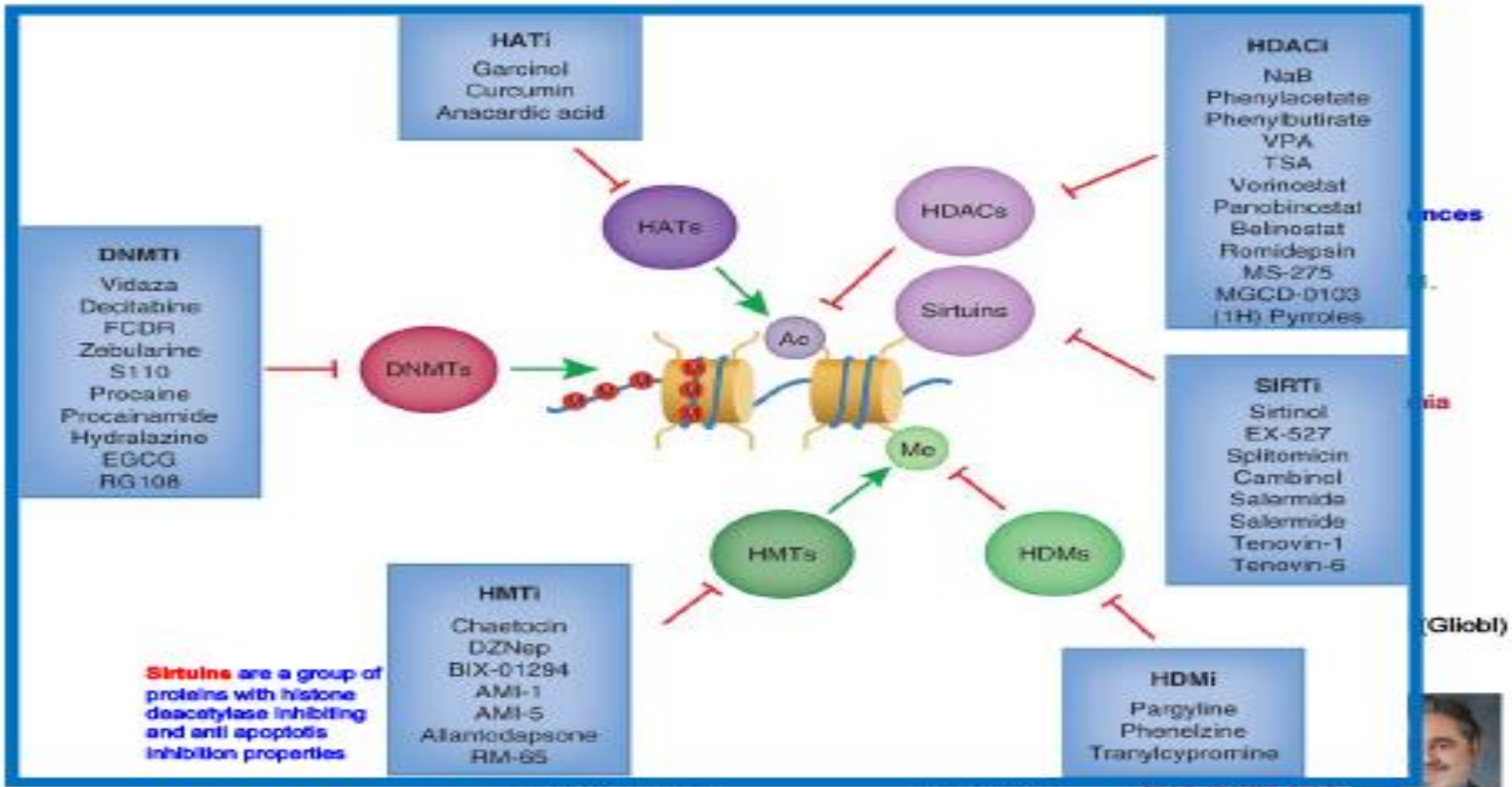
Adverse Experiences
SAHA
[illegible] 2007.
[illegible] 109:31.

- Dehydration
- Diarrhea
- Nausea
- Thrombocytopenia
- Vomiting

[illegible]

[illegible]

Methylation and acetylation enzymes



Histone deacetylase inhibitors

Table 4. Classification of Histone Deacetylase Inhibitors

Class	Compounds	Concentration needed for inhibition of histone deacetylase	Clinical trials	Notes
Short chain fatty acids	Phenylbutyrate	Milli-mole	Yes	Not ideal drug because of high dose requirement
Aliphatic compounds with hydroxamic acid	Trichostatin A, Suberoylanilide hydroxamic acid	Nano-mole Micro-mole	No Yes	Chelate Zn ion at catalytic site of HDAC.
Cyclic tetrapeptides	Trapoxin B, FK 228	Nano-molar Nano-molar	No Yes	FK228, a natural prodrug
Benzamides	MS-27-275	Micro-mole	Yes	Strong anti-tumor activity

Current Medicinal Chemistry, 2006, *13*, 2909-2919

HDAC 1, 2, 3, 8, 11 have been characterized (Khan, I , 2007)

Phase I study

Phase I study of epigenetic modulation with 5-azacytidine and valproic acid in patients with advanced cancers.

Braiteh F, Soriano AO, Garcia-Manero G, Hong D, Johnson MM, Silva Lde P, Yang H, Alexander S, Wolff J, Kurzrock R. Clin Cancer Res.14(19):6296-301. (colorectal cancer, melanoma and breast cancer)

5 Azacytidine
S.C. daily for 10 days

+

Valproic Acid
Orally daily to titrate to 75-100 ug/ml

28 Days Cycle

55 people with Advanced cancer Median age 60

Peripheral blood
- Pyrosequencing
- Chip

Analysis Day 1, 10 and 28

- **The maximum tolerated dose was 75 mg/m(2) of 5-AZA in combination with valproic acid.**
- **Dose-limiting toxicities were neutropenic fever and thrombocytopenia, which occurred at a dose of 94 mg/m(2) of 5-AZA.**
- **Stable disease lasting 4 to 12 months (median, 6 months) was observed in 14 patients (25%).**

A significant decrease in global DNA methylation and induction of histone acetylation were observed.

The combination of 5-AZA and valproic acid is safe at doses up to 75 mg/m(2) for 5-AZA in patients with advanced malignancies.

5-azacytidine, valproic acid and ATRA

Safety and clinical activity of the combination of 5-azacytidine, valproic acid, and all-trans retinoic acid in acute myeloid leukemia and myelodysplastic syndrome.

Soriano et al. Blood. 110(7):2302-8.

- **Combination of 5-azacitidine (5-AZA), valproic acid (VPA), and ATRA in patients with acute myeloid leukemia or high-risk myelodysplastic syndrome.**
- **A total of 53 patients were treated.**
- **The overall response rate was 42%.**
- **A significant decrease in global DNA methylation and induction of histone acetylation were achieved.**
- **VPA blood levels were higher in responders.**
- **The combination studied is safe and has significant clinical activity.**

This clinical trial was registered at www.clinicaltrials.gov as no. NCT00326170.

Histone inhibitors

Histone Inhibitors in Clinical Trials (Clinicaltrials.gov)

STATUS	STUDY
Recruiting	Safety Study of the Histone Deacetylase Inhibitor, CHR-3996, in Patients With Advanced Solid Tumours
Recruiting	Phase II Study of Histone-Deacetylase Inhibitor ITF2357 in Refractory/Relapsed Lymphocytic Leukemia
Recruiting	phII Study of an HDAC Inhibitor in Very High-Risk Relapsed/Refractory Hodgkin's Lymphoma Patients
Recruiting	Phase IIA Study of the HDAC Inhibitor ITF2357 in Patients With JAK-2 V617F Positive Chronic Myeloproliferative Diseases
Recruiting	Phase II Trial of the Histone-Deacetylase Inhibitor ITF2357 Followed by Mechlorethamine in Relapsed/Refractory Hodgkin's Lymphoma Patients
Recruiting	HDAC Inhibitor Vorinostat (SAHA) With Capecitabine (Xeloda) Using a New Weekly Dose Regimen for Advanced Breast Cancer
Recruiting	Valproic Acid, Temozolomide, and Radiation Therapy in Treating Patients With Glioblastoma Multiforme
Recruiting	Study of Vorinostat (MK0683) an HDAC Inhibitor, or Placebo in Combination With Bortezomib in Patients With Multiple Myeloma
Recruiting	Study of Vorinostat (MK0683), an HDAC Inhibitor, in Combination With Bortezomib in Patients With Relapsed or Refractory Multiple Myeloma
Completed	A Phase II Study of Epigenetic Therapy to Overcome Chemotherapy Resistance in Refractory Solid Tumors
Recruiting	Sorafenib and LBH589 in Hepatocellular Carcinoma (HCC)
Recriting	Phase II Study of Valproic Acid With FEC100 for Patients With Locally Advanced Breast Cancer

Total : 84 studies

http://clinicaltrials.gov/ct2/results?term=histone+inhibitors&pg=4

Methylation inhibitors

Methylation Inhibitors in Clinical Trials (Clinicaltrials.gov)

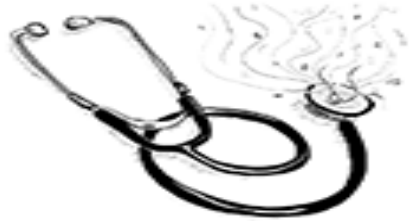
STATUS	STUDY
Completed	A Phase II Study of Epigenetic Therapy to Overcome Chemotherapy Resistance in Refractory Solid Tumors
Active Not Recruiting	Azacitidine and Valproic Acid in Patients With Advanced Cancers
Recruiting	Azacitidine With MGCD0103 or MS-275 in Treating Patients With Myelodysplastic Syndromes, Chronic Myelomonocytic Leukemia, or Acute Myeloid Leukemia
Active Not Recruiting	PhIII-Azacitidine Plus Valproic Acid and Preantelbe Beta in Intermediate II and High Risk MDS
Recruiting	Decitabine With or Without Interferon Alfa-2b in Treating Patients With Unresectable or Metastatic Solid Tumors
Recruiting	Hydralazine Valproate for Cervical Cancer
Recruiting	Hydralazine Valproate for Ovarian Cancer
Recruiting	Decitabine in Treating Patients With Previously Untreated Acute Myeloid Leukemia
Recruiting	Chronic Hepatitis C Non-Responder Study With Ado Met and Peginx
Recruiting	Azacitidine, Docetaxel, and Prednisone in Treating Patients With Metastatic Prostate Cancer That Did Not Respond to Hormone Therapy
Recruiting	Low Dose Decitabine + Interferon Alfa-2b in Advanced Renal Cell Carcinoma

Total : 51 studies

http://clinicaltrials.gov/ct2/results?term=methylation+inhibitors

Schering-Plough (Decitabine (5-aza-Deoxycytadine) Trial for melanoma) (8 hrs to inactivate DNMT1)
Bristol-Myers Squibb (other compounds)

Three-drug combination



Novel drug combination shows promise in advanced HER2-negative breast cancer treatment

A novel three-drug combination achieved notable responses in patients with advanced HER2-negative breast cancer, according to new research directed by investigators from the Johns Hopkins Kimmel Cancer Center.

The treatment included a histone deacetylase inhibitor, a drug that causes a chemical change to stop tumor cells from dividing, with two types of immunotherapy known as checkpoint inhibitors, which unharness the power of the immune response against cancer.

The multicenter phase IB study, which aimed to improve response to checkpoint inhibitors by sensitizing the tumor microenvironment, found that the combination therapy resulted in a 25%

Three-drug combination achieved notable responses in patients with advanced HER2-negative breast cancer

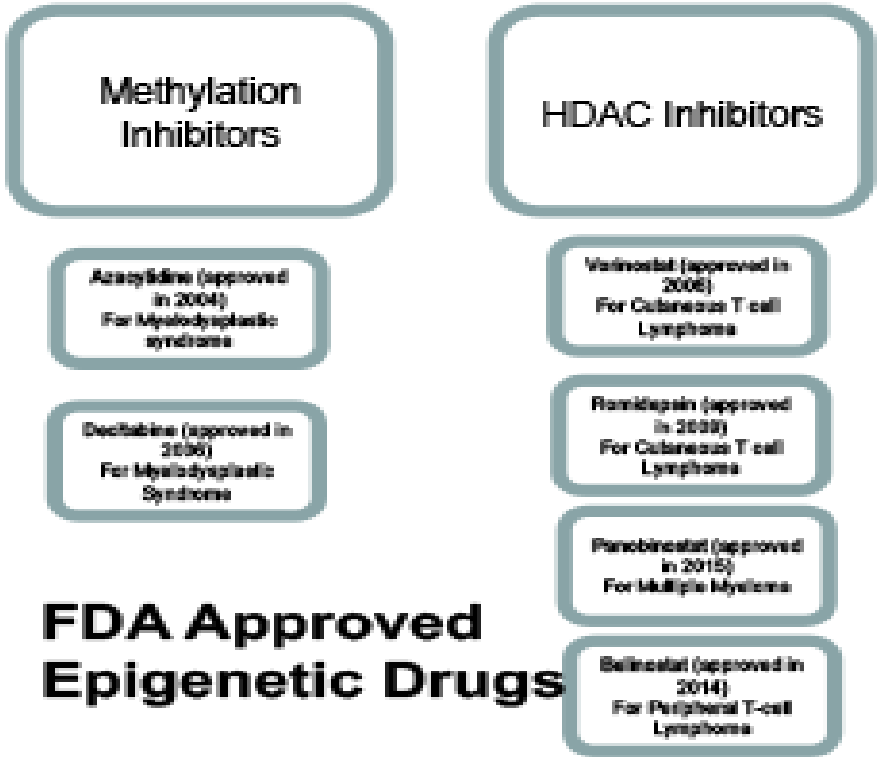
HDAC (entinostat)
Drug causing chemical change to stop tumor cell from dividing
Checkpoint inhibitors
PD-1/PD-L1 inhibitor nivolumab
CTLA-4 inhibitor ipilimumab

25% reduction in response rate in advanced breast cancer patients for 6 months (tumor either destroyed or reduced)

HER-2. Human Epidermal Growth Factor Receptor

Nature Cancer. February 2024

Approved epigenetic drugs

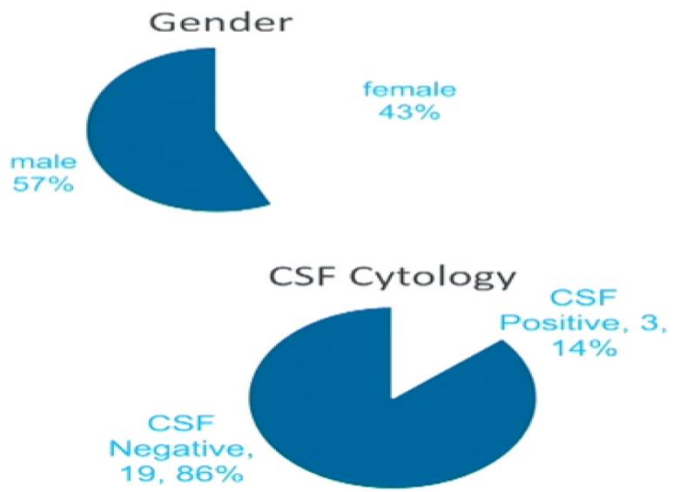


Childhood cancer data initiative

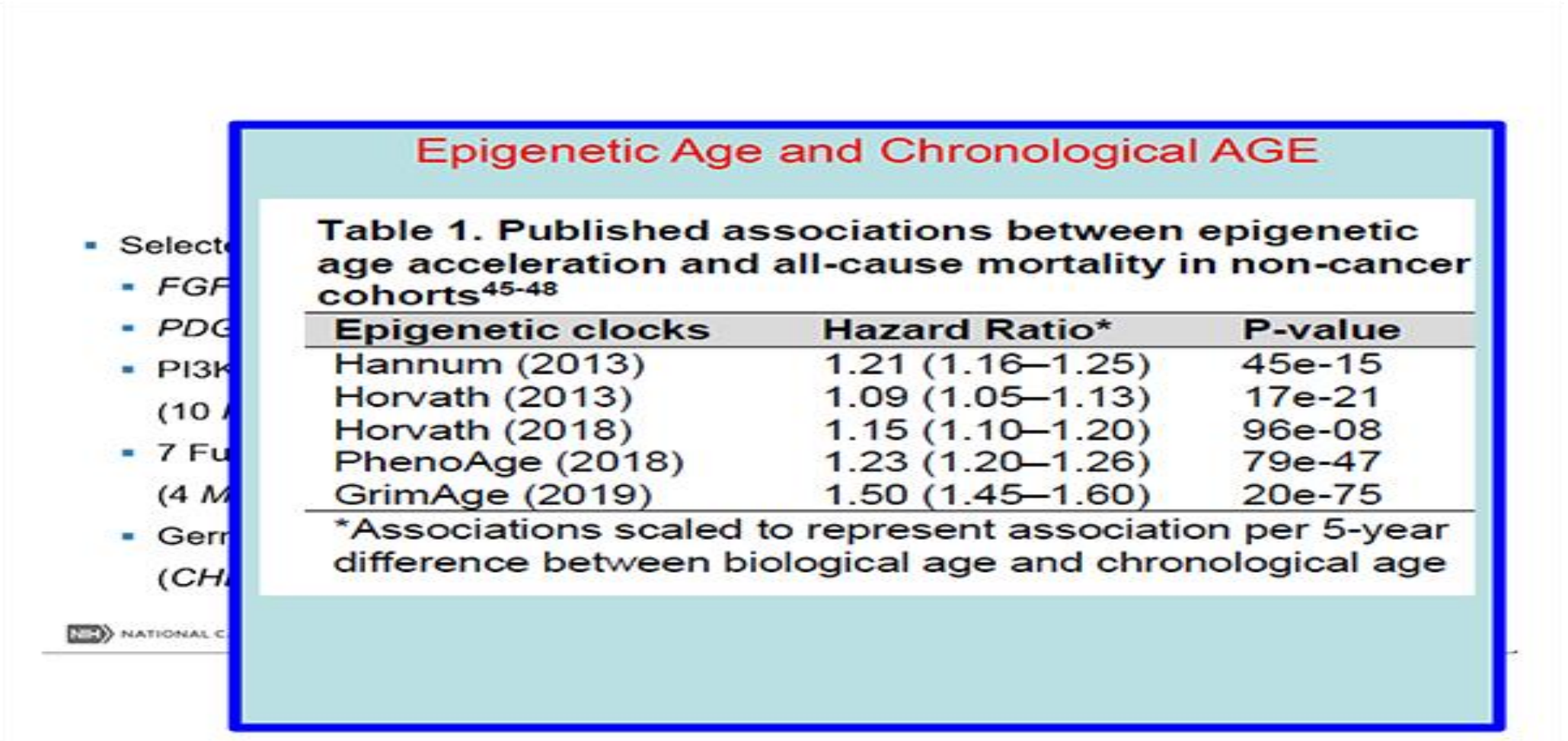
CNS Diagnosis

MCI CNS Diagnosis: Diffuse Midline Glioma, H3K27 altered (n=86)

- Median age: 9 years (range 3-20)
- Gender: 57% male:43% female
- Stage: 3/22 (14%) positive CSF cytology (most not tested)
- One Year Follow-Up available for first 14 patients: 43% survival
- All tumors with alterations in addition to H3K27



Epigenetic age



Clinical trials

nature REVIEWS CANCER

Table 1: Summary of clinical trials of epigenetic therapies in solid tumours as drug resistance modulators

From

Poised epigenetic states and acquired drug resistance in cancer

Robert Brown, Edward Curry, Luca Magnani, Charlotte S. Wilhelm-Benartzi & Jane Borley

Nature Reviews Cancer **14**, 747–753 (2014) | doi:10.1038/nrc3819

« back to article

Table 1: Summary of clinical trials of epigenetic therapies in solid tumours as drug resistance modulators

Cancer type	Epigenetic therapy	Drug combination	Patient selection	Response	Pharmacodynamic target validation?*	Refs‡
Gastrointestinal stromal tumours	Panobinostat (pan-deacetylase inhibitor)	Panobinostat and imatinib	Patients with metastatic gastrointestinal stromal tumours refractory to imatinib and sunitinib	1 of 11 partial response; 7 of 11 stable disease; 3 of 11 progressive disease	Yes	87
Wild-type KRAS metastatic colorectal cancer	Decitabine (demethylating agent)	Decitabine and panitumumab (monoclonal antibody against EGFR)	Patients with progressive disease on standard therapy and previously treated with cetuximab	2 of 20 partial response; 11 of 20 stable disease; 7 of 20 progressive disease	No	88
Advanced solid tumours	Azacytidine (demethylating agent); Valproic acid (pan-deacetylase inhibitor)	Azacytidine, valproic acid and carboplatin	Advanced cancer and progression following standard therapy (platinum-based) or no standard effective therapy available	6 of 32 stable disease; 26 of 32 progressive disease	Yes	89
			Initial response by			

Combination therapy

AML subtypes and combination therapy

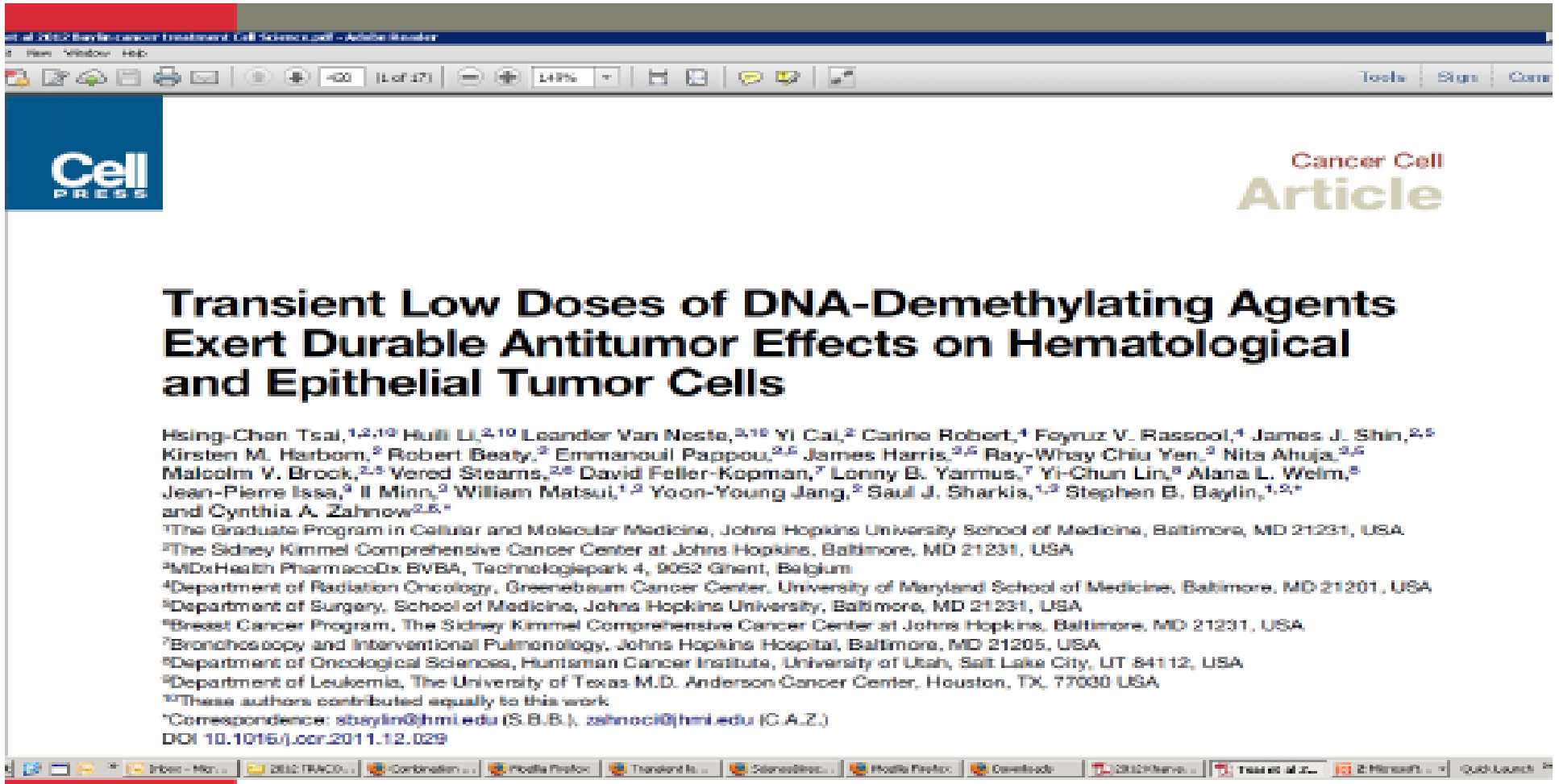
Pharmaceutical Participation

AML Subtype	Drug	Company
Tet2/WTI	CD33 + Aza	BI
IDH2 Mutation	Enasidenib	Celgene
MLL	Entospletinib (Syk inhibitor)	Gilead
CBF	Samalizumab (CD200 Ab) + induction	Alexion
P53 mutation	Entospletinib (Syk inhibitor) + Decitabine	Gilead
Complex Karotype	Entospletinib (Syk inhibitor) + Decitabine	Gilead
P53 mutation	Pevonedistat (Nedd8 inhibitor) + Aza	Takeda
Marker Negative	CD33 + Aza	BI
NPM1 w FLT3 WT	Entospletinib (Syk inhibitor)	Gilead
FLT3 mutation	Gilteritinib	Astellas
IDH1 Mutation	Ivosidenib + Aza	Agios

Source: Leukemia & Lymphoma Society

Cancer letters 17 July 2018

Low doses of DNA-demethylating agents



Cell PRESS

Cancer Cell
Article

Transient Low Doses of DNA-Demethylating Agents Exert Durable Antitumor Effects on Hematological and Epithelial Tumor Cells

Hsing-Chen Tsai,[1,2,10] Hulli Li,[2,10] Leander Van Neste,[3,10] Yi Cai,[2] Carine Robert,[4] Foyruz V. Rassool,[4] James J. Shin,[2,5] Kirsten M. Harbom,[2] Robert Beaty,[2] Emmanouil Pappou,[2,5] James Harris,[2,5] Ray-Whay Chiu Yen,[2] Nita Ahuja,[2,5] Malcolm V. Brock,[2,5] Vered Stearns,[2,6] David Feller-Kopman,[7] Lonny B. Yarmus,[7] Yi-Chun Lin,[8] Alana L. Welm,[8] Jean-Pierre Issa,[9] Il Minn,[2] William Matsui,[1,2] Yoon-Young Jang,[2] Saul J. Sharkis,[1,2] Stephen B. Baylin,[1,2,*] and Cynthia A. Zahnow[2,5,*]

[1]The Graduate Program in Cellular and Molecular Medicine, Johns Hopkins University School of Medicine, Baltimore, MD 21231, USA
[2]The Sidney Kimmel Comprehensive Cancer Center at Johns Hopkins, Baltimore, MD 21231, USA
[3]MDxHealth PharmacoDx BVBA, Technologiepark 4, 9052 Ghent, Belgium
[4]Department of Radiation Oncology, Greenebaum Cancer Center, University of Maryland School of Medicine, Baltimore, MD 21201, USA
[5]Department of Surgery, School of Medicine, Johns Hopkins University, Baltimore, MD 21231, USA
[6]Breast Cancer Program, The Sidney Kimmel Comprehensive Cancer Center at Johns Hopkins, Baltimore, MD 21231, USA
[7]Bronchoscopy and Interventional Pulmonology, Johns Hopkins Hospital, Baltimore, MD 21205, USA
[8]Department of Oncological Sciences, Huntsman Cancer Institute, University of Utah, Salt Lake City, UT 84112, USA
[9]Department of Leukemia, The University of Texas M.D. Anderson Cancer Center, Houston, TX, 77030 USA
[10]These authors contributed equally to this work
*Correspondence: sbaylin@jhmi.edu (S.B.B.), zahnoci@jhmi.edu (C.A.Z.)
DOI 10.1016/j.ccr.2011.12.029

Reprograming and editing

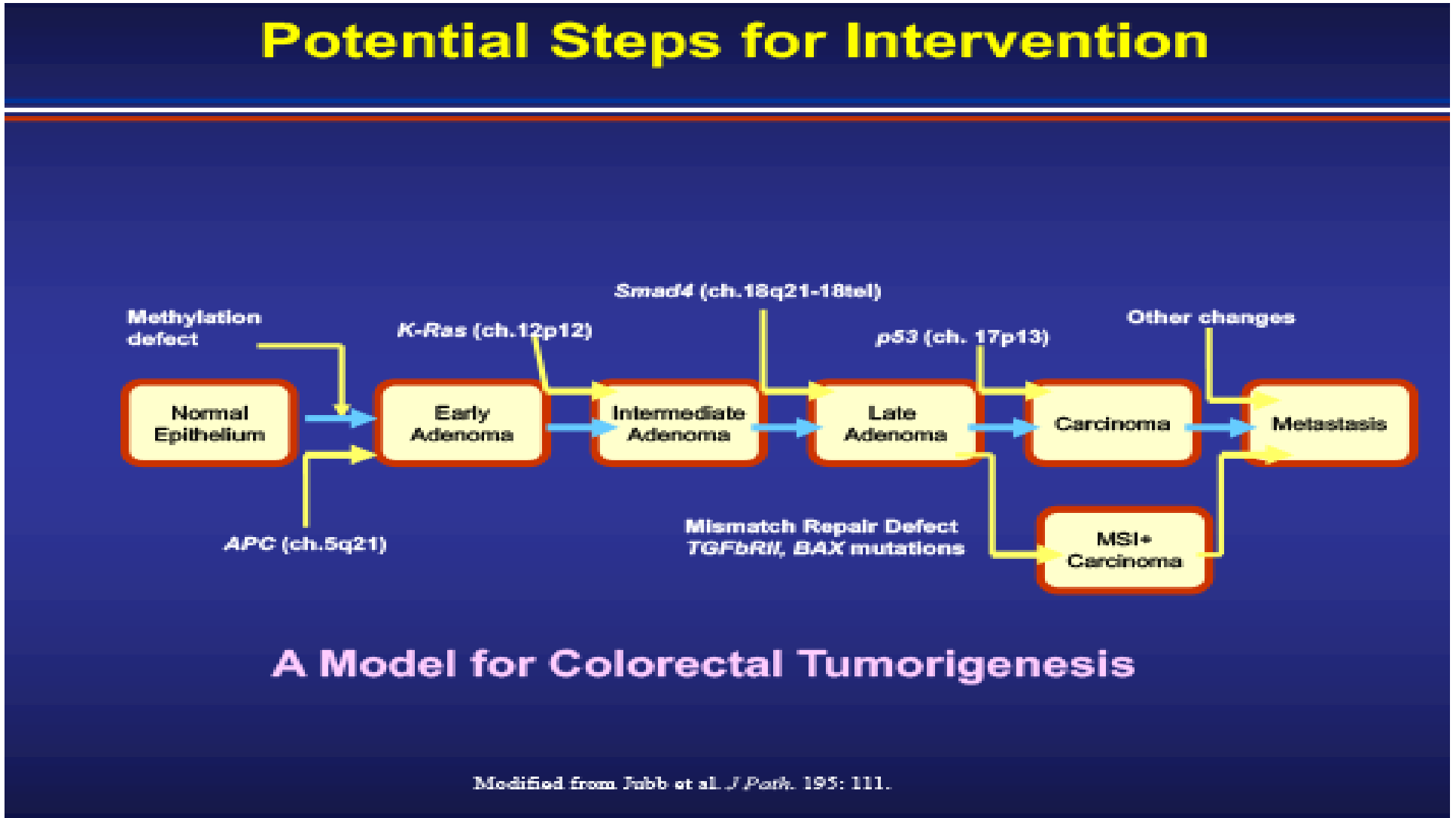
Epigenome Reprogramming and Epigenetic Editing

Table. Selected epigenomic editing companies

Company, Year Founded	Recent Funding Events	Selected ASGCT 2023 Presentations*
Chroma Medicine, 2021	$125M Series A (November 2021) $135M Series B (March 2023)	Development of a Human PCSK9-Targeting Epigenetic Editor with Durable, Near-Complete In Vivo Silencing Efficiency Multiplexed Editing without Chromosomal Rearrangements Using Epigenetic Editors
Epic Bio, 2022	$55M Series A (July 2022)	EPI-321: A Potential Cure for FSHD
Modalis Therapeutics, 2016[a]		Advancing Epigenetic Editing with CRISPR-GNDM: Novel Muscle-Tropic AAV Vectors Deliver Promising Single-Dose Treatment for LAMA2-CMD
Navega Therapeutics, 2018	$3.8M SBIR/NCI (September 2019) $2M NINDS (June 2021)	N/A
Tune Therapeutics, 2020	$40M Series A (December 2021)	Transient Delivery of Epigenome Editors Stably Represses PCSK9 and Lowers LDL Cholesterol in Nonhuman Primates
Rejuvenate Bio, 2017	$10M Series A (April 2021)	Relevance of Animal Data for Human Health Programs

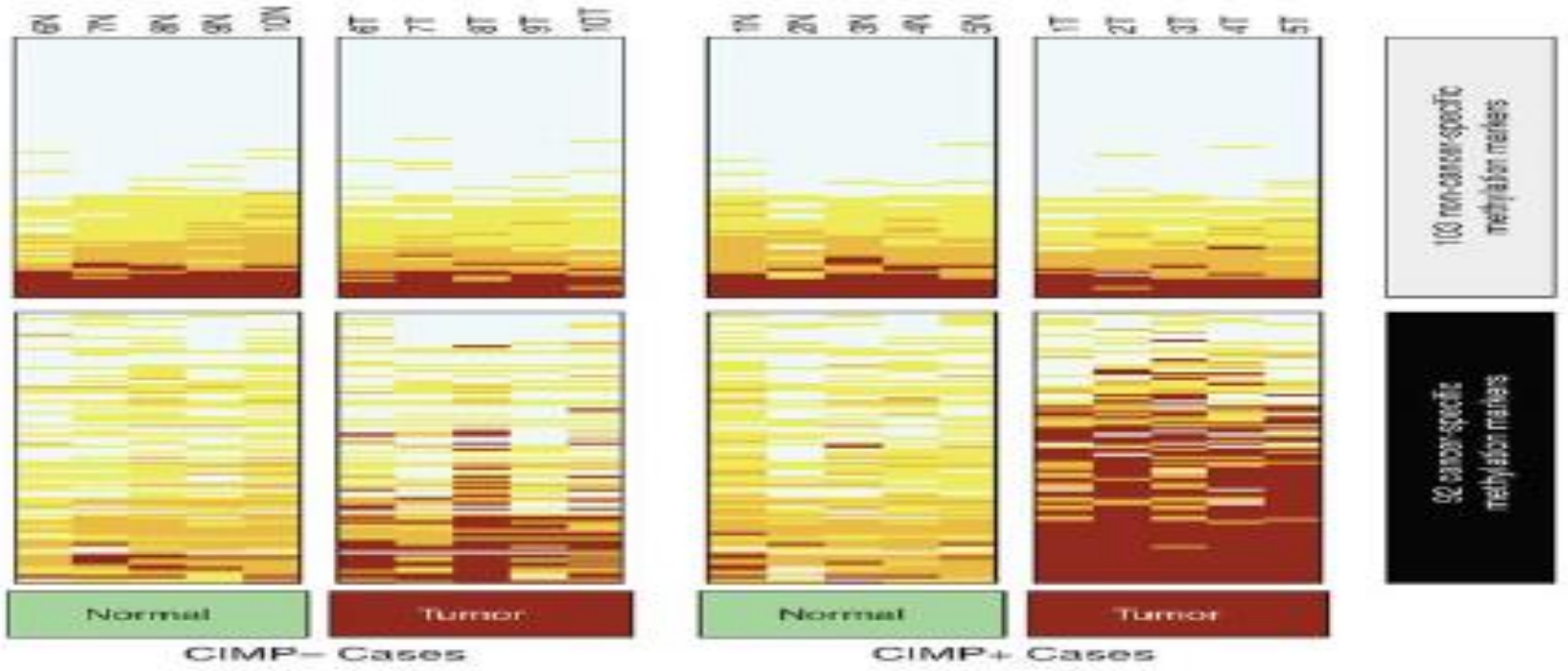
[a]Named EdiGene when founded in 2016 and renamed Modalis Therapeutics in 2019.
*Oral abstract session or scientific symposium.

Intervention



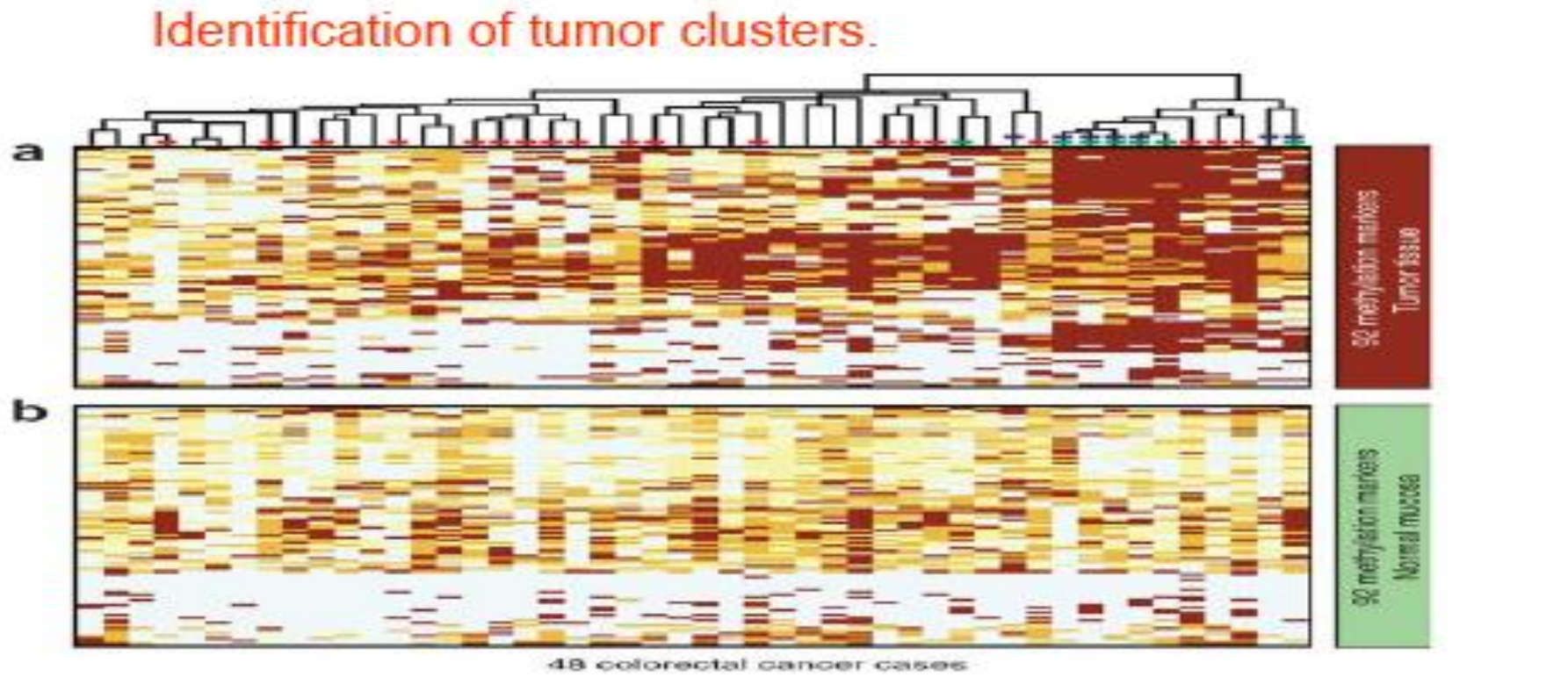
Microsatellite instability

CpG island methylator phenotype underlies sporadic microsatellite instability and is tightly associated with BRAF mutation in colorectal cancer



Nature Genetics 38, 787 - 793

Tumor clusters

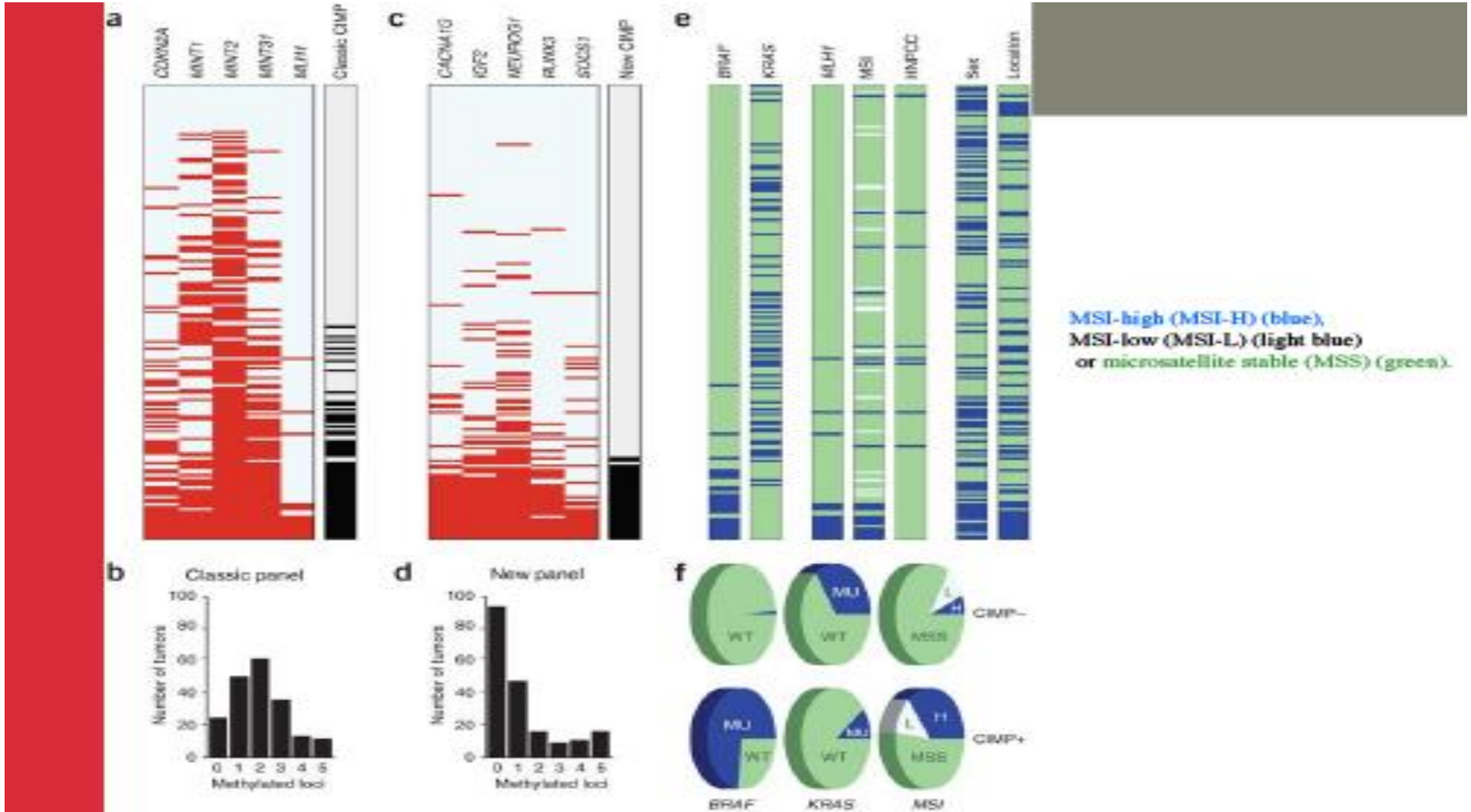


KRAS mutation indicated by a red rectangle overlaying the branch,
BRAF mutations indicated by a green rectangle
MSI-H cases designated with a blue rectangle.

48 Colorectal tumors

Nature Genetics **38**, 787 - 793

Genetic analysis



CRC markers

Validated CRC Markers in Clinical Trials

Table 1:

Validated DNA-methylation biomarkers for colorectal cancer

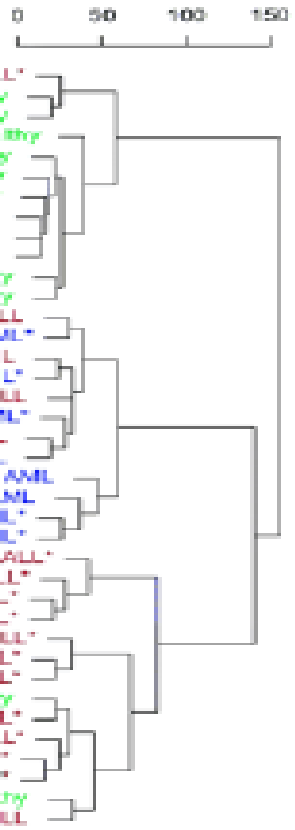
Clinical Use	Biomarkers	Available Commercial Assays	Study Design of Major Trials with Assay	Ref.
Stool-based CRC screening	mHLTM;	ColoSure™	Case (N=42) control (N=241) study	109
	mBMP3 and mNDRG4	Cologuard® (detects mutant KRAS and includes a FIT test)	Prospective cohort based clinical trial in screening population (N=9989)	110
blood-based diagnostic marker	mSEPT9	EpiproColon® 1.0, ColoVantage®; RealTime m99	Multiple trials. 1) Prospective cohort based clinical trial in screening population (N=7941) (Church);2) Case-Control study (N=269) (deVos); 3) Case-Control study (N=312) (Lofton-Day 2008)	135 135,136,139
	mSCATJ mWZFV	Colvera	Cross-sectional study (N=220)	138
Tissue-based prognostic markers	GIMP panel	NA	Multiple trials: 1. Case-Control study from 2 phase I/II clinical trials (N=31)(Ogino 2007); 2. Case-Control study from phase 3 clinical trial (N=618) (Shovitz 2014);3) Observational cohort study (N=2060)(Phipps 2015)	140, 142, 159, 188
Diagnostic tool to screen for Lynch syndrome	mMLAH	MLH1 Hypermethylation analysis	1. Cross sectional study (N=1066)	67

Gastroenterology. 2021 Feb; 160(3): 690–709.

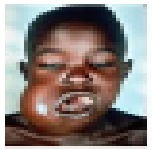
Methylation analysis

National Cancer Institute

Prediction of Tumor Class based on Methylation Analysis (AML and ALL)



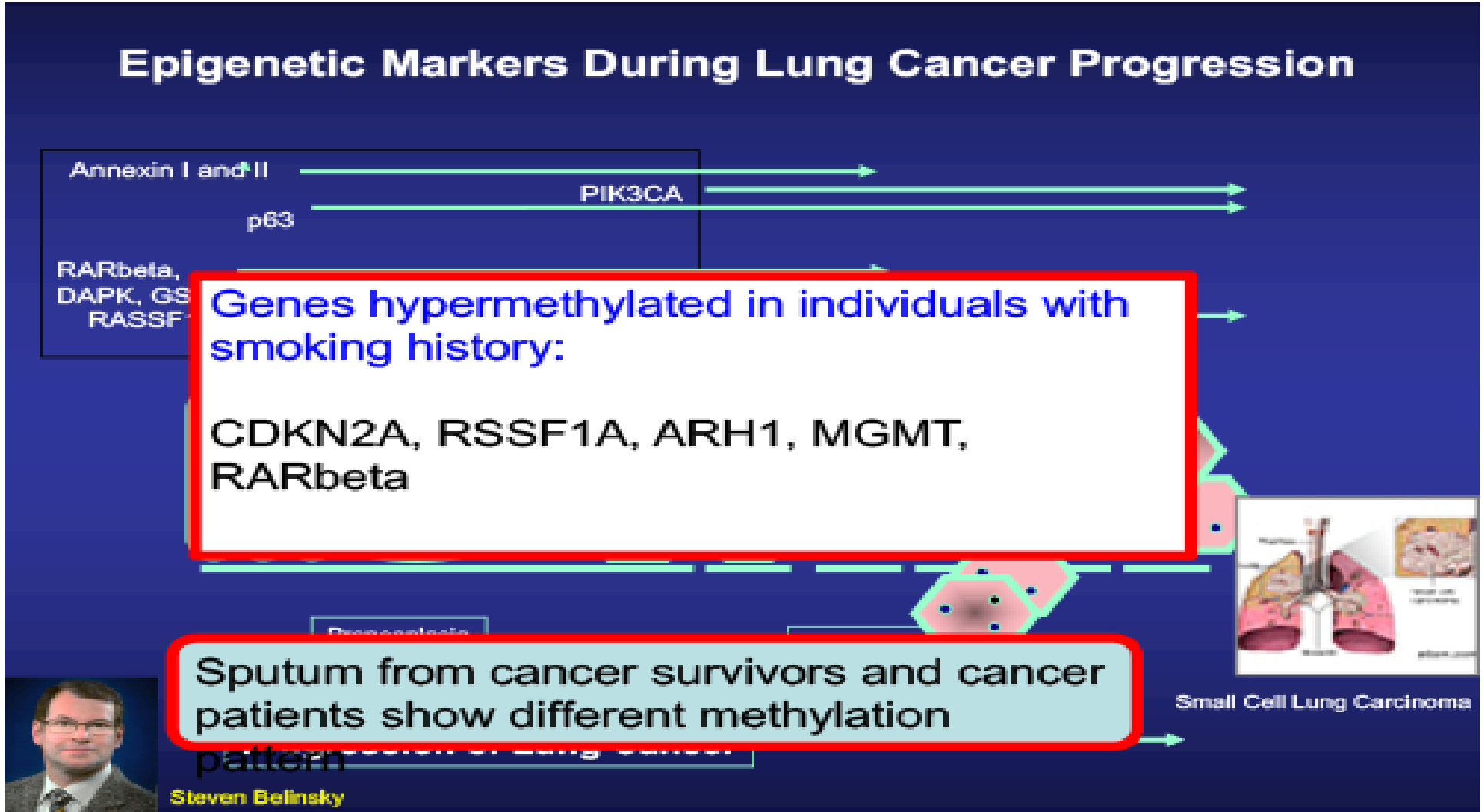
AML:Acute Myeloid Leukemia
ALL: Acute Lymphoblastic Leukemia



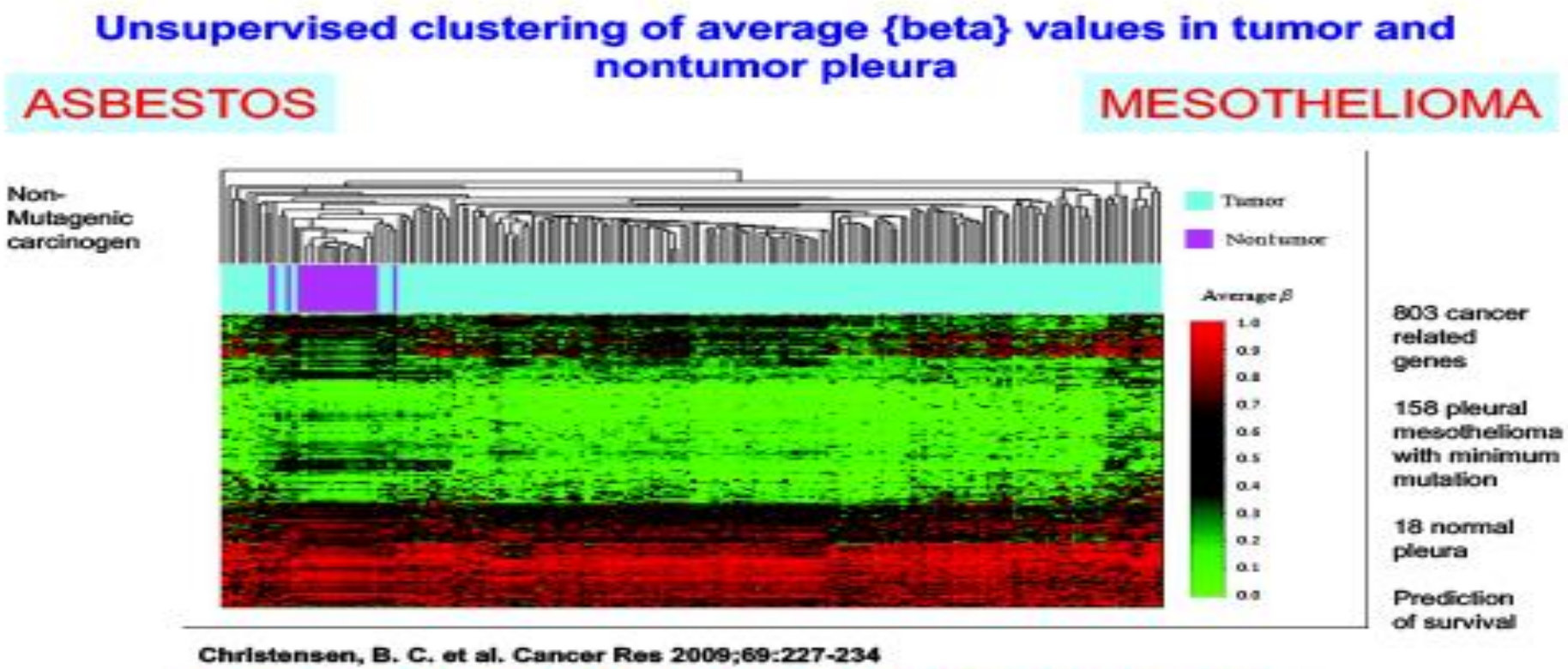
Lymphoma

Adorjan et al *Nuc Ac Res.* 30: e21

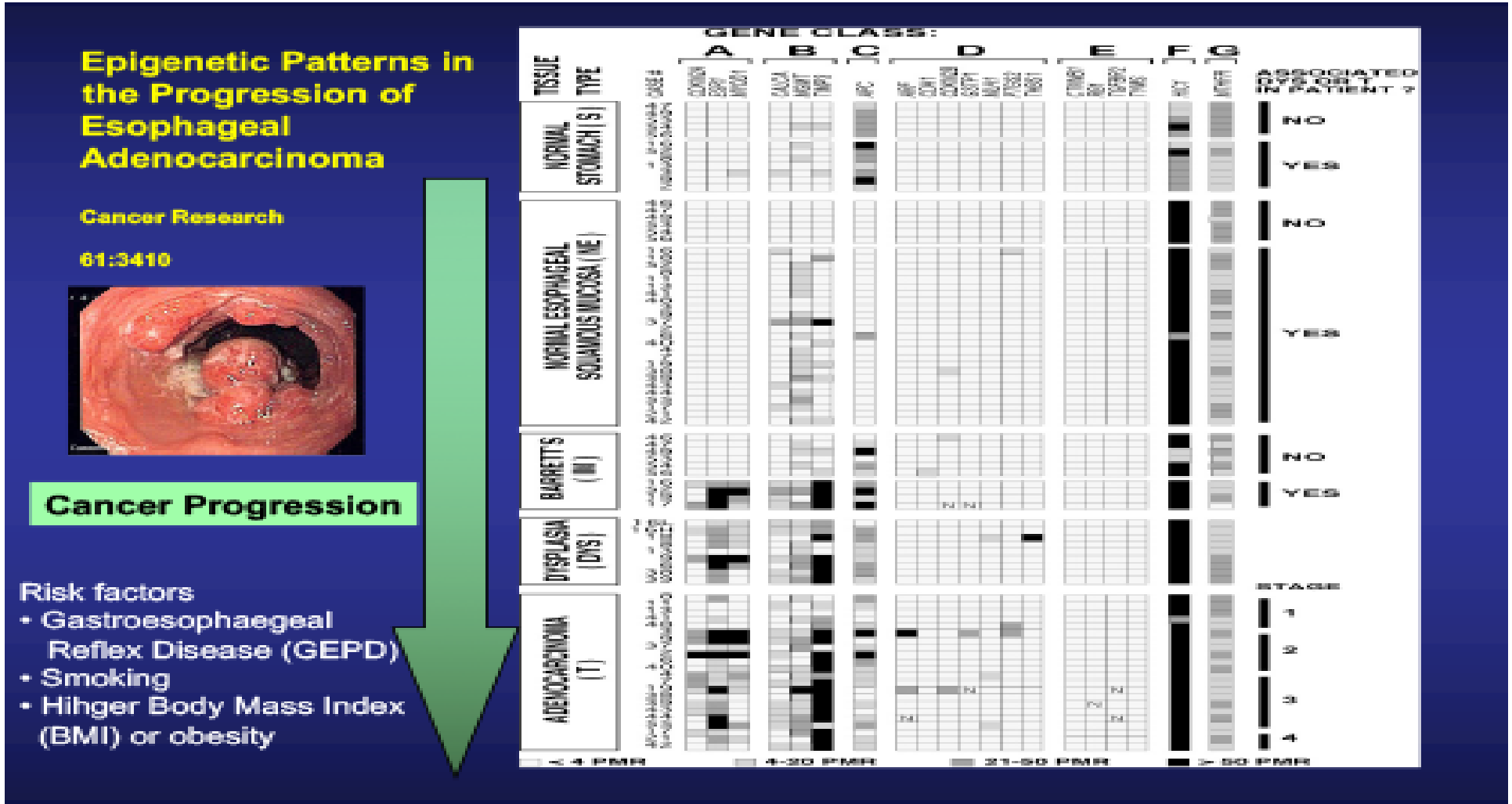
Epigenetic markers



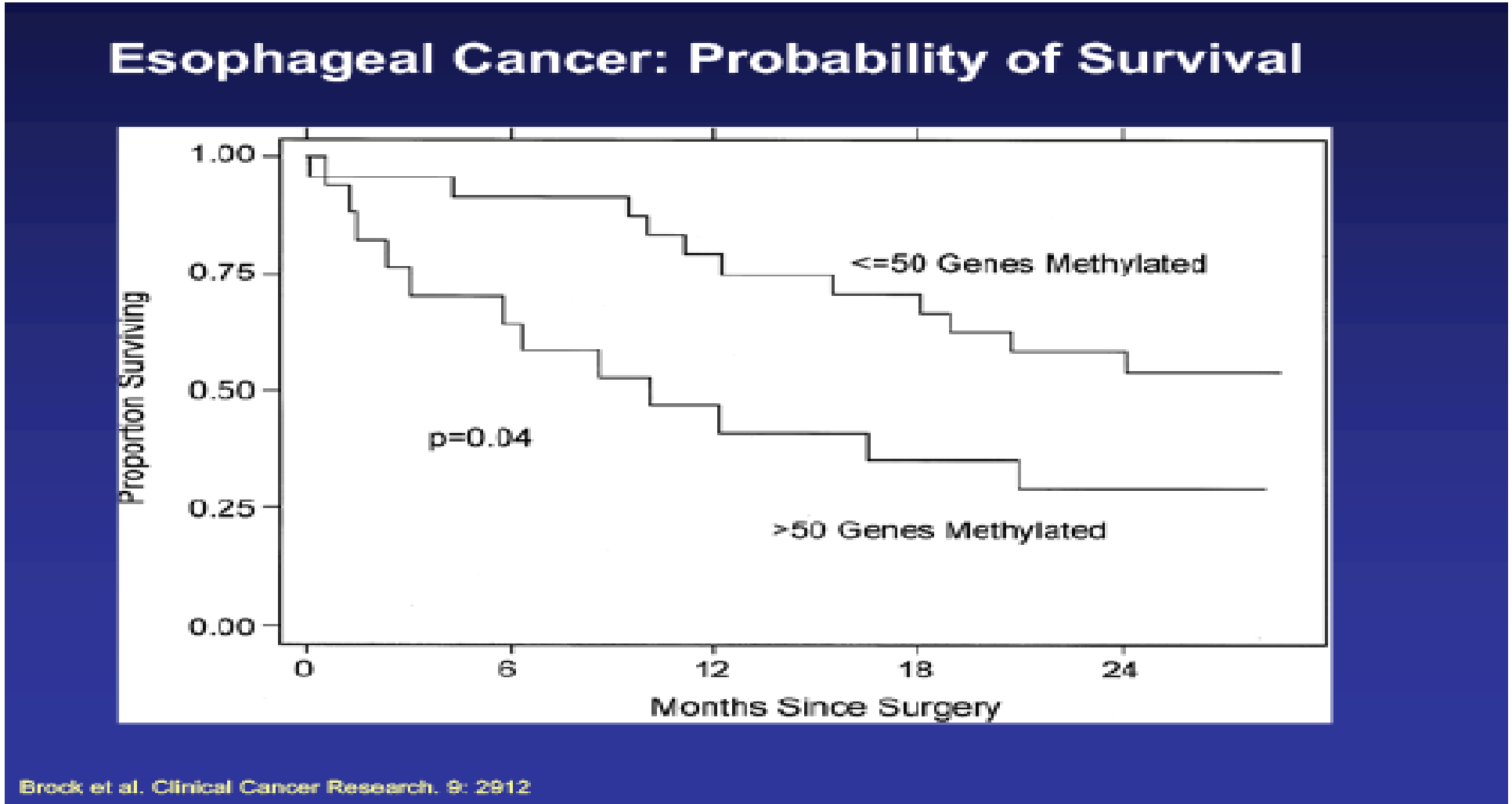
Mesothelioma



Epigenetic pattern



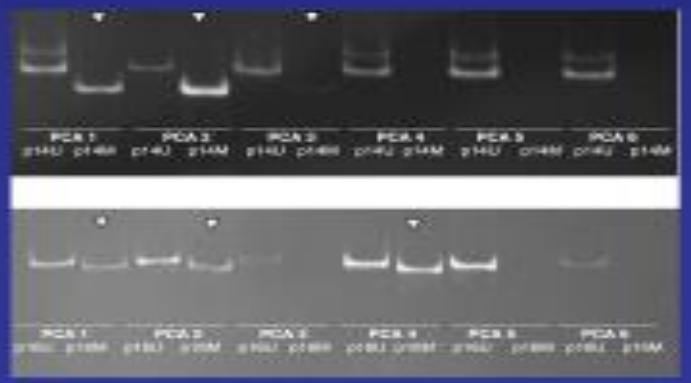
Esophageal cancer

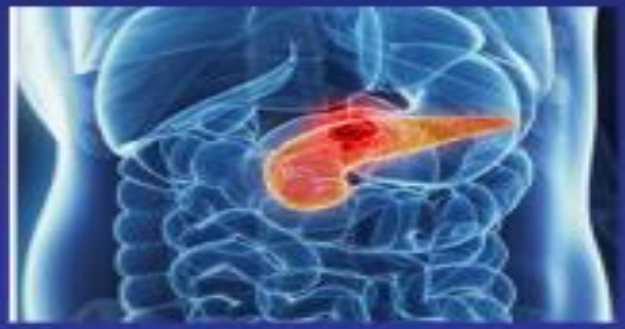


Pancreatic cancer

Pancreatic Cancer: Methylation of p14ARF and p16INK4a

Pancreatic Carcinoma (PCA) : 39	19/39	p16INK4a
Chronic Pancreatitis (CP) : 16	0/16	p16INK4a
Normal Pancreatogram (NAD) : 6	0/6	p16INK4a



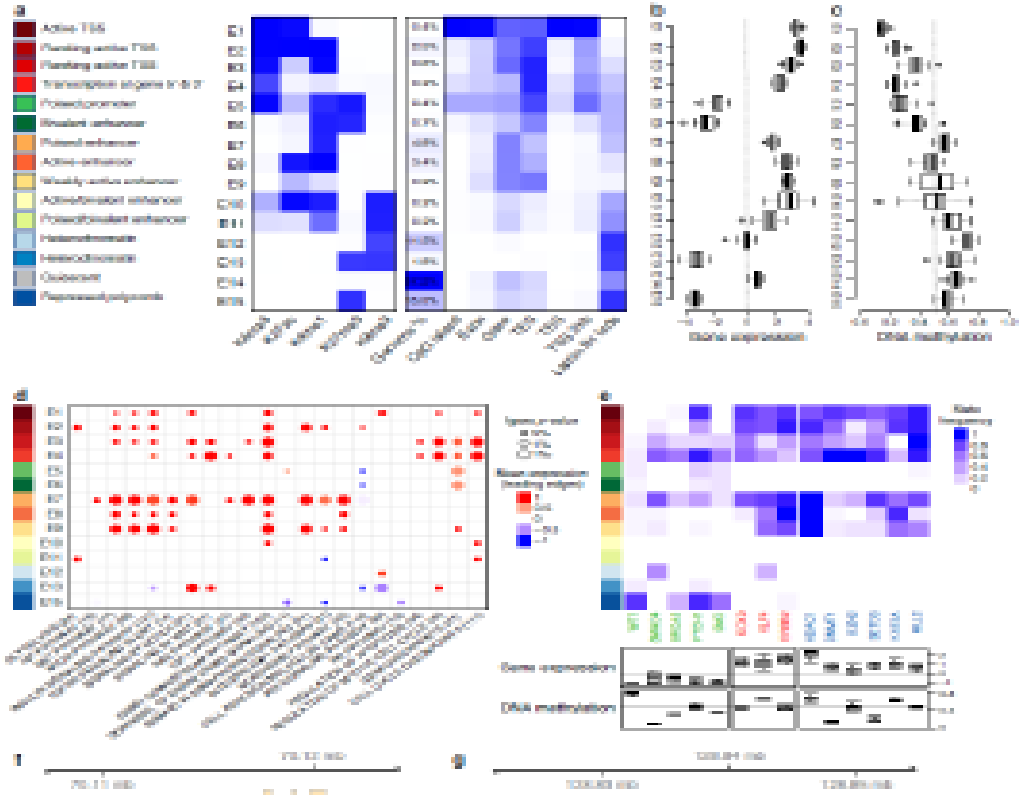


Sample: Pancreatic Fluid

(Klump et al. *Mol Cell Path* 88: 217)

Chromatin states

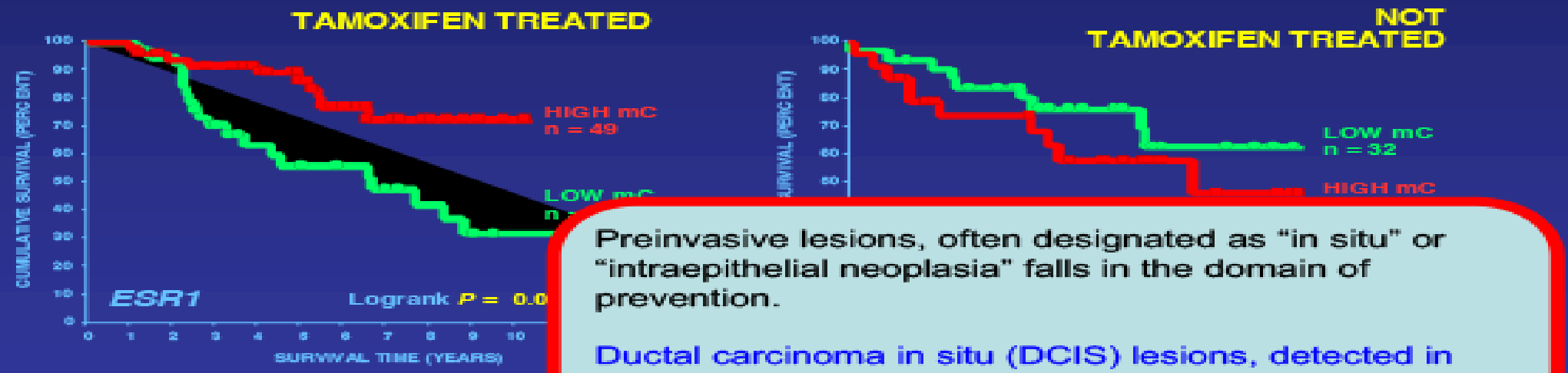
Distinct chromatin states of human PDAC



NATURE COMMUNICATIONS | (2018) 9:1978

Breast cancer

Breast Cancer Response to Tamoxifen Treatment by ESR1 Methylation



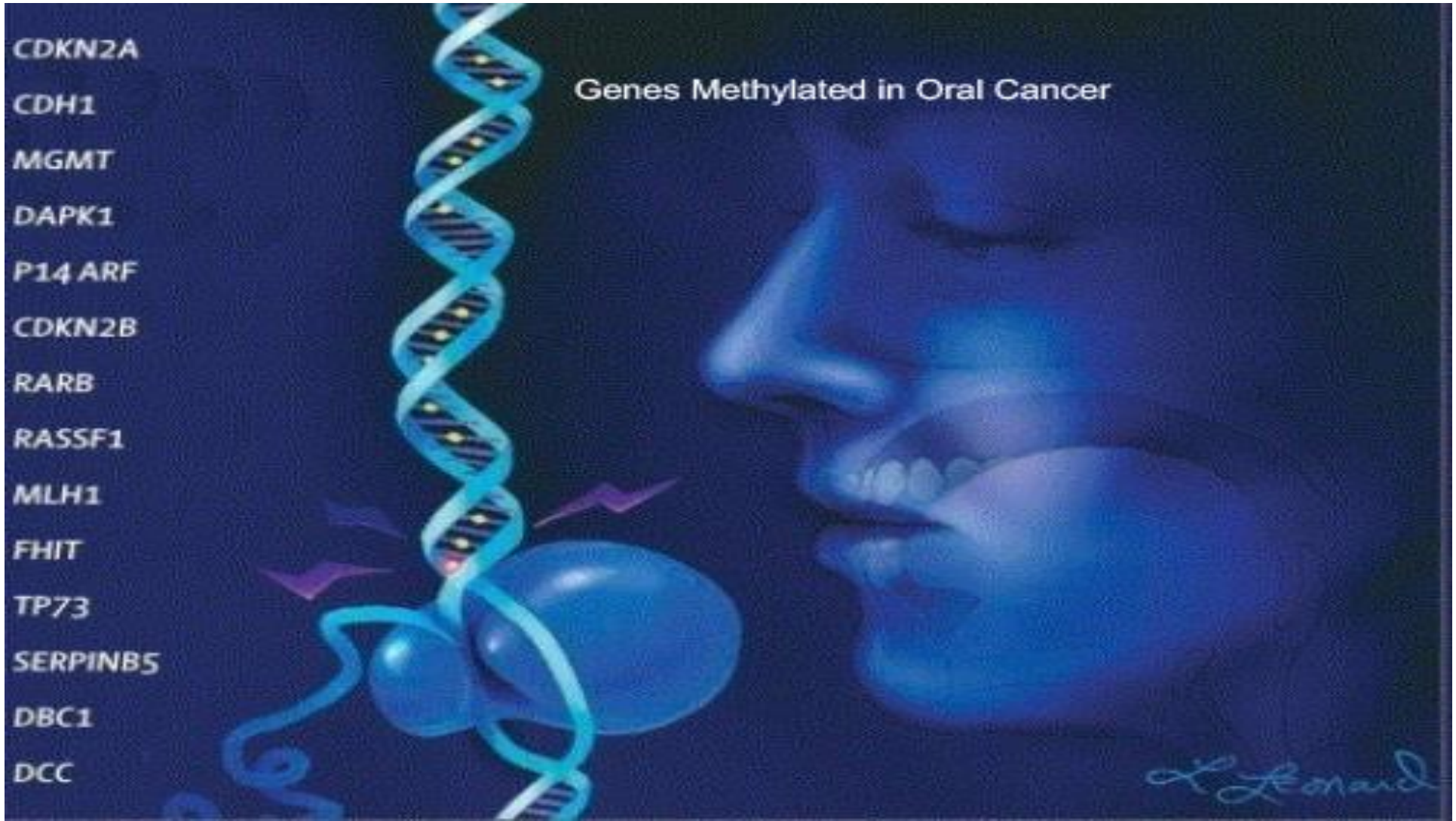
Widschwendter et al. *Cancer Research* 4, 380

Preinvasive lesions, often designated as "in situ" or "intraepithelial neoplasia" falls in the domain of prevention.

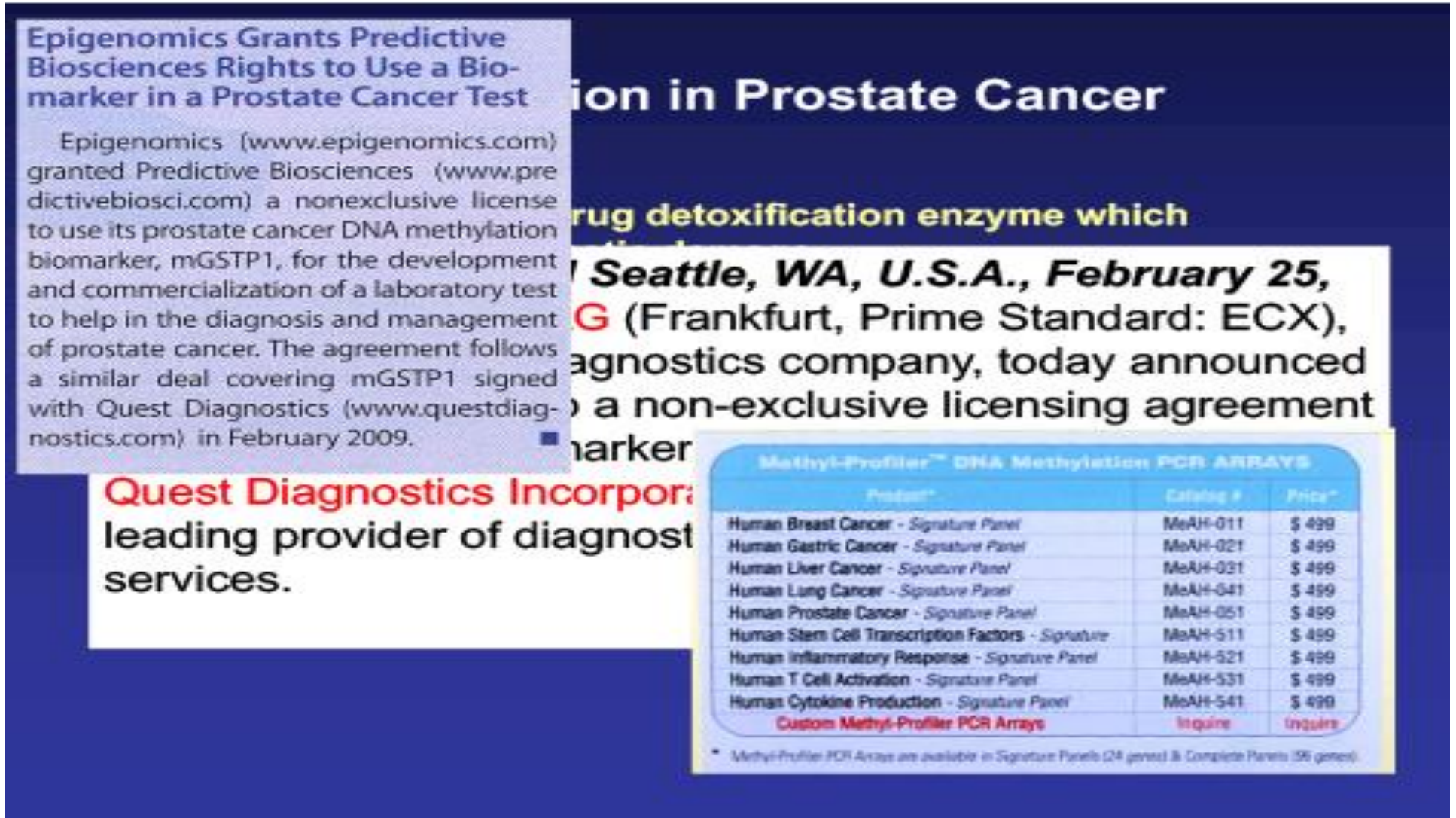
Ductal carcinoma in situ (DCIS) lesions, detected in screening are generally treated aggressively, although all DCIS do not lead to breast cancer (over treatment).

Methylation profiling of DCIS lesions can distinguish aggressive from indolent DCIS.

Methylated genes

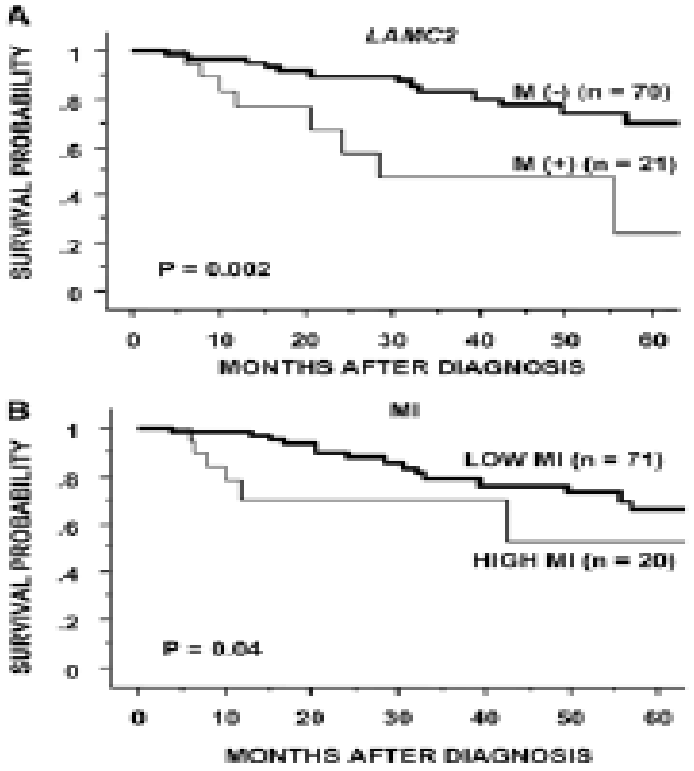


Biomarkers


Epigenomics Grants Predictive Biosciences Rights to Use a Bio-marker in a Prostate Cancer Test
Epigenomics (www.epigenomics.com) granted Predictive Biosciences (www.predictivebiosci.com) a nonexclusive license to use its prostate cancer DNA methylation biomarker, mGSTP1, for the development and commercialization of a laboratory test to help in the diagnosis and management of prostate cancer. The agreement follows a similar deal covering mGSTP1 signed with Quest Diagnostics (www.questdiagnostics.com) in February 2009.
ion in Prostate Cancer
rug detoxification enzyme which
Seattle, WA, U.S.A., February 25,
G (Frankfurt, Prime Standard: ECX),
agnostics company, today announced
a non-exclusive licensing agreement
arker
Quest Diagnostics Incorpora
leading provider of diagnost
services.
Methyl-Profiler™ DNA Methylation PCR ARRAYS
Product* Catalog # Price*
Human Breast Cancer - Signature Panel MeAH-011 $ 499
Human Gastric Cancer - Signature Panel MeAH-021 $ 499
Human Liver Cancer - Signature Panel MeAH-031 $ 499
Human Lung Cancer - Signature Panel MeAH-041 $ 499
Human Prostate Cancer - Signature Panel MeAH-051 $ 499
Human Stem Cell Transcription Factors - Signature MeAH-511 $ 499
Human Inflammatory Response - Signature Panel MeAH-521 $ 499
Human T Cell Activation - Signature Panel MeAH-531 $ 499
Human Cytokine Production - Signature Panel MeAH-541 $ 499
Custom Methyl-Profiler PCR Arrays Inquire Inquire
* Methyl-Profiler PCR Arrays are available in Signature Panels (24 genes) & Complete Panels (96 genes)

Bladder cancer methylation

Bladder Cancer
Methylation of LAMC2 in Exfoliated Cells Isolated from Urine

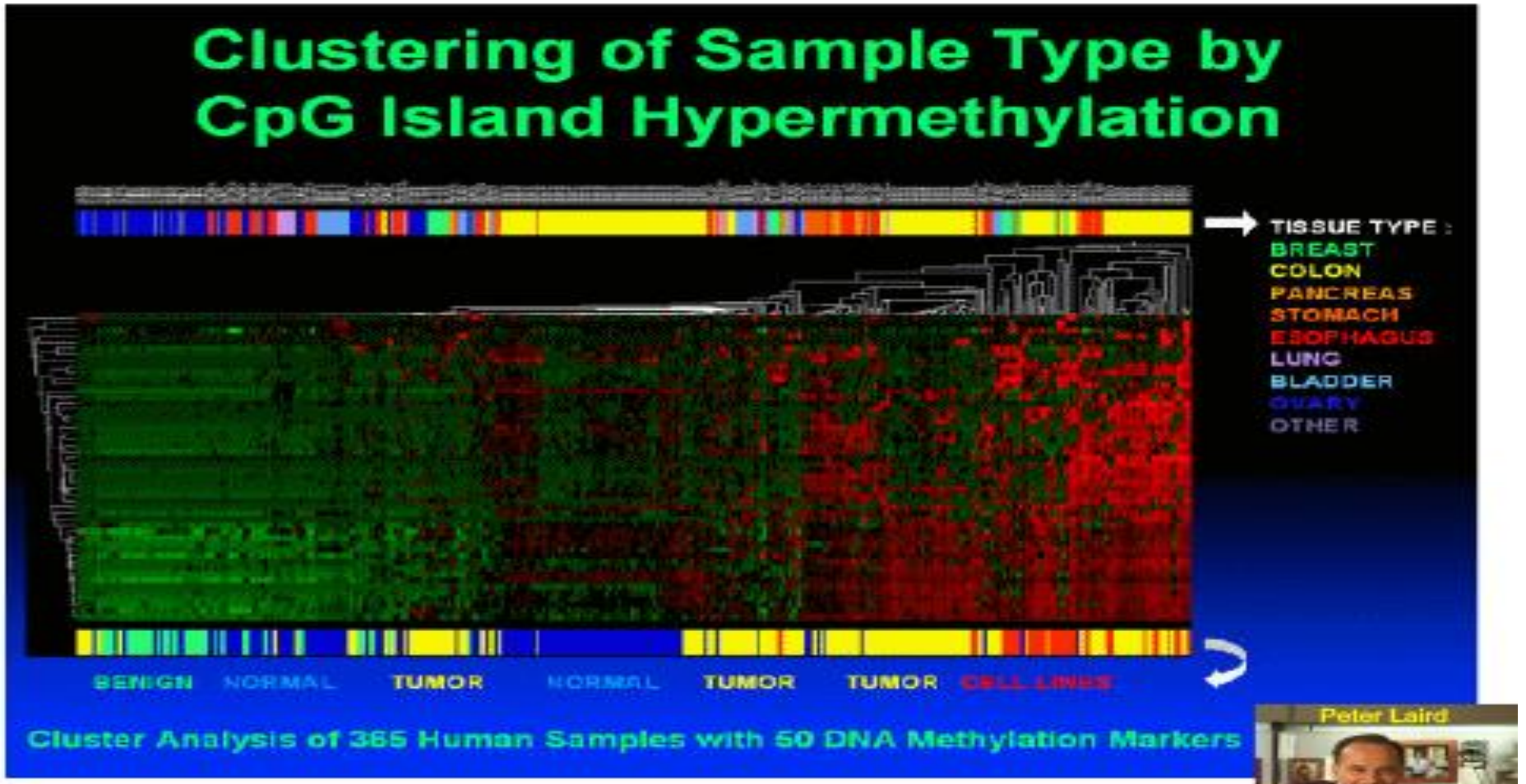


Another Study:
Schistosomes and Bladder Cancer

MI, Methylation Index

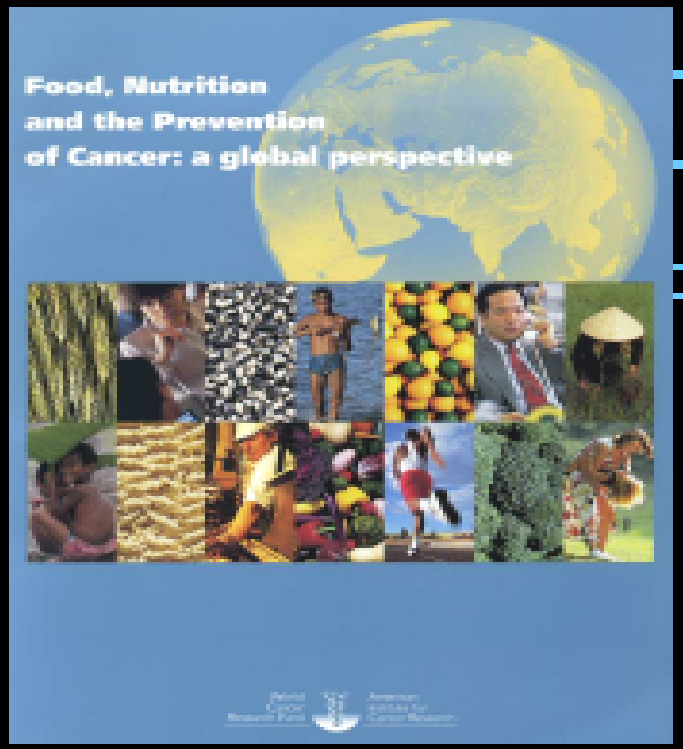
(Sathyanarayana et al. *Can Res* 64: 1425)

CpG island hypermethylation



Diet and cancer

DIET AND CANCER: FOCUS ON PREVENTION

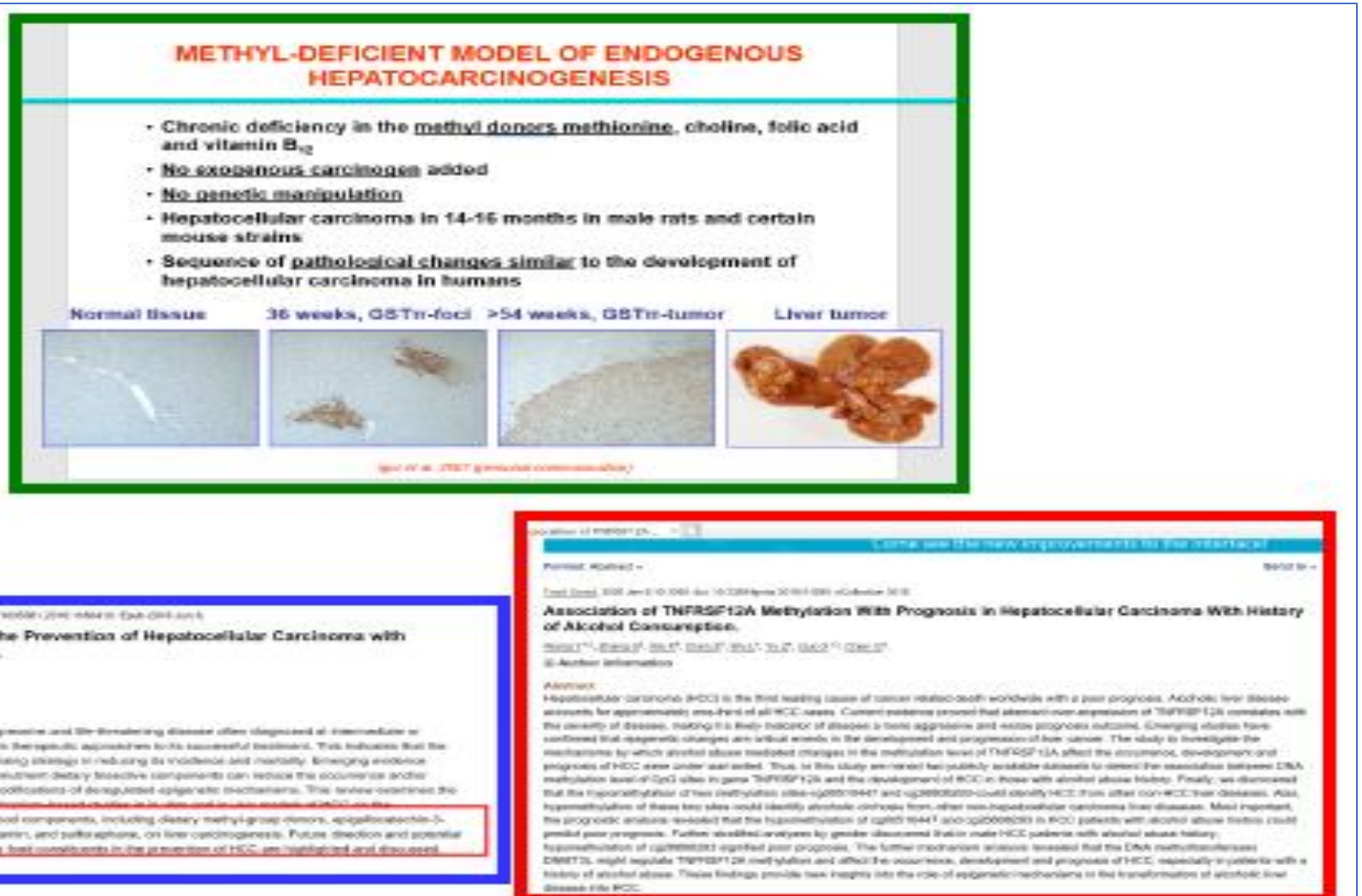


Cancer is principally caused by environmental factors, of which the most important are tobacco, diet and factors related to diet, including body mass and physical activity, and exposures in the workplace and elsewhere.

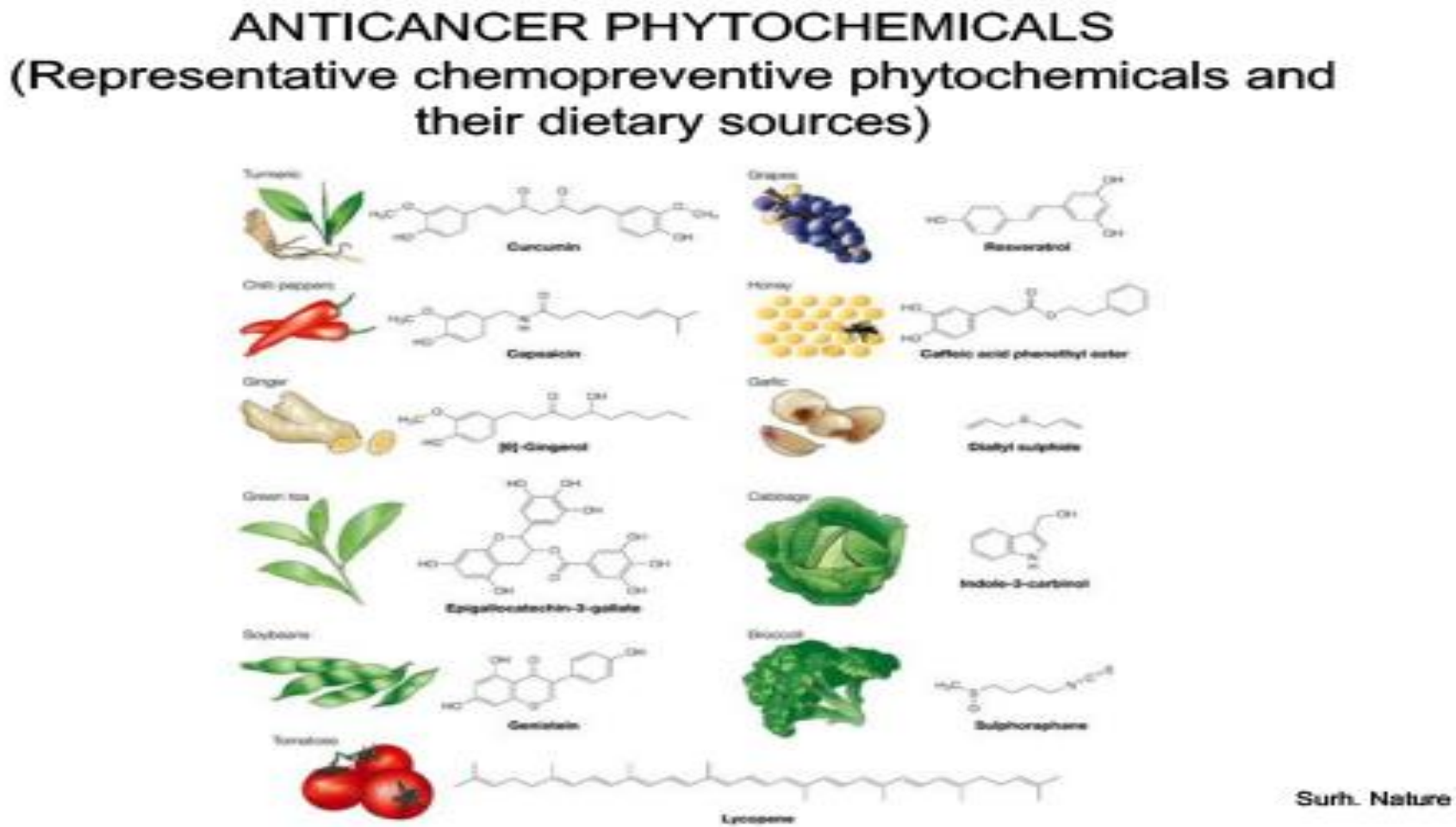
Between 30% and 40% of cancer cases throughout the world are preventable by feasible dietary means.

- Understanding the determinants of the earliest detectable phenotypes in initiated cells
- Uncovering the molecular mechanisms of action of dietary nutrients leading to cancer formation and prevention
- Defining effects of dietary compounds not only on cancer cells but on normal and preneoplastic cells
- Determining factors that can modulate effect of diet

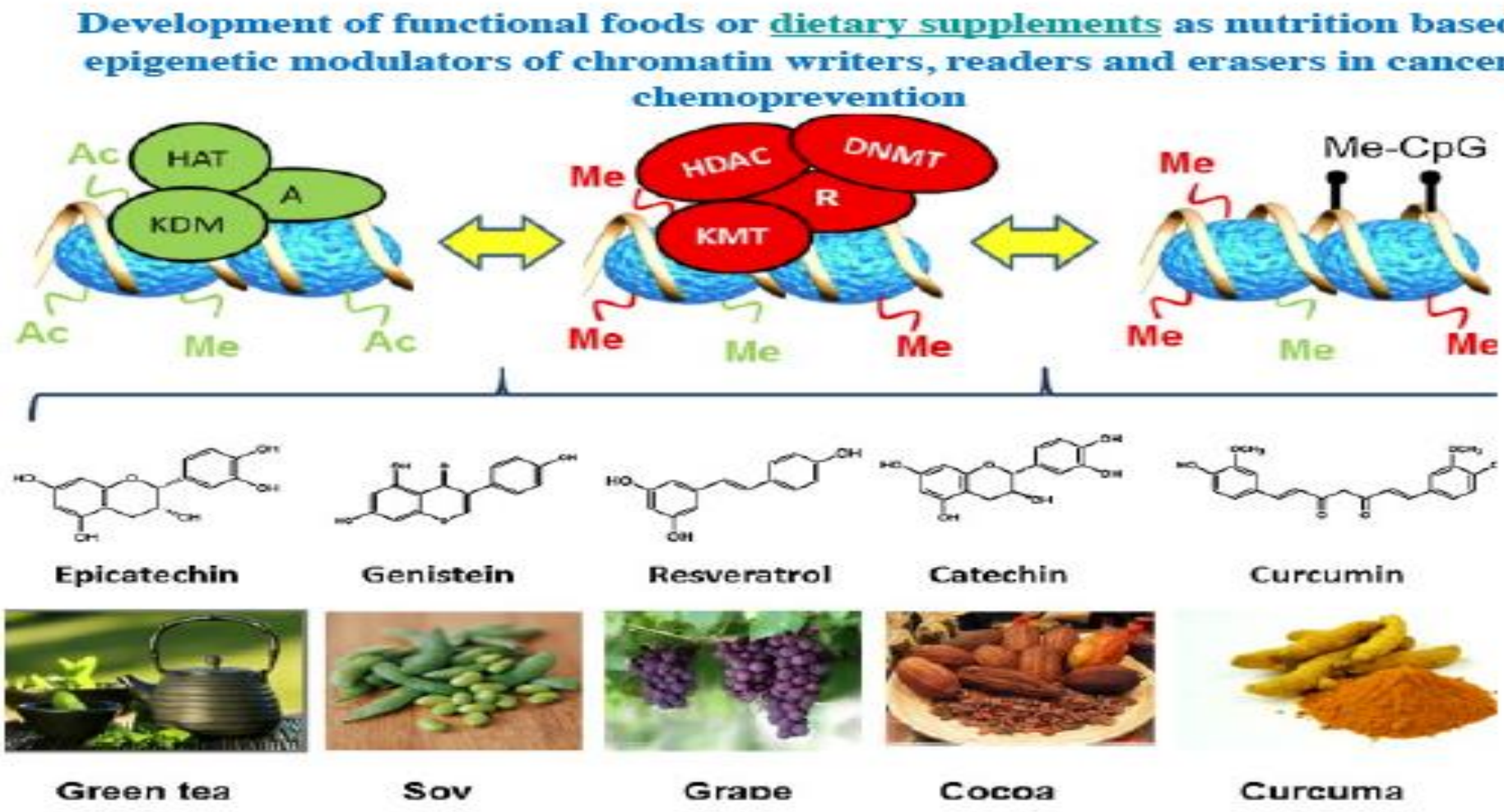
Methyl deficiency



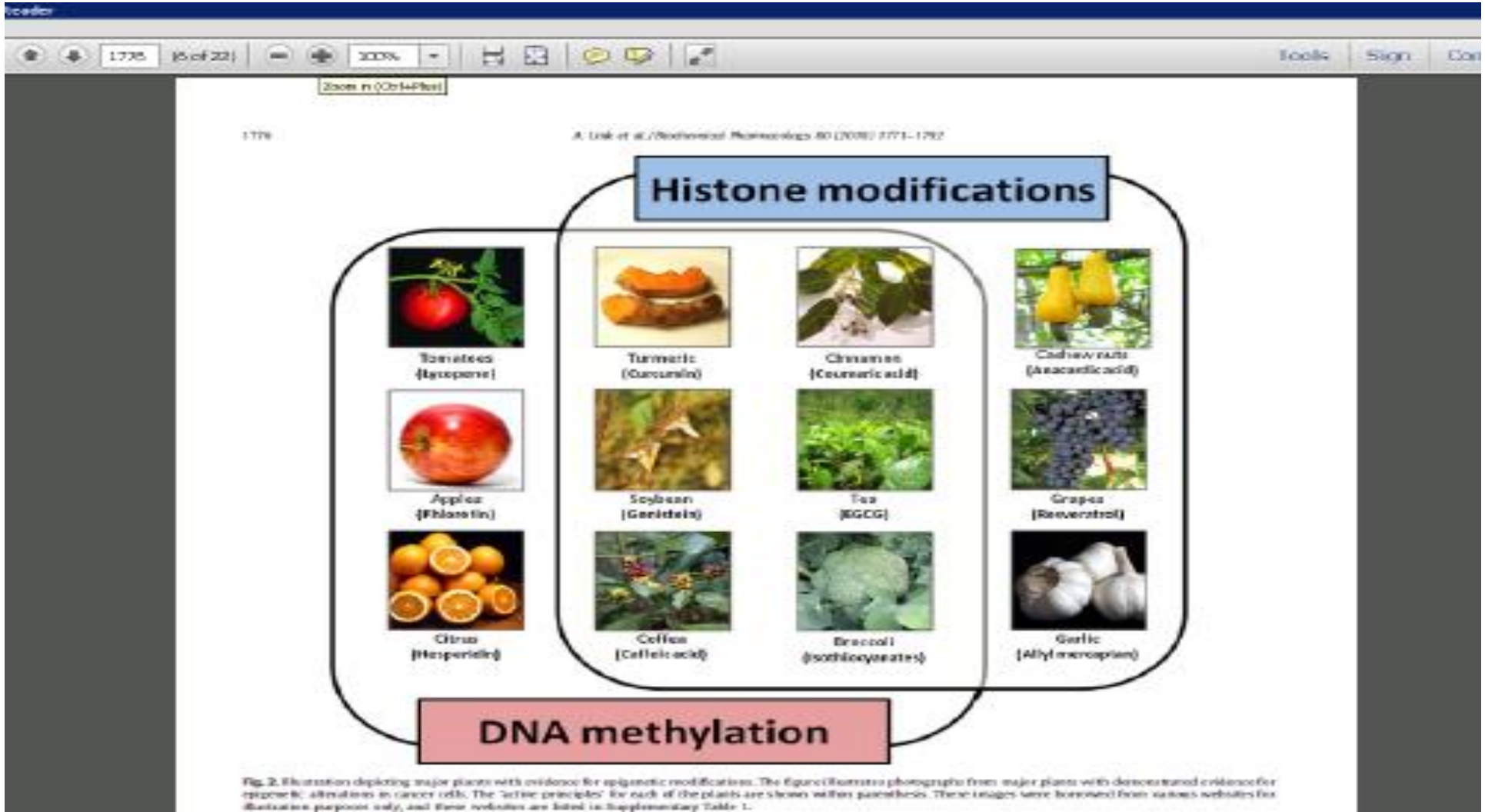
Anticancer phytochemicals



Dietary supplements



Epigenetic foods



Myplate

https://www.myplate.gov/

Mobile food record

Ahmad et al doi: 10.1145/2986035.2986038; (Zhu et al 2022)

Research opportunities

National Cancer Institute

Research Opportunities and Challenges

Will inclusion of epigenetic markers help in identification of new risk factors (modifiable factors and host factors) in different races and ethnic groups?

Will epigenetic markers in cohort and case-control studies improve sensitivity and specificity of markers and help in identifying high-risk populations?

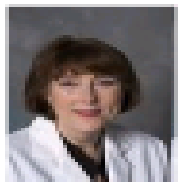
Are genetic and epigenetic events correlated during cancer development?

Are there race/ethnicity specific miRNAs and noncoding RNAs?

How can we use this information for better define cancer subcategories?

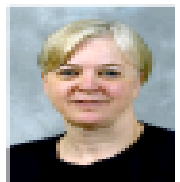
How can we overcome EWAS technical challenges?

Christopher Plass (Heidelberg)

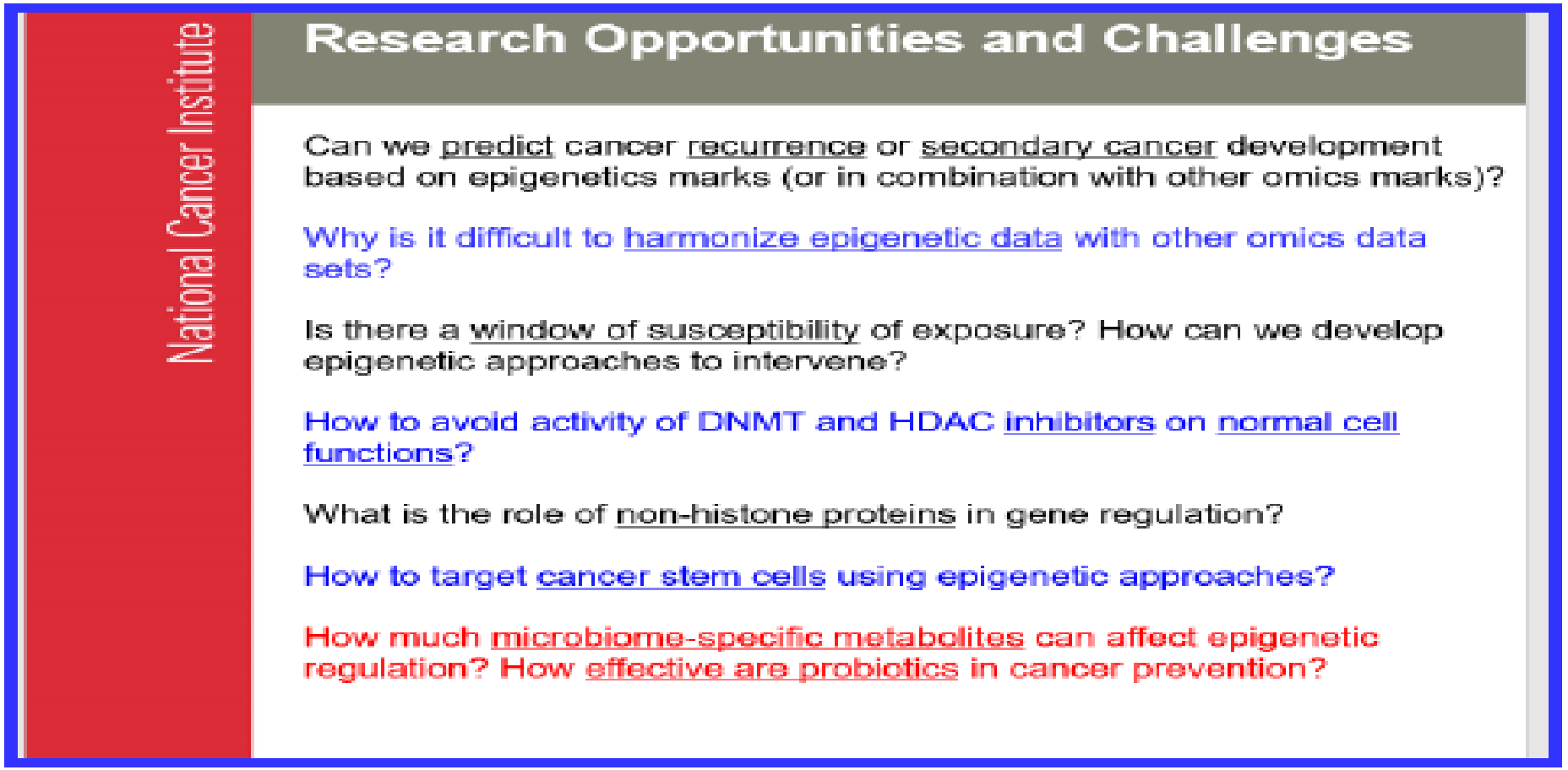


Nancy Kiviat (Seattle)

Christine Ambrosone (Roswell Park, Buffellow)



Research challenges



Conclusions

Conclusions

- **Epigenetic regulation is needed for normal development.**
- **External and internal environment contribute to alterations in epigenetic components and gene expression resulting in disease initiation and development.**
- **Epigenetic changes are reversible.**
- **Epigenetic inhibitors have been used successfully in combination therapy.**